# Made of Tiny Robots

An Investigation of the Ecology of Responsive Environments

Michael Philetus Weller

May 2012

Thesis Committee:

**Mark D Gross**
Professor, CMU (chair)

**Ellen Yi-Luen Do**
Associate Professor, Georgia Tech

**Seth Copen Goldstein**
Associate Professor, CMU

## Abstract

***ABSTRACT GOES HERE***

# Contents

# Chapter 1

# Introduction

What follows is an investigation into the ways the burgeoning **ubiquity of computation**[1][2] will reshape the way we relate to our physical environment. Putting computers and screens and sensors and networking and even motors in artifacts whose utility was previously primarily conferred by their physical form will give the artifacts in our environment internal states and behaviors; our physical environment will become responsive. In the extreme case of artifacts composed of **self-reconfiguring materials** the form of an artifact will become just another aspect of its behavior. This change from form-governed artifacts (where an artifacts's utility is conferred by its form) to behavior-governed artifacts (where an artifacts's utility is conferred by its behavior) is the hallmark of a **responsive environment**. Thus in a responsive environment our role shifts from being the sole actors who make use of the tools we surround ourselves with to being (perhaps leading) members of a social network of robotic[3] artifacts.

We suggest that taking an ecological perspective is important to understanding the shift to responsive environments for two reasons:

1. these networked robotic artifacts will serve as cybernetic extensions of our capabilities, and the level of the interface will be ecological; and

2. the complexity of producing these artifacts combined with their intimate connection with and knowledge of our personal lives will change the dynamics of their production, distribution and use.

[1]Terms rendered in bold on first use are defined in the Glossary.

[2]A trend identified by Weiser (1999).

[3]We will be considering **robots** in the broadest possible sense of any machine capable of sensing input and responding with various behaviors.

To be clear, when we speak of ecology we do not intend it in the sense of the natural environment. We will be investigating **artifact ecologies**, the systems we apply and roles we adopt in the creation and use of physical artifacts, and the network of relations thus engendered.

In the rest of the introduction we further elaborate on the evolution of artifact ecologies, how we will interface with responsive environments composed of robotic artifacts, and the roles we will adopt in creating and customizing these new robotic artifacts. We then argue that one of these ecologies is particularly well suited to engaging communities in specifying the behavior of their responsive environments, and outline how the following chapters will develop and support this claim.

## 1.1 The Evolution of Artifact Ecologies

To understand the manner in which we are embedded in ecologies of the creation, distribution and use of artifacts we need a theory of how we relate to individual artifacts. Gibson (1979) suggests that we are able to appreciate the value of physical artifacts through our (innate) recognition of the uses **afforded** by their form. We recognize without effort that a chair affords the possibility of sitting and a door in a wall affords the possibility of entering a building.

We propose that the history of artifact ecologies consists of two broad eras, and we are now on the cusp of a third era.

As our (primate) ancestors developed the faculties to recognize that, for example, flint could be knapped to produce a blade, which could then be used to skin animals to create clothing, we entered the first era of the *wild environment*[4]. These sorts of artifact ecologies are characterized by a distinction between a local collection of useful artifacts with clear affordances, generally carried on one's person, and a vast external environment that does not particularly respond to the human scale and within which affordances can be perceived only with significant knowledge and effort. Artifacts are generally crafted by the bearer for personal use from raw materials harvested from the wild surroundings. The chief social aspect of these artifact ecologies was the verbal transfer of the relevant methods to close acquaintances.

The next era was ushered in by the development of urban settlements. In these *leveraged environments* our artifact ecology has expanded to the horizon; we are now surrounded by manufactured artifacts designed to present a variety of helpful affordances. These artifacts give us leverage over our

[4]Terms coined here are emphasized on first use, and defined in the Glossary.

local conditions, for example doors allow us to easily restrict access to a space. Artifacts are no longer simply controlled by their bearer and encode complex social dynamics; roads and sidewalks are shared by citizens, stores provide artifacts in exchange for money, doors open for those who bear their keys. In order to produce these new artifacts in sufficient quantity to literally pave over the natural environment significant social changes are required; artifacts are designed by one set of specialists, produced by another, and distributed by yet another. As desirable artifacts are mass-manufactured through a complex bureacracy they are frequently unevenly distributed. The artifact ecologies of this era frequently engender social unrest due to inequities in the control of public artifacts and the distribution of private artifacts.

Many people already carry small computational devices with them and routinely interact with these newly familar robotic interfaces. As this computational ubiquity spreads we are already transitioning into a third era of artifact ecologies: responsive environments. These ecologies will be characterized by the promotion of our artifacts from passive tools to networked social peers. The intimacy of these relationships will place much more power over our behaviors and emotions in the hands of those who dictate the behavior of these artifacts. At the same time these artifacts have the potential to allow mass customization to the desires of those bearing a given artifact.

## 1.2 Where Do We Plug In?

Science fiction stories have led many people to ask: (when) will we have computer chips in our heads?[5] The answer for most of us is probably never, as we do not actually need to cut into our brains to become **cyborgs**; we are fully capable of interfacing with computers through language, through **GUI interfaces** and through **tangible interfaces**. By embedding ourselves in artifact ecologies populated with robotic devices with these sorts of interfaces, we in effect incorporate these other computational systems into our own thought processes. The best current example of this kind of cybernetic interface is **googling**; once one learns basic techniques for interacting with internet search engines and acquires a persistent network interface (such as a **smart phone**[6]) one becomes a sort of information-retrieval cyborg. The googlebot is so easily incorporated into our minds because our minds are

[5] I am indebted to William Gibson (2012) for this formulation.

[6] While this term is currently well known we expect that in the near future it will seem as antiquated as "personal digital assistant".

already just a collection of specialized computational units that in concert to form a "society of mind" (Minsky, 1985). As the philosopher of mind Daniel Dennett is fond of saying, "Yes we have a soul; but it's made of lots of tiny robots" (2003, p. 1). Although these tiny robots have historically happened to all be in our brains, with the advent of responsive environments we will be incorporating more and more robotic devices into our local cybernetic artifact ecologies.

Many of these devices constantly feed data to apparently discorporate[7] agents like the googlebot. As we enter into a cybernetic relationship with this new artifact ecology much of what we have until now considered our private personas will be determined by the behavior of the robotic devices we surround ourselves with, and by our relationship with the computational agents that manage these devices and mediate our interactions with other people. In light of our special relationship we will refer to these agents (like the googlebot) generally as *idols*[8]. We will call the handheld computers (such as a smartphone) that allow us to communicate with both peers and idols (through a constant connection to the network), *crystals*[9].

