PROGRAMMABLE FORMS

by

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ABSTRACT

This thesis is a record of work accomplished in building and studying concepts associated with a new construction material. Two types of prototypes for this material are described. These prototypes may serve as useful models for further work in this area, and each stands alone as an artifact that successfully embodies certain aspects of this material.

The model for the completed form of this material is as follows: It is to consist of modules whose size and shape may both be changed and set to change by a person using it. These modules are to be primarily triangular panels. It is planned that interconnections between these unit shape-changeable panels will allow the person using this material to make specifications for shape transformation to effect groupings of panels, causing them to change as a single unit, without the necessity of specifying the task that each panel is to take in this transformation. This work is done in the belief that this material, through great flexibility and directibility, will offer an extremely effective expressive and constructive medium.

This study is in three parts. The first is a description of the evolution of methods and materials for building in space, and is shown in a history of construction toys. The second is a description of the two types of prototypes mentioned above. The third consists of thoughts about the implications of this work for a constructive environment for children.

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Construction Toys in a Cultural Context
A Learning Environment

In 1837, Friedrich Froebel founded a learning environment for children and named it the kindergarten. In this environment an emphasis was placed on song, dancing in groups, gardening, and building with construction materials and methods that Froebel invented or appropriated. Education on specific topics was to proceed in an atmosphere conducive to personal creativity. He did not have a fixed conception of this environment, and once remarked that it would take 300 years to work out.

He believed that people "should, at least mentally, repeat the achievements of mankind, that they may not be empty dead masses, that judgment of them may not be external and spiritless."[E.M. 282]

"Could we but perceive what a burdensome mass of accumulated, mechanical, far-fetched knowledge and training, we already possess, and are foolishly striving day by day to augment; and on the other hand, how very little knowledge we have that has been developed out of ourselves, that has grown-up in our own souls; it would be well for our children, and for the saving of future generations, if we would but cease to be proud of our foreign thinking, foreign knowing, even foreign emotions and feelings: cease to set the highest fame and success of our schools therein, that they stuff our children's minds and hearts with all this far-fetched, veneered, knowledge and skill."[E.M. 230 - 231]

"To give firmness to the will, to quicken it, and to make it pure, strong, and enduring, in a life of pure humanity, is the chief concern, the main object in the guidance of ... [a child] ... in instruction and the school."[E.M. 96]

To Froebel, play seemed to define learning: the more that something is play, the more total the self-initiated and creative engagement and discovery there is of
something. He saw learning as a naturally occurring activity. This led him to examine the methods used in schools, with the assumption that from those methods came forces inhibiting, restraining, or in other ways not in tune with a child's predisposition to learn.

Froebel saw that schools could become environments rich with areas for a child to turn this disposition. To this end, he developed a set of about twenty interrelated sets of objects and activities. The theme of these activities was the construction and transformation of form. The most famous of the materials he developed are four small boxes of building blocks. The idea of these objects was to give a child media for independent work.

Froebel also developed sequences of activities to play out with these objects, meant to lead a participant through short narratives of geometric form transformation. Apart from their subject matter, these narratives were seen by Froebel to be similar to the types of songs and games traditionally sung and played by mothers with their children. Froebel saw his work to be, to a large extent, in the same tradition as nursery rhymes. He sets his description of the value of this work in the context of descriptions of spontaneous dialogues between infant and parent. For instance, a parent may sing to a child to communicate her attention and affection, or as a response to a child's interest in language and sound; a parent puts the palms of her hands out against the feet of a kicking child to offer the child something to press against, a way to engage with a responsive environment. The narratives of form description and transformation that he devised were meant to be ways to enliven possibilities for a child's engagement with the materials that he supplied.[M.P. 74]

However, the development of these suggestions for the use of the materials caused his work to take an unexpected turn. Much of what he had initiated and sustained under a protective aura of attitude towards childhood and play, soon ground to a halt in a relatively lifeless set of exercises based on the narratives he
recommended. Concepts initially derived during exploration with his materials were frozen into presentations for how the materials were to be used. These presentations were, unfortunately, widely imposed on children in place of more spontaneous use that would have resulted from play as he defined it. Froebel was working with the question of structure for a child's environment, a question that all people interested in creating learning tools must ask, and it is not at all clear that he had developed in himself a clear answer to it. He considered himself to be in a process of experimentation.

This turn of events happened in much the same way that the attitudes and ideas of Pestilozzi, Froebel's elder and teacher, were developed into object lessons. Object lessons were meant to help a person develop discriminative abilities by the process of mentally extracting attributes from everyday objects and then relating or classifying those objects based on their attributes. This process was also meant to lay a seed for a child's building of conceptual frameworks with which to organize experience. Object lessons instead became a kind of archetypal model for overprescribed guidance, leading to the prospective learner's detachment rather than engagement.

Two things have survived from Froebel's environment. The first is a set of ideas and models about what it means to learn and grow, and what it means to be a child. This includes the idea that environments can be structured with the needs of a child in mind, and be made rich with materials for play and invention. The second is the set of materials he invented and adopted. These materials took firm root in a world in which his clearly voiced description of learning - what has been called a description of the true meaning and value of play - had taken hold.
A Tradition of Materials

By the 1890's there had grown up a new body of educators for whom this definition of play was especially alive, and from them sprang both new materials and new conceptions of the environments that these materials were to be a part of. These people worked to remove the shell of formality that had encased the kindergarten. The prescribed activities were seen as inhibiting to play. One kindergartener said, "a crude, free hand drawing, all finger marks, perhaps, but indicating an effort to express some idea which the child had in mind, would have far more educational value than any number of daintily executed designs, which are mere lifeless copies of teacher's patterns." [N.D. 359] These reformers believed that materials for self-expression could come from many sources, and held Froebel's materials to be somewhat arbitrary, and worth reconsideration.

The new kindergarteners sought to provide for and publicly validate the importance of three neglected aspects of the child's learning environment. One was accommodation for role and fantasy play. Another was time and provision for interaction between children in play. Thoughts on these topics were fueled by ideas coming from the emerging field of psychology and from the educational innovations of the Dewey School at the University of Chicago. These two areas of focus, blended with a re-recognition of the need for an environment that accommodates needs for a child to larger scale physical activities in play, resulted in modification of the kindergarten building materials.

Froebel's materials had by this time been in widespread use for decades. They had first been produced in the United States in the 1870's, when Elizabeth Peabody, a pioneer of the kindergarten movement, inspired Milton Bradley to manufacture them. The first major change in the materials, as part of the work of the kindergartener, Patty Smith Hill, was the enlargement of the building blocks. Beginning in 1895, and continuing for several decades, she experimented with
construction materials, developing a building kit with which preschoolers could build enclosures for themselves. This kit consisted primarily of large boards and slotted corner beams to which the boards could be fastened with pegs. When she added wheels to the set, it was possible for children to make vehicles as well. The wheels were built so that they could also be used as pulleys for cranes and elevators. The *Patti Hill Kindergarten Floor Blocks* were first manufactured by the Schoenhut Company of Philadelphia in 1910, and again by Creative Playthings in the early 1950's.

In 1913 Caroline Pratt developed *Unit Blocks*. These were also derived from the blocks of Froebel. They were heavier and larger than Froebel's blocks, and lighter and smaller than those designed by Patty Smith Hill. Represented among these blocks was a slightly wider variety of shapes, including the cylinder, and curved forms made by cutting through flat rectangular slabs with arcs. Pratt designed them to be "more versatile" than the Hill blocks, and she based an entire early childhood curriculum around them. They were first manufactured by local craftsmen. In the 1930's, they were manufactured by the Educational Equipment Company, and later by Playschool, Creative Playthings, and Community Playthings.

Most non-interlocking building blocks still in common use are essentially the same as the unit blocks. Like Froebel's, they are primarily rectangular or square tablets, with some triangles made by cutting them across diagonals, and include the semi-circles, arches, and cylinders of the unit blocks.

Throughout the years, other materials have been introduced into the culture in which these blocks had been so widely adopted. For instance, about forty years after the development of unit blocks, the following block set was made available to children. It is described here to contrast it to the block sets described above, not because it had a wide popularity. It was special in that with it children were able to come into contact with an interesting assortment of shapes. This assortment included a selection of cones, each with a section trimmed off by a cut at a different angle; a
curved form in the shape of an egg; half of a sphere; a hexagonal and an octagonal prism each in the proportion of column; and two forms with triangular faces meant to represent square and triangular based pyramids. There was one of each of these and some other kinds of shapes in this group, and they stood out as strange special cases in a building world predominated by rectangles.

