Scaffolding Children's Exploration of Motion and Mechanism

by

Michelle Leigh Shook

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Signature of Author. ....
Department of Mechanical Engineering
August 4, 2000

Certified by..
Mitchel Resnick
Associate Professor of Media Arts and Sciences
Thesis Supervisor

Certified by..
David R. Wallace
Assistant Professor, Department of Mechanical Engineering
Departmental Reader

Accepted by................ ....
Ain A. Sonin
Chairman, Departmental Committee on Graduate Students

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Abstract

This thesis discusses the development of a software system and a collection of manipulatives that help young children, ages 7-10, learn about the core ideas behind the construction of mechanisms and the creation of mechanical motion. The software tool acts as a resource for children to access during their own building activities and provides a support structure for them to scaffold their knowledge of mechanisms and mechanical components. The software accounts for different learning styles, offering three distinct entrances into the system that overlap in content. Additionally, the software provides support for children to connect mechanisms with motions they observe in nature and their surroundings, and to post their own constructions for others to view in an online environment. In the thesis, I describe initial prototypes for the software environment and pre-built mechanisms. Primary observations of first and second grade children's investigations with these prototypes are documented and suggestions are made for further improvements to make the system more effective.

Thesis Supervisor: Mitchel Resnick

Title: Associate Professor of Media Arts and Sciences

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1 Learning to Build What You Didn't Know You Knew

The challenge in design and creation of mechanisms, whether it is replicating a certain motion or ascertaining its structural integrity and functionality, is not a trivial issue, no matter what your level of age or experience. There is a certain amount of revision needed between the stages of generating ideas, planning which mechanical parts will be needed, modeling the intricate connections between pieces, and assessing the outcome that is reflective of the iterative design process taught in most engineering curriculums at the university level. But for young children building with simple construction kits, this can be especially frustrating. Often the greatest strength of children is the imaginative energy and enthusiasm for the possibilities of what *could* be built. But without help and feedback from someone more experienced in modeling and construction, there is sometimes disappointment when they encounter the disconnect between the intricacies of building, and what they envision so clearly in their minds.

Imagine seven year-old Benjamin, excited that his first-grade teacher has just given his class a free afternoon to build with LEGO. There is no regimented activity to complete, this is meant to be a time for the children to create and construct what they want with limited supervision by the teacher. During the last LEGO play period, Benjamin worked with two other students to build a very large castle. The children paid close attention to the robustness of the structure and the color pattern of the bricks that were chosen for each distinct feature of the castle. After the children retrieve the castle from storage, they begin to add LEGO minifigs and create a play scenario. Another child, observing their play, interrupts them to comment that there should be a way for the minifig character at the bottom of the castle to be pulled up to the top level so it can visit the other minifig characters. The children are quiet as they consider this suggestion, which appears to be a legitimate issue. One child theorizes that there must be a hidden staircase for the character to climb. But Benjamin is not satisfied with this answer. He turns to a bin of LEGO Technic lying on the floor next to him and selects a large gear, putting an axle through the center. Benjamin has seen his older siblings work with LEGO Technic before, and explains to the group that gears are used to make things move so it should be able to lift the LEGO character to the top of the castle. He tries to attach it to the wall of the castle but it falls off. Another child has cut a piece of yarn and suggests the string could be used to lift the minifig. Benjamin ties it to the gear and tries again, unsuccessfully, to attach it to the castle wall. At this point, the other children are getting frustrated with the task and resume their play scenario. Not wanting to be left out, Benjamin tosses the gear and string to the side and begins to build an addition to the castle wall with a different color pattern of bricks.

This is a typical problem many young children find themselves facing when difficult learning challenges arise: either choose to test and expand the limits of your capabilities or resort to building what you know. In Benjamin's situation, several factors may have contributed to his decision to abandon the design challenge presented to him, but one of the most important was the lack of guidance from a more knowledgeable source. By recognizing that Benjamin missed an important opportunity to increase his knowledge of the basic principles of motion and mechanism in the natural context of play, it is possible to create a valuable learning structure which might help him solidify his ideas and scaffold his knowledge to the next level of understanding. Scaffolding, an educational technique based on the research of Russian psychologist Lev Vygotsky, aims to provide children with support for their inquiries so that they may learn to do it without any help in the future. Usually this support is provided in the form of a parent or educator acting as a source of aid when the child cannot find the answer alone. Vygotsky suggested that the true measure of what children can accomplish is not based upon what they already know, but what they can do when assisted by someone with more experience (Vygotsky, 1978). Therefore, the educator is not looking for ways to provide children with activities that are easy to master, but with mental challenges that are slightly above their level of functioning (Berk and Winsler, 1995). In Benjamin's case, this would mean providing a tool for him to learn how to build a mechanism that would lift a LEGO minifig up and down.

Even with such a scaffolding tool in place, the question remains whether increased knowledge about mechanisms and motion are necessary at such an early age. At a time when children are just beginning to understand the basics of building static structures with LEGO blocks, is it necessary to expect them to explore the intricacies of moving parts? Though children at this stage might not be ready to fully understand the physics and mechanics of such complicated concepts as mechanical advantage or gear reduction, early exposure to mechanisms can enhance spatial-reasoning skills and visualization techniques. Learning about mechanisms contributes to an overall spatial awareness and intuitive feel for the complexities of motion. Spatial learning encourages an appreciation for complex systems, promotes inductive reasoning, and requires an active use of visualization (Silverman, 1999). This is especially relevant to mechanical systems because the spacing and connections between the smallest mechanical parts can have a significant influence on the behavior and effectiveness of the resulting motion. Learning to anticipate the motions of mechanisms and create new and interesting forms of motion with mechanical pieces like gears, axles, cams, and wheels can be a very practical entrance into more complicated scientific and mathematical concepts (Parkinson, 1999).

With these justifications in mind, I have created a scaffolding tool that helps children in the 7-10 year age range explore a collection of mechanism primitives, modeled in LEGO Technic, and demonstrates how to combine these primitives in such a way that expands the range of their construction activities. No longer held back by their inability to build the motions they visualize existing in their fantasy world, the children will be able to select descriptions of mechanisms from key phrases and images in this Mechanism Constructopedia and learn how to implement the core ideas in their own constructions. The idea for a Constructopedia, as envisioned by Seymour Papert, Mitchel Resnick, Fred Martin, and others at the MIT Media Laboratory (Papert & Resnick, 1995), was based upon the need to provide children with learning resources during the design process. Much thought has been given to the design of such an electronic building resource and several prototypes have been created, such as KEGO, an electronic database of LEGO Technic designs (Plusch, 1995), and the Constructopedia that accompanies the LEGO Company's Mindstorms Robotics Invention System, which provides several building options for robot designs. The Constructopedia can be viewed as an encyclopedia of design, providing information about how a structure or mechanism is put together and what connections can be made between everyday motions and these mechanisms. Unlike encyclopedias and other reference books, the Constructopedia is a dynamic reference, growing in size and information as more people use and contribute to its content. The Constructopedia also differs from a normal encyclopedia in that it provides the student not with facts about constructions, but procedures to follow to create particular constructions. This procedural approach is often more valuable during construction activities than the declarative methods of typical encyclopedia resources, providing students with detailed building directions and examples of similar work. My version of the Constructopedia is designed mainly for younger children, who have had little or no experience with building and controlling things that move. Unlike the previous versions of the Constructopedia which provide an excellent description of detailed mechanisms and mathematical calculations, I wanted to design a system for younger children that would give them an introduction to the idea that mechanisms can be used to mimic motions they see in the real world. The aforementioned KEGO and LEGO Mindstorms Constructopedia are designed primarily for older children who have had experience building with mechanical components and need help with refining their understanding of part connection and for things like calculating gear reductions. The Mechanism Constructopedia is meant to scaffold young children to a level where they can view complex mechanisms as a collection of subassemblies that perform specific functions. When these subassemblies are put together, complex behaviors often emerge. Not only is it hoped that children will be able to learn how to build these mechanisms, but that they will be able to relate the behavior of these mechanisms to motions in the world around them, allowing them to make more personal connections with the building process.

Though Vygotsky's vision for education mainly referred to scaffolding techniques in the context of an adult watching over the work of a young apprentice, material resources can also play the role of a scaffold in the learning process, giving support for children's inquiries. In particular, computer technologies open up new possibilities for children's learning, providing resources with which the child can use during self-directed learning activities. It was with this thought in mind that I chose to create a web-based Mechanism Constructopedia, allowing children to access pertinent information at critical times during creative construction periods without interrupting the natural flow of play.

At the most fundamental level, the Mechanism Constructopedia is a web-based, Java enhanced, educational tool that is intended to scaffold young children's understanding of mechanisms and motion. The system is designed to take into account different styles of learning and becoming familiar with new information. For instance, the main selection screen gives the child an opportunity to choose one of three different entrances into the system. The user can either choose to search for a distinct type of motion from a collection of descriptive phrases and images, or to build from the basics up to a complete mechanism by looking through information about individual mechanical pieces and their functions.

These two approaches are representative of the two types of learning styles cited by Sherry Turkle and Seymour Papert (1992). According to Turkle and Papert's observations of programming styles within an introductory, collegiate computer science course, there are two different personalities with which individuals approach learning activities. One personality, known as the planner, starts by conceiving a plan and all subsequent building is reflective of the original vision of the plan. The planner adopts a top-down approach to learning that begins with designing the behavior of the system without knowing the small-scale details of how that behavior will be managed. The other personality reflects traits of the bricoleur. Originally used by Levi-Strauss to contrast abstract patterns of scientific thinking with more concrete methods, bricolage refers to a style of learning through which individuals construct knowledge by working with a set of well-known materials. Bricoleurs tinker with small parts of the system, developing a final vision from the relationships between parts. In the Mechanism Constructopedia, the option to choose a mechanism or motion with words or images is meant to reflect the planner approach. By selecting the desired type of motion as the initial step, the child has a clear idea of what he or she is trying to build and needs the scaffolding software to inform the child how it can be built and what are the core concepts behind the motion. Alternatively, by opting to investigate specific mechanical pieces and subassemblies as metaphorical 'building blocks' for a mechanism, the child is adopting a bottom-up approach to design, investigating how certain pieces might contribute to the overall behavior of the mechanism. This approach is representative of the bricoleur personality.

Though most individuals are thought to have some combination of traits characteristic of both planners and bricoleurs, the Mechanism Constructopedia also takes into account a different approach to building: that of a child who prefers to examine mechanisms that are already constructed. As an examiner, a child prefers the method of taking apart and investigating existing mechanisms to see what characteristics are particularly compelling and how they can be replicated and personalized. The software takes this into account by providing children with an interface between the virtual Constructopedia tool and the physical nature of LEGO mechanisms. The system is meant to be used in conjunction with specially designed, physical manipulatives that act as encapsulated modules, each highlighting a specific mechanism or a distinct type of motion. Each module is contained within a small plastic box, providing the structural integrity needed for the placement of mechanical parts while maintaining transparency for the child to observe the intricacies of the movement. The box can be disassembled and taken apart and used as a structure for the building of new mechanisms. Each pre-designed module contains an RF-ID tag in the bottom on the box and is identified by the computer through an RF-tag reader connected to the serial port of the computer. By swiping a module over the tag reader, the web browser automatically redirects the user to a new web page containing information pertinent to that module, specifically addressing how it works, how to build it, what it can be used for, what are the core mechanisms behind it, and what it resembles in real life.

The Constructopedia software not only provides different entrances to children's investigation of mechanical concepts, but allows children to utilize the mechanisms in ways that are personally meaningful and to share those ideas with others in an online environment. Each user of the website is given a virtual workbench that can be personalized to reflect his or her work. The workbench area can be used as a display for various projects they have completed using modules of motion found within the Constructopedia, or as a storage area for images of mechanisms that they have created and want to share with others. It is hoped that this will bring about a separate level of support and allow users to make connections to other members of the online building community. By observing how other users personalize the mechanisms and modules to enhance their own construction activities, children will feel that they too, can use the Constructopedia to learn how to creatively incorporate motion and mechanism into their own building activities.

With an emotional and intellectual framework established, children will be encouraged to construct and build in a manner that reflects a capability beyond their normal level of understanding (Papert, 1993). For instance, consider a different ending for the scenario about Benjamin mentioned above. Instead of feeling frustration at his lack of knowledge about Technic construction and resorting to building what he knows in the absence of help from someone more knowledgeable, Benjamin can use the computer to access the Mechanism Constructopedia website. He knows exactly what type of motion he wants to build, but he does not know how to translate his ideas into a tangible mechanism. He chooses to take the role of a searcher, looking through a menu of words to find a phrase that reflects his need for a mechanism to move a LEGO minifig up-and-down. He finds several phrases that mention an up-and-down motion, but he is not sure which one would work. He continues to look through a second animated image-based menu and finds one mechanism that looks like it might be suited for the task. After selecting it, the Constructopedia takes him to an overview of that mechanism. He is able to see an animated image of how it works, but it is only after he selects a link to see what others have done with it that he is convinced that this is what he wants to build. In the links to personal workbenches, he sees that another girl has made a LEGO elevator and has used this mechanism to lift a small elevator up to the top of her structure and lower it back down again. Benjamin knows this is the same type of motion he is looking to simulate and references back to the list of what Technic pieces are needed for him to build his own mechanism. Once he has gathered the pieces, he follows the assembly instructions and goes back to the LEGO play area. By this time the children he has been playing with have continued to build other things, but when Benjamin presents his solution to the problem, there is renewed excitement about playing with the LEGO castle. Several children ask Benjamin to help them build such a mechanism to incorporate into their play structures. He has now become an expert on that particular mechanism and feels satisfaction about public recognition of his skill. Benjamin has taken the initiative and been scaffolded into the position in which his fellow students now take the apprentice role and he becomes a source of knowledge and aid to others.

2 Theory and Background Research

2.1 Spatial Reasoning, Motion, Mechanism, and Who Should Benefit

In this section, I discuss the attributes of enhanced spatial reasoning skills and the disciplines of knowledge that require application of these abilities. I talk about the necessity of providing all children with experiences that develop intuitive feelings about motion and spatial reasoning, and why it is useful to introduce young children to thinking about mechanisms.

One of the primary motivations for encouraging young children to think about mechanisms in the context of creative building is to expand their spatial knowledge and intuitive understanding about simple and complex motions. Spatial ability is a specific type of visual thinking that requires the thought processes to be expanded from thinking in terms of flat, two-dimensional images to three-dimensional environments with depth, perspective, and volume. Although references to spatial ability are largely placed in the context of mathematics and engineering, spatial thinking is necessary in a wide range of disciplines. Spatial reasoning skills not only encompass an understanding of space and proportion, but also connote an association with balance, momentum, leverage and distance (West, 1991). An overall awareness of all of these attributes is clearly needed in technical disciplines. Engineers, architects, and physicists consistently deal with structural design, mechanical assemblies, and principles of dynamic space and time. Chemists and biologists deal with orientations of molecules and visualizations of the internal structures of living creatures. Mathematicians seek to translate equations into graphical representations that provide insight into the true behavior of a system. In some respects, many of the phenomenon scientists strive to explain and classify in terms of scientific terminology can only be described through visual techniques: "Clearly, spatial knowledge can serve a variety of scientific ends, as a useful tool, an aid to thinking, a way of capturing information, and a way of formulating problems, or the very means of solving the problem. Perhaps McFarlane Smith is right when he suggests that, after individuals have attained a certain minimal verbal facility, it is skill in spatial ability that determines how far one will progress in the sciences" (Gardner, 1983, 191).

But the need for spatial reasoning skills is not exclusive to scientific fields of knowledge. An inherent understanding of the core ideas behind spatial reasoning are also integral to artistic pursuits and athletic endeavors. Both sculpture and painting use light, shadow, and depth to communicate a powerful manipulation of space to the observer. Sports such as basketball and tennis require players to quickly assess the dynamic spatial behaviors of their opponent in order to develop strategy and score points. Though it is clear that different aspects of spatial thinking are called upon in artistic, athletic, and scientific situations, its centrality to a wide range of disciplines is apparent. Therefore, early exposure to methods of thinking about motion and mechanisms is not meant to be strictly interpreted as a pathway into scientific disciplines, but as a basic skill that will be called upon in various forms throughout a lifetime. Learning to question how and why things move can lead to a more complete synthesis of the core ideas behind motion and mechanism, the byproduct being enhanced spatial reasoning skills.

Though spatial awareness is recognized as an essential part of problem solving and design, it frequently is not fully appreciated that visual and spatial abilities can be encouraged in children that show little or no talent for visual tasks. Often, spatial ability is referred to as a style of learning through which children approach educational challenges. Individuals who show strong tendencies for expressing themselves through visual means are classified as "visual-spatial learners" and held in comparison to those with "auditory-sequential" abilities, who exhibit strong inclinations toward learning in terms of hearing and speech. Visual-spatial learners are found to do well on tasks like block construction, puzzles, and mental rotations (Silverman, 1999). Children who learn in this manner are quick to find connections between parts of a whole and create models of reality that reflect multiple dimensions. Visual-spatial thinkers have the inherent ability to mentally transform images through distortion and rotation and to create visual metaphors in their mind (West, 1991). Children who like to take things apart and investigate how they work are thought to be visually and spatially inclined. But while it is good to foster the talents that manifest themselves through the preferences of certain children, it is also important to encourage children who learn in different ways to explore activities that focus on spatial development. Spatial visualization techniques can be closely linked in an extended continuum to pattern recognition, problem solving, and creativity (West, 1991). Not all children will be able to master working in a spatial medium, but at the very least they will gain an appreciation for the idea that "space allows the coexistence of certain structural features, while disallowing others" (Gardner, 1983).

While it is clear that activities that encourage the development of spatial reasoning skills can be a valuable asset to all types of children, it is not as obvious at what stage in their spatial development it becomes useful to introduce children to concepts of motion and mechanism. Developmental psychologist Jean Piaget wrote extensively about the topics of the child's conception of speed and movement. Piaget observed a sensori-motor understanding of space which emerges during infancy. At this stage, infants gain an appreciation for object trajectories and develop their own sense of navigating between different locations. Mental visualization is entirely an internalized action. By the time children enter the concrete operations phase and begin to attend school, they have become capable of mentally rotating and manipulating imagery. A child can now use his or her new understanding of reversible mental operations to visualize how an object might look to a person observing from a different perspective. Frequently the most difficult challenge for a child in primary school is to make connections between the different experiences they have had with spatial reasoning: "Representing their piecemeal knowledge in another format or symbol system proves an elusive part of spatial intelligence. Or perhaps one could say: while children's spatial understanding develops apace, the expression of this understanding via another intelligence or symbolic code remains difficult" (Gardner, 1983).

