

Chapter 7

A Case Study in MachineShop

This chapter provides a brief account of one user's experiences building automata with MachineShop. Its purpose is to convey some sense of what the sessions were like, how the users interacted with the researcher, and give some insight into how user attitudes and abilities changed over the study. Sam¹ was 11 years and 5 months old and a sixth grader at a local middle school when he began working on his first automaton. Over the next 25 weeks, working one and sometimes two 60 minute sessions per week, Sam designed and built two automata. Sam's is an interesting case for two reasons. First, he showed the greatest change in all of the measures of any of the users. Initially, his understanding of mechanical principles and his apparent interest in participating in the testing were both poor but, about half way through, something clicked for him and in the remaining sessions he was knowledgeable and involved. Second, the two automata he built show a clear trajectory of increasing ability and provide a compelling argument for the capacity of children of his age to become skilled automatists given appropriate environments.

Sam's first session began with a tour of the lab and a discussion of what he would be asked to do during the testing as well as the overall goal of the testing. He was then introduced to the domain of contemporary automata by showing him pictures of automata from Cabaret Mechanical Theatre and allowing him to play with three automata created by researchers in our lab with earlier versions of MachineShop². He was given a short demonstration of the MachineShop software and

¹ Pseudonyms are used here and in Chapter 6.

² The automata that children had a chance to interact with were a flying bison, a swimming sea serpent, and a circus sea lion. Both the bison and sea lion served as archetypes for at least one automaton created by the users.

shown how the laser cutter operated. He was given the four pre-test problems to take home and was asked to come back the following week with at least one idea for his automaton and a drawing to help convey his ideas to the researcher.

7.1 The Soccer Player

On his return the following week, Sam brought the drawing shown in Figure 7.1. He had come up with the idea of a soccer player scoring a goal while at soccer practice and after some discussion he and the researcher decided that this would be a good project. The first item that needed to be resolved was the size of the automaton. Sam thought that he wanted the player to be about twelve inches from the goal and about four inches tall. Some rough approximations of the figure were cut from cardboard and a first layout using Sam's dimension was created. Sam felt that this put the player too far from the goal and with the options of shortening that distance or making the player larger, Sam opted for the latter and the player gained two inches in height. Sam and the researcher spent some time creating a new player from cardboard. A cardboard playing surface was also made which was large enough to locate the player and goal the way Sam wanted.

7.1.1 Designing the Soccer Player

Over the next several weeks Sam worked to design a mechanism. Sam's goal was a mechanism that would carry the ball quickly to the goal and return it slowly to the player's foot for another shot. The simple movements were examined extensively and the ones that showed some promise were discussed. At the researcher's request, Sam created his first design for a mechanism (Figure 7.2) based on a set of three pinwheel gears with the ball attached to the driven gear.

A lengthy dialogue ensued about this particular mechanism. It took Sam quite a long time to see three major flaws in this design. First, there is no way for the mechanism to move the player's foot. Second, the smaller horizontal gear is not needed and cannot mesh with the larger horizontal gear in the configuration shown. Third, attaching the ball to the gear as it is drawn will cause the ball to travel in a circle between the player and the goal, not from the player to the

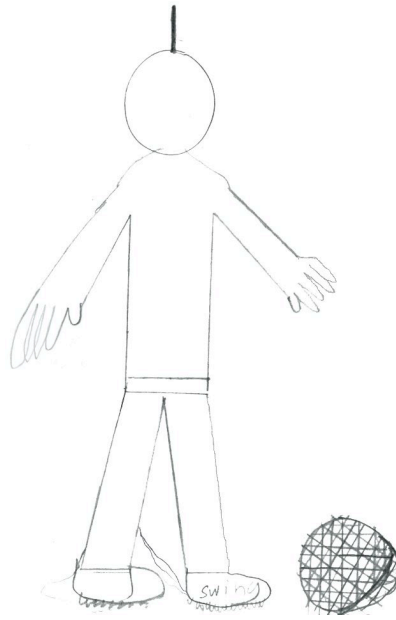


Figure 7.1: Sam's first conceptual drawing for the soccer player. Note the detail in the ball and cleats, but lack of any features in the face. Also note the only indications that this is not a static object: the word "swing" on the foot and what appears to be some means of connecting the heel to the mechanism. Although Sam couldn't remember, the line at the top of the head may have been an early attempt at a means for supporting the figure.

goal and back. Once these issues were identified, Sam and the researcher began to discuss the movement that Sam wanted and to look at the simple movements once again. This discussion would identify some desired behavior in the automata and then attempt to find a movement that would produce that or a similar behavior. Sometimes one of the simple movements would suggest a possible alternative behavior and those would be analyzed. For example, attaching the ball to a crank-slider mechanism (see Section B.3 for an explanation of this mechanism) would move it in a realistic arc to the goal, but would have moved it in an unrealistic arc below the "playing field" of the automaton on its return to the player's foot. Additionally, there was no way that the crank-slider would provide the change in speed (move quickly to the goal, slowly return to the player) that Sam wanted.

The difficulty lay in Sam's inability to think about alternative ways of getting the ball to

