

Chapter 2

Mechanical and Spatial Thinking: Concepts

What is it that makes thinking and reasoning about machines such a difficult task for so many people? There are many reasons, but three come readily to mind. First, the structure, composition, and behavior of machines do not easily lend themselves to being communicated in words, a situation that Wallace considers key:

The work of the mechanic was, in large part, intellectual work. This was true in spite of the fact that he dealt with tangible objects and physical processes, not with symbols, and that some of what he did was done with dirty hands. The thinking of the mechanic in designing, building, and repairing tools and machinery had to be primarily visual and tactile, however, and this set it apart from those intellectual traditions that depended upon language, whether spoken or written. The product of the mechanic's thinking was a physical object, which virtually had to be seen to be understood; descriptions of machines, even in technical language, are notoriously ambiguous and extremely difficult to write, even with the aid of drawings and models. [127, page 237]

Second, over the last three or four decades, the opportunities to view the internal operation of machines have been significantly reduced, even as our exposure to machines has increased. Part of this has to do with the replacing of mechanical controls with electronics, but to a greater extent this has come about through a deliberate trend towards the machine as *black box*. We are free to observe the input and output states of a machine, but we no longer have access to the works, and can no longer observe the machine as it operates. Users are advised against breaking the seals of black box machines with threats of injury and voided warranties and by assurances that there is nothing to be gained by opening the case. Illich emphasizes this point:

The nonspecialist is discouraged from figuring out what makes a watch tick, or a telephone ring, or an electric typewriter work, by being warned that it will break if he tries. He can be told how a transistor radio works but he cannot find out for himself. This type of design tends to reinforce a noninventive society in which the experts find it progressively easier to hide behind their expertise and beyond evaluation. [62, page 115]

Third is the marginalization of the master/apprentice model of instruction common during the two hundred years that saw mechanization and industrialization spread around the world. A young person (often a boy or young man owing to social norms) could apprentice to an older, experienced master in order to gain an intimate familiarity with the design and maintenance of machines and would be expected to pass along his knowledge to his own apprentices¹. Denis Diderot in his article “Arts” in the *Encyclopédie* highlights the importance of applied knowledge:

... every “art” [technique] has its speculative and its practical side. Its speculation is the theoretical knowledge of the principles of the technique; its practice is but the habitual and instinctive application of these principles. It is difficult if not impossible to make much progress in the application without theory; conversely, it is difficult to understand the theory without knowledge of the technique. In all techniques, there are specific circumstances relating to the material, instruments and their manipulation which only experience teaches. (quoted in [82, page 27])

Illich raises a genuine concern with respect to our general inability to think and reason about machines and our seeming indifference to that inability; we have become a noninventive society. We consume technology rather than create it. We use technology but we can no longer repair it when it fails, or adapt it to other purposes. We have lost our power over technology and consigned our technological choices to others. Understanding how mechanical thinking and reasoning occur and creating strategies to enhance them could go a long way toward letting us retake control.

¹ The sociological impacts of this form of *on-the-job training* were profound, but are beyond the scope of this discussion. I have concerned myself here only with the transfer of domain knowledge and skill in this working environment.

This chapter explores issues relating to thinking and reasoning about machines. It begins with a brief introduction to mechanical thinking² with an emphasis on why it is different than other types of thinking, why it is a valuable ability, and why its acquisition has become increasingly more difficult in the last few decades. This is followed by definitions of the terms *spatial cognition* and *mechanical reasoning* as they apply to mechanical thinking. It continues with a look at current research into, and models of, mechanical reasoning and looks at what, if anything, might be done to enhance the acquisition of mechanical reasoning in children. It then offers an argument for taking a *constructionist* approach to encouraging children to design and construct machines and situates the MachineShop system and research program within constructionism. It concludes by using the prior research into mechanical reasoning and constructionist education to identify methods by which changes in children's mechanical thinking might be observed during the assessment of the experiments described in Chapter 6.