2.2 The Design and Technology Curriculum: A Success Story

This section relates the progress made by educators in the United Kingdom's public school system within the new discipline of primary design and technology. It outlines the philosophy and target attainments for the curriculum and provides examples of children's successful understanding of mechanisms.

While it is a challenge to find ways for children to find consistent methods to make clear and expressive connections between various concepts of spatial awareness, motion, and mechanism, the United Kingdom has developed a national educational curriculum that provides innovative solutions for these concerns. The National Curriculum is split into 12 disciplines, covering the standard subject matter that is included in most primary and secondary educational programs including mathematics, science, history, art, physical education, and foreign language. Unique to United Kingdom's curriculum is the inclusion of the discipline of Design and Technology.

Divided into four key stages of investigation, the Design and Technology Programme of Study aims to prepare students to become creative problem solvers and developers of their own products and systems. By combining aesthetics, social and environmental issues, and function and industrial practices they are able to reflect upon past and present technologies and evaluate their own ideas for future products and systems (Department for Education and Employment, 1999).

The Design and Technology curriculum outlines an overall vision and specific attainment goals for each key stage. For purposes of comparison, it is important to note that key stages one and two roughly coincide with grades one through five in the American educational system. In key stage one, children are encouraged to investigate objects that are familiar to them by drawing and modeling their observations and talking about what they like and dislike in construction activities. An important component of key stage one is understanding materials and components, such as learning about the working properties of materials and how mechanisms can be used in different ways. For instance, the teacher might take time to show the class how to fold paper to make it stiffer or how to connect wheels and axles and make joints that allow movement (Department for Education and Employment, 1999). When pupils progress to key stage two, they learn to how to identify the positive and negative aspects of their own designs and to use computer technology as a supplemental resource. Children learn how mechanisms can be used to create certain patterns of motion and how to use simple switches and electrical circuits to make these mechanisms move autonomously. By exposing children to mechanisms through construction activities, children gain a practical understanding of how certain mechanisms create distinct motions. During the first two key stages, children focus on the uses of strings and rods, wheels and axles, levers and linkages, winches, pneumatics and hydraulics, pulleys, cams, and gears. An example of how the curriculum provides open-ended challenges in the exploration of mechanisms can be seen in a case study by Rob Johnsey:

> "Stacey and Jake were exploring the need to reach objects which were at a distance and out of reach. As part of their design-related research they were investigating a mechanical grabber that their teacher had asked them to make. They had made the grabber following a worksheet and were now considering how to control the 'fingers'. Their solution was to use a rod of stiff wire which would push or pull the moving finger. This required another pivot where the rod fixed to the finger and a guide sleeve to keep the rod in place" (Johnsey, 1991, 91).

From this example, it can be seen that Stacey and Jake are learning how to experiment with the behaviors of mechanisms to attain the controlled effect they are seeking.

Key stages three and four require more in-depth understanding of product development and address how to incorporate useful properties and aesthetic effects in the design of a product. The focus on materials and components in key stages one and two shifts to a focus on system and control in key stages three and four. In all of the key stages but particularly in stages one and two, the study and creation of mechanisms, especially with vehicles, plays an important role in the exploration of construction activities. These spatially-oriented tasks help to support more complex engagements with control technology in key stages three and four (Parkinson, 1998). Children eventually learn the importance of feedback and control, and become familiar with mechanical, electrical, electronic, and pneumatic control systems. One of the most important ideas that children come away with is that complex systems can be broken down into sub-systems to make analysis easier, and that each sub-system contains its own inputs, processes, and outputs (Department for Education and Employment, 1999). By looking at a complex mechanism in terms of being composed of smaller, task-specific modules, children are encouraged to explore the possibility that systems and sub-systems can be connected and reconstructed in creative ways to perform a range of independent functions.

It is in the spirit of this design and technology program that I designed the Mechanism Constructopedia system. The Constructopedia, like the design and technology curriculum, aims to help children put their ideas into practice. Both aim to give children the opportunity to start with pictures or words to describe what they envision and to help them use tools and materials to carry out that vision, with extra aid being provided when guidance is required. The Constructopedia reflects the idea that is embedded within the Design and Technology curriculum; that increasing spatial awareness and learning about mechanisms can occur in a creative way if children feel ownership over the design of a personally meaningful project.

2.3 The Roots of Scaffolding

Scaffolding is an educational technique that aims to elevate children's cognitive development through meaningful social interactions and a consistent support system. This section details the *roots of the scaffolding approach through the work of Lev Vygotsky and describes his vision for learning within a social environment.*

One of the attainment targets for England's Design and Technology curriculum is to adapt itself to the individual development of each student. Though the key stages are meant to provide guidelines for progression through the curriculum, there is no strict schedule for moving through the stages. Teachers assess individual performances and provide guidance for children who need extra help to achieve their goals. On the opposite end of the spectrum, the curriculum is designed to provide for opportunities to move into higher levels of development. This may mean choosing projects or highlighting skills from later key stages that allow individual students to demonstrate what they are capable of achieving with extra encouragement, or scaffolding their educational potential.

Scaffolding is a method of educational instruction by which students are enabled to perform tasks that would not be possible without additional support from a teacher or mentor. The act of teaching and encouraging students to acquire new skills has been practiced throughout history in the form of personal relationships between knowledgeable masters and untrained apprentices. By providing personal training and additional support when questions arise, the master was able to facilitate learning to a level where the apprentice had acquired the skills necessary to perform the task independently. Three types of guidance were combined by the master to provide the necessary scaffolding for the apprentice. First, the master demonstrated his skill and made verbal annotations of the process. Second, the master coached the apprentice during the apprentice's own attempts to replicate the process. Finally the master asked questions to help the apprentice articulate and reflect upon his own learning process and goals. (Guzdial, 1994). Similarly, students facing new learning challenges in today's educational system often need extra guidance to help them recognize what useful skills they already possess and how they can enhance these abilities by seeking additional resources, such as reference materials or individuals with more experience. The resulting method of scaffolding can be seen as "cognitive bootstrapping"—introducing children to a new educational domain and enabling them to build upon their previous knowledge as if they have access to a rich source of other's past experience (L.B. Resnick, 1989).

As mentioned in the introduction, the main roots of the theories behind educational scaffolding can be found in the work of Russian psychologist Lev Vygotsky. Vygotsky believed that children's mental functions and language development are derived from social origins. Social interactions during activities facilitating cognitive development are the critical links between multiple planes of human functioning. In other words, the fundamental manner in which a child's mental development occurs is through the use of psychological tools during activities shared with mentors or knowledgeable peers (Berk and Winsler, 1995). Vygotsky believed that scientific reasoning skills are enhanced as learners expand their knowledge. Because of the need for a solid foundation from which to scaffold new knowledge processes, systematic educational techniques are integral to the cognitive development of young children. The development of a child's scientific modes of thinking and his or her rate of maturation are a direct reflection of a cooperative relationship between the child and the teacher. If the children feel that they have access to dependable sources of information and assistance, they are much more likely to accept challenging intellectual tasks. In the specific context of concepts requiring scientific reasoning, Vygotsky believed children begin with an initial verbal definition and systematically refine their definitions until they describe the core phenomena. The difficulty with this approach and the problem that most young children struggle with is that many mathematical and scientific concepts are detached from a child's sense of reality, which makes it difficult to interpret meaningfully within the context of their own limited experiences.

As a child develops a framework for learning about scientific and mathematical concepts, there is a constant reevaluation that occurs in order to synthesize unorganized bits of information into a consistent mental structure. Vygotsky came to the conclusion that the development of new scientific operations does not coincide with the progress of a school curriculum, but that instruction is the precursor to development, with additional scaffolding resources helping to fill in gaps within a child's mental model. Therefore, the true measure of children's mental development is not what children already know and understand, but the method with which they approach subjects and problems in which they have no knowledge or experience. Vygotsky divided problem solving into three categories: tasks that can be performed easily by the child, tasks that the child cannot perform even with the help of an adult, and tasks that fall in between which can be accomplished by the child only with additional guidance. The discrepancy between children's capability to perform tasks on their own and the level of their accomplishments when assisted by adults is referred to as the zone of proximal development (ZPD). This is the area in which the child is ready to grow. Vygotsky believed that imitation was a skill in its own right, and that not all children could accomplish equally in the presence of guided assistance: "Psychologists today cannot share the layman's belief that imitation is a mechanical activity and that anyone can imitate almost anything if shown how. To imitate, it is necessary to possess the means of stepping from something one knows to something new. With assistance, every child can do more than he can by himself-though only within the limits set by his state of development" (187). Therefore, one of the best indicators of development potential can be gained from a child's ability to move between independent and guided learning.

2.4 The Role of the Educator and the Student Within a Scaffolding Framework

This section describes how successful scaffolding methods can be implemented when both the educator and the student are aware of the roles they play within the system.

With Vygotsky's system of guided instruction in mind, it is necessary to define the role of both the educator and the child in the scaffolding process. Keeping in mind that children gain the most from scaffolding when they are challenged to solve problems beyond their current level of development, the educator must aim to provide activities that operate within a child's zone of proximal development. This means that the teacher must bear much of the responsibility for ascertaining that children are consistently working at a level that is a step above their standard independent functioning and that they require occasional guidance and support (Berk and Winsler, 1995). Instead of regarding assignments that are quickly and correctly completed as indicators of competency in certain disciplines, educators aiming to implement scaffolding in their classrooms should consider creating tougher assignments with the intention of providing further support when problems inevitably arise. Integral to the idea of scaffolding is the notion that the scaffold structure will not be needed at some point in the future. With consistent challenge and help, a child's level of comfort with a task will increase until he or she is able to complete the task without any adult intervention. Proper scaffolding techniques will support the needs of the student and prevent them from wandering too far from the core ideas of the activity. The educator is meant to offer guidance, but not to take control of a child's developmental path:

> "Even though we may offer clarity and structure, the students must still conduct the research and fashion new insights. The most important work is done by the student. We simply provide the outer structure" (McKenzie, 1999, 9).

While the educator acts as a facilitator of the scaffolding process, the children actively construct their own mental models through guidance and feedback from the teacher. These scaffolding techniques are integrated into the design process such that the children become autonomous learners while taking advantage of outside resources, collaboration with the teacher, and by discussing their concerns and successes with peers (Soloway, 1996). One of the goals of scaffolding is to encourage the child to take an active interest in his or her own learning process and to participate to the fullest extent of their potential. Because the educator never calls attention to a child's inability to thoroughly complete a task without help, the child gains confidence and increases his or her level of comfort with learning new material. Simultaneously, the adult benefits from the child's increasing level of competence (Brown and Palinscar, 1989). In accordance with Vygotsky's vision, scaffolding encourages children to learn in a social context, with much collaboration between teachers and other students. The social environment acts as part of the scaffolding framework, supporting the exchange of ideas between students who are at different levels in their zone of proximal development. For instance, one child who has learned to complete a task autonomously because of consistent adult feedback can now assume the role of mentor for a child who has yet to master the same task. The advantage of this social exchange of learning derives from the large repository of collective knowledge that exists among students at various levels of cognitive development. In an isolated environment, problems arise when a child does not feel ownership over an idea or concept. Without ownership, children do not develop the necessary intuitive feel for the knowledge that allows them to adapt information and skills and apply them to dynamic situations (Brown and Palinscar, 1989). But with constant exchange of ideas in a social environment, students will be exposed to the combined knowledge of their classmates and instructors and will discover which individuals can be approached as a source of information for a wide range of learning scenarios.

2.5 The Realities of Scaffolding Education and the Possibility of Computers

This section emphasizes the importance of material resources in the scaffolding process and discusses how computers can be used to implement scaffolding techniques. There is also discussion of creating effective scaffolding software in the context of learner-centered design.

Vygotsky's vision of educational scaffolding is an excellent model for helping children consistently push the limits of their cognitive development with enhanced support. While a key component of the scaffolding process is the recognition that children need to feel responsible for their own learning process, guidance must always be available to provide pathways past difficult obstacles. Some children are able to find their own ways around these obstacles with minimal supervision, but other children find themselves discouraged and lacking motivation to discover solutions without additional sources of support. Though Vygotsky's system of progressive learning in a social context was intended to encourage the development of collaborative teacher-student relationships, the concept of scaffolding also emphasizes the tools and material resources which enable children to find their own solutions to questions as they arise during the learning process. With the increasing acceptance of computers and technology in the classroom, the use of educational software provides an additional resource for knowledge scaffolding on a personal level. In situations where children are looking for new ways to apply their knowledge or concretize abstract theories, effective computer software might provide structures for encouraging inquiry and offer methods to help fill in the knowledge gaps. There are also several clear benefits to be gained from the use of computers in educational scaffolding. One of the most useful tools in teaching difficult intellectual concepts is modeling of abstract ideas in a visual or tangible format. For example, building a model of the chemical composition of water with a molecular construction kit is an effective way to help children visualize the three-dimensional nature of chemical bonds between elements. But for more complex systems, especially dynamic systems, computers are extremely efficient tools for modeling and simulating scientific phenomenon. The representational capacities of computer software make it a powerful tool for encouraging discussion around graphic simulations (L.B. Resnick, 1989). Images of abstract concepts on a computer screen serve as a centerpiece for discussion among other students. Initial interactions with scaffolding software at the computer would eventually lead to offscreen collaborations and exchange of ideas between students, teachers, and others in the social learning environment.

Educational software should aim to provide children with the tools to investigate concepts about certain disciplines of knowledge. Many software programs use complex graphics and sound to keep the children engaged and entertained in the hope that some sort of "knowledge transfer" will occur between the computer, acting as teacher, and the student, acting as passive observer of the lesson. But educational software created with the explicit intention of implementing scaffolding techniques needs to satisfy more complex criteria. First and foremost, scaffolding software must provide children with the means to receive feedback during problem-solving tasks as they progress toward their final goal. There are two primary ways in which the software can facilitate this feedback. First, students can receive direct feedback from peers if several users work together on the computer. In this scenario, the software is used as an entryway into communication and collaboration in a social context. Alternatively, children also receive feedback directly from the thing they are trying to create, whether it is on the computer screen or in the physical world. For instance, creating Logo programs or building with LEGO Technic both inherently provide feedback to the designer. If the Logo program or Technic construction does not work, that is a signal to the student that the design approach must be revised or supplemented. If the program or construction works differently than initially expected, the student can reflect upon how the alternate behavior emerged. No matter which approach is used, scaffolding software should reflect the core idea of educational scaffolding- that mental development occurs in the context of a supportive social environment in which children are provided with the resources they need to find solutions.

Another characteristic of scaffolding software is that is aims to provide activities that keep the child in his or her zone of proximal development. While it is often difficult for a software program to gauge what a child is capable of achieving with additional support, the software can be designed to accommodate different levels of problem-solving. Tasks should be inquiry-oriented, allowing the child to use his or her own interest in finding answers to direct the learning process. When provided with a more open-ended task, children will find creative solutions within the boundaries of the problem constraints (Dodge, 1998). With constant feedback and support, the chances for disappointment and decreased motivation are reduced, increasing children's confidence in their problem-solving skills and encouraging them to reflect positively on the learning experience. Enhanced feelings of competency are particularly integral to the continued development of children that have no previous experience with self-directed learning and who doubt their own ability to think independently (L.B. Resnick, 1989). Successful scaffolding creates momentum in cognitive development, allowing children to continue building upon their sense of accomplishment and mental ownership of new concepts and skills (McKenzie, 1999).

Because scaffolding software has to account for differences in learning patterns across individual users, it must allow for several different points of entrance into the same problem. Often children have different motivations for taking up the same challenges. While one child might find the study of fossils compelling because of a fascination with dinosaurs, another child might like learning about the geologic conditions that make fossilization possible. Personalized learning implies that there is no one correct way to learn or single path to follow to satisfy a goal, and this attitude should be reflected in the design of scaffolding software. Software created with personalization in mind reflects the notion of user-centered design. In the user-centered approach to software design, much focus is placed on accounting for the diverse needs of a heterogeneous audience as well as methods to keep a wide range of users motivated. In a slight modification of this idea, learner-centered design can be seen as educational software specifically designed with the diverse needs of learners in mind (Soloway et al., 1996). Learner-centered design supports the idea that the key concepts of educational scaffolding can be effectively represented in a software format. The same methods of support that are provided by teachers in the classroom can be accounted for in a software environment, including diversity of learning styles, motivation, and cognitive growth from activities that are normally out of the child's normal capability. The software becomes a primary resource for investigation, with the program providing examples of expert behavior and helping to make abstract concepts more concrete and explicit (Brown and Palinscar, 1989). By demonstrating the challenges experts face when learning new material, the software helps children understand that knowledge is not something that is automatically generated, but a collection of ideas and concepts that are refined over the course of the learning process. Children can begin to see learning not just as an isolated experience, but as a continuous accumulation and readjustment of ideas that build on everyday experiences (Soloway and Guzdial). Learner-centered software not only addresses the ideas central to scaffolding, but issues relating to the development of effective software in general. Learner-centered software addresses four primary points during the design phase. First, the context of the software must be decided, including what environment it will be used in and how it will be used. Second, the supported tasks must be clearly established. Next, it must be decided which tools are needed to perform these tasks. Finally, the user interface to these tools must be designed (Soloway et al., 1996). By sensitively constructing a clear design framework in a workable software context, it is possible to provide effective scaffolding techniques through a virtual environment. In essence, the challenge in creating effective scaffolding software is to provide the fewest supports necessary while maintaining a clear goal and keeping children on track for finding their own unique solutions to that goal. A scaffold is a skeleton structure, meant to support a delicate work in progress until it is complete and strong enough to exist independently. Similarly, educational software scaffolding provides only what is needed to maximize learning potential. When the scaffolding tool is no longer useful to the student, new tools are needed to provide support for more advanced levels of learning.

2.6 Keeping Children Motivated During the Scaffolding Process

Finding motivation to learn new concepts is frequently a challenge for children in an educational environment. This section discusses ideas for maintaining motivation through scaffolding techniques with particular emphasis on how fantasy play and social recognition contribute to cognitive development.