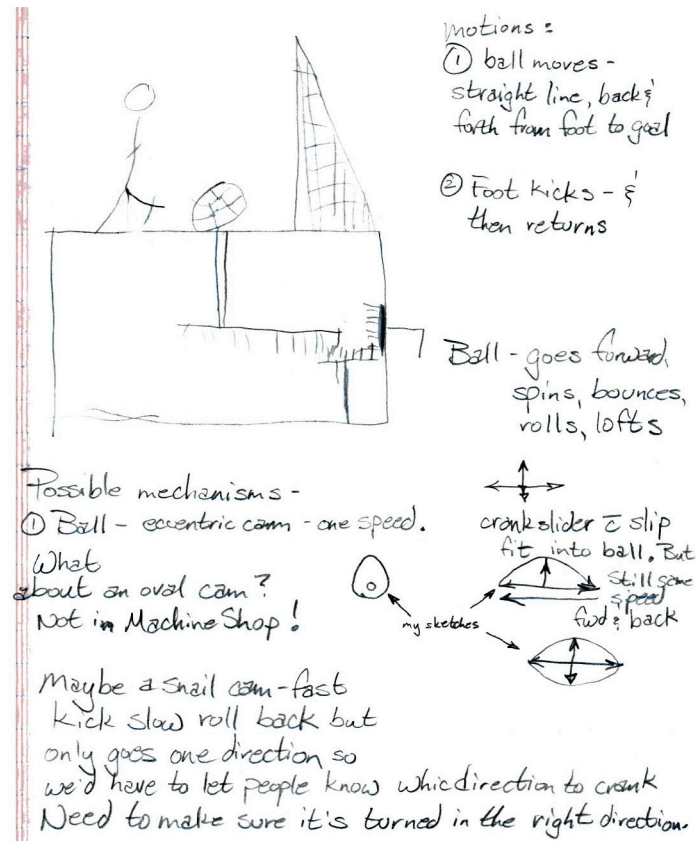


Figure 7.2: Sam's initial sketch for how the soccer player mechanism might be constructed (upper left). Based on his exposure to the simple example mechanisms, he has chosen a mechanism composed of pinwheel gears. This arrangement of gears contains unnecessary pieces and cannot provide the motion he desires. The annotations on the drawing were made by the researcher during the discussions he and Sam were having. These notes are a combination of comments on the desired motion and ideas for possible mechanisms that they were brainstorming.

move as he wanted without it being attached to the mechanism.³ To break the impasse, the researcher asked Sam to consider what might happen if, rather than having the ball attached to the mechanism, the impact of the player's foot provided the motive power to get the ball to the net. Sam concluded that, if this were possible, that the ball would travel to the net quickly (he tested this by snapping the ball with his finger) but figuring out a way to get the ball to return to be kicked again posed a challenge. As this problem was being discussed, Sam hit upon the idea of elevating one end of the surface on which the ball would roll so that the goal was higher

³ None of the users initially found considering alternatives easy. The ability to step back from a design and look at the behavior afresh only came with experience.

than the player's foot, allowing gravity to roll the ball back. He became quite excited about this prospect and a rectangular piece of cardboard the size he wanted for the automaton's top was cut to facilitate some testing of this new plan. It was readily apparent to Sam that this would allow the ball to return slowly to the player as he wanted but that some method of constraining the path of the ball would be necessary. His first thought was to install a pair of rails, one on each side of the foot that tapered out to the width of the goal at the other end.

It was now necessary to find a way that the player's foot could be moved so that it could kick the ball the full length of the automaton (12 inches) and into the goal. Sam was asked again about the motion of the ball and if there were any of the simple mechanisms that might provide that motion. Sam selected a pair of the snail cam mechanisms (the one-lobe and two-lobe variations) and thought that either might work. For simplicity he chose to work with the one-lobed cam and thought that by attaching a rubber band to the heel and hooking it over the lobe the rubber band would be stretched as the cam rotated (pulling the foot to the rear) and then quickly released when the rubber band slipped off of the lobe (Figure 7.3(a)). There were problems however:

Sam: The rubber band is about right there [*indicating the heel of the kicking foot*]... and it goes down to the snail... cam and is attached right there [*indicating the lobe on the cam*]. But then, I just thought of something.

Researcher: Okay.

Sam: When it comes off, how will it attach back on? For it to snap back?

Researcher: So you were thinking of putting the rubber band over the lobe on the cam kind of like a rubber band shooter.

Sam: Yeah.

Researcher: Okay.

Sam: But then I didn't know how to get it back on unless it, like, umm.

Researcher: So, why are we using the rubber band? Tell me again.

Sam: Because it needs to snap to kick it in.

Researcher: Okay. So we're going to use the force of the rubber band to bring the leg forward?

Sam: Yeah.

Researcher: Alright. So if that's the case, does the rubber band really have to attach to the cam?

Sam: Umm, *[very long pause while he rotates his hand back and forth rapidly]* maybe. It might. There might be ways to have it with and without.

Researcher: So let's talk about another way. How could we move the foot with the snail cam without attaching the rubber band to it?

Sam: Umm, maybe... have... I'm not really sure.

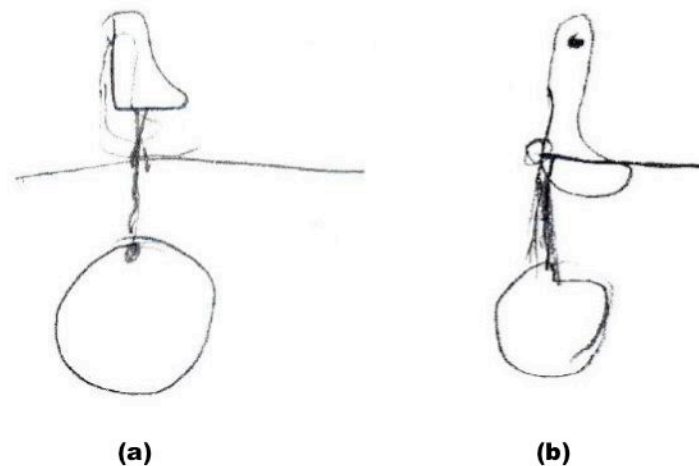


Figure 7.3: Sam's first drawings of the player's leg and the cam. (a): The foot is attached to the cam by a rubber band which is expected to snap the foot forward when it slips off the lobe. (b): The modified mechanism now shows the foot attached to the cam follower by one rubber band and being pulled forward by another. Attaching the follower to the foot will prevent the follower from remaining in contact with the cam. The other rubber band will keep the ball from contacting the foot. Note how the level of component detail is increasing as the design matures.

Researcher: *[The researcher takes the one-lobed snail cam from the box of mechanisms and gives it to Sam.]* So there's the snail cam. *[Sam cranks it several times]*

Sam: Um, maybe have a stick *[indicating the follower]* that attaches to the rubber band. So when it snapped down... it would *[cranking it again]*... when it... when... um... down maybe it would... then when it was going up it would make it go forward. Maybe?

Researcher: Okay. So the direction in the case where the follower is going up slowly... what direction is the leg going to be moving?

Sam: Umm, it would be... back. *[Which is the direction of slowest movement of the foot]*

Researcher: Okay. And then when we get to the point where the follower drops, that's where the leg's going to come forward?

Sam: Yeah.

While it was obvious that Sam understood the kind of motion the cam provided, and he could see that the motion mapped to what he wanted the foot and leg to do, he had no clear idea about how to combine the cam and follower, lever (the leg), and the rubber band that he needed to power the leg. He next talked about attaching the rubber band to the follower (Figure 7.3(b)), a move that would not provide forward motion to the foot. At that point, the researcher drew two arrows on the sketch pad, one indicating the vertical motion of the cam follower and the other indicating the horizontal motion of the foot and sketched a foot next to them (Figure 7.4(a)):

Researcher: *[Pointing to the drawing]* In this case, this is the follower going up, and this is the follower going down. *[The researcher picks up the mechanism and Sam takes the paper they've been drawing on.]*

Sam: So, like maybe um, when it was going up it would like hit, it would hit the foot make it go back. And then when it dropped it would unattach it, but then when it swung back, um, it would be going back up.

