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An Observational Study of How Objects Support Engineering Design Thinking and Communication:
Implications for the design of tangible media

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ABSTRACT

There has been an increasing interest in objects within the HCI field particularly with a view to designing tangible interfaces. However, little is known about how people make sense of objects and how objects support thinking. This paper presents a study of groups of engineers using physical objects to prototype designs, and articulates the roles that physical objects play in supporting their design thinking and communications. The study finds that design thinking is heavily dependent upon physical objects, that designers are active and opportunistic in seeking out physical props and that the interpretation and use of an object depends heavily on the activity. The paper discusses the trade-offs that designers make between speed and accuracy of models, and specificity and generality in choice of representations. Implications for design of tangible interfaces are discussed.

Keywords

Tangible media, augmented reality, interaction design, design thinking, user models, cognitive models.

INTRODUCTION

There has been an increasing interest in objects within the HCI field. This is manifested both in the increasing popularity of virtual objects, and the increasing interest in augmented reality and tangible media. Although the utility of physical objects is often asserted, we know relatively little about how they help us to think and to solve problems. In particular, we do not understand much about how physical and virtual objects differ in their abilities to support our activities. In this paper we study groups of engineers using physical objects to prototype a design, and show what roles physical objects play in supporting their design thinking and communications. In the discussion, we analyse the difference between how objects, CAD tools and sketching support thinking by drawing comparisons with the literature. The extent to which object supported thinking in engineering design transfers to everyday thinking with objects is considered. We draw conclusions about how to design tangible interfaces that support thinking and are easy to use.

BACKGROUND LITERATURE

Our research is based on the premise that if we can understand how humans interpret and use objects in activity, we will be better positioned to design devices and tangible interfaces to support human activity. The literature on interpretation and use of objects stems from a number of fields. Studies of human memory such as those by Rosch [17] have examined how humans categorise objects in order to reduce the cognitive burden of discriminating between the large number of objects in the world. In studies of designers at work, Harrison and Minneman [9] identified that objects are an integral part of design communications, altering the dynamics in multi designer settings and forming part of the pool of representations that are drawn upon by designers. Brereton [2][3] and Miller[13] have reported on how engineering students learn by prototyping with hardware. Writings on distributed cognition by Hutchins [10], and Chaiklin and Lave [6] report that cognitive achievements derive not only from the internal thought processes of people but also from the material systems and information technologies with which they work. Literature in HCI reports on the design of tangible interfaces. Examples are Weiser and Jeremijenko's Livewire [23], Brave and Ishii's Psybench and Intouch systems [1] and Bishop's graspable telephone answering machine in which messages are represented as marbles, reported in [5].

Norman's "Psychology of Everyday Things" [14][15] took the approach of observing how well we manage to use a variety of devices in a world of tens of thousands of different objects, many of which we would only encounter once. Norman's answer was that the appearance and feel of the device and the context in which it appeared should provide the critical clues required for its proper operation. Norman laid out a framework for designing intelligible devices that consists of devising a conceptual model and implementing it physically with appropriate physical mappings, physical constraints and physical affordances.

DATA COLLECTION

The research in this paper is drawn from a multi-year study of engineering students and professional designers engaging in design project work [2,3]. The broader study investigated how engineers learn through designing. The research highlighted that students and professional engineers are heavily reliant on the physical world and strongly influenced by things that they can see and feel. When their knowledge of theory suggests that a literal interpretation of what they are seeing and feeling is erroneous, they are inclined to disregard the theory rather than to disbelieve what they see. The study demonstrated that engineers learn by paying attention to discrepancies between the physical world and the conceptual model. Through continually challenging abstract representations against material representations they advance their conceptual model of the design in progress, their repertoire of familiar physical objects and behaviours, and their understanding of technical fundamentals. The comparison of representations reveals gaps in understanding which inspire further design and analytic activity.