Even with effective educational software scaffolding tools, it is a challenge to encourage children to initiate intellectual investigations and to keep them motivated enough to search for the answers. Often children experience frustration when they are required to follow a strict regimen and curriculum within a school system. Before the investigation has begun, the path and the results have already been determined. The role of the teacher in such an educational context is to make sure the child reaches the goal in the most efficient manner by remaining on the established path. The failing with this method is that is does not support the natural flow of exploration that fosters spontaneous curiosity and a child's commitment to providing compelling solutions (Bruner, 1966). Children feel no need to exert themselves in the search for the answer to a problem when they have already been provided with the solution. There is no sense of accomplishment or ownership in that task; it is merely an exercise in repetition.

Scaffolding techniques that provide guidance while accounting for expressive freedom during the learning process are one possible solution to this problem. Vygotsky hypothesized that imaginative play is the primary method of knowledge acquisition during preschool years. He observed that during play, children consistently operate in a stage above their level of development and that independent direction during play contributes to a child's ability to self-regulate their activities. But while play and learning are usually viewed as separate practices once a child enters into a formal system of education, children need to find some method of self-motivation to benefit from the learning process. Even when children are required to complete assignments as part of a curriculum, the knowledge they come away with is a direct reflection of how much of a personal connection they feel with the subject material. This level of personal motivation depends upon the level of challenge and the dynamic quality of the goal. Open-ended problems are frequently more attractive challenges to children because they provide varying levels of difficulty, encouraging the child to work at the highest level at which they still feel they are in control of their own learning. During the process of finding a solution to an open-ended task, children might discover their own sub-goals, encouraging them to continue in search of solutions to these emergent goals.

Often intrinsic factors are the key motivations for learning new material. Learning that is intrinsically motivated occurs without the need for direction from an adult or educator. Personal motivation to learn new material can be the result of several influences, as defined by Malone and Leper. If children recognize a skill will help them accomplish a higher goal, then they often view the learning process as a necessary step to a more desirable activity. For instance, if a child wants to open her own lemonade stand, she might ask her parents to teach her how to make change. Similarly, the context in which the material is presented can make a learning process more appealing. If the material is embedded into the context of a familiar fantasy, the child will choose to learn the skills necessary to perpetuate play within the fantasy world. Two types of fantasy play exist within the context of learning new skills. Exogenous fantasy is a linear fantasy that requires new skills to be acquired before the state of the fantasy can be affected. Endogenous fantasy is a reciprocating fantasy in which the skill being learned and the state of the fantasy depend upon each other (Malone and Leper, 1987). In the context of educational scaffolding, endogenous fantasy clearly provides constructive feedback within the fantasy world. Another benefit of endogenous fantasy is that it allows children to create metaphors for learning new skills in a manner that makes the knowledge more meaningful. Endogenous fantasy play creates a frame of reference for children to understand when the knowledge might be applicable during parallel situations in real-world settings. By creating links between learning and fantasy play, children experience a sense of control over their own learning process, another key motivation for continued success and development.

In addition to fantasy play, children often find cooperation and social recognition as key motivators for learning. Working together to accomplish a common goal can make the child feel like an integral part of a team's accomplishment. Similarly, successes attained while working independently can elevate the child's competence in the eyes of his or her peers and lead other children to attempt to imitate works that have been praised publicly by teachers. Social recognition of a child's work can occur in several ways. The product can be performed or displayed, the process and thinking behind the product can be demonstrated, or they can receive acknowledgement in the form of honors and awards. Often demonstration of the product or process is more effective than external recognition, such as an award, because other children benefit from the individual's newly acquired expertise. The recognized student gains confidence from his new position as a source of support and potential collaboration for classmates who seek to learn similar information.

2.7 Constructivism, Constructionism, and their Links to Scaffolding Theory

This section explores the ideas behind Jean Piaget's Constructivist theory and Seymour Papert's practical application of these ideas through his conception of a Constructionist approach to education that emphasizes meaningful educational experiences and their importance to cognitive development. Links are made between Papert's Constructionist model and the essential objectives of scaffolding techniques.

The concept that learning is a process through which knowledge is actively constructed is a core idea behind Jean Piaget's theory of constructivism. Central to Piaget's work was the idea that learning follows development in a constant revision of mental structures that have been previously established. Piaget believed that knowledge cannot be transmitted from one mind to another, but that individuals interpret information differently by reconstructing it their own workable mental model. The concept of constructivism applied primarily to the mental processes of cognitive development during learning activities. Piaget's colleague, Seymour Papert, created an extension of these ideas for direct application within an educational context. Papert established Constructionism as an approach to learning that put Piaget's Constructivist theories into practice in the classroom. With hands-on, experiential learning through the use of construction kits, Papert believed that children could work through the problem-solving process and make expressive connections to the material at the same time. Constructionists view learning as an active process on the part of the learner in which knowledge is constructed through the progression of learning. Constructionist theory even implies that children already possess distinct areas of undeveloped knowledge as a result of informal learning and observation, but that the act of constructing a formal cognitive model makes stronger connections between related areas of knowledge (Papert, 1993).

Constructionism reflects some of the inherent attainment targets for scaffolding in that it advocates the need for personally meaningful and self-directed learning in order to sustain motivation. With adequate internal motivations and in a suitable environment of emotional and intellectual support, children can complete tasks that were previously thought impossible (Papert, 1993). From the overlapping ideas common to both scaffolding and constructionism, it can be observed that methods derived from scaffolding theory not only raise children to higher levels of development, but provide children with the tools to create their own constructionist experiences of learning. Both constructionist theory and scaffolding techniques reflect the beliefs that knowledge is highly influenced by the environment in which learning takes place and that children build upon existing mental models when learning new ideas. Though scaffolding puts more emphasis on the social nature of education and the interactions that occur between teachers and students, constructionist theory acknowledges that the learning process can be enhanced with community support and feedback. Because Papert believed that construction of knowledge occurred as a direct result of personal experience, he regarded physical constructions as representations of a child's learning process. By bringing children's ideas "out into the world", others can then discuss, examine, and appreciate their problem-solving skills and creativity (142). When the techniques of scaffolding are designed to support a constructionist experience in an educational activity, children learn to construct their own knowledge while receiving the personal guidance necessary to lift them to a higher level of performance.

3 Personal Motivation

3.1 My Experience as an Mechanical Engineering Undergraduate

In this section, I describe my personal motivations for building the Mechanism Constructopedia and talk about my own experience in an engineering program that has helped me justify the need for such a tool.

In the preface to Mindstorms, Seymour Papert recounts how his childhood fascination with gears shaped his early understanding of mathematical relationships. With such an intense personal interest in the concepts behind his gears, Papert was able to make connections between gear behaviors and various mathematical applications such as multiplication tables and differential equations. His conceptual understanding of gears extended beyond a cerebral context to an empathic, bodily appreciation for the direction of rotation and speed with which a gear interacts with a system. Papert's use of gears as a way to relate to more abstract patterns of thinking reflects one of the core ideas behind his theory of Constructionism; that cognitive development is enhanced when the learner makes personal connections to the material in meaningful ways. It would be logical for me to claim at this point, since I am providing rationales for teaching young children to think about motion and mechanism, that I had a similar childhood connection with mechanical devices. But I cannot make this assertion. Much of my childhood was spent with my sister, making illustrated stories and directing 8-mm movies starring three plastic dolls, a pink cat, and a managerie of stuffed animals cast as 'extras'. This isn't meant to suggest that I had no exposure to construction activities and computer-based learning activities; I merely used those tools to enhance my primary fantasy world in which the dolls and stuffed animals were the key players. Wooden blocks and LEGO bricks were used to design cruise ships and jungle huts for my fantasy environment. Logo programs were used to make pixel-based images of my stuffed animals. As a child, I had no interest in building and controlling things that moved. Building LEGO Technic machines and investigating how my parents' car worked was not my primary concern. But despite my lack of interest in things mechanical, fourteen years later I found myself choosing to enroll at a university in a mechanical engineering program.

All throughout my four years as a mechanical engineering major, I found myself occasionally looking around my classes and trying to figure out how I became one of three women in a group with 25 male engineering students. When I talked to male students about their childhood experiences building RC cars and helping their dad rebuild his lawnmower, I felt increasingly convinced that they were better suited for a career in engineering because of their lifetime of practical experience with machines and complex systems. One fellow engineering student once observed that more women seem to be attracted to computer science and electrical engineering over mechanical, civil, and aerospace engineering because the former disciplines focused more on theory and the latter disciplines were more 'hands-on'. But despite the fact that my childhood experiences did not help me develop an inherent feel for how mechanisms worked, I still felt connected to the curriculum. With mechanical concepts, I could picture things happening in my mind. Though I struggled with some concepts that other students seemed to pick up quickly because of their familiarity with car engines or gearing systems, I was always able to create my own visualizations for learning the material. As I watched many students, females in particular, drop out of the curriculum during the first and second years, I realized that the one essential ability to succeeding in the engineering curriculum was good spatial-visualization skills. Memorizing energy balance equations for a carnot vapor power cycle is useless unless you can visualize the heat flow and change of state within the system.

Often the decision to drop out was based on poor test grades and difficulties keeping up with the assignments. But what it not obvious to a new engineering student is that the most valuable aspect of an engineering curriculum is the learning of a new method of problem-solving that makes you more aware of how things work in the world around you. Children who grow up building mechanisms and taking cars apart already have an awareness of this by the time they reach college. But that does not mean that children who don't know how to make personal connections to robots, cars, and machines can't share the same experience. Though I knew relatively nothing about how machines and mechanisms operate, I learned very quickly that all I had to do was break something to find out the answer. The first engineering class I took that meant anything to me instructed us to rip something apart and figure out how it works. From this class I was able to figure out the mechanisms behind bicycle pumps, doorknobs, mechanical pencils, and staplers. All the things most people regard as a single entity can be broken down into dozens of subassemblies, each with its own function. From this knowledge comes a sense of power and control, that answers to tough questions can be found by simplifying a system into smaller parts and that developing a complete mental model starts from the most basic elements. Don't know what is inside of a computer mouse? Rip it open and find out. And then think of ways to improve the design. Engineering taught me to break things apart so that, in the end, I might become a better builder. I have learned to develop an appreciation for systems and mechanisms that makes me a better designer, consumer, and critical thinker. But although I learned a great deal in a four year engineering curriculum, my late exposure to these concepts in some ways hinders me from having the same sort of deep connections as other engineers who played with mechanisms since early childhood. In some ways it is comparable to the difference between figure skaters who begin as children and those who start skating later in life. Rigorous practice will make any adult a competent and skilled skater, but they rarely acquire the same level of precision and intuitive feel for the movement as skaters who have been skating since primary school. It is clear that experiences in early childhood have a significant impact on how quickly one can master new ways of thinking as an adult. Because of my own experiences, I wanted to develop a tool that would give children who don't have refined talents for building an entry point into thinking about mechanisms and learning how motion can be creative and expressive. It is hoped that the Mechanism Constructopedia can help to scaffold young children up to a level where they are not restricted by their inexperience with mechanical components and they can learn to incorporate mechanism into their play environment.

3.2 The Gender Gap in Spatial Reasoning Skills

This section discusses the gap that exists between the spatial reasoning abilities of young girls and boys and describes the connection between playing with construction kits at a young age and entering into technical and scientific professions as adults.

Though I built the Mechanism Constructopedia with the intention of providing opportunities for a diverse range of children who feel uncertain about building with mechanical components, I hoped in particular it might provide entrances for young girls to start thinking about motion and mechanisms. This Constructopedia system was not designed as a tool to guarantee that large numbers of girls will feel compelled to take up engineering, but it is providing them with useful skills that will give them more confidence with their spatial reasoning abilities, should they choose to take that path. The ability to design motion and control it is a powerful skill to learn and one that provides an advantage to those who learn it at a young age. In a recent article, Henry Petroski described the popularity of Meccano and Erector sets with young boys in the 1950's. These construction kits, full of metal plates, gears, axles, wheels, screws, and comprehensive instruction manuals encouraged seven- and eight year-old boys to build complex machines and structures, just like real engineers. In the article, Petroski makes a connection between successes in the engineering profession and the use of construction kits as a young child:

> "Many an older engineer, looking back on his—there are very few older female engineers—childhood recalls assembling and disassembling all sorts of things around the house, from large grocery orders to small appliances. And even today, with deliberately crafted construction toys easily available, children still find adventure in corrugated boxes that make forts and houses and in blocks and cans that make steps and towers. There are manufactured toys, however, that have enabled children to build beyond the kitchen and the pantry and the nursery and the lawn" (41).

So why is it that there are no older female engineers to be found? Is it purely because these girls never took an interest in building forts, taking apart appliances, and playing with Erector Sets? Probably not. Most likely it was a lack of support in society for women entering into traditional male roles in the workplace. Young girls growing up in Petroski's time were not encouraged to play with toys like the Erector Set, that developed spatial ability or to show "a mechanical or inventive streak", as young boys tended to possess. (Petroski, 1998, 42). But after nearly a half-century, when the use of kits such as LEGO and Meccano has been linked repeatedly to developing scientific and technical tendencies in children at an early age, the majority of construction tools are still marketed predominantly toward boys. Petroski titled his article "The Toy That Built America", as a tribute to the Meccano and Erector sets and the inspiration they provided young engineering enthusiasts. But the sad connotation to this title is that women had no significant part in building this representation of America. On a personal level, I want to see more women go into the field of engineering because the engineers are the people who design and shape the future. The vision of the future is constantly being revised and it is important to make sure that all people have a hand in that.

According to a recent study, the gap between girls' and boys' spatial reasoning abilities is already in place before they even enter into the public school curriculum (Levine et al., 1999). The study found that males have a substantial advantage in spatial skill by the age of four years and six months. Though testing showed equivalent development in terms of intellect, boys demonstrated a greater aptitude for mental rotation and translation. All participants were given spatial tasks that required them to mentally transform images and build three-dimensional models based on two-dimensional visual representations. Previous to this study, the pervasive idea regarding spatial development was that the gender gap in ability occurred during the onset of puberty because of biological factors and hormonal changes. But surprisingly, Levine's study suggests that differences in spatial reasoning skills between the genders begin to emerge nearly a decade earlier than previous assumptions. This belief was further supported during the testing process when four- and five-year old boys were able to copy a three-dimensional LEGO model faster than girls of the same age (Levine et al., 1999). And as children advance toward puberty, the gap is most likely to become larger due to consistent exposure of young boys to activities requiring mental rotation of images. The concept of mental rotation is essential to the development of spatial reasoning skills. Mentally rotating an image in the mind reflects the ability to adapt an individual's perspective of the relationship between him or herself and the object being viewed. During the process of mental rotation, observers predict what the object would look like when rotated about its axis (Clements and Battista, 1992). Preschool boys might be gaining an advantage in spatial reasoning ability and mental rotation from their play activities, both alone and in collaboration with adults. According to D. A. Kolb, boys tend to be encouraged to build with blocks and construct models more often than young girls. This often gives them a headstart in spatial development:

> "Boys have greater access to so-called male toys (e.g. Lincoln Logs, Legos) than girls, and this accounts for at least a portion of the sex difference in performance on the Block Design Subtest of the Weschler Intelligence Scale for children" (Kolb, 1984, 947).

This discrepancy in development has long term implications manifested by the fact that young men often outnumber the amount of young women enrolling in technical and engineering programs at a university level. In many engineering disciplines, a student's spatial abilities predict how well he or she will perform in introductory drafting and design classes (Shepard and Metzler, 1971). Many engineering schools have begun to offer classes intended to improve visualization skills of incoming engineers, in the hopes of retaining female and minority students that are strong in math and science but are deficient in spatial reasoning. On a spatial visualization exam administered by Michigan Tech, almost fifty percent of incoming female students failed the exam as opposed to only fifteen percent of incoming male students. Beverly Baartmans, a mathematics professor at Michigan Tech, believes male advantages in spatial tasks are a result of their childhood activities:

> "...Playing with toys such as Lincoln Logs and Legos, participating in ball-and-net sports, taking drafting courses in high school, and tinkering with machines—activities traditionally considered masculine—all appear to contribute to strong visualization skills" (Ercolano, 1995).

Part of my desire to design the Mechanism Constructopedia came from my belief that there are many undiscovered ways in which children with deficiencies in spatial reasoning skills might be encouraged to take an interest in the basic ideas behind motion and mechanism and simultaneously strengthen their visualization abilities. If children learn an appreciation for the power of motion and control at a young age, then they are more likely to feel that they are worthy of creating tomorrow's technologies. Society will be better off for having a more balanced group of innovators who are active participants in the construction of the future.

3.3 Preliminary Investigations into the Need for a Constructopedia Tool

In this section, I describe my preliminary investigations to a first/second grade classroom to gauge the level of support needed in an electronic Constructopedia tool.

During my first year of graduate studies, I interacted with young children on a weekly basis, gaining insight from difficulties that emerged during design activities. I worked with Alma Wright, veteran teacher of twenty-five years, and her combined first and second grade class at the William Monroe Trotter Elementary School in Roxbury, Massachusetts. The racial and gender compositions of the classroom of twenty-four children broke down into nineteen African-American children and five Caucasian children, and thirteen boys and eleven girls. Because many of the children in the classroom came from lower income families, very few of the children had been exposed to commercial construction kits or had their own kits at home. As a progressive teacher with a firm conviction that working with computer technologies and engaging in construction activities provides children with necessary skills to succeed in an educational curriculum, Alma equipped her classroom with a range of technologies. In addition to a digital camera, video camera, and a television, the classroom contained two Pentium PC's and two Macintosh Power PC's that were connected to the internet, seven older Apple II computers for drill software, and a large LEGO play area with a substantial collection of LEGO bricks and Technic components such as gears, cams, and other mechanical pieces. The children were given several free periods during the week in which they could have their choice of 'LEGO Time' or 'Computer Time'. For my work with the children, I brought in Cricket technology from the MIT Media Laboratory and observed how the children approached design activities, both alone and in groups. Crickets, the name given to the new generation of programmable bricks, are the core component of a computational construction kit created by Randy Sargent, Mitchel Resnick, Fred Martin, and others at the MIT Media Laboratory (Sargent et al., 1996). The Cricket acts as a small programmable computer that can be used to control the behavior of a wide range of sensors and LEGO motors and can communicate to other devices through infrared technology. Using the Crickets to provide computational power, children can build robots, kinetic sculptures, scientific instruments, and other devices that they find personally meaningful using LEGO and an assortment of construction materials.

