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Between Bits and Atoms: Physical Computing and Desktop Fabrication in the Humanities

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Humanities scholars now live in a moment where it is rapidly becoming possible – as Hod Lipson and Melba Kurman suggest – for "regular people [to] rip, mix, and burn physical objects as effortlessly as they edit a digital photograph" (Lipson and Kurman, 2013:10). Lipson and Kurman describe this phenomenon in *Fabricated*, explaining how archaeologists are able to CT scan[1] cuneiforms in the field, create 3D models of them, and then send the data to a 3D printer back home, where replicas are made.

> [I]n the process [they] discovered an unexpected bonus in this cuneiform fax experiment: the CT scan captured written characters on both the inside and outside of the cuneiform. Researchers have known for centuries that many cuneiform bear written messages in their hollow insides. However until now, the only way to see the inner message has been to shatter (hence destroy) the cuneiform. One of the benefits of CT scanning and 3D printing a replica of a cuneiform is that you can cheerfully smash the printed replica to pieces to read what's written on the inside. (Lipson and Kurman, 2013:19–20)

Manifesting what Neil Gershenfeld calls "the programmability of the digital worlds we've invented" applied "to the physical world we inhabit" (Gershenfeld, 2005:17), these new kinds of objects move easily, back and forth, in the space between bits and atoms. But this full circuit through analog and digital processes is not all. Thanks to the development of embedded electronics, artifacts that are fabricated using desktop machines can also sense and respond to their environments, go online, communicate with other objects, log data, and interact with people (O'Sullivan and Igoe, 2004; Sterling, 2005; Igoe, 2011). Following Richard Sennett's dictum that "making is thinking" (Sennett, 2008:ix), we note that these "thinking," "sensing," and "talking" things offer us new ways to understand ourselves and our assumptions, as do the processes through which we make them.

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The practice of making things think, sense, and talk articulates in interesting yet murky ways with our various disciplinary pasts. For example, historians have written about the classical split between people who work with their minds and people who work with their hands, including the longstanding denigration of the latter (Long, 2004).[2] In the humanities, we have inherited the value-laden dichotomy of mind and hand, along with subsequent distinctions between hand-made and machine-made objects; between custom, craft, or bespoke production and mass production; between people who make things and people who operate the machines that make things. As we navigate our current situation, we find that a lot of these categories and values need to be significantly rethought, especially if, following Donna Haraway (1991), Sandy Stone (1996), and Katherine Hayles (1999), we resist the notion that cultural and technological processes, or human and machine thinking, can be neatly parsed. We also find that the very acts of making need to be reconfigured in light of new media, the programmability, modularity, variability, and automation of which have at once expanded production and framed it largely through computer screens and WYSIWYG interfaces (Manovich, 2001; Montfort, 2004; Kirschenbaum, 2008a).[3]

With this context in mind, physical computing and desktop fabrication techniques underscore not only the convergence of analog and digital processes but also the importance of transduction, haptics, prototyping, and surprise when conducting research with new media. Rather than acting as some nostalgic yearning for an authentic, purely analog life prior to personal computing, cyberspace, social networking, or the cloud, making things between bits and atoms thus becomes a practice deeply enmeshed in emerging technologies that intricately blend human- and machine-based manufacturing.[4] For the humanities, such making is important precisely because it encourages creative speculation and critical conjecture, which – instead of attempting to perfectly preserve or re-present culture in digital form – entail the production of fuzzy scenarios, counterfactual histories, possible worlds, and other such fabrications. Indeed, the space between bits and atoms is very much the space of "what if …"

Learning from Lego

One popular approach to introducing hands-on making in the humanities is to start with construction toys like Lego. Their suitability for learning is emphasized by Sherry Turkle, who made a study of the childhood objects that inspired people to become scientists, engineers, or designers: "Over the years, so many students have chosen [Lego bricks] as the key object on their path to science that I am able to take them as a constant to demonstrate the wide range of thinking and learning styles that constitute a scientific mindset" (Turkle, 2008:7–8). Besides being an easy and clean way to do small-scale, mechanical prototyping, Lego teaches people many useful lessons. One is what Stuart Kauffman calls the "adjacent possible," an idea recently popularized by Steven Johnson in *Where Good Ideas Come From*: "The adjacent possible is a kind of shadow future," Johnson writes, "hovering on the edges of the present state of things, a map of all the ways in which the present can reinvent itself" (Johnson, 2010:26). As new things are created, new processes are developed, existing things are recombined into new forms, and still further changes – lurking like specters alongside the present – become possible. Johnson (2010:26) uses the metaphor of a house where rooms are magically created as you open doors. Central to this metaphor is the argument that chance, not individual genius or intent, is a primary component of making and assembly. When things as well as people are physically proximate, the odds of surprise and creativity should increase. Put this way, the adjacent possible corresponds (at least in part) with a long legacy of experimental arts and humanities practices, including Stéphane Mallarmé's concrete poetry, the Surrealists' exquisite corpse, Brion Gysin's cut-ups, OuLiPo's story-making machines, Kool Herc's merry-go-round, Nicolas Bourriaud's relational aesthetics, and Critical Art Ensemble's tactical media and situational performances. Across this admittedly eclectic array of examples, the possibilities emerging from procedure, juxtaposition, conjecture, or encounter are privileged over the anticipation of continuity, certainty, concrete outcomes, or specific effects.