This paper draws upon a single design exercise, which is very limited in scope, in order to illustrate the role that physical objects play in supporting thinking and to develop a basis for a discussion of the roles that physical objects can play in augmented reality systems.

The design problem given was to develop a conceptual design for an internal mechanism for a kitchen weighing scale shown below. This problem is constrained in scope as the external appearance of the scale is already determined. (The essence of the problem posed is to devise some kind of mechanism that converts a vertical linear motion of the weight pushing onto a spring, into a horizontal rotational pointer motion that is proportional to the weight on the scale pan.) So this design brief does not embrace the full design project lifecycle of problem identification and framing, but rather it focuses upon a subset of design activity in which when one seeks to identify and embody possible working concepts to meet the constraints as currently understood. Such constraints are quite common (if temporary and tentative) once one gets to designing sub-systems. (In practice, if elegant embodiments of concepts cannot be found, the designer generally examine ways of redefining the problem in order to change the constraints.)

The data in this paper is drawn from nine 40-minute sessions in which groups of three undergraduate students were observed and videotaped developing a conceptual design for a kitchen weighing scale. Students were asked to develop ideas and present them on a sketch pad. Students were not given any prototyping materials for conceptual design, (since studying use of objects was not our original intent), however students were found to opportunistically seek out all sorts of miscellaneous objects to support their thinking. In a barren design environment consisting of a classroom full of chairs, tables, sketch pad and pens, students sought out inspiration from gesturing with pens, pulling and twisting a rubber band that was spotted lying on the floor and dissecting a ballpoint pen dug out from a student’s back pack. They made numerous references to prior experiences with objects. These references are an illustrative subset of those observed in longer (weeks and months) design projects undertaken by both students and professionals in which prototypes are produced. Such projects included motorised self-navigating all-terrain vehicles, a passive restraint system for a truck etc.

Having noticed the extent to which objects were used to support thinking, particularly in conceptual design, we examined the videotape records, to look at how the different objects were drawn into the activity and used to support design thinking and communication. In all cases, videotaping was implemented with a single unmanned camera supported by a desk microphone.

Problem Brief:

Design an internal mechanism for the kitchen scale concept shown left. The mechanism should transfer the weight from the scale pan in the vertical plane to the rotation of a pointer in the horizontal plane.

Pedagogical aims: to give experience in developing and embodying concepts; to generate curiousity about how everyday objects such as kitchen scales work inside; to give practical knowledge of the various mechanisms employed in scales by taking several scales apart.

DATA ANALYSIS

The technique of Video Interaction Analysis was used to identify typical ways in which objects are used to support cognition, [11]. An interdisciplinary team (of engineers, a linguistics expert, a sociologist, an anthropologist and a computer scientist) viewed segments of tapes selected by the primary investigator and identified routine practices, routine problems and resources for their solution. Only those practices confirmed by the raw data that occurred repeatedly in different parts of the tape were considered admissible in the analysis. This exploratory research technique [18] was adopted because it supports formulation of our understanding of natural activity. Such an approach does not attempt to define a controlled setting that affords comparison and statistical proof, because such experimental design and analysis tends to overlook some of the interesting, unforeseen natural activity. The examples presented in the paper are representative of activity in that they have been observed in many different groups and in many different segments of videotaped footage.

FINDINGS

The fundamental finding of our inquiry is that design thinking is heavily dependent upon experiences with physical objects and materials, as evidenced by the frequent references in design conversations.

Hardware[1] is a compelling medium because:

1. It is tangible -- can be seen and touched -- and is thus appreciated by at least two of our senses, often more.
2. It gives physical presence to conceptual models
3. Its behaviour reveals errors in conceptual models
4. It behaves in unpredicted ways which provokes the user to explore it
5. It behaves in different ways in different environments and different contexts of use.
6. Interaction with hardware, and integration of hardware components reveals properties and limits of the hardware and hardware components.
7. It is integral to communications, affecting the course of inquiry, idea generation, discovery and the dynamics of group interaction. Physical objects are used to command attention, to demonstrate and to persuade.