## 1.3 New Materials

While the heralds of responsive environments have been computers that will fit in your pocket, and interface with us through language and images, embedded computation has the potential to create artifacts that are much less familiar. Computation is coming out from behind a screen and into the physical objects in the world around us. These robotic artifacts may respond to being touched and manipulated, or may proactively reconfigure the spaces around us.

**Tangible interfaces** give us the opportunity to leverage our innate recognition of the uses afforded by different forms. Physical kits that can be used to describe forms and concepts predate responsive devices. Educators have

[7]The googlebot actually has a physical stature in line with its apparent omniscience; it fills several enormous buildings spread around the world and consumes enormous amounts of energy from both the grid and dedicated power plants.

[8]We chose the name 'idol' after Gibson's 'idoru'(1996), a literal AI rock star, with the accompanying cultural leverage of a teen idol; and after religious idols, to draw an analogy with the religious practice of asking powerful ethereal agents for advice and favors.

[9]As in a crystal ball that is used to view distant places and communicate with other agents through the ether, and as a reference to their current popular physical realization as a fragile glass-plated touchscreen.

developed a variety of such physical kits known collectively as **manipulatives**. Tangible interfaces—by enhancing manipulatives with embedded computation—tie digital models to physical objects to allow people to directly grasp and manipulate these models (Ishii and Ullmer, 1997). For example, our Posey kit allows people describe a 3D model to a computer by building it with a hub-and-strut construction kit rather than using an onscreen mouse-and-keyboard interface to manipulate graphical representations of shapes.

Tangible interfaces' physicality provides several inherent advantages: the physical system provides a representation of its own state (Jacob, Girouard, Hirshfield, Horn, Shaer, Solovey, and Zigelbaum, 2008); physical constraints can enforce the constraints of the digital model (Patten and Ishii, 2007); the **sensorimotor** feedback provided by manipulating physical objects helps to **scaffold** geometry and symbol manipulation tasks (O'Malley and Fraser, 2004); and several people can collaborate to provide input (Bonanni, Alonso, Vargas, Chao, and Ishii, 2008; Suzuki and Kato, 1995).

Traditional manipulatives are also the basis for **modular robotics** (Yim, Shen, Salemi, Rus, Moll, Lipson, Klavins, and Chirikjian, 2007), which add computation and actuation to create kits of parts for quickly assembling robotic devices. (We will refer to these robotic devices assembled to perform a particular task as *golems*[10].) By combining modular robotics and tangible interfaces, these golems can be programmed by directly manipulating them to demonstrate desired behaviors.

Making things—giving objects form—has traditionally involved a manufacturing process such as machining a block of material or pouring molten material into a mold. Recently, the techniques of modular robotics have been extended further to create a new kind of material that can receive a digital description of a desired form and arrange itself into that shape. One implementation of such a self-reconfiguring material is an **ensemble** of robotic modules. Each module runs a small program; together the programs encode the ensemble's behavior. By coordinating with neighbors, modules respond to external stimuli and arrange themselves into a potentially vast number of forms.

Self-reconfiguring materials promise to revolutionize the creation and distribution of physical objects much as digital audio files have revolutionized the distribution and content of music. The digital description of a chair or a bottle opener could be downloaded and then realized from a reservoir of self-reconfiguring material. Unused objects return to this reservoir to pro-

[10]After the mythological golem assembled from clay to do its master's bidding.

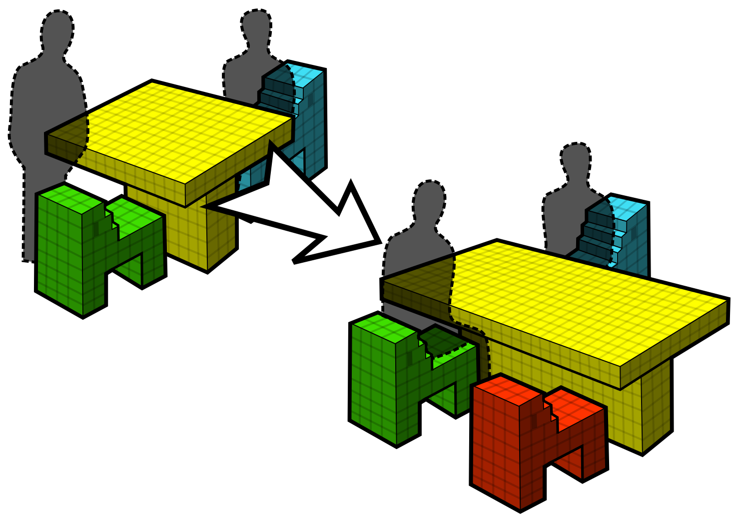

Figure 1.1: The social table, an example of a hyperform composed of self-reconfiguring robotic modules. As more people sit down, the table expands (drawing from a reservoir of modules) to keep one empty seat available.

vide raw material for other objects.

More significantly, an object composed of this new material need not be limited to a single static form. Instead, the currently running program can change its form. We call a form that varies in the four dimensions of space and time a *hyperform*; a single hyperform expresses itself as different shapes at different times. A new hyperform is realized just by loading a new program into the material. For example, the 'social table' hyperform (Fig 1.1) automatically expands as more people sit down. The table grows to make space for additional guests (drawing more material from a household reservoir as needed); as people get up from the table after dinner, the social table melts away leaving only a small dinette with a single empty chair. The material that had been part of the expanded table returns to the reservoir and later renders a sofa and coffee table for guests to relax after dinner.

Research towards even more advanced hyperform mediums is also underway. One vision is that a **claytronic** (Goldstein, Campbell, and Mowry, 2005) material could be composed of robotic particles (we will call them *clayticles*) so small[11] that objects formed from the material appear to be

[11]Individual clayticle modules are less than 1mm in diameter. They are fabricated using the same processes used to make microchips, except that they are designed to curl up into a ball when

molded out of clay rather than constructed out of blocks.

## 1.4 Tiny Robots

A particularly interesting subset of responsive artifacts are those systems extending traditional manipulatives with embedded computation. These tiny robotic modules can serve as design interface, cybernetic cognitive enhancement and implementation medium all at the same time. We propose to give them a name: *robunculi*[12]. This name is a play on **homunculus**,[13] an anthropomorphization of the human soul visualized as a little man sitting in our head issuing instructions, or sometimes as two little men on our shoulders whispering arguments into our ears. They extend our agency out into the environment by allowing us to impress behaviors upon the objects we construct out of them. By leveraging our innate facilities for sensorimotor manipulation and the recognition of spatial affordances, robunculi extend our capacity to describe and construct 3D forms and behaviors.

