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Problem Solving in the Management of Technology and Innovation: Choosing the Uncertainty-Ambiguity Boundary

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ABSTRACT

Technical problems are solved in an environment of uncertainty and ambiguity. Most research in technical problem solving has two characteristics in common: no differentiation between uncertainty and ambiguity occurs, and the degree of uncertainty and ambiguity is considered exogenous to the problem solving process.

This paper argues, first, that uncertainty and ambiguity are dissimilar concepts. Problem solving under ambiguity involves fundamentally different tasks than problem solving under uncertainty. Consequently, different organizational structures are appropriate. Second, it is argued that uncertainty and ambiguity are not exogenously given but at least partially determined in the problem framing process. In this process, problem solvers select explicitly or implicitly a specific uncertainty-ambiguity boundary. This boundary demarcates the areas that the problem solver frames as involving uncertainty from those that are framed as involving ambiguity. In the paper organizational consequences of the notion that problem solvers choose an uncertainty-ambiguity boundary are examined and implications for research on technical problem solving are discussed.

INTRODUCTION

Research on problem solving, especially on technical problem solving, has addressed such questions as the effects of ambiguity and/or uncertainty on the problem solving process (Marples 1961; Sutherland 1977), the interplay between uncertainty/ambiguity and organization structure (Marquis and Straight 1965; Lawrence and Lorsch 1969; Larson and Gobeli 1988), and the need for different communication channels under different uncertainty/ambiguity regimes (Tushman 1978; Tushman and Nadler 1980, Allen 1984). Most empirical work on uncertainty and ambiguity in technical problem solving has two characteristics in common. First, no explicit distinction between uncertainty and ambiguity is made; the two concepts are used as if they were interchangeable. Second, uncertainty and ambiguity are considered exogenously given variables, variables managers must react to.

In this paper, we first argue that uncertainty and ambiguity are dissimilar concepts[1] and that technical problem solving may involve both uncertainty and ambiguity. Recognizing the difference between uncertainty and ambiguity is important since the two concepts relate to different problem solving processes and thus to different ways of supporting them organizationally. Secondly, we propose that viewing uncertainty and ambiguity as exogenously given variables is a misrepresentation of the problem solving process. We argue that one core task in problem solving is the <u>selection</u> of the <u>uncertainty-ambiguity boundary</u>. This boundary demarcates the areas that the problem solver frames as involving uncertainty from those that are framed as involving ambiguity. Thus, we argue,

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[1] Similar arguments are made by March 1978; McCaskey 1982; Einhorn and Hogarth 1986; Martin and Meyerson 1988.

levels of uncertainty and ambiguity are not exogenously given, but are the results of explicit or implicit choice.

The notion that uncertainty and ambiguity are selected in the problem framing process affects our understanding of technical problem solving. Under conditions of innovation and technological change, it is important to focus attention on this selection process, since this is the point at which the nature and potential outcome of the subsequent problem solving process is determined. Consequently, research on the management of technical innovation should focus greater attention on the process of determining the uncertainty-ambiguity boundary. By viewing uncertainty and ambiguity as exogenously given, a crucial aspect of the problem solving process is neglected. Research results on the impact of uncertainty and ambiguity on the appropriateness of such aspects as communication networks (Tushman 1978; Allen 1984), project structure (Marquis and Straight 1965; Larson and Gobeli 1988) and team composition (Katz and Allen 1985; Ancona and Caldwell 1989) might need to be reinterpreted in light of the proposed notion that uncertainty and ambiguity are at least partly determined in the problem framing process. The observed impact of these variables on project performance might be due at least partially to a different choice of the uncertainty-ambiguity boundary for effective projects.

In this paper we first discuss the distinction between uncertainty and ambiguity. We then describe how uncertainty and ambiguity affect differently problem perception and appropriate solution strategies. Next, we propose that problem solvers, whether individuals or groups, have at least some control over the level of uncertainty and ambiguity in technical problem solving. They choose the uncertainty-ambiguity boundary. This proposition conflicts directly with the predominant concept that a problem can be characterized by specific uncertainty and ambiguity levels. Subsequently, we discuss the organizational consequences of the notion that the uncertainty-ambiguity boundary is the result of a choice process, and we demonstrate how this idea changes our perception of how research on technical problem solving should be designed, conducted, and interpreted.

