Expertise in the Age of Digital Fabrication

by

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Abstract

This dissertation investigates the history, development, and practical application of digital fabrication. I leverage past and current scholarship from the fields of information, science and technology studies, and the history of computing in order to examine the themes of automation, control, and expertise. As current developments in artificial intelligence demonstrate, emerging computational technologies continue to re-configure normative roles and relationships in society. Previous studies of computation and labour have demonstrated that certain kinds of abstract expertise or knowledge are privileged by these changes. Understanding how and why certain kinds of abstract expertise and knowledge were privileged in the past, and how this informs current versions of these systems, is therefore critically important given the current rhetoric around automation and the future of work. My research seeks to actively re-engage the role human actors play in the technological mediation of labour, addressing the epistemic hierarchies produced by digital design and manufacturing technologies. I accomplish this by combining historical analysis of archival resources and
ethnographic fieldwork to examine the origins of numerical control (N/C) and computer-aided design (CAD) in manufacturing and their shift into new professional contexts, specifically the field of prosthetics and orthotics (P&O). I chose P&O because the labour and expertise utilized by the profession is separate from the epistemic considerations of digital fabrication. As such, specific sets of knowledge practices within the field of P&O do not translate cleanly to computational outcomes. Yet, I found that professionals within this context were willing to adopt these technologies as it allows for their expertise and labour to be expressed to those outside the profession. Within the context of information studies, this dissertation provides the historical and evidentiary ground work necessary for understanding and addressing the processes behind why certain kinds of labour, expertise, and knowledge become configured as appropriate for humans.
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Chapter One

The Coming Revolution

1.1 Overview

In this introductory chapter, I provide an overview of my research into digital fabrication and issues of automation, labour, and expertise. My dissertation examines how human labour and expertise has been transformed beginning in the late 1940s as computers became seen as more intelligent. I contextualize my research in the larger narrative of the future of work by exploring the themes present in the monograph The Fourth Industrial Revolution by economist Klaus Schwab of the World Economic Forum. Through this context, I illustrate how technologies such as digital fabrication are discursively leveraged to alter the social and cultural institutions that govern work. I argue that while these narratives are often appealing, they do little to help us understand the historical, cultural, political and material contexts through which labour and expertise is transformed and, more importantly, who benefits from such transformations. I conclude with a breakdown of the remaining chapters of the dissertation.

1.2 Expertise in the Age of Digital Manufacturing

In August of 2016, I traveled to the Cambodia School of Prosthetics and Orthotics (CSPO) in Phnom Penh, Cambodia. While there I was given a tour of the training and rehabilitation facilities of the clinic. During this tour I was shown a centrally located cabinet that contained various prosthetic devices that had been fashioned and used by patients prior to their fitting by prosthetics and orthotics (P&O) professionals (Figure 1). These patient made devices allowed for a limited form of mobility and could only be worn for relatively short periods of time. As I was being shown these patient devices I was told that the clinic kept them as a reminder of both the “need” and “importance” of
P&O devices. This need was exemplified by the fact that these devices exist. That is, while these patient made devices are imperfect in many regards, they are still produced and used. Similarly, the importance of P&O devices was demonstrated by the fact that while these patient-made devices had their limits they returned a sense of normalcy to the patients. Or, to put it more simply, patients wore these devices in order to allow them to engage in activities that would otherwise not be possible. In my discussions with the clinicians at CSPO a great deal of emphasis was placed on these devices allowing patients to work. This was because many of the patients that the clinic saw were impoverished and, as such, being able to engage in activities that would allow them to generate income was seen as vital.

Following this tour I was given an opportunity to discuss the use of digital fabrication for P&O work with the clinicians at CSPO. Broadly construed, digital fabrication is a process of design and production that combines Computer-aided Design (CAD), or 3D models, with additive and/or subtractive manufacturing, or 3D printing and automated machining (Mellis et al., 2013). Given the perception of digital fabrication within the popular media, especially that of 3D printing, as a technology that essentially allows a labour free form of design and production, the response I expected from the clinicians was either that of enthusiasm or rejection in regards to its integration into P&O work. Yet, largely, I did not get this reaction. Rather, the CPSO P&O spoke both optimistically and skeptically about digital fabrication. The optimism stemmed from a belief that the traditional method for making P&O devices, which I will describe in more detail in later chapters, could be improved upon. The skepticism, conversely, was the result of the P&O professionals being unsure if digital fabrication technologies were an appropriate fit for their labour and expertise. The focus of my dissertation is this question about the appropriateness of digital fabrication in regards to the labour and expertise of P&O professionals, and what this can tell us about the construction of what is seen as appropriate labour and expertise for humans.
(Figure 1 – Patient-made prosthetic devices from CSPO)
The primary research question (R1) for this project is: how did concepts of machine intelligence transform the human labour in Prosthetics and Orthotics work? The popular perception of digital fabrication is as a technology or process that allows a model of design and manufacturing that is essentially labour free. Within this framework humans engage in the activity of conceptualizing a design which is then materially manifested by a computer using either additive or subtractive manufacturing. As such, referring to digital fabrication technologies or processes as ‘labour free’ is somewhat disingenuous as the abstract labour of producing the design remains a part of the process. Yet, despite this mischaracterization, these narratives are helpful as a means of grounding my research in the larger question of what is appropriate labour for humans. These narratives often lack clear criteria for explaining the processes by which tasks become configured as either appropriate for humans or appropriate for intelligent computers or machines. Thus, my examination into this question of the transformation of human labour requires an understanding of how and why certain kinds of work are seen as appropriate for humans, as well as what it means to refer to a computer or machines as intelligent.

To accomplish this understanding I used a cultural historical analysis and action research to develop and refine three secondary research questions. The first of the secondary research questions (R1A) was: what are the historical, cultural, and material moves that have contributed to this transformation? The second secondary research question (R1B) was: what are the notions of expertise that are fostered by this transformation? The final of these secondary research question (R1C) was: who benefits from this transformation of human labour and expertise?

I chose digital fabrication as a site because it offers a clear context in which the transformation of human labour in response to intelligent computers is the most extreme. Beginning with the development of Numerical Control (NC) in 1949, digital fabrication researchers have sought to redefine the kinds of labour that are appropriate for humans. Through this work, digital fabrication has spread into a variety of work and knowledge contexts including architecture (Negroponte, 1970; 1975) and prosthetics.
1.3 Another Industrial Revolution

The common claim about 3D printing and digital fabrication is that it allows for a model of design and manufacturing that is labour free. Over the next few sections of this chapter I contextualize this claim as part of a much larger narrative around the impact that digital technologies are having on work. My reasons for doing so are twofold. First, as part of this larger narrative, 3D printing and digital fabrication technologies are being leveraged as discursive resources by researchers and organizations seeking to have broad social and cultural impact. Second, this larger context allows me to introduce many of the themes and concepts that I examine in this dissertation.

In his monograph *The Fourth Industrial Revolution* (2016) economist and engineer Klaus Schwab, founder and executive chairman of the World Economic Forum, argued that the increased sophistication and integration of technologies across the physical, digital, and biological domains marked the beginning of a new industrial revolution (Schwab, 2016, pp. 11-12). Schwab justified this declaration of a new industrial revolution, as opposed to merely a continuation of the third industrial revolution, by suggesting that “technology and digitization will revolutionize everything, making the overused and often ill-used adage ‘this time is different’ apt. Simply put, major technological innovations are on the brink of fuelling momentous change throughout the world — inevitably so” (Schwab, 2016 p. 14). The momentous change described by Schwab include the erosion and replacement of the cultural, social, and economic frameworks that defined work since the early 20th century. It is this spectre of a new framework for governing something as fundamental as work that motivated Schwab to write his monograph, as he felt steps needed to be taken in order to ensure that the fourth industrial revolution was “empowering and human-centred” rather than “divisive and dehumanizing” in its transformations (Schwab, 2016 p. 9). All work, no matter the
nature of the job, would be affected by technology, and thus this framework needed to be established in order to ensure humans would not be relegated to the kind of dehumanizing, unimaginative, and routine work that was prime for automation.

After establishing his definition of the fourth industrial revolution, Schwab then provided an overview of its technological drivers (Schwab, 2016 p. 19). These, according to Schwab, can be clustered into the categories of physical, digital, and biological. The physical cluster is comprised of technologies such as 3D printing which are tangible in nature and have the capacity to directly interact with the material world (Schwab, 2016 p. 19). The digital cluster is comprised of technologies such as the internet of things (IOT) which allow for “a bridging between the physical and digital applications” (Schwab, 2016 p. 22). Also contained within the digital cluster are new economic models, such as Uber which uses a peer-to-peer model for a variety of transportation related services, that leverage ubiquitous digital computing (Schwab, 2016 p. 23). Finally, the biological cluster is comprised of technologies such as genetic engineering which allow for digital control over biological functions (Schwab, 2016 p. 24). The majority of Schwab’s discussion of these clusters is descriptive in nature, but it is worthwhile to acknowledge and unpack what Schwab means when he refers to the “technologies of the fourth industrial revolution” (Schwab, 2016).

Following the descriptions of these clusters of technologies, Schwab next discussed in more detail the various transformations to work that will occur. A central component of these discussions is the theme of automation. As Schwab explained:

Many different categories of work, particularly those that involve mechanically repetitive and precise manual labour, have already been automated. Many others will follow as computer power continues to grow exponentially. Sooner than most anticipate, the work of professions as different as lawyers, financial analysts, doctors, journalists, accountants, insurance underwriters or librarians may be partially or completely automated. (Schwab, 2016 p. 39)
Here, Schwab is highlighting how professions that have traditionally been seen as cognitively intensive and high-skill suddenly find themselves susceptible to logics of automation. Schwab notes that, “In the foreseeable future, low-risk jobs in terms of automation will be those that require social and creative skills; in particular, decision-making under uncertainty and the development of novel ideas” (Schwab, 2016 p. 43). What Schwab suggests is that human labour will become confined to tasks that are definitional and creative in nature while all other tasks can and will be handled by intelligent computers.

A key concern in this transformation is the effect automation will have on female-dominated job categories, which Schwab notes would be a significant detriment particularly to low-skilled women and by extension single-income, female-led households. Due to the prevalence of men in fields with specialized technical skills (i.e. computer science, mathematics), the transformations of the fourth industrial revolution have the capacity to further widen the gender gap with respect to the value of expertise and of wages. This widening would “increase both inequality overall and the gender gap, making it more difficult for women to leverage their talents in the workforce of the future.” (Schwab, 2016 p. 46). While Schwab conjectures that there could be an increased demand for work that is more female-dominated, “psychologists, therapists, coaches, event planners, nurses and other providers of healthcare”, he concedes that given many of these roles are less technically-focused there is a likely future in which these roles remain undervalued (Schwab, 2016 p. 46). The fourth industrial revolution, therefore, must take this opportunity to reframe labour and business practices to appropriately empower men and women.

Schwab places this transformation within the historical context of the transition from that of hand production to that of mechanical production that characterized the first industrial revolution. In doing so Schwab is seeking to highlight the seemingly

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1 The first industrial revolution, as described above, saw the transition from hand production to that of mechanical means of production. While there is no set period for when it occurred, historians and researchers generally attribute the period between 1760 to 1860 as the “first industrial revolution” (Deane, 1979). The second industrial revolution was a period of rapid industrialization which saw the widespread expansion of electricity, steel, and petroleum. Historians attribute the period between 1870
continuous impact that automation has had on work since the 18th century. Although this historical context is helpful in so far as it illustrates that the theme of automation is by no means novel to the fourth industrial revolution, it provides little insight in terms of why some forms of cognitively intensive and highly skilled labour become subjected to logics of automation while others do not. This dramatically undercuts the kinds of understandings that can be achieved through an examination of the historical record. In his monograph *The Forces of Production* (1986) historian David Noble examined the development of Numerical Control (NC), which was one of the central technologies of the third industrial revolution. In his analysis Noble illustrated the historical, cultural, and political context around the development of this technology as a means of explaining why the labour of machinists was specifically targeted for automation (Noble, 1986). In my own research I examine the development of digital fabrication as a means of how, beginning in the late 1940s, human labour was transformed as computers became seen as intelligent. Such an analysis reveals why certain kinds of human labour became subjected to the logics of automation.

**1.4 Expertise and Revolutions**

In Schwab’s analysis of the future of work he also discusses the theme of expertise. As I described earlier, Schwab argued that the jobs that were at low-risk of automation as the result of the fourth industrial revolution were those that required social skills and creative thinking (Schwab, 2016 p. 43). He goes on to suggest that:

> Traditional definitions of skilled labour rely on the presence of advanced or specialized education and a set of defined capabilities within a profession or domain of expertise. Given the increasing rate of change of technologies, the fourth industrial revolution will demand and place more emphasis on the ability of

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...
workers to adapt continuously and learn new skills and approaches within a variety of contexts. (Schwab, 2016 p. 47).

What Schwab suggests here is that the essential characteristic of expertise in the fourth industrial revolution is the ability to learn new skills and then to adapt them to different contexts. These concepts of continuous development and adaptability are so ingrained within Schwab’s framework of expertise that they supplant the traditional conceptions of expertise established during the second and third industrial revolutions in terms of domain specificity and advanced education.2

This narrative of technological revolutions defining, or re-defining as it were, expertise is not unique to Schwab. In the monograph Economy of Machinery and Manufacturing (1832) Charles Babbage provides a firsthand account of his experience visiting various factories in England during the 19th century (Babbage, 1963). Central to his discussions on the development of mass production is a distinction that he made between making and manufacturing. Making, Babbage explained, was the work of a single or small group of craftspersons whose production runs were small and in which accuracy and speed were not central factors (Babbage, 1963). Manufacturing, conversely, involved the organization of large groups of individuals with varying degrees of skill in order to produce large volumes of goods or small runs in which accuracy and speed of production were the most important characteristics (Babbage, 1963). In making this distinction between these two modes of production, Babbage was able to introduce a new form of expertise in the form of management and planning (Babbage, 1963). While making was dependent upon the skills of the craftspersons involved in the production, the locus of expertise in manufacturing had to be broadened to include the management that oversaw these factories and organized the labour (Babbage, 1963). Babbage’s framework of production led to widespread intellectual debate around what these new forms of labour would be, including a response from Marx in which he criticized Babbage’s framework for its contributions to

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2 Parallels can be drawn between Schwab’s analysis and Marxist theory on disassociation of labour from the skill of workers. Harry Braverman describes this disassociation in his monograph Labour and Monopoly Capital (1998).
the division of labour on an international scale, and its alienation of workers from their own labour (Marx, 1990).

Similarly, in *The Coming of the Post-Industrial Society* (1976) Daniel Bell, a professor of sociology at Harvard, discussed the development of a new kind of expertise, such as micro- and macro-economics, that supported the production of abstract or general knowledge as the result of the United States moving from a manufacturing based economy to a service based economy during the third industrial revolution (Bell, 1976). What these examples illustrate is that these narratives of technological revolution and expertise and their institutionalization with social and material infrastructures are a means of transforming the conceptions of human labour by suggesting that new kinds of knowledge or skills are now required.

As part of his discussions on expertise and the fourth industrial revolution, Schwab described how the cultural and social institutions and organizations that are responsible for work will need to adapt in order to support the skills and knowledge of these experts. As Schwab explained:

> My sense is that successful organizations will increasingly shift from hierarchy structures to more networked and collaborative models. Motivation will be increasingly intrinsic, driven by the collaborative desire of employees and management for mastery, independence, and meaning. This suggests that businesses will become increasingly organized around distributed teams, remote workers and dynamic collectives, within a continuous exchange of data and insights about the things or tasks being worked on. (Schwab, 2016 p. 60)

Here, Schwab describes a future of work that is dynamic in nature as a means of ensuring that the various kinds of expertise required for the task are available when necessary. What is important to note about the framework of expertise described by Schwab is that it is supposedly assumed to be non-hierarchical, meaning that different kinds or notions of expertise are all seen as equally valuable. Yet, as scholars such as
Susan Lee Star and Anselm Strauss (1999), Ursula Huws (2014), and Lucy Suchman (1996) have illustrated certain forms of expertise, knowledge, and information are often privileged within technological systems. Certain forms of labour and expertise, namely male-oriented, technical labour and expertise, become of the highest value as they are a means to a technical end.

As part of my dissertation I explore the notions of expertise and information that are fostered by digital fabrication systems. In doing so it is possible to understand why certain kinds of expertise and information became identified as more valuable or important in response to this transformation of human labour as computers became seen as more intelligent.

1.5 The Politics of Control

The final theme that I want to touch upon that Schwab discussed is that of control. In the previous section I highlighted Schwab’s argument that institutions and organizations will need to develop non-hierarchical structures as a means of effectively utilizing the kinds of expertise that are both produced and needed as part of the fourth industrial revolution. As part of these discussions Schwab suggests that they will result in a new framework of control that returns a sense of ownership of labour to workers (Schwab, 2016 p. 50). As Schwab explains:

For people who are in the cloud, the main advantage resides in the freedom (to work or not) and the unrivalled mobility that they enjoy by belonging to a global virtual network. Some independent workers see this as an offering of the ideal combination of a lot of freedom, less stress and greater job satisfaction (Schwab, 2016 p. 50)

For Schwab, the cloud refers to the human cloud, which is a catch-all term for services that allows organizations to hire independent workers to perform tasks for which they are specifically and highly qualified (Schwab, 2016 p. 49). The most important
characteristic of this cloud, according to Schwab, is the freedom that it gives to workers to pick how and where their labour and expertise are applied (Schwab, 2016 p. 49). Doing so not only gives workers a sense of ownership over their own labour, as they get to determine the conditions and context in which it is applied, but also restores a sense of purpose to workers as they can choose to work on tasks meaningful to them (Schwab, 2016 p. 51). Thus, this notion of freedom, defines the framework of control and supposedly alters the longstanding relationship between workers and their own labour established during the first industrial revolution. In other words, the cloud offers a response to the issues of alienation and commodification described by Marx (1990).

As part of his discussions about the theme of control and the fourth industrial revolution Schawb returns to the theme of automation as a means of noting how this freedom will contribute to the transformations of the social and cultural institutions that govern work. As Schwab explained:

Michael Osborne [a professor of machine learning at Oxford university] observes that a critical enabling factor for automation is the fact that companies have worked hard to define better and simplify jobs in recent years as part of their efforts to outsource, off-shore and allow them to be performed as “digital work” (such as via Amazon’s Mechanical Turk, or MTurk, service, a crowdsourcing internet marketplace). This job simplification means that algorithms are better able to replace humans. Discrete, well-defined tasks lead to better monitoring and more high-quality data around the task, thereby creating a better base from which algorithms can be designed to do the work. (Schwab, 2016 p. 43)

Here, Schwab describes how companies have become better at simplifying and defining tasks. This process has allowed companies to either use the labour of intelligent computers or, if no such machine is available, employ workers on an on-demand or as needed basis. Furthermore, because these tasks are simple and well-defined, the labour of these on-demand works can be turned into data that can be eventually used to produce an intelligent computer to perform these tasks. As such,
Schwab goes on to argue that only workers whose labour requires social and creative skills, that is to say workers with jobs with a low-risk of automation, will truly benefit from this new framework of control (Schwab, 2016 p. 55). This argument by Schwab is important as it effectively highlights the potential inequalities in the future of work that he describes but a broader perspective is required in order to address the power structures at play. Dianna Forsythe (2001), Philip Agre (Agre and Chapman, 1989;1997), and Rodney Brooks (1991a;1991b) have described how abstractions of work or labour do not fully capture the complexities of these tasks. This is because those creating these abstractions are often outside the context of the work and have their own political, social, and cultural reasoning for configuring these tasks as such. Within my own research I examine how the concept of intelligent computers affected the notions of expertise and work in regards to human labour and who benefits as a result of this transformation.

Through these themes of automation, expertise, and control, Schwab sought to address how the technologies of the fourth industrial revolution would alter something as fundamental as the concept of work. While his analysis serves as a good starting point, as it effectively captures many of the popular perceptions about these technologies, what I have illustrated in this section is that Schwab’s framework is built to conceptualize a future of work in which abstract knowledge plays a specific and central role. There are, however, other forms of labour and expertise that need to be accounted for which are essentially stripped from Schwab’s analysis. It is these other forms of labour and expertise I will be addressing in this dissertation, which I outline in the next section.

1.6 Overview of Chapters

In Chapter Two, I provide an overview of the methodology and the sites of this dissertation. The methods I used for this dissertation are a combination of cultural historical analysis and action research. I started by conducting archival research at the Institution and Special Libraries Archive at the Massachusetts Institute of Technology
in order to understand the historical narrative of labour and expertise in digital manufacturing that largely originated at MIT. For my field work I worked with Nia Technology, a non-profit social enterprise that is developing a 3D printing prosthetic solution for the developing world, in Toronto, Ontario. Finally, I visited and conducted interviews with prosthetic and orthotic professionals at four of the sites where Nia deployed this solution. I conducted in-person interviews at one site (Phnom Penh, Cambodia) and I used Skype for the remaining site interviews (Uganda and Tanzania).

In Chapter Three, I discuss the MIT Innovations in Manufacturing Technology Project which took place from 1949 until 1969. This chapter draws on material that I collected from the MIT Archive in order to answer my secondary research question (R1A): “what are the historical, cultural, and material moves that have contributed to this transformation?”. As part of this analysis I introduce the concept of the creative-routine dichotomy, a conceptual framework established and refined over the course of the MIT Innovations in Manufacturing Technology Project, as a means of explaining how the division between human and intelligent computer labour, was established.

In Chapter Four, I examine how the aforementioned creative-routine dichotomy contributed to the expertise of engineers moving from that of producing material objects to that of making abstract models. In this chapter I draw on Katherine N. Hayles’ (1999) concept of the Platonic backhand and forehand as a means of understanding the implication of this shift in engineering expertise. This chapter addresses my second secondary research question (R1B): “what are the notions of expertise that are fostered by this transformation?”

In Chapter Five, I use descriptions of the development of digital fabrication solutions for prosthetics and orthotics (P&O) starting in the 1960s to examine my final secondary research question (R1C): “who benefits from this transformation of human labour and expertise?”. By examining these various attempts at developing what is essentially an engineering solution to a P&O problem, I illustrate how the notions of expertise and
information that I described in previous chapters move into different contexts of work, and the resulting impacts and responses by P&O professionals.

In Chapter Six, I describe the exit and entrance interviews that I conducted with P&O experts that were trained on, and used, the Nia 3D printing solution. I use the data from these interviews to discuss how individual practitioners see the transformation of their labour practices. From these interviews I was able to draw two conclusions. First, many of the experts struggle with the underlying approach used in the Nia solution due to unfamiliarity with the technology as well as differences between the software and their own personal practices. Second, while the experts all had their concerns about the solution, the majority of them were in favour of its implementation due to the capacity to render their labour and expertise visible to those outside of the P&O community.

In Chapter Seven, I revisit the major themes of this dissertation, as well as Schwab’s concept of “the future of work” as a means of discussing the processes through which human labour and expertise is transformed by intelligent machines. After looking at my research questions and discussing the conclusions that I can draw based upon my analysis, I return to Schwab’s concept of the “future of work”. Drawing on the historical and ethnographic research I conducted I illustrate how the claims made by Schwab are technologically deterministic and simplify the process by which certain kinds of labour and expertise become re-configured as appropriate for human and intelligent computers. As part of these discussions, I present a framework that seeks to illustrate the complexities of this process. Next, I highlight the contributions that my dissertation makes to both the P&O community as well as the scholarly communities of Information Science, Science and Technology Studies (STS), and Human Computer Interaction. I conclude by noting the limitations of my dissertation as well as the future directions of my work.
Chapter Two

Methods for Understanding The Revolution

2.1 Overview

In the previous chapter I outlined the research questions and major themes of this dissertation. In this chapter, I discuss the methodologies used to develop and address these research questions. I begin by providing an overview of my work on the Camera Obscura Project. This project involved me producing and using several 3D printed cameras. As a result of this project I developed the early research questions for this dissertation. Next, I discuss my methodological approach that linked action research and cultural historical analysis. I then briefly discuss my perspective as a researcher and any potential issues of bias within my research. Finally, I describe the methods I used to collect and analyse my data, which included archival document analysis, fieldwork, and interviews.

2.2 Scope of the Project

In the introduction to this dissertation I outlined the research questions that guided my work. The primary research question (R1) was: how did concepts of machine intelligence transform the human labour in Prosthetics and Orthotics work?. The secondary research questions were: what are the historical, cultural, and material moves that have contributed to this transformation? (R1A); what are the notions of expertise that are fostered by this transformation? (R1B); and who benefits from this transformation of human labour and expertise? (R1C). In this section I discuss how these research questions were developed.
(Figure 2 – Photo taken with 3D printed pin-hole camera)
My research in this area began in the fall of 2013 with the Camera Obscura Project. In this project I 3D printed a series of cameras whose designs were freely available in the online depository thingiverse (www.thingiverse.com) with the goal of engaging in an analysis of the materiality of digital fabrication technologies.

Developed in the 1980s, 3D printing, or additive manufacturing, is a process by which material is joined in layers in order to make three-dimensional objects. The original application for the technology was for the prototyping of parts; as a result of the high costs associated with its use the technology was limited to industrial applications (Lipson & Kurman, 2013). Desktop 3D printing, that is hobbyist and consumer grade machines, emerged in the mid-2000s. In 2005, the RepRap project was started at the University of Bath, which sought to develop low-cost 3D printers that were capable of printing most of their own components. As a result of the RepRap project several companies formed which began selling 3D printer kits to hobbyists. These hobbyist desktop 3D printers, unlike their industrial counterparts, were infused with a political techno-utopian ideology that signalled to users that they now had the capacity to effortlessly reshape the digital and material world (Gershenfeld, Cutcher-Gershenfeld, & Gershenfeld, 2017).

To explore these claims about the material and the digital I printed a series of cameras. The various difficulties that I faced producing, or rather reproducing, these cameras and getting them to properly function highlighted that the design files I downloaded from thingiverse were somehow insufficiently detailed (Figure 2). I encountered difficulties in translating the files, which were designed in Europe and thus used European standards for screws and other components, when attempting to make the camera. Ultimately I was able to print the camera, but not assemble it due to these constraints. This process led me to examine the broader social, cultural, and material perspectives that made these challenges inherent to the reproduction process despite my expertise with these technologies. Based upon my experience with the Camera Obscura Project I developed two early questions. The first was, what is expertise in the
age of digital manufacturing? And the second was, where did this concept of expertise come from?.

For the purposes of this research and my dissertation, my definition of expertise is the material and abstract knowledge of an individual put into practice. Essentially, individuals express their expertise in their capacity to internalize, synthesize, and act upon the material world using their knowledge, particularly in situations where the material world contains ambiguous properties. This definition is focused on how an individual’s expertise is applied and used, not how expertise is formed or learned. This definition draws from Julian Orr’s concept of technical expertise: “expertise is in part the ability to interpret [...] anecdotes, to abstract the information about the machine from the context of the story” (Orr, 1986 p. 62; Orr, 1996), in which expertise is in part formed by individuals’ ability to build from prior experience in practical settings.

I refined these two early research questions through a combined engagement with a pre-existing 3D printing prosthetics project that was occurring at the Critical Making Lab at the University of Toronto, and historical work that had been written about the development of digital fabrication technologies.

In 2013, my supervisor Matt Ratto was approached by Christian Blind Mission (CBM) Canada regarding the possibility of developing a 3D printing solution to assist developing world clinics with prosthetics and orthotics (P&O) work. As a result of this work the non-profit Nia Technologies was formed in 2015 in order to produce a toolchain, that is a series of interconnected pieces of software, that would allow a prosthetist to use a 3D scanner to scan a patient’s leg, digitally design the prosthesis, and then 3D print the prosthetic device so it could be fitted to the patient. The development for this toolchain occurred in Toronto, Ontario at the Nia office and the Critical Making Lab which were both housed in the Robarts Library Complex (130-140 St. George Street). My involvement with the project, which I will discuss in more detail

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3 As an organization Nia Technologies has received funding from: cbm Canada; Grand Challenges Canada; Autodesk Foundation; Google.org; Stronger Philanthropy; and the Jericho Foundation (“Nia Technologies – Founders”, 2018.)
later in this chapter, started in a technical capacity. As I become more familiar with the project, I refined my first early research question: “what is expertise in the age of digital manufacturing?”. Specifically, I became interested in similarities and differences in the notion of expertise as understood in relation to digital manufacturing technologies and the notion of expertise as understood by P&O professionals.

I also began to explore the origins of 3D printing technology in order to get a better sense of the logics and assumptions of expertise that were embedded into the technology. As part of this exploration I looked into the development of G-code, which is the file format and standard used to convert design files into ‘instructions’ that can be used by 3D printers (Overby, 2010). This led me to the work of the late historian of technology David Noble, as G-code was originally developed in conjunction with Numerical Control (NC). In reading Noble’s monograph The Forces of Production (1986) I became familiar with the Massachusetts Institute of Technology’s (MIT) Innovations in Manufacturing Technology Project and the work of William Pease and Douglas Ross who were researchers at MIT’s Servomechanism Lab, and Steven Coons who was a professor at MIT’s Mechanical Engineering Department, into these digital design and fabrication technologies starting in the late 1940s. After examining some of the papers written by Ross and Coons in the late 1950s and early 1960s about the concepts of machine intelligence and the respective roles of humans and computers in the design process I began to refine my second research question: “where did these concepts of expertise come from?”. The questions that I started to developed focused on understanding what Ross and Coons meant when they referred to the concept of ‘machine intelligence’ as well as how the concept of ‘machine intelligence’ was developed.

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4 I want to briefly note some of the research topics that emerged during this process of refining my research questions that I will not be covering in this dissertation. In the 1950s and 1960s this concept of ‘machine intelligence’ by researchers other than Ross and Coons, most notably Marvin Minsky and John McCarthy who were also at MIT (Minsky, 1966; McCarthy and Hayes, 1981). Much has been written about the impact that Minsky and McCarthy respectively had on the development of ‘artificial intelligence’ both as a discipline and as a philosophical inquiry. The exclusion of their work might appear to be a major oversight but this was a choice I made deliberately, as the focus of my work is how these technologies have effected concepts of expertise and labour within different kinds of work contexts.
intelligence’ affected what were seen as ‘appropriate’ forms of expertise and labour for humans.

With my research questions refined, though not yet in their final form, I began to examine methodologies that would be appropriate means for examining them. The approach that I determined that would best allow me to address these questions combined action research and cultural historical analysis. I selected action research and cultural historical analysis to better understand where the expertise embedded in digital manufacturing originated and how it has been carried forward in these technologies, and to compare these claims to current practice in order to critically assess current systems of digital manufacturing and why they may or may not work effectively.