Researcher: If we're going to use the follower, do we need to push on the rubber band or can we actually push on the leg or the foot?

Sam: Umm, we can push on the leg.

Researcher: So if we were going to do that, where would we push on the leg?

Sam: Umm, in the heel. *[The researcher rotates the mechanism ninety degrees so that the follower is now horizontal.]*

Researcher: We want to push it back and then when we come around here *[indicating the sharp drop of the lobe]* this would come forward.

Sam: Yeah.

Researcher: And we'd use the rubber band for that?

Sam: Yeah.

Pushing back on the leg was not a practical solution since that would place the cam both above the top of the kicking surface and in front of the leg. Sam took the snail cam mechanism, oriented it vertically and tried to find a way to have the follower press vertically on the heel and move the heel back horizontally. He appeared to have little understanding of why what he was

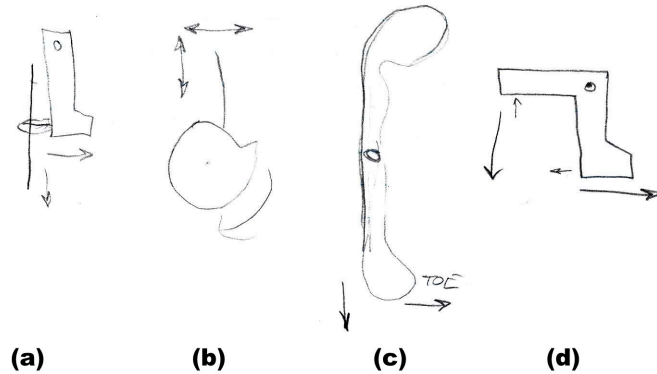


Figure 7.4: Refining the soccer player's leg. (a): Sam attaches the cam follower to the heel with a rubber band. (b): A sketch to show the cam and follower in relation to the motions that they need to produce. (c): Sam draws the leg as a lever of the first order. (d): The two lever solution (see text) is modified by rotating the upper part of the lever 90 degrees. This is the form that was used in the automaton.

trying to do would not work but he seemed to feel that he was on the right track (which he was) and that if he just thought about this (incorrect) combination of components that he would find a way to make them do what he wanted. The researcher asked how they could get the leg to move back by pushing straight up on it. Sam replied that the follower could be attached at the heel. The researcher pointed out that the follower will only move straight up and down, not backward and forward and Sam spent some time thinking about this.

The researcher asked Sam what type of component the leg was and after some thought Sam replied that it was a lever. The researcher removed the follower from the mechanism and replaced it with a lever. Sam turned the crank and saw that if one end of the lever moved along the profile of the cam, the other end of the lever moved like the foot needed to. This observation was tempered by the fact that any simple application of this method would again place the cam above the kicking surface. The researcher asked Sam to draw a cam and follower in the orientation Sam wanted them (Figure 7.4(b)) and then to draw the leg as a lever of the first order (Figure 7.4(c)). The researcher again added the directional arrows to the cam and follower drawing and asked Sam how the horizontal motion could be derived from the vertical motion. After making a number of unworkable suggestions, Sam decided that attaching a second lever at right angles to the leg would

work. The researcher asked if the assembly needed to be cross shaped and Sam soon worked out that by rotating the upper half of the leg 90 degrees an “L” shaped leg would function in the same way (Figure 7.4(d)).

The final requirement for the design was to allow the ball sufficient time to return to the foot after it was kicked. Sam had by now spent enough time with the simple mechanisms to know that he could do that by using gears. By letting the ball roll down the cardboard surface and pretending to crank at the same time he decided on a ratio of 3 to 1. Now that Sam and the researcher had the dimensions for the automaton and a workable first design for the mechanism they began creating the first prototype.

7.1.2 Prototyping the Soccer Player

The mechanism for the soccer player was relatively simple, consisting of a one-lobed snail cam with follower and a 2 spur gears with a 3 to 1 ratio. The structure to support the mechanism was a simple stretched cube with one end slightly higher than the other to facilitate the ball rolling back to the player's foot. Prototyping proceeded fairly quickly. First, Sam and the researcher cut a piece of corrugated cardboard to the size needed for the kicking surface (this would also become the top of the support structure) and the preliminary locations for the goal and player were determined and marked.

Next, a simple structure to support the mechanism and kicking surface was built from more cardboard (Figure 7.5). One end was made taller than the other so that it could be gradually trimmed to the correct height that would make the ball return to the player's foot at the desired speed. A base was cut that was shorter than the kicking surface and two braces were placed on the sides, spanning the distance between the ends. These braces not only kept the end pieces upright, they also provided the bearing surfaces for the shafts used by the mechanical components. The support structure was assembled with tape to allow it to be easily modified. At this time two wedge shaped guide rails were also cut. These would insure that the ball returned to the proper location in front of the foot for kicking. The top was placed on the support structure and Sam

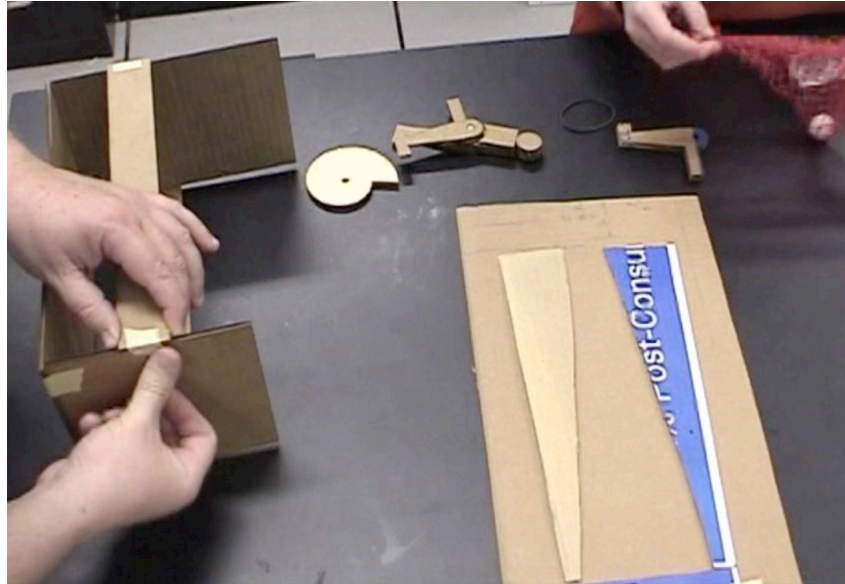


Figure 7.5: Rectangles and strips of corrugated cardboard were cut to approximate the look of the support structure of the finished automaton. These pieces were assembled using masking tape so that changes could be made easily. Notice the cardboard player figure and spare leg alongside the prototype snail cam. Sam is holding the net bag that had contained onions his mother had purchased and that would become the net for the goal.

