The Use of Tools

Rob St. Amant

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In this technical note I will try to organize a variety of tool-related ideas that I have considered over the past several months. My central concern is that there appear to be no strong candidates for a formal representation of tool use, which would enable us to

- Build agents that can use tools and, more importantly, learn to use tools by exploration, analysis, and observation. These agents may exist in the user interface, physical simulations, or even the real world.
- Build user interfaces to applications that capitalize on the natural tool-using abilities that people have.

I've divided this technical note into several areas: examples of tools in the real world and their characteristics; points to address in building a representation for tool use; possibilities for implementing real systems that rely on tool use. Some of this material is taken from an NSF grant proposal that you may have already seen, but much of it is new. All together, I hope that this material conveys my current understanding of the problem and a few directions for research.

Tool use in the real world

For most of this technical note, I'll concentrate on examples of hand tools, such as the following (in no particular order): hammer, screwdriver, saw, shovel, trowel, awl, clamp, drill, crowbar, ramp, wrench, chisel, plane, level, and T-square. What we want to do is to develop a well-founded theoretical understanding of the relationships between such tools and the abstract properties we associate with tool use.

Let's start with a definition of tool use. The concept is difficult to define precisely, but Beck's research on non-human primate tool use is an often-cited source [Beck, 1980; Vauclair, 1996]: "Thus tool use is the external employment of an unattached environmental object to alter more efficiently the form, position or condition of another object, another organism, or the user itself when the user holds or carries the tool during or just prior to use and is responsible for the proper and effective orientation of the tool." Researchers in a variety of fields, including social psychology [Semin, 1998], animal cognition [Ingmanson, 1996; Smitsman, 1997], anthropology [Keller and Keller, 1996], agents [Agre and Horswill, 1997], and different design disciplines have developed refinements or alternative characterizations [McGrew, 1993; Preston, 1998]. We can convey some of the complexity of the concepts of tools and tool use with the following informal description:

- *Tools are objects* [Beck, 1980].
- *Tools are external to the agent* [Beck, 1980]. The hand, for example, is not a tool.
- *Tools are held* [Beck, 1980]. This requirement is relaxed for cases such as industrial power tools and anvils, but the intuition is that tools are manipulable objects.
- *Tools are reusable* [Agre and Horswill, 1997]. Hammers, for example, are tools, but construction materials are not.

- *Tools are identifiable by use, rather than by labeling*. This has become a humorous aphorism for amateur auto mechanics: "In times of emergency, any nearby object becomes a hammer."
- *Tools are often amplifiers*. Many tools are designed to amplify an existing ability, as a sledge hammer enhances striking ability.
- *Tools often replace body parts or functions*. For example, a shovel can substitute for an open hand with fingers together, while a trowel is a replacement for an open hand with fingers spread. These tools also have an amplification role.
- *Tool use is "goal-directed activity"* [Ingmanson, 1996]. Incidental or even accidental use of an object is ruled out.
- *Tool use is often modal*. Many tools are designed to be used one at a time.
- *Tool use involves direct action* [Vauclair, 1996]. Some primates show uncanny accuracy in dropping objects onto researchers [Ingmanson, 1996], but this is considered tool-related behavior rather than actual tool use. Direct striking with the same object, however, to crack open nuts with a stone, for example, *is* tool use.
- *Tool use involves effective behavior.* One influential study involved a monkey given the task of pushing a reward out of a narrow, transparent tube; the monkey unwrapped a bundle of reeds held together with masking tape, but then tried to push with the tape instead of a reed [Visalberghi and Limongelli, 1996].
- *Recognizing tool use can depend on task context*. A pencil may be a tool to an artist, but the case is more ambiguous for a carpenter marking a line on a board.
- *Recognizing tool use can depend on culture or convention* [Preston, 1998]. The determination whether an artifact is a tool or not can be difficult; a fist-sized piece of flint may be stone tool to one archaeologist, for example, but only a leftover artifact from the production of flint arrowheads to another archaeologist [Preston, 1998].
- *Tool use is associated with effective use of space* [Kirsh, 1995; Vauclair, 1996]. Many experienced tool users lay out their tools before beginning a task, on the assumption that some common tools are almost always eventually needed and should be ready to hand.

It can be useful to consider decompositions of tools as well.

- Some tools modify materials, including creating relationships between them (e.g., a hammer, saw, screwdriver.)
- Some tools constrain but do not modify materials (e.g., a clamp.)
- Some tools measure but do not modify materials (e.g., a level.)
- Some artifacts are closely related to tools, but do not seem to fall squarely into the category of tools:
  - Some artifacts impose abstract properties or relationships on materials. For example, a pencil can mark lines on a board for it to be cut.
  - Some artifacts change the spatial relationship between materials. For example, a cart can move materials from one place to another; a ramp can allow a cart to move vertically.

  These may or may not be tools; their categorization may even vary, depending on context and interpretation.