2.3 Methodologies

Following my initial engagement with Nia Technology and historical archival work at MIT I refined my early research questions to specifically address how the concepts of expertise and labour in P&O were similar and different to those found in past research into digital fabrication technologies. In this section I provide an overview of action research and cultural historical analysis, the two methods I used in my dissertation, a discussion of why I selected them, and the limitations of my analysis. I conclude this section by restating the research questions that guided my work in this dissertation and explain why it was important to combine these two approaches in order to answer these questions.

rather than the evolution of the mechanical intelligence concept or the field of artificial design. I plan to return to Minsky and McCarthy's work in future research, as comparing and contrasting their concept of 'mechanical intelligence' to those found in digital fabrication technologies might provide new and novel insights.
Action research is an applied form of social research in which researchers and participants collaborate in order to solve a problem faced by the participant community (Jupp, 2006a; Whitehead and McNiff, 2006). The defining characteristic of action research is its collaborative nature, which is what sets it apart from other forms of evaluative research that seek to measure the impact of an intervention without the active participation of the participant community during the development process (Jupp, 2006a; Whitehead and McNiff, 2006). This deliberate inclusion of the participant community in the intervention development process, beginning with identification of the problem, is a means for reducing the social distance between the researchers and the research subjects as well as promoting change by empowering the participant community through their shaping of the intervention (Jupp, 2006a; Whitehead and McNiff, 2006).

The major limitations of action research is that of ambiguity regarding progress and concerns about objectivity. The development of interventions using action research is a fluid and ongoing process between researchers and the participant community; as such it can often be challenging to identifying the research stage or when major milestones in the project have been reached (Jupp, 2006a; Whitehead and McNiff, 2006). This can result in tensions between the researcher and the participant community who are actively looking for a solution to a problem (Jupp, 2006a; Whitehead and McNiff, 2006). As such, an important element of action research is managing the relationship between the researchers and the participant community in order to ensure the needs of both groups are being actively met (Jupp, 2006a; Whitehead and McNiff, 2006). Finally, this relationship between the research and the participant community might also lead to issues with objectivity. The closeness of the researcher to the participant community can lead to potential issues of bias (Jupp, 2006a; Whitehead and McNiff, 2006). Once again this speaks to the importance of managing the relationship between the researcher and the participant community and the objectives of the project, as this helps to ensure that there is a degree of independence between these two groups (Jupp, 2006a; Whitehead and McNiff, 2006).
The limitations of my role and research in the prosthetic and orthotic community are further described in Chapter Six.

In describing action research, Waterman et al (2001) suggested that it can break from the status quo and address questions regarding other possibilities as the collaborative nature of the research encourages both the researchers and participants to address or confront previously held assumptions. This was the reason why I selected action research as one of my methodologies, as it allowed for a deep reflection on how digital fabrication technologies could affect the labour and expertise of P&O professionals while also actively engaging this group in the process. Prior to my research other groups have attempted to develop 3D printing solutions using recent developments in the technology for P&O work, but P&O professionals had been left out of the development of these interventions (Zuniga et al, 2015; Zuniga et al, 2016). As such, the P&O community was deeply skeptical of 3D printing solutions while also acknowledging that the technology might be able to solve some of the issues faced by the profession (Diment, Thompson, & Bergmann, 2018). Action research, thus, allowed me to refine my early research questions to better address the impact the technology would have on the profession while also ensuring that the P&O community had an active voice within my research.

Cultural historical analysis, the other methodology that I used, involves researchers engaging in a systematic and disciplined review of written documents and other materials that have been left behind in order to make sense of the past (Jupp, 2006b; Pierson, 2004). For social research, cultural historical analysis is used as a means for providing context or background for the issue or problem being studied (Jupp, 2006b; Pierson, 2004). Through this engagement with the historical record, cultural historical analysis allows researchers to challenge present dominant social and cultural assumptions by illustrating their origins (Jupp, 2006b; Pierson, 2004).

The limitation of cultural historical analysis is its inability to address the voices of the marginalized. The historical record is predominately comprised of the voices of elites
and of the dominate social and cultural perspective of that era. As such, it can be challenging if not impossible to find the documents that speak to ‘other’ perspectives (Jupp, 2006b; Pierson, 2004). Addressing this limitation is by no means an easy feat, but in the very least it requires acknowledging that there are perspectives missing from the research.

The kinds of questions that cultural historical analysis allows social researchers to ask are variations of ‘how did we get to now?’ (Johnson, 2015). I selected cultural historical analysis because of this capacity to provide context. Using this methodology I refined my early research questions to address the logics and philosophies that have been embedded in digital fabrication technologies about the concepts of labour, expertise, and machine intelligence.

Based upon this approach of incorporating action research and cultural historical analysis the primary research question (R1) that I developed was: how did concepts of machine intelligence transform the human labour in prosthetics and orthotics work?. The secondary research questions were: what are the historical, cultural, and material moves that have contributed to this transformation? (R1A); what are the notions of expertise that are fostered by this transformation (R1B); and who benefits from this transformation of human labour and expertise? (R1C). The formulation of these questions reflects the seemingly strange technical, philosophical, and historical work that characterize my research in this dissertation. Taken as individual pieces these three perspectives might appear as if they are barely connected. Yet, when they are narratively taken as a whole they provide the capacity to understand complex insights both about the problems being faced by the P&O community that I was seeking to help and about how digital fabrication technologies have been leveraged since the early 1950s as means to socially and culturally reconstruct the concepts of expertise and labour. It is for these reasons that I have engaged in this form of research that sutures these methodologies together.
2.4 Research Perspective

Previously in this chapter I briefly outlined my work on the Camera Obscura Project. This was one of several projects that I undertook in the Critical Making Lab prior to my dissertation work as a means of becoming familiar with digital fabrication technologies. In this section I will briefly outline some of these projects, as they played an important role in developing my expertise both as a researcher and in digital fabrication technologies. I will conclude this section by discussing the biases of this project and how I navigated them.

As I have already noted, in the Camera Obscura Project I reproduced several cameras whose designs were freely available in online depositories using 3D printing as a means of engaging in an analysis of the materiality of digital fabrication technologies. The process of fabricating the cameras needed for the project allowed me to become highly proficient with the 3D printing process. The various issues I faced in assembling the camera, moreover, also made me aware of the larger social, cultural, and contextual landscape these technologies are embedded in.

In 2014 I worked on a Mitacs project\(^5\) funded by Autodesk Research entitled The Discrete Practices of 3D Printing. As part of this project I interviewed nine experts about their individual practices of 3D printing. This experience played an important role in shaping the interviews that I would later conduct with P&O professionals regarding their individual practices, their perceptions of digital fabrication technologies, and usage of the Nia Technology 3D printing solution. Moreover, as part of this project I complied and analyzed these interviews in a final report (Southwick and Ratto, 2015). What my analysis of these interviews indicated was that the 3D printing practices of these experts were highly individualized and reflected both their professional needs as well as the context in which they worked (Southwick and Ratto, 2015). This concept of

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\(^5\) Mitacs is a not-for-profit Canadian organization that supports applied and industrial research in mathematics, science and associated disciplines. ("About Mitacs," 2014)
individualized practices and contexts in 3D printing played an important role in shaping how I approach the issue with respect to expertise and labour in both engineering and P&O work.

Finally, beginning in 2013 I began running workshops in the Critical Making Lab that taught students at the University of Toronto how to design simple objects in computer-aided design (CAD) software and then 3D print them. While these workshops were fairly simple, my experience running them supported my development as an educator of the technical skills required for digital fabrication technologies. This proved to be a vital skill, as part of my engagement with the P&O community and Nia Technology was in educating P&O professionals on the use of these technologies.

These collective experiences uniquely qualified me to engage in the research project that makes up this dissertation. These same qualifications are also how I became involved with Nia Technology and their work on a 3D printing solution for prosthetic devices in the developing world. It is this involvement with Nia Technology that I want to address in terms of any potential bias within my research project.

First, and foremost, my supervisor Matt Ratto serves as the Chief Science Officer for Nia Technology. This role is a potential conflict of interest depending on the information obtained and analyzed in my research. In order to mitigate this, as part of my ethics application to the Research Ethics Board (REB) of the University of Toronto to interview members of the P&O community, a protocol was established in which any disputes that might arise between myself and my supervisor regarding my findings would be resolved by the Associate Dean, Research of Research at the Faculty of Information (iSchool). This protocol was not used during the course of the project.

Secondly, part of my dissertation work was supported through a Mitacs project funded by Nia Technologies. As part of this grant I was given access to the organization and took on a series of roles that supported Nia’s work on 3D printed prosthetics. Moreover, the interviews that I conducted with P&O professionals as part of this
dissertation were also used in a presentation that I would give to Nia Technologies on my findings. The structure and the analysis of these interviews were not governed by Nia, and the resulting analysis was focused on the research questions of the dissertation. The interview participants were also informed both verbally and within the consent forms that their choice to participate or decline to participate in the interviews would not preclude participation in the training or support being offered by Nia. While it was not possible to fully de-identify the interview material due to the small pool of interviewees available, every effort was made to ensure there would be no risk to individual interviewees as a result of sharing any interview data.

2.5 Archival Work

My research into the development of digital fabrication technologies began, as I discussed earlier in this chapter, through an engagement with David Noble’s monograph Forces of Production (1986). Through this text I became familiar with the MIT Innovations in Manufacturing Technology’s Project (1949-1970) and the respective work of Pease, Ross, and Coons who were researchers or professors at MIT’s Servomechanism Lab or Department of Mechanical Engineering. In this section I outline the method by which I collected, sorted, and analyzed documents and other materials produced by Pease, Ross, and Coons about their research projects. As part of these discussions I highlight the two trips I took to the MIT Archive in 2016 and 2018 to examine the Servomechanism Lab Collection, which was the research lab that both William Pease and Douglas Ross belonged to, as well as Douglas Ross’ personal papers collection. I conclude this section by detailing how my analysis of these documents and other materials contributed to the development of automation, expertise, and control becoming the major themes of this dissertation.

After I reading Forces of Production by Nobles I was able to identify the MIT Innovations in Manufacturing Technology Project as the origin of digital fabrication technologies in the United States, and the roles of Pease, Ross, and Coons as primary researchers responsible for its development. As such, I began collecting the various
research papers written by these three authors that corresponded to the Innovations in Manufacturing Technology Project, as well as any technical reports and media coverage from that era. Based upon an initial survey of these documents and other materials, I constructed a timeline of the MIT Innovations in Manufacturing Technology Project, which broke it down into three sub-projects: Numerical Control (NC) (1949-55); Automatic Programming Tool (APT) Language (1956-1959); and Computer-Aided Design (1960-1970). Using this timeline I then began to map the ‘issues’ or ‘problems’ that each of the three sub-projects sought to address based on the research materials and other documents that I had gathered.

For the NC project this entailed bringing the logics of automation to the ‘metal-cutting industry’ as a means of improving the accuracy and economy of parts through the production of an ‘automatic milling machine’ (Pease, 1952). The APT project, keeping with the themes of efficiency, sought to make the programming of NC mills more ecumenical through the development of a computer language that was easy to learn and use (Ross, 1978). Finally, the CAD project involved the production of various computational systems that sought to give designers and engineers more ‘control’ of the production process (Coons and Mann, 1965). With the ‘issues’ and ‘problems’ that these various project sought to resolve established, I travelled to the MIT Archive in Boston, Massachusetts in order to determine how these were established as problem spaces as well as the processes by which these technologies were configured as solutions.

I first travelled to the MIT Institution and Special Library Archive in August 2016, where I examined the various documents and artefacts that comprised the Servomechanism Lab collection and the Douglas Ross personal papers collection. In addition to collecting primary accounts from all three sub-projects during this trip, I was also able to locate other research articles that had been published by Pease, Ross, and Coons that my initial searches did not uncover. Within these collections there were also newspaper and magazine articles that covered the various press conferences held by the Servomechanism Lab in relation to the MIT Innovations in Manufacturing
Technology project. My process for collecting documents was based upon reviewing the contents of each piece and then determining if it addressed questions regarding the development of the various sub-projects, or provided insight into processes by which the various problem spaces had been created.

Upon my return from the MIT Archive I began a more detailed analysis of the various documents and other materials I had collected; a complete bibliography of these materials can be found in Appendix A. It was during this second stage of analysis that I surfaced the notion of ‘machine intelligence’. Specifically, I noted a project dubbed 'Saga II' that Douglas Ross was part of in 1960 to produce a computer program to automatically generate scripts for TV Westerns. From this I was able to connect other research objectives that occurred throughout the MIT Innovations of Manufacturing Technologies project to the production of what were essentially ‘intelligent machines’ capable of undertaking certain kinds of labour in the manufacturing process. This led me to questions regarding how these notions of ‘machine intelligence’ produced alongside the MIT Innovations of Manufacturing Technologies project altered or sought to reconfigure what was seen as ‘appropriate’ labour and expertise for humans.

I returned to the MIT Archive in June, 2018 and collected additional documents and other materials from the Douglas Ross personal papers collection about the Saga II project. From these papers I was able to make a direct connection between the kinds of ‘machine intelligence’ described during the Saga II project and those found in the CAD project.

After my second trip to the MIT Archive I was sufficiently satisfied that I had collected enough documents and other materials about the MIT Innovations in Manufacturing Technologies project to illustrate the key logics and philosophies embedded within digital fabrication technologies. Throughout my two-plus year engagement with these documents I would routinely return to them as a means of contextualizing my research project. It was through these routine engagements with the writings of Pease, Ross, and Coons that I surfaced the themes of automation, expertise, and control that I use
in this dissertation. This occurred as a result of my mapping how these three authors discussed the development of their respective projects and the ‘issues’ and ‘problems’ they sought to address with them.

2.6 Field Work and Interviews

My research into the use of digital fabrication technologies for P&O work began in 2016 as the result of the aforementioned Mitacs project supported by Nia Technology. Prior to this I had provided technical support to Nia Technology on issues related to 3D printing, but this was in an informal capacity. In this section I outline my engagement with Nia Technology and their work on developing a 3D printing solution for prosthetics work in the developing world, known as 3DPA. As part of these discussions I highlight the entrance and exit interviews that I conducted with P&O professionals being trained on 3DPA.

After joining Nia Technology as a research assistant in the winter of 2016 I began attending weekly meetings, which included discussions of the development objectives for 3DPA. My role in this early stage was to provide feedback on these objectives, as well as to provide support for development of 3DPA outside these meetings.

As I became more familiar with 3DPA my role grew and I was able to attend various meetings held between Nia Technology and P&O professionals in Canada that were supporting development by providing their professional opinions. Through these interactions I was able to establish both a sense of what P&O professionals saw as their expertise, as well as the role they saw digital fabrication technologies playing within their profession. I was also able to observe P&O practices in situ and to learn the context of digital fabrication technologies within the P&O profession in advance of my field work and interviews.

In the summer of 2016 I traveled with Nia to the Cambodian School of Prosthetists and Orthotics (CSPO) in Phnom Penh, Cambodia. There I supported the training of P&O
professionals on 3DPA. This training focused on teaching the prosthetists how to use the various software and hardware elements of 3DPA. The training was technically focused to ensure the P&O professionals were comfortable with operating the 3D printers and troubleshooting potential production issues. While the training’s overarching objectives were to install a baseline knowledge set on how the technology operated and its maintenance needs, there was also ample opportunity for the P&O professionals to guide their own learning according to their professional needs and day-to-day practices, which made the training more collaborative. After finishing the training, the expectation was that prosthetists would be able to produce a prosthetic device with little to no guidance from Nia representatives. This was also an iterative process with constant feedback, wherein the professionals involved provided feedback on the utility of the 3DPA system to their work and also worked with Nia to articulate areas where the system could better meet their needs.

The interviews were conducted in two stages. The first stage, which was comprised of entrance interviews, was carried out in June 2016. These interviews were conducted during the training periods with P&O professionals at CSPO with nine staff members. All nine interviewees were trained P&O professionals who held a variety of roles at CSPO including patient-facing work and administration. These interviews were conducted in-person at the CSPO clinic at the individual interviewee’s convenience, and ranged from thirty minutes to one hour in length. The interviews were semi-structured, with nine pre-established questions. The goals of these interviews were to understand P&O professionals early impressions of 3DPA as a tool for their work, to gain an understanding of interviewees’ perspectives on digital fabrication technologies and their role in P&O, and to better understand interviewees’ own definitions of their professional expertise.

The second stage of interviews, the ‘exit’ interviews, occurred from April 2017 through July 2017 once I had returned to Canada. Practitioners from four clinics using 3DPA participated: Comprehensive Rehabilitation Service in Uganda (CoRSU), Cambodian School of Prosthetists and Orthotics (CSPO), Comprehensive Community Based
Rehabilitation in Tanzania (CCBRT), and Tanzania Training Centre for Orthopaedic Technology (TACOT). All participating prosthetists had formal training in the field of prosthetics and orthotics. When they were interviewed they were either directly involved in the production of P&O devices or were responsible for running a P&O clinic. These interviews were conducted approximately six months to one year after the participants had begun using 3DPA.

These participants were identified through their involvement with the Nia study and were subsequently asked, either in person or through email, if they would be willing to be interviewed regarding their experience with digital fabrication technology. A total of eight interviews were conducted with individuals from the four clinics, rather than solely targeting follow-up interviews with CSPO staff, for two main reasons: first, to obtain a broader array of perspectives from individuals who may have been using the technology for different time periods; and second, because the interviews were not conducted onsite and therefore any willing individual could participate. These interviews occurred via Skype, and were generally between one to two hours in length.

The exit interviews sought to address more directly what the participants’ interpretations of 3D printing in relation to their profession were, after using the technology, as well as their opinions on whether 3DPA was considered a viable solution for their longer-term work. The interviews were reflexive in nature and sought to uncover any enablers or gaps in 3DPA from both a philosophical, or professional level, as well as a technical one. Interview questions were developed through conversation and feedback from participants during the training and during troubleshooting calls held after the in-person training.

Following the interviews, which were transcribed, I conducted a thematic analysis on a per-question basis to better understand how P&O professionals felt about digital fabrication technologies, whether early impressions of 3DPA were consistent with longer-term beliefs about the technology, and how P&O professionals viewed their
profession at baseline and follow-up in relation to 3DPA as a new technological resource.

2.7 Conclusions

The development of my research, from early questions about expertise and digital manufacturing to this dissertation, has been guided by my engagement with experts in their respective fields trying to come to terms with the far-reaching effects digital manufacturing could have on their professions and their work. In my historical work at the MIT Archives this manifested in my surfacing the vast scope of research described by Ross, Pease, and Coons into a number of technological fields, that would later result in far-reaching consequences in the world of 3D printing through automation and control. In P&O, this came about through understanding the tacit knowledge required to effectively act in this space and how digital fabrication had attempted and continues to attempt reconfigurations of expertise.

By intertwining cultural historical and action research in my dissertation, I have sought to speak with experts, both through interviews and field work and through archival remnants, about the 40-plus year history of digital manufacturing, its inherent failure to materialize fully in professional spaces, and its position as an acknowledged but under-utilized technological tool. This historical context and my position in the P&O space will continue to function throughout this dissertation as opportunities to understand “how we got to now”, and what we can understand about where we are going.
Chapter Three

The Creative Routine Dichotomy

3.1 Overview

In the previous chapter of this dissertation I discussed the methodologies I used to address the research questions that guided my research. In this chapter, I use the cultural historical method I outlined in order to explore the history of the MIT Innovations in Manufacturing Technologies Project (1949-1970). This exploration specifically addresses the first of my secondary research questions (R1A), what are the historical, cultural, and material moves that have contributed to this transformation? As such, what follows is a partial history of the work done by the researchers at the Servomechanism Lab on the various subproject that comprised the MIT Innovations in Manufacturing Technologies Project. My aim in this chapter is to use this partial history to surface the logics and philosophies that went into the development of the intelligent machines during this project and how this concept sought to alter human labour.

I begin this chapter by providing an overview of the Numerical Control (NC) project (1949-55), which was led by William Pease. As part of these discussions I highlight how the themes of automation, expertise, and control developed in relation to the technical work done on NC. I then move on to the Automatic Programming Tool (APT) project led by Douglas Ross. During these sections I examine how the themes of automation, expertise, and control that were established during the NC project, are built upon to include tasks that used abstract labour and expertise. Next, I detail the work done on, and around, the computer-aided design (CAD) project by researchers such as Douglas Ross, Steven Coons, and Ivan Sutherland. In examining this work I highlight both a conceptual framework that divides design and manufacturing work into ‘repetitive’ and ‘creative’ tasks as well as the formulation of the ‘design team’ concept that sought to combine the ‘best’ attributes of humans and computers together. I conclude this chapter by returning to my first secondary research question,
(R1A) what are the historical, cultural, and material moves that have contributed to this transformation?, in order to outline why this history is so important to understanding digital fabrication.

3.2 An Automatic Machine Tool

In September 1952, Scientific American published an article entitled “An Automatic Machine Tool”. In the article William Pease, a professor of electrical engineering at the Massachusetts Institute of Technology (MIT), described the development of Numerical Control (NC) at MIT’s Servomechanism Lab (Figure 3). In this section of the chapter I examine this article as it provides a clear technical explanation of NC as well as contextualizes the development of NC in the history of the machine tool. I begin by letting Pease, who acted as lead engineer on the NC project, describe the technology in his own words. Next, I discuss how Pease positioned the development of NC in the history of machine tools as a means of contextualize the technology within a much broader history rather than as something radically new. I conclude this section by returning to the theme of automation that I introduced in Chapter One in order to compare the writing of Pease and Charles Schwab.

In the introduction of the article Pease avoids any form of technical description of NC. Rather, after noting how the “speed, judgement, and especially the flexibility” of skilled machinists have not been “easily duplicated by automatic machines” he simply suggests that “new developments in feedback control and machine computation” are “opening the door” to new forms of automation (Pease, 1952 p. 101). It is not until after Pease contextualizes the development of NC in the history of both machine tools and feedback control that he provides a description of what the technology was. “The MIT system”, Pease explained, “combines digital and analogue processes under feedback control to govern a milling machine whose cutting tool moves in three planes relative to the work piece. In this case the ‘model’ of the object to be fabricated is supplied to the machine in the form of a perforated paper tape similar to that used in a teletype systems” (Pease, 1952 p. 109). In this description Pease has specifically highlighted
how the movement of the cutting tool is determined by digital and analogue processes which are based upon a model that is fed to the machine via paper tape. This description stands in sharp contrast to how traditional machine tools operated, requiring manual inputs by machinists who were reading and interpreting schematics of the part they were fabricating (Pease, 1952 p. 109).

(Figure 3 – The experimental NC produced by the Servomechanism Lab at MIT)

What makes Pease’s article such an important resource for understanding the development of NC is how he seeks to contextualize the technology. As I already mentioned, prior to providing any form of technical description of NC he first explained the history of machine tools. “From the beginning machine tools were created to reduce the amount of human skill required in manufacturing”, Pease explained, “[t]hese automatic aids to proficiency, always adhering to the double principles of accuracy for interchangeability and speed for economy, have increased through the
years” (Pease, 1952 p. 105). Here, interchangeability referred to the process of producing parts according to specifications that ensured they were nearly identical and could fit into any assembly of the same type. Similarly, economy referred to the lowering of the costs associated with manufacturing by decreasing the amount of labour and time required to produce a part. What NC did, according to Pease, was simply extend these double principles such that they could be used to “produce a variety of parts in relatively small quantities” (Pease, 1952 p. 109). As such, Pease did not see NC as a radical new technology at least on a philosophical level; NC was merely a continuation of the logics of automation established by machine tools in the 19th century applied at a scale that was previously not viable.

In Chapter One, I described how Klaus Schwab, in his monograph *The Fourth Industrial Revolution*, argued that developments in physical, digital, and biological technologies were altering the social and cultural institutions that governed work. As part of these discussions I highlighted how Schwab suggested that professionals that were traditionally seen as high-skill had become susceptible to the automation due to developments in computation. Within his article, Pease made almost identical claims about the relationship between NC and the labour of skilled machinists. Where the two authors differ is in how these technological developments should be read. Whereas Schwab suggested that the developments he described marked a radical shift in how the concept of work needed to be understood, Pease was more measured and saw NC as part of the larger history of the machine tool. Yet, despite this seemingly fundamental difference, both Schwab and Pease are describing a process by which forms of labour previously seen as *essentially human*, that is tasks that could not be performed by machines or computers, became automated. Understanding this process, as it relates to the development of digital fabrication technologies, and why certain *kinds* of labour and expertise remain ‘*essentially human*’ is one of my major foci of this chapter.
3.3 The Promise of Numerical Control

In the previous section of this chapter I described how William Pease saw the development of NC as the continuation of the logics of automation established by machine tools. In this section I outline the origins of the NC project. As part of these discussions I examine why the labour and expertise of machinists was specifically targeted for automation and how it was transformed through this process. First, I describe how previous work done by the Parson Corporation to automate the production of helicopter blades for the United States Air Force led to the creation of the NC project. Next, I explain how the researchers at MIT’s Servomechanism Lab became involved with the NC project and their vision of it as a liberatory technology that would free humans from the “drudgery” of manufacturing. I conclude this section by returning to the theme of expertise that I introduced in Chapter One as a means of examining how certain kinds of labour become identified as appropriate for humans.

In 1947 the Parsons Corporation produced a manual detailing a method for producing rotor blades that used boring mill tables produced on a standard IBM punch card machine (Parsons Corporation, 1950). Using these boring mill tables, which presented the rotor blade as a series of longitudinal and transverse index values that simply had to be followed in order to produce the part, both increased accuracy and reduced the amount of human skill required for manufacturing these parts (Noble, 1986; Parsons Corporation, 1950). The production of this manual was funded by the United States Air Force as part of a post-war initiative that sought to ‘improve’ how aircraft and aircraft parts were manufactured (Parsons Corporation, 1950; Noble, 1986).

When John Parson, the CEO of the Parsons Corporation, proposed what would become the NC project in 1948 he argued that it was the logical conclusion of the work the company had previously done for the United States Air Force (Parsons Corporation, 1950; Noble, 1986). Dubbed The Cardomatic Milling Machine by the Parsons Corporation, the project was approved by the Air Force in 1949 and work on it began shortly after (Parsons Corporation, 1950; Noble, 1986).
David Noble (1986) argued that while the United States Air Force faced new technological and economic challenges in the post-war era, their primary concerns were the social and political issues that arose from the organized labour movement following the conclusion of World War Two (Noble, 1986). In funding the Cardomatic Milling Machine the goal of the United States Air Force was, according to Noble, to develop a form of aircraft manufacturing that was reliable as it was not dependent upon the highly skilled labour of machinists who had the capacity to revoke their expertise at will (Noble, 1986). While Noble’s analysis provides vital insights into the political reasons machinists were targeted for automation through the development of NC, it does little to address the accompanying social and cultural moves that transformed how the labour and expertise of machinists were perceived. In order to understand those moves, I need to address how the researchers at MIT’s Servomechanism Lab became involved in the project and how it became positioned as what Murray Bookchin would refer to as a liberatory technology, that is a technology that supports personal freedoms and craftsmanship (Bookchin, 1975).

The term “moves”, which I have used here and throughout this dissertation, describes the various strategies or processes used by researchers that sought to reconfigure the concepts of labour and expertise.

After receiving the contract to build the Cardomatic Milling Machine from the United States Air Force in 1949, the Parsons Corporation began looking for technical subcontractors to help with development. This included the Servomechanism Lab at MIT who were asked to develop the power drive unit, which would move the tool head into the various positions given by the information handling unit (Servomechanism Laboratory, 1950; Reintjes, 1977; Reintjes, 1991; Noble 1986).

When he first approached the Servomechanism Lab about the Cardomatic Milling Machine, the descriptions Parsons provided were vague. Gordon Brown, the director of the Servomechanism Lab, later commented that the only initial detail Parsons would provide was that he needed a system that could “receive plus data as input” (Brown,
In spite of this vagueness Parsons and Brown agreed to meet in the summer of 1949 at which time Parsons was more forthcoming with his vision for the Cardomatic Milling Machine, and an agreement was reached that the Servomechanism Lab would undertake the development of the power drive system (Brown, 1970; Reintjes, 1977). The involvement of the Servomechanism Lab on the Cardomatic Milling Machine project stemmed in part from Brown’s desire to further research some of the models of feedback that researchers at the Lab had developed during World War Two (Brown, 1970; Reintjes, 1977). The model of research envisioned by Brown, however, was radically different from its traditional conception within engineering, as it focused equally on the production of applied and generalizable, or abstract, knowledge (Brown, 1962; Brown, 1963). This move to include abstract knowledge as a desirable outcome of engineering research marked an important reconfiguring of not only the kinds of expertise required for engineering work but, as Brown would later argue, all work performed by humans.

The September 1952 issue of *Scientific American* that featured William Pease’s article, “An Automatic Milling Machine” was featured in a special issue on Automatic Control. The goal of the issue, as explained in the introductory article “Automatic Control”, written by Ernest Nagel, was to survey “the principle content of automatic control theory, the problems that still face it and the role that automatic control is likely to play in our society” (Nagel, 1952, p. 44). This resulted in a tone of vague futurism present throughout the issue, as the authors were all describing a tomorrow that had yet to arrive but was surely on its way. In their article Control Systems (1952), Gordon Brown and Donald Campbell suggested:

> Even in the most robotized of automatic factories there will be many men, and they will have interesting and responsible jobs. They will be freed from the tiring, nerve-racking or even boring jobs of today’s mass manufacturing. To win this freedom, however, they will have to upgrade themselves in skill and sophistication. The new controllers and instruments will call for a higher level of precision of repair and maintenance. A $50,000 controller cannot be hit with a
hammer if the shaft does not fit into the hole on the first try. Men who have heretofore thought of electronics equipment as merely a metal chassis with tubes will become conversant with switching, flip-flop, peaking, and other circuits. (Brown & Campbell, 1952 p. 64)

Here, Brown and Campbell clearly articulated a vision of intelligent machines as a liberatory technology that would free industrial workers from the drudgery of manufacturing. This freedom had a cost, as workers would need to be re-educated with skills rooted in pure rather than practical knowledge. What is important about this narrative is how it re-contextualized certain kinds of labour and expertise once performed by humans as inappropriae for humans. This is accomplished by suggesting that there are new kinds of expertise which are more rewarding or fulfilling for humans to engage in.

