Microdevelopment of Co-construction of Knowledge
During Problem Solving:
Puzzled Minds, Weird Creatures, and Wuggles

by

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Submitted to the Program in Media Arts and Sciences
School of Architecture and Planning
In Partial fulfillment of the requirements of the degree of
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ABSTRACT

This thesis focuses on knowledge construction through problem solving. It analyzes knowledge construction from two points of view. One is the dynamics of the process — the microdevelopment of knowledge construction during a short time span. The other is the social aspect: the way knowledge develops through interaction among people, when they co-construct their knowledge together.

For the study, a situational method was developed: the problem-solving situation was well-structured, yet the task was open ended. The participants were asked to find out whatever they could about the way little Lego robots (called Weird Creatures, or Wuggles) functioned. Each robot-environment incorporated diverse stimuli that inconspicuously affected that robot. Within that problem-solving situation, the participants could construct their own problems and explore the robots the way they wanted.

The microdevelopment of the knowledge the participants co-constructed together was analyzed by using a macrodevelopmental (ontogenetic) theory — Fischer's skill theory. The analysis indicated a microdevelopmental process that recapitulated macrodevelopment. Parallels between micro- and macrodevelopment were analyzed and explained.

The results included analysis of developmental curves within microdevelopment; identification of three types of transition mechanisms; identification of building blocks of the co-construction of knowledge through interaction; a model for analyzing interactions in the process of knowledge construction, and analysis of the nature of knowledge co-construction, suggesting an alternative to the hierarchical, unidirectional model.
The microdevelopmental process consisted of several sequences. In the beginning of the experiment, each new sub-problem generated a new sequence that started with initial knowledge structures. Each sequence had an overall progressive trend, creating a step-like function. However, the sequence was not smooth; it consisted of a bandwidth, or Zone of Current Development (ZCD), within which knowledge structures alternated.

The process of knowledge construction included regressions. The analysis indicated that these regressions were extremely important to make phenomena accessible, to make knowledge more robust, and to create links between knowledge structures constructed at different levels.

The transition mechanisms identified in the study were bridging, differentiation, and reiteration. Bridging served in a top-down fashion by creating a shell, or template, for the next level of knowledge. Differentiation worked in a bottom-up way, starting from existing knowledge structures and elaborating on them. Between half and two thirds of the knowledge structures in the beginning of the experiment used one of these mechanisms. Reiteration was identified in the participants' actions, procedures, and questions; in the social interaction, through repeats that contributed to aligning the participants in their knowledge construction; and in the global organization of the microdevelopmental processes.

For analyzing the co-construction of knowledge, the "ensemble" was suggested as a unit of analysis. Aspects affecting the interaction were identified, as were the building blocks that created the dynamics of interactions. Using these building blocks, a model integrating different theories was suggested. With the model, different types of interactions, with varying degrees of relative expertise and of collaboration can be analyzed. Different degrees of collaboration generate different dynamics; different degrees of relative expertise generate different pathways in the co-construction of knowledge.

The analysis suggested a process of knowledge construction that was neither continuous nor unidirectional. Instead, it included cyclical, discontinuous, and discrete sequences. The process was multi-layered, and consisted of multiple pathways — bottom-up, top-down, and horizontal processes, pathways at times operating simultaneously.

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"Everything in the world has changed
Except our way of thinking."

Albert Einstein
A few years ago, I was sitting in a 3D movie theater. Like other people in the audience, I was wearing special glasses that created the three-dimension illusion. At some point, the movie showed a bird that seemed to fly toward the audience. The bird stayed in mid air, at what seemed to be within my arm's reach.

Amazingly, what I found myself doing, and saw other people do in the audience, is reach out to "catch" the bird. The theater was filled with laughter.

This event intrigued me. Why did we do it? Reaching out to catch the bird was a spontaneous reaction. I did not expect to feel the bird with my hand, of course. In fact, were it a real bird, I would not try to catch it. Why did I do it, then? Why did other people do it?

I also thought of the nature of research in these intricate realms of human thought. Were we all young children, a researcher observing the scene might have concluded that we do not understand yet the 3D illusion. Did the researcher ask me why I tried to catch the bird, I would not be able to explain it. If a similar event were happening not in EPCOT Center, Disney World, but instead in some remote place where an ethnographer studies a different culture, the ethnographer might have come up with a suggestion similar to that of the researcher studying children's thinking.
Yet, in this case, we certainly knew it was an illusion. We were wearing these special glasses in order to experience that illusion. We even stood in line for quite some time in order to experience it. What was going on, then?

This event happened during the summer before my first year at MIT. I have come full circle. I have studied phenomena that are as puzzling and, perhaps, as much fun. I tried to understand people's thinking, realizing that they themselves may not have the answers. I saw people reaching out their hands, spontaneously — not only toward that imaginary bird, but also toward "Weird Creatures" and "Wuggles" — little Lego robots that took an active part in my study. I saw people doing the same in the Epistemology and Learning group at MIT, when discussing several puzzling phenomena, from sliding fingers under rulers to balancing brooms in the air.

My study points at cases in which people respond spontaneously by trying to grasp or touch or explore with their hands phenomena they want to understand. I hope that being aware of this response will not cause the opposite reaction. The aim of this study is to point out how important it is to keep direct routes open between concrete experimentation and learning, between actual actions and discovery, between exploring with our hands and other — "higher" — levels of thinking. Of course we can refrain from touching and from trying out; we can think of phenomena and represent them in our minds; we can exhibit higher levels of thought. Our whole system of teaching is built on this ability. This thesis attempts to show that this is counter-productive; that this may be part of the ills that inflict our ways of teaching.
THE STUDY

This study was not based on one way of teaching or on another. Instead, it explored the ways people construct their knowledge spontaneously, the way they learn when no explicit external constraints are put on their learning process, when no one guides and directs their learning.

The results are described and analyzed throughout the chapters of this thesis. First, the next chapter, chapter 2, gives tribute to the approaches, theories, and studies that nurtured this research. The chapter reviews their different epistemological perspectives and shows how these perspectives were integrated in the present study. It is the integration of these perspectives that generated the specific questions of this research, its method, and the way the results were interpreted.

Chapter 3 describes the methodological approach developed and implemented in this study — the situational approach. The situational approach integrates aspects of ethnographic methods with aspects of experimental methods. It uses the advantages of both, and suggests an additional method for doing research. The chapter discusses the benefits of the situational method and describes the way it was used in this study. Chapter 3 also reviews the procedure and materials used in the present research, the subjects that participated in it, and other methodological issues.

Chapter 4 starts to reveal the results. It discusses the perspective of co-constructionism in the study. The chapter analyzes the way the participants constructed their knowledge, together, through construction of their own problems. The participants set for themselves their own goals, asked their own questions, devised their own activities, and chose strategies through which they solved the problems they created. Chapter 4 analyzes the attributes and the dynamics of the co-construction process.
Chapter 5 takes a closer look at the evolution of this process. It analyzes phases in the participants' co-construction of knowledge. The chapter discusses the characteristics of each phase. In each phase, different kinds of problems emerged. Each phase entailed a different way of negotiating the problems, expressed in the modes of exploration the participants used. In each phase, the participants thought of the problems differently, which translated to different "languages" — different modes of discourse — they used in the different phases. At the same time, the participants used techniques to link these phases to each other and integrate the knowledge they developed in each phase.

Chapter 6 zooms in on the phases. In the chapter, Fischer's (1980a) skill theory is used to analyze the participants' knowledge. The analysis indicates levels within the phases and specifies the nature of knowledge in these levels. Using skill theory, the analysis of the nature of knowledge in the different phases explains why knowledge evolves from one phase to the other, and, within phases, from one level to another.

Chapter 6 analyzes adults' knowledge throughout the process of problem solving by using tools specified by a theory of child development. The leap from the evolution of knowledge during problem solving (microdevelopment — the development of thinking during a short time span) to the evolution of knowledge during the life span (macrodevelopment, or ontogenesis) is not self explanatory. Chapter 6 discusses this leap and the meaning of parallelism between micro- and macrodevelopment, shows how this parallelism can explain two puzzles related to microdevelopment, explains the nature of this parallelism, demonstrates examples from the participants' explorations that indicate this parallelism, and analyzes these examples.

Chapter 7 progresses from analyzing knowledge structures toward analyzing the process. Three transition mechanisms are analyzed: bridging, differentiation, and reiteration. These mechanisms are demonstrated by examples from the study. The analysis indicates the function of these mechanisms and how they operate. Identification of these transition mechanisms and the transitional structures that they generate prepares
the way for analyzing the process of microdevelopment. Chapter 7 continues to lay the groundwork for the forthcoming analysis by discussing problems related to the analysis of free-flowing data and explaining the way microdevelopment was analyzed.

Chapter 8 focuses on the dynamics of the microdevelopmental process. With structures created by the transition mechanisms analyzed in chapter 7 and with the structures defined in chapter 6, five microdevelopmental sequences are analyzed. Four of these sequences are consecutive; in each one, the participants go back to construct initial knowledge structures. In each of these sequence, they start to construct their knowledge structures anew, in relation to a specific sub-problem. The sequences show step-like functions and indicate a "bandwidth" or a "Zone of Current Development", within which knowledge structures alternated at a given time.

Chapter 8 continues to expand the picture with additional cases that shed more light on the nature of microdevelopment. One of these cases is an exploration done by a person who has more familiarity with the domain. The analysis indicates factors that affect the microdevelopmental sequence. Another case relates to the participants' reports on their explorations, reports that skim a microdevelopmental sequence. The third case entails introducing a robot to a "novice". In this case also, the microdevelopmental sequence is followed. These phenomena are analyzed and explained.

Chapter 9 combines the attributes of microdevelopment analyzed in the preceding chapters and characterizes the nature of microdevelopment. An explanation for the microdevelopmental phenomenon is suggested. The chapter compares the findings about microdevelopment in this study with theories and findings of other researchers. On this larger basis, the occurrence of parallelism between micro- and macrodevelopment is explained. The discussion includes a general rule for the occurrence of such a parallelism, explanation for the parallelism, and explanation for the regression that precedes it. That regression, factors determining its extent, the ensuing progression and its attributes, and the interrelations between micro- and macrodevelopment are discussed.
Attributes of microdevelopment found in this study are compared with similar attributes indicated by other studies. These attributes are woven together to characterize the microdevelopmental sequence.

Chapter 9 continues by setting the bottom-up microdevelopmental sequences within a framework of other processes that co-occur at the same time. The chapter presents an alternative to the hierarchical, unidirectional, and linear process of knowledge construction. The alternative model suggests processes that are parallel, multidirectional, and multi-layered. Higher levels of thinking specify target structures which guide the microdevelopmental sequence and oversee cognitive processes at lower levels. Bottom up, top down, and horizontal pathways coexist and serve in the process of knowledge construction.

Chapter 10 and 11 turn to another aspect of the co-construction process: the interaction through which it takes place. Chapter 10 analyzes the techniques the participants use in order to construct their understanding together. The dynamics of co-construction is analyzed, and building-blocks for characterizing it are suggested. The chapter also discusses other aspects in the interactive co-construction, and indicates their significance for the process. The way these factors serve for the creation and preservation of intersubjectivity in the co-construction is analyzed and demonstrated.

Chapter 11 uses the building blocks identified in chapter 10 to characterize different types of interactions. An interaction model is suggested for analyzing different types of interactions in the process of knowledge construction. The model integrates different theories, developed by Piaget, Vygotsky, Bandura, and others, and shows that they all form part of a larger interactive scope. The types of interactions are analyzed and demonstrated by episodes from the study.

Chapter 12 concludes the thesis. It integrates findings described and analyzed in the different chapters, discusses and summarizes the findings, and indicates their implications.
Throughout the thesis, we encounter such reiterations. Uncovering the causality underlying the robots' functioning entailed reiteration that, on the surface, seemed redundant and inefficient. Were such activities performed by children at school, we would have probably disapproved of their activities. Yet the results of this thesis indicate that it is our disapproval that may be at fault; our understanding of the nature of learning may be wrong, as well as our expectations of the way children should perform, and our knowledge of "how they should know" (i.e., how they should learn; how their knowledge should be expressed). Perhaps the problem of our schools emanates from our understanding of learning, not from how children learn in order to understand.

The way the participants in this study created their learning was based on "regression" back in the sequence of knowledge structures. They anchored their learning to actual experimentation with the robots. Regression, which has such a negative connotation, proved to be, in this study, a most powerful and efficient tool for knowledge construction. Regression entailed anchoring knowledge in intuitive ways of understanding. It enabled the participants to access problems that otherwise would have been too difficult to process; it is similar to techniques used by scientists at the cutting edge of scientific discovery. Through regression, the participants could create links between knowledge structures at different levels.

Creating links between knowledge structures constructed at different levels may be most beneficial for understanding. It may also be an inherent need, which is, unfortunately, usually denied by institutionalized learning. Creating links to more primary knowledge structures, by directly experimenting with our hands, may also be a
spontaneous reaction. This may be the reason underlying reaching out to "catch" the 3D bird. Of course we all knew it was not there; but we also wanted to experience it anyway.
PRELUDE TO CHAPTER 2

The study of the way people understand the "Weird Creatures" or "Wuggles" integrates different epistemological perspectives. Essentially, it involves a problem-solving task. A group of people was presented with the Weird Creatures/Wuggles and asked to find out how these robots functioned. As such, the study belongs to a long tradition of problem-solving research. However, the present research adopts several perspectives that differ from conventional problem-solving studies.

The following chapter takes a stroll through the different epistemological perspectives that influenced this study. In the first part of the chapter, these perspectives are briefly reviewed. The second part shows how the integration of these perspectives contributed to form a different point of view. This, in turn, influenced the theoretical framework of this study and the directions it took when investigating the ways the participants explored the Weird Creatures.
CHAPTER 2

FROM INTEGRATION OF PERSPECTIVES TO A NEW OUTLOOK: THEORETICAL BACKGROUND

Following the tune of the prelude, this chapter briefly reviews five epistemological approaches that contributed to this study. Each of these approaches has a special perspective on thinking. The theoretical background of this study constitutes an intersection of these perspectives (see figure 2.1).

Figure 2.1: Five epistemological perspectives that contributed to this study

Problem Solving
Constructionism

Situated contextualized approaches to knowledge

Developmental Sequences - Microdevelopment

Co-constructionism
A STROLL THROUGH THE FIVE PERSPECTIVES

(i) The problem-solving perspective

<table>
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<th>How knowledge is treated</th>
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Different branches of problem-solving research treat the issue of knowledge differently. Some studies focus on problems in semantically rich domains — domains that entail a large knowledge-base (Bhaskar & Simon, 1977), or formal domains, that have a set of rules sufficient to solve problems in them (Larkin, 1981). Within these domains, many studies focus on the differences between experts and novices. Expert and novices differ in their use of the domain-knowledge. They differ in their representation of the problem (e.g., Larkin, 1983; Simon & Simon, 1978); in their recall of problem situations (e.g., Chase & Simon, 1973; McKeithen, Reiman, Rueter, & Hirtle, 1981); in the strategies they use (e.g., Bhaskar & Simon, 1977; Larkin, McDermott, Simon, & Simon, 1980a,b); and in the way they classify problems (e.g., Chi, Feltovich, & Glaser, 1981). For example, when classifying problems and when representing them, novices focus on surface features of the problem, while experts use underlying domain-specific concepts and principles (Chi, Feltovich, & Glaser, 1981; Larkin, 1983).

These studies investigate the way knowledge is used, but not the way it develops. Another approach to problem solving analyzes the way people acquire a knowledge base in a domain. Such studies, for example, indicate successive stages through which people progress, starting with the accumulation of declarative knowledge — domain relevant facts (Anderson, 1983). Still, although such studies analyze the way knowledge
develops, they focus on an existing body of knowledge in a domain. But what are the processes that create this body of knowledge?

Releasing the assumption of pre-existing knowledge base

Another branch of problem-solving research does not assume a pre-existing knowledge base. Instead, studies of this branch highlight the structure of the problem instead of focusing on its content. These studies often explore the solution paths of isomorphic problems, which have similar underlying structure and similar solutions although they relate to different content-areas and different domains (e.g., Gick & Holyoak, 1980). Instead of focusing on the use of domain-specific knowledge or its acquisition, studies in this branch of problem solving research focus on the formation of solution paths.

The formation of solution paths: Well-structured problems

When analyzing the solution paths that evolve while solving well-structured problems, researchers compare the structure of the problem to the way people negotiate it. Most prominent among these researchers are Allen Newell and Herbert Simon. According to their analysis, in a well-structured problem, all possible solution paths can be objectively analyzed and compared to the problem space — the person's representation of the problem (Newell & Simon, 1972; Simon, 1978). The problem solver uses heuristic search processes, such as means-ends analysis, in an attempt to reduce the distance between the current situation and the goal.
The evolution of solutions: Ill-structured or ill-defined problems

Other problems, which do not have a defined structure, are called ill-defined or ill-structured problems. In such problems, the criterion for reaching the goal is less definite, the information needed for solving the problem is not entirely contained in the instructions, and there are no simple legal moves (Simon, 1978). Theoretically, ill defined problems can be as open-ended as a task of composing a fugue (Reitman, 1965). However, many studies of ill-defined problems present the solver with problems that do have a definition, although it alludes the solver. When trying to solve such problems, only a small part of the relevant information is actively utilized in the solution process. Simon suggests that with increasing recognition of attributes of the situation, new elements from long term memory are activated, and the solver’s problem space gradually evolves. However, the processes used to solve ill-structured problems are the same as those used to solve well-structured problems, and can be simulated by a production system (Simon, 1973, 1978).

The problem-solving approach to knowledge construction

Following this path through different branches of problem-solving research, we encountered different views of the process of knowledge construction and of the use of knowledge. We have seen approaches that analyze different uses of knowledge, without focusing on the way this knowledge is constructed; approaches that analyze the way existing knowledge is acquired, without treating the development of new knowledge; and approaches that focus on the way new knowledge is formed, by comparing the solver’s knowledge to an objective analysis of the problem.
In contrast to these approaches, constructionism has a different view of the construction of knowledge.

(iii) The constructionist perspective

Constructionism was developed by Seymour Papert (1980, 1991, 1993). Constructionism builds on Piaget's theory: knowledge is not funneled into the child's mind, by parents, teachers, impressions from the outside word, and so forth. Instead, the child has to actively construct his or her own knowledge. Learning is a process of knowledge construction. This is the common infrastructure that constructivism and constructionism share (Papert, 1991, 1993). Constructionism, though, looks at the way construction that happens "in the head" is supported by "construction in the world" — with construction sets and concrete materials (Papert, 1993, p. 142). Then, constructionism focuses on the different types of construction, on the methods use, and on the nature of the process.

Playful construction: A different kind of learning

The typical process of learning at school has lost many of the attributes of "Piagetian learning" — the process of "learning without being taught" (Papert, 1980). The child learns to talk without deliberate and organized teaching. Learning to talk is a model of a different kind of learning — a model of "successful learning", learning that springs out of the child's inner motivation, that has its roots in the interconnections between the child and his or her living environment.

Constructionism intends to restore the joy of learning. "Children begin their lives as eager and competent learners" (ibid, p.40). However, this joy is later lost.
Playful, fun learning, does not have to be easy. Even cracking a most difficult problem can be fun. Fun learning has to be meaningful to the learner, to empower him or her, to grow in a natural way from the learner's activity. Fun learning is related to activities in which the learners are immersed, about which they care; activities they can create in their own ways, on which they have autonomy. Then, learning can be fun. As one of the children who participated in a project inspired by the constructionist approach said: "It's fun. It's hard fun."

Fractured knowledge versus whole knowledge

The process of teaching and learning at school often does not work. The teacher tries to teach, and the child tries to learn; but something gets broken in the way. The result is "fractured knowledge": the child knows something, but it is somewhat misunderstood; some pieces are broken (Papert, 1984).

How can fractured knowledge be repaired? When children are engaged in situations in which they do more than think about something inside their head, when they can externalize their ideas and see the results, then they can build up the little pieces and put them together. Then knowledge can be repaired; the process produces whole knowledge (Papert, 1984).

The continuity principle

Knowledge that "works" has to be connected to what the learner already knows. It has to be continuous with other knowledge one already has. The continuity principle says that when learning mathematics, it "must be continuous with well-established personal knowledge" (Papert, 1980, p. 54).
Learning environments can supply opportunities to create knowledge according to the continuity principle. This is what Logo does: when manipulating the "Turtle" on the screen, children can draw on their "body knowledge". They can identify with the Turtle; they can bring their knowledge about their bodies and how they move in space into the geometrical space on the screen. Their well established knowledge of "body geometry" bridges from their existing knowledge to formal geometry which they learn (Papert, 1980).

In his story about the gears with which he played in his childhood, Papert says that the gears served as "transitional objects". They became an "object to think with". On the one hand, they represented advanced mathematical ideas, such as groups or relative motion. On the other, they connected "with the 'body knowledge', the sensory-motor schemata of a child" (ibid, p. viii). By this double relationship to the abstract and to the sensory, they could create continuity between new and old knowledge, between formal mathematics and body knowledge.

| Microworlds |

One learning environment that supplies opportunities with the continuity principle is the microworld. A microworld is a little world within which the child can safely explore and experiment. It is discovery-rich, and includes "little nuggets of knowledge have been scattered around in it for you to find" (Papert, 1984, p. 29). As such, microworlds are "incubators for powerful ideas" (Papert, 1980, p. 126).

The microworld is designed to be interesting to people at different stages of development (Papert, 1984). It allows the child to learn in a new way, by exploring, in a self-motivating way. The Logo programming language is an example for such a microworld.
Epistemological pluralism: Multiple ways of knowing

The autonomy that children have within the microworld allows them to experiment in their own style, and construct their knowledge in a way that is meaningful to them. Constructionism accepts the validity of multiple ways of knowing and thinking (Turkle & Papert, 1991). The logical, analytical, hard style of thinking is not everybody's way of thinking. There are other ways, which are as respectable and as valid. In contrast to the hard style, there is the soft style — a relational, flexible, non-hierarchical style. In contrast to the "planner's approach", which advocates a structured, analytical way to solve problems, there is the "bricolage" approach, which is negotiational and contextual (Turkle & Papert, 1991). If people are allowed and are given opportunities to construct their knowledge in their own way, in a way that is meaningful for them, then learning may be both more empowering and more fun.

From constructionism to microdevelopment

Constructionism focused on the nature of learning as knowledge construction and on better learning environments. Constructionism probed into the conditions that allow the learning process to be better, more meaningful, more creative, more fun, and perhaps more natural. It questioned what is wrong in the way our culture structures the process of learning. Constructionism, then, focuses on the basis from which knowledge emerges.

The next perspective is its complementing aspect: these are approaches that focus on the evolution of the process.
(iv) Microdevelopment

**Definition and distinctions related to microdevelopment**

The term "microgenesis" was coined by Werner (1956, 1957) to refer to the unfolding sequence in perception or thinking processes during a short time span, until the relative stabilization of a cognitive response. Others referred to the same process as microdevelopment (Fischer, 1980a; Flavell & Draguns, 1957; Karmiloff-Smith, 1979).

Three distinctions can be made regarding microdevelopment. One pertains to the time scale: microdevelopment involves changes that occur during a short time span, from a second, to hours, days, or several weeks (Werner, 1948, p.37). The other distinction relates to the evolving nature of the process. Microdevelopmental processes should be studied before they become solidified and turn into automatic reactions (Vygotsky, 1978). The third distinction concerns the domain of change. "Microgenesis of thought", in contrast to "microgenesis of perception", focuses on the development of a conceptual response, rather than on conditions in the presentation of a task or a stimulus (Flavell & Draguns, 1957).

**Evolution of knowledge structures during microdevelopment**

Studies that follow subjects' performance on a specific task, often indicate an evolution of strategies and cognitive structures during short time spans. For example, Klahr and Dunbar analyze the scientific reasoning process as a search of two spaces—the hypothesis space, guided by prior knowledge and experimentation, and the experimental space, guided by the subject's current hypothesis (Klahr & Dunbar, 1988; Dunbar &
The scientific reasoning process is characterized by an overall microdevelopmental progression toward better mapping between theory and evidence (Kuhn, Amsel, & O'Loughlin, 1988; Kuhn & Phelps, 1982). During the microdevelopmental process, new knowledge structures are progressively constructed (Lawler, 1981). Their construction is preceded by problems that are not unusually difficult and by a transition strategy (Siegler & Crowley, 1991; Siegler & Jenkins, 1989). An overall progression to more advanced strategies is found in subjects of different populations — normally achieving individuals as well as subjects with learning disabilities (Wansart, 1990). Transition patterns show developmental ordering within age levels: more developmentally advanced children can more easily maintain a strategy that integrates a main goal and a sub-goal (Bidell, 1990). Analysis that focuses on transitions within the microdevelopmental process, often reveals qualitatively different phases (i.e., Draguns, 1984; Karmiloff-Smith, 1984, 1986a; Schauble, 1990).

Microanalysis — the study and analysis of microdevelopment — can contribute to understanding phenomena that otherwise are difficult to detect. Microanalysis is based on high density of observations relative to the rate of change of the phenomenon under scrutiny (Siegler & Crowley, 1991). This attribute allows researchers to identify transitional processes and investigate the mechanisms that promote change (Brown, 1982; Inhelder et al., 1976; Siegler and Jenkins, 1989; Wertsch & Stone, 1978); to trace the development of cognitive structures (Lawler, 1981), and to follow the evolution and modification of subjects' functional models (Inhelder et al., 1980). When studying the construction of strategies, microanalysis allows for identification of "leading indicators" for discovery, separation of the actual discovery from its subsequent use, and detection of
attributes characterizing the evolution of strategies (Siegler & Crowley, 1991; Siegler & Jenkins, 1989; Wertsch & Stone, 1978).

Microdevelopmental data can support certain explanations, raised in macrodevelopmental research, and eliminate others. During macrodevelopment diverse factors influence the individual, yet through microdevelopment some of these factors may prove irrelevant and unconnected to the phenomenon under study (Wertsch & Stone, 1978). Microanalysis, then, may enable researchers to take a new look at macrodevelopment (Karmiloff-Smith & Inhelder, 1974) and compare attributes of microdevelopmental modifications to those of macrodevelopmental change (Karmiloff-Smith, 1979).

From microdevelopment to macrodevelopment

Microdevelopmental studies focus on the evolution of a solution, or learning, or performance on a specific task, and so forth. They follow that evolving sequence during a relatively short time span, and analyze the way it evolves.

Another developmental perspective that influenced this study is the macrodevelopmental (ontogenetic) one — specifically, the study used Fischer's (1980a) skill theory. The leap from microdevelopment to the use of skill theory cannot be explained in this chapter; it takes several of the chapters of the thesis to do so. For now it may suffice that skill theory suggests transformation rules that apply in microdevelopment.
Fischer's skill theory

Skill theory (Fischer, 1980a) explains cognitive development as a series of skill structures with a set of transformation rules that relate these structures to each other. Skills are control structures of behavior that emerge through development in an unfolding sequence.

Tiers and levels in skill theory

Skill theory defines the sequence in terms of tiers (stage-like groupings of abilities) that progress from sensory-motor actions, to representations, and to abstractions. Each tier has a similar recurrent structure consisting of four levels. Skill theory formulates these structures in terms of set theory: since at each level the individual controls sources of variations of actions and thought, each such source is a collection, or a set.

In the first level of each tier, the corresponding skill (sensory motor, representation, or abstraction) appears as single sets that are not connected nor related to one another (see figure 2.2). In the second level of each tier, mapping and inter-relations develop between the single sets (e.g., mapping between means and end). In the third level, variabilities are formed and are coordinated to one another, thus forming systems of behavior. At this level, though, only one system can be controlled at a time. In the fourth level, these systems are integrated into a synthesized unit — a system of systems. This unit of the fourth level is also a single set (first level) of the following tier, which continues to develop in the same sequence of levels.

In figure 2.2, this structure is represented by a single dot (single set), in the first level; a link between two dots (mapping between two sets), in the second level; a plane,
in the third level (a system — coordination of two vectors of variabilities); and a cube (a system of systems — coordination of several systems, or "planes").

**Figure 2.2: Skill theory's recurrent structure of levels**

Fischer (1980a) defines five transformation rules that specify changes with different step-sizes, in microdevelopment or macrodevelopment (ontogenesis). One rule is intercoordination, which combines skills to produce a new skill, on another level. This transformation rule holds in macrodevelopment. For example, intercoordination occurs when two mappings (second level) are combined into a system (third level). Another transformation rule is compounding, in which two skills are combined to form a more complex skill on the same level. For example, compounding occurs when two mappings are combined to form a mapping between three element. Focusing (shift of focus) specifies smaller steps, related to moment-to-moment change. For example, focusing occurs when the child focuses his or her attention first on one dimension, then on another. Substitution involves an attempt to transfer a skill developed in relation to one task to the context of another task. The fifth rule is differentiation. Differentiation applies to separating what initially was one set into two distinct subsets.

The microdevelopmental transformations of differentiation, substitution, focusing, and compounding generate the macrodevelopmental transformation of intercoordination.

The links between skill theory and context specificity are well established. Skill theory explicitly defines knowledge structures as evolving within particular contexts. According to skill theory, skills are always defined by the interaction between a person and an environment: "The sets that describe the skill structures are always jointly determined by the actions of the organism and the environmental context that supports those actions: the organism controls its actions in a particular environmental context."
A similar claim is made by other researchers of the contextual approach.

**(v) Context-dependency of knowledge structures**

**Unevenness of knowledge structures**

In the last two decades, researchers have increasingly acknowledged the importance of the context in which knowledge develops. In contrast to Piaget's conception of knowledge structures that are unitary across domains, accumulated findings of décalage have given rise to the view that unevenness in development is the rule and not the exception (Fischer, 1980a, p. 480). The view of universal knowledge structures has been replaced with a contextual approach.

**Situated knowledge**

The contextual approach sees knowledge as situated in the context in which it develops (e.g., Brown, Collins, & Duguid, 1989; Lave & Wenger, 1991; Suchman, 1987). Knowledge, according to this approach, is based on contextualized reasoning and situation-specific competencies (Resnick, 1987).

Such an approach highlights the importance of both the social and the physical environment. Cognition is seen as directly related to the social context in which it develops (Bronfenbrenner, 1979; Rogoff & Lave, 1984; Vygotsky, 1978). For example, children will demonstrate different abilities in different support conditions — when they act spontaneously or when they get explanations and memory-prompts from adults (Fischer, Bullock, Rotenberg, & Raya, 1993). Similarly, cognitive ability is directly
related to the situational task-related context, objects, materials, and activity. Attributes of objects constrain what people can do with and the meaning they endow these objects with (Gibson, 1979).

Researchers who adopt the contextual approach highlight the influence of context both for learning and development (Brown, Collins, & Duguid, 1989; Brown & Reeve, 1987; Fischer et al., 1993; Lerner & Kaufman, 1985; Rogoff, 1982; Rogoff & Lave, 1984).

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The core idea of the contextual approach, which is adopted by this study, is that knowledge structures are directly related to the context in which they develop. In this view, knowledge is not seen as unitary structures that, due to their generality, transfer from one task and domain to the other. Instead, in different domains, and in respect to different tasks, one and the same person may have different levels of knowledge structures.

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The contextual approach highlighted the context in which knowledge develops. Context has two facets: one, the physical context; the other — the social context. The crucial role that social context plays for cognitive development is advocated by many researchers.
Knowledge construction through interaction

Following the Soviet school, researchers do not see cognitive change as a process that relates to the individual in isolation. Instead, the focus shifts to historical and social origins of thought (Cole, 1985; LCHC, 1983; Luria, 1976; Scribner & Cole, 1981; Vygotsky, 1978). Several aspect are highlighted in relation to the process of knowledge construction: cooperation and interaction (Leont'ev, 1981; Wertsch, 1979, 1984), the function of shared activities (Newman, Griffin, & Cole, 1989; Resnick, 1987; Rogoff, 1990). and the importance of environmental effects on the individual (Bronfenbrenner, 1979; Niesser, 1985; Reed, 1993).

However, when discussing the way social interaction affects cognitive change, different theories portray a different picture.

The Vygotskian School

Vygotsky highlights the importance of interaction between children and adults or "more capable" peers (i.e. Vygotsky, 1978; Wertsch, 1979). In this view, cognitive processes, which are initiated by adult-child interaction, are later internalized by the child (Vygotsky, 1978), in the same way that external speech becomes egocentric and then turns to inner speech (Vygotsky, 1962). Studies in the Vygotskian approach analyze adult-child interaction (Wertsch, 1979; Wertsch, Minick, & Arns, 1984; Saxe, Guberman, & Gearheart, 1987; Rogoff, Malkin, & Gilbride, 1984), intersubjectivity, and the shared meaning that evolves between the child and a more capable partner. Other studies analyze the cognitive change induced by peer cooperation (Forman, 1987; Forman & Cazden, 1985), showing the function of collaboration, shared meaning, mutual support, and exchange of guidance. Researchers indicate the advantages (Forman & Cazden, 1985)
and detriments (Tudge, 1985) of peer interactions, and compare peer versus adult-child interactions (Ellis & Rogoff, 1982; Radziszewska & Rogoff, 1988).

**The Piagetian School**

Several researchers compare the Vygotskian and the Piagetian perspective (i.e. Damon, 1984; Forman & Cazden, 1985; Tudge & Rogoff, 1989; Rogoff, 1990). When considering social interaction, the Piagetian school emphasizes cognitive conflict resulting from interaction among peers (i.e. Doise & Mugny, 1984; Doise & Palmonari, 1984; Murray, 1972, 1983; Perret-Clermont, 1980; Piaget, 1926). Cognitive conflict generates disequilibrium; by assimilating the other's point of view, equilibrium and cognitive restructuring take place. Piaget's followers show that interaction between unequal peers can also bring cognitive change (Mugny & Doise, 1978; Perret-Clermont, 1980). However, according to Piaget, children's interactions with adults usually generate compliance to adults' authority and prevent cognitive restructuring.

**Social Learning Theory**

Social learning theory (Bandura, 1977) focuses on human behavior that is learned observationally, through modeling. What children observe in others further guides their own actions. A model reinforces certain behaviors, and the way the individual thinks of herself in specific environments affects her interaction and cognitive development (Bandura, 1986).
Each of the theories reviewed above suggests a recipe for the way knowledge construction works best within social contexts. At the same time, they all agree on the main theme, which is adopted by this study: the social context has a crucial importance for cognitive development. From infancy on, throughout life, human beings construct their knowledge through interaction with their environments. As children grow up, their environments expand (White & Siegel, 1984) to include more distant environments. But just as the infant constructs his or her knowledge through interaction with the parents (e.g., Schaffer, 1984; Trevarthen, 1977), so do older children, through interaction with their caregivers (Rogoff, 1990).

**THE INTEGRATION OF PERSPECTIVES**

The integration of perspectives in this study created more than the sum of its parts. Each perspective became a lens through which other areas looked differently; each perspective shed a different light on the others.

Constructionism gave a different perspective to problem solving. Unlike most problem-solving research, the participants in the Weird Creatures/Wuggles study did not receive a well-structured problem, nor an ill-defined one. Instead, they were given a context within which they could construct their own problems — their own tasks, goals, activities, and set of rules that guided their activities. The participants learned about each robot by doing, by playing with it, and through their interacting with it. They learned by having "hands on" and "heads in" (Ackermann, 1987, p. 8). Through the constructionist
lens, then, this study explores the way people construct their own problems and, in that way, construct their knowledge.

Through the perspective of constructionism, this study also developed a methodology for exploring the construction of knowledge during problem solving. The situational approach, described in chapter 3, creates for the participants an equivalent to a "microworld" (Papert, 1980; 1984). Within that microworld, the participants are autonomous; they can pave their own paths of activities and learning. Like the Logo microworld, the microworld of the situational approach provides the participants with safe opportunities to experiment and explore; it is discovery-rich, and contains many "nuggets of knowledge" that are waiting to be found. It also supports different levels of knowledge.

The interactional approach painted constructionism in different shades, creating co-constructionism (see chapter 4). The framework of this study incorporated the view that knowledge construction is a social product, and as such it occurs between individuals as much as within individuals (see Vygotsky, 1978). The integration of this view with the area of problem solving and with constructionism created the setting of this study. It was not one individual at the time who was invited to explore the Weird Creatures or the Wuggles. Instead, a group of people explored these Weird Creatures or Wuggles together. They were talking with one another, sharing their understanding, questions, hypotheses, and constructing their knowledge together, through that interaction. Their sharing added another dimension to the analysis of knowledge construction, since their thinking processes were verbally expressed, by sharing them with their partners.

The contextual approach paved the way for yet another approach, which gave the study a twist that completely changed it. In light of the contextual approach, one can understand differences between research findings that, judging by their inherent underlying structure, seem similar. For example, children who could not consider the other's point of view in Piaget's mountain experiment, could do so when the task involved
dolls representing a policeman and a little boy who was hiding from the policeman (Donaldson, 1978). By the same token, adults who could not solve a logic problem, could easily solve a similar problem when it involved familiar materials, like stamps on envelops (Johnson-Laird, Legrenzi, & Legrenzi, 1972).

On the basis of findings of such experiments, it was possible to accept a microdevelopmental sequence in unfamiliar contexts. Such a microdevelopmental sequence was not interpretable if one held to the assumption of unitary knowledge structures. A microdevelopmental sequence would just take to extreme the problem of décalage, that posed enough difficulties to Piaget's theory. However, in light of the contextual approach, a microdevelopmental sequence was possible.

The twist, then, was looking at the co-construction of understanding, in the context of the problems related to the robots, through the lens of a developmental theory. Other findings indicated that while solving problems, the solutions evolve through qualitatively different phases. However, to examine these phases by using a macrodevelopmental tool — the definitions of Fischer's skill theory — gave a different twist to this study.

The following chapters reveal, one by one, aspects in this integrated perspective.
Chapter 2 reviewed the theoretical background of this study. It visited several epistemological perspectives that nurtured the present study. Then, the chapter discussed the way these perspectives were integrated to form the outlook characterizing this study.

Chapter 3 starts with the translation of these perspectives into the actual making of the present research. It describes the situational approach, developed in this study. The situational approach integrates the advantages of ethnographic and experimental methods, and has special benefits for studies with a focus similar to the one presented in this thesis.

The chapter continues with description of the study — the materials, procedure, and task used in this study, the subjects that participated in it, and so forth.
THE SITUATIONAL APPROACH

The situational approach, developed in this study, attempted to attend to two problems. One is related to the use of the "think out loud" technique, often used in problem solving research. The other is related to the dichotomy between experimental and ethnographic approaches. Both approaches have their advantages and disadvantages. The situational approach attempted to build on the advantages of both approaches in a way that can suit problem solving research.

(i) Natural communication in problem solving

Critique of the traditional "think-out-loud" technique

The traditional problem-solving paradigm uses a "think out loud" technique: the researcher presents an individual subject with a problem, and asks the subject to think out loud and verbalize his or her thoughts, when trying to solve the problem (e.g., Newell & Simon, 1972). Critics of the method claim that these verbal reports are distracting and are often delayed (Nisbet & Wilson, 1977; Draguns, 1984). The method, therefore, may
both distort the process and give wrong evaluation for the timing of sub-processes. Clearly, the technique enforces a highly unnatural mode of operation.

An alternative: Problem solving within a social context

The present research sets problem solving within a social context. Subjects who work collaboratively and try to solve a problem together naturally talk with one another. They call their partners' attention to the phenomena they observe, indicate to one another clues for solution, verbalize their hypotheses, and express their questions. Thinking processes are exposed in that way to a larger extent and in a more natural way (Radziszewska & Rogoff, 1988).

(ii) Recasting the experimental-ethnographic dichotomy:
Structured situation and laissez-faire — a situational method

Critique of the experimental method

Several researchers questioned the methodology used in laboratory experiments. Papert (1988/1985) challenged the experimental "treatment" model, which is "based on a concept of changing a single factor in a complex situation while keeping everything else the same" (p. 29). In evaluating certain educational phenomena, Papert maintained that "factors of this kind simply don't work one by one; they work as a web of mutually supporting interacting processes" (p. 38).

McCall (1977) claimed that researchers neglect important issues because these issues do not lend themselves to manipulative experimentation (p. 342). The manipulative experimental methods, in his view, come to dictate rather than serve research questions. For example, adults can learn nonsense syllables, but they rarely do
so in real life. "We rarely take the time to keep our experimental hands off a behavior long enough to make systematic descriptive observations in naturalistic settings of the several dimensions and circumstances of the behavior we wish to study" (p. 336). Furthermore, many important decisions are made a priori, rather than from a base of empirical, descriptive information.

Influenced by the study of animals in their natural habitat, researchers highlighted the importance of the environment — the ecology of human development. Several researchers claimed that the ecology is altered in a significant way by the experimental method. They critiqued, therefore, experimental settings for their artificiality and the distortion they impose on the ensuing behaviors (e.g., Barker, 1965; Bronfenbrenner, 1979; Neisser, 1985).

Increasing recourse to ethnographic methods — the "natural" context

In line with this critique, many researchers currently acknowledge the situational aspect of learning and of cognitive development (e.g., Rogoff and Lave, 1984; Suchman, 1987). As a result, increasing numbers of researchers have started to use ethnographic methods and to study phenomena in their "natural" context — children in the family, students at school, and so forth.

However, family, schools, and the like are social settings, and unlike the habitats of animals, they cannot be considered as natural. Peoples' behavior in these settings are constrained by social conventions and norms. Suppose, for example, that a study intended to compare an experimental school to a conventional one and to evaluate their respective influence on learning processes. In such a case, it would be inappropriate to say that one school is more "natural" than the other. One school may be based on a longer and more established tradition, but in no way is it more "natural". While the critique on experimental methods is persuasive, the answer suggested by the ethnographic
approach seems lacking: prevalence of environments does not make them more "natural".

Instead of focusing on the environment, then, we may want to focus on the process that takes place in it.

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Instead: Focusing on the process

It is a common belief that throughout time, and through a process of natural selection, animals adapt in the best way to their environment. While people also adapt to their environment, their adaptation may evolve in directions that are not socially desired. Since human environments are social constructs, they may be changed (as indeed they have been throughout history). Different environments may trigger different adaptation; in different environments, different social and developmental processes may evolve. Researchers may wish, therefore, to examine what processes evolve in different environments and under different environmental conditions.

For example, studying the way learning develops in different environments — in different kinds of schools, not only those currently existing — may lead to identification of ways to structure schools that are more fit than those currently accepted. Investigating learning processes that evolve under different environmental conditions, then, may be important for increasing our understanding of social processes.

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The core idea of the situational approach

Part of the idea underlying the situational approach is examination of social and developmental processes that evolve in different environments. Ethnographic studies can be performed in existing environments; however, if research wishes to study processes
that evolve in different environments, these environments have to be especially structured for the purpose of research.

However, unlike experimental situations that constrain the range of responses and behaviors, the situational approach advocates for leaving the process unconstrained. When experiments constrain the subjects' behavior, the resulting process may be artificial and distorted. The ensuing behavior may reflect the constraints imposed by the experimenter, rather than spontaneous behavior that might have evolved otherwise. Leaving the process unconstrained, then, is the complementary part of the idea underlying the situational approach.

The situational approach versus ethnographic and experimental methods

The situational approach is neither similar to traditional laboratory experimentation nor to conventional ethnography, yet it combines attributes of both. When the situational approach is applied toward the goal of studying learning processes, for example, a study may devise environments or situations that stimulate learning and then let the learning process evolve, without constraining nor molding it.

Unlike traditional ethnography, the situational approach sets a specific situation and induces certain conditions, in order to elicit social, developmental, or cognitive processes. Unlike traditional laboratory experiments, after setting the situation and the conditions, the researcher lets the subjects act freely (within the given structured situation). Like an ethnographer, the researcher then witnesses (and records) the processes that evolve.
"Ecological validity"

The situational approach may highlight processes in their extreme form, since these develop under specialized circumstances. To gain ecological validity (Brunswik, 1956), further research should examine whether similar processes exist — or can develop — in regular environments and situations. It may be easier to detect such processes, even in a more subtle form, after the situational approach has indicated them, since then the researcher knows what to look for.

Attributes of the situational approach in the present study

The present research (especially phase 2, see below) used the situational approach. The study focused on the way participants explored specific robots. The environment within which these explorations evolved was deliberately planned and well-structured, yet no constraints were imposed on the explorations themselves.

THE EXPERIMENTS

The study consisted of two experiments. The first was an exploratory study; it included more subjects, but less intensive data. The second experiment distilled the method (the situational approach). It involved a smaller number of subjects, and used extremely intensive documentation. These two experiments are described below.
(i) The materials

The bricks

The study uses Lego robots built from specialized Lego bricks (called Braitenberg Bricks, after Valentino Braitenberg, 1984). These bricks were developed in the Lego-Logo laboratory of the Epistemology and Learning group (Martin, 1988; see also Hogg, Martin, & Resnick, 1991). These Lego bricks incorporated sensors (i.e., light sensors — such as sensors sensitive to light above a certain threshold, or sensors differentiating the direction of light; sound sensors, and touch sensors). The bricks included also logic bricks (i.e., 'and', 'or', inverter, etc.), a battery, and a motor. Different wiring connections between the bricks generated varied and complex patterns of movement.

The robots

Different robots were constructed with these bricks. The robots included sensors detecting light, sound, and touch. However, not all robots responded to all stimuli: some of the stimuli activated a specific robot, while others did not.

When responding to stimuli, the robots behaved in strange ways. Each robot was built differently and exhibited a different "behavior." For example, one robot moved forward and sideways toward shadows, and after bumping into an obstacle it retreated and turned around. Another robot was avoiding light and retreating for a while when it bumped into something. A third followed the direction of light, and oscillated quickly on a shadow-edge. Still another robot, which was called by the participants the "wuggling" robot, "wugged" from side to side while moving forward, in response to alternating lights on the robot itself.
The robots' patterns of movements, then, were neither obvious, nor easy to understand. Due to the strange ways in which the robots "behaved", I gave them the nickname "Weird Creatures". In the second experiment, the robots were presented to the participants as "wuggles".1

The robots' environments

In the first experiment, a big room was divided into 6 robot-environments, one for each robot. In the second experiment, a room was divided into 4 such environments. Each environment was about 10'x5' in size.

Each robot was placed in an environment that consisted of objects producing diverse stimuli. Each environment incorporated many light sources. The environments were constructed with boxes, cardboard plates, chairs, and so forth. These were set in ways that generated diverse shadows. For example, cardboard plates or boxes were put on top of other boxes to create "bridges", under which (and in the shadow of which) the robots could move. Some objects created deep shadows while others created shallow ones; some generated sharper shadow-edges, while others did not. In the proximity of the environments, a cassette player was playing a seemingly "background music", which actually, from time to time, produced sounds that activated the sound sensors. Wrapping sheets of plastic bubbles were scattered on the floor around the environments; when the participants stepped on them, they popped and made a sound that activated the sound sensors.

1 One aspect of the results of the experiments was use of animistic mode of discourse. This was apparent already after the first experiment, in which the robots were called "Weird Creatures". The animistic mode of discourse could have been attributed to the name of the robots, although my hypothesis was that it emanated from other reasons. In the second experiment, therefore, the robots were called "Wuggles" — a nonsense word that has a nice "ring" to it. The wuggles were also referred to in plural (they), to avoid the use of 'he', 'she' or 'it'. Indeed, the results of the second experiment also indicated the use of animism. Unfortunately, due to time-space constraints, although this aspect of the results was analyzed elsewhere (Granott, 1991*), it is not included in this thesis.
sensors. Each environment was enclosed by boxes, into which the robots could bump, thus activating the touch sensors.

The robots' environments also included objects that could be used for generating additional stimuli (e.g., flashlights, mirrors to reflect light, objects to cast shadow with, clickers for sound, etc.)

In a corner of the room, there were extra parts, divided into small drawers with labels. In the first experiment, ready-made bases with a battery set on wheels were placed close to the spare parts. The participants could use these bases (indeed, they used them either for building additional robots, or for testing the function of specific bricks). In the second experiment, only the spare parts were included.

(ii) Subjects

The first experiment included 35 adult participants, mostly teachers from elementary schools in the Greater Boston area, who took part in a summer workshop held by the Epistemology and Learning group at MIT. Some of the participants came from other areas (Costa Rica, California, and Hartford, MA). These participants belonged to groups that were affiliated with the Epistemology and Learning group in some way and also participated in the summer workshop.

The second experiment included 8 adults, 4 men and 4 women, who were affiliated with Harvard University. Most of the participants were graduate
students at Harvard Graduate School of Education; one man was staff at the School of Education, and two men were graduate students at the Divinity School.

The subjects in the second experiment were deliberately chosen from the extreme top of the population distribution\(^2\). The subjects who were chosen did not have any special technical background\(^3\).

(iii) The procedure

The first experiment

In the first experiment, the participants were divided into 3 groups, 10-13 persons in each. Each group met twice, on two consecutive days. The duration of each meeting was about one hour and a half (three hours for the two sessions). Each session consisted of about one hour of exploration followed by about half an hour of group discussion. Three participants came for additional sessions or joined other groups for additional sessions (having a total exploration and discussion of four to six hours each).

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\(^2\) As will be discussed in the following chapters, part of the results in both experiments was that the participants first "regressed" in the sequence of knowledge construction. Some of the reactions I received after the first experiments was "who were your subjects?" — attributing the results to the subjects' abilities. The choice of subjects from the high end of the population distribution was intended to show that the results cannot be attributed to low intellectual abilities. In fact, the participants in the first experiments were also bright and highly skilled in their profession.

\(^3\) The subjects were screened before hand. The subjects who were chosen did not have technical background, were not familiarized with the materials, and did not take courses more advanced than high school physics. The intention was to choose subjects for whom the domain of the task (i.e., sensors, robots, signal transmission, etc.) was not familiar.
The second experiment

The second experiment was done during one weekend day. The participants came in the morning, met each other (and had a social "chat" over breakfast). The experiment was done in four sessions, each lasting one hour. There were two short breaks and a longer lunch break between the sessions. The four sessions were followed by a group discussion.

Within a few days following the experiment, each participant had an individual interview that lasted between one to two hours.

(iv) The task

An open-ended, fuzzy task

The task was deliberately fuzzy: the participants were asked to find out whatever they could about the robots and the ways they operated. The open-ended direction gave the participants the freedom to construct their own problems within that context (see chapter 4). No rules nor external constraints were a priori set on their activity: the participants could walk through the robot-environments, choose the robot that they wanted to explore, generate hypotheses and test them. In other words, not only could they set their own problems, but they could also devise the ways to solve these problems. They could choose for their activities their own goals, strategies, and activities. They could also choose their companions — those of the other participants they wanted to collaborate with.
The social aspect of the task

In both experiments, the social dimension of the exploration was left open. Teams formed, changed and reformed spontaneously. The social dynamics resembled more a cocktail party than a conventional experiment. When participants wanted to switch environments, they usually made some parting comments, left, and then joined other participants who were exploring another robot.

The presentation of the task

The first experiment was presented to the participants as a discovery workshop. The participants were invited to experience a process of discovery, which interested them as teachers. For the first experiment, a metaphor was used as a "cover story" for the context of discovery (a spaceship that arrives at an unknown planet and explores what is found there).

The second experiment was simply presented as a study on learning through problem solving.

Development of the situational approach

The first experiment was also an initial experimentation with the situational approach. During the group discussion, in which several people from the Epistemology and Learning group participated, some suggestions were offered to the participants about directions of exploration they might want to pursue. Although these suggestions were
accepted only in one session of one of the three groups\textsuperscript{4}, they were not in line with the situational approach.

The situational approach was more fully developed during the second experiment. On the one hand, the robot-environments were structured in more elaborate and complex ways; on the other, no guidelines, side-stories, or suggestions were given to the participants.

\textbf{(v) Documentation}

| The first experiment |

Most of the first experiment was videotaped by one video camcorder, and a small part of it by two video camcorders. The participants in each group divided into several teams, and there were several activities going on simultaneously. One or even two camcorders could not "cover" all these activities. The data of the first experiment, therefore, include episodes selected by the camera-person out of the myriad of activities that were going on at the time. The recording did not include time code, but the order of the episodes could be inferred from the sequence of the video recordings.

In the first experiment, the audio quality in the videotapes was very low. First, there were echoes in the big room. This was aggravated by the noise that the simultaneous talking generated. As a result, part of the audio recorded during the explorations could not be interpreted. During the group discussions, when usually one person was talking at a time, the audio was intelligible.

\textsuperscript{4} The suggestion entailed using the spare parts to build new robots. Only one of the groups, in one of its sessions, demonstrated a change in activity toward that suggestion. In the analysis of the mode of exploration, in chapter 5, this session was not included, in order to avoid distorting bias caused by that suggestion.
In addition to the video documentation, the data included notes that the participants wrote during their explorations.

The second experiment

For the second experiment, technological solutions were devised to overcome the problems that surfaced in the first experiment. Five - and for part of the experiment, six — video cameras recorded the activities. Four camera-persons were assigned, each to one robot-environment. In addition, one camera on tripod recorded a general view. The sixth camera-person chose and recorded segments of activities. In this way, each participant was recorded continuously throughout the experiment by at least one video camera.

In addition, each participant had a lavalier wireless microphone attached to his or her shirt. The microphones had transmitters, each transmitting on a different channel. The audio of each participant, throughout the experiment, was recorded on a separate audio track.

The video and audio recordings included time codes and were synchronized in the beginning of each hour (all camcorders recorded a time-code displayed on a monitor; it was the same time code that was recorded on one track of the audio recordings). This allowed synchronization of the cameras to one another as well as of the audio to the corresponding video recording.

In this way, in addition to the video recordings, there was a high quality audio recording for each participant. Both the audio and video recordings "covered" the whole sequence of exploration. Since the data was continuous, microdevelopmental sequences of the explorations could be analyzed.
In the second experiment, too, the participants were asked to write notes, and these were added to the data. As mentioned previously, each participant was also interviewed individually after the experiment. These interviews were recorded on video.

(vi) Scoring

There were two levels of analysis of the data. One was more extensive, and referred to the mode of exploration that the participants used. The mode of exploration was analyzed on the basis of the video data, without the audio. All the data from the second experiment were analyzed to infer the participants' mode of exploration (see chapter 5).