Though most of the Cricket design workshops and activities conducted by the Media Laboratory were targeted toward older children between the ages of twelve and sixteen, I had a particular interest in observing how younger children learned to build and think with Crickets. Having never worked very closely with children at the first and second grade level before, I had no idea what they would find most compelling about the design activities and what they would have difficulty understanding. For our first design challenge, I brought in a collection of Crickets, light and temperature sensors, LEGO motors, craft supplies, and a copy of Cricket Logo, the software used to program behaviors into the projects. I told the children to work in groups and build something that showed movement. We discussed what characterizes motion and talked about some examples of things moving in their daily lives. Not wanting to bias their interpretation of the activity, I did not provide them with any examples of what I thought they might build. At the end of the construction period, five of the six groups had small LEGO cars crawling at a snail's pace on the carpet and one group had disbanded due to creative differences. Interestingly enough, the children formed groups exclusively based on gender but all of the groups built similar vehicles. During another visit to the class, I brought in an example of a project that I had built using several Crickets and sensors. The construction knocked over a long chain of dominoes in sequences that were triggered when dominoes blocked light sensors, crickets sent signals to other crickets to initiate simple mechanisms, and LEGO minifigs fell on top of switches. After demonstrating the system to the children, I told them that their task was to extend the domino chain by each group building one simple contraption that would knock over another strip of dominoes. The children ran off excited and motivated to make the domino chain as long as possible. Two hours later when it was time to show and tell, the children returned with their solution to knocking over dominoes—cars that drove straight into the lineup with the help of Crickets and LEGO motors. Despite my hopes that an example with several different simple mechanisms might provide an inspiration for other objects to build, the children still returned to building cars. They attached their cars together and joyously programmed them to drive in a long convoy into the start of a domino chain.

During subsequent activities cars would always pop up in some form or the other, as solutions to a wide range of design challenges. The collection of LEGO Technic was consistently shoved to the side as the children scrambled to find more wheels. Perplexed by the children's fascination with cars, I finally asked one child why he didn't try to build something besides a car. His simple response was not that he had a particular fondness for cars, but that it was all he could build. Closer observation of other children confirmed that he was not the only one having difficulty building beyond his existing skills. When children began to build something with a different behavior, they would often desert it halfway through in frustration when they reached the limits of their experience. In their minds, building something, no matter how many times they had built it before, was better than making an attempt to be creative and having nothing to show and tell at the end of the day. Despite the fact that they were capable of building extremely creative projects with my guidance, such as pivoting diving boards and boat propellers, they could only return to what they made best—cars and other similar looking vehicles, when they were alone. I suspected that with additional support and coaching, children in this age range would be capable of building many simple and expressive motions using basic mechanical elements, like those found in LEGO Technic sets. It was with these thoughts in mind that I decided to build a web-based scaffolding tool that would help children investigate the motion they were trying to build, learn how to build it, and come away with the core idea of the mechanism behind the motion. By being encouraged to explore beyond the car plateau and learning to feel comfortable with the basic skills behind creating more complex constructions, young children will be able to express themselves in terms of motion and mechanism, and stimulate their spatial reasoning abilities at the same time.

4 System Design

4.1 Initial Concept Design

In this section, I describe my initial attempts to create manipulative tools for young children to think about motion and mechanisms and how I decided to add a software environment to make the system more effective.

From my observations that young children were capable of building creative mechanisms with extra guidance, I felt justified in designing a tool that would scaffold young children's construction activities. Not only would such a system provide children with support to excel beyond their existing level of building competency, it would allow children to enhance their spatial reasoning abilities and conceptual understanding of motion and mechanism. As I began the design process, I evaluated the benefits and drawbacks of using either a virtual environment or tangible manipulative approach to convey the core ideas behind motion and mechanism. In a virtual environment, the child could interact with a software program that investigates the workings of mechanisms through visual representations and three-dimensional simulations. A software tool could be developed within a multimedia framework, providing children quick access to information regarding building instruction and system constraints. Powerful graphic and auditory cues could be utilized to make sure that the children remain on a path which will help them attain their ultimate design goals. Contrastingly, the use of manipulative tools would account for direct observation and interaction with the intricate connections of mechanisms. The use of physical manipulatives as learning tools can be traced back to Friedrich Froebel's kindergarten 'gifts' in early educational activities. Froebel believed that these gifts, a collection of materials such as blocks, balls, and sticks, were the toys with which young children used to investigate abstract phenomenon that reflected the laws of science and nature. By making these concepts concrete, children are able to gain insight into advanced mathematical and scientific modes of thought (Brosterman, 1997). Recently, much work has been done to provide opportunities for learners in all stages of life, not just for children in kindergarten, to rediscover learning through manipulatives, particularly with technological enhancements that allow for an expanded range of investigation (Resnick, 1998; Resnick et al., 1998). From my own observations in the classroom of children's self-directed learning processes during design activities with Crickets, I initially chose to take a manipulatives approach to teaching young children about motion and mechanism. The use of manipulatives seemed to fit more naturally into the children's design methodology. When using Crickets to build vehicles or other construction projects, the children approached the design process from a framework of play. As they grew more comfortable with the idea that the Cricket was an extension of building with LEGO blocks and other construction materials, the children found that they could use the Cricket as a way to enhance their existing modes of play. The design process was broken up into several distinct phases: initial discussion of what they might build, description of their intentions through pictures and words, procurement of materials including Crickets and motors, construction of LEGO-based structures, interface between structure(LEGO) and control(Cricket), and re-entrance into realm of play. Only after the groups began to play with their final constructions did some children approach me with the interest of sitting at the computer and reprogramming their Crickets to experiment with different behaviors. It was clear that the children viewed the design process as a build-up to a play experience and did not want to take time out from the natural flow to sit in front of a computer, isolated from the play environment.

Based on these observations, I designed a system of manipulatives that would help children explore the core construction ideas behind motion and mechanism. This system initially consisted of six different mechanisms, each highlighting a particular type of motion or a key combination of mechanical pieces. For instance, the 'Flapper' mechanism highlighted three different modules—gear reduction, free rotation joints, and eccentric motion. Each principle was unique to a module of the Flapper mechanism. In the first module, a worm gear/twenty-four tooth gear combination reduced the speed of the motor when turning the central axle.

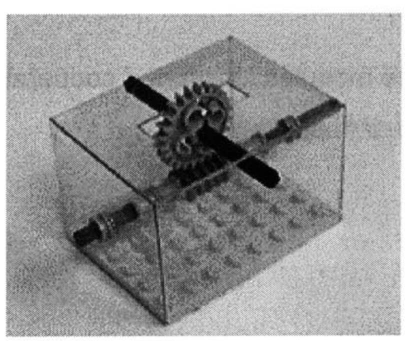


Fig. 1 Module 1: Gear/worm gear

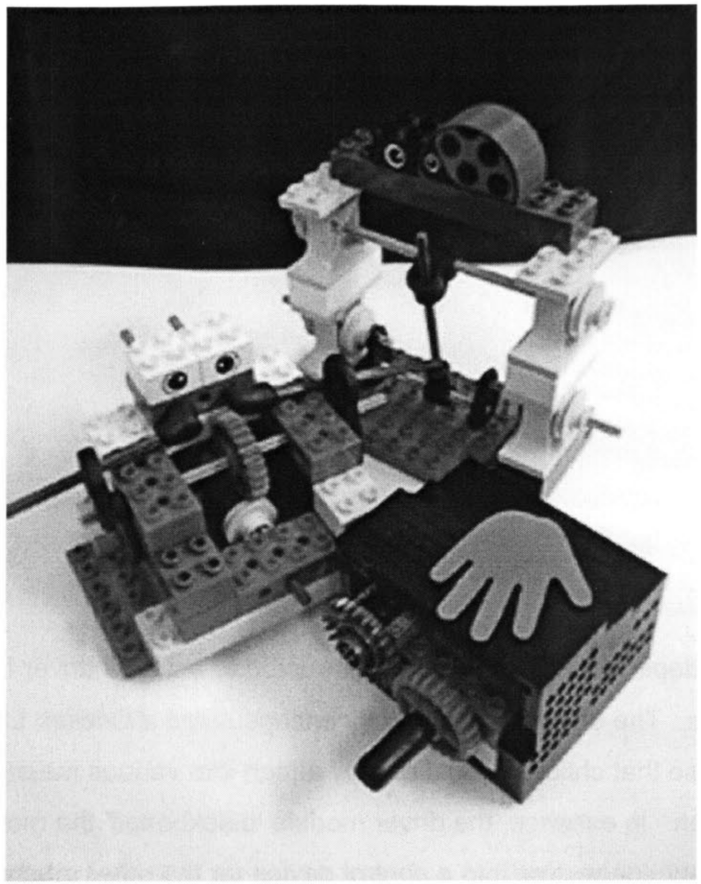


Fig. 5 Pre-built mechanisms constructed with LEGO Duplo: The Flapper and Driver Mechanisms.

Some of the benefits of the LEGO Dacta set included the use of large mechanical pieces, such as gears that range from two to three and a quarter inches in diameter, worm gears with one thread, and axles up to five inches in length. With mechanical components this large, it would be easy to see how only one thread on a worm gear is needed to drive the rotation of another gear oriented perpendicular to the original axis of rotation. Another advantage of the Duplo set was that the components where painted in bright primary colors. LEGO Technic targets an audience that is already at a competent level of construction, such that the gearing and mechanisms are meant to fade in the background as much as possible because they are not the primary focus of the construction. Because of this, the majority of Technic components are grey in color so that they will not distract from the colored bricks that usually make up the outer layers of the completed design. While this is useful for children who are already familiar with how mechanisms operate, I decided colorful mechanical pieces would be more appropriate for teaching a younger audience about mechanism because they draw attention to the

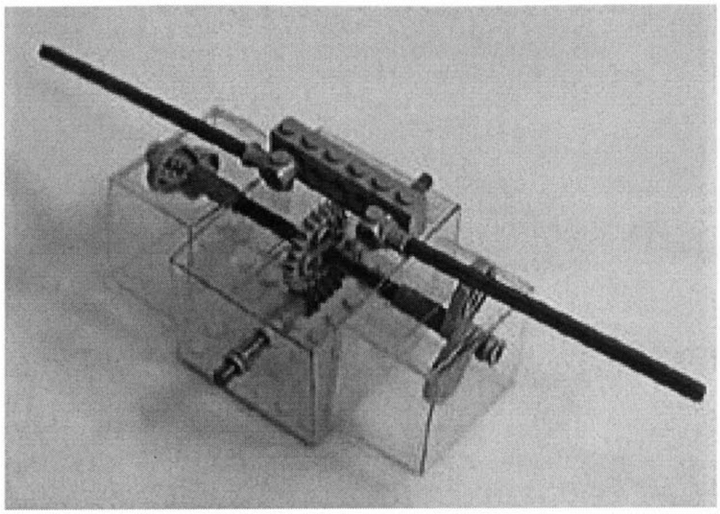
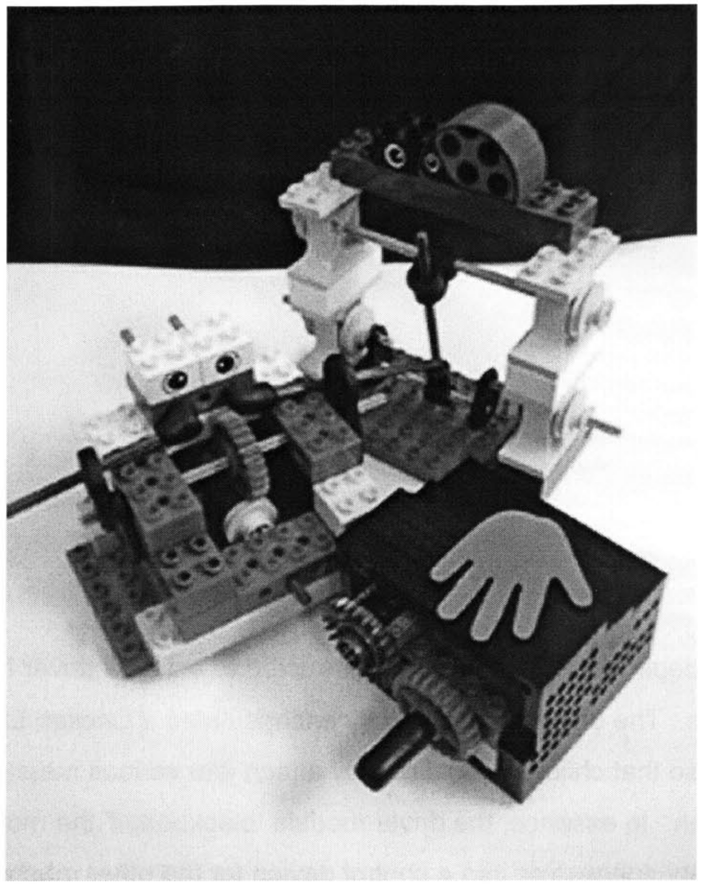


Fig. 4 Assembled Flapper mechanism.

Additionally, an independent module was constructed to act as a driver for the complete set of mechanisms. The driver module neatly encapsulated a Cricket, LEGO motor, and a gearing system so that children could quickly attach it to various mechanisms and start and stop the motion. In essence, the driver module 'blackboxed' the motor, power source, and element connectors into a control device for the other mechanisms. Though children could operate each mechanism by rotating the axles by hand, the driving module was designed to provide consistent power to a mechanism, allowing the child to observe the emergent behaviors of the module combinations.

Clearly, a limited collection of mechanisms cannot provide insight into every single existing mechanical connection known to humanity. But the system was designed to be a general introduction into some of the basic components of mechanical systems. On the structural design side of the system, my concern was that mechanisms that were built using LEGO Technic components would be too small for young children to catch the subtleties of motion. Technic is designed to allow for the creation of small compact mechanisms on a LEGO block scale. Fearing that children might view a collection of modules joined together in a small space as a single unit and not give consideration to individual connections, I decided to build the mechanisms on a larger scale. Using LEGO Duplo blocks and mechanical parts from the LEGO Duplo Early Machines set, I was able to enlarge the mechanisms by roughly three times the size of mechanisms constructed with LEGO Technic.



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Informal reactions of individual children from Alma's classroom who interacted with the mechanisms showed that the system facilitated group discussion about the collection of modules behind the motion and helped children to understand that specific mechanical components work in combination to create distinct behaviors. At the same time it was obvious that the use of the pre-built mechanisms was restricted to a discussion format and did relatively little to encourage creative play with the mechanisms or attempts to build their own mechanisms. Further observation and questioning revealed that, despite the benefits inherent to the color and size of the LEGO Duplo mechanical pieces, the mechanisms by themselves were just too big. Six- and seven-year old children in Alma's classroom had already moved beyond the use of Duplo sets, which LEGO markets primarily to children in kindergarten up to second grade. The children did not have enough experience to visually connect the large Duplo mechanical pieces with the smaller versions in their LEGO Technic collection so they did not feel comfortable imitating the mechanisms in a smaller Technic format. In a similar context, there were structural concerns about the largeness of the Duplo blocks themselves. Though the color and size of the mechanical pieces were assets, the Duplo building blocks were also colorful and large, obstructing the view of some of the underlying modules because of bulky structural requirements and lessening the colorful impact of the components. The mechanisms themselves, most likely because their largeness contributes to the perception that they are a single entity, did not provide enough emphasis on the idea that they were collections of modules, which is a core concept behind the idea that complex system behaviors are a result of the interactions between smaller components of the system.

Though the Duplo mechanisms showed potential for increasing discussion about mechanical motion, I did not want the models to be seen as an isolated learning tool, but as a system that could be explored in the context of fantasy and play, a key motivational factor for children learning new ideas. Because of this, I wanted to make the mechanisms smaller so they could be easily integrated with standard size LEGO bricks. While this would mean using LEGO Technic pieces which are smaller than the mechanical equivalents in the LEGO Duplo set, I believed that it would still be possible to create mechanisms that clearly accentuated the individual modules responsible for the resulting motion. My initial small-scale mechanisms were designed to be encapsulated within a clear plastic box with LEGO-compliant spacing of holes on all sides of the box, except for the top and bottom of the box which were small LEGO plates with studs, giving children the ability to attach them to their existing creations or build around the box and mechanism. Specially colored Technic components, that were more eye-catching than the standard grey pieces, were anchored and connected together within the plastic box.

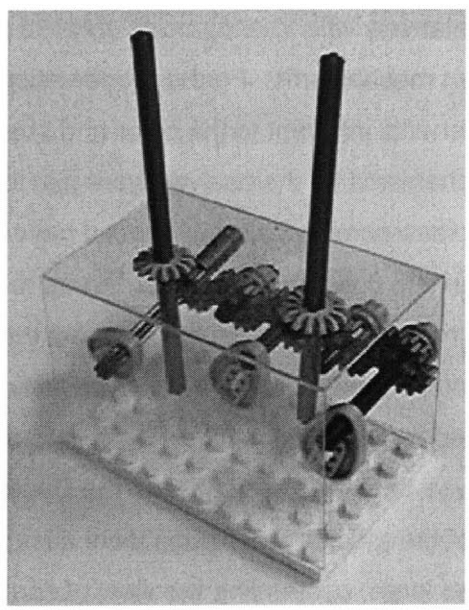


Fig. 6 Initial prototypes of smaller pre-built mechanisms, constructed using LEGO Technic and encapsulated in clear plastic.

The smaller, more compact nature of transparent mechanisms allows children to clearly see the mechanical components in operation and gives them the ability to integrate pre-built mechanisms into their construction activities. But while it is useful to have pre-built mechanisms for use in a creative context, there is no guarantee that these existing mechanisms will offer enough incentive for children to imitate or explore mechanical concepts in more depth. In this situation, mechanism manipulatives clearly provide additional motivation for children to make scientific inquiries in the context of open-ended play, but the use of these manipulatives needs to be supplemented by an additional learning tool in order to make the construction experience more complete.