In my initial discussion on Schwab I introduced the theme of expertise. In the future of work described by Schwab, the social and cultural institutions that govern work shift to non-hierarchical frameworks in order to allow for a dynamic model of work that ensures various kinds of expertise are available to perform a task when necessary. The expertise performed by humans within this framework is rooted in the capacity to continuously learn new skills and apply them across different contexts. While Brown and Campbell would agree with Schwab in terms of the kinds of expertise that is appropriate for humans, the two differ with respect to the kinds of knowledge required. It is the kinds of expertise and skills that are required for humans to develop that are central to Brown’s claims regarding the capacity of NC to act as a liberatory technology. These skills and expertise are rooted in abstract, or pure knowledge, which can be applied in different contexts.

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6 The “workers” that I describe here are universal male. Despite being present at the sites of design and manufacturing women are almost entirely invisible from this concept of “laboratory technology” as conceived by the researchers at MIT.
3.4 Numerical Control as an Information Technology

The Numerical Control (NC) Project, as I described in the previous section of this chapter, sought to reconfigure the concept of expertise and in doing so alter what was seen as appropriate labour for humans. In this section I examine how NC became positioned as an information technology. I begin by looking at a debate between John Parson and William Pease over the production of a single-axis, as opposed to a multi-axis, demonstration mill. Next, I examine the arguments made by Pease regarding the ‘information’ problems of manufacturing. I conclude this section by returning to the theme of control from the Introduction as a means of discussing the concept of authorship as it related to the NC project.

The automated milling machine showcased to the public by the Servomechanism Lab in the summer 1952 was radically different from the one described in the original Cardomatic Milling Machine contract (Figure 3). The milling process was done through continuous paths as opposed to the index based point-to-point system first proposed by the Parsons Corporation, and the information handling unit was a custom punch tape machine specifically designed by researchers at the Lab (Servomechanisms Laboratory, 1949; Servomechanisms Laboratory, 1951; Servomechanisms Laboratory, 1952; Parsons Corporation, 1950). This departure from the initial conception of the automated milling machine stemmed from a disagreement between John Parsons and William Pease early in the project over whether the focus should be on the production of a single-axis demonstration mill or a multi-axis experimental mill.

The approach favoured by John Parsons was the single-axis demonstration mill. When Parsons first proposed the Cardomatic Milling Machine to the Air Force there was no working prototype, which led to a great deal of concern about the technological viability of the project within the military which resulted in delays in its approval (Reintjes, 1977; Reintjes, 1991; Noble, 1986). Wanting to remedy these anxieties, Parsons pushed for the production of a single-axis demonstration mill that was designed to produce wing panels (Reintjes, 1977; Reintjes, 1991; Noble, 1986). Once the underlying approach to
the Cardomatic Milling Machine had been successfully demonstrated by this single-axis mill, Parsons argued that work could then begin on a more generalized automatic milling machine without worry of the project begin shutdown by the Air Force (Reintjes, 1977; Reintjes, 1991; Noble, 1986).

William Pease fiercely opposed the production of the single-axis demonstration mill, as he viewed it as a misunderstanding of both the purpose of an automatic milling machine and the essential problem of the technology (Reintjes, 1977; Reinyjes, 1991; Noble, 1986). In a report written in 1950 by Pease and the other researchers from the Servomechanism Lab working on the Cardomatic Milling Machine, it was suggested that:

> The general aim of the project from the beginning has been to devise a means for machining mathematically definable surfaces without resorting to the expensive practices of first constructing models having better than the required accuracy of the finished work. It soon became apparent that there is a wide variety of embodiments which would achieve the general aims. In all of these embodiments, the principle unknowns lay in the techniques of processing the information from which the machine tool is to be actuated. (Servomechanisms Laboratory, 1950)

What this brief excerpt illustrates is that Pease, along with the other members of the Servomechanism Lab, saw the production of an automatic milling machine that was capable of producing any part that could be mathematically represented as the core objective of the project. The central difficulty of creating this machine was determining how to best handle the volume of information that would be required to control the mill. This problem with the information requirements of the mill was more succinctly explained later by Pease in his article “An Automatic Machine Tool” (1952). Following the brief history of the machine tool, which I discussed earlier, Pease comments:
Flexible machines, capable of manufacturing a wide assortment of parts, are an essential part of modern manufacturing techniques. The reason why they have thus far been untouched by automatic control can be given in terms of the concepts of information flow....To perform a complicated operation such as manufacturing a metal part, we must build into the machine a great deal of information-handling capacity, for it has to carry out a wide complex of instruction...Suppose we want an automatic machine which will make not one particular production, or part, but a number of different kinds of production and only a few of each — as the versatile machine tool must do. Now the machine must handle a different set of instructions for each product...In other words, it must be able to deal with more information... (Pease, 1952 pp. 106-107)

Here, Pease has presented machine tools as, essentially, information technologies. Within this framework mechanisms for physically guiding the movement of the tool were the processes by which information capacity was built into the machines. This capacity to handle information, however, was limited to the production of a single part. That is to say, the machine tools did not have the inherent capacity to process information such that a different part could readily be produced on them. This was the essential problem, Pease argued, that the automated milling machine had to resolve (Brown, 1970; Reintjes, 1977; Reintjes, 1991). As such, the production of a single-axis demonstration mill would prove nothing about the technology because it did not adequately reflect the complex informational problem that was its defining characteristic.

Ultimately, it was Pease who won this argument and increasingly the project became wrapped up in his vision of the automatic milling machine as an information technology. This victory was the result of institutional requirements at the Servomechanism Lab as well, as the broader narrative that Pease was able to tell about the technology.
Pease’s construction of the automatic milling machine as an information technology also transformed the narrative around the technology in a way that made it hard for Parsons to demonstrate what he saw as the value of producing the single-axis demonstration mill. When the Parsons Corporation approached the Air Force with the Cardomatic Milling Machine project, it was pitched as a method for accurately and reliably producing wing panels that did not require templates (Servomechanism Laboratory, 1949; Parsons Corporation, 1950; Noble, 1986). For Pease, and the other members of the Servomechanism Lab, once work on the project began this initial conception of the automatic milling machine was quickly seen as profoundly limited, as it focused on a single production context and part type (Brown, 1970; Reintjes, 1977; Reintjes, 1991; Servomechanism Laboratory, 1952). As work progressed, and the information technology narrative developed, Pease began to articulate a vision of the technology in which a part could be rapidly and easily produced in any context due to the control equipment and the control tapes that contained the instructions. This vision was best articulated in the final report on the project that the Servomechanism Lab prepared for the Air Force in 1952. The report contained a list of advantages of the automatic milling machine, which included:

The control equipment can be changed from one job to another in negligible time by simply inserting a new set of previously prepared instructions...The instructions do not deteriorate with use, are readily modifiable through patching techniques, can be stored conveniently, shipped anywhere with economy and speed, and transmitted between factory insertions by means of conventional teletype circuits. (Servomechanism Laboratory, 1952)

The language used here is important as it attributes a sense of ease, speed, and reliability to the automatic mill and focused specifically on the control tapes that contained the part instructions. Within the information technology narrative of the automatic milling machine the control tapes became the central feature of the technology, as they allowed for a rational model of manufacturing based upon mathematically defined parts rather than skilled labour. The single-axis demonstration
mill, with its limited use case, simply could not compete with this grander vision of the technology.

In 1950 the Parsons Corporation, in response to the technical and conceptual changes in the project, changed the name of the automatic milling machine from the Cardomatic to The Digitron (Parsons Corporation, 1952). This name change, however, proved ill-timed, as the Air Force re-evaluated the project shortly thereafter. Given how much it had changed in scope, the Air Force decided to alter how the project was administered and, in late 1950, the funding was pulled from the Parsons Corporation in favour of full control by the Servomechanism Lab (Servomechanism Laboratory, 1952; Reintjes, 1991). It was at this point that the process by which the automatic milling machine operated was given the name Numerical Control (NC) (Reintjes, 1991). Work would continue on the NC milling machine project at the Servomechanism Lab with the Air Force acting as the sponsor for the research until 1952 when, as mentioned above, the experimental mill was showcased to the public (Noble, 1986; Reintjes, 1991).

Schwab, as I described in the Introduction, argued that the fourth industrial revolution would result in a re-organization of the social and cultural institutions that govern work into non-hierarchical structures. As part of these discussions, I introduced the theme of control, as Schwab suggested that this new method of organizing work would return a sense of ownership to some workers in terms of their own labour as they could pick the kinds of tasks to apply their expertise to. In Pease’s conception of the milling machine, a similar sense of control over individual labour is embedded in the technology, but his discussion focused on the immutability of the expertise that comes about through the creation of control tapes which mathematically define expert tasks. The labour of the designers and engineers is what is mathematically defined in this framework, whereas other forms of labour that are equally important to the system are re-defined in the context of their response to this specific, immutable expertise.
3.5 The Part Programmer

In the previous sections of this chapter I described how the NC project sought to alter the social and cultural institutions that governed the labour and expertise of manufacturing. In this section of the chapter I begin my analysis of the next phase of the MIT Innovations in Manufacturing Technology Project known as the Automatic Programming Tool (APT) project. Led by Douglas Ross, the APT project expanded upon the concepts of automation, expertise, and control that were established in the NC project. I begin this section by providing an overview of APT, and then examine the research of John Runyon into automatic programming systems for NC, which is the conceptual starting point for the APT project. I conclude this section by discussing how Runyon’s work built upon the theme of automation that was established during the NC project as a means of automating programming tasks that had been seen as cognitively complex.

From 1956 until 1959 Douglas Ross, a researcher at the Servomechanism Lab, led the APT project. In a manual for the language published in 1959 Ross described APT:

It is the name given to a technique for producing complex metal parts efficiently and reliably through a combination of a modern data processing and numerically controlled machine tools. A numerically controlled machine tool is a machine tool to which have been added servomechanism and electronic control circuits so that motions of the tool will respond to numerically coded instructions on punched tape or some other suitable control medium. The preparation of the instructions which specify the machine motions required to produce a particular part is called programming the machine tool, or part programming. Automatic programming is a new technique, made possible by modern computers, in which the instructions are not given in detailed numerical form, but in terms of English-like language convention for people to use. Automatic programming also permits all of the difficult mathematical computations associated with the use of numerical control to be performed atomically by the computer so that the job of the human part programmer is greatly simplified. (Ross, 1959a p. 1-1)
Ross’s description of APT focused on how it reduced the complexity of designing and manufacturing parts on NC mills (Figure 4). The reason these capacities were so predominately featured in the narrative of APT, both in this report and elsewhere, was because the language stemmed from earlier research conducted at the Servomechanism Lab that sought to respond to concerns regarding the practicality and the economic viability of manufacturing on NC mills (Jacoby, 1952; Wood, 1957; Reintjes, 1991).

The first automatic programming system was developed by John Runyon, a research assistant at the Servomechanism Lab, who began experimenting with the use of general-purpose digital computers as an aid for programming control tapes in 1951 (Reintjes, 1991; Runyon, 1953). Prior to these experiments, control tape programming was done, as described by J. Francis Reintjes the director of the Servomechanism Lab from 1953 to 1974, manually (Reintjes, 1991 p. 74). This manual control tape programming was a computationally intensive, tedious, time-consuming, and multi-stage process performed by the newly created position of the part programmer (Reintjes, 1991; Ross, 1978). The primary role of the part programmer was to translate the engineering drawing of the part and machining operations into numerical data, which could be used by the digital director of the NC mill in order to determine values, such as the linear interpolation of the surface of the part and the corresponding feed-rate (Reintjes, 1991; Ross, 1978).

The method for control tape programming developed by Runyon involved the part programmer using a general-purpose digital computer to perform the majority of the mathematical operations that were required (Reintjes, 1991; Ross, 1978; Runyon, 1953). Runyon accomplished this by creating a number of general programs, which he referred to as a library subroutines, that the part programmer could use to perform calculations specifically required for the control tape that was being programmed. Using these library subroutines, Runyon estimated, would improve the efficiency of the coding process by reducing the amount of new computer code produced by the part.
programmer by 75 to 90 percent depending upon the complexity of the part (Reintjes, 1991; Ross, 1978; Runyon, 1953).

In 1955, the United States Air Force awarded the Servomechanism Lab a new contract for a project that would build upon Runyon’s research in order to produce a method for the automatic programming of NC control tapes (Reintjes, 1991; Ross, 1978).

(Figure 4 – Visual Representation of a Part Programmed in APT with Accompanying Programming)
This focus on the reduction of repetitive or routine labour as a means of improving efficiency conceptually links the programming method developed by Runyon to the work of William Pease that I described earlier in this chapter. Runyon’s work, however, was notably different in that it extended the logics of automation and deskilling described by Pease into labour based upon abstract knowledge. The method developed by Runyon for control tape programming, then, marks the beginning of a much larger reconfiguration of the design and manufacturing processes into a dichotomy of creative or routine work.

### 3.6 “Automatic Programming”

The research of John Runyon, as I discussed in the previous section of this chapter, altered the dynamics of the MIT Innovations in Manufacturing Technology project by expanding the scope of automation to include both manual and cognitive tasks. In this section of the chapter I examine how Arnold Siegel used the research of John Runyon to develop a method of part programming that used English-like statements as a form of input. In doing so, Siegel was seeking to simplify the part programming process even further. My focus in this section is to provide an overview of the system developed by Siegel while he was under contract with the Servomechanism Lab. I conclude by examining how Siegel’s research contributed to the theme of expertise by requiring the part programmer to essentially translate the design of the part.

In 1955 Arnold Siegel, a researcher at the MIT Digital Computer Laboratory (an affiliate of the Servomechanism Lab), began work on the automatic programming project (Ross, 1978). The solution developed by Siegel, which he detailed in the article “Automatic Programming of Numerically Controlled Machine Tools” (1956a), was based on the concept that control tape programming was divided into two basic stages. The first, Siegel explained, was the planning stage in which the programmer determined how the part would be made. Making these determinations required:
Familiarity with machine tools and metal-cutting techniques because it was necessary to determine how each piece can best be cut, how to hold the work, what jigs and how many setups are buried and what spindle speeds, cutting shapes, and feed rates must be specified. In this stage of planning, in which initial decisions must be made by trained and experienced personal, empirical knowledge, experience, and judgement are the determining factors. (Siegel, 1956a p. 65)

Here, Siegel was specifically trying to note that during the first stage multiple decisions had to be made by the programmer in relation to the material, or metallurgic, process of machining. Moreover, these decisions had to be carried out by trained individuals who were exercising their professional judgement. The second stage Siegel described was *machining programming*, which involved “the computation of the actual machine commands translated to the numerical director” (Siegel, 1956a p. 65). Unlike the first stage, the second was “primarily routine” as “the earlier decisions affect the form of these instructions” (Siegel, 1956a pp. 65-66). It was the lack of any significant determinations or decision-making during the second stage that Siegel was trying to reinforce.

The separation of control tape programming into two stages Siegel outlined was directly inspired by the method developed by Runyon. Siegel’s underlying approach, a library of subroutines that could be used by the part programmer when it was specifically required for a part, was also modelled on Runyon’s work (Siegel, 1956a; Siegel 1956b; Ross, 1978). What was novel about Siegel’s method for control tape programming was its focus on “English-like statements” as a form of input (Siegel, 1956a; Siegel 1956b; Ross, 1978). “The input language” Siegel explained “consists of ‘statements’, some in plain English and some in semi-mathematics notion, that describe what the programmer sees on the blueprint and what [the programmer] wants the machine tool to do” (Siegel 1956 p. 66). The use of the word ‘describe’ here is important, as it is illustrative of a new form of expertise and labour introduced by this method. The move to English-like statements as a form of input was largely an attempt
to reduce the complexity of the method developed by Runyon (Siegel, 1956a; Siegel 1956b; Ross, 1978). With English-like statements, the part programmer did not need the same level of understanding of machine language or how computers functioned that was required to use Runyon’s library of subroutines (Siegel, 1956a; Siegel 1956b; Ross, 1978).

In 1956, the automatic programming project re-integrated into the Servomechanism Lab. This marked the end of Arnold Siegel’s direct involvement with the project, though his work on English-like statements as input continued to influence the project as it moved forward (Ross, 1978).

In order to use the automatic programming solution developed by Siegel the part programmer had to first translate the surface of the part into a series of points, lines, and circles, as these were the only geometric references understood by the system. This translation process was a new form of expertise and labour, as it essentially required the part programmer to make complex decisions regarding how to best represent a part within the system developed by Siegel. This work to translate designs into abstract spaces is the first step in the process of translation as labour that is later transferred to machines, which will be more fully examined in Chapter Four.

3.7 The Automatic Programming Tool (APT) System

Arnold Siegel’s research into an automatic programming language for NC control tapes that used English-like statements as input produced a new form of expertise. In this section of the chapter I discuss how Douglas Ross refined the research of Siegel in order to develop an automatic programming system that could be used to program control tapes for any ‘arbitrarily’ defined part. I open this section by outlining the fundamental issues that Ross had with the automatic programming systems developed by both Runyon and Siegel. Next, I describe the APT system and the hierarchical structure that Ross used in its development. I then briefly address the development of the first commercial system that used the APT system, 2D-APT-II, and the press event
that was held to showcase it. I conclude with a discussion of how Ross’s research built upon the theme of control by allowing for the shapes that parts are comprised of to be digitized.

When the automatic programming project returned to the Servomechanism Lab in 1956, the Computer Applications Group was established to administer it (Reintjes, 1991). Douglas Ross was designated as the head and lead developer of this group, predominantly due to his experience developing applications for general-purpose digital computers, with fellow Servomechanism Lab researcher John Ward acting as project engineer (Reintjes, 1991).

Following a review of the work done by Siegel on the problem of automatic programming, Ross concluded that while the input and output portions of the Siegel system could be expanded upon, the language and calculation methods were insufficient to handle “arbitrary 3-dimensional shapes or complex parts” (Ross, 1978 p. 67). In the technical report (1958), Ross explained:

If a limited variety of problems are to be solved (i.e. if a limited variety of machined parts is to be made), then the subroutine library with automatic programming is a highly efficient system, and can be made to satisfy completely the requirements of the part programmer…If, however, as is usually the case, an important aspect of the use of numerical control is that more and more elaborate machined parts can be made, then it is necessary for the subroutine library and the corresponding automatic programming executive routines to be in a continual state of flux and development. As new classes of machined parts are contemplated, additions must be made to the library and to the executive routines to allow the specification of these more complicated surfaces within the framework of the original library system. As the library grows in size and complexity, it becomes increasingly difficult to devise efficient executive routines for selecting and properly interconnecting the appropriate subroutines. (Ross, 1958 pp. 19-20)
Here, Ross highlighted how Siegel’s method for automatic programming was dependent upon pre-existing libraries of subroutines that had been specifically made either for a part or class of parts. This meant that when an arbitrary 3-dimensional shape or complex part had to be programmed entirely new subroutines would have to be created, or old ones extensively modified, before the part programmer could effectively and easily express it (Ross, 1978; Ross, 1959b; Ward, 1960). In other publications, as a means of describing the inherent part-specific limitations of these subroutines, Ross used the term “closed-form solutions” (Ross, 1978 p. 67; Ross, 1959b; Ross, 1956). This term is convenient as it helps to establish a divide, both temporally and philosophically, between the methods used by Runyon and Siegel and the researchers at the Servomechanism Lab in their research on automatic solutions for NC parts. If the systems developed by Runyon and Siegel between 1951 and 1956 embodied these close-form solutions, then from 1956 onward the systems for automatic part programming created by Ross were based upon what he would describe as “open-form solutions”.

The formal development of the APT began shortly after the review of Siegel’s work was complete, with the basic structure of the system completed near the end of 1956 (Ross, 1956; Ross, 1959b; Ross, 1978). In the technical paper *Some recent developments in automatic programming for numerically controlled machine tools* (1958), Ross elaborated on this structure by describing “the hierarchy of the APT systems as currently envisioned” (Ross, 1958 p. 6). The lowest level of the hierarchy, referred to as APT I, allowed the part programmer to “specify and produce a part by statements in the APT language” using “individual points” (Ross, 1958 p. 6). The mid-level of the hierarchy, APT II, allowed for parts to be specified using “space curves” (Ross, 1958 p. 6). The highest level of the hierarchy, APT III, allowed for the part programmer to describe the surface “regions” of the part (Ross, 1958 p. 6). This system’s structure had been designed to allow for each level to “translate the instructions of the part programmer, stated in successively more convenient languages, and carry out these instructions [through the] automatic programming of lower systems in the hierarchy” (Ross, 1958 p. 6). It was this capacity to automatically
program subroutines in the lower systems of the hierarchy that Ross sought to
describe with the term open-ended solutions (Ross, 1958; Ross, 1959b; Ross, 1978;
Ward, 1960). This capacity meant that using the APT systems, a part programmer
could readily express an arbitrary 3-dimensional shape or complex part, as the system
could automatically program any subroutines that were required (Ross, 1958; Ross,
1959b; Ross, 1978; Ward, 1960). Consequently, the part programmer was no longer
required to select from a series of pre-built subroutines as part of their work. This is not
to say, however, that no translation labour was required, as the part programmer still
needed to express the part in terms of a combination of points, curves, and/or regions
(Ross, 1958; Ross, 1959b; Ross, 1978; Ward, 1960).

The development of the APT systems continued throughout the latter half of the 1950s.
In 1957, following a meeting with Ross and members of the Aircraft Industries
Association’s (AIA) Subcommittee on Numerical Control (SNC), an agreement was
reached through which the Servomechanism Lab would develop the first commercial
system based on APT (Ross, 1958b; Reintjes, 1991). This project, which received
further backing from the United States Air Force itself, resulted in the 2D-APT-II
system (Ross, 1958b; Reintjes, 1991).

At a press event held at MIT in February of 1959, 2D-APT-II was publicly
demonstrated. In the lead-up to the event commemorative ash trays (Figure 5), which
had been designed in 2D-APT-II and then fabricated on a NC mill, were sent out to
press organizations and industry associations (Ross, 1978; Reintjes, 1991; Ward,
1960).

An article on the event published in the February, 26 1959 issue of The Washington
Post and Times Herald commented:

Top Air Force and science leaders announced today the development of a
mechanical brain language which they claim is a “tremendous breakthrough” in
American’s electronic superiority over Russia …In brief APT allows a master
electronic brain to design and supervise another man less machine’s production...APT is so simple it will “enable every engineer to do more” by increased use of electric brains. (Growald, 1959)

The language used in this article to describe APT is important, as it attributed an intelligence to the system. The role of the human within this framework was to define and describe what was wanted using the “simple and easy-to-learn” language (Ross, 1956; Ross, 1961; Ross, 1978; Ross, 1988). The role of APT was to determine how to produce what had been defined or described (Ross, 1958; Ross, 1959b; Ross, 1978). It was this concept of mechanic, or computational, intelligence that the researchers at the Servomechanism lab sought to build from and better define during Computer-Aided Design Project.

In the opening sections of this chapter I discussed how William Pease contextualized the development of the NC mill as part of the history of machine tools. As part of this narrative Pease described how the mechanisms that physically guided the operation of machine tools built into these machines the ability to handle and process information (Pease, 1952). The NC mills, Pease asserted, expanded upon the information handling and processing abilities of the machine tool by turning these physical guides into digital signals (Pease, 1952). The effect of this was that an NC mill could, unlike machine tools, produce any part so long as it could be mathematically expressed and was within the tolerances of the machine. It is this logic of digitization that Ross furthered with the development of the APT systems. The point, curve, and surface hierarchy of APT I, APT II, and APT III that was created by Ross essentially allowed for parts to be reduced to their essential characteristics and then digitally represented. In Chapter Four I will revisit this logic of digitization, as it is deeply connected to the theme of modernity and the processes by which expertise is valued and recognized.
(Figure 5 – APT Commemorative Ash Tray)
3.8 Repetitive and Original Design

The APT project, as I described in the previous sections of this chapter, built upon the themes of automation, expertise, and control established by William Pease and the other researchers at the Servomechanism lab during the NC project, in order to further a model of production that used intelligent machines to perform specific kinds of labour and expertise. Whereas during the NC project the kinds of expertise and labour performed by these intelligence machines was limited to the manual processes of machining during the manufacturing phase, the APT project began the process of broadening the kinds of expertise and labour performed by these intelligent machines to include some of the tasks that occurred during the design phase. In this section I begin my discussion of the final phase of the MIT Innovations in Manufacturing Technology Project which was the Computer-Aided Design (CAD) Project. I start by providing an overview of several meetings that were held between the researchers at the Servomechanism Lab and the Design Division at MIT’s Mechanical Engineering Department. During these meetings the concept of extending the logics and principles established during the APT to the design process was discussed. As part of these discussion I will specifically address a distinction made between ‘original’ and ‘repetitive’ design that resulted in the formulation of a new model of design that paired ‘man’ and ‘machine’. I conclude this section by analyzing how this new model of design contributes to the theme of automation I have discussed throughout this chapter.

In January of 1958 an informal meeting was held between the researchers of the Servomechanism Lab and the personnel of the Design Division at MIT’s Mechanical Engineering department. Following a presentation on the work done to date by the Servomechanism Lab on NC and automatic programming, there was an open discussion on the concept of automatic design, which involved the introduction of computers into the design process in some yet to be determined capacity (Reintjes, 1991; Coons, 1964). The meeting generated “considerable interest” from the personnel
of the Design Division, and an agreement was reached between the two parties “to continue discussions in this area” (Reintjes, 1991; Coons, 1964).

In order to facilitate further discussions, a seminar series was established between the Servomechanism Lab and the Design Division, the first of which was held in April of 1958 (Reintjes, 1991; Coons, 1964). After an introduction by the director of the Servomechanism Lab, J. Francis Reintjes, the conversation moved onto the potential uses of computers within the design process (Clements, 1958 p. 1). It was during these initial conversations that J. B. Reswick suggested that “there might be a possibility in going directly from sketch to part, by passing drafting” (Clements, 1958 p. 1). In response to this suggestion, and a brief discussion between D. Baumann and R.W. Mann regarding the kinds of decisions a design computer would have to make, J. Lewis purposed that there were “two kinds of design computers” (Clements, 1958 p. 1). The first kind of computers addressed cases of repetitive design in which parameter variation was the primary task (Clements, 1958 p. 1). The second kind of computers were “original design machine[s]” which focused on the task of producing new or novel designs (Clements, 1958 p. 1). The remainder of the first seminar was spent elaborating on these concepts of repetitive and original design computers, with Douglas Ross arguing that both concepts were equally important and Steven Coons noting the importance of incorporating “human judgement” within these systems (Clements, 1958 p. 2).

The second seminar between the Servomechanism Lab and the Design Division was held in May of 1958 (Reintjes, 1991). It was during this seminar that the specifics of the relationship between the human and the computer were established. The scenario imagined by the researchers at the Servomechanism Lab and the Design Division, as described by J. Francis Reintjes in his monograph Numerical Control Making: A New Technology (1991), was one in which:

The designer would be seated at a computer console, drawing a sketch of the device he had in mind on the screen of a cathode-ray tube with the aid of his
“light-pen” or other input device. It was envisioned that he would be able to modify the sketch at will and command the computer to redraw the device in accordance with his updated ideas. The computer also would be able to transform the designer’s rough light-pen motions into highly refined pictorial drawings and simultaneously produce digitized data that could be used to drive a numerical controlled drafting machine, or simply to do further processing in preparation of NC machining. (Reinjtes, 1991 p. 95).

Here, a radical new model of design and production was described in which a designer, aided by a computer, would be able to easily and rapidly move from sketches to a finished part. Yet, as Reintjes suggests, the most important feature of this new model of design and production is the kinds of feedback the computer provides to the designer. As he explains:

Most importantly, it was concluded that the computer should complement the work of the designer during the whole process; at some times it would be the designer’s slave, at others it would alert the designer to impossible requirements or constraints being imposed. (Reinjtes, 1991 pp. 95-96).

The working relationship, for lack of a better term, described here by Reintjes is one in which the computer has the capacity to provide intelligent feedback to the design based upon what has been inputted. It is this idea of intelligent feedback that becomes the conceptual link between the various sub-projects of the CAD project.

After the conclusion of the second seminar, an agreement was reached between the Servomechanism Lab and the Design Division to formalize a working partnership, which would further explore the concept of computer mediated design (Ross, 1965; Ross and Ward, 1968; Reinjtes, 1991). In June of 1959 the two groups submitted a proposal for funding entitled *Investigations in Computer Aided Design For Numerically Controlled Manufacturing Processes* to the United States Air Force. The proposal was

In the opening sections of this chapter, I described how during the development of the automatic milling machine Pease, and other Servomechanism Lab researchers, established a conceptual divide between design and manufacturing. Within this framework, design was seen as a creative task that required judgement, whereas manufacturing was a routine task that simply involved following instructions (Ross, 1965; Coons, 1966a; Coons, 1966b; Reinjtes, 1991). The concepts of the repetitive and original design computers established during this first seminar built into this divide. Certain tasks within design, specifically those that are based upon using or modifying pre-existing specifications, became seen as routine and thus subjectable to the same logics of automation Pease described. This distinction between routine and original, or routine and creative, is a lens I will be returning to for the remainder of this chapter and dissertation, as it plays a critical role in determining what is seen as appropriate labour for humans and computers.

3.9 The Intelligence of Computer-aided Design

In the previous section of this chapter I described how, in a series of meetings between the researchers at the Servomechanism Lab and the personnel of the Design Division at MIT’s Department of Mechanical Engineering, the logics of automation established during the APT project were extended to the design process. In this section of the chapter I discuss a research project led by Douglas Ross that sought to produce a program that automatically generated scripts for TV Westerns. While this might appear to be entirely unrelated, the creation of this program illustrates the kind of ‘intelligence’ that the CAD project was seeking to achieve in the systems being built. I begin by providing a brief overview of the activities of the CAD project. I then provide an overview of the development of Saga II, which was the name of the program that produced the western TV scripts. I conclude by discussing how this concept of ‘intelligence’ contributed to the theme of expertise.
The CAD Project was far more nebulous in nature than the two previous projects, both in terms of the nature of the deliverables and how it was administered. In the proposal for funding that the Servomechanism Lab and the Design Division submitted to the United States Air Force the goal of the project was broadly stated as: “to devise techniques for automatic programming of design information that are effective, economical, and adaptable for use by the aircraft industry in conjunction with the APT System and numerically controlled manufacturing” (Reinjtes, 1991). This nebulous, almost free flowing, structure of the CAD project is best exemplified by a research project conducted by Douglas Ross for CBS.