The other level was intensive, in-depth analysis. This referred to the microdevelopmental sequences of the participants. Five microdevelopmental sequences were analyzed. One sequence was from the beginning of the exploration of one team (two participants who worked together). The other four sequences were consecutive sequences from the beginning of the exploration of another two-persons team (see chapter 7). The analysis was based on Fischer's (1980a) skill theory, and applied skill theory's definitions to the context of the robots (see chapter 6).
(vii) Validity and reliability

**Validity**

As mentioned earlier, the analysis of microdevelopment was based on skill theory, and applied skill theory's definitions (Fischer, 1980a; Rose & Fischer, 1989) to the context of the robots. Skill theory examines knowledge structures as they are manifested in behavior within a specific context. The theory has been established in different domains, investigating abilities as diverse as mathematical (Fischer, Hand, & Russell, 1984), social (Watson & Fischer, 1980a), emotional (Fischer, Shaver, & Carnochan, 1988), reading abilities (Knight & Fischer, in press), and unconscious thought (Fischer & Pipp, 1984). The validity of skill theory is well established, and the analysis of microdevelopment in this study could build upon this validity.

**Reliability: Mode of exploration**

In the analysis of the participants' mode of exploration, over 46% of the data were tested for reliability. The data were analyzed separately by two judges. If initially there was no agreement between the two judges on a certain segment, that video segment was viewed again by each judge, re-analyzed according to the mode-of-exploration manual, and the analysis was compared again.

The categories for the analysis of the mode of exploration were quite unequivocal (e.g., holding the robot in the hand versus letting it move on the floor). A second, more meticulous check, therefore, solved most of the initial disagreements. After the second check, the agreement between the two coders was 98.9%.
For the analysis of microdevelopment, five sequences were analyzed. Each of these sequences was coded separately by two coders. The codes were then compared and discussed. In cases of initial disagreement, the statements on which the coders disagreed were discussed and re-analyzed. In cases of ambiguity, the video data were viewed again and discussed. Then the coding was re-examined by each of the judges and the codes were compared again. After that procedure, there was 97% agreement on the analysis of statements for one of the pair of participants, and 96.9% on the statements of the four microdevelopmental sequences of the second pair.

SUMMARY

A situational approach was developed for this study. The situational approach combines the advantages of the experimental and ethnographic methods. Like ethnographic methods, the situational approach does not constrain the range of processes and behaviors of the participants. Like experimental methods, it allows researchers to explore possibilities beyond what can be found in social environments. The discussion of the situational approach explained the rationale behind this combined approach.

The chapter reviewed the ways in which the situational approach was used in this study. The study included two experiments. One was an exploratory study, which had a larger number of participants and involved less intensive documentation. The other was an in-depth study, with fewer participants and more intensive documentation. The
situational approach that was partly developed in the first experiment was distilled and more fully elaborated in the second experiment.

The chapter reviews the method used in the study — the materials, procedure, task, and so forth.

When the participants started the experiment, they entered a "small world" that was carefully planned. Within this microworld (Papert, 1980, 1984), the situational approach lets the participants get together with their partners, construct their own problems, and develop their knowledge in their own way. The results indicate that this goal was achieved. If we look at what some participants said during the group discussions, it seems that they too felt what the approach was about:

Donald: "I think the fact that (...) there were lots of different shapes and variety materials and stuff sticking into different places (...) made it really natural to congregate in these little pockets and have your own little space and whatever, and I thought it really facilitated breaking into groups really fast."

(Second experiment, group discussion)

Patty: "I think what was interesting was, what appeared to be so simplistic really proved to be far more complex, and took a higher level of thought processing than what appeared immediately at looking at these things."

(First experiment, third group, first session, group discussion)
INTERLUDE 3/4

PROBLEM CONSTRUCTION:
PROBLEM SOLVING WITH A DIFFERENT FOCUS

Chapter 3 reviewed the methodology used in this study. The following chapter starts to outline, describe, and analyze the results by focusing on the constructionist approach. In the constructionist vein, problem solving gets a different focus. Instead of presenting the participants with a problem, the participants are invited to explore a new, unfamiliar "world" within which they constructed their own problems — their goals, tasks, and activities. Chapter 4 starts to examine general issues related to the co-construction of problems by the participants.
CHAPTER 4

CO-CONSTRUCTIONISM:
FIRST APPROXIMATION TO THE PARTICIPANTS' ENGAGEMENT

Greg: "When I woke up, I was very anxious to get involved in the activity. And I found myself towards the end getting very anxious and itchy about running out of time--"
  (Experiment 1, first group, second meeting; group discussion)

Marvin: "What we had figured out, what we liked was, because it was fun."
  (Experiment 2, fourth hour, toward the end of the experiment)

CONSTRUCTED PROBLEMS

Cindy: "We had a quick division of labor and really just focused, focused, focused on the problems that were unique to our individual situation."
(i) Constructed versus ill-defined or ill-structured problems

Problems that do not have pre-defined solution paths

Many problems have one right answer, and some correct — or optimal — strategies for reaching this answer. In such cases, one can analyze the problem, generate a space of all possible moves, and outline all the ways that lead to the right solution (see chapter 2).

The participants in this study did not encounter pre-specified problems. The problems they encountered cannot be "correctly" construed by an objective bystander who outlines all possible solution-paths. In fact, such problems do not even have well defined solution paths, nor do they allow for a clear definition of the problem itself.

In some of the "ill-defined" or "ill-structured" problems, the researcher gives the prospective solver a vague definition of the problem. However, often these ill-defined problems do have a definition — although, at first, the definition eludes the solver. In contrast, in this study, the problems the participants encountered were unspecified: the participants had to actually construct the problems.

To distinguish between this brand of problem and the ill-defined ones, I call problems like those the participants encountered "constructed problems". When problem-solvers face constructed problems, instead of having to uncover a definition previously constructed by the researcher, they create that definition themselves. In this respect, constructed problems involve a process similar to that of "problem finding" discussed by Gezels & Cskiszentmihalyi (1976).
As indicated in chapter 2, this study was based on a different approach than that usually adopted by problem-solving research. Instead of encountering an ill-structured problem, the participants faced a "well-structured" context-space which allowed them to construct their own problems.

(ii) Well-structured context-space

What is a context-space

A context-space is a micro-environment that stimulates the creation of problems and enables the participants to explore those problems. The materials that constitute the context-space are carefully selected; the relations among these materials are deliberately structured.

The purpose of structuring of a context-space is to facilitate and stimulate the construction of problems by the participants. The context-space materials empower the participants by giving them user-friendly means for exploring the problems which they themselves define. A context-space forms, therefore, a microworld-like environment (Papert, 1980, 1984; see chapter 2).

The context-space in this study

A context-space can be formulated in an abstract way, can be represented on a computer screen, or be made out of concrete objects. The context-space in this study was a concrete physical space — a vast room — which contained the robots and a variety of objects generating stimuli that affected the robots.
The relations among the objects that comprised the context-space were carefully planned ("well structured"): box-made bridges, underneath which the robots were moving, created shadows that activated the robots' light sensors; a seemingly background music activated the robots' sound sensors, and so on (see chapter 3).

Within that context-space the participants could act freely, choose whatever they wanted to do and how to go about it. They could also choose with whom, out of the other participants, they wanted to explore and co-construct their problems, and change partners and problems as they went along.

**CO-CONSTRUCTING THE PROBLEMS**

*Liz: "I have a lot to think about. Particularly to me about (...) the sort of group agenda and the evolution of it into the individual agenda which became a group agenda again in the process."*

(Experiment 2, group discussion)

The participants explored the robots in teams — pairs, threes, or more. The construction of the problem, therefore, was a mutual process. Together, the participants co-constructed the problem and reconstructed it, changing along their way the problem itself, their goals, and the activities as they pleased.
(i) Attributes of the co-construction process

Activity-based, emergent co-construction

Since the problem was not pre-defined, the co-construction of the problem emerged gradually. The participants co-constructed the problem through their interaction with the robots. It was the phenomena they observed that triggered their curiosity and led them to define problems that captured their attention.

During the whole-group discussion that followed the experiments, the participants articulated the way the construction of the problems emerged from what was happening in front of their eyes. Here is, for example, Dorothy's report:

"At first it seemed to go back a set distance. We weren't sure of that...and the three of us did that. It would go forward, hit something, go back a set distance. We'd try setting it back further and it still went back the same distance, no matter how far back we put it."

(Experiment 1, first group, first meeting; group discussion)

Dorothy and her team were intrigued by a strange phenomenon: the robot seemed to go backward a constant distance (although the distance it went forward clearly varied). The group tried to explore whether this, indeed, was the case.

Susan, Beth, and Jane saw that their robot was consistently attracted to the box, which, obviously, did not make much sense to them. There ought to be a different explanation for the robot's movement, they thought. The puzzling "behavior" of the robot generated the problem they set for themselves — finding out the cause for the robot's movement:
Beth: "But it seemed to be attracted to -" / Susan:... "I thought it seemed to be attracted to the box." / Beth: "Box, yea." Susan: "That doesn't make a whole lot of sense (...) and I wouldn't think that would be possible. I was trying to figure out what it was attracted to." (...) Jane: "I thought that light might be reflecting off of the boxes (...) Well, we noticed that, we tried turning off and on the lights to test it ..."

(Experiment 1, second group, first meeting; group discussion)

The puzzling phenomenon, the surface explanation of which did not make sense (attracted to the box?!) triggered their curiosity. It made them look for an alternative, more reasonable cause (lights reflecting off the boxes?) and experiment to test that hypothesis (turning off and on the lights).

Serendipity often was the starting point for new understanding:

Laura: "I got out and I was trying to move out of the way to see if there really was a pattern of how far it was going to go back and forward. When it heard a noise it stopped so I thought -- maybe it was lucky it happened."

(Experiment 1, third group, first meeting; group discussion)

Claire: "In looking at that one [robot], a piece came off the top. So I looked at it. This is not an ordinary Lego. There are little metal connectors underneath which is really funny."

(Experiment 1, second group, first meeting; group discussion)

Other participants had similar experiences: one robot changed its movement when they happened to be standing by and their shadow fell on the robot; another robot started moving differently when they put something in its path; a third changed its pattern of movement when they just passed by, or when they picked it up to examine it:

Judy: "When I was looking at the one that was called the "sun worshiper", it was just going back and forth underneath the top and I picked it up just..."
to see, to start investigating what it looked like, and that's how I got it into the light. (...) So it was accidental (...) I picked it up to look at it more closely. And in picking it up, I noticed it was out of the shadow and I noticed it was running completely differently, and that's what made me look at that for the cause of behavior.

(Experiment 1, third group, first meeting; group discussion)

Involvement, autonomy, and a sense of ownership

The problems did not just emerge out of the external context-space. As the previous examples demonstrate, the participants themselves were involved in the incidents that made the robot "behave" and triggered the problem construction. The problems arose, then, from trying to find out what were their actions that affected the robot, and how exactly these actions affected it:

Judy: "When I covered it up with the bubble sheet, it started to go crazy because it was, you know, it went back and forth and short".

(Experiment 1, third group, first meeting; group discussion)

These constructed problems, then, emerged from the context in which the participants were involved; the problems grew out of the participants' own actions. The participants did not decide to construct problems: the problems popped out when something the participants did or saw triggered their curiosity and made them want to understand what was going on.

Unlike most conventional school situations, constructed problems are not the teacher's problems, nor are they those of a textbook writer; they are not problems imposed by someone else. The participants in this study created their own problems; they had a sense of autonomy and authorship about these problems; they were their own masters. When they entered the context-space, they could go their own way. That is why
each of them could direct his or her explorations according to something that was personally meaningful and interesting.

**Constructional pluralism: Different problems, different goals**

*Liz:* "*Kevin was half-engaged in that idea and half thinking that there was another problem. And I think, for myself, I wasn't learning anything from that. I thought it was an interesting problem that I wasn't interested in.*"

(Experiment 2, group discussion. Emphasis added)

Liz did not deny the validity of Kevin's ideas. She admitted it was an interesting problem. It just was not her kind of problem: it did not interest her.

Clearly, what one person finds interesting may not seem interesting to someone else. Within the same context-space, each person may find different events interesting. As a result, each may want to explore different phenomena and set different goals for his or her activity.

Sally, also reflecting on her experiences, made a comment that tied her interest with her attitude toward the robots:

*Sally:* "*I found myself just deciding whether I liked the creature or not. (...) And I guess that would relate to how (...) interesting it seemed to behave (...) So you're trying to figure out how you could do something and have it respond or not respond...."*(...)

"*It didn't matter so much how much - - why it was working the way it did, but how it was reacting*."

(Experiment 1, first group, first meeting; group discussion)
Sally's comment brings to the fore the relational attitude toward the problem. Sally felt she "liked" certain robots more than others. She was attracted to certain problems because she could relate to them more than she could relate to other problems. What attracted Sally was the way she could — or could not — influence the robot's movement. She was interested in forming interaction with the robot.

Several other participants shared with her a similar attitude. For example:

Susan: "I really wanted to see if I could communicate with it — do something to it so that I get a response. (...) So I guess I kind of got involved in looking at each one to see what I can do to make it react or respond, and once I got it to do something, what else I can do to make it do something different."

(Experiment 1, first group, first meeting; group discussion)

Sally and Susan's comments highlight the relational attitude toward the problem, the closeness to objects, characterizing the soft style (Turkle & Papert, 1991; see chapter 2). Other participants formulated the problem differently, but still in terms of relationships:

Thomas: "I found myself reflecting on my need to have to control these creatures. And also, to think a lot about not the individual creatures but the creatures in relation to each other. (...) It's so easy to see what the creatures want, letting them take the lead is difficult for me. (...) My behavior is a key variable. How much do I want to interfere to control, to experiment?"

(Experiment 1, first group, first meeting; group discussion)

While some participants were involved in the issue of their relation with the robot, others had other interests. As a result, they created different kinds of problems and set for themselves different goals. See, for example, the goal Sam set for himself:
Sam: "I was interested in the creatures but I was trying to develop a system of classification of wheels, gears, sensors..."

(Experiment 1, first group, first meeting; group discussion)

Mary constructed yet a different problem:

Mary: "I was trying to figure out if the variable was speed, time or distance that was making it change the going forward"

(Experiment 1, second group, first meeting; group discussion)

Sam and Mary defined the problem in more objective, logical way; they represent the hard style in Turkle and Papert's discussion.

The context-space, then, allowed the participants to construct the problems that befitted them, problems that suited their own cognitive style. In line with Turkle and Papert's (1991) call for epistemological pluralism, the context-space allowed constructional pluralism. Within the context-space, different participants could construct different problems and set for themselves different goals.

(ii) Weaving different voices into a common tune

Jean: "I wanted to see what the different robots are and work with different people and, umm, try to, I knew that everybody would take different angles, it was like, I was going to hop around and see--"

(Experiment 2, group discussion. Emphasis added)
At the outset of the experiment, Jean accepted the different individual voices of the participants as a matter of fact. She wanted to “hop around” from one participant to another and be enriched by the different perspectives each of them had.

However, although she did benefit from these differences, being exposed to the different perspectives also took its toll:

Jean: "I got over here and it was a little different in having five [persons exploring together]. Well, this is kind of cool because you have all these voices and a lot more input. But then I started getting frustrated because when one person gets a hypothesis, we all have to wait for that person to test it out, and it was like, OK, let's just hurry up and do it. Because it might not be your hypothesis."

(Experiment 2, group discussion)

Co-construction of the problems had a powerful potential when the participants had similar agendas, developed similar hypotheses, and shared a common ground. During the discussion, Donald puts it very aptly:

Donald: "What seemed really odd was that at times when we shared a very similar agenda in terms of the kind of questions that we were really interested in trying to follow, then you know, we could follow that question really well. It was when we didn't share that same question that we had a lot more problem making any kind of progress that was satisfactory to any of us. It was as if we really not only needed to try to make progress in regards to the object we were considering, but also making sure that everybody, that it was progress to everybody that was there.

(Experiment 2, group discussion)
When co-construction does not work: the case of Liz and Cindy

The absence of such sharing, however, could hinder the learning process. The case of Liz and Cindy illustrated that point.

Liz and Cindy had different interests, different learning styles, and — as the enfolding of the episode proved — even different belief systems. No wonder their collaboration did not prove to be too beneficial. Liz first mentioned their difficulties cautiously during the group discussion:

Liz: “At first Cindy and I started working out on this together, and I think we discovered pretty quickly that we were coming at the problem from totally different angles, and I think that it wasn’t very informative for either one of us. Her problem, whatever she was working on, was not what I was working on. And I don’t think we were informing each other very much. And it was fun, but it was clear that I wasn’t taking Cindy anywhere and she wasn’t taking me anywhere and we split up.”

In the individual interview, though, Liz revealed that the process entailed more frustration than fun.

Liz: “I was very concerned with [it] and Cindy wasn’t interested in that at all. And it became very clear that we were a dysfunctional group... I think to both of us. And I felt badly about that. It turns out that she felt badly about that too. Umm... It didn’t stop me from pursuing my own agenda, nor did it stop her from pursuing her own agenda. But we... It was like a convenient thing for both of us, I think, that the machine broke when it did. So we could use that to sort of say ‘Oh, while it’s being fixed, why don’t we just work with another group. We’ll go catch up with somebody else’. Without saying, ‘Look, this isn’t working for us. We don’t work well together.’ Which we didn’t.”
Not that the collaboration between them did not bring any new knowledge. That was not the case. Each of them did learn something through their collaboration. In fact, some of their progress did come from their different learning styles.

Liz, for example, wanted to start by watching the robot, without intervening:

*Liz: "When Cindy came over, she wanted to ... I didn't even want to pick it up. (...) I really wanted to just let it do its thing and I wanted to watch it as closely as I could to see... how, what happened to it. Umm... and so, I think that was my initial take."

In her observations, Liz located the motor, but she was puzzled: "I don't see any electronic connections", she told Cindy.

Cindy did not share the same concerns. She started tinkering with the robot right away. She immediately turned the robot off and on, to Liz's surprise:

*Liz: "It didn't occur to me for a long time that I could turn it off."

When Cindy took the robot, she knocked off part of it. She was not sure where the part came from: "It just fell off". Liz, who wanted to keep track of the current situation without changing any variable first, was obviously upset. However, it turned out that the part that broke loose revealed a secret:

*Cindy: "Look at the little metal thing on here."(...)  
*Liz: "A connector."

The Lego part was a conducting strip. It had a metal base that served as a conductor, thus solving Liz's question where the electronic connections where.

However, in the collaboration between Liz and Cindy, the insights that one brought to the other were extremely rare. The interaction suffered friction. First and
Liz was interested in understanding why the robot moved the way it did:

*Liz:* “I don’t know why it was going straight. I want to see what happens. Yeah, I don’t think it’s very responsive to its environment.”

Cindy, however, did not see much point in the question itself:

*Cindy:* “What would be the point if you knew whether it was?”
*Liz:* “Huh? I want to know if it’s taking in data from the outside because I guess I want to know the process of it.”

After pursuing the exploration for a while, Liz summarized the knowledge she has constructed up to that time:

*Liz:* “OK, so I think what we’ve got is information that’s being processed through this motor then out (...)”
*Cindy:* “You are thinking in such a different way than I am, Liz.”
*Liz (continuing her line of thought):* “--Which turns this wheel, which turns this thing, which connects the energy to that, which takes the energy to that, which turns this big wheel. So that’s the drive power for that wheel...“

But after exploring the structural interconnections of the robot for a while, Liz returned to Cindy’s comment:

*Liz:* “When you say that I’m thinking about this in a totally different way from you, what do you mean?”
*Cindy:* “You’re thinking of it in terms of concrete, this connects to this, that does this, that does this. You’re kind of getting it down to the components of exactly where does the power come from, where is it going to, and what’s the next thing it does, and what’s the next thing it does. I’m thinking of it in terms of more as a whole. If you don’t have this piece it doesn’t work so this piece connects somehow. I guess I wasn’t following
the gears and the chains and... I don't know. What is it that made you want to make a picture of it?

Liz: "Because I wanted to know the path of the power. (...) I wanted to draw it because I wanted to trace that, so that I could actually see how this motion, there was only one thing that made it move, is its motor. But the whole machine moves because of it. So how come? And that's what I was tracing. (...) See I want to know about what makes it wuggle."

However, this issue, as Cindy said later, did not really interest her:

Cindy: "It doesn't really interest me which belt connects to what belt and which gear connects to which gear. I guess..."

Liz: "That doesn't interest you."

Later, in her interview, Liz referred to that point:

Liz: "I think the things that I was saying and my interests were really frustrating her. Her response was frustrating me. It was like: What the hell are you interested in? Well, I'm really sorry I'm interested in this, but I am! I don't know why."

Yet Liz and Cindy continued to explore the robot together for a while. About half an hour after they started their collaborative exploration, Marvin joined the two of them.

When presenting their robot, Cindy made a declaration that shed light on the source of the problem:

Cindy: "I don't believe in physics. Let's just start with that."

Liz: "And I do believe in physics."

Cindy: "So it makes perfect sense to me that every time you pick it up and put it down it will do something different. I don't believe in Physics."

That, of course, pulled the rug from under any collaboration. Cindy and Liz had different belief systems altogether. While Liz was intrigued by the changing patterns of
the robot's movement and was looking for the causes that generated these changes, Cindy could not care less. For her, the changing movement of the robot was not perplexing. Just as a person could once go to the right and the next time to the left, so could the robot. Therefore, it made perfect sense to her, as she said, that each time the robot will do something different. Of course, in that case, she could not see the point in the questions Liz was asking.

The group discussion and the interviews revealed another layer of the differences between the two, relating to the inner subjective meaning and the sources of their approaches. During the discussion Liz hinted at the reasons that, for her, made this issue so important:

*Liz: "I have a basic insecurity about being able to understand machines. And I sort of trained myself to think that I can, even though I'm insecure (...). So I wanted to find the motor and the drive shaft and then how was that motion, that turning motion translated to the motion that went into the wheels that made it go around. And I was really, that was really my first focus and that's what Cindy was totally uninterested in. But that was really important for me to believe that I could."

In her interview, Liz went into more details, explaining her personal background. Her story revealed the deep personal meaning she attributed to understanding the robots:

*Liz: "I had a sense of not being an electronically savvy or mechanically savvy human being. My... um, I have three older brothers and my father... they all know how to fix cars and paint houses and lawn mowers... He was always... my dad was always knocking down walls or remodeling the house, you know. There was a real sense of... um..., physical prowess. They knew how to deal with the world and with the things... with the physical stuff of the world. My dad was a professor of education and I, when I became a teacher, I took courses from him at our small college that he taught at in a small town (...) that I grew up in. And uh... he taught me a mathematics methods course and a science methods course. Both
courses were very hands on (...). We would be working on error, we're working on air, we're working on electricity... we would take them [the experiments], demonstrate them in front of the class and raise questions about them like what kinds of things were going on, trying to explain stuff. So there was a lot of experimental stuff. So, it's like I got from him the sense of dealing with stuff, but there was always a kind of a.. a. subtext for me of inadequacy in dealing with the physical stuff. And so there's... I have a sort of underlying agenda of proving to myself, which probably translates to proving to other people as well, I think I'm ultimately proving it to my father that I can do this stuff. You know, that I could figure out, I could figure out how a car works and how to make it work and how to fix it if I had the time or the inclination... It's not that I can't. I want to be very clear of that in my own mind. (...) So this is a... um, there's an ongoing tension about this kind of thing for me. I think a lot of people in my school environment recognized... they think of me as somebody who is very competent with this stuff. Probably even intimidatingly competent and confident about this stuff. Whereas my internal representation is really not there yet. You know, I continually have to work really hard to get basic level competence and understanding.

Cindy, indeed, saw Liz much like Liz's colleagues at school did:

"She [Liz] seems to have a very good grip on these things. (...) I believe that she comes from a position that she can figure this out, and I come from position that I can't."

In her interview, Cindy said she did not feel comfortable with sciences.

"I knew that I'd be very much at a loss, and I'd probably not be able to figure it [the robot] out. Because I have troubles with things like that."

When comparing her interests to those of Liz, Cindy said:
"I guess that I never thought that I would understand like when you switch it on where the power comes from and how the power makes anything move, but that you switch it on and it does move was more what I was interested in.

Apparently, within the realm of scientific inquiry, Cindy could feel more comfortable with characterizing phenomena, but she did not believe she could uncover their reasons. She thought she could describe them, but not explain them.

"And I don't think - I know that I wouldn't be able to figure it out how why if you switch it on it would move this way, I mean the gear would turn in one direction and not the other direction. I mean... Question: "Why do you know that you cannot figure out such things?"
Cindy: "Well, basically, because (...) I don't really...it's sort of philosophical/religious. I don't really believe in it, in laws of physics and things. I mean, (...) planting things in rules and laws doesn't really interest me very much. And some people I think get a lot of satisfaction of it."

Like Liz, Cindy's style and interest were deep rooted in layers of inner meaning and world view, in philosophical/religious beliefs, as she said. Cindy did not believe in "planting things in rules". Constraining things within laws and rules, which was other people's way of putting order in phenomena, did not satisfy her nor did it interest her.

As a result, the interaction with Liz was for Cindy more annoying than she revealed during the group discussion:

"She [Liz] was looking for something different, and I thought that what she was looking for is really the thing we are supposed to be looking for, so I wondered how I'm going to last all day. And that was part of that, that it seemed to be very absorbing her to do that, and it wasn't that absorbing to me."
Liz was worried about the negative feelings that such an interaction may arouse.

During the group discussion she said:

Liz: "Because I think there was an initial sense in the morning when I was working with Cindy, my immediate thought was sh-t, I'm too, I'm too engaged with mechanics here and I know why, and oh, well. But there was really a sense of, you know, this is inevitable that I'm going to be doing things differently from other people and piss them off and it troubled me."

In the past, Liz has learned to work alone in order to pursue her own interests. There seemed to have been only two mutually exclusive options for her: working with others and giving up on her own interests, or following her own agenda and working alone:

Liz: "I like to sort of follow my own agenda... I know I have my agendas and I know that they're fairly particular and so I, so I like to just work alone. But in fact, when there are people around, I like to work with people. And so I'm quite willing to abandon my agenda in order to do what people are doing. But then I do end up with a feeling that I didn't follow my own agenda all day."

Liz seemed to be worried that the third option — working together and pursuing her own interest — created a dynamics that was socially unacceptable. The group discussion, though, alleviated those apprehensions. It made her feel that the group accepted the differences among people. It became clear that in this setting each person could pursue his or her own agenda without offending the others:

Liz: "I think actually the talk, this talk is actually very helpful (...) I think it just makes, it just reaffirms the conversation that it was OK to, I don't mean [addressing to me] by your rules, I mean by our rules, by the inter
relationships in the group, to have their agendas and to deal with them differently."

Liz had to construct the norms and the meaning that the particular group (i.e., including myself) gave to behavior in that specific experiment.

Liz was not the only one that had to construct the meaning-in-context that the group endowed behavior. The mini-culture that was created in this experiment differed from either that characterizing conventional learning situation, or that characterizing traditional psychological experiments. Since the instructions were general and did not define the constraints on the activity, the participants had to construct by themselves not only the problem, but also the "rules of the game".

(iii) Co-constructing the "rules of the game": Self-imposed constraints

*Herbert: "I was thinking: This is an experiment. Some things aren't cool to do and some things are cool. So what are they? It was a gradual process of working through that."

(Experiment 2, group discussion)

The directions I gave the participants in the second experiment were: "Find out what ever you can about these wuggles and how they function." These directions were open ended. They left more unsaid than said. There were no instructions specifying what the participants could or could not do.

Yet, even though I did not impose constraints on the activity, the constraints were there. They were in the participants' own minds; they were based on their previous experiences, on their cultural-based expectations.
Herbert had the worse lot in this respect. Herbert was unfortunate enough to go to
the breakfast table for seconds just before the activity started. Although he was back in
time, he was certain he had missed the directions. When Jean joined him, he asked her:

"So let me get this straight. All we're supposed to do is to figure out what
makes it work?"

(Experiment 2)

Since Jean's response was a bit ambiguous, Herbert continued:

"My initial thought was that everybody knew something I don't already,
like when I went to the bagel counter and they told everybody."

Later, Herbert wanted to take off the robot a piece that covered a sensor and
looked like a smokestack. He started doing it when he stopped to check with Jean
whether it was within the "rules of the game":

Herbert: "No smokestacks." [He takes a "smokestack" off the top of one of
the bricks but then replaces it again].
- "Are we allowed to pull it apart?"
Jean: "Yeah, I like tore the whole other one. I dropped it."
Herbert (jokingly): "On to the next one!"

Herbert and Jean continued to experiment with the robot for a while. Jean took
one brick off the robot and they tried to reconnect it in different locations. Later, when
Herbert took the brick off again, he suddenly asked again:

- "Are we allowed to take it all apart?"
Jean: "Yeah, I don't see why not."
At that point, Herbert and Jean were not sure whether the robot responded to light or to heat. When they put a hand above one of the bricks, which, they assumed, was the sensor, the robot responded. But it could have responded either to the warmth of the hand or because the hand blocked the light. To isolate one of the variables, they wanted to create shadow by an object that would not generate heat. Jean looked at one of the boxes near them and said:

Jean: "Is there a box--"
Herbert: "Are we allowed to use any of this stuff?"
Jean: "I don't see anybody making any rules here."

They put the robot in the box and used one of the flashlights that were scattered around to test the robot’s response to light. Disquieted about their liberal use of the surrounding materials, Herbert started asking me:

"Are we allowed --"
He stopped, turned to Jean, and checked with her:
"Are we allowed to ask questions?"
Jean: "Do whatever you want."

With this confirmation, Herbert turned again to me and asked:
"Are we allowed to use anything around here?"
Nira: "Sure."

Throughout the continuation of his exploration with Jean, Herbert kept checking the rules. About twenty minutes after he and Jean started their collaboration he asked her again what the assigned task was, and proceeded to ask me the same question. Later he asked Jean whether it was OK to turn on the music in the cassette recorder, which by that time stopped playing. To his following "rules" question, Jean answered:

"I don’t know why you’re into so many of these rules. I mean, you can do whatever you want.”
Herbert was clearly preoccupied with the rules of the project throughout the morning session. His question to Donald later, during the group discussion, disclosed it again. Donald commented:

Donald: "I think in the morning, every group in the morning was basically explaining the phenomenon. We were basically exploring what was going on ..."
Herbert: "With the machines or with the project?"
Donald: "With the machines."

Donald was talking about trying to find out what was going on with the machines — the robots — but for Herbert the question was also what was going on with the project, the experiment itself. The discrepancy between the non-constrained activity in this experiment and the conventional learning and experimentation situations threw Herbert off because he believed he missed hearing the rules. He had a double mission: the one, shared with all other participants — related to the robots, and the other — in which he believed he was singled out — to discover what everybody had heard and he had missed.

Jean: The benefits of a robot's breakdown

It is ironic that Herbert collaborated at the time with Jean. Or perhaps not so: were he to have collaborated with someone who shared with him his concern for rules, perhaps the issue would have received more attention, clarification, and gotten out of the way. But, as it happened, Jean did not share with Herbert that preoccupation.

Before joining Herbert, Jean worked for a few minutes with Ann. In these first minutes of the experiment, she accidentally dropped the robot, and it completely fell apart. No major disaster; she and Ann simply got another robot.
Jean: "I think one thing that helped me was when I dropped the robot and (...) and I was OK that, I didn't wreck this thing [the experiment]. And I was, OK, well, here's another one. So I'm like, well, you can do pretty much anything if you can destroy the thing on the first touch."

However, like Herbert, most other participants were concerned about the constraints in the activity. Although there were no explicit external constraints, unknowingly, they assumed — or constructed — some self-imposed constraints.

Self-imposed constraints are tricky. We all have them, yet they are often invisible to their beholder. It was the encounter with other groups that highlighted for some of the participants their own self-imposed constraints.

Marvin and Kevin: Changing the wires! A wonderful idea!

Kevin and Marvin, who worked at first as a team, eventually split up. Each of them joined another group. It was the activity of the other group, then, that highlighted for them a self-imposed constraint they had not been aware of.

Marvin: "I came over to this corner and (...) Jean showed up over there and she was changing wires. I was like, oh, we get to do that! This is a wonderful idea!" (...)  

Kevin's experience was similar:

Kevin: "Going to the different groups, I really did find things that I wouldn't have done... I wouldn't have switched the wires if I hadn't seen other people doing it and I wouldn't be approaching different individual parts. If I hadn't seen people doing it, I would have sort of worked on it as a whole, and probably left it as intact as I found it"
Kevin later said he was extremely amazed to see that other people were changing the wires. Keeping the robot intact, without destroying it, was for him such a basic underlying assumption he did not even stop to question. The possibility of changing the wires did not even occur to him before he joined another group and saw others doing it.

**Cindy and Herbert: We just kept taking it further and further**

Invisible self-imposed constraints became apparent as the activity unfolded. Herbert, for example, went a long way from trying to uncover the hidden rules:

*Herbert: “And gradually it was an elimination of constraints that had been, like projected constraints, perhaps. It was an elimination of what we couldn’t do, in the end we just, there was a moment and I think we made, Cindy and I made contact on that we can do whatever we want.”*

Cindy expressed how she experienced that transition:

*Cindy: “I think that we all had sort of an idea of an experiment and that there was (...) and I guess we imposed constraints on ourselves about what we could do with it and then gradually it became clear that we could do anything we wanted. And then it became a case of, well, let’s think of an idea and wait until she [referring to me] says no. So we just kept taking it further and further and I think that’s what made, for me, it was a really fulfilling experience especially in the afternoon because I think that what Herbert and I hooked up to was that we needed some kind of context other than just the machine and figuring out how it works.”*

Cindy and Herbert chose to do something that did not fall under my own hidden definition of what the experiment could possibly included (definition I was not aware of, of course). Cindy and Herbert ended up developing an animation project. They took one of the robots apart and used its parts as building blocks. With Lego bricks and gears of
different sizes, Herbert constructed an animation device. Cindy drew pictures for the animation. Occasionally they consulted each other. Later, reflecting on the experience, Cindy said:

*Cindy:* "I feel really lucky because I don't consider myself to be really scientific and (...) I just can't get the interest (...) and say well, this gear turns this wheel and this turns this way and the motor goes on that way. And I just, so I was really glad to be involved in a project where skills that I had could be applied to making the toy. Like Herbert was really into making the mechanism and I was really interested in making the pictures and putting them on the ... so that was really fulfilling and from time to time, I'd get a question like, well, how can I connect these two pieces, and I won't (...) have to think of the whole science of it."

*Herbert:* "I found that our project in the afternoon went in a really happy way. That it was sort of a specialized division of labor and at the same time it was a cooperative venture where I could ask you [Cindy] about how the machine works and you could ask, well should I change the picture this way or that way. (...)"

*Cindy:* (...) "I felt really comfortable solving the problems with the mechanism and I felt really comfortable with solving the problem of how the picture was going to go together, and how fast (...) it should move, and how many frames there should be."

(Experiment 2, group discussion)

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**Shedding the self-imposed constraints**

As the activity unfolded, each of the participants gradually constructed the social code that applied to the specific situation of the robots' exploration. Gradual construction of a sub-culture's social code is not unique to the present experiment. What was unusual in this case was the discrepancy between the attributes of the specific situation and the
participants' expectations. The relative scarcity of constraints on the activity in the current situation, compared to the norm in similar situations (of learning or experimentation) highlighted the self-imposed constraints and the gradual construction of the context-specific social code.

It is interesting to note that the issue of constraints took center stage in the second experiment, but less so in the first one. As mentioned in chapter 3, the participants in the first experiment were part of a summer workshop conducted by the Epistemology and Learning group at MIT. When these participants started the experiment, they already were familiar with the constructionist approach. A learning situation based on activity, involvement, and personal interest and less so on outside constraints fell, therefore, within the range of their expectations. This was not the case with the participants in the second experiment.

The appropriation of the context-specific social code was a co-construction process. It tapped all the resources available to the participants: watching their partners, talking with them, asking deliberately for directions and indications — in fact, using every hint in the events they participated in, and relying on every clue they could get from their environment.

During the experiment, Marvin started a collaborative exploration with Jean, and shed the constraint of leaving the robot intact. Kevin joined Ann and Donald, and cast off the same constraint. Herbert and Cindy started a long collaboration, through which they gradually departed from the initial activity, abandoning all self-imposed constraints. It was an evolving process, through which the participants gradually reconceptualized their task, finally saying:

*Cindy [to me]:* "In terms of making our own goals, (...) you sort of made it clear to us that whatever our goals were, were OK with you."
(i) **Intra-individual transformations**

Earlier in the chapter we have seen that different participants had different interests which translated to different goals and differences in their constructed problems. A shift of perspective to the dynamics of the process indicates intra-individual transformation as well as inter-individual differences.

**An ongoing change in goals**

During the robots' explorations, as the activity went on, many participants kept setting new goals for themselves:

*Betty: "I looked upon it as a great big puzzle, and I wanted to see what the whole puzzle was and then (...) I was pretty systematic about taking each part of the puzzle and seeing each part ..."

(Experiment 1, first group, first meeting; group discussion)

In the first meeting, Betty wanted to see first the whole picture — all the robots that were scattered in their environments. To achieve this, she set herself a sequence of sub-goals, each taking "part of the puzzle" — one robot — and exploring it for a while.

In contrast, in the next session, she deliberately wanted to set for herself different goals:
"I tried not to do what I did yesterday. I tried to investigate different ones differently, even though I did watch for quite a while before I selected which one I was going to play with yesterday."

In her second session, Betty had a two-step goal. At first, she wanted to watch without intervening. Then, after finding out what the robot was doing on its own, she wanted to intervene, to make changes, and test her understanding:

"This time I just wanted to watch and see if I can figure out what happens. And that's exactly how I discovered how it went forward in the light (...) After I was sure that that's what it did, then I could intervene and start changing to make sure that my hypothesis was correct."

(Experiment 1, first group, second meeting; group discussion)

A change in approach

During the group discussion, the reports of other participants also revealed the intra-individual change they were going through. For some, the change was mainly a change of approach. Such was the case of Sam. In the first session, when comparing his approach to the problem to that of other participants, Sam said:

Sam: "I approached it differently. (...) Nobody thought about the atmosphere, (...) friendly or unfriendly --"

(Experiment 1, first group, first meeting; group discussion)

In the second session, though, his approach changed:

Sam: "I approached this as a dissection thing -- We tried to change the variables on it. (...) I would like to know more about the electronics behind it."

(Experiment 1, first group, second meeting; group discussion)
A change in activities

The changes in goals and approach translated to the kinds of activities the participants chose to undertake. For example, Dorothy who, in the first session, was trying to figure out the pattern of movement of the robot, chose a different activity in the second session:

*Dorothy: "We decided that rather than do a dissection, to try to clone it. So we ended up not really taking it apart except accidentally (...) We tried to build another one. That was after we watched it for quite a while. (...) So we spent most of our time figuring out connections, what worked and what didn’t work and I found it very enjoyable and I felt like we worked really well on that."

(Experiment 1, first group, second meeting; group discussion)

At times, the ongoing change stirred up the social fabric.

(ii) Inter-individual transformations

*Liz: "We started designing problems as a group which was working really well for a while, and then there was a break, and when we came back after lunch it seemed like we were ending up with, again, different agendas."

(Experiment 2, group discussion)

Changes in social constellations

When the group Liz was talking about ended up with different agendas, the group disintegrated: a few participants left and joined another group. This was not an uncommon incident: throughout the exploration, participants were moving from one
group to another, from an exploration of one robot to another. The dynamics of co-construction underwent, then, many transformations through the changing group configurations.

Changing groups was one of the means the participants used to direct their course of activity. Different group constellations brought about different foci and different activities. In this way, the changing group configurations affected the process of co-construction.

The benefits of regrouping

The process of co-construction benefited from the grouping and regrouping. Earlier in the chapter we have seen how regrouping solved the friction when the participants' learning styles clashed, as was the case of Liz and Cindy. We have also seen how regrouping helped dissolve self imposed constraints, for instance when Kevin and Marvin discovered through their interactions with new groups that they could change the robots' wire connections.

Regrouping had other benefits as well. By circulating among the groups, participants could find partners they could work with better than with others. Cindy and Herbert, for example, could work together in a way that accommodated their interests and personal styles. When they built together a robot, in the beginning of their collaboration, their focus was totally different than that of the previous partners of either of them. Look, for example, at their criteria for changing the robot:

*Cindy: "I think there was something unbalanced about it. It was esthetics. You know, we just didn't like, we thought Pepe [the name they gave their robot] would look better that way, and still work. I especially remember there was this long piece in the middle, and we wanted to move it so that it wouldn't stick out so much in the front. So we took it off, and then Pepe*
didn't work any more. And we realized how it would have to be connected for the robot to work."

(Experiment 2, personal interview)

Cindy and Herbert had more than compatible interests. They may have shared similar belief systems. See, for example, what Herbert told Jean when Jean raised the possibility of having a sensor in their robot:

*Herbert: "Oh, OK, like an elevator door is supposed to be, which I never believe."*

His statement does remind of Cindy's declaration that she does not believe in physics. Later in his exploration with Jean, Herbert said:

*Herbert: "So, I think that's going to be the next thing to find out, like you have to figure out why, my hunches will never be related.""

Again, this self image which is not compatible with scientific thinking is similar to Cindy, who said she "had troubles" with "things like that".

Due to their similar interests and inclinations, the collaboration between Cindy and Herbert was satisfying for both of them. Once they started working together, therefore, they carried on their collaboration until the end of the experiment.

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**Co-construction across groups: The case of the mystery box**

The migration from one group to another had another benefit: it also served a fertile ground for the knowledge construction process. Participants brought with them chunks of knowledge from their previous explorations with other groups and shared them with their new partners.
The case of the mystery box was an insightful illustration of how this process worked.

Since early in their exploration, Ann and Donald wondered what the blue boxes were:

Ann: "What's the connection to the blue box?"
Donald: "We don't know what this one does, do you? You have a sense what that does?"
Ann: "No."
Donald: "I don't either."

Throughout their exploration, they hypothesized what the blue box indicated:

Ann: "That was, whether, when it's moving it [the light] was always on"

They found patterns in the LED on the blue boxes and related these patterns to the gears and the wheels. When Kevin joined them, about half an hour after they started their exploration, they explained to him:

Donald: "This blue one is hooked up to this gear, this... / Kevin: "Hmm." / Ann: "... backed up by the lights that go on..." / Donald: "The lights go on when that gear is being driven."

(Second experiment, second half hour)

When Liz joined the three of them, about ten minutes later, they still had not solved the puzzle of the blue box:

Liz (following wire connections): "It goes through-" / Donald: "It goes through there, comes into here, we don't know what this one (indicates the blue box) does."
Liz: "OK."

(Second experiment, second half hour)
About an hour later, still not having figured out how the blue box functioned, they were joking:

*Donald*: "We were sure, we were really only sure of the first half of the wiring. (Starts singing the following sentence): The sound sensor is connected to the mystery dial (they all laugh). The mystery dial is connected to the blue box. The blue box is connected to the other blue box. And then what happens underneath here, we haven't figured out."

*Ann*: "One of those T-shirts that say "Then a miracle happens."

*Donald*: "And then a miracle happens." (They laugh).

*Ann*: "All these equations, and then a miracle happens."

*Liz*: "This is a creation of physics."

*Ann*: "Right!"

*They all laugh.*

(Second experiment, second hour)

Later, Ann joined Marvin. In the beginning of the fourth hour, Kevin and Liz joined Marvin and Ann. Marvin and Ann showed Liz and Kevin what they found out first through Marvin's exploration and then through his exploration with Ann. They were analyzing signal transmission between different bricks and the motor.

*Liz*: "What are the blue boxes?"

At that time they did not have an answer. About four minutes later, as Marvin continued his explanations, Liz asked again:

*Liz*: "What are the blue things? Because we have two blue things over on that other truck that we never figured out."

But at this time, they have not figured out the blue boxes in here either. Liz kept insisting, though. When Marvin went to bring some spare parts, about two minutes later, she asked:
Liz: "OK. Get a blue, look for a blue box." (...

Marvin comes back.

Marvin: "I have a blue box." Kevin: "Light sensor."
Liz: "What are the blue boxes?

They started exploring the blue box. Now it did not take them long to discover, about three minutes later:

Marvin: "Oh, blue boxes." Liz: "Wait a minute." Marvin: "Yeah, what happens with the blue box, stays however it was until it gets a signal."


Marvin: "A permanent toggle..."

The blue boxes, indeed, were flip-flops. Soon after this discovery, Kevin left the group and went back to Donald and Jean, to bring the news:

Kevin: "Marvin has a lot of experience with these things. Speed and direction--"

Kevin started explaining about the speed and direction sockets in the motor. He continued the explanation with "or", "and", and inverter bricks, and then got to the mystery box. He drew a picture.

Kevin: "We have these two blue things. They both get current when we turned it on. So we get current in order. This guy got it first, this guy got it second. (...) The blue boxes' function, flip to whatever. If it's on, it stays on until you get current and stay that way. This first one passed power and said, "Hey, switch from whatever you are." So this guy went off because that guy came over and told him.--"

(Second experiment, about half an hour before the end of the experiment)
Like the communication between the bricks, so passed the information between the participants. Kevin came over from the other group to bring the information that he, Donald, and Jean — together with the rest of the previous group— were looking for at the time.

(iii) The evolution of co-construction

Donald: "That's actually why we wanted to change the agenda. That's why we were not interested in continuing to try to sort out this pattern where (...) we weren't getting anywhere with it. (...) So, I think that's why we wanted to change the whole form altogether.

(Experiment 2, group discussion)

The common path of co-construction evolved through many changes. The changes were partly due to the reason Donald mentioned: when the participants felt they were pursuing a futile activity, they changed direction. But other reasons also accounted for these changes. At times, other questions competed for the participants' attention and gained center stage in their exploration. At other times, the participants continued to pursue a certain problem until they felt they knew enough about it and were satisfied with the way they understood it. Then again it was time for change.

The evolution of co-construction: The case of Ann and Donald

During their common exploration, Ann and Donald raised many questions. Each question triggered a sequence of exploration, through which they tried to come up with answers to that question.
Table 4.1 summarizes and analyzes the first 15 minutes of Ann and Donald's common exploration. The table covers one sequence, but the main focus of the exploration changes at 15:55, generating different column-labels. In the table, the main problems that Ann and Donald raised are marked by shading. The four columns to the right code the questions they were focusing on and indicate sub-problems by index numbers.

Analysis of Ann and Donald's sequence of co-construction shows clusters of experimentation, each focusing on a similar question. If the experimentation bore results, it was pursued further. If it did not, it was abandoned.

As the table shows, Ann and Donald raised at first mainly two kinds of problems. One was related to sound, and the other — to the movement of the robot. First (at 08:19), they noted the movement (a progression in the movement), which they mentioned later again (08:37). Then (at 08:49), they discovered that the robot reacted to sound: it started moving in reaction to voice.

The reaction to sound (which was, indeed, the main attribute of the robot) triggered most of the exploration in the first part of the exploration. When Ann and Donald first noted the reaction to sound, they raised two sub-questions which form the first cluster (s1, and s2, at 08:53, 09:20, and 10:15). Later they proceeded to explore systematically the qualities of sound that affected the robot, raising many sub-questions (s3- s7, from 13:00) and testing them. These explorations formed another cluster. The initial discovery, then, triggered clusters of exploration that increasingly got more elaborate.
### Table 4.1: Ann and Donald's focus of exploration

<table>
<thead>
<tr>
<th>Time (min:sec)</th>
<th>Content</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>08:03</td>
<td>(--Starting as a team)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>08:19</td>
<td>Progression of movement</td>
<td></td>
<td></td>
<td></td>
<td>M</td>
<td></td>
</tr>
<tr>
<td>08:29</td>
<td>Reacts when hitting the box?</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>O1</td>
</tr>
<tr>
<td>08:37</td>
<td>Progression of movement</td>
<td></td>
<td></td>
<td></td>
<td>M</td>
<td></td>
</tr>
<tr>
<td>08:49</td>
<td>Voice start</td>
<td></td>
<td></td>
<td></td>
<td>S</td>
<td></td>
</tr>
<tr>
<td>08:53</td>
<td>Directional?</td>
<td></td>
<td></td>
<td></td>
<td>S1</td>
<td></td>
</tr>
<tr>
<td>09:20</td>
<td>Starts and stops with a clap</td>
<td></td>
<td></td>
<td></td>
<td>S2</td>
<td></td>
</tr>
<tr>
<td>09:32</td>
<td>Pattern of movement</td>
<td></td>
<td></td>
<td></td>
<td>m1</td>
<td></td>
</tr>
<tr>
<td>09:46</td>
<td>Pattern of movement</td>
<td></td>
<td></td>
<td></td>
<td>m1</td>
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</tr>
<tr>
<td>09:58</td>
<td>Clockwise and counterclockwise</td>
<td></td>
<td></td>
<td></td>
<td>m1</td>
<td></td>
</tr>
<tr>
<td>10:15</td>
<td>Not directional</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>S1</td>
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<tr>
<td>10:23</td>
<td>Pattern of movement</td>
<td></td>
<td></td>
<td></td>
<td>m1</td>
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</tr>
<tr>
<td>10:32</td>
<td>Spins on left wheel</td>
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<td></td>
<td></td>
<td>m1</td>
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</tr>
<tr>
<td>10:56</td>
<td>Usual spin</td>
<td></td>
<td></td>
<td></td>
<td>m1</td>
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<tr>
<td>11:28</td>
<td>Regular spin clockwise, stopping</td>
<td></td>
<td></td>
<td></td>
<td>m1</td>
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<tr>
<td>11:41</td>
<td>This is the sensor?</td>
<td></td>
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<td>SS</td>
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<tr>
<td>11:43</td>
<td>How subtle is it?</td>
<td></td>
<td></td>
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<td>SS1</td>
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<tr>
<td>11:50</td>
<td>Testing: trying to block the sound</td>
<td></td>
<td></td>
<td></td>
<td>SS2</td>
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<tr>
<td>12:32</td>
<td>This plastic isn't blocking</td>
<td></td>
<td></td>
<td></td>
<td>SS2</td>
<td></td>
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<tr>
<td>13:00</td>
<td>How far away?</td>
<td></td>
<td></td>
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<td></td>
<td>S3</td>
</tr>
<tr>
<td>13:05</td>
<td><strong>Qualities of sound</strong></td>
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<td></td>
<td>Analyzing qualities:</td>
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<tr>
<td></td>
<td>sharpness; background noise</td>
<td></td>
<td></td>
<td></td>
<td>S4</td>
<td></td>
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<tr>
<td>13:11</td>
<td>Loudness difference</td>
<td></td>
<td></td>
<td></td>
<td>S4</td>
<td></td>
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<td>Time</td>
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<tr>
<td>13:23</td>
<td>Is it reacting to voice at all?</td>
<td>s</td>
<td></td>
<td></td>
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<tr>
<td>13:38</td>
<td>Gradual difference in loudness</td>
<td>s5</td>
<td></td>
<td></td>
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<tr>
<td>13:45</td>
<td>Distance</td>
<td>s6</td>
<td></td>
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<tr>
<td>13:55</td>
<td>Behind the knee</td>
<td>s7</td>
<td></td>
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<tr>
<td>14:05</td>
<td>Distance</td>
<td>s6</td>
<td></td>
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<tr>
<td>14:10</td>
<td>Experimenting with distance</td>
<td>s6</td>
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<td>15:16</td>
<td>Effect of obstacles: behind the box</td>
<td>s7</td>
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<tr>
<th>Main focus</th>
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<td>15:55</td>
<td>How the robot works</td>
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<td>16:01</td>
<td>Analyzing the processing of sound, the robot's structure</td>
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<tr>
<td>17:21</td>
<td>We could adjust the speed</td>
<td>mw</td>
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<td>17:43</td>
<td>Change the spin</td>
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<td>Wires</td>
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<td>Changing a wire</td>
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<td>Exploring the new movement</td>
<td>mw1</td>
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<td>18:37</td>
<td>Rewiring to original configuration</td>
<td>w</td>
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<td>18:53</td>
<td>Writing down summary</td>
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<td>21:23</td>
<td>The only sensor?</td>
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<td>o</td>
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<td>21:24</td>
<td>Testing reaction to light</td>
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<td>o2</td>
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<td>21:28</td>
<td>Exploring the movement</td>
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<td>mw1</td>
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<td>Testing reaction to light</td>
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<td>o2</td>
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<td>22:07</td>
<td>Testing reaction to light</td>
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<td>o2</td>
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<td>22:21</td>
<td>LED</td>
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<td>22:26</td>
<td>Relations LED-wheels</td>
<td></td>
<td>l1</td>
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<tr>
<td>22:36</td>
<td>Relations LED-gears</td>
<td></td>
<td>l1</td>
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<tr>
<td>22:45</td>
<td>Relations LED-sensor</td>
<td></td>
<td>l2</td>
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<tr>
<td>22:52</td>
<td>Relations LED-movement</td>
<td></td>
<td>l1</td>
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<tr>
<td>23:11</td>
<td>Relations LED-gears</td>
<td></td>
<td>l1</td>
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Table 4.1: Main problems are marked by shading. The four columns to the right present problems and sub-problems (indicated by index numbers). Double frame indicates a backward transitions to a previous step.

The robot's pattern of movement was complex; it was one of the issues that first called Ann and Donald's attention. After analyzing the pattern of movement (9:32 - 11:28; first movement cluster), and once that pattern was understood, they left it aside. Later (at 17:21 - 21:28; second movement cluster) they picked up the issue of movement again, that time in order to explore it in relation to wire connections. The question of movement, then, also generated clusters of exploration in relation to its sub-problems.

In the beginning of the table, the fifth column indicates explorations related to the sound sensor (ss, at 11:41-12:32). This question did not lead to fruitful results at that time; it was abandoned, then, and was pursued again later in their exploration.

Ann and Donald also explored alternative explanations for the robot's movement. These are indicated in the last column. At 08:29, before discovering the reaction to sound, they raised a possibility of reaction to touch. Since the discovery of sound immediately followed and brought fruitful results, they abandoned the touch hypothesis for the time (later, beyond the time presented in the table, they returned to that hypothesis and tested it too). At 21:23 they raised another possibility, this time testing the robot's reaction to light. A brief test showed negative results, and they abandoned that hypothesis.

At 15:55 Ann and Donald shifted their interest to the structural attributes of the robot and the interrelations between its structural and the functional attributes. Yet they
continued to follow a similar pattern of clustering their experimentation around each question and sub-question.

The issue of wires generated two clusters of exploration (w and w<sub>1</sub>, between 17:49 and 18:37, and a second cluster — w<sub>2</sub> and w<sub>3</sub>, between 23:23 and 23:36). Another new discovery, of LED (light emitting diodes) also triggered a cluster of exploration (l, l<sub>1</sub>, and l<sub>2</sub>, at 22:21 - 23:11). This direction of exploration was fruitful, and they continued to develop it later, beyond the time frame presented in the table.

Ann and Donald also picked up an issue that proved significant earlier — the pattern of movement — and continued to explored it in light of their new focus of interest — wires (mw, at 17:21 - 21:28).

Twice in their explorations Ann and Donald went back to previous steps. These backward transitions are marked by a double frame. The issue of backward transitions, its meaning, and its significance will be discussed and analyzed in the following chapters.