2.1 Thinking and Reasoning About Machines

Wallace makes two crucial observations in his quote above. First, the work done by those who design, create, and maintain machines (*mechanicians*) is just as much intellectual work as that done by any other professional. Second, the realization of the mechanician's intellectual work in physical objects makes the work substantially different than intellectual work that produces answers, ideas, or other thoughts. The understanding of the mechanician is encapsulated in her machines and it is through those machines that other mechanicians can learn what she knows. The same is not true, for example, of a botanist. While her understanding might help her develop a hybrid plant strain with some desirable property, showing that plant to other botanists would have no effect on their ability to duplicate or extend her accomplishments.

In Wallace's analysis, the roles of the elements of thought and their grammars are reversed when comparing his two categories of thinking. In linguistic and mathematical thinking the syntax

² Mechanical thinking is used in this work to refer to understanding and reasoning about machines and not to its often used meaning of thinking in a mechanical fashion.

of thought is known a priori, and it is the words or phrases which, when taken together according to that syntax, give meaning to the thought. In mechanical thinking, the components available for use in a machine are previously known and it is in the order and structure of their composition that the meaning of the thought is revealed.

The former pattern of thought is the one that most people feel comfortable with and it is the pattern of education in most of its forms. The latter is rarely encountered and seldom taught. It is small wonder that many people find it foreign. But is this a situation with which we should be satisfied? Wallace and Illich clearly believe it is not and Section 2.2 will argue that when children are better able to think and reason about machines it benefits them in a variety of ways.

2.2 Visuospatial Reasoning

The ability to reason about machines falls into the broad arena of visuospatial reasoning. Tversky [123] places a variety of tasks in this category, some of which, at first glance, aren't obviously visuospatial. For example, she says that many abstract reasoning tasks such as chronologically situating two events or determining if a conclusion follows logically from its premises are visuospatial tasks and that they require the same abilities as running to catch a ball, stacking suitcases, designing a museum, or determining whether gears will mesh. This is true, she claims, because humans need to acquire spatial knowledge about the world and the things it contains in order to survive. Visuospatial reasoning becomes our first, and for many years primary, tool for accumulating this critical knowledge and its importance is reflected in the large number of spatial figures of speech that we routinely employ:

... we feel close to some people and remote from others, we try to keep our spirits up, to perform at the peak of our powers, to avoid falling into depressions, pits, or quagmires; we enter fields that are wide open, struggling to stay on top of things and not get out of depth. [123, page 209]

The ability to reason visuospatially has been shown to affect an individual's success in a number of areas far beyond the realm of the vocational. Elementary school-aged children with

well developed spatial abilities tend to perform better when working with high-level mathematical concepts, particularly those that require problem solving in three dimensions [46]. When students enter college their spatial abilities are good indicators of the success they will experience in mathematics [106], the physical sciences [105], and engineering [100]. Certainly there is some evidence that admitting students to programs in engineering and the physical sciences based solely on their mathematical and verbal performance on standardized tests such as the Scholastic Aptitude Test (SAT) or the Graduate Record Examination (GRE) keeps many talented individuals from pursuing studies in these important fields [61].

Visuospatial reasoning comprises creating internal representations of objects, performing transformations on those representations, and making inferences based on the transformed representations. Representations are composed of static properties of objects such as color, shape, and texture, relations between objects and reference frames such as distance and direction, and dynamic properties of objects such as direction, path, speed, and manner of movement. Transformations are operations that either use the information contained in a representation or change it in some way. While the number of distinct visuospatial abilities as well as their distinctness are still open research topics [56, 16], three factors recur in the study of visuospatial reasoning [71]: spatial perception, spatial visualization, and mental rotation. Each plays a key role in the two components of mechanical thinking of salience to us here: spatial cognition and mechanical reasoning.

2.2.1 Spatial Cognition

Spatial cognition is concerned with the acquisition, organization, utilization, and revision of knowledge about objects and space. This ability serves us in many ways beyond simply navigating in our surroundings. It allows us to make sense of the visual stimuli our eyes send our brains, and to communicate that information using language [99], to make inferences and predictions about occurrences in the world [38], and is fundamental for a host of other basic and high-level cognitive tasks. With respect to mechanical thinking, spatial cognition establishes what can be

known about the relationships and dependencies among mechanical components in a machine and provides the information necessary to make inferences about causality in their motions. It allows an individual to map structure, form, and function from machine to diagrammatic representation and vice versa and it supports reasoning about the outcome of operations that the machine might perform. Spatial cognition provides the basic tools that are brought to bear on mechanical reasoning tasks.