Where do these shapes fit into the world described by the rectangular building sets? A parent having found this kit, perhaps attracted and fascinated with form, would have had little cultural support to consciously wonder about what they might suggest for different ways to build. The child might love these forms, indeed have come to associate them with parents and home - most of them were foreign to the rest of the child's experience. But for the child there was no context to support considering them as building modules - each was in isolation from other like or similar shapes. Perhaps one form would demonstrate that one of its special attributes, like the curve of its surface, contained special, usually unused functionality as well. For instance, the egg might begin to demonstrate this by the way it rolls after taking off end over end unexpectedly. But it was the primarily-rectangular blocks that were meant to be built with. The others all became special individuals for which special places were made on sturdy, secure, and familiar structures with rectangular block walls and terraces.
A Variety of Ways to Build

Now let us go back to the original work of Froebel. After a description of the kindergarten materials he designed, we will focus on some of these materials and ideas that were not developed to the same extent as the blocks, by him or by other people. We will then look at the derivation of the forms he chose for his blocks, forms that became the model for the tradition of materials just described. In these things may be lessons about how to make materials that will be successful as vehicles for free and fruitful exploration and invention; materials that, by their structure, will suggest this use.

The construction materials and processes of Froebel’s kindergarten had a wide variety. Froebel thought of the materials and activities he invented as a cycle for form exploration: a child would move from play with solid materials towards play with planar and linear ones, and then back through activities involving the child’s reconstruction of planes and solids with points and lines. The objects first introduced were named gifts, the later activities were named occupations. The gifts and occupations are now briefly described.

The first gift is a set of six soft cloth spheres of different colors. Infants and parents could play with them together; perhaps the most significant aspect of this gift is that its manufacture reinforced the value of offering play objects to very young children.

The second gift includes a rack from which hang a cube, cylinder, and sphere. This array of forms was meant to lay a foundation for a child to use to build a frame of reference, or sorting file, in which to incorporate other experience with form. These objects were to be compared in play by touching, dropping, rolling, and spinning them. In one interesting activity, Froebel makes forms visible inside these forms by spinning them. A cube spinning on an axis through two of its opposite faces
shows a cylinder embedded within it; spinning a cylinder on an axis through its curved face causes a sphere inside it to become visible.

Froebel's fascination with the concept of forms implicit within other forms may have been fed by his study of mineral structure. The exterior forms of crystals of a mineral, for instance, are implicit in the shape of the underlying atomic lattice of that mineral. When Froebel was at play with solids, it was as if he looked into a finely grained hypothetical lattice within them to find other forms. This is like when a gem cutter taps on a stone in order to have planes materialize within its invisible atomic structure.

The third through sixth gifts are four small cubical boxes of blocks shaped as cubes, rectangular prisms, and right triangular prisms. The triangular prisms were derived from slicing some of the other blocks along diagonals. One of Froebel's favorite activities with these blocks, and with other kindergarten materials, was to express a concept that can be called non-additive building: the same set of blocks used to make one form could be reconfigured to make another form. In this activity there was an emphasis placed on trying out different kinds of symmetric reorganization, and watching the new forms or patterns that occur. For instance, if cubic blocks stacked tightly together are each rotated around their own centers, the perimeter of the overall form will expand. This kind of play does not seem to have been formalized, or conclusions reached about what it meant or why it might be valuable. However, in an 1868 manual describing uses for the gifts, the author states, "A fresh delight comes to the child when he discovers how one object may be transformed into another, and particularly when there is some connection between each new figure and the child [when the forms produced are representations of actual objects]." [P.C. 116]

The seventh material consists of four types of triangular tablets, and of square tablets with an edge length that makes them compatible with the triangles for arrangement into mosaics or tesselations. Half of the tablets are light hued, and half
dark. Represented are equilateral triangles, halves of equilateral triangles, triangles that are diagonally halved squares, and triangles that are halves of rectangles made from dividing squares. The equilateral triangles in this set of tablets offer the only concretization in the kindergarten materials of non-rectangular based forms beside the sphere and cylinder. "So far the right angle has predominated in occupations with the tablets, and the acute angle only appeared in subordinate relations. Now it is the latter alone which governs the actions of the child in producing forms and figures." Of the categories of patterns that come from this work it is stated, "These are of particular interest because they present entirely new formations." Observation is made that, "To undertake to produce forms of life [representations of objects in the child’s environment] with these tablets would prove very unsatisfactory." [P.C. 158]

The eighth gift consists of sticks of various lengths for laying into patterns and images. These sticks were presented primarily as a way to produce flat linear constructions, but comparisons to the edges of blocks and tablets were also to be made. The writer of the manual quoted above suggests leaving the door open on ways for a child to make this material more appropiable. After stating, "The sticks lead us another step farther, from the material, bodily, toward the realm of abstractions," [P.C. 169] he suggests encouraging "simultaneous occupation with the building blocks", and that the material may be "augmented by the introduction of sawdust to represent foliage, grass, land, moss, etc." [P.C. 172] He also recommends that teachers consider that stick placements can be made permanent with glue, or by binding them together with needle and thread. This creates the possibility of representing solid forms. Together these extensions - augmentation to materials and joining them - might lend less of a feeling of abstraction to work with these materials, making it more interesting or comfortable to a child..

Supplying forms to model, like the cube, is another way of possibly maximizing the extent of appropriation of a building material like this one. Children love to re-create. Froebel writes, "For what a person tries to represent or to do he
begins to understand."[E.M. 76] When evidence is given that models are options and not necessarily the expected results of investigation and construction, then they are at their best. The presentation of models is, however, double sided. Part of what caused the kindergarten environment in the late 1800's to be less of a place for creation and invention than it might have become may have been a feeling in the classroom that in Froebel's inventory of forms all of the important forms were probably represented. Teachers were told of the inventory of the sphere, cylinder, and cube, "Its strongest educational value consists in the fact that it represents the fundamental forms of the universe. The ball is the symbol of the earth, the sun, the moon and all the heavenly bodies. The cube symbolizes the mineral kingdom, and connecting these is the cylinder, which is the prevailing type of animal and vegetable life."[P.C. 87] This was an expression of awe about geometry. A sense of wonder about these forms contributed to their being enjoyed as the sustained focus of attention. But it was also a set of choices that, having been incorporated, became a framework for expectations of how work in form study was to proceed. Enforcement of expectations of what is important, able to be, or should be, can cause a child's attention and interest to split away from the activity. This is certainly what the kindergarten reformers were drawing attention to.

Would another choice of models have contributed less to an underlying feeling of closure, or completion, for both teacher and child, of the process of understanding what may be built? Might another inventory of forms have served as a more effective pointer towards variety and diversity, and generally to a feeling of newness, even in the re-creation of a cube?

Discussion about building with sticks has brought up the topic of creating forms in a different way than discussion of building with blocks did. It is as if sticks have given us the opportunity to make the solid blocks plastic and flexible. By rearranging sticks to join them into new configurations in space we change the shape of the basic building blocks we work with.
Representing things through stick construction means working with certain abstractions: surfaces and volumes are often implied by edges. Allowing free play in an environment rich with materials for constructing things - offering a choice of using either the block forms or the sticks - is offering something more basic than an opportunity for form study; it provides room for a child to choose an approach for working with concepts of abstraction. It is presenting media to use in inventing and discovering a personal sense of what abstraction is, or at least, in this particular case, a personal meaning for the abstraction of volume to lines. Even more essentially, perhaps, this environment offers room to develop a feeling of comfort with the concept of abstraction. This, at least, was a goal of the kindergarteners. An educator wrote in 1868 of the value of constructive materials for children, "... nothing in our whole system of education is more worthy of consideration than the sudden and abrupt transition from life in the concrete, to a life of more or less abstract thinking to which our children are submitted when entering school from the parental house." [P.C. 149] Without a personal approach to abstraction a person becomes divided, working in a realm separate from what that person understands.

To broaden the kindergarten environment as a place to work with the concept of abstraction of form into line, it was suggested that it be demonstrated to children that patterns of sticks could be converted into drawn patterns. The learning environment of Maria Montessori, initiated seventy years after Froebel's, offers strong parallel: Children in her classroom first traced, with their fingers, the edges of thin forms, then the borders of paper cut-outs of these forms fastened onto a surface, then the drawn outlines of these forms. This was part of her work to give children a way to more comfortably gain familiarity with abstractions by allowing them to freely utilize many kinds of sensation. She writes in 1914 that the outcome is that the child, "can connect the concrete reality with an abstraction. The line now assumes in his eyes a very definite meaning; and he accustoms himself to recognize, to interpret and to judge the forms contained by a simple outline." [M.H. 98]
In the kindergarten, the conversion of patterns of sticks into drawn patterns was offered as an alternative to fastening the sticks to make the constructions feel more complete, real, or concrete. Perhaps work with abstraction is, to a large extent, work to find or make a medium in which some idea or process may comfortably and clearly reside.