The probability that a designer will draw upon a particular object to support their thinking depends on:

1. The context (in particular the design problem at hand)
2. The physical availability of an object
3. The likelihood that the designer identifies an attribute or affordance of the object that facilitates thinking in the context. This thinking could be tacit or explicit.
4. Availability of the object in memory - ability to recall an episode of using the object that has some link to the current context
5. The likelihood of the designer making a connection between an object and another object already being used to support thinking. Designers often make connections between objects tacitly or explicitly by identifying common affordances, common physical attributes, common geometric attributes, common sub-components etc.

The roles played by objects in supporting design thinking are summarized in Table 1.

Hardware Starting Points

Hardware and prior experiences with hardware are often the starting points from which students develop design proposals. Students look for possibilities in existing hardware to meet design requirements. The videotape revealed that in order to support conceptual design, students draw upon memory of experiences with hardware and are opportunistic in seeking out any kind of miscellaneous hardware to think with, such as rubber bands, pencils and a ballpoint pen which they dissected to examine its internal workings.

The Roles of Physical Objects and Prototyping Materials in Supporting Design Thinking and Communication
Hardware as a Starting Point Hardware is tangible. It exists. It serves as a starting point it easily noticed, remembered, seen and touched. It offers a basis for comparison.
Hardware as Chameleon Hardware is always in a context of use. What the hardware reveals depends upon the context of use. A variety of informal experiments in different contexts reveals different facts.
Hardware as Thinking Prop Hardware objects have all sorts of properties that afford different actions. Hardware that was easily accessible and had a useful property was adopted as a gestural aid to support thinking.
Hardware as an Episodic Memory Trigger Episodes of experiences with physical objects serve as memory devices.
Hardware as Embodiment of Abstract Concepts (Functional and Theoretical) Observing and testing hardware reveals fundamental concepts, physical embodiments of abstract concepts; and unanticipated design issues in hardware behaviour
Hardware as Adversary Challenging theoretical model predictions against hardware behaviour reveals discrepancies and provides clues to modelling errors. This reveals theoretical assumptions, and causal relations
Hardware as Prompt Device behaviour prompts student questions and suggests experiments. Through repetitive interaction with hardware students bring order, distilling out key operational parameters and their relationships.
Hardware as a Medium for Integration Integrating components in their functional context reveals practical limits of use, characteristics of operation, methods of connection, causal relations, and physical quantities. This empirical knowledge extends the student's hardware repertoire.
Hardware as a Communication Medium Hardware is integral to learning communications, affecting the course of inquiry, idea generation, discovery and the dynamics of group interaction. Hardware is used to command attention, to demonstrate and to persuade.

Table 1: The roles of physical objects and prototyping materials in supporting design thinking and communication.

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[1] We use the term ‘hardware’ to refer collectively to physical objects and physical prototyping materials.

Hardware as Chameleon

Hardware relies upon its context of use for its functional meaning[2]. In this design context a pen was used as

- Something to prototype a linkage with (see below)
- Something to take apart (see below)
- Something to write with
- Something to point with.

In other situations one could imagine a pen used as

- Something to prod with
- Something to prototype an axle with etc
- Something you use to press a recessed button in order to restart a computer etc.

The selection of a device for design prototyping relies upon the context of use and the device having an attribute relevant to the context of use. Once a prototype design has been built, what the prototype reveals depends upon its context of use. Different experiments in different contexts reveals different facts.

