Appendix A

Observations on the User Testing

This appendix is intended to provide the interested reader with more information on the process and results of the user testing presented in Chapter 6 and to add breadth and context to the case study of Chapter 7. A large amount of interesting and instructive data were gathered during the testing and what follows is a sampling from those data. This appendix begins with examples of the language users employed, with an emphasis on the kinds of information contained therein. Next, it examines a number of activities and knowledge areas that proved problematic for the users. It continues with a brief discussion of the role of the MachineShop software in the tests and the ways in which the users interacted with it. It concludes with a look at how the overarching apprentice model used in the testing was implemented to meet the varying needs of the users.

The reader is directed to Chapter 6 to gain a better understanding of the context in which these results were obtained, to Appendix B for a more detailed description of the automata created by the users, and Appendix D for information on the sample automata and mechanisms available to the users.

A.1 The Use of Language During Testing

The language employed by the users was only one of the metrics used for evaluating the results of the testing, but proved to be tightly coupled to the other metrics, particularly with regards to components, motion, and complexity (see Section 6.2.3). The dialogues between several of the users and the researcher that are presented here show the nature of the language used during the course of the testing and much can be gleaned from them about the how effectively users have internalized domain information. These examples are representative of those seen across all users and have been selected to highlight growth in vocabulary with respect to mechanisms and movement, changes in abilities to effectively express ideas and concepts within the domain, and statements or exchanges that indicate the nature of the users' understanding of the domain. Session numbers are given to indicate relative chronological occurrences.

A.1.1 Abbie

Abbie built one automaton; the Drowsy Dragon (see Section B.1). Her goal was to have the dragon's wings flap and tail move while breathing fire. She described her previous construction experience as being fairly limited; she had worked with LEGO Mindstorms and she and her father were in the process of building a whirligig.

A.1.1.1 Vocabulary

Abbie had little experience in this or related domains, and after her initial introduction to automata and mechanisms her language was filled with general terms and vague descriptions. During session one, as she and the researcher were discussing her requirements, we see this reflected in her suggestion for a possible means to make the dragon's wings flap. Here she is referring to one of the crank-slider mechanisms (Figure D.9) she saw during the introductory session:

> Abbie: So, like, maybe, you know that thing where you turned it and then the pole would go up and down? Maybe that's what we could use for the wings.

Imprecise terms like "thing" and "pole" continued to be a major part of Abbie's vocabulary throughout the testing. Even terms that she was exposed to during almost every session, particularly those that described the mechanism she was building, failed to become familiar. This exchange is from session nine:

Researcher: Remind me where we were last week.

Abbie: Okay, so we were on making the gears *[pause]* I mean planning where *[pause]* how big the thing is gonna be. And where the *[pause]* how *[pause]* well, what gears we're gonna use on the…

Researcher: Are we going to use gears? *[long pause]*

Abbie: Maybe *[long pause]* yes. *[pause]* Well no, not exactly gears. There's like…

The researcher hands her the simple pinwheel gear mechanism
Researcher: These are gears. Are we going to use these?

Abbie: We're going to use this one without the *[pause]* things.

Researcher: Without the things.

Abbie: Uhhh…

The researcher points to the teeth of one gear.
Researcher: What are these things called? *[Abbie doesn't answer]* These things are called teeth. So if we're not going to use gears, what are we going to use? What are they called?

Abbie: I don't remember.

Researcher: *[gently]* Come on…

Abbie: I'm thinking, I'm thinking, I'm thinking. *[pause]* Well anyway, they're these things. *[picks up the sea lion and points to the eccentric cams]*

Researcher: Right.

Abbie: Spinners!

Researcher: But those things are called…

Abbie: *[pause]* Cams.

Researcher: Right. And these ones in particular are called…

Abbie: Wait. What ones are you talking about?

Researcher: The ones that move Celia's[1] tail back and forth.

Abbie: Contracting.

Researcher: Eccentric.

Abbie: Encentric [sic] cams.

[1] See Section D.3

A.1.1.2 Expressing Ideas and Concepts

Abbie often found herself searching for a word or concept and this was reflected quite often in her use of incomplete sentences that either ended abruptly or simply trailed off. This example comes from her final interview at the end of the user testing:

> Researcher: What have you done in the past? Have you worked with LEGOs, have you built models, . . .
>
> Abbie:I have worked with LEGOs, um LEGO Mindstorm. Where you program the LEGO thing that you built to do things. So that's kind of like this only it has gears and things and you *[pause]* and so yeah.

Abbie also found it difficult to explain the operation of the mechanism she had built in words and relied heavily on pointing to her automaton in an effort to clarify her descriptions. The following is also from her final interview:

> Abbie: . . . And then how it works is when you, if you were to turn this *[pointing to the crank]*, turn it, these *[paired eccentric cams at the tail]*[2] would go around and make the tail go back and forth.
>
> Researcher: And those are called what?
>
> Abbie: These are called, called, um, *[pause]* uh, *[pause as she looks up]* cams I, yeah, cam. And they're. . .
>
> Researcher: Do you remember what kind of cam those are?
>
> Abbie: Um, I think they're, um, I for *[pause]* flat cams or something?
>
> Researcher: They have a strange name. They're called eccentric cams.
>
> Abbie: Yeah, eccent *[pause]* um huh, and so this thing's *[the entire mechanism]* mostly were made out of eccent, it's uh egcetric [sic] cams, and so this one *[the tail]* would just move back and forth. And then on the wings we had a couple of ideas where just keep the wings like sta *[pause]* down. Um. Like from right here *[points to wire connected to wing]* there's actually a little hole right here where, so it actually is this thing is the thing that makes it go up and down, instead of just having another thing pushing it up and down. It just has one thing now. So then we put on this thing *[the large follower to which the wires are attached]* which would help it come down

[2] This particular mechanism is one I refer to as a Markey oscillator after Peter Markey. While he may not have invented it, he was the contemporary automatist who made it popular in many of his works. A description of how it functions can be found in Section D.3.