A software component to the system in the form of a Mechanism Constructopedia was a logical addition for use in combination with the collection of pre-built mechanisms. Though the mechanism system would help lead children to active play and interaction with mechanical constructions, there would be no method to provide additional support or way to ascertain that the children were coming away with the core ideas behind motion and mechanism. Thus there was no provision for a system of scaffolding, only an introduction of mechanism into the play environment. A true mechanism construction scaffolding tool would provide children with additional support and feedback as they investigate how to build a mechanism, what types of mechanisms create specific patterns of motion, and how motion in the real world could be imitated and controlled from a mechanical standpoint. By using physical manipulatives in association with a Mechanism Constructopedia, the biggest benefit afforded by this dual approach to learning about motion and mechanism would be a reinforcement of visual representations at a concrete level. Because visualization skills are integral to the design and understanding of mechanisms, a software component would provide an alternative representation of mechanisms, modules, and individual components via three-dimensional images and graphics. Physical manipulation of pre-made mechanisms and construction of modules from scratch would enable children to make concrete connections between the images they explored on the computer screen and the pieces they hold within their hands. Once these concrete relationships are created, the software would provide further vision for practical application of this knowledge by emphasizing the possibilities inherent in mechanism construction at all levels of building competency. The software and manipulative approaches would work together to supplement the weaknesses of each separate system, providing a more complete presentation of concepts relating to motion and mechanism and encouraging expressiveness through these ideas.

4.2 Framework for Software System Design

This section discusses the theoretical framework around which the software component, the Mechanism Constructopedia, is designed. I talk about the vision for the system, the implementation of scaffolding techniques, and subgoals for the system and their design rationale.

4.2.1 Overview of System Model

The Mechanism Constructopedia was designed to help the user recognize the existence of distinct relationships between the following categories: Motion, Mechanism, and Mechanical Pieces.

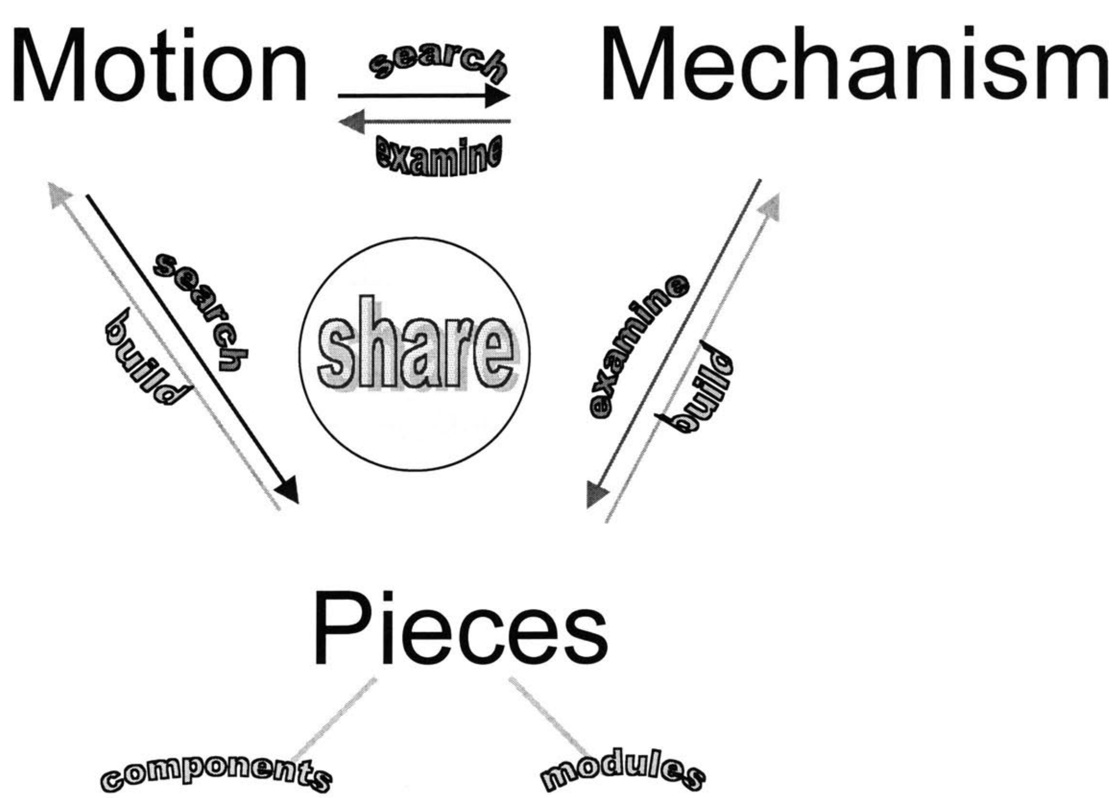


Fig. 7 Overview of the Mechanism Constructopedia's Trifold Entry System.

Each of the three categories provides an entrance point into the exploration of different aspects of mechanism construction. This purpose of the trifold system is not only to give children a feeling for how these categories interrelate and overlap, but to accommodate several different approaches to learning. As mentioned in the introduction, Sherry Turkle and Seymour Papert observed two different styles of programming in an introductory college-level computer science course. One type of student approached problems through methods of bricolage, or playing and tinkering with bits and pieces of a system in order to build from the bottom up with a set of well known materials (Turkle and Papert, 1992). Conversely, the other type of student used a top-down approach, in which a general structure was planned ahead of time and used as a structured guide during the design process. These two approaches to programming can be generalized as representative of two different styles of learning new material. In the Mechanism Constructopedia, the three entrances to the system are designed to support the learning styles of the planner and the bricoleur, as proposed by Turkle and Papert, and additionally for a different approach to learning that is more applicable to construction activities: that of the examiner. In the context of mechanisms, children can choose one of three different approaches to building. First, they can become a bricoleur, acquainting themselves with the basic components of mechanical constructions and building a mechanism that emphasizes the attributes of individual pieces or a combination of several of those components, known as modules. Second, they can choose to plan what they want to build ahead of time, deciding on the type of motion they will be creating and finding components to model that vision. Finally, they can choose to examine an existing mechanism that captures their interest and break it down to investigate how it works. Knowledge gained from the examination process can be used to build different mechanisms with similar key components. From Figure 7, it can be seen that each of these learning styles corresponds to one of the three entrances into the Mechanism Constructopedia System. By choosing to start with motion, children start with an idea of the type of motion they want to construct and search through lists of words and images to find an appropriate mechanism. This entrance is most closely associated with the planning style. If children begin with pieces, here being defined as both modules and individual components, they are looking to learn how particular pieces and modules operate in order to construct a certain behavior in the motion. This is the approach of the tinkerer, or bricoleur. Finally, if children enter into the system through mechanism, they have already selected a pre-existing mechanism that they want investigate in more depth. They will use the knowledge they gain from studying this mechanism and gain an understanding of the driving components behind the motion. This approach is typical of examiners. Though children can choose whichever entrance into the system that best suits their learning style, the three categories link to one another through the investigation methods listed in the main menu: Search, Build, and Examine. Unifying all of these approaches together is the common space in between the categories of Motion, Mechanism, and Pieces. This area represents the community of users that share the results of their projects with others and add to the knowledge content of the system.

4.2.2 Criteria for the Addition of Scaffolding Techniques

The design for the Mechanism Constructopedia system also focused on criteria integral to the implementation of educational scaffolding techniques. Unless the software provides enough support for the child to move beyond his or her own individual functional competency in mechanism construction, it will not be a successful scaffolding tool. The criteria are for educational scaffolding techniques are as follows (McKenzie, 1999):

1) *Effective scaffolding software should provide clear instructions.* The Mechanism Constructopedia was designed to allow quick access to information regarding motion, mechanism, and components. As children progress through the software application, menus provide them with options that keep them in control of the learning process. If at any time the child becomes lost, they can easily return to the main menu and begin their investigation anew.
2) *Scaffolding tools should clarify their intentions.* The use of the Mechanism Constructopedia in collaboration with the motion modules aims to familiarize students with the components of mechanical motion and to provide a support structure for learning how to build mechanisms. It aims to give children an understanding of the idea that mechanisms are built from collections of subassemblies, each with distinct behaviors. The Constructopedia also helps children make connections between mechanisms and other sources of motion they observe on a daily basis.
3) *Scaffolding keeps students on task.* From an educational standpoint, keeping children on task is typically interpreted too strictly, with the educator acting as watchdog to ensure that the student does not deviate from the predetermined activity. In the context of the Mechanism Constructopedia, the child's task is not to follow a structured path to a single goal, but to utilize resources to remain focused on

the vision for their own personal project. As the students use the system, they will discover that all three of the primary categories are linked closely through overlapping content, so it is difficult for the child to come to a dead end in the learning process.

4) *Scaffolding offers assessment to clarify progress.* Though there are no direct assessments administered within the Mechanism Constructopedia in the form of system feedback, the ultimate assessment that a child can receive is the successful construction of a working mechanism. This creation can then be used during play or documented in the public workbench space of the Constructopedia system in the form of an online show-and-tell. Within the Mechanism Constructopedia system there is a public collection of 'workbenches' that allow children to showcase their own mechanism constructions. Positive feedback from other contributors to the workspace and imitation by others are other methods of assessing one's increasing level of competency.
5) *Scaffolding points students to worthy sources.* Central to the theory of scaffolding is the idea that worthy sources of information provide children with the tools they need to take control of their own learning process. The Mechanism Constructopedia software itself provides a valuable reference for children as they learn from the construction process. If the child seeks examples of similar work, the Constructopedia directs children to the virtual workbench space in which other students and system users have documented their projects and experiences.
6) *Scaffolding reduces uncertainty, surprise, and disappointment.* Also known as "the Teflon lessons—no stick, no burn, no trouble", educational scaffolding techniques help to maximize efficiency and learning without causing children to feel frustration at their lack of skill. The Mechanism Constructopedia provides detailed instructions and explanations for the construction of mechanisms, giving children the confidence to explore beyond the intricacies of mechanism design and connection into the expressive qualities of motion and mechanical control.

With these ideas in mind, the Mechanism Constructopedia was designed to scaffold children to higher levels of comfort and competency in the study of motion and mechanism.

4.2.3 Target Goals for Progression Through the System

In addition to considerations given to scaffolding criteria, I designed the software around key stages through which children progress as they learn to build with mechanisms. In many ways, progression through these phases is similar to following a scientific method of investigation to solve problems. I focused on the following progressive target goals for children's explorations as they seek to enhance their understanding of mechanism construction:

> **Investigate.* By learning that there are many different approaches to simulating motions and building mechanisms, children will learn that there are often multiple solutions to one problem, particularly when working on projects with open-ended goals. Initial investigation of a range of possible solutions to a design challenge will frequently manifest unforeseen problems and point to benefits of alternative methods and materials.
>
> **Divide and Conquer.* In the proposed five sequential levels of geometric reasoning in young children, the initial level is purely visual (VanHiele, 1985). In introductory activities with geometric configurations, children tend to view shapes as a whole entity and not the sum of its parts. Though this observation was in the context of children's understanding of geometry, it is also reflected in their interactions with mechanisms. Frequently, children do not understand that the final, observable motion is a result of many different subassemblies of mechanisms working together to create that behavior. When attempting to make their own mechanisms, young children will often abandon the task in frustration because they attempt to solve the entire thing at one sitting. If they recognized that it would be more effective to build parts of the system and then combine them into a whole, they might not be as discouraged with their progress (Papert, 1996). In one study of children working with the direct support of their mothers, children were found to perform best at spatial construction tasks when their mothers simultaneously performed two tasks. First, the mother stepped back and allowed the child to control the investigation, while at the same time, the mother "chunked" or divided the task into smaller, more manageable pieces (McCarthy, 1992). If children approach mechanism design in the same manner

by connecting subassemblies together, they will receive sufficient motivation to continue building.

**Manipulate.* As children grow older, learning becomes more abstract and interactions with manipulatives are less frequent (Resnick, 1998). This is particularly frustrating for young children when the concepts being taught are more abstract and difficult to grasp without tools to aid in visualization. But sometimes the isolated use of manipulatives will not convey the core ideas behind some mathematical and scientific concepts. In the Mechanism Constructopedia, children are encouraged to examine the components and core concepts of motion within pre-built mechanisms and to ultimately use mechanical components with support from the system to create their own manipulatives. By making connections between the visual representations of mechanisms in the Mechanism Constructopedia and the actual act of creating and manipulating a mechanism, children will gain a more practical understanding of the possibilities and limitations of mechanism construction.

**Connect.* Motivation is a primary factor in the learning process for children and adults. One method for maintaining motivation within an educational context is to provide ways in which children can feel more connected with the material. While it is difficult for most children to make a personal connection with mechanisms, children seem to have an inherent attraction to motion, both natural and man-made. The Mechanism Constructopedia gives children the option of searching for mechanisms that imitate motions they encounter in their daily lives, like the flapping of birds' wings or the twisting and lifting motion of a bottle opener. Though some of the connections made between a mechanism and a similar motion found in the child's environment might not emphasize the exact same implementation of the motion (i.e., use of similar mechanical principles), they demonstrate that motion is found in all areas of human life and that basic patterns of motion can be replicated in the form of mechanisms.

**Look at Examples.* Children can also enhance their understanding of mechanisms from close inspection of mechanisms built by others. In the Constructopedia system, children can examine the work of others in two different ways. First, they can use the pre-built mechanisms. By playing with the mechanisms, taking them apart, or accessing information about them through the Constructopedia, children can learn how the mechanism operates and what components are needed to replicate the most compelling aspects of the motion. Another method for learning by example within the Constructopedia system is to utilize the resources within the personal workbenches. By looking at the work of others who have learned to build mechanisms from the Constructopedia system, children will be able to find inspiration for project ideas or discover distinct modules that others have been created for certain tasks. Generalizations are often developed from exposure to examples of successful work (Chi and Bassok, 1989). Multiple examples can help a child make inductions about basic principles of motion and mechanism.

**Reflect.* Upon completion of a project, self-reflection is necessary for the child to make assessments about the successes and failures of the design process. When a child is completely absorbed in the tasks of investigation and construction, he or she cannot be objective about evaluating the experience. By taking a moment to reflect on the positive and negative aspects of the construction activity, children learn what they might do differently during future challenges. Edith Ackerman believes that children "must take the role of the external observer or critic and they must revisit their experience 'as if' it were not theirs. They need to describe it to themselves and others, and in doing so, they will make it more tangible" (1996). After creating a mechanism, children are encouraged to engage in this reflection process by sharing their work with other users of the Mechanism Constructopedia. By writing a brief description of the mechanism that they investigated or created, children will be able to objectively assess their experience and post it in an environment where other children can view it and provide feedback.

Though these target goals are not explicitly pointed to as a guide to be followed through the learning process, the concepts behind them are reinforced within the framework of the system. Because each individual has a unique approach to learning, not all of the target goals might be attained during the course of a single design experience. But it is hoped that consistent use of the tool will allow children to understand the reasoning behind these goals and gain an appreciation for the ultimate satisfaction resulting from completing the design process.

4.3 Mechanism Constructopedia Prototype

In this section, I provide technical specifications for the software portion of the system, also known as the Mechanism Constructopedia. Additionally, I describe how the user navigates through the system during the learning process and how the pre-built mechanisms interface with the software.

4.3.1 System specifications

The Mechanism Constructopedia is a software tool that combines Java applets, Javascript, and three-dimensional graphics into a web-based system. Though the system could have been implemented as an application and distributed as a CD-ROM like the majority of educational software, the online format offers several benefits. In 1999, the School Technology and Readiness Report found that the percentage of public schools with Internet access more than doubled, from 35 percent to 78 percent, between 1994 and 1997 (CEO Forum on Education and Technology). As these numbers continue to increase over the coming years, more children will be exposed to the resources of the Internet. Software designed for an online format will take advantage of the expanding popularity of the web and eliminate the need for downloading applications onto a local computer or the use of CD-ROM's. The most important implication of web-accessible software is that it can allow for direct involvement and feedback on the part of the users. By nature, the format of applications or CD-ROM's dictates that the computer is providing the user with information in a one-way learning process. With a web-based framework, it is possible to allow users to make contributions of their own ideas to the system, expanding the functionality of the system to reflect the needs of the user that were not addressed in the content of the software. In the Mechanism Constructopedia, children can take advantage of the personal workbench space to share images and text descriptions with other users. The process of documenting a project for a public workspace will help facilitate reflection upon the design experience.

Because interactive software responds to the input of users, specially designed interfaces are required within the graphical environment. When this type of interaction is required for web-based systems, the capabilities of the standard HTML language must be extended. Java applets and Javascript are designed explicitly for this purpose. Java applets are applications designed specifically for use over the Internet. Applets are dynamically downloaded across the network and executed in any Java compatible browser. The difference between applets and other downloadable media items is that applets can react to user input and change the content of the webpage accordingly, which is essential in the context of learning tools. The Mechanism Constructopedia utilizes the Java 2 Swing classes that contain flexible components such as buttons, scroll panes, and text fields to accept user input. The benefit to the use of Swing components is that they are written entirely in Java code and platform-independent. Similarly, Javascript is a scripting language that allows you to create dynamic web pages. It is not as powerful as the Java language, but it is easy to implement and interfaces quickly with HTML. In the Mechanism Constructopedia, Javascript is used to make the system menus more dynamic and responsive to mouse movements by the user.

Used in combination with motion manipulatives, The Mechanism Constructopedia software tool encourages children to make stronger connections between visual representations of motion and the tangible complexities of mechanism construction. Children are encouraged to use the Constructopedia software to investigate the inner workings of pre-built mechanisms. Using RF-ID tag technology developed by Rich Fletcher at the MIT Media Laboratory (1996), the software redirects the child to relevant information about specific mechanisms. By embedding a tag in the bottom of each pre-built mechanism and programming the tag reader to recognize a unique signal, the web-browser is automatically redirected to the appropriate web page, containing details regarding the modules of motion contained within the mechanism and directions for building up from those modules to a complete mechanism. The tag reader is connected through the serial port of the computer and configured to register changes when a tag is swiped over the top of the reader. Though the Mechanism Constructopedia is freely accessible to those with Internet access, tag readers and pre-built mechanisms will need to be purchased for use in tandem with the software. Because several entrances into the exploration of mechanisms is accounted for in the framework of the software, it is possible to use the Mechanism Constructopedia as a stand-alone tool, but the richest experience is gained when the pre-built mechanisms reinforce the manipulative aspects of mechanism construction.

There is one introductory menu and three secondary menus that control the content of learning provided by the Mechanism Constructopedia. The main menu after the title screen provides an overview of the possibilities of exploration within the system.