In the case of Lego, the original bricks had studs on the top and holes on the bottom. They stacked to form straight walls, but it was difficult to make things that were not blocky. When Lego introduced the Technic line for building more complicated mechanisms, they created a new brick that had horizontal holes in it. The Technic brick still had studs on top and holes on the bottom, so it could be stacked with regular Lego bricks as well as Technic bricks. But the horizontal holes created new possibilities: axles holding wheels or gears could be passed through them, and bricks could now be joined horizontally with pegs. In newer Technic sets, the Technic brick has been more or less abandoned in favor of the Technic beam. This piece still has the horizontal holes, but is smooth on top and bottom, and thus cannot be easily stacked with traditional Lego bricks. With each move into the adjacent possible, whole new styles of Lego construction have flourished while older styles have withered, even if the history of the Technic beam cannot be unhinged from Lego's original bricks. Consequently, attending to Legos as processes – rather than as objects conveniently frozen in time and space – affords a material understanding of how *this* becomes *that* across settings and iterations. It also implies that a given object could have always been (or could always become) something else, depending on the context, conditions, and participants involved.

It is easy to study how people make things with Lego – both fans of the toy and the company's designers – because many of them do what Chris Anderson (2012:13) calls "making in public." Plans for every kit that Lego ever released are online, along with inventories of every part in those kits. You can start with a particular widget and see every assembly in which it was used. People share plans for their own projects. Want a robotic spider? A Turing machine? A computer-controlled plotter? A replica of an ancient Greek analog computer? They are all there waiting to be assembled. A number of free, computer-aided design (CAD) packages make it easy for children and adults to draft plans that they can share with one another. There is a marketplace for new and used Lego bricks. For example, the BrickLink site lists 180 million pieces for sale around the world. If you need a particular part (or a thousand of them in a particular color), then you can find the closest or cheapest ones. Of course, what is true for construction toys like Lego is also true for the modular systems that make up most of the built world, especially when – returning to Gershenfeld (2005) for a moment – digital programmability is applied to analog artifacts. People who start designing with Lego can then apply the knowledge they gain to electronic components, mechanical parts, computer software, and other technical systems.[5] Each of these domains is based on interoperable and interchangeable parts with well-specified interfaces and has associated CAD or development software, open source proponents, and online repositories of past designs.

At the edges of Lego design, people can experiment with the "small batch production" afforded by 3D printing (Anderson, 2012:78). For example, when working with standard Lego bricks, it is difficult to make an object with threefold symmetry. But on Thingiverse (a website for sharing plans for desktop fabricated objects), it is possible to find triangular and three-sided bricks and plates (e.g., at http://www.thingiverse.com/thing:38207 or http://www.thingiverse.com/thing:13531). As Anderson notes, with desktop fabrication:

> [T]he things that are expensive in traditional manufacturing become free: 1. Variety is free: It costs no more to make every product different than to make them all the same. 2. Complexity is free: A minutely detailed product, with many fiddly little components, can be 3-D printed as cheaply as a plain block of plastic. The computer doesn't care how many calculations it has to do. 3. Flexibility is free: Changing a product after production has started just means changing the instruction code. The machines stay the same. (Anderson, 2012:86)

Of course, as we argue later in this chapter, practitioners must also consider how physical computing and desktop fabrication technologies intersect with administrative and communicative agendas, including labor issues. After all, Anderson ignores how "free" variety, complexity, and flexibility are culturally embedded and historically affiliated with planned obsolescence: the obsolescence of certain occupations and technologies in manufacturing, for instance.[6] His interpretations of physical computing and fabrication technologies are also quite determinist (i.e., technology changes society), not to mention instrumentalist (i.e., technology is a value-neutral mechanism for turning input into output), without much attention to the recursive relationships between cultural practices and modular manufacturing.[7]

That said, Anderson's point about rendering traditional manufacturing accessible (at least in terms of materials and expertise) should still be taken seriously. For example, in the case of physical computing, Lego objects can be augmented with electronic sensors, microcontrollers, and actuators, allowing people with little to no knowledge of electronics to build circuits and program objects. Comparable to the do-it-yourself Heathkits of yore (Haring, 2007), the company's Mindstorms kits offer an official (and easy-to-use) path for these kinds of activities, providing an embedded computer, servo motors, and sensors for color, touch, and infrared. Kits like these also spark opportunities for humanities practitioners to think through the very media they study, rather than approaching them solely as either concepts or discursive constructs.[8] By extension, this ease of construction is quite conducive to speculative thought, to quickly building prototypes that foster discussion, experimentation, and use around a particular topic or problem. Such thinking through building, or conjecturing through prototyping, is fundamental to making things in the humanities. Borrowing for a moment from Tara McPherson in *Debates in the Digital Humanities*: "scholars must engage the vernacular digital forms that make us nervous, *authoring* in them in order to better understand them and to recreate in technological spaces the possibility of doing the work that moves us" (McPherson, 2012:154). Similarly, through small batch experimentation, we should engage physical computing and fabrication technologies precisely when they make us nervous – because we want to examine their particulars and, where necessary, change them, the practices they enable, and the cultures congealing around them. An important question, then, is what exactly *is* the stuff of physical computing and desktop fabrication.

What is Physical Computing?

According to Dan O'Sullivan and Tom Igoe, "[p]hysical computing is about creating a conversation between the physical world and the virtual world of the computer. The process of *transduction*, or the conversion of one form of energy into another, is what enables this flow" (O'Sullivan and Igoe, 2004:xix). Advances in the variety of computing technologies over the past ten years have created opportunities for people to incorporate different types of computing into their work. While personal computers are the most common computational devices used by humanities scholars for research, the proliferation of mobile computers has introduced some variability of available consumer computing platforms. That significant decrease in the physical size of computing devices is indicative of a more general shift toward smaller and distributed forms of computer design. In addition to the proliferation of mobile computers such as smartphones and tablets, there are various microcontrollers that can be embedded in artifacts. Microcontrollers are versatile computers that let signals enter a device (input), allow signals to be sent from a device (output), and have memory on which to store programming instructions for what to do with that input and output (processing) (O'Sullivan and Igoe, 2004:xx). Although microcontroller chips have been commercially available and relatively inexpensive since the 1970s, they have remained cumbersome to program. However, integrated boards that contain chips, as well as circuitry to control and regulate power, have been recently developed. Most of these boards have an integrated development environment (IDE) – software through which you write, compile, and transfer programming to the microcontroller chip – that is free to use and makes the processes of programming (in particular) and physical computing (in general) easier to accomplish.