Froebel’s ninth set of gift materials consists of metal rings and semicircles for laying into patterns. Later, quarter rings were added to this set. Like the sticks, their prescribed use is in creating flat linear patterns. The rings were used as drawing modules, or picture elements. Illustrations show things like leaves, circles, and mandala-like forms, built from these three modules.

Eleven activities follow these nine gifts. These activities are the kindergarten occupations. They are: drawing in chalk upon slate faced with a grid of squares; pricking patterns in paper; embroidering; paper cutting; paper weaving; weaving flat sticks together into flat tension structures; working with an object made from slats jointed at their ends; intertwining paper; folding paper; connecting wires, sticks, or straw in space to build structures by piercing half-dried peas; and building with clay.

The colored cloth spheres, the three hanging forms to be compared and spun, the blocks, the materials for building strut and node structures with peas and sticks, and the clay together comprise the activities meant for exploring multi-directional space; the other work remains more planar or linear. Each of these five artifacts and activities offer interesting vehicles with which to look at space and structure, but only one has taken seed in popular culture until very recently. These were the blocks, whose assimilation into our culture is described above.

Recently another building method has begun to approach an equal prominence. This is the method for exploring space by building out into it with
connected sticks. We have looked at each of the materials that Froebel developed, now we will continue our examination by a focus on this construction method, which he provided for with peas and wires.

To think about this we will look at a set of events that may be seen as the story of a spark of insight carried as an idea in a section of Froebel's materials, and quietly taken up by a preschool child in 1899. By the middle of the 20th century, this child had supplied the design world with a multiplicity of objects and ideas about building that have become the backbone of what has been called a "design science" revolution. The significance of these new objects and ideas is not easy to assess at this time because this work has only recently begin to spread from the domain of a very few people and emerge as a widespread cultural phenomenon. The most frequently produced artifacts of this revolution are the extremely strong-but-light structural grids called "space-frame lattices".

This child was R. Buckminster Fuller. "... the invention [of the space-frame configuration called the "Octet Truss"] can be traced back to 1899 when Bucky was given toothpicks and half-dried peas in Kindergarten. So extremely farsighted and cross-eyed that he was effectively blind (until he received his first pair of eyeglasses a year later), Bucky Fuller did not share the visual experience of his classmates and therefore lacked the preformed assumption that structures were supposed to be cubical. Thus, as other children quickly constructed little cubes, young Bucky groped with the materials until he was satisfied that his structures were sturdy. The result, much to the surprise of his teachers (one of whom lived a long, long life, and periodically wrote to Fuller recalling the event) was a complex of alternating octahedra and tetrahedra. He had built his first Octet Truss - also the first example of what was to become a lifelong habit of approaching structural tasks in revolutionary ways.

"The experience had a great impact on the four-year-old, as he recounted in a 1975 lecture:
'All the other kids, the minute they were told to make structures, immediately tried to imitate houses. I couldn't see, so I felt. And a triangle felt great! I kept going 'til it felt right, groping my way... .'

The truss's omnisymmetrical triangulation distributes applied forces so efficiently that the resulting strength of such an architectural framework is far greater than predicted by conventional formulae." [F.E. 141]

Included in the artifacts being produced in the light of this new kind of building are construction materials for children that represent the first major steps in the embodiment of the strut and node building concept for children since Froebel's presentation 150 years ago. Most of these newer materials seem to be based directly on Buckminster Fuller's building systems; some inventors credit him, and even describe their purpose in distributing these materials to be the spread of concepts that he worked with. These are designed and promoted as ways to offer children materials for work as builders and inventors of emerging cultural phenomena.

The newest of these, when looked at in this way, illuminate qualities in much older materials, and show them as embodiments of parts of the same family of ideas and trends of thought that now are expanding and taking prominence. In 1901 in England, Frank Hornby invented the Meccano construction kit. In 1913 in America, A. C. Gilbert designed the Erector Set, adding gears. In 1914, Tinkertoys were released. In contrast to the system for joining long strut-like construction members with screws, Tinkertoys were simple to assemble and take apart, and could be used by young children. These materials are the most famous of the tradition of materials characterized by their primarily linear members. Some of these kits have an almost equal emphasis on building by joining facings for forms. Examples are Mecanno's inclusion of sheet metal panels and the wall facings for more modern strut-frame construction sets. None of these strut systems were as
popular as building blocks. All of them shared the primarily rectangular building framework of the block sets, although now offering an opportunity to "define" forms of wider variety within this framework.

Two newer linear building kits offer an interesting contrast to these ones and to each other. The *Universal Node System* (or *SuperStructures*, as it was called in 1966), designed by Peter Pearce and described in his 1978 book, *Structure in Nature is a Strategy for Design*, offers an effective guide for studying the world of non-rectangular space. This is achieved by supplying struts and connectors whose shapes lead to the construction of a variety of regular space-filling grids. For instance, if the kit's struts with a triangular cross-section are used, the nodes insure that a lattice of rhombic-dodecahera will be formed; if struts with a rectangular cross section are used, the builder will find that a grid of tetrahedrons and octahedrons is being built, and struts with a square cross-section will come together into lattices of cubes. In contrast, *Geo D-Stix* allows these regular configurations to be built, but does not act as much as a guide. The branches of the nodes are rubbery, so connected struts can vary in relative orientation. This has the advantage of allowing the construction of more irregular forms.

The *Ramagons* kit is another strut and node construction toy. It is similar to Pearce's design tool: it allows building off from nodes in twenty-six prescribed directions. (Ramagon struts are a little more difficult to disconnect, but are sturdier.) It is different in that its two strut sizes do not allow the three interwoven matrices, that appeared with Pearce's, to exist simultaneously in structures. Included as part of Ramagons are snap-on triangular and square panels. What is perhaps most unique about this kit is that its ridged grey struts give it a look that might make it a more likely material for use in fantasy-and-reality play - for building "things" as well as shapes. It is less purely geometric looking than the Universal Node System and Geo D-Stix. Equally inviting for it to be used in this kind of play are panels to which Lego blocks can be joined. This means that this kit has an interface to a generally more familiar construction world. Ramagons are advertised...
as being used at NASA to help in designing space stations. Perhaps this is partially due to the characteristics that make it good for role-playing.

Newest in the progression of linear building materials are those allowing the builder to begin to explore the world of objects where struts do not touch each other, but are connected to each other with strings. Struts and strings are of equal structural importance in this material. A great variety of forms can be built, all of which have the special combination of stability and resiliency associated with this kind of structure.

These building kits are modeled directly on the work of Kenneth Snelson, who built the first of his structures in 1947, and Buckminster Fuller, who worked with Snelson to further develop ideas and methods for this kind of building. Earlier manifestations of string and strut structures were found in the elaborate riggings of masted sailing ships, and in the string supported wings of the earliest airplanes. The mass production of steel, begun in 1851, and the subsequent building of the Brooklyn Bridge with steel cables, in 1883, ushered in the beginning of an era of tensional structures. Because the tensional strength of steel is the same as the load bearing capacity of stone masonry, 50,000 pounds per square inch, tension was finally "brought into parity with compression".[F.E. 246]

*Fantastix*, a simple building toy no longer in production, offers plastic struts about 6 1/2 inches long, each of which is strung with an elastic tendon. Using a few simple building procedures, a great variety of regular and irregular forms with a wide range of complexities can be embodied as "tensegrity" structures: structures in which the tension, or string, elements form an unbroken connection throughout the structure, but the compressive, or strut, elements do not touch.

