Making Core Memory: Design Inquiry into Gendered Legacies of Engineering and Craftwork

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ABSTRACT

This paper describes the Making Core Memory project, a design inquiry into the invisible work that went into assembling core memory, an early form of computer information storage initially woven by hand. Drawing on feminist traditions of situated knowing, we designed an electronic quilt and a series of participatory workshops that materialize the work of the core memory weavers. With this case we not only broaden dominant stories of design, but we also reflect on the entanglement of predominantly male, high status labor with the ostensibly low-status work of women's hands. By integrating design and archival research as a means of cultural analysis, we further expand conversations on design research methods within human-computer interaction (HCI), using design to reveal legacies of practice elided by contemporary technology cultures. In doing so, this paper highlights for HCI scholars that worlds of handwork and computing, or weaving and space travel, are not as separate as we might imagine them to be.

Author Keywords

Woven memory; gendered labor; craft; handwork; computing history; participatory workshops.

ACM Classification Keywords

K.4.0 Computers in Society: general.

INTRODUCTION

Our methods of inquiry shape not only how we *do* design and technology development but also how we come to understand *who counts* as a designer and *what counts* as design practice, extending the very definition of design. Just as HCI's methodological toolkits have continued to expand — enrolling a wider array of instruments, techniques, and frameworks for data collection and analysis [3,17,18,58,60,67] — our definitions of technology have broadened, too. From establishing the Jacquard loom as a precursor to the Babbage Analytical Engine [66] to recalling that the first "computers" were young women [11,19,31,40], gendered narratives of craftwork and engineering both haunt and inform HCI's ideas of technological belonging, participation, and differentiation [44].

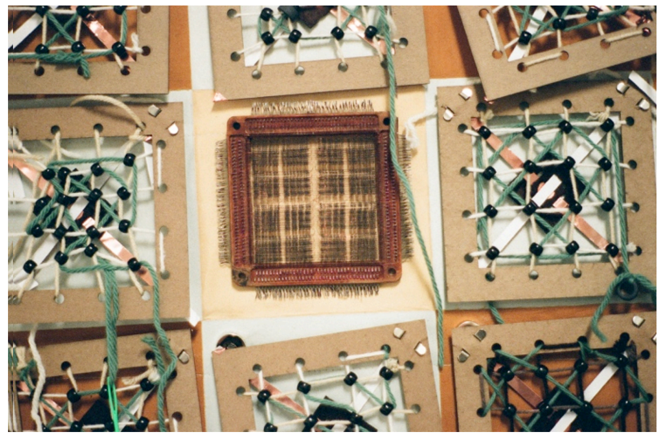

Figure 1: Close up view of the Core Memory Quilt.

Our focus in this paper is the gendered forms of craftwork underlying digital production and their valuation as technical work. We explore our own handwork as HCI designers in relation to the people we acknowledge as central contributors to engineering innovations. We describe our process of collaboratively making a historically-informed design artifact that reconstructs the story of magnetic-core memory. Core memory constitutes one of the principal mechanisms by which computers stored and retrieved information during the first two decades of the Cold War. The Apollo mission computers, for example, stored information in core memory ropes: threaded wires, passed through or around magnetized rings. NASA engineers nicknamed this hardware "LOL memory" for the "Little Old Ladies" who carefully wove wires around small electro-magnetic ferrite cores by hand. Later versions of hardware required even smaller weaving instruments and microscopes. But scholars still know little about the core memory weavers: what their work looked like or what they contributed to space travel.

Drawing on feminist, historical, and designerly approaches [18,27,53,55,63], this paper details the development of Making Core Memory, a project of design inquiry that unfolds in two parts: first, the making of an electronic quilt (Figures 1 and 2) composed of core memory planes that act as quilt patches; and second, the presentation and engagement of the quilt in workshops. During three workshops across the west coast of the United States (Mountain View, CA, Seattle, WA, and Los Angeles, CA) we asked a range of historians of technology, design educators, and members of the public to help us materialize the work of the core memory weavers by weaving core memory "patches" and revisiting the weavers' history together. We gave participants "patch kits" comprising a simple metal matrix, beads and conductive threads (in place of ferrite core and wire). Plugging the completed patch kits into the electronic quilt (Figure 2) triggered the quilt to play firsthand accounts of 1960s core memory production while sending tweets via our @lolweavers account. This approach allowed us to bring hidden stories of innovation work to the people building tools, histories, and pedagogies for design—recontextualizing their own practices within stories of handwork heretofore eclipsed.

The paper that follows contributes to HCI scholarship along three key dimensions. First, by recognizing the hidden, feminized work involved in specific contexts of 1960s core memory production, we comment on the particular legacies of expertise and knowledge on which core memory work relied. This analysis moves beyond HCI's dominant focus on material capacities (what a technology can do) to focus instead on the histories of practice that make those capacities possible. Second, our work contributes new perspectives on the process of building embodied, experiential knowledge. Specifically, we offer a different conceptual frame that broadens ongoing HCI conversations on digital labor and handwork. We shift debates from an assumed separation between cognitive (masculine, innovative, high-status) and manual (feminine, menial, low-status) labor toward an active examination of their entanglement. Third, this paper highlights the centrality of feminist historical perspectives, and argues for historical-participatory inquiry as a core approach by which different practices, ideas, and ethical stances get recognized and examined. Sites of digital manufacturing require new forms of inquiry that challenge the current valorization of individual innovators and users. This observation acts as a direct call for HCI scholars to take up new collective methods that expand the ethical and historical horizons of contemporary design research.