The simplest microcontroller inputs are components such as push-button switches, but many more complex components can be used: dials or knobs, temperature or humidity sensors, proximity detectors, photocells, magnetic or capacitive sensors, and global positioning system (GPS) modules. Simple outputs include light-emitting diodes (LEDs) that indicate activity or system behaviors, and more complex outputs include speakers, motors, and liquid crystal displays. The inputs and outputs are chosen based on the desired interaction for a given physical computing project, underscoring the fact that – when designing interactions between analog and digital environments, in the space between bits and atoms – the appeal of microcontrollers is that they are small, versatile, and capable of performing dedicated tasks sensitive to the particulars of time and space. For most practitioners, they are also low-cost, and physical computing parts (including microcontrollers, sensors, and actuators) are highly conducive to reuse. Put this way, they encourage people to think critically about access, waste, obsolescence, repair, and repurposing – about “what Jonathan Sterne (2007) calls ‘convivial computing.’”

Arduino has arguably become the most popular microcontroller-based platform. It began as an open-source project for artists, who wanted to lower the barrier to programming interactive artifacts and installations. Introduced in 2005, it has since gone through a number of iterations in both design and function, and various builds – all of which work with a common IDE – are available. Typically, an Arduino board is about the size of a deck of playing cards, and it has onboard memory comparable to a 1980s-era computer (meaning its overall computational processing power and memory are limited). There are easily accessible ports on the device that one can define, through software, as either inputs or outputs. There are digital and analog ports on the device, so it can negotiate both types of signals. There are also ports necessary for powering other components, as well as ports that can be used to send serial communications back and forth between devices. Arduino can be powered by batteries or plugged into an electrical outlet via common AC-DC transformers. Couple this independent power source with the onboard memory, and Arduino-driven builds can stand alone, untethered from a personal computer and integrated into infrastructure, clothing, or a specific object. Additionally, the open-source nature of Arduino has sparked the development of custom peripherals, known as shields. These modules are designed to plug, Lego-like, directly into the ports of an Arduino. They are compact and often designed for a specific function: to play audio, control motors, communicate with the Internet, recognize faces, or display information via a screen. Resonating with the original purpose of Arduino, shields lower the barrier to making interactive artifacts, letting practitioners focus on ideas and experimentation while prototyping.

To be sure, the introduction of Arduino has lowered the costs of creating custom devices that think, sense, or talk, but such reductions have extended across computing more generally. Microprocessors capable of much more computational speed and memory are available at prices comparable to Arduino and can be set up with free, Linux-based operating systems for more computationally intensive projects. The Raspberry Pi and Beagle Bone are two such computer boards that occupy the space between an Arduino-level microcontroller and a personal computer. They work as small, standalone computers, but have accessible input/output ports for custom devices and interaction. As small computers, they can also connect to the Internet, and – like Arduino – they can be used to build interactive exhibits (Turkel, 2011a), facilitate hands-on approaches to media history (Sayers *et al.*, 2013), construct electronic textiles (Buechley and Eisenberg, 2008), control autonomous vehicles, and support introductory programming courses (Ohya, 2013).

What is Desktop Fabrication?

In the spirit of speculation and conjecture, humanities practitioners can also prototype designs and fabricate objects using machine tools controlled by personal computers. These tools further blur distinctions between analog and digital materials, as physical forms are developed and edited in virtual environments expressed on computer screens.

Such design and fabrication processes are accomplished largely because hardware and software advances have lowered manufacturing costs, including costs associated with time, expertise, infrastructure, and supplies. In order to produce an object via desktop fabrication, several digital and analog components are required: a digital model (in, say, STL or OBJ format), the machine (e.g., a 3D printer or laser cutter) to manufacture it, the material (e.g., wood, plastic, or metal) in which to fabricate it, and the software (e.g., Blender, MeshLab, or ReplicatorG) to translate between analog and digital. Given the translations across these components, advances in desktop fabrication have unsurprisingly accompanied the development and proliferation of low-cost, microcontroller-based hardware (including Arduino) that transduces analog into digital and vice versa. These microcontrollers tighten the circuit of manufacturing and digital/analog convergence.

At the heart of desktop fabrication are precise, computer-controlled devices. Generally referred to as CNC (computer numeric control), these machines bridge the gap between CAD (computer-aided design) and CAM (computer-aided manufacture). They allow a digital design to be fabricated rapidly. Such a digital approach is scalable. It works on massive, industrial scales; but as smaller fabrication tools become available, it can be used on smaller scales, too. Tabletop CNC milling machines and lathes are also available for small-scale production; however, the rise of accessible 3D printing is currently driving desktop fabrication practices, hobbyist markets, and interest from non-profit and university sectors (especially libraries). 3D printing is an additive manufacturing process whereby a digital model is realized in physical form (usually PLA or ABS thermoplastic). Most consumer-level 3D printers are CNC devices with extruders, which draw plastic filament, heat it to its melting point, and output it in precisely positioned, thin beads onto a print bed. Software slices an object model into layers of uniform thickness and then generates machine-readable code (usually in the G-code programming language) that directs the motors in the printer, the temperature of the extruder, and the feed rate of the plastic. Gradually, the digital model on the screen becomes an analog object that can be held in one's hand.