For the purposes of this research, spatial cognition is understood to provide knowledge of the absolute positions of components within a machine and the relative positions between components. It underlies understanding of the transmission of motion from input to output, the identification of both permitted and forbidden motions based on component selection and placement, and the ability to locate and correct errors and malfunctions in a mechanism.

2.2.2 Mechanical Reasoning

Defining mechanical reasoning is not an easy task. It goes by many names (mechanical aptitude, mechanical ability, mechanical ingenuity, mechanical sense, and many others) and has equally many meanings. A survey of the literature shows these used somewhat interchangeably which further confounds efforts to present a consistent definition. As will be seen in the discussion which follows, there are two key abilities which are studied. The first of these, which is commonly termed mechanical reasoning, is the ability of an individual to perceive and understand the movement or function of mechanism (usually of simple design and composition) either from interacting with the mechanism or by observing the mechanism or an illustration of it [48, 57]. The second ability, which is sometimes called mechanical ability, is the ability of an individual to describe a mechanism that, when given some specified input, will produce a desired output [23, 51].

It seems reasonable that being able to infer the operation of a mechanism and being able to design a mechanism to achieve some desired function have a great deal of overlap. The teasing apart of these skills has resulted more from divergent research agendas than from any real differ-

ence in abilities. On this basis, mechanical reasoning will be used in the following chapters to include the ability to understand the functioning of a mechanism or machine (mechanical reasoning) as well as the ability to conceive of a mechanism or machine that is suitable for a specified purpose (mechanical ability).

2.3 Research in Mechanical Reasoning

While human societies have relied upon individuals who can create and understand machines for centuries, it has only been in the last one hundred years that concerted research has been undertaken to study how mechanical reasoning takes place. This section provides an overview of that one hundred years of research and describes the goals and conclusions reached.

2.3.1 Industrial and Vocational Psychology Research

The field of industrial psychology emerged early in the twentieth century [96]. While much of the work in this field formed the basis for studies in industrial processes and efficiency (the time and motion studies of Taylor for example [116]), it also gave rise to a body of research which would become vocational psychology. Vocational psychologists were (and are) interested in discovering which intellectual capacities predispose an individual to a certain occupation or set of occupations and in devising methods to identify those capacities in an individual. Vocational psychology arose concurrently with technologies that promoted mass production at one extreme and mechanization on much smaller scales than previously possible on the other. Given this parallel development, it was all but inevitable that vocational psychologists would become interested in the trades of the mechanic and engineer.

Researchers such as Cox [23] and Paterson [95] were interested in *mechanical aptitude* as a measure of potential success for individuals interested in careers as engineers, draftsmen, machinists, mechanics, ornamental ironworkers, and similar occupations. Cox sought evidence for a special *mechanical intelligence* which was separate from, and complementary to, Spearman's general intelligence quotient (*g*) [108]. His thesis presupposes the existence of this special intel-

ligence (which Cox calls m), and is primarily concerned with the development of tests to provide a measure of this aptitude and methods by which those measurements can be used to predict vocational success. In constructing his tests, Cox and Paterson built upon the work of other researchers in this nascent field, most notably that of Stenquist [110] who had devised some of the seminal tests for this purpose.

While assessments of this type were widely used to measure aptitude³ towards a variety of occupations (including engineering and home economics [113]) into the latter part of the twentieth century, they are predominantly used now with occupations such as drafting, machining, and vehicle maintenance.

2.3.2 Cognitive Psychology Research

Cognitive psychologists began studying mechanical reasoning in earnest during the 1980s, drawn by questions of how the brain acquires, processes, and uses information about mechanisms and machines. This form of mechanical reasoning research has focused on a number of areas (presented here in approximately chronological order):

- The use of rules in the construction of mental models of mechanical reasoning
- Differences in the accuracy of reasoning between individuals and the sources of those differences
- The cognitive costs associated with individual components of mechanical reasoning tasks and their effects on working memory
- Inferring motion from static representations of mechanical systems
- Using text and diagrams in the construction of mental models
- The effects of animated diagrams on mechanical reasoning

³ While there may exist some natural affinity to the domain of machines in individuals who perform well on these kinds of psychometric tests, much of what is revealed arguably reflects experience and familiarity.