> *[due to its weight]* because it wouldn't just do it with one so we put two more *[the follower is laminated from three pieces of wood]*.
>
> Researcher: So why wouldn't it come down with just the one?
>
> Abbie: It was, um. These *[the wings]* were, are made like out of, um, like really light stuff *[craft foam]* so it wasn't heavy enough with these *[wings]* and just that *[follower]* so we put three more to help it come down easily and not just get stuck up there. And then so another cam *[for the wings]* only this one, *[pause]* oh yeah. And then this one is for the fire as you can probably see in here *[points to mouth]*. And so, if we were not, if we didn't have this *[the cam has a retainer disc for the follower]* we could see that it has, um, a little cam inside. And then, um, it would turn and this thing *[the ring follower]* would, um, turn with it. So to help it just turn. And so, that, those ones can go, um, anyway it wants *[referring to the ring follower's ability to function in any orientation]*. It can be sideways, up and down, um, upside down, and so hmmm.

A.1.1.3 Domain Understanding

When Abbie began the testing she was almost a complete novice in her knowledge of mechanics. One unexpected example came during session seven, the following exchange occurred:

> Researcher: ...and it also has to be able to work on the friction of these joints.
>
> Abbie: What's friction?

Abbie's understanding of the domain did increase over the course of the testing, but she sometimes still found it difficult to express her new knowledge in words. For example, when using ring followers with eccentric cams it is necessary to provide some method for preventing the follower from sliding off the cam. In Abbie's dragon, the ring follower that provides the motion for the fire breathing is kept on the cam by the support framework on one side and a thin disc that is glued to the cam on the other. During her final interview, Abbie was asked the purpose of that disc:

> Researcher: Why does that have the ring follower on that cam?
>
> Abbie: You mean this one? *[points]*
>
> Researcher: Uh huh.

Abbie: Well *[pause]*

Researcher: So, the other cams don't have that piece *[retainer disc]* on the outside of them. Why does that one have it?

Abbie: Well, I think that it's to keep the little tiny cam *[this cam is the same diameter as the other three]* from going in and out. From getting out of it.

Researcher: Can you think of any other reason we might done that?

Abbie: Unh uh. *[shakes head no]*

This shows that while she knows that the disc exists to maintain the alignment of the cam and follower, she is misstating the potential problem. Since the cam is glued to the main shaft and the disc is glued to the cam, the disc cannot hold the cam in place but serves to hold the follower in place.

A.1.2 Dylan

Dylan built two automata; the Leaping Lion (see Section B.3) and the Busy Beehive (see Section B.4). His craft and construction experience before the testing was the most diverse of any of the users and included model rockets, several challenging science fair projects, creating and modifying objects using found materials, along with the more common use of construction kits and toys seen in all users. The examples presented here come from his work on the lion which was the first of his automata.

A.1.2.1 Vocabulary

Dylan seemed to sense early on that he would be more likely to convey his ideas to the researcher if he used the terminology of the domain. As early as his second session he had already acquired a number of component labels that were specific to what he needed to do although his dialogue still contained a large number of ambiguous references. The researcher asks him to describe the mechanism he is thinking of using during the second session:

Researcher: . . . remind me now what we talked about for a mechanism.

> Dylan: Um, the, uh, uh, wheel thing that we have on the buffalo. Or it was one of those three *[crank-slider mechanisms]*. It was one of the three that we showed ...
>
> Researcher: Do you want me to get those again?
>
> Dylan: Yeah.
>
> Researcher: Okay.
>
> Dylan: I think it was the one which wasn't, which didn't need the little plastic piece *[the eccentric cam with ring follower]*.
>
> *[The researcher hands him the crank-slider mechanisms.]*
> Yeah, it was that one *[points to the disc with offset pin]*. This one. And then we were going to have a little, uh, a little thing which stuck up and the wall would, I mean the jaw, the lower jaw would be a lever. And it'd push up on this *[he pivots his right hand around the palm]* which would push down when it comes down.

The only specific term he used is when he identified the moving part of the jaw as a lever. The rest of his explanation was vague, but a few minutes later, when preparing to design components he needed with the MachineShop software, this occurred:

> Researcher: We need to design a couple of things. We need to design a cam first of all. This is the cam tool *[MachineShop's cam editor]*. Show me what you're ...
>
> Dylan: I wanted the ratchet one so you could only make it jump forward.

Not only did he correctly name the component he wanted, but he also provided a correct rationale for his choice. This continued over the course of the testing and while he continued to use ambiguous references, he was quite capable of using specific terminology when he wanted.