As in these 15 minutes, in most of their exploration together Ann and Donald followed a similar pattern. Their questions emerged from their observations; once a question emerged, it triggered a cluster of exploration; and the more fruitful were these explorations, the more they elaborated on them.

Through this strategy of clustering, Ann and Donald continuously developed their understanding of the robots. The clusters formed an evolving sequence of knowledge co-construction. The attributes of this sequence are analyzed in the following chapter.
This chapter follows the paths the participants paved when exploring the "Weird Creatures" and the Wuggles. The chapter starts by distinguishing between the kinds of problems the participants dealt with in this study and conventional ill-structured or ill-defined problems. Unlike most problem-solving research, what the participants encountered was a well structured context-space, within which they could construct their own problems, with their own tasks, goals, activities, and rules. The attributes of co-constructed problem-solving, as they emerged in this study, are analyzed and demonstrated by examples and case studies.

Co-constructing the problems was an evolving process, throughout which the participants changed their goals, approaches to the problems, and activities. The group constellations also changed, bringing with them new stimulation to the co-construction of knowledge. A segment of the exploration of two participants, Ann and Donald, demonstrates the dynamic and evolving sequence of co-construction of knowledge.

The co-construction of knowledge related to the robots was not an easy process. Due to slight changes in conditions that eluded the observers, the robots seemed to "behave" differently on different trials. Interwoven into the serious explanations the participants generated, then, were others that indicated their puzzlement:

"What if somebody outside the whole thing is doing it? Like what if we have nothing to do with this at all?"

Or:

"OK, it's on battery release and it behaves one way for fifteen minutes and the next fifteen, it does something completely different to throw you off."
Some participants did not like facing the unknown and confronting it without guidance. Others enjoyed it, even though the process was not easy:

Betty: "I felt stimulated not to be told. It just forced me to be... I'm basically curious anyway. It forced me to use my own resources, to test and to try. And because I didn't find all the answers, I'm more excited now to find and try. (...) And that's fun to discover."
Chapter 4 reviewed the co-construction of knowledge by the participants. By the end of the chapter, we have seen the long path the participants walked through to achieve this co-construction.

The path was not straight, nor was it short, nor simple. The explorations of the "Weird Creatures" and the Wuggles evolved through a long process, during which these explorations changed foci, form, and content. The changes indicated three major phases, qualitatively different from one another.

These phases are defined and analyzed in the following chapter.
CHAPTER 5

PHASES IN THE EVOLUTION OF KNOWLEDGE CONSTRUCTION

Transformation

Ann and Donald were clapping, snapping fingers, and making their robot hit a box. They were testing what stimuli caused changes in the robot's pattern of movement. They varied the direction of the sound stimulus, its distance, and its loudness. They compared the effect of sharp sounds to that of background sounds.

After about eight minutes of such an exploration, Donald asked Ann:
"So what do you suppose this is, how do you suppose this is really working?"

(Second experiment)

Donald's question marked a qualitative change in the way he and Ann were exploring the robot. Instead of testing its response to stimuli, as they have been doing earlier, they started exploring the mechanism that produced the changes in the robot's pattern of movement. Having clarified the pattern of movement and its causes, they were ready for a change in their focus of interest. Following Donald's question, he and Ann started exploring how the sound sensor was wired to the motor, how the robot was structured, and the relations between the sensor, the motor, and the wheels.
As in the example of Ann and Donald, the exploration of other participants also underwent qualitative transformations. These transformations formed distinct phases in their explorations.

| Phases — definition |

A phase, as defined by Webster's dictionary, is a particular appearance or state in a regularly occurring cycle of changes. In this thesis, the term "phase" will indicate qualitatively distinct changes that correspond to internal re-organization, or reconstruction, of knowledge. These changes are manifested in the person's actions and discourse (external manifestations that are equivalent of the "appearances" contained in Webster's definition).

The term "phase" was used in literature to denote such qualitatively distinct changes in behavior (e.g., Duncker, 1945; Fischer, 1980b; Karmiloff-Smith, 1986a). Karmiloff-Smith (1984; 1986a,b) defines "phases" in distinction from "stages". The term "phase", according to Karmiloff-Smith, refers to recurrent changes, both within domains and across domains. Unlike stages, these changes are not age related, and a person can simultaneously be at different phases in relation to different contexts.

In similarity with Karmiloff-Smith's use of the term, in this study "phase" implies changes that are not age related; a person can simultaneously be in different phases in relation to different contexts. These changes are recurrent; they can reappear in relation to new contexts, and show the same cycle of changes.
Phases in the participants' explorations and explanations

There were distinct phases both in the way the participants interacted with the robots and in the kinds of explanations they gave to the phenomena they observed. The different phases of exploration were expressed in the actions the participants performed while testing the robots' responses. The modes of discourse manifested in their vocabulary and in the content of their talk, and reflected the participants' changing focus of attention throughout their exploration.

A the previous example of Ann and Donald indicates, the

DIFFERENT PHASES OF EXPLORATION AND EXPLANATION

Ann (putting the robot on the floor close to a box): "I tried to experiment with, if it would -- now I've broken it, hmm, -- if it would react if it's hitting the... [box]."

(Second experiment)

The three phases

When the participants interacted with the robots, they usually started by watching the "behavior" of the robot as it was moving on the floor. At that time, they were trying to understand the robot's pattern of movement and, usually, to figure out the causality underlying that pattern. They did it by playing with the robot and by learning through
their actual actions and observations. This phase, therefore, is called the *actual phase* \(^1\) and is characterized by focus on the "behavioral" patterns of the robots.

Later, the participants often held the robot in their hands while continuing to explore it. By then, the robot's pattern of movement was well recognized. As they were meticulously testing the robot's reaction to a stimulus (which, as they previously identified, was affecting the robot), they could represent the change in the robot's movement without actually watching it move on the floor. At the same time, the level of details they were focusing on in their observations changed. They were looking at the structural traits of the robot, relating these traits to the robot's functional attributes. This phase, therefore, is called the *representational phase*, and is characterized by a close-up investigation of details.

Still later, the participants' explorations became more technically oriented. While they were trying to understand the operation of specific bricks, they often disassembled the robot and tested each brick separately. By now they discussed such abstract problems as signal and power. This phase, therefore, is called the *abstract phase*, and is characterized by in-depth, technical investigation.

(i) **The actual phase: "Behavioral" investigation**

> In the beginning of the exploration, Liz observed a robot swivel from side to side as it advanced on the floor. After a minute, Cindy joins her as Liz is picking up the robot and examining it.

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\(^1\) The term "actual", which was chosen for the first phase, indicates knowledge structures that are based on actual actions and perceptions. This term gives tribute to the German word "Aktualgenese", which was the origin of the term "microgenesis", coined by Werner (see Flavell & Draguns, 1957; Werner, 1956).
Cindy: "What does it do when you put it down?"
Liz: "Oh, (putting the robot down), "it Wuggles."
Cindy (laughing): "It Wuggles?!
Liz (indicating the robot's movement): "That's what it does."

(Second experiment)

"Behavioral" exploration through actual actions and observations

As mentioned earlier, during the actual phase, the participants focused on the robot's "behavior," while it was moving on the floor:

Jean joins Herbert, who has already started exploring a robot. Herbert shows Jean the way the robot "behaves".

Herbert: "See how it's spinning this way and then it changes direction?" (While talking, he puts his hand above the robot). "There it is."

(Second experiment)

In this phase, the participants tried to understand the robots through their actual actions and observations, by playing and by doing. When they were exploring a robot, they touched it, put their hands above it, flashed lights on it, or put it in the shadow. They clapped, whistled, snapped fingers, and sometimes, jokingly, shouted at the robot. They used flashlights and lamps to illuminate the robot, brought it close to the window through which the sun light penetrated, and reflected light upon it with a mirror.

How does the robot behave? A descriptive mode of discourse

In the first phase, the participants' discourse was related to the global behavior of the robots, and had a descriptive quality:
Donald: "You noticed how it was spinning one way and at the very end, as it gets slows down and ready to stop, it swirls back around (...) the other way?"

(Second experiment, first hour)

Ann: "I think its regular thing is clockwise, and its stopping thing is counterclockwise."

(Second experiment, first hour)

In this phase the participants' accounts of the robots' "behavior" were often tinted by animistic references:

"It seems to escape the light."

(First experiment, third group, first hour)

"He liked Patty— you were blocking all the light sources from behind you—so he kept going toward you..."

(First experiment, third group, first hour)

"What did you find out?"—"It didn't like total darkness."

(First experiment, third group, second hour)

The participants used such terms as "like" (he liked Patty; he didn't like darkness) or referred to the movement using the word "escape". Their focus on the behavior of the robot was sometimes accompanies, then, by a relational mode of discourse.

Describing the robot's behavior as "liking Patty" or "not liking darkness" was not just a joke. There was some consistency in the robot's pattern of movement (like going toward Patty or stopping still in darkness) that triggered that description. The playful animistic talk went along with the more serious descriptive perspective, characterizing
this phase. Underneath the participants' descriptive mode of discourse lay an important search for — and perception of — patterns in the robot's movement.

### Looking for patterns

- "We noticed a pattern of going forward more and back less."
  
  (First experiment, second group, first session)

Noticing patterns in the robot's "behavior" implies putting some structure on its movement — it characterizes the movement, tags or labels it. Perceiving patterns, therefore, is a step toward understanding the robot's behavior.

**Beatrice:** "Is it just a certain amount of time? After a certain amount of time you are going [it is going] one direction, it automatically changes?"

  (First experiment, second group, first session)

**Mary** was observing a robot that kept alternating between moving forward and backward.

**Mary:** "It stops in the same place!"

  (First experiment, second group, first session)

Sometimes the robot's pattern of movement was very complex:

**Laura:** "He goes a little bit further back, and he goes [forward] a little further than he does going back. And then these two lights will come on and then you'll hear some noise and then he'll go back again"

  (First experiment, third group, first session)

When the "behavior" was as complex as in the last example, the participants used more elaborate measuring techniques in order to detect patterns in that behavior. At times relying on external devices for that purpose. For example, when Mary was experimenting
with the same robot that Laura described above, Mary tried to look at her watch to measure the duration of the forward versus the backward movements. She also put underneath the robot pages from her notebook and marked on them its path, trying to estimate the distance the robot was going on each alternating move. Mary also spread a plastic sheet of bubbles along the robot's path, and estimated the distances of the robot's movement by counting the numbers of bubbles it passed. Other participants, in the absence of a seconds' indicator in their watches, estimated the time duration by counting (one, two...) at a constant speed. They used these counts to evaluate the consistency in the robot's pattern of movement.

Once the robot's pattern of movement was recognized, the participants already had expectations regarding its "behavior". These translated into questions such as:

"I wonder what it will do when it reaches that corner where there's all that shadow"

(First experiment, first group, first session)

Understanding the pattern of movement was a step toward understanding the causality underlying the robot's movement. For example, when Tim, Lucy, Jill, and Sherry explored their robot, first they just observed two different kinds of movement:

Tim: "There seems to be two different behaviors when the light is on and when the light is off".

Then they tried to make distinctions and explored the relation between these two kinds of movement:

Lucy: "Maybe it was a backwards behavior and then a forwards behavior."
Still later, they tried to identify the conditions related to these kinds of movement, which could point at the cause for the movement:

Jill "Maybe it went away from the light."
Sherry: "See, he is going away."

(First experiment, third group, first session)

Looking for causality — a painstaking effort

Identifying the robot's pattern of movement involved a process of approximation, testing the conditions that were related to those patterns and, in turn, discovering the related causality

Lynn: "So it flashes when it's on the--" / Cynthia: "The light, the light--" / Lynn: "or the heat, right." / Cynthia: "and it stopped flashing under the umbrella."

Lynn and Cynthia identified a pattern, but were not sure whether the conditions under which it appeared (under the umbrella) were related to light or to heat. They decided, therefore, to test it:

Lynn: "Put it in the box. I want it in the box. I wonder if it's heat activated."

By inducing different conditions, the participants varied the robot's responses until the causality underlying its pattern of movement became apparent.

Kevin and Marvin begin to explore a robot. The robot moves on the floor and then stops. Marvin puts his hand at one side of the robot, then at
another, and then at different locations around the robot. Suddenly the robot starts moving forward.
Kevin: "Oh, OK, looks like we got a reaction there... that side."

At first Kevin and Marvin just noticed a reaction. Later, they indicated the conditions related to it:

(A few seconds later)
Marvin: "But sometimes it goes one way..." (he changes the robot's location. The robot moves forward and then starts bouncing on their shadows' edge).
Kevin: "OK, (...) look, we've got light problems too (...)

They identified the varied conditions that were related to differences in the robot's movement:

(Two and a half minutes later):
Kevin flashes light on top of the robot, as he did before, but this time the robot does not move.
Marvin: "So what happened?"
Kevin (looking up and around.): "Maybe that this. (...) ambiance light is too much."
Marvin (indicating the light around them with his finger): "Yeah".

That, in turn, helped them understand the causal rule related to that movement:

(About a minute later, after continuing to experiment with the robot's reaction to light):
Kevin: "OK, if it's dark, or if it's light, (...) if it switches between dark and light, then it changes directions."

(Second experiment)
Like Kevin and Marvin, other participants also experimented with the robots in diverse ways. They were trying to understand how varying the external conditions affected the movement of the robot, and to sort out the cause-and-effect relations:

- "We don't know what happens — you put your hand and it stops forever."
- "Look—look—look!! See — it's much easier with the light on top!"
- "Let's try turning on the little light...Why does it go to the box?"

(First experiment, second group, first session)

The way to understanding causality, though, was long and demanded painstaking investigations. Since we rarely have an opportunity to observe such processes, we do not expect them to be that long and hard. Not only can the present study highlight the lengthy duration, complexity, and intricacy of the experimentation on the way to uncovering causality, but it also indicates why these attributes are inherent and necessary for that process, as the following examples demonstrate.

Looking for variables

The crucial issue in this experimentation was to isolate the relevant variables that affected the robot's movement:

Ann: "We saw that, but we just had to determine what the variables were."

(Second experiment, second hour)

Mary: "I'm] trying to decide whether it's speed or distance or time that--[causes the change]"

(First experiment, second group, first session)
By identifying the relevant variables, the participants took a step toward developing a theory that explained the "weird" behaviors of the robots:

- "Our theory is that it circles until it finds the light..."
- "Change with sound will cause it to change direction...same with the change of light."

(First experiment, second group, first session)

Varying the stimuli

In order to identify the relevant variables, the participants kept experimenting with the robots. When their explorations led them to hypothesize that light made a change, for example, they tried the robot's response to different light sources — flashlight, lamp, or sunlight. They also attempted to make shadows, using different objects — a box, a shoe, a notebook — or create shadows with their body, fingers, or hands. In a similar way, they explored other stimuli such as touch and sound.

Even as they understood the crucial variables that affected the robots' movement, the participants proceeded with more elaborate experimentation. Not only did they vary the sources of a stimulus, but also its other qualities. For example, when they moved their hands to create a shadow, they did it at varying speed; they looked for the effects of different densities of shadows and different shadow lengths; they varied the distance and the relative position between their hands and the robot (putting their hands above the robot, then around it from different sides, closer and further away from it, and so on).

Ann and Donald have examined a robot for about 6 minutes, exploring its reaction to sound.

Ann: "The question is, what else does it do. And how far away? (...)"
Donald: "Yeah, (...) I wonder how far it can go from." (...)
The question about the distance triggered an extensive experiment:

*Donald goes a bit further away, and claps. Ann watches the robot. The robot reacts to the clap.*

*Ann: "Yeah-"

*Donald goes still further away and claps again, he then goes still further and claps again, and so on.*

*Ann: "Yeah, that's all, that's all, yes, all of those have worked."

*Donald goes still further away and tries again.*

*Donald: "Did it go...?"
Ann: "No, that one didn't. (Donald claps again). That did it, that did."

*Donald goes still further, out of the room.*

*Ann: "Where are you? ... No! " (laughing)
Donald: "It didn't work?"
Ann: "No."
Donald comes back.*

(Second experiment)

After trying to vary one variable (such as shadow or touch), and varying its qualities, the participants also eliminated it altogether and checked how its absence affected the robot.

*Laura: "Clap behind him doesn't make him respond." (...)
Wanda: "Maybe two claps stop it when it's in reverse." (...)
Wendy: "Let's see what it does, have you seen what it does without clapping?"
Inefficient and redundant experimentation?

The participants' experimentation was often extremely redundant. Sometimes they even seemed to ignore previously observed evidence. For example, Betty and David were trying to elicit from a robot a jerky movement which they had previously caused. It seemed that they succeeded in their mission — they found out how to cause that jerky movement. Yet, they still continued to perform the "wrong" actions — actions that did not bring about the desired reaction. Like the children Karmiloff-Smith and Inhelder (1974) observed, it seemed that their goal was not success but understanding. Yet, even when they seemed to understand how to cause the jerky movement, they continued to make the wrong acts:

Betty puts her hand in front of the robot, and it goes backward. She then changes slightly the position of her hand, and the robot goes forward. Again she slightly changes the position of her hand above the robot; the robot makes a jerky movement.
Betty: "It's above."
David: "It's above!"

At this time, not only did they succeed in eliciting the desired response, but they also defined the position that caused it: when the hand was above the robot, the robot "performed" the jerky act (indeed, in that position the hand casts a narrow shadow on the robot's light sensor, which makes the robot bounce back-and-forth on the shadow's edge).

As if that was not enough, Betty continued to test alternative positions, once putting her hand in front of the robot and then behind it, in positions that do not cause the desired bouncy movement:
Betty puts her hand behind the robot, and it moves forward. Betty: "Here--"
She puts her hand in front of the robot, and it moves backward.

Betty even reiterated that test:

*Betty alternates her hand's position in front of the robot, behind, and above it, and the robot continues the same pattern of movement as it did before, with a jerky movement when the hand is above.*

As an observer, you could conclude by now that Betty and David understood that when the hand was above the robot, the robot made the jerky bounce, could you not? Betty made the robot do that movement; David was observing her do it. When Betty succeeded eliciting the desired response, David repeated her conclusion "It's above."

And yet, look at what follows:

*David puts his fingers again in front of the robot and behind it. He puts his fingers at the sides of the robot. Then he backs away from the robot (...)
He continues varying the movement of his fingers around the robot, saying: "At one point it was like dancing..."*

David should have known by now why the robot was "like dancing". He said previously: "It's above", implying that "above" elicited the jerky "dance-like" movement. Why, then, did he put his fingers again in front of the robot, behind it, at its sides, and away from the robot — instead of putting his hand above it? Did he forget what he just saw and said previously? Apparently, he did not:

*David puts again his hand above the robot. The robot makes a jerky movement. David: "Oh, sto[p], yeah, if you go above it --"
Betty: "Yeah".
David: "It's above really changes it."

(First experiment, first group, second session)

The importance of reiteration

A close examination of David's exploration, as well as the explorations of other participants, reveals the function of these repeated reiterations. This supposedly "redundant" and "unnecessary" experimentation, presumably "ignoring the facts", played an extremely important role.

A previous episode with Betty, David, Kathy, and Peter emphasizes the function of their repeated trials:

Betty, David, Rachel, and Peter explore a robot and test its response to light. Betty holds the mirror behind the robot, reflecting upon it the light of a lamp. Peter follows the robot and flashes the flashlight on it as it moves.

Peter: "Hmm, we need a brighter lamp." Betty: "That's right."
David picks up another lamp and shines its light on the robot. (...) Betty: "OK, shine the lamp on the mirror (...)"
David directs the lamp's light toward the mirror. (...) He follows the robot with the light. (...) Betty puts the mirror in front of the robot and the robot begins to move toward the mirror. As the robot moves, Betty keeps moving along, holding the mirror in front of the robot. The robot keeps following the mirror.

Betty (delightfully): "Aha!"
Rachel: "What if you pull the mirror away?"

As the analysis in chapter 6 indicates, these repeated and redundant experimentation are similar to children's circular reaction. In this chapter, the analysis indicates the importance and the function of these reiterations. Children's circular reactions may serve a similar function.
Betty pulls the mirror away. The robot continues moving in the same direction as it did when it seemed to move toward the mirror.

Betty (laughing): "It still goes!"

(First experiment, first group, first session)

On logic, redundancy, and building theories

Why is the redundant reiteration important for understanding the underlying causality? The study of logic tells us that in order to prove that X causes Y, it's not enough to see that when you do X, Y ensues (for example, when put a mirror in front of the robot, the robot follows; or when you put your hand above the robot, it makes a jerky "dance"). The rule of logic also says that you have to make sure that when you do not do X, Y does not occur.

This is exactly what the foursome did in the last example, and Betty and David—in the previous one. The mirror episode is a perfect demonstration why it is crucial to test for non-occurrence, as indeed the rule of logic says. In the mirror episode, the robot seemed to follow the mirror's light. Only when Betty put away the mirror, could she find out that it was not the mirror that affected the robot's movement: the robot still kept going the same way. Adopting a causal explanation without performing over and over the "wrong" actions, therefore, may prove to be a self-fulfilling wrong prophecy.

Building theories, though, demands more than what the rule of logic specifies. A double check that X causes Y and (not X) causes (not Y) may not be enough. Take, for example, a child who watches the moon "following him". When the child walks, the moon "follows". When the child stops, the moon "stops". From the point of view of the rule of logic, then, the theory seems to be confirmed: (going) causes (follow), (not going) causes (not follow). Logic, as it turns out, may not be enough: to confirm a theory, one
has also to test alternative explanations and to make sure that the explanation one holds makes sense.

This is indeed what the participants did in their explorations. The continuous reiteration, changing the conditions of the stimulus and repeatedly testing the robot's response, were all geared toward the very same goal of testing alternative theories. Not only were David and the other participants assessing their current theory ("it's above"; or: "it follows the light reflected from the mirror"), but they were also trying to make sense of that theory and to eliminate alternative explanations.

Redundancy in a search for consistency

The redundant experimentation also became a means in the search for consistency. The participants had to ascertain that the phenomena they observed were consistent and not a mere artifact. To do so, they had to re-test the robot's response and watch it over and over again, making sure that they were getting consistent results:

_Claire:_ "Now look, watch these two lights. That's the rocking.... although its' not... somehow it's moving at the same time. 
_Do you want to watch it again?"

_Joanne:_ "Yeah."

_They turn on the robot and observe it again._

(First experiment, second group, first session)

At times, the participants somewhat changed the conditions under which the robot operated. At other times, they let the events take their own course and separate the true causal rules from the chaff:

_Diane:_ "We thought we discovered something when we put it in the box and we blocked most of the light, and peeked in and it stopped. And so
our first theory was that that [darkness] would make it stop. When we tried it again, we found that what made it stop was that the box bottom wasn't smooth and it just got stuck. So that just blew that idea."

(First experiment, second group, first session)

In the next chapter, we will see that the superfluous experimentation has another crucial role for the transition from level to level and from phase to phase in the process of knowledge construction. But before doing that, let us examine the attributes of the other phases, and find out what these phases have in common — and in what respects they differ — from that first actual phase.

(ii) The representational phase:

Detailed close-up Investigation

Marvin: "I started looking at components (...) and we played with that."

(Second experiment, group discussion)

In the second phase of the exploration, the participants were usually holding the robot in their hands and examining it closely. They continued to generate different stimuli and to look for the robot's ensuing reactions, as they did before. However, in this phase they did not focus on understanding the pattern of movement as much as they tried to relate the movement to the functioning of the robot's components — its sensors and the logic bricks. Donald's question, which, as we have seen, marked the transition to the second phase, highlighted this change: "So (...) how do you suppose this is really working?"
Representing the robot's movement

By now, the pattern of movement and the stimuli causing it were quite well recognized. While holding the robot in their hands, the participants could, therefore, represent that pattern of the movement. They relied on "hints", such as the direction in which the wheels rotated, or the change in the noise of the motor, for representing that movement:

*Liz:* "Can I hold it while you guys do the pause, do the clicking?"
*Donald:* "Uhmm."
*Ann:* "Yup."
*Liz:* "And let's watch the wheel..."

(Second experiment, second hour)

By watching the wheels, they could check the way the clicking sound, picked up by the sound sensor, affected the robot's movement without actually observing the robot move.

In another episode, Marvin put his notebook above the robot, thus obstructing the robot from Kevin's view. Kevin asked him then to take his hand off, suggesting that they listen to the sound:

*Kevin to Marvin:* "Take your hand off and let's listen to this sound of the, whether, see the wheel does...."

(Second experiment, first hour)

When the motor and the wheels changed direction, their sound changed. The change of sound, then, could stand for the direction of movement. In both examples, the participants wanted to get an indication of the robot's pattern of movement when they were holding it still in their hands.
The participants also represented the pattern of movement in their mind, without actually watching the robot move, when they discussed the robot’s movement. For example, when Kevin joined Ann and Donald, he watched the robot and listened to their conversation for a few seconds. Then he asked them what caused the robot response. Donald and Ann started describing the pattern of movement of the robot and its response to sound, without turning on the robot. They described the movement with the original wire configuration, then with the new wiring, and only after that did they turn the robot on again.

Similarly, when analyzing the causes underlying the robot’s behavior, the participants could rely on representations of patterns of movement they had previously observed:

Kevin: "Maybe there is some (...) sensitivity to... um... / Liz: "The tension?" / Donald: "To resistance--" / Kevin: --"how much progress it's making-- Donald: "Yeah, but if that's the case, then (...)it should have turned off when it would run into the cardboard box--/Ann: "Into the box, which it didn't."

(Second experiment, second hour)

The ability to represent a complex pattern of movement enabled the participants to create theories related to the way the robot functioned:

Liz: "So, so it's a two-state model(...)"
Donald: "Either way, we're still going to need to describe it in terms of its two options."
Ann: "Right."
Liz: "Yeah."
Donald: "I mean, it's like option one is the circle option and option two is the straight option and something like that. It's going to switch between circle and straight."

(Second experiment, second hour)
In this case, the robot was switching between two alternating patterns — one, moving straight forward, and the other, spinning around in a circle. Liz, Ann, and Donald could analyze the pattern and create their theories ("two phase model") without having to experiment with the robot the way they had previously done.

Understanding frees attention-space for new observations

Once the pattern of movement and the stimuli causing it were understood, the participants could pay attention to details they did not notice before. For example, often it was only in this phase that they first noticed the blinking indicator lights (LED — light emitting diodes) on the bricks:

*Fifteen minutes after starting their exploration together, Donald and Ann were immersed in intensive investigation of the robot.*
*It was already seven minutes and five seconds into their second-phase exploration when they first mentioned the LED.*
*Donald: "That's kind of interesting, I haven't noticed that before, that, it's funny, I didn't notice those lights going on and off."*
*Ann: "I haven't either."*

(Second experiment, first hour)

Even later, as they continued to explore the robots, they kept noticing details that escaped them earlier. In the beginning of the second hour of the experiment Donald said:

*Donald: "...They've got two, what is it, like two dials on these things and we never noticed them until we were all done (laughing). (...)"

*Ann: "We never even, we never even looked at the dials, I mean, we just like focused right on the wires."*

(Second experiment, second hour)
It seemed that after identifying one problem, exploring it, and clarifying its nature, the participants got it "out of the way". Only then were they in the position to notice other details. In Donald and Ann's case, it was first the LED, then the wires, and still later the dials on the bricks that gained their main attention. They did not notice the LED or the dials in their prior explorations, although these were there all along.

They were paying attention to details that they did not even consider previously, such as the position of a brick on the robot:

- "Do you know on the sound sensor whether that has to be sticking out or that?"
- "Maybe the motor has to be plugged [in] a certain way?"

(First experiment, second group, second meeting)

Once they noticed these new elements and interconnections, they were trying to relate them to the pattern of movement they have previously observed.

A new mode of discourse: Translating the movement into functional parts

The participants' mode of discourse reflected their new focus of attention on the robot's structural parts, but was also linked to their former involvement with the robot's pattern of movement. In this phase, they were trying to translate the pattern of movement they have previously observed to LED, bricks, parts, and the interconnections among them:

Loretta: "When the one sensors hits, the lights on the blue box ...the light on the blue box lights up and stays lit. Each time it [the robot] changes directions, the blue lights switches to on or not on."

(First experiment, first hour)
Donald: "What it really is, is it's two (...) separate, aae, gears (...). But that also explains why it's [the robot] switching at the end. It stops itself, it first switches to the other sensor...."

(Second experiment, first hour)

Donald: "OK, so the lighting goes: both of them on, then the right, then the left. (...)"
Ann: "And the behavior is... clockwise, pause, counterclockwise."

(Second experiment, second hour)

The robot's pattern of movement was now reestablished in terms of structure and function:

Liz: "It's changing, this wheel operates and the snap makes that wheel operate. That's why it changes direction."

(Second experiment, second hour)

Liz: "Why does it? (...) So there's differential speed to the wheel. (...) So you've got a longer belt! Ann: "Yeah" / Kevin: "Yes." / Liz: "So that means that this thing is slower." (...) Kevin: "Well, the problem is that when we turn it on, this one [wheel] just doesn't go. It somehow doesn't get into as much traction. Umm. It's perhaps because... Oh! The tension is not the same. (...) This one is tighter." (...) Liz: "So there is a lot more slippage on this belt."

(Second experiment, second hour)

The robot's movement was now translated to hypotheses and explanations related to the "speed" and "direction" sockets in the motor:

Donald: "This says speed, here. I wonder if we could adjust the speed."
Ann: "Oh! If we could change how fast it spins."

(Second experiment, first hour)
Sam: "Maybe that's what it is... a set speed. (...) speed, direction. (...) When it's in forward, it reverses."

(First experiment, first group, second hour)

Ellen: "This was connected to that direction. So light determined the change in direction, now it's gonna do the speed because we just plugged it into the speed."

(First experiment, third group, second hour)

Phenomena the participants have previously seen, like the sound stimuli activating the robot and making it move, were transformed now into second-phase accounts related to the interconnections between the motor and the sound sensor. Distinctions between sound stimuli that activated the robot and those that did not, generated explanations about the processing of sound stimuli:

Donald: "If the sound met some criteria, that's an on, if the sound didn't meet some criteria, that's an off".

(Second experiment, first hour)

The new observations, explanations, and hypotheses relating the robot's parts to its pattern of movement created new problems for the participants' exploration.

New problems: Exploring patterns related to parts

The participants were now asking a new kind of questions, looking for new patterns. Just as they were previously looking for patterns in the robot's movement, now they were looking for patterns related to sensors, wire connections, LED, and logic bricks.
For example, when the participants were exploring the LED, they were comparing different LED to each other, trying to understand patterns related to them:

- “Now why is this constant and this blinking?”
- “Oh, you see, it goes either on or off. But the green one stays”

  (First experiment, second group, second meeting)

Kevin: "We have enough energy for the LED. Donald: "Yeah." (...)
Kevin: "Because this was on with the other one too... Oh..."
Donald: "No, because this light stays on".

(Second experiment, second hour)

Focusing on parts and their interconnections

During this phase the participants followed wire connections, relating one brick to another:

Donald: "This one goes to this blue, and where does this one go?"
Ann: "To that one. Where's this go? Oh, this goes to this box."
Donald: "Aae, there's the one, there's the one coming in to the box (...)"

(Second experiment, first hour)

Liz has recently joined Ann, Donald, and Kevin. Now she looks closely at their robot and starts following with her finger the wire connections.

Liz: "So this thing is connected to this, which is connected to that...."
Donald: "Well, if you want to look at it from [the point of view of] wiring, probably look from the sound coming in," / Liz: "Ummm," / Donald: "Sound comes in," / Liz: "goes through here-" / Donald: "goes through here where it's converted to an electrical signal -" / Liz: "in here ," / Donald: "in the black." / Liz: "Yeah. It goes through-" / Donald: "It goes through there, comes into here..." .......

(Second experiment, first hour)
The participants also developed working hypotheses that were related to these wire connections:

- "Maybe we have to connect it to both! Let's connect it to both! ... Oh, there's only one place to put it in..."
  (First experiment, second group, second meeting)

In this phase, the participants sometimes started to build up new robots from parts, or "clone" an existing robot; at other times they changed the order of the components on a robot, and experimented with the function of each part:

- "So we spent most of our time physically working with the parts, explaining what connections worked and didn't work..."
  (First experiment, first group, second meeting)

When building a new robot, the participants set themselves specific goals, trying to make the robot perform specific functions and exhibit a specific pattern of movement. They attempted to accomplish this by using the different components they had at their disposal. For example, a team that was building a robot with the touch sensor said:

- "We need something to make it completely back...We need to add something else here. Maybe a timer..."
  (First experiment, second group, second meeting)

Building new robots or changing parts on existing ones could, indeed, create new patterns of movement, and take the participants off to uncharted territory. The participants developed an interesting strategy for dealing with this problem.
The new explorations, characterized by the second-phase attributes, were frequently linked to the first-phase mode of exploration. From time to time, the participants went back to the "behavioral" examinations characteristic of the actual phase. While trying to expand their understanding, they frequently alternated between the two modes of exploration. It seemed as if, while they were testing the water with one foot, they placed the other on the solid ground of their previous understanding. It looked as though the participants wanted to establish the connection between the new phenomena they were currently watching and those they had investigated before, in order to anchor the new understanding to the one previously constructed.

For example, after Donald and Ann changed a wire connection and examined the resulting change in the robot's movement, Ann wanted to make sure that the original pattern of movement was still the same:

\[
\begin{align*}
\text{Ann: } & "I just want to make sure that--" (...) \\
\text{Donald: } & "So let's, shall we try to move it to another one?"
\text{Ann: } & "No, I want to put it back to the way it was to see if it goes back to the same behavior". \\
\end{align*}
\]

(Second experiment, first hour)

The newly constructed understanding of the second phase was tested and assessed by using first-phase methods. When the participants developed an explanation in terms of wheels, LED, and other parts, relating them to the robot's movement, they went back to actual-phase experimentation in order to test, verify, and confirm their explanation:

\[
\begin{align*}
\text{Liz: } & "This wheel is being powered and then you snap and then it makes this one be powered." \\
\end{align*}
\]
Donald: "Well, the first snap has to power it. The first snap turns on this wheel. The second snap switches the power to this wheel and then turns it off."

Kevin: "Let's see that in action."

(Second experiment, second hour)

Lynn: "This one [wheel] as it turns, it turns that one." (...)

Lynn takes the robot and demonstrates to Rachel what she said, by rolling the robot on the table, without turning it on.

Lynn: "These wheels aren't motorized."

Rachel: "Oh."

Lynn: "Try it and you may prove me wrong."

(First experiment, third group, second meeting)

When the participants made any change in the wire connection, they often reverted to phase-one exploration. Even after predicting the resulting change in the robot's movement, they turned it on and tested its pattern of movement while clapping, snapping, or illuminating it with a flashlight.

"It changed, instead of plugging it into direction we plugged it into the speed!...So I guess it doesn't back up any more — let's change it again and see if it works."

(First experiment, third group, second meeting)


Donald: "You're OK there?" Ann: "Yeah!" Donald: "All right. So, then let's—" / Ann: "go back—" / Donald: "see what happens."

Donald turns the robot on and claps. They watch the robot. Donald claps again. Nothing happens. They start laughing...

(Second experiment, first hour)
To summarize, the participants often alternated between the two modes of exploration, making a change in the robot and immediately testing the effect of the change or the validity of their analysis.

The following table shows a fragment of one such example. In the episode, Beatrice and Molly were building a robot with a touch sensor.

Table 5.1: Alternating between modes of exploration
(An episode with Beatrice and Molly)

<table>
<thead>
<tr>
<th>Duration (MIN: SEC)</th>
<th>Activity</th>
<th>Mode of exploration</th>
</tr>
</thead>
<tbody>
<tr>
<td>01:13</td>
<td>Building the robot</td>
<td>B</td>
</tr>
<tr>
<td>00:04</td>
<td>Letting the robot go, watching it</td>
<td>A</td>
</tr>
<tr>
<td>00:03</td>
<td>Stopping the robot, analyzing its movement</td>
<td>B</td>
</tr>
<tr>
<td>00:04</td>
<td>Letting the robot go, watching it</td>
<td>A</td>
</tr>
<tr>
<td>00:35</td>
<td>Building the robot</td>
<td>B</td>
</tr>
<tr>
<td>00:11</td>
<td>Letting the robot go, watching it</td>
<td>A</td>
</tr>
<tr>
<td>00:12</td>
<td>Building the robot</td>
<td>B</td>
</tr>
<tr>
<td>00:05</td>
<td>Letting the robot go, watching it</td>
<td>A</td>
</tr>
<tr>
<td>00:23</td>
<td>Stopping the robot, analyzing its structure</td>
<td>B</td>
</tr>
<tr>
<td>00:14</td>
<td>Letting the robot go, testing its response to touch</td>
<td>A</td>
</tr>
<tr>
<td>00:39</td>
<td>Building the robot</td>
<td>B</td>
</tr>
<tr>
<td>00:08</td>
<td>Letting the robot go, testing its response to touch</td>
<td>A</td>
</tr>
<tr>
<td>00:14</td>
<td>Rewiring the robot</td>
<td>B</td>
</tr>
<tr>
<td>00:05</td>
<td>Letting the robot go, testing its response to touch</td>
<td>A</td>
</tr>
<tr>
<td>00:05</td>
<td>Rewiring the robot</td>
<td>B</td>
</tr>
</tbody>
</table>
The episode presented in table 5.1 starts when Beatrice and Molly almost finished constructing the robot. At that time, they turned the robot on and briefly tested its movement, analyzed that test, and watched it again. Then they continued building and changing their robot, frequently reverting to letting the robot move on the floor and pressing its touch sensor — a first phase mode of exploration. In the table, the first-phase mode of exploration is marked by A, second-phase — by B.

While alternating between the two modes of exploration, though, the participants sometimes did not alter their perspective. Although they were at the time pressing the touch sensor, or clapping and snapping to activate the sound sensor, and observing the robot move on the floor — they still focused on the operation of the sensor, LED, motor, gears, or wheels. The actual-phase mode of exploration served, then, their continued knowledge construction in the representational phase. Their second-phase point of view was reflected in the participants' discourse:

*Ann, Donald, Kevin, and Liz are watching a robot move on the floor. From time to time they snap their fingers, to make the robot move. They watch closely the LED. Liz: "And the lights [LED] conform." Donald: "And the lights conform. They show that... But we were looking this way, we haven't determined when that light--! Ann: "I think that might be the sound sensor." Kevin: "It's a motion sensor. Whether actually it's counting. And then when it blinks, it's probably indication, like it says: I'm changing direction."

(Second experiment, toward the end of the first hour)*

The four were watching the LED, relating them to the movement of the robot (the LED conformed to the movement; the blinking declared a change of direction). The
recourse to the first-phase mode of exploration, then, deepened and strengthened the ties between the first-phase and the second-phase ways of understanding.

Back to the first phase, grappling with a new problem

Sometimes, a change in the robot's wiring created a whole new problem. Unexpectedly, after being rewired, the robot started to "behave" in an unknown way. In such cases, the participants went back to the actual phase. Since they did not recognize the new pattern of movement of the robot, they needed to start exploring it anew, through their actual actions and observations. In cases like this episode, both the mode of exploration and the mode of discourse of the participants reflected the return to the actual phase:

Donald: "Here's another hole. (He disconnects the wire and reconnects it to the socket he just discovered). I can't say exactly what."
Donald put the robot on the floor and lets it go. He claps.
Donald: "It's not a bit...I wonder what we're doing to it. Doesn't look as healthy."
Ann: "It does, seem, slower. (She laughs). It's dying."
Donald: "Look at that. See, we've definitely changed him. He's no longer behaving the way it did at all." / Ann: "Now this is--" / Donald: "Look at this! (clapping). (To the robot): Hey!! (He laughs). Ann (clicking her fingers, calling aloud to the robot): "Hey!!"

(Second experiment, first hour)

The rewiring of the robot created a new problem and, in order to understand it, Ann and Donald started again to explore the robot from the beginning of the first phase.

Unlike cases in which the change of wiring created unpredictable pattern of movement (thereby generating an unfamiliar problem), the explorations of existing wire connections and the
relations between bricks brought increasing understanding of how the robot's parts functioned. This understanding gradually led to the third phase, the abstract one, with a different perspective on the function of the robot's parts.

(iii) The abstract phase:

In-Depth, technical Investigation

Donald: "...We wanted to change the agenda. (...) We actually wanted to break it all down into all of its component pieces and testing it back up from the power strip on up."

(Experiment 2, group discussion)

Like each of the previous phases, the abstract phase had its own characteristics. During the abstract phase, the participants no longer explored the robot as such. Now they were disassembling the robot and exploring each brick separately, investigating its signal transmission, and comparing the way signals were transmitted by different bricks.

From robots to bricks: A different mode of exploration

In contrast to the first phase mode of exploration, in which the robot was moving on the floor, and the second phase one, in which the participants held the robot in their hands, they now took it apart altogether:

Donald to Jean: "OK, All I did was take everything apart, everything off, it is all separated and all the wiring out."

(Second experiment, fourth hour)
In this way, the participants could select a single brick and explore it separately:

*Donald*: "Uhmm, and before, we can just try testing some of the parts too, just one at a time to see what these things do."

(Second experiment, fourth hour)

Having reduced the problem to isolated bricks, this mode of exploration sometimes generated a more systematic investigation than observed in previous phases. When dealing with a single brick, the participants could more easily isolate and change one variable at the time:

*Donald*: "I just think, it's too complicated as a variable as it all put together, and if we took it all apart, and just built up--"

(Second experiment, beginning of the fourth hour)

In the first experiment, Dorothy came for additional time after her two sessions were over. She chose one brick of each kind from the collection of spare parts. She set the bricks on a paper, and wrote down next to each brick its name (as was marked on the spare-parts drawer). Then she systematically connected one brick at a time to a battery and to a motor, and explored what each brick "did":

- "So you've written the names of all the pieces, and now you're trying one by one?"
- "To see what if anything they do."

(First experiment, third hour)

The answers to the question: 'what did the bricks "do"?' entailed a new perspective. During the abstract phase, this perspective was translated to a new mode of discourse.
Donald: "These white ones are the ones that must connect to the bottom of this in order to make a current."

(Second experiment, fourth hour)

In the abstract phase, the participants developed a new perspective for explaining the functioning of the bricks. Now they were looking for indications to such abstract constructs as current and circuit:

Donald: "It's gotta go up from one row and complete the circuit through the motor and back down the other way. If we're through here to here, (...) we're never completing the circuit."

(Second experiment, fourth hour)

The participants used now a yet different mode of discourse, "techno-talk", which reflected their new way of thinking. They started to explain the way the sensors functioned by translating the sensor's operation to signal transmissions:

Donald: "Let's say your touch sensor, like if you wanted to switch directions (...) You just wait for a second signal."

(Second experiment, fourth hour)

Marvin: "When you hit it [the touch sensor], it turns that light on. (...) This light sends to the dial..."
Liz: "Sends WHAT to the dial?"
Marvin: "Sends the signal."
Liz: "OK."

(Second experiment, fourth hour)

They also explained the logic bricks in terms of on/off signals:
Kevin: "An 'or' says either one of them coming in has to be on, and it can spit out on. 'Not' is a switch. If it's on, turn it off."

(Second experiment, fourth hour)

The new mode of exploration also solved the puzzle of the "mystery box", the blue brick, which they could not figure out previously:

Marvin: "Yeah, what happens with the blue box, stays however it was until it gets a signal / Ann: "To toggle." / Marvin: "to toggle. aae...(...)\n
Kevin: "That's what that little wire was doing in the (...) / Liz: "It was turning it off." Kevin: "Yes, by passing it over and saying: switch from whatever you are and... and stay that way."

(Second experiment, fourth hour)

In their new explorations, the participants also looked at the interconnections between bricks as input and output:

Marvin: "If you did something like a toggle into this. (...)"
Kevin: "Now it has some sort of input going in and it would turn it on."

(Second experiment, fourth hour)

Ann: "So this is an input. Um, the light into the speed ..."

(Second experiment, fourth hour)

Donald: "So this one operates as a sensor, but its... its output that it sends is (...) a switch output, doing opposite of what you're doing."

(Second experiment, fourth hour)

Jean: "Look at this one, look at my speed."
Donald: "Pulsating! (...) That's a pulsating output!"

(Second experiment, fourth hour)
A term like "pulsating output" is probably one that would not be found in a textbook. While exploring the phenomena they encountered, the participants freely created terms to account for their observations.

**Forming their own language**

During the experiments, the participants developed their own understanding without any guidance in a domain with which they had no familiarity. Under these conditions, they used language creatively and sometimes invented their own terms when referring to signals.

Rachel, for example, used the Lego-LOGO term "talk to" in her explanation of the robot as a system transmitting signals. "Talk to" stood for the same abstract function as signal transmission in the communication between bricks:

"You want these parameters (shows the bricks) to talk to each other, how do you make them talk to each other? [shows a wire]: You know, that's the way they 'talk to', that's like you write 'talk to'. So now you want which parameter you want to talk with which parameter (...) and you're creating different dialogs through these wires (shows the wires). So I would feel more comfortable to decide myself which one I want to talk to which one. Do I want to talk to- to say to another part 'go when there is light', so 'go' means movement, so I need the movement parameter to be connected to the light parameter. I think this is the easiest way for me to look at it."

(First experiment, first group, her fourth session)

Rachel thought of the communication between the bricks in terms of the Lego-LOGO command 'talk to'. The wires, connecting between the bricks, as if transmitted that command. In this way, communication between the bricks (the light sensor and the
motor) could be formed, and 'the movement parameter' could 'be connected to the light parameter'.

Later, Dorothy commented on Rachel's explanation, indicating her own way of understanding the "communication" between the bricks:

"I understand what she says about 'talking to'. I don't think I think of it as 'talking to.' (Thinks for a moment). You know, the electric current has to flow from the battery to the motor, the power or whatever it is, and it has to be in the order that... [referring to the order of the bricks]. (...) And so it's a matter of really understanding what these command-blocks in here are doing."

(First experiment, first group, her third session)

Like Rachel, Dorothy understood the system in an abstract way. However, her own way thinking was in terms of electric current flowing from the battery to the motor and through the bricks, in the order in which the bricks were connected. Dorothy, in turn, used her own term: she called the bricks "command-blocks", indicating that she thought of their function in an abstract way.

In the second experiment too, the participants used their own terms to describe the phenomena they observed and analyzed. Here are a few examples, picked from different times across the second experiment:

Ann: "Now, put an impulse in speed."
---
Kevin: "Were you, aae, output speeding?"
---
Donald: "Its output that it sends is a switch.... a switch output."
---
Marvin: "If you have a delay hooked into this flashing circuit, (...) the delay keeps it running through both of the flashes."
---
Liz: "Well, well, well, bolt jiggles but the result is that the machine turns when one of the wiggles, one of the wheels is jiggling."

(Second experiment, fourth hour)

As weird as these sentences may sound, each of them made perfect sense in its context. These sentences were completely understood by the other participants, and they clarified the way the participants understood the robot as a system of signal transmission. These creative and inventive expressions served their task: to represent, communicate, and share their understanding, putting meaning and finding patterns in the phenomena they were exploring.

Looking for patterns in signal transmission

In the first phase, the participants were looking for patterns in the robot's movement. In the second, they were looking for patterns in the LED, and relating them to pattern in the robot's movement. In this phase, they were again looking for patterns, though of a different kind:

Donald: "It's following the same pattern. Two, three, right? There is on, off, two, the first time it goes off it stays off for one, the second time it goes off, it stays off for two. So (...) the next time should be on, off, on, on, off. That means the first time...
Jean: "Two offs in the row."

(Second experiment, fourth hour)

Donald and Jean were looking for patterns in the signal transmission — in the on/off states of the bricks. Furthermore, just as they did in the second phase, relating the new patterns to those observed in the first phase, so they did now. They were relating the
pattern they were observing now to their previous second-phase exploration, when they explored the sequence of operation of the two blue bricks.

Like Donald and Jean, other participants made connections between the phenomena they explored in the third phase to those previously explored. Ann, for example, was relating the LED to the signal that the motor receives through the speed socket and relating the two patterns:

Ann: "Those lights flashing will make it go on and off. So speed is going on and off in synchronization with the lights flashing."

(Second experiment, fourth hour)

Representation of the previous phenomena they have explored in the previous phase, therefore, served them when they analyzed the transmission of signal in the third phase. For example, when Ann, Liz, and Kevin were trying to explain the way in which the blue boxes operated, they related on what they had observed previously, during their second-phase explorations:

Ann: "Because think about it, we never saw them both go off or them both go. (...)"
Liz: "No, no. (they laugh). No wait, because there were two blue toggles in the circuit, sometimes it would run --> Kevin: "In one way." / Ann: "No, one has to ... one has to be in .. at one point in the circuit, so when we do the snap it was always the right one that went off first."

(Second experiment, fourth hour)

Previous knowledge, developed during the previous phase, directly contributed to the process of knowledge construction during the third phase.
During the second phase, the participants went back to the first-phase explorations, to test their understanding and assess it. Similarly, during the third phase, the participants often used the typical second-phase and even first-phase modes of exploration.

*Dorothy is experimenting with single bricks, mounting them one at a time on a motor and a battery mounted on a wheel base. From time to time she looks at her notes.*

*Dorothy connects a brick to the motor. Then she turns the battery on. Nothing happens. She looks perplexed. She fastens the brick, the motor, and the battery to each other. Then she turns the battery on again. The motor starts working. Dorothy puts the 'robot' on the floor, lets it go and, using a flashlight, she illuminates the brick. She stops, looks again at her notes, and again flashes light on the brick while stopping the robot with her other hand. Then she turns a dial on the brick. The robot starts moving the other way. Dorothy flashes light on it again.*

In this part of the episode, Dorothy tested the robot by going back to the first-phase mode exploration: illuminating it with a flashlight and testing its response while its moving on the floor. After doing that, she "revisits" the second-phase mode of exploration:

*Dorothy picks the robot up, holds it in her hand and, while holding it, illuminates it with the flashlight while holding it. She flashes light for a while, then directs the light away from the robot and continues to alternate between flashing light on the robot and observing it without light. All that time, the robot is turned on while she is holding it in her hand.*

(First experiment, third hour)
When the robot is turned on but held in the hand, its noise and the direction in which the wheels turn give indication of its response to the stimuli. Just as the other participants (and she herself) did during the second phase, so did Dorothy now.

Like Dorothy in this episode, other participants explored the bricks during the third phase by using the first- and second-phase methods. Those modes of exploration could give them indication of how the bricks operated, as well as strengthen the links between their different levels of understanding. The backward transitions to the previous modes of exploration served this phase, then, in a way similar to the way they served the second one.

Re-establishing previous knowledge apparently was more necessary than it seemed to an outside observer.

Rediscovering old facts? The importance of backward transitions

Jean: "But this is supposed to be sensor."
Donald: "What is this bumper?"
Jean: "I don't know, I thought it was a mike thing, but it doesn't start and stop with voice."
Donald: "Is it a light bulb?" (he puts his hand over, above, and around the brick).
Jean begins to clap and says: "It's not switching directions."

(Second experiment, fourth hour)

Not only did Jean and Donald go back to a previous phase of exploration, they also raised questions that I assumed were crystal clear to them by now. They already knew how the light and sound sensors looked. The robot that Donald has explored for three hours by now had a sensor similar to the one Jean was currently experimenting
with. He and Ann noticed that it responded to touch as well (the robot reacted when it touched the box), and discussed the possibility that the touch generated a sound. Furthermore, for the last hour and a half Jean has explored the same robot after joining Donald’s group. Still, amazingly enough, Jean and Donald raised the question what that sensor was.

It seems that previous knowledge has to be assessed and reassessed over and over, coming to it from the point of view of different levels of knowledge. At each phase, knowledge may be assessed anew, as is done in this example by Jean and Donald. If that may be the case, backward transitions are all the more crucial — having an extremely important role in creating consistency between segments of knowledge constructed at different levels. Links to previous phases of exploration may, thus, be more necessary than it seems, in order to integrate previous knowledge into higher levels of understanding.

To answer their question and find out what the sensor did, Jean and Donald started to use the same old methods of the previous phases: they clapped and put a hand over the brick and around it:

\begin{quote}
Jean presses a part on the sensor and it reacts.
Donald: "Bingo. Oh, it’s a touch sensor... it is depending on how much pressure..."
Jean: "So when you go into the wall..."
Donald: "Aae, you go into the wall, it changes directions and backs out."
\end{quote}

Jean and Donald found out again that the sensor reacted to touch (although they misinterpreted what the sensor was). Interestingly enough, what they wanted to know, in addition, was how a robot with that sensor would react if it bumped into a wall (had they actually checked it, it would constitute a first-phase exploration). Although they did not actually try it, they represented that "behavior" while talking about it and analyzed it.
(...) Jean: "Touch it. It's not connected. So if that's true, then that's touch."
Donald: "It's touch but it's also... if you pull this thing off the top and the circuit already runs by itself, then..."

(Second experiment, fourth hour)

Revisiting the first and second phases of understanding, Jean and Donald continued to discuss the bricks and their interconnections at the third phase, starting to analyze the circuitry. Through their continued experimentation, they finally did identify the sensor correctly.

<table>
<thead>
<tr>
<th>New explanations for old problems</th>
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Through the new mode of exploration developed in this phase, the participants generated new explanations for the old problems they have previously pursued. They dealt again with the "speed" and "direction" sockets in the motor:

Kevin: "Speed is actually on and off."
Ann: "Yeah, I would say that."
Kevin: "So this is.--/ Ann: "Running or not."

(Second experiment, fourth hour)

Marvin: "Somewhere I figured out that (...) each motor has two slots in it. One that does speed and one that does direction. (...) / Liz and Ann: "Uhmm." / Marvin: (...) It gives the signal if the light's on..."

(Second experiment, fourth hour)

This time, though, as these examples show, they looked at "speed" and "direction" from the point of view of signal transmission ("on/off", "gives the signal").
Marvin and Kevin raised again the problem of the first robot they explored in the beginning of the experiment. In this phase, without looking again at that robot, just by thinking about it, they generated a whole new explanation for the way it operated:

Marvin: "So the first one [robot] we had... the first one we looked at? Must have had the light sensor. (...) So the ... light sensor was connected somehow into -- / Kevin: "Connected into the direction." / Marvin: "Into the direction, right." 
Kevin: "So that (...) we had no inputs going into speed because it was always on."

(Second experiment, fourth hour)

The new third-phase understanding also shed light on a problem that baffled the participants previously, leaving them with no explanations to what seemed to be inconsistent and appeared to make no sense:

Liz: "Oh that's the delay!" / Ann: "Yeah! / Liz: "Oh!. / Ann: "So that's what, what produces what we sort of thought was kind of this.-" /Liz: "chaotic." / Ann: "chaotic behavior." Liz: "Random. Random behavior." 
Ann: "Yeah."
Kevin: "That's fantastic."
They all laugh.