- Differences in mechanical reasoning using diagrams and real machines
- The use of diagrams as external memory in mechanical reasoning

In early research, Hegarty, Just, and Morrison [51] presented subjects with diagrams of pulley systems and asked them to answer questions based on the diagrams. Figure 2.1 is typical of these problems.

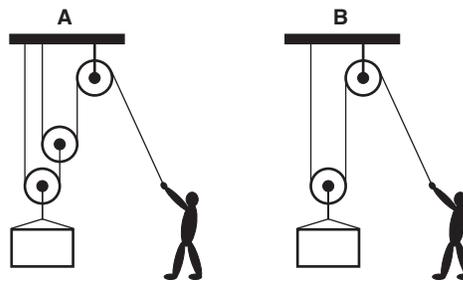


Figure 2.1: A diagram of a pulley system used to understand how test subjects reasoned in this domain. Subjects were asked to choose which pulley system would require the greatest effort in order to lift the weight; A, B, or C if there were no difference. (After Hegarty)

Their goal was to identify the rules subjects used to accomplish these tasks and to account for individual differences in performance [51]. A production system was created to simulate the performance of the subjects and the production rules were assessed by comparing the performance of the system with that of the subjects. Three abilities were identified to account for individual differences: distinguishing between relevant and irrelevant system attributes when creating rules, consistent use of rules, and the ability to combine information about multiple attributes into a single rule. They concluded that these rules and their application reflect an individual's understanding of the causal relationships between the attributes of the system and that this causal understanding of a mechanical system constitutes a mental model of the system. They further asserted that low-scoring subjects used only qualitative mental models while high-scoring subjects used both qualitative and quantitative models.

The three abilities identified by Hegarty and her colleagues relate directly to the visuospatial reasoning factors of spatial perception and spatial visualization mentioned in section 2.2.

Further research addressed the role of the third factor, mental rotation, in mechanical reasoning. The type of mental manipulation necessary to reason about the functioning of a mechanical system relies not on the individual's ability to rotate the mechanism as a unit, but the ability to mentally set the components of the mechanism in motion and observe their operation [48].

While predicting system behavior from static diagrams was shown to enhance subjects' understanding of the system [53], mental animation can reduce the accuracy of mechanical reasoning. Since these animations are carried out in working memory, the limits on the capacity of working memory can be exceeded as the number of system attributes increases [49], with the result that errors increase with a component's distance from the beginning of the causal chain due to the increased number of intermediate motions that must be stored in working memory, then retrieved and evaluated [54]. This is similar to what is seen in standard mental rotation studies where the time necessary to compare two shapes increases with the angular differences in their orientations [115]. The capacity of working memory also seems to be a factor in individual differences in that subjects who can combine attributes of the system by chunking [81] perform better than those who cannot.

With respect to mental models of mechanical systems, those constructed using text and diagrams have been shown to be superior to models constructed using either medium alone [50]. Diagrams serve as external memory aids in support of the text which frees up working memory while the text directs the inspection of the diagrams and the encoding of information in them. Diagrams become even more useful external memory aids when users are encouraged to annotate and embellish them [55]. Not surprisingly, it was found that when reasoning about the pulley systems used in all of this research that the best mental models were constructed during interactions with physical systems [35] where multiple visual viewpoints were available and tactile feedback of the system kinetics was available.

It should be noted that all of the cognitive research examined here has been based on systems of pulleys that, for the most part, were represented as textual descriptions and two-dimensional diagrams. This is not the only research of this kind however, and other researchers

do choose to study other kinds of systems including a few that are heterogeneous and more complex [57]. Hegarty and her colleagues [51] defend their choices by citing previous research on similar psychometric testing. They assert that this research shows that it is not essential to the validity of the tests to manipulate physical objects and that restricting experiments to pulley systems does not compromise the generality of the research. If all that we are interested in is the quality of the research methods this will suffice. But while much may be learned from text and diagrams, it seems likely that even more can be learned from real machines, particularly when those machines are authentic, heterogeneous collections of components rather than simplistic, homogeneous assemblages.

