3D Printing in the Commons:

Knowledge and the Nature of Digital and Physical Resources

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A thesis submitted for the degree of
Doctor of Philosophy
Michaelmas 2015

To the natural organisms that build our world layer by layer

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Abstract

3D printers are a type of digital fabrication tool being used by communities committed to shared software, hardware, and digital designs. This shared digital knowledge can be understood as an emerging common resource for the fabrication of physical goods and services. Yet the knowledge associated with physical resources used in 3D printing is less understood. This thesis explores what factors enable or prevent knowledge about physical materials entering the commons.

3D printing, with its particular configuration of digital and physical goods, offers a unique angle to advance the field of commons scholarship. This thesis elaborates the use of commons theory for traversing the boundary between knowledge associated with physical materials and digital content from the perspective of 3D printer users. Particular contributions are made to the branch of knowledge commons theory: notably, how design rules in technological systems can be used to theorise boundaries; how differentiating between the nature of underlying resources can help explain the inclusion of knowledge in the commons; and, how patterns of user engagement with types of knowledge in the commons can be studied over time.

To develop these contributions I employ theory on the design rules of technological architecture, and use insights from the study of peer production in online communities. Empirical data comes from a qualitative study of users of Fab Labs, community workshops for digital fabrication, as well as from a quantitative study of the online user forum for the Ultimaker 3D printer.

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List of Acronyms

ABS: Acrylonitrile Butadiene Styrene

ASTM: American Society for Testing and Materials

CAD: Computer Aided Design

CNC: Computer Numerical Control

FDM: Fused Deposition Modelling

IAD: Institutional Analysis and Development

ICT: Information Communication Technologies

IP: Intellectual Property

MDF: Medium-Density Fibreboard

MIT: Massachusetts Institute of Technology

NDA: Non-Disclosure Agreement

PET: Polyethylene Terephthalate

PLA: Polylactic Acid

SLM: Selected Laser Melting

SLS: Selected Laser Sintering

Glossary of Key Terms

3D Printing	The fabrication of objects through the deposition of a material using a print head, nozzle, or another printer technology (ASTM International)
Additive Manufacturing	The process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies (ASTM International)
Fab Lab	‘Fabrication Laboratory’, community workshops for digital fabrication
Material Extrusion	Additive manufacturing process in which material is selectively dispensed through a nozzle or orifice.
Open source	In production and development, open source as a development model promotes a universal access via a free license to a product's design or blueprint, and universal redistribution of that design or blueprint, including subsequent improvements to it by anyone (Lakhani & Hippel, 2003).
RepRap	Open source 3D printer (see http://reprap.org)

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1 INTRODUCTION

In the last decade, 3D printing has developed as a technology produced and used by communities committed to sharing digital resources. Many open access digital models, software programs, and hardware designs are accessible and widely distributed on the Internet. These shared resources can be understood as an emerging knowledge commons[1] for 3D printing users.

3D printing is a method of fabricating a physical object layer by layer, directed by a computerised design file[2]. This makes 3D printing a type of digital fabrication, where digital information plays an active role in the fabrication of physical objects.

It is the integration of digital and physical resources that makes digital fabrication an interesting empirical phenomenon. A product can now be designed digitally in one location, sent over the Internet to a 3D printer anywhere in the world, and physically fabricated on site. When a 3D printer prints a physical object, it must use materials sourced from material supply chains. Despite this physical basis, little attention has been paid to the knowledge associated with the materials in use[3]. This observation motivates the following research question:

> *What enables or prevents access to knowledge about 3D printing materials entering the commons?*

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[1] A 'commons' indicates a shared resource subject to social dilemmas resulting from the difficulty in excluding others from use (Ostrom & Hess, 2001). Knowledge commons theory will be elaborated in section 1.4.3 and discussed in full in Chapter 2.

[2] Defined by ASTM International as a type of additive manufacturing. Definitions are elaborated subsequently in section 1.1.

[3] Knowledge about materials is a term used in this study to refer to useful information about composition and behaviour from the perspective of 3D printer users (see section 1.4.2).

The specific formulation of the question stems from the theoretical aims of this research. 3D printing, with its particular configuration of digital and physical goods, offers a unique angle to advance the field of commons scholarship. From its early formulations in addressing common-pool resource dilemmas (Ostrom, 1990), to its more recent branching into knowledge commons mediated by distributed digital technologies (Hess & Ostrom, 2003; Frischmann, Madison, & Strandburg, 2014; Benkler, 2013), the focus on types of goods and knowledge access remains central. This thesis elaborates the use of commons theory for traversing the boundary between knowledge associated with physical materials and digital content from the perspective of users of 3D printers. Particular contributions are made to the branch of knowledge commons theory: notably, the influence of technological system design on access to knowledge, how knowledge entering the commons relates to the nature of the underlying resource in use, and user engagement with types of knowledge in the commons over time.

To develop these contributions I employ theory on the design rules of technological architecture, and use insights from studies of peer production in online communities. Although significant scholarly attention has been paid to understanding the peer production and use of open source software (Benkler, 2016), the production and use of knowledge about physical goods in the commons is less understood. This thesis provides an empirical window into this area. Empirical data comes from a study of users of Fab Labs, physical community spaces for digital fabrication, as well as the study of the online user forum for the Ultimaker 3D printer.

The remainder of this introductory chapter is structured as follows. To begin I introduce 3D printing as a type of digital fabrication. I then discuss the relationship between 3D printing technology and open source communities. Next, I introduce my research approach, including research framework, methodology and design. I then describe my empirical context and data sources. I conclude the chapter by summarising original contributions and detailing the organisation of the thesis.

1.1 3D Printing and Additive Manufacturing

1.1.1 Defining terms

3D printing is defined by the standard setting organisation ASTM International[4] as ‘the fabrication of objects through the deposition of a material using a print head, nozzle, or another printer technology’ (ASTM International, 2012). 3D printing is part of a family of additive manufacturing techniques that share a common logic of layer-by-layer digital fabrication. ASTM defines additive manufacturing as ‘the process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies’. The definition of subtractive manufacturing is: ‘making objects by removing of material (for example, milling, drilling, grinding, carving, etc.) from a bulk solid to leave a desired shape, as opposed to additive manufacturing’ (ibid).

ASTM International (2012) goes on to note that while 3D printing is often used synonymously with additive manufacturing, it is primarily ‘associated with machines that are low end in price and/or overall capability’. In today’s market, most low cost machines extrude material through a nozzle or print head. By

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[4] This terminology is under the jurisdiction of Committee F42 on Additive Manufacturing Technologies and is the direct responsibility of Subcommittee F42.91 on Terminology.

contrast, additive manufacturing encompasses industrial sintering machines that use lasers or electron beams to solidify successive layers of polymer or metal powder.

In this research I use the term additive manufacturing when referring to industrial machines or applications. When referring to low cost or desktop machines at the individual or community-scale of production, I use the term 3D printing. Desktop 3D printers are defined by Wohlers (2013) to be any machine under the price of $5,000 USD. It is important to contextualise desktop 3D printing within the larger field of additive manufacturing for two reasons. First, although desktop 3D printing has emerged as a relatively new empirical phenomenon, the roots of the technology go back to the 1980s. Second, to understand 3D printing as a technological tool, it is useful to relate it to a larger family of evolving methods for additive, layer-by-layer, digital fabrication (Wohlers, 2013).

Additive manufacturing was developed first in industrial prototyping markets, where it offers advantages in customised, on-demand production. The first patent for an additive manufacturing technology was granted in 1977, although it wasn’t until 1988 that the first machine for stereolithography (a method of additive manufacturing) was commercialised. Metal sintering additive manufacturing was also developed in the 1980s, followed in the 1990s by Fused Deposition Modelling (FDM) and other methods. FDM is the method most commonly used in desktop 3D printing, for reasons discussed in section 1.3.3. The following diagram explains the main categories of additive manufacturing technologies.

Table 1.1: Additive Manufacturing Technologies (ASTM definitions)

Category Name	Material used	Description
Binder Jetting	Metal, Polymer, Ceramic	Additive manufacturing process in which a liquid bonding agent is selectively deposited to join powder materials.
Directed Energy Deposition	Metal: powder and wire	Additive manufacturing process in which focused thermal energy is used to fuse materials by melting as they are being deposited. Focused thermal energy means that an energy source (e.g., laser, electron beam, or plasma arc) is focused to melt the materials being deposited.
Material Extrusion	Polymer	Additive manufacturing process in which material is selectively dispensed through a nozzle or orifice.
Material Jetting	Photopolymer, Wax	Additive manufacturing process in which droplets of build material are selectively deposited. Example materials include photopolymer and wax.
Powder Bed Fusion	Metal, Polymer, Ceramic	Additive manufacturing process in which thermal energy selectively fuses regions of a powder bed.
Sheet Lamination	Hybrids, Metallic and Ceramic	Additive manufacturing process in which sheets of material are bonded to form an object.
Vat Photopolymerisation	Photopolymer, Ceramic	An additive manufacturing process in which liquid photopolymer in a vat is selectively cured by light-activated polymerization.

Adapted from Manfredi et al., 2014

1.2 Digital Content and Physical Materials

Software, hardware, firmware[5], and materials are interrelated in 3D printing systems[6]. This is important for examining the types of knowledge associated with the use of the technology. I now examine the relationship between digital content and physical resources in the process of additive manufacturing. My purpose is to show the level of control over physical materials that additive manufacturing methods provide. I discuss the main features of digital modelling and design, and examine the ways materials are being manipulated through the process of fabrication. Some of these examples are in the research and development phase. I use them to illustrate the intriguing ways additive manufacturing is integrating digital content and physical materials. I end by exploring how the software-defined nature of additive manufacturing is opening up access to its use.

1.2.1 Digital manipulation of physical materials

In additive manufacturing processes, digital manipulation of physical materials can be seen in the design and modelling phase as well as in the build phase. In its use of digital design and modelling tools, additive manufacturing is similar to other digital fabrication technologies (Gibson, Rosen, & Stucker, 2010). An integral technology to digital fabrication is Computer Aided Design (CAD) and Computer-Aided Engineering more generally. 3D CAD software is the current standard for designing and testing products digitally before being sent to additive manufacturing machines. Computer-Aided Engineering software allows properties

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[5] Software that is programmed onto the hardware of a 3D printer

[6] I differentiate firmware from the hardware and software components in later chapters. For the purpose of introduction, I describe the basic relationship between digital content and physical resources.

like forces, flows, stresses, and dynamics to be calculated before a product is built (ibid, p. 14). However, Gibson et al. (2010) note that 3D CAD was initially developed for subtractive methods such as CNC (Computer Numeric Control) milling, where material is cut away to create the desired shape. This has proved a limitation for additive manufacturing. This is because its additive process allows more flexibility and complexity in the internal design than the software can cope with. This challenge is currently being addressed through new software innovations. Additive manufacturing is also closely associated with reverse engineering technologies that involve 3D imaging technology and software, allowing users to scan and replicate objects (ibid).

As the range of materials being used in additive manufacturing continues to grow, there are radical innovations in the ways polymers, metals, and natural materials are being manipulated throughout the build process. One area of innovation and development is in functionally graded materials. To illustrate, Stratasys PolyJet[7] is a patented technology that sprays photopolymer streams out of 2 or 3 printing heads simultaneously. By adjusting the volume and type of each photopolymer being mixed, a large range of resulting material properties can be obtained. These properties can be adjusted throughout the build process, creating variation in material performance at different parts of the object.

Functionally graded materials using additive manufacturing techniques are also being experimented with in metals. Shishkovsky et al. (2012) demonstrate functionally graded structures using titanium and aluminium powders. A similar line of manufacturing research is with Selected Laser Melting (SLM) technologies that use lasers to selectively fuse layers of metal powder. By varying the processing

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[7] See http://www.stratasys.com/3d-printers/technologies/polyjet-technology

parameters of width, height, and contact angle of the laser scan, Spierings, Levy, and Wegener (2014) state, ‘This offers the opportunity to locally design the mechanical behaviour of a structure not only by its geometrical design, but also by adjusting the material porosity’ (p. 448). This is an illustration of the important interrelationship between digital machine inputs and resultant material properties.

Manipulating structure to create material performance characteristics is also being done with natural materials. By mimicking cellular structures found in nature at the meso-structural level (length scales of centimetres to micrometres), researchers are designing materials with honeycombs and lattices. These structures offer the benefits of strength with minimal amount of material. They are also good at absorbing energy, and have important thermal and acoustic properties (Chu, Graf, & Rosen, 2008).

Researchers from Harvard University used additive manufacturing methods and a new epoxy-based ink to mimic the alignment of fibres in balsawood. They state the importance of this work as follows: ‘The most ubiquitous cellular composite is wood, which not only supports substantial self-weight and wind loading, but efficiently transports nutrients over long distances to sustain growth. By controlling composition and architecture over multiple length scales, natural materials are able to achieve remarkable properties from biological polymers, e.g. cellulose and lignins’ (Compton & Lewis, 2014, p. 1). The key to exploring the potential of digitally manipulating material properties is fabricating structures at smaller and smaller scales. Micro-scale 3D printing is a growing area of commercial technology and development[8].

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[8] Micro-scale 3D printing is named one of the 2014 breakthrough technologies by the *MIT Technology Review.* See http://www.technologyreview.com/featuredstory/526521/microscale-3-d-printing/

1.2.2 Distributed access to 3D printing

I now examine how the relationship between digital and physical resources in additive manufacturing and 3D printing relate to the technology's use. As discussed, a large part of the additive manufacturing process is defined by software. This allows unlimited variations of a product to be printed without the extra expense of retooling hardware components. Cotteleer (2014) examines the implications of software-defined fabrication for barriers to entry in manufacturing, and the types of goods produced. By reducing the capital required to reach a minimum efficient scale of production, additive manufacturing effectively lowers barriers to entry for fabricating complex physical goods. By lowering or eliminating the costs of retooling and increasing product customisation possibilities through flexibility of design, additive manufacturing 'facilitates an increase in the variety of products a unit of capital can produce' (Cotteleer, 2014, p. 150).

A recent IBM study brings these ideas of capital, scale and scope together with the concept of the 'software-defined supply chain' (Brody & Pureswaran, 2013). Rather than 'Production lines…carefully built for volume and speed, and production planning systems…designed to minimize the number of times reconfiguration is required…3D printing allows companies to go directly from design to product, all through software and at a touch of a button' (ibid, p. 7-8).

Applications of additive manufacturing take advantage of this software-defined nature. Additive manufacturing made its first high profile market successes in dental implants and medical prosthetics. These are both markets where customisation is highly desirable. Early industrial applications were in tooling and mould making. The recent transition into direct part production in the automotive and aerospace sectors has raised the profile of additive manufacturing considerably across the general manufacturing landscape. On-demand part production, such as for spare parts, is another area that is promising.

The software-defined nature of 3D printing opens up new interfaces between customers seeking 3D printed goods, and digital product designers. Shapeways, Sculpteo, and Ponoko are three main service bureaus serving this consumer market. These companies work through online platforms, where customers can choose independent artist's designs, or upload their own CAD models, and the service bureau does the printing and distribution of the final product. In this way, the customer can be highly involved in the design of custom products although knowledge of the production process is still removed.

A more radical change can be seen with customers who have bought desktop 3D printers and are producing goods for others. The exponential growth of 3D Hubs illustrates this. For any person who wants to have a digital design 3D printed, 3D Hubs makes visible all the people in their local area who offer 3D printing services. These can be companies as well as individuals. A user selects a person in their local area to print their design, transfers the file and payment, and arranges to pick up the finished product (see https://www.3dhubs.com/).

3D printers have also been part of the growth of community spaces for digital fabrication, including Fab Labs, Makerspaces, Hackerspaces, Tech Shops, and others that go by their own, unique brand. These spaces can be described as community workshops for digital fabrication. Members are given access to 3D printers and other digital fabrication tools, and often serve the interests of diverse interests and purposes. An empirical study of Fab Lab users forms Chapters 4-6.

1.3 Open Source 3D Printing

Access to the knowledge needed for 3D printing depends on many factors. However, there is a major feature of 3D printing that is radically changing the knowledge landscape: the open source movement[9].

3D printing has become part of an open source movement around a shared set of digital resources. This has expanded from open source software and digital designs to open access to the designs of physical 3D printing hardware. I now introduce the open source movements in each of these areas.

1.3.1 Open source software

Open source software is software developed under a General Public License (GPL). The license specifies that anyone can access and develop the software, no one can have the rights to exclude others, and everyone must share developments publically. Examples include the Linux operating system, Apache Web Server, Php (a scripting language), Firefox web browser, and OpenOffice software (Schweick, 2007). For 3D printing systems, open source software for modelling and designing 3D objects is increasingly sophisticated and diverse. A list of open source software for 3D printing is available on many 3D printing forums[10]. This also includes open source firmware, software that that is programmed on a hardware chip.