LITERATURE REVIEW

Craft practices like weaving, sewing and other forms of textile making embody processes of creative production historically associated with women [2]. Within public narratives of technology and engineering, journalists and pundits tend to depict craft expertise as menial labor traditionally associated with women that is inherently different from (and often less valuable than) the sophisticated cognitive labor of engineering associated with men. Despite this continued bifurcation of manual and cognitive work, the development of textile crafts has long occupied a crucial place in

Figure 2: Plugging a woven patch onto our Quilt.

the disruption of women's exclusion from science and technology cultures, both presently and in historical narrative. Notably, women have encoded critical messages during times of distress, particularly around quilting [43,64,68]. Using handwork as a device for encryption frames textile artifacts as complex forms through which to catalyze technical and strategic innovations.

Within CSCW and HCI, similar techniques for technical invention and encoding through craft have informed a robust body of work on digital manufacturing. One strand of this work examines the forms of human-machine collaboration that emerge with the introduction of digital fabrication tools within studio-based arts practice [10,16] and other sites of traditional craftwork [3,35,54,57,59]. Devendorf and Ryokai's *Being the Machine* project [16], for instance, challenges a stable division of labor between maker and machine by altering the coordination between them. In other work, HCI researchers explore contributions of craft within emerging forms of digital cultural heritage [24,51,52], including core memory [15]. Work by Petrelli, Ciolfi and others [12,51,52] draws on textile traditions to explicitly identify embodied practices as key modes of HCI research.

A related strand of HCI work has examined techniques of textile production *as* innovation work, broadening the historical resonances and present-day possibilities of dexterous handwork traditions. While some position historical machines such as the groundbreaking Jacquard loom running on punch card technology as important sites for investigating embodied interaction [21], others consider platforms for electronic-textiles making as mechanisms for intervening into [48–50] and even improving [7,8] environments of STEM learning. Leah Buechley, for example — known for her origination of a sewable microcontroller that connects circuitry with conductive thread instead of wire — has argued that sewing circuitry provides a case for shifting metaphors of engineering development from brittle and mechanical solutions toward open-ended possibilities [8]. This is especially true for women, 40% of whom come to technology innovation spaces from a background in arts & crafts (rather than engineering) [20].

In what follows, through the confluence of historical analysis, quilting, and participatory workshops, we draw together these separate strands of work to investigate the influence of craftwork on the methods, processes, and narratives of engineering that continue to inform programs of HCI research. We show that revisiting craft-based practices within and as part of engineering histories may challenge those histories, enlivening new features of the technological past (revealing links between weaving and engineering inventions, for example). But it may also expand conversations on design research methods more broadly. This work involves engaging new histories of production that set hardware inventions in motion—reconsidering not only what counts as innovation work but also *who* does it and *how*.

BACKGROUND

HCI's cases of hardware development tend to focus on cutting edge tools, methods, and infrastructures. Yet, sites of collective digital manufacturing have a much longer history and reveal deeper insights about how the innovation of things unfolds [25]. Apollo 8, the first "manned" mission to the moon and back, required the work of over 400,000 people—a collaboration that popular discourse often elides in its tendency to valorize the work of individuals [22]. Below we contextualize the development of our Core Memory Quilt in this history, beginning with the NASA mission that catalyzed a new reliance on weaving techniques for digital information storage.

Apollo Mission

The design of the Apollo Guidance Computer (AGC) began in 1961 [69]. Among the greatest challenges faced by the team of Apollo engineers was building one of the world's first portable computers [41]. The Apollo missions needed an on-board guidance system that could direct the spacecraft, independent of mission control stations on Earth [42]. Room-size machines running on punch cards, equipment that was too heavy and too large to fit in the cone of a rocket, dominated computer technology in the 1960s. One of the key solutions was a form of information storage called "core rope memory."

Core rope memory is a mechanism for information storage that uses wires running through or around magnetic ferrite cores to create binary "zeros" or "ones." During the early 1960s, female line workers (the "Little Old Ladies," as engineers called them) assembled the AGC code by hand in Waltham, Massachusetts. Employed by the Raytheon Corporation, they sat across from one another at long desks, passing wires back and forth through a matrix of eyelet holes, each comprising a magnetic core bead. Passing a wire through the core created a "one," while bypassing the core created a "zero" (see Figure 3) [13].

Although astronauts wouldn't touch the moon's surface until Apollo 11, each of the Apollo missions was defined by the need to leave Earth's atmosphere and travel an extraordinary distance with living humans onboard [69]. Among the many unique environmental factors facing a computer leaving the Earth's atmosphere, the AGC had to withstand the extreme vibrations of takeoff and potential power loss during the mission [69]. Rope memory answered the need for information storage that fit the temporal and spatial constraints of the storage environment—extreme cold, intense vibrations—while also responding to the limited resources of electricity and weight load [22,69]. It minimized the number of circuits required, the number of components used, and "packed them as tightly as possible" [70].

Because the core ropes in the Apollo Guidance Computer (AGC) "hardwired" binary code, engineers promoted the technology as "a permanent storage device" [38] and thus ideal for storing navigation information. In archival interviews with Apollo engineers, the AGC is repeatedly praised for being extremely "robust." Don Eyles, a programmer for the Lunar Module, went so far as to say "that code probably still exists, despite being left on the moon" [22]. Indeed, hobbyist engineers presently tinker with recovered surplus AGC modules bought on the scrap market with the hope of reading the original AGC code [46].