UNCERTAINTY AND AMBIGUITY

The concepts of uncertainty and ambiguity have been defined in a number of ways in the organizational literature, depending on the nature of the research question being addressed. In this section we will briefly review these definitions, and then offer definitions which we find appropriate for discussing problem solving in a technological environment.

Information theorists define uncertainty most abstractly: "the uncertainty of an event is the logarithm of the number of possible outcomes the event can have...." (Garner 1962, p. 19). Decision theorists define uncertainty more broadly, as the situation where possible future outcomes are known, but where the probability distribution is unknown, or at best known subjectively (e.g. Luce and Raiffa 1957; Owen 1982). (Decision theorists also define the concept of risk as a special case of uncertainty; that is, uncertainty with known probabilities, e.g. Shubik 1982. We argue below that in technical problem solving no situations with objectively known probability distributions exist.)

Organizational researchers have built on the above definitions, broadening them to fit the organizational context. At the broadest level uncertainty is defined in organization theory as a lack of clarity of information, a lack of knowledge of causal relationships, and a lack of timely, definitive feedback (Lawrence and Lorsch 1969). This coincides with early definitions of uncertainty provided by researchers on the psychology of problem solving (e.g.

Miller and Frick 1949), as derived from the mathematical theory of communication (Shannon and Weaver 1949). In both lines of research, uncertainty is viewed as stemming from a paucity of information.

In an effort to develop specific measures of uncertainty in the context of organization research, Duncan (1972) operationalizes uncertainty as containing three components:

> "(1) the lack of information regarding environmental factors associated with a given decision-making situation, (2) not knowing the outcome of a specific decision in terms of how much the organization would lose if the decision were incorrect, and (3) inability to assign probabilities with any degree of confidence with regard to how environmental factors are going to affect the success or failure of the decision unit in performing its function."

The first two of these components focuses on the lack of information, in a manner similar to the broad definition of Lawrence and Lorsch (1969). The third component is similar to the narrower definitions such as proposed by information theorists and decision theorists, but emphasizes that participants assign probabilities to outcomes subjectively, leaving doubt as to the accuracy of these probabilities.

A common thread running through these definitions is that in each case uncertainty relates to a lack of information. Consequently, if problem solvers wish to reduce uncertainty, they must gather information about possible outcomes.

Several authors, however, argue that management decision making frequently is not well described by models of decision making under uncertainty (e.g. Conrath 1967; March 1978; McCaskey 1982; Daft and Lengel 1986; Einhorn and Hogarth 1986; Gimpl 1986; Martin and Meyerson 1988). They propose that often possible future outcomes are not well defined, and that there may be conflict with regard to what these will or should be. These authors therefore maintain that decision making and problem solving are often carried out under conditions of ambiguity, rather than uncertainty, where ambiguity is defined as lack of clarity regarding the relevant variables and relationships (Martin and Meyerson 1988, p. 112).[1]

As many as twelve sources of ambiguity faced by business managers have been suggested (McCaskey 1982). However, three basic causes of ambiguity seem to capture the fundamental issues (Kosnik 1986; Meyerson and Martin 1987): confusion caused by ignorance, unpredictability resulting from unknown future states, and contradictions due to paradox or irreconcilable conflicts. To illustrate how these three factors could be associated with a technological choice problem, consider the problem of choosing a high capacity storage device for a new computer. If the remainder of the computer design is not yet fully defined, the engineer will be ignorant of the proper characteristics for the device; the information necessary to determine his or her informational needs does not yet exist. Such ignorance produces ambiguity about the choice. Further, suppose that each of the available devices offers different adaptability for future changes. It may not be possible to predict which characteristics will be needed in the future, because that is a complex and unknown function of user needs, application software requirements and hardware capability. This unpredictability of future directions produces ambiguity. Finally, suppose that device memory capacity and device access speed are both desirable dimensions of merit, and that

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[1] Ambiguity relates directly to Daft and Lengel's (1986) notion of equivocality, which they define as "...ambiguity, the existence of multiple and conflicting interpretations about an organizational situation."

one can be maximized only at the cost of the other. This need to decide between desired characteristics leads to conflict, which also produces ambiguity.

In sum, ambiguity is seen as resulting from a lack of clarity about choices, stemming from needed information which does not yet exist, needed knowledge of future conditions which cannot be predicted, and conflict over choices which must be made that cannot be reconciled for technological or other reasons.