(Second experiment, fourth hour)
Method of analysis

The mode of exploration was analyzed for all the data in the second experiment. The data were videotapes of each of the activities that occurred during the experiment. A videotape could show an activity of one person, if that person explored a robot by him- or herself, for a while, or of a group. Groups consisted of 2-5 persons; the number of participants in a group changed from time to time, since the participants switched groups throughout the sessions.

In order to show the evolution in the distribution of modes of exploration across sessions, each session was analyzed separately. In each session, each activity was weighed by the number of the participants in that activity.³

In each videotape, each activity was divided into consecutive segments. Each segment ended when the mode of exploration changed. The modes of exploration in the segments were analyzed, coded, and tested for reliability (see chapter 3).

In order to calculate the distribution of modes of exploration in a session, the duration of each segment was computed. Segments were sorted then according to mode of exploration. For each session, the total duration of each mode (weighed by the number

³ At a given time, there could be several activities going on in the room. For example: one activity with two participants, another with one, and a third with five participants. If the activities were not weighed by the number of participants, an activity performed by one participant would weigh as much as an activity performed by five participants. To prevent such distortion, the activities were weighed by the number of people participating in them.
of participants) was summarized. The analysis presents the distribution of modes of explorations (in percentages) for each session.

(i) Modes of exploration in each session

| First session |

The distribution of mode of exploration in the first session is presented in figure 5.1. As the figure demonstrates, in the first session, 39.7% of the activities consisted of the first mode (mode A). The second-phase activities, manifested by mode B and AB alternations, amounted to 59.7%. These consisted mainly from mode B (39.2%), and less of alternation between the modes (20.5%). A small fragment of the activities (0.6%) indicated mode C (third-phase mode of exploration).

Figure 5.1: Activity in the first session according to mode of exploration

(Percentages)
Second session

While in the first session more than a third of the activity corresponded to the first-phase mode, in the second session the second-phase mode prevailed (see figure 5.2). Almost all of the activities (99.9%) corresponded to the second-phase mode. These activities consisted mainly of alternation between the two modes (97.5%). A fraction (0.1%) of the activity still represented A mode.

Figure 5.2: Activity in the second session according to mode of exploration

(Percentages)\(^4\)

\[B + AB = 99.9\%\]

\[B (2.4\%)\]

\[A (0.1\%)

\[AB (97.5\%)]

\(^4\text{Percentage is rounded}\]
In the third session, even the small fraction of mode A disappeared (see figure 5.3a). Mode B was still prevalent (74.5%), and mode C started to emerge (3.8%).

During the third session, Herbert and Cindy started their animation project. Their activity, marked "others", consisted of 21.7%.

Figure 5.3b presents the activities without the "other" category, in order to show the distribution between the modes A, B, and C. Figure 5.3b demonstrates that mode B amounted to 95.1%, and consisted mainly of alternation A/B (85.1%). Mode C accounted for 4.9% of the activities.

**Figure 5.3a: Activity in the third session according to mode of exploration**

(Percentages)

![Pie chart showing activity percentages]
Figure 5.3b: Activity in the third session

According to A.B.C modes of exploration

(Percentages, without category "others")

Figure 5.4a presents all the fourth session activities, including the animation project (which amounted to 26%\(^5\)). The figure demonstrates that the third-phase mode (C and ABC) became dominant (65.1%). Mode B decreased to 8.9%.

When the animation activities were deducted (figure 5.4b), the third phase exploration amounted to 87.9% of the activity, and the second phase to only 12.1%.

---

\(^5\) During the fourth session, other participants joined the animism project from time to time.
Figure 5.4a: Activity in the fourth session according to mode of exploration (Percentages)

- B (8.9%)
- ABC (9.2%)
- OTHER (26.0%)
- C (55.9%)

C+ABC=65.1%

Figure 5.4b: Activity in the fourth session According to A.B.C modes of exploration (Percentages, without category "others")

- B (12.1%)
- ABC (12.4%)
- C (75.5%)

C+ABC=87.9%
(ii) The evolution of mode of exploration across sessions

Table 5.2 summarizes the evolution of mode of exploration without the animation project. The table shows that the second-phase exploration peaked in the second session. It was somewhat reduced in the third session (due to the emergence of the third phase exploration), but still accounted to a substantial amount of the activities. In the fourth session, though, the second decreased significantly (12.1), and the third-phase activity became dominant (87.9%).

Table 5.2: Mode of Exploration — second experiment
(Percentages; third and fourth sessions without category "others")

<table>
<thead>
<tr>
<th>Session</th>
<th>1st phase</th>
<th>2nd phase</th>
<th>3rd phase</th>
<th>all phases</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mode A</td>
<td>Mode B</td>
<td>Modes A/B</td>
<td>Total</td>
</tr>
<tr>
<td>1</td>
<td>39.7</td>
<td>39.2</td>
<td>20.5</td>
<td>59.7</td>
</tr>
<tr>
<td>2</td>
<td>0.1</td>
<td>2.4</td>
<td>97.5</td>
<td>99.9</td>
</tr>
<tr>
<td>3</td>
<td>--</td>
<td>10.0</td>
<td>85.1</td>
<td>95.1</td>
</tr>
<tr>
<td>4</td>
<td>--</td>
<td>12.1</td>
<td>--</td>
<td>12.1</td>
</tr>
</tbody>
</table>

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The chapter examined the evolution of knowledge construction. The process of knowledge construction evolved through qualitatively distinct phases, each different from the other in the mode of exploration and in the mode of discourse that the participants used.

The phases evolved from an actual phase, based on actual actions and perceptions, to a representational phase, and then to an abstract one. Each phase entailed a search for pattern and for causal relationships; yet in each phase this search involved a different kinds of phenomena. In the actual phase, the participants looked for causal patterns related to the movement of the robot and the environmental stimuli. In the representational phase, they looked for patterns related to the functional parts. In the abstract phase, they looked for patterns related to transmission of signals.

The analysis of each phase indicates the differences between the knowledge developed in each phase. The meaning of the shift from one phase to another is explained and analyzed.

The participants' explorations were replete with redundant reiterations, which, on the surface, seemed extremely inefficient. The analysis demonstrates the importance of these redundant reiterations for building theories and understanding causal patterns, whether through knowledge structures of one phase or of another.

When the participants progressed to the second and third phase, they frequently shifted back to modes of explorations characterizing previous phases. These shifts helped create links between the knowledge structures that were developed in the different phases. Throughout the sessions, there was a gradual progress toward more advanced phases. Analysis of the mode of exploration that the participants used indicated that an
increasingly larger portion of the time was spent on explorations related to increasingly more advanced phases.

During the group discussion at the end of the second experiment, the participants talked about their experiences. Their reports added a personal voice to phenomena I viewed as an outside observer. Although they were deeply involved in the issues they were pursuing, they also felt a qualitative shift in their experiences, marking a difference between the sessions:

Donald: "In the morning, every group in the morning was basically explaining the phenomenon. (...) In the afternoon, we were using the knowledge trying to do something. We were either trying to alter them or to break them down and understand sub-pieces or to build different things."
INTERLUDE 5/6

ZOOMING IN ON THE PHASES

By now we have followed the evolution of the participants' understanding through a sequence of three phases. During these phases, the participants' modes of exploration and explanation underwent substantial transformations.

Chapter 5 characterized these phases and analyzed their attributes. The chapters that follow take a few steps further. Chapter 6 uses a developmental theory — Fischer's skill theory — to refine the analysis of the phases. Fischer's theory gives more depth and precision to the analysis. Using skill theory, the analysis differentiates sub-phases (levels within each phase). More importantly, the in-depth analysis of chapter 6 indicates how each phase develops out of the previous one. It gives meaning to the evolution from level to level and from phase to phase (capturing the dynamics of development), and compares that short-term evolution (microdevelopment, or microgenesis) to the longer-term one (macrodevelopment, or ontogenesis).

To compare microdevelopment and macrodevelopment is not an obvious thing to do. It contradicts some conventional assumptions we hold about thinking processes. The next chapter attempts to explain the meaning of such a parallelism, to indicate evidence for this parallelism, and to establish the value of viewing the common attributes shared by the two processes.
CHAPTER 6

DEVELOPMENTAL PARALLELISM:
MICRO- AND MACRODEVELOPMENT

Marvin: "I think the first thing [I noticed was] that I picked it up, and (...) it turned the other way and it ran back into that wall. The question was why is it running back into that wall? And it was a bit of trial and error".

In contrast to what grabbed his attention in the beginning, this is what Marvin said about what happened later in the experiment:

"[I] got entirely bored with watching it and decided to make something else. And (...) I wanted to figure out how the components break down so that I can make the kind of toy I want to play with."

(Second experiment, group discussion)

The transition between phases: Only a shift of interest?

One can explain the qualitative change in the participants' explorations as a shift of interest. At first, the robot's pattern of movement triggered Marvin's curiosity. He wanted to know why the robot kept moving toward the wall. However, as he and Kevin continued to explore the robot's movement, and as the answer to the initial question was gradually revealed, other interests emerged.

Such a shift of interest makes an intuitive sense: when we have answers to one question, if we still find the phenomenon interesting, it is because other questions
replace the first one. A shift of interest, then, could be a good enough explanation for
the evolution of phases in the exploration the robots.

However, it seems that a principle more general and deeper than a mere shift of
interest underlies the transition between phases. The phases evolved through a familiar
sequence — from knowledge based on actions and observations, through
representations, and to abstractions. This sequence resembles the sequence of
knowledge structures prevailing in child development.

The similarity between the short-term developmental sequence
(microdevelopment¹, or microgenesis) and the longer-term one (macrodevelopment, or
ontogenesis) is the topic of this chapter.

Likening the process of complex problem solving to child development from
infancy through adolescence is not intuitive. Not only is it unconventional, but it also
contradicts our traditional understanding of adults' thinking (and its supremacy over
infants' and children's thinking). Therefore, first I try to explain the argument
developed in this chapter and make intuitive sense out of it.

Even though the parallelism between micro- and macrodevelopment is not
intuitive, denying that parallelism leaves us with two microdevelopmental puzzles that
are no less mysterious.

---

¹In literature, both the term "microdevelopment" and "microgenesis" are used for the same phenomenon
(e.g., Flavell & Draguns, 1957). Following Fischer (1980) and Karmiloff-Smith (1979), the term
"microdevelopment" is preferred in this thesis. The term "microdevelopment" avoids confusion with
contemporary uses of the term "genetic", such as behavioral genetics or generally research related to genes.
TWO MICRODEVELOPMENTAL PUZZLES

(i) First microdevelopment puzzle: Why do older children and adults start performing like young children?

The first puzzling microdevelopmental phenomena is the following: Several researchers mention in passing that the performance of older children in the beginning of their experiment was similar to that of younger children. For example, Karmiloff-Smith and Inhelder (1974) indicate the similarity between the problem-solving sequences of 18-39 month olds and of 4-6 year olds. Like the younger children, the older ones started by pressing with a finger on the point of contact of blocks they tried to balance, although the older children proceeded to progress and developed more advanced strategies.

In a similar vein, Kuhn, Amsel, and O'Loughlin (1988), in their investigation and analysis of the development of scientific thinking skills, state that the initial performance of many adults is similar to that of children (p. 205).

These reports on the similarities between children's and adults' exploration form the first microdevelopmental puzzle. How can these similarities be explained?

The assumption underlying the question

As often is the case, a clue to an answer can be found by uncovering the assumption underlying the question itself. If we maintain that knowledge structures are unitary and universal, then we expect children who are at a concrete operational stage to perform on that stage across the board. Similarly, we expect formal operational children to operate on a formal operation stage on all domains and tasks.
However, this is precisely the assumption that attracted the critique of the contextual approach. Comparison of two classical experiments can illustrate the contextual claim and show its relevance to understanding microdevelopment. The first experiment is one of the well-known Piagetian conservation tasks.

| Beads and magic experiments suggesting an answer |

In one of his conservation tasks, Piaget put in front of children two similarly-arranged rows of beads. Both rows had the same number of beads and, indeed, the children judged them as such. Then, in front of the children's eyes, Piaget dispersed one of the rows, increasing the space between the beads, thus making the row longer. When asked, most children (at the ages of six-seven years or younger) said that the longer row contained more beads. Piaget concluded that these children could not conserve number (Piaget, 1952).

Compare this experiment to another, the "magic experiment", performed by Rochel Gelman (1972). In the magic experiment, children had to choose the winner of two plates in order to win a prize. On the plates Gelman put 2 or 3 green toy mice. According to the implicit "rules of the game", the plate with the bigger number was the winner (or, in another version of the experiment, the smaller number always was the winner). The children, through, were never told the "rule". They only found it out by playing with the experimenter. The "magic" was that, occasionally, the experimenter surreptitiously changed the number or the arrangement of the toy mice on the plates: took away one, added one, or changed the length or density in the way they were dispersed on the plate. When the number of the toy mice changed, the children showed surprise; when one toy mouse was missing, they often searched for it. But although they noticed changes in length or density, and often mentioned these changes, they behaved as though these displacements were irrelevant. As it turned out, then, in the
magic experiment, whether the toys were put together or dispersed, even younger children, at the age of 3 years, could judge the winner correctly with only few mistakes. In other words, they could conserve number.

Simplicity and familiarity of the task as the crucial attributes

Let us examine the differences between the two tasks—the Piagetian and the "magic" one. In the magic experiment, the numbers involved were small (2 and 3). The task was conducted within a playful setting, which is akin to the typical and familiar activities of children at that age. There was no verbal definition of the task. In other words, the task was simpler and resembled more the children's usual and familiar activities. When comparing the two tasks, then, the crucial issue seems to be the task's context—its familiarity and simplicity.

When may we expect a microdevelopmental sequence?

The comparison of these two experiments indicates that when a task is simple and familiar, children may perform at their best level of performance (as did the children in the magic experiment). Yet, on another task that is more complex and unfamiliar (like the Piagetian conservation task), children will perform at a lower level. Under some conditions, as children continue to engage a more complex problem and the problem becomes familiar, we may be able to observe a microdevelopmental sequence, in which the children gradually perform better.

This may explain why, according to the anecdotal reports mentioned above, the performance of older children and adults started, in those experiments, like that of younger children. When first encountering the task, as it was unfamiliar and may have seemed complex, older children as well as adults started performing at a lower level,
like younger children. While negotiating the task, though, they became increasingly familiar with it, and their performance improved.

Acknowledging the importance of the complexity and unfamiliarity of the context, without expecting similar performance in simple and familiar tasks and in complex and unfamiliar ones, explains the first microdevelopmental puzzle.

(ii) Second microdevelopmental puzzle: What is the parallelism between micro- and macrodevelopment?

The other microdevelopmental puzzle is somewhat related. In the literature, several researchers have discussed parallels between microdevelopment and macrodevelopment. Parallelism between developmental sequences can be defined as resemblance, correspondence, or analogy between these sequences. In other words, the parallelism insinuates a structural and functional similarity between the two sequences.

The claim for parallelisms and recapitulations between developmental processes of different times scale has recurrent — and has been much debated — during the last century. Siegel and White (1975) reviewed parallelism in time sequences pertaining to perception, cognition, learning, development, recovery, and disturbances of psychological functions.

Within this more inclusive scope, there are discussions of specific parallelism between micro- and macrodevelopment. The puzzling phenomenon, however, is that in this context, different researchers referred to a different kind of parallelism.
Parallelism between micro- and macrodevelopment: Four theories

Werner (1957) developed an orthogenetic theory, which described development as a process of differentiation and hierarchical integration. Werner claimed that this sequence holds both in micro- and macrodevelopment.

Vygotsky (1978) described development as a transition from interpersonal processes, between a child and an adult, to intrapersonal processes, in the child's mind. Wertsch and Stone (1978), adopting the Vygotskian paradigm, found that the same sequence holds in microdevelopment as well.

Karmiloff-Smith (1986a,b) developed a three phase model, according to which knowledge is redescribed and transformed from implicit to explicit knowledge. Karmiloff-Smith claimed that this transition occurs both in micro- and macrodevelopment.

Kurt Fischer (1980a) developed skill theory, in which he defined transformation rules for the transition between knowledge levels. These rules, according to Fischer, prevail both in micro- and macrodevelopment.

Perplexing disparities among the theories—refuting the claim?

Although the four theories entail parallels between micro- and macrodevelopment, each of them implies parallelism of a different nature. Each theory points at a different direction when indicating the parallelism between these two processes. Such contradictions are perplexing; the disparity among the directions indicated by different theories may hinder further research, unless it chooses one of the approaches and follows it.
However, by looking at the contradictions among these theories differently, the puzzle can be solved. Suppose there really is parallelism between the two processes. A possible explanation, then, is that each of these researchers uses his or her guiding theory as a lens through which to look at reality. Out of the overall parallelism between micro- and macrodevelopment, each theory selects some parallel aspects. Instead of seeing the differences among the theories as contradicting, then, we may assume that there is an underlying parallelism between micro- and macrodevelopment, which is corroborated from different perspectives by using different theories.

(iii) Where does the solution to the two microdevelopment puzzles lead us?

The combined explanation for the two microdevelopmental puzzles implies that if we take a task that is complex and unfamiliar, give it to older children, and give them time to explore the task and become familiar with it, we may expect a microdevelopmental sequence which will parallel macrodevelopment, and will start with a behavior similar to that of younger children.

Taking the same argument to the extreme, we may expect the same thing to happen if we take an extremely complex and unfamiliar task and give it to adults. Which is, indeed, what happened when the participants of this study encountered the little robots. As we have already seen, the problems were pretty complex, and certainly unfamiliar.

The solution to the two puzzles leads us to an explanation of why adults' microdevelopmental sequence may start at a lower level, somewhat similar to that of younger children. How young, though, was a surprise to me when I started analyzing the data from that point of view.
MICRODEVELOPMENTAL KNOWLEDGE STRUCTURES

Ann: "Look at, if we're just talking here, it doesn't start up. I mean it's a sharp of either the clapping or the snapping, it's more sharp noise, right? I'm talking pretty loudly here, / Donald: "Uhmm" / Ann: "right, and it's not, and there's background and it's not picking that up at all."
Donald: "Not only that but it goes not from the tal-king but the diff-erence in the loud-ness -- See, I think that it must have to sense that there's loudness difference..."

(Second experiment, first hour)

How to analyze rich, intricate, and free-flowing data?

Analyzing data such as the example of Ann and Donald, in which the two are creating problems, raising hypotheses, and building on each other's ideas is not simple. In this example, as in other episodes we have already encountered in the previous chapters, the participants' performance during the experiments was rich, intricate, and free-flowing. It had attributes more similar to real-life situations, with all their complexity, than to traditional experiments, which usually are more controlled. Analysis of this data from a developmental point of view raised a problem, then.

Context-specific structures, disregarding macrodevelopment

The way I confronted the problem was again based on the non-unitary contextual assumption. According to this assumption, it is possible to define knowledge structures within the specific context of the robots, disregarding the person's knowledge structures in other familiar contexts. In other words, the analysis can focus
on the context-specific structures and examine them independently of the ontogenetic stage in other domains.

How skill theory can be used across contexts

To analyze knowledge structures, I used Kurt Fischer's skill theory (1980a). Several attributes of skill theory facilitated its application for the analysis of microdevelopment. One attribute is its domain specificity. Skill theory examines knowledge structures as they manifest in behavior within a specific context. The domain- and context-specificity of skill theory can allow the examination of specific cognitive abilities, directly related to the task at scrutiny. As a result, it is possible to analyze specific abilities that evolve during microdevelopment within a given context.

Skill theory is also relatively easily applicable to new contexts. The theory gives clear rules and operative categories by using behavioral indications. The structure of the levels (i.e., sensory-motor single sets; mapping between sensory-motor sets, etc.) is general and abstract enough to allow the generation of operative categories within new contexts (by identifying single sensory-motor sets in those contexts, mappings between such sets, and so on).

Taking skill theory's definitions for levels, I constructed parallels for those definitions applied to knowledge structures in the specific context of the robots.

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2 Fischer (1980) uses the term "skills" to indicate control structures of behavior. Instead, the term "structures" is used here. "Structures" convey the underlying organization of knowledge implied by behavior (as in skill theory) and, especially (after the acquisition of language), by statements.
Table 6.1: Application of skill theory's second representational level to the robot's context

<table>
<thead>
<tr>
<th>Skill theory Definition</th>
<th>Robots' Context</th>
</tr>
</thead>
<tbody>
<tr>
<td>REP2</td>
<td>REP2</td>
</tr>
</tbody>
</table>

Representational mapping:
One representational set is mapped onto another representational set

Example:
A weight pulls the spring:
REP2 stands for the causal mapping between the spring and the representation of the weight:

[Stringing — Weight]

Example:
A sensor affects the robot's movement:
REP2 stands for the causal mapping between the sensor and the representation of robot's movement:

[Sensor — Representation of the robot's movement]

Table 6.1 gives an example of the application of skill theory's definition to the context of the robot. The general definition is the same for both contexts. For instance,
according to skill theory's definition, in the second representational level, mappings between two representations are formed. To illustrate that level, take the example of a child who plays with a weight attached to a spring. In the second representational level, the child can understand the causal relation between the weight and the spring. In other words, the child can form a causal mapping between the length of the spring and the representation of the weight. Similarly, in the context of the robot, in the second representational level, a person can form a mapping between representation of a sensor and representation of the robot's movement.

| Surprise: Where does the sequence start? |

When I began analyzing the data, I thought that if the participants began the sequence earlier than their ontogenetic stage, they may have started at a representational level instead of an abstract one. I looked for representations such as REP2 level in Table 6.1, and indeed found them. Then I wondered whether the participants started with earlier structures and, indeed, I found those too. I continued looking for earlier and earlier knowledge structures and, finally, I went all the way back to early sensory motor structures and, to my amazement, that was where it all started.
THE ACTUAL PHASE, CORRESPONDING TO THE SENSORY-MOTOR TIER

The meaning of the actual phase

The actual phase accesses knowledge through actual actions and perceptions or, in other words, through sensory-motor structures. Saying that adults construct their knowledge through the actual phase does not imply that they behave like infants; that would be ridiculous. What such a statement does imply is that they access a problem through actual experimentation, by using sensory-motor structures, and that — because the situation is unfamiliar — they cannot yet access the problem through representations.

In some cases, forming representations is impossible, even for adults. Suppose, for example, that you see for the first time a new material, currently developed in experimental laboratories. How will the material react if you bend it? What will happen if you drop it? Were you not told how it would react, you would not know unless you tried. In order to represent the way certain objects react to specific actions, then, these reactions have to be known. When they are not, one has first to try and see what the reactions are.

"Sensory-motor knowledge" is based on actual actions and perceptions. It allows one to access a new situation when there is no prior information about it. Furthermore, when accessing a new task through sensory-motor structures, one may be able to perform, without first being aware of how one does it. Any person who — as an adult — learned to golf, ski, ice-skate, juggle, or dance may know it from his or her own experience.

In this sense, the following parallelism between the actual phase in microdevelopment and the sensory-motor tier (stage) in macrodevelopment should be read.
"Levels" — definition

The term "level" is used in this thesis to indicate a sub-division within a phase. Levels are used, then, in parallel to skill theory's use of the term; skill theory sub-divides each tier to levels; here, each phase is sub-divided to levels\(^3\). Levels within phases are, like the phases, not age-linked and a person can simultaneously be in different levels in relation to different contexts.

(i) First actual level, ACT1 — parallel to SM1

Applying SM1 definition to the robot's context

In skill theory, the first sensory-motor level is characterized by single sensory-motor sets (such as looking, touching, and so forth). The infant cannot yet relate these single sets to each other. For example, if the infant is in her crib, her arms flailing and knocking a mobile that hangs from the crib's hood, the infant can see the mobile move, but cannot yet understand the relation between her moving arm and the movement of the mobile.

Table 6.2 presents the parallel to skill theory's first sensory motor level (SM1). In the context of the robots, within the actual phase, the first level (which parallels SM1) is marked ACT1, indicating the first actual level.

\(^3\) The use of the term "level" in this thesis is to be distinguished from Karmiloff-Smith's use of the term. According to Karmiloff-Smith (1984; 1986a,b), "levels" describe changes within a domain in contrast to "stages" and "phases" that indicate changes across domains. While Karmiloff-Smiths's definition of "phases" was adopted in this thesis, the term "levels" follows Fischer's (1980) skill theory's definition.
Table 6.2: Application of skill theory's first sensory-motor level (SM1) to the robot's context

<table>
<thead>
<tr>
<th>Skill theory Definition SM1</th>
<th>Robots' context ACT1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single sensory-motor sets:</td>
<td>Single sensory-motor sets, related to the robot's movement, and related to the subject's actions: A participant does not understand the relations between these sets.</td>
</tr>
<tr>
<td>The child does not understand the relations between sets.</td>
<td>The participant does not differentiate between the inherent attributes of the robot and his or her own actions that influence the robot.</td>
</tr>
<tr>
<td>The infant does not differentiate between the inherent attributes of objects and his or her own actions that affect these objects.</td>
<td></td>
</tr>
</tbody>
</table>

Evidence from the participants' self reports

When the participants started their exploration of the robots, they did not differentiate between the inherent attributes of the robot and its reactions to what they did:
Dorothy: "At first it seemed pretty random, and then it became clear it wasn't random at all (...) Somebody would make a sound, it would change direction..."

(First experiment, first group, first session; group discussion)

The participants' reports emphasized the role that actions and manipulation of the object play for the construction of knowledge (note again the parallel to macrodevelopment, according to Piaget's theory):

Sally: "I wasn't being really observing until I felt like I was doing something. You know, I didn't just watch it so much until I felt like I could do something, like if I could shine a light on it and see it move. Then finally later I would notice that it was interacting with shadows and light and that it had been doing that even without me around, in a way, but somehow I wasn't watching for that..."

(First experiment, first group, first session; group discussion)

They noticed the robots' reactions to their own actions as well as to actions of others:

Loretta: "I thought: Gee, that's just programmed to go the same distance every time, that's going to be boring, and I was starting to turn toward those things that were sort of loud and calling attention to themselves when Jennifer walked by and it changed, when she's just gotten near it, it started to change its distance that it was going, and I was like: Oh!!!..."

(First experiment, first group, first session; group discussion)

The participants' reports during the group discussion indicated initial undifferentiation between cause and effect, between the robot's attributes and its response to their actions. They could report about their previous undifferentiation once those distinctions were already formed and therefore accessible to them:
Laura: "I happened to be standing in front of it and I didn't realize it. But then I moved away and I noticed my shadow was gone..."

(First experiment, third group, first session; group discussion)

**Evidence from the exploration data**

The intensive data collection of the second experiment exposed initial undifferentiation also in the way the participants talked about a robot while they were exploring it. For example, when Donald joined Ann, he first asked her about the robot's movement, referring to it as "doing what it's doing":

Donald: "And this one is --! Ann: "aae--" Donald: "doing what it was doing" Ann: "This is how" Donald: "when it started?"

(Second experiment, beginning of the experiment)

Similarly, when Kevin and Marvin first encountered their robot, they said, jokingly:

Kevin: "OK, this guy doesn't know what he wants / (Marvin joining him, saying together, laughingly) to do."

(Second experiment, beginning of the experiment)

Not knowing the robot yet, Kevin and Marvin, like Donald, referred to it in vague terms, without describing its pattern of movement—of which they were not familiar yet—and without referring to the stimuli causing its reactions, stimuli that were still unknown to them.

Initially, then, the robot's movements seemed random, sometimes constant, and uninteresting. The participants did not differentiate between a robot's movement and its response to their shadow or to noise they made. This initial undifferentiation, through,
lasted only a few seconds. When there was a change, due to their movement or action, differentiation started:

Laura: "And then I made a noise, of my notebook actually, and it stopped..."

(First experiment, third group, first session; group discussion)

(ii) Second actual level, ACT2 — parallel to SM2

Applying SM2 definition to the robot's context

In the second sensory-motor level, according to skill theory, single sets are mapped to each other (see Table 6.3). For example, at this level, when the infant's hand knocks the mobile and it starts moving, the infant can relate the movement of the mobile to her hand that just knocked it. In the robots' context, at the second actual level, the participants started to establish causal mappings between the stimuli that affected the robot and its resulting movement.
Table 6.3: Application of skill theory's second sensory-motor level (SM2) to the robot's context

<table>
<thead>
<tr>
<th>Skill theory Definition</th>
<th>Robots' context</th>
</tr>
</thead>
<tbody>
<tr>
<td>SM2</td>
<td>ACT2</td>
</tr>
</tbody>
</table>

Sensory-motor mapping:
One SM set is mapped onto another SM set

A child can use an action in order to bring about a second action
E.g. Touches a mobile — moves

A person performs certain actions in order to bring about a certain movement of the robot.
E.g. Touches a robot — moves

Evidence from the explorations: How are ACT2 structures formed?

An example from Ann and Donald's exploration can demonstrate the formation — the "birth" — of ACT2 structures:
Ann: "It's making a progression this way, yeah. It's not just spinning in place. (The robot stops). Oh! What - why. That's the o-- That's what I was, what caused it to stop."
Donald (loudly): "W E L L-" (The robot starts moving).
Ann: "Voice start! Voice!"

(Second experiment, first hour)

Table 6.4: Structure of understanding—ACT2

During ACT2 the participants started to form causal mappings between the robot's pattern of movement and their actions. For example, they made a sound — and one robot changed direction; they made a shadow—and another robot stopped its movement.

(iii) Third actual level. ACT3 — parallel to SM3

Elaboration of previous structures, forming variabilities

The third level, ACT3, involved increasing differentiation. The participants started to relate variability in their activities to variability in the robot's movement. They made comparisons between the different mappings they have noticed by that time. For
example, moving the hand above the robot made it react, while moving the hand in front of it did not:

"I'm not quite sure how I figured out that it was things above it that were making the difference. I think I had my hand and I was going back and forth to go in front of its bases and I noticed that it was not reacting to the front and back part, it was reacting when my hand was at the top. So we worked with that theory for a while."

(First experiment, first group, first session; group discussion)

In the example mentioned earlier (page 179), we saw that Ann was relating diverse sounds to the way they affected the robot, forming a system of variabilities:

Ann: "....Look at, if we're just talking here, it doesn't start up. I mean it's a sharp of either the clapping or the snapping, it's more sharp noise, right? I'm talking pretty loudly here, / Donald: "Ummm" / Ann: "right, and it's not, and there's background and it's not picking that up at all."

(Second experiment, first hour)

Extracting ACT3 structure of knowledge out of data

Ann put together the variabilities of the sound stimuli, on one hand, and variabilities in the corresponding movement of the robot, on the other. In this way, she formed a system, ACT3 (see table 6.5).
Donald, in his answer, continued to add mappings to this system (see table 6.6):

Donald: "Not only that but it goes not from the tal-king but from the diff-
ere-cence in the loud-ness -- See, I think that it must have to sense that there's
loudness difference..."

(Second experiment, first hour)
Table 6.6: Structure of understanding—ACT3

(Second example)

<table>
<thead>
<tr>
<th>Talking</th>
<th>Goes not (doesn't go)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Difference in loudness</td>
<td>Goes</td>
</tr>
</tbody>
</table>

(iv) Fourth actual level, ACT4: Transition to the representational phase

Capturing on video the formation of representations

In skill theory's fourth sensory-motor level, the different variabilities of the sensory-motor system are chunked together and form one representation. This transition is as amazing in microdevelopment as it is in child's development. In order to show how the transition from ACT3 to ACT4 (or REP1) occurs, let us see an example of this transition, as captured on video. This example can also contribute to the explanation of why the ability to chunk variabilities does form a representation. The episode is a larger context to an example that was previously analyzed (see chapter 5). Notice the actions David and Betty perform (underlined throughout the episode) and their conclusions (highlighted).
[Betty and David are exploring a robot that is moving on the floor. The robot has a light sensor, but they have not discovered that yet. The robot moves backward in shadow, forward in light, and oscillates on shadow edges].

David puts his feet along the robot's path. The robot moves forward, gets to David's feet, backs off, then goes forward, and so on. David puts his feet at the front and back ends of the robot's path. The robot's movement changes, the distance it passes shortens. Betty exclaims: "Ah!!" The robot keeps moving forward and backward between the feet. David says: "So it hesitates... with distance!" (...) David: "[unclear] the distance it travels." He puts his finger behind the robot. Betty: "You changed him -- [unclear]. David: "I changed him, by putting something behind him, like this -" He puts his finger in different locations behind the robot. Betty: "You changed him -- [unclear]." David: "Now look, it stops - Oh!- When I move my fing--" He tries again putting fingers in front of and behind the robot. (...) Betty puts her hand in front of the robot, and it goes backward. She changes slightly the position of her hand, and the robot goes forward. Again, she slightly changes the position of her hand above the robot. The robot makes a jerky movement. Betty says: "It's above." David repeats: "It's above!" Betty puts her hand behind the robot, and it moves forward. She says: "Here". She puts her hand in front of the robot, and it moves backward. She alternates her hand's position in front of the robot, behind, and above it, and the robot continues the same pattern of movement as it did before, with a jerky movement when the hand is above. David puts his fingers again in front of the robot and behind it. He puts his fingers at the sides of the robot. Then he backs away from the robot, saying: "It [unclear], if it keeps going forward?" The robot goes further forward, then backs again. Betty says: "No." David says: "Again, it will more rapidly go back and forth if it... somehow..." Betty: "Your hands were crossing." David continues varying the movement of his fingers around the robot, and says: "At one point it was like dancing..." He puts again his hand above the robot. The robot makes a jerky movement. David says: "Oh, st[p], yeah, if you go above

(First experiment, first group, beginning of the second session)

On reiterations and circular reactions

The continued variation and reiteration of David's actions, which are underlined in the example, are similar to children's circular reactions, described by Piaget (1952). The function of the variations in David's case is clear: to identify the conditions under which the causal relations between his actions and the robot's responses hold. (Probably, when a child drops something over and over again, her goal is similar: assessing the causal relation between his action and the result. See Ackermann, 1990, for analysis of the function of circular reactions). The example demonstrates that the continuous reiteration helped David and Betty to gradually eliminate alternative interpretations (highlighted throughout the example) and identify the correct causal rule, as discussed in chapter 5.

The continuous reiteration also serves another function. The diverse variations of his actions allow David to synthesize the information and extract the causal rule underlying it (see table 6.7). As the example illustrates, David tested how the robot responded to fast and slow movement of his fingers and hand, to putting his hand above the robot and at its side, to positioning his feet close the robot and further away from it, and so forth. It was the mental juxtaposition of all these examples that allowed him to chunk the information he has observed, extract the common denominator among these events, and understand the phenomenon on a higher level, when he said: "So it senses like the light? (...) So what am I doing — blocking the light?"
Table 6.7: Structure of understanding—ACT4 = REP1

<table>
<thead>
<tr>
<th>At the robot's sides</th>
<th>Shorter back/forth</th>
<th>Robot's movement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feet location</td>
<td>Robot's movement</td>
<td>Longer back/forth</td>
</tr>
<tr>
<td>Away from the robot</td>
<td></td>
<td></td>
</tr>
<tr>
<td>In front of</td>
<td>Shorter back/forth</td>
<td></td>
</tr>
<tr>
<td>Feet location</td>
<td>Robot's movement</td>
<td>Longer back/forth</td>
</tr>
<tr>
<td>Behind</td>
<td></td>
<td></td>
</tr>
<tr>
<td>In front of</td>
<td>Shorter back/forth</td>
<td></td>
</tr>
<tr>
<td>Fingers location</td>
<td>Robot's movement</td>
<td>Longer back/forth</td>
</tr>
<tr>
<td>Behind</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Slow</td>
<td>Shorter back/forth</td>
<td></td>
</tr>
<tr>
<td>Fingers movement</td>
<td>Robot's movement</td>
<td>Longer back/forth</td>
</tr>
<tr>
<td>Fast</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Above</td>
<td>Shorter back/forth</td>
<td></td>
</tr>
<tr>
<td>Hand location</td>
<td>Robot's movement</td>
<td>Longer back/forth</td>
</tr>
<tr>
<td>Behind</td>
<td></td>
<td></td>
</tr>
<tr>
<td>In front of</td>
<td>Shorter back/forth</td>
<td></td>
</tr>
</tbody>
</table>
Reprise: The intuitive meaning of the actual phase

Before David understood that the robot had a light sensor and responded to his shadow, he knew that when his feet were in a certain position, the robot moved in a certain way; when he changed the position of his feet, the robot moved differently; when he moved his hands in a certain way, again the robot's movement changed. Although he could change the robot's reaction by his actions, he could not label his actions and the ensuing responses of the robot, since it was not clear what exactly in his actions triggered those responses. At that time, he could control the movement of the robot, but without understanding why. His experimentation illustrated the essence of "sensory-motor knowledge" — knowledge based on actual actions and perceptions.

A self-reflective report written by Jim Parziale, my colleague who collaborated with me on reliability test for this study, illuminates this essence of sensory-motor knowledge. Jim started his acquaintance with the study by playing with the robots. He then wrote a report, describing his experience when interacting with the robots for the first time:

"... I clearly felt this when I tested the first wuggle with a shadow cast by my hand. When it responded to the change in stimulus I reacted and further changed and adjusted the shadow, but without a conscious understanding of what I was doing.

In other words, I quickly learned that I could control the wuggle's direction as it rapidly moved towards furniture, but how I was doing it was not at first available to me on a conscious level. I had to observe the actions that I was taking to steer the wuggle so that I could understand how I was doing it."

(Jim Parziale, self report)
THE REPRESENTATIONAL PHASE

The intuitive meaning of the representational phase

In the first phase, the participants could control the robots by their actions. They constructed their knowledge through actions and perceptions, but they could not yet label what they were doing.

In contrast, in the second phase, the quality of their knowledge drastically changes. For example, when David understood that a light sensor was involved, that the robot moved toward light, and that it moved backward in shadows — he could represent the robot's movement without actually observing it.

A short thought-experiment can clarify this point. Put yourself in David's situation. Suppose you knew that the robot moved forward toward light. You could infer, then, that if you put a lamp in front of the robot — it will go forward toward the lamp; if you flash light on it — it will move forward; if you put it close to a window, it will move toward the window. You could conjecture the ensuing movements of the robot without actually putting it in those places. Similarly, if you knew that the robot moved backward in shadow, you could infer that if you put it under a table, in the shadow, it will go backward.

Understanding the causality underlying the robot's pattern of movement, therefore, allowed the participants to represent the robots' movement without actually doing anything.

This is why, during the representational phase, the participants could hold the robot in their hand and continue exploring it that way. When flashing light on it, for instance, they already knew that it would go forward; they did not have to check that. They could focus their attention on other issues.
As a result, new questions emerged. As we have seen in chapter 5, in the representational phase the participants wanted to know why the robot moves forward toward light; why it stops when they make a sound. Now the participants usually wanted to know more about the robot's structure, in order to understand what caused that pattern of movement in reaction to the stimulus.

Representations — forming a different "language"

The episode with David demonstrates how the representations were constructed on the basis of the participants' actual experience. As we have seen in chapter 5, the representations also "translated" the first-phase experience into a different language, referring to the robots in structural and functional terms. The building blocks of the representational-phase language were sensors, logic bricks, wire connections, gears, and motors; they all represented certain patterns in the robot's movement.

Interestingly, the formation of a new language in the representational phase, at a microdevelopmental scale, parallels children's acquisition of language, at the macrodevelopmental scale. The new language in microdevelopment reflects the ability to represent the robot's movement; the development of language in macrodevelopment reflects the ability to represent objects and events.

The analysis of David's example explains the implications of the ability to represent. This new ability involves a different kind of understanding — understanding of rules, consistence of phenomena, and their causality. This explains why there is such a qualitative shift between the first actual phase and the continued experimentation in the representational phase.
(i) First representational level, REP1
(= the fourth actual level, ACT4)

Applying skill theory's definition of REP1 to the robots' context

As David's example demonstrates, in the first representational level the participants could represent attributes of the robot (such as responding to light) independently of their own actions on it. This knowledge structure is parallel to skill theory's definition of the first representational level in macrodevelopment (see Table 6.8).

Table 6.8: Application of skill theory's first representational level to the robot's context

<table>
<thead>
<tr>
<th>Skill theory Definition</th>
<th>Robots' Context</th>
</tr>
</thead>
<tbody>
<tr>
<td>REP1</td>
<td>REP1</td>
</tr>
<tr>
<td>Single representational sets:</td>
<td>Single representational sets:</td>
</tr>
<tr>
<td>Representing properties of objects, simple events and people independently of the participant's individual's own immediate actions</td>
<td>Representing properties of the robot independently of the robot immediate actions that affect the robot</td>
</tr>
</tbody>
</table>
ACT4/REP1: Transition between phases

During the first representational level, the actual knowledge, constructed during the actual phase, was put together, synthesized, and chunked into simple representations. As we have seen in the previous chapter, this transition involved translating the functionality of the robot (the way it responded to stimuli) to the functionality of its parts (what the sensors, logic bricks, and gears "did" to make it react the way it did).

What characterizes the first representational phase, in contrast to other representational levels, is a fuzzy, undifferentiated understanding of this "translation". The participants did not form yet mappings translating the movement to the functionality of the parts. Instead, they were asking questions related to this "translation"; they were striving to form this translation.

When Donald asked his question that marked the beginning of the representational phase ("how do you suppose this is really working"), Ann's answer reflected an attempt to translate the robot's movement to the operation of its parts:

\[
\text{Ann: } "\text{Well, if that's actually the sensor } (...)\text{, right, } / \text{ Donald: } "\text{Umm"} / \\
 \text{Ann: } "\text{its got to translate...it's got a motor, right? I mean it's got to translate the sound into aae, electrical signal, right } (...)?"
\]

In her answer, Ann did not assert yet the direct mappings related to their specific robot. She tentatively said "if that's actually the sensor", and suggested "it's got to translate", without yet indicating where and how this "translation" is done. Donald's answer had the same tentative quality:

\[
\text{Donald: } "\text{Well, does it translate the sound into electrical signal, or does it, to me, it seems like... I mean, it has to - it has to evaluate } (...)\text{ the sound.} \ni
dl
\]

(Second experiment, first hour)
Like Ann, Donald used a formulation ("it has to") which indicated a translation from the actual sound to its processing ("evaluate"), but did not specify how and where this was done.

This kind of formulations constitute the undifferentiated knowledge of the first representational level. Comparison with the following knowledge structures, at the second representational level, clarifies the distinction between the two levels.

(ii) Second representational level — REP2

Mappings between parts and the robot's movement

In the second representational level, the participants were relating the functional parts of the robot to the way the robot moved, and formed mappings between the parts and the movement:

*Marvin:* "There are two little lights, only one of it goes on at a time. (...) An it changes directions when the lights change."

(Second experiment, about 11 minutes after starting their exploration)

*Kevin:* "OK. This light here (he indicates a LED on a brick), this bottom one, says it's going in the direction towards this way."

(Second experiment, about 13 minutes after starting their exploration)

In both examples, Marvin and Kevin formed mappings between the LED and the robot's direction of movement.

The robot that Ann and Donald were exploring had a complex pattern of movement. While in the first phase Ann and Donald were exploring that pattern of
movement, in the second representational level they formed mappings between the sensor and the robot's movement:

*Donald:* "...It (...) lets the other sensor go and then--" / *Ann:* "and then it just stops" / *Donald:* "it stops."

(Second experiment, about 14 minutes after starting their exploration together)

---

**Mappings between parts**

In the second representational level, undifferentiated understanding related to sensors, parts, and the processing done by the robot's parts was established and got differentiated:

*Donald:* "These are probably two separate, aae, gears, and -- / *Ann:* "and the sensor is telling you which switch turn is setting it to" / *Donald:* "Yeah, and the sensor is going to tell which one is going to turn off."

(Second experiment, about 14 minutes since they started their exploration)

Like *Donald* and *Ann*, in the second representational level (REP2), the participants discussed connections between the sensor and other parts. They also used the LED as indication for these connections (see table 6.9):

*Donald:* "Oh, I see the lighting tells you when it's working on too, do you see that?"
*Ann:* "Oh, it's the wheel, right? Yeah."
*Donald:* "That's the wheel that is going around. / *Ann:* "Yeah" / *Donald:* "That's the side..."

(Second experiment, about 14 minutes since they started their exploration)

The participants also made mappings between the logic bricks and the gears or the robot's wheels:
Dorothy: "OK, so the inverter makes the wheels go backwards."

(First experiment, first group, additional third session)

At this level, the participants also started to map a property of one sensor to a property of another. By now, each property represented for them a familiar pattern of movement. For example, they mapped the way the sound sensor functioned (it was not working in the backward mode, i.e., when the robot moved backward) to the way the touch sensor did:

Jean (about her exploration with Sam: "We figured out some things we didn't even notice yesterday. (...) It has a touch sensor as well as the sound sensor that we found yesterday. But we discovered that none of the sensors work in the backward mode, the sensors only work when the creature is moving forward").

(First experiment, first group, second session; group discussion)

<table>
<thead>
<tr>
<th>Table 6.9: Structure of understanding — REP2</th>
</tr>
</thead>
<tbody>
<tr>
<td>(LED) light — the wheel that is going around</td>
</tr>
<tr>
<td>inverter — the wheels go backward</td>
</tr>
</tbody>
</table>
Table 6.9: Structure of understanding — REP2 (cont.)

<table>
<thead>
<tr>
<th>Sound sensor</th>
<th>Touch sensor</th>
</tr>
</thead>
<tbody>
<tr>
<td>doesn't work</td>
<td>doesn't work</td>
</tr>
<tr>
<td>in the backward mode</td>
<td>in the backward mode</td>
</tr>
</tbody>
</table>

The connection between bricks came to the fore in their exploration at this level:

Dorothy: "But they seem, it's like, probably, words in a sentence, they only make sense together.

(...) It seems like there's a couple of things I have to think about. One is what is the brick and what it's supposed to do, and two is the sequence they're hooked in."

(First experiment, first group, additional third session)

(iii) Third representational level — REP3

On the verge of REP3

In the second representational phase participants have related two sensors, but without further differentiating the variability in the operation of each of the sensors. In contrast, in the third representational phase (REP3), they make such differentiated coordination.
The emergence of this phase was indicated in Sally's statement, declaring what she would have liked to do, had she had another session (which she did not):

"We didn't quite get to the point of analyzing the effects of each of the pieces and how you'd have to, maybe remove a piece and reconnect it in a different way to see how that would change it. But some of it, you could still see, well - oh, it's a flip-flop, oh, it's connected to direction, so, no wonder it's going back and forth."

(First experiment, first group, second session, group discussion)

Sally talked about the connection between the flip-flop and the "direction" socket of the motor. Though she did not explicitly distinguish yet between different states in the flip-flop, she understood that its "flip-flopping" attribute, when related to direction, will affect the back and forth movement of the robot. Exploration in this line of thought could bring a differentiated coordination between variations in the states of the flip-flop and variation in the movement of the robot, forming a system.

In another example, after her third session, Lynn said:

"I originally thought that the engine was programmed to always go forward. I realized from changing plugs that the directionality is controlled by one of the plug outlets on the top of the little machine."

(First experiment, second group, additional third session)

Lynn referred to two sockets ("plug outlets") of the motor brick. A wire that connects a brick to a motor can be plugged to either of these sockets. Lynn mapped, then, two possible connections of the wire to states of operation (forward, backward) of the motor ("engine"). Although Lynn did not state yet these interconnections as a system, she indicated that she already somewhat understood them as such.
Ann: "Wait. This one is the connection to the front. This one the connection between-" / Donald: "Right" / Ann: "the two boxes."

(Second experiment, 16 minutes after starting their exploration together)

Ann and Donald were following wire connections between bricks. They were trying to understand the interconnections between those bricks. During these explorations, they formed systems, comparing different wires and the parts on the robot that were connected to them (see table 6.10).

By continuing to explore the interconnections between LED and the wheels, which they started mapping in the second representational level, Ann and Donald expanded these interconnections into a system:

Donald: "That light is certainly the left wheel, and that-" / Ann: "I mean, that gear" / Donald: "the left gear, and the right gear" / Ann: "gear, Yeah."

(Second experiment, 18 minutes after starting their exploration together)

Table 6.10: Structure of understanding — REP3

<table>
<thead>
<tr>
<th>This one (wire)</th>
<th>Connection to the front</th>
</tr>
</thead>
<tbody>
<tr>
<td>That one (wire)</td>
<td>Connection between the boxes</td>
</tr>
</tbody>
</table>
(iv) Fourth representational level, REP4
 (= first abstract level, ABS1)

A new qualitative shift: How abstractions started to be formed

During the previous representational levels, the participants have explored the interconnections between bricks, anchoring that understanding to the patterns of movement of the robot, and elaborating the interconnections between bricks to account for their variabilities. Having done that, the participants were now ready for the next qualitative shift. From their previous explorations they knew how the parts worked. Now they were interested in finding out why the parts worked the way they did. Why did the sensor make the gear turn at one time, and stop at another? What were the conditions that determined whether the parts worked or not? Looking for answers, they started exploring the level of signal transmission, power, and electronic circuitry.

The third representational level paved the way for the formation of abstractions, much in the same way as the third actual level prepared for the formation of representation. The participants have, for example, noted a multitude of variations in the activation of a sensor and the corresponding variations in the turning of the wheels. Now
they could chunk all these states together, and synthesize them into one system that conveyed and abstract idea:

Donald: "So if you put it under that, it works, but if you put it under that, it doesn't work. Just because it isn't a complete connection."

(Second experiment, fourth hour)

This abstract idea ("complete connection") could serve as an organizing rule, determining when the parts worked. At this level of explanation, systems of representation (variabilities in interconnections among bricks) could be linked together, as the example of Donald's statement demonstrates.

The previous exploration supported the current one with its new focus. Marvin's retrospective account of how he figured out the signal transmission in a robot (although conveying by that time a higher level of abstraction) traces back the deep ties between the previous exploration and the new kind of understanding. Marvin's account indicates how looking at LED and interconnections among bricks led him to understanding the signal transmission:

Marvin: "And you trace backwards from what's plugged into that to each of the sensors have a light on them. It gives the signal if the light's on, it doesn't if the light's off."

(Second experiment, fourth hour)

The new focus translated LED — light indicators— to signal or input:

Liz: "Wait a minute, what do you mean if you "switch it"? You mean, if it's on one?"
Kevin: "Whether there's... so a light going into it..."
Marvin: "Whether or not there's an input going into it."

(Second experiment, fourth hour)
The participants started, then, exploring the abstract function of bricks. As we have seen in chapter 5, instead of thinking of the robot's movement, as they did in the first phase, or on its structural connections, as they did in the second, in the third phase they started thinking of the robot as a system transmitting message, information, or signal. The interconnections between bricks were now understood in terms of flow of information, transmission of signal, or power circuits.

THE ABSTRACT PHASE

(i) The first abstract level — ABS1

Dorothy: "I know it's not going to run until I've got a complete circuit, so I've got to figure out...What I think it ought to be is from the sensor to the inverter, and from the inverter to the direction, that's what I have, but I don't have complete circuit..."

(First experiment, first group, her third session)

An undifferentiated, tentative start

Like the first formulations in REP1, the first abstract level was characterized by a global idea which was still undifferentiated. In the last example, Dorothy talked about a "complete circle". The transitional attribute of this level is manifested in the way it leans heavily on the previous representational structures. Dorothy related the circuit to interconnections between bricks — "from the sensor to the inverter, and from the inverter to the direction" — a compounded mapping of representations. This representational structure served as part of the new abstract structure, the "complete circuit".
As we have seen in chapter 5, the participants used different terms during the abstract phase. One of these terms was "power". In a tentative manner, similar to the one we encountered in the first representational level, Donald first used the term "power" in the formation of the first abstract level:

*Donald: "And it seems like, these are, seems like these are power strips."*  
(Second experiment, beginning of the fourth hour)

As in the first representational level, comparison with the more assertive mappings at the level ABS2 clarifies the distinction between the two levels of abstractions.

(ii) The second abstract level — ABS2

*Ann: "Whatever comes in, it changes it."

(Second experiment, fourth hour)

The way ABS2 grew out of ABS1: Comparing signal transmission

Once the participants started to look at signal transmission, the evolution of ABS2 out of ABS1 became very natural. Since they were focusing on signals, differentiation almost inevitably generated a comparison between two states, which led to mappings. Ann, in the previous example, compared two states — the signal coming into a brick, and the signal going out of it (see table 6.11). Kevin formulated a similar idea:

*Kevin: "Yellow ones are "ands" or "nors". They are a way of changing the signals coming in into signals coming out."

(Second experiment, fourth hour)
Comparison also generated differentiation:

Donald: "They're all the same."
Jean: "No, the direction thing could flip flops.. Flip flops it back and forth."

(Second experiment, fourth hour)

Abstract mappings started to form, then, through differentiation and comparison. Like the comparison of states on a brick, comparing two bricks in terms of signal or power also generated abstract mappings:

Kevin: "But you know that one of them is getting power before the other."

(Second experiment, fourth hour)

Table 6.11: Structure of understanding — ABS2

<table>
<thead>
<tr>
<th>signal coming in</th>
<th>signal coming out (changed)</th>
</tr>
</thead>
<tbody>
<tr>
<td>one (flip-flop)</td>
<td>another (flip-flop)</td>
</tr>
<tr>
<td>getting power (before)</td>
<td>getting power (after)</td>
</tr>
</tbody>
</table>
Kevin was comparing two flip-flops that were sequentially connected. The evolution of his explanation illustrates how focusing on signal transmission led to the formation of abstract mappings:

*Kevin: "We have these two blue things. They both get current when we turn it on. So we get current in order. This guy got it first, this guy got it second."*

(Second experiment, fourth hour)

**Linking levels of knowledge**

As they did in the other levels, at this level the participants also tried to relate their current way of thinking (about signal) to their previous understanding. The previous example illustrated how comparison of two bricks in term of signal is based on following interconnections between them, the way the participants did during the representational phase. However, the participants did more than that: they also tried to relate their understanding of the system in terms of signal to the movement of the robot:

*Dorothy: "After a set time it starts going forward, again. Is it because it's not a continuous signal?"*

(First experiment, first group, her third session)

Understanding on an abstract level contributed to their understanding of the movement of the robot when they could not understand that movement before. Such was the case with the "Wuggling" robot which Liz was exploring at the outset of the experiment. Now they could explain its movement:
Kevin: "Without an input it doesn't do anything." (...
"It would go forward, stop, forward, stop, (...) You see, but it would always stop whenever the blinking went off..."

(Second experiment, fourth hour)

(iii) The third abstract level — ABS3

Kevin: "On coming in, off going out. If it's off coming in, then it's on going out."