## 1.5 Potential Responsive Environment Ecologies

As we move toward responsive environments several potentially stable ecological niches are emerging. The character of our artifact ecology, and what it means to be and individual within this new order, will depend largely on which of these modes of artifact production, deployment and use thrive. In distinguishing between these ecologies, we suggest that our goal should be to engage as wide a spectrum of the population as possible into shaping the behavior of the responsive artifacts they wield.

To this end we suggest three desiderata for our future artifact ecology: the transparency of behaviors, the reconfigurability of devices, and local production. By transparency of behavior we mean something like open source for software, except applied to the entire ecology—from production of the hardware, to the software on the device, to the network it communicates over, to the idols it interacts with. For people to exert control over their

they are released from their substrate. Electronic actuators etched into their surfaces allow these tiny spheres to attach to each other and to self-reconfigure. (TODO: citation)

[12]Applying the Latin plural diminutive '-unculi' to 'robot' gives 'robunculi', literally 'little robots'.

[13]Latin 'homo' (man) + '-unculus' (singular diminutive) = homunculus (little man).

environment it is critical that the mechanisms underlying its behavior are transparent to them. It seems obvious that giving people the opportunity to reconfigure the physical form of their environment, as robunculi and hyperforms can, would encourage participation in shaping the built environment. And by encouraging local production in hackerspaces or other high-tech local fab shops potentially gives people many more options (as devices do not need to be stocked, only feed materials) as well as the opportunity to produce customized devices.

To illustrate the tensions in this space we characterize four potentially stable ecologogical niches and evaluate which of these desiderata each supports (Figure 1.2):

1. Popsicle ecologies center around mass-produced single-purpose devices. We call the devices that typify this ecology *popsicles* as many are produced in a single configuration (like popsicles from a mold) and they are frozen in a single configuration. A prime example are smartphones like the iphone and android phones. Due to the economics of this model, popsicles are likely to be closed systems. The iphone, for example, is particularly opaque: it runs a closed-source operating system; it limits owners to installing whitelisted software from a single repository vetted by the manufacture; and the device itself is physically sealed—opening the case, even to change the battery, voids the warranty. While android phones are somewhat more transparent (the android operating system is open source) they often ship with software and hardware locks to obstruct owners from tinkering with their behavior. Thus, as shown in Figure 1.2, popsicles at best are somewhat transparent, and by definition support neither local production or reconfiguration. However an advantage of popsicle ecologies is that this sort of mass production has been successful at producing vast quantities of devices at low prices.

2. Spoke ecologies are characterized by *spokes*, bespoke devices produced locally using open source software and open hardware modules. An example is the bicycling jacket with integrated turn signal lights built with a LilyPad **Arduino** described in (Buechley and Hill, 2010). This ecology is generally more inclusive than a popsicle ecology, supporting transparency and local production. While it can support reconfiguration in the limited sense that devices are generally built with modules (such as the LilyPad) that could be scavenged from old devices and reused, this generally results in the destruction of the original device and requires a fair amount of techical knowledge.

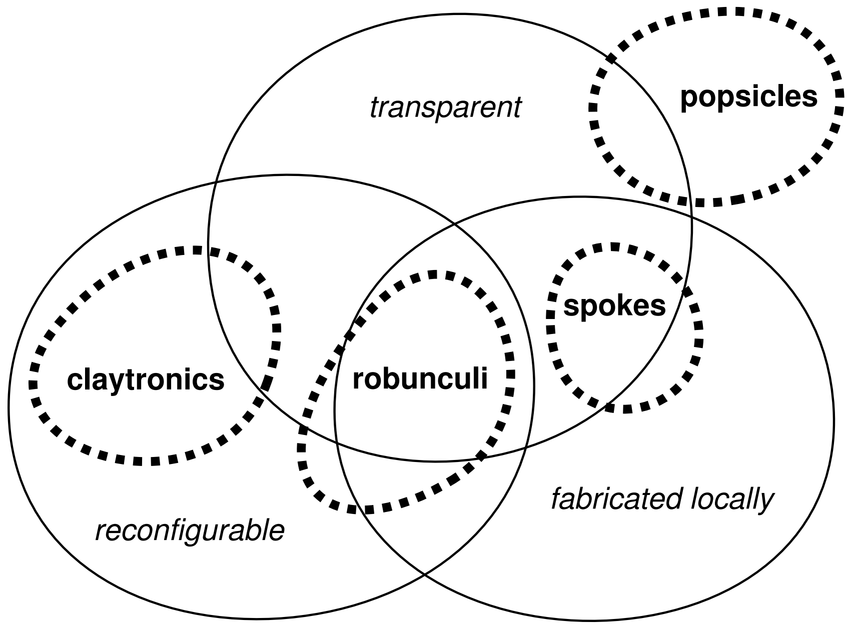


Figure 1.2: Venn diagram showing which desiderata could be fulfilled by each responsive environment ecology.

3. Robunculi ecologies present the greatest opportunity to fulfill all of our desiderata. The systems are by definition reconfigurable, and lean heavily towards open source and hardware designs. Local fabrication could allow systems to be customized, but mass production may be necessary to make these systems economically feasible.
4. Claytronic ecologies are still somewhat speculative, clayticle materials will probably (at least initially) be produced in centralized factories. Although the systems themselves may not be produced locally, that is less of an issue with claytronics as these systems' extreme reconfigurability allows them to serve as a sort of universal fabricator. It remains to be seen whether these sysems will run open source software—even if they do the complexity of distributed local control is potentially an obstacle to their transparency.

Of course several of these ecological niches may coexist, and influence each other. It seems that the only system capable of producing artifacts on a global scale in the near future is some kind of popsicle ecology. While ecologies dominated by popsicles may not support widespread participation as well as others, unless they are able to acquire responsive artifacts people will not be able to participate in responsive environments at all. For example the cell phone ecosystem is dominated by popsicles, and while cell phones are often not particularly transparent, they are broadly available almost everywhere[14]. Even if popsicle ecosystems continue to dominate our ecology, developing spoke and robunculi ecosystems could place pressure on popsicles to support transparency and reuse (if not reconfiguration). We propose that our best opportunity for building an inclusive artifact ecology is to support the development of spokes and robunculi. Robunculi in particular can help to engage more people in design roles and help to scaffold participation in local fabrication scenes.

There are several potential advantages to adopting robunculi as the building blocks of our built environment: we could customize the form and behavior of the devices and structures around us; we could give many previously static objects the capacity to express behaviors; and we could decompose objects not currently in use to provide raw materials to be reused elsewhere. More significantly, robunculi have the potential to change the way we manipulate our environment much as googling has changed the way we gather information. With robunculi we can all be furniture-designing, golem-wrangling **maker** cyborgs.