A.1.2.2 Expressing Ideas and Concepts

Dylan's brief explanation above for his choice of a ratchet was one of the earliest indications he made that he was not only learning about the domain, but learning to talk about the domain. The lion took just over two months to complete and in that time Dylan's ability to express his understanding of the domain continued to improve. While still relying on pointing to features of his automaton to aid in his explanations (a common action with all of the users), he was still able to describe dependencies in an understandable way. This exchange is from the interview conducted when the lion was complete:

> Researcher: Explain to me what you have in your hands.
>
> Dylan: Um, well, it's a simple machine and it's got a ratchet, and the, when the ratchet goes around it pushes this *[slider rod]* up causing the lion to go up. And when it goes up, this little piece here *[the bottom stop on the actuating rod for the jaw]* hits this top *[the top of the support framework]* closing the mouth. Then, when it goes around and back down *[he tries to turn the ratchet by hand]* it comes around . . .
>
> Researcher: So what were you just doing there? You were turning it and then you turned it the other direction.
>
> Dylan: I was turning it the wrong way because of the pawl *[he smiles]*.
>
> Researcher: So when it goes down, then what happens?
>
> Dylan: Uh, then that *[the upper stop on the actuating rod for the jaw]* hits there *[the framework top]* causing this *[the actuating rod]* to open this *[the jaw]*.
>
> Researcher: How does that rod that you're holding in your hand right now, how does that open and close the jaw of the lion?
>
> Dylan: Well, uh, there's, uh, a little piece in here *[showing where the lever is in the lion's body]* and when you push up on here *[the rod]* 'cause this gets stuck *[the rod]* and so it starts to push up because this, the lion is still trying to go down, it opens the jaw because the jaw is pivoting on this *[points]* rod.
>
> Researcher: What kind of component is the jaw?
>
> Dylan: A first lever, uh, a first order lever.
>
> Researcher: What does that mean? That it's a first order lever?
>
> Dylan: Uh, the pivot, the fulcrum is in between the force, where you put in the force and where you get out the effort.
>
> Researcher: What else is kind of unique about this mechanism? I see some things that I haven't seen anybody else do.
>
> Dylan: Um *[pause]*
>
> Researcher: So, why did you pick a ratchet?
>
> Dylan: Well, 'cause I like, I don't think it's very realistic when lions jump, like, backwards. So if you put that up *[he raises the pawl and turns the crank in the opposite direction that it normally goes]* then the lion looks

like he's jumping backwards. And so I didn't think that looked very realistic so I made it so he could only jump forward.

Researcher: So how does the ratchet do that?

Dylan: Well, the ratchet moves around and it's got these points and the pawl gets stuck on 'em. So, when you try and push 'em go backwards, the pawl is stuck on the points. So it can't go backwards.

Researcher: And when you go forward what happens?

Dylan: Then it *[the pawl]* just bounces up and down.

Researcher: Where did you get the idea of *[pause]* So the ratchet does do what you wanted it to. It makes sure that the lion only goes one direction. But this is the first time I've ever seen anybody put an offset on a ratchet to move the lever up and down to move the body. How did you come up with that idea?

Dylan: Well, uh, I was sort of playing around, and when I was looking at the software I saw that you had one which was just plain round with the little hole at the top *[this was actually in the sample mechanisms]*. And I said "hey, why don't we do that but use a ratchet? Wouldn't that work the same? Because then that'd just make it so it couldn't turn backwards, but it'd still be offset and make it go up in a oval."

...

Researcher: When you first came in and we started talking about the lion you had some things that you wanted it to do. Do you remember what those things were?

Dylan: Jump up and down, have its jaw go up and down, and have its tail move around.

Researcher: So I'm looking at it right now and I don't see a tail. What happened to the tail?

Dylan: Well, I, I don't really know how we could do it. But I could probably make a second try at this and do most of this about the same and then make, and then make the, this part *[the support framework]* a little wider out here and make a bar go up, and make the tail.

A.1.2.3 Domain Understanding

Because Dylan was the first user, he helped define the form that the testing assumed. He had more time to "play" with both the software and the sample mechanisms than did the other users (although all users did spend unstructured time interacting with both) and he was able to visit some of the more conceptual aspects of the domain. From session three:

Researcher: . . . look at the crank that you're thinking about using *[disc with offset pin]* and look at the one that we used in the buffalo *[eccentric cam with ring follower]* and think about, which one of these do you think might be stronger? Or do you think that there's any difference?

Dylan: Probably, this one's stronger *[pointing to the eccentric cam]*.

Researcher: Why do you think so?

Dylan: Um, 'cause it's not got this little thing *[pin]* which might pop out.

While experimenting with the design of snail cams later in the session, he asks this question:

Dylan: Can you put zero lobes on it?

Researcher: What would a zero lobe cam look like?

[Dylan moves the graph points so that they coincide and the profile becomes a disc.]
Dylan: Pretty much that.

Researcher: Okay, that's a disc. What does an eccentric cam look like?

[He switches to the eccentric cam tool.]
Dylan: That, only *[pause]*

Researcher: It's kind of a zero lobe cam when the hole is in the middle.

[Dylan moves the hole from the middle of the cam to an offset of about three-quarters of an inch.]
Researcher: How many lobes does it have when you do this?

Dylan: Zero.

Researcher: What's a lobe?

Dylan: One of the little stickie up things.

Researcher: That's how it's represented on the snail cam, but what's the function of a lobe? What does the lobe do?

Dylan: Push up the follower?

Researcher: Right. And let it go back down. What does an eccentric cam have? Can it push up a follower?

Dylan: Yes it can.

Researcher: So for every time it goes around, how many times does it push it up?

Dylan: Once.

Researcher: So it has how many lobes?

Dylan: One. But it's not exactly this kind of lobe *[indicating a snail cam]*.

