



Spotlight

Using Solid Diagrams for Tangible Interface Prototyping

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In most design disciplines, early concept development involves paper-and-pencil brainstorming. However, we've found that when designing a tangible user interface, it's best to start with a *solid diagram*—a 3D “sketch” created using simple construction materials. In the early stages of research and concept development, solid diagrams are more suitable for rapid reconfiguration and exploration than pencil sketches. They also let us analyze modes of correspondence between physical structures and abstract-information structures. Furthermore, because we can manipulate these diagrams, they help us explore usability properties and certain design trade-offs.

CREATING A SOLID DIAGRAM

Professional product designers create sketches to test alternative concepts, capture fleeting mental images, and discover new configurations or relationships. This “conversation with the materials” is central to the reflective design practitioner's experience.¹ Computer software developers occasionally sketch their ideas, though less often—perhaps when negotiating or reinterpreting rough versions of design diagrams. However, in the case of pervasive computing and augmented physical objects, the sketch processes used to create the physical forms are often quite separate from the design of the underlying software and information structures. This work might even be performed by different people who, if they sketch at all,

do so using tools of different craft traditions. We've tried to find sketching tools that allow physical objects to be created and analyzed from an information-structure perspective, providing common ground for teams who might come from different educational backgrounds.

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We use sketching materials that we can deploy with minimal training and that provide maximum opportunity for creative exploration and evocative experiences. Some of the materials—index cards, Post-it notes, and basic drawing materials—have proved successful in paper and low-fidelity prototyping.² However, we also use foam boards, plasticine modeling clay, wooden spatulas, pipe cleaners, string, stickers, paint, glue sticks, and a variety of other fasteners and decorative attachments (see figure 1). These materials are readily available in art- and school-supply stores, and most people are already familiar with them. We also provide more sophisticated tools (including craft knives and sculpting

tools) for those with more physical-design experience. We store the materials in large plastic chests with wheels, so that we can easily transport them either to invited workshops (see the sidebar, “A Tangible-Prototyping Workshop”) or just down the corridor for a design session in our own department.

UNDERSTANDING CORRESPONDENCE

A key component to developing tangible prototypes is the analysis—understanding how a prototype achieves its purpose is a driving factor when designing future iterations of the prototype. For this analysis, we can view individual physical objects and aggregations of objects as manipulable solid diagrams. They share all the syntactic and semantic properties of graphical diagrams and can be readily manipulated by a human user (see figure 2).

The *syntactic correspondence* in such diagrams, adopting Yuri Engelhardt's 2D schema,³ is determined by the object-to-space relations, object-to-object relations, and attribute-based relations (such as size, shape, color, and texture) between the diagram's component parts. Containment, linking, and superimposition (stacking) are interobject relations that take on added significance in solid diagrams, compared with their graphical counterparts. Textural attributes and ways of distorting metric space (such as using nonplanar surfaces) similarly become more salient.



Figure 1. Solid sketching materials in a workshop setting.

The *syntax* of a solid diagram defines which of these relationships the prototype designer considers meaningful, and the *computational correspondence* determines how they are interpreted digitally as an information structure. These should both be chosen to reflect what a user would find meaningful in the particular context. So the designers must be able to understand the *cognitive correspondence* in solid diagrams—that is, how objects in the diagram and actions on them can be used to stand for other objects and actions in the problem domain.

Finally, we can also analyze the objects themselves as independent carriers of information. An object's appearance should correspond with its intended actions, and the experience of using the object should give tactile guidance on how to perform those actions. For example, a steering wheel's appearance suggests it could be used for turning with both hands, and its weight and self-centering characteristics suggest slow and deliberate movements. For a steering assemblage, as with all mechanical objects, the number and range of degrees of freedom are determined by the way in which the object is constructed from physical moving parts. These also affect the object's look and feel and thus ultimately the interpretation of how the object should be used.

A TANGIBLE-PROTOTYPING WORKSHOP

For our workshops, we typically place materials at the center of a big table, leaving work space around the edges. Each participant has a seat, and we provide many tools so that nobody has to wait. (Note that researchers usually prefer black over colored pens, and fat pens can reduce verbosity.) Separate containers hold the smaller items—pens, card bundles, and so forth. We document the session with photographs, using a small stage, tripod, and macro lens. We record what each prototype is and what it does on an index card. A display stand for products and cards helps illustrate the process and inspire other participants.