In early 1960s the researchers at the Servomechanism Lab were asked to participate in a TV special for CBS, one of the three major television broadcasters in the United States (Wolf, 1960). In a letter to J. Reinjtes, Thomas H. Wolf, a producer at CBS, explained that the special would “deal with human intelligence and artificial intelligence” (Wolf, 1960). Since the viewers would be “general” and “non-captive”, Wolf was looking to produce segments that would “intrigue and hold our audiences” in order to support the underlying concept of the series — “making the non-scientific community aware of the excitement and importance of science and the scientists” (Wolf, 1960). As such, the segment suggested by Wolf for the Servomechanism Lab was:

We could do nothing more intriguing than to program a computer to “write”, “direct”, and/or “produce” a short playlet. I’m wondering how feasible and how costly it would be to program a computer with some basic information about “boy-meets-girl, boy-loses-girl, boy-gets-girl”. With this program the computer could write the plot for a five-minute playlet, which we would have to enact by a professional cast. Additionally, it would be relatively easy to program a computer to “direct”. This means which camera to use under what circumstances, which lens, which angles, etc., etc., (Wolf, 1960)
In this letter Wolf established an essential element of the creative act that the computer was being asked to perform; it was routine in nature. In the previous section of this chapter I described the design team as configured by the Servomechanism Lab and the Design Division, and this example will help to illustrate how the concepts of intelligence and creativity were understood within this team.

After meeting with Wolf and other CBS producers in the spring of 1960, an agreement was reached wherein the Servomechanism Lab would produce a computer program to generate scripts for television Westerns (Ross, 1961).

When the program was finished Ross sent the producers at CBS several scripts to choose from (Ross, 1960). While he left the selection of the scripts up to the judgement of the producers Ross did express a preference for the one, which featured a sheriff and bandit, the two characters of the playlet, as such an outcome was statistically highly unlikely (Ross, 1960).

The special aired on October 26, 1960 and was entitled *The Thinking Machine* (1960). Three of the Westerns produced by SAGA II were shown, all of which featured the traditional situation of the aforementioned sheriff and bandit engaged in a shootout following a bank robbery (Figure 6).

During the first playlet, the sheriff enters the bandit’s hideout and a shootout follows, during which the bandit is mortally wounded. After taking one final drink the bandit dies, leaving the sheriff to reclaim the money and walk off into the proverbial sunset. The second playlet is almost identical, but this time it is the sheriff that is mortally wounded, leaving the bandit free to escape with his ill-gotten gains. Upon seeing this second iteration the host of the special, actor David Wayne, comments: “[w]ell I can see that there is one thing the computer doesn’t know — in television the bad guy is supposed to lose”. The final playlet riffs on Wayne’s comment for comedic effect, and has the two characters engage in a series of bizarre activities due to the computers failure to “know” how something is supposed to work. After entering the hideout the
The bandit is seemingly stricken by a mania and begins to count the bullets in his gun indefinitely. The sheriff, who is completely unnoticed by the bandit, uses the opportunity to place his gun in the bandit’s empty holster. He then proceeds to pour himself a drink into a nearby glass, only to proceed to take swigs directly from the bottle (CBS, 1960).

Ross, who was interviewed for the special, commented that while they had a great deal of fun developing the program the intention was not for levity, but instead to demonstrate the potential for computers to engage in “creative” acts (CBS, 1960). The process of developing SAGA II began with providing it an “elementary education”. Everything in “the world”, such as the bandit’s hideout, had to be defined in terms of what actions could and could not be performed with them. What happened when the world was poorly defined was exemplified by the third playlet, as the actors engaged in a series of behaviours that were logical to the computer but surreal to a human viewer (CBS, 1960; Ross, 1961b; Pfeiffer, 1962).

Drawing upon these relationships the program generated scripts using a pre-determined structure. Each script began the same way, with the bandit entering the hideout and placing the money on the table. Once this action had been performed there was the first “switch”, a feature in the program, which determined what action would happen next by randomly generating a number (Ross, 1961b; Pfeiffer, 1962). As part of the program, Ross also incorporated an “illogical behaviour” that would increase the probability of a character doing something strange based upon how many drinks they had taken (Ross, 1961b; Pfeiffer, 1962).

Ross described the development of SAGA II as a process of “trial and error” (Pfeiffer, 1962). This is predominantly due to one of the most important features of the program. Each time SAGA II ran, a new script was generated, the results of which were seemingly unpredictable. This, of course, was done intentionally, to prove the computer was the one engaging in the creative act and there wasn’t a “man behind the curtain” (Pfeiffer, 1962). Yet, in doing so, it made the process of determining how the
computer “understood” the world of the bandit’s hideout quite complex. For example, it wasn’t until the script was generated for the third playlet that Ross realized they needed to better define the relationship between holster and guns in order to prevent the sheriff from trying to place his gun in the bandits holster again (Pfeiffer, 1962).

Following the airing of *The Thinking Machine* in a memorandum to J. Reintjes about materials to be included in the yearly *President’s Report* of MIT, Ross explained the connection between the TV special and the CAD project:

> Mr. Douglas Ross and Mr. Harrison Morse participated in the CBS television Program, “The Thinking Machine”, by writing and demonstrating a program for the TX-0 computer which writes scripts for pantomime TV westerns. Techniques developed for this program, which represents a demonstration of techniques for making machines behave intelligently, will be incorporated in future work in the Computer-Aided Design Project. (Ross, 1961a).

Here, as well as in other letters written shortly after the airing, Ross tied the intelligence and creativity demonstrated by the computer in the SAGA II program to the kinds of intelligence and creativity that the Servomechanism Lab were trying to directly incorporate into the CAD systems under development.

In looking at how Ross articulates the intelligence of CAD, I outline a specific hierarchy in which humans define systems, machines produce, and humans judge. This further automates the translational labour I described previously into a system where humans merely define elements of what is being produced, in this case the elements of a Western. These systems preserve the position of human expertise as one of judgement, a dichotomy that firmly places all other forms of intelligence in the realm of the machine.
(Figure 6 – The Western playlets being filmed based upon the script by SAGA II)
3.10 The Design Team

In late 1960, following the initial six months of work on the CAD project, the Servomechanism Lab and the Design Division each produced reports describing the philosophy that both groups planned on using for approaching the problem of how to use computers to assist humans in the design process.

The report for the Servomechanism Lab was written by Douglas Ross and entitled *Computer-aided Design: A Statement of Objectives* (1960c). In the opening of the report, Ross explained the underlying approach used by the Servomechanism Lab for understanding this problem as:

> The primary problem is not how to solve problems, but how to state them. It is proposed that outside-in problem statements, in which a problem is described first in general terms and then refined and made precise by further elaborative statements, is required, rather than the inside-out problem statement form which characterizes present computer-programming. General problems are viewed as internally strutted by means of interconnected “objets”. An objet is an abstract entity of meaning, and the computer’s “understanding” of a problem is represented by the structure connecting the objets of the problem. The human’s understanding is in terms of a language which is isomorphic to the structure of the objets. This language for problem statement will consist of pictorial as well as aliphatic representations, and can be molded to suit particular problem areas (Ross, 1960c p. iii).

Here, Ross established a framework for mechanical design in which the primary task was stating a problem. Once this problem had been stated connections could be established between characteristics of the design object and the desired outcome based upon pre-established conditions. Steven Coons and Robert Mann wrote the report of the Design Division, entitled *Computer-aided Design Related to the Engineering Design Process* (1960). The approach to the problem of computer supported design as outlined by the two authors in the opening of the report was:
The engineering design process is viewed as a stochastic iterative process in which a recognized human need leads to a preliminary tentative concept of a means for its achievement; subsequent analysis, evolution, and judgement leads to modification of the concept and even possibly to a modification of the original goal, until certain standards are met and the need is satisfied...In general, the conclusion is drawn that for the present the computer can be most effective in replacing man-power in routine drafting, minor design decisions, engineering computation occurring in analysis, (particularly stress computations) and as an aid in the selection of standard parts (Coons and Mann, 1960 p. iii).

The framework for mechanical design established by Coons and Mann was one in which the primary task was making judgements. As these judgements were made by the designer, the role of the computer was to provide information that could either help with refinement or highlight potential issues with the design.

While the Servomechanism Lab and the Design Division established two very different approaches to the problem of CAD, the two groups shared a similar vision as to what CAD would look like. In a technical report (1963) the researchers at the Servomechanism Lab, which at this point had changed its name to the Electronic Systems Laboratory, described a proposed design terminal the system could use. Beginning with the console and slowly moving to the various kinds of input devices required, much of the description within the article focused on the concepts of flexibility and expressive communication, which would allow the designer to effortlessly engage in a wide range of design practices (Electronic Systems Laboratory, 1963). In describing the design process itself, once again, the concept of flexibility was the central focus. The designer would not be required to stick to a “single mode of expression”; they would be free to explore the concept by pursing specific details through the use of incomplete or semi-complete information statements or quick sketches (Electronic Systems Laboratory, 1963). Coons and Mann’s description of their proposed design terminal was almost identical; the only noticeable difference
between the two was that the writing of the Design Division tended to focus more heavily on the light-pen and other input functions for original or creative work (Coons and Mann, 1960). Regardless of who was articulating this vision of the CAD terminal, what was being described was, as Ross referred to it as, the “intimate coupling [of] the best characteristics of the [man and computer] so the team works better than either one alone” (Ross, 1967).

In his monograph on the MIT Innovations in Manufacturing Technology Project, Reintjes commented that the discussions regarding the design team served to “crystallize our thinking about the potential impact of numerical control on the mechanical design and production process as a whole” (Reintjes, 1991). By 1963 Ross was working on the Automated Engineer Design (AED) Language whereas Coons and Mann were developing experimental design terminals (Ross, 1967; Coons, 1964; Coons and Mann, 1960). By this point, serious questions were being raised about the role “mechanical drawings” actually played in the design process and if they were in fact the best medium for the total manufacturing process given the kinds of information they contained (Reintjes, 1991). During the development of Sketchpad II, Ivan Sutherland began to explore properties for computer drawings and argued that they were fundamentally different than paper drawings. He based this argument around the observation that it was easier and quicker to be accurate with computer drawings and that unlike paper drawings, computer drawings could be easily modified after being completed (Sutherland, 1963). This led Sutherland to the conclusion that drawings were better understood as constructs; that is to say, representational artifacts with material properties that could be directly linked to the manufacturing processes (Figure 7). As such, the use of computers within the design process was the work of an engineer and not a draftsman, as the expertise used embodied the knowledge and practices of the former (Sutherland, 1963). This marked the beginning of a new design paradigm in which a small group of engineers, with the aid of computer systems, were able to quickly and accurately develop designs for a new part, system, or device without the influences or translations labour of outside parties.
The effects that CAD would have on design and manufacturing were described by Mann and Coons in an article entitled “Computer-aided Design” (1965). At its core CAD would, according to Coons and Mann, greatly improve the speed and accuracy of the design process (Mann and Coons, 1965). Yet, as they freely admitted, there was a price to be paid. What originally took an “army of men six months to perform” will be “reduced to one-man one-machine tasks taking only several seconds” (Mann and Coons, 1965 p. 1). As such, that army was effectively out of jobs. What makes Coons and Mann’s position so important here is that it is a break from the previous claims of the NC project and the APT project described earlier in this chapter. Rather than better or more rewarding employment, CAD was positioned to bring whole-scale unemployment. As Coons and Mann described, in this CAD future, “a comparatively few extremely capable people, coupled with computers and machines, should be able to provide goods for the entire world” (Mann and Coons, 1965 p. 8).

The accuracy of this statement is unimportant, as obviously this future never came to fruition, but the central claim is worth noting in more detail. Wrapped in this claim is the
concept that a select few individuals would have the capacity to effectively design and produce all goods that were required for the entire world. This is the central characteristic of the new philosophy of manufacturing that emerged during the CAD project. In coming to terms with this philosophy Coons and Mann purposed the question: “certainly in all the material ways man will be the master of his universe. It remains only to be seen whether he will succeed in the deeper and more important ways of the spirit” (Mann and Coons, 1965 p. 9). This, in my analysis of how digital fabrication technologies reconfigured the concepts of labour and expertise, is the question that I will further unpack moving forward in this dissertation.

3.11 Conclusions

Digital fabrication is haunted by a pervasive myth that it has the capacity to materialize objects at will. I have examined the MIT Innovations in Manufacturing Technology Project in this chapter in order to better understand the context under which this myth evolved, and how concepts of production and expertise are dichotomized through the work of MIT’s scholars. In examining how we arrived at the current state of digital fabrication, I have highlighted a number of small and important decisions that have led to the shift toward a system in which outside input is reduced in favour of a single individual in control of defining a space which is then taken over by machines. In the following chapters, I will further address what this evolution means for the definition of expertise in these systems, and its implications for our use of these technologies in the present day.
Chapter Four

The Expertise of Abstract Models

4.1 Overview

In Chapter Three of this dissertation I examined the historical, cultural, and material strategies that contributed to the transformation of expertise during the MIT Innovations in Manufacturing Technologies Projects (1949-1970). This analysis specifically addressed the themes of control, as seen through the development of a model of design and manufacturing that used mathematically defined parts, as well as the theme of expertise, as seen through what I referred to as the creative routine dichotomy. The implications of the MIT Innovations in Manufacturing Technology Project was a reconfiguration of the production process such that labour and expertise associated with material processes became seen as less valuable than that of the labour and expertise associated with abstract forms of work.

In this chapter I address my second secondary research question, (R1B) what are the notions of expertise that are fostered by this transformation? I begin by outlining the research of N. Katherine Hayles on the information/material hierarchy and her strategy of complicating the leap between embodied reality and abstract information (Hayles, 1999). Hayles’ work provides a theoretical lens for further surfacing and understanding the implications of processes by which abstract expertise and labour became reconfigured as more important than material expertise and labour. I then use Hayles’ concept of the Platonic backhand and forehand, which are two conceptual moves through which the information/material hierarchy is produced, to illustrate how the MIT Innovations in Manufacturing Technology contributed to the expertise of engineers moving from making material objects to making abstract models. Next, I describe how abstract models, in addition to their material and instrumental aspects, are discursive and communicative devices that allow engineers to perform and express their labour.
and expertise. This is the process by which the labour and expertise of engineers are validated by those external to the process and profession.

4.2 The Hayles Maneuver

In the Introduction I described the common claim that 3D printing and digital fabrication technologies are tools that produce “things” without material labour. In this section I introduce the work of N. Katherine Hayles as a means of providing a theoretical lens for understanding how expertise was reconstructed by these moves. I begin this section by providing an overview of Hayles’ work on cybernetics and abstract information. I then discuss Hayles’ strategy for complicating the move from embodied reality to abstract information through the deployment of the Platonic backhand and forehand. I conclude this section by explaining why Hayles’ strategy is applicable to my own research and how I will be deploying it in this chapter and in the remainder of this dissertation.

Emerging in the wake of World War Two, cybernetics examined the flow of information between human, animal, and machine systems (Hayles, 1999; Galison, 1994). Norbert Weiner, a professor of mathematics Massachusetts Institute of Technology (MIT), pioneered this field with his research into feedback mechanism of steam engines. In noting that these mechanical systems were in effect able to “self-regulate” due to devices such as centrifugal governors, Wiener began to draw parallels between human and mechanical agents (Hayles, 1999; Galison, 1994). During the War, he extended this research into the development of anti-aircraft weapons and began to argue that the actions of enemy pilots could be effectively “modelled”, and thus countered, using feedback mechanisms (Hayles, 1999; Galison, 1994). While his early research began to blur the distinction between humans and machines, it was not until after the War that Weiner began to see humans and “intelligent machines” as essentially similar.

This refined perspective came as a result of Wiener combining his research into feedback mechanisms with MIT researcher Claude Shannon’s information theory, or
mathematical theory of communication. This allowed Wiener to conceptualize all systems in terms of information. What is important to note here is the meaning of “information” within this context. For Shannon information was a probability function with limited connection to “meaning” (Hayles, 1999; Shannon, 1948). Within Shannon’s own research this definition of information served a practical purpose. By removing “meaning”, or context, information was given a stable value. Doing so allowed information within systems, or interactions, to be represented as a series of choices among a range of possible messages. For communication engineers, the group Shannon specifically argued that information theory was initially intended to support, this allowed them to conceptualize the kinds of circuits they needed to design by mathematically determining the number of messages needed for a system or interaction (Hayles, 1999; Shannon, 1948). Despite the limitations that Shannon placed on it, Wiener saw information theory as having broad philosophical and technical implications. In defining information as probabilistic and contextually unbound it became free to flow unchanged between different material substrates. It is this “freedom” that allowed Wiener to fully equate humans with intelligent machines, as both could be defined as “information processing entities”. As such, the difference between the two was merely how information is processed, with humans using their sensory organs and intelligent machines using various technical devices, rather than anything truly profound (Hayles, 1999; Shannon, 1948). It is this capacity to synthesize humans and machines that lies at the heart of cybernetics as a field.

In her monograph How we became post-human: virtual bodies in cybernetics, lecture, and information (1999), N. Katherine Hayles suggests that cybernetics’ ability to liken humans and machines together has resulted in a fundamental shift in human ontology. In C.B. Macphersons analysis of possessive individualism, which Hayles refers to as one of the definitive texts on liberal humanism, this ontological shift is illustrated. “The human essence”, according to Macpherson, is “freedom from the wills of others, and freedom is a function of possession” (quoted in Hayles, 1999 p. 3). Cybernetics challenged the liberal human subject through the introduction of what Hayles refers to as the “post-human” ontology. The post-human is a “view that privileges informational
pattern over material insertions, so that embodiment in biological substrate is seen as an accident of history rather than an inevitability of life” (Hayles, 1999 p. 2). In other words, within the post-human world view information is the essential and defining characteristic of reality, whereas the material is the substrate through which that information has manifested. Not only does this allow the body to be seen as the “original prothesis we all learn to manipulate”, but it also “configures human beings so that they can be seemingly articulated with intelligent machines” (Hayles, 1999 p. 3). The result of this post-human view is the end of the isolated and private individual as described by Macpherson. This is instead replaced by a perception that the individual is a collection of autonomous agents acting as a single unit to make a “self”. This post-human view is predicated on the fact that all systems, from a human “within” their body or a human driving a car, can be equally considered as information seeking entities (Hayles, 1999). The post-human view is important to my analysis as it provides a means for understanding how and why computers became seen as “intelligent machines”.

Hayles’ focus, however, in writing *How we became post-human* is not to challenge the post-human ontology, or to suggest a return to the perspectives on liberal humanism as described by Macpherson. Rather, she is seeking to contest the “material/information separation” that is emblematic of the work of Wiener and Shannon. This separation is extremely important - the post-human ontology depends upon it (Hayles, 1999). The strategy that Hayles’ adopts for doing so is to “complicate the leap from embodied reality to abstract information”. In doing so, Hayles is seeking to illustrate the complex, and often politically and ideologically driven processes, through which the material is stripped from the abstract. Ultimately, in deploying this strategy, Hayles is seeking to understand how society got to the point in which the separation between information and the material became accepted.

As part of her strategy to *complicate* this “information/material hierarchy” Hayles identifies two particular moves, which she refers to as the Platonic backhand and
forehand, that played an important role in its “construction” (Hayles, 1999 p. 12)

As the name suggests, the Platonic backhand has a history dating back to the Greeks (Hayles, 1999). In this move “the world’s noisy multiplicity” is inferred into a “simplified abstract” (Hayles, 1999). This, in and of itself, is not a problem. As Hayles notes, this kind of abstraction is “what theorizing should do” (Hayles, 1999). The issue is when the Platonic backhand “circles around” such that the abstraction becomes constituted as the original form “from which the world’s multiplicity derives” (Hayles, 1999). As such, complexity becomes perceived as “fuzzing up” the “essential reality rather than as a manifestation of the world’s holistic nature” (Hayles, 1999 p. 12).

The second move, the Platonic forehand, is a more recent development. This is because the Platonic forehand is dependent upon computers. Beginning with “simplified abstractions”, this move uses “simulation techniques”, or complex algorithms, in order to “evolve” the abstraction such that it is complex enough to be seen as representing the material world. (Hayles, 1999 p. 12). As such, the Platonic forehand operates in the opposite direction of the Platonic backhand. Whereas the backhand “goes from noisy multiplicity to reductive simplicity”, the forehand “swings from simplicity to [multiplicity]” (Hayles, 1999 p. 12). In her work on Computer-aided Design (CAD) Katherine Henderson described how the abstract models produced by engineers effectively sought to capture, or represent, the materiality of the manufacturing processes (Henderson, 1999). As I will discuss in an upcoming section in this chapter, Hayles’ concept of the Platonic forehand is a useful conceptual framework for addressing and understanding the limitations of these abstract models.

Both of these moves, Hayles argued, are part of a shared ideology that seeks to privilege the abstract and downplay the material (Hayles, 1999 p. 13). When combined, the groundwork is laid for disembodied information to become seen as the ultimate Platonic form. (Hayles, 1999 p. 13).
In the opening of this section I briefly returned to the common claim that 3D printing technology and digital fabrication technologies are tools that allow objects to be materialized. One of the major claims of digital fabrication technologies, including CAD and more recently 3D printing, is that information is separate or independent from the human or material context. Hayles’ work, as outlined above, reveals the long-standing nature of such claims. Equally, she highlights some of the work that such claims have done in the past. She notes how the Platonic forehands and backhands that she describes have been utilized to produce a post-human ontology in which there is essentially no difference or demarcation between bodily existence and computer simulation. An important point for Hayles was to look historically at the pragmatic impacts of the epistemological activities present in cybernetics.

Similarly, my strategy is to address this leap between embodied reality to abstract information in order to understand how the historical, cultural, and material moves that I described in Chapter Three contributed to the reconfiguration of the concept of expertise through the production of an information/material hierarchy. This is the focus of the next section.

4.3 The Information/Material Hierarchy and Digital Fabrication Technologies

In the previous section of this chapter I outlined Hayles’ concept of the information/material hierarchy and how the Platonic backhand and forehand contribute to its construction. In this section I return to the historical, cultural, and material moves that I detailed in Chapter Three. I use these concepts to understand the reconfiguring of the concept of expertise through the production of an information/material hierarchy. I begin by returning to the research of Pease, Ross, and Coons in the establishment and development of a model of design and manufacturing in which the design of parts are mathematically defined. I then connect this model of design and manufacturing to the Platonic backhand through the theme of control. Next, I examine the work of Brown, Runyon, Ross, and Coons in the production of the creative routine dichotomy.
As part of these discussions I link the creative routine dichotomy discussed in Chapter Three to the Platonic forehand through the theme of expertise.

In Chapter Three I described how William Pease argued that Numerical Control (NC) was an information technology. As part of this argument Pease articulated a sweeping technological narrative in which NC could be used to rapidly and easily fabricate a part in any context as a result of the control equipment and the control tapes that contained detailed mathematical instructions for the part. This narrative marked an important conceptual development for the MIT Innovations in Manufacturing Technology Project, as it established a model of design and manufacturing in which the design of parts that were sufficiently mathematically defined could be readily produced in any context. During the APT project Douglas Ross built upon this model of design and production by producing a system that simplified the processes by which parts were mathematically defined. Comprised of a hierarchy of points, lines, and surfaces, the APT system allowed engineers to detail parts with geometric expressions and relationships using English-like terms. The use of this digital geometry made it easier to mathematically express complex parts as a series of simple English-like statements using the base “shapes” which it was comprised of.

The CAD project saw Douglas Ross and Steven Coons both further refine this model of design and manufacturing through the concept of human-computer design teams. Rather than working on the part itself, the human-computer design concept had engineers focus on effectively stating the ‘problem’ that required the part. Based upon these problem statements the computer would then generate a design for a part that the engineer could then accept, reject, or modify by altering the problem statement. If the part was accepted by the engineer the design, which the computer had fully mathematically defined, would be sent to an NC mill for production. This ‘division of labour’ had dramatic impacts on how teams of workers were organized.

My examination of this research by Pease, Ross, and Coons in Chapter Three focused on the theme of control. The model of design and production established and
developed by this work was one in which the design of parts had become sufficiently mathematically defined such that they could be readily produced in any context. As a result, the labour and expertise of the engineer or designer became immutable, as any deviations from the part design became perceived as ‘noise’ or unwanted input. This closely aligns with Claude Shannon’s concept of communication, in which the goal is to send messages over a noisy channel and receive them with the lowest probability of error (Shannon, 1948). This reconfiguration of the labour and expertise of the engineer as being immutable is important as it helps to inscribe the abstract material knowledge hierarchy.

The Platonic backhand, as I described in the previous section, is a move described by Hayles by which the complexity of the material world is converted into an abstraction. A problem emerges when these abstractions become seen as the ‘original’ form and the complexity of the material world become construed as distortions in an essential reality, i.e. as noise. Once an abstraction has been constituted as the original form, any attempt at recovering the complexity of the world results in a version of the abstraction that is seen as diminished. It is through this value proposition that abstract information is seen as somehow more representative of the real than embodied or material representations. Just as Hayles demonstrated that the information/material hierarchy produces a posthuman perspective in which human intelligence can be modelled and represented with intelligent machines, in the history of CAD we can see similar conceptions. Within their respective research Pease, Ross, and Coons all described machines performing tasks that once required the labour and expertise of humans. This has implications in terms of how labour and expertise were defined and understood and, specifically, in what is counted as creative and routine forums of labour.

As part of Chapter Three I discussed the research of Brown, Runyon, Ross, and Coons that led to the development of what I referred to as the creative routine dichotomy. During the NC project Brown argued that the automatic factories of the future would “free” workers from the most boring and stressful jobs of ‘todays’ mass-
production. This freedom, however, had a cost as the jobs that would replace the boring and stressful ones would require workers to upgrade themselves in both their base knowledge and their skills. This concept of NC as a liberatory technology is the first instance in which clear distinctions are made between the various tasks of the manufacturing technology as being either stimulating or boring. For Brown and the other researchers on the NC project this distinction was important as it was used to determine if a task was appropriate for humans to perform. This simple distinction between tasks that were either stimulating or boring was greatly expanded upon during the research that led up to the APT project. Prior to the research of Runyon the distinction between the two kinds of tasks referred to essentially mental tasks as stimulating, and material or physical tasking being boring. In examining the part programming process Runyon realized that this distinction was insufficient, as many of the mental tasks involved with part programming were simple and repetitive mathematic operations derived from the design of the part. In developing the first automatic programming system for NC tapes Runyon established a distinction between original and routine that equally viewed mental and material or physical tasks as potentially routine.

The CAD project took this distinction between original and routine tasks even further. In the meetings between the researchers at the Servomechanism Lab and the design division of the MIT Mechanical Engineering Department that helped to formulate the CAD project, a distinction was made between creative and routine design. Both kinds of designs were seen as important and involving human judgement. Whereas creative design covered the tasks involved in producing a new or novel design, routine design was perimeter based and covered the tasks involved in modifying a pre-existing design. This conception of these two kinds of designs resulted in the distinction between original and repetitive tasks being reformatted into what I refer to as the 

*creative routine dichotomy*. Within this dichotomy the act of either creating a new design or modifying a design is seen as creative, and all other tasks that follow in the design or manufacturing process are seen as routine. The creative routine dichotomy is an important tool for understanding the CAD project as it explains the conceptual
leap that allows for intelligent machines to handle so much of the design and manufacturing process.

The creative routine dichotomy serves as a filter by which tasks associated with the design and manufacturing process are assessed and assigned to either humans or intelligent machines. Within this dichotomy any tasks that are definitional or require judgement are seen as the domain of humans, whereas all other tasks can be given over to intelligent machines as they merely substantiate the judgements or definitions of the humans. As such, the expertise of humans in the creative routine dichotomy is that of understanding problem spaces and being able to clearly define need or want statements that effectively address that problem space. Hayles’ concept of the Platonic forehand, as I described in the previous section, is a move that involves a simple abstraction developing sufficient complexity or multiplicities as to be seen as the world in its own right. The process by which these complexities or multiplicities are layered onto the simple abstraction involves the use of computer simulation techniques. The layering of complexities or multiplicities onto the simple abstraction through computer simulation does not result in the production of what is seen as a diminished version of the abstraction. The simulations are comprised of abstract information and, as such, rather than adding noise to the abstraction they effectively make it more real.

The Platonic backhand and forehand are two concepts that Hayles highlights that contribute to the construction of the information/material hierarchy. In this section I revisited the historical, cultural, and material moves involved in the development of digital fabrication technologies that I described in Chapter Three and, using the Platonic backhand and forehand, I illustrated how the labour and expertise of manufacturing became reconfigured around notions of abstract information. The effect of this is that the expertise and labour of engineering moved from that of making material objects to that of abstract models.
4.4 The Expertise of Abstract Models

In this section I discuss how this expertise in making abstract models affects the labour of engineers. Drawing on Louis Bucciarelli’s concept of *object worlds*, I describe the processes by which these abstract models allow for a division of labour and expertise (Bucciarelli, 1996). Next, I look at how these abstract models allow engineers to *perform* their expertise for both legal bodies as well as the general public.

My earlier description of the reconfiguring of the expertise of engineers from the production of material objects to abstract models focused on how this reconfiguration occurred. This begs the question of *why* these changes occurred. Or, to put it more simply, what are the advantages of abstract models that lead to this reconfiguring of engineering expertise?

In his own work, Louis Bucciarelli (1996) refers to this process as developing “object worlds”. The overall description he provides in terms of the nature of engineering drawings and the work they afford adds an important element by focusing on the “abstracting” capacity of these drawings (Bucciarelli, 1996). In producing these drawings, designers and engineers are able to define an object not only for production but also in terms of its “outputs” (Bucciarelli, 1996). This allows for a more complex and specialized form of engineering to occur. Rather than requiring everyone to understand a wide variety of specialized knowledge, a component can be designed and then “reduced” to its essential characteristics, such as its dimensions, weight, and how much “energy” it generates, so that other engineers within the design team can take it into consideration (Bucciarelli, 1996). Or, to put it simply, these “object worlds”, or abstract models, allow for a division of labour and expertise to occur.

Aside from these *organizational* level capacities that allow for a division of labour and expertise, abstract models also serve an important role *outside* of the engineering firm. In the article “The Olympus 320 Engine “(1992), John Law examines the physical, legal, and organizational barriers involved in the design processes. As part of his
analysis Law makes an important distinction between those on the *inside* and *outside* of these barriers (Law, 1992). In doing so Law is able to illustrate how abstract models serve as a means by which those on the inside of barriers express their authority and control to those on the outside of them (Law, 1992). While each of these barriers is interesting in its own right, I want to specifically address the organizational barrier as it more directly addresses the discussion at hand. The organizational barrier, as described by Law, is a fairly simple distinction between those who are working *directly* for an engineering firm and those who are not (Law, 1992). For those on the outside of this barrier an abstract model effectively serves as a *window* in. That is to say, it allows those on the outside to see and understand the labour and expertise of those on the inside. As such, the abstract model plays an important role for those on the inside to *perform* their expertise and labour for those outside. This performance, as Law suggests, is important as it is how *trust* is established between the parties on the inside and the outside of the organization.