Structures in which the struts do not touch each other can be extremely interesting looking; we try to understand an interplay of forces as we study them, to understand how the form remains intact. This balance of forces is like our images of
structure at an atomic level, where things don't "touch", but cohere. And it is similar to the way we think of the solar system. After describing how the sphere, unlike the strut, will not buckle if used to bear pressure, Amy Edmondson writes in her book on the work of Buckminster Fuller, "A splendid design! The solar system is thus a magnificent tensegrity: discontinuous compression spheres (i.e., the planets) are intercoordinated - never touching each other - by a sea of continuous tension." [F.E. 247]

She summarizes Fuller's message on this topic by saying that in order to enjoy the fruits of this understanding, "We must abandon our building-block concept of structure in favor of comprehensive solutions which take advantage of the inherent qualities of tension and compression. The latter tends to do the local, isolated structural tasks in nature, while the former specializes in cohering systems over great distances. While we understand that the universe is not structured like a stack of bricks, that awareness has not effected our approach to construction. A "building-block" approach has persisted more or less unchanged for thousands of years, pitting structural bulk against gravity's vigilant force. Instead, argues Fuller, we must think in terms of whole systems in equilibrium, omnidirectional forces interacting in self-stabilizing patterns. If, emulating nature, structural design capitalizes on the integrity of tension, these "whole systems" will prove far stronger than analysis of their separate parts predict." [F.E. 249]
New Forms

Had he drawn more broadly and with more equal representation on the entire range of forms presented to him as caretaker of crystals and minerals at a mineralogical museum in Berlin in 1815, what might have been the effects that the work of Fredrich Froebel would have had on design precedents passed on to the present through his building blocks? What might these effects have been had he offered children, instead of four boxes of cubes and cube divisions, a box of blocks for one of each of the several kinds of regular forms he was familiar with from his study of the structure of minerals? The following is a description of one such imaginary set of block boxes. The block forms are representative of the forms Froebel worked with and discussed.

One box would be a solid mosaic of tetrahedra and ocahedra. Another would be a closepacking of rhombic duodecahedra. A third would be a box of cubes. Other boxes would contain subdivisions made from these different shapes, much the way Froebel supplied four boxes of blocks that are essentially variations on division into cubes. Perhaps these subdivisions would be made to create modules useful for inter-relating the shapes by commonalities that could be discovered in their interior geometries.

Froebel described three categories or aspects of play that could be done with construction materials. The first is play at the construction of objects that are like things that already exist, and includes the most familiar area of block-play: building houses, people, and landscapes. The second is play reflecting a fascination in structure, form, size, and number. It could include sorting or counting blocks, and organizing them in ways that facilitate or embody understanding of these things. The third can be seen as typified by play using both understandings of structure, form, and number, and those gained from play in the reconstruction of existing cultural phenomenon, and this play would be in creating things because of the beauty
they have. These aspects of construction were called by Froebel play at building "forms of life", "forms of knowledge", and "forms of beauty".

What will a child do with a set of tetrahedral and octahedral building blocks? So much of a child's interest in block play is in reconstructing familiar things to use them as backdrops or characters in role playing. These forms are probably not familiar. But the set of materials we are imagining that Froebel made contains rectangular blocks as well; a child would be offered a choice of forms, some familiar and some new and rare. All of them would be found, however, to be functional building materials. Their juxtaposition in the constructive environment would have ensured exploration with each.

The heritage to our culture, eventually so ready to receive Froebel's materials, would have been both an inventory of forms, and a model of rectangular forms that shows them to be one member from this inventory - one of many kinds of forms that may be chosen when a time comes for building. Children would certainly have treated them as such.

Building with a small set of forms causes questions to arise about how to use them. Caroline Pratt's unit blocks were made in a variety of shapes because, for instance, a set of cubes alone does not allow a child an obvious means to build large roofed enclosures. With cubes alone there are also no triangular blocks for modeling peaked roofs. This has been seen as a reason to offer a wider vocabulary of forms in these rectangular building sets than that of cubes alone; standard building sets supply blocks to meet these needs. A child who had decided to appropriate octahedrons and tetrahedrons to build a large roofed house would have a problem similar to that of a child with only cubes: there would seem to be pieces missing to construct a structure that made sense. In this case the child might assume to be missing the forms normally used to make roofs on familiar, rectangular houses, when other forms might actually be more structurally suited to roofing this new kind of building. This has a great deal to do with the nature of blocks. A block kit is
effective as an environment that offers an inventory of shapes to work with, but weak as an environment for inventing forms that could be called forth as solutions to sets of structural design needs not specifically provided for in the set. The block sets of less familiar forms would very likely have raised needs for solutions to unexpected structural design questions.

Froebel offered a means for working out these kinds of solutions; this is in the possibility of the invention and definition of shapes by using struts. It seems likely that the inclusion in the kindergarten constructive environment of unusual forms like the tetrahedron and octahedron would have fed an interest in building and inventing in space with struts.

This new inventory of block forms serves to beg the question, "Where does this set of forms fit into a larger inventory of forms, possibly one including all forms?" Cubes and rectangular forms alone do not cause us to pose this question; they are so familiar, and we have habits of thinking about space in terms of them that can cause us not to ask this question without other stimuli, without other evidence that highlights our assumptions. The inventory so simply presented by Froebel - in the row of hanging sphere, cylinder, and cube, like the inventory of rectangular forms, does not seem to have been strongly enough adopted as a frame of reference to cause this question to be asked in a culturally widespread way.

This is not because Froebel's inventory did not have scope; his inclusion of curved forms establishes scope, and may be its central feature as a catalogue. It is also not because mental cataloging does not happen; when unknown forms are shown to us, if we begin to try to make sense of them, to order them, this larger framework for thinking about form begins to be built.

Froebel's solution to the question of how forms are inter-related was to see these other forms in terms of the geometry of a cube; his framework grew by expanding his definition of a cube. He writes, "Thus the study of the necessary
results of the force acting spherically, and manifesting itself in material crystallization, has revealed to us three bodies, bounded by straight lines and planes, of which the cube is the first, and, as it were, the central one, and the tetrahedron and the octahedron the two derived bodies.”[E.M.177] Fuller’s framework with which to relate these forms is different: “This matrix constitutes an array of equalilateral triangles that corresponds with the comprehensive coordination of nature’s most economical, most comfortable, structural interrelationships employing 60-degree association and disassociation.”[F.E. 130]

It is interesting to wonder whether more play with his own pea-and-wire building materials might have lead Froebel to a like conclusion. What he did instead was to offer a tool, for it to be taken up by another person to continue thought about forms, including ways to find and inter-relate them, through the process of constructing them.

Fuller was able to place almost all of the possible regular and semiregular polyhedra in the matrix he discovered. Additionally, those that did not have homes in this matrix became highlighted as unique, inviting special focus to be put on them. Most notable of these is the twenty-triangular-sided icosahedron. To describe its place outside of this matrix, Fuller says, “The vector equilibrium railroad tracks [of the matrix] are trans-Universe, but the icosahedron is a locally operative system.”[F.E. 229], and he examines this form to utilize its special force distribution capabilities. The icosahedron is used as the basis of most of the thousands of domes that have been constructed around the world on the model of Fuller’s work. His matrix is used as the structural fabric for many of these domes.

While thinking about these things, the thought might come, "But I don’t see icosahedrons lying on the ground. After all these ideas about them; aren’t they, as intuition tells us, anomalies without much use for us?" A second thought follows, "I don’t see any cubes on the ground either." To a person in such a state, all of the rectangular houses by the side of the road have suddenly begun to look a little funny, and the feeling comes, "This is planet earth in the 20th century, where most houses..."
are rectangular." Working with materials like the Universal Node System or Fantastix, new information is available for us to think with.

Work constructing space-frame structures, like the pea-and-strut work, make the cube's relative position of importance in our architecture and thinking seem rather arbitrary. However, in the kindergarten, this work went on under some strong models reinforcing the image of cubes and rectangles as the basic constituents of space. A learning environment at odds with itself had been set up: There was, to a certain extent, both an invitation for invention and personal expression while exploring form, and an unspoken convention about what forms were important.

The triangular tablets of the seventh gift offer another example. A child's work with its equal sided triangular tablets had the potential to be truly revelational. A child's time in the kindergarten was in all probability the only time that child ever was offered and encouraged to play and build with triangles. If there was anything for a child to experience, discover, or express in such play, this was a unique opportunity to do so. However, built into this environment of objects was the suggestion that these triangles actually constituted their own world and that this world of triangles was a small one, embedded in but somehow not part of the more real world of rectangular forms. This suggestion was strong because of the great dominance of rectangular forms in an environment recognized by its inhabitants, on some level, to have been designed for form exploration. The model affected the children in a twofold way: once through their observations of these objects placed around them, and once through the direction they received from their teachers, also at work under the influence of this model.

"Fuller decided that through sufficient observation of both naturally occurring and experimentally derived phenomena without reference to a specific framework, nature's own coordinate system might emerge." [F.E. 9] He observed both those things that he found in the world, and those that he put there, with a
feeling that to keep working fruitfully he would not entirely hold himself to the understandings he had of these things. New discoveries were meant to create new frameworks; models for what was possible were to be updated frequently.