A variety of 3D printer models are currently available, and the technology continues to be developed. Initiated by the RepRap project and popularized by MakerBot Industries (a commercial innovator), early desktop 3D printers incorporated microcontroller boards into their systems. Makerbot started by offering kits to assemble 3D printers, but also created Thingiverse, a site where people either upload their 3D models or download models created by others. Thingiverse is one of the few places online to acquire and openly share 3D models, and making digital 3D models has also become easier with software aimed at consumers and hobbyists. For instance, Autodesk has partnered with Makerbot and now offers a suite of tools for 3D development. Free software, such as Blender and OpenSCAD, provide other options for creating models, and Trimble's SketchUp is an accessible software package popular with designers, architects, artists, and historians. That said, not all models are born digital. 3D scanners, depth cameras, and photogrammetry can be used to quickly create models of physical objects. One of Autodesk's applications, 123D Catch, works well as an introduction to photogrammetry, and other open-source – but more complex – options exist (e.g., the Python Photogrammetry Toolbox and VisualSFM). Depth cameras, such as Microsoft's Kinect, can also be used to create 3D models, and tool chains for transducing analog objects into digital formats continue to be developed and refined. Across the humanities, these fabrication techniques are supporting research in museum studies (Waibel, 2013), design fiction (Sterling, 2009), science and technology studies (Lipson *et al*., 2004), geospatial expression (Tanigawa, 2013), and data visualization (Staley, 2013). Their appeal cannot be attributed solely to the physical objects they output; they also afford the preservation, discovery, and circulation of replicated historical artifacts; the communication of data beyond the X and Y axes; the rapid prototyping of ideas and designs; and precision modeling that cannot be achieved by hand.

For instance, consider Cornell University's Kinematic Models for Design Digital Library (KMODDL), which is a persuasive example of how 3D modeling and desktop fabrication can be used for teaching, learning, and preserving history. KMODDL is a web-based collection of mechanical models of machine elements from the nineteenth century. Among other things, it gives people a tangible sense of how popular industry initiatives such as Thingiverse can be translated into scholarly projects. Each model is augmented by rich metadata and can be downloaded, edited (where necessary), and manufactured in situ. The models can be used in the classroom to facilitate experiential learning about the histories of technology and media. They can prompt students, instructors, and researchers to reconstruct the stuff of those histories, with an emphasis on what haptics, assembly, and speculation can teach us about the role old media and mechanisms play in the production of material culture (Elliott *et al*., 2012). Pushing humanities research beyond only reading and writing about technologies, this hands-on approach to historical materials not only creates spaces for science and technology studies in digital humanities research; it also broadens our understanding of what can and should be digitized, to include "obsolete" or antique machines – such as those housed by our museums of science and technology – alongside literature, art, maps, film, audio, and the like.

Returning for a moment to this chapter's introduction, Lipson and Kurman (2013) show how this digitization results in more than facsimiles. It intervenes in the epistemological and phenomenological dimensions of research, affording practitioners new perspectives on history and even yielding a few surprises, such as learning what is written inside cuneiform. These perspectives and surprises are anchored in a resistance to treating media as distant and contained objects of scholarly inquiry (McPherson, 2009). And they are useful to researchers because they foster a material awareness of the mechanical processes often invisibly at work in culture.

With these particulars of physical computing and desktop fabrication in mind, we want to elaborate on their relevance and application in the humanities. Here, key questions include: how do we integrate physical computing and desktop fabrication into a longer history of criticism? How do we understand hands-on experimentation and its impulses in the humanities? What are some models that emerged prior to our current moment? Additionally, how do we communicate the function of making – of working with artifacts in the space between atoms and bits – in academic contexts? Where does it happen? How (if at all) does it enable institutional change, and in what relation to established frameworks? We answer these questions by unpacking three overlapping lines of inquiry: the design, administrative, and communicative agendas of physical computing and desktop fabrication.

Design Agenda: Design-in-Use

One particularly rich source of physical experiments in the humanities has traditionally been analytical bibliography, the study of books as material artifacts. For instance, Joseph Viscomi's *Blake and the Idea of the Book* (1993) brilliantly reverse-engineers the nineteenth-century British artist's illuminated books through hands-on experimentation involving the tools, materials, and chemicals Blake routinely used in his printmaking shop. Similarly, Peter Stallybrass and collaborators (2004) explored Renaissance writing technologies by recreating the specially treated, erasable paper bound into so-called "tables" or "table-books," which figure prominently as a metaphor for memory in Shakespeare's *Hamlet*. Perhaps more than any other literary subdomain, physical bibliography is a hands-on discipline involving specialized instruments (collators, magnifying glasses, and raking lights); instructional materials (facsimile chain-line paper and format sheets); and analytic techniques (examination and description of format, collation, typography, paper, binding, and illustrations). Book history courses frequently include not only lab exercises, but also studio exposure to bookbinding, printing, and papermaking. To study the book as a material object, then, is to make extensive use of the hands.

Closely associated with physical bibliography is the art of literary forgery. Derived from Latin *fabricare* ("to frame, construct, build") and *fabrica* ("workshop"), "forge" is etymologically related to "fabricate." While both terms denote making, constructing, and manufacturing, they also carry the additional meaning of duplication with the intent to deceive. In *Forgers and Critics: Creativity and Duplicity in Western Scholarship*, Anthony Grafton (1990:126) argues that the humanities have been "deeply indebted to forgery for its methods." These methods are forensic: they include the chemical and microscopic analysis of paper, ink, and typefaces. But they are also embodied: they are dependent on the tacit and performed knowledge of experts. For example, Viscomi's extensive training in material culture eventually led to his identification of two Blake forgeries. The plates in question were lithographs with fake embossments: "the images easily fooled the eye," he has remarked, "but not the hand" (Viscomi, in Kraus, 2003:2).