Despite this, Apollo engineers faced trepidations about the reliability of computers, in general, and fears around the possibilities of human error because of the handmade nature of core rope, in particular. Modern computing was in its earliest stages of development and was not seen as a dependable technology. Eldon Hall, hardware designer for the Apollo missions, expressed this clearly: "The biggest problem was convincing people that a computer could be reliable. That was harder than designing it" [22]. The handmade nature of many of the components amplified this persistent awareness of potential error in the manufacturing process. Despite relying on the hand-weaving of cores by the "Little Old Ladies," an early ACM publication introducing core rope memory assured readers, "this process has been automated to the fullest extent possible in order to…minimize the chance for human error" [38]. At each stage of assembly engineers meticulously tested the rope to ensure that it had been wired correctly—three separate tests in total. Additionally, program managers continuously inspected the work of the weavers. Apollo line worker Mary Lou Rogers recounts 50 years after her experience: "the components had to be looked at by three or four people before it was stamped off. We had a group of inspectors in from the Federal Government to check our work all the time" [22].

As David Mindell argues in his book *Digital Apollo,* the Apollo moon missions represent one of the earliest forms of contemporary human-computer interaction [42]. The software (manifested materially in core rope memory) was collaboratively designed and built in a complex web of institutional arrangements amounting to hundreds of thousands of people. And, perhaps more importantly, the flight of the Apollo mission required collaboration between pilots and the first automated flight systems. Along with pioneering software, the Apollo missions also required the invention of methods of "software verification"—reducing the chance of errors in the ropes to 1 in 3 billion [65]. The core memory weavers were implicated in all of these achievements. In sum, the weaving of cores offers a compelling early case of

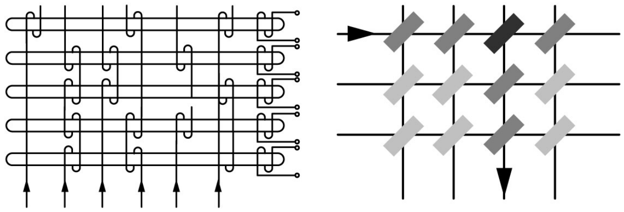

Figure 3: Rope memory (left), core memory plane (right).

digital technology development in its response to a design constraint: offering an extremely dense, light mode of storing information.

Core Memory Technology

Core memory comprises an array of tiny donut-shaped ferrite magnets (or "cores") that each store one bit of memory. Although *core rope* memory stored information using a physical distinction—passing a wire around or through a magnetized core—*core planes* relied on electronically controlled changes in polarity due to the direction and amount of current flowing through the ferrite cores. This meant that rope memory comprised read-only memory (ROM) whereas core planes consisted of re-writeable memory.

Both core rope memory and core memory planes shared a mobility and reliability, storing information indefinitely without the use of electrical current — once the cores were polarized they would remain so. However, unlike core rope, core planes comprised at least two types of wire that made the machinery readable and writable: vertical and horizontal *write wires* (also called "X" and "Y" lines) that polarized each core and *read wires* (also called "sense" lines) that ran diagonally through each core and detected voltage changes. To write to a core, the computer sent just enough electric current through an X and Y wire so that only the core at the intersection changed polarity. To read that core, the machine first had to write: sending that same electrical current through each core while sensing for a polarization change (signaled by a spike in voltage). The core memory weavers critically assembled those sense lines: weaving through or around cores in the case of core rope memory, and weaving through each core in the case of core memory plans (the process we would introduce in workshops, outlined below).

OUR PROJECT

We developed the Making Core Memory project with the hope of examining the forms of technical labor performed in early processes of core memory production. We also aimed to use core memory production to expand HCI methods of design research: positioning embodied, personally situated, and historically inspired encounters as valuable processes of investigation. We wanted to explore how our own valuations of technical labor might inform understandings of craftwork: exploring and even challenging the prevailing purification of high status cognitive labor associated with male engineers from the ostensibly low-status practices of women's hands. Our development of the Core Memory Quilt (hereafter, the Quilt), in this sense, stemmed from an interest in examining how HCI scholars come to know technical labor, but also from our concern for the role of historical investigation in design research.

Methodology

Our methodological approach draws from feminist approaches to situated inquiry [27,28,63] and strands of interventionist inquiry within traditions of critical and speculative design [17,18,47], a position summarized elsewhere as critical fabulations [55] (see also [29]). Where feminist approaches to intervention foreground the generative and highly situated forms of knowledge produced by frictions, complications, and breakdowns, programs of speculative design cast designed objects as tools for interrogating alternative futures.

Our project draws from the above perspectives to explore the specific bodies, practices, and narratives under-acknowledged in historical accounts of innovation and contemporary understandings of engineering work. Specifically, we harness our design process to explore two central questions. First, how do craft legacies of innovation inform HCI's ideas of technical labor? Second, how might historically-informed objects expand existing instruments of design research?