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[9] I do not refer to additive manufacturing here, for the open source movement is predominantly a feature of the low cost desktop market. While open source hardware, and software, and designs are not limited to desktop models, it is most prominent in this segment of the market.

[10] E.g. http://www.3ders.org/3d-software/3d-software-list.html, http://reprap.org/wiki/Useful_Software_Packages

1.3.2 Open source CAD models

There are many repositories and online communities for CAD models, ready to be downloaded and 3D printed. Makerbot Thingiverse is one of most popular, and is interesting from the perspective of open source design. Makerbot founded Thingiverse when the company was initially open source, although it has now moved towards a proprietary business model. This means that while CAD models are still largely free and open to download, the question of design ownership has emerged as a contentious issue. Other sites for open source designs include Shapeways, YouMagine, Autodesk 123D, My Mini Factory, and GitHub. While some designs are available for download for a price, sold by particular designers, others are free and allow customisation.

1.3.3 Open hardware

Similar to software, open source hardware is any device that has been licensed to allow anyone to use, replicate, and modify the design specifications. The open source Arduino is a single-board microcontroller that uses sensors and actuators to interact with its environment. It can be programmed to interact with a computer, and has been integrated into many robotic and sensory technologies, including a wide range of 3D printers. Its hardware reference designs are available for download and modification, and users can freely download the software or program their own source code (http://arduino.cc). As a clear example of the synergy between 3D printing and open source electronics, Arduino boards have become the integrated ‘intelligence’ of many open source 3D printers.

Physical 3D printer components such as the build chamber and extrusion system have become part of the open hardware movement. Like Arduino and

Linux, open source 3D printers make available the hardware designs for download and modification, and run on open source software and firmware that similarly can be used and adapted. Adrian Bower and collaborators at the University of Bath made the first open source 3D printer in 2007, naming it RepRap. Bower started the RepRap project with the vision of making a machine that could replicate a significant number of its own parts, use readily available low cost parts for anything that it couldn't print itself (e.g. nuts and bolts), and be open source for anyone to build and modify. It is licensed under a GNU GPL copyleft license[11]. The designs of the first open source 3D printers came from copying expired patents in Fused Deposition Modelling (FDM). Since the RepRap designs were made open source, a growing community has made, modified, and commercialised a large variety of 3D printers based on the initial RepRap blueprints.

In 3D printing, the domain of open source is not necessarily disconnected from the domain of proprietary technology. RepRap based printers include Makerbot and Ultimaker, two leading 3D printing models. Although sharing common roots, these two models have diverged significantly in their business model. Makerbot, initially an open source machine based on an expired FDM patent from Stratasys, came full circle by being bought by Stratasys in 2014. In the process they removed their hardware and software intellectual property from the public domain, creating a visceral response from the open source community (Molitch-Hou, 2014). By contrast, Ultimaker has chosen to remain open source, and is sustained by a large and active community of makers. The user forum for the Ultimaker community is studied in Chapter 7.

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[11] A General Public License for the open GNU operating system, see https://www.gnu.org/copyleft/

The open source 3D printing community continues to evolve with the continued expiration of industry patents in additive manufacturing. For example, the expiration of the key Selected Laser Sintering (SLS) patent in February 2014 sparked new efforts to create low-cost SLS printers. Using a laser to precisely melt layers of thermoplastic powder, SLS allows more control and accuracy than FDM methods (Hornick, 2013).

1.3.4 Summary

In summing up the important parts of this introduction to additive manufacturing and 3D printing, the following observations can be made. First, 3D printing is part of a family of additive manufacturing methods that shares the approach of building up an object through successive layers of material, directed by a computerised model. Second, the digital nature of the fabrication process means that digital content is being used to manipulate physical materials in new ways. The software-defined nature of the additive manufacturing is linked to falling barriers to entry in digital fabrication, as well as opening up access to the use of 3D printing through digital service bureaus, network platforms, and local community workshops. Third, knowledge about 3D printing is increasingly accessible due to the open source movement. This includes open source software, CAD models, and open hardware designs. These observations underpin my research question and motivation, detailed in the following section.

1.4 Research Approach

Here I introduce my research motivation and main guiding question. I detail my theoretical approach, research framework and methodology. Finally, I introduce my empirical context and describe the organisation of empirical chapters. This serves as a brief introduction; I discuss my research approach in detail in Chapter 3.

1.4.1 Theoretical motivation and research question

From the introduction to 3D printing technology, one can see an emerging set of shared knowledge resources in the desktop market comprised of open source software, hardware designs, and CAD models. This set of shared resources can be described as a 'knowledge commons', following Hess and Ostrom (2007a) in defining the commons as a shared resource that is vulnerable to social dilemmas[12].

Framed as such, the study of knowledge commons associated with 3D printing is an opportunity for theoretical development. Scholars of commons theory, with historical roots in theorising commons dilemmas concerning biophysical resources (Ostrom, 1990), have recently turned their attention to knowledge commons, information resources subject to social dilemmas that become a collectively produced and accessed through the use of distributed digital technologies such as the Internet. While theoretical and analytical tools from the study of biophysical resource commons can be fruitfully applied to the study of knowledge commons, research must systematically study the actors, institutions, and actions situations particular to shared knowledge resources (Cole, 2014).

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[12] A social dilemma is most often associated with collective action situations, where individual incentives differ from what is in the collective interest. For example, incentives for individuals to profit from a finite physical resource can lead to over-extraction, whereas free riding with a nonrival resource like information can lead to the under-provision of the resource in question.

Developing this field promises new insights into the role that commons play in current societies and market economies (Benkler, 2013).

3D printing as an empirical lens provides an opportunity to study knowledge related to both physical and digital resources, as both digital content and physical materials are interrelated in the design and fabrication of objects. From the perspective of knowledge commons scholarship, one can ask whether knowledge about physical resources is entering the commons, following the entrance of knowledge related to digital resources. This motivates the following research question:

> *What enables or prevents access to knowledge about 3D printing materials entering the commons?*

My study of this research question aims to clarify the application of established frameworks for studying biophysical resource commons to new knowledge commons, a project in need of empirical studies to aid theoretical elaboration (Frischmann, Madison, & Strandburg, 2014). In particular, my study is well positioned to inform: (1) the task of theorising boundaries in knowledge commons; (2) the study of dilemmas associated with types of knowledge in the commons; and (3), the study of knowledge commons communities over time. Contributions to these areas are summarised in section 1.6.

1.4.2 Clarifying knowledge about materials

Central to this thesis is the concept of knowledge about materials for 3D printing. There are two important dimensions that help clarify this concept as it is employed throughout: knowledge as a concept, and knowledge as a type of good. These inform my empirical and theoretical approach respectively.

First, in defining knowledge as a concept, I follow Machlup (1983) in adopting the distinction between data, information, and knowledge. Information is defined as organised, or structured raw data, and knowledge as assimilated information accompanied by cognitive understanding of its use. As such, a person with appropriate knowledge is needed for information to be processed and used (Foray, 2004). Knowledge can be explicit and codified, or tacit as when 'we know more than we can tell' (Polanyi, 1966, p. 4). Tacit knowledge can reside in people, institutions, and routines, and is hard to transfer and reproduce effectively (Foray, 2004). Knowledge can also be thought of as more or less fragmented or dispersed from the perspective of a user in a given context. Knowledge can also be of a scientific nature, or be more locally contextual, and both types are useful for gaining understanding (Hess & Ostrom, 2003, referencing Hayek, 1945).

These aspects of knowledge as a concept underpin my empirical exploration of knowledge of materials. Rather than attempting to distinguish tacit from explicit knowledge, I instead allow for both dimensions to be interrelated as the context demands from the perspective of my interview subjects. For example, from the perspective of 3D printer users, knowledge about materials often refers to material composition (the existence of certain chemicals) or behaviour (such as the rate of flow through the printer nozzle) during the print process. Such knowledge may be arrived at through a combination of tacit and explicit knowledge from the user's perspective, involving a feel for the material based on past experience, as well as information provided by others or the company that produced the material. He or she may also produce knowledge in the process of 'learning by doing' (Arrow, 1962). Knowledge of materials is quite clearly not an absolute quantity, and should not be approached simplistically as either being present or absent. In my empirical analysis, I aim to provide the context that users are referring to when they explain what knowledge they have or do not have about materials. In Chapter 8 I reflect theoretically on these context specific instances of knowledge about materials as explored in the empirical chapters.

The second dimension considered is the nature of knowledge about materials as a type of good or resource. A foundational pillar of commons theory is the categorisation of goods according to their rivalry (how subtractable a good is) and excludability (how difficult it is to exclude a good from anyone seeking to use it). Knowledge is classically understood as a public good, being both nonrival and difficult to exclude others from (Foray, 2004). This typology provides analytical insight into the forms of governance (commons-based or otherwise) that may accompany the resource, bringing with them related benefits or drawbacks to its use and sustainability. In order to assess whether knowledge about materials is entering the commons around 3D printing, one must understand the concept within this theoretical framework. This is discussed throughout Chapters 2 – 4, and forms the basis for a key theoretical contribution of this thesis. Although knowledge can be understood as close to a public good, I find it critical to take into account the type of good that the knowledge relates to (i.e. physical materials versus software) in order to understand why knowledge may or may not be entering the commons.

1.4.3 Theory, Framework, and Methodology

This study aims to contribute to the theoretical project of evolving the Ostrom School[13] of commons research to better approach the study of knowledge commons. Knowledge commons are shared information resources related to the use of technologies such as the Internet. While the roots of commons theory centre on collective action problems involving physical resources and pre-existing institutional arrangements, the knowledge commons must contend with non-distinct community boundaries mediated by distributed digital technologies that change the capture and use of information (Hess & Ostrom, 2003). As such, new challenges arise in theorising the role of technology in affecting knowledge as a resource (ibid), and in analysing the boundaries or openness of shared knowledge resources (Fischmann, Madison, & Strandburg, 2014). These theoretical challenges are central to the contributions of this research.

Knowledge commons theory is associated with the work of, among others, Hess and Ostrom (2003; 2006; 2007a; 2007b), Schweik (2007; 2014), Benkler (2013; 2016), Frischmann, Madison, and Strandburg (2014), and Cole (2014). This community of scholarship is characterised by a focus on commons spaces opened up by new digital technologies, with the acknowledgement, application, or adaptation of the IAD research framework.

The theoretical task of evolving commons theory for the study of new knowledge commons is motivated by the rich and nuanced understanding that the Ostrom School has provided to the study of biophysical resource commons, and by the open-ended ambition of the field to adapt and evolve to fit new empirical

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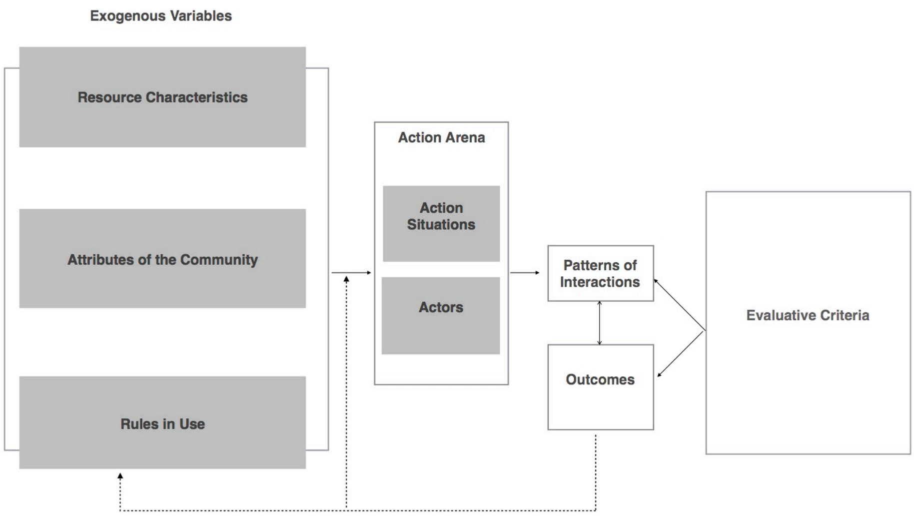
[13] Following the term used by Benkler (2013), connoting the foundational work of Elinor and Vincent Ostrom and collaborators (see Cole & McGinnis, 2014).

situations while preserving an adherence to context-specific analyses using shared research frameworks (Castiglione, 2014; Cole & McGinnis, 2014).

I also draw on the literatures of the design of technological artefacts (Simon, 1962; Baldwin & Clark, 2000) and models of peer production (Benkler, 2016). The former is particularly useful in theorising the role of 3D printers as technological systems in the knowledge commons, while the latter informs my approach to studying the Ultimaker 3D printer forum. I explain the ways these literatures help form my analytical and theoretical contributions in section 1.6. An in depth review of all areas of scholarship I drawn from is found in Chapter 2.

To structure my research approach I use the Institutional Analysis and Development (IAD). The IAD framework was designed by Elinor Ostrom and collaborators for the study of diverse commons environments (Ostrom, 2005), and is illustrated in its basic form in Figure 1.1.

Figure 1.1: IAD Framework



Adapted from Ostrom (2005), Madison et al. (2010)

I choose to use the framework for the principal reasons that (a) it allows for nested levels of organisational variables; (b) it includes multiple variables concerning complex interacting material, institutional, and community factors, and (c) it specifically allows for inquiry into dynamic situations of resource use, where actors are operating with different logics, incentives, constraints, and opportunities. These points are important for my study, as I use it to analyse and integrate findings from the distinct yet overlapping communities of different Fab Labs in diverse geographic locations, as well as the online Ultimaker user community forum.

To use the framework, I analyse the action situations described to me by Fab Lab actors in order to understand whether particular exogenous variables relate to my outcome of interest. For analysis in Chapters 4-6, I define my main outcome of interest as ‘access to knowledge about materials’ from the perspective of Fab Lab users. Given that Fab Labs are governed by common-property regimes and engage in open access 3D printing communities, I assume knowledge can be defined as part of the commons if it is available in a Fab Lab. Therefore, by analysing what enables or prevents Fab Lab members accessing knowledge about materials, I aim to understand whether knowledge about materials is entering the commons.

To define the exogenous variables in my qualitative study, categorised as resource characteristics, attributes of the community, and rules-in-use (Chapters 4-6), I used the IAD framework in combination with the multitier framework (Ostrom, 2007), developed for identifying relationships of interest in complex commons environments. This allows me to take into account a diversity of nested variables specific to my empirical context, while adhering to the general hypothesised relationships, language and organisational structure of commons studies. See Appendix I for details of the multitier framework applied to this work. I elaborate on this analytical approach in section 1.61.

The IAD is designed as a meta-theoretical framework, meant to identify a common set of variables that can be selected from based on one's theory and research question[14] (Ostrom, 2005). This framework allows for different methodological tools to be used in exploring the questions asked. I make use of this flexibility by gathering interview data as well as using statistical tools. While the majority of my enquiry is built upon qualitative foundations, I use statistical tools to clarify and reveal particular aspects of variables of interest that came to light in interviews. See Figure 3.5 for the IAD adapted to the variables and contexts of this study.

1.4.4 Chapter sub-questions

Use of the IAD framework motivates in-depth consideration of main categories of variables that have been found to influence a wide variety and number of commons situations (Ostrom, 2005). These are labelled as 'exogenous variables' in Figure 1.1 (above), and are *physical resource characteristics, characteristics of the community,* and *rules-in-use,* respectively[15]. I use these categories to structure sub-questions that guide this work.

Chapter 4 is directed by the following question:

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[14] The IAD model is developed as a common institutional language for examining the underlying structure of diverse action situations in commons environments. Action arenas come from work in game theory where the aim was to specify the variables and relationships of an action situation that could be used within a common framework, theory, or model (Ostrom, 2005).

[15] An assumption of the framework is that actors are boundedly rational operating with imperfect information according to incentives and costs of action. This is aligned with my enquiry into how Fab Lab users can or cannot access knowledge about materials. This assumption comes from the work of Herbert Simon, noted to be an important influence on Elinor Ostrom's work (Cole 2014).

What resource characteristics influence whether knowledge about materials enters the commons?

This question explores the important distinction between physical materials and digital content in the commons, and is the source of my theoretical contribution to the knowledge commons based on insights from common-pool resource theory.

In Chapter 5 I study the attributes of Fab Lab communities. Community attributes are important given the diversity of communities that are involved in commons-based 3D printing. Chapter 5 is guided by the following question:

What attributes of the community influence whether knowledge about materials enters the commons?

Another major element of commons research is analysis of rules related to the governing of the resource in question (Ostrom, 2005). I review commons theory on rules-in-use in Chapter 3. Empirically I investigate rules-in-use in Fab Labs in Chapter 6, directed by the following question:

What rules-in-use influence whether knowledge about materials enters the commons?