Historically, the figure of the bibliographer has often been implicated in forgery, either as a perpetrator or as an unmasker, and sometimes as both. Thomas J. Wise, the most notorious literary forger of the past two centuries, is a case in point. An avid book collector and bibliographer, Wise discovered and documented many previously undetected fakes and was himself ultimately exposed as an inveterate producer of them. He specialized in what John Carter and Graham Pollard (1934) called "creative" forgeries: pamphlet printings by renowned nineteenth-century poets that allegedly pre-date the earliest known imprints of the works. These printings are not facsimiles of extant copies; they are invented first editions made up entirely out of whole cloth. In Alan Thomas's words, they are "books which ought to have existed, but didn't" (Thomas; quoted in Drew, 2011). Part fabulist, part fabricator, part scholar, Wise left behind a legacy of over 100 bogus literary documents that exemplify the strange blend of fact and fiction at the heart of forgery.

As varied as they are, many of the undertakings described here share the common goal of using historically accurate tools, models, and materials to reconstruct history, while acknowledging what Jonathan Sterne claims in *The Audible Past*: "History is nothing but exteriorities. We make our past out of the artifacts, documents, memories, and other traces left behind" (Sterne, 2003:19). Indeed, we cannot live, see, hear, or experience the world like they did back then; we only have the physical stuff of history at our disposal (Turkel, 2011b). Nevertheless, the significance of these undertakings has less to do with their evidentiary value than with the exploratory mindset they promote – a mindset that is alive to meanings emanating (directly or not) from the materials themselves. The haptic experience of following a nineteenth-century recipe for acid-resistant ink can cognitively function as a kind of solvent that breaks up preconceptions and dissolves entrenched perspectives and ideas, without assuming that hands-on experiences are somehow immediate, romantic, or any more authentic than other modes of analysis.

Nearly every discipline has developed one or more methodologies designed to help us do this work: to unlearn what we think we know, to denaturalize perception and epistemology, to yield genuine surprise in our research. In sociology, the method is known as *infrastructural inversion*; in literary studies, *ostranenie* or *defamiliarization*; in critical theory, *symptomatics* or *deconstruction*; in human–computer interaction, *reflective design*. By drawing on elements of these techniques, making in the humanities is able to fulfill its promise as a tool for not only prototyping the past, but also envisioning a future. As the Provost of the Rhode Island School of Design, Roseanne Somerson, puts it, making can "manifest what has not existed previously – in many cases what has never even been imagined" (Somerson, 2013:28). In many ways, Somerson's remark resonates with Johnson's take on the adjacent possible. Unlearning does not end with identifying gaps or problematizing working assumptions; it responds affirmatively, with an alternative model or practice that can be enacted, tested, and examined by others.

Often the products of haptic inquiry are overlooked in the humanities because they fall below the waterline of published scholarship. Part of what Dan Cohen (2008) calls "the hidden archive," they assume tangible yet ephemeral, undocumented, and seemingly unremarkable forms that co-mingle with the notes, sketches, fragments, low-fidelity prototypes, and drafts from which a "final" scholarly work emerges. This type of making is pervasive; however, it requires a categorical shift in thinking. A good historical example is the compilation of the *Oxford English Dictionary* (OED) in the nineteenth century. Seventy years in the making, the dictionary eventually ran to 12 volumes when it was finally published in 1928. The lifeblood of the dictionary – the thing that set it apart from its predecessors – was the tissue of quotations, nearly two million in number, used to illustrate the history of every word (Brewer, 2008). The dictionary's indefatigable editor, the Scottish philologist James Murray, crowdsourced the massive project of collecting these quotations by calling on the public to supply examples they encountered in books and newspapers. The process of classifying, arranging, and making sense of the thousands of slips of paper on which the quotations were recorded is memorably described by Murray in his 1884 presidential address to the Philological Society:

> Only those who have made the experiment, know the bewilderment with which editor or sub-editor, after he has apportioned the quotations … and furnished them with a provisional definition, spreads them out on a table or on the floor where he can obtain a general survey of the whole … shifting them about like pieces on a chess-board, striving

> to find in the fragmentary evidence of an incomplete historical record, such a sequence of meanings as may form a logical chain of development. (Murray, 1884:510–11)

Color-coded, stored in sacks and boxes, parceled out to cubby holes, and sometimes pasted into volumes (Brewer, 2008), the scraps of paper were like pieces of a jigsaw puzzle or the raw elements of a collage that are physically assembled into a larger artistic whole.

As an extended case study, the making of the OED illustrates what Ron Wakkary and Leah Maestri call *design-in-use*, a type of everyday design in which artifacts are seen as "resources for further [creative] action" (Wakkary and Maestri, 2007:163). Quotidian examples include using the back of a chair as a coat rack, or temporarily repurposing the cushion of a sofa as a table for a coffee cup. Design-in-use is characterized by use patterns that stress the affordances of objects, thus allowing them to be modified to perform new, different, or unintended functions. Although Murray eventually imposed order on the OED quotation slips by filing them into pigeonholes, they were originally stored in a variety of makeshift containers, including hampers and baby bassinets, and inscribed on a range of surfaces, such as the backs of envelopes (Murray, 2001:174). Design and use thus thoroughly converged on one another in Murray's nineteenth-century scriptorium, making them virtually indistinguishable. The porous boundary between them is a ubiquitous feature of humanities scholarship, as well as emblematic of design-in-use more generally. For instance, when we copiously annotate the margins of our novels and anthologies, we are taking advantage of the fact that – as Matthew Kirschenbaum suggests in "Bookscapes" – the pages of books are writeable as well as readable surfaces, a key affordance of the contemporary codex (Kirschenbaum, 2008b). In short, we are redesigning our books in the process of using them. Wakkary and Maestri point out that design-in-use has important implications for technology and interaction designers. They recommend designing tools, technologies, services, and artifacts that materially and structurally invite re-engineering and appropriation. One lesson for the humanities, then, might be to approach speculative prototyping, physical computing, and desktop fabrication with design-in-use in mind, creating objects, resources, and projects that beckon people to creatively refashion them.