2.3.3 Educational Research and Practice

To complement the vocational and cognitive research agendas already mentioned, there is a third body of research and practice in which an individual's ability to reason about machines and mechanisms plays an important role; the classroom. The use of physical manipulatives in structured educational settings is not a new phenomenon [10, 104], but the purposes to which mechanical devices and components as *objects-to-think-with* [92] are used go far beyond anything that Froebel or Dewey might have imagined. Most elementary school children in the United States will see *simple machines*⁴ in general science units dealing with force and mechanical advantage [22], and some research [78] has examined ways in which reasoning about simple machines can be enhanced in these settings. In mathematics classrooms children may encounter levers and pulleys for lessons in algebraic reasoning [84, 85], or they may use gears as aids in understanding mathematical theorems [5]. These have been the standard methods of using machines as manipulatives in education for many years. More recently though, curricula are once again including elements intended to teach children about technology, its design, construction, uses, and societal implications, and research and practice have turned to how best to structure this educational

⁴ The five classic simple machines are the lever, inclined plane, wheel and axle, screw, and pulley. The wedge is sometimes included in this group, but is really a form of inclined plane according to my fifth grade teacher, Mrs. Barby.

focus.

One way to study children's notions about mechanisms is to look at how they assign roles to components in mechanisms as an indication of their understanding of the causal relationships between the components. Causal reasoning, as mentioned previously, is one of a number of abilities gathered under the umbrella of visuospatial reasoning and is an important constituent of generalizable abstract reasoning. Among approaches to studying causal reasoning is the *mechanism approach* which posits that causation relies on some sense of a force being transmitted from one component in the causal chain to another [1] just as forces are transmitted between the mechanical components in a machine. Lehrer and Schauble [69] have taken advantage of this proposition to examine how children reason about causality in compositions of gears with no purposeful function as well as in machines with which children are assumed to be familiar⁵. Their research showed important age related stages in children's abilities to discover, internalize, and communicate causal relationships between components and suggests approaches to structuring educational contexts to better support learning and reasoning about machines.

This desire to teach children about machines is not new. In the United States, technology education (formerly know as the *mechanical* or *industrial arts*) has a history going back over a century. Educational philosophers such as Dewey believed it to be an important area of knowledge, but all too often they felt that its study was not socially and culturally at the level of other educational subjects. This attitude is still prevalent and has hindered many attempts to mainstream technology education, particularly in the elementary grades [39]. This has not been helped by the "trivial and methodologically flawed" [63, page 29] research on technology education in the latter part of the twentieth century, and the very small amount of that research that was specific to elementary education [40]. Many current attempts work towards an understanding of technology through the process of designing technology that is conceived and developed by the

⁵ The choices of crank driven eggbeater and bicycle are interesting. In the case of the eggbeater, it is probably rare that a child has encountered such a device without a motor until the testing session. And while bicycles are said to have *gears* they more correctly use *sprockets* to transmit power from the pedals to the rear wheel. Sprockets differ fundamentally from gears in the direction of rotation of connected components. Direction of rotation is one of the attributes of interest in this study.

children themselves. This process of providing design guidelines (providing the design process with constraints) to students, rather than design briefs (explicit courses of action), works to create a more authentic experience for students which in turn makes the skills and knowledge acquired more relevant and meaningful [59, 121]. Curricula of this type are being used in many places around the world (the United Kingdom [86] and New Zealand [64] for example) and in many state, provincial, and local school districts in North America.

2.4 Constructing Mechanical Reasoning

The correlation between visuospatial reasoning and success in a number of academic areas is compelling and it would seem that we would be doing children a service if we were able to design learning environments to stimulate and support the creation of this kind of reasoning. As an example, much has been learned about how mechanical reasoning occurs; the mental models that are constructed, the limits imposed by working memory, the discovery of causal relationships, and a host of other cognitive features. Other research has shown how this knowledge can be put to use in creating learning environments for technology education. But what about the *acquisition* of mechanical reasoning?