Dylan was one of only two users (the other being Sam) to incorporate gears into an automaton when he built the beehive. But even before he started fabricating components for the lion, he was learning about gears. This occurred during session three:

> Researcher: So, we know what cams do. What do cams do?
>
> Dylan: Um, cams. They uh, make something go up and down or back and forth.
>
> Researcher: Right. So what they do is change rotary motion, which is the circular motion of the cam, into linear motion, which is the up and down or side to side motion. What do gears do?
>
> Dylan: They change the direction of stuff.
>
> Researcher: Of what kind of stuff? Do they change the direction of hurricanes?
>
> Dylan: *[laughs]* No. The direction the machine is going so if you turn the gear one way the other gear will turn the other way. And faster if it's smaller.
>
> Researcher: And what kind of motion is that? We just talked about it with the cams.
>
> Dylan: Rotary motion.
>
> Researcher: Is that always the case? Does a gear always change the direction of the rotary motion?
>
> Dylan: Uh, yeah. Oh, no. Um, yeah if it's right next to each other.
>
> Researcher: That's right. For gears that are touching, they always rotate in the opposite direction. But what about gears that aren't touching? Like in these three gear sets that you have right here?
>
> Dylan: If they aren't touching? Then they're going to go the same way if they're odds and the same way if they're evens.
>
> Researcher: Animate that and take a look. Which direction are those two going?
>
> *[Dylan moves his index finger in the direction the outer gears are turning.]*
> Researcher: Clockwise. Are they going the same speed?
>
> Dylan: No. This one *[the smaller gear]* is going a lot faster. It's going once for every ten ones this one *[the larger gear]* is going.
>
> Researcher: Not quite. What does it say here for gear ratio *[2:7]*?
>
> Dylan: For every two this *[the larger gear]* this *[the smaller gear]* spins seven. What's the biggest ratio you have?
>
> Researcher: In this tool right now, four to one or one to four. But is there any limit?

Dylan: Uh, no. Just how big you could make it.

He and the researcher then went on to discuss the relationships between speed and power and how the ratios of gears and the ratios of levers were related. These types of exchanges occurred on and off during the testing and the knowledge that Dylan built from them played out prominently when he designed the mechanism for the beehive by deconstructing the complex motion he wanted into simpler constituent parts.

A.1.3 Iris

Iris built one automaton; the Globe Trotter (see Section B.6). Her first concept was an automaton of an old woman pouring milk for a kitten, but she discarded that idea as being too complex, even before she had any familiarity with automata mechanisms. The person (eventually a man) with the globe seemed the ultimate in simplicity; a static figure with a spinning globe. Getting Iris to add motions, and consequently interest, to this automaton took several sessions and in some cases needed to be prompted by the researcher. It is particularly interesting that at the conclusion of her time in the project, Iris had a different recollection of the original form of the automaton and its evolution (see Section A.1.3.3). She had built some items from wood (a box at summer camp and a chicken coop built with friend and the friend's father), played with LEGOs on occasion, and liked to draw and paint, but she had never built an object that incorporated movement before making her automaton.

A.1.3.1 Vocabulary

Iris' automaton was among the simplest of those built by all users, and because the mechanism was very similar to that of Celia the sea lion (Section D.3) she spent little time exploring other mechanical options. Even with this focus on a mechanism with few component types, her vocabulary showed little change over the course of the testing. While discussing the mechanism for the sea lion in the second session the following exchange occurred:

> Researcher: When you turn the crank, what happens?
>
> Iris: It well, it takes the uh, it takes the um, big thing which rotate, which turns...
>
> Researcher: Okay. So this is the ball up here *[pointing to the disc that turns the ball]*...
>
> Iris: And that would be the tail *[pointing to the eccentric cams for the tail]*.
>
> Researcher: Right.
>
> Iris: So that turns that, right? *[the disc that turns the ball follower]* And that's connected to the ball.

Iris' use of generic and ambiguous terms ("big thing" or "that") far exceeded her use of domain specific terms during early sessions. This was mitigated only slightly by the end of the testing, and often more specific terms were used incorrectly. During the interview held at the completion of the project, Iris was asked to describe her automata:

> Researcher: So why don't you explain to me what your automaton is and how it works.
>
> Iris: My automaton was a person pushing a globe and then watching the globe go around and looking at the cranker. The gears worked because, well pushing this *[the crank]* it turns all the bottom ones. The bottom ones turn the globe 'cause it's, and we had to taper it because I wanted the globe to be more realistic and so we put it on a stand.

Iris uses "gear" for any of the circular cams and discs that comprise the mechanism for her automata. Indeed, her use of the word is puzzling, as gears were never discussed with respect to her mechanism and none of the sample automata she examined contained gears. Notice also that she is still using ambiguous terms such as "ones" and "this".

A.1.3.2 Expressing Ideas and Concepts

When Iris would explain how a mechanism worked it was common for her to skip around from feature to feature rather than progressing through the mechanism based on its dependencies ("cam A pushes on follower B which moves the short end of lever C ..." for example). When describing her automaton in the final interview, she says:

> Iris: My automaton was a person pushing a globe and then watching the globe go around and looking at the cranker. The gears worked because, well pushing this *[the crank]* it turns all the bottom ones. The bottom ones turn the globe 'cause it's, and we had to taper it because I wanted the globe to be more realistic and so we put it on a stand.
>
> Researcher: So it sits at an angle like the real Earth does.
>
> Iris: Yeah. And it pushes the globe to turn around. And there's a wire there *[indicating the globe]* so it pushes the arm *[pause]*
>
> Researcher: And the arm can move because *[pause]*
>
> Iris: Because we have a spring right there.
>
> Researcher: Okay.
>
> Iris: These two *[the eccentric cams]* are gears that control the head and they aren't centered perfectly so the head will go up and down and they have wires on 'em to stop the head from going all the way around and not catching.