And as claytronic technologies mature, the ecologies developed by robunculi-wranglers could diverge significantly from those developed on top of popsicle ecologies with more limited opportunities for design input. Many of the methods currently being developed to support interacting with robunculi could be transferred to claytronic systems. Without this intermediate developmental stage claytronic systems may feature relatively impoverished mechanisms for encouraging input from those wielding (and inhabiting) these systems.

## 1.6 Method and Goals

Our current artifact ecologies provide extremely limited opportunities for people to participate in the design of their built environment. As we transition from leveraged to responsive environments the artifacts we surround ourselves with are being elevated from a variety of useful tools and spaces to cybernetic extensions of our personas. The question at hand then is: how

[14]citation?

we can live amongst robots in a way that empowers us to take control of the sorts of environments that ubiquitous computation will soon allow?

### 1.6.1 Thesis

*Robunculi ecologies empower people to control the behavior of the responsive environments they inhabit.*

There are several features of these systems and their supporting ecology that make robunculi well suited to the development of engaged cybernetic communities. By supporting interaction methods that leverage our innate sensimotor capabilities robunculi make the specification of form and behavior accessible. By providing people with little training the opportunity to take on (relatively limited) design roles this ecology can scaffold skill development. And by developing an engaged community of skilled practitioners robunculi ecologies can serve as fertile ground for local scenes specializing in fabrication, software and hyperform behaviors.

### 1.6.2 Method

We support these claims by identifying these features in prototype robunculi systems currently being developed, first in a broad survey and then in several more focused case studies. To facilitate this discussion we first develop (in Chapter 2) an ontology of responsive environments describing the roles we may adopt in relating to responsive artifacts, the interrelations between these roles and the methods of relation that typify each role. We devote particular detail to the roles and interaction methods supported by robunculi.

In Chapter 3 we survey responsive artifact prototypes from a variety of fields including tangible interfaces and modular robotics, with a focus on projects that satisfy our definition of robunculi. By describing them in terms of our ontology we call attention to the advantages of robunculi for supporting an engaged design ecosystem.

In Chapter 4 we present case studies of several projects developed by the author and others in further detail. We will focus on identifying reusable techniques and components of successful robunculi projects, on useful metrics for comparing the relative merits of different projects, and on how individual projects could relate to a larger ecosystem.

We conclude in Chapter 5 with an assessment of the current state of robunculi development and directions for future research.

# Chapter 2

# An Ontology of Responsive Environments

As we enter the age of ubiquitous computing our relationship with our artifact ecology is changing. There are several factors to these changes: we have new ways to fabricate artifacts; we have new ways of relating to artifacts; and our artifacts increasingly perform tasks that were once the exclusive domain of people. To facilitate a discussion of these changes we here describe the components of these responsive ecologies in more detail, and coin several terms to refer to these components. In Section 2.1 we suggest some categories for distinguishing different kinds of artifacts according to their purpose and means of production. In Section 2.2 we discuss how these categories help to structure the roles we can play in relation to the production and use of artifacts.

In Section 2.3 we describe the responsive artifact ecologies introduced in Chapter 1 in more detail. We suggest that one of the key distinctions between these different ecologies is the roles that are available for members of each society to play; ecologies structured around more transparent technological mechanisms and more reconfigurable artifacts will present more opportunities for people to adopt roles that shape the behavior of their environment. Of particular interest is what we are calling a robunculi ecology: manufacturing is focused on producing robotic kits of parts rather than devices that perform a single role; these kits can either be assembled, or can self-assemble, into a variety of forms on demand.

To promote the potential for involving a wide spectrum of society in design roles we develop our ontology of robunculi further in Section 2.4. We examine in more detail the roles people can play in producing and using

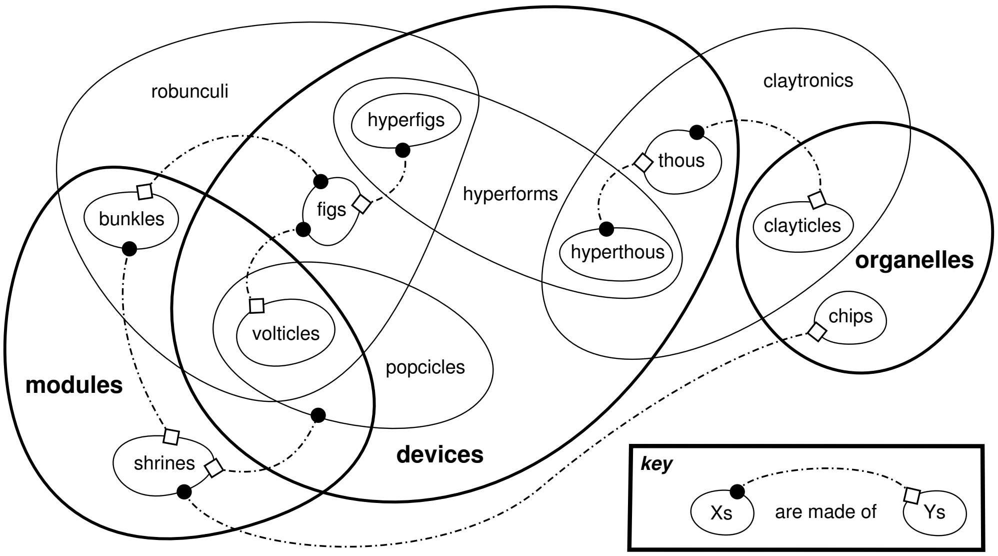


Figure 2.1: Venn diagram of computational artifact hardware categories.

robunculi, and the interaction methods available for people adopting various roles.

## 2.1 Kinds of Artifacts

By embedding computation in artifacts we can expand both the purposes they can serve and our means of producing new artifacts. We have developed some terminology to describe artifacts in both of these axes. Together the categories of production and purpose help to determine the roles we can play in relating to a given artifact.

### 2.1.1 Artifact Production Typologies

In a popsicle ecology we are used to purchasing packaged preconfigured devices. As illustrated in Figure 2.1 there are several ways a device can be implemented in a responsive environment.

Two important factors in the production of responsive hardware are scale and tooling. At the smallest end are chips, analog electronic components, sensors and actuators. We will refer to this group collectively as *organelles*, after the tiny machines that power biological cells; these components are generally produced in high volumes in and require expensive, technologically sophisticated tooling usually found in factories. Even supposedly **open hardware** systems are built around these closed organelles.

At the next scale are modules that package these organelles to make them more accessible to spoke developers (for example an **Arduino** board), or to present a tangible interface (like our Posey kit). (The Arduino is an example of a *shrine*, a computing module that can, among other things, allow a device to communicate with idols.) This stage of production can take place at a sophisticated local fab shop (with tools such as a **pick-and-place**) but often takes place in a more traditional factory because of the economic advantages of scale.