Two particularly influential rules-in-use emerge from my analysis in Chapter 6: open source and modularity design rules. This is particularly interesting given that prior to gathering my interview data, I did not anticipate the concept of modularity as a design rule of importance to accessing knowledge in 3D printing systems.

In Chapter 7 I study how users in an online community forum engage with different types of knowledge associated with the open source 3D printer Ultimaker. The following question directs my approach:

> *Do users cross the boundaries between types of knowledge in a commons-based 3D printing community over time?*

The nature of the data allows me to study how users engage in the Ultimaker forum with respect to types of knowledge associated with the 3D printing system.

Chapter 8 comprises the final chapter. There I discuss the theoretical contributions of this thesis as well as recommendations for practitioners and policymakers. I end by noting the limitations of this research and future research directions.

1.5 Empirical Context and Data Collection

In this section I introduce the two empirical contexts for this research: Fab Labs, and the Ultimaker 3D printer online user forum. After summarising general characteristics I give an overview of the type and means of data collection.

1.5.1 Introduction to Fab Labs

Fab Labs, the abbreviated name for Fabrication Laboratories, are community workshops for digital fabrication. What defines Fab Labs is a shared set of technological capabilities, and a commitment to Fab Labs as a community resource.

The first Fab Lab was set up by the MIT Centre for Bits and Atoms in Boston in 2001. Neil Gershenfeld and colleagues at MIT influenced early Fab Lab design, based on the idea of creating local community capabilities in digital fabrication. In more recent years, Fab Labs have increasingly been organised organically by local community members who see value in the lab as well as affiliation to the Fab Lab network. As of July 2014 when interviews were conducted, there were 350 Fab Labs from 40 countries[16]. The Fab Foundation, founded by Neil Gershenfeld and collaborators, is a not-for-profit set up to help facilitate the founding of Fab Labs and collaboration between them. However, the majority of Fab Labs are highly independent and the influence of the Fab Foundation is most visible as a network coordinator for common events such as the Fab Lab annual conference.

There are other types of community spaces for digital fabrication besides Fab Labs, exhibiting slightly different organisational principals. Tech Shops, Makerspaces, and Hackerspaces are all variations of community spaces with digital fabrication tools. They differ in resources such as facilities and tools, the characteristics of the communities they serve, and the rules they are governed by. I choose Fab Labs as my empirical focus for the reasons that (a) they identify as commons-based communities with a commitment to open source and shared

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[16] As of November 2014, 415 are listed on the Fab Foundation (http://www.fabfoundation.org/fab-labs/) as opposed to 435 on the open wiki site (https://www.fablabs.io/labs). The number at any given time is a subject of debate: the wiki site list is loosely curated, meaning that many Labs may register themselves and may or may not have the full machine capabilities stated in the Fab Lab charter. I use Fab Labs as empirical windows into commons-based 3D printing; as such all interviewees were affiliated with Fab Labs with the capacity for 3D printing.

community resources, (b) they are distributed globally, offering insight into a diversity of community contexts for knowledge about materials, and (c) 3D printers are central to the set of tools they have. These three characteristics make Fab Labs empirically useful for understanding access to knowledge about materials in the commons.

1.5.2 Introduction to the Ultimaker community

Ultimaker is model of open source 3D printer that was developed from the initial RepRap blueprints. Ultimaker was originally designed in a Fab Lab in the Netherlands[17] in 2011 and has since evolved to be one of the most popular 3D printers on the desktop market[18]. Ultimaker is also a recommended printer on the Fab Lab inventory[19], making a study of its community a particularly appropriate addition to the study of 3D printing use in Fab Labs.

Ultimaker hosts an open, online user forum, set up for users in the community. Some main uses of the forum are (a) to trouble shoot problems with the printer, (b) to offer new ideas for improvement, and (c) to find out new ways to modify the Ultimaker machine. Developers of the Ultimaker system, employed by the company, are also present on the forum. This means that they can offer help and support, but also gain new ideas for improving the printer over time. Chapter 7 provides a more thorough introduction to the forum.

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[17] Ultimaker was first created in ProtoSpace, a Fab Lab in Utrecht. See http://protospace.nl/

[18] As an example, see 3D Hubs review of desktop machines based on user feedback: https://www.3dhubs.com/best-3d-printer-guide#enthusiast

[19] The standard inventory for a Fab Lab is a living document that has changed over time with the needs of Fab Labs worldwide as well as the changing technological landscape. The inventory is a guideline set by the Fab Foundation, and is not strictly followed. In particular, the inventory reflects the US market rather than providing examples of local, comparable, tools. I discuss this in detail in chapter 4. The inventory link can be found on the following page: http://fab.cba.mit.edu/about/faq/.

1.5.3 Data collection

The main data collected for this study is from qualitative interviews with Fab Lab users. Between July 2nd-9th 2014 at the Fab 10 conference in Barcelona I conducted 49 semi-structured interviews with users from 45 Fab Labs representing 30 countries. Interview subjects were primarily chosen on a basis of geographical representation. More details on data collection are found in Chapter 3.

Data on the Ultimaker community was collected from the open access online forum. Each user post was captured from the forum's founding in 2011 to the date of data collection in March 2015. The architecture of the community forum is organised according the architecture of the 3D printing system, with hardware, software, and firmware represented as areas of the forum. This data allows me to study patterns of user engagement in types of knowledge associated with these areas of the 3D printer over time. More details on the Ultimaker data structure and analysis can be found in Chapter 3 and Chapter 7.

1.6 Summary of Original Contributions

I align this work with the field of knowledge commons by employing the IAD as my research framework, and adapting it to include variables necessary for my empirical subject. I discuss briefly the analytical contributions that result. I also study the relationship between types of knowledge associated with digital and physical resources. This leads to two main theoretical contributions: first, how technological design rules aid in theorising boundaries in the knowledge commons; and second, how differentiating between physical and digital resources can help explain the inclusion and exclusion of types of knowledge associated with these resources in the commons. After briefly discussing these themes I conclude this section with an overview of empirical contributions. Chapter 8 details both theoretical and empirical contributions in full.

1.6.1 Analytical contributions

I build on the analytical tools of commons theory for the purpose of studying 3D printing in the knowledge commons in three main ways. First, I combine the IAD with an adapted multitier framework used to study complex social and ecological systems (Ostrom, 2007), the better for analysing nested levels of complex variables within a consistent methodological framework (see Appendix I). Second, I employ technological design rules as rules-in-use within the IAD framework, focusing on modularity and openness as design rules-in-use. This is useful for systematically studying the role of technology in knowledge commons. Third, I frame the study of the Ultimaker 3D printing community as a linked action arena. By drawing on the framework of levels of analysis for rules-in-use (see Figure 3.6), I am able to study the overlapping communities in commons-based 3D printing (illustrated in Figure 3.4) within a coherent framework. These contributions are illustrated throughout my empirical analysis and summarised in more detail in Chapter 8.

1.6.2 Theoretical contributions

The first contribution of this thesis concerns the issue of studying boundaries in knowledge commons, where community membership can be diffuse and permeable, and knowledge resources highly distributed. This is related to the idea of openness to participation in the knowledge commons (Frischmann, Madison, &

Strandburg, 2014), where openness depends on rules of governance, community attributes, and resources in use. My contribution to this theoretical challenge is in conceptualising modularity and openness as technological design rules-in-use (see Figure 6.2), allowing me to study them as constitutive of boundaries for participation in the knowledge commons. From a user perspective, I find that these technology design rules regulate the exclusion or inclusion of types of knowledge in commons-based 3D printing. To illustrate, I find that the relative modularity and openness of 3D printing systems influence whether knowledge about materials as well as hardware and software can more easily enter the commons through efforts to hack or experiment with system components. My aim here is to introduce a systematic treatment of technological artefacts that accords with the theoretical foundation of knowledge commons.

The second theoretical contribution stems from clarifying differences between of types of knowledge in the knowledge commons. This elaborates Frischmann, Madison, & Strandburg's (2014) recognition that understanding the 'openness' of knowledge resources depends both on the natural characteristics of the resource and its social construction. I find that the dilemma of enclosure regarding knowledge of materials is fundamentally different from dilemmas of enclosure associated with knowledge of software and hardware designs. By demonstrating how the underlying nature of the good matters for whether knowledge associated with that good enters the commons, this study integrates the biophysical resource roots of commons theory into the knowledge commons.

Furthermore, when one distinguishes between these physical and digital resources related to knowledge, one can identify different points of entry into the commons. For example, in this study I find that the exclusion of production facilities of 3D printing materials from any common-property regime condition the possible points of entry into the commons for knowledge about materials. The control over information facilities and artefacts for software and hardware designs are, by contrast, governed by commons arrangements within open source communities. Points of entry in the knowledge commons is an idea recognised as being in need of theoretical and empirical development (Hess, 2008) as studies of natural resource commons, with pre-existing resources and institutional arrangements, do not give much direction (Hess & Ostrom, 2003).

By differentiating between types of knowledge in the commons, this study also furthers the understanding of open source peer production as a new organisational paradigm (Benkler, 2016; David & Shapiro, 2008). By traversing the boundary between knowledge associated with physical and digital system components, one can explore the question of how physical resources fit into peer production models that have been empirically focused on digital resource production (Benkler, 2016). This can lead to new insights. Upon examining user engagement in distinct types of knowledge associated with digital and physical resources in the Ultimaker 3D printing forum over time, I find that users increasingly engage across knowledge types the longer they are in the forum. This finding supports theory on endogenous knowledge accumulation and learning effects in peer production communities (David & Shapiro, 2008).

1.6.3 Empirical contributions

This study offers three main empirical contributions. First, I introduce a new, heterogeneous set of actors who are engaging in the commons. As Hess and Ostrom (2007) observe, ‘The case of distributed digital technologies is particularly complex and problematic, as many stakeholders seek to renegotiate their interests in the new digital environment' (p. 12). New stakeholders include Fab Lab users and 3D printer users. The recent proliferation of Fab Labs, as well as other community spaces like them, is an important empirical phenomenon. My study adds empirical depth to this new area of commons study by exploring who uses 3D printing systems for what purposes, and how digital fabrication spaces as physical commons play important roles in their respective communities.

Second, Fab Labs lie at the intersection between physical and digital resource commons. This is a novel empirical moment as we see online open access knowledge commons intersecting with physical spaces. This study introduces two new types of nested communities: digital fabrication communities (Fab Labs), and 3D printing communities (Ultimaker user community). These communities are located in physical and digital space, respectively. Yet they are also nested: an Ultimaker 3D printer is physically present in a Fab Lab, while being partially developed in an online setting. Studying these digital fabrication spaces can also reveal 'semicommons', complex combinations of private property rights and commons arrangements (Madison, Frischmann, & Strandburg, 2010). For instance, I find varying levels of knowledge inclusion in Fab Lab common property regimes when it comes to knowledge about hardware, software, and materials.

Third, this study highlights 3D printing systems themselves as an important empirical context. As a technology that integrates hardware, software, firmware, and materials, 3D printers offer considerable scope for investigating the interaction of physical materials and digital content that is produced in commons environments. My investigation of user engagement in hardware, software, and firmware knowledge in the Ultimaker 3D printer forum adds a new empirical context to studies of open source peer production (Benkler, 2016; 2002a; David & Shapiro, 2008; von Krogh, Spaeth, & Lakhani, 2003; Langlois & Garzarelli, 2008).

1.7 Organisation of the Thesis

In Chapter 2 I review the relevant literature to this study. This includes commons theory, literature on technological architectures, and peer production scholarship.

In Chapter 3 I detail my research design and methodology, and introduce how Fab Labs and the Ultimaker community as conceptualised as commons.

In Chapter 4, I study the boundaries of Fab Lab common-property regimes. This adds explanatory value for investigating why knowledge about materials is prevented from entering the commons. The chapter also uncovers ways actors are disrupting the boundary of common-property regimes by bringing knowledge of materials into the commons.

In Chapter 5 I study the attributes of Fab Lab communities and how they relate to knowledge of materials entering the commons. Attributes include types of users, their various purposes and forms of collaboration; collaboration between Fab Labs; management of the Fab Lab as a whole; knowledge recording strategies; and, the presence of norms such as knowledge openness and local production. The aim of this chapter is to understand how the community attributes of Fab Labs may influence knowledge about materials entering the commons.

In Chapter 6 I study how modularity and openness as design rules in 3D printing systems affect the ability of Fab Lab members to access knowledge about materials. I explore how Fab Lab members are adapting 3D printing systems to experiment with and use new materials, impacting the inclusion of knowledge about materials in the commons.

Chapter 7 investigates how users of 3D printing systems engage across the boundaries between types of knowledge over time. Data comes from the Ultimaker 3D printer user forum. Motivated by qualitative findings on user engagement in new types of knowledge, I look at patterns of user contributions in hardware, software, and firmware areas in the forum over time. This chapter helps broaden the scope of the emerging field of open source peer production.

In Chapter 8 I revisit the overall research question, integrate the findings of my empirical chapters, and develop my main analytical and theoretical contributions. I reflect on the implications of this study for practitioners and policymakers, and conclude with a discussion on the limitations of this study and suggested avenues for future research.

2 LITERATURE REVIEW

2.1 Introduction and Aims

The aim of this chapter is to provide a theoretical and empirical grounding for the present study, establish theoretical terms and concepts employed, and establish the basis for assessing the significance of this study for relevant fields of scholarship.

In the last decade, 3D printing has emerged as a technology produced and used by communities committed to the open sharing of knowledge about digital and physical goods. This makes commons theory particularly appropriate as a theoretical framework. From its early formulations in addressing common-pool resource dilemmas (Ostrom, 1990), to its more recent branching into knowledge commons in online communities (Hess & Ostrom, 2003; Hess, 2008), the relationship between types of goods and the knowledge associated remain central. 3D printing, with its particular configuration of digital and physical goods, offers a unique angle to advance commons scholarship.

This study demonstrates the use of commons theory for traversing the boundary between knowledge associated with physical materials and digital content in 3D printing. I advance particular aspects of commons theory: notably, the influence of technological system design on access to knowledge, and engagement with types of knowledge in the commons over time. To make this contribution I draw from literatures on design rules in technological systems and peer production in open source communities.

I begin with a summary of these areas of literature, reviewing in greater depth the reasons for selecting particular bodies of work to draw from and contribute to. The review of the literature is organised thematically. For each area I identify the main theoretical and empirical works, discuss important findings, identify particular gaps and inconsistencies, and describe how this research aims to contribute.

2.2 Summary of the Literature

The following table provides an overview of the areas of scholarship reviewed, the main works discussed, and central concepts used.

Table 2.1: Theoretical Overview

Literature	**Main works**	**Concepts used**
Theory of the Commons	Ostrom (2005) E. Ostrom & V. Ostrom (1977) Hess & Ostrom (2003, 2007a, 2007b) Benkler (2013; 2016) Frischmann, Madison, & Strandburg (2014) Schweik (2007; 2014) Cole (2014)	Property regimes; types of goods; rules-in-use; nested levels of analysis
Peer Production in online communities	Benkler (2002a, 2013; 2016) Langlois & Garzarelli (2008) David & Shapiro (2008) von Krogh, Spaeth, & Lakhani (2003)	Peer production in open source communities Modularity in community-based production
Modularity of technological systems	Baldwin & Clark (2000, 2006a) Simon (1962)	Modularity as a technological design rule

The rationale for drawing from and contributing to this particular set of literature is as follows. First, commons scholarship has an established theoretical tradition and rich methodological toolkit that enables fruitful application to new empirical settings. This is particularly useful in an empirical setting marked by new technology and production methods. The recent branching of commons scholarship into the digital domain, called the knowledge commons, provides important background for using common-pool resource theory and institutional analysis in studying knowledge resources. In order to contribute to knowledge commons scholarship, one must review the background of common-pool resource theory and institutional analysis. This provides my study of knowledge of 3D printing with the analytical tools needed to theorise physical resources as well as digital content. As I employ the Institutional Analysis and Development (IAD) framework in my methodological design, the theoretical basis for the IAD must be understood. In addition, the wider study of forms of governance under the umbrella of institutional theory are useful for outlining a broader research agenda around peer production of physical and digital goods.

Second, the rationale for drawing on both theories of technological architecture and peer production stems from identifying a particular gap in knowledge commons literature. Although stated by Hess and Ostrom (2003) as important, the role of technological system design is under-theorised in the knowledge commons literature. This is a significant gap given the fundamental role that new digital technologies are playing in opening up knowledge commons. To address this I draw on studies of technological architectures in product design and modes of organisation and governance in peer production.