In her automaton, the "gears that aren't centered perfectly" are the eccentric cams responsible for turning the head back and forth in the Markey oscillator (Section D.3). The wires she mentions are not attached to these cams but rather to the follower they rotate, and they constrain the motion of the follower so that it can turn only a limited distance in each direction.

Iris was obviously more comfortable discussing the layout and motions of the tableau components than she was with the mechanical components. From the final interview:

> Researcher: How did you choose this mechanism? So you had an idea about how you wanted it to work.
>
> Iris: I just, I just thought about this *[the figure and the globe]*. I didn't, I had no idea how we were going to make it work.
>
> Researcher: So once you had thought about that though, some decision was made to come up with the mechanism that's inside of that.
>
> Iris: Yeah, we were drawing it out and I'm just like "that doesn't look real 'cause the globe is standing straight up, not at a slant so it doesn't look like a globe."
>
> Researcher: So did you get any of these ideas from other examples or from books or from . . . ?
>
> Iris: Well, I was looking at the globe and I'm just like "that doesn't look like a globe" because it's at a hundred and *[pause]*

> Researcher: So we figured out how to slant it. What about getting the guy's head to turn from side to side?
>
> Iris: *[pause]* That's a good question. *[long pause]* Give me that question again.
>
> Researcher: Did you look at other automata or look at pictures or books or websites or anything to come up with this idea?
>
> Iris: Mmm *[pause]* Well, I could just picture it going like that *[she turns her head and moves her hand]* and looking at the, watching the globe and then it would keep going.
>
> Researcher: But for actually coming up with the mechanism to get the head to turn like that though, did you have any examples that you saw that did similar kinds of things?
>
> Iris: I think we looked at um, Celia the seal and her hind tail, her tail flippers went like that *[moves her hands back and forth]* so we used the same thing for the head.

A.1.3.3 Domain Understanding

Iris' understanding of mechanisms and mechanical components increased only slightly during the testing. Much of the knowledge she used in making her automaton was only seen in the short term and little was reflected in many of her responses during the final interview. One example:

> Researcher: So that was your original idea, and you decided that that was too tough so you came up with this second idea which was simpler. In the beginning, did the head turn and the arm move and the globe spin? Were all three of those things there?
>
> Iris: No. Well, we first thought "oh my gosh, there's not going to be enough room, the head can't move." So we just thought it would be *[pause]*
>
> Researcher: So the arm was always going to move?
>
> Iris: Yeah. 'Cause then it wouldn't, 'cause if it didn't move the globe would just be hitting like that *[she presses on the fingertips of one hand with the fingers of the other]* and getting tripped. And then we didn't know how, we didn't know how we were going to get this, the wire, to get the hand to move. Then I thought we were going to have like a wire attached to the hand that went around so it wouldn't, wouldn't, but it didn't work. After I thought about it, and we, I didn't know there's going to be these wires down here.

> Researcher: We needed those when the head started turning around backwards and it started looking like the Exorcist.
>
> Iris: Yahhh! *[she claps]*

This is actually a quite different take on the way the automaton would function than she presented initially. Here she says that the arm was always going to move, but after abandoning her first idea as too hard, her original idea for this automaton was overly simple. During her first session, the researcher asked about her preliminary sketch:

> Researcher: Okay. So what am I looking at?
>
> Iris: You're looking *[pause]* the globe spins around.
>
> Researcher: Does the person do anything?
>
> Iris: Umm, no, not really.
>
> Researcher: The person doesn't push the globe *[pause]* or point or *[pause]*
>
> Iris: I don't know what it would do but it could do something.
>
> Researcher: Just getting the globe to spin is just like getting the ball to spin on the nose of the seal. That's pretty simple. We can do that easily enough. But you've got a person there. So maybe the person, I assume the person is interacting with the globe in some way.
>
> Iris: It could have eyelids, eyelids that blink.
>
> Researcher: Would you want to have one of the hands push the globe as it spins?
>
> Iris: That'd be cool.

Iris never seemed to become comfortable with either the essence of contemporary automata or with the mechanisms that they contain. While having the eyelids blink would not have been overly difficult, in the context of her automaton it was not as central a motion as having the man appear to rotate the globe.

A.2 What Users Found Difficult in This Domain

Building automata is a challenging task, as any automatist will admit. The users in this study encountered a number of difficulties while working to complete their projects. Individual differences in style, background, and ability presented themselves many times in situations that perplexed and confounded the users. Quite often, these situations were unique to one or two users, but almost all of the users experienced enough similar problems that the general categories that follow were readily apparent.

A.2.1 Size and Scale

All of the test users experienced some difficulty when thinking about either the size or the scale of their automata. These difficulties fell into three general categories: in choosing a size for the tableau that would be practical, in determining the correct proportions of tableau members, and in selecting appropriate sizes for mechanical components. A majority of these problems presented themselves because all of the users worked from the design of the tableau to that of the mechanism in a purely linear process. The method used by more skilled builders (and by both Dylan and Sam with their second automata) is to work alternately on both designs, starting with the tableau and moving between them until both parts form the desired whole. Novice users possess no skills or knowledge that would encourage them to proceed in this manner.