Following the path of differentiation: variabilities in abstractions

On a simple example like the previous one, the road from ABS2 to ABS3 seems very short. (Compare, for example, Ann's comment "Whatever comes in, it changes it" to Kevin's formulation in the example above). Once an issue is understood, in retrospect, the road seems short; it looks as though not much has been gained. But before that road is paved, it takes considerable experimentation to come up with such concise statements as the one Kevin said.

Like systems at the previous phases, ABS3 coordinates variabilities in two abstract sets. Kevin, in his simple sentence, compared a signal coming in with a signal going out, when each of the signals can assume two values: on or off (see table 6.12).

Other statements, taking a road less traveled, do not look as simple. Kevin and Marvin, for example, discussed the delay (timer brick) in the following way:

Marvin: "The dial, what the dial does is at one position that is how long it stays on, and as I switch the dial, it stays on longer... Kevin: "Aha."

Later Kevin says:
"And the delay, the delay only responds to a positive current- / Marvin: 
"Aae Hugh. / Kevin; "it doesn’t respond to the absence of current."

These two examples reinstate the flavor of the complexity of a system of variabilities, once it has to be developed from scratch. Marvin and Kevin could come up with systems such as those they mentioned in their statements only after a long experimentation. Noticing that there was some correspondence between the dial and a signal was not enough. They had to form differentiations related to the position of the dial and to the length of the signal and to correlated these differentiations, in order to express the relation the way Marvin did. Similarly, they had to make differentiations related to the operation of the dial, understanding when it responds and when it does not, to make differentiations related to the signal the timer receives ("current") and correlate these differentiations in order to express a statement like the one Kevin did.

Table 6.12: Structure of understanding — ABS3

<table>
<thead>
<tr>
<th>on</th>
<th>off</th>
</tr>
</thead>
<tbody>
<tr>
<td>signal coming in</td>
<td>&lt;--&gt;</td>
</tr>
<tr>
<td>off</td>
<td>on</td>
</tr>
</tbody>
</table>
Table 6.12: Structure of understanding — ABS3 (cont.)

<table>
<thead>
<tr>
<th>One position</th>
<th>How long it stays on</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dial</td>
<td>(signal)</td>
</tr>
<tr>
<td>Switched (other position)</td>
<td>stays on</td>
</tr>
<tr>
<td></td>
<td>longer</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Responds</th>
<th>Positive</th>
</tr>
</thead>
<tbody>
<tr>
<td>Delay</td>
<td>Current</td>
</tr>
<tr>
<td>Doesn't respond</td>
<td>Absence of</td>
</tr>
</tbody>
</table>

SUMMARY

This chapter traces the long road of evolution of a microdevelopmental sequence within the context of the exploration of the "Weird Creatures", in parallel to
macrodevelopment. The analysis takes off from the definitions set by Fischer's skill theory, and defines their parallels within the specific context of this study.

To set the groundwork for transferring definitions across timescales, the chapter starts by making the idea of parallels between micro- and macrodevelopment more intuitive. The first part of the chapter analyzes the implications underlying the assumption of unitary knowledge structures, gives interpretation to well known and less well known findings, and explains a seeming contradiction among several theories related to microdevelopment. An assumption of parallelism between the two developmental processes, it is claimed, can put at peace those different findings as well as the different theories.

Following the path of parallelism, skill theory's definitions are applied to the context of the "Weird Creatures". Each structure is demonstrated by statements the participants made during the experiments. Along the road, the analysis focuses on three points. One, it explains the meaning of skill theory's structures within the microdevelopmental sequence, trying to make them intuitive, while using the examples analyzed in the text. Two, the analysis highlights the transitions between levels and especially between phases. Using the demonstration of the examples, the way one level or phase leads to the formation of the other is explained in terms of evolution in the participants' focus and interest.

During the experiments, the participants went a long way. They started the experiments with diffuse understanding, entailing statements like: "this one is doing what it's doing when it started?" or: "this guy doesn't know what he wants to do." At the end of the experiment, their analysis of the robots was complex and intricate, like the following one:

Donald: "This depends on which way it's going. If we do it this way, it alternates. This one, they both come on, that one, they both come on. But if we put it on this way, this will always come on. No flip flopping."
The statement looks impressive. The participants really made a considerable progress, learning about the robots.

The sentence that Donald said, though, just before uttering those words, was:

"We already decided we don't know what's going on."
Chapter 6 laid the groundwork for analyzing microdevelopment with a macrodevelopmental tool — Fischer's skill theory. The chapter gave the rationale for examining the parallels between micro- and macrodevelopmental sequences and demonstrated the application of skill theory's structures to the context of the current study.

The next chapter makes a transition from the analysis of microdevelopmental structures to the dynamics of the microdevelopmental sequence. The continuous and full video and audio documentation of the explorations provided insight to one of the most interesting and intriguing questions in developmental research — the question of the mechanism of transition in cognitive development.

In the following chapter, three aspects to the mechanism of transition are analyzed — bridging, differentiation, and reiteration. Bridging is a process that creates a link (bridge) between two levels or phases. Bridging generates a tentative structure that enfolds elements of both levels or phases, and thereby serves for the transition between
the two. Five kinds of structures generated by bridging were analyzed in the data; these are discussed and demonstrated in chapter 7.

Another type of transitional mechanism is differentiation. Differentiation is one of the transformation rules in skill theory (Fischer, 1980a; see chapter 2), and is one of the cognitive processes highlighted by Werner (1948, 1956). The analysis of the data underscores the process of differentiation as an extremely important transformation mechanism. Differentiation proved to be most prevalent throughout the microdevelopmental sequences of the participants. Examples from the study highlight the function of differentiation and enrich our understanding of how it serves to trigger transitions from one level to another.

A third transition mechanism is reiteration. Reiteration emerged as a recurrent theme throughout the chapters of this thesis. It appeared in the analysis of phases in the analysis of levels within the phases. The previous encounters with reiteration are put together in this chapter.

The spontaneous formulations that emerged during the exploration was replete with partial formulations, implicit references, and simultaneous talk. These demanded a special treatment, which is also clarified in the chapter.
CHAPTER 7

ANALYZING A PROCESS:
TRANSITION MECHANISMS

Kevin: "Looks like we got a reaction there..."

(Second experiment, 23 seconds after starting the exploration)

The emergence of the transition mechanisms from the data

When Kevin said "reaction", he obviously meant that the robot responded to something. Since he was observing Marvin, who was putting his hand around the robot, and saw the robot's response, by "reaction" he probably meant the robot's reaction to something Marvin was doing.

The term "reaction" implies cause and effect, action and response (re-action). But is the cause and what is the effect in Kevin's statement? Kevin specified neither. It is not clear what exactly in Marvin's action was the cause, nor what the robot did differently as a reaction.

When analyzing the data, cases like this presented a problem. Although Kevin's statement implied a second level mapping between action and perceived response (ACT2), he did not say anything that could be put into skill-theory's structure of mapping [X — Y]. In fact, Kevin only used one term: reaction. Still, his statement indicated more than the undifferentiated ACT1, where cause and effect are still elusive.
TRANSITION MECHANISMS

(i) Bridging

The function of bridging

Kevin's statement is an example of structures generated by bridging — structures that indicate a transformation from one level or phase to the next. These structures serve as a bridge, enfolding the structure of a current level or phase with glimpses of a new one. Bridging serves as a "grappling hook", pulling the process of knowledge construction upward, toward the next level or phase. The tentative structures generated by bridging, then, precede and pave the way for more advanced ones.

During the exploration of the robots, subjects used five kinds of structures generated by bridging: bridging terms, bridging format, bridging question, bridging intention, and bridging reiteration.

Bridging term

Like the term "reaction", bridging terms are terms that contain the structure of the current level with elements of the next one. When using a bridging term, the participants expressed a statement that implied a more advanced level than they have ever shown previously. Yet, that statement did not explicitly specify the constructs of the more advanced level. Such was the word "reaction", which implied a causal mapping. Although Kevin could not yet specify neither the cause nor the effect of that mapping, the word "reaction" by itself set a foothold at that mapping, thus pulling his and Marvin's knowledge upward, toward the second level.
About two and a half minutes later, when Marvin used a flashlight to test the robot's reaction to light, Kevin suggested:

"Go all around it see what light does in various ...[locations]"

Kevin and Marvin have just established a mapping between light and the robot's reaction (a second level structure — ACT2):

[Light — Movement]

Now, without stating it explicitly, Kevin used the word "various", implying that in different locations, light may trigger a different response. This formulation implicitly alluded to a system (third level, ACT3), linking variations in light with variations in the robot's responses (see table 7.1), without saying that explicitly.

Table 7.1: Structure of understanding — Bridging term

(1) "Reaction"

(...?...) — (...?...)

(2) "what light does in various..."

<table>
<thead>
<tr>
<th>Light (in location 1)</th>
<th>(...?...)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light (in location 2)</td>
<td>(...?...)</td>
</tr>
<tr>
<td>Light (in location 3)</td>
<td>(...?...)</td>
</tr>
<tr>
<td>Light (in location 4)</td>
<td>(...?...)</td>
</tr>
</tbody>
</table>
As table 7.1 demonstrates, the formulation that would have comprises the more advanced structure is implied (marked in parenthesis) or missing altogether (empty parenthesis).

| Bridging format |

The second kind of structures generated by bridging is bridging format. In that structure, the format of the participants' statement (its template, or mold) indicated a structure of a higher level, yet the content they formulated did not.

For example, after Kevin and Marvin noticed that Marvin's hand triggered a change in the robot's movement, Kevin told Marvin:

"...maybe that's why you're getting a different reaction when you're putting your hand on it instead of when you put your hand..."

Kevin never completed his statement. The explicit information indicated a mapping between "hand on" and "reaction". Yet, the formulation "a different reaction" and "instead of when you put your hand" implied that there was more to it. The format of the statement, then, indicated a system (third level, ACT3): when the hand was on, the robot responded with one reaction, and when the hand was at another, unspecified location, the robot responded with another, different reaction. The information itself, the content that should have filled in that sentence format, though, was missing: what other position of the hand triggered another reaction was not clear at that point, or could not yet be easily expressed (see table 7.2).
A bridging format also served well Jean and Herbert. Jean and Herbert had difficulty distinguishing between two reactions of their robot — one, when it stopped, and the other — when it changed direction. Notice, then, Jean's formulation:

Jean: "...It might also be like (...) heat sensor, (...), and not shadow, like the closer it gets?"

(Second experiment, about 2 minutes into their exploration)

Jean's sentence conveyed an implicit mapping, although — conveniently enough — she omitted the confusing information. The format of the sentence implied a mapping: the closer the (hand) got to the robot — the more the robot was likely to react. Yet the information was missing: when the hand got closer — did the robot change direction? Or, when the hand got closer — did the robot stop? Since the reaction was not clear, Jean conveyed a mapping without filling in the information.

The bridging format, then, made a scaffolding for the next knowledge structure. It supplied a mold for the next structure, a mold that the next structure would eventually fill in.

Table 7.2: Structure of understanding — Bridging format

<table>
<thead>
<tr>
<th>Hand (at...?)</th>
<th>(a reaction)</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;––&gt;</td>
<td>a different</td>
</tr>
<tr>
<td></td>
<td>reaction</td>
</tr>
</tbody>
</table>
A bridging question is a question that pulls knowledge-construction up, toward a level above the one last evidenced. The question itself serves as a grappling hook, directing further exploration toward the more advanced level.

In the study, many of the participants' questions indicated, for example, causal mapping, without yet having any glimpse of the cause itself. Such was, for example, Ann's question:

*Oh! What, why. (...) what caused it to stop*

Or Jean's question:

*"But it keeps going in the same direction, so when does it change directions?"

The directive function of the bridging question can be demonstrated by a counter-question exchange between Kevin and Marvin:

*Kevin: "Oh, actually, does it have anything in relation to the sound of the tape recorder is playing?"

*Marvin: "The question is, is it doing something in relation to this?" While talking, Marvin turns the lamp around so that it projects light in the direction of the robot.*

(Second experiment, a minute and a half into their exploration)

Kevin's question outlined a mapping between the sound of the tape recorder and the movement of the robot. In order to answer this question, he and Marvin would have to make diverse sounds and test the robot's response. However, Marvin, who by that time did all the actual actions which Kevin only observed, was probably more convinced than
Kevin that the mapping involves light and not sound. Although the exact influence of light was not yet clear, by his counter-question, Marvin refocused the exploration on light. Indeed, the ensuing exploration concentrated on the effect of light.

Table 7.3: Structure of understanding — Bridging question

<table>
<thead>
<tr>
<th>Tape recorder’s sound</th>
<th>??</th>
<th>anything (reaction)</th>
</tr>
</thead>
<tbody>
<tr>
<td>This (lamp)</td>
<td>??</td>
<td>doing something (reaction)</td>
</tr>
</tbody>
</table>

Bridging question has, then, a directive function. Like bridging term and bridging format, bridging question creates a shell within which the next structure can grow. Bridging question traces a direction that helps navigate the process of knowledge construction.
When Jean joined Herbert, he told her:

"I'm trying to figure out if it changes directions on time thing or there's a sensor that does it and what the sensor is".

(Second experiment, beginning of the first hour)

Herbert stated his intention, which conveyed a causal mapping not yet affirmed. In this respect, bridging intention is similar to bridging question. However, the bridging intention often conveys a higher degree of certainty than a bridging question.

For example, when Marvin stated his counter-question mentioned earlier and adjusted the lamp, the robot indeed started moving steadily in one direction. At that time, Marvin proceeded to formulate two consecutive bridging intentions with increasing certainty:

The robot continues to move, passes under a bridge, continues to the other side of its environment, and stops close to a box.

Marvin: "Let's see if I can make it come back".
Kevin: "OK".
Marvin turns off the lamp close to the robot. The robot starts moving back.
Donald: "Now are you going to conclude from that that you made it come back?"
Marvin turns off the lamp in the first location and says: "We'll make it go back that way again".

(Second experiment, beginning of the first hour)

While reading the episode or watching it on videotape, it seems that at this point Marvin knew exactly what he was doing. However, the context and the following exploration indicated that this was not the case. At that time it was not clear what would
make the robot go the other way, since Marvin and Kevin have never done it yet. Marvin, as it turned out, could control the robot by actual actions, without realizing yet what exactly induced the robot's reaction.

Table 7.4: Structure of understanding: Bridging intention

<table>
<thead>
<tr>
<th>I</th>
<th>it</th>
</tr>
</thead>
<tbody>
<tr>
<td>make</td>
<td>???</td>
</tr>
<tr>
<td>(something...)</td>
<td>comes back</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>I</th>
<th>it</th>
</tr>
</thead>
<tbody>
<tr>
<td>make</td>
<td>???</td>
</tr>
<tr>
<td>(something...)</td>
<td>(will) go back</td>
</tr>
</tbody>
</table>

Although Marvin did not formulate the mapping explicitly, his statements did convey some mapping. With each reiteration, Marvin seemed to be more certain that he would be able to control the robot's. The first time he formulated his statement as a question: "...Is it doing something in relation to this?"; the second time, he declared it as an tentative intention: "Let's see if I can make it come back". The third time, the intention was more assertive: "We'll make it go back that way again".
Bridging intention, then, outlines a structure that, although not yet affirmed, its silhouette already exists in the participants' mind.

### Bridging reiteration

The last type of structures created by bridging is bridging reiteration. In this type of bridging, the participants formulate an idea twice. One of the formulations (usually the second, but sometimes the first) is more sophisticated, and gravitates toward the next phase.

For example, when Donald made differentiations related to the robot's pattern of movement in response to sound, he said:

"So it's going around, OK, (gestures clockwise), and then we get ready to stop it (claps), and before it stops, it turns around counterclockwise."

Then he reiterated the idea of the changed direction:

"All I'm saying is that it just changes directions where it stops, and then that puts, that sets it up in a different position to start the next time."

(Second experiment, 2'20" into their exploration)

Donald's first statement described a compound mapping in terms of actual actions and perceptions (ACT2/compound):

- We (the robot) turns it
- (clap) around stops
- counterclockwise
In his second statement, through, Donald tried to describe it from the point of view of the processing done by the robot, instead of referring to the perceived movement: "...it sets up in a different position to start..." Although the reiteration did not yet have the attributes of the representational phase, it did pull the formulation up in that direction, approaching a focus on the robot's processing and on the way its structure contributed to its reaction to sound.

In another example, Donald first suggested:

"It goes not from the talking but from the difference in the loudness".

Then he reiterated:

"It must have to sense that there's loudness difference".

(Second experiment, 5'13" into their exploration)

Although in both formulations Donald used similar words (difference, loudness), there was a difference between these formulations. The first related to actual actions and perception; it was based on observing the robot's movement and relating it to differences in the sound loudness. In contrast, Donald's reiteration concentrates on the processing of the stimulus by the robot (it must have to sense). As in the previous example, this formulation did not yet ferret out the structural attributes of the robot that made it do what it did. All the same, the reiteration outlined the direction of a new focus on the robot's way of operation, thus pulling understanding up, toward the next phase of thinking.

While the other types of bridging structures pull understanding toward the next level, bridging reiteration pulls understanding toward the next phase (which is also the next level when the current level is the third one).
Combination of bridging

After stating the mapping between sound and the robot's reaction, Ann asked:

"Is it, is it directional?"

Statements like this one combine more than one kind of bridging structures. In this example, Ann used a bridging term, while also formulating a bridging question. The term "directional" indicated that the robot would follow the direction of the sound: if the sound came from a certain direction — the robot will follow that direction. Ann and Donald have previously seen the robot turning one way and then the other. In this statement, Ann hypothetically alluded to relating variation in the direction of the sound to variation in the robot's movement, a third level structure (ACT3).

Having just discovered that the robot responded to sound (ACT2), Ann did not yet know if "it is directional". Her question formed a bridging to a higher level. Indeed, later she tested if clapping from different directions affected the robot's movement, establishing her knowledge at the level set off by this combined bridging.

Actual use of bridging

How frequent was the actual use of bridging? Table 7.5 demonstrates the number of bridging structures and their percentage out of the total number of stated structures during the first five minutes of the explorations for two teams — Kevin and Marvin, and Ann and Donald.
Table 7.5: Use of bridging
(During the first 5 minutes)

<table>
<thead>
<tr>
<th></th>
<th>Number of stated structures</th>
<th>Number of bridging structures</th>
<th>Bridging Structures %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ann &amp; Donald</td>
<td>37</td>
<td>12</td>
<td>32.4</td>
</tr>
<tr>
<td>Kevin &amp; Marvin</td>
<td>37</td>
<td>11</td>
<td>29.7</td>
</tr>
</tbody>
</table>

As table 7.5 demonstrates, both teams stated 37 structures during the first 5 minutes of their exploration. Out of these, Ann and Donald stated 12 bridging structures (32.4% of their stated structures). Kevin and Marvin stated 11 bridging structures, which formed 24.3% of their stated structures. More than a quarter of Kevin and Marvin's stated structures, and almost a third of Ann and Donald's, then, were bridging structures.

A top-down process

As demonstrated earlier, the five types of structures generated by bridging direct further explorations toward more advanced structures of knowledge, by providing a grappling hook, a scaffolding, or a shell for the future structures, to assist their development. Bridging gives a glimpse of following structure in the developmental sequence, although the content of those future structures is still missing. In that respect,
bridging serves as a top-down mechanism: it set the grappling hook at a higher level, then pulls understanding up toward it.

(ii) Differentiation

A bottom-up process

In contrast to the bridging, differentiation works in a bottom-up fashion, starting from the existing structures and working its way up. Differentiation is part of a reiterative process of knowledge construction that will be discussed later.

For example, when Donald and Ann explored their robot's reaction to sound, they continuously made further distinctions and differentiations that elaborated their knowledge structures. They differentiated between a gradual increase in loudness and absolute loudness:

*Donald: "The same loudness that you said hello, / Ann: "If you build up to it-- / Donald: "Right, if you build up to that very slowly, and it--"

They continued to make further differentiations, related to the distance of the sound, having two locations as its source, and having an obstacle close to the sound source:

*Ann: "Well, there was a different thing, too, you did that distant thing."

*Ann: "[It didn't] pick that up, from that sharp snapping 'cause we did it both ways-

*Donald: "Well, you were behind the knee, too, / Ann: "Yeah" / Donald: "so maybe it can't hear this"

(Second experiment, about 4 minutes after starting their exploration together)
Differentiation as a transitional mechanism

Why is differentiation a transitional mechanism? The beginning of Ann's and Donald's exploration can demonstrate the way differentiation departs from the previous structure. When Donald joined Ann, his statements indicated, as we have previously seen (chapter 6), a fuzzy, undifferentiated ACT1 structure:

Donald: "And this one is doing what it was doing when it started?"

The following statements in their conversation conveyed more differentiation related to the robot's movement:

Ann: "Yes. (...) But it progresses. Watch."

Then they continuously made other differentiations:

Ann: "It started over here"

Donald: "This one makes different noises"
Ann: "It's making a progression this way. Yeah. It's not just spinning in place."

With these differentiations, they departed from the initial undifferentiated structure with which they had started.

Differentiation leading to the next level

When Ann and Donald started making differentiations related to the robot's movement, they have not developed yet the structure of mapping. What helped them come up with the mapping, soon thereafter, was differentiation related to the robot's
movement (a change in its pattern of movement) and to other things in the robot's environment (like the sound of their voice). As Ann and Donald observed a change in the robot's movement (it started moving), and discerned a change in the environmental conditions that concurrently occurred (a loud voice), they related both changes to a mapping: the robot starts moving with voice.

After making the mapping between sound and movement, Ann and Donald started making differentiations related to either of these factors. Just as they made differentiations related to the sound source, so they did in relation to the pattern of movement of the robot, which was pretty complex:

*Donald: "You noticed how it was spinning one way and at the very end, as it gets slows down and gets ready to stop, it swirls back around the other way?"

(Second experiment, about 3 minutes after starting their exploration together)

They try it out, and make another differentiation, introducing the directions — clockwise and counterclockwise:

*Donald claps.*

*Ann: "OK, (makes a gesture clockwise).*

*Donald: "You see? It's going around, OK, clockwise, and (...) before it stops, it turns around counterclockwise."

As they continue to experiment with the robot, they make further differentiation — which wheel the robot turns on:

*Donald: "This is the left wheel, this is the wheel it's going to spin on".*

Then they differentiate between the regular spin and the other spin:

*Ann: "No, I think it only does its regular...(she motions clockwise)*

*Donald: "That's clockwise*"
All these differentiations, then, started to be coordinated into a system (ACT3) related to the robot's movement:

*Ann:* "*I think it's regular thing is clockwise, and its stopping thing is counterclockwise.*"

Which formed the structure:

```
[ Regular  Clockwise  ]
[ Stopping  Counterclockwise ]
```

In this was, differentiation paved the way from mappings to a system just as the continued differentiation of a single set, in the beginning of Ann and Donald’s exploration, paved the way to a mapping.

**Reprise: The issue of "redundancy"**

In chapter 6, we reviewed an episode in which David experimented with a robot in a way similar to children's circular reactions. In chapter 4 we followed Ann and Donald's long and twisted path of exploration. Those were but two examples; the participants' explorations were replete with seemingly redundant, playful, and repeated experimentation. To an observer from a culture valuing efficiency and short-cuts, these repetitions appear to be a regretful waste of time.

The importance of this redundancy was pointed out in the previous chapters. In this section, another aspect of this redundancy is discussed in respect to the role of differentiation.
Since Ann and Donald started their exploration together, each of the problems they set for themselves generated an increasing process of differentiation. We have seen at the end of chapter 4 the cluster of experimentation triggered by their questions. When they were intrigued by variations in the robot's movement, they clapped and watched the robot's reaction over and over, analyzing and making differentiations related to the sequence of movement they observed. When they explored the qualities of sound, they experimented with its direction, volume, the distance of the sound source, and the effect of obstacles, making differentiations related to the sounds that affected their robot.

The repeated exploration contributed to the formation of differentiation. Differentiation, in turn, seemed to be an important transition mechanism, as discussed previously. How frequently did the participants actually use differentiation in their explorations?

Table 7.6 presents the number of differentiated structures in relation to the total number of stated structures for two teams — Kevin and Marvin, and Ann and Donald — during their first five minutes of explorations.
Table 7.6: Recourse to differentiation

(During the first 5 minutes)

<table>
<thead>
<tr>
<th></th>
<th>Number of stated structures</th>
<th>Number of differentiated structures</th>
<th>Differentiated Structures %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ann &amp; Donald</td>
<td>37</td>
<td>13</td>
<td>35.1</td>
</tr>
<tr>
<td>Kevin &amp; Marvin</td>
<td>37</td>
<td>9</td>
<td>24.3</td>
</tr>
</tbody>
</table>

As we have seen earlier (table 7.5), both teams stated 37 structures during the first 5 minutes of their exploration. Out of these, Ann and Donald stated 13 differentiated structures (35.1% of their stated structures). Kevin and Marvin stated 9 differentiated structures, which formed 24.3% of their stated structures. Their use of differentiated structures was similar to the use of bridging, discussed earlier. Almost a quarter of Kevin and Marvin's stated structures, and above a third of Ann and Donald's, then, were differentiated structures.
(iii) Reiteration

A third transition mechanism that emerged throughout the analysis is reiteration. Reiteration is discussed here only as a first approximation — as an initial presentation of this transition mechanism. Additional and new ways in which reiteration operates are discussed in chapter 8, in regards to overall processes, and in chapters 10 and 11, in regards to social interaction. In this section, our encounters with reiteration in the previous chapters are put together in order to characterize this transition mechanism.

| Reiteration of actions and procedures throughout the chapters |

In chapter 4, we examined Ann and Donald's focus of exploration. We saw that Ann and Donald constructed their common exploration through clusters of activities. Each cluster had a core focus (such as the qualities of sound that affect the robot, or the pattern of movement). The cluster formed reiteration around that core focus.

In chapter 5, we highlighted the importance of detecting patterns as a step toward understanding the causality underlying the functioning of the robots. The initial negotiation with the enigma of the robots, before much was known about them, involved reiteration of actions similar to children's circular reactions. It was through this reiteration that the participants identified the relevant variables (like light or sound), tested variations in these variables (like different kinds of lights and shadows), and diagnosed the effect that these variations had on the movement of the robot (like clapping at different distances, and examining the related reactions of the robot). This repetition of actions and procedures, which, on a superficial level, seemed to be redundant and extremely inefficient, proved to be a crucial mechanism for building theories.
As the participants constructed their knowledge and proceeded to a second-phase exploration, reiteration underwent superficial changes but did not disappear. The participants repeatedly changed wire-connections and experimented with the resulting changes in the robot's movement; while holding the robot in their hand they repeatedly snapped fingers and looked for patterns in the changes of LED, or related the patterns in LED to changes in the wheels' rotation. Similarly, at the third phase, they connected a functional brick (sensor, or logic brick) to the battery and reiterated procedures while testing the way this functional brick operated. A search for patterns in the robot's movement gave way to a search for patterns related to parts, and that, in turn, to search for patterns in signal transmission. Reiteration in the second and third phase was as elaborate and prolonged as it was in the first phase.

In chapter 5 we also saw another kind of reiteration: old foci of exploration that are reiterated in the following phases. We saw the importance of such reiteration for creating links between knowledge structures at different levels. These links are not obvious. When they are not explicitly made, knowledge constructed at previous phases seems to "disappear," as in the case of the participants who started exploring anew, at the abstract phase, the nature of a sound sensor.

In chapter 6, we analyzed a new function of reiteration. We saw the example of David, who discovered the light sensor through reiteration that was extremely similar to circular reactions. We recognized the way this reiteration generates the qualitative jump that characterizes the emergence of a new phase (or, in macrodevelopment, stage).

Skill theory gave us a new perspective on the importance of reiteration. When we compare the structures of the levels, we can comprehend the way in which, through reiteration, an undifferentiated and tentative first-level structure
can become differentiated enough to generate understanding of a mapping. Similarly, we saw how coordination of these sets creates mappings, and how coordination of mappings, generated through reiteration, creates a third-level system. Reiteration that is related to systems, in turn, leads to the chunking that creates the first set of the next phase.

**Reiteration through exploration related to questions and answers**

Throughout the chapters, then, we have seen different ways in which reiteration operates during the explorations. By reiterating the same question on different phases, participants created links between knowledge structures developed at these phases. By reiterating the same question within a given level, the participants generated diverse answers on that level. For example, for a question about the quality of sound that affects the robot’s movement, the participants came up with answers related to distance, loudness difference, gradual versus abrupt sounds, and relation to obstacles. In this way, they formed a cluster of experimentation around a specific focus. On the other hand, they also reiterated experimentation related to the answer for a question. For example, when a possible answer for the relevant quality of sound was distance, they reiterated their experimentation related to distance.

**Reiteration of exploration within and across levels**

Similarly, we have seen reiteration of exploration within levels and across levels. Within a level, reiteration contributed to the formation of more level-related structures. When analyzing LED patterns, for example, the participants continued to generate more mappings. If their second level knowledge leaned on
only one stated structure, it would be "lean" knowledge. The more structures are
generated within a level, the more robust the knowledge.

Reiteration operates also as a transition mechanism across levels. We
have seen its function when analyzing skill theory's structures, and recognizing
that reiteration generated the processes that linked one structure to the next-level
one. In addition to this role of reiteration in and of itself, it also serves the two
other transition mechanisms — bridging and differentiation.

| Interconnections between reiteration, bridging, and differentiation |

As we have previously seen, bridging makes a link to the next level by
forming a mold of a structure that was not yet constructed. It is through
reiteration that this mold is later filled with content. If continued experimentation
departed to other questions, actions, or processes instead of reiterating previous
ones, it would not supply the appropriate content for that mold.

Similarly, differentiation is heavily dependent on reiteration. By
reiterating actions that are related to the same structure, differentiation of that
structure can develop. If, instead of reiterating actions and processes that are
related to one and the same structure the experimentation took off to other
questions, the initial structure could not be differentiated.
Donald: "Uhmnn."

Ann: "Both.

Kevin: "One of those is... a tiny... is going."

Ann: "Right".

Donald: "OK."

Ann: "Stop those..."

Kevin: "That's from like the wrong number of snaps."

Donald: "It didn't, you see--" / Ann: "No, that was only, it stopped on its own--"

(Second experiment, second hour)

(i) On hanging references, partial formulations, and the importance of context

<table>
<thead>
<tr>
<th>Obscure formulations</th>
</tr>
</thead>
</table>

The ethnographic aspect of the situational approach demanded analysis of episodes that at times were as obscure as the last example. Exchanges like the one between Donald, Ann, and Kevin derived their meaning from their context. The discussion between Donald, Ann, and Kevin followed Liz's suggestion to observe the robot's wheels. Their comments ("both") referred to which wheel was turning, and could be understood while observing the same occurrences they were observing at the time (which the video data made possible).

Other ambiguous formulations became intelligible by anchoring them to their predecessors. The "history" of such exchanges often lent meaning to implicit statements
which followed. When a previously stated meaning was clear in the participants' minds, they did not bother to reformulate it.

Microdevelopmental sequences and a need for continuous analysis

An analysis of examples can be based on "stronger" segments, in which the participants' formulations were unequivocal. However, in order to analyze a microdevelopmental sequence, more than that was necessary. Analysis of a sequence cannot ignore a significant percentage of occurrences, which, if analyzed, could have changed the sequence.

The analysis of the microdevelopmental sequences, therefore, attempted to extract the underlying knowledge structures of any statement and utterance that was analyzable. To do that, several steps needed to be taken.

"Hanging references"

In a free-flowing conversation, people often omit formulations which — they have a reason to believe — are clear to all parties involved. This omission simplifies the resulting formulation, shortens it, and facilitates the conversation. Were the exact formulation always required, the result could have resembled a legal contract. A brief browse of any of these specimen makes it immediately clear why people do not talk that way.

Specific conditions make people believe that their partners in a conversation are aware of the reference of a statement. One of the reasons is that they have just said that statement, or heard the other saying it. The omitted formulation is "hanging in the air", vibrating in their minds, live in the shared context between them.
Hanging references do not go far; they do not "hang" for long. After several exchanges, they have to be reformulated. But within the span of a few exchanges, they can easily be retrieved. Having an access to the whole "history" of the interaction between the participants (i.e., by a continuous recording) allows outside observers to share those "hanging references" and be able to retrieve them just as the participants to the conversation could.

"Hanging reference" in the study

After formulating a mapping, the participants often left one side of the mapping "hanging", and continued to elaborate on the other. For instance, after making a mapping between light and the robot's movement, they started comparing different kinds of lights that affected the robot. When comparing those lights, both of them knew that the lights affected the robot's movement. First, they have just said it. Second, while they were talking, they were often observing the robot's reactions to the lights they were analyzing. Repeating over and over the "movement" part of the mapping (e.g., "then it changes directions") would be unnecessary, cumbersome, disruptive, and would divert their focus of attention from the new issue (different kinds of lights). Such an omission, then, simplified the situation, and in this way contributed to the process of knowledge construction.

Partial formulations

The participants often did not complete their statements. Sometimes the reason for that was that they were not sure how to finish the sentence. This was the case with bridging and, at those times, their partial formulations related to structures that have not been expressed previously.
At other times, partial formulations related to "hanging references". In those cases, the structure referred to by the partial formulation was expressed within the span of a few exchanges, and could be easily retrieved from the context of the statement, from the visual data, and from the previous formulations.

**Tricky references**

Although usually the context of ambiguous formulation could easily be inferred, sometimes it posed more problems. Some of the references were "tricky". For example, the participants used at times the pronoun "it", when "it" could refer either to the robot or to the sensor involved. On several occasions, if the formulation referred to the robot (e.g., "it perceives the sound"), the resulting structure would correspond to the actual phase, whereas if "it" referred to the sensor, the structure would correspond to the representational phase. One of the issues that needed special attention, then, was examination of alternative possible interpretations of those "tricky" references.

**Validating inferences**

During the analysis, the goal was to analyze every statement that could possibly be analyzed. However, when a participant's statement was too ambiguous, so that it could be interpreted in more than one way with similar plausibility, that statement was dropped from the analysis.

The meaning attributed to partial formulations, "hanging" references, and tricky references was inferred separately by two judges in the reliability test (see chapter 3). These judgments were then compared, and if they were different, both judgments were analyzed and discussed. If, after the discussion, the meaning of a statement seemed equivocal, the statement was omitted from the analysis.
(ii) General versus specific structures

Herbert to Jean: "I'm trying to figure out if it changes directions on time thing or there's a sensor that does it and what the sensor is."

(Second experiment, 58 seconds after he approached the first robot)

An encapsulated context?

When Herbert said that, he did not know what the sensor could be. He could not infer from his brief observation of the robot that it even had a sensor. But a sensor or a timer could be a possible explanation for the robot's behavior. Herbert knew, of course, that there are such things as sensors and timers. This is part of the general knowledge that he brought with him to the context of the robots' exploration before starting the experiment. How is this general knowledge treated when analyzing microdevelopment?

General knowledge spilling over

The subject of the microanalysis was the microdevelopment of knowledge structures within the specific context of the robots (see chapter 6). Obviously, the participants had vast knowledge in many familiar domains; this general knowledge was to be differentiated from the specific understanding the participants were developing during the experiment within the specific context.

Cases like the last example, in which general knowledge was spilling over into the specific context, presented a problem. However, that process is not an artifact: interaction between domains of knowledge does happen; knowledge is transferred from
one domain to another. Moreover, this transfer is well thought of and considered desirable, especially in education.

The crucial factor, then, was not to prevent general knowledge from spilling over, but to differentiate between the general and the context-specific knowledge. The distinctiveness of the context — the specific robots — allowed such differentiation.

For example, when Kevin and Marvin explored their first robot together, Kevin said:

"Oh, do you know, there's some like buttons in elevators where you touch it with your hand you break the electric current, and maybe that's why you're getting a different reaction when you're putting your hand on it instead of when you put your hand..."

(Second experiment, about a minute after starting their first exploration)

In this example, general knowledge — knowledge "imported" from outside the investigated context — is clearly applied to the specific context of the robots. Kevin retrieved general knowledge related to buttons in elevators and the way they function and applied it, explaining the reaction of the robot.

| Treating general knowledge |

In the study, general knowledge was treated in two different ways. The analysis of microdevelopment attempted to diagnose the construction of new knowledge structures. General knowledge, though, was not constructed through the participants' exploration; it is knowledge that the participants have developed long before the experiment. For the purpose of the analysis of microdevelopment, therefore, general knowledge was not included.

On the other hand, the ways in which general knowledge is applied to a specific context is extremely important. It is interesting to know how general knowledge
contributes to the construction of knowledge. The issues of the application of general knowledge and the inter-relations between it and microdevelopment are picked up and analyzed, therefore, at a later chapter.

(iii) Co-constructed structures

Donald: "But then when we clap-" (he claps) /
/ Ann: "It switches-" /
/Donald: "-it switches --/
/ Ann: "-and then it stops."

The analysis was applied to statements the participants told each other during their collaborative exploration. The participants' statements were not neatly organized, separated from the other's statements. Like the example of Donald and Ann, the participants were often talking simultaneously, expressing similar ideas in somewhat different words. They often repeated each other's words, reformulating the same idea; many times they completed each other's sentences (see chapter 10).

Obviously, for statements like those of Ann and Donald, it was not possible to analyze knowledge structures for each participant separately. In Ann and Donald's statements, for example, together they constructed a coordinated mapping:

Co-construction, literally
In such cases, when the participants were talking together or completing each other's sentences, they constructed together one and the same structure.

In other cases, a statement made by one of the participants conveyed a structure. The microdevelopmental sequence of knowledge construction, however, was constructed out of the verbal exchange between the participants. Even when a participant formulated an idea that "stood alone", it was based on the previous ideas developed by both participants during their discussion.

Analyzing the "ensemble"

The unit of analysis, as discussed in chapter 10, was the interacting team — the "ensemble". Participants who collaborated on the exploration of a robot (often a pair, but sometimes three, four, or even more participants working together) formed the "ensemble". It was the team — the "ensemble" — who explored the robot together and constructed understanding together. The microdevelopmental sequence of knowledge structure referred, therefore, to a team interacting together — an "ensemble".
ANALYZING MICRODEVELOPMENT

(i) Dimensions and units

One dimension for microdevelopmental analysis: The time line

The video and audio data were recorded with time-code (see chapter 3). Each statement of the participants, therefore, had a time-code "address", identifying the exact time it was said (the time since the experiment started).

The time line served as one dimension for the microdevelopmental analysis. Each statement that was analyzed had two values: its structure (analyzed according to the manual, applying skill theory to the robots' context) and its time.

When the experiment started, the participants circulated in the room and chose one robot for their exploration. The beginning of a team's exploration was the starting point of their common microdevelopmental sequence.

A second dimension for analysis: Knowledge structures

For the microdevelopmental sequences, skill theory's structures in the robot's context were coded on an ordinal scale (see table 7.7).
Table 7.7: The codes of knowledge structures

<table>
<thead>
<tr>
<th>Structure</th>
<th>Code</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACT1</td>
<td>1</td>
</tr>
<tr>
<td>ACT2</td>
<td>2</td>
</tr>
<tr>
<td>ACT3</td>
<td>3</td>
</tr>
<tr>
<td>ACT4 = REP1</td>
<td>4</td>
</tr>
<tr>
<td>REP2</td>
<td>5</td>
</tr>
<tr>
<td>REP3</td>
<td>6</td>
</tr>
<tr>
<td>REP4 = ABS1</td>
<td>7</td>
</tr>
<tr>
<td>ABS2</td>
<td>8</td>
</tr>
<tr>
<td>ABS3</td>
<td>9</td>
</tr>
</tbody>
</table>

Coding transitional structures

The coding of transitional structures posed some problem. There seemed to be a difference between different kinds of bridging structures in respect to how advanced they were, even when these structures appeared between the same two levels. For example, when a bridging intention and a bridging question formed a transition the same levels, say REP2 and REP3, the bridging intention could indicate a more advanced knowledge than the bridging question (see page 228).

When coding the structures generated by bridging, however, these distinctions were ignored for three reasons. First, the distinctions were very subtle; they could change from one example to another; and estimation how much one bridging structure was more
advanced than the other could have been impossible to make. Second, inserting a sub-scale between every two levels would have made the analysis cumbersome, too complex, and ineffective for use. Third, the benefit of making these distinction was questionable, since the distinctions are extremely subtle. For simplification purposes, therefore, all bridging structures were coded as half-steps. For example, REP2/3 bridging term was coded as 5.5.

Differentiation posed a similar problem and was treated similarly. When differentiation was made, it constituted a progress in respect to the initial structure in relation to which the differentiation was done. A series of differentiations, therefore, could create an increasingly more advanced sequence of structures. However, as in the case of bridging, giving each differentiation an absolute level-code would have depended on the specific context and case (i.e., the number of differentiations done in an episode and the kinds of differentiations that were made). Even if these distinctions could be reliably done (which is doubtful), they would have been very subtle, and would have made the resulting analysis extremely cumbersome. Differentiations, therefore, were also collapsed to half-step codes. For example, differentiations related to a REP2 mapping was coded as 5.5.

Collapsing bridging and differentiation to half-steps did not reduce the validity of the results. Such distinctions, if included, could have just improved the correlation coefficients of the microdevelopmental sequences.

The data included a few cases of compounded structures, as defined by skill theory. A compounded structure is more complex than the corresponding ordinary structure. In contrast to the two sets mapped in REP2, for example, REP2 compound constitutes of a mapping between three sets. Yet it is not as complex as REP3, which coordinates four sets. Although it is difficult to estimate whether REP2 compound is exactly half-way between REP2 and REP3, for simplification purposes, compounded structures were also coded as half-steps.
(ii) The macro task of microanalysis

Combing through the data

Analysis of microdevelopment is an extremely time-consuming task. In this study, it involved many lengthy steps. First, the manual had to be developed, which demanded great familiarity with the robots' explorations. For that purpose, the video data were watched several times. Then, in addition to preparation of a transcript, extensive observation of the videotapes has to precede the analysis itself. To account for partial formulations, hanging references, and tricky references, the participants' statements had to be evaluated against the context of their previous and current observations and their previous and their following statements.

Prerequisite for the analysis: Understanding

In order to analyze the structure underlying the participants' statements, it was first necessary to understand their theories and way of thinking.

For example, Kevin and Marvin discussed for a long time the robot's reaction to light as "changing directions":

Kevin: "OK, if it switches between dark and light, then it changes directions."

(Second experiment, about 5 minutes into their exploration)
Their robot indeed went forward in light, and backward in shadow. Changing directions in response to light could be interpreted, therefore, as ACT3 structure: when there is light, the robot goes one direction; when it's dark, it goes the other direction:

\[
\begin{array}{c}
\text{Light} \\
\text{dark} \\
\end{array} \quad \leftrightarrow \quad \begin{array}{c}
\text{(one)} \\
\text{changed} \\
\text{direction} \\
\text{direction} \\
\end{array}
\]

However, a careful analysis of Kevin and Marvin's way of understanding (agreed by both judges) indicated that neither of them made that distinction at the time.

About half a minute after expressing the last statement Kevin said:

"So now here it looks like now the flashlight's light has taken the place of this overall light".

That comment did not make sense if Kevin thought that the robot went one direction in the dark and another in the light. In such a case, both the flashlight and the overall light would have the same effect.

What Kevin meant by that statement was not clear at this time. But two minutes later, eight and a half minutes into their exploration, Kevin's formulated a statement in a way that shed light on his understanding:

"So when it's over here, it's already partly in the light then it needs stronger light to change, whereas over here, when you covered it with the notebook, it needed more dark..."
The last statement clarified the previous ones. Apparently, Kevin thought at that time that the robot changed direction (whether from forward to backward or the other way around) when there was a change in the light. According to that understanding, some light would make the robot change direction, and still stronger light would make it change direction again. That way of understanding the robot's pattern of movement implied the following structure, which is ACT2 mapping:

```
[ ] Change in [ ]
    light       direction
```

In this case, understanding Kevin's theory was needed in order to code his first statement as ACT2, the way he understood it, and not ACT3, the way we (the judges) first attributed to him. Analysis of Kevin's statements, then, depended on understanding his theory.

This example underscores the complexity of microanalysis. Analyzing the participants' statements per se was not enough. The underlying theories that the participants developed along the way endowed their statements with a specific meaning, which had to be analyzed and understood before starting the analysis of the underlying knowledge structures.

After understanding the participants' theories, every sentence they uttered had to be considered and analyzed. The whole procedure of the microanalysis entailed many hours per second of video data.

Obviously, such a microanalysis of all the data collected for this study was impossible. Instead, several segments were chosen for an intensive analysis of the microdevelopmental sequences. These are presented in the following chapter.
The chapter analyzes transition mechanisms in the microdevelopmental process. It presents three transitional mechanisms — bridging, differentiation, and reiteration; demonstrates these mechanisms, and analyzes their use. The three mechanisms complement each other: bridging works in a top-down fashion, differentiation — in a bottom-up manner, and reiteration operates in a cyclical way that creates links between knowledge structures at different levels. Reiteration also supports the two other mechanisms — bridging and differentiation. Identification of the transitional mechanisms paves the way for the analysis of microdevelopmental sequences.

The chapter also discusses issues in the analysis of microdevelopmental processes. Specific problems that emerged from the need to analyze continuous sequences are discussed, like the analysis of "hanging references" and partial formulations. Two aspects in the analysis of knowledge structures are discussed. One relates to the distinction between general knowledge (which is imported to the process) and context-specific knowledge (which is constructed during the microdevelopmental sequence). The other aspect relates to the co-construction of knowledge by participants who work together — an "ensemble".

Having identified transition mechanisms and the structures created by them, and having devised solutions for special problems in the analysis of microdevelopment, this chapter prepares for the actual analysis of microdevelopmental sequences.
INTERLUDE 7/8

FROM PREPARATION TO OPERATION:
ANALYZING MICRODEVELOPMENT

Chapter 7 laid the groundwork for the analysis of microdevelopment. With the identification of transition mechanisms, the transitional structures created by these mechanisms can now be analyzed. The chapter also prepared for the way special problems in the analysis — like partial formulations, implicit references, and simultaneous talk — are treated.

Chapter 8 takes the next step and dives into the analysis of microdevelopment. When partial formulations and transitional structures created by bridging, differentiation, and reiteration were analyzed, the results indicated evolving microdevelopmental sequences. Five of these sequences are analyzed, charted, and explained in the following chapter.

In addition, chapter 8 analyzes three kinds of vignettes that shed more light on the microdevelopmental process. These vignettes only indicate directions which, to be assessed, demand more research. However, the vignettes illuminates aspects of the microdevelopmental process that are important for understanding the nature of the process.
The choice of segments for the microanalysis involved several considerations. The data selected were from the second experiment, that had full and continuous audio and video documentation, throughout the whole experiment, for each participant. The continuous data made it possible to extract knowledge structures of continuous microdevelopmental sequences.

Throughout the experiment, the evolution of knowledge structures of the participants was extremely interesting. The choice, therefore, was not easy. However, while choosing any segment throughout the experiment would have been instructive, the beginnings of the microdevelopmental sequences were most illuminating. It is the early starting point of the microdevelopmental sequences that contradicts our traditional understanding of adults' thinking, and that does not meet our expectations of unitary knowledge structures. It is also this early starting point that can shed light on many other perplexing phenomena related to learning and epistemology (see chapter 12). The choice of segments for the analysis of microdevelopment fell, then, on the beginning of the second experiment.
After the first few minutes of the second experiment, the participants started working in four two-person teams, each team exploring a different robot. Different aspects of the explorations of the teams are discussed and analyzed in different chapters. One of the teams, Herbert and Jean, chose a difficult mode of exploration that hampered their learning process. While it is instructive to understand how the mode of exploration affects learning, their difficulties can be better understood in light of the way other participants, who were more successful, explored their robots. Herbert and Jean's exploration, therefore, was not chosen for the microanalysis.

Another team was Liz and Cindy. Liz and Cindy, as we have seen (chapter 4) had different learning styles, different belief systems related to science, and different interests. These differences, in turn, projected on their interaction and exploration. As in the case of Herbert and Jean, Liz and Cindy's exploration was instructive, but their difficulties derived their full meaning when compared to the exploration of other participants.

The choice, therefore, fell on the other two teams — Kevin and Marvin, and Ann and Donald. Kevin and Marvin explored their robot together for about half an hour; then they split and joined other participants. The first 15 minutes of their exploration formed a microdevelopmental sequence. At that time they raised another problem and started a new sequence. Kevin and Marvin's first collaborative sequence was one of the sequences analyzed.

Ann and Donald explored their robot together since a few minutes after the experiment started (see below). About half an hour later Kevin joined them. During that half an hour, their exploration indicated four microdevelopmental sequences. The microdevelopmental sequences in Ann and Donald's exploration, before Kevin joined them, were the other sequences chosen for the microanalysis. The results of the analysis of those microdevelopmental sequences are presented below.
(i) Kevin and Marvin's microdevelopmental sequence

The span of Kevin and Marvin's collaborative microdevelopmental sequence

Kevin and Marvin approached their robot's environment about 3 minutes after the experiment started (following a short introduction and guidelines, see chapter 3). Within a few seconds they started their exploration together. About a minute later Donald joined them for about a minute; then Donald left and joined Ann. Kevin and Marvin continued their collaboration. The first 15 minutes of the explorations formed their first collaborative microdevelopmental sequence. After 15 minutes, they changed their perspective and problem, and started a new sequence. Their first microdevelopmental sequence, which started at 03:32 (3 minutes; 32 seconds) and continued up to 18:19, is analyzed below.

The knowledge structures — Kevin and Marvin's microdevelopmental sequence

Kevin and Marvin's knowledge structures were extracted by analyzing their statements. Throughout those first 15 minutes, they stated about 70 structures, starting with ACT1 (level code 1), and reaching an upper limit of REP3 (level code 6).
Figure 8.1 presents a scatter plot of Kevin and Marvin's microdevelopmental sequence. Every point in the plot presents a statement, with its knowledge-structure value on the Y axis (see table 7.7 for the coding of knowledge structures) and its time (x axis).

Figure 8.2 presents a graph outlining the evolution of Kevin and Marvin's stated structures. As figure 8.2 demonstrates, the microdevelopmental progress is not smooth: it
entails a continuous alternation between more advanced and less advanced structures. A first attainment of a new peak does not mean the apex is conquered: see, for example, points B and C in figure 8.2. Point B represents a progress over point A, the initial starting point of the microdevelopmental sequence. Point B was followed by further progress to point C. However, the following exploration alternated between the levels set by points B and C. Similarly, when a peak was reached at point D and later at E, the following sequence alternated between levels set by the higher (E) and lower (D) points.

Figure 8.2 The outline of Kevin and Marvin's microdevelopmental sequence

(line, connecting points)
The trend of Kevin and Marvin's microdevelopmental sequence

Throughout the whole sequence presented in figure 8.2, there is a clear trend of progress. Figure 8.3 presents a linear regression on the same data, highlighting that trend of overall progress.

Figure 8.3: Linear regression on
Kevin and Marvin's microdevelopmental data

R = 0.919

As figure 7.4 demonstrates, the linear regression has a pretty high correlation coefficient (almost .92).
Blocks, steps, and bandwidth of understanding: Zone of Current Development

In spite of the high correlation coefficient, the microdevelopmental sequence does not progress in a linear way. Instead, it consists of "blocks" that create a step-like sequence.

As figure 8.4 shows, these blocks form a "bandwidth" (Brown & Reeve, 1987). At a given time, there is a developmental range within which knowledge structures tend to alternate. This "bandwidth" of structures can be seen as the "Zone of Current Development" (or ZCD), corresponding to Vygotsky's (1978) Zone of Proximal Development.

Figure 8.4: Steps of bandwidth oscillation:
Kevin and Marvin's microdevelopmental data
The step-like progression of Kevin and Marvin's microdevelopmental sequence

Figure 8.5 accommodates for those steps in the microdevelopmental sequence. It presents a fifth-order polynomial curve fit for the same data. As figure 8.5 demonstrates, a fifth-order polynomial function creates a step-like curve. Such a curve fits the traditional notion of development in stages. It shows the appearance of steps during the microdevelopmental sequence, in similarity with the macrodevelopmental sequence.

Figure 8.5: A step curve fit for Kevin and Marvin's microdevelopmental data

As figure 7.6 demonstrates, the step-like function fits the data more than the linear one, with a correlation coefficient of almost .95.
(ii) Ann and Donald's first microdevelopmental sequence

The span of Ann and Donald's first microdevelopmental sequence

Ann and Donald started their exploration together about 8 minutes after the beginning of the experiment (about 5 minutes after the introduction and general directions ended). Before that, Donald circulated among the environments, and joined Kevin and Marvin for a short time. Ann and Jean began first to explore together one of the robots. The robot, however, broke down just as they were starting to experiment with it. They waited to get another robot, but meanwhile Jean left and joined Herbert, who was exploring a robot by himself. When Ann received another robot, she called Donald and asked him to join her. At that time (08:03) their collaborative exploration started.

Ann and Donald's first microdevelopmental sequence continued for about 10 minutes. At 17:49 Donald disconnected one of the wires and reconnected it differently. That ended their first microdevelopmental sequence and started a new one. Ann and Donald's first microdevelopmental sequence, therefore, lasted from 08:03 till 17:49.

The evolution of Ann and Donald's first microdevelopmental sequence

Ann and Donald's stated structures during their first microdevelopmental sequence are presented in figure 8.6.
Figure 8.6: Ann and Donald’s first microdevelopmental sequence

As in figure 8.1 each point in figure 8.6 represents a statement. During that time interval, Ann and Donald formulated over 60 statements that indicate their knowledge structures.
A specific segment in Ann and Donald's first microdevelopmental sequence is of special interest. This is the part marked by points A-G in figure 8.6, within the time span of 11:41 to 13:23. Before that, Ann and Donald's sequence resembled that of Kevin and Marvin: it began at the same initial starting point (level 1), and proceeded to oscillate between levels 1.5 and 2.5.

At 11:41, though, an interesting phenomenon occurred: Ann and Donald skipped part of the sequence, "jumped" to level 4 (point A), proceeded with 3 statements at level 4.5 (point B and the adjacent points), and even continued to a statement at level 5 (point C). However, this jump was premature; it did not lead them anywhere. Most of their statements that corresponded to the span between points A and C were bridging, other questions, or negations — experiments that did not produce any result (e.g., "The plastic isn't blocking that, sound thing"). Ann and Donald returned, therefore, to their previous level 2.5 (point D). They continued to progress slowly from level 2.5 (point D) to levels 3 and 3.5 (points E, F). However, although they slowed down their pace, their previous skip may have shaken the process: they plummeted back to level 2 (point G), and just then continued the sequence from level 3.5 and up.

Figure 8.7 presents a graph that outlines the evolution of Ann and Donald's understanding and highlights the peak (at A) and trough (at B) in their sequence.
Figure 8.7: The evolution of Ann and Donald's first microdevelopmental sequence
A trend of progression

In spite of the up-and-down jumps in Ann and Donald's sequence, throughout the sequence there was a general trend of progress. Figure 8.8 presents a linear regression on the data, highlighting that trend of overall progress.