The factors associated with ambiguity differ significantly from the accepted cause of uncertainty, i.e. the lack of information. None of these factors is, in fact, susceptible to amelioration through information gathering alone. Because the causes of uncertainty and ambiguity are different, organizational responses to uncertain and ambiguous situations differ as well. For example, Daft and Lengel (1986) argue that in situations of ambiguity, information media of greater richness (for example, face-to-face communication as opposed to written reports) are needed than in situations of uncertainty.

Mental Models and the Distinction Between Uncertainty and Ambiguity

What is different between a situation that is characterized by a lack of information (uncertainty) and a situation characterized by a lack of clarity (ambiguity)? We propose that characteristics of the mental models used by problem solvers can help to distinguish more clearly between ambiguity and uncertainty and to determine organizational consequences of this distinction. The typical mental models are quite different in these two situations. This difference has considerable ramifications for how problems are solved and for how to manage the problem solving process.

Mental models guide individuals' behaviors, especially their problem solving behavior (Mintzberg 1976; Brief and Downey 1983; Simon 1987; Clement

1989). "In effect, managers (like everyone else) use their information to build mental models of their world, which are implicit synthesized apprehensions of how their organizations and environments function. Then, whenever an action is contemplated, the manager can simulate the outcome using his implicit model" (Mintzberg 1976, p. 54). Mental models determine what is relevant for understanding a specific phenomenon or for solving a problem. A well defined mental model implicitly predetermines the relevant solution space to a problem (Clement 1989).

When facing a problem, problem solvers might feel that they know what to do, what specific information to look for, and what results to strive for. In this case, the problem solvers have mental models available to them that they consider adequate for the problem. This model demarcates the boundaries of the problem and identifies the specific tasks necessary to solve the problem.

Alternatively, problem solvers might think they do not yet have a "good grip" on the problem. This would imply an inability to decide on the problem scope, to define the tasks involved, to discriminate relevant from irrelevant inputs, or to identify the desired outcome. In other words, no mental model for problem structuring is available to the problem solver that is perceived as adequate. Problem solvers must find or create an appropriate model before problem solving activity can begin.

The first situation characterizes problem solving under <u>uncertainty</u>. The uncertainty is created by the problem solver not yet knowing the precise characteristics of the outcome of the problem solving process. If the outcome were known <u>a priori</u>, this would not be a case of problem solving. But the problem solver has a clear understanding of the problem and possesses a mental model that guides the problem solving process. The problem solving process involves specifying the precise values of the variables of the mental model. The informational needs are well defined.

The second situation characterizes problem solving under ambiguity. Ambiguity exists because the problem solver does not yet know the precise structure of the problem and consequently of the problem solving process. The problem solver does not have a mental model available that is considered adequate to guide problem solving behavior. The problem solver must first determine a mental model to guide problem solving behavior.

According to this distinction, uncertainty implies that the problem solver has a mental model to work within and (explicitly or implicitly) considers this model to be sufficient for dealing with the problem. A sales manager planning next month's sales activities might use a problem solving rule for predicting sales volume, specifying that next month's sales will equal this month's sales plus or minus five percent. No ambiguity exists in regard to which variables to consider, however, uncertainty exists as to the exact values. Similarly, an engineer calculating the friction of a surface might apply a standard formula to his specific problem. He knows that the formula is rigorously applicable only to idealized problems, and therefore is likely to provide only an approximate value. However, as long as the engineer considers the method to be sufficient to obtain a value which approximates the true value within acceptable limits, he is solving the problem under uncertainty.

In the case of ambiguity, the problem solver does not have a model available that he or she considers adequate to the problem. For example, the sales manager might have the problem of forecasting sales for a new product line. The old forecasting method might be considered inadequate because there are no relevant past sales and trends from which to extrapolate. Thus, our sales manager perceives the need to determine another way to forecast sales. This implies identifying the variables that might be relevant and determining the functional relationships. In other words, he needs to develop a model that he considers appropriate to the problem. Likewise, an engineer might be faced with the problem of estimating the friction to be expected in an automobile engine piston assembly incorporating new ceramic parts. The new materials are thought not to be amenable to the approximation methods used for more traditional materials and the engineer does not yet know how to take these new factors into consideration. He faces ambiguity since he does not have a model available that helps him determine relevant variables and which prescribes the problem solving steps to take. Alternatively, ambiguity might exist because several conflicting friction models are available and no criterion is available for deciding among them.