Popsicles are generally manufactured as a monolithic design including the necessary organelles on a custom circuit board, and sandwiched inside of a factory-produced case. Spoke and robunculi ecologies make use of modules to lower the barrier to device design. Sharing high-level components reduces the amount of technological knowledge required to create and customize devices. Open hardware circuit modules abstract away from the complexity of organelles and electronics, and are generally accompanied by online code samples and tutorials. Open hardware designs for cases and mechanical components can also be downloaded, customized and then fabricated with **rapid prototyping**[1] technologies at local fab shops (such as **hackerspaces**). Robunculi kits require no manufacturing at all, a device can be realized by assembling it from a kit, or by loading a program so that it self-reconfigures.

With robunculi systems the artifacts being manufactured are no longer devices but rather kits of *bunkles* (our term for an individual component of a robunculi kit; analagous to a single lego brick) that can be used to create devices (among other things). We call a device that is implemented as a particular configuration of bunkles a *fig* (as in a configuration). Robunculi make customization of a device design as accessible as playing with a construction kit. They support reuse by allowing different figs to be implemented at different times with the same bunkles. And a kit can be customized by printing new bespoke bunkles at a local fab shop.

While a single bunkle is not generally useful without a whole kit, it is possible that a device such as crystal (i.e. a smart phone) could interoperate

[1] Some examples of rapid prototyping technologies commonly available at local fab shops are **fused deposition modeling (FDM)** 3D printers and **computer numerically controlled (CNC) mills**.

with a robunculi kit;[2] it could be connected as a part of a fig to provide a display, or better networking, or a more powerful processor. We will call such a device that can function both on its own (as a popsicle) and as a part of a fig a *volticle*, an abbreviation of 'Voltron[3] popsicle'. Volticles are one example of how spoke and robunculi ecologies can influence larger popsicle ecologies to support transparency and reconfiguration.

Robunculi capable of self-reconfiguration can be used to create hyperforms (objects capable of changing their shape over time). We call a robunculi hyperform a *hyperfig*; one useful way of characterizing a hyperfig is by defining a series of intermediate fig keyframes that the system self-reconfigures between.

Hyperforms can also be implemented by claytronic systems. While robunculi are composed of bunkle modules claytronic systems are composed of tiny clayticle organelles. We call the claytronic analog of a fig a *thou* after the T-1000, the shape-changing robot made of 'liquid metal' from the 1991 movie Terminator 2. A self-reconfiguring claytronic system could be used to implement *hyperthous*. In the example of the T-1000 (Figure 2.2), it is capable of assuming a thou that mimics an actual person. Its hyperthou involves rapid self-reconfiguration of just the limbs of these mimic thous into piercing or slashing weaponized thous, as befits a killer robot from the future.

### 2.1.2 An Enumeration of Artifact Purpose Typologies

While the intended purpose of a non-computational artifact generally dictates its form, the physical form of a computationally enhanced artifact is often less constrained. By distinguishing devices according to their purpose we can develop a consistent language and reusable modes of interaction. We enumerate several categories of artifact purpose typologies below, as illustrated in Figure 2.3.

[2]For example Google and Arduino collaborated to produce the Arduino Mega Android Development Kit (`http://labs.arduino.cc/ADK/Index`), an open hardware module for creating spokes that interface with devices running the Android operating system.

[3]Voltron is a fictional mecha (a robot with a human driver inside) from the Japanese animated series of the same name. It is composed of five smaller mechas that can operate on their own or join together to form Voltron.

Figure 2.2: Still from *Terminator 2* showing the T-1000 implementing a mimic thou with a weapon thou in place of its left arm.

### Ducks

Our name for objects that derive their utility directly from their form—rather than serving as an interface to some computational affordance—comes from Venturi's term (1972) for a building that expresses its purpose symbolically through its form.[4] For example, a shovel implemented with a claytronic system would be a duck thou—because the clayticles' computational affordances are being used to realize the desired form, but the shovel's only affordances are derived from its form. Mass-produced non-computational artifacts such as a bowl and spoon (Figure 2.3, *D*) are *duckcicles*. A hyperform that derives its affordances from its changing forms, for example the social table hyperfig illustrated in Figure 2.3 at *F*, is a *hyperduck*.

### Tinks

This is a device that supports tinkering as a means of expression. For example an audio mixing console features an array of dials and faders that adjust the relative characteristics of a collection of instruments and microphones. The faders and dials serve to both illustrate the current state of the system

[4]Venturi's example was a poultry store on Long Island that sold ducks and eggs that was shaped like an enormous duck.

and as an input for adjustment. We call a kit that supports tinkering, such as Siftables tiles (Merrill, Kalanithi, and Maes, 2007) (Figure 2.3, *C*), a *tinkit*.

### Shrines

This is a system that features computation and networking, and the name is an allusion to their primary function of communicating with idols. These come in many forms. A collection of computers capable of hosting an idol (such as a server farm) is a *temple*. A shrine with a touchscreen (i.e. a smartphone or a tablet) is a crystal (as in a crystal ball). A more powerful desktop computer is a *bench* (as in a work bench, shown in Figure 2.3 at *A*). And a system that supports viewing and interaction with a group of people is a *theater*.

### Golems

Devices whose primary purpose is not interfacing with people but rather performing tasks for people fall into this category. An example of a popsicle golem is BigDog (Raibert, Blankespoor, Nelson, and Playter, 2008), a quadraped robotic pack animal designed to carry gear for soldiers. Robunculi golem kits could be used to quickly construct a golem to perform a particular task (for example the quadraped fetchbot golem shown in Figure 2.3 at *F*); the same bunkles could later be reused to create a different golem with different capabilities.

A golem that is under direct control of a human operator (like many military drones) is a *sockpuppet*. A golem that is assigned tasks (or controlled directly) by an idol instead of a person is an *avatar*. And a golem that people can ride on (or in[5]) is a *mount*.

### Sticks

While many devices in a responsive environment may operate autonomously, it will often be desirable for people to give direct input to control a device. We call a device that facilitates realtime control input a ‘stick’, after the classic video game input device the joystick.

There are several varieties of sticks. For example a device that gathers together several buttons and directional controls such as a game controller, or an aerial drone sockpuppet’s dedicated control panel, is a *stickboard*. The smaller fetchbot model (built with a tinkit) shown in Figure 2.3 at *E* could be

[5]For example Google’s driverless car.