proceeded to determine what height was needed for the taller end. Since there was no specified amount of time for the ball to return from the goal, Sam would let the ball roll from the goal area to the other end three or four times and decided if the ball seemed to roll too fast for him. If it did, the top was removed and one-quarter of an inch of cardboard was cut from the longer end. This process was repeated until Sam was happy with the speed of the ball (Figure 7.6).

At this time the spur gear train that Sam had designed with the MachineShop software was fabricated from basswood and test fit with the previously fabricated snail cam. These components were made from wood initially because of the difficulties inherent in assessing the functional qualities of cardboard mechanical components. Sam spent some time playing with the gears and cam to get a feel for how they would work together as well as their orientation and location within the support structure (Figure 7.7).

The mechanism was installed in the support structure and checked for proper location,

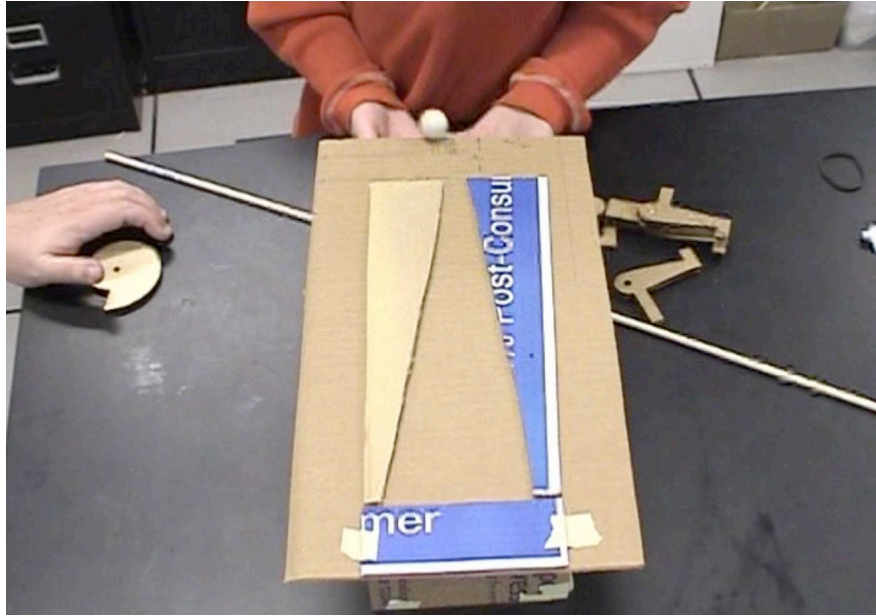


Figure 7.6: Sam tests the speed of the returning ball. If the speed was determined to be too great, a small amount of material was removed from the top of the tall end piece. This continued until he was satisfied with the performance.

alignment, and function. Once this had been done, the kicking surface was installed and secured to the supports with tape. The final location of the player was determined so that the cam follower would be properly located on the leg. Sam took a few minutes to see if the amount of motion that would be supplied by the follower would be adequate to get the ball from the foot to the goal and was somewhat confident that it would (Figure 7.8). At this point, prototyping was nearing an end and it was expected that the fabrication of the final components would commence with the next session.

7.1.3 The Soccer Player as Science Project

Sam returned the following week with an announcement; he would need to complete the automaton in three weeks for use at his school's science fair. This was a worrisome proposition for the researcher. First, a number of mechanical issues dealing with the action of the leg had not been resolved with the cardboard prototypes and he suspected that at least the first wooden

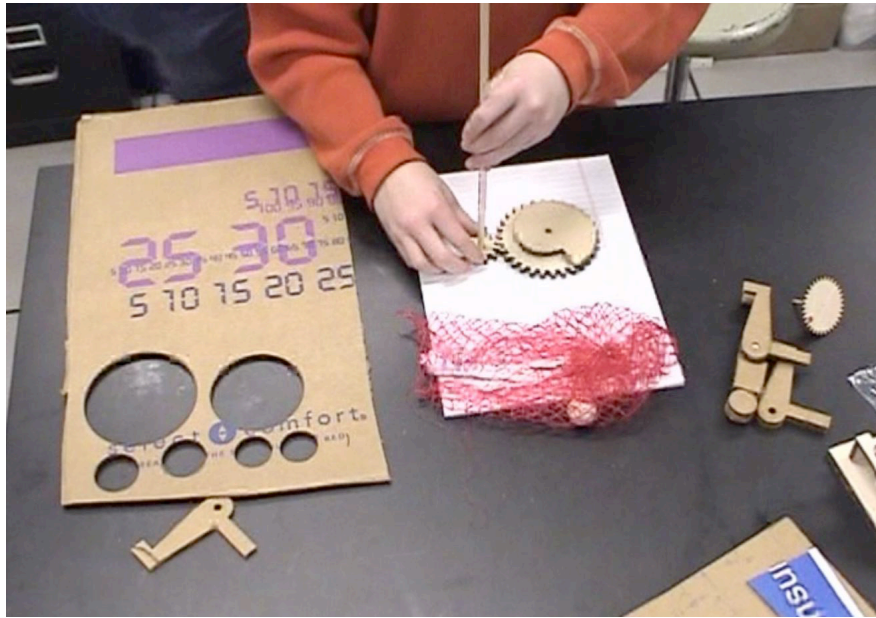


Figure 7.7: Sam tests the operation of the spur gear train and checks to see that there will be no interference when the cam is attached. The smaller gear in Sam's right hand supplies the input motion to the mechanism. Being smaller than the driven gear it will be necessary to turn it three full revolutions to get a single revolution from the larger gear. This was Sam's solution for allowing the ball sufficient time to return from the net before the player kicked again.

version of the automaton would need moderate to substantial changes in order to function correctly. Second, while Sam's domain knowledge and his mechanical reasoning had shown some improvement since the beginning of the project, his general attitude during sessions had been a passive one and to see his automaton completed in such a short period of time would require that he take a much more active role.