Design-in-use has also flourished in what are often collectively called the GLAM (Galleries, Libraries, Archives, and Museums) professions. At first blush such an assertion might appear counterintuitive, notwithstanding the ready example of interactive museum exhibits. After all, the purpose of archives and museums is to preserve and sustain our cultural heritage, not make or design it. Moreover, GLAMs are also industries in which the hand has historically been viewed with suspicion: it is understood as an instrument that breaks things as well as repairs them; deposits dirt and grime as well as removes it; accelerates an object's physical degradation as well as reverses it. At its most destructive, it loots and plunders culture rather than restoring and repatriating it. Indeed, it is precisely to protect them from the hands and other environmental stresses that museums enshrine artifacts in glass cases.

By the same token, nearly every successful preservation strategy, with the exception of basic environmental controls, involves some form of active intervention. In the conservation world, for example, collections care can run the gamut, from cleaning a corroded metal artifact or wiping the fingerprints from a statue to boldly reconstructing the missing parts of a painting or adding new architectural elements to a building. Consequently, the tolerance for change in historical antiquities will vary according to time and place. At one end of the spectrum is the view that restoration is the wrecking ball of history, resulting in – to quote William Morris (1877) – "a feeble and lifeless forgery." At the other end is a celebration of restoration as a "means to reestablish [an object] to a finished state, which may in fact never have actually existed at any given time" (Viollet-le-Duc, 1854; quoted in Viñas, 2004:4). Untethered from any obligation to historical fact, the latter view gives license to what has been called "radical subjectivism," a form of creative restoration that sanctions any alteration whatsoever, no matter how seemingly arbitrary or capricious (Viñas, 2004:147–50). The conservator, then, with her paints, varnishes, stabilizers, and glues, is making history, attempting to mediate between the two extreme poles of the restoration continuum. The established principle of discernibility can help: it dictates that any intervention must be visually distinct from the original and yet, paradoxically, harmoniously integrated with it. In practice this may be accomplished through a variety of means, including the application of thin, striated brush strokes known as *tratteggio*, or even by creating a recessed zone on the canvas that can function as a safe harbor for experimenting with more audacious conjectures (Grenda, 2010).

Recently, Amit Zoran and Leah Buechley (2013) have explored restoration practices within the context of desktop fabrication, using the traversal of content from the offline world to the online and back again as a framework for thinking through the principle of discernibility. Beginning with a broken ceramic bowl, they glued several fragments back together, scanned the resulting incomplete reconstruction, virtually restored the remaining parts, and finally 3D-printed a new lattice-like structure designed to hold some of the physical pieces together, while leaving gaps elsewhere that acknowledge the history of breakage and repair. The project is of interest not only for its hybridity (in which digital and analog components engender each other in a causal loop), but also for the way it offloads some (but not all) of the conjectural work of restoration onto CAD software algorithms. They write:

> In the restored bowl, the contrasts between new parts and old are emphasized by different surfaces, forms, textures and colors. The 3D-printed surface is smooth and white, while the original bowl's surface is rough and earthy in color. The new bowl respects both the qualities of the handcrafted object and those of the digitally fabricated restoration. (Zoran and Buechley, 2013:8)

In this instance, as with others involving the principle of discernibility, the different stages in the life cycle of an object are kept purposefully discrete. Each temporal plane is perceptually cordoned off from the others to prevent confusion, even as the digital and analog converge. More important, the original bowl becomes an artifact prompting further action, and – as one example among many – it enacts one of the more persuasive functions of physical computing and desktop fabrication in the humanities: to unlearn working assumptions about material culture and perception by speculating about what else a given object (as a process frozen in time) could be or might have been.

Administrative and Communicative Agendas: Makerspaces

Physical computing and desktop fabrication often flourish in a shared, collaborative space anchored in the use and reuse of shared materials. Typically referred to as makerspaces (as well as hackerspaces, maker labs, and fab labs), such spaces take design principles for collaboration seriously, not only because the frameworks for in-situ collaboration matter, but also because – as Anne Balsamo argues – the critical and creative practices at work in maker cultures are intricately tied to "the production of physical objects (i.e., through the acts of tinkering with various materials)" (Balsamo, 2009). Due to this emphasis on material production, the collaborative research conducted in makerspaces is deeply aware of the infrastructure, resources, and social conditions conducive to making. One of the key premises of makerspaces is that their infrastructure should be flexible, modular, and economical. When compared with research laboratories across many science and engineering disciplines, it should also be low-cost (e.g., between $10,000 and $100,000) and facilitate the repurposing of "obsolete" technologies, the demanufacturing of "dead" media, and the reuse of materials at hand. In fact, many makerspaces and allied organizations (e.g., Free Geek) have areas dedicated to reusable parts, supplies, and electronic waste. This messiness actually says a tremendous amount about a space's culture and research. Echoing John Law, "[i]t looks behind the official accounts of method (which are often clean and reassuring) to try to understand the often ragged ways in which knowledge is produced in research" (Law, 2004:18–19). In makerspaces, messiness also corresponds with a cultural investment in process and transduction, or the idea that how *this* becomes *that* is (even if untidy and complicated) fundamental to knowledge production. Thus, wherever possible, messiness, process, and transduction should not be masked, rendered opaque, or excised from the output of collaborative initiatives. As types of mediation, they are – to echo the recent work of Alexander Galloway, Eugene Thacker, and McKenzie Wark (2013) – basic conditions of mediation that we should take seriously in our research.[9]