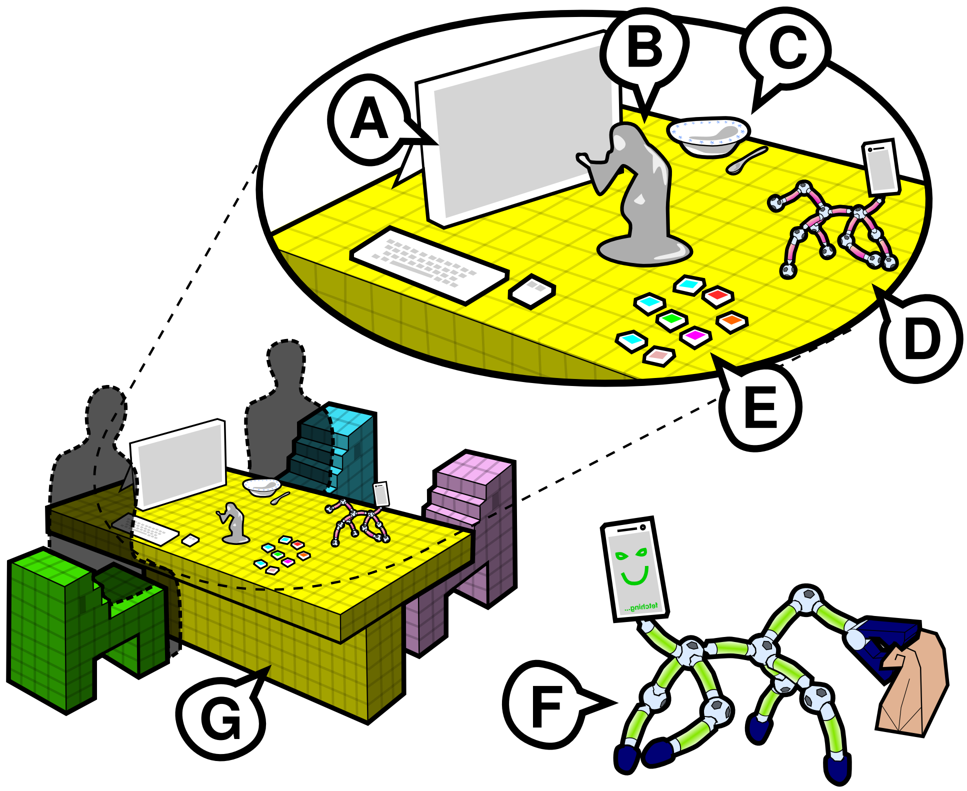


Figure 2.3: An illustration of various kinds of artifacts found in responsive environments: ***A*** a (work)bench computer (a popsicle); ***B*** an avatar hyperthou; ***C*** a tile tinkit; ***D*** a bowl and spoon (duckcicles); ***E*** a stickpuppet fig (with a hub-and-strut tinkit body and a volticle crystal for a head); ***F*** a golem fig fetching lunch; ***G*** a social table hyperfig (composed of prismatic cube bunkles).

used as a *stickpuppet* to directly pose the fetchbot golem shown at *F*. More nuanced input could be gathered from a partial[6] or full-body[7] *sticksuit* that uses either an instrumented space or integrated sensors in clothing (or both) to capture human movement with high fidelity.

### Badges

While people are adept at visually identifying artifacts and other people, most computational systems need a hint. Badges are devices that can be attached to an artifact or worn by a person to facilitate their identification by responsive devices. Passive badges such as **QR codes** and **RFID tags** need to be scanned by a sensor, while active badges such as crystals generally track their own position[8] and broadcast it over the network.

## 2.2 Roles for Responsive Environments

One of the most important aspects of an artifact ecology are the roles available for people to relate to the artifacts within it. In some ecologies only a select few highly trained professionals have any input on the behavior of devices, while other ecologies provide opportunities for a broader spectrum of society to participate. We will not discuss the role a 'user' of a locked-down device plays, but only roles that allow some level of input back into the larger ecology.

The roles described here are not meant to define individual people, but rather are different stances that a single person could take toward an artifact at different times. For example a researcher that designs prismatic cube bunkles could also take on the role of a fig designer and create a social table hyperfig. And then later at home the same person could eat dinner at a social table and write up an evaluation of the experience.

The roles are also not separated by discipline (e.g. electrical, mechanical, code) but by level of accessibility. This reflects the ideal of open hardware design that a single person can have an idea for a device and build a pro-

[6]For example the g-speak system (Zigelbaum, Browning, Leithinger, Bau, and Ishii, 2010) uses motion capture to identify hand gestures made while wearing special gloves in a space populated with high-resolution video cameras.

[7]For example with a Kinect, an inexpensive system (sold as a peripheral for the XBox video game console) that captures both a depth mapping (using an infrared laser and sensor) and a video stream. This data can be combined to reconstruct a person's full-body pose.

[8]Using the **global positioning system (GPS)** or radio triangulation from known cell towers and wi-fi access points.

totype to demonstrate it. Spoke and robunculi ecologies attempt to support this development model by packaging the more technologically demanding features in reusable modules. And our organization of roles reflects the reality that modules often span these disciplinary boundaries. (For example the Arduino project packages both electrical and software components, and many of its extension modules include mechanical, electrical and software bits.)

### 2.2.1 Taster

A person adopting this role, for example a person sitting down at a social table, is relatively passive in relation to the artifact in question. Tasters participate in the ecology by providing critical feedback in relevant forums. This could be as simple as having a specialized gesture expressing approval (or disapproval) of a given hyperfig that is then incorporated into rankings on the online hyperfig repository, or as involved as filing a bug report.

While even in a popsicle ecology journalists and bloggers can play this role, the online design repositories of spoke and robunculi ecologies provide an opportunity for tasters' feedback to be used as debugging data and a filter for identifying successful systems.

### 2.2.2 Wrangler

Many devices require substantial input from a person, for example many military sockpuppet drones are operated remotely by a trained pilot at a stickboard. While adopting the roles described below requires some kind of expertise in customizing or building devices, wrangling demands expertise at piloting or otherwise managing devices' behavior in real time.

As wranglers possess a unique perpsective on the behavior of the devices they wrangle, it would be desirable for ecologies to also attract wranglers to serve in design roles. Tinker roles in particular (discussed below) offer an opportunity for wranglers to give design input without a great deal of investment in training.

### 2.2.3 Tinker

Many people are motivated to understand more about the mechanisms underlying the behavior of responsive devices but lack the technical knowledge required to address systems at the same level as their designers. A strategy for engaging this community is to create devices with tink interfaces. An example is a golem robunculi kit with instructions for building a given golem that can then be varied, much like lego kits come with instructions that can serve as a jumping-off point for more creative endeavors. And while such mechanical tinkering is straightforward, tangible interfaces can also be used to allow tinkering with algorithms[9] and electronics[10].