In the context of organizational problem solving, ambiguity frequently arises because different members of the organization may use different, conflicting models. Only if this conflict is somehow resolved does the ambiguity give way to uncertainty.

The Difference Between Uncertainty Reduction and Ambiguity Reduction

Problem solving is frequently characterized as a process of uncertainty and/or ambiguity reduction (e.g. Sutherland 1977). It follows from the discussion of uncertainty and ambiguity provided above that the processes of uncertainty reduction and ambiguity reduction must be quite distinct and qualitatively different in structure, content and approach.

Uncertainty reduction is the process of gathering information relevant to the variables defined within one's mental model. The problem solver has a model that he or she considers adequate to the problem. This model corresponds to an integrated conception of all relevant factors and their functional relationships. Problem solving involves gathering information relevant to this model and integrating this information according to the assumed functional relationships. In short, one knows what one doesn't know and one tries to reduce or eliminate this lack of knowledge.

Reduction of ambiguity is the process by which a model considered to be appropriate to the problem is found or built. Ambiguity, as we have seen, is the state of not knowing what the relevant variables and their functional relationships are — it is lack of clarity in a problem situation. Constructing a model to specify the relevant variables and the relationships between them is a creative process requiring rethinking of inputs, processes and outputs. Thus, ambiguity reduction is inherently less structured, less amenable to organization and management, and less predictable than uncertainty reduction. One does not know what one doesn't know (but should know), and one seeks a model to define this.

The difference between these two processes implies that they involve different tasks. In the case of uncertainty reduction the key tasks are information gathering and integration. In the case of ambiguity reduction, the tasks are model building, negotiation, problem framing, evaluating and reframing, and model testing.

Also implicit in the difference is that the two processes will be different to manage. With uncertainty, one can manage the content of the problem solving process, since one knows the tasks involved (e.g. Was the experiment run as specified?) In the case of ambiguity, one can manage only the process (e.g. Has the software engineer explored options which will speed up the program?)

Similarly, the difference between uncertainty reduction and ambiguity reduction leads to different control measures. In the case of uncertainty reduction, content oriented control measures can be used. In the case of ambiguity reduction, only process or output oriented control measures are relevant.

THE UNCERTAINTY-AMBIGUITY BOUNDARY

We suggest that no a priori criterion exists for determining fully whether a situation contains uncertainty or ambiguity. Most of the discussion of uncertainty and ambiguity found in the literature has the assumption in common that the uncertainty and/or ambiguity in a given situation is exogenously given. We propose that, contrary to this assumption, uncertainty and ambiguity are not exogenous to the problem solver, but rather that the relevant levels of uncertainty and ambiguity are at least partially determined in the problem framing process.

The prediction of heads or tails in a coin toss will serve to illustrate this proposition. The problem of tossing a coin and predicting the outcome is usually regarded as a problem of known risk, i.e. of a known probability distribution. But is this necessarily the case? The person tossing a coin might assume that heads and tails are equally likely — he is not able, however, to know this with certainty. Or the person might assume that heads and tails occur in a fixed but still unknown ratio and may decide to use Bayes' theorem to reach a better estimate of this ratio. In this case, the problem solver would frame the problem as one of uncertainty. He knows the relevant variables (occurrences of head and tails in trial tosses) and thus can collect information regarding these variables. But another alternative exists: the player may reject the proposition that the game is fair or even that the ratio is constant. He could decide to attempt to determine factors that affect the outcome distribution. He might not know, however, which variables are likely to influence the outcome. Ambiguity exists regarding the problem structure. He may investigate whether the coin is bent or has any physical defect which produces a bias. He may experiment to determine whether the way the coin is thrown has an influence on the outcome. Or he may consider the possibility that the coin might sometimes land on its edge, thus introducing another outcome. In other words, the player (or problem solver) must choose the scope of the problem and thereby the levels of uncertainty and ambiguity involved.

Two conclusions can be drawn from this example:

(1) The traditional distinction between risk (known probability distribution) and uncertainty (unknown or subjective probability distribution) is not helpful in the context of problem solving. The decision maker never knows with certainty if an objective probability distribution exists and what the precise characteristics of this distribution are. He can at best estimate those characteristics — in other words, he has to decide on what to consider a useful representation of reality.