Models may on a certain level inspire exploration but do not need to be studied themselves, do not need to be "starting points" for a line of exploration. Often work more intuitively directed will lead to the reconstruction of those models from the inside out, as special cases arising from work with more general principles. "I did not copy nature's structural patterns. ... I began to explore structure and develop it in pure mathematical principle, out of which the patterns emerged in pure principle..."[F.E. 239]

This is not mean to suggest that in order for a child to feel successful, an entirely new form must be discovered by the child. A person's progressive "invention" of partially known things is one way to look at how learning happens, and is part of the work of building from a model. The point that seems to have been made by the development of the kindergarten is that provision for the acceptance and valuing of original work, and for the creation of new models, is essential to a learning environment in which this re-creation of things can live.

Valuable tools for allowing the experience of discovery and invention have been supplied through the early kindergarten environment, and they sometimes bore visible fruit. Their functionality was, however, invisibly negated to a certain degree by a lack of an environmental context that said more strongly, "new forms that you might create are really as much about the world, and at least equally as useful to it, as the models we supply you with."
Polydrons, Bristle Blocks, and other Joined Surfaces

Froebel's materials covered and defined a large range of possibilities for ways to build. Because of this, it is interesting to find gaps in this inventory. One such gap is the lack of a joining method for panels like the triangular and square tablets of his seventh gift, that would have allowed them - like the peas and struts - to be brought off of the flat plane of the tabletop, and into play at the discovery of forms in multi-directional space.

It is also interesting to note that the final goal of most building is towards the creation, not of solids, or lattices of struts, but of space compartmentalized by surfaces. Thus there is a special satisfaction to be found in building with constructive panels.

Since the time Froebel helped plant the seed that a child understands by inventing, many other building toys have been made for children. Some of these toys, looked at together, describe generally less popular but evolving precedents for ways to build objects. One of these ways of building is with linear elements, from the flat metal Meccano struts meant to be joined with screws, to Fantastix and Tensegritoy kits, in which struts are suspended from each other by strings to form a wide variety of sturdy, stable, and resilient structures in which the struts do not actually touch each other.

Now we will consider a variety of toys with which things may be constructed from planar building elements. We will also look at an interesting reoccurrence and variation on a joining method that accompanies instances of planar construction toys.
In the 1860's, a log cabin toy was manufactured in Springfield, Vermont. The pieces of this toy interlocked in a way similar to the way those of a full sized cabin interlock. Lincoln Logs, a later version of this toy, was designed in the 1930's by John Lloyd Wright (son of the architect, Frank Lloyd Wright, another person strongly influenced in childhood by the work of Froebel), and manufactured by Playschool. This system represents an early instance in an evolving stream of joining systems for building kits. When gravity was no longer the only way to keep them together, construction toys had begun to move out of the realm of "blocks". Lincoln logs can be seen as a construction kit that lives in the area between these types of joining; it relies on gravity to pull it together against the earth, and uses notches to keep the walls vertical, allowing gravity to continue to be utilized for this purpose.

In 1867, Charles Crandell invented several toys using a finger joint that he originally devised for the corners of boxes for toy croquet sets. The interpenetrating arrays of fingers, like rows of mortices and tenons, held the pieces together by friction. It was as if the Lincoln logs comprising one wall of a small building had been glued together, and their wide tips removed. Two such walls could now be slid together at their ends, and the angle between them varied.

In 1874, W. E. Crandell designed and patented building blocks which were precursors to the Lego units developed in plastic by Gottfried Christianson in Denmark almost sixty years later. This joining system could be described as a finger joint in which the "fingers" do not extend only from edges, to interlock with the fingers of another module, but reach out from its entire surface. This allows greater variation in the relative placement of blocks to each other, which now stack flat instead of being connected at edges to form larger surfaces. However, the ability to hinge, to remain both interlocked and able to change in relative orientation, is lost; solid objects rotate around lines, not planes. Joining face to face was carried further in the 1970's with English Stickle Bricks and American Bristle Blocks, manufactured by Playschool in 1976. Here the greater part of the object is
comprised of its joining mechanism, and blocks feel like they are merging as well as connecting on surfaces.

To this general category of joining method, we add perhaps its most popular embodiment: Velcro. Taken to an opposite extreme from bristle blocks - becoming a thin connection space that can be applied to unrelated surfaces - and additionally translating fingers into springy hooks and loops, this is what we have. Velcro is used on a construction kit for configuring gears onto a flat surface without the constraints of a specific grid size that might be used in pegging the gears in place.

Currently several companies produce building modules that interlock with variations on the older finger joint - the one along edges that allows hinging. In contrast to Velcro, there might be as few as one or two fingers, or tenons, on each of these edges. Most notable of these are Polydrons, and the Waffle Block like modules. Polydrons are colored triangular, square, and pentagonal panels about 2 1/2 inches in length that can be joined into flexible mosaiced sheets defining complex curved forms. The hinging at the joining place, and the characteristic of sheets of polydrons to be able to be "unzipped" along lines running through the mosaic, make this material one in which the builder can easily change direction and configuration, revising or adding to building plans in a relatively impromptu manner. The emphasis on triangular modules allows a tremendous increase in the variety of forms that can be built. In combination with the squares, the triangular panels of Polydrons can be joined into large curved surfaces.

An interesting feature of Waffle Blocks is their ability to have edges of panels join to the faces of other panels. To allow for this, some of the Waffle Block panels have a grid of square holes in them (thus the name, Waffle Blocks).

Waffle Blocks come in large sizes as well as small. Snap Land panels are even bigger and allow the construction of forms that children may get inside and climb on. Comparing these panels to polydrons makes the degree of form versatility
that is provided for by the inclusion of Polydron-like triangular panels apparent. Polydrons the size of Snap Land panels would allow children to build a very large variety of "little houses"; large triangular panels seem to be due soon.
María Montessori, born in 1870, writes in her 1914 book, Spontaneous Activity in Education, of her first experiences with some materials she had brought to preschool children in 1907. These materials had been designed for work with children with learning difficulties, and she had used them for many years in that way. She was a doctor (the first woman in Italy to become an M.D., in 1896), and had an interest in child development. She had turned her time to research based on observation of children. In 1907 she had been given the task of establishing newly conceived child care centers that were to be part of large housing developments for low income families in Rome. She was beginning her essays in applying to this new setting the principles and some of the materials from her past experience.

"I happened to notice a little girl of about three years old deeply absorbed in a set of solid insets, removing wooden cylinders from their respective holes and replacing them. The expression on the child's face was one of such concentrated attention that it seemed to me an extraordinary manifestation: up to this time none of the children had ever shown such fixity of interest in an object; and my belief in the characteristic instability of attention in young children, who flit incessantly from one thing to another, made me particularly alive to the phenomenon." [S.A. 67]

"I counted forty-four repetitions, when at last she ceased, it was quite independently of any surrounding stimuli which might have distracted her, and she looked round with a satisfied air, almost as if awakening from a refreshing nap." [S.A. 68]
On the basis of continued observation she wrote, "Those children who have long been occupied with these [experimentally] determined objects, showing every sign of absorbed attention, will, all of a sudden begin to rise gradually and insensibly like an aeroplane when it completes its short journey upon the ground." [S.A. 78]

"It made one think of the life of man which may remain diffused among a multiplicity of things, in an inferior state of chaos, until some special thing attracts it intensely and fixes it; and the man is revealed unto himself, he feels that he has begun to live." [S.A. 69]

Her conclusion of the extent to which, "Psycological development is organized by the aid of external stimuli." [S.A. 69], is based on the consistency with which she found this sequence of events repeated in her classrooms.

What was it about the above material that made it so attractive to a child? She describes the object that had so strongly held this child's attention: It was a block in which solid geometric forms were set. Into corresponding holes in the block were set ten little cylinders, the circumferences of which vary to form a fine gradation of change. "The game consists in taking the cylinders out of their places, putting them on the table, mixing them, and then putting each back in its own place." [M.M. 169]

To Montessori, the interesting thing about this material was that children seemed to be absorbed with it, first, because by its structure it implied a task to be accomplished, and second, because this structure left no doubt for the child as to whether that task had been accomplished yet, and even offered clues as to the status of the sorting work while it was being carried out. If a cylinder was found to have no place in which it seemed to fit, this was because another must have been put in its place. The child would try a different arrangement. Because of this "dialogue", the object seemed to define for the child a special, distinct place in the classroom,
seemingly set aside for independent play that could be completed uninterrupted.