The most common problem seen was that users wanted to make their automata too small. This presented itself in two ways. First, the user would choose a size for the primary tableau element without sketching or measuring, and that was, in all cases, too small. When Dylan began working on his lion (Section B.3), he made the first body four inches long. With a cardboard prototype in hand, it became clear to him that this was much smaller than he had thought it would be and subsequently the body size was increased to about six inches. If this decision had not been made at this early stage, it would have been necessitated by the constraint of making the lever actuated jaw function properly. Frank encountered this problem when the initial body size for his cat (Section B.5) was too small to house the mechanical components needed to make it work. To overcome this, he made the second version roughly double the size of the first. Interestingly, Sam's first automaton, the soccer player (Section B.7) was designed large from the beginning and was built to those dimensions. But he had wanted his second automaton, the carousel (Section B.8), to be much smaller and, as it turned out, it too was unable to house the mechanism he eventually developed and it ended up being made larger.

The second problem occurred when working with relative size or scale in the tableau of an automaton. This presented itself in three automata in these tests; the Globe Trotter (Section B.6), the Soccer Player (Section B.7), and the Carousel (Section B.8). When a simple tableau had only one element (like the Dragon, Section B.1) or when all of the elements were created and constructed with the laser cutter (like the Cat, Section B.5), this was not a problem. But when users brought found materials into the tableau, it was often a challenge to make the proportions of all of the elements correct. The Carousel became larger than Sam had originally wanted in part because of the mechanism needed, but just as importantly because of the size of the animals he found. With both the Soccer Player and the Globe Trotter, the balls used had some effect on the size of the human figures. Since the height of the soccer kicker had been determined early in the design process, Sam had to determine an appropriate size for the wooden ball he would use. Iris found the globe she was going to use at a toy store and while real globes come in a variety of sizes, it was necessary to see if the scale sizes of the globe and the man were acceptable. To do this, Iris needed to convert fractional measurements to their decimal equivalents and to use a scaling factor on elements of her tableau. From her third session:

> Researcher - ”So you’re good at fractions?”
>
> Iris - ”Yeah.”
>
> Researcher - ”Have you done fractions to decimal conversions?”
>
> Iris - ”No. I don’t think so. Not the conversion part. Like one half is point five?”
>
> Researcher - ”That’s exactly what we’re going to do. One quarter is *[pause]*”
>
> Iris - ”Okay, we didn’t do that.”
>
> Researcher - ”Alright. Well, what’s the relationship of a quarter to a half?”
>
> Iris - ”Two quarters equals a half.”
>
> Researcher - ”So one quarter is *[pause]*”
>
> Iris - ”Is *[pause]* three point five? point, point three five, point three five.”

Researcher - ”Let’s worry about the relationship to a half. So one quarter is how much of a half?”

Iris - ”Half?”

Researcher - ”It’s half of a half. So, what’s half of zero point five?”

Iris - ”Zero zero point five?”

Researcher - ”No.”

Iris - ”Oh.”

Researcher - ”What’s half of fifty?”

Iris - ”Twenty five. So, two point five. So, point two five.”

Researcher - ”Right. What’s an eighth?”

Iris - ”Twenty five. Oh shoot! *[pause]* twenty five *[pause]* one twenty five.”

Researcher - ”Exactly . . . ”

. . .

Researcher - ”I’m almost six feet tall. If we assume that this six inch tall person is six feet tall, how many inches equals a foot?”

Iris - ”Twelve.”

Researcher - ”Well, in real life. But we have a six inch tall person *[pause]*”

Iris - ”One inch equals one *[pause]* twelve *[pause]* two meters would equal one foot?”

Researcher - ”Let’s just worry about inches right now. You said it right. In this case one inch equals one foot. If I’m six feet tall, we’re going to shrink me down to six inches tall. Every foot of me becomes an inch here.”

Iris - ”Okay.”

Researcher - ”So we can use this same conversion, we know that the globe is roughly one and a half inches . . . ”

Iris - ”So it would be one and a half feet?”

The third problem occurred when users attempted to create mechanical components that were of appropriate sizes for their tableaus and behaviors. This is actually two issues. First, users had difficulty deciding on the size of any necessary support framework for their mechanisms, determining the location of the components with respect to the tableau elements, and properly sizing components so that they would work together correctly. One example was seen as Abbie worked on the dragon. Her initial belief was that the support framework for the mechanism would be as long as the dragon's body (nose to tail). It wasn't until she and the researcher determined the location of the mechanical components on the cardboard prototype that she understood that while the framework's size was more dependent on mechanical considerations than on the size of the tableau. For her dragon, the framework's minimum length was determined by the locations of the cams that moved the fire and the tail while its minimum width was the result of the distance between the wires that actuated the wings. Choosing these minimum sizes allowed the dragon to extend past the framework on all sides, making the tableau the dominating visual component.

The behavioral issue arose when users had to design components that would provide a desired type and amount of movement. Dylan saw it when the jaw of the lion didn't move as far as he'd hoped because the small size of the lion's body prevented him from using a longer lever. Iris saw it when the man's head turned farther than she'd imagined due to the large amounts of lift provided by the eccentric cams. Sam saw it when trying to get a sufficiently large movement of the soccer kicker's leg in order to get the ball to the goal and he was forced to use a high lift for his cam to counteract the size of the leg lever that couldn't be changed. And nowhere was it more troublesome than in the intricate linkages of Frank's cat that had to move a number of tableau elements (the mouse as well as the cat's paws and eyes) in different ways from a single input.