(2) The scope of the problem and the range of potential outcomes are selected in the problem framing process. This conflicts with the traditional view that the level of uncertainty and ambiguity are objective characteristics of a given problem. As the example shows, the problem solver has at least some control over determination of the levels of uncertainty and ambiguity that will be considered.

The last conclusion has particular relevance in technological problem solving, since the technical scope and the characteristics to expect of the outcome (for example, which technologies to use in development and what performance to expect of a new product) are not known _a priori_. Organizations seem often to be inclined to frame problems as problems in uncertainty rather than ambiguity, thereby limiting the possible solutions to the ones that fit within existing mental models (Schon 1967; Henderson and Clark 1990). Conversely, if the organization does not reduce ambiguity appropriately, it risks technical wandering and corresponding missed schedules as well as high development cost (McDonough and Leifer 1986). Thus, it is of central importance to understand and manage the process of choosing the boundary between uncertainty and ambiguity in technological development.

Choosing the Uncertainty-Ambiguity Boundary

As argued above, the problem solver can choose how to frame the problem. It is often the case that for a complex problem some parts may be seen as certain, some as uncertain, and some as ambiguous. Setting the uncertainty-ambiguity boundary is the process of deciding which parts of the problem fit into which category.

In setting the uncertainty-ambiguity boundary the problem solver chooses which technical aspects of the problem are well enough understood to accept his or her mental model as appropriate, and where the important relationships are to be regarded as not fully known. For the aspects of the problem where the mental models are considered appropriate, the problem solving task consists of determining the values of the specified variables (uncertainty reduction). In the areas in which the relevant relationships and variables are regarded as not yet known, problem solving implies establishing which variables are important and how they interact (ambiguity reduction).

Different problem solvers can frame the same problem in different ways. Thus, the levels of uncertainty and ambiguity are not inherent in the task, but rather are established as part of the process.

Since problem solvers decide on what aspects of problems to consider as uncertain and what parts to treat as ambiguous, this boundary can be moved. Moving the boundary implies that parts of the problem which have been perceived and treated as uncertain may now be viewed as ambiguous, and vice versa. This further implies that the problem solver now chooses to address the problem differently.

An illustrative example of how a given situation may be formulated with different conceptual locations of the uncertainty-ambiguity boundary can be found in the production of semiconductor chips.

Suppose that the process for production of a particular type of semiconductor chip has an average weekly yield of 50 ± 10% (not uncommon for a complex microchip product requiring many precision steps in its manufacture). The production manager can choose to regard this yield and its variability as inherent characteristics of the process. In this case, the manager regards his situation as one of irreducible uncertainty. His mental model is such that it does not allow for uncertainty reduction. There is no problem to be solved. Alternatively, he may regard the problem as a mixture of a set of random factors, which cannot be influenced, combined with others which are controllable and known to him. Thus, he might gather information on (for example) the quality of photoresist from various suppliers, on the performance and training level of the operators and on other known factors that he regards as having a controllable influence on the process yield. This would be typical of an effort to reduce the process variability by controlling incoming photoresist quality, for example. This is still a case of uncertainty. The process yield is viewed as dependent on a combination of random and controllable factors. The process manager can reduce the uncertainty by using a model that he believes and by measuring the variables in the model. As a third alternative, the manager may decide that he does not know all the factors which influence chip yield, and he may study the process to attempt to discover new yield-influencing factors. This approach might be used in an attempt to improve the overall yield. Here the problem is viewed as ambiguous, and a new model must be constructed. Initially it is not apparent which variables are important in affecting the yield nor what their influence is. Problem solving is complex, and there are varying approaches that the manager may use to find a solution.

Problem solving within the bounds of an accepted model is working with uncertainty; challenging the model is opening the door to ambiguity. Management's task when technology, innovation and change are issues is frequently to challenge pre-perceived uncertainty-ambiguity boundaries. ("Let's take a fresh look.")