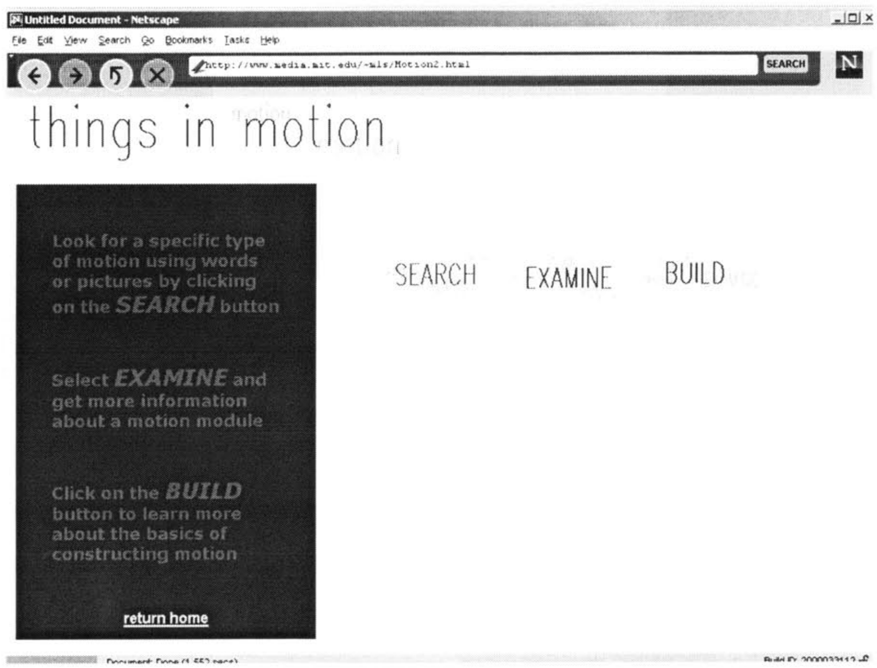


Fig. 8 Primary menu in Mechanism Constructopedia system.

Each one of the three menu options: Search, Examine, and Build, corresponds to a different approach to building mechanisms.

4.3.2 Search option

If a child chooses the Search option, he or she is redirected to a page containing two pull-down menus. Instructions prompt the child to search through a menu of text phrases if they have a verbal sense of what they want to build, or to browse through a second graphical menu of pre-built mechanisms if they are hoping to simulate a particular type of motion.

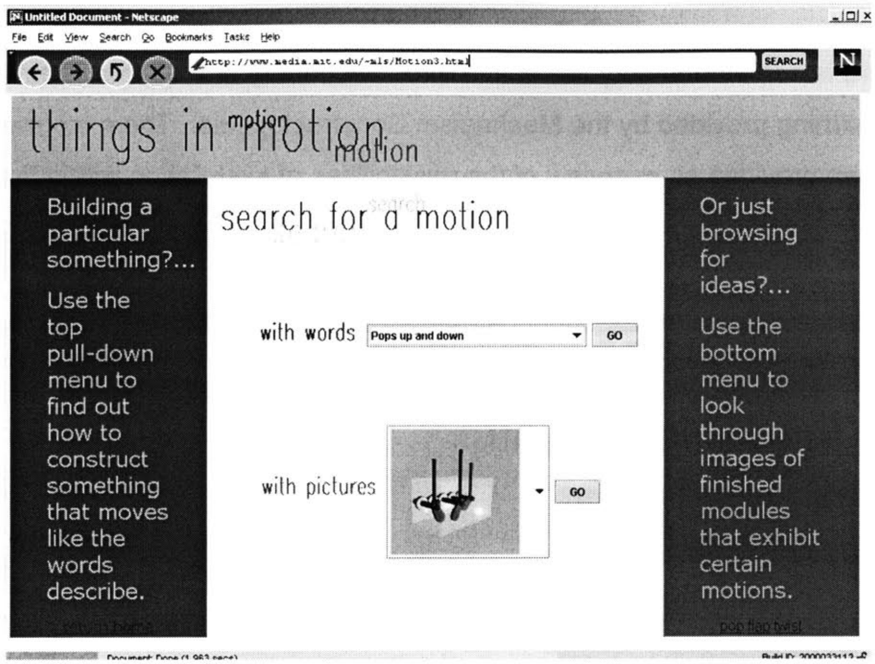


Fig. 9 Menu for the Search option.

Once the selection is made, the web browser is redirected to a page that highlights a particular mechanism that satisfies the user's motion criteria. For instance, if a child is looking for something with a motion that flaps like a bird, the browser is redirected to information about 'The Flapper' mechanism.

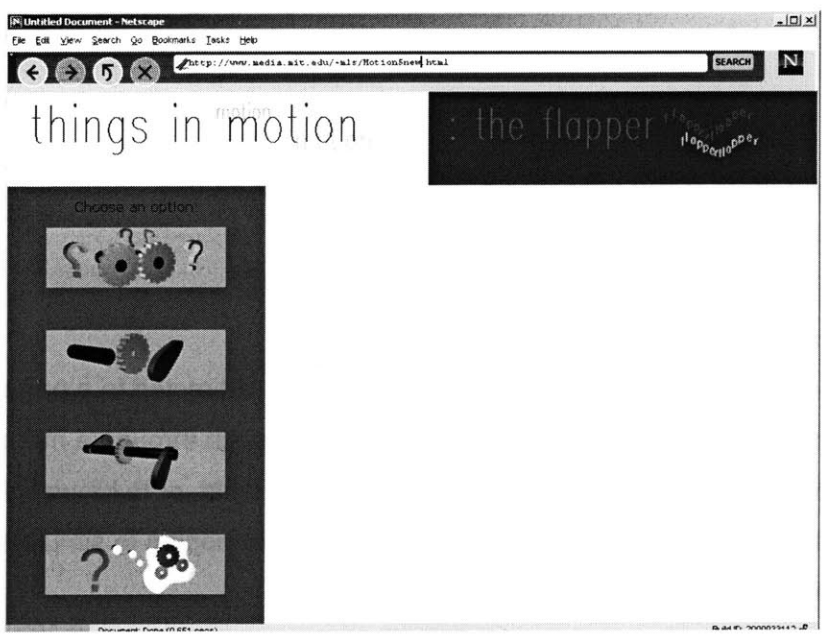


Fig. 10 Menu Option for The Flapper mechanism.

When information about a particular mechanism is requested, a menu is provided with four additional choices, each one addressing one of the following questions that the child might have about the motion: how does this work?, what pieces do I need?, what else can I do with this?, and what does this remind me of?. If the child selects the option to find out how the mechanism works, a screen appears with a verbal explanation of the motion and an animation of the motion in action.

Fig. 11 Detailed information about how the Flapper mechanism works.

An additional menu option describes how the entire mechanism is broken down into modules and which individual mechanical components are needed to build the construction.

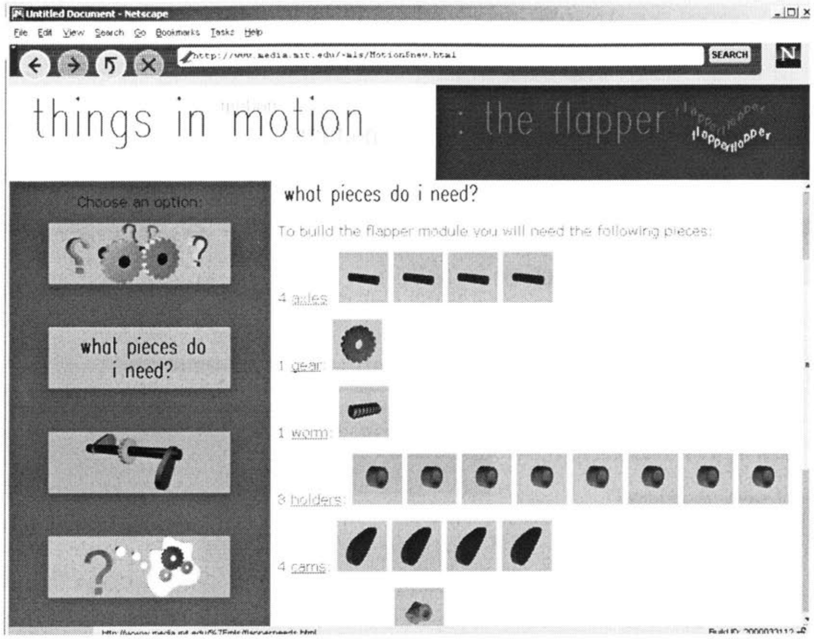


Fig. 12 Detailed information about modules and components contained within the mechanism.

The child can also find out about other uses for the mechanism by selecting the third menu option. By choosing to investigate what else can be done with a particular mechanism, a list of projects created by other users of the Constructopedia system appears, along with images of the projects and their creators, and a paragraph of text describing what the child was trying to accomplish with this construction. If a child likes the work and ideas of a particular user, they can follow links to view the personal workbench of that user, containing additional project ideas and completed mechanisms.

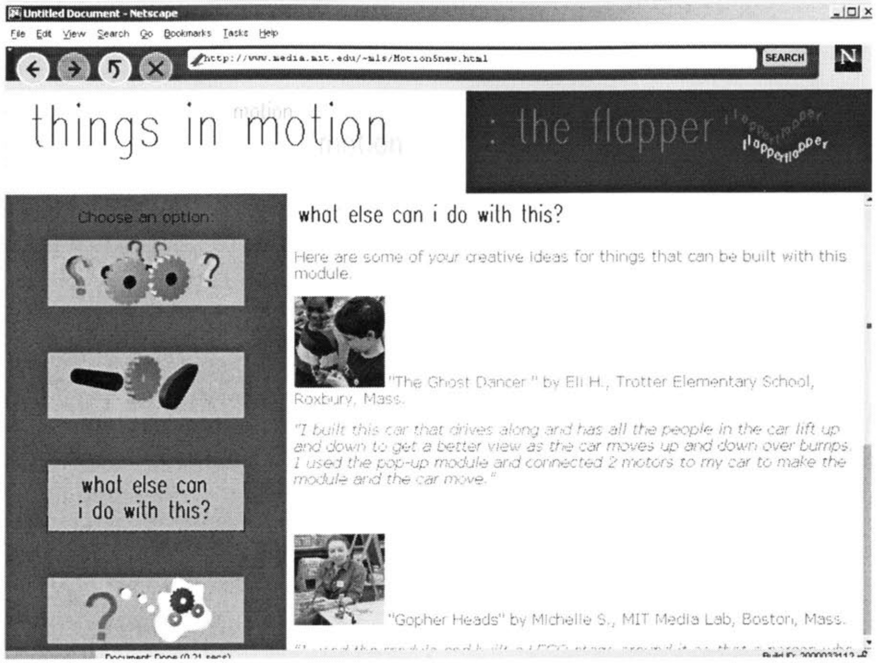


Fig. 13 Menu option to discover other uses for a mechanism.

Finally, the child can also make connections between mechanisms and similar motions in the world. By selecting the last menu option in this area, the child can see images of mechanical systems and biological entities that reflect the core motions behind the final mechanism. For instance, the flapper mechanism mimics the motion of a bird's wings, or the up-and-down rotation of two halves of a drawbridge. Making these connections helps to provide the child with a clearer understanding between the practical applications of mechanism and its reflections in nature.

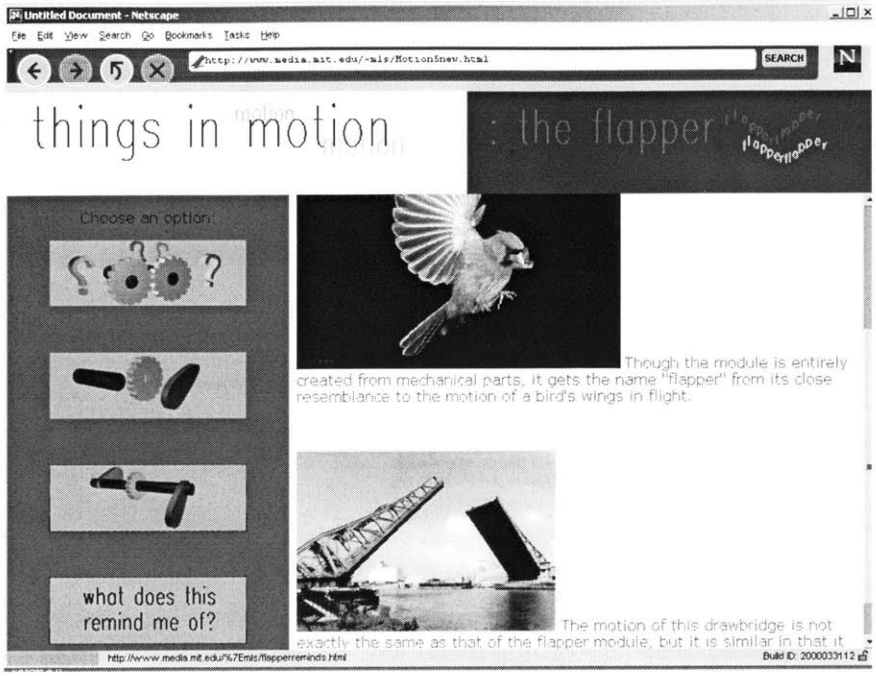


Fig. 14 Reflections on the practical applications of mechanisms.

4.3.3 Examine option

If children instead favor the approach of investigating pre-built mechanisms and want to learn about the core modules of motion behind a particular mechanism, they can choose the Examine option from the main menu. Once this option is selected, the web browser is redirected to a new page prompting the child to choose a pre-built mechanism to investigate more closely.

Fig. 15 'Examine' menu option.

The screen directs the child to hold the selected motion mechanism over the scanning mouse pad. The scanning mouse pad is essentially the tag reader mounted under a normal computer mouse pad. When a child swipes a pre-built mechanism over the mouse pad, the tag reader identifies the tag contained within the bottom of the mechanism and redirects the web-browser to the same web-pages accessed during the Search option, described above. For instance, if the Flapper mechanism was scanned over the mouse pad, the main page for the Flapper would appear on the screen, providing the user with the same four menu options described earlier.

4.3.4 Build option

The final option on the main menu gives children the option to build a mechanism from the bottom up, using information about individual pieces and modules representing core primitives of mechanical motion. After choosing the Build option, children are given the choice of either learning about the functions of individual mechanical pieces or modules.

Fig. 16 'Build' menu option.

If a child wants to learn what a particular mechanical piece looks like or the typical uses of such a component, he or she will choose the 'Component' option and be directed to a graphical menu of the common mechanical parts referenced in the Constructopedia system.

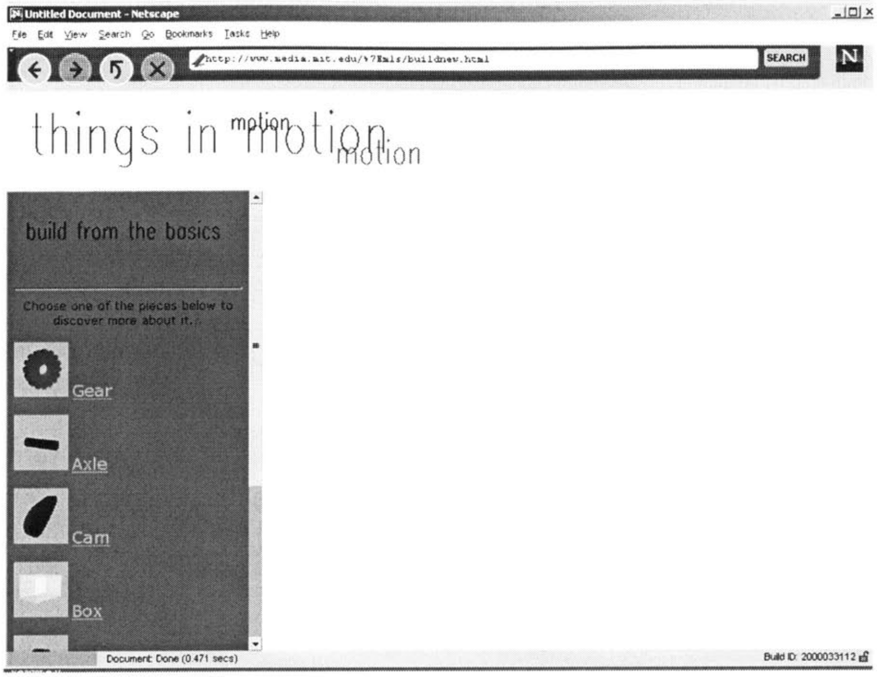


Fig. 17 Description of components.

From this menu listing, children can choose an individual component and additional information about that mechanical piece will appear. For instance, if the child selects the image of a gear, more information will be provided about how gears translate rotation from a power source and how they are used in combination to slow down or speed up motion. Links are provided for the child to access mechanisms that can be made using gears and gear combinations.

If the child instead chooses to access information about modules, they will be provided with information about basic mechanisms created from the assembly of two or three essential mechanical pieces into a smaller unit or module, such as a wheel and axle or gear and worm gear combination.

Fig. 18 Description of common modules used for building mechanisms.

By learning to connect several modules together, children will simplify their design process and minimize frustrations encountered when starting to build from scratch with concepts they do not yet fully understand. Again, links are provided for the child to investigate which mechanisms contain certain modules.

4.3.5 Workbench spaces

Finally, one of the most important benefits of the Constructopedia software is the personalization of virtual workbench spaces by users of the system. The workbench spaces provide children with areas to post their own work and to look at the work of others, offering support through a virtual community with common interests.

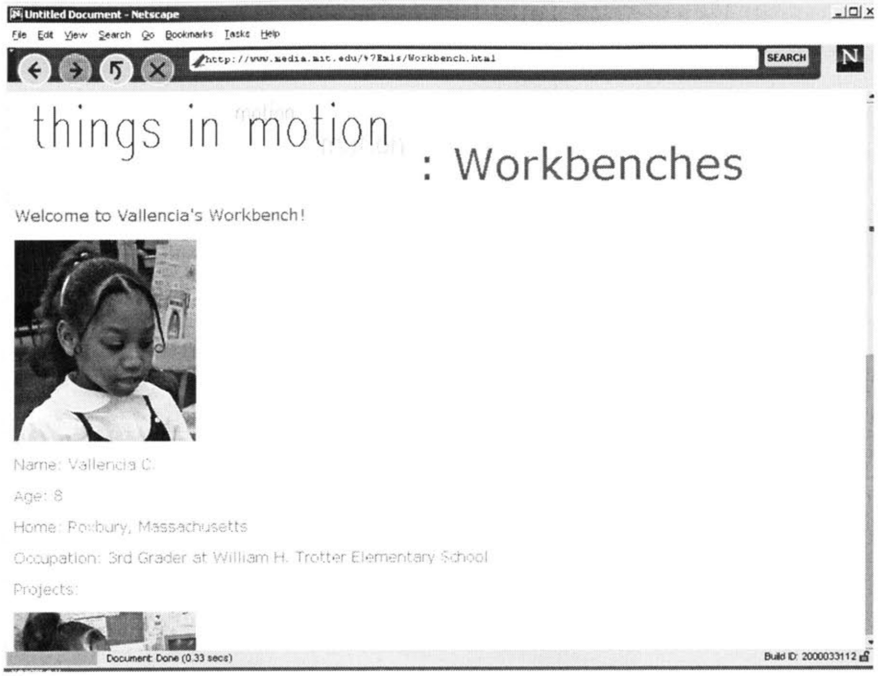


Fig. 19 Virtual workbench spaces.