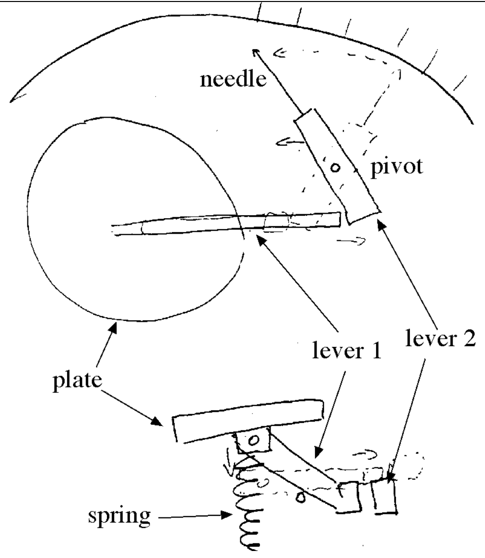
The way that the device may be classified generally (out of the context of use) has little or no bearing on how it is used to support design activity. This has important implications for figuring out good mappings when designing objects for use, a point that will be considered in the Discussion section.

Hardware as a Thinking Prop

What hardware was adopted to support thinking depended upon (a) availability and (b) whether it had any attributes that afforded exploring the design space. Hardware objects have all sorts of properties that afford different actions as the example of pen usage above indicates. Students adopted hardware tools that were easily accessible and also had affordances or convenient properties that supported thinking and communicating. Pens were long and slender like linkage links and afforded gesturing the workings of a linkage mechanism in space. Rubber bands were stretchy like springs. One group explored a rubber band to see if it could provide the kind of motion they were looking for in the scale -- a vertical linear motion of the load translated into a horizontal rotational motion of a scale pointer. They relaxed a stretched, twisted rubber band to see if it would tend to unravel when tension was released.

Several groups adopted pens and used the pens as links in a linkage. They held two pens tightly together at one point (the pivot in the diagram of Figure 1) and tried to figure out if moving one pen in one direction would cause the other pen to move in the desired direction. Pens were adopted because they were long, skinny and rigid and afforded thinking about linkage mechanism motions. Figure 1 below shows a design developed by a group who gestured with pens in their hands to develop a linkage mechanism. The pens formed the two levers of the linkage mechanism.

The properties of appropriated objects were not necessarily optimal or entirely suitable for supporting design thinking. It is probably not possible to specify in advance of being in the design situation what kind of props would be desirable. The hardware was simply conveniently available and had some attribute that meant students found it helpful to gesture and think with. This behaviour lends support to the idea that an accurate model is less important than a quick model that helps the designer to explore the space.



Above: Student concept sketch of a kitchen scale designed by gesturing with pens.

Below: Transcript of student describing his group's design to the class. While describing the design, the student gestures with pens and points at the sketch. Typed labels and arrows are added for clarity by author

Daniel:	*"I was working on the kitchen scale design.* *There's a spring there and there's a plate pushing down on top Ok. And that's pushing down this lever which, as that is pushed down on [the top] end, this [lower end] is moved out.* *And that movement in that direction is pushing the base of another lever here which is pivoted over here. So as that moves out that moves the needle around. So it' s a really simple design."*

Figure 1. Hardware as thinking prop: students appropriate convenient hardware to support their thinking.

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[2] We could say that hardware function is indexical. Expressions that rely on their situation for significance are commonly called indexical, after the "indexes" of Charles Pierce [15], [from p58 Suchman, Plans and Situated Actions, 1987]. Heritage (1984) p158 offers as an example the indexical expression "that's a nice one," pointing out that the significance of the descriptor "nice" has different meanings if it refers to a photograph or to a head of lettuce.