A.2.2 Simplification and Generalization of Mechanisms

All of the users, at least initially, had considerable difficulties moving beyond the form and function of the example automata and mechanisms that they used as references. This seems to be a reasonable response when learning a new domain, but for some of the users this was a persistent issue. For example, the mechanism in Abbie's dragon is based on the one in Celia the sea lion. Both mechanisms use a collection of eccentric cams or discs and followers to obtain all of the motions. Celia also uses a lever hidden inside the body to convert the motion of one of the follower rods to the oscillating motion of the front flippers. The dragon needed to do the same in order to get the fire to alternately move in and out of the mouth but because the lever in Celia's body is hidden and there were no example mechanisms with levers available for Abbie to view, a considerable amount of time was spent attempting to find ways in which other mechanisms, particularly crank-sliders and snail cams might be used.

A.2.3 Considering Alternative Mechanical Solutions

Because the users were all new to the domain, there was a tendency to stop looking for solutions once one was found. Again, this is not a surprising result, but in a number of cases a better solution existed and was only discovered after some problem or problems with the initial solution had been discovered. In these tests the process of discovering those faults often led to increased domain understanding, so the time lost in pursuing a flawed solution was seldom wasted. While the number of users and automata in the tests were not large, it is interesting to note that in the cases of the carousel and the beehive, both second automata for their builders, that the experience gained from the previous builds was brought to bear on the new designs and a number of plans were conceived and evaluated before selecting the final candidate.

A.2.4 Reorienting Extant Mechanisms

When the users turned to example automata and mechanisms for ideas and understanding an interesting trend was observed. Because all of the examples had obvious top and bottom orientations, users would put them in that orientation before working with them. This usually meant that the base was placed on the work surface before the crank was turned and even when they were held in the hand, the base was almost always kept as the lowest part. It required explicit instructions from the researcher to get any of the users to rotate or invert any of the example machines. This was not something that seemed to change over the course of the testing and even the users who exhibited the greatest increases in domain ability would rarely spontaneously change the orientation of an example.

A result of this bias occurred when some alternate orientation of a component or mechanism was required to produce a desired behavior. In these cases, the users were puzzled by the solutions proposed by the researcher, even when the basic function of the components in their "standard" orientations were understood. An example of this is the lever behind the mouth of Abbie's dragon that moves the fire in and out. This linear output motion is roughly horizontal while the linear input motion is applied vertically by the cam follower. In order to make the translation from vertical to horizontal motion, the lever had to be placed at roughly a 45 degree angle. Even when experimenting with this arrangement as an oversized cardboard mockup, it took some time for Abbie to appreciate the ability of the angled lever to do what she wanted.

A.2.5 Mechanical Dependencies

All of the automata built by the users contained multiple motions. This created dependencies between the motions that were not always obvious or easy to identify. These dependencies show themselves most often in either the timing of movements or when motions become conflicting or confounding. A simple example occurred when Iris wanted the head and the hand of the man with the globe to be operated from the main shaft. Because of the close proximity of those tableau elements, it was not possible to create a mechanism to move them both, and it was not until she hit upon having the spinning globe move the hand that both motions were possible. Another example is Abbie's initial plan to have the body of the dragon move up and down to produce the flapping of the wings as is done with Ralphie (Section D.1). Moving the body would have created a number of problems with the cam followers for the fire and tail that weren't obvious to her at the time and, in the case of the fire, would almost assuredly have proved impossible to overcome.

A.2.6 Lack of Mechanical Education or Experience

This category presented itself in a number of ways, and varied considerably from user to user. Some of these problems were related to the physical properties and interactions of the mechanical components and tableau elements. Users had little understanding of mechanical effort being lost to friction or how the proper choice of a fabrication material depended on attributes such as density and strength. For many users, this was a first experience in the real world uses of mathematics. Making accurate measurements, calculating size and position, and working with both fractional and decimal measurements were unfamiliar activities. While some users picked these skills up quickly, others did not. None of the users came to the projects with a knowledge of proper construction techniques. Users were not likely to test fit pieces before gluing to determine the fit and operation of the mechanisms and to identify a reasonable series of steps for final assembly. All users needed instruction in the proper preparation of components and in the correct use of glue to secure them. Finally, none of the users were initially able to see the tableau as an extension of the mechanism. It took some time before users could see that the motion of their automata didn't simply proceed from the mechanisms to the tableaus, but was a closed loop in which each module acted on and reacted to the other.

A.3 User's Experiences with the MachineShop System

For all users, the amount of time spent interacting with the MachineShop software was a small fraction of that total time spent creating their automata. Some users such as Iris and Calum spent only the time necessary to make their mechanical components, although in neither case did this prevent them from creating high quality automata. Abbie and Frank spent more time with the software designing the more non-standard components found in their automata. Sam and Dylan were the most active users of the software and both spent a considerable time beyond creating components to explore the capabilities of the software.

The most often-used tools were the component editors. All users spent time with these tools creating and modifying mechanical components for their automata. Users rarely took advantage of the software's ability to save and open component files. This may be due in part to all of them sharing a computer in the laboratory and not having MachineShop available to them at home where they might have been more inclined to create components and save files that they then would have brought to the project sessions. It may also be a result of the simple nature of the components that they designed and the lack of difficulties they experienced in creating them. When users first created a component, they would create a fabrication file and a prototype part would be made. Quite often, this part would have acceptable properties with respect to size and function and a revision would not be necessary. If the part did need modification, most users would simply recreate the component and apply any necessary changes rather than retrieving a saved file from the library.