4.4 Final Mechanism Prototypes

This section provides technical documentation for the creation of pre-built mechanisms, for use in association with the Mechanism Constructopedia software tool.

The final versions of the pre-built mechanisms were constructed from one-quarter- and one-eighth inch thick sheets of clear acrylic. A laser cutter was used to cut out the basic rectangular plates that assemble together to form a structure upon which mechanisms can be built. Each acrylic plate contains several rows of three-sixteenth diameter holes with LEGO standardized spacing. The plates connect together through an interlocking system of tabs and holes. Aside from providing a more robust structure to facilitate mechanism construction, these plates allow children to quickly build up a relatively large structure without the time required for stacking LEGO Technic beams together.

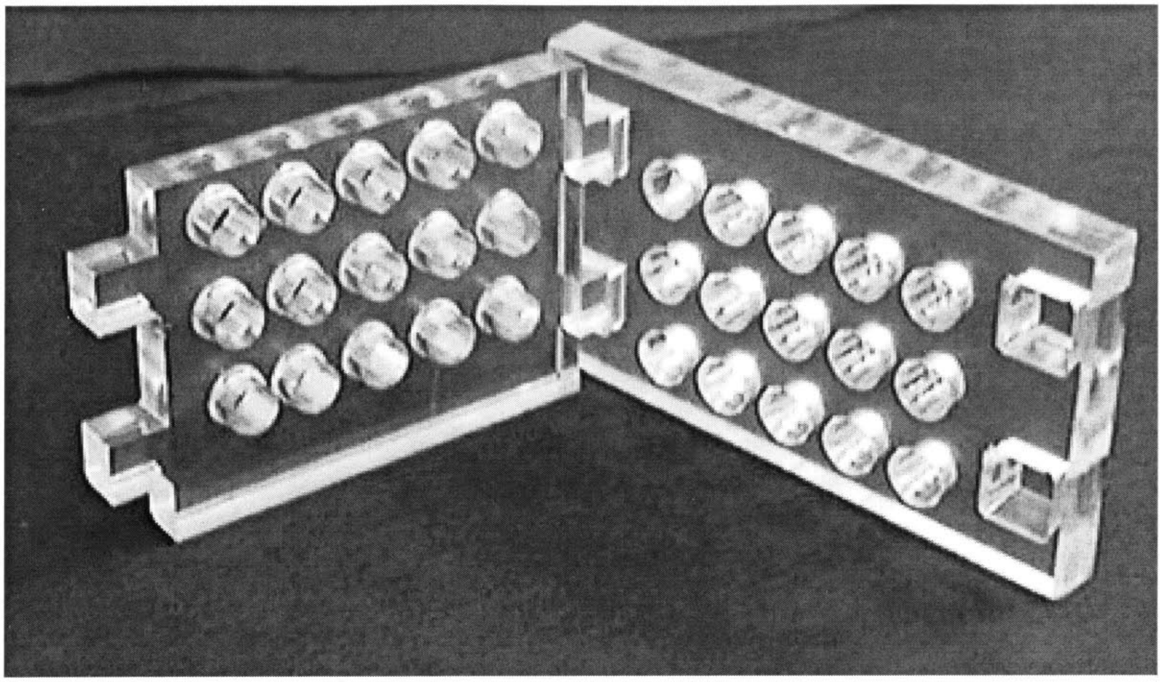


Fig. 20 Acrylic plates with LEGO Technic compatible holes.

Consequently, more time can be focused on building or investigating the mechanism as opposed to the structure. Clear acrylic was chosen to create transparency and give children an unobstructed view of the components and modules within the construction. The RF-ID tags are embedded into a separate clear box that attaches to the bottom of a pre-built mechanism. Because the acrylic provides more stability than the previous prototypes made out of thin-walled plastic, modules can easily be attached and removed from each other, giving children the ability to build up larger motions from groups of modules.

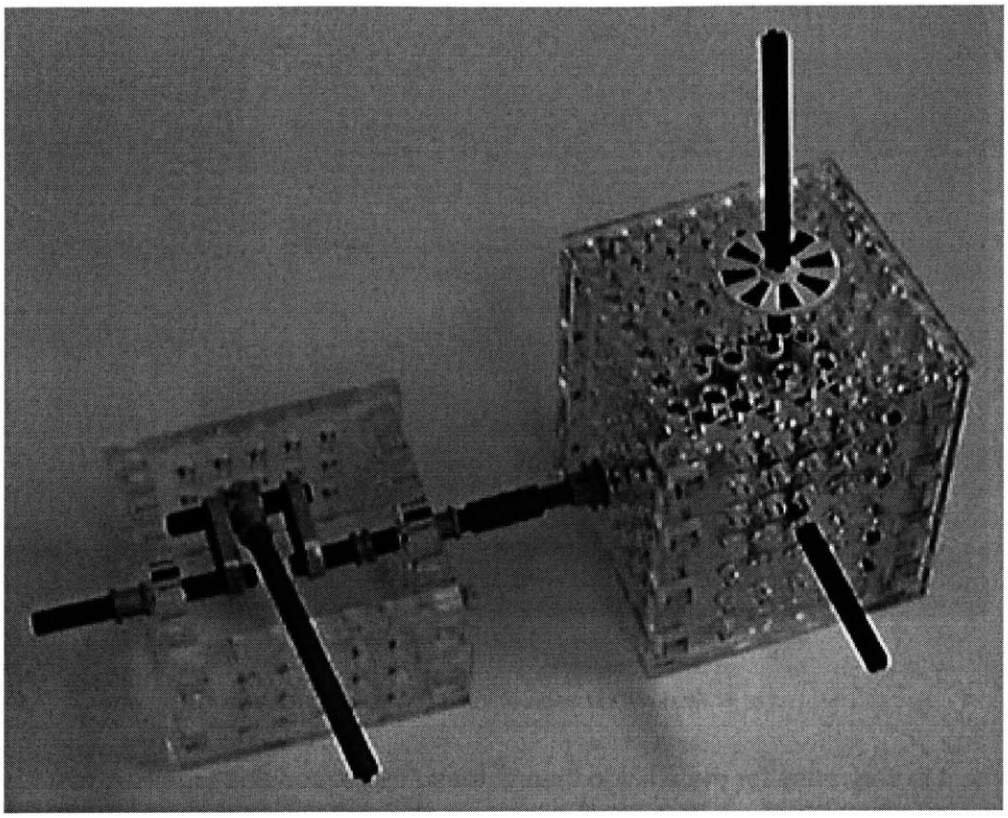


Fig. 21 Modules connected together to make a new mechanism.

Children can also easily separate the acrylic plates and see how modules work together to create motion. For instance, if a child investigated the Twist-and-Lift mechanism, they would easily be able to break it apart into three separate sections: a worm gear, a cam follower, and a gear and cam combination (see Fig. 22, left to right).

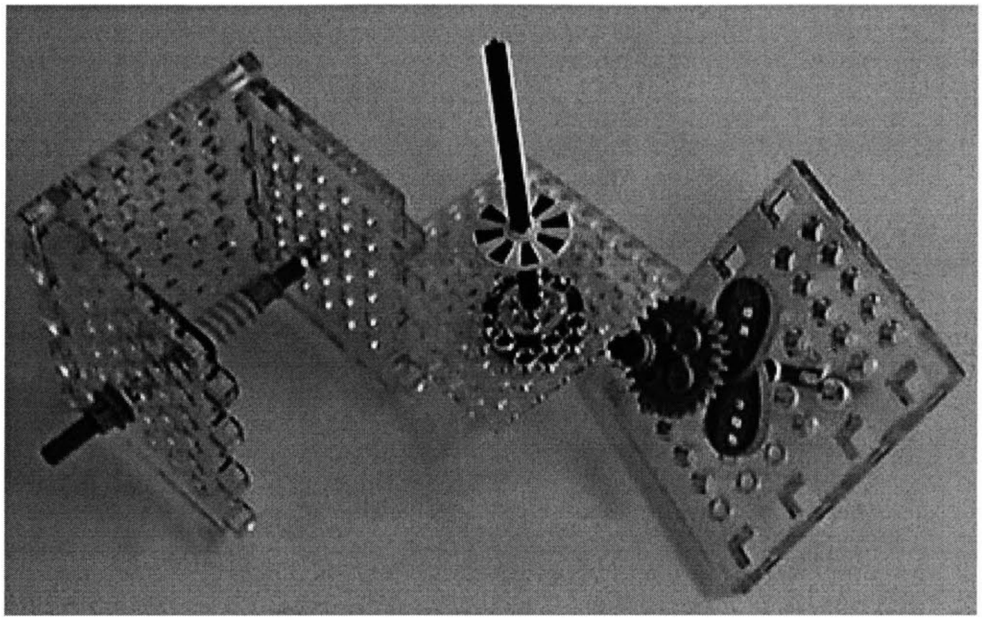


Fig. 22 Twist-and Lift mechanism broken into smaller modules.

Similarly, it is very easy for the child to then fit these three modules together, resulting in the fully assembled mechanism.

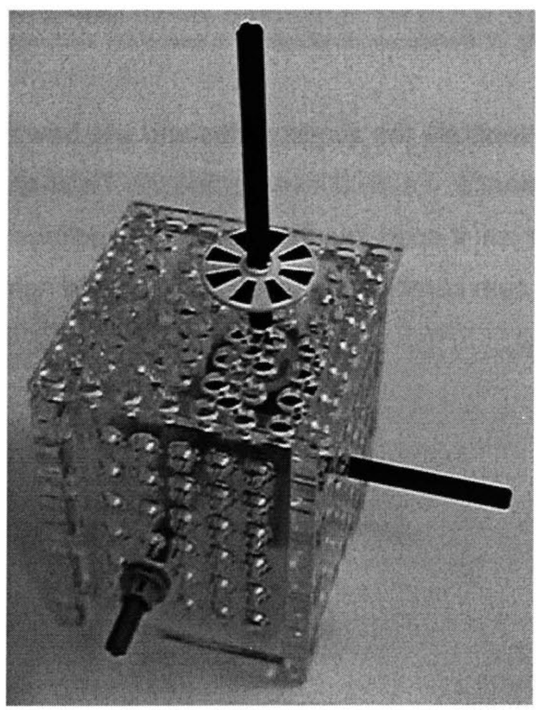


Fig. 23 Twist-and Lift mechanism fully assembled.

These acrylic modules are designed to allow a young child to quickly assemble and disassemble mechanisms without encountering frustration from the initial need to build up appropriate structures before even beginning an investigation into the use of mechanical pieces.

5 Assessment and Plans for Improvement

5.1 Observations in the Classroom

This section documents my direct observations of young children using pre-built mechanisms in the classroom and describes the testing process, procedures, results, and concerns of this process.

5.1.1 Justification for Observation

At this early prototype stage in the design of the Mechanism Constructopedia system, it is necessary to gain an initial understanding of how children approach learning activities with motion and mechanism. It is important to establish a justification for the implementation of a modular approach to learning about mechanisms from direct interaction with children. Problems and concerns that emerge from these interactions will help to clarify the needs of the child during the design process and the content that must be addressed within the system. As the system is refined throughout several phases of future development, observations will focus more on technical detail and user-interface issues at the software level, including how easily children navigate through the software and how quickly they find information that is valuable to them. The design of the Mechanism Constructopedia software and pre-built mechanisms reflects two core ideas—that children have the most success in understanding mechanisms when they break complex motions down into smaller modules of motion, and that children will learn to build more quickly and efficiently when they have resources to consult for support during the building process. The following guided classroom activities with mechanisms were conducted with the intention of investigating the validity of these claims.

5.1.2 Participants

For the investigation of these ideas, I again visited Trotter Elementary School in Roxbury, Massachusetts and worked with Alma Wright's combined first and second grade classroom. Though I had been visiting this classroom for over one and a half years, the testing occurred at a point after which approximately half of the first class graduated from the second grade. Eight children remained from the previous year, now as second-graders, and an additional fourteen children were added as first graders. For the purposes of observation, the large group of twenty-two children was divided into six smaller groups, each containing three to four students.

5.1.3 Focus of Investigation

Before entering the classroom, I constructed six distinct mechanisms, each highlighting a different motion. Testing occurred over a period of two consecutive days. The students were given a distinct activity on each day, designed to provide insight into different aspects of the learning process by which children make connections between mechanisms and motion. For the first activity, I was interested in observing several things:

1) *How the children initially connect the motion with the mechanisms.*
Do the children focus on describing the overall nature of the motion or do they break it down in terms of mechanical pieces or modules? In other words, are they viewing the mechanism as a complete entity or the sum of its parts?

2) *How closely the children investigate the mechanism.*
Are the children experimenting with different ways to drive the mechanism or are they just looking for one motion that is representative of the entire mechanism? In some instances, a unique behavior might occur if the motion is initiated by a different mechanical component contained in the mechanism.

3) *How much additional support the children need in deciphering the mechanism.*
Because the design of the Constructopedia system is based on the need for effective scaffolding techniques, it is important to investigate how much outside help the children require to decipher the function of the mechanisms.

After making these primary observations of the children's first reactions to the mechanisms, I wanted to focus my investigation on the more creative context of the activity:

1) *Are the children viewing mechanisms as tools for expression?*
Do the children feel they can incorporate mechanisms into their play space in terms of adding LEGO pieces, minifigs, and other construction materials?

2) *How does the level of comfort with mechanisms change over the course of the activity?*

Do pre-built mechanisms help to motivate the children to build their own unique mechanisms? Do the children at least seem to feel more comfortable experimenting with mechanical pieces?

3) *What drives the play scenario?*

Will the children use the mechanism as the central focus for the stories and play scenarios they create or will the story emerge from additional LEGO elements or construction materials that are added during the design process?

5.1.4 Procedure

For the first activity, each of the six groups was assigned a single mechanism that they were responsible for investigating. No initial demonstration of the use of the mechanism was given to the class. The children in the group were given one sheet of paper to describe the internal mechanisms, as well as the resulting pattern of motion. The children then shared their results during a final show-and-tell period. Because there are often different methods through which children feel comfortable documenting their observations, no strict requirements were specified regarding the method in which ideas were to be communicated on the paper. A drawing, text description, or combination of both was acceptable.

The second activity on the following day again required the class to be split into six groups. Each group was allowed to pick one of the six mechanisms studied on the previous day. The new task was issued as a design contest, in which the six groups were challenged to build creatively with or on top of the chosen mechanism and to make a story describing what role the mechanism plays in the final construction. No external reward was given, except the reminder that the children would unveil their constructions during show-and-tell and receive peer feedback. For this activity, the children were given a sheet of blank paper and a ruled piece of paper, on which they would write their final story.

During both activities, the groups were told that they could ask for help from the teacher or from me when they encountered difficulties.

5.1.5 Results

For the first activity, four out of the six groups drew a picture and wrote a short paragraph (one to two sentences) describing how the mechanism works. The other two groups concentrated mainly on the picture, trying to capture as much detail as they could, such as including the correct number of holes in each Technic component. All of the groups began their investigation in a similar manner. After initially receiving the mechanisms, the children sat them down in the center of their workspace and started to move individual mechanical pieces in a methodical fashion, looking for the one piece that would initiate a larger motion.

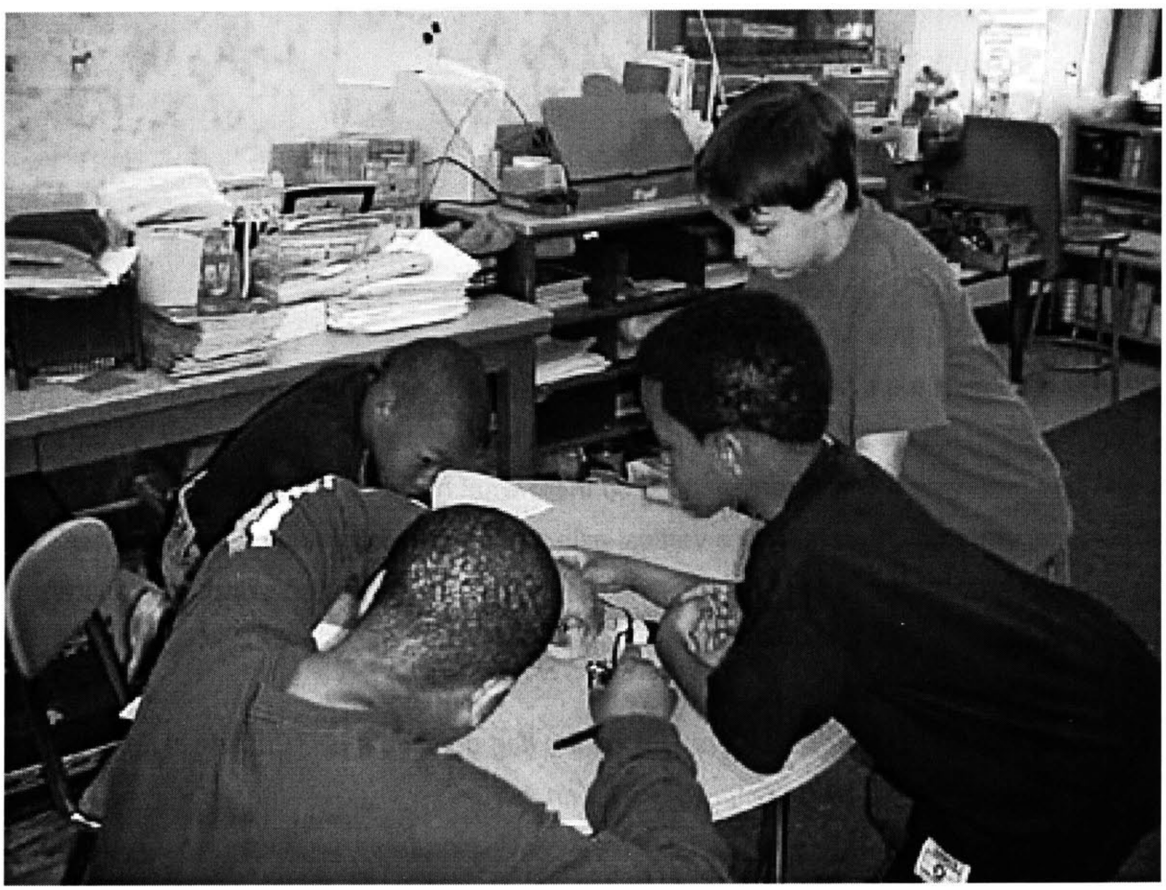


Fig. 24 Group work with mechanisms.