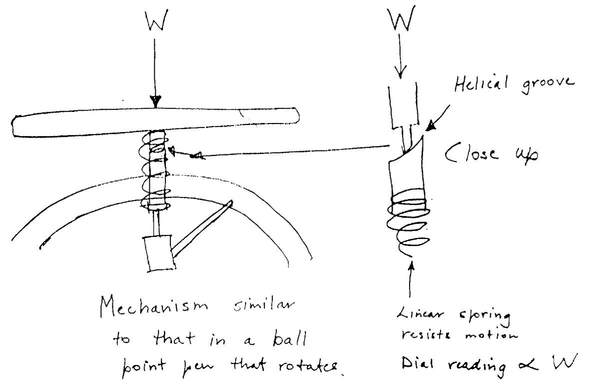
Hardware as an Episodic Memory Trigger

Students often recalled prior experiences with hardware to help their thinking. They mentioned winding clock springs, and watching music boxes unravel. They recalled with varying success how moving coil galvanometers, pressure gages, wind up toys and ball point pen deploy-retract mechanisms worked. In doing so most students did not make any explicit reference to the abstract function or actual mechanisms employed in these devices. Rather, they referred to the way they experienced the devices, referring to the kinds of movements they made, how they were operated and how they felt. For example, in the case of a ballpoint pen, one student stated, "you know how with a ballpoint pen, when you push the button down it turns around." Hardware behaviour was often referred to using the linguistic expression "like a". The scale mechanism could be “like a ballpoint pen” or “like a wind up toy” (See Transcript 1). These observations provide evidence that one way in which we think about designing devices is through analogy to other experiences with devices. That is if we try to design a catch mechanism, one way to go about it is to seek inspiration from all sorts of things that we open and close; our umbrellas, CD holders, doors, egg cartons, brief cases, computer lap tops, and VCRs. Novice designers do not appear to store a library of different kinds of abstract catch mechanisms where they remember the particular geometric configurations of each catch; whether or not experts do is an open question. Rather, novices recall experiences of products that need catches to keep them open or shut. And they recall the catch in its particular context of use, remembering the feel of opening it. Transcript 1 illustrates how novices designers refer to prior experiences with hardware.

Vivian:	If this is em you know like one of those farmer toys where you pull the string and it rolls back, maybe it's something like that where it's maybe a spring loaded coil or a spring loaded em disk with a thing attached to it
Vivian:	Did you ever watch a music box unravel? Like you know these kinds of springs like this, so if you squish it causes some kind of rotation
Juan:	Mmmm right
Vivian:	And if you have rotation in one orientation you can usually translate it into another
Juan:	Yeah you're right I guess watched have those too
Vivian:	Yeah exactly right… right

Transcript 1: Students Draw Heavily on Existing Experience with Devices as they Design Scale Mechanisms.

Figure 2 shows a design developed by one student who searched his bag to find a ballpoint pen or Biro ® when he noticed that the desired motion of the scale was similar to his recollection of the motion of a retractable Biro ®. In many retractable ballpoint pens or Biros ®, when you push the button down to eject the point, the point twists around as it ejects and retracts. The student proceeded to dissect the Biro ® in order to learn how it worked. The students' design builds heavily upon the ballpoint pen deployment-retraction mechanism.



Above: Students sketch showing a design based upon a ballpoint pen deploy-retract mechanism
Below: A design conversation in which students build on the design sketched to the left

Raoul:	[looks in bag for a biro (ballpoint pen]. I've had the experience of taking apart a Biro ®. I reckon it could be like a Biro ®.
Mark:	[laughs] you reckon it could be like a Biro
Raoul:	It could be when you think about it. [examines Biro ® and sketches for a while]
Mark:	What's there?
Raoul:	That's a close up of that area there. (see sketch above). It's like a pen you know how one of these pens as you're pushing it down that's got those tags in it and they make this go around, like when you put that in it pushes round and so that rotates it should do that and I was thinking like it could be like that with these grooves and if instead of having gaps you have like one spiral groove there you could press this down and this is spring loaded at the bottom for resistance and so however much you push this down this rotates an amount (inaud).
Mark:	Like if your helical groove thing was like and you had your tongue thing sitting out here on the groove like a screw thread that screws it around

Figure 2.. Hardware as Starting Point and Episodic Memory Trigger: designs build on experience with existing hardware devices.

Hardware as Embodiment of Abstract Concepts and Conceptual Models

Hardware gives physical tangible presence to conceptual models. This helps students to remember theories. Many students did not know what a "pin-joint" that they had seen in numerous abstract diagrams might look like in real life. When they dissected bathroom scales they found many examples of "pin-joints" that looked like knife-edges resting in grooves.