These areas of scholarship offer considerable clarity when it comes to understanding the role of technology and types of engagement in commons spaces. I draw from the literature on technological architecture primarily in Chapter 6 in order to theorise the use of 3D printing systems at an operational level. I draw from the literature on peer production primarily in order to situate my study of the Ultimaker community forum in the context of scholarship on other online communities. In this review chapter, I also include a section specifically on modularity in the peer production of open source software. While I do not directly draw on this area of literature in my empirical analysis, it is important background for thinking through the design of 3D printing systems from a multilevel perspective: at the level of community production, as well as operational use. My study of types of knowledge in the Ultimaker 3D printing forum can be seen as a step towards a more in-depth understanding of how the structure of 3D printing systems relates to their development in online peer production environments.

2.3 Theory of the Commons

In this section I discuss the historical roots of commons theory in the Bloomington School of public choice and institutional theory, common-pool resource theory, and knowledge commons scholarship. These branches of scholarship are highly related, and are closely associated with the work of Elinor and Vincent Ostrom, as well as many collaborators (Aligica & Sabetti, 2014). As such, I follow Benkler (2013) in referring to this set of scholarship as the Ostrom School of commons research.

A parallel literature in commons theory can also be identified, described as the 'open-commons school' (Benkler, 2013). As described by Benkler (2013), the open-commons school takes as its starting point the particular institutional arrangements that characterise 'symmetric access and use privileges based in the commons and the public domain' (p. 1151). This means that the open-commons school focuses on open access resources, rather than common-pool resources associated with the Ostrom School, and takes as principal subjects of analysis institutional forms characteristic of the public domain in intellectual property, open standards, and free and open source software.

As such, the open-commons school is closely related to the knowledge commons literature. The main difference is that the knowledge commons takes as its starting point resource characteristics and social dilemmas while the open-commons school starts from the institutional arrangements for symmetric access rights for an open class of users (Benkler, 2013). This distinction drives my choice to align this study primarily with knowledge commons literature, as I start from the perspective of underlying resource characteristics in order to study knowledge. I do, however, use analytical tools and insights from the peer production literature, a subset of the open-commons school.

2.3.1 Theoretical Foundations in the Bloomington School

The Ostrom School of commons research has its roots in the Bloomington School of public choice theory. Public choice, defined as the application of economic reasoning to collective, social, or political decision-making, arose in the 1960s and is primarily associated with James Buchanan, Gordon Tullock, William Riker, and Elinor and Vincent Ostrom (Aligica & Sabetti, 2014). As explained by Elinor and Vincent Ostrom (1971), public choice emerged as a community of interest for the study of nonmarket decision-making. In part public choice theory emerged a response to Herbert Simon's (1964) critique of the field of public administration regarding the assumed importance of perfect hierarchies in decision-making structures dating from Woodrow Wilson (1877). Simon argued that attention to alternative organisational forms was necessary to studying efficiency of resource allocation in public administration (E. Ostrom & V. Ostrom, 1971).

Broadly stated, what sets the Bloomington School apart from other schools of public choice theory is: its questioning of economic rationality and acceptance of normative values in human decision-making; rejection of the dichotomy between market and state, their respective modes of organisation, and the idea that such modes cannot be mixed; incorporation of interdisciplinary insights under a common framework[20]; the broadening of the basic categorisation of public and private goods to incorporate toll-goods and common-pool resources; and, a core acceptance of the endogenous nature of institutional development (Castiglione, 2014).

The foundational work by Elinor and Vincent Ostrom on the nature of public goods and public choices (V. Ostrom & Ostrom, 1977) and polycentric governance by Vincent Ostrom (1991) greatly informed the development of the interdisciplinary field of institutional analysis that marked a departure from early public choice theory (Aligica & Sabetti, 2014). Institutional analysis was formed along with many collaborators as a 'method for analysing public economies and diverse forms of collective action' (Ostrom, 2011, p. 239). As Ostrom (2011) explains, 'Instead of presuming the existence of only two kinds of order – the market and the government – political economists have come to recognise that order can be achieved in *public economies* where large, medium, and small governmental and nongovernmental enterprises engage in both competitive and cooperative relationships' (p. 241, *emphasis in original*).

Ostrom (2011) cites four main 'intellectual challenges' that shaped the development of institutional analysis: public (rational) choice theory; the tragedy of

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[20] Explicit disciplinary contributions include anthropology, sociology, law, political science, and economics (Castiglione, 2014).

the commons debate; ‘new’ institutional economics; and, behavioural game theory. The main ideas of interest in these traditions include incentives and rules that govern the behaviour of rational, or boundedly rational, actors; the importance of scarcity in predicting outcomes; the centrality of property rights and how they can self-organise; and, the provision of public goods and appropriation of common-pool resources. This leads to the overall position of institutional analysis as an interdisciplinary endeavour that lies at the interface between economics and political science (ibid). Ostrom (2011) sums this up the overall approach as follows:

> *To study public economies, one has to examine multiple levels of organization ranging from small neighbourhoods to international regimes, rather than focusing on only one level of a single, isolated, government. System-level outcomes are generated through a series of linked action situations that exist in both public and private realms of activity and generate both upward and downward causal processes. The old-fashioned dichotomy between ‘the market’ and ‘the state’ has been replaced. Institutional analysts recognize that markets cannot exist without well-defined property rights, police to enforce these rights, and courts that enforce contracts. Nor can a centralized government do all of the above by itself (p. 244-45).*

One of the main points of departure for institutional analysis from mainstream public choice theory was the explicit recognition of rules. Ostrom (1986) noted that although public choice included a tacit assumption that humans followed rules, a more explicit and self-conscious emphasis was needed. By contrast, mainstream public choice theory prioritised choice, incentives, and information (Aligica & Sabetti, 2014). A further departure involved the questioning of positivist epistemology and the formal modelling of rationality that dominated public choice theory. In institutional analysis rules, rather than being prescriptive, offered ‘choice sets’ involving more probabilistic rather than deterministic outcomes (ibid).

2.3.2 Common-pool resource theory

Common-pool resource theory stemmed from work in public choice and institutional theory. The literature is closely aligned with the tradition and analytical tools of institutional analysis. It also has a particular empirical focus on the governance of a specifically defined type of good, common-pool resources. Unlike either a pure private good, which is both excludable and subtractable, or a pure public good, which is neither excludable nor subtractable, a common-pool resource is both subtractable and difficult to exclude beneficiaries from (Becker & Ostrom, 1995). This particular type of resource was considered to be, by definition, vulnerable to free riding and over-exploitation; that is, a ‘tragedy of the commons’ (Hardin, 1968). Hardin’s (1968) argument was inferred from the underlying assumptions of the theory of collective action, in which ‘individuals independently make anonymous decisions and primarily focus on their own immediate payoffs’ (Ostrom, 2007). If these assumptions are valid, then commons do tend to be overharvested (ibid). The only viable options to dealing with the tragedy of the commons dilemma were assumed to be market privatisation or centralised state control.

In taking a different approach, Ostrom (1990) allowed for the ‘complexity of the motivational structure and capabilities people have in solving social dilemmas’ (Castiglione, 2014, p. xv). From careful empirical study, Ostrom (1990) demonstrated that the commons could be governed, overcoming the social dilemmas of over-exploitation and free-riding (Ostrom, 1990; Becker & Ostrom, 1995; Ostrom, 2005). Common-pool resource theory thus elaborated the institutional design principles for various communities governing common-pool resources effectively, dealing with biophysical resource linkages, and evolving rules that governed the resource effectively. As an empirical focus, common-pool resource theory has predominantly been concerned with the study of how local communities create institutional rules to effectively govern common-pool resources such as fisheries, forests, and irrigation systems (Ostrom, 1990).

One of the strongest findings of commons scholarship is that users of common-pool resources, if governed by a common-property regime, have significant amounts of local knowledge about the resources in use (Schlager & Ostrom, 1992). This knowledge is central to emergent rules of governance that mitigate tragedy of the commons issues (Ostrom, 1990).

The influence of the Ostrom School is wide reaching, and has gained particular prominence in complex, seemingly intractable, common-pool resource issues such as climate change, tropical deforestation, and trans boundary pollution exploitation (Anderies, Janssen, & Ostrom, 2004; Dietz, 2003; Ostrom, 2007). Commons theory has been applied using a variety of methodological tools. Case studies, meta-analyses, large-N field research, experiments and modelling, and empirically grounded agent-based models are all as ways to investigate governing the commons (Poteete, Janssen, & Ostrom, 2010).

2.3.3 Institutional Analysis and Development (IAD) Framework

A mark of the Ostrom School of commons scholarship is the commitment to extensive comparative and meta-analysis, led by Elinor and Vincent Ostrom and collaborators at the Workshop in Political Theory and Policy Analysis at Indiana University over many years. The IAD has been an important vehicle for this to take place. Developed by Elinor Ostrom and collaborators, the IAD has been applied in diverse settings. The IAD was designed to help study institutions at multiple scales (Ostrom, 2005) and has been used in many empirical studies along with a common grammar for institutions, a typology of generic rules to be considered, and common factors of institutional change (ibid).

A list of exemplary IAD research is reviewed by Blomquist and deLeon (2011), and includes articles ranging from health care as a resource (Bushouse, 2011) to national parks (Oakerson & Parks, 2011) and interstate river systems (Heikkila, Schlager, & Davis, 2011). The flexibility and use of the IAD across many disciplines and empirical areas of study means that any claim of a comprehensive review of commons scholarship in the IAD tradition is problematic. Yet among this diversity, common concepts include: (a) analysis of types of goods, (b) close attention to the difference between common property regimes and common pool resources, (c) roles of actors and community characteristics, (d) attention to types of rules as governance mechanisms, and (e) the nested nature of many resources and governance arrangements. Thus, while the range of commons scholarship has continued to grow, challenging and adapting some components of the IAD, one can see a persistent adherence to the main theoretical concepts and methodological tools laid out by Ostrom and collaborators.

Development of the IAD has also continued as a theoretical enterprise. For example, the ways that the IAD helps researchers take into account polycentric governance analysis is advanced by McGinnis (2011), where the importance of considering a network of adjacent policy arenas is emphasised. Other authors have focused on developing the concept of rules within institutional analysis with the IAD, and have queried the distinction between rules and norms (Siddiki, Weible, Basurto, & Calanni, 2011). The continued development of the IAD is important for this research as I seek to add to its analytical toolkit based on my empirical application.

2.3.4 The knowledge commons: theoretical and empirical works

Commons theory has been recently extended to consider shared knowledge resources. Frischmann, Madison, and Strandburg (2014) define this study of knowledge commons as follows:

> *Knowledge Commons is shorthand. It refers to an approach (commons) to governing the management or production of a particular type of resource (knowledge)…Knowledge Commons is…the institutionalised community governance of the sharing and, in some cases, creation, of information, science, knowledge, data, and other types of intellectual and cultural resources (p. 3).*

Relating the knowledge commons back to the starting point of collective action problems concerning common resources, Hess and Ostrom (2007a) state that ‘knowledge can be considered a commons if it is a shared resource that is vulnerable to social dilemmas’ (p. 13). Knowledge as a resource is defined in the context of information and data: ‘data being raw bits of information, information being organised data in context, and knowledge being the assimilation of the information and understanding of how to use it’ (Hess & Ostrom, 2007a, p. 8).

In explaining the reasons for why the knowledge commons arose as a field of interest, Hess and Ostrom (2006) state, ‘the adaptation of the commons to the realm of knowledge and information is a relatively recent phenomenon. Prior to the mid-1990s, the commons referred almost exclusively to shared land to and other types of natural resources’ (p. 335). The conceptual development of the knowledge commons was sparked by observations of how new spaces of interaction, mediated by digital technologies, are opening up and changing the provision and access to information goods[21]. In summarising the link between traditional and knowledge commons scholarship, Hess and Ostrom (2007a) state that the ‘unifying thread in all commons resources is that they are jointly used, managed by groups of varying sizes and interests’ (p. 5).

Hess and Ostrom (2007a) elaborate the role of digital technologies in the knowledge commons, remarking that ‘the technologies that allow global, interoperable distribution of information have most dramatically changed the structure of knowledge as a resource’ (p. 9). These are information communication technologies (ICTs) labelled as ‘distributed digital technologies’, for example, personal computers and the Internet.

Given this empirical rationale for the field of knowledge commons, one must acknowledge a critique levelled at the ‘practical’ agenda of some commons research. Cole points out that in knowledge commons work, Hess and Ostrom (2007a; 2007b) conflate outcomes with normative evaluations of these outcomes. There is a strong tendency to ascribe positive value to outcomes that increase open access and sharing of resources. Aversion to normative claims is aligned with the

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[21] I use both the terms ‘information’ and ‘digital’ throughout this thesis. I choose to refer to information goods or resource flows during more theoretical, or abstract discussions. This follows the adopted terms of Hess and Ostrom (2003). I use the term digital resources when referencing an empirical or practical context of use. This reflects the language of users during interviews, and focuses attention on the digital nature of 3D printing system components.

extensive body of work in natural resource commons, known for its cautious, context-specific policy recommendations and firm warnings against the idea that there are any panaceas when it comes to governance arrangements, including common-property regimes.

In knowledge commons studies, caution against normative analysis is warranted. As Cole (2014) states, ‘These are still early days in the social-scientific study of information as a good, whether public, common, or private’ (p. 63-4). This means that one should not ‘expect quick and decisive results about appropriate governance institutions…one of the chief lessons of the large and growing literature on natural common-pool resources’ (ibid). I follow Cole in being circumspect. For example, although Fab Lab actors generally attribute significant positive value to shared resources, many users of Fab Labs are private companies who choose not to share their knowledge nor partake in the norms of open source communities. This suggests that knowledge in the commons does not serve everyone’s interests. My analysis of whether knowledge about materials is entering the commons is not concerned about whether this is a good thing; rather, it is driven by theoretical aims and empirical curiosity.

In addition to the empirical motivations for knowledge commons scholarship, contributors have developed a comprehensive theoretical rationale for the need to apply the Ostrom School of commons theory to shared knowledge resources. For example, Frischmann, Madison, and Strandburg (2014) find a fruitful analogy between knowledge commons and natural resource commons from the perspective of dominant governance assumptions. The authors examine the nature of knowledge as a public good, where the outputs of invention, creativity, and research and development are neither rivalrous nor easily excludable. This increases incentives for free riders and reduces incentives for production of the knowledge resource. If one uses the same assumptions of collective action used by Hardin (1968), the result is the tragedy of the commons outcome, but in reverse: while common-pool resources suffer from over-exploitation, public goods suffer from under-provision.

This logic has led mainstream policymakers and scholars to consider a seemingly inevitable dichotomous response: encourage market exchange through intellectual property law by 'employ[ing] proprietary rights sanctioned by law to control development, distribution, and exploitation of intellectual resources', or 'maintain a public domain…through direct or indirect provisioning by government' to knowledge producers such as university researchers (Frischmann, Madison, & Strandburg, 2014, p. 7-8). In a statement that resonates with commons scholarship dating from Ostrom (1990), Frischmann et al. (2014) observe:

> *In a remarkable parallelism with the history of the tragedy of the commons allegory and its role in environmental circles, many analysts of knowledge production issues simply assume the free-rider allegory describes a normal rather than exceptional problem (p. 7).*

Echoing Ostrom's (1990) critique of this simplistic market/central government dichotomy that still dominates tragedy of the commons debates, Frischmann, Madison, & Strandburg (2014) state,

> *Where propertisation is insufficient, government subsidy is seen as the primary alternative. Communal and collectivist institutions, particularly those that blend informal normative structures with*

> *formal governance rules, are generally regarded as exceptional and dependent upon pre-existing property entitlements (p. 5).*

Taking issue with this situation, authors in the field of knowledge commons scholarship are motivated by the observation that the reality of knowledge resources and the communities that interact with them are diverse, complex, and worthy of careful analysis. ‘Reality is considerably more complex than the free-rider allegory suggests, and there is no good reason for systematically marginalising the many situations in which free riding does not reduce incentives to invest’ (Frischmann et al., 2014, p. 9). This accords with the field of open-commons research, where many authors have questioned response of intellectual property law as the most appropriate way of dealing with free-riding (Benkler, 2002b, 2004a, 2006; von Hippel & von Krogh, 2003; von Hippel, 2005).

I now turn to reviewing the empirical work on knowledge commons. Frischmann, Madison, and Strandburg (2014) state:

> *We anticipate that study of a large number of cases using the [knowledge commons] framework, ranging broadly across different knowledge and cultural contexts, is likely to demonstrate that successful knowledge production and management occurs within a wide variety of formal and informal institutional arrangements. We suspect that the logical and normative priority assigned to proprietary rights and government intervention will turn out to be misplaced (p. 5-6).*

As in natural resource commons, an increasing number of scholars are finding numerous examples of more self-organised, collective, and norm-oriented property-right regimes in the governance of knowledge resources. Reflective of traditional commons scholarship, authors contributing to the knowledge commons are highly interdisciplinary, with perspectives from institutional theory, political economy, legal scholarship, and information science most prominent.