This is an important point that I will return to in Chapter Five when I discuss my case study, as it is connected to one of the reasons prosthetic and orthotics (P&O) professionals support the adoption of digital fabrication technologies. As tools of communication, abstract models allow engineers to express their labour and expertise to others in an immutable way. This allows for the division of labour and expertise that I described above. What is important to note is that both the discursive and commutative roles of abstractions are dependent upon a model of information that is independent from humans or the material context.

### 4.5 The Limitations of Abstract Models

In the previous section I examined how abstract models act as discursive and commutative devices that allow engineers to perform and express their expertise. In this section I follow Hayles’ approach of examining the leap between embodied reality and abstract information in order to illustrate the limitations of these abstract models. I begin by looking at the use of these abstract models in practice. As part of these
discussions I draw on the work of researchers Harley Shaiken, Julian Orr, and Katherine Henderson as a means of showing the tension between the production of abstract models and their usage in producing material objects. I conclude this section by analyzing the nature of abstraction and why they are an inherently limited means for addressing issues related to labour and expertise.

Harley Shaiken, in his monograph Work Transformed (1984), described a form of resistance that machinists engaged in that he called “refusal to redesign” (Shaiken, 1984 p. 19). Following a disagreement either with management or engineers in which the machinists felt “harassed”, they begin to produce designs exactly as depicted in technical drawings or other abstractions (Shaiken, 1984 p. 19). The result, according to Shaiken, was “mountains of scrap” and a “disruption” to the flow of work that was often more costly and harder to address than a formal strike (Shaiken, 1984 p. 19). This description by Shaiken of this form of resistance raises questions regarding the role that abstractions play in the design and manufacturing process. In the last section of this chapter I discussed how abstractions act as discursive and commutative devices that allow engineers to perform and express their expertise. Yet, as the resistance described by Shaiken illustrates, these abstractions are seemingly a limited means to fully encompass the design and manufacturing process. Shaiken is not alone in his analysis. Within their respective works Orr (1996) and Henderson (1999) have all noted how various kinds of abstraction, not just those produced in regards to engineers work, do not sufficiently encompass the complexity or multiplicity activity or object represented.

Lucy Suchman in her article “Supporting Articulation Work” (1996) noted that those responsible for making abstractions are either unfamiliar with or unaware of the embodied realities of what is being abstracted. As such, complexities or multiplicities that would otherwise be seen as essential are overlooked. This problem of distance within abstractions, Suchman explained, is connected to power dynamics. Rather than engaging with those who might otherwise be able to explain the complexities or multiplicities of an embedded reality, the processes by which an abstraction is created
systematically marginalize these kinds of inputs as they are seen as less authoritative. In an earlier section of this chapter I described Hayles’ concept of the information/material hierarchy. When this hierarchy is applied to the process by which abstractions are made it becomes evident that any form of input that would “fuzz-up” the abstraction, to use a term from Hayles, would be ignored, seen as less valuable, or actively removed from the process.

The politics of abstractions, for lack of a better term, described by Suchman is not the only reason why these limitations occur. In her own work on abstractions Diana Forsythe (2001) engaged in a series of interviews with software engineers about the processes they used for developing tools for automating tasks. What Forsythe found is that these engineers were reductive in terms of what they saw as the essential elements of a task in that they only described one specific task as their job, like coding, rather than describing their role more fully. Yet, this reductive tendency was not limited solely to the tasks that these software engineers were seeking to automate. When asked to describe their own profession and what the essential elements of it were, the software engineers only identified “coding” as a professional activity. Any other task they performed in a given day was seen as external to their professional activities. What this demonstrated, according to Forsythe, is that there is a strong tendency to ignore the social and cultural elements of technical work during the abstraction process. It is these “cultural” and “social” elements that I want to address more fully in the next section of this chapter, as it is through them that the complexity and multiplicities of the world are re-connected to the abstract, allowing design and manufacturing work to get done.

4.6 Engineering In and Out of Context

In the previous section of this chapter I described the insufficiencies of abstract models for design and manufacturing work from both a material as well as a cultural and social perspective. In this section I continue to follow Hayles’ approach of examining the issues that arise as the result of the leap between embodied realties and abstract
information as a means of addressing how expertise has been reconfigured through digital fabrication technologies. I begin this section by providing a brief history of technical drawings in order to highlight the culture of ‘openness’ around these abstractions that was more directly apparent. I then return to John Law’s distinction of ‘inside and outside’ to situate these abstractions in a modern context. Next, I detail how these abstractions are used within design and manufacturing work to denote the social and cultural context of this work.

In the “Introduction” chapter of *Picturing Machines 1400-1700* (2004) the volume’s editor Wolfgang Lefevre’ provides a brief overview of the development of technical drawings during the Renaissance. This chapter acts as a primer for the reader by discussing the similarities and differences between the technical drawings produced by “early modern engineers” and those produced by their “modern” counterparts. Functionally, early modern and modern technical drawings are identical. Both allow engineers to “communicate” the functions and specifications of a design to craftspeople for production (Lefevre, 2004 p. 3). Where the two differ is in the nature of this communication. As Lefevre explained, early modern technical drawings were not intended to be “exact plans” (Lefevre, 2004 p. 7). Rather they allowed engineers to specify “some discrete details” about the design while “leaving the concrete shaping” to the craftspeople charged with its production (Lefevre, 2004 p. 7). In the following chapter in the volume, “why draw pictures of machines? the social contexts of early modern drawings”, Marcus Poplow characterizing these early technical drawings using terms like “openness” and “gaps” as a means of discussing how certain aspects of the design were intentionally left by the engineer to the skill and judgment of the craftspeople (Poplow, 2004 p. 34). Earlier in this chapter I described how the expertise of engineers moved from that of making material objects to abstract models. As part of this move the “openness” and “gaps” of the technical drawings became problematic, as it was through them that “noise” or unwanted input distorted the abstract model produced by the engineer. This is exemplified by the model of design and production described by Coons outlined in Chapter Three.
Yet, this reconfiguration of technical drawings from essentially “open” abstractions to “closed” abstractions needs to be understood as part of a discursive move that was intended to allow engineers to both perform and express their expertise. Previously, I described the distinction that John Law made in terms of inside and outside of the design and manufacturing process. As part of this analysis Law notes that the “openness” or “closeness”, to borrow a term from Lefevre, was relative to where a person was inside or outside of the design and manufacturing process. That is to say, those on the outside of the process perceived the abstractions as closed, and were encouraged to do so through both discursive means as well as physical, organizational, and legal barriers whereas those on the inside of the process perceived the abstractions as open and were equally encouraged to do so through both discursive means as well as physical and organizational barriers. This is not to say, however, that those on the inside of the process were totally free to interpret design abstractions as they saw fit. Rather, there were organizational channels that were created that allowed various groups to provide input in a controlled manner. It is these channels that I am interested in as they illustrate a social and cultural context to the design and manufacturing process that is seemingly ignored by the kind of expertise fostered by digital fabrication technologies.

Katherine Henderson in her monograph On Lines and On Paper (1998) described the introduction of computer-aided design/computer-aided manufacture (CAD/CAM) technologies into several different engineering contexts. As part of this research Henderson interviewed different individuals involved in the design and manufacturing processes from the design office and the workshop. During one of these interviews a machinist commented that CAD/CAM technology resulted in what can best be described as excessive “definitions” from the engineers. What the machinist meant by this was that using CAD/CAM technologies allowed engineers to “define” a design almost completely. While this allows for a “complex” understanding of how the component will perform once it has been manufactured, to actually produce the component is either impossible or potentially prohibitively expensive due to the specifications provided. This leads to a working relationship in which the skilled labour
required that either have the engineers re-introduce “vagueness” into the design by lowering the specification or, alternatively, work with the engineers so that the “completeness” can remain but is more reflective of the material context in which the component will be produced.

Eugene Ferguson (1994), Richard Sennett (2008), and Steven Shapin (1989) describe a similar narrative within their respective research. What I seek to add to this discussion through my research is how the channels that allow for these inputs, which are essential to the social and cultural context in which design and manufacturing work is performed, are unofficial. What I mean by this is that as a result of the information/material hierarchy, as well as the limitations of abstractions that I described earlier, the social and cultural contexts that foster these unofficial inputs, for example the process of “fudging” I describe in Chapter Six, are both undervalued and ignored when digital fabrication technologies are discussed in relation to the contexts in which they exist.

This incomplete model of the work context of digital fabrication technologies is important to note as it has implications for the kinds of expertise that are fostered when these technologies are deployed into new contexts. My central argument in this chapter has been that digital fabrication technologies played an important role in reconfiguring the expertise of engineers from that of making material objects to that of making abstract models. As such, when these technologies are deployed in a new context, that is the kind of expertise that is fostered. The issue with this is that the internal workings of engineering, what Law terms the “inside”, become severed when the models of work that are a part of digital manufacturing become abstracted. This results in difficulties when translating this work into new contexts, and the social and cultural channels that were once internal are removed from the work. The resulting tension is what I will be addressing in Chapter Five.
4.7 Conclusions

As part of this chapter I described the limitations of abstract models and how they are addressed through the social and cultural context in which design and manufacturing work is performed. Yet, there is a larger issue at play here regarding the kinds of knowledge that are valued and fostered. Since the social and cultural context of labour and expertise is largely unofficial it is perceived as less valuable to the process. This establishes a problematic framework as without this unofficial input digital fabrication technologies cannot function. I address this issue more closely in the conclusion of this dissertation by proposing an alternative model to the current politics of computation that seeks to recognize the importance of these unofficial inputs.
Chapter Five

How We Became Engineers

5.1 Overview

In the previous chapter I described how digital fabrication technologies contributed to the reconfiguring of the expertise of engineers from that of making material objects to making abstract models. In this chapter I examine the process by which digital fabrication technologies migrated from the context of design and manufacturing to that of prosthetic and orthotic (P&O) work and how these technologies sought to transform the expertise of the P&O professional from that of making material devices to that of making abstract shape patterns. This analysis will address my third secondary research question (R1C); who benefits from this transformation of human expertise? In the first section of the chapter I provide an overview of the early research into digital fabrication technologies for P&O work and the problems these technologies were intended to solve. I then discuss the development of Computer-aided Socket Design (CASD), one of the first commercially available digital fabrication technologies for P&O, as a means of illustrating how these technologies alter P&O professionals’ relationship to the fitting process. Next, I look at a clinical trial perform by the Veterans’ Health Administration (VA) with the University College London – University of British Columbia (UCL-BC) system and resulting in the development of the Shapemaker system. As part of this analysis I address the moves that contributed to the labour and expertise of P&O professionals moving away from material based practices to that of abstract based practices. In the next section I outline what I refer to as the new errors that became a part of the P&O profession as a result of digital fabrication technologies, and how they contributed to a narrative that sought to further align the P&O profession with that of engineering. I conclude this section by connecting the migration of digital fabrication technologies into the P&O context with the larger trend of evidence-based medicine.
5.2 Foundations of Digital Fabrication in Prosthetics and Orthotics

In this section I outline the early discussions that resulted in digital fabrication technologies being developed for the prosthetics and orthotics (P&O) profession as a means of discussing how researchers initially positioned these technologies within this new context of work. I begin by detailing the ‘problems’ of socket production that led digital fabrication technologies being investigated for use in the P&O context. I then provide an overview of a meeting held in 1969 at the Manitoba Rehabilitation Hospital, which the early research on digital fabrication technologies came from. Next, I look specifically at the research of James Foort in order to highlight the logics that went into early research into digital fabrication for P&O work. I conclude this section by returning to the historical, cultural, and material moves that I surfaced in Chapter Three and draw parallels between this early research into digital fabrication technologies and the MIT Innovations in Manufacturing Technology project through the theme of control.

The traditional socket fabrication and fitting process could best be described as a “craft” practice. The first step in the traditional process involves creating a “negative model” of the residual limb using plaster wraps (Foort, 1979; Kohler et al., 1989; Saunders et al., 1985; Wilson, 1989). Next, a positive model is created by pouring plaster material into the negative model, allowing it to harden, and removing the wraps. The positive model is then used in the rectification process, which draws upon the skill and judgment of the prosthetists to add and subtract material in order to properly distribute weight and pressure across the residual limb. Once the prosthetist has finished the rectification of a positive model, a socket is fabricated over it. Finally, the socket is freed by shattering the positive model and it is fitted to the patient after some light post-production, such as sanding rough edges (Foort, 1979; Kohler et al., 1989; Saunders et al., 1985; Wilson, 1989). During the actual fitting process, minor modifications can be made to the socket based on feedback from the patient (Foort, 1979; Kohler et al., 1989; Saunders et al., 1985; Wilson, 1989). If, however, major modifications are required, usually as a result of the socket being either too large or
small, the entire process must begin again. This is because all of the “shape modification information” of the rectification process is lost when the positive model is shattered to free the socket. Moreover, even after a “good” fit is achieved the shattering of the positive model means that there is no “record” of the process. Thus, when a patient requires a new socket the entire process begins again (Saunders et al., 1985). It was this heavy dependency of the skill and judgement of the prosthetists, as well as the lack of a record of the socket once it had been fabricated, that became the perceived problem that researchers sought to address with the development of digital fabrication technologies for P&O professionals.

In the fall of 1969, a group of technologists gathered at the Manitoba Rehabilitation Hospital to discuss the possibility of using “shape sensing” techniques to capture an artificial limb and then “replicate it by machine methods” as a means of addressing the lack of records from the traditional fitting process (University of British Columbia et al., 1975; Foort, 1979). Following demonstrations and discussions of various methods it was determined that there was indeed a case to be made for incorporating these technologies into the practices of P&O professionals (University of British Columbia et al., 1975; Foort, 1979). At the conclusion of the conference the group decided to seek funds from the National Research Council of Canada (NRC Canada) and the Prosthetics Research and Development Unit in Manitoba on the topics of photogrammetry and holography respectively.

From an organizational perspective this 1969 conference is important because of the network of researchers that it helped to form. As the research projects into photogrammetry and holography began to progress, reports on their findings began to circulate. This led to a community of scholars from across Canada, the United States, and Europe to become interested in the work being conducted on issues related to digital fabrication technologies and P&O (University of British Columbia et al., 1975; Foort, 1979).
Among the researchers at the 1969 conference was James Foort, whose later research into digital fabrication technologies for P&O would be highly influential. After completing his Master’s degree in Chemical Engineering at the University of Toronto in 1951, Foort joined the Department of Veterans Affairs at Sunnybrook Hospital in Toronto, Ontario where he stayed until 1953 when he took a position at the University of California, Berkeley Biomechanics Laboratory (Hobson, 2002). While at Berkeley, Foort developed a series of “jigs” designed to improve the efficiency and accuracy of the process used to make a total-contact quadrilateral socket (Foort, 1979; Hobson, 2002).

Work on the jig system began with a search for “the measurements and contours” to base the designs on (Foort, 1965; Foort, 1979). Over the course of several months, Foort systematically measured a “variety of sockets and stumps” and began to note patterns in the “basic shape” of above-knee sockets. Based upon these observations, Foort concluded that “proximal fit” of a socket could be determined based upon three measurements found on the residual limb and hip: the ischial tuberosity, the tendon of adductor longus, and the greater trochanter. What is important to note about this “triangle” was its predictive capacity for shape not only in terms of the overall dimensions of the socket but also where, and by how much, the rectification process should occur for the patient in order to ensure a “comfortable” fit (Foort, 1965; Foort, 1979; Hobson, 2002).

Foort’s work on the jig system had a profound effect on how he approached and understood the fitting and rectification processes for the remainder of his career. After returning to Canada in 1963, Foort began work on an array for matching patients to prefabricated sockets. Comprised of 10 left and 10 right sockets, Foort viewed the development of this array as a major achievement as it represented a step towards realizing the potential of the P&O profession as a science of measurements and mathematics, and not craft based as it had long been perceived (Foort, 1965; Foort, 1979). By simply measuring a patient, this system allowed a P&O professional to easily and rapidly fit a socket to a patient. The major challenge going forward was that
regardless of how many different versions of a prefabricated socket were produced, individuals would “fall outside the range of such a socket series and inevitably suffer neglect” (Foort, 1979 p. 73). A solution, then, needed to be devised that would allow data related directly to the individual to somehow influence the design of a prefabricated socket. While seemingly paradoxical, Foort saw an opportunity to build such a system with digital fabrication technologies following his attendance at the conference in 1969 in Manitoba (University of British Columbia et al., 1975; Foort, 1979.)

In 1970, Foort began working on a project that sought to capture the photogrammetric data of a patient’s remaining limb so that a “cosmetic” cover could be produced on an N/C mill. The underlying intention of the project was to use patients’ own “data” to produce the shape and size of the cosmetic cover in order for it to appear more “natural” (University of British Columbia et al., 1975). By 1979, Foort was comparing the “use” of computers to the way a “potter uses his thumb” and had sketched out, at least on a philosophical level, a system that would allow prosthetists to “change the dimensions and size of pre-established shape” on “television screens” in order to make a socket (Foort, 1979).

As part of my analysis of the historical, cultural, and material moves that contributed to the transformation of expertise in Chapter Three, I described how a model of design and manufacturing was established and developed around mathematically defined part designs. This model of design and manufacturing was an attempt to make these processes more reliable by shifting the locus of control away from the labour and expertise of machinists to that of the engineer. The early research into digital fabrication technologies for P&O work mimic this move in many regards. Foort and his colleagues actively sought to develop systems that produced definitive records of the rectification process in order to make the process of producing and fitting a socket for a patient more reliable. Where these two projects differ is in how the labour and expertise was reconfigured. Whereas the MIT Innovations in Manufacturing Technology project sought to essentially remove the input of the machinists, these
early digital fabrication technologies for P&O sought to transform the labour and expertise of P&O professionals from that of craftspersons to engineers.

5.3 Shape Libraries

In this section I look at the development of Computer-aided socket design (CASD) system at the University of British Columbia’s Medical Engineering Resources Unit (MERU), University College London (UCL), and West Park Research Centre in order to illustrate how this concept of a reliable alternative based upon mathematically defined designs was manifested. I begin by examining the underlying research project that led to the development of the CASD system. Next, I detail how the system was used. As part of these discussions I highlight the use of a primitive socket model which was intended to dramatically reduce the complexity of the fitting process. I then outline a clinical trial that was conducted using CASD in the early 1980s and the resulting changes that were incorporated into the system, specifically that of a reference shape library which expanded upon the primitive socket model concept. I conclude this section by returning to the theme of expertise as well as the creative routine dichotomy as a means of explaining how digital fabrication technologies were used to alter the relationship between P&O professionals and the fitting process.

Development of CASD began in the late 1970s with three separate research groups: MERU, UCL, and West Park Research Centre. Each group was responsible for the development of a specific system that was “dedicated” to P&O applications: the West Park Group worked on a “shape sensing system” tailored for capturing the residual limb for patients with above-knee amputations that used photogrammetry; the UCL group worked on a computer-aided manufacturing (CAM) system which comprised of a “modified” numerically controlled milling machine designed to work with wax or plaster, which were the materials typically used for the rectification processes; and the final group at MERU was responsible for the development of the computer-aided design (CAD) software (Fernie et al., 1985;Lawerence et al., 1985;Saunders et al., 1985).
At its core, the CASD system sought to address the “inherent difficulties” that “plagued” traditional socket manufacturing as a result of difficulties in “quantifying and recording the modifications used to produce comfortable sockets” (Holden and Fernie, 1986; Sanders et al., 1985; Torres-Moreno et al., 1989). To accomplish this the researchers devised a system consisting of two software packages that digitally mimicked aspects of the traditional model of socket production, while also seeking to improve upon them by “qualifying the art of socket design” through a systemized approach (Dean & Saunders, 1985).

The first software package of CASD can be broadly considered the “modelling” suite. Here, the prosthetist was able to “manipulate” a “primitive socket model” in order to produce a “digital customized socket”. To begin the prosthetist entered the measurements of the patient’s residual limb (Holden and Fernie, 1986; Sanders et al., 1985; Torres-Moreno et al., 1989). Once the measurements had been entered, the prosthetist was shown a digital representation of the patient’s residual limb. Using this digital representation the prosthetist would then begin to “manipulate” and/or “transform” a “primitive socket shape” until it was the “appropriate shape” for the patient. The primitive socket shape was based upon the “experience from thousands of fittings” and had some “relief and compressive surfaces ‘built-in’” (Klasson, 1985; Saunders et al., 1985). What is important to note about this entire process is that any manipulation and/or transformation of the primitive socket shape is quantified as a series of measurements. This, in theory, meant that at the end of the “digital rectification process” if the socket fit, and was comfortable, it could be easily reproduced if it was damaged or lost. Alternatively, if the socket did not fit or was uncomfortable, the prosthetist could return to the digital model and engage in a systematic and iterative approach of manipulation and/or transformation until it did.

Once the digital rectification process had been completed the prosthetist would move onto the second suite, which handled “production”. Here the “socket data” was converted into a series of commands which instructed a computer-numerically-controlled (CNC) milling machine to carve a positive model (Torres-Moreno et al.,
This process, in contrast to the work done in the modelling suite, was far more automated in nature. Options were limited as the primary focus was on allowing the prosthetist to quickly move from what they saw on screen to a physical model (Foort et al., 1985; Holden and Fernie, 1986; Sanders et al., 1985; Torres-Moreno et al., 1989).

Following the successful demonstration of the technology at the 1983 ISPO conference in London, MERU and UCL began a series of clinical trials of the CASD system that employed a systematic and iterative approach to below-knee (BK) socket design. A total of 17 participants received BK sockets during these experimental fittings; 14 were fitted at three sites in the United Kingdom and the remaining 3 were fitted in Canada (Foort et al., 1985). While both sites followed the same process, they employed different kinds of operators. In the United Kingdom experienced prosthetists were employed, whereas in Canada the operators were complete novices who had never fitted a socket or any other prosthetic or orthotic device before. This approach was taken for three reasons. First, to determine what “level of success” could be achieved in BK socket fitting by an operator with no previous experience using a systematic and iterative approach. Second, to see if a “direct transfer of skills” from experienced prosthetics and orthotics professionals into CAD system was possible. Finally, to compare the difference between what would be a purely systematic and iterative approach used by the inexperienced operators and one governed, at least in part, by the “intuition” of the experienced operators (Foort et al., 1985).

By the end of the trial, 36 BK sockets had been produced, none of which were rated as “completely comfortable” by the participants. Many of the trial’s shortcoming can be attributed to an “inability” within the CAD program to properly scale the model socket in such a manner to allow for “total contact” with the residual limb (Foort et al., 1985; Holden and Fernie, 1986). Yet, despite this fairly glaring issue, a degree of success was still achieved by both kinds of operators. Both the inexperienced and experienced operators were able to produce sockets that allowed participants to “walk for over half an hour with minor discomfort”. The major difference between the two is that
experienced operators were able to produce a useable socket in far fewer iterations than their inexperienced counterparts. (Foort et al., 1985; Holden and Fernie, 1986).

While the clinical trials of the CASD system were successful overall, in so far as they proved that a digital fabrication solution could produce a socket, the researchers felt there was still room for improvement in terms of both fit and efficiency. As previously mentioned, none of the sockets produced were rated as “comfortable” by the participants and it took several design iterations for the prosthetists to create them. Based upon this feedback, the researchers introduced a “reference shape library” into the system. Similar in concept and function to the “primitive socket shape”, the reference shape library had prosthetists manipulate and/or transform a predefined socket shape to match a graphic representation of the patient’s residual limb. The major difference between the two was that the primitive socket shape was comprised of only a single geometry whereas the reference library had “a matrix of 27 shapes” in order to accommodate “larger physical variability” (Torres-Moreno et al, 1989). This increased capacity came at a trade-off, and during the early clinical trials “non-experts” were able to produce a socket that “fit”, but was not comfortable, to a patient. Providing a matrix meant that the operator required a degree of judgement, as they had to select which of these shapes was appropriate for that specific patient (Torres-Moreno et al, 1989). In many ways this trade-off between ease-of-use, efficiency, and operator judgement is at the centre of the issue of the adoption of CAD/CAM solutions within P&O.

In Chapters Three and Four I described the theme of expertise and the creative routine dichotomy. As part of this analysis I noted how during the NC project researchers at the Servomechanism Lab, namely William Pease and Gordon Brown, positioned the technology as liberatory. Within this narrative, NC technologies freed workers from the boring and stressful jobs of “today’s mass-manufacturing” so that they could be retrained in order to perform more interesting and rewarding tasks. The creative routine dichotomy, as developed through the research of Runyon, Ross, and Coons in the later work on the MIT Innovations in Manufacturing Technology Project, expanded
this concept in order to include both material and abstract forms of labour and expertise and essentially acted as a filter by which tasks could be determined to be ‘appropriate’ or ‘inappropriate’ for human labour and expertise. While the researchers behind the CASD system used different language from the researchers at the Servomechanism Lab, the theme of expertise and the creative routine dichotomy can be used to help illustrate how digital fabrication technologies were used to transform the relationship between P&O professionals and the fitting process. Both the primitive socket shape and the reference shape library were devices that sought to dramatically reduce the amount of labour and expertise required for the majority of fittings, and transform them into relatively simple affairs. This freed P&O professionals to work on the complex cases that required a custom P&O device and were interesting and professionally rewarding. As such, the theme of expertise and the creative routine dichotomy, as I have discussed, can be used within the context of P&O work to illustrate how elements of the fitting process were essentially removed from the professional practice of P&O workers through transforming digital fabrication technologies into boring or routine tasks that are inappropriate for human labour.

5.4 Hard vs. Soft Automation

In the previous section of this chapter I used the theme of expertise, which I have touched upon throughout this dissertation, as well as the creative routine dichotomy to help explain how digital fabrication technologies were used to alter the relationship between P&O professionals and the fitting process. In this section I describe how digital fabrication technologies sought to transform the labour and expertise of P&O professionals from that of making material devices to that of making abstract shape templates. I begin by looking at the development of the UCL-BC system and how it differed from the CASD system. I then outline a clinical study conducted by the VA using the UCL-BC system, and the recommendations that were generated from it about digital fabrication technologies for P&O work. Next, I detail the development and functionality of the Shapemaker system, which was designed to directly incorporate the recommendations of the VA clinical study through the inclusion of three levels of
control. I conclude this section by returning to my analysis of abstract models from Chapter Four as a means of explaining how digital fabrication technologies like Shapemaker reconfigured the concepts of labour and expertise as they relate to P&O professionals.

Beginning in the mid-1980s the group at University College London began to develop their own design software for prosthetics. The “UCL-BC system”, as it was referred to both internally and in publication, functioned almost identically to CASD. Where the two systems differed was in the process used to create the “digital representation”. For the UCL-BC system a probe was used by the prosthetist on a cast of the patient’s residual limb. From the perspective of the researchers at UCL-BC, this probe based approach to scanning made the most sense; as not only did it leverage pre-existing skills and workflows within the P&O community, but it also addressed the lack of context specific data, namely the topology of the residual limb, of the measurement based approached used by the CASD system (Boone and Burgess, 1989; Kohler et al., 1989; Sidles et al., 1989).

By the late 1980s, a series of clinical trials had successfully validated the underlying approach of the UCL-BC system. As with the trials conducted for CASD, a relatively small number of patients were fitted using the UCL-BC system and asked to rate the comfort of the socket. With the exception of two patients, who had to drop out of the trial, the prosthetics fabricated using the system were rated favourably (Boone and Burgess, 1989; Kohler et al., 1989; Sidles et al., 1989).

The success of these trials led to an increased interest in the UCL-BC system. By the early 1990s, it was the most widely used digital fabrication technology for P&O work in North America (Housten et al., 1992). As a result of this, when the United States Department of Veterans Affairs (VA) became interested in conducting a large scale clinical trial of these technologies for the “automatic” production of mobility aids within their health care network, the UCL-BC system was selected as the primary program of use. The motivation behind this clinical trial was that the VA was looking to improve
quality of the sockets they produced as well as reduce delivery times (Housten et al., 1992).

The results of the VA clinical trial were published in a 1992 article entitled “Automated fabrication of mobility aids (ADMA): below-knee CASD/CAM testing and evaluation program results.” (Houton et al., 1992) Overall, the trial was deemed a success as the 90 patients fitted generally had favourable opinions regarding the fit and comfort of their sockets, and the prosthetists had no major issues with the UCL-BC system (Houton et al., 1992). While this would make this trial noteworthy in and of itself, the recommendations generated as a result of the trial also warrant further discussion.

In their concluding statements on the clinical trial the authors of the article noted that the fundamental “design philosophy underlying the UCL-BC system” was sound (Housten et al., 1992). What they meant by this is that the use of a “shape-library”, or a series of pre-defined socket shapes that the prosthetists can pick from, is at its core a successful strategy for automating aspects of the prosthetic fitting and production processes. That being said, several recommendations were given in order to improve upon this system. First, the library used for the clinical trial was quite limited in terms of the kinds of sockets it could produce. Most notably there were few options for prosthetists to select from when they were dealing with patients with shorter residual limbs (Housten et al., 1992). Second, during the clinical trials, in order to achieve a fit that was deemed acceptable the prosthetists had to make a “relatively large number of modifications” to a pre-defined socket shape (Housten et al., 1992). The effect of this was “long work times” for the prosthetists as well as several “test” sockets having to be produced for each patient (Housten et al., 1992). Both of these limitations, from the perspective of the authors of the article, pointed to not an issue with the tools themselves but rather the fit afforded by the shape library that was in use (Housten et al., 1992). In order to solve this problem, and to allow digital fabrication technologies to reach its “full potential as a truly effective and productive clinical prosthetics tool”, the authors suggest revisiting the criteria used in the development of the pre-defined socket shapes (Housten et al., 1992 p. 116). This, however, was not merely a passive
suggestion. As the authors noted, during the clinical trial the VA became involved in the development of their own system for prosthetics called “Shapemaker”. Intended to operate as a “catalyst” to promote other developers to “improve and upgrade” their systems rather than to be a direct commercial competitor, Shapemaker played an important role in re-defining how CAD/CAM tools were developed for P&O (Housten et al., 1992).

In terms of its basic function and workflow, Shapemaker is similar to the systems that came before it. After inputting an “anatomical form”, that is to say a scanned residual limb, the prosthetist digitally manipulates a pre-defined socket shape in order to design a custom socket for the patient. What made Shapemaker unique, as compared to other systems of that era, was how the pre-defined socket shape library was generated (Boon et al., 1994).

Boon, Harlan, and Burges (1994) in their article “Automated fabrication of mobility aids: review of the AFRMA process and VA/Seattle Shapemaker software design” discussed the three levels of control afforded to the prosthetist by Shapemaker. In describing the three levels, which were named Automation, Modification, and Creation respectively, the authors proposed that a “good analogy would be different grades of sandpaper” in which rougher grades are used for “shaping” and finer grades are used for “finishing details” (Boon et al., 1994 p. 47).