The common wisdom is that an individual's visuospatial abilities are constrained by aptitude and little research exists that runs counter to that claim. In one notable exception, Brinkmann showed that the spatial visualization test scores of students participating in a carefully crafted course of programmed instruction were significantly higher than either their pre-instruction test scores or the post-instruction test scores of a control group [8]. While these results are encouraging, the students were unhappy with the programmed instruction technique and it might have proven difficult to get these students to volunteer for another course of instruction to determine if their scores could be raised even further. The work described herein uses another educational technique that has proven itself to be more agreeable and engaging to its users; constructionism.

2.4.1 Constructivism and Constructionism

Constructivism is a psychological theory of learning which has its roots in the works of Vygotsky and Piaget [94]. Piaget's contributions to this theory are sometimes termed *cognitive constructivism* while Vygotsky's are termed *social constructivism* [20]. In the Piagetian view, the learner constructs knowledge internally from a series of experiences with the implication that the role of the teacher is to provide rich environments for exploration. In contrast, the Vygotskian view places emphasis on learning that is situated in particular contexts and socially mediated. This implies that while the learner still constructs knowledge, teachers and peers play a key role in the mediation of that process. Both views are strongly related by their central tenet of experience in learning.

Constructionism can be seen as an effort to meld the two facets of constructivism and to extend the resultant. Its principles come from the work of Papert who explains it simply:

Constructionism—the N word as opposed to the V word—shares constructivism's connotation of learning as “building knowledge structures” irrespective of the circumstances of the learning. It then adds the idea that this happens especially felicitously in a context where the learner is consciously engaged in constructing a public entity, whether it's a sand castle on the beach or a theory of the universe [91, page 1].

Both constructionism and constructivism place the emphasis of knowledge construction with the learner, putting them at odds with the instructionist view that knowledge can be handed down from some authoritative source (such as a teacher) and then fully integrated by the individual with her existing knowledge. Papert addresses this dichotomy in his observation that while there exists a word for the art of teaching (*pedagogy*) there is no word in popular usage that describes the art of learning⁶ [93]. Constructionist learning environments that are computational [65], physical [112], and combinations of both [103] show much promise for work in this area and suggest that, in many educational activities, constructionist methods provide greater potential

⁶ Papert proposes the word *mathetic* to mean the art of learning from the Greek *mathmatikos* meaning “disposed to learn”.

for enhanced learning outcomes.

2.4.2 A Constructionist Approach to Mechanical Thinking

The current work takes a constructionist approach to mechanical thinking and the acquisition and enhancement of mechanical thinking and reasoning. By placing the user in a position where she must create a “public entity”, in this case a small machine of her own design, the domain becomes a much richer environment in which to work and her path toward knowledge construction becomes far less structured than an instructional activity would have allowed. With little epistemological data available concerning how children design and construct machines and even less pedagogy, it was necessary to rely heavily on previous constructionist research and prior experience to deconstruct this domain in order to develop an environment suitable for study.

The first step was to choose a mechanical domain that would be authentic and rich in character while being small and well defined and would allow for the creation of physical objects that children would find within their abilities. To this end a number of types of small mechanisms were evaluated. Some proved overly simple or superficial and were not thought compelling enough to maintain children’s interest over consecutive projects. Others which looked initially promising were later discovered to contain some feature or features that rendered them unsuitable from an intellectual or mechanical standpoint. In one instance, some considerable time was spent in trying to devise solutions to mechanical issues with a family of objects only to discover that they were really only of interest when combined together into larger aggregates. The search finally settled on mechanical automata and in particular that subset described as contemporary automata. Chapter 4 explores these devices in detail and discusses the reasons that they were selected for this study.