As one example, Hess and Ostrom investigate how open access digital repositories of scientific research changed the ability to share as well as restrict access to scientific knowledge (Hess & Ostrom, 2003). By changing the capture and use of information, these new distributed digital technologies create new social dilemmas regarding under-provision, enclosure, and free riding. Other empirical cases studied include communities contributing to patent pools, Wikipedia, open science publications, free and open source software projects, and digital libraries (Frischmann, Madison, & Strandburg, 2014; Cole, 2014; Schweik, 2007, 2014; Hess, 2008; Hess, 2012; Madison, Frischmann, & Strandburg et al. 2010; Kranich, 2007).

2.3.5 Relating physical and digital resource commons

A number of key works have approached the interrelationship of physical and digital resource commons. First, there is an interesting relationship between physical and digital commons in the literature on infrastructure. Rose (1986) examines the positive externalities (such as commerce) from increased usage of public infrastructure, a type of open access commons, and in doing so, lays the foundation for thinking about the positive externalities of open access information and communication networks (Benkler, 2013). Frischmann (2012) brings both types of commons together under a broad conception of infrastructure, one that encompasses both information resources and physical goods. However, Benkler (2013) makes the point that context-specific approaches are needed in order to interrelate these two types of commons while maintaining the analytical ability to distinguish between property regimes in place.

Another study that interrelates digital and physical resources is Hess and Ostrom's (2006) analysis of the dilemmas that arise when the genomes of organisms become translated into digital information. When this happens, genome information becomes subject to patenting and exclusion from the knowledge commons. This article points out that a study of the 'microbiological commons' must include variables such as the organisms as physical resources, scientific knowledge content, intellectual property rights, open source software, and the values actors place on access to genome information as a common good (ibid, p. 336). While the study itself pays attention to only the knowledge content (explicitly leaving aside the physical organism as a resource, while recognising its importance), the application of commons scholarship to technologies that combine physical and digital resources sets an important precedent for my study.

2.3.6 Theoretical debates and gaps in the literature

While seemingly heterogeneous in the context of study, commons scholarship has always been marked by a commitment to apply a common framework to a set of diverse commons environments. The idea of searching for 'new commons' is core to the research tradition (Hess & Ostrom, 2003). Cole (2014) notes that Elinor Ostrom 'recognised the knowledge commons as a separate realm from the natural commons, which would not admit simple transfer of lessons learned from her earlier work, but required systematic study of its own resources, actors, institutions, action situations, and so forth' (p. 45). It is in this spirit that I identify particular debates and areas for theoretical contribution.

As a digital production technology, 3D printing in the commons intersects with digital environments where information and knowledge are principal resources. As the knowledge commons is a young field of research, there is the opportunity to contribute and extend its scope. I aim to do so by anchoring my analysis to the basic foundations of common-pool resource theory. This includes the categorisation of types of goods by Ostrom and V. Ostrom (1977) and the importance of rules including types of property rights in governing behaviour.

As might be expected, there is a great deal of variation in the types of questions asked in knowledge commons scholarship. Yet the key focal points remain consistent with traditional commons scholarship. Three themes are important for this research: (1) dilemmas of knowledge access and enclosure that arise from the capture and use of knowledge by distributed digital technologies; (2) boundary setting in knowledge commons; and (3), accessing and producing knowledge in a commons over time. I describe each theme in terms of the literature, by way of background to my intended contributions.

The dilemmas that emerge in commons environments marked by new digital technologies are in need of empirical elaboration. Hess and Ostrom (2007a) describe dilemmas in knowledge commons in the following terms:

> *The rapidly expanding world of distributed digital information has infinite possibilities as well as incalculable threats and pitfalls. The parallel, yet contradictory trends, where, on the one hand, there is unprecedented access to information through the Internet but where, on the other, there are ever-greater restrictions on access through intellectual property legislation, overpatenting, licensing, overpricing, withdrawal, and lack of preservation, indicate the deep and perplexing characteristics of this resource. Knowledge, which*

> *can seem so ubiquitous in digital form, is, in reality, more vulnerable than ever before…On the other hand, collective-action initiatives, such as open access, and Free/Libre and Open Source Software development, are ensuring much greater accessibility and robustness of digital resources (p. 14).*

My contribution to this literature emerges from studying how 3D printing systems change the capture and use of knowledge about digital *and* physical resources. I examine how Fab Lab actors use physical as opposed to digital resources under a common-property regime, causing different dilemmas of access, production, and use of knowledge. Hess and Ostrom (2007a) have the aim of 'developing a more careful understanding of the processes of providing and producing the information and artefacts, providing and producing information facilities, distributing artefacts to facilities and to users, and the various forms of consuming and using the information content of these artefacts' (p. 14). This is important especially as new technology in a global environment introduces new challenges (Ostrom & Hess, 2003).

My study is a way to look at differences between types of knowledge, associated with digital and physical resources. This addresses the point that any definition of knowledge as a resource must come with considerable ambiguity in terms of measuring it as a unit of analysis. As Madison, Frischmann, and Strandburg (2010) state:

> *By contrast [to natural resource commons], intellectual or cultural resources do not necessarily come to us in 'natural' sizes or scales. The definition of an intellectual resource, such as a copyrightable work of authorship, a patentable invention, a book, or a new machine, is clearly moulded in part by market and historical*

> *considerations, but it is also driven to a significant degree by legal and other public-policy considerations (p. 843).*

These types of caveats are shared by most knowledge commons scholarship. To deal with such ambiguity, I follow these authors by seeking to ‘incorporate…identification and delineation of resources and their scales as questions to be asked, rather than as premises or assumptions (ibid, p. 844). Knowledge about materials is investigated in this way, by describing the concept from the perspective of users of 3D printers.

The second debate concerns the boundaries of knowledge commons. This is a subject of such ambiguity and debate that they are often assumed rather than empirically observed. This debate arises from the adaptation of institutional analysis tools from their application in natural resource commons to knowledge commons. As introduced, there is a fundamental distinction between the two fields based on the underlying nature of the physical versus knowledge resources. While biophysical common-pool resources are rival and non-excludable, knowledge is considered a public good. This leads to a debate on how ‘degrees of openness and the character of control’ define the boundary of commons regimes (Frischmann, Madison, & Strandburg, 2014, p. 28). Where natural resources are often finite, and their boundaries coextensive with the boundaries of common property regimes (Ostrom, 1990), knowledge commons may be accessed and contributed to by an online community with a somewhat undefined and permeable boundary. This means that openness and control are often interrelated, and careful consideration must be given to openness as it applies to the resource, the community, and how they interrelate. Frischmann et al. (2014) describe openness as ‘a relational variable that describes the structure of relationships among potential users’ (p. 29). As such a contingent concept, boundaries in the knowledge commons are in need of further theoretical and empirical development.

Related to the question of boundaries, there is also the consideration of 'entry points' into the commons. As Hess (2008) states in her survey of knowledge commons literature, 'I'm not aware of any studies that look as this question of entry into the commons, perhaps because traditional commons, for the most part, are pre-existing institutions' (p. 12). Studying the inclusion of knowledge about materials in Fab Lab common-property regimes is an intriguing example of entry into the commons, and offers a way to extend commons theory in this domain.

The third debate I highlight here also concerns the difference between common-pool resource theory and knowledge commons theory. Regarding incentives for accessing and producing knowledge, Madison, Frischmann, and Strandburg (2010) state that unlike natural resource commons, actors in knowledge commons often produce as well as access and use resources. Ostrom (2010) notes that this production of knowledge resources in a commons 'leads to more difficult legal relationships between those who produce knowledge and those who use the knowledge that others produce' (p. 812). My study of feedback between the commons-based 3D printing system of Ultimaker, and the use of these 3D printing systems in Fab Labs, is designed to build on and empirically extend this observation.

2.4 Technological Artefacts and Peer Production

Researchers of knowledge commons assume a central role for digital technologies. Indeed, Hess and Ostrom (2003) note that digital technologies fundamentally alter the distribution of knowledge as a resource. However, there is a gap in theorising the role that the design of technological artefacts may have in the structure and governance of knowledge commons. I find there is a need to draw on new analytical tools for studying technological artefacts in the knowledge commons. For this reason, I use theory on the architectural design of technology artefacts, particularly the concept of modularity, that has its foundation in the work of Herbert Simon (1962), and more recently the work of Baldwin and Clark (2000).

Second, I draw from literature on peer production concerning the organisation and governance of open source software communities (Benkler, 2002a, 2002b, 2006, 2016; David & Shapiro, 2008; von Krogh, Spaeth, & Lakhani, 2003). This literature explicitly takes into account the role that the architectural design of software plays in incentivising participation and structuring the way the community is governed. I also review select works on shareable physical goods (Benkler, 2004b), and the peer production of tangible goods (Raasch, Herstatt, & Balka, 2009). I review this set of literature for two reasons: first, in order to properly situate my study of the Ultimaker online community forum (see Chapter 7) within the context of scholarship on online open source communities; and second, in order to signpost the direction for future research in peer production models for 3D printing systems. My study of user engagement in types of knowledge in the Ultimaker forum is a step towards further analysis of the architectural design and evolution of 3D printing systems in peer production environments. This will be reflected upon in Chapter 8.

2.4.1 Technological artefacts and the concept of modularity

The concept of modularity draws from the work of Herbert Simon (1962) on the dynamics of hierarchical systems. Simon explains that dynamic hierarchies are *nearly decomposable*, meaning that 'intracomponent linkages are generally stronger than intercomponent linkages' (Simon, 1962, p. 204). As a result, such complex systems can be represented as hierarchies with little loss of information. Rather than specifying all the interactions going on within each component, one can simply specify the interfaces between the components that account for aggregate system behaviour.

This theoretical concept of modularity is used in highly diverse literatures, from management science and computer science to engineering, psychology, and biology (Campagnolo & Camuffo, 2010). In management science alone, its terms of use are highly heterogeneous. In an extensive review of the use of modularity within management science, Campagnolo and Camuffo (2010) point towards the foundational roots of the concept as defined by Simon (1962) and organise the many diverse contributions according to three main levels of analysis: product design modularity, production system modularity, and organisational design modularity. This allows me to orient my use of modularity within the broader landscape of its conceptual use.

Considering the importance of product design architectures, Baldwin and Clark (2006a) describe three main benefits. First, modularity makes a system 'cognitively economic', that is, more manageable overall. Second, modularity 'organises and enables' simultaneous, parallel work on system components. Third, modularity is 'tolerant of uncertainty' and 'welcomes experimentation' in each module or component. This is because a modular design 'allows modules to be changed and improved over time without undercutting the functionality of the system as a whole' (p. 6-7). My particular focus is on how modular design relates to the third benefit, experimentation, for Fab Lab members often relate experimentation and access to knowledge about materials.

Baldwin and Clark (2006a) note that modularity can be studied in use, in production, and in design. I primarily focus on Fab Lab members who are engaging with the modular design and use of 3D printing systems.

I employ these standard definitions of product modularity, and as such do not presume to contribute directly to the theoretical literature. Rather, by examining the influence of modular product architectures in the context 3D printing systems, an empirical contribution can be made. The theoretical significance related to modularity in this research is the application of it as a design rule-in-use within knowledge commons theory.

2.4.2 Peer production scholarship

The theoretical contours of peer production are interdisciplinary in nature and empirically driven in character. What common-pool resources such as fisheries and forests are to commons theory, open source software goods like Linux operating system[22] are to peer production scholars. However, unlike commons theory, there are fewer adherences to common terminology and a framework to guide theoretical and methodological choices. The term 'peer production' (Benkler, 2006; 2016) can be seen alongside 'community-based production' (David & Shapiro, 2008; Grewal, Lilien, & Mallapragada, 2006; Lee & Cole, 2003) and the 'private-collective model'

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[22] Linux operating system is an example of a toll good altered to become a public good by institutional choice; that is, through the use of open source licensing.

(Hippel & Krogh, 2003) for organising innovation, and are all applied to the study of open source software communities.

Paul David and Joseph Shapiro (2008) explain that the various approaches to the study of the 'open source phenomenon' has reflected disciplinary orientations of scholars. Economists, organisation, and management scholars have tended to be preoccupied by the motivations for contributing freely to a public good as it constitutes 'a significant behavioural anomaly'; legal scholars have been interested in new contractual licenses that have structured the space; political and organisational scientists have tended to view open source as a new paradigm for organising production (David & Shapiro, 2008, p. 365-6). I explore many of these approaches in this review.

Here I adopt the term 'peer production' as a term in use that is clearly defined by Benkler (2016) as distinct from other concepts such as crowdsourcing or open innovation. The characteristics that demarcate peer production as an organisational innovation are 'decentralised conception and execution', the centrality of 'diverse motivations, including a range of non-monetary motivations', and the fact that 'organisation (governance and management) is separated from property and contract' (ibid, p. 2). Benkler goes on to state that when peer production relies on open access commons, where there are symmetrical access privileges granted to an open class of users, peer production can allow diverse people to self-organise available resources into dynamic collaborations and projects in a way that may outperform markets or bureaucracies (Benkler, 2016).

Empirically, peer production studies often take as their subject matter intellectual public goods and what is termed 'free/libre and open source software' (FLOSS). Crowston, Wei, Howison, and Wiggins (2012) provide a comprehensive overview of this literature. The authors organise the reviewed studies according to analysis of 'inputs' such as member characteristics, 'outputs' such as project performance and community evolution, 'processes' such as decision-making and community leadership, and 'emergent states' such as roles and mental models (Crowston et al., 2012). A large part of the empirical literature on open source software takes a more sociological point of view of individual incentives and motivations (David & Shapiro, 2008; Bitzer, Schrettl, & Schröder, 2007; Shah, 2006; Roberts, Hann, & Slaughter, 2006; Hertel, Niedner, & Herrmann, 2003).

The literature on peer production is closely related to commons theory and open innovation theory (Frischmann, Madison, and Strandburg, 2014; Hess & Ostrom, 2003). While the interface between peer production and commons theory forms the basis for the theoretical contributions of this research, the interface with open innovation is more peripheral. Peer production is related to open innovation theory through the work of innovation scholars such as von Hippel and von Krogh (2003), Lakhani and von Hippel (2003), and Benkler (2006), while the field also encompasses a more firm and market centric approach to understanding innovation and organisational structure (Chesbrough, 2006; Maula, Keil, & Salmenkaita, 2006). Given that I draw from peer production as a supplemental theory for my empirical analysis, I focus selectively on two themes. These are the role of modularity in product and community architectures, and the evolution of community structure in peer production.

2.4.3 Modularity and peer production

Here I review studies that have focused on modularity in models of peer production. Modularity in peer production has to date been studied primarily through the lens of open source software projects. Langlois and Garzarelli (2008) build on Simon's (1962) contribution in the following definition of modularity applied to open source software:

> *[A] modular system is a nearly decomposable system that preserves the possibility of cooperation by adopting a common interface. The common interface enables, but also governs and disciplines, the communication among subsystems (p. 128).*

Modularity in peer production has been studied from the perspective of incentives related to product development and overall contributions, learning and knowledge specialisation. Of the two areas, the first is most extensive and pairs with the large focus on incentives in community-based production as a whole. In open source software communities, the modularity of the good is used as an explanatory factor in enabling community-based production by mitigating the issue of incentives (Benkler, 2002a, 2004a). The more modular the good, the more an individual can contribute a small part of the project (for example, fixing a bug in the source code) with little time and energy, and receive the benefit of using the entire good produced by the community.

Baldwin and Clark (2006b) model this by examining two properties of the architecture of software code: modularity and option values. They consider a new design to be an 'option value' in the financial sense, with options having associated payoffs. This allows them to create a formal public goods game. Their findings are '…that codebases that are more modular or have more option value (1) increase developers' incentives to join and remain involved in an open source development effort and (2) decrease the amount of free riding in equilibrium. These findings resonate with the research on public goods games in commons theory (Ostrom, 2005).

The second main area of this literature relates to learning and knowledge specialisation. Langlois and Garzarelli (2008) identify a main benefit of modularity in open-source software collaboration as enabling the effective use of local knowledge, as well as institutionalised coordination and economies of substitution. This learning effects have to do with the way that modular product architectures are tolerant of uncertainty, where loosely coupled interfaces allow modules to be experimented with and modified without causing changes in other modules.