Design process

Our process of developing the Core Memory Quilt comprised two phases: 1) making the Quilt, and 2) organizing workshops for people to engage with the Quilt. We began the first phase by reviewing existing historical resources on core memory production (a selection of which we describe in the prior background section). We then ordered core memory planes made in the 1960s from e-Bay and noticed the samples held a surprising resemblance to quilt blocks, the square pieces of fabric that compose a decorative pattern across layers of fabric and stitching. We drew on this visual metaphor to explore quilting as a complementary (gendered) form of memory production and presentation. This connection inspired the first author to seek out Helen Remick, who she had learned about through a mutual acquaintance. A master quilter, Remick had developed a practice creating quilts from obsolescent technology including 35mm slides, CDs and filmstrips. Collectively the team met weekly to articulate several design concepts and iteratively explore our design ideas alongside our ongoing archival analysis. While choosing extracts from our archive to be played by the Quilt, we confronted a complete lack of first person accounts from the core memory weavers themselves; indeed, we have yet to locate an informant who can provide such an account! Caught between using the voices of male managers or removing such accounts altogether, we decided to select extracts of the male voices, a female managing engineer Margaret Hamilton, and contemporary news coverage that highlighted the skill involved in the weaver's work. Later, while designing the patch kits (Figure 5), we charted a middle ground once again. We carried out a progressive critique of the patch kit designs until we arrived at a concept that proved challenging, technically resonant with the weaver's work, and still actionable within the timeframe of a short workshop. Our iterative process resulted in our Quilt design (Figures 1 and 2).

During the second phase we organized three workshops at:

1. The *Command Lines* software studies meeting in Mountain View, CA; 20 workshop participants, including historians of technology, technology practitioners, and museum curators.
2. The *Converge* Design Educators Conference in Los Angeles, CA; 12 workshop participants, including design educators, film makers, and practicing visual designers.
3. The *Maker Summit* in Seattle, WA; 12 participants, members of the public drawn to design.

The workshops each lasted roughly an hour and a half (Figure 4). We chose these events to engage and learn from the people writing design histories, teaching budding designers, and imagining new technologies within a focused setting.

Data collection

Foregrounding feminist traditions of situated knowing, our process of data collection and analysis drew from our own contingent, layered, and embodied engagements while making and sharing the quilt. Unlike conventional HCI accounts that report on the design and use of a technology, the data we reflect on in this paper encompasses our co-occurring encounters with historical resources, workshop attendees, and the quilt itself. Although the history of core rope memory production remains largely unexplored, we used a range of archival material and experiential reflections. Our aim was not to produce a comprehensive account of core memory development. Instead, following prior design-led research [14], we sought to create descriptive documentation that we could iteratively cluster, refine and use to chart our design space. The data gathered included:

- *Fieldnotes* based on our first hand accounts of creating the quilt and running the workshops. Developing an understanding of how core memory was made, for example, involved creating iterative weaving experiments while drawing on a variety of archival materials, each documented in our notes across the studio session.
- *Audio, video and images* captured during our three workshops and ongoing studio sessions unfolding between winter 2016 and winter 2017, and culminating in the spring of 2017. We later transcribed relevant episodes for analysis.
- *The @lolweavers twitter archive* comprising 29 tweets, 17 retweets and 126 interactions through replies, quoted replies, and mentions of the project.

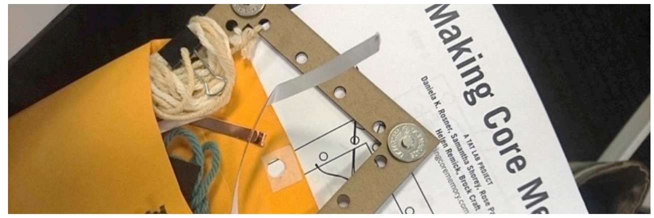

Figure 5: Patch kit comprising beads and conductive threads.

- *Phone and email correspondence* with 11 engineers who worked for IBM on core memory planes after the Apollo Guidance Computer.
- *Second-hand oral histories* of twenty key engineers who worked at NASA at a variety of institutions contracted to produce the Apollo Guidance Computer: the MIT Instrumentation Laboratory (later known as Stark-Draper Laboratory), Raytheon, and A.C. Sparkplug made available online through the "Apollo Guidance Computer History Project."
- *Digitized personal "papers"* of notable figures, such as software engineer Margaret Hamilton and Raytheon manager Jack Poundstone.
- *Core memory assembly machinery patents*: a method for wiring ferrite core matrices and an apparatus for wiring personalized core storage array [23,32].
- *Additional archival material,* including the cataloging of the AGC engineers' stories in museum footage [70], television docuseries [13], newspaper & magazine articles [22,41,61], first-person scholarly accounts [26], and notable texts by David Mindell [42] and James Tomayako [65].

Data analysis

We analyzed our data thematically based on how they shed light on the nature and value of technical labor. Drawing on inductive techniques [9], we developed reflective memos derived from our field notes and other empirical materials. During later rounds of analysis, we iteratively refined our interpretations and used the data to develop the below themes such as invisible work and technical expertise.

The Core Memory Quilt

The Core Memory Quilt is a mobile, electronic textile artifact that plays audio recordings and tweets first-hand accounts of core memory development when people plug their hand-woven patches into it. The Quilt comprises a four foot

Figure 4: Our Making Core Memory workshops: (left to right) Mountain View, CA, Seattle, WA, and Los Angeles, CA

square made of 49 patches: 13 PDP-8 planes made by 1960s core memory weavers; four foam core planes woven by Remick with beads, thread and wire; and 32 planes awaiting assembly by workshop participants. We hoped the weaving of core memory would create parallels between the participant's actions and those of the core memory weavers, opening understanding through experience.

We call the last set of 32 hand-woven planes *patch kits* (Figure 4) since they comprised a yet-to-be assembled array of parts: conductive fabric, yarn and beads that we chose to represent the original copper wires and ferrite cores in the core memory planes. During subsequent workshops, we invited people to weave the patch kits, an act that engaged them in a process of exploration and discovery—additionally mediated by the audio samples played by the quilt. The handcrafted patches acted as switches that unlocked pieces of the core memory history (oral history transcripts from a dozen different Apollo engineers), while inviting reflection on that history and whose contributions shape its performance and presentation over time.