The second step was to create a methodology for design and construction that would support novices as they explored the domain. The end result combined a number of features from both the craft apprenticeship and modern engineering traditions. Craft apprenticeship showed the value of having novice designers working alongside a researcher with a significant level of

domain knowledge and experience. This would provide the novice with a primary source of information and a guide in new and unfamiliar areas of the domain. To keep novices engaged and involved, some traditional features were eschewed. For example, an important area of inquiry was to examine the changes that occurred in children's mechanical reasoning as they worked from their initial concepts through to realized machines. This was simply not done in the craft tradition where it was customary for apprentices to work on projects that were envisioned and supervised by their masters. This meant that much of an apprentice's involvement with any project was repetitive and menial. While this was necessary to encourage the acquisition of manual abilities and aesthetic sensibilities, it meant that it was many years before an apprentice would be allowed to work on his own creations. Borrowed from current engineering practice were features such as the use of hierarchical decomposition of the intended movements during the design phase, the use of iterative prototyping for design refinement (including changes to the design requirements), and the reuse and modification of existing design elements. This approach is believed to provide both sufficient freedom for the users to create without being overly constrained while offering an adequate level of assurance that designs could, and would, be brought to completion. The application of these principles is presented in Chapter 6.

The third step was to design the tools that children would need to support their work in this domain and several key issues needed to be addressed in the requirements of this support system:

- (1) The system must be usable by children.
- (2) The system should support users with varying amounts of domain knowledge and skills.
- (3) The system should reduce the complexity of difficult tasks (such as component fabrication) in order to keep users focused on more engaging tasks.
- (4) The system should support multiple styles of use and allow for variety in workflow

- (5) The system should be integrated into the environment in such a way as to allow users to work holistically.

The system that resulted from the implementation of these requirements is presented in Chapter 5.

2.5 Changes in Mechanical Thinking

The cognitive, vocational, and educational research into mechanical reasoning suggest a number of phenomena whose manifestation would suggest that changes in mechanical thinking have occurred. When viewed through the filter of constructionist educational activities it is possible to identify several criteria, qualitative in nature, that could be used to evaluate the efficacy of educational methods whose focus is the acquisition and enhancement of mechanical thinking in children. Some of these, such as causal inference, have been explicitly targeted in the research literature [69], while others such as discrimination and integration (Section 2.5.4) have not. They all provide indications of an individual's ability to think and reason mechanically and those that follow were considered important metrics for evaluating the user testing for MachineShop (described in Chapter 6).

2.5.1 Changes in the Use of Domain Specific Language

These occurrences can be of two types, both with a continuum of possible observations. The first is a change in the correct use of terminology. When dealing with individual components, for example, this continuum would proceed from the use of abstract terms ("thing", "star", "doo-hickie") to the use of generic category names ("cam", "gear", "lever") to specific identifiers ("three-lobed snail cam", "a set of pinwheel gears with a two-to-one ratio"). It would also be expected that there would be occasions where unfamiliar objects would be placed into familiar categories using identifiable similarity measures or that new objects might be referred to using some combination of previously acquired terms combined in a novel fashion.

The second is a change in the ability to describe and discuss mechanical components, assemblies, and complete machines with increasingly sophisticated technical language. This ranges from the proper use of terms to the ability to describe some aspect of a machine in a concise and logical manner, to the ability to discuss mechanical processes in the abstract. While this is the more sophisticated of these two facets, it would be expected to see it arise more or less concurrently with increases in terminology proficiency.

2.5.2 Changes in the Use of External Representations

External representations serve key roles in the design process. With the design of automata they take two primary forms: drawings and artifacts. Tversky calls drawings "... an integral part of the dialogue a designer conducts with him or herself during design." [122] and argues that they reflect conceptualizations rather than perceptions of reality. She further contends that they use a small number of elements to map the important attributes of a domain and that the elements used and the order in which they are drawn reveal the manner in which the domain is schematized. Kavakli has investigated the how the use of sketching compares in novice and expert designers [74]. While users will not become expert automata designers during the course of this research, changes in the number of drawings created and the information they contain would indicate changes in reasoning.

The same should be true for physical artifacts, which Chandrasekaran calls kinesthetic representations [17]. The information gained from manipulating objects complements that found in drawings, particularly when dealing with the structural or dynamical properties of the object (Suwa and Tversky refer to this as functional information [114]) which may be difficult to represent statically or in two-dimensions. Observing how the use of artifacts changes over the course of the experiments would also be expected to reflect how reasoning is changing.

2.5.3 Changes in Mappings from Structure to Motion

The shape of a component in a mechanism is its most readily identifiable feature and would be the expected manner in which novices would refer to it. These descriptions rely on static representations of components that only become interesting when placed in motion. Changes in the ability to describe the mappings that exist between the static features of a component and the behaviors it exhibits when moving reflect associated changes in reasoning.