Montessori believed that work with these materials was causing the formation of a stable launching ground for continued engagement of the powers of a child, powers moved into a greater state of organization: "The aviation ground is not the sphere of action proper to the aeroplane, but it is the part of terra firma necessary for flight ..." [S. A. 81] This activity had been a "starter" or a "renewal" for the experiences of engagement and success. "The phenomenon of discipline needs as preparation a series of complete actions ..." [M. M. 350] "The first dawning of real discipline comes through work. At a given moment it happens that a child becomes keenly interested in a piece of work, showing it by the expression of his face, by his intense attention, by his perserverence in the same exercise." [M.M. 350]

Montessori worked to create an environment made for children; she called instances of this environment "children's houses." They were to offer nourishment for a child's psychic development. But they had another aspect as well: she meant them to offer a haven for a child. Her descriptions of the process of child development are framed with the idea that often adults are at odds with what are actually essential needs to a child. The establishment of an environment of objects was meant to be the beginning of the construction of a place where children were able to chose their own workspaces, away from the influence of presuppositions by adults as to what is important for a child. "We must wake up to the great reality that children have a psychic life whose delicate manifestations escape notice and whose pattern of activity can be unconsciously disrupted by adults." [S.C. 133]

With the following words, Montessori offers a strong image with which we may better understand her meaning. "Let us imagine to ourselves certain adults, not mature and stable like the majority of grown men, but in a state of spiritual auto-creation, as are men of genius. Let us take the case of a writer under the influence of poetic inspiration, at the moment when his beneficent and inspiring
work is about to take form for the help of other men. Or that of the mathematician who perceives the solution of a great problem, from which will issue new principles beneficial to all humanity. Or again, that of an artist, whose mind has just conceived the ideal image which it is necessary to fix on canvas lest a masterpiece be lost to the world. Imagine these men at such psychological moments, broken in upon by some brutal person shouting to them to follow him at once, taking them by the hand, or pushing them out by the shoulders. And for what? The chess-board is set for a game. Ah! such men would say, "You could not have done anything more atrocious! Our inspiration is lost; humanity will be deprived of a poem, an artistic masterpiece, a useful discovery, by your folly.

"But the child in like case does not lose some single production; he loses himself. For his masterpiece, which he is composing in the recesses of his creative genius, is the new man."[S.A. 22]

"If the child is to be treated differently than he is today, if he is to be saved from the conflicts that endanger his psychic life, a radical change, one upon which everything else will depend, must first be made; and that change must be made in the adult. Indeed, since the adult claims that he is doing all that he can for his child and, as he further declares, he is already sacrificing himself out of love for him, he acknowledges that he is confronted with an unsurmountable problem. He must therefore have recourse to something that lies beyond his conscious and voluntary knowledge."[S.C. 18] Words of Fredrick Froebel from 1826 strike a harmonious counterpoint: "Let us all, Fathers and Mothers too, be candid for once and confess, that we feel mental wounds ... hardened spots in our hearts ... dark places in our intellects ... and all this because noble human feelings, and thoughts natural to childhood, were crushed or lost, chiefly through early misdirection. It would be a blessing to our children if this confession can be made and acted on. ... it were better to turn back to that beginning, to childhood even, than finally to miss what could yet be recovered."[E.M. 329 - 330]. For a person somehow at work directed to this end, the presence of children can be a boon: "... the psychical manifestations of
children evoke something more in him than interest in phenomenon; he obtains from them the revelation of himself, and his emotions vibrate at the contact of other souls like his own.\[S.A. 135]\n
How can a person "unconsciously" at odds with the needs of another, build an environment such as the one Montessori worked towards? She describes the first children's house: "We started by equipping the child's environment with a little of everything, and left the children to choose those things they preferred. ... A child chooses what helps him construct himself.\[A.M. 223 - 224\] "There was no method to be seen, what was to be seen was the child ... The first thing to be done therefore, is to discover the true nature of the child and then assist him in his normal development." \[S.C. 166 - 167\] In order to do this, "the teacher must bring not only the capacity, but the desire, to observe natural phenomena ... She must become a passive, much more than an active, influence, and her passivity shall be composed of anxious scientific curiosity, and of absolute respect for the phenomenon which she wishes to observe."\[M.M. 87\] Finally, she writes. "The teacher, when she begins to work in our schools, must have a kind of faith that the child will reveal himself through work."\[A.M. 276\]
Access through all of the Senses

"The method used by me is that of making a pedagogical experiment with a didactic object and awaiting the spontaneous reaction of the child."[M.M. 167] "... the children were given special materials with which to work. They were attracted to these objects which perfected their sense perceptions, enabling them to analyze and facilitate their movements. These materials also taught them how to concentrate in a way that no vocal instruction ever could have."[S.C. 168]

Montessori had a strong feeling for and belief in the value of offering children means to most fully utilize their many sense capabilities for understanding things. She developed specific exercises directed to each of the senses - including smell and taste. She included in this array exercises that were directed to facilities like sensitivity to temperature variation and to the weight of objects.

For instance, she wanted the school curriculum for children to allow them to touch and move objects. She observed that children often take pleasure in the recognition of objects by touching them. She writes, "Many psychologists have spoken of the stereognostic sense, that is, the capacity of recognizing forms by the movement of the muscles of the hand as it follows the outline of solid objects. This sense does not consist only of the sense of touch, because the tactile sensation is only that by which we perceive the differences in quality of surfaces, rough or smooth. Perception of form comes from the combination of two sensations being sensations, tactile and muscular, muscular sensations being sensations of movement."[M.H. 104] She says, "It is the special muscular sensibility of the child from three to six years of age who is forming his own muscular activity which stimulates him to use the stereognostic sense."[M.H.105] Montessori supplied materials to these children, meant to be a help with this development. "There are many exercises which he can do to enable him to recognize with closed eyes objects of well defined shapes, as, for example, the little bricks and cubes of Froebel, marbles, coins,
beans, peas, etc. From a selection of different objects mixed together he can pick out those that are alike, and arrange them in separate heaps."[M.H. 105]

In the materials she designed there are, "**geometric solids** - pale blue in color - a sphere, a prism, a pyramid, a cone, a cylinder. The most attractive way of teaching a child to recognize these forms is for him to touch them with closed eyes and guess their names, the latter learned in a way which I will describe later. After an exercise of this kind the child when his eyes are open observes the forms with a much more lively interest."[M.H. 106]

Another material is a set of triangles. Children fit triangular cut-outs of different shapes into matching openings. Much the way they sorted cylinders by size, they sort triangles by shape. Other sets of triangles are offered to very young children as units with which to build other shapes, like quadrilaterals and hexagons. When a teacher first presented one of these materials to a child, she would demonstrate how the perimeters could be traced with the fingertips. This was to encourage the use of one of the child's facilities. "... among the various forms of sense memory, that of the muscular sense is most precocious. Indeed, many children who have not arrived at the point of recognizing a figure by looking at it, could recognise it by touching it, that is, by computing the movements necessary to the following of its contour. The same is true of the greater number of children; - confused as to where to place a figure, they turn it about in vain to fit it in, yet as soon as they have touched the contours of the piece and its frame, they succeed in placing it perfectly. Undoubtedly, the association of the muscular-tactile sense with that of vision, aids in a most remarkable way the perception of forms and fixes them in the memory."[M.M. 198]

Montessori wanted to offer a child the choice for how learning would happen. She did not want assumptions about what methods or powers were most effective to hide more direct and natural methods with which a child could work. She wanted instead to provide for the opportunity for a child's access to the nature of the
world by means of any of the senses that the child might wish to utilize.
Sensitive Periods

A concept that helped Montessori to keep an open mind with which to consider the suitability of materials for the environment that she was preparing for children was that of "sensitive periods". She describes a child's ability to become interested and engaged with one thing or another as being connected with particular needs and abilities that arise in a child at particular times. These are both strong and transient. "A sensitive period refers to a special sensibility which a creature acquires in its infantile state, while it is still in a process of evolution. It is a transient disposition and limited to the acquisition of a particular trait. Once this trait, or characteristic, has been acquired, the special sensitivity disappears. Every specific characteristic of a living creature is thus attained through the help of a passing impulse or potency."[S.C. 46] Montessori observed children in an attempt to understand these special sensitivities so that she could structure the environment with especially appropriable materials.