In the first level of control, Automation, the focus is on the “bigger picture” rather than the “fine details”. This involves the prosthetists relying heavily upon pre-defined “rectification patterns” in order to seemingly “automatically” generate a socket design. Once the socket design had been generated using this level of control any further modification was meant to be minimal (Boon et al., 1994 p. 47).

For the second level of control, Modification, a similar workflow is followed in which the prosthetist selects from a series of pre-defined rectification patterns. The major difference is that once they have done this the prosthetists then begin to manipulate
the design using a series of digital tools in order to address the “individual variations” of a patient’s residual limb. As such, the second level of control parallels how other digital fabrication technologies handled the production of prosthetics in both function and design philosophy (Boon et al., 1994 p. 47).

The final level of control, *Creation*, gave the prosthettist “complete control over the finished product”. Meaning they were able to manipulate the digital representation of a patient’s residual limb in a process that digitally mimicked the traditional methods of adding or subtracting material from a plaster positive (Boon et al., 1994 p. 48). One of the essential features of the third level of control was that after finishing a design it allowed prosthetists to save “templates”, which could then be used as the “rectification patterns” at either the *automation* or *modification* level of control. Doing this allowed Shapemaker to deal with one of the major issues that prosthetists raised about digital fabrication technologies during the VA’s clinical trial, namely the inability of these system to accommodate for “different design styles” (Boon et al., 1994 p. 48).

Because this knowledge of prosthetic production manifested at the level of the individual, many of the prosthetists interviewed during the VA trial noted the challenge of having to adapt to a “foreign technique” that might be “radically different from [their] own design style” when using the shape libraries (Boon et al., 1994 p. 48). This resulted in many of the prosthetists either struggling to select a primitive socket shape to begin with or having to make substantial modifications once a shape had been selected in order to bring it more into line with their usual work patterns. In both cases the effect was a high number of modifications and iterations, which increased the time it took for a patient to be successfully fitted as well as the amount of labour required by the prosthettist. The developers of Shapemaker sought to solve this problem by giving the prosthetists more control than previous systems, which they could in turn use to develop their own libraries that reflected their own practices rather than an abstracted model of the rectification processes (Boon et al., 1994). The major trade-off, as the developers themselves noted, is that the development of this library would take time.
and would be of little value to anyone aside from prosthetist who developed it (Boon et al., 1994).

Because the library was built upon the “personally created techniques” of the prosthetist, fewer modifications were needed during the design phase as well as a smaller number of iterations during fabrication phase. What this represented is a “softer” approach to automation. In an article published in 1985 that examined the potential impact of the first generation of CAD/CAM technologies on the P&O professional, D.F. Radcliffe used “hard” and “soft” to denote two different kinds of automation. “Hard” automation denoted machines that were designed to perform single, specific tasks in order to maximize output. These were generally seen as the tools of mass production (Radcliffe, 1986 p. 3). Conversely, “soft” automation referred to tools that were more “flexible” in their purpose (Radcliffe, 1986 p. 3). In highlighting the distinction between these two forms of automation, Radcliffe was trying to highlight that with the introduction of digital fabrication technologies, a “soft” technology, the traditionally small production context of prosthetics could for the first time benefit from some of its work being automated (Radcliffe, 1986). Yet, as I have illustrated, there is somewhat of a mismatch between the expertise used within the profession and how that expertise was represented in the early digital fabrication technologies for P&O. While the “shape library” concept was intended to help deal with the individual contexts, it proved to be too general. As such, with the creation of systems such as Shapemaker, the shape library concept had evolved into a much more “flexible”, or “softer”, version of itself in order to more actively address these local contexts.

In Chapter Four I drew on the work of Katherine N. Hayles in order to explain how digital fabrication technologies contributed to the reconfiguring of the expertise of engineers from that of making material objects to that of making abstract models. As part of this analysis I describe how abstract models that were discursive and communicative devices allowed engineers to perform and express their expertise and labour. Earlier in this chapter I detailed the underlying logic of the primitive socket shape and the reference shape library as devices intended to reduce the complexity of
the fitting processes for the majority of patients. While these devices proved to be insufficient in this regard, as they were too foreign to the individual practices of the P&O professionals who tried to use them, they helped to establish a model of P&O work based upon the selection of abstract shape templates. This resulted in the development of systems such as Shapemaker which helped to contribute to this process by making the essential labour and expertise of a P&O professional the production of their individualized library of shape templates and worked to align the profession more closely with the model devised for engineers.

5.5 New Errors

In the previous section of this chapter I described how digital fabrication technologies contributed to an attempt to reconfigure the expertise of P&O professionals from that of making material devices to that of abstract shape templates. In this section I discuss the errors associated with digital fabrication technologies in P&O as a means of highlighting how these technologies were positioned to alter the social and cultural context of P&O work. I begin by looking at the concept of systematic and random errors as related to the validating devices produced using digital fabrication technologies. I then examine the practices associated with digital fabrication technologies and issues of reliability. I conclude this section by using my analysis from Chapter Four about the limitations of abstract models in order to analyse how these errors contributed to a narrative that sought to further align the P&O profession with that of engineering.

Published in 1998, “Accuracy and precessions of volumetric determination using two commercial CAD systems for prosthetics: a technical note”, details a study conducted by Sven Johansson and Tommy Oberg that sought to determine the “validity and reliability of volume determinations” of two commercial digital fabrication technologies for P&O (Johansson and Oberg, 1998). The motivation behind this study was that while digital fabrication technologies had increasingly been introduced into the manufacturing of prosthetics “in the hope that such techniques will reduce errors in the
production process” since the mid 1980s, little work had actually been done to support these claims of error reduction (Johansson and Oberg, 1998 p. 27). Attributing this lack of research to the “common misbelief that computerized and advanced equipment makes no errors in measurements”, the authors performed a series of experiments designed to illustrate the kinds of inaccuracies that were common within these technologies (Johansson and Oberg, 1998 p. 27).

Johansson and Oberg were able to determine that both digital fabrication technologies “had systematic and random errors”. Whereas systematic errors are inaccuracies within measurements that are reoccurring and can be accounted for once they are known, random errors fluctuate and can generally only be addressed by altering or reconstructing the measurement devices (Johansson and Oberg, 1998 p. 28). Moreover, the size and type of error varied between each application, meaning that any solution implemented to resolve the systematic or random errors in one application would not resolve these issues in the other application (Johansson and Oberg, 1998).

The results of this study, as the authors were quick to point out, should by no means be seen as an attempt to suggest that digital fabrication technologies have no place within the P&O profession. Systematic and random errors have always been a part of the P&O profession; they simply went by different names and manifested in different ways. In the traditional craft-based approaches, errors and anomalies are the result of the individual practitioner’s practices and processes. It might be a long and frustrating process but the individualistic scale of these errors meant that they could be addressed through the development and refinement of the craft skill and knowledge associated with the practice (Johansson and Oberg, 1998; Sanders et al. 2007; Sanders et al. 2012). However, the systematic and random errors that occur within digital fabrication technologies for P&O are not tied to the practices of the professionals using them. Rather, they are the result of inaccuracies within the architecture of these applications. This makes these kind of errors hard to reveal to the user or to compensate for, because often little is known about the algorithms used in these applications for calculating factors such as measurements (Johansson and Oberg,
The challenge moving forward, according to Johansson and Oberg, was that the P&O profession needed to be more critical regarding digital fabrication technologies as a tool. This meant not only accepting that these technologies produced errors, but also coming to terms with the kinds of errors they produced and developing methods for addressing them (Johansson and Oberg, 1998).

By the mid-2000s these “technical notes”, or critical evaluations of digital fabrication technologies, had become a far more common practice within the P&O profession. While many of these articles were similar in style to the research conducted by Johansson and Oberg, others began to examine the practices associated with these technologies themselves as sites of error or inconsistencies.

The early vision of digital fabrication technologies, as pioneered during the 1970s, was built upon the assumption that these technologies would replace the workflows and practices of prosthetic production. While “central fabrication facilities” were seen as possible solutions for small practices and those in remote areas, it was believed that most P&O professionals would simply augment their current workshops in order to include technologies such as Numerical Controlled (NC) mills. By the early 1990s, however, this assumption proved false, predominately due to the high cost associated with purchasing, running, and maintaining digital fabrication technologies. The majority of the P&O professionals who used digital fabrication technologies, then, used a central fabrication facility in order to produce either the plaster positive or socket.

In a series of studies beginning in the mid-2000’s, Sanders et. al. began a systematic evaluation of the sockets produced by these facilitates in order to determine how accurate they were as compared to the original digital designs produced by the prosthetists (Sanders et al. 2007;Sanders and Severance, 2011;Sanders et al. 2012). During the first study, sockets were designed in Shapemaker for three patients by prosthetists and then sent to 10 different central fabrication facilities; all of which were instructed to produce a finished socket. Upon receiving all 30 sockets back from the
central fabrication facilities the volumes of each were measured. The results showed a “considerable variability in quality” as “some companies consistently made good sockets, some companies consistently made poor sockets, and some companies sometimes made good sockets” (Sanders et al. 2007 p. 405). What these results translated to in terms of the actual physical sockets were variations within “socket regions” that were either larger or smaller than the digital files by between 1.1% and +1.1% (Sanders et al. 2007 p. 400). More problematic was that while some companies produced “consistent” errors, others were far more random with how these “shape distortions” presented. As Sanders explains, these inconsistency makes errors much harder to account for as they are fundamentally “undocumented” changes to the sockets’ designs (Sanders et al. 2007 p. 404). This can result in serious issues during the fitting process, as the resulting socket might not fit because of errors within the manufacturing processes rather than the design produced by the prosthetists.

During his concluding remarks in a 1985 article discussing digital fabrication technologies and the P&O profession, Klasson suggested that these technologies were the future (Klasson, 1985). The implication of this was that the profession may have to “sacrifice many things that are more or less sacred now” such as the “emphasis on craftsmanship” in favour of increased emphasis on “basic engineering, data processing, and other sciences” (Klasson, 1985 p. 10). What the errors discussed here illustrate is that, in many ways, the adoption of these technologies served not only to justify these changes but also make it a requirement. The practices of a P&O professional, though now thoroughly quantified, used in producing a socket using digital fabrication technologies remained remarkably similar to those used in the traditional craft-based approach. This is predominately due to the highly contextualized nature of both a patient’s “individual needs” and how individual prosthetists enact the knowledge and skills of the profession. Yet, what these errors indicated was that a new level of “base knowledge” was required within the profession. Or rather, an epistemic shift had occurred.
As part of my analysis in Chapter Four I described the limitations of abstract models within the context of design and manufacturing work. Drawing on John Law’s distinction between inside and outside the context of work, I argued that there are social and cultural channels within engineering work that allow different kinds of knowledges, that are systematically ignored or marginalized, to be deployed that are essential to these processes. I also noted that because social and cultural channels are inside the context work, and thus not apparent to the outside world, they are ignored when the digital fabrication technologies that produce these abstract models are moved to a different context of work. This analysis regarding the limitations of abstract models can be used to help explain this narrative about further aligning the P&O profession with engineering, as it points to a tension that needs to be addressed due to the missing social and cultural channels. The research into these new errors, as I refer to them as, are essentially about the various shortcomings of P&O professionals from a labour and expertise perspective, rather than technical notes that describe or address fundamental system or architectural issues with digital fabrication technologies for P&O work. As such, the recommendations within the research are often suggestions that involve P&O professionals becoming more familiar with various quantitative methods for evaluating devices, and as such aligning ever further with engineering concepts.

5.6 Conclusions

The change in expertise I outline in the work of P&O professionals is paralleled in the history I laid out in Chapter Three. It is also worth noting that this trend is not isolated to P&O work, but rather part of a larger shift towards evidence-based medicine that is more directly grounded in objectivity and outcome-oriented science. What this shift fails to account for, however, is the social and cultural context that is present in individualized medicine, which is in large part stripped out by a focus on engineering concepts. In this way, digital fabrication technologies both cause and solve a problem in requiring abstract models to be seen as the essential reality and also providing the tools to create these abstract models. I will continue to unpack this specific shift and its
impact on the P&O profession in the ensuing chapter, and begin to provide a framework for an alternative solution to questions of expertise in digital manufacturing.
Chapter Six

Nia Case Study

6.1 Overview

In Chapter Five I provided an overview of the historical, cultural, and material moves that sought to transform the expertise of P&O professionals from that of making material devices to that of making abstract shape patterns through the adoption of digital fabrication technologies. The focus of this chapter is the analysis of a series of interviews conducted with P&O professionals during a study that sought to compare the efficiency of prosthetic and orthotic devices fabricated using 3D printing technologies with devices made using traditional methods. This study was carried out by NIA technology, a Toronto based not-for-profit formed in 2013, from June 2016 to September 2017. Four clinics participated in the study: Comprehensive Rehabilitation Services in Uganda (CoRSU), Cambodian School of Prosthetics and Orthotics (CSPO), Comprehensive Community Based Rehabilitation in Tanzania (CCBRT), and Tanzania Training Centre for Orthopaedic Technology (TATCOT).

As was the case in Chapter Four, my research in this chapter addresses my third secondary research question (R1C), “who benefits from this transformation of human expertise?” This chapter begins with a brief overview of the use of 3D printing within the P&O profession. While this technology has increasingly become more commonplace within the P&O profession in recent years, early explorations of 3D printing in a clinical context date back to the early 1990s. In examining this history, it becomes possible to understand how various factors prevented the technology from being widely adopted despite its reported benefits of “direct production” of prosthetic devices. Moreover, this history also provides an opportunity to examine early attempts at using 3D printers to produce do-it-yourself (DIY) prosthetic devices that emerged in the late-2000s. In the next section I provide a detailed examination of the 3D printing solution developed by NIA technology known as “3DPA” and the four clinical sites in...
which the interviews were conducted. In the following section I provide an overview of the entrance interviews performed at CSPO. Next, I detail the exit interviews conducted at the four clinics. Finally, in the discussion section, both the entrance and exit interviews are discussed in detail using themes discussed in earlier chapters.

6.2 3D Printing and Prosthetics

In 1990, a research group at Northwestern University, in conjunction with Baxter Healthcare, made a single trans-tibial (TT) socket using a form of 3D printing known as stereolithography (SLA) (Rovick, Chan, Van Vorhis, & Childress, 1992). Shortly thereafter, the University of Texas at Austin and the University of Health Science Centre at San Antonio began experimenting with Selective Laser Sintering (SLS), which led to an amputee briefly wearing a 3D printed socket in a controlled clinical setting in 1992 (Rogers, Crawford, Beaman, & Walsh, 1991).

While quite limited in scope, these early studies in the application of 3D printing within the P&O profession had a large impact in the profession. In the conclusion of the 1992 report written by the Department of Veteran Affairs (VA) on the *Automated Fabrication of Mobility Aids* (AFMA), which was discussed in detail in the previous chapters, six areas of research concentration are suggested.

Of these six, one specifically called for further research into methods for “automating the prosthesis manufacturing process”, and the eventual direct prosthesis manufacturing from CAD files through “rapid prototyping CAM technologies” (Houston et al., 1992). The reasoning behind this move was that “rapid prototyping CAM technologies”, or 3D printing, seemingly allowed for the manufacturing of prosthetic devices without the interruptive craft methods used in the traditional methods during the fabrication of the device. As I described in Chapter Five, the underlying goal of the VA’s study into digital fabrication technologies was to find an alternative method of producing prosthetic and orthotic devices that was more reliable than the traditional one. As such, the inclusion of this research concentration is obvious as it seemingly
extends and further bolstered this narrative of digital fabrication technologies as a reliable alternative (Houston et al, 1992).

Yet, despite the apparent advantage of this “direct prothesis manufacturing” method and a clear desire to support the development of this technology, following the publication of the VA’s report there was relatively little success in incorporating 3D printing into the P&O profession. This was predominately due to issues associated with costs, durability, and time.

In a study conducted in 1998 by Donald Freeman and Leslie Wontorick, for example, SLA TT sockets were produced and fitted to patients (Freeman & Wontorick, 1998). Although the overall quality of the sockets was good, with Freeman and Wontorick specifically noting that the “tolerances” were “more than sufficient for a prosthetic test socket”, the cost per unit and the associated capital costs “exceeded those of current methods of fabrication” (Freeman & Wontorick, 1998 p. 19). Additionally, the production time on the first test socket took 58 hours. While this was reduced over the course of the study, with the second test socket taking only 26 hours, the production time for SLA was still significantly longer than the traditional method. Finally, and potentially the most problematic of all, the resins used for the SLA printing did not offer “the necessary material properties for a definitive prosthetic socket”; meaning that the resin lacked the necessary durability to produce a socket for day-to-day use (Freeman & Wontorick, 1998 p. 19). During their concluding comments Freeman and Wontorick suggest that “[i]n the future, as resins merge with new material properties and SLA machines speeds increase, the use of this growing technology may become a cost-effective method of manufacture for the orthotic and prosthetic industry” (Freeman & Wontorick, 1998 p. 19). This remark sums up this era of research into the use of 3D printing in the P&O context as it notes the limitations of the technology while passively acknowledging its potential.

A new kind of study into the application of 3D printing in P&O work emerged in the late 2000s, which differed from earlier studies in that they were a direct response by the
P&O community to developments in technology and to new non-expert actors in the field. The introduction of the MakerBot Cupcake CNC and the Thing-O-Matic, in 2009 and 2010 respectively, marked an important turning point in the development of 3D printing technology from both a cost and usability perspective (Lipson & Kurman, 2013). Under such slogans as “If you can think it, you can make it” Makerbot began to actively promote the concept that “desktop manufacturing” was leading to a future of de-centralized production (Lipson & Kurman, 2013). This led to various hardware and software developments that not only further reduced the costs of 3D printing, but also made the technology far more accessible to users without backgrounds in engineering (Lipson & Kurman, 2013).

These cheaper and more accessible 3D printers created by companies like Makerbot effectively addressed the major issue of cost associated with the technology. Yet, in doing so, a new type of problem was introduced in the form of non-expert actors developing DIY prosthetics. In the late-2000s various organizations with little to no connection to the P&O profession began to use 3D printers as a means to provide cheap and easily accessible prosthetics for both the developed and developing world by allowing users to fabricate their own devices (Burn et al., 2016; Diment, Thompson, & Bergmann, 2018).

The P&O profession responded to these devices by studying them in various contexts. While acknowledging that these devices were useful for training patients to wear devices, on a functional level they were severely lacking (Ten, Smit, & Breedveld, 2017). The durability of these prosthetics devices also proved problematic, with joints and areas of pressure frequently breaking (Zuniga et al., 2017). Finally, and most importantly from the perspective of the P&O profession, was the fit of these devices. Whether intentional or not, many of these devices mimicked the approach used with the CASD system. Meaning that fit and rectification were achieved by measuring the residual limb and then scaling a pre-determined pattern accordingly. The Raptor Hand created by Project E-nabled, for example, is a device that uses three measurements on the wrist and the palm in order to determine the size of the prosthetic device. In
their critiques of this approach the P&O community note that this not only limits the “kinds” of amputations these devices can be used for, but it also fails to properly transfer the biomechanical forces that act on the limb (Burn et al., 2016; Diment, Thompson, & Bergmann, 2018; Zuniga et al., 2017).

While the overall assessment of DIY prosthetics within the P&O community is fairly negative, those who have examined these devices often acknowledge the potential of 3D printing technology for the profession. Thus, the challenge going forward is to develop a system that better understands the various nuances of the P&O profession, while also leveraging the potential benefits of these technologies. This, in of itself, is a substantial undertaking. What has made this task even harder is the popular perception of 3D printing and prosthetics that formed due to the early “successes” of DIY prosthetics organizations (Birrell, 2017). The intervention staged by these DIY prosthetic organizations drew the interest of popular media, resulting in stories that presented these devices as “solving” the various issues related to the availability and cost of prosthetic devices. A split narrative began to form as those outside the P&O community saw these technologies as fully formed technological interventions whereas practitioners were quite aware of the limitations. This narrative, moreover, also served to undercut the authority, expertise, and labour of trained P&O professionals as these “solutions” were a technologically mediated equivalent. The effect of this is that while the P&O community remained interested and somewhat invested in the development of 3D printing technology, there was a deep skepticism that also accompanied it.

6.3 3DPA

In the previous section of this chapter I provided an overview of the use of 3D printing within the P&O community and how various historical, cultural, and material moves have resulted in a complex perception of the technology by many P&O professionals. In this section I describe the workflow of 3DPA, a 3D printing tool chain developed by Nia Technologies for P&O work in the developing world. The workflow of 3DPA can be broken into four stages: shape capture, rectification, 3D printing, and fitting. I describe
each of these stages in order and note the various tasks that are performed by the prosthetists as well as those handled semi-automatically or automatically by the various pieces of software used. It is, however, important to keep in mind that the linear nature of this textual description that I provide does not fully reflect the reality of using 3DPA as there is a back-and-forth to this process that is hard to properly address in a textual medium. I conclude this section by comparing 3DPA with the digital fabrication technologies for P&O that I discussed in Chapter Four in order to highlight the kinds of logics used by the system as well as denoting what is novel about it.

3DPA was developed by Nia Technology, a Toronto based non-profit social enterprise. Founded in 2015 the goal of Nia Technology is to develop a 3D printing solution for the developing world to aid P&O professionals in their work in order to ensure that underserved populations have access to P&O devices.

After a patient has been determined to meet the “requirements” established by Nia technology, which included parameters for age, weight, and the kind of device “needed” the process begins with an initial questionnaire, which covers patient history and information specific to their amputation or disability.

Once the initial questionnaire has been finished the next step is shape capture. This involves the prosthetists using a scanning device to capture a 3D scan of the patient’s residual limb. The scanning solution used differed between sites; prosthetists at CoRSU and CSPO used a hand-held Sense 3D Scanner attached to a Dell laptop running the Skanect 3D scanning software, whereas the prosthetists at CCBRT and TTACOT used Structure Sensor 3D Scanners connected to an iPad Mini running the Nia 3D scanning application based upon the Structure Sensor SDK. Both scanning solutions are based on structured light scanning technology, and while there are differences between the two, at a functional level they are comparable in terms of the end results.

Additional detail about Nia Technologies can be found at: https://niatech.org/
Before the patient’s limb can be scanned, however, it needs to be “marked up”. Using raised tape that has been cut up into squares, the prosthetist denotes “key anatomical areas” of the patient’s limb. This is done either on the patient’s bare limb or over a nylon sock. The reason for doing so is twofold. First, it aids with orientating the 3D scan. Once a limb has been scanned, or “digitized”, it can be challenging to determine its position, as the digital representation is only a small part of the patient’s body. Thus, these markers effectively act as reference points to make this process easier. Second, because these markers are placed on “key anatomical areas” it improves the “precision” of the rectification. Since the size and placement of the tape squares are pre-established they can act as reference points for the prosthetists as material is digitally added or subtracted from the limb. An additional benefit of these tape squares is that they can be used as reference points for macros within the rectification software. The use of these macros, from both an educational and professional perspective, will be discussed in more detail below.

With the patient’s limb “marked up” the prosthetist then puts the limb in the “scanning position”. For TT sockets, this entails positioning the patient such that the limb is 1 mm off the ground in order to ensure that the scanning device can capture the entirety of the residual limb. For AFOs, the process is slightly more complex, as the patient’s limb has to be placed on a raised surface that allows the patient to put weight on it while it is scanned.

The final part of the shape capturing component involves the prosthetists actually using the scanning device to scan the patient’s limb and then visually inspecting to ensure that no areas are missed (Figure 8). Regardless of the scanning solution used, the scanning process simply involves moving the scanning device in a series of arcs. The overall processes takes about two to five minutes per scan and inspection and it is recommended that three scans are completed per patient. The reason that multiple scans are performed is to ensure that at least one of them will be useable for rectification, as it is possible to miss potential issues with the visual inspection in the
scanning software. Once all the scans are completed, the prosthetists exports them as STL files using the scanning software and the shape capture component is complete.

(Figure 8 – A limb being scanned in Skanect)

Next the shape rectification component begins. The first step is importing the STL files into Orthogen. Developed by Nia Technology using the Autodesk’s Meshmixer API, Orthogen allows prosthetists to prepare both scans for rectification and rectification positives mesh for 3D printing. Once the scan has been imported into Orthogen the prosthetists goes through a process called “scan clean-up and repair”. This is a semi-automated process that repairs non-manifold geometry and inverted faced normals and removes any free-floating artefacts in the scan data in order to make it usable for the rectification process. To start, the prosthetist simply presses the “auto repair” button within the software. After visually inspecting the resulting “repaired mesh” the prosthetists can then either “accept it” and move on to the next step in scan clean-up and repair process or, if the repaired mesh appears to be deformed or incomplete in some way, “reject it” and import a different STL file.

Once the prosthetist has a repaired mesh they are satisfied with they then “highlight” the area around the tip of the limb using the “mark limb tip” tool. After the area around the tip is highlighted three new options become available: “grow,” “shrink,” and “max”.

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Using these three options the prosthetists can alter the “size” of the highlighted area of the residual limb with the aim being to highlight “as much of the limb as needed” in order to make a “good socket”. What is important to note here is that this determination is based upon the professional judgement of the prosthetist. When the highlighted area is deemed sufficient by the prosthetist they then select “keep selection” and everything that is not highlighted is deleted.

The last step in scan clean-up and repair processes is “smoothing” the top of the limb. Because the “grow,” “shrink,” and “max” options do not uniformly increase the size of the highlighted area when the “keep selection” option is selected, the top of the limb is left with a “jagged outline”. Using the “plane cut” tool the prosthetists can smooth this area by “removing” a portion of it. How much is removed is left up to the prosthetist, but the goal is to have a relatively flat surface that is parallel to the tip of the limb. After the prosthetist finishes with the “plane cut” tool, the scan clean-up and repair processes is finished, and the resulting “repaired and clean-up” mesh is exported out of Orthogen as an STL file (Figure 9).

With a repaired and cleaned-up mesh prepared the next step in the shape rectification component is the rectification process. This uses the aforementioned Canfit software. Developed by Vorum, Canfit is design software specifically tailored for P&O work. The first step in the rectification process is importing the repaired and cleaned-up mesh into Canfit. In doing so the prosthetists is also asked to orientate the mesh by “identifying” the “top,” “bottom,” “front,” and “back” of the limb. This is one of the instances in which the marks on key anatomical locations play an important role as they make it easy to readily identify the orientations.

After orientating the mesh, the prosthetist selects the kind of device that is being created. This affects the tools available to the prosthetist during the later stages of the rectification processes. While Canfit is capable of producing a wide variety of P&O devices for the purpose of 3DPA the only two that matter are “Below-knee sockets” which is alternative terminology for TT and AFO.
The next step is optional and depends on the preference of the prosthetists. Using the “cross-section,” “coronal cross section,” and “transverse cross section” windows the dimensions of the repaired and cleaned-up mesh are compared to the measurements of the patient. If there is a disparity between the two, the prosthetist has two options. The first is to modify the mesh using tools within Canfit to bring it in line with the patient’s measurements. The second option is to return to the scan clean-up and repair process and either try again with the same data or use a different scan.

Once this setup is complete, the prosthetist is then ready to begin rectifying the repaired and cleaned-up mesh. This is a process that involves adjusting the mesh by “adding” and “subtracting” the geometry in certain areas. While Canfit provides various tools for making these modifications the actual process of rectification is guided by the individual prosthetist's professional experiences and preferences. This is the other area in which the marks on key anatomical locations play an important role. Not only do they help with accuracy by acting as reference points, but they can also be used in conjunction with “macros”. These are a series of “pre-recorded steps” that can be executed “one-by-one using a play, pause, and stop functionality within the software”.

(Figure 9 – Scan of a limb post repair and clean-up)
The primary function of these macros, from the perspective of Nia, was educational as they allowed prosthetists being trained on the software to “see examples” of different “rectification patterns”. That being said, there was nothing stopping prosthetists from using the macro functionality within Canfit to semi-automate their process once they had become more comfortable with the software.

(Figure 10 – The region tool can be used to add or subtract from the geometry of the mesh)

The methods for adding and subtracting the geometry of the mesh starts with the prosthetist using the “region” tool to select an area of the mesh. This is done by placing a series of points on the mesh. As few as three points can be used to define a region, but with more points comes more “control” of how the region is defined. After the region has been established, the prosthetist then defines the apex point(s) by once again placing a series of points. The prosthetist then enters a value in millimetres to represent how much the apex either adds to or subtracts from the geometry of the mesh. Finally, using a series of sliders the prosthetist can then control the “curve” of the apex. This allows the prosthetist to determine the grade of the region leading to the apex (Figure 10).

As the prosthetist engages in these modifications of the repaired and cleaned-up mesh, changes are visually indicated in the “cross-section,” “coronal cross-section,”
and “transverse cross-section” windows. A blue outline indicates the “current” mesh, whereas a grey one indicates the “starting” mesh.

Once the prosthetist is satisfied with their modifications to the mesh they create the trim-line. Using the “trim-line” tool, which functions similarly to the region tool, the prosthetist uses a series of points to define the trim of the device. The exact shape of the trim line is left up to the professional judgement and preferences of the prosthetist. As they define the shape of the trim line they “preview” it and make as many modifications as needed until the results meet their expectations. When they are done with the trim line the “rectified mesh” is complete and it is exported out of Canfit as an STL.

For the last step in the shape rectification component the prosthetists once again import an STL into Orthogen in order to make a 3D printable device. This is a semi-automated process that is supported by a different interface. To begin, the prosthetist imports the rectified mesh into the Orthogen. Once imported, the mesh is automatically repaired as a hole is automatically generated at the bottom of the socket due to legacy consideration in the export function of Canfit.

After the hole in the rectification mesh has been repaired the “thickness” and “shell” options become available within Orthogen. These options allow the socket to become “printable”. The rectified mesh that is exported out of Canfit lacks any form of “depth”. These two semi-automated processes first add the depth needed for printing and then convert the mesh from a “positive rectification pattern” into a “socket”.

To begin, the prosthetist selects the “thickness” option. They are then presented with the variables of “gap” and “thickness”. Gap represents the size of the soft liner that will be placed in the socket and thickness determines the wall size of the socket. The default value for these variables are 3mm and 5mm respectively but depending upon the prosthetist’s professional judgement and preferences they can be modified. Nia, however, recommends that the thickness variable stays at or above 5mm (Figure 11).
Next the prosthetist selects the shell option in order to convert the positive rectification pattern into an actual socket. There are no options or variables presented at this point and the entire process is left to internal settings.