2.5.4 Changes in Discrimination and Integration Skills

One of the most difficult tasks in mechanical thinking is being able to look at a new collection of components and determine the function of the assembly. This process has two parts and successful causal reasoning depends on both. The first is discrimination; the ability to look at a mechanism and determine what role each component plays in the operation of the whole. The second is integration; the ability to see not only how the combination of individual component behaviors work together to produce the observed function of the mechanism, but also to see how changes or rearrangements would affect that function. This skill is also important in the design of new mechanisms with a predefined behavior.

2.5.5 Changes in the Ability to Deal with Complexity

The complexity level of mechanisms and machines can range from the very simple to the virtually incomprehensible. As the ability to think mechanically increases, it should be possible for an individual to make sense of increasingly more complex mechanisms.

2.5.6 Changes in Design Abilities

Increased ability to think mechanically would present itself in an individual's approach to designing new mechanisms in a number of ways. Changes made during the design of a single machine during the iterative design/prototype/evaluate cycle would provide evidence. Making

incremental changes to the current design during this process would reflect changes in understanding at a very fine scale while making radical changes (replacing one component with one of another type for example) would show either deep understanding of function or a lack of understanding depending on whether the modifications move the design toward or away from the intended goal.

Changes in reasoning across subsequent designs would be seen in the time necessary to refine the design, the willingness to undertake the design of more complex machines and the number and nature of sketches and notes created during the design process. This would also be seen in reduced time spent in fabrication and construction from entering those phases with improved designs.

2.5.7 Changes in Confidence Levels

Working at or beyond the limits of their abilities can be a frustrating experience for children. Failure, or the likelihood of failure, can lead children to conclude that they are incompetent, a condition they often believe cannot be modified by learning or practice [31]. Because children have little or no experience working with machines, spending extended periods of time working in this domain can easily frustrate them. But increased confidence should be evident in the ways in which work in the domain is approached. Maintained interest over the extended time frames necessary to create unique machines, self-directed investigation of the domain, excitement during the conceptual phase, the desire to build on previous accomplishments and to reach into untried territory, a sense of playfulness during the process, and satisfaction with the results of the long hours are all indicative of increased confidence which is itself an indication of positive changes in mechanical thinking.

2.6 Summary

Thinking and reasoning about machines is difficult for many people for a number of reasons. First, descriptions of machines and their functions are not easily conveyed in words, the

medium of many other disciplines. Second, even as technology has become more ubiquitous, it has simultaneously become less accessible to scrutiny and comprehension, particularly for children. Third, the work of creating and caring for machines has become trivialized to such an extent in society that the study of machines is not included in substantive ways in mainstream educational curricula. This is unfortunate, as the kinds of visuospatial reasoning fostered by designing, constructing, and maintaining machines and mechanical devices are important in any number of human endeavors, many with no apparent connection to the work of the mechanician.

Research into how individuals reason about machines falls broadly into three categories. Those interested in industrial and vocational psychology seek to identify traits and predispositions that will indicate success in mechanical occupations. Those interested in the cognitive underpinnings of mechanical reasoning attempt to create models of how mechanical thinking is handled by the brain in order to better understand the workings of the human mind. Those interested in children's education use machines to support learning in science and mathematics and to help children develop abstract reasoning abilities, but only attempt to teach children *about* machines in mostly traditional ways which isolate their study. Constructionism offers an alternative approach to learning that has the construction of artifacts as a core feature and constructionist methods were fundamental in structuring the research that will be described in subsequent chapters. Constructionism and cognitive research have also suggested ways in which changes in mechanical thinking and reasoning might be revealed. Several of these have been chosen for inclusion in the assessment of the experiments that are reported later in this work and provide a qualitative counterpoint to the quantitative assessment of method and product.

The discussion of mechanical and spatial thinking begun here continues in Chapter 3 which looks at a variety of tools that have potential as starting points or key elements in constructionist environments designed to help children learn about machines and acquire and enhance their mechanical reasoning and spatial cognition in the process.