The researcher then received a second surprise as Sam proceeded to use the MachineShop software to give his mother an overview of the mechanical components that he intended to highlight on the poster that would accompany the soccer player. His explanations were technically correct and his use of vocabulary was better than had been seen or expected. It now appeared that Sam had acquired more knowledge and skill from working on his automaton than was obvious from his detached interactions with the researcher.

Even though time was short, this session was devoted to creating components and images

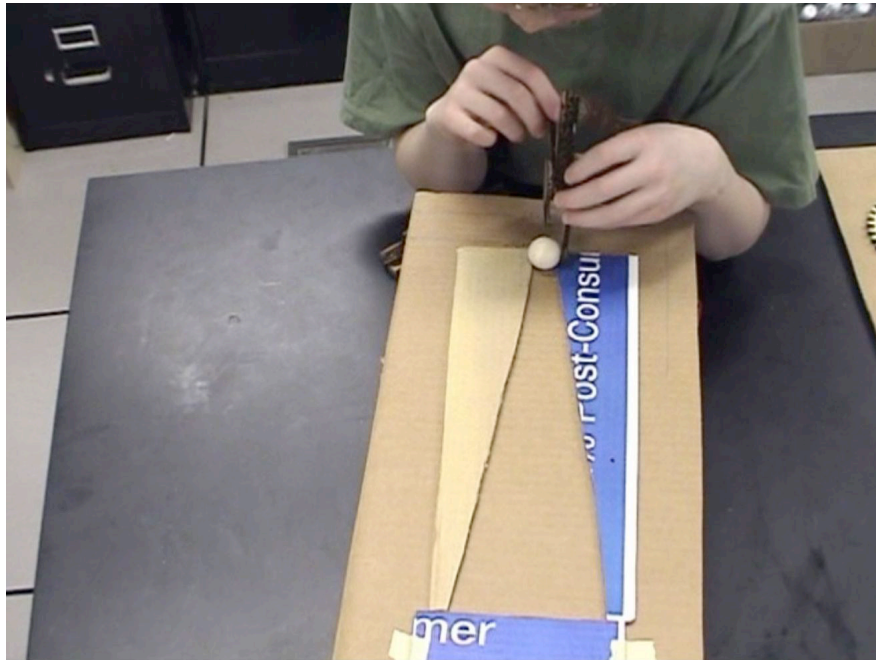


Figure 7.8: Sam works to determine if the amount of motion that the cam will supply to the leg is sufficient to propel the ball into the goal.

for Sam to use on his poster. While doing that, he and the researcher talked about the components he was designing and it was obvious that his thinking processes about the components had changed significantly over six weeks. He made one lever and saved its profile as an image file. He would use this same image on his poster to illustrate the three orders of levers:

Researcher: So a first order lever is like what in the real world?

Sam: A teeter totter. *[He selects the second order lever in MachineShop.]*

Researcher: This is the second order lever and it's like? *[He thinks.]* Look at the interesting thing about this. In the first order lever which direction were you applying the force? Up or down?

Sam: You're pushing down.

Researcher: ... you're applying the force down in the first order, and the effort you're getting out is going in the opposite direction. But now in a second order...

Sam: You're pulling oh, like a wheelbarrow.

Researcher: Exactly. Because you're pulling up the effort is also coming up because the fulcrum is out at the other end.

Sam: And this one *[indicating the third order lever]* is kind of a hard one.

Researcher: The third order is a little harder. Which way are the force and the effort going?

Sam: With this one the force, they're both going up.

Researcher: Well they both go in the same direction, so they don't necessarily both have to go up. *[He thinks.]* You just reverse the positions of the effort and the force *[from those in the second order]*.

Sam: So that might be like... I can't really think of anything.

Researcher: Well, I can think of a couple. Have you ever seen pictures of a castle and the main gate where you go through across the moat? What is it they always pull up last to keep the bad guys out?

Sam: Um, the... Oh, the, the drawbridge!

Researcher: Think about the drawbridge. Let's go back to the third order lever there. So here's the big hinge... *[Pointing to the fulcrum]*

Sam: Oh yeah...

Researcher: back at the castle...

Sam: Oh yeah...

Researcher: and here's where they hook the chains *[pointing to where the force is applied]* and here's the end of the drawbridge. *[Pointing to where the effort is returned.]*

Sam: Oh yeah. Oh yeah!

Researcher: Another thing where you've seen this is probably in a fishing pole. Where your left hand *[Sam is right handed]* is the fulcrum, your right hand is where you're applying the effort, and the tip of the pole is moving back and forth.

Sam: But a lot more.

Researcher: You'll see that here *[pointing to the computer screen schematic of the lever]*. The distance that travels... It's the same thing with the drawbridge. By putting the chains in the middle the chains only have to come up half as much as the end of the drawbridge.

Sam: To save chains.

Researcher: And to also make it go what?

Sam: Faster!

It was obvious that Sam was still acquiring and assimilating knowledge about the domain, but this change was unexpected. During the creation of the materials for his poster, he was quite

animated and it appeared that all he needed was some purpose for what he had been doing. The next two sessions were very busy. As suspected, there were a number of issues that had not been apparent with the cardboard prototypes (alignment and support for the cam follower for instance) and wooden pieces were designed, fabricated, tried, and modified when needed. At the end of the last session before the science fair, Sam's automaton was little more than a pile of parts which he took home to assemble with the help of his mother and father.

The week after the science fair, Sam returned with the completed soccer player (Figure 7.9) and the poster he had created (Figure B.22). He and his parents had finished the soccer player the night before it was due and had done a good job. There were still a few small issues that affected its performance, most notably that the rails for the ball return did not constrain the position of the ball in front of the foot well enough, so Sam and the researcher set about correcting those problems. Sam was quite pleased with the project and progress on the repairs sometimes had to wait until either he or the researcher had stopped watching it in action. Sam left the automaton in the lab since the next session would be his opportunity to talk about the soccer player and his experiences in its construction.

7.2 The Carousel

At the end of the soccer player interview, Sam told the researcher that he would like to make another automaton. He said that it would help him to better understand what doesn't work (his mechanical thinking now included that knowing what won't work is sometimes more important than knowing what will), that it would help him be more proud of himself (his confidence in his abilities was increasing), and that he wanted to prove that his success with the soccer player was more than beginner's luck. He also wanted to make a smaller automaton so that it would be easier to transport. He told the researcher that he had an idea for the next one:

Sam: A carousel.