Modularity has also been linked to knowledge specialisation in the community. von Krogh, Spaeth, and Lakhani (2003) study the open source project Freenet, 'a decentralized and anonymous peer-to-peer electronic file sharing network' (p. 1217). These authors observe that the literature on software development 'suggests that modularisation of the software code may increase a project's transparency, lower barriers to contribute, and allow for specialisation by enabling efficient use of knowledge…Furthermore, efficiency in the innovation process requires that individuals specialise in certain areas of knowledge' (von Krogh et al., 2003, p. 1218). They contribute to this theme by examining the joining and contributing behaviour of newcomers to the Freenet project, finding that newcomers tend to specialise in the knowledge they contribute when joining the project. They define 'specialisation' as indicating that the same modules within the code base where changed over time by the developer, while 'generalisation' indicates that a developer changed multiple modules. The authors find that newcomers to Freenet specialise in particular modules of code architecture. Their theoretical explanations include how contribution barriers may be associated with different modules in terms of the knowledge needed to contribute, and how the contribution of ‘feature gifts’ to the code, based on prior knowledge, may be linked to specialisation of newcomers. von Krogh et al. (2003) reflect on this research as follows:

> *Specialisation in the project incurs benefits for newcomers. More research should be devoted to test if the same patterns of newcomer specialisation can be identified across a population of projects. Future studies should also investigate whether or not developers change their degree of specialization over time, as they “move down the learning curve” in the software architecture (p. 1235).*

In Chapter 7, I explicitly look at this question by examining user contributions to the Ultimaker forum over time. While significant differences exist between the two empirical contexts, I find the theoretical construct of generalists and specialists useful and appropriate.

A final reference regarding the structure of open source software communities is Grewal, Lilien, & Mallapragada's (2006) study of the effects of network embeddedness on the success of open source software projects. Their approach to modelling open source communities as bipartite affiliation networks provides a useful example to guide my analysis in Chapter 7.

2.4.4 Peer production of physical goods

As a final theme in this review, I discuss recent work on open source ‘tangible’ goods. Moving beyond open source software, Raasch, Herstatt, and Balka (2009) propose the model of ‘Open Source Innovation (OSI)’ that includes the peer production of physical goods. 'OSI is characterised by free revealing of information on a new design with the intention of collaborative development of a single design or a limited number of related designs for market or non- market exploitation' (ibid, p. 383). As a foundation for this model, the authors cite user-based innovation (von Hippel, 2005) and the private-collective model of organising innovation (von Hippel & von Krogh, 2003). In their findings, Raasch et al. (2009) state the importance of modularity:

> *These open design projects make a particular effort to develop the artefact in a modular way. Thus, the open design even of very complex objects is considered feasible, as long as they can be modularised (p. 387).*

Empirically, this study reviews many diverse 'open design' projects, including the open source RepRap 3D printing project. Their contributions are mainly conceptual, asserting the importance of peer production models for tangible goods as an important empirical focus. My study of the Ultimaker 3D printer community builds on this, although the data used focuses on knowledge engagement in the user forum, and thus does not directly examine the production of physical goods themselves.

In a closely related theme, Benkler (2004b) outlines a theory for the emergence of 'shareable goods' that extends analysis of free and open source software 'to the domain of both rival and nonrival goods and services' (ibid, p. 273). Physical goods that exhibit the dual characteristics of (1) providing functionality in discrete packages, as well as (2) being widely distributed among owners who's demands are less than the capacity provided, may become a viable class of goods for sharing outside of the price system. Although these goods are not suggested to be peer produced, the social sharing that results from the latent capacity is introduced as a new modality of economic production.

What is particularly relevant about this argument is the fact that 3D printers fit the criteria for shareable goods. While most sharing to date has been in the realm of digital files in the 3D printing ecosystem (software, hardware designs, and CAD models), the concept of shareable goods introduces a logical extension into the shared production of 3D printed objects. This idea will be discussed further in Chapter 8, as it is particularly intriguing for further research into 3D printers as providing distributed production capabilities.

2.4.5 Theoretical debates and gaps in the literature

In my analysis I integrate insights from these literatures on modularity in technological architectures, as well as in open source software communities. This task is eased by the similarity in theoretical constructs between institutional analysis and modularity. As Campagnolo and Camuffo state (2010, p. 260):

> *Modularity is a 'relative' attribute of complex systems: within the same system there may be different levels of analysis and, consequently, different levels of modularity. Moreover, the same module may be part of different, nested systems. Therefore, the degree of modularity (a) is contingent upon the type of system under analysis, (b) may vary with the unit of analysis, (c) needs to be measured along a continuum from an integral structure to a modular one, and (d) may change over time, as modularity is also a design principle.*

The nested construct of modularity provides a natural avenue for studying it at different levels of analysis (Ostrom, 2007). However, there exists an empirical need for studies that do so, particularly in the knowledge commons. This research aims to address this need.

Second, it is important to note that empirical studies in the peer production literature have been almost exclusively focused on open source software. While this is understandable given the number of projects that now exist in this space, the opportunity to contribute data on open source hardware projects is significant. Moreover, 3D printers are integrated systems of software, hardware, firmware, and materials. 3D printers offer the opportunity of investigating how users engage with these different types of knowledge. My study of the Ultimaker user forum in Chapter 7 informs the larger body of academic work grappling with the application of peer production models to both digital and physical goods (Benkler, 2004b; von Hippel & von Krogh, 2003; Lakhani & von Hippel, 2003; Raasch, Herstatt, & Balka, 2009).

2.5 Alternative approaches

It is important to discuss other theoretical approaches that have relevance to the subject of knowledge in communities centred on the use of technology. Of note are social movement theory, science and technology studies, and economic history with a focus on knowledge and technology.

First, social movement theory is a fruitful avenue for studying the emerging culture around the ‘maker movement’, a self-identifying community committed to DIY and having access to the means of production (Anderson, 2013). 3D printers are a core technology in use by this community, offering a means of localised production supported by open source software and hardware (ibid). A social movement approach could reveal how such actors may be embedded in communities and networks, and the ways these can be constitutive of society (Flacks, 2004). In the case of technology-oriented movements, there is a focus on alternative forms of culture relating to the incorporation of technology (Smith, Hielscher, Dickel, Soderberg, & van Oost, 2013). In a study of digital fabrication technologies in Makerspaces, Smith et al. (2013) state that such social movements are also about 'contests to cultivate certain sociotechnical configurations' (p. 9).

As it relates to this thesis, one can interpret findings in Chapter 5, around community norms surrounding openness, sustainability, and locality from such a perspective. This provides a fruitful starting point for future research, reflected upon in Chapter 8. However, I choose not to engage with this literature directly for the reason that social movement analysis can imply a certain level of coherence around positions and strategies related to values and norms held by the community. As related by Crossley (2002), a social movement often is associated with 'collective enterprises' (Blumer, 1969, p. 99), 'moments of collective creation' (Eyerman and Jamison, 1991, p. 4), or even 'sustained interaction with opponents' (Tarrow, 1998, p. 2). While these definitions may apply to open source software communities, and can be argued for communities developing open source 3D printing hardware, extending this framework to studying knowledge about materials among heterogeneous users of Fab Labs risks overstating the strength of an assumed collective. By contrast, knowledge commons theory starts from the perspective of the resource in question rather than a social community, and thus is more amenable to identities that have yet to be delineated.

Second, an economic history perspective is informative, particularly when situating 3D printing within a wider historical lens on innovation, knowledge and technology. In this tradition, Mokyr (2005) notes that understanding the history of technology is synonymous with the history of knowledge, and that any historical analysis must 'stress the basic complementarity between the creation and diffusion of new technology and the institutional factors that allowed this knowledge to be applied…' (ibid, p. 1119). These two lines of reasoning support my focus on knowledge associated with 3D printing, in addition the use of institutional analysis as a fundamental starting point for study of this technology. Foray (2004) situates the study of knowledge within the larger development of the 'knowledge economy', a viewpoint that forefronts the role of information communication technologies (ICTs) as altering the production, reproduction, and distribution of knowledge. This resonates with Freeman's (1974) recognition of the role of ICT technologies in shaping an emerging information society. This area of scholarship is reflected upon further in Chapter 8, while discussing future research into the range and evolution of 3D printing technologies in the market. I find such historical analysis beyond the scope of present research, although highly complementary to this analysis.

Lastly, a relevant area of literature is Science and Technology Studies (STS), an approach to the sociology of scientific knowledge. Here one finds a different starting point to studying knowledge and 3D printing. The lens of STS reveals actor networks, where intricate relations between humans (e.g. users of 3D printers) and non-humans (e.g. 3D printing hardware and materials) emerge through practices of inscription (e.g. instructions for printing with a particular material) (Amin & Cohendet, 2004). Such inscriptions can act as governance mechanisms, contributing to the 'ordering and alignment' of relations in actor networks that can generate a body of tacit or codified knowledge for a given community (ibid, p. 69). This perspective offers a way to understand ‘the ways in which social embedding and social connectivity instantiate knowledge’ (ibid, p. 70). To fully utilise an STS approach, one would need to explicate actor networks through repeated observation. While this may be an interesting direction for future research, an STS approach is fundamentally at odds with theory informed by the IAD as a meta-theoretical framework, given the assumed starting point of the researcher. Starting with actor networks risks losing sight of underlying distinctions between types of goods in use, and the institutional arrangements that can shape their use. For the purpose of this study, insights gained from the IAD and knowledge commons perspective outweigh benefits from an STS approach.

In sum, while each have there relevance to my empirical subject, I choose to focus on knowledge commons research, and to a lesser extent, draw from peer production literature, for the sake of clarity in my intended theoretical contributions. I choose commons theory as my area of contribution for the principal reason that it allows a study of physical and digital resources from the useful perspective of emergent social dilemmas. Furthermore, foundational insights regarding the typology of goods and the distinction between resource type and property regime are found to be particularly illuminating to my empirical puzzle of knowledge about materials in the commons. Enriching the meta-theoretical enterprise of applying the Institutional Analysis and Development framework to new empirical contexts is also important for embedding the new social and technological phenomenon of 3D printing within an experienced research tradition.

3 RESEARCH METHODOLOGY AND DESIGN

3.1 Introduction to the Data

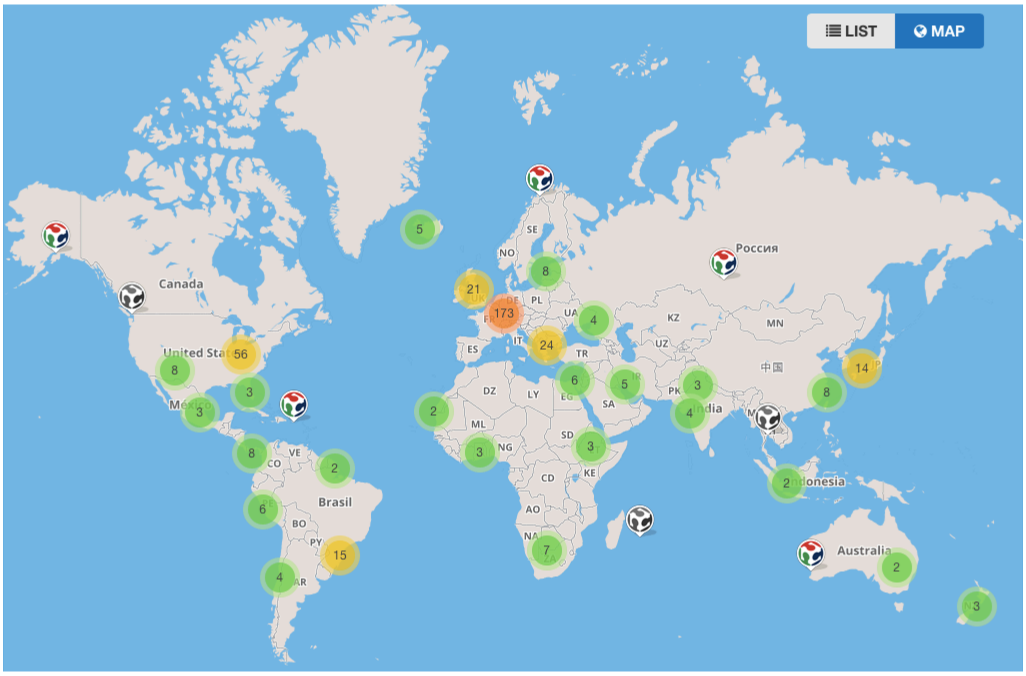
I begin by introducing the data used in this research. I then discuss my research framework, and the particular reasons why it is appropriate for my empirical setting. Following this I describe my research design, including how I identified variables of interest. I conclude with a review of my analytic methods and approach, including issues of data validity, reliability and generalisability.

3.1.1 Data source (1): interviews with Fab Lab members

For empirical chapters 4-6, data comes from interviews with members of Fab Labs. I chose Fab Labs as an empirical setting for two main reasons. First, Fab Labs are places of where commons-based 3D printing is taking place, and can be characterised as being governed by common-property regimes. This makes them appropriate for exploring how knowledge about materials may or may not be entering the commons. Second, Fab Labs are distributed all over the world, and have largely arisen organically based on the needs and interest of local communities. This means they provide access into commons-based 3D printing in very different local settings, important for uncovering more general patterns about knowledge of materials entering the commons.

More specifically, interview data was collected at the 10th annual Fab Lab conference, called Fab 10. Fab 10 took place in Barcelona from July 2nd-9th 2014. Members of 450 Fab Labs from 50 countries attended, giving me an opportunity to collect a diverse geographical sample of in-person interviews. Over the period of the event I conducted 49 semi-structured interviews with users from 45 Fab Labs representing 30 countries. Interviewees were either the managers or technical directors of their Fab Lab. As such, they had a good understanding of their community, the purpose of their lab, as well as knowledge of inventory and 3D printing activity. Three interviews via Skype were conducted after Fab 10 with individuals working in or connected to Fab Labs. These individuals were not in attendance in Barcelona, but were recommended to me by workshop participants as being relevant to my research. Although interviews took place within a short period of time, and thus present a limited time window of data collection, the benefits of gathering data from representatives of many diverse parts of the world through in-person interviews was deemed an appropriate trade-off. Figure 3.1 illustrates global distribution of Fab Labs at the time that interviews were conducted.

Figure 3.1: Fab Labs Worldwide



Source: Fab Foundation (2014)

On the map in Figure 3.1, the locations of individual labs are marked by the Fab Lab logo. Areas with more than one Fab Lab have a circle with the number of Fab Labs located there, with colours signifying increasingly dense concentrations of Fab Labs.

Interview subjects were primarily chosen on a basis of geographical representation in order to cover a wide variety of possible local circumstances, material environments, and community dynamics. Figure 3.2 shows the location of Fab Labs selected for interviews. For reasons of data anonymity, the specific locations of Fab Labs are not given. All names and Fab Lab affiliations have been omitted for reasons of data protection.

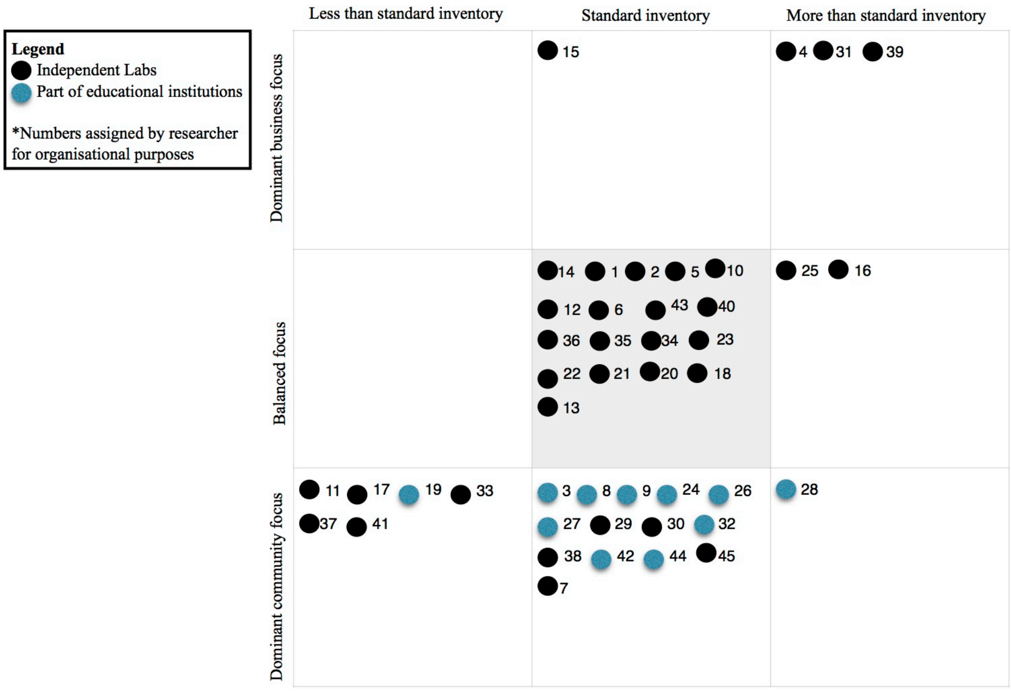
Figure 3.2: Locations of Fab Labs selected for interviews

Secondary criteria for selecting Fab Lab representatives for interviews were variation in:

- Equipment inventory, corresponding to the financial resources of Fab Labs as well as roles in their respective communities;
- Orientation towards business or the general community, where a dominant community focus means the output of the Fab Lab is primarily focused on education and community projects, and a dominant business focus means the output of the Fab Lab is oriented towards serving the needs of business users; and,
- Independence or affiliation with an educational institution.