Model building which takes place in the process of ambiguity reduction can be thought of as hypothesis formation (Clement 1989). If so, then data gathering in problem solving may serve the dual purposes of uncertainty reduction (within the model) and hypothesis testing, possibly leading to revision or rejection of the model (Einhorn and Hogarth 1986). This implies a problem solving strategy under ambiguity of tentatively establishing the uncertainty-ambiguity boundary so that structured problem solving (uncertainty reduction) can begin, followed by adjustment of that boundary if information emerges which is not consistent with the hypothesis-model first chosen.

Subjectivity of the Uncertainty-Ambiguity Boundary

The boundary definition depends strongly on prior experience. Different problem solvers are likely to frame the same problem in different ways, depending on their training and experience. Thus, one person or organization might perceive a given problem as uncertain while another perceives it as ambiguous. Successful problem solving leads to a reinforcement of the models used and a reduced likelihood of challenging these models (Schon 1967; Hannan and Freeman 1984; Henderson and Clark 1990). Failure, on the other hand, encourages reconsideration of the models being used (Hedberg 1981; Tushman and Anderson 1986; Anderson and Tushman, 1990). Firms with divergent histories are thus likely to frame similar problems differently.

Not only do interorganizational differences in problem framing exist, but also a given problem may be perceived differently in one and the same organization. Aspects of a complex problem may be framed as uncertain by some members of the organization and as ambiguous by others. For example, if a roller skate manufacturer wants to produce low friction bearings for a new high speed skate, different parts of the organization will perceive this problem in different ways. The project manager may have confidence that the engineering specification can be met within the existing organizational framework, but may not know exactly what the technical solution will be or how much it will cost. The cost and the design that meets the specifications are outputs from the design process which are important to the manager, but the details of how they are determined remain unimportant to him. Based on prior experience, he might believe, for example, that he knows how to adequately estimate the costs. Consequently, the manager perceives this aspect of the problem as one of uncertainty. The variables important to him are known, although their specific manifestation is still open. The engineer responsible for selecting the bearings may view the problem differently. If product specifications exceed the capability of bearing technology currently in use at the company or known to the engineer, for example, he must expand the search for a solution to new areas. It may be necessary to use a new bearing material, or a different type of seal, or to redesign the bearings so that they do not overheat. It is not clear a priori which of these or other steps will be necessary or desirable, so the problem presents ambiguity to the engineer.

Considerable ramifications for organizing technical problem solving stem from the recognition that one and the same task may be framed by some members involved in the problem solving process as containing ambiguity while others may frame it as containing uncertainty. For those members who frame the problem as ambiguous, different organizational support measures are needed than for those who perceive the problem as uncertain.

ORGANIZATIONAL CONSEQUENCES

The appropriate organizational structure for searching for a problem solution depends on how the problem is perceived on the uncertainty-ambiguity dimension. Similarly, the method of search depends on whether the problem is perceived as uncertain or ambiguous.

Problem solving under uncertainty is characterized by the availability of a mental model that is considered adequate to the problem. This mental model characterizes the relevant variables and their functional relationships. Problem solving consists of gathering and integrating information required by the model. In other words, it is known which information is needed and how to integrate it.

Consequently, the problem solving process can be specified a priori. The problem solving task can be decomposed into well defined subtasks, using such rules as minimizing interdependence between separate tasks (Hippel 1990). Smith and Eppinger (1991) demonstrate that the Design Structure Matrix can be used to structure a well-understood design task consisting of several interdependent subtasks so that an optimal task partitioning and ordering can be determined ex ante.

Since the tasks are definable in situations of uncertainty, it is possible to describe precisely the content of specific roles that need to be fulfilled in order to complete the problem solving task. Job descriptions that precisely describe the content of the job are possible. Similarly, communication networks can be structured that support the problem solving process. The project boundaries can be defined, and the interfaces to other parts of the organization or environment can be specified. Project plans that define meaningful tasks and milestones can be established (Nicholas 1990). Consequently, it is possible to control the content of the problem solving process using measures that can be defined before the actual problem solving commences. In short, the problem solving process can be structured and controlled using well established approaches such as described in Frank (1971) and in Newman (1973). An appropriate organizational structure for this kind of activity will tend to show the characteristics of a mechanistic organization as described by Burns and Stalker (1966). It is interesting to note that this holds true even if the variance of future states of the world is high (i.e. low predictability in a statistical sense) as long as the organization has clarity about the information needed and how to use the information.