Hardware as Adversary

Hardware behaviour reveals errors in conceptual models. One group proposed a screw-type mechanism for their scale, based on the idea that as a nut turns it moves linearly along a bolt. On implementing this model in hardware the team discovered that even though when you turn a nut it moves linearly along a bolt, the reverse is not true. When you push on a nut (as a weight pushes on a scale), neither the nut nor the bolt turns, they just sit there. There is too much friction unless the thread is at a particularly steep angle. Building devices reveals errors in conceptual models, particularly errors in assumptions and causal relations. In a similar way, when a device does not work as you expect it to, it reveals that the designer had a different conceptual model than the one that you used, or that the device is broken.

Hardware as Prompt

Device behaviour prompts student questions and suggests experiments. When the students touch the scale pan of an existing kitchen scale, they notice what is does and it invites more exploration. They press again to see if it does exactly the same thing. They vary where they press to see if it does something different. Through repetitive interaction with hardware students gradually bring order to their observations and build a conceptual model, distilling out key operational parameters and their relationships.

Hardware as a Medium for Integration

Integration of hardware components reveals properties and limits of the hardware and hardware components. This is why learning through synthesis -- bringing things together to create a new whole -- is so powerful. In the simple example of the screw mechanism above, by trying to integrate a nut and bolt together in the context of designing a scale, the students extended their knowledge about the characteristics and limits of nuts and bolts. Typically, integrating components in a functional context reveals:

- practical limits of use,
- characteristics of operation,
- methods of connection,
- causal relations,
- physical quantities.

This empirical knowledge extends the student's hardware repertoire -- the students knowledge of devices and their experiences from which to draw episodic knowledge.

Hardware as a Communication Medium

Hardware is integral to learning communications. Hardware is used to command attention, to demonstrate and to persuade. Whoever holds the hardware tends to command attention, particularly if the hardware is a mouse or remote control that provides a means of control. Thus objects affect the dynamics of group interaction. Further, hardware objects affect the course of inquiry, idea generation and discovery. The groups that accessed the rubber band and the pens to support their thinking would have had different design processes, different ideas generated and made different discoveries had the available hardware been different.

DISCUSSION

In this discussion we consider these findings and draw comparisons with the literature on how objects and other representations such as sketches and CAD primitives support thinking.

Our primary finding of significance to HCI and tangible media is that the interpretation and use of an object depends heavily on the context in which it placed. The problem context drives what attributes of an object people notice and in which ways they try to use an object.

This finding, derived from exploring how objects are used, differs quite sharply from the findings of memory studies, which explore how people categorize objects outside of any particular context of use. Rosch's studies of memory [17] showed that people categorize objects based upon similarity or dissimilarity of attributes. She found that categories of objects become definitively structured because they are coded in cognition in terms of prototypes of the most characteristic members of the category. The most cognitively economical code for a category is a concrete image of an average category member. Although general categorization provides for cognitive economy in recognition or description of objects presented out of context, this does not apply once we consider objects in a context of use. Further work is needed to determine how people understand objects that they encounter and the extent to which understanding is governed by context, by particular attributes, or by belonging to a common class of objects.

Our study confirms Norman's observation that the appearance and feel of the device and the context in which it appeared should provide the critical clues required for its proper operation. Norman argued for appropriate cognitive models, physical mappings, physical constraints and physical affordances . The question this raises, is how to identify appropriate physical mapping or affordances Should the guide to what is appropriate be the context of use of the object or the class of the object as it would generally be categorised. Our work suggests that in some contexts of use (designing being the case in point), the context of use is the dominant factor and should be the guide for what is considered an appropriate conceptual model and mapping.

The effect of contexts of use on tangible interface design needs to be explored through designing and testing tangible interfaces. This paper identifies the kinds of trade-offs between context of use and object category that need to be considered in order to design useable systems.