By providing opportunities for people to tinker with their devices robunculi ecologies can help to both engage people in a conversation about their devices, and recruit people to expand their technological capabilites so that they are able to adopt more technologically demanding roles. By providing places for people to expand and apply their skills, a spoke ecology and its associated hackerspaces can help these new recruits find productive technical roles to play.

### 2.2.4 Tek

Here we have reached the realm of the professional designer (and engineer). A tek is a person who comes up with ideas for and builds new devices. While professional designers are traditionally grouped according to their specialized technical discipline, we suggest that such compartmentalization works against a tek's ability to envision and create useful devices.

In particular, within spoke and robunculi ecologies the availability of modules that package complex technologies lower the barrier to assuming the role of a tek. With robunculi kits the distinction between a tinker and a tek is even somewhat blurred, but as we will describe in Chapter 4 the creation of a device with new behaviors (rather than a variation on an existing device) will generally involve more advanced tools alongside the bunkles themselves, requiring tek-level proficiency. We predict that the character of these artifact ecologies with a broad community of people able to assume the role of device designers will contrast sharply with popsicle-dominated ecologies where the character and behavior of devices are largely dictated to the community.

[9]For example Scratch (Resnick, Maloney, Monroy-Hernández, Rusk, Eastmond, Brennan, Millner, Rosenbaum, Silver, Silverman, and Kafai, 2009) has established a model for a visual, fault tolerant tinkering-style programming interface that involves shuffling puzzle-piece chunks of code, although it is screen-based. Tern (Horn and Jacob, 2007) applies similar ideas with a tangible interface composed of literal wooden puzzle pieces. With Cubelets (nee RoBlocks) (Schweikardt and Gross, 2006) a fig specifies both mechanical and algorithmic properties at once.

[10]For example littleBits (Bdeir, 2009) package electronic components to afford tinkering with circuits.

### 2.2.5 Tooler

Much of the growth of the open hardware scene and the spoke ecology comes from people who are thinking not about creating devices, but about the tools that can help teks to create devices. In doing so these people are assuming the role of a tooler. While a tooler may build a literal tool, such as a 3D printer, they also focus on packaging technologies in modules that make them more accessible. This is common practice in software development (even in popsicle ecologies) and is quickly spreading to electronic and mechanical development in spoke and robunculi ecologies. Again, toolers are not generally defined by discipline as many modules package components from several disciplines. In robunculi ecologies toolers design the bunkles (and their control algorithms) that teks and tinkers use to create devices.

### 2.2.6 Wiz

Because of the complexity of the technologies involved in creating responsive artifacts, at some point there is a demand for specialization. We call someone who considers the deep issues of a discipline, either to extend what can be done, or to make its capabilities more accessible, a wiz. In adopting the role of a wiz a person could be developing a new programming language, designing a computer chip, developing a new actuator, or creating a new rapid fabrication technology. While people able to play such a role are generally prized in any artifact ecology, we suggest that expanding the community of teks has the potential to develop a greater number of wizs, thus advancing the capabilities of the entire ecology.

## 2.3 Examples of Artifact Ecologies

### 2.3.1 nodes of power

1. manufacturing
2. data transmission
3. data stores
4. shrines (high-powered computing clusters)
5. leaf node control

## 2.4 Robunculi: an Ontology

1. robunculi typologies
   (a) idols
   (b) tangible sketches
   (c) golems
      i. sock puppet (dumb rc golem)
      ii. avatar (golem serving as interface to idol)
   (d) hyperforms
2. morphologies
   (a) tile
   (b) block
   (c) skeleton (graph)
   (d) panel
   (e) glass (screen / projection interface)
   (f) shrine (idol-scale computing facility)
3. affordances
   (a) parallel affordances are synergistic
   (b) placing / self-reconfiguring
   (c) posing / flexing (self-posing)
   (d) commanding (pointing) / signalling (haloing)
   (e) listening (tagging) / responding (texting)
   (f) graffing (accepting drawings) / gramming (responding with drawings)
   (g) puppeteering / puppeting (present puppeteering interface)
   (h) sinks generate structured data to be accessed through idols
   (i) logging (recording interactions to data stores) (sink)
   (j) crawling (indexing data stores) (sink)
   (k) tracking (id-ing and classifying agents with sensors) (sink)
   (l) slamming (exploring and mapping environments) (sink)

# Chapter 3

# A Survey of Robunculi

# Chapter 4

# Robunculi: Case Studies

# Chapter 5

# Conclusion

## 5.1 Potential (Artifact) Ecological Impacts of Responsive Environments

### 5.1.1 Idols

While we have related to our leveraged environments primarily as tool-users, as our environment becomes responsive this relationship is becoming more of a partnership amongst ourselves and various computational agents. For example in a leveraged environment professionals would often supplement their memory by using a notebook and appointment book, and supplement their expertise with a small private library. In a responsive environment, professionals supplement their memory through a small computer carried on their person (which we will call a *crystal*[1]) that manages notes and appointments through the interaction of a variety of software agents over a network; they supplement their expertise by using this same device to query an idol (i.e. the googlebot). Of course professionals in a leveraged environment also practice division of labor, with secretaries managing appointments and engineers on call to make judgements using their personal libraries to supplement their domain knowledge. The difference is that in a leveraged environment partnerships are between people, and artifacts only effect change when operated by a person. Now when people send us invitations (from their crystals,

[1]We call this class of handheld computers that provide a constant connection to the network 'crystals', as in a crystal ball that is used to view distant places and communicate with other agents through the ether, and as a reference to their current popular physical realization as a fragile glass-plated touchscreen.

over the network) an idol helpfully inserts them into our calendars and then buzzes us through our own crystals at the appropriate time to tell us where to be.

We suggest that the outlook for accepting these idols into our cybernetic consciousness varies from the utopian to the orwellian largeley depending on: how much control we (the citizens of idol-mediated societies) have over the behavior of our devices and idols; and how transparent (to us) the mechanisms governing these behaviors are. But before we can discuss the qualities of these computational artifacts we should discuss what kinds of artifacts we expect to see.