Usually there is one axle in every mechanism that, when turned, initiates the complete motion. When the children did not immediately find the primary driving source of the motion, they seemed to gain greater insight into the subtleties of the modules within the mechanism. For instance, Group 1 received a particularly complicated looking mechanism and was initially having trouble figuring out how to make it move.

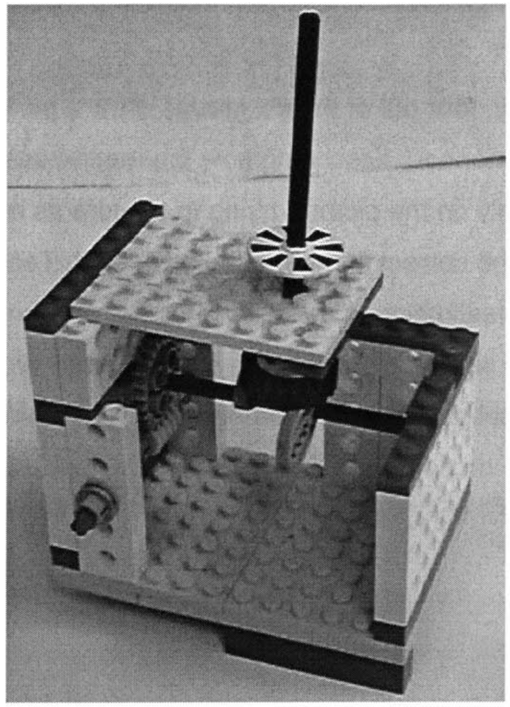


Fig. 25 Group 1's mechanism-- twists and lifts at the same time.

By the time I reached their table to observe their discussion, they had found a way to make the vertical axle lift up and down by moving the highest horizontally oriented axle back-and-forth (see Fig, 25). When I asked them what happens if they turn the lower horizontal axle, they found that the vertical axle not only lifted and lowered to a higher degree, but that it rotated at the same time. In their sketch and description, the children accounted for this new discovery:

> *"When you move the two gray things the flag goes up a bit. But when you move the other black thing the flag moves with it."*

The children had discovered one of the central ideas behind a worm gear/gear module: that a worm gear can drive a gear, but a worm gear essentially locks the motion when the gear attempts to drive the worm gear in the reverse process. In this case, the worm gear still allowed the vertical axle to lift up and down a bit, but significantly reduced its range of motion when compared to the complete range of motion provided by the other axle.

Most of the other groups were able to quickly find the one obvious component that drove the larger motion. Instead of taking time to further investigate what happens when other components can be used as the source for the motion, another group of children focused their attention on describing the system through a chain of events, starting with the driving component. For example, Group 2 approached me to ask for specific names of components that they could use in their description. While Group 1 described the motion in very general terms referring to the color and shape of parts, Group 2 took a very technically detailed approach to the description of their own mechanism:

> *"The lego machine has a knob that is attached to a black cross axle, the black cross axle is attached to a cam, the cam is attached to another black cross axle. If you turn the knob, it will move everything."*

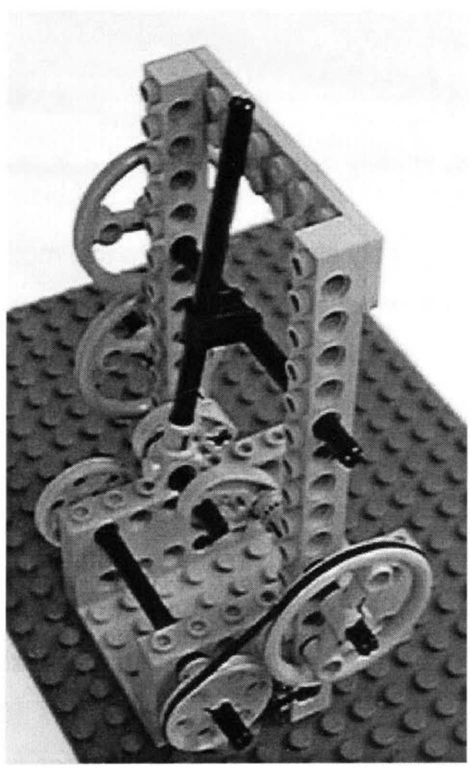


Fig. 26 Group 2's mechanism—lifts up and down in an eccentric motion.

taken by the various groups. Group 3, now working with the mechanism that twists and lifts at the same time (see Fig. 25), also had initial difficulties figuring out how it works, despite a brief demonstration by Group 1 on the preceding day. After asking me a few questions about some of the mechanical components, the group decides that the motion reminds them of a person twisting his head back and forth. They immediately jump into providing a head and cape for the person using pipe cleaners and fabric. Additionally, one of the children is inspired by the mechanism and extends an additional small gearing system off of the main driving axle.

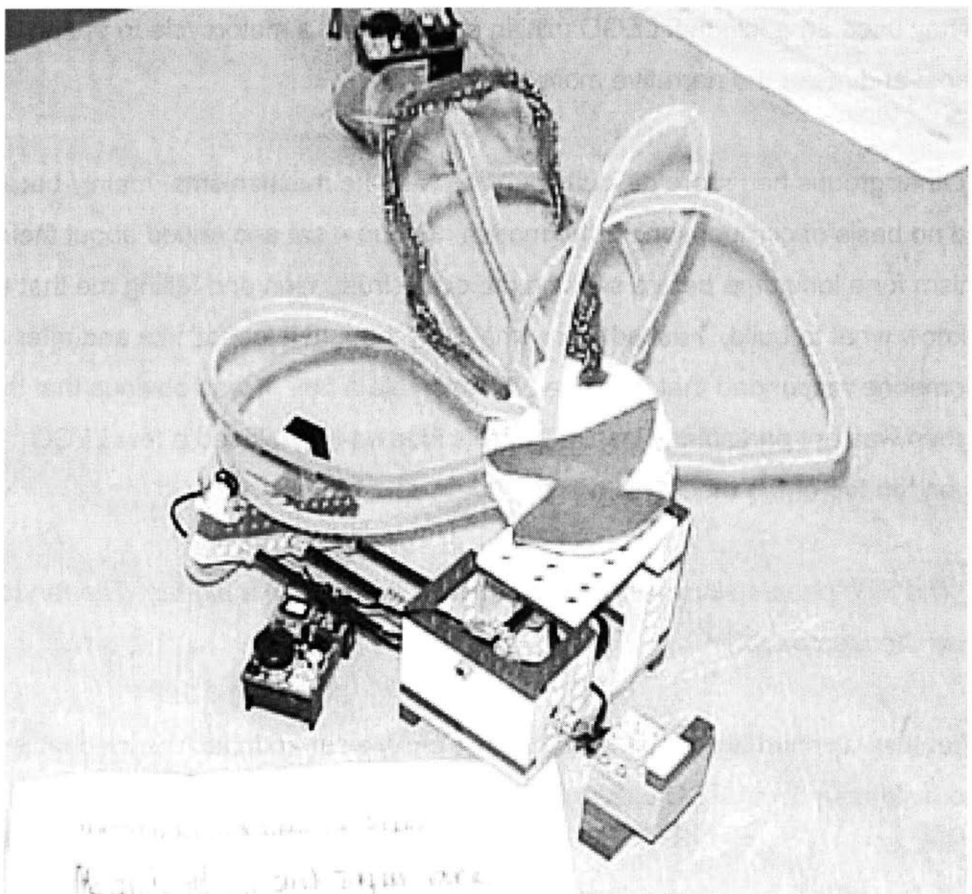
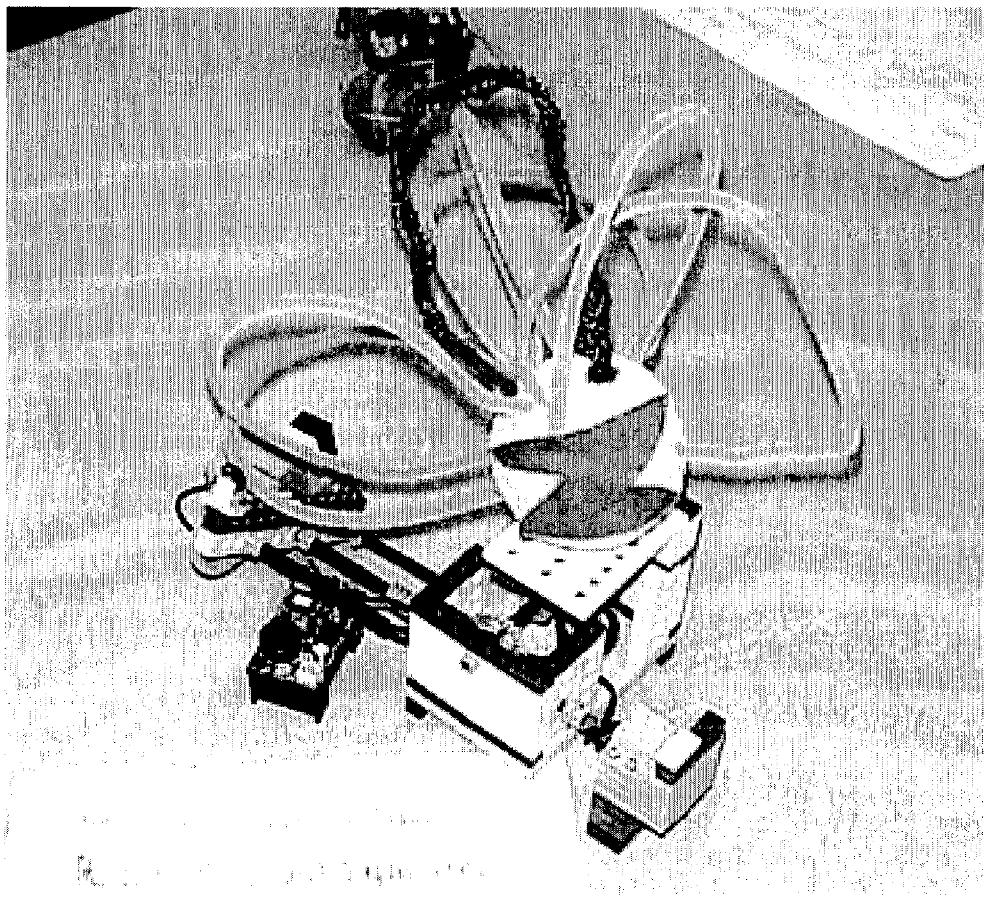


Fig. 28 Group 3's creative use of the Twist-and-Lift mechanism.

Another group chose to focus on the creative development of a story that reflected unexpected behaviors that occurred as they were experimenting with the mechanism. After Group 5 discovered how their mechanism worked, they attached a LEGO ghost minifig to the top of a pivoting axle. They discovered that turning the mechanism quickly enough caused the minfig to fly off the top on the axle and land on the table. Though they only added this one LEGO character to the mechanism, they taken by the various groups. Group 3, now working with the mechanism that twists and lifts at the same time (see Fig. 25), also had initial difficulties figuring out how it works, despite a brief demonstration by Group 1 on the preceding day. After asking me a few questions about some of the mechanical components, the group decides that the motion reminds them of a person twisting his head back and forth. They immediately jump into providing a head and cape for the person using pipe cleaners and fabric. Additionally, one of the children is inspired by the mechanism and extends an additional small gearing system off of the main driving axle.



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"This story was about a lady who was riding on a bike. Then the lady saw a machine and a ghost. Then she got hit by the machine then the ghost saw her then the lady made a trap for the ghost. And then the ghost fall over the machine to the trap."

In this instance, the children used the emergent motion of the mechanism to drive the story. They used an additional LEGO minifig character on a motorcycle to observe the flying ghost and make the narrative more complex.

Other groups had more difficulty building with the mechanisms, mainly because they had no basis of comparison for the motion. Group 4 sat and talked about their mechanism for a long time before seeking me out in frustration and telling me that they did not know what to build. I asked them what they thought it looked like and after a while, someone responded that it seemed to resemble a fan. It was obvious that the rest of the group was not particularly inspired by this idea so they placed a few LEGO minifigs on the top of the mechanism and wrote a very brief story:

"The lego people sit in front of this because it looks like a big fan. The fan blows cold air on the lego people."

Soon after they finished writing up the story, the children abandoned the mechanism and began to build their own LEGO castle.

5.1.6 Discussion

From these observations, it can be seen that several trends emerged from the investigation and construction activities with the pre-built mechanisms. First, the children seemed to take two general approaches to learning about mechanisms:

1) Breaking the motion into pieces and describing the chain of interactions between these pieces, which leads to the final motion.

2) Relating a motion to things they know and understand from their own experiences and by explaining the mechanism in terms of things they already understood.

These methods reflect the need for a Constructopedia tool that takes different learning styles into account. The styles of both the planner and tinkerer are clearly visible among the six groups of children. Additionally, there seems to be much support for providing links between mechanisms and real-world motions. Most of the groups who seemed enthusiastic about the activity were able to describe another motion that they felt closely resembled their mechanism. Making a connection between what a child knows and what a child is trying to learn seems to make the situation more personally meaningful. Finally, the social nature of the design experience seemed to help most of the groups progress past particularly difficult obstacles. Often a single question posed to me, the teacher, or another group member would help the team come up with a workable solution.

Some additional concerns were raised after watching the children investigate the pre-built mechanisms. For some of the more complicated devices, it seemed that the children could have learned even more effectively if they had been able to physically break them apart into smaller sub-assemblies or modules, and then put them back together. Smaller modules and modules with limited mechanical components seemed to cause less frustration for the children as they investigated and built with the mechanism. Furthermore, the method in which the activity was presented did not fully reflect how effective the system might be during a more typical application. For instance, in this activity, the children were presented with a limited number of pre-built mechanisms from which they could choose one to investigate. In a more typical classroom situation, children would have already started to construct a project and would turn to either a more extensive collection of mechanisms or the Constructopedia software to help them build the mechanism they need. Because I have not built enough mechanisms to account for a more complete range of motion, these activities did not provide as much room for self-directed learning and expression as would normally be the case. But despite some of the limitations of these initial learning activities, it is clear that there is a need for an effective tool that provides consistent support for the investigation of mechanisms by young children. In particular, a software tool satisfying this criteria must account for several different approaches to learning, provide methods to make personal connections with mechanisms, and point children in appropriate directions to receive answers to questions that arise during the design process.

6 Conclusion

6.1 Future Work and Summary

In this section, I summarize the rationale behind creating a system that scaffolds children's understanding of motion and mechanism, and provide a vision for future work on the Mechanism Constructopedia.

Because the Mechanism Constructopedia is now in an early prototype stage, there are many additional functionalities that must be added before it can support a large community of users. First of all, the Java 2 API is not yet fully supported by today's web browsers. Currently, Netscape 6 is the only web browser that includes support for Java 2 Swing components. This is not viewed as a major drawback because of the rapid pace of software development. Within a year, both Internet Explorer and Netscape Navigator should contain full support for Java 2 applets. Another related concern is that the Mechanism Constructopedia is highly graphics- and applet-intensive, requiring a lot of system power and speed. This can cause frustration for those trying to access the system from pre-Pentium computers with slow modem connections. Because this is typically the situation for many public schools without the financial budget for high performance computers, many children will not be able to effectively use the system at this point in time. But again, as technology continues to improve and support for technology in the classroom increases, this concern will likely vanish over the course of the next few years.

As a prototype meant to demonstrate the capabilities of an online building resource, the Mechanism Constructopedia has the potential to become a larger system. Eventually, the Constructopedia will become a database of knowledge, storing information about thousands of mechanisms and modules. One of the system's biggest assets is that it is entirely accessible through the Internet, allowing it to dynamically grow in content depending on the number of active users. The future version of the Constructopedia will provide recognized users with logins and passwords for their own workspace in the system. In that workbench space, users can use a web interface to submit images and text descriptions of their projects for others to investigate. When a user creates a particularly useful mechanism construction, he or she can store a picture of it in their workbench area and directions for assembly for future reference. These new mechanisms can also be added to the content of the database itself, allowing the system to grow in response to the users' needs and to give new users the advantages gained by those who have been scaffolded to a more advanced understanding of mechanisms. All of these ideas help contribute to the underlying vision for the system; that sources of online support and extensive information about modules and mechanisms will help to scaffold young children to a more complete familiarity with and understanding of the core concepts behind the creation of motion and mechanism.

Initial testing and observation provides much reinforcement for the need for scaffolding tools that support young children as they learn about motion and mechanism. The Mechanism Constructopedia system is specifically designed to address the needs unique to children with little or no exposure to the concepts of mechanism. Guided investigation into these concepts at such a young age helps children enhance their developing spatial awareness and intuitive understanding for the important role that mechanism and motion plays in their daily lives. As a scaffolded support system, the Mechanism Constructopedia reflects the importance of a support structure for self-directed learning. Instead of becoming frustrated with the complexity of building mechanisms from the bottom up, children will be able to quickly access information about building in a style that is consistent with their unique approach to learning. Whether a child likes to examine pre-built mechanisms, plan out a strategy for completing a mechanism, or tinker with pieces or modules until a pattern emerges, there is a compatible entrance into the software system. The Constructopedia system is not a stand-alone piece of educational software, but a resource for children to access when they want to enhance their play environment with the novel elements of motion and mechanism. Children's understanding of mechanisms will progress more quickly with online support from the Mechanism Constructopedia system and with additional feedback and help from other children in the classroom. When questions arise, children will be able to find answers quickly before they lose motivation and interest. The Mechanism Constructopedia system provides children with resources to help them build the things they want when they want, and at the same time, help them develop the skills they need to build bigger and better mechanisms in the future.

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