Researcher: A carousel. Okay. Why a carousel?

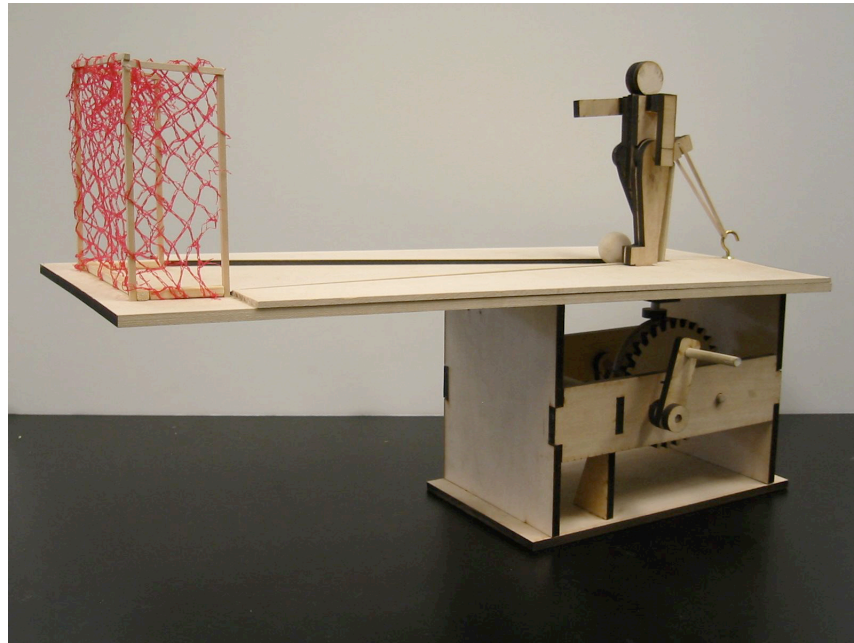


Figure 7.9: Sam's first automaton. This was the largest of all the automata built by users and was the only one to use either snail cams or spur gears. The netting, ball, and leg return mechanism were materials either found or purchased; something that all users were encouraged to do. Sam said that he was afraid that by the time the science fair was over the automaton might be broken since viewers couldn't resist playing with it.

Sam: Just because nothing would be loose like this one [*meaning the ball*] so it's a change. And the only thing that I would be using that's the same is the dowel and the crank. And I wanted something circular [*draws a circle in the air parallel to the table*].

Researcher: So we're talking a carousel like at an amusement park or a circus. With animals on it?

Sam: Yeah. Four [*he marks out their locations with his finger*].

Researcher: Are they going to be stationary or are they going to move up and down?

Sam: Two of them are going to move up and down and two of them will move side to side. And I've figured out how.

Researcher: You have? That's excellent!

...

Researcher: So, four animals, something about four by five or five by six. Now you're talking that the structure for the mechanism is that size?

Sam: No, the carousel itself is that size.

Researcher: So the carousel will be pretty small.

Sam: You know how at the top of the carousel it has that tent like thing? It's going to have to hold a tiny bit of the mechanism which will make them move up and down. Because it would interfere with the other dowel to make it turn.

Researcher: Do you know how carousel animals go up and down on real carousels?

Sam: Doesn't it twist? Or does it...I'm not sure because all I've seen is the outside.

Researcher: But you've ridden them. Have you ever looked up to see where the rods go?

Sam: No, not really.

Researcher: Well, I'm not going to tell you what it is right now. I'm going to let you think about it.

Sam: [*Grins*] Eccentric cams with followers?

Researcher: No, they're not eccentric cams with followers, but you're on the right track. It's interesting that you're thinking about putting the mechanism up above which is where the mechanism really is in a carousel.

Sam: Yeah, but some of it's going to have to be below. Wait. Would it be a lever? [*He holds up his hands to show what he's thinking.*] So it's like a lever and it goes...maybe a second order...actually, wait. That would be...a third. Yeah, a third order so that it pushes up from the middle and it pulls it up and down.

Researcher: That's not how it's done either, but that also would work. So even though that's not the way they do it in real life, both of those would do exactly what they do. And I think that when you get downstairs next week and you see what's in the box you'll figure it out. But it's going to be very much like your's because the mechanism that drives the carousel around in circles...

Sam: Is at the bottom.

Researcher: Is at the bottom and the mechanism that pulls the animals up and down is in the top. I think that a lot of the size is going to depend on how big your animals are. It's good to think it will be small now but once you get the animals we can figure out the scale from there. I'll tell you what. There's some paper, there's a pencil. I want you to show me how the mechanism to turn the carousel is going to work. I'm seeing two parts.

Sam: Yeah, there's only two parts I'm thinking of. [*He starts to draw*] It's gonna be a...I couldn't think of another way but to use a pinwheel gear. So that's pretty much it. 'Cause, like is there anything else I should be doing?

Researcher: No. We'll have to put some structure in there to hold everything. So are you going to use one to one gears?

Sam: One to one just because it doesn't need to go slower or faster.

Researcher: So were going to use a pair of pinwheel gears to take the motion from the crank and to rotate the base of the carousel. Now show me how, when the carousel goes around, the animals will go...so two of them are going to go up and down and two of them are going to go side to side?

Sam: Yeah, 'cause that's also kind of realistic, that's what they do for the parents to ride on, the one's that are stationary. My mom always rides on them.

Researcher: The stationary ones don't move though.

Sam: Don't they move around?

Researcher: They go around with the carousel...

Sam: But they don't go up and down.

Researcher: So when I say stationary they could just be glued on dowels to the carousel base because they don't have to move separately from the base.

Sam: But they usually have that thing up and down so you can hold onto them. I'm just going to draw it like this even though it would be the other way around. So, it would be like this...

Researcher: I see. This is a disk and you're showing it face on rather than side on. So these look like eccentric cams.

Sam: Yeah, with followers...I can't think of another way to make it go so you'd have to use more pinwheel gears...and then the dowel [*he connects the cams to the gears with shafts*] like that.

Sam's sketches can be seen in Figure 7.10.