A second primary finding of this paper is the large extent to which designers appropriate objects to help them think. This section of the discussion considers why this is so. It draws upon other studies of CAD tools and sketching in design to explain this phenomena and to identify what it is about objects that supports design thinking and communication.

It is helpful to begin with Goel's [7] comparison of sketching and CAD. Goel's empirical studies of designers found that sketches facilitate design idea generation and concept development while CAD does not. Goel presents evidence that sketches support design thinking because sketches are a dense and ambiguous symbol system. A line made using an informal representation method such as sketching could represent an edge, a piece of rope, or a rod. Designers working around a sketch are constantly asking for clarification of the sketcher’s intent and also suggesting new designs based upon misinterpretations of the sketch. The ambiguity in the sketched representation is appropriate for designers when developing concepts because it represents the level of the designer's thinking when they draw the sketch The sketcher draws a shape paying attention to one aspect or attribute of the shape, but because they are in the process of defining the design they have not fully determined what they are drawing. They can pay attention to only one, or at most a few attributes at a time. Schon's [19][20][21] observations of designers sketching reveals a process of negotiation with the sketch, in which the designer draws, then interprets their own sketch then continues drawing out the idea.

Although CAD primitives (lines, circles, cuboids etc.) have potential for misinterpretation in the same way as do sketch elements, the designer using CAD is forced to pay explicit attention to which geometric primitives s/he will use to represent an idea. The representation forces attention to the internal logical consistency of drawing rather than just what it looks like, for example to draw a circle one has to pick a centre point and then a radius. Further, CAD tools focus attention to precision so that the drawing looks neat. As a result of this cognitive overhead, designers tend to work out what they will draw before they begin in CAD. Goel's experimental data showed that designers who worked with CAD were forced to make commitments early in the process and that CAD drafting facilitated fewer instances of concept generation and development than sketching.

CAD systems are designed to produce drawings to engineering and architectural standards that minimise ambiguity in representation, because by allowing only one possible interpretation, parts can be built from drawings without making errors. Perhaps as a consequence, CAD systems have focused on accuracy and integrity of representation of the final design, rather than supporting the fluid process of idea development.

The fluid process of sketching and the ambiguity of the sketched representation have analogues in physical prototyping. Because physical objects can be interpreted in multiple ways depending upon their context of use, they too are ambiguous and facilitate context-dependent interpretation as do sketch elements. The physical prototype helps the engineer by bringing to the fore specific attributes of an object. The particular attributes that are emphasised depend on the context of use. Objects and physical prototyping materials give rapid visual and tactile feedback and afford gesturing in 3D space, physical testing and so on. Our research has indicated that quick rough prototypes are often preferable to time consuming accurate prototypes because they allow the designer to explore the space quickly. Professional engineers often use Lego or Meccano to prototype ideas, yet while these models are fairly quick to construct, designs are always constrained by the limiting ways in which joints between parts can be made. This is in some ways analogous to the attention to detail one has to pay when producing a CAD drawing. This suggests that there is some in-between ground to be explored for tangible prototyping interfaces. For example a system could take advantage of gestures and affordances of objects in physical space, combining them with a variety of joining methods implemented in virtual form so that such procedures facilitate rapid explorations and give rapid feedback, but do not force an exact representation.

CONCLUSION

This paper has articulated with examples, the roles that hardware objects play in supporting engineering designers thinking and communication. The fundamental findings of our inquiry are that:

1. Design thinking is heavily dependent upon references to physical objects and gesturing with physical objects. Designers are active and opportunistic in seeking out physical props to help them think through design problems and communicate design ideas.
2. The interpretation and use of an object depends heavily on the context in which it placed.
3. Quick rough prototypes that model key attributes of designs are often preferable to time-consuming accurate prototypes
4. Tangible interfaces need to make a trade off between exploiting the ambiguity and varied affordances of specific physical objects and exploiting the power of general representations

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See also:
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