Quilts conventionally comprise three layers of fabric sewn together by hand or machine, often using the same pattern at multiple scales. Our Quilt built on this material tradition in two central ways. First, we used the three layers of fabric to insulate conductive threads connected to power (positioned on the front of the quilt) from those connected to ground (positioned on the back of the quilt), thus keeping the circuit open until closed by a hand-woven patch kit, acting as a switch. Second, following a traditional "Trip Around the World" quilt pattern, our Quilt incorporated patches woven at different scales (Figure 5): a 128x128 matrix (the PDP-8 planes), a 13x13 matrix (Helen's planes), and a 4x4 matrix (the patch kits). By using the quilt as the connective mechanism unlocking our archival materials, we aimed to explore how craft practices don't just decorate existing approaches to technology; but they also offer ways to imagine new processes of technology making.

MAKING CORE MEMORY

In the sections below we report on our process of building, preparing and engaging the Core Memory Quilt.

Building the Quilt

Crafting a quilt that required working with atypical materials—incorporating original 1960s core memory array artifacts as quilt patches, for example—posed unique challenges. The quilt needed to be strong enough to support the core memory boards and other electronic elements, and it needed be layered in a way that the fabric would act as an electrical insulator between circuits woven into the quilt. We assembled the quilt in such a way that it would both support the addition of surface patches and insulate the circuitry inside. To understand these challenges, we first turn to an episode during our making of the Core Memory Quilt.

On our hands and knees on the floor, we had fused large pieces of felt and nylon with "wonder under," an iron-on adhesive for combining two pieces of fabric, to prepare the fabric for holding electronic circuitry and nearly five pounds of material. This weight, much more than a typical quilt, made the object difficult to run through the sewing machine, creating "wobbly" lines that Remick described as antithetical to the precise character of the quilting process. One week earlier she had used laser beams on a drafting table — a tool originally designed for engineers —to align the orthogonal cuts on cotton fabric. Quilting felt at once demanding and inviting, requiring investments of the whole body. At one point Remick captured this sensibility, stating, "quilting isn't just hand work, it's back work, neck work and knees work."

The laser Remick used to align the quilt derived from the very same drafting practice her high school teachers had denied her years earlier. Growing up in the Bay Area during the 1950s, she recalled teacher stating girls were too much of a distraction for drafting class. Since she required drafting experiences for admission UC Berkeley's engineering college, she and other girls from her high school could not major in engineering there. In the coming decades, she would take such challenges to equal opportunity as opportunities to fight new programs of responsibility and action, implementing some of the first affirmative action initiatives for women at the University of Washington.

Applying these lessons to the Quilt, Remick's early version of the core memory plane, or what would become our eventual quilt "patch" (Figure 5c), catalyzed our efforts to reverse engineer the core memory planes and later informed our discussions with early core memory engineers. We learned through multiple attempts to weave the "sense" line that the orientation of the ferrite cores (which we began calling "beads") was likely the key component that remained hand woven in the PDP-8 planes. We later confirmed this intuition during conversations with engineer Ed Boyd who explained that machines directed the X-Y wiring (the *write* wires). Needles fed the X and Y wires through the core beads as the beads lay on a plastic plate with depressions at each core position. A magnetic field then held the beads in place. "The problem," he explained, "was the sense line since it was not orthogonal to the x-y lines." This "problem" (i.e., hand-weaving the sense lines) comprised the central work of the core memory weavers. Designing these patches involved more than simply organizing a sturdy material for our quilt. It meant learning how the weavers worked: what tools they used, what techniques they applied, and how they solved the problem at hand.

Preparing The Quilt

Preparing the Quilt for our upcoming workshops meant learning to displace our fears of "human error" — a practice that resonated with descriptions of core memory production. At an early meeting with our design team, Remick used clips to attach each line of conductive thread to software running on a microcontroller. This set up allowed us to keep track of each thread independently (in computing terms, making each thread "addressable"). When project lead Daniela Rosner explained to technologist Brock Craft that the conductive thread we were using could be soldered, he was intrigued. For him, adding hot metal alloy to a material that looks and acts like thread without burning it was both curious and exciting. "I tried it, and it worked!" he exclaimed one afternoon. Soldering soon replaced our more bulky thread/wire clip design.

This decision turned out to be a complicated one. Having the solder-able thread "work" meant that it carried current across the metal alloy that Rosner soldered to it, thus reducing visual clutter on the quilt. Yet, the metal alloy also made the thread more brittle, causing it to break with only a bend of the soft, quilted fabric.

This problem re-surfaced a few days earlier when Rosner decided to cut all the loose threads hanging off the quilt. Viewing them as exposed wires, Rosner naively assumed they added unnecessary complexity, both visually and mechanically. Once cut, however, more than half the threads on the quilt stopped being able to receive electric current, rendering much of the quilt unusable. When Remick arrived later that morning she calmly suggested taking a needle and thread to each of her cuts, mending the gaps in conductive thread and thus flexibly allowing current to flow across the circuit they comprised. Later, when Rosner set up for the workshop we conducted at the 2017 software studies meeting *Command Lines,* the brittle metal alloy continued to break. Fixing gaps in the circuitry with conductive thread became far easier than with solder, and the "fiber" proved far stronger than the "metal."

Mending the quilt illuminated the material possibilities of thread as opposed to solder, the dominant means of connecting wires in contemporary circuit making practices. This experience also became a lens with which to consider the contributions of core memory weaving, as a historical technology making process. When viewed retrospectively, historical technologies are often described as being lo-fi or merely a steppingstone towards advancement. For example, there's the oft-made observation that man went to the moon with less computer memory than an iPod [13]. Yet, using woven wires in the Apollo Guidance Computer wasn't merely a default: it was a design solution to particular situational constraints.