7.2.1 Designing the Carousel

Sam had done a great deal of the preliminary design before work commenced on the carousel. His basic ideas were sound and the decision to split the mechanism into two parts was insightful. The next session was used to refine his design and to identify problems with it. The researcher had found one issue that had to be corrected; Sam's idea of putting the animal moving mechanism at the top of the carousel. He gave one of the pinwheel gear mechanisms to Sam and asked him to use it to demonstrate how the animals would move. Sam explained that a shaft

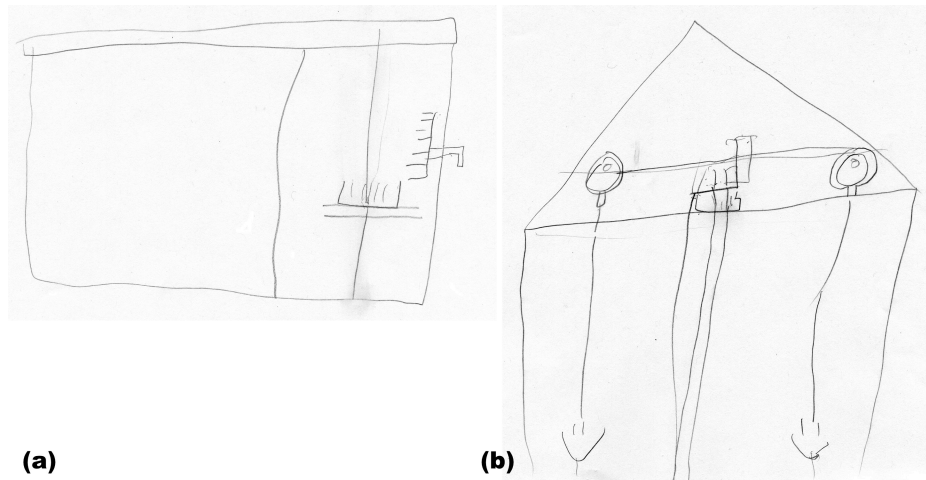


Figure 7.10: (a) Sam's sketch for the base of the carousel showing the two pinwheel gears that will convert the rotation of the crank into rotation of the carousel. (b) Sam's sketch for the mechanism to move the animals. His idea is to use eccentric cams with ring followers (which can work in any orientation) to move the animals up and down and to drive the cams with a set of pinwheel gears that receive their power from the base. Compare these first drawings to his first drawing of the soccer player in Figure 7.1 where the figure of the player is central and no hint of mechanism or structure is shown. In these drawings the structure and mechanism are key and the animals only represented by smiling faces.

would come up from the base, through the center of the carousel and connect to the central pinwheel gear which in turn would drive the secondary pinwheel gears. These would be attached to the eccentric cams that would move the animals. The researcher asked how the rotation of the carousel would affect what Sam had just described.

Sam had some difficulty in seeing the problem so the researcher asked him to take the mechanism he had, place it on the table and spin it around the axis of the horizontal gear since this would approximate the mechanism Sam was thinking about. Sam did this, but was still unclear about what he should be seeing. The researcher pointed out that rotating the entire mechanism did not cause the gears to turn. Sam replied that the shaft from the base would turn the horizontal gear when the crank was turned. The researcher asked if that shaft and the carousel would turn at the same speed and Sam said they would. The researcher asked Sam to look at the pinwheel mechanism as he again rotated it on the table. While Sam was doing this the researcher reminded

him that the framework represented the top of the carousel as it turned and he asked Sam to describe the relative motions of the framework and the shaft for the pinwheel gear. Sam was still puzzled, but slowly it became apparent to him that the shaft and the framework were turning at the same rate. The researcher then held the horizontal gear stationary while Sam continued to rotate the framework. This caused the vertical gear to start rotating and Sam seemed to understand what was wrong with his design; there could be no motion imparted to the cams if the driven gears were revolving around the drive gear at the same speed the drive gear was rotating.

Sam asked if there were some other way to make the cams move and the remainder of the session was used to consider alternatives, none of which would work. The researcher asked him to think about the problem during the week, and especially think about alternative placements for that part of the mechanism. Sam was also told to think about why holding one gear stationary and rotating the framework produced the same motion as turning the gear while holding the framework stationary.

When Sam returned the following week saying that in order for his idea to work he would need to find a way to keep the drive gear stationary while the carousel revolved. The researcher asked him if he thought that was possible if the gear was located above the carousel and Sam said that he had not thought of a way and reminded the researcher that the two of them had failed to find a method the week before. He said he thought it might be possible if there was some way to attach the drive gear to the base which would be stationary with respect to the carousel but that he had not figured out a way to transfer the motion up to the cams. At this point the researcher suggested something radical; could it be made to work if the base were placed above the carousel? Sam assumed that this was a joke, but the researcher asked him to consider it seriously. Sam concluded that such a solution might work but that it would not be practical to build the automaton that way. The researcher agreed, and asked Sam how this new mechanical arrangement could be made practical. Sam was left alone to think it over. After spending nearly ten minutes alone on the problem, Sam said that the carousel could be flipped over. This would put the base back on the bottom, but would leave the animals upside down. The researcher

suggested that there was an easy solution to that problem and Sam, seemingly a little embarrassed, said that the animals could be turned over as well.

This would place the mechanism for the animals between the base and the bottom of the carousel rather than on top as Sam had originally planned. But it did away with the problem of getting the proper behavior and was adopted as part of the next design which, it was agreed, should have a prototype constructed.

7.2.2 Prototyping and Constructing the Carousel

Sam and his mother had made a visit to a local thrift store and obtained four small plastic animals: a lion, a panda, an elephant, and a moose. While some were not typical of what would be found on most carousels,⁴ they showed a great deal of promise. As Sam and the researcher had earlier discussed, the size of the animals determined the size of the carousel which ended up being almost twice the diameter that Sam had originally wanted. Armed with dimensions for the carousel, they began building a first prototype in corrugated cardboard (Figure 7.11).

Because of the complexity of the mechanisms for this automaton almost all of the prototyping for the base and mechanical components was done in wood. Since this was a more expensive material to use and not as plentiful as cardboard, Sam and the researcher spent a greater percentage of the prototyping time calculating and planning than they had for the soccer player. They first designed and constructed the gears that would rotate the carousel. During earlier discussions, Sam had decided that his original 1:1 pinwheel gears would allow the carousel to rotate faster than he wanted and he also knew that by slowing down the input he could gain some extra power for the rest of the mechanism. A pair of pinwheel gears with a ratio of 2:1 were constructed. The gears were used to determine the size of the structural framework for the base and some preliminary drawings were made. Sam's design had the weight of the carousel and animal mechanism supported by the shaft from the pinwheel gears. The researcher asked him if he could think of a way to support the carousel independent of the drive train while still allowing it to turn. Sam had

⁴ Particularly the moose who at some point in his life had acquired a green head and antlers.