This situation differs strongly from problem solving under ambiguity. Problem solving under ambiguity refers to the construction and validation of a model that is to guide subsequent uncertainty reduction efforts. The individual tasks are not known a priori, although the process for finding a solution (such as the basic scientific method) may be well understood (Simon 1978; Simon 1979). Consequently, only the process and not the content of the problem solving task can be managed. The inability to define the problem solving content becomes apparent when one investigates the task definitions of projects that are seen as involving a high degree of ambiguity. Typical tasks descriptions are "understand market needs", "define desirable product characteristics", "develop a conceptual design", and design and test prototype". These descriptions, although meaningful, do not allow deduction of what is being developed. They refer to the process and not to the content of the task.

Because ambiguity implies that it is still unclear what needs to be done, roles can be described in general terms only. Roberts and Fusfeld (1981), for example, define the roles idea generating, championing, project leading, gatekeeping, and sponsoring. Again, these roles refer to the problem solving process and not to the problem solving content. Consequently, tight managerial control of the project in regard to content issues is not possible. Only the process by which the organization searches for an answer to the problem and the functionality of the outcome (i.e. market success) can be controlled and measured. Management tasks will be primarily to facilitate both communication and creativity while providing an overall context to assure that solutions are compatible with organization goals (McDonough and Leifer 1986). Thus, management might create periodic meetings in which group members discuss different approaches, manage documentation requirements, provide access to external information sources, and articulate the organization's mission, goals and values.

In sum, organizational characteristics and measures that support the problem solving process are quite different in situations in which a problem is defined as ambiguous and those in which it is seen as involving primarily uncertainty. Table 1 summarizes these differences. Since a specific problem solving task can be framed so that it contains elements involving both uncertainty and ambiguity, the actual appropriate organization structure might be a combination of the two ideal types.

Table 1: Difference between Problem Solving under Uncertainty and Problem Solving under Ambiguity

DIMENSION	PROBLEM SOLVING UNDER UNCERTAINTY	PROBLEM SOLVING UNDER AMBIGUITY
Nature of Problem Solving Process	Application of model	Development of model
Task Definition	Content and process known	Process known (at most)
Task Partitioning	Specifiable	Unknown
Output Definition	Solution-oriented definition possible	Only functional definition possible
Information Needs	Can be defined and described	Can at most be vaguely described
Structure of Communication Networks	Mechanistic	Organic
Communication Interfaces	Well specifiable	Fluid
Project Boundaries	Well defined	Fluid and fuzzy
Role Descriptions	Precise	Vague
Control Mechanism	Prior definition of control criteria possible	Only process and functional control possible

The uncertainty-ambiguity boundary is decided on by the organization; the way in which the boundary is selected has broad implications for the organization. Successful problem solving requires that there be good alignment between the skills and capabilities of the organization and those needed to solve the problem. This alignment may be achieved either by setting the boundary of the problem to match the skills of the organization, or by matching the organization to the problem at hand (by hiring or retraining). The first case is likely to encourage problem solving under uncertainty. This type of problem solving is controllable and predictable, but precludes solutions outside the mental models that are predominant in the organization. The second case introduces ambiguity and can be thought of as having two variants, evolutionary adaptation and radical change, depending on the extent of the mismatch between the organization's existing capabilities and the demands of the problem as it is framed, i.e. the level of ambiguity chosen.

Evolutionary adaptation is a cycle of framing, learning and reframing in which organizational skills are expanded incrementally (Argyris and Schön 1978; Schein 1980). The skill set available determines the available models for problem framing. Choosing to consider skills which lie outside the organization's capabilities is choosing to deal with ambiguity; new models must be built. However, if the skills are similar to those already existing in the organization, then the new model will still be similar to existing models in the firm, and change will be incremental. Once an incremental change has occurred, the new model becomes the starting point for further incremental change.

Radical change involves problem framing without considering the skills of the organization (Abernathy and Clark 1985, who use the term "architectural change" for change that make both market and technical skills obsolete; see also Ettlie, Bridges and O'Keefe 1984). The problem solver frames the problem very broadly, accepting a high level of ambiguity. This produces models so different from those recognized by the organization as valid, that they may be incompatible with the existing organization. This accounts for techniques sometimes adopted by organizations such as the establishment of "skunk works" operations (see the example provided by Kidder 1981), or the formation of new venture groups (Roberts 1980) to operate outside the existing organization structure for radical projects. Such techniques, if successful, can result in very innovative solutions and great progress, but at the cost of controllability and predictability.