The variation in these secondary dimensions among the Fab Labs I selected for interviews is captured in Figure 3.3. The numbers beside the points should not be interpreted: they are randomly assigned and are merely for the purpose of data organisation.

Figure 3.3: Fab Lab variation



Note that variation was interpreted from interview questions related to inventory and community orientation. The diagram does not reflect an exact inventory survey, for example, and thus should be read as qualitative interpretation that helps the reader understand the nature of the data.

To discuss Figure 3.3, one can see that most Fab Labs chosen for interviews fall within the central shaded area of the diagram: this means they all share a general set of tools and have balanced output to business and community users. This is not surprising given the general set up and approach of the Fab Lab charter that specifies a set of tools as well as lays out the intended orientation towards serving the general community as well as businesses. One also sees that a good number of Fab Labs have a standard inventory yet are dominantly focused on community rather than business users.

One also can see that Fab Labs supported by educational institutions are oriented towards the community rather than business, an intuitive finding given their education focus. The large number of Fab Labs with tools that fall in the middle of the inventory spectrum signifies the overall adherence to the core toolset set out in the Fab Lab inventory. I provide detail on the tools and inventory of Fab Labs at the beginning of Chapter 4.

Some labs fall outside of this pattern, having more or less than the standard inventory. An outlier is number 28: with a more extensive toolset and a dominant community focus, it makes sense that an educational institution supports the Lab. Variation around this toolset suggests financial resource constraints as well as orientation to business versus general community users. The cluster of labs in the bottom left corner of the figure are all located in developing countries and particularly financially underprivileged communities. By contrast, those labs high on the business axis and/or those with extensive inventory are predominantly in wealthy industrialised countries.

One also observes that the quadrants marked by less than standard inventory, but with a focus towards business (either balanced or dominant), are not represented by Fab Labs in this study. This is intuitive given that business users are commonly using the Fab Lab almost exclusively for its tools on offer. If a Fab Lab has a less than standard inventory, it means that it likely will not have much equipment of interest to a business user. In this situation, a Fab Lab can still cater effectively to community users who may not need as many tools to engage in low-tech projects. This is evidenced by the Fab Labs in the lower left-hand quadrant.

As stated, my main criterion for interviewee selection is geographic diversity. It makes sense, therefore, that the variation in Fab Labs interviewed along secondary dimensions is weighted towards general characteristics of Fab Labs, such as a standard toolkit and balanced community/business focus. There are more Fab Labs studied here with a dominant orientation towards community, rather than business. Again, this reflects the general definition of a Fab Lab: openness towards the community is a requirement of being a Fab Lab, while service to the business community is the choice of individual labs, often made for financial reasons. The impact of variation along the dimensions of geography, inventory, and community orientation will be discussed throughout my empirical analysis.

3.1.2 Data source (2): Ultimaker 3D printer online community forum

Motivated by findings from Fab Lab interviews, in Chapter 7 I use data from the online community forum for Ultimaker 3D printer users. The Ultimaker forum data covers all user contributions to the forum from the period of October 2011 when the forum was founded, to March 2015 when data was collected. Over this period, the Ultimaker 1 and Ultimaker 2 printers were developed and released. There were 2,423 unique users in as of March 17th, 2015. Detailed information on the nature of the data is given in Table 7.1.

The structure of the user forum follows the overall design of the 3D printing system: the forum is organised into the three areas of hardware, software, and firmware. Within each of these areas, there are subject categories; within each subject, there are forum threads; and within each thread, there are individual posts. Thus the data represents a nested architecture of user contributions according to parts of the 3D printing system. The data allows investigation into patterns of contributions to the forum over time. More detail is given in Chapter 7.

3.2 Research Framework

I study Fab Labs using the tools of institutional analysis. My research framework is the institutional analysis and development (IAD) framework. This framework was designed for researching commons environments. In this section I first introduce the main assumptions underpinning the application of commons theory and the IAD to my empirical context. I introduce how Fab Labs can be conceptualised as being governed by common-property regimes, and describe rules of access, use, and production of goods in Fab Labs. As will be illustrated, commons-based 3D printing consists of overlapping communities, where Fab Labs as physical spaces are overlaid with open source hardware, software, and digital design communities. The Ultimaker community constitutes an example of a digital commons layered over Fab Lab commons.

I then introduce the details of using the IAD framework. This includes viewing Fab Labs as action arenas where specific actions and interactions result in outcomes relevant to answering the research question . I also discuss how action arenas can be linked through different levels of analysis, and how this applies to linking Fab Labs and the Ultimaker community. I discuss particular critiques of the IAD from scholars in the knowledge commons literature as they relate to my research design.

3.2.1 Defining framework, theory, and methods

It is first worth noting the definitions of research framework, theory, and methods that I adopt. Following Ostrom (2005), I use the definition of a research framework as '…providing the most general set of variables that should be used to analyse all types of settings relevant for the framework' (p. 28). Having identified the IAD as appropriate for analysing 3D printing in the commons, the elements in the framework helped me generate a series of nested conceptual maps of the explanatory space relating to my research question.

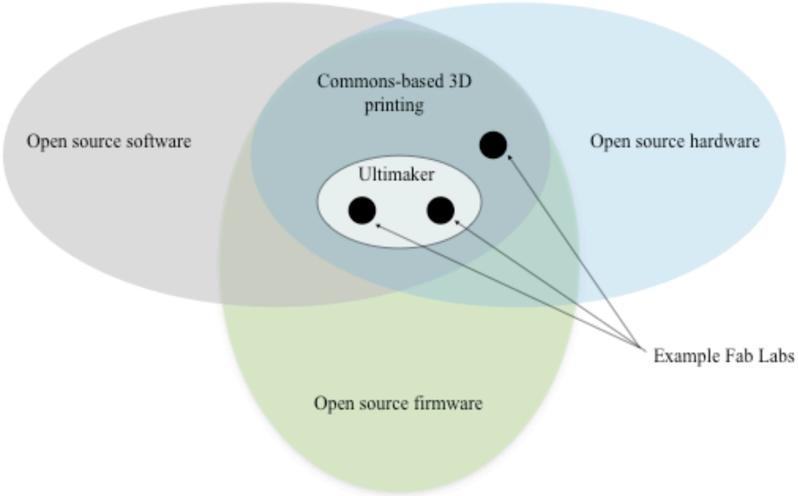
Theory is defined as a nested level of specificity to 'enable the analyst to specify which components of a framework are relevant for certain kinds of questions and to make broad working assumptions about these elements' (Ostrom, 2005, p. 28). Multiple theories can be compatible with the meta-theoretic research framework. While using the IAD framework to organise the elements of inquiry, I draw on common-pool resource theory, knowledge commons, and theory on community-based production. My chosen methods are a combination of semi-structured interviews and statistical analysis. These are detailed in the subsequent section on research design.

3.3 Theorising Commons-based 3D Printing

The basic characteristic that distinguishes a knowledge commons is institutionalised sharing of resources among members of a community (Madison, Frischmann, & Strandburg, 2010, p. 841). I use this definition as the basis for describing Fab Labs as action arenas in the knowledge commons, and as such being appropriate for institutional analysis. This section provides an overview of why I choose to use the IAD as my research framework, and the tools of commons theory and analysis.

To understand the context of my empirical data, it is useful to conceptualise the multi-layered communities in commons-based 3D printing. This is illustrated in Figure 3.4.

Figure 3.4: Overlapping communities in commons-based 3D printing



This diagram helps visualise how my study of Fab Labs and the Ultimaker community fits into the overall phenomenon of commons-based 3D printing. Ultimaker is an example of a commons-based 3D printing community, with a technology system made up of overlapping open source software, hardware, and firmware. Fab Labs are physical spaces within the 3D printing commons. Based on whether they choose to use Ultimakers or other 3D printer models, labs can be thought of as part of the Ultimaker community or not. If a Fab Lab is a user of an Ultimaker 3D printer, then the Fab Lab is part of the overall evolution of printer community, and by extension, the users and developers active on the online forum. This does not mean that Fab Lab members are necessarily part of the online user forum studied in Chapter 7, or that members of the Ultimaker forum are members of Fab Labs. Figure 3.4 is a way to explicate the various commons communities that interact to make up commons-based 3D printing, allowing a clearer picture of how my empirical contexts relate to one another and the wider commons.

3.3.1 Fab Lab organisational structure

The organisational structure of Fab Labs can be understood along three main dimensions: internal community, institutional context, and Fab Lab network. At the level of the individual community, the Fab Foundation has provided a general template for organisational structure, recommending that one manager, and at least one technical director run the Fab Lab[23]. The manager is framed as having close ties to the community in order to leverage the necessary resources to sustain the Fab Lab, while the technical director is focused more on working with users of the Fab Lab in the day-to-day use of the equipment[24]. Larger Fab Labs may have more than one technical director and many more technical support personnel. Although this general role structure may not be adhered across all Fab Labs, I found it to be sufficiently

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[23] See http://www.fabfoundation.org/fab-labs/setting-up-a-fab-lab/the-people/

[24] ibid

general to the Fab Lab users I interviewed, as well as a commonly held view on ‘how to run a Fab Lab’ within the community.

The second dimension of organisational structure is institutional context, closely related to the business model of a Fab Lab. Recalling Figure 3.3, this study encompasses Fab Labs that are independently funded and run, and those that are part of an educational institution. Fab Labs often benefit considerably from financial stability by being part of a university, yet at the same time, some Fab Lab members describe a certain loss of freedom in terms of the ability to make decisions as a collective community. Furthermore, there can be differences between the types and priorities of users in Fab Labs that are part of existing institutions; for example, meeting the expectations of faculty and curriculum demands rather than the business community. Hybrid models also exist: one Fab Lab reported that they work with an educational institution at arms-length, while also having the freedom to cater towards the business community. In order to fully understand such variation, one would need to conduct a comparative study where rules of affiliated organisations are investigated on a case-by-case basis. This was deemed outside of the scope of this study, and is an important area of further research.

The third dimension of organisational structure is the Fab Lab network itself. One differentiating factor between Fab Labs and other models of digital fabrication workshops such as Makerspaces and Hackerspaces is their belonging to a global network. Although there is no formal structure to the network, there are identifiable drivers of connectivity between Fab Labs that can be seen. One is the Fab Academy, an online course run by Neil Gershenfeld from MIT, and offered at Fab Labs around the world[25]. As students of the Fab Academy often maintain personal connections with one another, the Fab Labs that offer the course are often more connected and visible to one another. Another driver comes from regional networks: as the number of Fab Labs has grown over time, there have emerged regional networks that coordinate activities and knowledge sharing within a geographic area. Examples are Fab LAT[26], a network of Latin American and Caribbean Fab Labs, and the Fab Lab Asia network[27]. Lastly the annual Fab Lab conferences bring together members of Fab Labs worldwide, helping to build ties between Fab Labs, as well as maintain an overall conception of the network whole.

While these levels of organisation may be considered general across Fab Labs, they operate at multiple scales and may be more or less influential when it comes to the operational activities within Fab Labs. In my interview methodology I took into account these organisational variables (see Appendix I, Level 2, Governance System and Related Systems). Upon coding my interview responses, these variables did not emerge as strongly related to my research question. Thus, I discuss them here as important contextual factors, and concentrate instead on other variables that had more explanatory weight.

3.3.2 Fab Labs as common-property regimes

As Madison, Frischmann and Strandburg (2010) state, just ‘as a resource or set of resources may have an open character, so may a community’ (p. 696). One general manager and one technical director usually manage a Fab Lab, although a number of other volunteers or paid staff may help. While these community leaders may take

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[25] See http://fabacademy.org/about/fab-academy-2016-sites/ for a list of Fab Labs presently offering the Fab Academy course as of 2016.

[26] http://fablat.org/

[27] http://www.fablabasia.org/

decisions relating to the provision of materials, purchasing of equipment, funding models, and time and space allocation, a Fab Lab overall is governed by the community as a commons.

In order to theoretically characterise the common property regimes governing Fab Labs, one must define property rights in terms of their application to resources. ‘A property right is an enforceable authority to undertake particular actions in a specific domain’ (Hess & Ostrom, 2003, quoting Commons, 1968). The following list of property rights by Schlager and Ostrom (1992) provides the basis for this task:

- Access: The right to enter a defined physical area and enjoy non-subtractive benefits;
- Extraction: The right to obtain resource units or products of a resource system;
- Management: The right to regulate internal use patterns and transform the resource by making improvements;
- Exclusion: The right to determine who will have access rights and withdrawal rights, and how those rights may be transferred; and,
- Alienation: The right to sell or lease management and exclusion rights.

Schlager and Ostrom (1992) state that common-property regimes are marked by rights of access, extraction, management, and exclusion; but importantly, not rights of alienation. Open access property regimes are marked by the presence of the first three rights only. Both common-property regimes and open access regimes in Fab Labs are further detailed in Chapter 4 with respect to the governance of digital and physical resources.

3.3.3 The importance of rules, norms and strategies

A central component of institutional analysis is the concept of rules. Rules can have many different meanings in different literatures, and can, for example, be used to mean regulations, instructions, precepts, or principals (Ostrom, 2005, referencing Black, 1962). For institutional analysis, the concept of rules is closely aligned with rules in the 'regulation' sense (Ostrom, 2005). Such rules can be 'announced, put into effect, enforced (energetically, strictly, laxly, invariably, occasionally), disobeyed, broken, rescinded, changed, revoked, reinstated' (ibid, p. 109). For use with the IAD framework, 'rules can be thought of as a set of instructions for creating an action situation in a particular environment…Rules combine to build the structure of an action situation'. As such, 'The property rights that participants hold in diverse settings are a result of the underlying set of rules-in-use' (ibid).

In the context of common-pool resource scholarship, rules are 'shared understandings by participants about enforced prescriptions concerning what actions (or outcomes) are required, prohibited, or permitted' (Ostrom, 2005). This means understanding how they rule in or rule out activities in a given situation. Such rules may or may not be written or codified in law, and often occur in multiple layers of governance. The IAD framework assigns rules according to the nested layers of operational, collective action, and constitutional rules-in-use. This categorisation is based on theorised impact on the parts of an action situation (Ostrom, 2005).

In this research, the regulatory conception of rules proves a useful analytical tool for two main reasons. First, in absence of having longitudinal data when studying Fab Labs, focusing on rules can help identify regularities in behavioural patterns. This idea rests on the assumption of rule stability: 'The stability of rule-oriented actions is dependent upon the shared meaning assigned to words used to formulate a set of rules…[and] upon enforcement…If individuals voluntarily participate in a situation, they must share some general sense that most of the rules governing a situation are appropriate' (Ostrom, 2005). Given that Fab Labs are highly dynamic and evolving contexts for conducting research, identifying rules allows me to have greater confidence in the robustness of the empirical relationships I find. Second, I find that rules as conceptualised in institutional analysis significantly aid in answering my research question. One of the central contributions of this thesis is showing how rules embedded in the design of 3D printing systems rule in and rule out certain behaviours of users that relate to accessing knowledge about materials.

In institutional analysis, rules are one type of 'institutional statement', alongside strategies and norms. '[A]n 'institutional statement' encompasses a broad set of *shared* linguistic constraints and opportunities that prescribe, permit, or advise certain actions or outcomes for participants in an action situation' (Crawford & Ostrom 2005, p. 138). To summarise the similarities and differences between rules, strategies, and norms, I paraphrase Crawford and Ostrom's (2005) 'syntax' as follows:

- Shared strategies include descriptions of actions and outcomes for a set of people with particular attributes, within the confines of certain conditions.
- Norms are defined as above with the addition that any actions are specified as permitted, obliged, or forbidden.
- Rules are defined the same as norms with the addition that consequences come with not following the rule.

Not only are these concepts conceptually nested, the categories themselves are mutable. For example, Crawford and Ostrom (2005) note that strategies and norms can evolve into rules. Strategies, norms, and rules as not self-evidently separate; rather, differentiating between them is useful for creating a common language across different institutional contexts (ibid). In other words, separating them as stated is a useful analytical device. For my study, differentiating rules from strategies and norms serves to emphasise the importance of consequences for not following rules within the context of commons-based 3D printing. As will be discussed, the design rules of 3D printing systems have considerable behavioural consequences for the end user. By comparison, not engaging in the norms I discuss (see Chapter 5), in general does not result in significant consequences for users. Thus my use of Crawford and Ostrom's (2005) differentiation between rules, norms and strategies should not be interpreted as a general definitional statement, but rather a statement of use for my analytical context. Employing this, I enquire directly into the consequences of design rules with respect to access to knowledge about materials (see Chapter 4). By contrast, I find that community attributes are better described as norms and strategies that have interacting effects (see Chapter 5).