On the morning of our first workshop, the Quilt had the considerably less daunting task of travelling a few hundred miles by airplane. When we unfurled the quilt the conductive thread remained intact, but the brittle solder had broken. Wire and thread offered something that the solder couldn't: it was flexible and tolerant. For most of that morning, Rosner crouched over the quilt on the floor of the Computer History Museum café. What was glitching: was there a break in the sewn circuits? Was it the software? Was it the microcontroller wiring? We had four patches we knew had completed connections, triggering the historical audio clips. Only four of thirty-six!

Our debugging sessions expanded these historical accounts and technical papers by depicting "human error" as not the only concern around the design of the Apollo's core memory. While engineers viewed core rope memory itself as highly reliable in its finished state, they saw the process of construction as fraught with "human error." By contrast, our use of solder offered another lens on breakdown. The responsibilities lay in the cost of removing textile flexibilities rather than in the skills of our team members alone. As the participants in our workshops would soon experience—and much like the core memory weavers before us—we used these challenges as moments of opportunity.

Making Core Memory: The Workshops

Across each of the workshops we introduced participants to histories of core memory production by asking them to weave 4x4 matrixes on 5-inch square pieces of cardboard. The process was exacting, strange and frustratingly full of opportunities for error. In the sections that follow we draw from all three workshops but focus on the *Command Lines* workshop due to its encompassing site of computer history.

At the *Command Lines* workshop, core memory production was an expected topic both for this academic community and for this venue in particular, the Computing History Museum in Mountain View, California. The museum displayed an extensive collection of various memory technologies, including a rectangle of Apollo core memory produced at Raytheon in 1963. The artifact was bolted to the wall behind glass. Directly adjacent was a picture of a white-haired woman—a Little Old Lady—and the Apollo 11 at blast-off. "It could take days to change one line of program," the caption read, with no further information about the process. Alongside these references to core memory production, our workshop presentation would do more than draw attention to particular sites of software development. It would also enliven the forms of labor underlying this history.

To understand how, consider the reaction of participants as we handed out the patch kits, envelopes holding a core memory plane-sized cardboard loom, plastic beads, yarn, and illustrated instructions. "We're *actually going to do this?*" one man in the front row asked, with surprise. Some confusion followed as participants began the first step: "thread needle and string four beads onto the thread." An engineer who we later learned had actually worked on the Apollo mission asked for help threading a needle, at one point becoming so flustered that he dropped the parts to his kit on the floor (leading us to hunt for spare parts). Others encountered tangled yarn, misplaced knots and tiny round beads that were constantly rolling away. While everyone found it obvious that the thread goes through the eyehole of the needle, many of them thought that the thread needed to be *tied* to the needle as well. Mid-way through the workshop, one man explained to the women sitting next him, "I'm literally on step one. I spent most of the time putting the beads back on the string. That's where I'm at." Others moved through the instructions with ease only to later realize they had skipped a bead or, more often, run through a bead in the wrong direction. Many started their patches over again. "It's humbling," someone observed.

Yet at the back of the room sat a row of attendees who built their squares with amazing precision and craftsmanship. A museum curator finished her square beautifully with perfectly faced beads. The relative ease or discomfort with weaving provided a small insight into the way that certain types of skills become naturalized differently in sewing and scientific fields. Inspired by the weaving techniques of the Little Old Lady weavers, the Core Memory Quilt invited people to create their own woven structures, walking through the weaving process step-by-step while reflecting on the tacit skills they brought to the work. For participants, moments of confusion while weaving became openings for inquiry as well, as we describe further below.

Responses to the outcomes of technical work

Once they completed their patches, participants at each workshop gathered around the quilt with cell phones in hand. Some attached the cardboard planes to the electronic quilt (the planes snapped into place with magnetic clasps) while others photographed the engagement. At each installation, audio began to play. The voice of Richard Battin, Director of the AGC project, emanated from a nearby speaker: "we called it the LOL method, the Little Old Lady method of wiring these cores. Not very nice," [13] he chuckles before he's interrupted by another patch snapping into place "It's an extremely time consuming process," Don Eyles starts [13]. Participants gathered round, hearing each new bit of information unlocked by the patches. "Ooh, something's talking," a woman from the *Maker Summit* giggled. One woman at the *Converge* conference popped her head behind the quilt to see how it worked. The collection of completed patches transformed the quilt into a collection of potential information. After installing a patch, people could press other patches in sequence, in effect playing the quilt like a musical instrument.

Plugging in the patches also triggered tweets on the @lolweavers account with a corresponding quote. The quotes appeared automated and bot-like. They all were in the same format and weren't directed at anyone in particular. With cell phone in hand, participants quickly recontextualized the tweets using the quoted-reply feature on twitter, saying things like "these tweets are coming from the quilt!"

Beyond the confines of our meeting room, the tweets generated something to interact with online while we were busy running the workshop. It would have been impossible for any one of us to tweet while we were instructing, helping, filming, photographing, troubleshooting, restarting, and advancing presentation slides. The tweets created ripples of interest throughout the conference—linked to the #sigcis hashtag—heightening the visibility of the project. The most highly engaged tweet from the conference was viewed over 5,000 times. Harnessing the participation of the *Command Lines* attendees, our project exposed the embodied practices that make designing and producing technology possible, but also invite reflections on the performance and representation of that work.