After the socket has been created the prosthetist then “attaches” a 3D coupler model to it. This coupler model acts as an interface to the standard ICRC semi-circular disc; meaning that standardized pre-fabricated prosthetic devices produced by the Red Cross can be attached to the socket once it has been printed. In order to attach this coupler, the prosthetist uses the “add connector” option. This automatically generates a coupler below the socket at 75% of its maximum width (Figure 12). The prosthetist is then free to scale the size of the coupler and position it where ever they think is best. Once the coupler has been sized and positioned the prosthetist “accepts” the changes and Orthogen automatically attaches it to the socket.
The final step in shape rectification component is analyzing the socket and making any required structural and aesthetic modifications. After selecting the “analyze” option the prosthetist is presented with a visual representation of the socket that highlights any areas in which the wall of the socket is below the thickness set in a previous step (Figure 13). Using various tools that allow the prosthetist to add to the geometry of the mesh these areas are re-enforced. The analyze option is then selected again and the process continues until the prosthetist is satisfied that the device is structurally sound. Next, using similar tools, the prosthetist is given the option to make aesthetic changes to the device. The purpose of this step is to create a more uniform outer shell, as the various modifications made throughout the entire rectification process tend to result in a “bumpy” appearance. In addition to tools that allow the prosthetist to add to the geometry during this process there are also tools for subtracting and “smoothing”. Once the prosthetist is happy with the appearance of the device the analyze option is selected once more to ensure that the walls of the device are still at the proper thickness. It is important to note that these structural and aesthetic modifications do not alter the “internal” geometry of the socket in any way. All the changes occur only on the shell of the device, as any changes to the internal geometry of the socket would change the rectification pattern.
With the socket now finished, the prosthetist saves and exports the design as an OBJ file. If the socket is over 30 cm in height the socket is automatically divided into two equal pieces and saved as two different OBJ files. The reason this is done is two-fold. First, dividing larger sockets into two pieces reduces the amount of “print time” required to fabricate the device. Second, the printers supplied by NIA have a maximum “z-height” of 60 cm; meaning any socket with a height greater than 30 cm could not be fabricated unless it is divided in two.

The final component of 3DPA is 3D printing. This involves the prosthetist “uploading” the OBJ files to a Raspberry Pi running Octoprint. The “slicing” of the OBJ files in order to make them ready for printing is automatically carried out by Octoprint. This is a process that involves making various considerations regarding the settings of the printer, all of which have been pre-determined by Nia based upon experimentations with the provided printer and the 2.85 mm diameter nylon filament used in fabrication.

After the files have been automatically sliced they are then sent to a connected Taz 5 or Taz 6 fused deposition modelling (FDM) printer. These printers were on-site at each of the clinics, with the exception of TATCOT due to logistical issues. As such, TATCOT emails the OBJ files to CCBRT where they were fabricated and then mailed back for assembly. The sockets are then printed which generally takes between 5 and 12 hours depending upon the size of the device.
Lastly, the printed sockets are then “cleaned” and “assembled”. Once the socket has been removed from the print bed the prosthetist visually inspects it for defects. These defects can be caused by a variety of issues, such as power outages or the print “shifting” during fabrication. If there are no defects the socket is then “cleaned”. This involves removing any “filament strains” or “artefacts” caused by the 3D printing processes. After it has been cleaned the device is assembled. If the socket was printed in two pieces this first involves “welding” them together. This is done using a mirror welder. The welded joint is then re-inforced by running a length of nylon filament through a plastic welder along its seam (Figure 14). Finally, the various components associated with prosthetic device are attached to it. This includes the production of a soft liner.
The fitting process, which involves the prosthetist checking the fit and alignment of the prosthetic device, then occurs. This process, however, is essentially identical in both the 3DPA and traditional fabrications methods.

In Chapter Five I outlined and described several digital fabrication technologies for P&O work. As part of these discussions I used the terms hard and soft automation in order to specifically address the kind of logics used within these systems in terms of how the labour and expertise of P&O professionals was handled. Within this dichotomy 3DPA would be considered a soft automation system as the various judgements involved in making a device are left to the individual experience and preferences of the prosthetist. In terms of the novelty of 3DPA the workflow of the system mimics that of other soft automation approaches such as that of Shapemaker. The novelty thus lies in the capacity of the 3DPA to handle and process scan data as well as the ability to turn a digital rectification pattern into a 3D printable socket.
6.4 Entrance Interviews

In the previous section of this chapter I described the workflow of the 3DPA system. In this section I detail a series of entrance interviews that I conducted at the Cambodian School of Prosthetics and Orthotics (CSPO), in August of 2016. The purpose of these interviews was to record the initial thoughts and impressions of the various members of the clinic regarding the use of digital fabrication technologies in a P&O context. These interviews followed the training on the 3DPA toolchain by a Nia representative, during which several test sockets and AFOs were produced. I begin this section by providing biographical information about those I interviewed as well as a brief overview of the structure of the interviews. During the course of the entrance interviews four predominate themes of practical consideration, professional considerations, technical consideration, and perception of professional practice emerged.

A total of eight interviews were conducted (Table 1). Each of the individuals interviewed had formal training in the P&O profession and was either a Category 1 or Category 2 prosthethist at the time of their interview8. While everyone who was interviewed is involved in the design and fabrication of prosthetic and orthotic devices, only five out of the eight individuals identified that as their primary responsibility on a day-to-day basis. Of the remaining three participants, two identified managing clinical sites and P&O based organizations as their primarily responsibilities. The final individual identified P&O education as their primary responsibility.

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8 P&O professionals have different Category designations to denote differing levels of education and professional scope. Category 1 professionals require a university degree and an additional year of professional training, and are more common in industrialized countries where resources are more widely available. The Category 2 designation does not require a formal university education and these professionals are generally supervised by a Category 1 in the industrialized world. Category 2 professionals in low and middle income countries generally hold the same responsibility as a Category 1. Both Category 1 and 2 professionals engage in patient care and participate fully as members of clinical teams (International Society for Prosthetics and Orthotics, 2010).
(Table 1. Demographic Information of Entrance Interview Participants from CPSO)

These interviews were semi-structured with an interview guide comprised of 19 questions (Appendix B). The average length of the interviews was just over 25 minutes. After the interviews were completed they were transcribed. I then engaged in thematic analysis using emergent coding. Four predominant themes emerged: practical considerations, professional considerations, technical considerations, and perceptions of professional practice.

The first of these themes, practical considerations, addresses the potential positive implications that digital fabrication technologies might have on some of the issues facing the P&O community that were discussed during the interviews. A concern that was shared amongst all the participants was the cost associated with designing and fabricating P&O devices using the traditional methods. The consensus was that these traditional methods are too resource intensive in terms of the required labour and materials. As one of the participants explained, “I think in the future 3D printing, if it works accurately, it will help my job a lot. It will reduce my workload and it will reduce the material I use for fabrication.” While the resource intensiveness of the traditional
method in and of itself was seen as a serious problem as it means clinics have high operational overhead and, to make matters worse, the demand for devices is increasing. This has left many of the participants worried that the clinic might not have enough “human resources” to ensure that everyone who needs a device gets one.

It is these cost related concerns that led to an interest in digital fabrication technologies at CSPO. Participants hoped that 3D scanning and 3D printing would allow for “more effective uses of resources”. One of the participants noted that in introducing 3D printing to CSPO a major consideration was the impacts the technology would have “on cost effectiveness” in terms of “human resources management” and “reducing our material use”. From the perspective of labour this means a reduction in the time it takes to make a device. What is important to note here is that this does not necessarily mean that digital fabrication methods need to produce a device faster than the traditional methods. While reduced fabrication times would be beneficial in reducing the amount of time patients need to be at the clinic, the overall desire is to reduce the time in which a prosthetist has to actively spend working on a device. The overall effect of this would be that prosthetists could see and fit more patients without having to work more hours. From a material perspective a more effective use of resources means less dependency on consumable goods. Both casting and fabricating were identified by the participants as sites in which a great deal of resources were consumed and wasted. These costs add up over time and are one of the clinic’s financial concerns. Although the production of devices using digital fabrication technologies still uses consumable goods in the form of the filament or resin used in the 3D printers, the overall volume is far less compared to the traditional methods. As such, many of the participants identified digital fabrication technology as a positive development in terms of managing material resources.

The next theme, professional considerations, deals with how digital fabrication technologies were seen as potentially improving the perception of the P&O profession. Participants referred to the process of designing and fabricating a P&O device as “messy” or “unhygienic”. A participant commented that their experience using the
technology was positive because the traditional method was “so messy, some people think we’re construction workers”. This is predominately due to the sheer volume of “dust” produced during casting and rectification. For some of the participants this resulted in health concerns as, regardless of the safety measures taken, some of the dust would be inhaled. For others this dust was part of a larger problem regarding the perception of the P&O field. While all the participants acknowledged the importance of the traditional methods to the field of P&O, this desire not to be seen as construction workers highlights a real desire for the abstract and theoretical knowledge of the profession to be more directly apparent.

After using the digital fabrication technology following their training, several of the participants commented about how these methods supported a “cleaner” method of working. Moreover, there was also a general sentiment that the adoption of this technology was important as a means of showing that the profession is still developing and seeking out new approaches. Several of the participants also commented that using the 3DPA method involved far less physical exertion, which allowed them to focus on the “mental” aspects of design and fabrication.

The third theme, technical consideration, focuses on the various concerns that the participants had regarding the use of digital fabrication technologies for P&O work. After using the 3DPA system following their training, many of the participants found that the devices they were producing did not meet their expectations. This was attributed to, for the most part, unfamiliarity with the software. One of the participants, in describing the sockets produced, commented that “At the moment with my experience with the rectify tool I can see outcome [as] like 80% acceptable. But because [I am] new if I do more [a 3D printed socket] can be like the conventional P&O devices.” Several of the participants commented that the tools and operations of Canfit did not adequately map onto their current practices. This led to confusion as sometimes the resulting modifications were not what the participants were expecting. For the most part the participants were fairly forgiving, as they acknowledged that the
logics behind Canfit were something they were simply not familiar with and they merely needed to spend time with the software in order to come to terms with them.

This issue of being unfamiliar with the logics of Canfit, however, was also a part of a much larger concern regarding how the technology functioned. During the interviews many of the participants expressed a general sense of uneasiness about the use of digital fabrication technology within P&O because they were unaware of how 3D printers and 3D scanners specifically worked. Some of the participants worried that this lack of knowledge would lead to issues regarding the general usage and maintenance of these technologies. One of the participants went on to suggest that “My overall impressions are very, very favourable. One of my small concerns is just reliability and serviceability of the printers.” Others expressed a much larger concern regarding the “transferability” of the skills they were learning, meaning that they were unsure if they would be able to apply their training to P&O cases not covered during their training or if they would be able to teach other prosthetists how to effectively use the 3PDA system. As one of the participants explained, “Can this technology be transferred to other colleagues...If you invent something that is really good, but if it can’t be transferred then that’s a problem.”

In discussing the devices produced during training the participants also identified several material concerns they had regarding the processes. These included the strength of the sockets being produced, the kind of material being used, and the need to weld two pieces together to make larger devices. The focus of these concerns was predominately around both the durability and appearances of the devices. Since the majority of patients only receive a new device every five years, a great deal of care is placed on ensuring it will last that long and that the material used in making it is appropriate. One participant suggested that, “The only thing I am not keen on is that it’s printed in two parts. I know if we put them together it’s as strong as anything else, but in the back of my mind I keep thinking anything that has been put together can come apart.” Moreover, within the context of Cambodia, few patients want to “show
their hardware” due to the stigma around disabilities. As such, the overall appearance of the device is of great concern.

Finally, a few of the participants were also worried about the appropriateness of 3D printing in Cambodia due to issues regarding electricity. Brownouts and blackouts occur frequently, and while precautions can be taken in order to ensure that prints do not immediately fail, there are no guarantees. Because of this, some of the participants questioned whether a model of production that involved overnight printing, or one that required a device operating for long periods of uninterrupted time was a functional solution.

The final theme, perceptions of professional practice, deals with what the participants view as the core expertise of the P&O profession, regardless of the methods used in designing and fabricating a device. When asked to describe their practices several of the participants noted that many of their processes are focused on “getting to know the patient”. This involves not only touching the patient in order to get a sense of what is “below the skin”, but also listening to the patient describe their lives and disabilities. It is through these interactions that the participants are able to get a sense of the kind of device required for the patient. Moreover, these interactions also inform design choices for the device, as they are able to determine where an individual patient can and cannot take pressure.

As many of the participants suggested, the reason it takes so long to become a “skilled” P&O professional is due to this complex relationship between “theory” and its “practical applications”. As one of the participants suggested, the knowledge of a prosthetist is comprised of “40% of what they learn in school, 40% of what they learn and steal from their colleagues in the field, and 20% the dark arts”. Because of this relationship to professional knowledge, many of the participants suggested that while 3D printing and 3D scanning is merely a “new tool” for producing devices they would not allow students learning the profession to use it. This is because students have yet to develop a proper understanding of the “philosophy” of P&O work and they worry that
by immediately jumping into the use of digital fabrication technologies some of these core concepts might be either missed or undervalued.

One of the more surprising elements to emerge over the course of these interviews was that all of the participants shared a concern about the costs, from both a material and labour perspective, associated with P&O work. Because of these concerns, moreover, almost all of the participants were willing to accept some form of technological intervention that automated elements of their workflows as a means of cost mitigation. This narrative seemingly runs counter to many of the discussions regarding workers and the introduction of technology that automates elements of their work. Yet, P&O work is different due to both the increasing demand for the devices as well as the nature of the expertise used during design and fabrication. Because each device is customized to an individual patient’s needs, and the process of doing so is quite complex, it is hard to entirely remove humans from this process. Moreover, since there are not currently enough P&O professional to actually meet the demand for these devices, technology that seemingly improves worker efficiency is seen as beneficial.

Yet, for all the potential positive impacts that digital fabrication might have on the profession, there is still a fair bit of concern regarding the technology. This can be particularly attributed to concerns regarding the “functional” nature of these devices. The role of a P&O professional is to fabricate a device that helps aid a patient’s mobility. This is a duty that is taken very seriously not only because of the impact that it has on a patient’s life, but also because of the potential effect that a defective device might have. It is therefore understandable that many P&O professionals approach new methods and technologies with apprehension until they are satisfied that all due diligence has been performed. The other factor that leads to some concern, is understanding how these technologies will affect the “core expertise” of the P&O profession. Each of the participants interviewed firmly stated that the base theories that inform P&O work cannot be changed. As such, any new method developed needs to clearly demonstrate that these values are perceived within its logics.
What these interviews illustrate is that P&O professionals are willing to experiment with new methods and technologies. The barrier for entry, however, is that these new methods and technologies need to preserve what are seen as essential skills while also producing a device that is seen as “trustworthy”.

6.5 Exit Interviews

In the previous section of this chapter I discussed the entrance interviews with P&O professionals that I performed at CSPO. In this section I detail the exit interviews that I conducted at Comprehensive Rehabilitation Services in Uganda (CoRSU), Cambodian School of Prosthetics and Orthotics (CSPO), and Comprehensive Community Based Rehabilitation in Tanzania (CCBRT) from June to August of 2017. The purpose of these interviews was to determine the perception of digital fabrication technologies by P&O professionals following an extended period of usage. By the time the interviews occurred each of the sites had been using the 3DPA toolchain for at least four months. I begin this section by once again providing brief biographical information about those I interviewed as well as the structure of the interviews. I then discuss the four themes that emerged over the course of these interviews: standard cases, non-standard cases, technological complexities, and device quality.

A total of seven interviews were conducted (Table 2). All the individuals who were interviewed had formal training in the P&O profession and were either a Category 1 or Category 2 prosthetist at the time of their interview. Each of the participants identified the designing and manufacturing of prosthetic and orthotic devices as their primary responsibility in their work and had used the 3DPA toolchain to design and fit at least one patient when they were interviewed.
These interviews were semi-structured with an interview guide comprised of 13 questions (Appendix C). Before the interview participants were emailed the interview guide in order to give them proper time to prepare. The average length of the interview was around 50 minutes. After the interviews were completed they were transcribed. I then engaged in thematic analysis using emergent coding. Four themes emerged: standard cases, non-standard cases, technological complexities, and device quality.

The first of these four themes, “standard” cases, addresses the areas in which the participants saw the 3DPA system as a successful intervention for P&O work. When asked to describe the benefits of using 3D printing and 3D scanning over the traditional methods of producing P&O devices, most of the participants focused on the technology’s ability to “preserve” the patients’ “shape data”. This was viewed as a major time saving benefit as any mistakes made during the rectification or fabrication
processes could be resolved without having to re-capture the patient’s shape data. As one of the participants explained, “You can reprint it. You can adjust and rectify it when you’ve made a mistake…everything’s on the computer.” Several of the participants, in keeping with the entrance interviews, also commented that using digital fabrication technologies was a benefit simply because it is not as “messy” as the traditional methods. Finally, some of the participants suggested that while they got a sense that using digital fabrication technologies saved “time” it was hard for them to determine if it was really that much more efficient overall. A participant commented that “I’m fairly expert to rectify [with] the traditional [method]. So I can rectify, for example, in 30 minutes, an AFO or trans-tibial prosthesis. But for the 3D printer, I’m new. I’m not an expert. So it still takes me longer, honestly, to rectify”. Several of the participants, in fact, suggested that one of the major improvements they would like to see is a reduction of print times as they felt these lengthy times were slowing down their overall workflows.

In discussing their actual experiences using the technology many of the participants commented that “at first” getting “used to” 3DPA “took time”. They were, however, eventually able to get a “sense” of hardware and software. Once they had become “familiar” with the 3DPA toolchain the overall sense was that using it was relatively “easy”. When asked to describe the devices being produced by these digital fabrication methods the responses were quite conservative, but the overall impression was that for “standard” patients needing TT sockets the results were “good”. What is important to highlight here is that “fit” was achieved using the 3DPA system for these patients. While all of the participants suggested that “improvements” could be made to the overall toolchain, which will be discussed in more detail below, these devices still functioned.

The second theme, non-standard cases, deals with the limits of the 3DPA system. As already mentioned, the participants suggested the 3DPA was able to produce devices for “standard” patients requiring TT sockets. What they meant by this was that patients
with “severe deformities” or requiring more “complex” devices proved to be challenging to “fit”. This was due to a combination of technical, conceptual, and material issues.

After a patient has been interviewed and assessed to determine what kind of device is needed, the first step in the design and fabrication processes for 3DPA is scanning. This requires the patient to hold their limb still, as any movement will “distort” the scan. The participants commented that this proved challenging for patients who were children and/or “spastic”. In describing the process of scanning a child with cerebral palsy one of the participants explained that, “You know, with cerebral palsy, most of the children are spastic and most of them are hyperactive. So when you place them, you know, when you’re scanning, you need the child to be really settled and calm for you to get a good scan. Now these children, sometimes they’re spastic. Sometimes they’re scared. When they’re scared, they become really spastic. So it was difficult to scan”. The resulting “shape data” for these kinds of patients often proved to be either unusable or required a great deal of “clean-up”. Many of the participants thus suggested that these kinds of patients were therefore “unsuitable” for methods involving 3D scanning technologies.

Once a patient’s shape data has been captured, the next step is rectification. In the traditional method when a patient is cast, “corrective” measures are taken from the outset, meaning that before the formal rectification process begins the volume and shape of the patient’s limb has already been modified. Within the current 3DPA system these pre-emptive corrections do not occur. For many of the participants this proved to be quite problematic as it meant that a great of “work” had to be done to the shape of the patient’s limb in Canfit. As one of the participants explained, “If the patient doesn’t need much correction, especially on the orthotics, it’s easier to use the 3D. But if the patient has many deformities on the foot, it is easier using the traditional method.” As such, for patients with severe deformities many of the participants suggested that the volume of changes required in Canfit meant that it was simply not worth using the 3DPA system as it took too long and increased the potential for errors.
Finally, the fitting process also proved to be somewhat challenging due to the materials used for 3DPA. Sockets and AFOs made using the traditional method are fabricated from polypropylene. This plastic can be heated and modified during the fitting processes in order to ensure a better fit. The sockets made using the 3DPA system were produced out of 3D printed nylon filament, which makes these post-fabrication adjustments difficult. For some of the participants the solution was modifying the soft liner, but this did not provide as much “control” over the final fitting. What this effectively means is that the fit of the devices is more or less determined in “the software”. While this is problematic for all patients, as subtle changes are constantly occurring to limbs, it is even more so for those with severe deformities as it increases the likelihood of the device not fitting.

The next theme, technological complexities, focuses on underlying issues that the participants had with the software and hardware of the 3DPA system. When asked to reflect on the “quality” of the devices being produced, several of the participants commented that what was being produced on the 3D printer differed from the designs displayed in the software. In describing this experience one of the participants commented, “So sometimes we slice [the socket]. We [then] save it into the print file. But when we come to print, it doesn’t print the way we want. We find it depends on something which is completely not understandable.” While this in and of itself was a serious problem, it was further compounded by a general sense that the technology was “unreliable”. For many of the participants scanning also proved to be a site in which the technology was seemingly at odds with the expected results. This often led to participants double checking the measurements of the “shape data” against physical measurements taken during the patients’ assessments. Much of the frustration expressed by the participants stemmed from the fact that they were unsure what caused these errors or mistakes.

This inability to explain why these errors were occurring also speaks to a much larger concern expressed by some participants regarding their own understanding of digital fabrication technologies. During the interviews the participants commented about the
“formulaic” nature of the 3DPA system. While this allowed them to readily deal with “standard cases”, as already discussed, it also resulted in several of the participants suggesting that they did not have a proper grasp of the various functions and tools in the software. This made it challenging to deal with more “complex” patients, as sometimes they were unsure about how to proceed in order to make an effective device. As one participant suggested, this problem is particularly due to simply being unfamiliar with the technology. As they become more “comfortable” with software and see more patients with “different needs” they will slowly develop an understanding of how to make different kinds of devices. Yet, there is also a much larger problem here that is not as easily remedied. During some of the interviews, participants commented that 3DPA used a different approach from their own. Moreover, because they did not necessarily understand all of the functions and tools of the software, they felt that they could not entirely map their own professional logics into rectifying a device. This resulted in them “following along” step-by-step and making decisions when appropriate. Because of this, many of the participants strongly felt that while 3DPA could be used for “standard” or “easy” cases, anything with a degree of complexity would require the traditional methods.

The final theme, device quality, deals with the overall sentiments held by the participants regarding the kinds of devices produced using digital fabrication technologies. One of the primary concerns expressed by all of the participants had to do with the “strength” of the material. Overwhelmingly, the sense was that nylon filament was simply not strong enough to produce P&O devices. Moreover, the “thickness” of the socket resulted in a few of the participants commenting that the devices were too “bulky”. One of the participants suggested more work needed to be done to “optimize” the design of these devices overall in order to both improve the strength and weight of the device.

Many of the participants also expressed concerns regarding the “compatibility” of the nylon filament. Since these devices were welded to standardized components provided by the Red Cross and were made of polypropylene, many of the participants were
worried that this introduced a “breakage” point to the device. Many of the clinics attempted to resolve this by various methods, with one of the participants noting that “we used to put some screws, like normal spiral screws, three or four around. So the screws will pass through, down the pylon, and bisecting the 3D cup and the bottom of the socket”. Their solutions, however, were seen as stop gaps that did not address the underlying problem.

Finally, the appearance of devices remained a concern of the participants. As discussed during the entrance interviews a great deal of care is placed on ensuring that these devices do not stand out. Having to mirror weld two parts together was seen as producing an “ugly” device that stands out. Moreover, there were also concerns regarding the “lines” generated on the devices as part of the 3D printing processes. At a functional level the participants were worried that this would cause skin irritation and at a practical level there were concerns that it would make the device hard to clean.

Comparatively, the biggest difference between the entrance and exit interviews is in perception of the value of digital fabrication technologies. All of the participants in the entrance interview, in some way or another, discussed 3D printing and 3D scanning as a potential method for reducing the cost and time associated with designing and fabricating P&O devices. By the exit interview the majority of the participants suggested that while there appear to be some savings, from both a cost and time perspective, they were not entirely sure if there was by any real noticeable margin. This is not to say that the participants did not suggest there were other benefits, such as the reduction of dust and preserving the shape data, but one of the primary interests of the technologies listed during the entrance interviews did not come to fruition. This issue might be resolved if the participants are given more time to explore the technology in order to become more familiar with it, but that would require further study.

One of the biggest takeaways from the exit interviews is a better sense of what kind of devices digital fabrication technologies can currently produce. While during the
entrance interviews concerns were raised about “acceptable patients” these were primarily focused on issues regarding the actual properties of the technologies, such as the size of the printer. What the exit interviews illustrate is that with the current methods many of the participants feel that only “simple” or “standardized” cases can be significantly handled. The limiting factors here is both the complexity of the technology, which makes it hard for individual P&O professionals to translate their practices and processes into the software due to uncertainties regarding its functions and tools, and the “volume” of modification needed for complex patients. Again, this issue might be resolved through further usage of the software, but it also points to a much larger issue regarding the use of digital fabrication technologies within the P&O field due to the underlying logics of labour and expertise.

Lastly, the exit interviews also surfaced problems regarding the materials used in digital fabrication technologies. All of the participants shared concerns regarding the strength and compatibility of the nylon filament used. Moreover, the inability of the material to allow for modifications during the fitting process negatively impacts the overall quality of the device. This remains a major concern for all the participants, with the majority suggesting that more appropriate materials will need to be used before digital fabrication technologies can be fully incorporated into P&O work.

6.6 Discussion

In the previous two sections of this chapter I described the entrance and exit interviews that I conducted with P&O professions in regards to their experiences using the 3DPA system. In this section I draw upon those interviews as well as my analysis from the previous chapters of this dissertation in order to examine the impact that digital fabrication technologies have on the concepts of expertise and labour within the context of P&O. I begin by looking at issues related to professionalism and how digital fabrication technologies function as discursive and communicative devices that allow P&O professions to express and perform a certain kind of expertise. Next, I describe how the P&O professionals I interviewed see digital fabrication technologies altering
their practices as a means of illustrating what the core values of P&O work are. I then discuss the negative response of those I interviewed to the material used for the production of devices, nylon filament, in order to highlight both the social and cultural channels of input within P&O work as well as how material devices allow P&O professionals to express and perform a kind of expertise. I conclude this section by returning to my third secondary research question, (R1C), “who benefits from this transformation of human expertise?”, to reflect on the nature of technological interventions into professional practices and my role in this process.

During the entrance and exit interviews, one of the major advantages of 3DPA over the traditional methods of production established by the participants was that it was “clean” and that the work was done on a computer. In explaining why this was an advantage, many of the participants responded that it tied to a larger perception of the P&O profession in regards to the kinds of labour and expertise used in producing a device. That is, many of the participants suggested that because the material nature of making devices, which results in them getting covered in dust, they are not perceived as professionals engaged in a cognitively complex task. Similarly, many of the participants also suggested that the adoption of systems such as 3DPA was important as it showed that the P&O profession was actively developing new methods for the production of P&O devices. As part of my analysis in Chapter Four I described how abstract models produced by digital fabrication technologies were discursive and communicative devices that allowed engineers to express and perform their labour and expertise. What these comments from the entrance and exit interviews indicate is that digital fabrication technologies were seen by the participants as a means of expressing and performing their expertise and labour in ways that would be more validated than traditional methods. This need for the validation of the labour and expertise of the P&O profession, as a few of the participants discussed, stemmed in part from a general sense that the work of P&O professionals was somewhat marginalized within the medical community due to its focus on material rather than abstract practices. As such, digital fabrication technologies were seen as a tool for improving the overall perception
of the P&O profession, to make it seem more professional, to the larger medical community.

This goal of being able to perform and express their expertise and labour to the larger medical community, however, does not mean that there were not concerns about digital fabrication technologies. Over the course of the entrance and exit interviews, the participants expressed an uneasiness about the 3DPA due to a certain degree of uncertainty and unfamiliarity within the system that sometimes resulted in a device being fabricated that was characterized as unexpected. In Chapter Four I discussed the research of Katherine Henderson into the adoption of digital fabrication technologies within the context of engineering work. As part of this research Henderson uses the term “visual cultures” to denote the different methods used for design work (Henderson, 1998). Through extensive interviews she found that many engineers who were trained to do “pencil and paper” design found adapting to digital fabrication technologies quite challenging. This was because the “logics” and “methods” used within the software differed from their own visual cultures developed by doing design using pencils and papers (Henderson, 1998). Clear parallels can be drawn between Henderson’s work and the experience of these participants. Many of them commented that they needed “more time to explore” the tools and functions of 3DPA. Given enough time, and the introduction of new P&O professionals trained from the beginning on digital fabrication technologies, some of the concerns regarding the use of these methods may resolve themselves as new “visual cultures” are formed.

Another major concern raised by the participants had to do with what they saw as the core values of the P&O profession. In my discussions with the participants they identified fit as the primary criteria they used for evaluating a successful intervention. The process by which fit is achieved is based upon the individual practices, experience, and judgement of the prosthetists. Any attempt to challenge or alter this dynamic, as the participants explained, would be met by a great deal of resistance or simply rejected outright. Sherry Turkle, in her monograph *Simulations and its Discontents* (2009), used the term “sacred spaces” as a means to denote professional
practices that are seen within the profession as essential to their identity and are thus not easily altered. It would thus be apt to reference “fit” as the sacred space of P&O professionals. Yet, this still leaves a great deal of room for altering other elements of the methods by which P&O devices are produced. Several of the participants explained to me during the exit interviews that they were able to achieve fit easily for ‘simple’ trans-tibial sockets. As such, they were able to reduce the burden of the fitting process, from an emotional and labour perspective, on both themselves and the patients. What this response demonstrated was that so long as digital fabrication technologies were not seen as fundamentally altering the relationship that the P&O professionals had to the fitting processes, they could be integrated into their professional practices, and seen as a viable tool for certain kinds of devices, without a great deal of resistance.

The final concern that I want to touch upon has to do with the material used to fabricate devices during the 3DPA trial. Nylon filament, the material used, was universally disliked by all of the participants due to its appearance and its properties. When asked to describe the various devices they produced using 3DPA many of the participants commented that the devices were not “smooth”. While this was more of a reflection of the process used to make the devices, as the lack of smoothness was the striation caused by the 3D printing process, the overall appearance of the devices greatly concerned the majority of the participants. In Chapter Four, as I mentioned above, I described how abstract models allowed engineers to express and perform their expertise. What this response from the participants illustrates is that material objects can similarly allow professionals to perform and express their experience. In explaining their concerns regarding the lack of smoothness of the devices produced the participants had concerns both about the durability of the device and its overall appearance. The concerns about durability were largely a result of the participants being unfamiliar with nylon filament, whereas the concerns about the appearance of the device came from them being concerned about how the device would reflect upon their own expertise if it looked poorly made. This clearly illustrates how, much like
abstract models, material devices play an important role in the process of professionals performing and expressing their expertise.