Some of the points above are controversial. For example, Norman and others would argue for the existence of cognitive tools, including mental constructs and actions [Norman, 1993; Norman, 1991]. Others have describe a variety of forms of external representations, which may not be completely cognitive [Zhang, 1997; Zhang and Norman, 1994]. Hutchins has probably done the best-known work in the area of cognitive tools. He makes a distinction between physical tools, which he associates with amplification, and cognitive tools, which are concerned with problem transformation [Hutchins, 1995]. It's not yet clear to me whether we should take a broad or narrow interpretation of tool use. It would be nice to have a single framework that encompassed both interpretations of tools, plus all the other points above.

Representational issues for tool use

What does "a formal representation of tool use" involve? I'm using the term "representation" as it is commonly used in the AI literature; we can imagine a representation for tool use that derives from research in planning, qualitative and spatial reasoning, cognitive modeling, and possibly other areas. Here are a few questions relevant to selecting a specific representation.

- *What does the tool do? That is, what are its effectivities?*
- *How can a tool's effectivities be recognized? What role does vision play?*
- *What is a good agent/tool/environment relationship, such that effective and efficient tool use is supported?*

One of the most obvious components of an appropriate representation is the ability to handle constraints. In the use of physical tools, constraints play a large role.

Most tools can be used in an unconstrained fashion, if ineffectively. One might wave a saw or a hammer in the air, for example, or twist a screwdriver randomly, as a young child might do. Effective use, however, requires the establishment of a constrained relationship between the tool and the material it acts on. Some aspects of tools are designed to facilitate such establishment, as with magnetized screwdrivers, which can force a screw into a particular relationship with the blade of the driver.

The constraints we are considering can be of different types:

- *Spatial* constraints describe the spatial relationships associated with a tool and its use in an environment. For example, to use a hammer effectively you need enough room to swing it.
- *Physical* constraints describe physical relationships in the use of the tool, such as weight or size. For example, I would choose a sledge hammer rather than a carpenter's hammer to drive a stake into the ground, because of the weight of the former.
- *Dynamic* constraints describe movement-related properties of tool use. For example, I need to swing a hammer with appropriate speed in its use; swings that are too weak or too strong can produce poor results.

These give the general flavor of what I mean by constraints, and there may be other types. It's not clear whether these specific distinctions themselves are useful. Nevetheless the general notion of constraints appears to be important. How do these constraints arise? There are several sources.

Tool design. The most obvious contributor to constrained behavior in the use of a tool is its deliberate design. Tools have affordances: designed relationships between their physical/dynamic properties and the properties/abilities of their intended users. These relationships impose constraints on the proper use of a tool.

Agent characteristics. Recall that physical affordances, closely related to constraints, are mutual, relationships that involve both the agent and the artifacts it manipulates. For example, when using a hand tool such as a hammer or saw, I sometimes need to brace myself, so that I can take a repetitive action in a more effective or consistent manner. The implication here is that we need to take the properties of the tool-using agent into account in the constraint representation.

An interesting perspectives on this relationship is due to Schlesinger et al. [Schlesinger *et al.*, 2000], who studied the relationship between constraints and the activity of reaching. Schlesinger et al. describe "emergent constraints" that arise from such activity; these include joint locking, coactivation of muscles, stereotyped approach movements, and movement slowdown.

Environment properties. We also observe that it is not only the tool and agent that can facilitate the establishment of constraints, but the environment or materials themselves. A saw blade, for example, will tend to follow a straight line (usually a desirable course) as it cuts a groove for itself through a board. Lateral motion is no longer possible. The friction between a screwdriver and the slot of a screw help to preserve the contact between the two.

Not all environmental properties enforce constraints; some only suggest appropriate relationships. Feedback is one way this happens. For example, when a hammer hits a nail, the desired effect is for the nail to be driven into the surface. Some visual feedback is present, but more important are haptic and auditory feedback: one feels a solid blow and hears the appropriate sound. There is different environmental feedback for correct and incorrect use.

We can also see some procedural patterns in the use of tools. Tool use often falls into two distinct stages. First, we set up a what I'll call a *configuration*, a set of constraints between the tool and its environment, which may include materials. Second, we execute some action that depends in some way on this configuration. A few examples:

Tool	*Set up*	*Execution*
Hammer	Place nail; raise hammer	Strike
Saw	Position along line/groove	Stroke
Screwdriver	Position perpendicular to screw, in slot	Twist

It may make sense to integrate a procedural representation with a constraint representation to encompass tool use.

A tool-based interface

What does all this mean for our development? Let's consider building a software environment that might better support the kinds of properties we associated with tool use above.

In current systems, we have access to relatively powerful tools that have been designed into a software application. These are cognitive tools in the Hutchins sense: they transform hard problems into simpler problems. It's not clear that they exploit any of the properties of physical tools we have described. In the real world, tools are often not nearly so specialized. In fact, we sometimes have to rely on tools that we build ourselves, to make solving specific problems easier. For example, I might build a pattern, or stencil, or jig, which I can use to help produce a number of identical pieces.