Each workshop usually contains five phases. The first is a warm-up phase, when participants become familiar with the materials and context. Participants from art and design backgrounds usually have little difficulty during this phase, while research scientists sometimes feel threatened by the focus on artistic and craft skills or else feel childish using the materials. A simple warm-up activity might involve having each participant create a name badge. Facilitators can help overcome participants' resistance by creating their own attractive or whimsical badges.

If the workshop focuses on the technique rather than a specific application, then the second stage involves having participants select a technical focus—successful examples include mobile phone accessories, collaboration tools, or games. If the participants are unfamiliar with digital transducers, the facilitator might emphasize the wide range of sensors and actuators available, asking participants not to worry about technical feasibility but to focus on any physical action or object that can be digitally augmented.

Next, participants start using the materials—we call this the direct-exploration phase. If participants have no idea where to start, the facilitator might suggest they pick up one or more materials that attract them and simply play with them until an idea comes. This advice might seem vague, but it never fails!

The next phase—refinement—depends on the audience involved. A technical audience might consider transducers, an interaction design audience might consider various use scenarios, and a design audience might find it hard to tear themselves away from the physical materials, completing several refinement iterations.

The final phase, analysis, involves facilitated discussion in terms of analytic categories (see table 1 in the main text). This can take place in a discussion group, a studio class, or a one-on-one session.



Figure 2. Some typical solid diagrams.

This correspondence-based analysis provides a device-centric framework for interpreting manipulable solid diagrams. Table 1 presents an example of how to apply correspondence analysis to tangible prototypes.

UNDERSTANDING USABILITY

A further analytic perspective that complements the device-centric analysis of solid diagrams is a user-centric focus on the information structure of users' tasks. We analyze a tangible user interface's (TUI) usability using the *cognitive dimensions of notations* framework.^{4,5} This set of discussion tools includes 14 analytic dimensions, each describing different aspects of a given interface. Analyzing a TUI in this way lets us articulate design issues and express them as a sys-

tem of trade-offs, outlining inherent strengths and weaknesses. By taking into account the intended activities to be performed, we can begin to understand how particular design decisions might affect the prototype's overall usability.

Consider how trying to improve a TUI along one dimension for a particular task might reduce usability along another dimension. For instance, *progressive evaluation* describes a user's ability to check what he or she has done up to a given point—the ease of which depends on design decisions involving the TUI. Although the current status might be obvious if you've connected the TUI to a graphical display that gives constant feedback, progressive evaluation might be difficult if multiple parts of the TUI must all be set into place before you

know whether the user has taken the correct action. Although feedback might be delayed in the latter scenario, you might see a benefit along another dimension—*provisionality*. Having a flexible spatial arrangement that lets the TUI represent and communicate different concepts might encourage users to more freely explore different configurations than they would with a graphical interface. Although provisionality lets users sketch their ideas without penalty, the increased flexibility might make it difficult to warn of hidden dependencies. Representing such dependencies graphically is relatively simple using 2D diagrams, but connecting two distant parts of a tangible prototype to show their relationships is problematic.

As this example shows, the cognitive dimensions of notations framework encourages users to focus on making a prototype usable for intended tasks while recognizing that doing so might render the interface less suitable for other tasks. Understanding that a prototype's usability isn't wholly good or bad but a function of the design and tasks at hand allows for a more thorough and constructive evaluation.

We have applied this solid-diagram prototyping method in a wide range of environments, including walk-up-and-play “micro courses” for an appliance-design conference, demonstrations at an experimental social-research workshop investigating possible conditions and outcomes of interdisciplinary design (see www.crashh.cam.ac.uk/events/2003-4/socialpropertyMay.html), and group workshops for interaction design students, researchers, and teachers. In these contexts, researchers and teachers found real stimulation in the novel perspective of treating physical objects as configurable information structures. The abstract perspective of our analytic process is made more comprehensible by embodying it in software and colorful physical materials, extending the potential audience for such collabora-

TABLE 1
Applying correspondence analysis to tangible prototypes.

Focus	Correspondence	Question
Syntax	Object : Object Object : Space	What meaningful configurations are possible with your prototype?
Computational semantics	Data : Information	How would a computer program interpret data from your prototype?
Visual suggestion	Observable form : Action possibility	How does the “look” of your prototype suggest the intended actions?
Tactile guidance	Experiential feel : Action performance	How does the “feel” of your prototype guide action performance?
Cognitive semantics	Shown : Meant	Will people understand how your prototype works?

tion. We also apply these techniques in our own pervasive computing research, as an essential early stage of projects that might involve many phases of iterative prototyping. (See “The Webkit Tangible User Interface: A Case Study of Iterative Prototyping” in this issue, which describes one such project as an extended application case study.)

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