In sum, the choice of the uncertainty-ambiguity boundary has considerable consequences. In those areas that are framed as involving uncertainty, it is appropriate to employ content-oriented control mechanisms within an organizational structure that tends to be mechanistic in nature. In areas involving ambiguity, the organization's control mechanisms have to be more process-oriented, and the structure more fluid (Daft and Weick 1984). Compatibility between chosen levels of uncertainty and ambiguity, control mechanisms and organization structure can be expected to have important performance implications.

CONSEQUENCES FOR RESEARCH ON THE MANAGEMENT OF TECHNICAL INNOVATION

The choice of the uncertainty-ambiguity boundary is an important step in finding a solution to a technical problem. This choice will affect which possible solutions are considered, how long it will take to find a solution, who is needed to solve the problem, and how to support the problem solving process organizationally. In spite of wide-ranging and important consequences, this choice is often made implicitly, based on problem solvers' mental models of reality stemming from personal preferences, educational background and experience, superimposed upon the capabilities, policies and needs of their organizations.

Research on the management of technical innovation has neglected the problem framing process. No attention has been paid to the selection of the uncertainty-ambiguity boundary. Research has investigated the notion that the problem solving process and its structure is contingent on the degree of uncertainty and ambiguity involved (Tushman 1978; Allen 1984; Larson and Gobeli 1988). This research has failed, however, to distinguish clearly between uncertainty and ambiguity and to conceptualize that the relevant level of uncertainty and ambiguity is endogenously determined. In most cases, externally ordained criteria for measurement of the degree of uncertainty or ambiguity in a given problem solving situation have been employed. These measures might not coincide with how the problem solvers themselves frame the problem, i.e. how they determine the uncertainty-ambiguity boundary. In other cases, ambiguity or uncertainty are measured by the perceptions of mangers who are located at a different organizational level than those whose problem solving behavior is studied, again creating the possibility to misjudge the degree of uncertainty or ambiguity as determined by the problem solvers.

Two normative consequences for research on the management of technological innovation result from our proposed framework. First, the terms ambiguity and uncertainty need to be distinguished explicitly. They refer to different aspects of the problem solving process, model building on the one hand and model using on the other. And they are not directly linked. Situations exists in which the relevant variables are characterized by considerable variance (high uncertainty), in which, however, the problem solvers are convinced that they have an adequate understanding of the situation (low ambiguity). By lumping the terms uncertainty and ambiguity together, the possibility to derive helpful suggestions for managing situations that are characterized by one or the other is largely precluded. A case in point is the research on how to structure R&D projects. Different researchers come up with quite conflicting suggestions (e.g. Marquis and Straight 1965; Larson and Gobeli 1988; Elmes and Wilemon

1991), partially because they have paid little attention to conceptualizing and measuring ambiguity and uncertainty separately.

Second, researchers must determine empirically the relevant uncertainty-ambiguity boundary. That is, uncertainty and ambiguity need to measured at the same level of analysis as the problem solving that is studied. In addition, researchers have to be aware that the uncertainty-ambiguity boundary can be set differently in different organizations. Even if apparently similar tasks, i.e. developing a new microelectronic device, are studied, organizations might frame the problem in various non-comparable ways. One approach for addressing these issues is provided by Allen (1966). He controls for interorganizational differences in determining the uncertainty-ambiguity boundary by studying problem solving situations wherein a high degree of structure is externally imposed on the problem. He accomplishes this by studying problem solving behavior of multiple organizations which work in parallel on government sponsored projects. Thus, the project definition is fixed in advance. Furthermore, the competing organizations are similar, since they are in the same technology area and industry grouping (aerospace), allowing the assumption that they will frame the problem similarly.

Several problems, (e.g. organizations' apparent inability to embark on new technologies or the failure of traditional project management techniques for innovative projects,) would benefit if we paid more attention to how the problem is framed, i.e. how the uncertainty-ambiguity boundary is determined. In the field of Management of Technology and Innovation, however, this issue has been overlooked. Problem solving processes have been studied intensively without paying attention to issues of problem framing. The tendency exists to see a problem and its fundamental structure as given. However, problems and their uncertainty-ambiguity boundaries are not given, but chosen.

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