Imagine an interface that gives the responsibility for building tools to the user, rather than depending on a forward-looking designer. The interface I'm thinking of would look more like a busy tool bench in use, rather than a static canvas. The user would have access to a number of general tools, or meta-level tools, which could be used to construct more specific tools. Such an environment would move away from "build-and-go-away" dialogs for creating and editing objects and relationships. Instead, it would produce persistent tool objects, that would show object parameters and allow them to be edited.

(Note: These tool objects could be treated as manipulable objects in their own right. This could lead to a form of end-user programming, perhaps even to a form of programming by example. Presumable, users who became familiar with indirect action via the actions of tools would find programming a more comprehensible task.)

We might build such an interface to a system in many possible domains. Here are a few possibilities: CAD, anatomy/medical/molecular biology, circuit design, graphic design for web pages, 3d modeling, mechanical/aerodynamic design, architectural design, MUD design, information navigation design, musical composition, scheduling, traffic engineering, directing activities of a personal assistant, placement of information kiosks in a VR environment, crowd control simulation, herding animals simulation, shopping mall navigation design, museum design, work management, process control, robot behavior control.

In one of the design domains above, we might imagine metaphorical tools patterned on physical tools, such as

- Clamps, to automatically reduce space between components;
- Spacers, to maintain space;
- Wedges, to increase space;
- Rods, to create fixed angular relationships between components;
- String, to enforce line-of-sight access between components;
- etc.

We might even think about how physical tools could interact with software tools, by integrating physical artifacts into the computational environment. For example, if the user is working with a stylus on a drawing tablet, would would be the benefit of providing a plastic protractor, or a compass, or straightedge, or letter stencil, that could be used in conjunction with the stylus to produce software objects? Everything I can think of for physical tools can be done in principle in software, but am I missing anything? Perhaps the user might simply find it easier to interact with physical artifacts.

In addition to helping us refine a representation of tool use, the domain should let us explore these related issues:

- Low-level affordances.
- Learning or "sequential" affordances.
- Tool suites.
- Collaborative design
- 3d/immersive interfaces.

References

Agre, Philip and Horswill, Ian 1997. Lifeworld analysis. *Journal of Artificial Intelligence Research* 6:111–145.

Beck, B. B. 1980. *Animal Tool Behavior: The Use and Manufacture of Tools.* Garland Press, New York, NY.

Hutchins, Edwin 1995. *Cognition in the Wild.* Cambridge, MA, MIT Press.

Ingmanson, Ellen J. 1996. Tool-using behavior in wild *pan paniscus*: Social and ecological considerations. In Russon, Anne E.; Bard, Kim A.; and Parker, Sue Taylor, editors 1996, *Reaching into Thought: The minds of the great apes*. Cambridge University Press, Cambridge, UK. chapter 9, 190–210.

Keller, Charles M. and Keller, Janet Dixon 1996. *Cognition and tool use: The blacksmith at work*. Cambridge University Press, Cambridge, UK.

Kirsh, David 1995. The intelligent use of space. *Artificial Intelligence* 73(31–68).

McGrew, William C. 1993. The intelligent use of tools: Twenty propositions. In Gibson, Kathleen R. and Ingold, Tim, editors 1993, *Tools, language, and cognition in human evolution*. Cambridge University Press, Cambridge, UK. 151–170.

Norman, Donald A. 1991. Cognitive artifacts. In Carroll, John M., editor 1991, *Designing interaction: psychology at the human-computer interface*. Cambridge University Press. 17–38.

Norman, Donald 1993. *Things that Make Us Smart*. Addison-Wesley.

Preston, Beth 1998. Cognition and tool use. *Mind and Language* 13(4):513–547.

Schlesinger, Matthew; Parisi, Domenico; and Langer, Jonas 2000. Learning to reach by constraining the movement search space. *Developmental Science* 3:67–80. http://www-anw.cs.umass.edu/papers/2000/SchlesingerParisiLearning2000.ps.gz.

Semin, Gün R. 1998. Cognition, language, and communication. In Fussell, Susan R. and Kreuz, Roger J., editors 1998, *Social and Cognitive Approaches to Interpersonal Communication*. Lawrence Erlbaum, Mahwah, NJ. 229–258.

Smitsman, A. W. 1997. The development of tool use: Changing boundaries between organism and environment. In Dent-Read, Cathy and Zukow-Goldring, Patricia, editors 1997, *Evolving explanations of development: Ecological approaches to organism-environment systems*. American Psychological Association, Washington DC.

Vauclair, Jacques 1996. *Animal Cognition*. Harvard University Press, Cambridge, MA.

Visalberghi, Elisabetta and Limongelli, Luca 1996. Acting and understanding: Tool use revisited through the minds of capuchin monkeys. In Russon, Anne E.; Bard, Kim A.; and Parker, Sue Taylor, editors 1996, *Reaching into Thought: The minds of the great apes*. Cambridge University Press, Cambridge, UK. chapter 3, 57–79.

Zhang, Jiajie and Norman, Donald A. 1994. Representations in distributed cognitive tasks. *Cognitive Scienc* 18(1):87–122.

Zhang, Jiajie 1997. The nature of external representations in problem solving. *Cognitive Scienc* 21(2):179–217.