Other than Sam and Dylan, the users also spent little time in the Movement Explorer tool. Overall, this may have resulted from their having access to the physical mechanisms that were created for the video files used by the software. Users found it more convenient to simply pick up a mechanism of interest and interact with it than to go through the necessary steps to see it on screen. The physical mechanisms also encouraged the users to compare similar mechanisms and to manipulate them in ways not shown in the video. The researcher was available to answer questions about the mechanisms and to ask questions that the users could then explore. For other users of the software, the Movement Explorer will certainly be a more useful tool and it will be interesting to see both the ways in which users leverage it and the amount of time they spend using it when either the mechanisms or a mentor are not available.

A fair question at this point would be: What advantages did the MachineShop system give the test users as they designed and built their automata? The goal of the system, both software and hardware, was to provide support for children whose skills and understanding were not sufficient to allow them to build automata without assistance. In that respect, the system has proven quite successful. The children who participated in these projects were able to produce accurate and robust mechanical components with the same ease as any skilled artist. The system helped them do that by allowing them to focus on what they wanted without having to worry about how they would then accomplish it. The system was able to do this in three ways. First, the software encapsulated significant domain knowledge that was transparently available to users. Much of that knowledge relies on mathematics that most users will be unfamiliar with: trigonometric functions to calculate the profile of a snail cam, or the involute curves found in manuals of gear design for instance. Second, the system acknowledged that these users are most likely inexperienced tool users with little or no knowledge of the properties of the materials they will need to use. By incorporating fabrication tools that can work with a wide range of materials, that are capable of producing objects more accurately than almost any skilled individual could, and that can do all of this in the fraction of the time it would take by conventional means, the system allows the users to create beyond their abilities. Third, by coupling the software and the hardware in such a way that no information is lost, the process of moving from idea to object becomes a path that users can easily navigate. The need to produce drawings and to transfer the information they contain to raw materials for fabrication is eliminated through the use of files that are created by the software and utilized by the hardware.

A side effect of all this is that users spend less time fabricating and more time creating. Early experience with skilled adult builders had shown that creation of even the simplest of components, such as an eccentric cam, took significantly longer to do with traditional methods than using MachineShop. To create an eccentric cam with compass, band-saw, power sander, and drill can easily take five or more minutes. With MachineShop the finished cam is ready in no more than two minutes and is of considerably higher quality and finish. When creating more complex components, such as spur gear trains, this difference is even more pronounced. What this meant for the users was that they could accomplish in twelve or fifteen hours what might otherwise take them hundreds of hours. For two of the users, Sam and Dylan, this allowed them to make two automata each during the testing. It also gave several users additional time to become more knowledgeable about the domain as the extra time available to them in project sessions was used to explore facets of automata and machines that they found interesting.

A.4 Apprenticeship in Practice

Apprenticeship means different things to different people. In the crafts and trades, an apprentice learned by first watching a master work and then copying that process to the best of his abilities. Depending on the temperament of the master, those efforts could be gently guided to help the apprentice gain skill, or they could be denigrated in a desire to have only the strong survive. As applied to this research, apprenticeship was an opportunity for novices to engage in a challenging activity knowing that they had support in the form of the researcher. While not precisely what has historically happened in the guilds, it very much embraced the philosophy of learning by doing inherent in that model.

Because of the age of the users, there was great variability in the the knowledge and skill that users brought to the testing and in their goals and desires. Each user had different needs and in the one-on-one setting of the project sessions the researcher was able to tailor his involvement as much as possible to meet those needs. Based on the needs of the users, the support provided by the researcher fell broadly into three categories.

First were the users who were only marginally engaged in the process. This occurred for a number of reasons. Some users seemed timid when asked to challenge themselves, possibly because they were afraid that they would not do well unless they were told what to do. These users rarely asked the "what if?" questions and were passive participants in defining their project's trajectory. These children were intelligent and in some cases very outgoing. This was the most difficult group for the researcher to support. While the desire was to see that these users were very successful, it was often necessary to withhold ideas or information that might have been more freely shared with other users. The researcher hoped to have the finished automata represent the user's designs without being too much a product of the researcher's input. These users were indirectly (and on a few occasions directly) guided toward possible solutions in the hope that the they would make exciting discoveries. This didn't happen as often as hoped, but did happen often enough that the resulting automata were very satisfying.

The second group of users were what could be described as archetypal. They were engaged and inquisitive and weren't afraid of doing something over again until it was right. They were among the most frequent users of the MachineShop software, and explored many aspects of the domain when away from the project sessions. These users challenged the researcher as much, if not more, than the researcher challenged them. This group was also the most prolific in terms of the number of automata they created. These users could be expected to provide a thoughtful answer to abstract or esoteric questions about the domain, even if it wasn't always correct. The interactions between these users and the researcher were the most lively of any of that seen in any of the groups.

The third group of users were the boundary pushers. These were the users whose early design ideas could only be minimally supported by the MachineShop software but who decided to continue on anyway. This was the most challenging group for the researcher. Not only were these users exploring novel mechanical devices, but there was variety to that novelty. These differences were accentuated by differences in working styles. One of the users proceeded in a very trial-and-error manner, making quick decisions and then trying them out. The other was very methodical and reasoned through to a decision before applying it. Interestingly, it was the latter user who made the greatest number of prototype mechanisms. This was partly due to its greater complexity, but it was also due to his method of constantly refining the components for his mechanism. At many times during these projects, the researcher's knowledge and understanding of the domain were stretched past their limits. On a number of occasions, the researcher and user could be found sitting side by side pondering and discussing some subtle aspect of a mechanism that needed clarification. These interactions were more that of peers than of student and mentor.