Using the Quilt to Broaden Metaphors of Production

At the *Command Lines* workshop it didn't take long for conversations to turn toward the language used to describe the patch kit process. Some asked how the weaving compared to that of the core memory engineers. We explained that we had seen few uses of the term "weaving" in either oral histories or scholarly accounts of core memory. One participant asked what engineers called the weaving process. This question prompted us to connect back with the 1960s core memory engineers we had corresponded with in the prior weeks. In a press conference, Ralph Reagan, Deputy Director for NASA programs at MIT once stated: "we essentially have to build a weaving machine" (as cited in [42]). But most accounts of the process referred to the weavers as "operators" [1,70] or "assembly labor" [38]. Frederick Dill, a pioneering engineer and co-inventor of the semiconductor laser, later told us he had "never heard of 'stringing cores' as a weaving problem. When we asked what he meant by this comment, he later told "I looked at the wires through the cores in terms of what electrical signals they provided… Your focus on 'weaving' is an equally valid viewpoint, but a different one. It sort of assumes that some particular configuration of weaving will produce what is needed… which is totally correct."

By attending to weaving rather than the electrical cores, Dill and others began to see different stories of contingency and embodied practice, identifying the weave structure as a pivotal innovation; the mechanism that "will produce what is needed," as Dill asserted. This insight was unusual not only due to its widespread omission from core memory literature, but also due to its deeper recognition of women's embodied practice — or bodies at all – as core contributors to engineering. Echoing Remick's description of quilting, core memory production consisted of *back work, neck work and knees work*.

In one telling of core manufacturing sparked by our workshop discussions, an IBM engineer described a later form of core memory plane development wherein women and "limited mobility men" would weave the sense line. They worked at home under contract, he explained. A courier delivered and picked up the memory planes each day. He described this piecemeal domestic work as done by "mostly mothers of school children, who wired the planes while the children were at school" [6]. Other core memory engineers we spoke with referred to the assembly as "menial work" well suited to women. Describing his tour of core memory assembly around 1959, one told us, "I distinctly remember […] the manager mentioning that there was no machine that could do it. He also noted that all the people threading the wire were women as they had found that men did not have the patience to do it."

In addition to possessing feminized ideals of "patience" and "tender, love and care," the core memory weavers were experts in mechanical assembly. In an oral history interview, Ed Blondin of A.C. Sparkplug observes, "there was a technique about how you positioned [the needle], your hand shook, and these female operators were good at it. Those that stood around telling them what to do were terrible at it." Blondin's observations counter the most public narratives given of the core memory weaver's work. In the MIT Museum *Computer for Apollo* [70] footage introducing the Apollo Guidance Computer the interviewing journalist observes as a woman passes the wire back and through an eyelet hole. "She doesn't have to think about which core it goes through next?" he asks. "No" Jack Poundstone, Raytheon manager responds, "The machine does that for her" [70]. These accounts present the weavers as unthinking and unskilled laborers—perceptions that simply couldn't be held after we experienced the precision process ourselves.

Back at the workshops, several participants exclaimed "ahh!" and "wow!" upon seeing the 1960s core memory planes up close, finding new appreciation for their intricacy. "These are stunning!" a woman at the *Converge* conference exclaimed. Their patch kits were equivalent to only a few *millimeters* of weaving on the PDP-8 core memory planes. Constructing the quilt similarly reframed the material capacities of woven wire and the women doing the weaving. Weaving wire wasn't a quaint work-around, it was the right tool for the job. This was especially important considering the tendency for craftwork, such as weaving, to be considered traditional, old fashioned, and non-technical. The quilt showed thread to be a material of possibility, and in the workshop participants also experienced its constraints.

DISCUSSION

So far we have explored how the Core Memory Quilt helped us challenge who gets acknowledged for their involvement in technical work over time. Rather than trivialize this process — casting core memory production as a labor of love or the female weavers as naturally suited for core memory production — we began to intervene in valuations of creative labor, blurring a binary view of design and craftwork. We saw what Lisa Nakamura [45] cautions against while peering inside the machine: "not… dancing bunny-suited clean room workers, happily making chips for free." Instead, she suggests, "Looking inside digital culture means both looking back in time to the roots of the computing industry and the specific material production practices that positioned race and gender as commodities in electronics factories" [45], p.937. What it means to be innovative is deeply connected to what it means to be free and empowered. Core memory acts as a powerful case for challenging histories that not only reassert divisions between cognitive and manual labor but also hide the locales, practices, and bodies rarely associated with innovation work.

Below we explore this implication along three dimensions: cognitivist legacies of engineering, sympathetic contexts for design, and our technique of materializing absences. While the first two concerns lend themselves to exploring craft legacies of innovation, the last highlights the lessons our work holds for methods of design research more broadly.

System Behaviors versus Engaging Systems

Producing woven patches with the core memory weavers in mind brought to the foreground the contributions of weaving and the explanatory power of craftwork metaphors in cutting edge technology production. Throughout our engagements, the discourse of "weaving" opened possibilities for encountering obstructions to the weaving process, the piecemeal nature of the work, and the material conditions under which the weaving process might have taken place.

Our encounters suggest that the prevailing emphasis on the cores and their behavior (material *capacities*) instead of the work to connect them (material *assembly*) reflect a basic orientation toward information dating back to cybernetic discourse. Just as cyberneticists conceived silicon as inscribed with information [5,31], many of the core memory engineers described the cores as "holding" information. Fredrick Dill's focus on the *behaviors* of the cores reflects a view of information as a disembodied phenomenon that can move freely between various earthly and artificial components. However, "[w]hen information loses its body," explains Katherine Hayles [30], p.2], "equating humans and computers is especially easy, for the materiality in which the thinking mind is instantiated appears incidental to its essential nature." This view contributes to classifying the weavers' work as basic, rote, and ultimately unworthy of remembrance.