Figure 8.8: Linear regression on Ann and Donald's data
of the first microdevelopmental sequence

\[ R = 0.81 \]

In spite of the exaggerated oscillation that occurred with the brisk pace of progress at 11:41, the linear regression in figure 7.9 has a correlation coefficient of .81. This is quite a high coefficient, although it is lower than that of Kevin and Marvin's.
Ann and Donald's first sequence also shows "blocks" of steps, although those are interrupted by their up-and-down oscillation (see figure 8.9). The "up" block, marked A in the figure, highlights the brisk out-of-sequence jump. This was somewhat offset by a compensating "down" block, marked B. If these two blocks are ignored for a moment, the other blocks form a step-like progression. All blocks, however, whether those of continuous progression or the out-of-sequence ones, are characterized by a bandwidth, or ZCD, within which knowledge structures oscillated. This attribute is similar to the one that characterized Kevin and Marvin's microdevelopmental sequence.

Figure 8.9: Steps of bandwidth oscillation: Ann and Donald's first microdevelopmental sequence
The step-like progression of Ann and Donald's microdevelopmental sequence

Figure 8.10 shows a fifth-order polynomial curve fit for Ann and Donald's first sequence. As in Kevin and Marvin's case, the fifth-order polynomial function creates a step-like curve.

**Figure 8.10: A step curve fit for Ann and Donald's first microdevelopmental sequence**

As figure 8.10 demonstrates, the step-like function fits the data more than the linear one, with a higher correlation coefficient than that of the linear regression (about .86, in contrast to .81).
(iii) Ann and Donald’s second, third, and fourth microdevelopmental sequences

| The spans of Ann and Donald's second, third, and fourth microdevelopmental sequences |
|----------------------------------|---|
| Ann and Donald's second sequence | 17:55 to 28:35 |
| Ann and Donald's third sequence   | 28:35 to 34:15 |
| Ann and Donald's fourth sequence  | 34:15 to 34:28 |

Ann and Donald's second sequence began at 17:55, when they started exploring the reconfigured robot. The second sequence continued until, at 28:35, they started writing down their notes, summarizing their previous understanding. The summary started a third sequence, that continued until 34:15. At that time, again they rewired the robot. They thought they reinstated a previous wire connection; however, the robot started to "behave" differently. Its "behavior" puzzled them and triggered a fourth microdevelopmental sequence, starting at 34:28, and continuing until Kevin joined their discussion, asking about the robot's pattern of movement, and thereby triggering a new sequence.

The second sequence

Interestingly enough, Ann and Donald's second microdevelopmental sequence was about as extensive as the first. It was similar in its time span (9:18 versus 9:46 in the first sequence) and had a similar number of statements (see table 8.1). Figures 8.11, 8.12, and 8.13 present the evolution of statements, the linear regression, and the fifth order polynomial for the second microdevelopmental sequence. These figures present a picture similar to the first sequence. Figure 8.11 shows similar alterations, although without the sharp up-and-down jump evidenced in the first sequence. Figure 8.12 demonstrates a linear regression. Due to the smoother progression, the correlation coefficient in the second sequence is higher than the first (about .89 in contrast to .81 in the first sequence).
As in the other cases, a fifth order polynomial indicates the better fit with a step-like function (.91).

**Figure 8.11:** The evolution of

Ann and Donald's second microdevelopmental sequence
Figure 8.12: Linear regression on Ann and Donald's data of the second microdevelopmental sequence

\[ R = 0.89 \]
Figure 8.13: A step curve fit for Ann and Donald's
second microdevelopmental sequence
Figure 8.14 presents a scatter plot of the four sequences. It can be seen from figure 8.14 that the third and fourth sequences skimmed the process in shorter time spans. The four sequences are compared in table 8.1.
Table 8.1: Comparison of Ann and Donald's four microdevelopmental sequences

<table>
<thead>
<tr>
<th></th>
<th>Time span (min:sec)</th>
<th>Number of structure-statements</th>
<th>Lowest level</th>
<th>Highest level</th>
<th>Rate of growth</th>
<th>correlation coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>First sequence</td>
<td>9:46</td>
<td>63</td>
<td>1</td>
<td>5</td>
<td>.28</td>
<td>.81</td>
</tr>
<tr>
<td>Second sequence</td>
<td>9:18</td>
<td>63</td>
<td>1</td>
<td>7</td>
<td>.62</td>
<td>.89</td>
</tr>
<tr>
<td>Third sequence</td>
<td>5:40</td>
<td>20</td>
<td>2</td>
<td>5.5</td>
<td>.63</td>
<td>.92</td>
</tr>
<tr>
<td>Fourth sequence</td>
<td>2:14</td>
<td>15</td>
<td>1</td>
<td>4</td>
<td>1.2</td>
<td>.87</td>
</tr>
</tbody>
</table>

The first and the second sequences were of a similar order of magnitude in respect to time span and number of statements. The third skimmed the sequence faster: it was much shorter (5:40 in contrast to 9:46 and 9:18 in the first and the second sequences, respectively), and had consisted of about a third of the stated structures (20 versus 63 in the previous sequences). The fourth sequence was interrupted; its duration, therefore, is not indicative.

Progression and regression across sequences

Three of the sequences (the first, second, and fourth) regressed all the way to the first level (ACT1) in the sequence. The second sequence also started at an early level (the second level, ACT2), although it did not regress as much as the others. At the higher
end of the sequences, the second sequence advanced more than the first: the second reached up to level 5 (REP2), while the third progressed until level 7, ABS1. The third sequence, through, did not progress as much as the second. Like the alteration within a sequence, where reaching a peak does not guaranty its appropriation, so is reaching a peak across sequences. The progress across sequences is not smooth, and while there may be an overall trend of progress, it is not smooth, and entails progressions and regressions.

| An increasing growth rate? |

Table 8.1 indicates an increasing growth rate across sequences. The indicator for growth rate was the slope of the linear regression of the sequence. The second sequence, with its somewhat shorter time span and its considerable higher reach than the first, has a much higher rate of growth (.62 versus .28). The third sequence had a similar rate of growth (.63). The fourth sequence was interrupted; however, the rate of growth of its sequence before it was interrupted is higher than the preceding sequences (1.2).

The growth rate, then, progress from .28 in the first sequence, to .62 in the second, .63 in the third, and 1.2 in the fourth. Comparison of a much larger number of sequences is needed in order to assess such a trend. However, this analysis indicates the possibility that across sequences, the rate of growth increases as the sequences recapitulate themselves. If this is indeed the case, comparison between microdevelopmental sequences may have a common attribute with comparison between micro- and macrodevelopment. As the developmental sequence recapitulates itself, the rate of growth increases. Recapitulation of the sequence, then, may be related to an increasing rate of growth between microdevelopmental sequences as it does between macro- and microdevelopment.
Reiteration across sequences

The four sequences in the beginning of Ann and Donald’s exploration indicate reiteration of the microdevelopmental sequence. This seems reasonable: knowledge based on a single sequence may be lean and fragile. Reiterative sequences broaden its base, thicken it, and make it applicable to more occurrences.

The analysis of the four sequences indicated that, as a general trend, repeated sequences may evolve faster and may, over time, proceed to more advanced levels. This trend may involve progressions and regressions: some sequences may reach less high than their predecessor. However, their accumulation may generate an overall progression. Such an overall progression seems to consist, then, of several microdevelopmental sequences, reiterating the process, and every so often pulling it upward, reaching toward more advanced levels than those previously achieved.

(iv) Comparison of Kevin and Marvin’s and Ann and Donald’s microdevelopmental sequences

Table 8.2: Comparison of Kevin and Marvin’s first microdevelopmental sequence with the first sequence of Ann and Donald

<table>
<thead>
<tr>
<th></th>
<th>Time span (min:sec)</th>
<th>Number of stated structures</th>
<th>Lowest level</th>
<th>Highest level</th>
<th>Rate of growth</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kevin and Marvin</td>
<td>14:47</td>
<td>69</td>
<td>1</td>
<td>6</td>
<td>.28</td>
</tr>
<tr>
<td>Ann and Donald</td>
<td>9:46</td>
<td>63</td>
<td>1</td>
<td>5</td>
<td>.28</td>
</tr>
</tbody>
</table>
Kevin and Marvin's first sequence was longer than that of Ann and Donald: it lasted 14:47 minutes, five minutes more than Ann and Donald's first sequence. As we have seen in chapter 4, Kevin and Marvin did not realize they could change the wires or make other changes in the robot's structure. That may have accounted for their longer sequence, although not necessarily so; other factors could also influence the length of the sequence. The length of a sequence may depend on attributes of the problem, the participants' personality, their learning styles, interests, and the attributes of the interactions between them. Kevin and Marvin explored a different robot than that of Ann and Donald; their questions and the problems they set for themselves were also different.

During their longer sequence, Kevin and Marvin stated a larger number of structures than Ann and Donald (69 versus 63), although proportionally to the span of time they stated less structures. (In their first 9:46 minutes, which equal Ann and Donald's first sequence, Kevin and Marvin stated only 54 structures).

Both sequences started at the first level (ACT1). Ann and Donald's continued until level 5; Kevin and Marvin's longer sequence continued until level 6.

Most interesting is the similar rate of growth in both sequences (.28). In spite of the differences between the two sequences, their overall trend and developmental rate were similar.

This similarity is highlighted in figure 8.15, which presents both sequences. Ann and Donald's sequence shows the up-and-down jump discussed earlier, which deviates from the overall trend. However, both sequences, when presented together, indeed show a similar overall trend.
Figure 8.15: Comparison of the evolution of Kevin and Marvin's and Ann and Donald's first microdevelopmental sequences
Serendipity contributed its share, giving a glimpse of the effect of familiarity with the domain. In the first experiment, after one of the sessions, Ben, a guest, dropped by and wanted to "play" with the robots. Ben had previous experience with sensors, although not with the robots used in the experiment. To my request, he agreed to be videotaped. The episode with Ben is analyzed along with segments from the transcript, according to their order of occurrence.

Where does the sequence start?

*Ben takes one of the robots (which has both a light and a touch sensor). He starts exploring it while holding it in his hands. Then he turns the robot on, and while holding it in his hands he presses the touch sensor, lets it go, presses it again, and experiments with it for a few times.*

Ben started his exploration by holding the robot in his hands, the way the participants did only after exploring the robot for quite a while and after understanding its pattern of movement. In other words, he started by using the representational-phase mode of exploration.

Representing the problem — a learned skill

As the episode enfolded, it became apparent that Ben could indeed represent the way the robot functioned just by watching its structure and checking its bricks. He
started with a brief examination of the robot, in which he identified the two sensors. He then isolated the variables and tested each of sensor separately. First, he experimented with the touch sensor while holding the robot in his hands. Activating the touch sensor for several times seemed to satisfy him; he then turned to explore the light sensor:

Ben: "Let's see, I'll get the light out of this. (...) This probably has an extremely simple rule underneath it. However. O.K."

Interestingly, Ben started with the simpler sensor — the touch sensor — explored it, and got that problem "out of the way". Then he was ready to explore the light sensor, which was more complex.

Reiteration — not only for novices

Ben starts experimenting with the light sensor: he covers one "eye" of the sensor with one finger and watches the robot's reaction while holding it. Then he covers the other eye with the other finger, and so forth; he does that several times.

Ben reiterated his examination of the light sensor, and then, still through a second-phase mode of exploration, assessed:

"It's responding to light."

Yet after confirming that the sensor indeed was a light sensor, Ben tried again. He checked the light source, reiterated his experimentation several more times in order to reconfirm his hypothesis, and only then was he satisfied:

Ben looks up at the lights on the ceiling. Then he tries again to cover each "eye" in the light sensor, and then says: "That's probably good enough."
Although Ben only checked the robot by holding it in his hands, he could represent its pattern of movement on the floor without ever trying it. Examination of the way the robot was structured and the way the wheels rotated sufficed for that purpose, even though he had to think twice to infer the robot's movement:

"So, it looks like it's a light follower — no, it's a light avoider."

By now Ben was prepared for more advanced analysis. Using a flashlight, Ben checked again his conclusion:

*Ben illuminates one side of the light sensor with a flashlight, while holding the robot in his other hand.*
*If that's [referring to the light] at this side, that wheel goes that way.*
*He flashes light on the other side of the sensor and continued: "If that's at this side, that wheel goes that way.*

In his statement, Ben made a mapping between the position of the light source in relation to the sensor and the rotation of the wheel (REP2 level), shifting from one mapping to the other and almost relating them together to a system (REP3).

"However, all I have to do to reverse that (he touches the touch sensor) is to run into something."

Not only could Ben infer the pattern of movement in which the robot responded to light stimuli, but he could also represent the integration of the two patterns — the robot's response to light and its response to touch. He understood that activating the touch sensor would reverse the robot's movement.
Creating links between phases

While holding the robot in his hand and activating the touch sensor, Ben described the event not in terms of the way the wheels turned, which he could observe at the time, but in terms of how the robot moved on the floor ("run into something"). In this way, he linked the second-phase representational knowledge to the first-phase actual knowledge.

Although Ben has reiterated his experiments many times by now, he still tried again and re-tested the robot's reaction, again by using the second-phase mode of exploration. Once again he confirmed his hypothesis:

*Ben tries again to illuminate the light sensor with the flashlight, then says, in a confirming way: "Uhum."*

Now he was ready to summarize, again by using a first-phase description:

*"So, it looks like it ought to- (he puts the robot on the floor, lets it move, and flashes light on it) follow light for a while- aae, avoids light for a while, (he touches the touch sensor) until it hits something."*

Only now, for a final test of his theory, Ben put the robot on the floor and examined the way it actually moved. For a final time, Ben reiterated his test of the light sensor, now through the actual mode, while the robot was moving on the floor — although he has already done it several times while holding the robot in his hands:

*Ben laughs and says: "That is cute." Again he flashes light on each side of the sensor, while the robot is moving on the floor (...) Then he laughs again, saying: "I love it."*
Like the participants in the experiment, Ben went back from the representational mode of exploration to the actual mode, assessing his understanding through — and anchoring it to — the first-phase structures of knowledge.

**Familiarity and the starting point in the microdevelopmental sequence**

The short episode with Ben indicates that the extent of regression in the sequence may be a function of familiarity with the task, the materials, or, generally, the task-domain. When a person is familiar enough with the task or the materials, he or she may start negotiating the problem at a relatively higher level. This is why, in contrast to the participants, Ben started exploring the robot on a representational level.

**(ii) The effect of complexity**

After exploring the first robot, Ben started exploring another one. As it happened, the second robot was the most complex of the robots in the first experiment. His exploration of the second robot illuminates the effect of the complexity of the task.

**First attempt — the starting point of the exploration**

Holding the second robot in his hand, and without even turning it on, Ben started examining the different bricks:

"First thing I'll understand what these things are. Each of these blocks is just some function or something." Ben examines the robot closely. "That is a lever-trigger, inverter, light- aae- sound sensor, and that's all."
Ben started by stating what the bricks are, indicating their function by using representational structures. He did that just by looking at the bricks, identifying their function from their shape or (in the case of the inverter) from the name printed on the brick.

Representational structures stand for actual ones

After that brief examination Ben turned the robot on. He checked the robot and inferred its pattern of movement on the floor without having ever seen the robot move:

*Ben turns the robot on, while holding it, and laughs at the sound: "It's got a good motor." He watches the robot while holding it, and says: "O.K., it made some sound," (he laughs at the sound that the robot makes) "and then it backed, and then it went forward. And it can't turn" (he checks the structure of the robot), "poor thing."

By holding the robot in his hand and watching the direction of the wheels' rotation, Ben inferred that "it backed and then went forward", although the robot was held in his hand all that time and did not move at all.

Like other examples from the representational phase, this example demonstrates how representational structures organize and stand for concrete actions and observations. In this case, however, Ben has not seen and has not experimented with the robot through the actual phase, unlike the other participants. He used his general knowledge of the task-domain [*] in order to access the task through the representational phase and infer the robot's behavior on the actual phase.
Re-accessing the problem through the actual phase

However, probably due to the complexity of this specific robot, it was too difficult to infer the causal relations that explained the way this robot operated (which, previously, Ben did easily for the other robot). Ben's account of the robot's movement this time was descriptive; he could infer what the robot did, but not why it changed its direction of movement. Ben put the robot on the floor, therefore, and started exploring it in a way that corresponded to the actual phase:

*Ben puts the robot on the floor. and says: "O.K. Let's see." The robot moves on the floor.*

*Ben: "Let's be quiet." (He claps his hands; the robot changes its direction of movement. Ben laughs.) "So, after a while it gives up—it gets tired, and then it makes its little noise, it goes..." (He claps his hands several times, varying the speed and the loudness of the claps). When asked what he makes out of it, Ben says: "I can't tell if it's the volume or the number, but it's sensitive to him."

The way Ben explored the robot now was a typical actual-phase mode: he clapped and examined the robot's response to his claps; he varied the quality of his claps and checked how these variations affected the robot's movement.

In the previous example, Ben first inferred the causal relations that accounted for the robot's movement, and then went back to the actual phase in order to test and confirm his understanding. Such inter-phases shifts occur in order to assess representational structures, as we have seen with the other participants. In contrast, at this time Ben did not understand yet the robot's operation at the actual phase. It was not clear what triggered the robot's movement ("I can't tell if it's the volume or the number"). When Ben tried to access the task through representational structures and realized it was too hard a
task, he regressed up to the actual-phase mode and started to explore the robot through sensory-motor structures.

| The complexity of the task and the starting point of the sequence |

The last example demonstrates that when the task is too complex to be processed at a more advanced level, backward transitions may occur. The person may regress in order to access the task through more primary knowledge structures. Like the participants who had no familiarity with the task-domain, Ben also chose to use in such a case the actual mode of explorations.

Accessing the task through earlier structures paves the way for more advanced exploration. After constructing the earlier structures, it is possible to proceed in the microdevelopmental sequence, as the continuation of the episode with Ben demonstrates:

*Ben experiments with varied clapping. (...) Then he takes the robot in his hands and starts examining the bricks.*

Now, at the representational phase, Ben was talking about the function of a brick using a representational structure, describing it as "Some sort of time lag".

Still later, Ben referred to the robot by using abstract structures:

*"So the point is just focus here your attention on the signal."

The two episodes with Ben indicate the effects of the complexity of the task and familiarity with it. Ben explored the same robots, but had more familiarity with the task-domain than the participants. Comparison between him (in the first episode) and other participants shows the effect of familiarity: he started his exploration at a higher level than the participants did. Comparison between Ben's first episode and the second one shows the effect of complexity: when the problem was more complex (in the second
episode), Ben regressed more than he did when (in the first episode) the problem was simple.

(iii) Reconstructing the microdevelopmental sequence:

Telling a story

On several occasions, the participants recounted the story of the robot they were exploring. This happened during the group discussion, or when one participant joined others that have already explored a robot for some time, and was briefed about the way the robot worked.

A miniaturized sequence

Interestingly enough, on many of these occasions, the story-teller constructed a miniaturized version of the microdevelopmental sequence. Such "stories" started with an ACT1 statement, referring to the robot's movement in a general, non differentiated, diffuse way; proceeded with some differentiation; went on to ACT2 mapping of sensory-motor structures; continued by elaborating the latter to an ACT3 system, and proceeded to a representational statement. Often, a sentence or even part of a sentence composed such a structure, while the following sentence-segment already presented the following step or half-step in the sequence.

The story of Joanne, Yulanda, Claire, and Susan

Susan shows the robot they were exploring, and says: "That one moves in very random ways. It turns and moves but at the same time, it turns a
In her first sentence, Susan presented the robot as moving randomly. The continuation of her description and Yulanda's addition immediately indicated that the robot's movement was not random, but had a specific pattern; still, Susan's first statement introduced the robot in that way. We have already seen (chapter 6) that describing the robot's movement as random characterizes ACT1 level. In such a description, there is no differentiation related to the robot's movement, and its movement is not attributed to causal conditions in its environment.

The next sentence already makes differentiation in the movement: "it turns and moves" — and immediately proceeds to making more differentiation: "at the same time, it turns a little, moves back in a forward direction or side to side."

Table 8.3 presents the sequence of structures in the story of Joanne, Yulanda, Claire, and Susan.
As the story evolved, they formulated ACT1/2 bridging intention:

Susan: "I was trying to figure out what it was attracted to."

In this statement, Susan conveyed an intention related to the cause underlying the robot's movement. Later, they postulated an ACT2 mapping between light and the robot's movement, and then proceeded to indicate an elaborate ACT3 system:
Joanne: "The flat light, which is low, it just went right into it and ran into it, but whenever the light was on, it would come with it, maybe six inches or four inches and then start to do this dance and rotate in this way."

This last statement indicates the following ACT3 structure:

```
[Flat low light]  [went right into it]
                     [↔]
[the light was one]  [dance and rotate]
```

They continued to elaborate a more differentiated ACT3:

Claire: "If you left it alone in the light that wasn't too much light to make it move too fast, it would actually move in circles..."

As figure 8.16 shows, the story of the four created a miniaturized microdevelopmental sequence.
Why do stories skim the microdevelopmental sequence?

In their story, the foursome skimmed the microdevelopmental sequence. Many other participants did the same in their reports. Why did the participants do it?

One reason is that telling the story in this way makes it more interesting. When the story opens by describing the robot's movement as random, and then proceeds to gradually reveal that it is not random at all, the story grabs the listeners' attention.

However, there may be another reason for this genre of story telling. If the four started with Joanne's or Claire's complex ACT3 description, they would immediately lose their listeners' comprehension. When the story follows the microdevelopmental sequence, it builds up the listeners' understanding gradually, step by step. With each
statement, only one layer of information is added. Brick by brick, the listeners' knowledge construction develops much in the same way as it would have developed had they constructed it by themselves. The strategy of following the microdevelopmental sequence while telling a story could be, then, a good story-telling strategy.

(iv) Guiding a novice: skimming the phases

Starting at the actual phase

In the beginning of the third hour of the second experiment, Marvin started to explore the "wuggling" robot. When Ann joined him, some time later, he introduced her to the robot by using the same technique of following the microdevelopmental sequence.

At first, Marvin just referred to the robot in an undifferentiated, diffuse way, using words like "it wuggles", or "goofy things":

Marvin: "So, OK, well, if this, I think this one wuggles. See how the back does goofy things..." Ann: "OK."

(Second experiment, beginning of the third hour)

Marvin then proceeded with some differentiation:

Marvin: " And the front does ...just straight on."

Before Ann joined him, Marvin was holding the robot in his hands and examining it through the second-phase mode. But when he started to introduce Ann to the robot, he put it on the floor and let it move. In this way, Ann could process the movement of the robot first through the actual mode of exploration. Marvin did it for a few seconds; the battery was very low, and Ann could not see much of the robot's pattern of movement.
He took, then, the robot in his hands, and started to explain its operation on the representational level. But Ann still wanted to know:

Ann: "And that happens just when you flip the switch." Marvin: "Just flip the switch."
He puts again the robot on the floor and shows it to Ann.

Ann's question referred back to the actual phase; Marvin put it back on the floor, then, returning momentarily to a first-phase mode. Then, after watching the robot move on the floor, they immediately proceeded to the representational phase. Within seconds, Ann was a partner for a complex exploration on the representational and then on the abstract phases.

What is behind a first-phase introduction

As in the case of story-telling, introducing a novice to a robot slowly and gradually makes it is easier for the novice to follow and understand an explanation. If there is a reason why the microdevelopmental sequence starts with early structures, that reason should hold for introducing the robot to someone else much in the same way as it holds for constructing knowledge by one's own experimentation. When a novice starts the encounter with the robot with a brief first-phase exploration, this exploration apparently facilitates the understanding of the robot. It seems that people intuitively know it: "expert" participants introduced a "novice" partner to a new robot by following the microdevelopmental sequence, starting from the first-phase mode of exploration.

When those who already had experience with the robot started, instead, with a verbal description, what followed was often similar to what Liz asked in such a case:

Liz: "Can I see that?"
SUMMARY

In this chapter, five microdevelopmental sequences are analyzed. One is Kevin and Marvin's first sequence, the one that starts their common exploration. The four others are consecutive sequences that form Ann and Donald's first half hour of exploration.

The five sequences show some similarities. None of the sequences is smooth; they all consist of alternation between more advanced and less advanced structures. They all consist of a "bandwidth" of structures, which form a "Zone of Current development", in similarity with Vygotsky's (1978) Zone of Proximal Development. All sequences have a clear upward trend, and proceed in a step-like fashion.

The first sequences (both of Kevin and Marvin and of Ann and Donald) have a similar rate of growth. The following sequences have an increasing higher growth rate and tend to be shorter.

The overall microdevelopment seems to consist of reiteration of many microdevelopmental sequences. Each sequence regresses and then reiterates the progression with some changes. The continuous reiteration makes knowledge more robust and expand its context. It is the accumulation of the reiterative sequences, that, together, seems to pull development upward, toward more advanced levels. However, the process is not smooth: like the continuous regression and progression within sequences, there is a regression and progression across sequences. Some sequence regress more and some less, and the peak of one sequence may not be reached by the following one.

In addition, three other cases that shed more light on the nature of the microdevelopmental process were analyzed. These involve the effect of familiarity with the task and its complexity; microdevelopmental sequence in story telling, and initiation of a novice.
Chapter 8 demonstrated examples of microdevelopmental processes, analyzed them, and explained the processes underlying these examples.

The examples and sequences analyzed in chapter 8 and in the chapter preceding it attest to the existence of microdevelopmental processes that parallel macrodevelopment. The gap between indicating the existence of a certain process and proving its generality is large. Chapter 9 attempts to reduce this gap by putting together the attributes of microdevelopmental processes analyzed in this study on the one hand, with theories and findings of other researchers, on the other. On the larger basis created by the integration of several theories and findings, chapter 9 characterizes and explains the nature of microdevelopment in a more general way. The generality and applicability of the analysis and explanation suggested in chapter 9, though, remain to be examined by further research.

In the chapter, the processes evidenced in the study are analyzed. These processes show multiple pathways of knowledge construction. The analysis suggests an alternative to the unidirectional and hierarchical model of knowledge construction.
EXPLANATION OF THE MICRODEVELOPMENTAL PHENOMENON

(i) Why do microdevelopmental sequences that parallel macrodevelopment occur?

A general condition: When higher processing is impossible

Understanding a problem through representations entails an ability to think of possible actions and events without actually performing those actions or perceiving these events. However, when dealing with unknown objects or processes, this may be impossible even for an adult. If, within a specific context, primary structures have never been constructed, then one has first to access the problem by actual experimentation — through the actual phase.

By the same token, when understanding a problem through abstract knowledge structures is difficult, accessing it through representations facilitates the process. Abstractions are based on representations; they involve the ability to manipulate representations in one's mind. In order to do that, the representations of an issue have to be well established. But if these representations are not immediately accessible — if one is not fluent with them — it may be difficult to access the problem through abstractions. In such a case, one has to access the problem first through the representational phase.

To put it more generally, when a problem is not simple, accessing it through earlier knowledge structures helps to simplify it and make it more intuitively understood.
Recourse to more primary structures

Good presenters know the trick: when presenting a complex issue, they begin with examples that make the issue more concrete. In the Piagetian sense, these examples form representations of concrete cases, allow concrete thinking, and thereby endow the abstract issue of the talk with intuitive meaning. Similarly, we all use graphs, charts, models, simulations, and so forth to facilitate the understanding of abstract issues.

A rule: When higher processing is impossible, go down a level

When an issue cannot be accessed through higher knowledge structures, then, the individual may descend in the sequence and access that issue through structures that correspond to an earlier part of the sequence. Such knowledge structures are more primary: not only do they appear earlier in the sequence, but they are also simpler and allow easier processing.¹

This strategy can be formulated as a general rule that reads as follows: "when it is not possible to process a task on a certain level, go down a level."

(ii) Reconceptualizing regression

Initial conditions for the appearance of regression

¹ The term "primary" also has a positive connotation, indicating a more basic phenomenon. Since terms like "early" knowledge structures or "lower" have a somewhat less favorable connotation, the term "primary" is used instead.
The earlier section formulated a general rule for regression as a strategy. The analysis of the previous chapters indicated two conditions under which this rule applies — one, the complexity of the task, and two, the person's familiarity with the task, which is related to his or her level of expertise in the context of the task. When a task is unfamiliar or complex, it may not be possible to process it on a higher level. In such cases, the individual may regress in the sequence in order to access the task through more primary structures. In contrast, familiarity with a task, or expertise in its context, have an opposite effect: when knowledge structures are available, due to relevant experience, for processing a problem at a higher level, the individual does not have to regress in order to process it.

The complexity of a problem is not an objective measure, but a subjective one. Its complexity resides in the "eye of the beholder"). How complex a problem is depends on one's previous knowledge, on one's experience, and on the relations perceived between that problem and other familiar ones. By the same token, the familiarity of a problem is subjective. Experts who classify problems according to their underlying domain-specific principles (see chapter 2) see these problems as familiar. In contrast, when novices classify problems according to their superficial attributes, they cannot see through these attributes. These problems, then, do not look to novices as familiar although experts view them as such.

Starting to negotiate a task does not necessarily make it less complex nor does it have to make the task familiar. Even within a given task, there is variation in difficulty between sub-tasks. Specific sub-tasks (such as the same type of a problem assigned with different parameters) may be more difficult than others. For example, when children learn to add numbers, adding 9 to 3, or even 3 to 9, is more difficult for them than adding 3 to 3. By the same token, sub-tasks may differ in their familiarity. The relative complexity of certain sub-tasks may conceal the underlying common structure they share with simpler sub-tasks. Therefore, not only are special cases of sub-tasks more complex,
but also they often seem less familiar to the individual. When exploring these sub-tasks, therefore, the individual may have to regress again to more primary modes of exploration.

**How much regression?**

The extent of regression depends on the subjective complexity and familiarity of the task. The individual regresses until reaching knowledge structures through which he or she can easily process the task at hand. The more does the task seem complex and unfamiliar to the individual, the more does the individual have to regress in order to access it at a comfortable level. This is why the participants in the study, for whom the robots were extremely complex and unfamiliar, had to regress until the initial actual level (ACT1). This is also why Ben, who had more familiarity with the task-domain, could access the simpler robot on a representational level. Still, in spite of his familiarity with the task-domain, even Ben had to regress when confronting a more complex task. When Ben explored the more complex robot, he had to regress to access it through the actual phase.

**The positive functions of regression**

Regression is usually tainted with negative connotation. Yet, when exploring unfamiliar or complex tasks, regression may be a necessary and important step, which enables appropriation of these tasks. Regression can simplify a phenomenon and make it more accessible through more primary knowledge structures.

Throughout the last chapters, we have seen how regression to earlier phase and levels enabled the participants to access the difficult task. After accessing the task through more primary knowledge structures, the participants continued to progress to increasingly more advanced knowledge structures.
The example of Ben (chapter 8) indicates that regression makes it possible to access a task that otherwise would have been too difficult. When Ben could not understand the more complex robot through a second-phase exploration, he regressed to a first-phase exploration. Using the more primary knowledge structures of the actual phase, he indeed constructed his understanding and continued to progress in the sequence.

The other examples brought in chapter 8 — those of telling a story and guiding a novice — also indicate the importance of regression. Regression to earlier knowledge structures, as indicated by those examples, is an important technique for helping others understand as well as for constructing one's own knowledge.

Other examples highlighted another important function of regression. Regression also helps creating links between knowledge structures at different levels. We have seen that when the participants explored the robots at the second phase, they often made frequent regressions to the first phase, in order to test their understanding and assess it. By the same token, at the third phase, they regressed to the second and the first phases for similar purposes.

The case of Donald and Jean (chapter 5) also underscores the importance of regression for creating links between knowledge structures constructed at different levels and phases. Although both Donald and Jean have previously experimented with the sound sensor for quite a long time, when they started exploring the sensor at the third phase they did not identify it correctly. This case indicates that knowledge constructed at earlier phases is not simply appropriated at a higher phase; instead, links between structures of knowledge at different phases have to be deliberately constructed. Regression, then, may be crucial for making further progress possible: it creates links, unifies, and assesses knowledge constructed at different phases.
Regression and its explanation — corroboration by other studies

Regression in other studies

Regressions to earlier knowledge structures or earlier forms of experimentation, as found in the present research, are also indicated by other studies.

For example, in his seminal study of problem solving, Duncker reports of "shifting back and forth" that occur frequently (1945, p. 13). When trying to solve problems, subjects make transitions, shifting from an unproductive line of solution to another line. "Every such transition involves a return to an earlier phase of the problem; an earlier task is set anew" (ibid, p. 13). The extent of regression varies "Sometimes a S [subject] returns to the original setting of the problem, sometimes just to the immediately preceding phase" (ibid). As in the present study, although the subjects regress in the sequence, they do not regress to exactly the same point regarding the exact same question: "In such retrogression, thinking would naturally not be taken back to precisely the point where it had been before. For the failure of a certain solution has at least the result that now one tries 'in another way'." (Ibid).

Karmiloff-Smith and Inhelder (1974) asked children to balance blocks on a bar. In their results, they also found regression in the performance of the task. Three year olds tried to balance the blocks by repeatedly pressing hard with a finger above the point of contact, as if the finger were a nail. Four and six year olds, who started balancing the blocks similarly, proceeded to systematic exploration. Yet, when trying to balance difficult blocks with uneven weight distribution (which could be balanced only by using counterweights), these children regressed and again started by pushing hard with the finger above the point of contact (ibid, p. 201).

Werner performed numerous microgenetic studies. His results indicated regression to more primary knowledge structures. Werner referred to accessing earlier
knowledge structures through such regressions as "primitivation" (e.g., Werner, 1948, p. 38). However, his use of this term should not be interpreted as value-laden, as viewing regression negatively: quite the contrary.

Support from other studies: Viewing regression in a positive light

In his theory, Werner (1957) views regression as a mechanism that enables further progress. According to Werner, the individual may have to regress "back to the point from which new development can take place" (ibid, p. 130). The individual's progress "will be accomplished through partial return to a genetically earlier, less stable level. One has to regress in order to progress" (ibid, p. 139).

Karmiloff-Smith and Inhelder (1974), in the experiment mentioned above, demonstrate that regression to a lower level of performance is related to theory-driven processes. As children develop a theory that blocks should balance in their geometric center, they no longer succeed in balancing blocks with uneven weight distribution. These children rely on the theory rather than on proprioceptive feedback. The temporary regression in performance, in this case, is an important part of the developmental process, since it reflects the emergence of theories.

An experiment done by Brown (1976) can be interpreted in a way that also illustrates the beneficial effect of regression. Brown gave 3.5 to 5 year old children three kinds of modeling of the linguistic passive form. One group received verbal modeling accompanied by enactment with toys, conveying the idea of the passive-form sentence. Another group received linguistic modeling accompanied by pairs of photographs, representing an example similar to the enactment. A third group received only linguistic modeling, and a fourth was a control group. Brown found that the group that received modeling with enactment demonstrated a significantly higher comprehension than all
other groups. Modeling with pictorial referents increased comprehension, but less substantially; modeling alone was still significant but had a smaller effect.

The treatments that Brown gave the children corresponded to accessing the task through different phases. The enactment with toys corresponded to accessing the task through actual actions and perceptions, while the photographs portraying objects corresponded to accessing the task through representations. Brown's findings show, then, that accessing the task through the actual phase contributed more to comprehension than accessing it through the representational phase. When the children could regress and access the new linguistic form through more primary knowledge structures, they benefited more from the modeling.

| Support from other studies: The effect of complexity and unfamiliarity |

Several studies that report on the appearance of regression relate it to the difficulty or unfamiliarity of the task. For example, Kuhn and Phelps (1982) report that three out of four subjects who had mastered the use of a valid strategy when dealing with simpler problems, showed regression to a false strategy when they proceeded to more advanced problems (ibid, p. 31). In their words: "All we had to do was complicate the problem slightly or modify its format and the invalid strategies typically reappeared" (p. 38). In their study, then, a slight increase in the complexity of the problem, or modification of its format (which, apparently, makes it somewhat less familiar) sufficed to generate regression.

Inhelder et al. (1980), in the experiment reported above which entailed loading and unloading blocks, varied the complexity of the task by varying the number of the blocks. Their finding also indicates regression related to the complexity of the task. Six years old did not understand at first the inverse relationship between the sequences of
loading and unloading. Later, they developed the right procedure for two blocks, but regressed when three blocks were involved.

Karmiloff-Smith & Inhelder's (1974) experiment, mentioned previously, also indicates the effect of complexity and unfamiliarity. The task of balancing blocks with uneven weight distribution was both more complex and unfamiliar, since the children have not encountered such blocks previously. Children who succeeded to balance simpler blocks, when trying to balance the blocks with uneven weight distribution again regressed to a more primary mode of exploration. In the more primary mode, when pressing with a finger on the point of contact, they received proprioceptive feedback on their actions (ibid., p. 200). This action, then, gave them access to more direct understanding of the problem through primary actual knowledge structures.

Brown (1976), in the experiment discussed earlier, also has findings that indicate the effect of familiarity. Brown compared children with higher initial comprehension of the passive form (higher performance on pretest) to those with less initial comprehension. He found that children with higher initial comprehension benefited more than other children from modeling with pictures and from linguistic modeling alone. The higher the child's initial comprehension, the more effective were these treatments (ibid, p. 198).

Higher initial comprehension of the passive form implies more expertise, and indicates, therefore, more familiarity with the task. Brown's findings indicate, therefore, that children who were more familiar with the task could benefit also from modeling that accessed a higher phase; they did not have to regress as much as other children.

These findings support, then, the explanation that complexity and unfamiliarity serve as conditions for the emergence of regression.
(iv) Attributes of the progression that follows

Regression does not necessarily imply an ensuing parallelism

Even as a regression occurred, the ensuing sequence did not necessarily have to recapitulate the macrodevelopmental sequence. After an initial familiarization with the task, the sequence could have skipped levels to join the person's macrodevelopmental level in other domains. Yet, the findings of the present study indicate that this is not the case. As we have seen, the findings indicate parallelism between micro- and macrodevelopment, similar to the parallelism suggested by several theories (see chapter 6).

Is the parallelism between micro- and macrodevelopment necessary?

Why does the parallelism between micro- and macrodevelopment occur? When discussing parallelism between diverse developmental sequences, Siegel and White (1975) suggest that there are Main Sequences in the progressive organization of human behavior, and these involve discrete ordered states.

If we look at Main Sequences in that broader sense, there is another relevant parallelism that is discussed in literature — parallelism between the history of science and ontogenesis (Piaget & Garcia, 1983). Piaget and Garcia indeed explain this parallelism from the point of view of progressive organization. Piaget and Garcia suggest that similar functional mechanisms hold both in ontogenesis and in the history of sciences. They attribute the latter parallelism to mechanisms such as reflective abstraction and to the way a lower level influences the formation of a following one (ibid., p.8). Piaget and Garcia maintain that similar conditions of possibility and necessity
pertain both to ontogenesis and to the history of sciences. Whether the process of knowledge construction relates to the development of the individual or to the evolution of social aggregates of bodies of knowledge, during the process each stage is a result of possibilities opened up by the preceding stage. At the same time, each stage is a necessary condition for the following stage. In this way, previous structures are reconstructed and integrated into those that follow: "the ideas articulated at a higher level of thought, even those of a theoretician, must necessarily rest on substructures of actions which sustain them" (p. 66).

Piaget and Garcia's explanation can serve to explain the parallels between micro- and macrodevelopment as well. Just as the theoretician's ideas must rest on substructures of actions, so do the adult's structures when exploring an unfamiliar context. If structures of action do not exist within that specific context, these structures have first to be constructed.

In similarity with Piaget and Garcia's explanation, after the missing structures are constructed, the sequence of knowledge construction continues in a way that parallels macrodevelopment since the same mechanisms apply to both processes. If knowledge structures that correspond to a later part of the sequence are constructed through coordination and integration of earlier structures, microdevelopment cannot skip segments of the sequence. If a segment is skipped, its corresponding structures will be missing. In their absence, more advanced structures would not develop: the more advanced structures need the previous ones as building block for their development.

The first microdevelopmental sequence of Ann and Donald illustrates this point. In their first microdevelopmental sequence, Ann and Donald skipped a segment and jumped to higher structures (see chapter 7). However, the jump was premature, and was not fruitful; Ann and Donald could not continue to develop their sequence, and had to regress back in order to continue in their microdevelopment.
Piaget and Garcia's explanation, attributing the similar sequences to a similar functional mechanism, can be supported by a phenomenon from another domain — fractals (Mandelbrot, 1983). A fractal is "a geometrical figure in which an identical motif repeats itself on an ever diminishing scale" (Lauwerier, 1991, p. xi). In fractals, the "degree of their irregularity and/or fragmentation is identical at all scales" (Mandelbrot, 1983, p.1).

In fractals, the same algorithm generates similar structures at different spatial scales. In this respect, the process is similar to micro- and macrodevelopment, in which there are similar structures at different time scales. In fractals, new structures are generated by an algorithm that is defined on coordination of previous structures. In this respect too, the analogy holds. It is possible, then, that in development, as in fractals, a mechanism that generates new structures out of coordination and integration of previous ones, generates a similar sequence along an increasing scale. In development, that scale may extend from the shortest microdevelopmental processes that are consumed within a single second (Werner, 1948) and up to aggregates of body of knowledge in the history of science, as Piaget and Garcia (1983) claimed.
Miniaturization and acceleration in microdevelopment

The similarity between processes in micro- and macrodevelopment was noted by Werner and his predecessors. Werner (1957) contended that the processes are similar or parallel, though not materially identical (p. 126). One of the ways in which these processes differ is their density, or their time scale. Macrodevelopment spans years, while microdevelopment — as the term indicates — occurs in a concise, miniaturized and accelerated process.

According to Werner (1948), microdevelopment (or, to use his term, microgenesis) can either be "consummated in a single second's duration", or can take hours, days, and weeks (ibid., p. 37). The sequence that follows a regression in microdevelopment, then, consists of miniaturization and acceleration of the ontogenetic sequence (Catán, 1986).

Why is microdevelopment accelerated?

The analysis done in this study was based on a distinction between context-specific knowledge and general knowledge, related to other familiar domains. During microdevelopment, as we have seen, primary knowledge structures are constructed within a complex unfamiliar context. These context-specific structures correspond to general structures at the same level that the individual already has. For example, context-specific sensory motor structures, like ACT1 or ACT2, correspond to already existing sensory motor SM1 or SM2 structures. After the new specific structures are constructed, the individual can append them to the corresponding general structures which relate to other contexts. In this way, the process of within-context knowledge construction precedes and paves the way for the assimilation of the new context. However, once the new context is
assimilated, the whole body of general knowledge-structures (at the level corresponding
to the one just constructed in microdevelopment) can apply to the new context. Thus the
new context is anchored, at that level, to a pool of well established knowledge structures.
This robust anchor enables the individual to start immediately exploring the specific
context of the task at a higher level. The result is, therefore, a sequence that parallels
macrodevelopment in a miniaturized and accelerated way.

How much progression? Macrodevelopment as an upper bound

The miniaturized, accelerated process of microdevelopment can continue as long
as it is supported by the pool of existing general structures. In this way,
macrodevelopment poses an upper limit on the sequences of microdevelopment, since
beyond the macrodevelopmental stage and level, knowledge structures have not yet been
developed.

The implication of this conjecture is that microdevelopmental processes of
younger subjects should stop evolving before those of older subjects. In other words,
since the macrodevelopmental level of younger children is lower, if macrodevelopment
poses an upper bound on microdevelopment, their microdevelopment should also stop at
a lower level.

Indeed, this implication is supported by findings of other researchers. Several
studies indicate that the microdevelopmental sequence of younger children stops while
that of older children continues. This is the other side of the first microdevelopmental
puzzle we have seen in chapter 6. The microdevelopmental puzzle showed that older
children and adults start performing like younger children. At the other end of the
sequence, older children stop their microdevelopmental sequence at a higher level than
younger children do, and adults stop at still a higher level.
For example, in Karmiloff-Smith and Inhelder's (1974) block-balancing experiment, younger subjects (at the age of 18-39 months) did not progress beyond pressing with a finger on the blocks' point of contact. Older children (at the age of 4-6 years) started the sequence similarly, but continued to develop more elaborate procedures. They started a systematic exploration of each dimension of the block.

Wertsch & Stone (1978) examined the performance of mother-child dyads when solving a puzzle according the a model. As mentioned earlier, they found a microdevelopmental sequence that corresponded to Vygotsky's theory (see chapter 6). Wertsch and Stone noted that the microdevelopmental sequence of younger children sometimes stopped earlier than that of older children: "some of the younger subjects (three-and-a-half years old) did not make the microgenetic transition from other-regulation to self-regulation, presumably because they were not "cognitively ready"" (ibid, p. 9).

Another microdevelopmental study done by Metz (1985), which distinguished different problem spaces when exploring a task related to gears, found that most 11-12 year olds started exploring the task in similar problem-spaces as 8-9 year olds did, but continued to a more complex problem-space, which none of the younger subjects reached.

It is suggested, therefore, that the individual's highest macrodevelopmental level constrains the possible progress of his or her microdevelopmental sequences.

The inter-relations between the micro- and macro-sequences, however, are bidirectional. On the one hand, the macrodevelopmental sequence poses an upper bound to the micro-sequence. On the other, breakthroughs that take place in microdevelopment, within a specific context, feed back to macrodevelopment.
How much progression: Breakthroughs through microdevelopment

Micro- and macrodevelopment affect each other both ways. If macrodevelopment constrains microdevelopment, microdevelopment, in turn, expands macrodevelopment, which then expands the potential of other microdevelopmental processes.

Each breakthrough in macrodevelopment first occurs within a specific context and, as such, it occurs during a microdevelopmental process. A breakthrough occurs when new structures, which do not yet have corresponding macrodevelopmental structures in any other context, are constructed during microdevelopment. As this happens, the new structures expand the individual’s abilities in at least that single context. This, in turn, raises the upper limit on microdevelopmental sequences developed in other contexts. In this cyclical manner, the micro- and macro-sequences influence and expand each other.

How much progression: The importance of time-on-task

The amount of time that subjects have for exploring a task also influences the amount of progress on their microdevelopmental sequence. Microdevelopmental sequences can be very short — as Werner (1948) indicated, they can even last for only a second. However, microdevelopmental sequences are not necessarily that short. When subjects explore an unfamiliar and complex phenomenon, the microdevelopmental evolution of their knowledge structures may last hours or even days.

For example, in an experiment done by Kohler, subjects were asked to wear lenses that distorted half of their visual field. The microdevelopmental adaptation of the subjects to the distorting lenses continued for 50 days; the aftereffects that followed the removal of the lenses lasted 40 more days (Werner & Wapner, 1955).
In the present study, during four hours of explorations, the participants developed several microdevelopmental sequences, and usually only at the fourth hour did their sequences evolve to the abstract phase.

If not allowed enough time to explore a task, therefore, subjects may not reach their highest ability. Their microdevelopmental sequence, in such a case, will stop before reaching its upper bound, set by macrodevelopment.

(v) Variations in microdevelopment: Comparison with other studies

Although several microdevelopmental studies indicate microdevelopmental attributes on a par with this study, not all microdevelopmental studies do. How can these differences be accounted for?

| Two main techniques used by microdevelopment studies |

Siegler and Crowley (1991) point out that researchers have developed two main strategies for investigating microdevelopment: one involves tasks from everyday environment; the other — novel tasks. This distinction corresponds to the aspect of familiarity with the task, which was suggested as a factor related to the amount of regression evidenced in microdevelopment.

Building on Siegler and Crowley's distinction and taking it a step further, these two techniques correspond to two extremes on a continuum, as portrayed in figure 9.1.
Different microdevelopmental sequences

Figure 9.1 orders microdevelopmental processes along one dimension, ranging from processes that relate to extremely unfamiliar and complex contexts and up to familiar ones. The other dimension in the figure indicates the degree of regression in the microdevelopmental sequence. Sequences that are related to highly unfamiliar and complex contexts (on the left side of the dimension) will show relatively more extreme regression, as discussed previously. Microdevelopment, however, can occur also in contexts that are familiar, when the individual continues to develop his or her knowledge within these contexts. In such cases, microdevelopmental sequences may not show regression, except for the back-and-forth alteration previously characterized as the bandwidth or ZCD of understanding (see chapter 8).

Figure 9.1: Differences among microdevelopmental processes

Figure 9.1 demonstrates a hypothetical link between the unfamiliarity and complexity of the context and the degree of regression in the microdevelopmental sequence. The figure is not intended to imply a specific form of function, but to highlight the inverse relation between the two variables.
One end of the dimension — unfamiliar complex context and microdevelopmental evolution

The present research belongs to microdevelopmental studies that correspond to the left end of the dimension on figure 9.2. Such studies involve novel tasks, new activities, or unfamiliar materials. The resulting processes start with considerable regression, followed by a progressing microdevelopmental sequence. Several of these studies were discussed and analyzed previously. Others include, for example, Werner (1957), who studied processes related to novel tasks such as classification of colors with fine hue variation; differentiations related to a musical micro-scale consisting of semitonal intervals (Werner, 1978); or the gradual understanding of the meaning of an artificial word by the context in which it is embedded (Werner, 1957).

Microdevelopment in familiar contexts

At the other extreme of the dimension are microdevelopment studies that involve familiar tasks, or tasks that are based on existing cognitive skills. Such studies attempt to focus on the cutting edge of cognitive abilities and to identify breakthroughs in development. By focusing on the upper limit of children's abilities — their optimal level (Fischer, 1980a, Fischer & Pipp, 1984) — the density of observation characterizing microdevelopmental studies (Siegler and Crowley, 1991) can help researchers capture the processes of change as this upper limit expands.

For example, Siegler and Jenkins (1989) explored the strategies developed by 4 and 6 year olds for adding numbers. They followed closely the discovery of a new strategy — the "min" strategy — in which children started counting from the larger addend the number of times of the smaller addend. By following the development of this
new strategy, Siegler and Jenkins captured the process during which children's abilities of adding numbers extend. Lawler (1981), who also studied a 6 year old's learning to add numbers, identified the use of problem-solving structures (which he called "microworlds"). These structures developed separately in different contexts, such as counting assisted by fingers, counting related to coins, and operations written on paper. Lawler followed and analyzed the subsequent correlation and integration of these structures which, in turn, extends the child's ability to add numbers.

Other studies of microdevelopment do not use everyday materials and tasks, but include a period in which they familiarize the subjects with the context or the task. For example, Bidell (1990) made an extensive study on the microdevelopment of children's solutions of the Tower of Hanoi problem. Bidell first presented each child with a two-disc version of the problem, in order to familiarize them with the task. Only after the child had completed two successive trials successfully, did Bidell present them with the three-disc version, for which he analyzed their microdevelopment. Bidell indeed found interesting interrelations between micro- and macrodevelopment. On the one hand, he found that macrodevelopment affected the entry-level of the children (which indicates the amount of regression). Younger children started at a lower level than older children did. On the other hand, Bidell found that microdevelopment served for extending current macrodevelopmental skills. According to his findings, children of the same age, who shared a common macrodevelopmental level, exhibited a common representational ability, as indicated by their tacit errors when describing their experiences. However, within that macrodevelopmental level, there were differences among the children. Some of them could more easily extend their current skills to the new context than others could. Bidell concluded, therefore, that microdevelopment had a role in extending macrodevelopmental skills to new contexts.
ATTRIBUTES OF MICRODEVELOPMENT

In this section, attributes of the microdevelopmental sequence, as analyzed in this study, are compared with and corroborated by theories and findings of other researchers.

(i) The structure of a microdevelopmental sequence

| A recurrent structure — integration of theories |

The microdevelopmental sequence found in this study corresponds to the sequence indicated by Fischer's (1980a) skill theory. The sequence has three phases, and within each phase it has a recurrent structure of levels which emerges anew in each phase (see chapter 2, for skill theory's structure; chapter 6, for the analysis in the context of this study).

The recurrent structure of levels has common attributes with other theories and findings. Put together, these attributes characterize a coherent and identifiable microdevelopmental process.

The first level of the microdevelopmental process can be characterized by diffuse knowledge. At this level, knowledge is undifferentiated (Fischer, 1980a; Werner, 1957), global and holistic (Werner, 1957). It includes single sets that do not map yet onto each other (Fischer, 1980a). In this level, the definition of a problem is still diffuse (Fischer, 1975, 1980b) and implicit (Karmiloff-Smith, 1986a).

In the second level, mappings between the single sets (Fischer, 1980a) are being formed. Procedures that were not explicitly related to one another now become explicitly related (Karmiloff-Smith, 1986a).
In the third level, the discrete sets, which were previously mapped onto one another (Fischer, 1980a), evolve through a process of differentiation (Fischer, 1980a; Werner, 1957) and articulation (Fischer, 1975, 1980b; Karmiloff-Smith, 1986a; Werner, 1957). During this process, each of the sets is differentiated into a vector of variabilities, thus forming a system (Fischer, 1980a).

In the fourth level, the previous knowledge is synthesized together (Werner, 1957). The different components — and in the representational phase, the different representations (Karmiloff-Smith, 1986a) — are linked to one another and integrated into a single set (Fischer, 1975, 1980a, 1980b).

**Support from other findings**

Findings of other researchers also support the attributes of this microdevelopmental sequence. For example, G. Mandler (1962), in his analysis of learning processes, indicates a process that proceeds from discrete responses (similar to the characteristics of the first level) to integration of the components into one unit (as in the fourth level).

Schauble (1990) analyzes reasoning strategies of fifth- and sixth-grade children. She identifies (ibid, p. 41) low level plans that are vague and global and seem to have no discernible purpose (and are similar, therefore, to the first level characteristics). Schauble distinguishes between these low-level plans and high-level ones that, later in the sequence, gradually increase in number. In the high-level plans, two or more features are compared and linked to one another (like the characteristics of the second and third levels).

Inhelder et al. (1980) report on an experiment in which children had to load blocks on a toy truck and then unload them gradually. The task entailed two sequences, one of loading, and the other of unloading. Inhelder and her colleagues found that at
first, children did not differentiate between the two sequences (undifferentiation that is
similar to the characteristics of the first level). Later, children could relate the two
sequences to each other (ability that corresponds to a second-level mapping). Similarly,
in that report as well as in another (Inhelder et al., 1976), Inhelder and her colleagues
analyze two categories of procedures. One is teleonomic, oriented toward a goal, and the
other causal, oriented toward understanding. Inhelder et al. found that these categories
are at first isolated (like single set that characterize the first level), later they alternate and
interact (like mapping at the second level), and then the procedures are gradually
integrated (like the coordination and integration done at the third and fourth levels).