The other concern raised by the participants about nylon filament had to do with the fitting processes. When fitting a patient the participant described a “fudging” process in which they made minor modifications to the socket in order to ensure that the fit of the device was correct. These modifications are not recorded, but are seen as essential to the process. In the entrance and exit interviews several of the participants explained that nylon filament did not allow them to engage in this fudging process due to its inability to be re-heated and re-shaped. In Chapter Four I described the social and cultural channels in the design and manufacturing process that allowed for other kinds of knowledge. Clear parallels can be made between these channels and the fudging process, as both are avenues that allow for unofficial or unrecorded forms of knowledge and expertise to be performed. As such, this highlights a fundamental issue with this version of 3DPA, as it does not allow for cultural and social knowledge of P&O work to be used.

The question that has guided the research of the last two chapters of this dissertation has been, “who benefits from this transformation of human expertise?”. Answering this question is not a direct comparison of benefits and disadvantages due to the trade-offs that need to be taken into account when digital fabrication technologies are migrated into the context of P&O work. These technologies are a product of an industrialized viewpoint of P&O work that has been grafted onto lower and middle income practicalities that requires a more complex analysis. I was able to witness first-hand the tensions that arose throughout this adoption process. These tensions can best be described as a back-and-forth between the needs of the participants and the various capacities of the technical system. During these back-and-forth movements there was a great deal of debate and decision regarding what kinds of practices and judgements needed to be perceived and what could be changed. The trade-off experienced is a representation of the complex and standard case dichotomy that the participants described in their exit interviews, in which prosthetists are essentially giving up parts of
their professional practices and labour in order to take on these technologies and adapting their knowledge in relation to the technologies in order to validate their individual labour and expertise while also doing their work. As such, a more nuanced approach needs to be taken when looking at digital fabrication technologies within P&O as this adaptation is a continuing and iterative process that will continue to change as 3DPA becomes more ingrained in P&O practice.

6.7 Conclusions

The 3DPA system, in the context of this work, can be said to have moderate success in a small subset of cases. This success, however, needs to be contextualized within a much larger conceptual framework. As I discussed in the previous chapters of this dissertation the kinds of expertise and labour that are fostered by digital fabrication technologies are those that are abstract in nature. It should be, then, unsurprising that many of the concerns raised by participants during the entrance and exit interviews regarding the usability of 3DPA could be attributed to material practices being overlooked.
Chapter Seven

Conclusion

7.1 Overview

In this concluding chapter, I revisit the major themes of this dissertation and discuss the processes through which abstract labour and expertise have been configured as appropriate for humans in digital fabrication. I begin by looking at my research questions and the conclusions that I can draw based upon my analysis of the knowledge hierarchy present in digital fabrication technologies. I then return to the analysis of Klaus Schwab on the “future of work” as a means of illustrating how the historic and ethnographic research that I conducted for this dissertation addresses the technologically deterministic claims made by Schwab regarding the process by which certain kinds of labour and expertise become re-configured as appropriate for human and intelligent computers. Next, I note the contribution of my research, both to the prosthetics and orthotics (P&O) community as well as the scholarly communities of Information Science, Science and Technology Studies (STS), and Human Computer Interaction (HCI). Subsequently, I discuss the limitations of my research. I conclude by discussing the future direction of my work. As part of these discussions I will briefly outline, among other scholarly perspectives, Alan Turning’s concept of embodied computing as a means of addressing the practical and epistemic limitations of digital fabrication technologies in terms of material labour and expertise.

7.2 Expertise in the age of digital fabrication

My primary research question (R1) for this dissertation was: how did the concept of machine intelligence transform human labour in prosthetic and orthotics work? In order to answer this question I used a combination of action research and historical analysis, and I devised three secondary research questions, which were: what are the historical,
cultural, and material moves that have contributed to this transformation? (R1A); what are the notions of expertise that are fostered by this transformation (R1B); and who benefits from this transformation of human labour and expertise? (R1C) In this section, I will expressly answer my research questions by returning to my analysis from the previous chapters. I will begin by looking at each of the secondary research questions in order. Next, drawing on my discussion of the secondary research questions, I will answer my primary research question. In concluding this section I will address why my research is important to the P&O community but also how it can contribute to the development of a new form of computational politics that allows for a better representation of labour and expertise based upon material knowledge.

The first of my of secondary research questions (R1A) is: what are the historical, cultural, and material moves that have contributed to this transformation? I primarily addressed this question in Chapter Three, in which I described the various research projects of the MIT Innovations in Manufacturing Technology Project (1949-1970). Using the theme of control I detailed how the research of Pease (1952), Ross (1957;1978), and Coons (1966) resulted in the establishment and development of a model of design and manufacturing based upon mathematically defined designs as a means of ensuring ‘reliability’. Similarly, using the theme of expertise I discussed how the research of Brown (1962;1970), Siegel (1956a;1956b), Ross (1958;1978), and Coons (1966) led to the creation of what I referred to as the creative routine dichotomy which positioned digital fabrication as a liberatory technology that freed workers from the boredom and stress of manufacturing jobs. I identified these two moves in particular as they played an important role in contracting the underlying logics used within digital fabrication technologies through which different kinds of labour and expertise were evaluated and a knowledge hierarchy was created.

My second secondary research question (R1B), what are the notions of expertise that are fostered by this transformation?, was dealt with through my analysis in Chapter Four. Drawing on Katherine H. Hayles’ (1999) concept of the Platonic backhand and forehand I described how digital fabrication technologies contributed to the expertise of
engineers moving from that of making material objects, to that of making abstract models. While these abstract models function as discursive and communicative devices that allow engineers to perform and express their expertise, as part of my analysis I also noted how they are socially and culturally limited. As such, what I describe as ‘channels’ exist that allow for other kinds of labour and expertise to enter the design and manufacturing process. This allows ‘work’, for lack of a better term, to get done but implies that when digital fabrication technologies move beyond the design and manufacturing work, as understood in the context of engineering, an important mode of introducing other kinds of knowledge and expertise that are not formally recognized within these technologies do not necessarily migrate with it. In detailing this transformation of expertise from making material objects to abstract models I was able to demonstrate how digital fabrication technologies foster expertise based upon abstract knowledge, but remain dependent on other kinds of expertise that are not specifically valued or acknowledged as part of the technology.

The final of my secondary research questions (R1C) is: who benefits from this transformation of human labour and expertise? I looked at this question in Chapters Five and Six, which comprised an overview of the use of digital fabrication technologies in P&O and through a case study of the 3DPA system developed by Nia Technologies respectively. My analysis in Chapter Five detailed how digital fabrication technologies were positioned as a means of altering the expertise and labour of P&O professionals from that of making material devices to that of making abstract shape patterns, as part of a much larger epistemological move intended to enforce the information/material hierarchy. From this perspective, the transformation of P&O labour and expertise can be seen as benefiting from models of expertise and labour based upon abstract knowledge, as it produces a new context in which they can be applied.

Building upon this analysis, in Chapter Six I described a series of interviews I conducted with P&O professionals who were trained on 3DPA, a digital fabrication technology for P&O developed by Nia Technologies for the developing world. As part of these discussions I described how questions of who benefits from the adoption of
digital fabrication technologies within P&O cannot be approached from a zero-sum perspective. 3DPA, as explained by the participants, effectively allows P&O professionals to express and perform a subset of their labour and expertise to a larger medical community. This benefits them professionally as their expertise and labour, which has traditionally been seen as craft based, has tended to be marginalized or undervalued within the larger medical community. Yet, at the same time, 3DPA was seen as only effective in terms of what the participant described as ‘standard’ cases, which means large elements of P&O expertise and labour remains unrepresented. A tension is thus created in regards to 3DPA, and digital fabrication technologies as a whole, as it represents a trade-off in terms of important kinds of expertise and labour that are essential to the profession but invisible to these systems, and the larger recognition and validation of the profession within the larger medical community.

In creating these three secondary research questions my goal was to create a conceptual framework through which I could answer my primary research question (R1), how did the concept of machine intelligence transform human labour in prosthetic and orthotics work?. What my analysis indicates is that machine intelligence is part of a larger historical, cultural, and material transformation through which a hierarchy is created with abstract knowledge on the top and material knowledge on the bottom. As such, both the labour and expertise of the P&O professionals is transformed as the subset of their work that draws upon abstract knowledge - namely that of the fit shape patterns - becomes reconfigured as the core competency of the profession, whereas all other tasks can be performed by intelligent machines. Digital fabrication technologies' role in this framework is as the medium by which this transformation both occurs and is enforced. Yet, in practice, this transformation of the labour and expertise of the P&O professional remains incomplete largely due to the inherent epistemic limitations of the underlying logics of digital fabrication technologies.

During the exit interviews of my case study at Comprehensive Rehabilitation Services in Uganda (CoRSU), Cambodian School of Prosthetics and Orthotics (CSPO), and Comprehensive Community Based Rehabilitation in Tanzania (CCBRT) many of the
participants commented that 3DPA, while effective for ‘standard’ cases, was not appropriate for the production of devices for ‘complex’ cases. This was largely as a result of the inability for complex cases to be reduced to some kind of abstraction, which meant that it was a time consuming and taxing process to produce the device using 3DPA. What this indicates is that while the concept of machine intelligence has resulted in systems which have allowed for subsets of the labour and expertise of P&O professionals to be abstracted, there are elements of the profession that remain unchanged because of the materialistic and individualistic nature of the tasks involved.

7.3 The Future of Work

In the introduction of this dissertation I discussed economist Klaus Schwab’s monograph *The Fourth Industrial Revolution* (2016). The central argument made by Schwab was that increasing sophistication and integration of technologies across the physical, digital, and biological domains marked the beginning of a new industrial revolution (Schwab, 2016). The effects of this “new” industrial revolution include, among other changes, the erosion and replacement of the cultural, social, and economic frameworks that define work (Schwab, 2016). In this section I return to Schwab’s description of the “future of work” in order re-evaluate and re-contextualize his claims based upon my analysis from this dissertation.

Schwab’s description of the future of work can be associated with three themes: automation, expertise, and control. The first of these themes, automation, denotes how professions that have traditionally been seen as free from the logics of automation due to their complexity are now susceptible to these logics due to the technologies of the fourth industrial revolution. As such, Schwab argues humans will become responsible for the kinds of work in which creative or social skills are required, particularly in instances where decisions must be made in uncertain circumstances or in situations where novel ideation is required (Schwab, 2016).
The second of these themes, expertise, describes how the fourth industrial revolution has resulted in the emergence of a new form of expertise. Schwab suggests that the essential characteristic of this new expertise is its fluidity; or, to put it more simply, the ability to rapidly learn new skills and apply them to different contexts (Schwab, 2016). This new kind of expertise, according to Schwab, will result in a continued shift away from hierarchical structures within organizations in order to more effectively utilize personnel (Schwab, 2016).

The final of these themes, control, details the process through which organizations simplify and define tasks. This allows organizations to either use the labour of intelligent machines or, if no such machine is available, employ a worker on an on-demand basis (Schwab, 2016). The future of work as described by Schwab, then, is one in which humans are relegated to tasks that are ill-defined, require novel outcomes, or have limited demand whereas everything else will be handled by intelligent computers.

More importantly, Schwab indicates that this is a natural and simple progression of technology. What I have demonstrated in this work is the complexity of the moves by which certain kinds of labour and expertise are re-configured as appropriate for humans and intelligent machines.

7.4 The Post-Futurism of Work

This section outlines a model of the process by which certain kinds of labour and expertise become re-configured as appropriate for human and intelligent computers as a result of the historical and ethnographic work and analysis I conducted throughout this dissertation (Figure 15).
The first step in this model is essentialization. At this initial stage, a value proposition occurs in which a task is studied and the labour and expertise associated with that task is actively re-evaluated and defined in terms of its value. In my historical analysis, this is exemplified by the creation of the creative routine dichotomy, in which the engineer becomes valued and the machinist becomes “noise” in the system. For P&O work, it is the delineation of fit as a standardized and quantifiable characteristic, which places higher value on labour and expertise that can achieve “fit” over traditional practice.

The second step in this model is abstraction, the process by which the valued tasks and labour in the essentialization stage become reduced to their basic and defined forms. Abstraction ensures that tasks are defined in terms of outcomes that occur in a standardized, measurable, and routine way, and removes the processes of how things happen in favour of the final product of a task. This is illustrated by the mathematical definition of parts that occurred in the development of N/C, APT, and CAD, as well as the increased focus on the science of measurement that takes place in P&O work.
The third step in this model is informationalization, which is how tasks are carried out. Informationalization refers to the translation of the outcomes defined in the abstraction stage into information that can allow tasks to be conducted by computers. In digital fabrication this involves, for example, turning mathematically defined parts into the code that can be used on an N/C mill. In P&O work, this is the 9x9 grid described by Foote that is used to determine fit.

The fourth step in this model is validation, the process by which the informationalization is shown to effectively produce the outcomes and tasks required. It is achieved through commercialization, as in the case of N/C, and the clinical trials conducted in P&O work.

The final step in this model is articulation. Once an intelligent computer is produced, it is at this point that human labour and expertise and the material knowledge that was under-represented throughout the proceeding process become reintroduced. This is exemplified by the concept of standard and complex cases I introduced in Chapter Six, and Shaiken’s concept of unofficial input.

The process by which Schwab articulated his work presents a simple view of transforming labour and expertise to account for intelligent computers. However, rather than asking questions about how these processes occur, Schwab focuses on the looming spectre of the fourth industrial revolution. This undermines a more critical analysis of how the technologies of the fourth industrial revolution are transforming concepts of human labour and expertise. Moreover, it builds a self-fulfilling prophecy of the future of work in which the forms of labour and expertise Schwab’s model places at the forefront become the forefront of the fourth industrial revolution.

My work in this dissertation provides a framework that allows for a more critical reflection around how human labour and expertise become transformed, and what is actually happening in this transformation. Specifically, I have highlighted the insufficiencies of models like Schwab’s by surfacing the epistemic hierarchy I have described in this section (Figure 15). In doing so I am seeking to highlight the
complexities of the process by which certain kinds of labour and expertise become re-configured as appropriate for human and intelligent computers. This is not a natural approach, but instead a complex trajectory with significant trade-offs that are integral to our understanding of the future of work.

7.5 Contributions

For the P&O community the impact of my research is the establishment of a scheme through which the implications of digital fabrication technologies in the field can be negotiated. As I described in Chapter Six, there is a desire within the P&O community to adopt technologies such as 3D printing as they allow prosthetists to perform and express their expertise to the larger medical community in a way that is recognized and validated. Yet, there is a real risk that by embracing technologies such as 3D printing, whole subsets of the professionals’ labour and expertise could become rendered further marginalized or undervalued as their knowledge outside the system is not considered meaningful. As such, what my research points towards is a scheme by which P&O professionals could seek to mitigate the negative effects of digital fabrication technologies, while also using them to effectively perform and express elements of their labour and expertise.

In addition to these implications for the P&O community, my research also contributes to the fields of Information Science, Science and Technology Studies (STS), and Human and Computer Interaction (HCI) by giving a framework for understanding how different forms of labour and expertise become valued and de-valued. This is important in understanding how certain kinds of information and skills become prioritized and enforce a specific kind of epistemic hierarchy in which abstract knowledge becomes more valuable. This also illustrates what kinds of labour and expertise are not a part of those narratives, and what this might mean for work in the future. As I described earlier, 3DPA was only effective for ‘standard cases’ as the flexibility and judgment required needed for ‘complex cases’ was not adeptly addressed by the system. What this helps to illustrate is the conceptual and epistemic limits of not only 3DPA, but also
digital fabrication technologies as a whole as the result of the focus on abstract knowledge. As such, if these ‘complex cases’ are to become recognizable to digital systems a different underlying logic and philosophy to digital fabrication technologies will need to be used.

7.6 Limitations and Future Directions

My work in this dissertation touches on a number of practical and theoretical frameworks in order to describe and analyze digital fabrication, labour and expertise. In this section I outline some key areas of study that I have not employed in this dissertation and how they might contribute to the future directions of my research.

Firstly, from an historical perspective it is important to note that female labour and expertise is conspicuously absent from Chapter Three. This is not discussed in my narrative, as the historical discussions of liberatory technology I engaged with are focused on technologies relating to male-dominated industries and labour. While it is fascinating to consider what the liberatory potential of these technologies would be for female labour, it is not outwardly present in the historical analysis I conducted. Marie Hicks (2017), Jennifer S. Light (1999), and others have discussed women in the early days of computation and their roles in ways that could be further elaborated in my future historical work.

Similarly, the ways in which I define machine intelligence are narrow, and specifically associated with the historical definition given from MIT. Marvin Minsky (1986) and Nicholas Negroponte (1970) all offer alternative frameworks for the creative and routine dichotomy in fields such as architecture that would broader this definition, but in this work I have focused on tracing one specific industry as a way of understanding the continuity of embedded values. Considering other forms of computation creativity, such as Alan Turing’s concept of embodied computing, could produce a different and potentially more gender-balanced narrative.
In the article *Computing Machinery and Intelligence* (1950) Alan Turing sought to devise a method in which it could be determined if a machine could think. From this line of reasoning Turing devised what has become known as the *Turing Test*. The test involves a human communicating with either another human or a computer over a teletype, with the goal being to determine if the ‘person’ on the other end is a human or a computer. As noted by Brook (1991) the kind of intelligence described by Turing is totally disembodied as it requires no understanding of the material or outside world.

Yet, when Turing moves to the subject of how to program a thinking machine he saw a reason to embody thinking machines, in order to allow them to “learn” as a means of resolving some of the complexity of programming these machines for certain kinds of tasks. As such, Turing argued that thinking machines could be achieved in one of two ways. The first was the unembodied way, which would produce a thinking machine focused on ‘intelligent activities’ such as chess. The second was the embodied way, which involved giving a computer “the best sense organs that money could buy, and then teach it to understand and speak English” and focused on more contextually specific activities (Turing, 1963). The approach that had been used by computational systems, as argued by Brooks (1991), had been that of the disembodied with the embodied largely being ignored. Given the epistemic limitations of digital fabrication technologies that I have described in previous chapters in regards to material labour and expertise it is worth considering what a system based upon an embodied approach would look like and what tensions it would resolve.

During my case study I noted how the selection of nylon filament for 3DPA proved problematic as it prevented the participants from engaging in ‘fudging’ during the fitting process - that is making minor modifications that are not recorded elsewhere. These are part of the larger culture and social practices of P&O work that play an important role in how the profession understands their expertise and labour. From an epistemic standpoint this kind of material or contextual knowledge is problematic for digital fabrication technologies such as 3DPA as they cannot be easily abstracted or computationally represented. Turing’s concept of an embodied thinking machine that used some form of sensor as a means of learning can be used as a means of
articulating an alternative model here, in which contextual and material knowledge become central elements of the computational model. Not only would this allow for the preliminary devices that I described earlier to incorporate important necessary kinds of information or data that would otherwise be ignored, but it also moves us towards a politics of computation in which abstract and material knowledge are considered of equal importance and value.

Finally, from a practical perspective, my work in P&O ties together narratives of digitally manufactured prosthetics in highly industrialized context with the work currently being conducted in lower and middle income countries. My work in this field indicates that P&O practices are highly individualized, and my small case study population only captures a fraction of the processes by which technologies like 3DPA could be implemented. Continued work is needed to compare and contrast the practices of P&O in differing global contexts to understand more fully how expertise is employed and shifted through the introduction of new technologies.

7.8 Conclusions

My dissertation seeks to address how and why certain kinds of labour, expertise, and knowledge become configured as appropriate for humans. By telling and analyzing the history of the MIT Innovations in Manufacturing Technology project I was seeking to illustrate the origins of the claims regarding the capacity of digital fabrication to materialize the digital came from. In examining this history I was able to surface the epistemic hierarchy embedded within digital fabrication technologies that values abstract knowledge over situated knowledge. By combining this cultural historical analysis with ethnographic practices, I was able to show the epistemic and ontological tensions that occur when digital fabrication tools get deployed in non-engineering professional contexts, such and Prosthetics and Orthotics, that are increasingly seeking to leverage these technologies.
There is also a larger implication to the research that I have begun with this dissertation. As technologies underpinned by what can be broadly described as “artificial intelligence” increasingly find their way into our day-to-day experience, they are reconfiguring the social and cultural institutions that govern fundamental human activities like work. Critical research into the relationship between labour, creativity, and machine intelligence is crucial as it will provide frameworks for understanding the epistemic values that end up embedded within future AI technologies. The history that I presented could potentially play an important role in these discussions by re-contextualize other areas of research whose impacts we are more aware of — namely cybernetics. As N. Katherine Hayles (1999) and Philip Agre (1997) note, the servomechanism plays an important role in the development of the field of Artificial Intelligence. Yet, At some point along the way the story of digital fabrication and AI were divested from each other. On February 2,1955 Gordon Brown, who was the director of the Servomechanism Lab during the development of Numerical Control, and Norbert Weiner gave a joint lecture on the negative and positive impacts of automation to the New York City Club of the MIT Alumni Association (Brown and Weiner, 1984). During his talk, Brown commented:

“now [we] have techniques by means of computers — by the exploitation of computers — where we can let machines do the things that machines do best, where we can let people do things that people like to do best — namely, sit on comfortable chairs and think. And then by means of this technology of automation aided and abetted by computers, we have at our disposal a means of marrying the person to the machine in a way that brings about the end objectives of greater production, greater product quality, and greater satisfaction at less physical effort to all us expect this miserable thing called the intellectual challenge that hits us in relation to keeping the beastly thing running.” (Brown and Weiner, 1984 p. 377)

Later, Weiner echoed this sentiment by suggesting that “[I]f we’re going to replace the human being, not in his higher activities, but when he is used as he is used in so many
factories, as a cheap replacement for a mechanical decision apparatus… it seemed to me that the obvious thing was that a machine could do that sort of thing better and faster” (Brown and Weiner, 1984 p. 382). What these remarks point to is the shared intellectual history that exists between digital fabrication and cybernetics regarding what is understood as appropriate work for humans and computers. By bringing the digital fabrication and cybernetics back together, we have an opportunity to critically understand the underlying metaphors embedded in AI technologies. This is necessary if we wish to develop more equitable and fair alternatives to them.
References


Appendices

Appendix A – Bibliography of Materials Collected From MIT Institution and Special Libraries Archive


Appendix B – Entrance Interview Script

Section One – Biographic

1) Name:

2) Occupation/Title

3) Education (where and when):

4) How long have you been practicing in the field (P&O):

5) How would you describe your job to others:

Section Two – Expertise, Technology, and Labour

6) What role do you see 3D printing playing in your day-to-day practices:

7) What was your initial thoughts about 3D printing and scanning?:

8) After working with 3D printing and scanning technologies for a but has your perception of them changed:

9) What kind of changes would you like to see to 3D printing and Scanning:

10) What need do you see 3D printing and scanning filling in prosthetics:

11) How do you see 3D printing and scanning changing your job:

12) When using the Nia System was there any tasks that you found confusing or were you couldn’t do something the way you wanted to do it:

13) What do you think of the overall workflow of the Nia system:

14) What do you think the major differences are between making a socket or AFO by hand and with the Nia System:

15) What was the most difficult part about scanning; What was the most difficult part about 3D modeling (rectification); what was the most difficult part about printing:

16) What do you think of the sockets/Afos being produced:

17) Does using this technology feel different than how you worked before; will it make your work easier; harder; or will it be the same:
18) What would you say the most useful aspect of 3D printing and scanning is; what is the least useful:

19) Would you want to continue to use 3D printing and scanning in the long term; why:
Appendix C – Exit Interview Script

Oral Questionnaire

1. How would you describe your profession (expertise/labour) to others? Has 3D printing/scanning changed the way you would describe it? Why/why not?

2. Can you walk me through the process you go through with a typical patient (walking through the door to leaving with a prosthetic) before 3DPA?
   - **Probe**: about steps that aren’t in the official workflow, decision-making, details about what they like/didn’t like about process, time to complete tasks

3. Can you walk me through the process you go through with a typical patient (walking through the door to leaving with a prosthetic) using 3DPA?
   - **Probe**: about steps that aren’t in the official workflow, decision-making, details about what they like/didn’t like about process, time to complete tasks

4. What would you say are the biggest differences between your old process and the 3DPA process?
   - **Probe**: are they good/bad differences? What would you change?

5. What skills from your current way of making prosthetic devices were easily applicable to 3D/digital tools? What new skills did you have to learn?

6. Was your transition from your previous process to 3DPA difficult? Why/why not?
   - **Probe**: what were the difficulties (knowledge, technical, resources, etc)? Were you able to address difficulties on your own? What would have made this transition easier?

7. Aside from what we’ve already discussed, was there any part of using the 3DPA processes you found challenging to use or unnecessary? If so why?

8. Aside from what we’ve already discussed, was there any parts of using the 3DPA processes you found that improved your workflow or was easy to learn? If so why?
9. What do you think of the 3D scans being produced? Could they be improved, if so how?
   • **Probes:**
     • Are they better/the same/worse quality?
     • Do they look better/the same/worse?
     • Are the more/less accurate?
     • Does it take more/the same/less time to do?

10. What do you think of the 3D models (post rectification) being produced? Could they be improved, if so how?
    • **Probes:**
      • Are they better/the same/worse quality?
      • Do they look better/the same/worse?
      • Are the more/less accurate?
      • Does it take more/the same/less time to do?

11. What do you think of the 3D prints being produced? Could they be improved, if so how?
    • **Probes:**
      • Are they better/the same/worse quality?
      • Do they look better/the same/worse?
      • Durability?
      • Are the more/less accurate?
      • Does it take more/the same/less time to do?

12. Do you think this technology is useful? Why/why not?

13. Any other thoughts about your overall experience during the 3DPA trial?
    • **Probe:** anything we haven’t discussed you want to add?
Appendix D – Interview Consent Forum

CONSENT TO PARTICIPATE IN:
*Expertise in the Age of Digital Manufacturing*

This is to state that I agree to participate in a program of research being conducted by Daniel Southwick of the Faculty of Information at the University of Toronto.

PURPOSE
I have been informed that the purpose of this research is to be interviewed for the dissertation work of Daniel Southwick dealing with automation, labour and expertise in digital manufacturing. I will be interviewed regarding my experiences and the decisions that I make in regards to 3D printing and/or Prosthetics. I will also engage in a walkthrough/demo of my process or the tools I’ve developed involving the production of 3D printed prosthetics and/or prosthetics following the interview. I understand that at the conclusion of the walkthrough or demo samples of the work produced, either model or data files, will be requested.

PROCEDURES
Each interview and walkthrough/demo should take 1.5 to 2.5 hours, and will be conducted in-person or over Skype and recorded using call-recording software. The interview will be scheduled at a mutually-agreeable time between myself and Daniel Southwick. I understand that I may opt for my identity and professional affiliation to be either confidential (my real name will *not* be revealed in the study) or non-confidential (my real name will be revealed in the study). I also understand that I may opt to allow for copies of any files produced during the interviews to be kept for later reference.

DISCLOSURE
Part of the funding for this research is being provided by Nia Technology, as part of a Mitacs Cluster grant. In exchange for this funding Daniel Southwick is acting as a technical advisor to the non-profit company. While a report will be generated as the end of the contract the organization itself does not influence the research being conducted.

CONDITIONS OF PARTICIPATION
I understand that my participation in this interview is completely voluntary.

I understand that I may decline to answer any questions without negative consequences. I also understand that I am free to withdraw my consent and discontinue my participation at any time in the interview process, and with the project, without negative consequences. Upon withdrawal from the interview, I have the right to ask that
all transcripts and recordings be excluded from the study and destroyed.

I understand that the interview will be recorded in-person using a digital audio-recording device, or conducted over Skype and recorded using call-recording software, for the purposes of transcription only. It will be kept on a hard-drive that is locked in Daniel Southwick personal office for a period of three years, after which it will be destroyed.

I understand that photos will be taken, if permission is given, of the walkthrough/demo of my processes. These photos will be used for analysis only. They will be kept on a hard-drive that is locked in Daniel Southwick personal office for a period of three years, after which it will be destroyed.

I understand the copies of the files, if permission is given, will be kept for the purposes of analysis only. It will be kept on a hard-drive that is locked in Daniel Southwick personal office for a period of three years, after which it will be destroyed.

I understand that unless I choose to remain confidential, the interview will be on the record; quotes and corresponding files will be identifiably attributed. I also understand that I will have the opportunity to approve and correct the specific quotes and interview passages before they are incorporated into the dissertation work of Daniel Southwick and/or submitted to publishers for future scholarly publications and/or academic conferences. If I choose to have my identity be confidential, I can choose a pseudonym and I will have the opportunity to approve and correct the specific quotes and interview passages before they are incorporated into the dissertation.

RISKS AND BENEFITS
There are no anticipated risks involved in participating in this research project. The resultant dissertation will explore how expertise is understood and performed in systems of digital manufacturing. It is anticipated that the work will be of value to the scholarly community as well as practitioners.

This research study may be reviewed for quality assurance to ensure that the required laws and guidelines are followed. If this study is chosen for review, a representative of the Human Research Ethics Program may access the study and consent materials as part of the review process. Information accessed by the Human Research Ethics Program will be upheld to the same level of confidentiality stated by the researcher.

If at any time you have questions about the proposed research, please contact Daniel Southwick (Faculty of Information, University of Toronto):
Daniel.Southwick@mail.utoronto.ca

Or his Supervisor Professor Matt Ratto (Faculty of Information, University of Toronto):
Matt.Ratto@utoronto.ca
If you have any questions about this research protocol, or your rights as a participant, you may contact the Office of Research Ethics at ethics.review@utoronto.ca or 416-946-3273.

I HAVE CAREFULLY STUDIED THE ABOVE AND UNDERSTAND THIS AGREEMENT.

__________________________ (please initial)

I FREELY CONSENT AND VOLUNTARILY AGREE TO PARTICIPATE IN THIS STUDY.

__________________________ (please initial)

I WISH TO HAVE MY IDENTITY:

_________________ NON-CONFIDENTIAL; ___________________ CONFIDENTIAL (please initial)

PHOTOS OF THE WALKTHROUGH/DEMO CAN BE:

_________ TAKEN; ___________________ NOT TAKEN (please initial)

COPY OF FILES CAN BE:

_________ KEPT; ___________________ NOT KEPT (please initial)

Name (please print):

______________________________________________________________

Signature:

______________________________________________________________

Date: ___________________________