Our project contributed to challenging this disembodied conception of early information storage. The weavers' process took some 8 weeks of work to produce [4] and it could take days to redo one line of the software, work unfathomable to us as our hair got caught in the yarn and as our bodies hunched over the patch kits. Our project challenged a prevailing commitment to disembodied forms of knowing.

Within HCI we see this focus on behaviors over practices continue through the plug-and-play suite of Internet of things (IoT) devices and wearable microcontrollers that displace a focus on practices like sewing with Lego-like modules (e.g., [39]). Our concern for handwork expands and deepens this longstanding historical focus on the code and programmers [11,33,45] (Margaret Hamilton, Grace Hopper, the women of ENIAC [37]) to account for acts of creating the machine — and not least, the role of women's bodies in doing so [18]. It moves debates from an assumed separation between cognitive (masculine, innovative, high-status) and manual (feminine, menial, low-status) toward an active examination of their entanglement. Alongside moments of conceptualization and design, this work stresses the importance of understanding the conditions under which systems get made and maintained such as the labor of assembling smart phones [34,56]. It suggests a broader shift in the field's treatment of design as a process concerned as much with the contexts of extracted and commodified labor as with the contexts of end use.

Building Sympathetic Contexts

When work is made invisible, it is often those in power who are in position to define it. Whether by associating it with technical functions or trivializing its routines, these definitions fail to reflect the experience of those who perform these processes [36]. Through making invisible the work of core memory production, the managing directors of the Apollo Guidance Computer likewise demonstrated their lack of embodied, experiential knowledge, or what Star and Strauss have called a “sympathetic context” [62]. Our quilt offered a counter-narrative by presenting new associations and experiences connected to the work of the core memory weavers. Through their weaving practices, workshop attendees could build their own sympathetic understandings of weaving—acting as a corrective to the perception that invisible workers like the Little Old Ladies lend their manual and not their cognitive skills to the project. The weavers did not simply execute a plan outlining exactly what to do; they also drew on their situated knowledge [27].

The Core Memory Quilt called new attention to fears of “human error” and how those fears were associated with gendered forms of production. This thematic contribution provided content for the making core memory workshop (in the form of audio clips, played from the electronic quilt). And perhaps more importantly, the themes were animated and expanded again through our material engagement while debugging the quilt — mending broken circuitry with conductive threads and accepting the limits of solder.

Today similar promises of reduced human error arise around the development of self-driving cars and robotic agents. Beyond core memory, readings of handwork as routinized and thus codifiable labor offer lessons for reworking how HCI scholars come to know technical labor, from early forms of computing machinery to emerging sites of factory work. Today MTurkers, Lyft drivers, remote programmers among many others comprise the “crowd” of low-status, low-wage labor. Just as our design team and workshop attendees constructed weaving as a process entangling tacit and cognitive labor, certain forms of low-status design labor may require their own forms of re-weaving. Using design to build sympathetic contexts, HCI scholars may find new opportunities for examining and even disrupting the extraction of labor tied to vulnerable groups.

Figure 6: Raytheon photo courtesy of the collection of David Meerman Scott, author of Marketing the Moon: The Selling of the Apollo Lunar Program

Materializing Absences

In some ways our quilt and the ensuing participatory workshops offered a familiar format for HCI design research. We designed the Quilt with the hope of re-enlivening the weavers’ contributions to engineering history. And, in this sense, our work continues to expand an already growing body of design research techniques that focus on trying to fix current and future problems. But as HCI continues to chart its own stories of technology development, the precise form such inquiries take deserves some scrutiny. Was the Core Memory Quilt, in Bill Gaver’s terms, a *cultural probe* that served to provoke reactions in the participatory workshops? Was it a *critical technical object*, after Phil Agre, that elicited reflections on the design process? Was it a *participatory object* that surfaced collective investments and desires? Or, following media scholar Jüssi Parikka, was it a function of *media archeology* wherein the reassembly of past artifacts recovers their instrumentation for the present?

Each of these constructs seems to capture some aspects of our process while overlooking others. Collectively they suggest that HCI’s methodological toolkits for design research, critical making, or adversarial design may need new tools for turning activist aims and participatory proposals toward social and historical inquiry. Historically-informed design artifacts such as the Quilt present their own inquisitive propositions for understanding design labor — both today and in historical narrative. Our work thus pushes HCI researchers to partner with historians and other cultural critics in materializing absences: revisiting the design and engineering practices that systematically disappear but still haunt our present. By forging new alliances between archival resources and design techniques, HCI scholars might formulate *materializing absences* as an approach to confronting and investigating fading historical horizons.

CONCLUSION

By interrogating connections between textiles and engineering, and enlivening a forgotten legacy of woven software, our project brings important histories to HCI today. Here we suggest that HCI’s gendered visions of innovation in the past create absences about what we can know in the present. Doing this project meant facing the fact that perhaps every woman who could tell this story is now gone. And while the accounts of the engineers and astronauts are canonized through our achievements — our giant leap for all mankind — we may never know the experiences of the Little Old Ladies (Figure 5). Because we neglected to collect their stories in the past, we fail to know them in the present. Reviving their accounts informs our contemporary understanding of what innovation looks like and, in turn, shapes possibilities for building technology otherwise.

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