Karmiloff-smith (1986a) finds a sequence that has some attributes similar to the
sequence characterized above. Her sequence progresses from implicit knowledge with
procedures that are not related to each other (like implicit single sets of the first level);
through primary explicitation, in which relations across representations are formed (like
the second-phase mapping); and up to further explicitation in which multiple
representations of the same knowledge are linked (like systems of the third level).

Karmiloff-Smith's sequence evolves in respect to representation. Generally, the
levels described above evolve within one or more of the microdevelopmental phases.

<table>
<thead>
<tr>
<th>Attributes of the microdevelopmental phases</th>
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In the actual phase, knowledge is based on actual actions, specific observation and
perceived events. It is related, therefore, to the specifics of the situation. For example,
one of the exploratory behaviors that Wansart (1990) found is "led by the action and by
the current state of the materials" (p. 167).

In the representational phase, on the other hand, a person can think of diverse
possible occurrences and represent them in his or her mind. At this phase, therefore,
knowledge is not constrained by the specifics of the current state.
The abstract phase which follows is still different: in the abstract phase, knowledge is related to arrays of possible representations, and is understood as concepts or broad categories.

Although the microdevelopmental sequence evolves through these phases and across the levels within each phase, the sequence is not smooth nor unidirectional. Instead, several researchers indicate a process that is characterized by a range of variability.

(ii) A range of variability

A bandwidth of performance, or ZCD

The microdevelopmental sequence found in this study did not progress in a neatly ordered way. Instead, it consisted of a bandwidth of variabilities, creating a "Zone of Current Development". On the whole, though, the bandwidth of alterations had a trend of growth (see chapter 7).

Such variability in performance level is reported by other researchers of microdevelopment. For example, Werner (1957) views the back-and-forth alteration as "a most important genetic principle, that of oscillatory activity in terms of progression and regression" (p. 130).

A similar range of performance is conveyed by Fischer's distinction between a functional level and an optimal level. The optimal level "specifies the upper limit on the complexity of skill that an individual can control" (Fischer & Pipp, 1984, p. 47). The optimal level indicates the person's best performance, which is induced by supportive environmental conditions. This performance exceeds the spontaneous performance of the
same person under regular, non-supportive conditions. The latter performance indicates the functional level (regular level of functioning), in contrast to the optimal level.

Ann Brown and Robert Reeve (1987) refer to Vygotsky's Zone of Proximal Development as bandwidths of competence. They discuss the "concept of bandwidths of competence, or zones of proximal development created in contexts that vary in degree of support" (ibid, p. 177).

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**A range of performance — peaks are "rediscovered"**

As in the present study, Siegler and Jenkins (1989) indicate a range of alteration in performance during microdevelopment. Siegler and Jenkins find that children's strategies when learning to add numbers do not evolve in a unidirectional progression from less advanced to more advanced strategies. Children rarely use the new strategy after discovering it. They even rediscover the same strategy several times before starting to use it appropriately. However, over the whole course of the experiment, Siegler and Jenkins also found that children tend to use more the more advanced strategies, indicating an overall trend of growth.

Schauble's study is another example of variability within a range of performance. Schauble (1990) indicates that "no child, even in the high-coordination group, consistently used higher-level strategies" (ibid, p. 48).

The microdevelopmental sequence did not show, then, a neat, unidirectional progression. The following section focuses on this attribute. Adding other processes found in the present study, it suggests that the process of knowledge construction contains multiple pathways that work in different directions.
MULTIPLE PATHWAYS: AN ALTERNATIVE
MODEL OF KNOWLEDGE CONSTRUCTION

The findings of this study indicate an alternative to the hierarchical and unidirectional process of knowledge construction. Instead, an alternative model, consisting of parallel access to multiple pathways is suggested in this section.

(i) Not a unidirectional process

Cyclical, discontinuous, discrete processes

The previous chapters demonstrated that although there was a general upward trend of knowledge construction, this trend did not consist of a unidirectional, continuous process. Instead, the process could be cyclical, discontinuous, or it could consist of discrete sequences. These attributes were manifested in three different ways.

First, the exploration consisted of reiterated cycles across modes of explorations (see chapter 5). A mode of exploration of a more advanced phase temporarily gave way to modes of previous phases, thus creating a cyclical sequence.

Second, each microdevelopmental sequence consisted of a bandwidth or zone of current development (ZCD) within which knowledge structures alternated (see chapter 8). Within this ZCD, the sequence consisted or irregular up-and-down shifts.

Third, knowledge construction consisted of multiple discrete microdevelopmental sequences. Each microdevelopmental sequence stopped at some point and gave way to a new sequence.
The discrete sequences generated a multi-layered process of knowledge construction.

We have seen that when, for example, the participants changed the wire connections and this very change created a new problem, they then started a new microdevelopmental sequence. The new sequence referred to a slightly altered context, such as a different wire configuration, or a different problem. Each of these sequences added another layer to knowledge construction. Instead of "lean knowledge", based on a single problem, each layer broadened the context of the constructed knowledge, thus making it more robust. The reiteration of the microdevelopmental sequence, then, created a multi-layered process, ranging across diverse sub-problems (see figure 9.2).

Figure 9.2: Multi-layered process of knowledge construction
In figure 9.2, each layer represents a microdevelopmental sequence that evolved in relation to a specific sub-problem. For example, the first layer represents Ann and Donald's first microdevelopmental sequence, the second — their second sequence, and so forth.

(ii) Multiple pathways

Knowledge construction does not necessarily occur through a single pathway. Bidell and Fischer (1992) suggested that development occurs along simultaneous strands that form a developmental web. The strands proceed from several starting points, and form different pathways, some of them converging, some diverging, others separate.

In addition to simultaneous strands that proceed in a general, similar direction, as Bidell and Fischer suggest, the present study indicates that there are simultaneous processes that evolve in different directions as well. These include bottom-up, top-down, and horizontal processes.

<table>
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<th>Bottom-up processes</th>
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Each microdevelopmental sequence traced a process with a general bottom-up trend. As the previous analysis indicated, the sequences started in the first or the second actual level (see chapter 8). Then, in spite of alternations, there was a general upward trend in the sequence. The linear and polynomial curve-fits clearly indicated this trend.

The bottom-up process was also noticeable in the operation of differentiation. As we have seen (chapter 7), differentiation built on existing structures and worked its way up, thus working in a bottom-up fashion.
In chapters 6 and 7, a distinction was made between general and specific knowledge structures. General structures refer to knowledge constructed in the past in other domains. These structures were distinguished from specific knowledge structures which were constructed during microdevelopment in the context of the robots.

The participants in the study had general knowledge about sensors. Of course, they encountered uses of sensors in everyday life (e.g., elevator doors, garage remote-control operated door). Yet none of them directly experimented with sensors, and only one saw a sensor (i.e., saw the sensor itself). However, the participants read about sensors, heard about sensors, and knew about them. When they first encountered the robots and their weird patterns of movement, they thought that some kind of a sensor may be responsible for these patterns. As we have previously seen, 58 seconds after approaching his first robot, Herbert told Jean:

"I'm trying to figure out if it changes directions on time thing or there's a sensor that does it and what the sensor is."

Similarly, when Kevin and Marvin approached their robot, after joking about its "indecisive" pattern of movement (an ACT1 statement), Kevin asked:

"Does he have any sensors?"

The existence of sensors could explain the robots' patterns of movement. Like Herbert, Kevin did not know yet if the robot had any sensor and what the sensor was. It took each of them a long process of experimentation to find that out. However, in both cases, their general
knowledge directed the process of experimentation. For example, Marvin started passing
his hand around and over the robot, trying to elicit some response by his actions.

In this way, the participants' general knowledge directed and guided the
construction of primary knowledge structures (from ACT1 to ACT1 differentiated,
ACT2, and so forth).

Similarly, the participants had other general knowledge that also guided their
exploration: they had general knowledge about causal relations, about hypothesis
generation, hypothesis testing, and methods of scientific inquiry (e.g., testing one variable
at a time).

This general knowledge served in a top-down process. Within the specific
context, the participants just started to develop primary knowledge structures that form
the beginning of a microdevelopmental sequence. However, at the same time, their
general knowledge guided this process in a top-down manner.

As we have previously seen (chapter 7), bridging also worked in a top-down way.
Bridging specified target structures, which were later filled with content.

Therefore, while the bottom-up microdevelopmental sequence was evolving, this
sequence was also assisted by top-down processes, triggered by general knowledge and
bridging.

| Horizontal processes |

Horizontal processes occur when general knowledge serves not in a top-down
manner, but when it is applied directly to the current microdevelopmental level.

For example, when Marvin put his hand close to the robot and the robot reacted,
Kevin said:

"Oh, do you know, there's some like buttons in elevators where you touch
it with your hand you break the electric current, and maybe that's why
you're getting a different reaction when you're putting your hand on it instead of when you put your hand..."

In this case, Kevin applied general knowledge from the context of elevators; with this general knowledge, he constructed his current structure in the context of the robot: "you're getting a different reaction when you're putting your hand on it instead of when you put your hand..."

General knowledge, then, can serve also through a horizontal pathway. This happens when knowledge constructed in other domains is appended to the context in which knowledge structures are currently constructed.

Parallel pathways

The findings of this study indicate that knowledge structures at different levels coexist: while the participants had abstract knowledge structures in other domains, they constructed primary knowledge structures in the specific context of the robots.

It is also suggested here that the alternative pathways — the top down, bottom up, and horizontal processes — coexist. Each pathway can be used as the need arises within a given context. For example, in the context of the robots, the participants could access a problem through each of these pathways. When their actions or observations could be processed through one of these pathways, that pathway was activated. That is why at times they used a top-down process and at times a horizontal process, while they were constructing a bottom-up microdevelopmental sequence.

The web of pathways, which Bidell and Fischer (1992) describe, can be seen, therefore, as a three-dimensional web, comprised of multi-directional pathways.
INTERLUDE 9/10

CHANGING A FOCUS:
FROM MICRODEVELOPMENT TO INTERACTION

The last few chapters focused on the "construction" aspect of "co-construction."
The way knowledge structures develop through microdevelopment was analyzed (chapters 5-6); the participants' microdevelopmental sequences were traced, analyzed and characterized (chapters 7-8); the general attributes of microdevelopment were outlined, and an explanation for the phenomenon was suggested (chapter 9).

The following chapter turns to the "co-" part of "co-construction". It analyzes techniques people use for constructing their knowledge together, through interaction.
CHAPTER 10: CO-CONSTRUCTION OF KNOWLEDGE:
ENSEMBLE THE INTERACTING TEAM

TECHNIQUES FOR CO-CONSTRUCTION THROUGH INTERACTION

*Donald:* "So we are out of sequence here."
*Ann:* "We disabled something."
*Donald:* "So we disabled something."

*Kevin:* "OK, that was just a hit, yeah."
*Ann:* "That was just a hit, yeah."

(i) **Repeating each other's sentences**

One of the techniques the participants frequently used was repeating each other's sentences. The transcripts are replete with examples like the two presented above.

<table>
<thead>
<tr>
<th>Acknowledgment and affirmation</th>
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<tr>
<td>Repeating the other's utterances serves an important function during interaction. Repeating what the other said gives the other a feeling that he or she was heard; it acknowledges the other's idea, and it gives affirmation for that idea.</td>
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</tbody>
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As in the previous example, the participants' repeats often included a lot of affirmative utterances:

*Donald:* "...The left gear-/  
  /Ann: "gear--"/  
*Donald:* "and the right gear"/  
  *Ann:* "gear. Yeah."  
  *Donald:* "Yeah."
  *Ann:* "Yeah."

These affirmations served the same function as the repeats and when they accompanied these repetitions, they strengthened them even more.

| Aligning with each other: internal reconstruction |

These repeats served another function too. By repeating each other's sentences, the participants aligned with each other's ideas. A repeat did more than sending the other the message "I follow you." It also said: "I am with you."

The repeat, however, was more than a mere message. By repeating the other's sentence, the participant reconstructed the other's idea and internalized it. The difference between listening and repeating is similar to the difference between watching the other do and doing. Like learning by doing, repeating the other's idea is a process of internally reconstructing that idea.

These repeats, then, had an active role in aligning the participants' knowledge structures. When one of them took a step forward in the sequence of knowledge structures, the other reconstructed the same structure by repeating the idea. In this way, the participants aligned with each other on the microdevelopmental sequence.
The internal reconstruction was manifested in another attribute of these repeats. When repeating the other's sentence, the participants often changed the other's formulation.

(ii) Repeating and changing

Ann: "That's when it spins continuously on its right."
Donald: "On its - right."
Ann: "Right, right."
Donald: "Yeah, it spins with its right, or, it spins around its left leg."
Ann: "Yeah."
Donald: "OK."

By changing the formulation, as Donald did in this example, the participants reconstructed the other's idea in their own words, in a way that was meaningful to them. The altered formulation, in turn, was a source of differentiation.

A source of differentiation

When the participants repeated a statement with a different formulation, they also somewhat changed the idea itself:

Donald: "How do we know-"
Ann: "How would we be able to tell that?"
Donald: "How would we be able to test it..."

Donald and Ann repeated each other's idea with some changes. The overall structure of the repeat served the functions of affirmation and alignment with the other, by keeping a similar formulation: "How do we"/"How would we", and repeating the
formulation "How would we be able to". Still, each reiteration introduced some change: "know" is vague and implicit, "tell" is explicit and gives external indication; "test" indicates an operational criterion and guides to further action.

These changes almost necessarily generated differentiation:

*Kevin:* "Only the black."

*Ann:* "I think- only the metal thing."

Ann's differentiation took a step forward in the identification of a functional part. Through these repeats-with-changes, the participants often generated differentiation, which, as we have previously seen, plays an extremely important role in the process of knowledge construction. These differentiations sharpened and recast the other's idea:

*Ann:* "*We were trying to invert it, we were... but we were never able to...*"

*Donald:* "*We were trying to ... right, we were trying to make it go the opposite way, but it seems...*"

As in other examples, by repeating part of the formulation and refraining from changing the format of the sentence, the participants preserved the power of the repeat. In the last example, Donald still strengthened the repeat further by adding an affirmation ("right"). In his sentence, Donald repeated both the formulation and the format of the sentence: "*We were trying to -- we were -- but --*. Within the format and content of this repeat, he rephrased Ann's sentence ("make it go the opposite way" instead of "invert it"). His differentiation reformulated the knowledge structure that Ann expressed and made it more explicit.
A trigger for further development

Through the changes in their repeats, the participants often took the other's idea a step further. In this way, they generated a process of continuous development of the idea:

*Kevin:* "It does stop."
*Donald:* "It does stop."
*Ann:* "It only stops..."
*Donald:* "It does two times around and then stops."

(iii) Developing each other's ideas

*Donald:* "The same loudness that you said hello-"/
//Ann: "If you build up to it-"/
//Donald: "Right, if you build up to that very slowly and it-"/

Taking small steps forward

The exchange between Donald and Ann demonstrates how repeats were interwoven into a process in which one developed the other's ideas. Ann finished Donald's sentence and completed an idea that he may have had in mind. Donald, in turn, confirmed her completion ("right") and reiterated her phrase ("if you build up to that") while continuing to develop the idea further ("very slowly").
Reformulation and development

Recasting the other's idea in different words usually took the idea a step further:

Kevin: "It's rotating a bit now."
Marvin: "Uh huh. That's a sort of bouncing back and forth."

"Bouncing back and forth" reiterated the idea of "rotating". At the same time, by thinking of the rotation in this way, Kevin and Marvin were more likely to perceive the common denominator between that rotation and other elongated back-and-forth movements that they had observed previously.

Each differentiation that was based on the other's idea, therefore, continued to develop that idea and contributed to the team's co-construction of knowledge.

Development in bigger steps

The participants developed each other ideas not only through closely neat exchanges as in repeats, but also by picking up an idea previously expressed and continuing to elaborate it.

For example, about 5 minutes after Ann and Donald started their exploration together, Ann raised the factor of distance:

Ann: "The question is, what else does it do, and how far away?"

Forty five seconds later, when she and Donald analyzed differences in sound, she mentioned again the distance factor when she told Donald:

Ann: "You did that distant thing, so..."
Twenty seconds later Donald picked up the idea and reiterated Ann's question, taking it a bit further:

*Donald: "I wonder how far it can go from."*

This was followed, as we have seen previously (chapter 5), by an extended experimentation clapping at different distances and testing the robot's response.
Integration of techniques

Although each of these technique was discussed separately, the participants often used them together. The development of knowledge structures, then, consisted of an amalgam of techniques. The participants' utterances were comprised of repeats, affirmations, completing each other's ideas, developing these ideas further, and, together, constructing knowledge structures:

*Donald*: "What it really is, is it's two, it's just two separate, these are probably two separate, ah, gears, and-"/

*/Ann*: "And the sensor is telling you which switch turn is setting it to-"/

*/Donald*: "Yeah, and the sensor is going to tell which one is going to turn off-"/

*/Ann*: "and this is a toggle, I mean, you go, it just goes back and forth."

Donald, in his first statement, formulated part of a structure; Ann, then, completed the structure. Donald affirmed her completion ("Yeah") and repeated her formulation, making some differentiation ("going to turn off"). Ann, in turn, continued to develop the idea further ("this is a toggle").

Using all these techniques, the participants, together, co-constructed their knowledge structures.
ANALYZING CO-CONSTRUCTION: THE PARTICIPANTS' DISCOURSE

(i) A process not divisible to its separate individual participants

Donald: "It spins-"/
/Ann: "Clockwise-"/
/Donald: "on noise"/
/Ann: "Uh-hum."

Structures cannot be attributed to individual participants

In this example, as in others that we have seen throughout the chapters, the participants constructed one and the same knowledge structure together. It is impossible to attribute this knowledge structure to one of them; it is the integration of fragments of sentences, each expressed by one of them, that, together, makes the structure.

When structures were constructed together, one part of the structure could be expressed by one participant, and its other part — by the other:

Donald: "But basically, the light that is on, is the side"/
Ann: "Yeah, it's on the same side as the gear"/
/Donald: "that has the gears...on."
Analyzing knowledge structures constructed through interaction, like the structures expressed in the episodes described above, cannot use the individual as a unit of analysis.

The previous analysis highlighted the way in which each of the participant's sentences depended on the other's, through repeats, slight changes, and developments. The participants' sentences are like bricks in a construction. A construction cannot be attributed to single bricks, but to the way the bricks are built one on top of the other. Attributing the process of knowledge co-construction to single individuals is as meaningless as attributing a building to single bricks.

Instead of using the individual as a unit of analysis, therefore, a different unit is suggested — the ensemble. An ensemble is an interacting team — pair, threesome or group — working together.

The term "ensemble" uses the metaphor of a musical ensemble. In a musical ensemble, when a few musical instruments are playing together, the resulting music is the product of the ensemble as a whole. Although it is possible to analyze the tune played by each instrument, this analysis has a meaning only in relation to the whole musical piece. Similarly, in an interactive event, the resulting interaction is a product of all the participants that take part in the process and the "tunes they play" — their input to the interaction.
(ii) The dynamics of co-construction

Symmetry in turn-taking

Table 10.1 presents Ann and Donald's first microdevelopmental sequence, by attributing fragments of sentences to the one who uttered them. Table 10.1 is not intended to show that the co-construction process is divisible to the individual participants. Quite the contrary. The previous analysis took an unequivocal stand against such a view. What table 10.1 intends to show, instead, is the dynamics through which the participants co-constructed their knowledge.

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As table 10.1 demonstrates, Donald and Ann contributed quite evenly to their mutual process of knowledge construction. Sometimes (when marked D&A), they co-constructed structures together — each of them formulated part of the structure. In these cases, each part of the statement did not form a structure; instead, the combined statement, made out of both of their sentences, makes a single structure. In other cases, each of them formulated a structure, which continued the sequence previously developed. In some parts of the sequence they "took turns" in the formulation of structures — each of them formulated one structure at a time. At other times, one of them stated several structures before the other took a turn.

<table>
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<tr>
<th>Qualities forming the dynamics of co-construction</th>
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</table>

The symmetry of the interaction is one attribute of the knowledge construction process. Other attributes of the process, which characterize the participants discourse, indicate the degree of "togetherness" in the process — its "harmony". The process can be characterized by identical or similar statements (repeats), reciprocity (e.g., "I didn't either"), agreeing with each other (affirmations), and building on each other's ideas.

A less "harmonious" process may have different attributes. A more antagonistic interaction may be characterized by less repeats, less affirmations or confirmations, more negations, and more argumentation (see table 10.2).
In antagonistic interactions, the participants' statements may be more separate, disconnected from others' previous statements. More separate statements indicate less building on each other ideas, in contrast to argumentation, which builds on the other's ideas but in a negative way.

During antagonistic interactions, even as the participants co-construct their knowledge in a common process, the process is not smooth nor pleasant. In contrast, interaction that is characterized by responsive interchanges, affirmations, repeats, building on the other's ideas, and developing these ideas further — is more likely to generate a fruitful as well as pleasant co-construction process.

The qualities characterizing the dynamics of the interaction are not related to the participants' initial expertise in relation to each other, nor to the symmetry of the co-
construction process. Even when one of the participants had substantial more expertise than the other, their interaction often had "harmonious" qualities. The case of Donald and Liz can illustrate this point.

At the last quarter of the first hour, Liz joined Donald, Ann, and Kevin. Before that, together with Cindy, Liz had explored only one robot. Liz and Cindy's robot did not have much in common with the robot Donald's group was exploring: the two robots had different sensors, and their patterns of movement were different (Liz and Cindy's robot "wugged" in response to light, while the other robot turned in different directions depending on the number of claps). The new robot was, therefore, absolutely unfamiliar to Liz. There was a substantial difference between Liz's expertise, related to that robot, and that of Donald, who has explored the robot almost since the beginning of the experiment.

Ann, Donald, and Kevin introduced Liz to the robot and explained its functioning. Then Liz wanted to check the robot's wiring:

*Liz looks closely at the robot and follows with her finger the wire connections: "So this thing is connected to this, which is connected to that...."

*Donald: "Well, if you want to look at it from [the point of view of] wiring, probably look from the sound coming in, / Liz: "Uh-hmm," / Donald: "Sound comes in-"

By that time Donald understood the relation between the structure of the robot, including the wire connections (second phase issues) on the one hand, and the effect of the stimulus on the movement of the robot (first phase issues), on the other. It was easier for him, therefore, to look at the wire connections in a more meaningful way. In order to understand the way the robot operated, it was more helpful to follow the wire connections not from a random point in the sequence, but inserted from the beginning of the processing — the sound sensor that detected sound. In a very friendly tone Donald
suggested to Liz, therefore, to start where the sound comes in, and immediately helped her with that. Watch, now, the attributes of the evolving dynamics:

Donald: "Sound comes in-" / Liz: "goes through here-" / Donald: "goes through here where it's converted to an electrical signal" / Liz: "in here" / Donald: "in the black."/ Liz: "Yeah. It goes through-" / Donald: "It goes through there, comes into here, we don't know what this one does.. Liz: "OK, ... It comes out-"/ Donald: "Comes out of here, ......."

The dynamics between Donald and Liz was filled with completing the other sentences, repeats, and building on each other statements. When Donald started (Sound comes in), Liz completed his statement (goes through here-). Donald then repeated her sentence, in this way affirming and acknowledging her contribution. He immediately went on to develop the sentence and add more information (goes through here where it's converted to an electrical signal). Liz completed again, adding by indicating where that occurs (in here). Her contribution did more than adding a piece of information. As we have seen previously in regard to repeats, her completion sent a message to Donald, indicating that she understood, and also served for internally reconstructing that knowledge. Knowing that Liz followed him, Donald, in turn, could then continue to develop the ideas further, as he indeed did.

"Harmonious" dynamic of interaction, consisting of repeats, affirmations, and building on each other's statements could develop, then, disregarding the symmetry of the dynamics and the symmetry of expertise between the participants.
Asymmetry of dynamics: The example of Kevin and Marvin

Although Kevin and Marvin co-constructed their knowledge together through their interaction, the dynamics of their discourse was not symmetric. In the beginning of the interaction, Kevin did more of the "talking" (see table 10.3).

Table 10.3: A sequence of co-construction
Kevin and Marvin's first microdevelopmental sequence

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1 As mentioned in chapter (x*), Donald joined Kevin and Marvin for a short time (less than a minute) before starting to collaborate with Ann. During that time, Donald stated one structure, as the table demonstrates.
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As table 10.3 demonstrates, the dynamics of the interaction between Kevin and Marvin was different than that between Ann and Donald. In the beginning of Kevin and Marvin’s common co-construction, Kevin stated more structures than Marvin did. Toward the end of their first microdevelopmental sequence, the process became more symmetric.

However, the analysis of statements did not give the full picture of the interactive dynamics. The videotaped data revealed another aspect: in the beginning of their sequence, while Kevin did more of the talking, Marvin did more of the acting.

The analysis of discourse, then, disclosed a part of the knowledge-construction process, sometimes even a major part, but not all of it. In order to understand the dynamics that contributed to the participants’ process of knowledge construction, other factors had to be taken into account as well.

**OTHER ASPECTS IN THE INTERACTIVE CO-CONSTRUCTION**

(i) Actions and gestures

When Donald first analyzed the robot’s pattern of movement, he referred to it by saying: "it was spinning one way" and then "it swirls back around."
Ann wanted to see:

Ann: "Try again."
Donald claps.
Ann: "OK," She gestures clockwise.
Donald: "You see? So it's going around, OK," Donald repeats Ann's motion and also gestures clockwise.
Donald: "clockwise," / Ann: "Yeah"/ Donald: "And then (...) it turns around, counterclockwise."

The distinction clockwise-counterclockwise first grew out of the level of actions: Ann made a clockwise gesture and Donald repeated her gesture. Only then did he incorporate the distinction in his verbal description.

| Meaning retrieved from actions and gestures |

During the interaction, the participants' actions and gestures were often inseparable from their discourse. In the first phase, the meaning of their statements could often be retrieved from the way they interacted with the robot:

Kevin: "OK, but if you did it this way, it should be able to continue going in the one direction."

Marvin did not have a problem understanding Kevin's meaning. Nor did we, as observers of the videotapes, since the video captured Kevin's actions. Kevin's statement "this way" retrieved its meaning from what he did at the time:

Kevin puts his notebook close to Marvin's notebook and moves it forward, accompanying the robot's movement. In this way, the robot stays under the notebook while it moves forward.
Similarly, in the second phase, the parts the participants indicated gave meaning to their statements:

*Donald:* "So far we've got out here, and into here, into here, and into there-" / *Ann:* "Right, these are connected somehow" / *Donald:* "Right, out of here, and into here..."

All the while, Donald and Ann were following with their fingers wire connections. When Donald said "into here" and "out of there" Ann had no difficulty understanding him; she shared with him the same meaning, as her statement indicated.

The third phase was no exception in this respect:

*Donald:* "The next time you stick it in, it starts it?"
*Jean:* "Yeah."

Jean did not have a problem understanding Donald's question. As in the previous examples, the actions and gestures endowed the participants' discourse with meaning, when the words themselves were obscure.

(ii) **Sub-context**

Sub-context is the part of the context on which each participant focuses. When two participants form a team, they usually share a sub-context, but not necessarily all the time.
Marvin looks at what Kevin is doing. Kevin puts his notebook above the robot, which starts oscillating under the notebook.
Kevin: "OK, in this case, it's stuck here,"
Marvin starts writing in his notebook and mumbles softly while writing: "Question why it changes..."
Kevin continues to talk: "It's already got light, so more light doesn't change anything...."

In the beginning of this episode Kevin and Marvin shared a sub-context. Within the same context of the robot's exploration, both of them were looking at the same sub-context — the same event. However, later they split their attention, and had two different sub-contexts: Marvin was writing in his notebook, while Kevin continued to explore the robot.

Sub-context and intersubjectivity

The importance of intersubjectivity for interaction was highlighted in literature (see chapter 2). Intersubjectivity, which indicates between-subjects (between individuals) sharing of meaning and understanding, is crucial for the process of knowledge co-construction.

A shared sub-context is a prerequisite for intersubjectivity (see discussion, this chapter, for analysis of the distinction between sub-context and intersubjectivity). If, during the interaction, participants have different sub-contexts — they have different foci of attention — intersubjectivity is at least temporarily suspended.
Different sub-contexts and a breakdown in co-construction

In the analysis of the data, the participants' sub-context was another aspect that gave meaning to their process of knowledge co-construction. While sharing a sub-context was a prerequisite for a constructive process, non sharing a sub-context could lead to at least a temporary breakdown in co-construction, as the following example demonstrates:

Marvin: "Uh-hm".
Kevin: "So when it's over here, it's already partly in the light. (...) whereas over there, when you covered it with the notebook, it needed more dark, maybe that was, aae..."
Marvin looks around in different directions.
Marvin: "Is there a tape around?"
Kevin puts his notebook above the robot. The robot goes back in the shadow of the notebook...

In the beginning of the episode, Kevin and Marvin shared a sub-context. However, Marvin quit the interaction temporarily. He looked around and asked about a tape, but did not share with Kevin his idea — the reason he wanted a tape for
due to the shared sub-context, the participants had no difficulty in understanding each other. When there was some indication that others did not understand, the participants continued to elaborate and gave more explicit information (see, for example, chapter 11, the episode of mutual collaboration). The breakdown of communication at this point, therefore, can be attributed to the different sub-context frames.

2 During the interactions, there were many implicit and partial formulations, as discussed in chapter 7. However, in those cases, due to the shared sub-context, the participants had no difficulty in understanding each other. When there was some indication that others did not understand, the participants continued to elaborate and gave more explicit information (see, for example, chapter 11, the episode of mutual collaboration). The breakdown of communication at this point, therefore, can be attributed to the different sub-context frames.
During an interaction, participants send each other clues that indicate their sub-context. These clues can be picked up by their partners, as well as by an outside observer.
Indicators for sub-context — the sub-context frame

Kevin's and Marvin's different sub-contexts could be retrieved in these episode through several indictors. One, their sub-context was manifested in their discourse. In the first episode, Marvin was mumbling softly while writing his notes; Kevin was describing and analyzing the robot's movement. In the second, Marvin was talking about a tape, Kevin about the robot.

In addition, there were several visual clues indicating their sub-contexts: their direction of gaze (e.g., looking around the room at different directions; looking at the robot), their body postures (e.g., hunching over a notebook, leaning toward the robot, turning the head around), their actions (e.g., putting a notebook over the robot) and gestures (e.g., indicating the robot).

During an interaction, individuals use these indicators to "frame" their sub-context. Like Bateson's (1972/1955) concept of frame, which refers to a meta-message shared through interaction, the concept "sub-context frame" refers to a message people send each other which indicates their sub-context. People send this message through indicators such as body posture, actions and gestures, or discourse.

An episode between Ann and Donald demonstrates the way sub-context frame works during interaction:

Ann: "Interesting!"
Donald: "Which is really kind of, interesting."
Donald takes his notebook, and gets ready to start writing.
Ann: "Look at it, it'll start up again." She claps.

Ann called Donald's attention, indicating by her statement and by her clap that she wanted to continue the exploration. By sending these indicators, she invited Donald to continue sharing with her the sub-context, which Donald indeed did.
The lack of shared sub-context between Kevin and Marvin (demonstrated by the episodes discussed above) did not last long. Were such episodes abundant in their interaction, their process of co-construction would have necessarily changed. Sporadic episodes, then, do not determine the process of co-construction; it is the stream of episodes, the dynamics of the sequence of sub-contexts, that determines the nature of the co-construction process.

Having segments of non shared sub-context is not necessarily destructive for the co-construction process. Some types of interactions are characterized by segments of independent activity, in which each individual has a separate sub-context, followed by segments of sharing (see chapter 11). Such interactions generate different characteristics of a co-construction process. It is the dynamics of the way sub-contexts are shared — or not shared — throughout the interactions, then, that gives the co-construction process its quality.

THE ANALYSIS OF CO-CONSTRUCTION — THE "SCORE"

The participants' discourse, their actions and gestures, and their sub-context frames are different aspects that characterize and endow meaning to the process of knowledge co-construction. The analysis of co-construction can, on the one hand, infer the knowledge structures underlying the participants' discourse. On the other, in order to understand how knowledge co-construction operates, these other factors have to be
considered. The following section describes a framework for representing the different aspects operating in the process of knowledge co-construction.

(i) The score

<table>
<thead>
<tr>
<th>Juxtaposing the aspects that play a part in co-construction</th>
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</table>

The factors operating in the process of co-construction are dynamic — they change throughout the interaction. These factors could be seen, therefore, as variables that change values across time (when their value at a given moment characterizes the co-construction at that time).

<table>
<thead>
<tr>
<th>Representing these aspects</th>
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</table>

Figure 10.1 represents these aspects in relation to one another. The representation is based on the notation of musical scores. Scores for a musical piece represent the music played by each of the participating musical instruments. These representations are synchronized and, thereby, can be related to each other. Similarly, the notation of "score" for interaction represents each of the factors that contribute to the co-construction; these can then be characterized and inter-related to each other.

In figure 10.1, the different components are synchronized along a time line (bottom row, left to right). For each participant (two, in this example), several factors are

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3 The analysis of knowledge structures in the previous chapters indeed took these factors into account. These were especially important for understanding partial formulations and "hanging references", as discussed in chapter 7. The present chapter makes the consideration and analysis of these factors explicit.
presented: their sub-context frame, their actions and gestures, their discourse, and the knowledge structures indicated by their discourse.

Other factors can be added in a similar way, according to attributes of specific interactions. For example, in interactions where the goals of the participants play an important part, representation of the goal of each participant can be added. If the participants' facial expressions are important for the interaction, that factor can be added, and so forth.

Figure 10.1: The Score
(ii) The quality of co-construction: "Score" analysis

Building blocks for the score

The same attributes that characterize the discourse dynamics (see table 10.2) endow meaning to the other factors as well. Similarity and reciprocity can be expressed on the level of actions and gestures (e.g., when both Ann and Donald made a clockwise gesture). Similarity and reciprocity can also be expressed on the level of sub-context frame (e.g., when both participants turn toward the robot and watch it, or turn toward each other). By the same token, separate statements, non related to other statements, on the level of discourse, have their counterpart on the level of actions and gestures (separate, non related gestures and actions) and on the level of sub-context frame (separate sub-contexts).

These are, then, the building blocks for the "score" analysis. These building blocks, such as similarity, reciprocity, separateness, and so forth, qualify the interaction. Understanding them can contribute to understanding how the co-construction process occurs.

How intersubjectivity is achieved? The case of Ann and Donald

Ann and Donald's process of co-construction had a wonderful quality of intersubjectivity — sharing, symmetry, and building knowledge structures together. A short episode demonstrates how this intersubjectivity was immediately restored when it was temporarily lost. The episode demonstrates the importance of "score" analysis, since the restoration of intersubjectivity could not be understood on the level of discourse alone.
Ann and Donald were following wire connections.
Ann: "Awe, swap them."
Donald: "Right."
Ann: "Yeah, yeah."

This part of the episode has similar attributes to most of their co-construction process; it is marked by sharing, agreement, and affirmations.

Donald: "Something happens, and it gets in there, and it goes to there--" / Ann: "What do we think this is?" / Donald: "and then this comes up here."

Donald started following the wired connections. At this point Ann asked about the nature of a specific brick (this was the "mystery box" discussed in chapter 5). Donald, however, did not respond; he ignored her question. Notice Ann's reaction to this temporary breakdown:

Ann: "it's coming out of here. What's the connection to the blue box?"

What Ann did is represented on the score (see figure 10.2). As figure 10.2 indicates, at the time of the breakdown Ann completely aligned herself with Donald both on the level of sub-context frame and of actions and gestures. While their sub-context frames were similar before, in this segment they were literally identical. Ann got closer to the robot; both she and Donald held [maintained] the same posture.

On the level of actions and gestures, an amazing identity emerged at this time. Ann joined with both hands the mixture of wires that Donald was following with both of his hands. At this time, their actions and gestures became so coordinated, that it seemed all four hands belonged to one person.
Figure 10.2: Restoration of intersubjectivity:

The case of Ann and Donald

On the level of sub-context, the frames of Ann and Donald were similar at the beginning of the episode; so were their actions and gestures.

On the level of discourse, at points 1, 2 a breakdown occur. Donald expresses statement 1, Ann expresses statement 2. Each statement is separate, none relates to the other. After Ann's statement 2, Donald does not respond: he continues the idea expressed in statement 1. At this time, Ann aligns both her sub-context frame and his gestures, so that they are completely identical with Donald. She also expresses statement 4, which is similar to Donald's statement 3 (repeat). On the three levels — sub-context frame, gestures, and discourse, she aligns with Donald. Then she expresses again (statement 5) the idea she expressed previously (in statement 2). At this time, Donald responds with reciprocity of the idea.

ID = Identical
SM = Similar
SP = Separate
RC = Reciprocity

The lines on the level of discourse represent connections between ideas.
In the context of her reaction on the level of sub-context frame, actions, and gestures, her short alignment with Donald on the level of discourse receives its powerful meaning. Ann abandoned, for a little while, her question, and joined Donald in his agenda (It's coming out of here.). But it is the powerful alignment on the other two levels that pulled them together again. From the standpoint of this alignment, Ann immediately repeated her question (What's the connection to the blue box?) Now Donald was with her, and he immediately responded:

Donald: "We don't know what this one does, do you? You have a sense what that does?"
Ann: "No."
Donald: "I don't either. So,..."

Interestingly, the technique Ann used is discussed in literature in respect to a different kind of interaction: this is the technique used in parent-infant interaction. When interacting with their infant, parents align with the infant's point of view and repeating the infant's utterances in order to create first intersubjectivity with the infant (e.g., Schaffer, 1984).

Alignment of the actions and gestures may be, then, a powerful interaction technique not only in infancy, but throughout life. Alignment on the level of actions and gestures was apparent throughout several episodes between Ann and Donald, and was used by both of them.
(i) Unit of analysis

A need for a different unit of analysis

When analyzing interaction, the unit of analysis cannot remain the individual, as in traditional psychological research. Acknowledgment of the social aspect of co-construction of knowledge has to be reflected in the unit of analysis. In literature, there are many discussions about the nature of a new and more appropriate unit of analysis. Instead of referring to an individual or to isolated psychological processes measured by various tests (LCHC, 1983), researchers indicate that units of analysis should reflect the social origins of cognitive processes (Wertsch, 1985).

Units suggested in the literature

In the literature, various "candidates" for such units have been suggested. For example, different levels of activities (Leont'ev, 1981) can serve as units of analysis (Wertsch, Minick, & Arns, 1984). Other units can be socially assembled situations or cultural practices (LCHC, 1983); task-within-practices or job-task (Scribner, 1984, 1986); "whole task" (Newman, Griffin & Cole, 1984), and activity, task or event (Cole, 1985). By using such units of analysis, the focus of the analysis shifts to the active changes involved in an unfolding event or activity (Rogoff, 1990).
The problematic of these units

These new units of analysis, though, pose a problem. Units of analysis such as activities, events, tasks, and the like are prone to specificity. Indeed, the way cognitive processes evolve does depend on their context. However, the progress of research depends on the possibility to compare and integrate results of different studies. To allow such comparison and integration across contexts and events, the unit of analysis has to reflect the dynamics of the interaction, yet not be defined by the context and the situation. The analysis, therefore, has to transcend the specificity of given activities, events, tasks, or situations. Context has to be reflected in the content of the analysis, instead of in the units themselves.

The problem of a new unit of analysis is, therefore, that it should be able to relate to specifics yet be general enough to unify interactive cognitive experiences across events and contents. In order to overcome this problem, the unit of analysis suggested above is the ensemble.

The "ensemble" — comparison with literature on infant-parent interaction

The choice of the ensemble as a unit follows the lead of research on infant-parent interaction. Schaffer (1984), for example, views the parent and the child as one mutually accommodative interactive system. Analyses of infant-parent interaction examine the dynamics of the interaction by looking at the interchanges between the parent and the infant as components of one and the same process (e.g., Stern, 1977, 1985; Trevarthen, 1977). As in parent-infant analyses, the use of "ensemble" as a unit of analysis refers to the participants in an interactive episode as composing a single process together.
(iii) The "score" — factors in the analysis of co-construction through interaction

<table>
<thead>
<tr>
<th>The score analysis — factors that are relevant across ages and level of expertise</th>
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</table>

The "score" method of analysis looks at the co-construction of knowledge as a product of all the components that take part in the process: the dynamics of the participants' discourse; their actions and gestures, and their sub-context frames. These components exist in interactions among peers, whether children, adolescents, or adults; in interactions between an expert and a novice, or an adult and a child, as well as in infant-parent interactions.

The factor most analyzed in literature is the participants' discourse. In addition, the participants' actions and gestures form an important factor, which is an inseparable part of the interaction (Pike, 1954). Actions and gestures become particularly significant when the participants collaboration on an activity that involves objects.

When two people interact, their body postures help to frame the relevant sub-context. Their body postures can open up the interaction for other participants to join in, as well as close it down from other people by framing a closed space between them (e.g., Scheflen, 1972). Using body postures, an individual can stop the interaction temporarily and create a secluded private space with an individual sub-context. Later he can join the others’ sub-context and resume the interaction.

<table>
<thead>
<tr>
<th>The distinction between sub-context and intersubjectivity</th>
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</table>

A shared sub-context is a prerequisite for intersubjectivity. Trevarthen & Hubley (1978) coined the term "secondary intersubjectivity", referring to intersubjectivity that is
formed when a parent and an infant focus on the same object or event. The concept of sub-context is aimed at distinguishing between looking at the same event and the formation of intersubjectivity. Two individuals, at any age, may look at the same object or event and still attribute to it a different meaning. Shared sub-context, therefore, is necessary but not sufficient as a condition for intersubjectivity.

Frame and sub-context frame

"Sub-context frame" is the reciprocal or complementary of Bateson's (1972/1955) concept of frame. Bateson's "frame" refers to a meta-message that frames in a specific way the meaning of what is said. Sub-context frame refers to the infrastructure that enables the formation of such messages. For example, the individuals' positions — whether facing each other or looking away from each other — enable them or prevents them from sending a wink as a meta-message. A common sub-context frame allows two individuals to attribute the same meaning to a given occurrence. They can share a common "text" by sharing what constitutes for them "con-text" (what underlies, or "goes with" the text). When sharing a sub-context frame, the same context can be simultaneously active in their minds.

Adding other factors to the "score" analysis

In the score analysis, several factors that were relevant to the context of this study were represented. However, other factors can be added in a similar way, according to attributes of specific interactions. For example, the participants' facial expressions (e.g., Stern, 1974; Trevarthen, 1977); evaluation of performance, and so forth.
SUMMARY

This chapter made explicit the analysis and interpretation that supported the meaning-making in the previous chapters. In the analysis of knowledge structures, the attribution of meaning to the statements that the participants made often had to rely on the context in which these statements were made (see chapter 7). Just as the participants could understand each other by retrieving cues sent by their partners, so did us, the observers of the videotapes. The techniques the participants used to support the co-construction process are analyzed in this chapter.

The chapter highlights three techniques the participants used in their discourse: repeating each other's sentences, repeating while introducing changes to these sentences, and developing the other's ideas further. The analysis indicated the function of these techniques not only to facilitate the social interaction, but also to align the knowledge-construction process.

Two aspects of the participants' discourse are underlined: the non-divisibility of co-construction into the individuals who participate in the process and the attributes of the dynamics of the co-construction. The chapter also discusses the way other factors support the meaning of the discourse — the gestures and actions, and the sub-context frame. A representation of "score" analysis was used to integrate these factors together, when trying to understand the dynamics of the co-construction process.

The elements represented on the score could indicate identity, similarity, and reciprocity, or differences, opposition, and separateness. The former indicate harmonious dynamics, while the latter — antagonistic one.

Harmonious dynamics facilitates the process of knowledge construction. It creates a feeling of togetherness, of sharing, and of mutuality in the process of knowledge
construction. This attribute of togetherness was expressed in Ann and Donald's formulations:

Ann: "What do we think this is?"

And later:

Donald: "We don't know what this one does."
After taking a close view at the dynamics of interaction and the way it serves for the co-construction of knowledge, the following chapter zooms out to take a more global picture. The building blocks that served for characterizing the dynamics of the interacting team can serve for characterizing types of interaction.

In the literature, several debates have taken place between different approaches that advocate for one type of interaction or another. These specific interactions, it was argued, contribute to the individual's construction of knowledge.

Chapter 11 portrays a more global framework for analyzing interactions — an interaction model. The model selects two dimensions for this analysis. Onto the span delineated by these dimensions, different types of interactions could be mapped. These types of interactions include those advocated by different approaches in literature in addition to other types.

Using framework of the interaction model, the different types of interactions, which previously did not seem to have a common ground, can be integrated, compared, and analyzed.
CHAPTER 11

PATTERNS OF INTERACTION
IN THE CO-CONSTRUCTION OF KNOWLEDGE

THEORETICAL FRAMEWORK FOR ANALYZING INTERACTIONS

In the literature, different theories suggest specific types of interactions that promote cognitive change. As the review in chapter 2 indicates, the type of interaction highlighted by one theory is different than that highlighted by another. Vygotsky focuses on the importance of interaction between children and adults or "more capable" peers (i.e. Vygotsky, 1978; Wertsch, 1979). Studies in the Vygotskian approach analyze adult-child interaction and focus on the intersubjectivity and shared meaning created in the process (e.g., Wertsch, 1979; Wertsch, Minick, & Arns, 1984; Saxe, Guberman, & Gearheart, 1987; Rogoff, Malkin, & Gilbride, 1984). On the other hand, the Piagetian school emphasizes cognitive conflict resulting from interaction among peers (i.e. Doise & Mugny, 1984; Doise & Palmonari, 1984; Murray, 1972, 1983; Perret-Clermont, 1980; Piaget, 1926). According to Piaget, children's interactions with adults usually generate compliance to adults' authority and prevent cognitive restructuring. Both of these approaches are still different than social learning theory (Bandura, 1977, 1986). Bandura

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1 The framework and analysis suggested in this chapter appeared in Granott (1993). The present chapter was adapted to the format of chapters in the thesis.
highlights the importance of modeling and focuses on the way children learn by observing adults.

This chapter attempts to show that the patterns of interaction suggested by Vygotsky, Piaget, Bandura and their followers form only part of the interactive spectrum that affects cognitive change. The chapter suggests a theoretical framework for analyzing interactions. The framework, or interaction model, is based on categories generated through the analysis of the data. These categories were further elaborated and structured theoretically. The characterization of the types of interactions is based on the building block of interactive dynamics, identified in the previous chapter.

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<th>Dimensions for analysis</th>
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The interaction model suggests two major dimensions from which interactions can be analyzed. One is the degree of collaboration. Collaborative patterns can involve high mutuality and evolve through intersubjectivity of shared understanding and common focus of attention (Rogoff, 1990). Yet, other interactions can only involve some exchange of ideas and turn-taking activity. The other dimension refers to the participants' relative knowledge and expertise in the context of the interaction. For example, in some cases, one participant joined a group who has been exploring a certain robot for a long time. If the newcomer had previously explored a robot that did not have much in common with the group's robot, there was a difference in the relative expertise between the newcomer and the group (in respect to the group's robot). The expertise of the group, in relation to the robot under scrutiny, was greater than the expertise of the participant who just joined them.

Figure 11.1 presents these dimensions of analysis. The horizontal dimension, representing degree of collaboration, extends for positive values of collaboration from the
intersection of the two axes (indicating no collaboration, or independent activity), through increasing degree of collaboration, to highly collaborative activities. Collaborative interactions are characterized by united effort and continuous sharing. Interactions marked by independent activity, on the other hand, are typical to situations in which participants construct their understanding individually. Disruptive activities are characterized by open conflicts, in which one participant's actions interrupt the other's activity and, to some extent, impede the other's process of knowledge construction. For negative values on the collaborative dimension, activities increase in interchange of disruptive interaction toward the far left end of the dimension, culminating in highly interlocked and inter-disruptive activities.

Figure 11.1: A framework for analyzing interactions

Figure 11.1: A framework for analyzing interactions according to degree of collaboration and relative expertise. Point A, in the intersection of the dimensions, represents symmetric expertise and independent activity.
The vertical dimension characterizes relative knowledge and expertise between the participants. This dimension ranges from symmetric expertise, in which the participants have similar knowledge related to the context of the interaction; it continues through increasing degrees of asymmetry, to a highly asymmetric expertise, in which one participant is more knowledgeable and has greater expertise than the other (in areas relevant to the interaction). Additional factors, other than relative expertise, may affect the types of interaction; these other factors are discussed later.

<table>
<thead>
<tr>
<th>Mapping interactions according to the two dimensions</th>
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</table>

Many types of interactions map onto the span delineated by these two dimensions. The intersection of the axes is characterized by a situation in which participants with symmetric expertise are each involved in an independent activity. The top-right area (marked W in figure 11.1) indicates highly collaborative interactions between participants with asymmetric knowledge and expertise. Adult-child interaction, with evolving shared meaning and highly collaborative support in the Vygotskian-school vein, corresponds to this area. In area X, interactions are characterized by moderate collaboration between partners of some asymmetric expertise. The Piagetian-school examples of a child conserver and a non-conserver, when each of them tries to explain his already formed view to the other, can demonstrate such an interaction. As we will see later, other types of positive interactions also map to different areas between these two dimensions.

The area to the left of the intersection of the axes, indicating negative (disruptive) interactions, has a similar structure. For example, interaction between peers (like two classmates) of equal expertise, who are involved in mostly independent activity but disturb each other's actions occasionally, corresponds to the area marked by Y. The top
left area (Z), on the other hand, indicates an interaction between partners of asymmetric expertise (expert-novice, or adult-child) that is highly interlocked and disruptive.

Interactions that correspond to different values on the two dimensions have different attributes and different cognitive effects. Collaborative interactions of diverse types can promote the participants' cognitive growth in different ways, as demonstrated by examples below; disruptive interactions can hamper cognitive progress. The following section describes the different types of interactions and indicates some of their cognitive effects.

**TYPES OF INTERACTIONS**

(i) Collaborative interactions

Conceptually, the dimensions for analysis (degree of collaboration and relative expertise) are continuous. In order to characterize the attributes of diverse interactions, three ordinal levels—high, medium and low—are set for each dimension. Figure 11.2 represents collaborative (positive) interactions.

Findings from other studies fit with this analysis (see for example Forman & Cazden, 1985, for levels of procedural interactions; Bandura, 1977, for imitation of a model, and Mugny & Doise, 1978, for cognitive conflict that differs from imitation).

**Mutual Collaboration**

Mutual Collaboration is characterized by a highly collaborative interaction between peers of equal expertise (bottom-right area in figure 11.2). This type of
interaction is reciprocal and symmetric, and is often accompanied by intensive verbal exchange. The participants are about equally dominant in the activity (when dominance is measured by their utterances or timed actions relative to one another), with quick shifts of dominance from one to the other. They are engaged in a common activity, sharing materials, products, observations, and hypotheses. The participants co-construct their knowledge by continuously sharing their ways of understanding. Their knowledge structures, therefore, evolve simultaneously. The mutual quality of the process is indicated by talking spontaneously, often simultaneously, using abbreviated speech (Vygotsky, 1962), and completing one another's sentences. During Mutual Collaboration, participants may suggest to one another courses of activities, discuss the suggestions, agree on a common activity, work it out together, share comments on the occurrences, discuss their implications, and co-construct their understanding together (see table 11.1, for a summary of the attributes of different types of interactions).

Figure 11.2: Collaborative interactions
Symmetric Counterpoint

Symmetric Counterpoint occurs between peers of equal expertise who interact while alternating dominance on an activity. As in musical counterpoint, the participants retain some independent activities, which are woven together into a common moderately collaborative interaction. During Symmetric Counterpoint dominance shifts from one partner to another for chunks of the activity, but throughout the interaction dominance is about equally distributed. Even when the participants are "passive", they watch their partners attentively.

During Symmetric Counterpoint the partners share common situations, materials, and feedback on their own and their partners' explorations. However, their understanding of the situation evolves individually, before or during the interaction. Their knowledge, therefore, often develops in unsynchronized spurts. During the interaction, their separate ways of understanding are compared and, if divergent, they may be confronted and changed. After the entire interaction, therefore, the participants' cognitive change may often be similar.

For example, in Symmetric Counterpoint, during a problem solving activity, typically one participant at a time tries a solution while the others watch. Another example is a group discussion, in which one participant talks at a time while the others listen.

Parallel Activity

Parallel Activity is an interaction among peers of symmetric expertise, engaged in an activity that is mostly independent. The individuals work in parallel, with some degree of exchange that nourishes and stimulates one another's activity. During the independent
segments, the participants are absorbed in their own activity, while in the interactive segments they watch the other's activity or talk and exchange information. The interactive parts may be, then, explicit or implicit, verbal or non-verbal (Rogoff, 1990). In contrast to Symmetric Counterpoint, in which the "passive" participant watches and listens attentively to the other, during Parallel Activity the independent activities are not shared but rather form separate simultaneous processes. The activities and the feedback to the activities are separate, as are the processes of knowledge construction. The interactive segments generate partial and sometimes unidirectional sharing that confronts and compares some knowledge structures.