By extension, the ethos and everyday of makerspaces are imbricated with questions of labor, including the labor of an increasingly casualized academic workforce. Bethany Nowviskie suggests a connection between stable employment and both the time and level of institutional connection required to engage intellectually as well as practically with the messiness of knowledge production:

> If the vast majority of our teaching faculty become contingent, what vanishing minority of those will ever transition from being passive digital tool-users to active humanities makers? Who among them will find time to feel a productive resistance in her materials? Casualized labor begets commodity toolsets, frictionless and uncritical engagement with [pre-packaged] content, and shallow practices of use. (Nowviskie, 2013)

Nowviskie's investment in active making here intersects with the argument that, through makerspaces, people can access, use, construct, and experiment with the "middle states"[10] of technological development instead of becoming recipients (or consumers) of neatly bundled, auto-magical gadgets. Through attention to this middle state – to the gradual transformation of one material into another – physical computing and fabrication in makerspaces also afford opportunities to ask who is building technologies, for whom, under what conditions and assumptions, and to what effects on social relations. In fact, many groups, including Double Union in San Francisco, Liberating Ourselves Locally in Oakland, and Dames Who Game in Toronto, are articulating social justice issues (including the representation of women and people of color in technical communities typically built on white male privilege) with making and makerspaces.[11] Similarly, Nina Belojevic (2014) argues that – as an applied approach to media studies – "circuit bending" is a compelling way to better understand the exploitation and spectral labor of videogame industries. Importantly, her work, and other work like it (Hertz, 2009), is conducted in a makerspace.

While online modes of social organization no doubt lend themselves to social justice research, the cultural climates of makerspaces and their dedication to place-based organizing, trial-and-error investigation, haptic engagement, and learning alongside others foster an inimitable kind of embodied community building, which does not always manifest through the avatar or the social network. However, in the context of the academy, a pressing challenge is feeding the work of makerspaces back into existing infrastructures and policies in order to prompt institutional change. Otherwise, makerspaces risk being perceived as "experimental" domains peripheral to "serious" research. Worse, if care is not taken to apply lessons learned in makerspaces to the remaking of their surrounding institutions, they will not realize their full administrative and communicative potential. They will fail to contribute positively to advanced thinking and policy development around critical issues such as privacy, surveillance, intellectual property, consumerism in education, data exploitation, and sustainability and the environment. As sites where humanities practitioners can engage thoughtfully with embodiment in all of its forms, makerspaces may also foster productive thinking on issues of representation, contingency, privilege, and other structural problems in academic labor. Finally, spaces for fabrication and physical computing can foreground the role of technology and design in fashioning new audiences for academic research. As digital humanities performance moves off the screen and into mobile computing, wearable technology, and augmented reality, the value of the humanities (and therefore of the institutions that host and foster humanities research) may be articulated to new publics in new ways.

In this area, Fashioning Circuits – directed by Kimberly Knight at the University of Texas, Dallas – is an inspiring example project. It expands digital humanities, with an emphasis on fashion, performance, and the manufacture of wearable technologies. Instead of digitizing historical artifacts, it prompts people, including beginners, to make their own. For Knight and her team, physical computing renders programming and electronics approachable to non-experts. When making things, participants can conjecture about alternate histories and possible futures (e.g., how political organizing could change alongside networked wearables). In this sense, Fashioning Circuits encourages scholars to prototype new technologies and designs, through which problems – not just content or processes – are modeled (Siemens and Sayers, 2015). Crucially, it also stresses the ways in which physical computing and fabrication emerged in part from a complex intersection of textiles, handicraft, class, and gendered labor that is frequently overlooked by popular histories of science and engineering (Plant, 1997). Its blend of historical and futurist frameworks draws attention to the cultural embeddedness of computing while inviting active participation in the nervousness of it all (McPherson, 2012). Given that the social, cultural, political, and ethical implications of wearables are starting to unfold, Fashioning Circuits thus becomes a kind of public humanities project, too. Similar to initiatives such as High-Low Tech, Local Autonomy Networks (Autonets), Machine Project, and the GO::DH Minimal Computing Working Group, it engages pressing political issues relevant to an array of audiences in and beyond the academy, inviting contributions across disciplines, interest areas, and degrees of expertise. In so doing, it resists the perception that maker cultures are not particularly ideological or invested in social justice (Sadowski and Manson, 2014).

As Fashioning Circuits suggests, one way to achieve a recursive relationship between makerspaces and academic institutions is to underscore why making things in the space between bits and atoms matters right now. As we have argued throughout this chapter, the ability to navigate the full circuit of manufacturing – from analog to digital and back again – fosters something historically unique: an engagement with the cultural implications and creative possibilities of making things think, sense, and talk. As Bruce Sterling (2005), William Gibson (2007), and Steven E. Jones (2013) observe, cyberspace has turned itself inside out, through what Gibson calls the "eversion" and what Sterling renders an Internet of Things. Whatever the preferred nomenclature, a full circuit of manufacturing implies that sculpture, architecture, historical artifacts, and other cultural objects can be digitized, modeled, rematerialized, and programmed with a granularity and elasticity difficult, if not impossible, to achieve prior to the emergence of physical computing and desktop fabrication.