Figure 7.11: The first carousel prototype assembled and with the animals arranged to get feel for size and scale. The curved structures on the top are for future draping with cloth.

seen microwave ovens with rotating trays and had observed that these used rollers near their circumference to stabilize the tray and help support its weight and thought that this was something that could be used to stabilize and support the carousel. A set of four rollers were created and the top of the base was modified to hold them. The base was then assembled (see Figure 7.12).

Since the animal mechanism would be located between the base and the floor of the carousel, the next job they began was to design that mechanism. Work was deliberate although progress was slow and there were many design decisions that had to be carefully thought through. In the end a ring was made that would rest on the base rollers. Attached to this ring were the supports for the carousel floor and for the bearing surfaces of the cam shafts. A large pinwheel gear was created that would be attached to the top of the base coaxial with the shaft that would turn the carousel. Two smaller pinwheel gears were made that would be attached to the shafts for the eccentric cams and would mate with the large gear. The amount of motion that Sam wanted the moving animals (the lion and moose) to have was determined and eccentric cams were made that would produce this movement and two crescent shaped cam followers were made to reduce

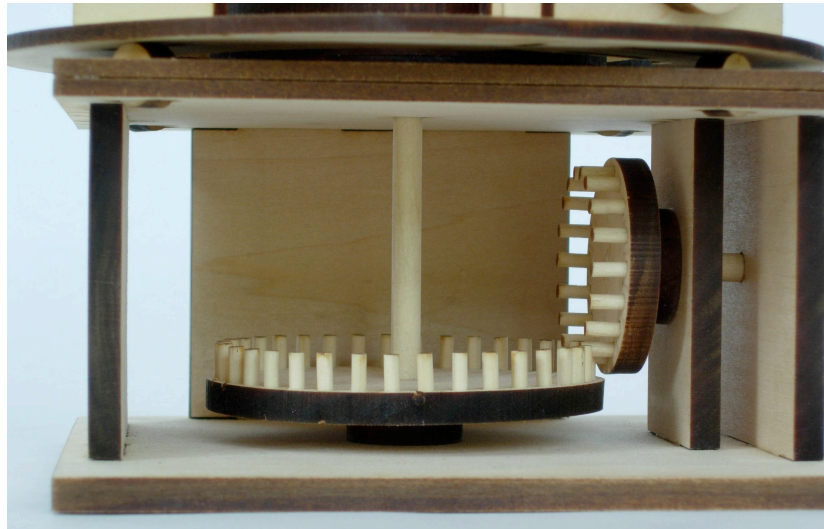


Figure 7.12: When the user turns the crank attached to the pinwheel gear at right, that motion is transmitted to the vertical shaft which is attached to the carousel. Note the rollers at the corners of the mechanism top that support the carousel as it turns.

the friction that a simple rod follower would have created. To complete this assembly for testing, a carousel floor was made from wood using the same file that had been used for the cardboard prototype. This mechanism in its final form is shown in Figure 7.13.

Once performance issues with the mechanisms had been corrected, the remainder of the carousel was completed quickly. The animals had small holes drilled in their backs (a process the researcher found somewhat gruesome) and wooden dowels were inserted. The researcher had told Sam that in his experience the center of carousels where the machinery was located were blocked from view, often by mirrors and that since they had some mirrored acrylic available to them it might be visually interesting to do the same. So a wooden framework was fabricated to both hold the mirrors and provide additional support for the roof. These pieces were assembled and along with the animals added to the carousel. Since Sam was planning on draping cloth over the top, it was necessary to create a false roof to keep the moving shafts of the animals from protruding into this space. With this done the roof pieces were put together and the carousel was complete (see Figure 7.14).



Figure 7.13: The mechanism that lifts the animals was one of the most complicated created during the user testing. The large horizontal pinwheel gear is attached to the mechanism base and does not turn. As the carousel rotates it carries with it the shafts connected to the smaller gears which causes them to turn. This motion is transmitted to the two eccentric cams which alternately lift and lower the lion and moose. The rollers which support the carousel can also be seen in this view.

7.3 Discussion

The results from Sam's test session, while impressive, are not unusual. Several others in the test user group have similar stories which show a trajectory of increased domain competence and improved mechanical thinking and while these comprise a small number of cases, there is little reason to doubt that similar results would be seen if these tests were run again with a different set of users from the same population. The results presented here support the claims made in Chapter 6. Specific examples for each of the evaluation measures include:

- **Talking about Automata**, Section 6.2.1: The changes in Sam's ability to use the terminology appropriate to the domain is seen when comparing his use of "stick" in an early transcript during the construction of the soccer player to the correct use of "follower" when describing his proposed design for the carousel.



Figure 7.14: The carousel in its final form. Turning the crank (lower right) causes the lower horizontal pinwheel gear to turn. This rotation is transmitted to the carousel proper via the central shaft that passes through the upper horizontal pinwheel gear which is fixed to the automaton's base. As the carousel rotates the small pinwheel gears are forced to turn as they move about the central gear. These in turn rotate the eccentric cams that move the lion and moose up and down through the motion of their followers. As can be seen, this automaton is both complex and visually stunning.

- **Using External Representations**, Section 6.2.2: The changes in Sam's use of drawings can be seen by comparing the items of prominence in the initial drawing for the soccer player where the figure of the player and the ball are seen in the absence of any mechanical details and the initial drawings for the carousel where the mechanisms are the key features and the animal figures are only hinted at.
- **Components, Motion, and Complexity**, Section 6.2.3: The changes in Sam's ability to deal with complexity is easily seen between the initial difficulty he has with the simple mechanism in the soccer player and his ability to deal with significantly more demanding issues with the carousel mechanisms.

- **Confidence Levels**, Section 6.2.4: Sam indicates how his confidence has increased both when he decides to put the soccer player on very public display as his science project and when he attributes his desire to construct a second automaton in part to his belief that doing so will make him feel better about himself.
- **MachineShop System Usage**, Section 6.2.5: Sam proves that his use of the software is becoming more sophisticated when he demonstrates its abilities to his mother.

Similar examples were seen with a majority of the test users. In some cases these examples were even more striking than those observed with Sam. In all cases, users took away some skill or ability that they had not previously demonstrated and for that reason alone the tests were a success.