"A child learns to adjust himself and make acquisitions in his sensitive periods. These are like a beam that lights interiorly or a battery that furnishes energy. It is this sensibility which enables a child to come into contact with the external world in a particularly intense manner. At such a time everything is easy; all is life and enthusiasm. Every effort marks an increase in power. Only when the goal has been obtained does fatigue and the weight of indifference come on."[S.C. 49]

A wide enough variety of materials in her classroom would allow children to choose what was of interest to them, and thereby begin to describe the nature of these periods. "When one of these psychic periods is exhausted, another is enkindled. Childhood thus passes from conquest to conquest in a constant rhythm that constitutes its joy and happiness."[S.C. 49]

For example, one well known sensitive period has to do with language
acquisition. Between the ages of two and six, a child is daily learning new words at a remarkably high rate. The naturalness and spontaneity with which this happens can feel both wonderful and astounding. Montessori describes an early stage in the period of language sensitivity with the following narrative: "As different sounds play chaotically about a child's ears they are suddenly and distinctly heard as something charming and attractive, like the sounds of an unknown language clearly pronounced. The soul which is still without thought hears a kind of music that fills its world. ... The only thing that can make us appreciate the sensitive state of the child is his smile, the joy he manifests when he is addressed in short words clearly spoken, so that he can distinguish the various sounds like the tolling of bells in a cathedral tower." [S.C. 52 - 53]

Another sensitive period is connected with interest in the relative placement of objects. "That order produces a natural pleasure may be seen from the type of games played by very small children. They surprise us by their want of logic. The sole pleasure they afford is that of finding objects in their places. Before illustrating this further I should mention an experiment made by Professor Piaget in Geneva with his own child. He hid an object under the cushion of a chair and then, sending the child out of the room, he took the object and placed it under the cushion of another chair opposite the first. ... The child was not interested in finding the object, but in finding it in its place. He obviously thought that it was the professor who did not understand the game." [S.C. 66 - 67]

"... nature endows a child with sensitiveness to order. It is a kind of inner sense that distinguishes the relationship between various objects rather than the objects themselves. It thus makes a whole of an environment in which the parts are mutually dependent. When a person is oriented in such an environment he can direct his activity to the attainment of specific goals. Such an environment supplies the foundation for an integrated life." [S.C. 68]

Montessori gives an example of a sensitive period that might be a little
harder to define. "From the beginning of its second year a child is no longer carried away by gaudy objects and brilliant colors with that transport of joy so characteristic of the sensitive periods, but becomes interested in tiny objects that escape our notice. We might even say that he is interested in what is invisible, or at least in what is found on the fringes of consciousness.

"I noticed this sensibility for the first time in a little girl fifteen months old. I heard bursts of laughter coming from her in the garden, quite unusual for such a small child. She had gone off by herself and was sitting on the bricks of the terrace. Nearby was a magnificent bed of geraniums blooming under an almost tropical sun. But the child was not looking at them. She had her eyes fixed on the ground, where there was apparently nothing to be seen. I was confronted by one of those childish whims that can be so puzzling. I went up to her slowly and looked carefully at the bricks without being able to see anything in particular. Then the child explained to me in almost measured tones, "A small thing is moving there." Helped by this remark I saw a microscopic, almost imperceptible insect of practically the same color as the bricks running with great rapidity. What had struck the child's fancy was the fact that there was such a small being and that it moved and even ran!" [S.C. 80 - 81]
Prototypes
for a
Constructive Fabric
Goal

Certain things feel very liberating to use. In this thesis I have been looking at building kits that allow ways to build and things to be built that have been especially delightful, satisfying, and engaging to me. As my hands moved these materials, as my fingertips touched them, and as they became parts of forms that I could touch, I felt myself becoming active, alert, and rested in a world more visible to me and in which I felt more of a sense of home.

Work to embody certain concepts has had a similar effect. A concept that I am working to embody is that of the fluid transformation of form. I am working to establish a means to create a class of flexible objects, objects that would be able to flow and melt from one form to another. With this aim, I have been creating models that come successively closer to this goal.

What was once an idea for work to build a structure whose parts could be set to gradually change their relative orientations to define either a tetrahedron, a cube, or a form with some attributes of both, while always keeping its volume constant and edges and faces taut, in a kind of flowing or melting motion, has, by repeated phases of modelmaking and simplification, begun to turn up means that are successively more applicable to the creation of transformable objects in general.

Through modelmaking, the form of the goal I am working towards has become clearer. I envision what can be called a constructive fabric. This fabric would have the following traits: It is to consist of modules whose size and shape may both be changed and set to change by the person using it. These modules are to be, primarily, triangular panels. It is planned that interconnections between unit panels will allow a person to make specifications for shape transformation to effect groupings of these panels, causing them to change as a single unit, without the necessity of specifying the task that each panel is to take in this transformation.
In the following section will be considered traits for a triangular building module that contains some of the functionality needed for it to be a module for such a fabric.
Shape-Changeable Triangles

"Plato was apparently the first person to attempt a geometrical description of structure in nature. He also explored the possibility of developing an inventory of basic geometric shapes (in this case, right triangles) which could be recombined to form the five regular polyhedra. Plato's insights anticipated the concept of modular structures built up from elementary constituent parts."[S.N. 2]

Shape-changeable triangles have edges of variable length which are hinged together. At each vertex is a snap with which a triangle may be joined to other triangles. These triangles embody part of the functionality of the building material I have described. Working with them it is possible to get a feeling for some of what this kind of construction has to offer.
Comparing these building modules to the modules of some other building materials will help to understand them. A comparison to Polydrons is a good starting place.

It is possible to construct interesting forms with Polydrons partially because of the shapes of its panels. Its equilateral triangles create a potential for a tremendous diversity of forms to be built. This advantage over squares can be seen by thinking about the number of triangles that can be joined to form a single vertex. Three triangles together form the corner of a tetrahedron; four, the corner of an octahedron; five an icosahedron. Six together form a flat surface. With squares, there is only one configuration that does not form a flat surface: three squares form the corner of a cube. This means that all shapes made entirely of squares consist of a combination of flat surfaces and this one kind of corner; shapes made from triangles can contain the three types of corners described, as well as many variations made possible by the way the triangles are hinged together.
This hinging is a central feature of Polydrons. A builder can adjust the orientation of two panels without unsnapping them from each other. Without the need to disconnect and reconnect repeatedly, impromptu experimentation and reconsideration is more comfortable, and therefore more likely.

One of the nicest features of a Polydrons kit is simply that it is a way to build surfaces. Complex volumes can be clearly described with these surfaces. There can be, partially because of this, a feeling of having made something that is not so much a model of something as it is an "actual thing." This is due to the fact, as noted earlier, that the purpose of almost all of the building we are familiar with is to partition or enclose space with surfaces. When we build with blocks or struts there may be a feeling, to one degree or another, of overcompleteness or undercompleteness in relationship to the familiar world of houses and vehicles.

The simplicity of Polydrons make work with them enjoyable for a number of reasons. Their obviousness is one: once you discover how to put two together there
is little else you need to know, but there is a great deal to find out. Another thing that the simplicity of Polydrons affords them is beauty: working with them feels like working at a folk craft, they feel like a "natural" medium. In their simplicity, they are also very durable: there are few construction toys that are as impervious.

Now we look at shape-changeable triangles:

The diversity of forms that can be built from the single shape-changeable module is very great. The size and shape for unit triangles can be chosen by the builder. The diversity of form afforded by the equilateral triangles of the Polydrons kit makes them a magnet for exploratory tendencies and provides an opportunity to build, disassemble, and rebuild a whole class of forms that are normally only found in interesting geometry books; they are brought onto the floor of a child's room. Adjustable triangles go a step further, and allow the builder to establish a firsthand context for the place that these forms hold in a wider, less known inventory of forms.
The hinging method I have chosen for these triangles allows an adjustment ease for relative orientation of neighboring modules that is similar to that of Polydrons. Additionally, more than two triangles can be joined at an edge. While a shape-changeable triangle is swung on its hinge, it can be expanded, contracted, or leaned to one side or another, as the builder tries out different ways to place it.

While we are on the subject of the joining mechanism, it is interesting to compare an adjustable triangle to a Lego block. When they are in proximity of each other, a correspondence occurs between the array of cylindrical snaps on the top of a Lego block, and the three snaps at the tips of the triangle. The triangle looks like a Lego block whose joining places have been allowed to move in relationship to each other. It is as if redundancy was taken away from the Lego block, so that instead of having a joining place waiting everywhere on it, for the eventuality that another block might be positioned there, it has a few joining places that can be moved where they will be needed. The whole form of the module reflects the needs of the moment, and there is no reason for it to remain as one particular shape.
These shape-changeable triangles are, at this stage of their development, missing a very important feature: they do not have surfaces. I am currently investigating ways to face them with fabric so that their forms can be changed while at the same time taut, complete surfaces are maintained on them. If this proves feasible, it will probably involve having fabric being drawn in and released from the inside of the panel when it is needed. This is very high on the priority list for work on this material.

By their nature, shape-changeable panels can not be as structurally simple as Polydrons, but they might feel as simple if an economy of structure matches the functionality well. It is likely that impressions of their functionality would outweigh those of their necessary complexity, and that they would feel simple.