1. radical transparency - big brother and little brother
2. means of production 2 - factories vs 3d printers
3. battle of the heavens - corporate clouds vs govt clouds vs community clouds
4. digital serfdom and device transparency

[TODO: figures showing axes] (transparency - physically secured state/corp rental -¿ drm'd black box -¿ open source hardware) (reconfigurability - mass-manufactured widget -¿ bespoke popsicle -¿ kit of parts -¿ hyperform)

# Appendix A

# Glossary

**afford** a possibility for use we are able to recognize in an object; our recognition of these possibilities structures our perception of the environment (Gibson, 1979)

**affordance** a use afforded by an object (see **afford**)

**direct manipulation** introduced by Shneiderman (1983) to describe on-screen interfaces that allowed the mouse to grab and manipulate things; applied here to describe tangible interfaces that allow your hand to grab and manipulate things

**ensemble** a group of objects that coordinate to produce a global behavior (especially a group of robotic modules)

**ensemble of robotic modules** (see **ensemble**, **robot**)

**golem** an agent capable of performing useful tasks; from the fictional golem, an agent formed out of clay to serve and protect its creator

**homunculus** (plural: **homunculi**) an anthropomorphization of a cognitive process or the soul as a tiny person, often depicted as sitting inside someone's head; from the latin diminutive of man (homo)

**hyperform** a form that varies over time; from 'hyper-' indicating extent into the fourth dimension as in hypercube

**maker** a person versed in the skills necessary to craft objects

**manipulative** an object or kit of objects intended to engage children in discovering a particular concept or group of concepts through play

**manipulative morphology** one of the classes of forms developed to serve as manipulatives (see **morphology**)

**modular robot** a **robot** intended to serve as a member of an **ensemble** of physically coupled modules

**morphology** the structure and configuration of an object

**purpose** the broad use case an **ensemble of robotic modules** is intended to support

**robot** a device capable of sensing, planning and acting

**robunculi** the modules of a **robunculi kit**; from **robot** and **homunculi**; these 'little robots' extend our agency out into the environment by allowing us to impress behaviors upon the objects we construct out of them

**scaffold** (verb) to put a student in a position in which they are able to make discoveries

**sensorimotor** sensory integration for example between the hand and the eye

**tangible interface** a physical interface to digital information

**tangible sketch** a model built from a kit that communicates spatial information to a computational agent

[1]

[2]

[1]Quick Response (QR) codes are a black-and-white printed pattern designed to be interpreted by a device with a digital camera such as a cell phone.

[2]A radio-frequency identification (RFID) tag is a small radio transmitter with no battery. When it passes near to a tag reader it captures power from the radio signal and transmits a unique number.

# Bibliography


Ayah Bdeir. Electronics as material: littlebits. In *Tangible and Embedded Interaction (TEI)*, pages 397–400. ACM, 2009.

Leonardo Bonanni, Jason Alonso, Greg Vargas, Neil Chao, and Hiroshi Ishii. Handsaw: Tangible exploration of volumetric data by direct cut-plane projection. In *Human Factors in Computing (CHI)*, pages 251–254. ACM, 2008.

Leah Buechley and Benjamin Mako Hill. Lilypad in the wild: How hardware's long tail is supporting new engineering and design communities. In *Designing Interactive Systems (DIS)*, pages 199–207, 2010.

Daniel C Dennett. *Freedom Evolves*. Viking, New York, 2003.

James J Gibson. *The Ecological Approach to Visual Perception*. Lawrence Erlbaum Associates, Hillsdale, 1979.

William Gibson. *Idoru*. Viking Press, New York, 1996.

William Gibson. *Distrust That Particular Flavor*. Putnam Adult, New York, 2012.

Seth Copen Goldstein, Jason D Campbell, and Todd C Mowry. Programmable matter. *IEEE Computer*, 38(6):99–101, June 2005.

Michael S Horn and Robert J K Jacob. Tangible programming in the classroom with tern. In *Ext. Abstracts of Human Factors in Computing (CHI)*, pages 1965–1970. ACM, 2007.

Hiroshi Ishii and Brygg Ullmer. Tangible bits: towards seamless interfaces between people, bits and atoms. In *Human Factors in Computing (CHI)*, pages 234–241. ACM, 1997.

Robert J K Jacob, Audrey Girouard, Leanne M Hirshfield, Michael S Horn, Orit Shaer, Erin Treacy Solovey, and Jamie Zigelbaum. Reality-based interaction: a framework for post-wimp interfaces. In *Human Factors in Computing (CHI)*, pages 201–210. ACM, 2008.

David Merrill, Jeevan Kalanithi, and Pattie Maes. Siftables: Towards sensor network user interfaces. In *Tangible and Embedded Interaction (TEI)*, pages 75–78. ACM, 2007.

Marvin Minsky. *The Society of Mind*. Simon and Schuster, New York, 1985.

Claire O'Malley and Danae Stanton Fraser. Literature review in learning with tangible technologies. Report 12, NESTA FutureLab Series, 2004.

James Patten and Hiroshi Ishii. Mechanical constraints as computational constraints in tabletop tangible interfaces. In *Human Factors in Computing (CHI)*, pages 809–818. ACM, 2007.

Marc Raibert, Kevin Blankespoor, Gabriel Nelson, and Rob Playter. Bigdog, the rough-terrain quadruped robot. In *Proc. of the World Congress of the Intl. Fed. of Automatic Control*, pages 1–16, 2008.

Mitchel Resnick, John Maloney, Andrés Monroy-Hernández, Natalie Rusk, Evelyn Eastmond, Karen Brennan, Amon Millner, Eric Rosenbaum, Jay Silver, Brian Silverman, and Yasmin Kafai. Scratch: programming for all. *Commun. ACM*, 52(11):60–67, November 2009.

Eric Schweikardt and Mark D Gross. roBlocks: a robotic construction kit for mathematics and science education. In *Intl Conf on Multimodal Interfaces (ICMI)*, pages 72–75. ACM, 2006.

Ben Shneiderman. Direct manipulation: A step beyond programming languages. *Computer*, 16(8):57–69, 1983.

Hideyuki Suzuki and Hiroshi Kato. Interaction-level support for collaborative learning: Algoblock—an open programming language. In *Computer Support for Collaborative Learning (CSCL)*, pages 349–355. L. Erlbaum Associates, 1995.

Robert Venturi, Denise Scott Brown, and Steven Izenour. *Learning from Las Vegas*. MIT Press, Cambridge, 1972.

Mark Weiser. The computer for the 21st century. *SIGMOBILE Mobile Computing and Communations Review*, 3(3):3–11, 1999.

Mark Yim, Wei-Min Shen, Behnam Salemi, Daniela Rus, Mark Moll, Hod Lipson, Eric Klavins, and Gregory S Chirikjian. Modular self-reconfigurable robot systems. *Robotics and Automation*, 14(1):43–52, 2007.

Jamie Zigelbaum, Alan Browning, Daniel Leithinger, Olivier Bau, and Hiroshi Ishii. g-stalt: a chirocentric, spatiotemporal, and telekinetic gestural interface. In *Tangible and Embedded Interaction (TEI)*, pages 261–264. ACM, 2010.