More important, we are only beginning to comprehend the assumptions, effects, and trajectories of these technologies. A majority of them have yet to congeal around particular standards or normalizing workflows; they have not gained popular traction or been naturalized across demographics and settings; they are only now being tested by GLAM practitioners, historians, and theorists of material culture; and (like makerspaces) they are still rare in humanities research. That said, working in the space between atoms and bits routinely reminds researchers that things could have happened differently – that history, politics, aesthetics, and culture always have adjacent possibilities. In makerspaces, such possibilities are not simply imagined; they are repeatedly prototyped and tested. While, as with any technology, physical computing and desktop fabrication can be exploited and deployed for oppressive purposes (e.g., surveillance, warfare, privilege, or monopolization), they also allow scholars to build alternatives, construct what-if scenarios, and create what, until recently, they may have only conjectured.

NOTES

1 "CT scan" is short for an x-ray computed tomography scan, which produces topographic images using computer-processed x-rays.

2 For a brief history of this split, see Sayers, "Technology," in the second edition of *Keywords for American Cultural Studies* (2015), edited by Bruce Burgett and Glenn Hendler. There, he notes that, during the culture wars of the late nineteenth century, arguments for the primacy of both science and the arts in education rendered technical work peripheral to the ideal university. Technology was either for Philistines (the populace without culture) or mechanics (the working-class industrialists who systematically applied science).

3 WYSIWYG stands for "What You See Is What You Get."

4 On the notion of maker cultures as nostalgia for analog life before cyberspace, Evgeny Morozov (2014) examines making through "[t]he lure of the technological sublime" and technophilia, accusing maker cultures since the Arts and Crafts movement of being more or less blind to institutional, political, and structural change. While many of his critiques of maker cultures (both historical and contemporary) are accurate and compelling, his argument is subtended by the logic that making romantically longs for the immediate. It also assumes that all maker cultures think technologies single-handedly determine social change. Put differently, Morozov first establishes a neat-yet-false distinction between technology and culture and then proceeds to build a self-fulfilling argument based on that distinction. Meanwhile, the actual, historical practice of maker cultures (as well as hacker cultures) is quite messy, often exhibiting recursive relationships between technology and culture, politics and media, and society and manufacturing. For some among many examples of such hacking and making, see Dick Hebdige, *Subculture*: *The Meaning of Style* (1979); Nick Dyer-Witheford, *Cyber-Marx*: *Cycles and Circuits of Struggle in High-Technology Capitalism* (1999); Andrew Ross, Hacking away at the counterculture (1990); Elizabeth Losh, Hacktivism and the humanities: programming protest in the era of the digital university (2012); and Cynthia Selfe and Gail E. Hawisher, *Literate Lives in the Information Age*: *Narratives of Literacy from the United States* (2004). In short, Morozov's argument substitutes what he identifies as a technological sublime (in maker cultures) with a sublime life of the mind (in intellectual cultures), without accounting for how the particulars of the former intersect with the practice of the latter. In this essay, we avoid such a split between intellectual agendas and technologies, without assuming that all maker cultures necessarily do the same.

5 For instance, see littleBits Electronics, which allows beginners to prototype with electronics in a fashion quite similar to Lego.

6 For more on the emergence of planned obsolescence, see Giles Slade, *Made to Break* (2006).

7 For a more historical take on modularity, see Tara McPherson, who writes: "We must historicize and politicize code studies. And, because digital media were born as much of the civil rights era as of the cold war era (and of course these eras are one and the same), our investigations must incorporate race from the outset, understanding and theorizing its function as a ghost in the digital machine. This does not mean that we should simply add race to our analysis in a modular way, neatly tacking it on or building digital archives of racial material, but that we must understand and theorize the deep imbrications of race and digital technology even when our objects of analysis (say UNIX or search engines) seem not to be about race at all. This will not be easy. In the writing of this essay, the logic of modularity continually threatened to take hold, leading me into detailed explorations of pipe structures in UNIX or departmental structures in the university, taking me far from the contours of race at midcentury. It is hard work to hold race and computation together in a systemic manner, but it is work that we must continue to undertake" (McPherson, 2012:153).

8 For an example application of DIY kits in a humanities context, see the Kits for Cultural History project at the Maker Lab in the Humanities at the University of Victoria.

9 In *Excommunication*, Galloway, Thacker, and Wark write: "Have we not forgotten the most basic questions? Distracted by the tumult of concern around what media do or how media are built, have we not lost the central question: *what is mediation*? In other words, has the question of 'what' been displaced by a concern with 'how'? Have the theoretical inquiries been eclipsed by the practical ones? Is it sufficient that media be understood as simply bi-directional relationships between determining apparatuses? Is it sufficient to say that a medium is always a tool for influence at a distance?" (Galloway *et al*., 2013:9).

10 For more on the notion of "middle-state," see Mattern and Mirzoeff on "middle-state publishing" in *The New Everyday* [*TNE*], where "[c]ontributions are longer than a blog post, but shorter than a journal article; they're typically between 900 and 1500 words. Contributions represent ideas that are in-formulation, taking shape but not yet fully formed; *TNE* offers an opportunity for you to think through a project in public, and to

solicit feedback from the … community as part of the process of developing your ideas" (http://mediacommons.futureofthebook.org/tne/about).

11 For instance, on intersecting social justice with the production of games, merritt kopas (2013) writes: "One of my long-term goals is to establish a workshop space to work with youth in which we'd read written work on social systems and try to make games with the goal of telling stories about living with structural violences. I especially like the idea of working with youth for this, and trying to show that games can be used for a wide variety of purposes beyond 'fun,' and that the tools do exist to make them."

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