A familiar example of Parallel Activity is young children's parallel play. Although they play separately, there is some interchange that stimulates one another's play. Another example is a research group, in which each member works on her research project, but all share a common interest and occasionally exchange information and ideas.

| Asymmetric Collaboration |

Asymmetric Collaboration represents a collaborative interaction between peers of some asymmetric expertise. The degree to which the participants take part in, or responsibility for, an activity is consistently unbalanced (i.e., one is more dominant, or often directs and guides the other). The participants have common operative goals, share a common activity, and their spontaneous continuous sharing often generates incomplete sentences. While sharing their knowledge and hypotheses, they co-construct their understanding together (see table 11.1).
Table 11.1: Attributes of types of interactions

<table>
<thead>
<tr>
<th>Imitation</th>
<th>Guidance or Apprenticeship</th>
<th>Scaffolding</th>
</tr>
</thead>
<tbody>
<tr>
<td>Separate activities; a less capable partner imitates a more capable one</td>
<td>Complementing goals; short periods of guidance interspersed throughout independent activities</td>
<td>Common activity with complementing goals</td>
</tr>
<tr>
<td>Partial or no sharing</td>
<td>Periods of asymmetric and often unidirectional sharing of knowledge</td>
<td>Sharing the situation, materials, observations; asymmetric sharing of knowledge and hypotheses</td>
</tr>
<tr>
<td>Unguided activity and observation</td>
<td>Partially guided activity, observations and analysis</td>
<td>Guided activity, observations, and analysis</td>
</tr>
<tr>
<td>Asymmetric flow of information, verbal or visual</td>
<td>Alternating shifts of unequal dominance, shifting between independent and guided segments of the activity</td>
<td>Throughout the interaction, a trend of shift of dominance from the scaffolding to the scaffold partner</td>
</tr>
<tr>
<td>Unsynchronized, separate, and highly unbalanced processes of knowledge construction</td>
<td>Asymmetric flow of information</td>
<td>Asymmetric communication</td>
</tr>
<tr>
<td>Swift Imitation</td>
<td>Guiding and demonstrating (by the expert) vs. task-solving (by the novice) information and action</td>
<td>Guiding (by the scaffolding) vs. task-solving (by the scaffold) information and action</td>
</tr>
<tr>
<td>Separate activities in which a less capable partner temporarily shifts to imitating a more capable one</td>
<td>Mostly complete sentences</td>
<td>Mostly complete sentences, focused on shared understanding</td>
</tr>
<tr>
<td>Partial or no sharing</td>
<td>Unsynchronized, separate, and highly unbalanced processes of knowledge construction; activity aimed at the novice's construction of knowledge</td>
<td>Unsynchronized, separate, and highly unbalanced processes of knowledge construction; activity aimed at the scaffold's construction of knowledge</td>
</tr>
<tr>
<td>Asymmetric flow of information, verbal or visual</td>
<td>Asymmetric Counterpoint</td>
<td>Asymmetric Collaboration</td>
</tr>
<tr>
<td>Common goal embedded in individually initiated activity, that is unequally alternating among the participants</td>
<td>Common operative goals and activity</td>
<td></td>
</tr>
<tr>
<td>Sharing the situation, materials, feedback; possible partial and mostly unidirectional sharing of knowledge structures</td>
<td>Sharing the situation, materials, products, previous knowledge, observations, hypotheses, and understanding</td>
<td></td>
</tr>
<tr>
<td>Partly guided or directed sequence of activity, based on one partner's previous knowledge</td>
<td>Evolving sequence of activity, based on the shared activity of the participants and one partner's previous knowledge</td>
<td></td>
</tr>
<tr>
<td>Alternating shifts of unequal dominance</td>
<td>Unequal dominance.</td>
<td>Asymmetric flow of information and action</td>
</tr>
<tr>
<td>Asymmetric flow of information and action</td>
<td>Asymmetric flow of information and action</td>
<td></td>
</tr>
</tbody>
</table>
Table 11.1: Attributes of types of interactions (cont.)

<table>
<thead>
<tr>
<th>Swift Imitation (cont.)</th>
<th>Asymmetric Counterpoint (cont.)</th>
<th>Asymmetric Collaboration (cont.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unsynchronized, separate, and unbalanced processes of knowledge construction; possible partial comparison or confrontation of knowledge structures.</td>
<td>Unsynchronized, separate, and unbalanced processes of knowledge construction; possible partial comparison or confrontation of cognitive structures.</td>
<td>Co-construction of knowledge through the interaction, in unbalanced processes.</td>
</tr>
<tr>
<td><strong>Parallel Activity</strong></td>
<td><strong>Symmetric Counterpoint</strong></td>
<td><strong>Mutual Collaboration</strong></td>
</tr>
<tr>
<td>Separate activities with temporary shifts to periods of interaction</td>
<td>Common goal shared in individually initiated activity that equally alternates between the participants.</td>
<td>Common operative goals and activity.</td>
</tr>
<tr>
<td>Partial or no sharing during the interaction</td>
<td>Sharing the situation, materials, feedback; possible partial sharing of knowledge structures.</td>
<td>Sharing the situation, materials, products, observations, hypotheses, and understanding.</td>
</tr>
<tr>
<td>Separate activities, partial or no continuous common sequence of activity</td>
<td>Evolving sequence of activity, based on previous activity of all partners and on the corresponding feedback.</td>
<td>Evolving sequence of activity, based on the shared evolving activity of all participants.</td>
</tr>
<tr>
<td>Symmetric or asymmetric flow of information, verbal or visual</td>
<td>Alternating shifts of equal dominance for chunks of the activity.</td>
<td>Equal dominance with very quick shifts from one partner to another.</td>
</tr>
<tr>
<td>Unsynchronized separate processes of knowledge construction, but similar during the entire activity; comparison or confrontation of cognitive structures.</td>
<td>Symmetric flow of information and action.</td>
<td>Symmetric flow of information and action.</td>
</tr>
<tr>
<td></td>
<td>Little information sharing during independent construction of knowledge.</td>
<td>Talking spontaneously and simultaneously; abbreviated speech due to shared understanding.</td>
</tr>
<tr>
<td></td>
<td>Unsynchronized processes of knowledge construction, but similar during the entire activity; comparison or confrontation of cognitive structures.</td>
<td>Co-construction of knowledge through the interaction, in balanced symmetric and shared processes.</td>
</tr>
</tbody>
</table>
Asymmetric Counterpoint

Asymmetric Counterpoint is a moderately collaborative interaction among peers of some asymmetric expertise. As in Symmetric Counterpoint, the partners share feedback within a common situation but construct their understanding independently. However, the interaction is asymmetric due to the unequal expertise of the participants. There is asymmetric alternations of unequal dominance. The flow of information is often unidirectional (the more capable peer directs the exploration). The processes of knowledge construction are unsynchronized, and the interaction reflects previously or independently constructed knowledge of the more capable partner.

Examples of Asymmetric Counterpoint occur when heterogeneous groups of students work together on given tasks, or during discussions between experts and novices.

Swift Imitation

Swift Imitation is an interaction among peers of moderately asymmetric expertise, engaged in an activity that is mostly independent (non collaborative). The independent activities are interspersed with short periods of imitation of a more capable peer, with or without verbal exchange. The information flow, whether verbal or visual, is mostly unidirectional and asymmetric. The processes of knowledge construction are unsynchronized; the construction of knowledge of the more capable peer may have occurred prior to the interaction (see table 11.1).

Swift Imitation occurs, for example, in the lower grades at school, between children who see each other’s drawings, pick up an idea and integrate it in their own
drawings. Similar examples occur in older children's writings or in computer graphics they create.

**Scaffolding**

Scaffolding (Wood, Bruner, & Ross, 1976) corresponds to a guiding collaborative interaction between partners with asymmetric knowledge and expertise. The guiding partner assists the other's construction of knowledge. In a supportive and approving manner, the guide subtly directs the other's observation and activity step by step, while accommodating to the other's wishes and ability.

**Guidance or Apprenticeship**

Guidance or Apprenticeship are interactions among participants with asymmetric expertise, characterized by periods of guidance interspersed throughout an activity or discussion. The more experienced partner, parent, expert, or guide, gives some directions to the other. These periods of guidance are preceded and followed by unguided activity (which sometimes includes interaction on unrelated issues). The guide may volunteer help, indicate when he is available for helping, or be asked for help explicitly. The guidance is unidirectional, from the guide to the guided, and is more informative and directive than the implicit support given during Scaffolding.

In familiar examples of Guiding, students are engaged in an activity, while the teacher passes from one student (or group) to another, gives feedback or directions, and proceeds to another student (or group). Another example is parent and child, who are each involved in their own activity, when from time to time the child asks the parent for
help or information, or the parent approaches the child and offers hints and suggestions. For examples of apprenticeship, see Rogoff (1990).

**Imitation**

Imitation corresponds to interaction among partners of asymmetric expertise. It consists mainly of independent (non-collaborative) activities, with limited interaction, in which the less experienced partner imitates the more experienced. In contrast with Swift Imitation, in which one partner "borrows" a core idea from a more experienced peer and then develops it independently, in this type of interaction the imitation may be more substantial to the activity. If the activity is complex or non-trivial for the novice, just borrowing an idea may not suffice. The novice may have to imitate the model of an expert more closely. During Imitation, the more experienced partner may be involved in his or her own activity, and may not explicitly try to guide the novice.

**(ii) Disruptive interactions**

Disruptive interactions form a mirror image of the collaborative interactions, having a similar structure with negative connotations. Disruptive interactions interfere with a discussion, destroy a product, or stop an exploration; they can impede achievement of a goal, prevent completion of a task, and hinder the related processes of knowledge construction. Disruptive interactions can evolve between partners with different values of relative expertise (e.g., two children with similar ability; different-age siblings, or an adult and a child). The least inter-disruptive interactions, like their low-collaborative parallels, consist of mostly independent activities. The participants are each engaged in their own activities, but these are interspersed with short negative interchanges. Highly
inter-disruptive interactions are characterized by extremely interlocked and interfering activities (e.g., participants who talk simultaneously in a way that neither of them can express his views or listen to the other, or children who simultaneously try to use the same materials and dominate an activity). In moderately interlocked activities, there is a counterpoint between the participants' activities, and the activities of at least one participant are disruptive.

Negative interactions occur in research situations as well as in everyday life. For different reasons, negative interactions emerge between parent and child, or among adults (i.e., Glick, 1985; Goodnow, 1990; Hess & Shipman, 1965; Shweder, 1990; Valsiner, 1984). When an expert (or adult) undermines the novice's (or child's) ability, prevents access to materials, stops certain activities, or deprives her ability to pursue certain directions of inquiry, the interaction can hinder the novice's (or child's) development in the domain of the interaction.

(iii) Other factors affecting interactions

Factors other than asymmetry of knowledge and expertise and degree of collaboration also affect interactions. One factor is knowledge and expertise in irrelevant domains, which may affect participants' expectations of each other's expertise. Another factor is social roles. For example, an authority-submission relationship between two persons at work may affect interaction between them in unrelated contexts. Similarly, a child may comply to adult's authority and defer his own point of view (Piaget, 1965). Gender-related patterns may affect boy-girl and man-woman interactions, often giving more dominance on the interaction to the male; race and class differences can have similar effect. Previous patterns of interaction between the same participants, molded through common experiences in the past, can also affect their present interactions. Personality traits (such as leadership, initiative, or passivity) and the individual's self
image will also affect interactions. Finally, participants' interest in the task at hand and the importance they attribute to it may affect the interaction.

When these factors do not correspond to the participants' relative knowledge and expertise in the context of the interaction, they divert the nature of the interaction. In such cases, the interaction may be less productive and may have diminished effect on cognitive growth.

The effect of these other factors can be detected by comparing the participants' relative expertise and their relative dominance on the activity. The expertise of each participant in the context of the interaction can be evaluated by independent measures (e.g., pretest). Dominance on the activity can be measured directly from the interaction, by counting each participant's utterances or timing each participant's actions. Whatever scale is used for deriving these estimates, the relation between the score of one participant and the score of the other gives an indication of their relative expertise (or relative dominance).

Throughout the interaction, the participants' relative dominance may change. In such a case, the interactive event can be sub-divided to segments which are each more homogeneous in nature. Furthermore, between the same participants in a given interactive event, dominance on actions may differ than dominance on discourse. The range of relative dominance on discourse during given sub-segments can be compared, then, to the range of relative dominance on action and to the relative expertise.

Figure 11.3 demonstrates such discrepancies between relative expertise, dominance on activity, and dominance on discourse. In the example illustrated in figure 3, the independent measure of relative expertise between two participants is indicated by the gray arrow-line. The range of relative dominance on action between those participants is indicated by (A). The relative dominance on discourse between them in one interactive segment is (B), and in another (B').
Figure 11.3: In this example, independent measure of relative expertise between two participants, as measured by pretest, is indicated by the gray arrow-line. The range of relative dominance on action in two interactive segments between those participants is indicated by (A). The relative dominance on discourse between them in one segment is (B), and in another (B').

The model indicates diverse types of interaction. Before discussing the model and its implications, some of these types of interactions will be illustrated by examples from research data.
(iv) **Building blocks for characterizing interactions**

The building blocks analyzed in chapter 10 (see table 10.2) can serve for characterizing the types of interactions. We have already seen that the harmonious or antagonistic attributes are not dependent on the relative expertise of the participants. Similarly, we have examined the symmetry (or asymmetry) of the interactive process between the participants in the study (see chapter 10).

Table 11.2 presents the building blocks characterizing the dynamics of three types of interactions. By using these building blocks, the attributes of each type of interaction can be identified.

**Table 11.2: Building block characteristics of types of interactions**

<table>
<thead>
<tr>
<th>IMITATION</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>SUBCONTEXT FRAME</strong></td>
</tr>
<tr>
<td>Int-intersecting Each participant is looking partly at a common scene (or at each other) and partly at a different scene</td>
</tr>
<tr>
<td>Uni-unidirectional overlapping One participant has a separate subcontext (e.g., looking away), the other's subcontext includes the first (looking at the other and the other's subcontext)</td>
</tr>
<tr>
<td>Rd-reduction Doing approximately the same action as the other, in a more simplified way</td>
</tr>
</tbody>
</table>
Table 11.2: Building block characteristics of types of interactions (cont.)

<table>
<thead>
<tr>
<th>SUBCONTEXT FRAME</th>
<th>ACTION</th>
<th>DISCOURSE</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>MUTUAL COLLABORATION</strong></td>
<td><strong>ACTION</strong></td>
<td><strong>DISCOURSE</strong></td>
</tr>
<tr>
<td>I-identical</td>
<td>I-identical</td>
<td>I-identical</td>
</tr>
<tr>
<td>Common frame (2) - looking at exactly the same scene as the other</td>
<td>Doing exactly the same action as the other</td>
<td>Saying exactly the same words as the other</td>
</tr>
<tr>
<td>Sm-similar</td>
<td>Sm-similar</td>
<td>Sm-similar</td>
</tr>
<tr>
<td>Looking at about the same scene as the other</td>
<td>Doing approximately the same action as the other</td>
<td>Saying about the same content as the other (1)</td>
</tr>
<tr>
<td>R-reciprocal</td>
<td>R-reciprocal</td>
<td>R-reciprocal</td>
</tr>
<tr>
<td>Looking at each other</td>
<td>Doing complementing action as other’s</td>
<td>Saying complementing content to other’s</td>
</tr>
<tr>
<td>Cn-confirming</td>
<td>Cn-confirming</td>
<td>A- agreeing</td>
</tr>
<tr>
<td>Confirming the other’s action</td>
<td></td>
<td>Agree with what the other says</td>
</tr>
<tr>
<td>E- expanding</td>
<td>E- expanding</td>
<td>E- expanding</td>
</tr>
<tr>
<td>Expanding the other’s action</td>
<td>Expanding the other’s talk(3)</td>
<td></td>
</tr>
<tr>
<td>D- developing:</td>
<td>D- developing:</td>
<td>D- developing:</td>
</tr>
<tr>
<td>Building on the other’s action and developing it to another action</td>
<td>Developing the other’s idea(4)</td>
<td></td>
</tr>
<tr>
<td>BC- building on and changing</td>
<td>BC- building on and changing</td>
<td>BC- building on and changing</td>
</tr>
<tr>
<td>Building on the other’s action and changing it</td>
<td>Building on the other’s idea and changing it</td>
<td></td>
</tr>
<tr>
<td>N- new:</td>
<td>N- new:</td>
<td>N - new:</td>
</tr>
<tr>
<td>Performing a new action/gesture</td>
<td></td>
<td>Raising a new idea</td>
</tr>
</tbody>
</table>
Table 11.2: Building block characteristics of types of interactions (cont.)

<table>
<thead>
<tr>
<th>SCAFFOLDING</th>
<th>SUBCONTEXT FRAME</th>
<th>ACTION</th>
<th>DISCOURSE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>I-identical</td>
<td>G-guiding</td>
<td>G-guiding</td>
</tr>
<tr>
<td></td>
<td>Common frame (2) - looking at exactly the same scene as the other</td>
<td>Guiding, demonstrating</td>
<td>Guiding, giving directions; giving hints; ask guiding questions</td>
</tr>
<tr>
<td></td>
<td>Sm-similar</td>
<td>Dm-demonstrating</td>
<td>El-explaining</td>
</tr>
<tr>
<td></td>
<td>Looking at about the same scene as the other</td>
<td>Confirming the other's action</td>
<td></td>
</tr>
<tr>
<td></td>
<td>R-reciprocal</td>
<td>Cn-confirming</td>
<td>Cn-confirming</td>
</tr>
<tr>
<td></td>
<td>Looking at each other</td>
<td>Confirment the other's action</td>
<td>Confirming the other's discourse</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Q-questioning</td>
<td>Q-questioning</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ask questions leading to action</td>
<td>Ask questions leading to verbal response</td>
</tr>
</tbody>
</table>
Table 11.2: Building block characteristics of types of interactions (cont.)

<table>
<thead>
<tr>
<th>SUBCONTEXT FRAME</th>
<th>ACTION</th>
<th>DISCOURSE</th>
</tr>
</thead>
</table>
| **Sp-Separate**  | Each participant is doing a different action | **Sp-Separate**
| Each participant is looking at a different scene | The discourse of each participant is unrelated to the other’s discourse |
| **Int-intersecting** | Each participant is looking partly at a common scene (or at each other) and partly at a different scene | |
| **Uni-unidirectional overlapping** | One participant has a separate subcontext (e.g., looking away), the other’s subcontext includes the first (looking at the other and the other’s subcontext) | |
Table 11.2: Building block characteristics of types of interactions (cont.)

<table>
<thead>
<tr>
<th>Subcontext Frame</th>
<th>Action</th>
<th>Discourse</th>
</tr>
</thead>
<tbody>
<tr>
<td>I-identical</td>
<td>I-identical</td>
<td>I-identical</td>
</tr>
<tr>
<td>Common frame (2) - looking at exactly the same scene as the other</td>
<td>Doing exactly the same action as the other</td>
<td>Saying exactly the same words as the other</td>
</tr>
<tr>
<td>Sm-similar</td>
<td>Sm-similar</td>
<td>Sm-similar</td>
</tr>
<tr>
<td>Looking at about the same scene as the other</td>
<td>Doing approximately the same action as the other</td>
<td>Saying approximately the same content as the other (1)</td>
</tr>
<tr>
<td>Int-intersecting</td>
<td>Rd-reduction</td>
<td>Rd-reduction</td>
</tr>
<tr>
<td>Each participant is looking partly at a common scene (or at each other) and partly at a different scene</td>
<td>Doing approximately the same action as the other, in a more simplified way</td>
<td>Saying approximately the same content as the other, in a more simplified way</td>
</tr>
<tr>
<td>Uni-unidirectional</td>
<td>E- expanding</td>
<td>E- expanding</td>
</tr>
<tr>
<td>overlapping</td>
<td>Expanding the other's action</td>
<td>Expanding the other's talk</td>
</tr>
<tr>
<td>One participant has a separate subcontext (e.g., looking away), the other's subcontext includes the first (looking at the other and the other's subcontext)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>D- developing:</td>
<td>D- developing:</td>
</tr>
<tr>
<td></td>
<td>Building on the other's action and developing it to another action</td>
<td>Developing the other's idea</td>
</tr>
<tr>
<td></td>
<td>BC- building on</td>
<td>BC- building on</td>
</tr>
<tr>
<td></td>
<td>and changing</td>
<td>and changing</td>
</tr>
<tr>
<td></td>
<td>Building on the other's action and changing it</td>
<td>Building on the other's idea and changing it</td>
</tr>
<tr>
<td></td>
<td>N- new:</td>
<td>N- new:</td>
</tr>
<tr>
<td></td>
<td>Performing a new action/gesture</td>
<td>Raising a new idea</td>
</tr>
</tbody>
</table>
TYPES OF INTERACTIONS: ILLUSTRATIVE EXAMPLES

Episodes from the participants' explorations demonstrate different patterns of interaction. There are similarities among the patterns of interactions that emerged during the explorations and those also observed among children. Clearly, interactions among children differ from adults' interactions in the sophistication of social skills and the subject-matter knowledge involved. However, especially when adults engage in knowledge construction through spontaneous informal interactions, the underlying structure of their interactive patterns seems to be similar to patterns prevailing across ages.

The socially unconstrained nature of the situation, discussed in chapter 3, generated rich data. Small segments from episodes, transcribed from the video data, are described and analyzed below. The excerpts are marked by index numbers to which the analyses refer.

(i) Episode 1: Mutual Collaboration

In the following episode, together, three subjects watch little blinking lights that occasionally turn on and off on a robot, and try to understand the related causality.

1 Yolanda: "The other one is --" 2 Susan: "I think that it's up, once every time it hits-" 3 Yolanda (almost simultaneously): "Any time it hits-" 4 (The three together): "Right--aha--ok--" 5 Susan: "And the blue-" 6 Mary (simultaneously, reading aloud): "Blue-" 7 Susan: "-stays on until a-" 8 Yolanda: "Aha." 9 Mary: "So, (reading aloud while writing) the top light on yellow blinks on impact --" 10 Susan: "yeah-- [unclear]" 11 Yolanda:"yeah!" 12 (The three simultaneously): "Yes! Yeah! Yea!...Yep!" 13 Yolanda: "It's also right behind here!" (points). 14 Susan is writing. Mary leans forward to watch). 15 Mary: "Where?" 16 Yolanda
(indicates): "Behind this front [deck?]. 17 Now watch --" 18 Mary: "Oh, yeah--" 19 (Susan leans forward, watching) 20 Yolanda: "That's the top --" 21 (Susan says something unclear, simultaneously) 22 Mary (simultaneously): "It only blinks when --" 23 Yolanda (simultaneously): "I don't know of the --" 24 Mary (continues) "[it goes?] forward."

In the episode, Mary, Susan, and Yolanda work in close collaboration. Dominance of the exploration and the discourse is distributed among them with quick shifts from one to the other. Mary shares her notes with the others by reading them aloud (9). The three talk in abbreviated speech, agreeing with one another to half formulated sentences (3-4; 7-8). Only when one does not understand, is there a need to be more explicit or even to point. This happens when Yolanda notices another light (13), which Mary does not see (15). Yolanda describes explicitly where the light is (16) while indicating it, further directing her partner's attention: "Now watch" (17). The three often talk simultaneously (4, 6-7, 12, 21-24), but at the same time they listen and respond to what the other says (4, 8). They share observations (1, 7, 13-17) and co-construct their knowledge by together formulating rules for the phenomena they observe (2-3, 5-9, 20-24).

(ii) Episode 2: Symmetric Counterpoint

In this episode, Sam and Dorothy explore a robot that has a light sensor. The robot moves backwards in the shade and forward in the light, but only when the light falls directly on the sensor.

1 The robot moves forward, reaches the wall and gets stuck there. 2 Sam approaches it, extends his hand and reaches for the robot. 3 The robot makes a sudden back-and-forth jerk. 4 Sam stops, 5 puts his hand on top of the robot, and slowly moves his hand back and forth above it. 6 The robot doesn't respond. 7 Sam takes a flashlight and illuminates the robot. 8 Still no response. 9 Sam takes the robot carefully, holding it from behind. 10 He
turns the robot around, watches it, then illuminates it with the flashlight. 11 Still no response. 12 Sam puts the robot, facing a different direction, on the floor. 13 The robot starts moving, bumps into a box and gets stuck there. 14 Dorothy approaches the robot and carefully puts her hand on top of it, close to the robot. 15 The robot reacts — it starts moving backward instead of forward.

After previous shifts of dominance, in this segment Sam is dominant (2-13) while Dorothy watches him. After the surprising reaction of the robot (2-3), Sam attempts to find what causes it (5; 7; 10), while Dorothy watches without interrupting. When Sam stops exploring (12-13), Dorothy takes over (14). However, this time (unlike her previous explorations) she can control the robot in her first attempt (15), which indicates that she was attentively watching Sam, learning from the robot's responses to his interventions, and forming her own understanding through his explorations. Between the two, there is no collaborative planning, nor shared analysis. Their knowledge, then, develops for the most part independently, in unsynchronized spurts. Yet, at the end of the interaction, their knowledge is similar—Dorothy understands the robot while watching Sam, and Sam, later, while watching her.

(iii) Episode 3: Asymmetric Collaboration

In the following episode, Mary and Abigail are building a new robot together. They connect a special brick to the new robot and try to find out the function of that brick.

1 Mary is holding the new robot. 2 Abigail says: "This is a..." 3 Mary: "Timer... 4 and I don't know what this is." 5 Abigail takes the new robot and checks it. 6 Mary is watching her and the robot. 7 She adds: "Sometimes it would [unclear] (...) 8 Mary indicates a certain brick on the robot that Abigail is holding, turns the brick and continues: 9 "It looks like they told
him what to do. (...) Abigail returns the robot to Mary and says: "We need to [connect a sensor?]" Mary: "But where? I don't see any [unclear] where it's supposed to go on this, that's one thing. Maybe just..." Abigail turns around, takes the ready-made robot, and checks it. Mary watches her and continues: "It's like this, they're connecting--(while looking at the robot that Abigail examines) Oh, here?" Mary indicates something on the ready-made robot that Abigail is holding, and continues: "This one?" Mary takes apart a similar brick on their own robot and shows to Abigail: "Look, this one doesn't work any more. It appears to have..." Mary checks it and Abigail watches the brick Mary is showing her. (...) Mary: "Let's just try it. Let's try it here." Abigail: "All right." (...) Abigail: "Oh, oh, look, maybe we have to figure out where to put some wires in?" (...) Abigail turns around, checks the ready-made robot. Then she turns back to Mary, takes their own robot, indicates an extension on the sound sensor and says: "That's where it is." Abigail takes a wire, connects it to the sound sensor at the place she indicated before, and connects the other side of the wire to another brick. Mary: "Ahaaa!!"

In the episode, Mary and Abigail set for themselves common operative goals (11; 22-23; 24). They share a common activity and are continuously interacting. When Abigail is checking the robot, Mary is not just watching her, waiting for her turn, but rather continues to share her way of understanding the robot (7; 9; 18; 20), indicating to Abigail what she's referring to (8; 17; 19). Abigail's exploration (13) triggers Mary to generate more hypotheses, which she immediately shares (17-18). In turn, when Abigail finds out where to connect the wire, she doesn't simply do so, but rather shows Mary first where the wire should be connected (27), and only then connects it (28).

Mary and Abigail share their understanding and hypotheses (2-4, 7, 9, 11-12, 18, 20, 24; 27). In contrast to Mutual Collaboration, what causes incomplete sentences in this case is not that "the subject is the same in the two minds" (Vygotsky, 1962, p. 239), but rather accommodating to the different activities of the other (15-16; 20). The
collaboration is asymmetric: Mary shares more information with Abigail than vice versa: since the beginning of the episode the asymmetric structure of the interaction is set when Mary completes Abigail's sentence (2-3). Mary continues to tell Abigail what she knows and does not know about the robot and specific bricks (4, 7, 9, 12, 20). Mary is more dominant in the interaction—she talks more and is more elaborate in her suggestions and hypotheses. Yet, Abigail contributes to their common understanding too—and she, in fact, finds the solution to their problem (27-28).

(iv) Episode 4: Swift Imitation

In the following episode, Tim, Lucy, Jill, and Sherry are about to start their exploration for the first time, when one of them sees Lynn's exploration. Lynn already participated in two sessions with another group and joined this group to continue her explorations.

1Tim, Lucy, Jill, and Sherry observe a robot move, and 2consult with one another how to explore it. 3Tim says: "--Since there are apparently different things here..." 4Others say: 5."We must have [unclear] here something we can try..." 6."Maybe looking at the forwards and backwards movement?" 7."Let's make it--" 8At that moment, light flashes on them. 9Lynn is passing by, following her robot. 10She holds a flashlight, projects light on the robot, and explores its reaction. 11Sherry says: "Oh, look at that! 12...Let's see, the forward behavior is with the light, right?" 13While talking she approaches a nearby box, picks up a flashlight, and uses it to project light on their robot. 14The others join her.

The episode shows a short and partial interaction, based mainly on imitation of a peer, Lynn, who has greater expertise. Tim, Lucy, Jill, and Sherry, are engaged in their own activity, before (1-7) and after (13-14) their encounter with Lynn. While the four are discussing how to start their exploration (2-7), Lynn's light flashes on them (8) and calls
Sherry’s attention. When seeing Lynn flashing light on her robot (9-10), Sherry suggests that they do the same thing (12). In this case, the interaction is partial and nonverbal. The four participants pick up an idea, and then integrate it in their own exploration (13-14).

The data included examples of other types of interactions, through not all those delineated by the interaction model. Due to space limitations, these cannot be described in this chapter.

VIEWS OF THE ANALYSIS OF INTERACTION IN THE LITERATURE — COMPARISON AND DISCUSSION

(i) Integration of different theories

In the last decade, researchers have increasingly acknowledged the importance of social interaction for the development of the individual’s cognition. However, as mentioned earlier, theorists of different schools suggested different mechanisms for the process. Advocates of these theories debated over findings that supported one theory or another. In contrast, several researchers view different theories — mainly those of Piaget and Vygotsky — as complementing each other (i.e. Damon, 1984; Forman & Cazden, 1985). Other researchers also see social learning theory as complementing those schools of thought (Tudge & Winterhoff, 1991). The interaction model discussed in this chapter follows these views: the model establishes a framework for comparing and integrating the different theories.
Different views of the cognitive effect of interaction

The differences among the theories of Piaget, vygotksy, and Bandura were discussed in chapter 2. Chapter 2 also reviewed other theories that discuss negative interactions.

Disparity among the theories

The theories developed by Vygotsky, Piaget, Bandura, and their followers, each suggested different mechanisms for the way interaction affected cognitive change. Studies within the conceptual approach of each theory had assessed the theory's claims, often challenging other theories. However, there was no common ground on which the theories could meet and become integrated.

The interaction model — a way for integrating the different theories

The interaction model suggested in this chapter shows that the patterns of interaction, as suggested by Vygotsky, Piaget, Bandura and their followers, form only part of the interactive spectrum that affects cognitive change.

Without undermining the context of the interactive events under scrutiny, the model indicates dimensions for analysis that could be compared across studies. These two dimensions — degree of collaboration and relative expertise — affect the attributes of interactions and the cognitive change they generate. These two factors can serve as a baseline for evaluating the effect of other factors.

The two dimensions open a span which, as we have seen, includes types of interactions suggested by the different theories. Within that span, different types of
interactions can be compared and analyzed. The model defines the variables along which situations addressed by one theory can be transformed into situations addressed by another, and suggests how other types of interactions, not discussed by these theories, could be integrated too.

Different types of interaction, portrayed by the interaction model, have different dynamics, attributes, and implications for cognitive processes of knowledge construction. Yet, there are overlaps and similarities between types of interactions. Interactions that map to different values on one dimension (e.g., have different levels of relative expertise) but have a similar value on the other dimension (e.g., highly collaborative interactions) overlap in their attributes that characterize the latter (characteristics of high collaborations; see Granott, 1993, for discussion of this aspect).

(ii) Implications

| Multi-interaction approach: |

The suggested model and the examples from the study indicate that there is no one "right" type of interaction that promotes cognitive change in one way, but rather many types that affect cognitive change in various positive and negative ways. This multi-interaction view has several implications for research. First, it is important to find out what kinds of interactions evolve in given cultures, contexts, and conditions. There may be cultural variations in patterns of interaction. In addition, in a given culture, the same individuals may develop different types of interactions in different situations and contexts and with different people. Second, in this multi-interaction view, an interesting question is not only which type of interaction best induces cognitive change, but also how
prevalent is that type of interaction in a person's life. For example, scaffolding may prove very powerful in promoting cognitive change, but may be rare for children from certain socioeconomic backgrounds and family-structures. Third, the interrelations among the different types of interactions and their cognitive implications is crucial. Cognitive change at a specific time is an end-result of complementing or compensating effects of diverse interactions. (A similar phenomenon relates to developmental problems: these result from combination of various factors; see Kopp, 1983). A child conserver, for example, may regress to non-conservation after interacting with a non-conserver adult (i.e., Kuhn, 1972). The temporary nature of this regression may reflect the child's other experiences and the continuous interactions he has with other people. A multi-interaction approach, therefore, may better suit the complex issue of interactions and their cognitive effects.

<table>
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<th>Spontaneous versus constrained interactions</th>
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Many studies that explore interactions and the related cognitive change use a context that constrains the interactions. The experimenter often teams peers together for the experiment's sake (e.g. conserver and non-conserver), sets specific goals for the activity, or enforces collaboration by putting constraints (such as turn taking or imposed coordinated actions). When interactions are the subject and the goal of the study and the collaboration is the backbone of the co-construction of knowledge, it seems improper to constrain these aspects of an experiment. The ensuing activity will necessarily be influenced by these constraints. Therefore, the results will reflect and often confirm what the researcher is looking for. However, when the participants choose their own goals, team up and interact spontaneously, the emerging types of interactions and their cognitive change may be richer, more diverse, and more complex. The goal of the situational
approach described earlier (chapter 3) was to create a space within which these processes could emerge without intervention.

This chapter suggests a model for analyzing interactions and their cognitive effects, while integrating various theories and without sacrificing the contingency of interactions on specifics of context, situation, culture, etc. The model suggested in this chapter may contribute to compare results of different studies. The issue of interactions and their cognitive effects is intricate and complex, and includes several puzzling phenomena. Many questions still remain open: when does interaction among peers of some asymmetric expertise generate regression, resulting in adoption of less advanced knowledge structures (Forman, Cordle, Carr, & Gregorius, 1991; Tudge, 1985)? What is the effect of cultural practices on interactive patterns? What are the specifics of the mechanism of cognitive change through interaction? These questions, as many others, are subject to further research.
Chapter 12 takes us to the closure of this thesis. In reviewing the results, we have come a full circle. We started with an overview, taking the perspective of co-constructionism, and increasingly zoomed in on the process of co-construction. First, we zoomed in on the microdevelopmental aspects, evolving through phases, levels, and in a specific dynamics of development. Then we shifted our view at the dynamics of the interaction. We stayed with a close look at the dynamics that evolves between the collaborating team. Finally, we zoomed out again, to take a more global view of the co-construction through interaction.

Chapter 12 summarizes and concludes the thesis. It reviews the main points of the study. The chapter revisits the use of reiteration as a transitional mechanism, discussing two additional uses that we encountered in the last chapters. One is in the microdevelopmental dynamics and the other — in interaction. Chapter 12 is terminated with discussion of the implications of the study presented in this thesis.
CHAPTER 12

SUMMARY AND CONCLUSIONS

REVIEW OF THE STUDY AND ITS MAIN RESULTS

This thesis analyzes the way people construct their knowledge when solving an unfamiliar and complex problem. The problem was not given to them. Instead, they were invited to explore a complex, "well-structured" context-space, in which small robots — "Weird Creatures" and "Wuggles" — reacted to diverse stimuli in puzzling ways. The study used a situational approach: the situation was carefully planned, but no external constraints were explicitly imposed on the participants' behavior within that situation. The participants could set for themselves their own goals, generate their own problems, devise ways to find solutions for these problems, choose their own activities, and decide on the "rules of the game". Within the situation, which set for them the robot's environments and the group of people that came to explore the robots at that time, they could choose what robot to explore and with whom to do so, and switch to other choices as they pleased. They had autonomy, were involved, and had a sense of ownership on what they did. They could develop their learning in a way that was meaningful to them. The goal of the situational approach was to allow a spontaneous, unguided process of co-construction of knowledge to emerge.
The evolution of knowledge structures

During four hours of explorations, different teams formed, changed, and reformed. In each team, together, the participants co-constructed their knowledge. Throughout the process their knowledge evolved from no understanding of the way the robot functioned, to elaborate understanding of the complex technical details.

Like other studies that explored the evolving process of solving a problem, this study found that the process evolved in qualitatively different phases. The study, however, used a different lens through which to examine these phases. The co-construction of knowledge was analyzed as a developmental process. From a developmental perspective, the phases evolved from an actual phase, to a representational one, and then to an abstract one. The actual phase revolved around understanding the "behavior" of the robots through actual actions and perceptions. In the representational phase, the participants understood the causality underlying that "behavior" and could represent it. At this phase they focused on the robot's structure and the way it generated that "behavior". In the abstract phase, these representations were established; having understood the relation between structure and function, the participants started to explore why the functional bricks made the robot do what it did. They focused on issues of signal transmission, trying to understand the operation of specific sensors and logic bricks.

A more detailed and precise analysis used Fischer's (1980a) skill theory to analyze levels within these phases. By applying skill theory's definitions to the specific context of understanding the robots, the participants' statements were analyzed. The use of skill theory made it possible to identify and analyze the participants' microdevelopmental sequences.
The analysis showed microdevelopmental sequences — sequences that developed through short time spans — and which paralleled the macrodevelopmental (ontogenetic) sequence. The relations between the two sequences were analyzed: on the one hand, macrodevelopment sets an upper bound on microdevelopment; on the other, breakthroughs in macrodevelopment occur through microdevelopment.

The structure of the microdevelopmental sequences was as predicted by skill theory, and also resembled findings of several other researchers. Similarities between the present study and other ones were related also to the properties of the sequence, and these were reviewed and compared.

The results indicated that microdevelopment consisted of reiteration of the microdevelopmental sequence. The participants progressed in a microdevelopmental sequence, and then regressed again to construct a new sequence, applied to a slightly different aspect of the problem. Throughout these reiterations, there is an indication of the possibility that the pace of knowledge construction increases.

Each microdevelopmental sequence consisted of a step-like progression. This progression, however, was not smooth. Instead of tracing a line of progression, the microdevelopmental sequence consisted of a bandwidth of alterations. At a given time, knowledge structures tended to alternate within the range of that bandwidth. The range marked a Zone of Current Development (ZCD), in similarity with Vygotsky's (1978) Zone of Proximal Development. Peaks within the range of the ZCD were not established by one occurrence, then. Like findings of other studies, the findings of this research indicate that "discovery" occurs and recurs again and again before being well internalized and appropriated.
The thesis discusses, analyzes, and explains the parallelism between micro- and macrodevelopment. When, in the beginning of the microdevelopmental sequence, adults express statements that indicate correspondence to sensory-motor knowledge structures, this does not mean by any way that these adults behave like infants or babies. These bright and highly competent adults preserved all the knowledge structures they had previously developed. They could apply general scientific-inquiry skills, such as hypothesis generation, hypothesis testing, and isolation of variables. However, within the specific context of the unfamiliar robots, even identification of the variables that could possibly be involved was difficult. The adults had to explore directly the robots, through actual actions and perception — by "playing" with the robots, making diverse actions, and perceiving the robots' responses to these actions. They had to form some understanding of the robots before they could relate and link this unfamiliar context to their general knowledge structures. By the same token, these adults clearly exhibited abilities to form representations and reason in an abstract way; yet they had to construct representations and abstractions within the specific context of the task through laborious explorations.

The importance and positive value of "regression"

"Regression" to more primary knowledge structures is an efficient strategy for confronting an unfamiliar context which too complex to be simply assimilated to existing structures. Exploring the problem through more primary knowledge structures facilitates its understanding and simplifies the problem. This is why people refer to examples when presenting a complex issue: the examples form representations of concrete cases, and endow the abstractions with intuitive meaning. To understand a complex unfamiliar
context, then, the individual may first have to "regress" and construct more primary
knowledge structures in that context.

Regression is usually tainted with a negative connotation. Yet the analysis
indicates the importance and positive function of this regression. Not only does it enable
people to construct understanding in an unfamiliar issue, by simplifying a phenomenon
and making it more accessible through more primary knowledge structures. It also
creates links between knowledge structures constructed at different levels, broadens the
knowledge construction process, and makes knowledge more robust.

### Transition mechanisms: Bridging, differentiation, and reiteration

The analysis identifies three transition mechanisms: bridging, differentiation, and
reiteration. Bridging creates transitional and tentative structures that combine the
person's current level of knowledge with glimpses of the next level or phase. In this way,
bridging serves as a grappling hook, pulling knowledge-construction up. Five types of
bridging were identified in the study. Differentiation is another transition mechanism.
The importance of differentiation is indicated in skill theory (Fischer, 1980a), which
identifies it as one of the transformation rules. Werner (1957) also highlighted
differentiation as one of the main cognitive processes. Throughout the explorations, the
participants made differentiations on the basis of their current knowledge structures. The
use of skill theory's definitions allowed to pinpoint the way differentiation leads from one
level to another, and detect examples which illustrate how a new phase, or a new level
within a phase, emerge through such differentiation.

The analysis of the data in this study shows that the participants'
microdevelopmental sequences included a substantial use of differentiation. Between a
quarter and a third of their statements were based on differentiation. The use of bridging
was of a similar order of magnitude. Between a half and two thirds\(^1\) of the statements in the microdevelopmental sequence, then, were constructed by using these two mechanisms.

Previously, we discussed the way reiteration operates as a transition mechanism in the reiteration of the exploration. In the last few pages, we encountered two other uses of reiteration. These are discussed below.

**REITERATION AS A TRANSITION MECHANISM: AN EXPANSION**

(i) **Reiteration during social interaction**

Chapter 12 explored a different function of reiteration — the role it plays in social situations of co-construction of knowledge. The chapter highlighted the participants' tendency to reiterate each other's statements. As we saw, this reiteration was important for acknowledging what the other said and affirming it, and as such it lubricated the process of co-construction, facilitated it, and made it more pleasant. But this reiteration, as we recognized, had an additional role, no less important. By reiterating the other's statement, the participants reconstructed the other's idea and internalized it. The process of inner reconstruction was manifested by the slightly changed formulation of these reiteration.

The inner reconstruction of the other's idea has a crucial function during the co-construction of knowledge. When one participant took a step forward in the sequence of knowledge construction, the other did not fall behind. Reiteration eased the process of keeping up with one another: by reiterating the other's statement, one could more easily

\(^1\) These categories were mutually exclusive.
reconstruct the same knowledge structure. In this way, reiteration helped the participants to align with each other in the process of knowledge co-construction.

We also saw how reiteration supported the other transition mechanism — differentiation — in social situations as well as through the explorations. By reiterating and slightly changing the other's formulation, participants generated differentiation. This, as we discussed, triggered further progress in the co-construction process.

The analysis in chapter 10 indicated another role of reiteration in social settings. Through reiteration, the participants built each on the other's ideas, and carried them on, developing them further. Furthermore, reiteration served as an important mechanism in the collaborative process of knowledge construction for aligning the participants in respect to their knowledge structures.

Chapter 11 enlarged the picture to portray different types of interaction. Different levels of expertise between the participants will create different processes of alignment through interaction. In an interaction between peer of symmetric expertise, the process of alignment may be also symmetrical. An interaction between expert and novice, or adult and child, alignment helps to pull the novice or child up in the sequence. To enable that alignment, the adult often simplifies his or her talk (e.g., "baby talk") and so does the expert (simplified explanation). This takes into account the other's knowledge structures, but is also similar to the way the participants went back in the microdevelopmental sequence when a novice joined them.

In the social dynamics, then, reiteration also had an important function, from leveling off with the other in relation to current knowledge structures, through catching up with the other who stepped forward, and to pulling up the other.
(ii) Reiteration of processes

Dynamic versus static views of reiteration

From a static point of view, reiteration may be manifested by recurrence related to a given level of knowledge. We have seen such examples when discussing the other two types of reiteration, the one related to explorations and the other — to social settings. However, there is another kind of reiteration that we encountered in the previous chapters. If we think about reiteration not from a static point of view but, instead, from a dynamic one — reiteration can apply to processes just as well. In this case, a whole process is reiterated. This, indeed, is evidenced in the microdevelopmental sequences.

A function of reiteration of processes

One function of reiteration of processes is creating links between levels of knowledge. In chapter 5, we encountered the participants' reiterations through short cycles of modes of explorations. In the second phase, the participants reiterated a B/A cycle, alternating between the second-phase mode of exploration and the first-phase mode. Similarly, in the third phase, we saw a more extensive cycle — C/B/A — reiterating the modes of exploration of the three phases. These cycles had the same function: creating links between knowledge structures constructed at different phases.
Reiteration of processes within microdevelopmental sequences

In chapter 7, we saw that each microdevelopmental sequence consisted of irregular alteration within a Zone of Current Development (ZCD). The ZCD created a bandwidth of knowledge structures. The sequence of the participants' statements alternated in an irregular fashion within that zone, and this alternation was reiterated throughout the sequence.

Reiteration of processes across microdevelopmental sequences

An overview of the larger microdevelopmental process showed that it consists of reiteration of separate microdevelopmental sequences. The analysis of the first four microdevelopmental sequences of Ann and Donald (chapter 7) indicated that after progressing for a while, they stopped and reiterated the sequence, regressing anew to a similar starting point.

Chapter 9 analyzed the function of this reiteration. It indicated the positive value — and the importance — of the regression to a previous point on the sequence. When higher processing is not possible, regression allows the person to access the issue under scrutiny. Understanding a problem, for example, through abstract knowledge structures is difficult; accessing it through representation facilitates the process. By the same token, accessing a problem through sensory-motor structures, through direct actions and perceptions of the actual phase, simplifies the problem and makes it more intuitive.
The thesis analyzes the process of co-construction of knowledge, as it occurs in social situations. The techniques that the participants used for co-constructing their knowledge through interaction are analyzed. The analysis indicates that reiteration in interchanges, in which people repeat each other's statement, is an important technique both for facilitating the social interaction and for internalizing the other's ideas. In this way, repeats serve for aligning the participants with each other (in respect to the content of knowledge and to its level) in the process of knowledge construction. The participants also used repeats with changes, and developed further each other's ideas. It was demonstrated that the co-construction process leans on several aspects: the dynamics of the discourse, the actions and gestures of the participants during the interaction, the their sub-context frame. The sub-context frame sends their partner an indication of their object of attention and helps to interpret their statements and direction of thought. In this way, it is an important condition for forming intersubjectivity.

Similarities versus differences and separateness in statements, gestures, and sub-context frames were suggested as important building blocks for understanding the dynamics of the interaction and the way it affect the nature of co-construction. The intercoordination of these factors (represented by the "score" analysis) can explain how intersubjectivity is formed, and also how it is lost.

By using the building blocks of similarity, separateness, reciprocity, antagonism, symmetry, asymmetry, and so forth, different types of interactions were identifies. A model for analyzing these different types uses the dimensions of degree of collaboration and relative expertise. Using these dimensions, different types of interactions suggested by different theories (Piaget, Vygotsky, Bandura, and others who discuss negative
interactions) can be compared and integrated. These different types of interactions had different attributes, different dynamics, and affected differently the process of knowledge co-construction.

Different degrees of collaboration, indicated by the interaction model, generate different dynamics of interaction. The extremely collaborative interactions are more harmonious in nature; interactions that are closer to the intersection of the dimensions are more separate; and interactions that get closer to the negative end of the dimension become increasingly antagonistic.

Differences in relative expertise can generate different pathways in the co-construction of knowledge. Interaction between an expert and a novice may be characterized by top-down and bottom up interchanges. In contrast, interactions among peers of similar expertise may be characterized by horizontal interchanges.

PATHWAYS OF KNOWLEDGE CONSTRUCTION

The analysis of pathways suggests that the process of knowledge construction consists of cyclical, discontinuous, and discrete processes. The process is also multi-layered: different sub-problems trigger additional layers with new sequences. It is suggested that the process of knowledge construction has multiple pathway that co-exist. In addition to the bottom-up processes, evidenced in microdevelopment, there are top-down and horizontal processes. These can operate simultaneously, as the need arises.
IMPLICATIONS OF THE STUDY

**Implications for macrodevelopment**

The study sheds light on the nature of co-construction of knowledge and on the mechanism of cognitive change in relation to microdevelopment. Many parallels, however, were indicated between these processes and other that occur in macrodevelopment. The parallelism between the micro- and macro-sequences was analyzed and discussed. In addition, other parallels were indicated. For example, techniques the participants use for establishing between them intersubjectivity (chapter 10) resemble techniques used in parent-infant interaction. By the same token, the types of interactions analyzed in chapter 11 encompass patterns that occur across ages. For example, interactions between children (like parallel play) resemble interactions of a similar pattern between adults (parallel activity); interaction between child-adult parallels an interaction of a similar pattern between an expert and a novice.

The analysis of microdevelopment suggested an explanation for the parallelism between it and macrodevelopment. If the parallelism indeed hold because similar functional mechanisms apply to both processes, then the resemblance works both ways. In this case, it is possible to make implications from microdevelopment to macrodevelopment. For many processes, the analysis may be easier on a microdevelopmental level: due to the shorter time scale, it is possible to have intensive documentation that covers all the occurrences related to the phenomenon under scrutiny. On the basis of microdevelopment, then, it may be possible to draw more easily inferences and explanations that may hold for macrodevelopment, and then investigate whether these indeed hold in macrodevelopment. Identification of mechanisms in
macrodevelopment, once they were identified and studied in microdevelopment, may be
easier then.

Specifically, it is reasonable to expect that the mechanisms identified by this study
— bridging, differentiation, and reiteration — serve in macrodevelopment as well.
Differentiation was identified as such, as discussed above. The other two mechanisms
may also apply to macrodevelopment; this is an open question, subject to further
research.

### Implications for research related to knowledge structures and cognition

Studies in psychology often involve tasks that are somewhat unfamiliar to the
subjects. In these cases, usually a warm-up period is introduced before the study begins.

The microdevelopmental sequences found in the present study indicate that a
short warm-up may not be enough. The reiteration of the microdevelopmental sequences
only strengthens this point. When studies investigate children's performances, in these
cases, if not enough time-on-task is given to the children, what the studies identify may
be a point on the children's microdevelopmental sequence instead of indicating their
ontogenetic abilities.

### Implications for research related to interaction

The implications for research related to interaction were pointed out in chapter 11,
and will only be mentioned here. One implication is a multi-faceted view of interactions.
Instead of looking for the "right type" of interaction, the diverse interactions that promote
— in different manners — cognitive change may be investigated. The interrelations
among these interactions and the way they join together may be more significant than the appearance of one of them.

The other implication was related to constraining aspects of the interaction when the interaction is a main research question. The results of this study indicated the importance of the activity and of many aspects related to the participants' discourse, actions and gestures, and sub-context frame, as crucial factors that determine the nature of the interaction. If factors related to the interaction or the activity are constrained, the generality of the results may be undermined.

**Implications for understanding knowledge structures**

The implication of the microdevelopmental sequences found by this study is that knowledge structures that were previously constructed in other contexts cannot be simply transferred to a complex unfamiliar context. Instead, these structures have to be constructed anew within the new context. A complex unfamiliar context, then, cannot be directly assimilated to existing structures; within the new context, knowledge structures have to be constructed anew.

The results of this study indicate that knowledge structures are not replaced by more advanced structures. Instead, knowledge structures at different levels coexist. The microdevelopmental sequence is accelerated because of the existence of general knowledge structures. These are defined as knowledge structures that synthesize previously existing specific structures across contexts. While negotiating the new task, the individual is guided by the general structures, and at the same time constructs — through the microdevelopmental process — specific structures within the unfamiliar context.
The findings of the present study strengthen the claim that knowledge structures are context-specific. The disparity between specific and general knowledge structures, as seen during the microdevelopmental sequences, implies that not always is there evenness in ability across domains and contexts (see Fischer, 1980a). Unevennes may especially emerge when the individual has substantially different degree of familiarity with these domains and contexts.

This theoretical implication can also be translated to practical implications, especially for education.

### Implications for Education

The implications discussed above indicate that knowledge structures have to be constructed anew within a new context. In this case, we should not expect a straight-forward transfer of knowledge from familiar to unfamiliar contexts. Instead of swift assimilation of unfamiliar contexts to existing structures, a microdevelopmental process may have to take place.

In educational settings, findings often show that students at different levels, from school and up to college, fall short in their comprehension and performance when the formulation or the context of the problems they encounter change (e.g., Gardner, 1991). However, a change in the context or the formulation of a problem affects it apparent familiarity. The previous analysis indicates that when students confront unfamiliar or complex problems, one cannot assume transfer and cannot expect evenness of performance. In such cases, the students may need to undergo a process of knowledge construction within the specific context of the problems at hand. In other words, the students may have to regress, and process the task by using more primary knowledge structures. Brown, Kane, & Echols (1986) demonstrated that transfer depends on
children's level of analysis or level of representation. If students have to regress to more primary structures, as indicated by the microdevelopmental sequence suggested here, transfer related to more advanced structures will not occur during that phase. Only later, after regressing and progressing again, could such transfer occur. To allow this process to happen, we should change our negative view of regression.

The results of the present study also highlight the importance of creating links and bridges between knowledge structures at different levels. If these links are not created, knowledge can be "fractured" (Papert, 1980). In contrast, if they are created, new knowledge makes intuitive sense; it is anchored to "body knowledge" (Papert, ibid). All the vast pool of existing knowledge structures, in this case, supports that knowledge.

In order to create links between knowledge structures at different levels, students may be encouraged to explore new unfamiliar contexts through diverse knowledge structures, including hands-on manipulation of concrete materials. This is done, usually, only in the early years of elementary school. We assume that older children do not need such activities; they can use representations, and at a later age, abstractions. However, scientist working at the cutting edge of science do use techniques and activities through which they access problems through knowledge structures at different levels. See, for example, the story of the discovery of the DNA: the scientist who were trying to crack the structure of the DNA built 3 dimensional models (Watson, 1968). Constructing a model of something that is not known yet seems to be an activity that will not be recommended at school. However, the activities of constructing the model, changing, and reconstructing it, established a strong access through sensory-motor structures. This, in turn, facilitated the representations of these hypothetical structures, since the representations were anchored to the sensory-motor structures. When there is a stronger intuitive sensory-motor basis for the representations, it is easier to manipulate them in one's mind. It is also easier, then, to relate these representations to one another and to process the ideas on abstract levels, too.
Creating links to more primary levels of knowledge structures should not demand much times. The microdevelopmental sequences found in this study were not long. That time will be gained when the ensuing learning will make more sense to the learners.

CODA

This study offered some explanations for the nature of microdevelopment, of co-construction, and of the mechanism of cognitive change. At the same time, it opened the door for many other questions. Is the bigger microdevelopmental sequence indeed composed from reiteration of many microdevelopmental sequences, as the four microdevelopmental sequences in this study indicated? How is the overall trend of performance created? Does the pace of microdevelopmental sequences — the rate of growth of cognitive structures — indeed increase across time? These are open questions, subject to further research.

More research is needed also to establish the inter-connections between the dynamics of interactions and the attributes of the co-construction of knowledge. This is a complex and intricate domain, which is relatively young in the field of psychological research.

The parallels between micro- and macrodevelopment, as discussed earlier, open another vast ground for further research. Do the three mechanisms of transition suggested here indeed operate in macrodevelopment? What else can we learn from microdevelopment for better understanding the nature of human development?

The questions, it seems, far exceed the answers. This, it seems, is the nature of knowledge. The more knowledge one has, the more it seems elusive: new questions
replace the former ones. I saw the participants in the study in this continuous pursuit, replacing one answered-question with several new ones. When raising a new question, about which they did not know the answers, they expressed their frustrations about this elusive nature of knowledge:

*Donald:* "*So maybe we should just treat this one as a totally new entity.*
*We don't have any idea how--"

But then, there is always the other perspective. Like looking at the half-filled glass, instead of the half-emptied one:

*Liz:* "*No, that's not true. We do have an idea.*" / *Donald:* "*OK.*" / *Liz:* "*We have a lot of ideas.*"
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