Lastly: A very important feature to give these panels is one that would allow them to be moved easily into certain configurations. For instance, it should be easy for a builder to establish an equilateral triangle. Builders should also be able to
record triangle configurations of their choice with this mechanism, to be able to
easily reestablish them at another time. This might be possible with a mechanism as
simple as one allowing changing edges to "click into place." It might be useful to also
connect special sounds with the adjustment of a triangle's edge lengths. A different
quiet tone might sound whenever certain prechosen lengths were reached. The
construction activity would be greatly enhanced by cueing like this.
Building at a Lower Level

The mechanism pictured here and on the next pages was built to allow an arrangement of strings and struts to gradually change from a configuration defining a tetrahedron to one defining a cube. The volume was to remain constant throughout this transformation. In order for these elements to move in this way, strings are pulled in some places and released in others according to a fairly complex set of specifications. For instance, for an edge to get shorter, the string that defines that edge is drawn up elsewhere in the mechanism. During the transformation, all of the edge lengths are simultaneously lengthening or shortening according to these specifications. The strings defining these edges travel in through the vertices, along the struts, and then into tubing that runs out to the source of these instructions: At the end of the tubing each string is looped over a curved piece of wire. When this wire is slid past the area that the string emerges from, its curve
causes the string looped over it to be pulled up or let out. The curve of the wire determines how that string's edge length will change.

For the cube to become a tetrahedron of the same volume, four of its edges shorten until they disappear, while the remaining six increase in length.

There are two special concepts that have taken form in this object. The first is that the specifications for its transformation may be put into a set of curved wires; and that changing the curve of the wires will cause different requests to be made of the structure when the wires are pulled through the form's "keyhole": The form is programmable.

The second point of interest is about the structural system used to describe a transforming shape. This object has tensile bonding between its elements: struts push on strings, strings pull on struts; the struts are configured by a structural net of strings, this net of strings is supported in space by the struts. This arrangement
is what enables the flexibility of the form and its ability to respond to specifications for reconfiguration so fluidly. The struts are floated into desired positions by adjusting the strings from which they hang from one another. The constraining net of strings changes its interior configuration, and the struts pushing against this net change orientation.

This solution to the question of how to make a form flexible evolved through modelmaking. I was able to discover this kind of structure on my own as I worked with more effective and simpler means to meet these goals. It was as if the set of requests I had made of "the nature of things" necessitated a very specific answer; specific in that, to a higher degree than usual, what was not essential to the situation was not there in the answer. Apparently, the excess of compression components (like the struts) normally included in building were getting in the way as this kind of flexible structure was being built.
One area of great interest to me is in finding means with which to more
naturally and simply determine, record, and transmit specifications for complex
form transformation. For instance, in order to build this model I needed to
determine a selection of edge lengths for the form, then convert that information
into bent steel wires sheathed in translucent Teflon tubing. The first discovery made
while trying to answer the question of how to embody fluid transformation of form
was the concept of programmability, the second, tensegrity. Perhaps this question
will once again lead to gold, while working with ways to determine, record, and
transmit complex form change specifications.
Specifying Form Change with a Program

Pictured above is an adjustable triangle to which is connected a motor. This motor can be plugged into a computer, by which it may be turned on and off and its direction reversed. Turning the motor on causes the edge it is attached to to increase or decrease in length.

Imagine that a switch has been made so that, depending on the instructions that come out from the computer, the motor may cause any or all of the three edges of a triangle to change in length. Procedures could then be written like to equilateral, to scalene, or to scale-change.
Now imagine four adjustable triangles connected to make a tetrahedron. Each would have the functionality described above. What happens if one of these interconnected triangles is directed to change in shape? If it changes an edge length, then its neighboring triangle who shares that edge of the tetrahedron with it, will also change. To program these triangles, we are invited from the start to begin to think of rules for the way groups of triangles change together. An example of a rule like this might be, "If the edge of the triangle next to you is going to change, then you change with it. Activate your motor in order to help and not hinder the transformation". Or a rule might be, "Finish the shape transformation you are engaged in, then respond to your neighbor with rule one." This rule could easily lead to conflicts. This offers a way to think about and develop rules for dealing with conflict resolution.

Larger mosaics of modules offer other kinds of ways to look at form transformation. This could involve trying out rules for having change in module shape spread in different kinds of patterns through the mosaic.
Most interesting perhaps would be the level of form direction where very general qualities of the object could be specified. A closed fabric of panels could be directed to become rounder, or flatter.

Finally, forms could be directed to move across the room. It is easy to imagine a tetrahedron doing this: It could lean to the side until it fell over and pivoted onto a new face, and then repeat this process moving in a regular sequence around its circumference of faces.
Thoughts about
A Constructive Environment
A Model for Making Models

When we looked at the original kindergarten materials we saw how models with the potential to inspire exploration of form had become instead the presupposed end products of that exploration. Materials were supplied with which to explore, but a strong model was given in the classroom, directly and indirectly, as to what the "important" results of that exploration would be.

In a constructive environment that I imagine, shape-changeable panels, and variable length struts would be available as a model for variation. Imagine that a child is building a structure. The child picks up an adjustable panel and immediately and instinctively begins to alter its shape. The child's hands are already moving, trying out shapes while, eyes fixed on the structure, the child is looking to see what shape seems good to add to this structure now. Specific structural needs can be met by squeezing and pulling the triangle, and combining it with other triangles, and then putting it in place.

This is qualitatively different from working with the kindergarten struts. The important difference is elusive, even though some differences are quite apparent. When comparing the two, it can be seen that with the struts, a child moves to put them in place, or to remove them, but between these motions, there is nothing in the child's hand to think with that mirrors the mental process of trying things out.

Of course the material difference is very great too: it is now easy to create new shapes to work with. This might show itself in very free-form building, or it might arrive more quietly in the work of a child who has been building with triangles in equilateral configuration and decides one day to try out variations in the panel shape.
It seems that the desire to be able to change the shape of many modules at once would grow naturally out of this activity. "If all of the triangles got small at the same time, then the whole form would get small!", "If they all get half as large as they are, then the whole large form will get half as large as it is!"

Automating a single adjustable triangle could be distancing from the feeling of the change; it "makes telling about doing" become the means for doing. A level of abstraction is added to an otherwise very directly sensoral, bodily process. On the other hand, the ability to embody or carry out complex specifications for the change of objects normally not even seen, seems as though it might have the effect of making a feeling of concreteness about things become lively and strong.
The Computational Trellis

Peter Pearce describes the advent of new ways of building, and what he sees as the things that are making this possible. In his description, it is as if the new space frame structures are growing on a kind of computational trellis. What I mean by this is that the complex structures of these buildings could not have been built without their preconstruction as computer simulations. After the concept has been modeled, the building can be built on the basis of that model.

"One reason for the slow development of space frame technology during the earlier history was the lack of adequate analytical tools necessary to design and engineer space frame structures and exploit the potential of the technology. The analytical tools for properly realizing calculations are now available through computer modeling techniques. NASA mandated the mathematical community to develop computer techniques and rigorous structural analysis methods for complex structures of any sort, including space frames. This was taking place as early as 1967 when the Gyraton, at Montreal, Expo '67, was designed and analyzed by computer. One estimate was that the equivalent calculations if done by hand would have taken some 30 years."[S.F. 3]

"What we are witnessing is the marriage of the technology and techniques of the information age with structural systems rooted in a tradition of natural form. Space frame provides the vocabulary of form. The computer gives voice to the vocabulary by providing the syntax, allowing for sophisticated manipulation and synthesis of the basic elements of the vocabulary. Building form will derive from the interface between the designer and the automated system incorporating the vocabulary of space frame technology."[S.F. 5]

"... each pound of space frame typically embodies more "information," in
the form of design and engineering, than a corresponding pound of conventional structure. In conventional structures there are far fewer members to be engineered and they are typically sized conservatively [more massive than might be needed] to further reduce engineering involvement."[S.F. 3]

"The advent of the mini computer has been revolutionary. What has been happening in the past 4 or 5 years is really astounding. Until very recently the computer analysis of space frames required main frame computers and inaccessible software. Now it is possible to analyze very large structures using small mini-computer engineering work stations. Before the end of this decade the new generations of desktop engineering work stations, incorporating significant developments in user friendly computer technology, will be the essential tool for space frame design and engineering."[S.F. 3]

"There are [with this method of building] so many possibilities for architectural breakthroughs. All kinds of building form and forces are now possible to analyze. An entire vocabulary of form language for the building arts is being generated. ... Herein lies the ultimate significance of the technology." [S.F. 2]
Pictures

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