Rules-in-use must also be defined in contrast to rules-in-form. To be a rule-in-use, the rule must have influence on the outcomes of an action situation; that is, a rule must be a 'shared institutional statement that participants know and use' (Crawford & Ostrom 2005, p. 172). The rules discussed here are those articulated by the actors themselves as relevant to their Fab Lab environments. By contrast, rules-in-form such as a patent of a 3D printing system may or may not be known to actors and do not need to affect their behaviour directly (ibid). To illustrate why, one only needs to listen to the rules articulated by Fab Lab actors. While a multitude of patents exist for

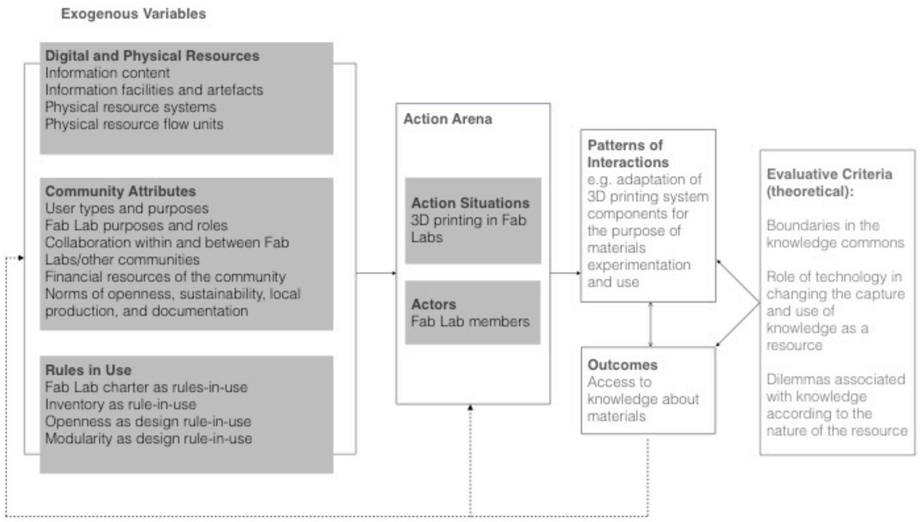
3D printing systems, Fab Lab users do not refer to patents specifically as barriers to actions. Rather, they discuss how the designs of the 3D printing systems enable or prevent certain types of modification and use. For this reason, I ascribe the design rules of 3D printing systems to the category of rules-in-use.

As a final note, it is important to note certain drawbacks of this analytical approach. While it is assumed in institutional analysis that one's attention to rules-in-use offers the potential to capture regularities in patterns of interaction that help account for particular outcomes of interest (Ostrom, 2005), this does not mean to say that rules are always predictive and stable. Their strength may vary over time, as well as with actors' willingness to enforce or follow them. Without longitudinal data, it is difficult to view such change. As a partial remedy, I consider how rules-in-use interact with norms and strategies. Cole (2014) notes that regularised patterns of interaction may reflect norms of social behaviour. I look at whether norms and strategies of Fab Lab actors reinforce or run counter to rules-in-use with respect to my outcome of interest.

3.3.4 The institutional analysis and development (IAD) framework

Scholars examining multiple types of knowledge commons have employed the IAD framework (Frischmann, Madison, & Strandburg, 2014). Summing up its use in this branch of commons scholarship, Cole (2014) states that the IAD framework is of particular use to those seeking 'understanding of information and information flows under alternative institutional arrangements' in addition to 'diagnosing problems or dilemmas in existing institutional arrangements' (p. 46). As such it is well suited as an analytical framework for understanding access to knowledge in commons-based 3D printing. Figure 3.5 adapts the basic IAD framework introduced in Figure 1.1 for the purposes of this study. In addition to the variables specific to this study, I also include feedback arrows between outcomes and interactions, and the starting conditions denoted as exogenous variables. This is important to capture the dynamics of knowledge commons environments (Madison et al., 2010).

Figure 3.5: Research Framework: Adapted IAD



Adapted from Ostrom (2005), Madison et al. (2010)

The IAD is a meta-theoretical framework, designed to provide the researcher with the most general set of variables one should consider when studying commons environments. Action arenas are dynamic. Although data comes from one period of time, the IAD as a framework is designed to conceptualise variables and relationships that are part of dynamic systems (Hess & Ostrom, 2007). I now discuss the application of the IAD to Fab Labs, and discuss the ways that the framework clarifies and raises important issues for my analysis.

3.3.5 Using the IAD: Fab Labs as action arenas

My main unit of analysis in this study is the action situations that are contained within the Fab Lab, itself an action arena. ‘Action situations are the social spaces where individuals interact, exchange goods and services, solve problems, dominate one another, or fight....’. The ‘action situation’ is ‘a conceptual unit...that can be utilized to describe, analyse, predict, and explain behaviour within institutional arrangements’ (Ostrom, 2011, p. 11). In each action situation considered, Ostrom (2011) references the following variables as important to consider in understanding the behaviour of actors in an action situation:

1. The resources that an actor brings to a situation;
2. The valuation actors assign to states of the world and to actions;
3. The way actors acquire, process, retain, and use knowledge contingencies and information; and,
4. The processes actors use for selection of particular courses of action.

Action arenas involve actors with identified roles taking specific actions, with consequences that are measured according to evaluative criteria of the researcher. Actors are the users of Fab Labs in this study, and action situations constitute the digital fabrication activities of users.

Action arenas can be studied along two main dimensions: first, by exploring the influence of exogenous variables at multiple levels of analysis, and second, by linking action arenas at different levels of analysis (Ostrom, 2005). These two dimensions guide the design of this research.

Deeper levels of analysis are also acknowledged in institutional analysis. Two main avenues for this are studying deeper 'factors that affect the structure of the situation' such as the motivational and cognitive processes of actors (Cox & Ostrom, 2010), and exploring 'how an action situation changes over time in light of how the outcomes at an earlier time affect perceptions and strategies over time (Kiser & Ostrom, 1982). Although parts of my analysis probe these themes (e.g. in interview responses concerning motivations for using open source, and the longitudinal study of the Ultimaker community), such deeper levels of analysis should be framed as fruitful directions for future research.

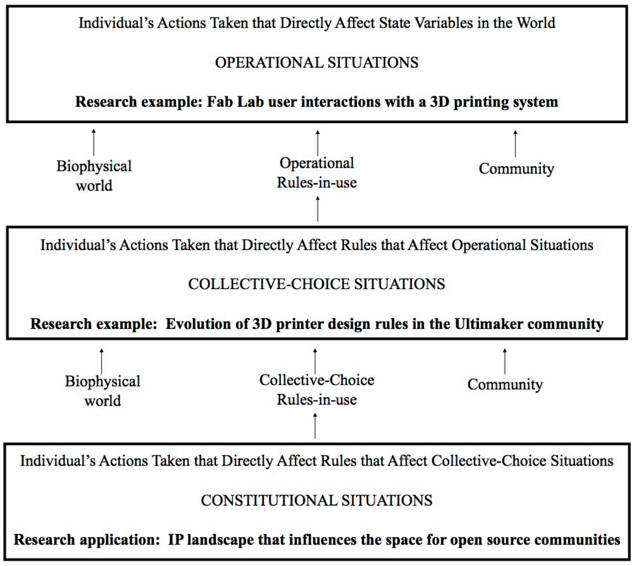
3.3.6 Multiple levels of analysis and linked action arenas

One of the important reasons for using the IAD framework is its inclusion of multiple levels of analysis for the exogenous variables in the framework, as well as linked action arenas. The focus on multiple levels of analysis is born out of a recognition that the when analysing institutions and institutional change in commons environments, 'changes in rules used to order action at one level occur within a currently 'fixed' set of rules at a deeper level, [and] changes in deeper-level rules are usually more difficult and more costly to accomplish, thus increasing the stability of mutual expectations among individuals interacting according to the deeper set of rules' (Ostrom, 2005, p. 58).

These insights have led to three nested levels of rules being integrated into the IAD framework: operational, collective-action, and constitutional rules (Ostrom, 2005). Operational rules govern daily interactions between participants in the commons. Collective-action rules structure who is eligible to participate in changing operational rules as well as what specific rules are to be used for any change to operational rules. Constitutional rules are the next level above, determining who can participate in setting and changing collective-action rules (ibid). These three levels of analysis are fundamental to understanding the complex institutional environments of commons.

Moreover, this approach is fundamental to my research design. For material resources in a Fab Lab, the operational level concerns the rules that govern daily use of materials in a Fab Lab, while the collective action level can be conceptualised as the Fab Lab management who set these rules of usage for the community, and the constitutional level may be the Fab Lab charter that affects the collective choices of individual communities. Regarding technological design rules in a 3D printing systems, the operational level can be understood as the use of 3D printers in Fab Labs, while the collective-action level can be understood as the open source communities who develop the design of software, hardware, and firmware components. The constitutional level can be framed as the intellectual property landscape that structures the collective choice set of open source communities. Figure 3.6 provides an illustration of these levels using the example of technological design rules.

Figure 3.6: Levels of analysis for rules-in-use



Source: Adapted from Ostrom (2005)

Through a linked action arena, the Ultimaker 3D printer community, I study an example of the collective-choice level that in part, structures the open source and modular design rules-in-use present in Ultimaker 3D printers being used in Fab Labs. I say ‘in part’, because the rules that govern the design and production of the Ultimaker 3D printer are not made explicit in the data on the community forum. Therefore, the rules of collective choice for the Ultimaker community cannot be directly studied. My study of the Ultimaker community is a step towards a more comprehensive analysis of the structure and governance of online communities that produce open source 3D printers in use in Fab Labs. Taking this into account, Figure 3.6 illustrates a framework to theorise the way these action arenas in the knowledge commons can be related.

In a similar way, the constitutional level is out of scope for the present research. For open source 3D printers, the intellectual property landscape can be understood as a linked action arena, where rules influence what can become open source, such as the 20-year time lag between the filing and expiry of patents in US patent law. Given the complexity and new forms of empirical data required, I discuss this as a subject of potential future research in the closing chapter of the thesis.

The constitutional level pertaining to modular design rules-in-use may also be conceptualised as distinct from intellectual property rights. The reason for modular design rules in complex products and industries as a whole is a large field of research (Campagnolo & Camuffo, 2010). For such a study one would need to gather data on the design of the many 3D printers in today's market, as well as historical data on their evolution. The breadth of the empirical data required means it is currently out of scope. However, the level is important to acquiring a deeper understanding of how design rules evolved and affect the use of 3D printing systems.

3.4 Research Design and Analytical Methods

In this section I begin by explaining my interview structure and analytical techniques. I explore some analytical issues that come with my chosen research design and methodology. I then assess the overall validity and reliability of my study and discuss the generalisability of my results in relation to data presentation.

3.4.1 Identifying relevant variables

Before conducting interviews, I visited three Fab Labs in the United Kingdom to understand the space, tools, and models of organisation. I also spoke to members of the Fab Foundation who are involved in various Fab Labs worldwide. These visits and conversations allowed me to adapt the Institutional Analysis and Development (IAD) framework to a specific set of variables deemed relevant for studying 3D printing in Fab Labs.

The IAD specifies the exogenous variable categories of resource characteristics, attributes of the community, and rules-in-use (see Figure 3.1). In the IAD, these categories are conceptualised as interacting in action situations taking place in action areas. The categories have been used repeatedly in commons studies, and are the result of extensive meta-analysis (Ostrom, 2005). Within each of the categories I populated a set of variables specific to my empirical context and research question. For this task I used the multitier framework specified by Ostrom (2007) for the study of complex social and ecological systems. It is on the basis of this combined framework that I constructed my interview questions.

Here I provide a brief description of the variables included. A more detailed list can be found in Appendix I. Under the category of resources, I considered biophysical and digital resources, adding considerable complexity to their corresponding attributes. In general, the research design is set up to investigate how different attributes, such as rivalry and excludability, influence action situations and outcomes of interest. I pay particular attention to the nature of goods in a Fab Lab, and differences between resource units and resource facilities with respect to the Fab Lab's common-property regime. The characteristics of resources are discussed in detail in Chapter 4.

The second category of exogenous variables is attributes of the community. This is important for understanding how various roles, purpose, and dynamics within and between Fab Lab communities affect the research outcomes of interest. In the broader terms of institutional analysis, attributes of the community are important for understanding how communities can self-organise rules for governing common-pool resources. The variables included under this category are:

- User types, purpose, and collaboration;
- Collaboration between Fab Labs;
- Fab Lab organisation and management;
- Financial resources of the community;
- Knowledge recording strategies;
- Open source norms; and,
- Norms of local production and resource sustainability.

Finally, the third category of exogenous variables considered is rules-in-use. As discussed, rules are a central tenet of institutional analysis, and are associated with considerable explanatory power. In this study I both adopt rules-in-use that are common in institutional analysis, and add a specific category of rules, technological design rules, that I find are influential in the empirical setting of Fab Labs. In making this conceptual connection, I employ theory on modularity in technological architecture and open source communities. Rather than add technological design rules as a new category in the typology of rules used in institutional analysis, I position modularity and openness as examples of Aggregation Rules and Information rules, respectively. These definitions are introduced and detailed in Chapter 6.

I evaluate patterns of interaction and outcomes based on their relationship to the main outcome variable of interest: access to knowledge about materials in 3D printing. The core assumption underpinning this outcome variable is the idea that if a Fab Lab member accesses knowledge about materials, it represents this knowledge entering the commons. I base this assumption on the observation that Fab Labs are governed by common-property regimes, and are part of overlapping communities of shared knowledge resources for 3D printing.

3.4.2 Analytical approach: qualitative data

As stated, within the categories of exogenous variables described, I created a nested list of variables that related to Fab Labs as action arenas by adapting the multitier framework for complex social and ecological systems (Ostrom, 2007). As an example of the nested structure, under the Fab Lab *Facility* (part of the larger category of Resources), I include the variable *materials,* and nested within this are variables *material type, material source, material cost*, and whether the material is *open/closed source*.

I adapted this framework so as to study knowledge in the 3D printing commons. In knowledge commons contexts, the production of information goods introduces slightly different categories: information goods involve the threefold distinction between information facility, artefact and content, while physical resources involve resource facilities and flows (Hess & Ostrom, 2003). Using this as guidance, I mapped extensively the layers of variables present in Fab Labs. See Appendix I for the detailed list on all variables included in the study, as well as their nested organisational structure. These variables formed the basis of my semi-structured interviews.

This set of nested variables were also used as organisational categories in my analysis phase. I used the software NVivo to code my interviews, using my nested variables as 'nodes'. This allowed me to systematically code interviews according to whether the interviewee was talking about particular variables in my research design framework. I then analysed whether particular nodes were being related in the interview responses to my main outcome of interest: knowledge about materials. I also kept track of which variables were not specifically connected to knowledge about materials by interviewees. This approach allowed me to identify emergent themes in the data as particular variables were cited again and again by respondents as being related to access to knowledge about materials. This formed the basis for the themes and findings discussed in my empirical chapters.

Of note is the variable of *modularity* in the study. This concept emerged from interviews as Fab Lab members described 3D printing systems in use, rather than a preformed list of variables generated from the combined IAD and multitier framework. The flexibility in the semi-structured interview design was important for uncovering modularity as a key explanatory factor related to my research question.

3.4.3 Analytical approach: quantitative data

In Chapter 7 using the Ultimaker data, the main variables and relationships of interest were identified based on the findings from my qualitative interviews. In particular, the subject of learning over time from the perspective of users engaged in different parts of the 3D printing system was deemed particularly interesting for studying user engagement in parts of the Ultimaker forum associated with hardware, software, and firmware.

My design thus follows a 'sequential exploratory strategy' for mixed methods, where qualitative data collection and analysis is followed by quantitative data collection and analysis, and finally an integrated analysis phase (Clark & Creswell, 2007). By combining qualitative and quantitative analysis, I aim to increase the breadth and depth of understanding, as well as enrich findings from different perspectives (ibid).

When the guiding questions were formulated, I used statistical methods to analyse the Ultimaker community data. In particular, I use bipartite affiliation network techniques to descriptively study user contributions to hardware, software, and firmware modules in the 3D printing community forum. I also use regression analysis to investigate hypothesised empirical relationships in the data. In both cases I use the software program R.

3.4.4 Analytical issues: institutional analysis

It is important to note some critiques and drawbacks of using the IAD as my main analytical tool. First, one cannot assume that by using the IAD framework, all relevant variables affecting my outcome of interest in Fab Labs can be accounted for. Indeed Ostrom (1999) notes that institutions have many latent or unobserved variables. Alston et al. (2009) also note that institutional change cannot be captured in its full complexity. In an area as new and fast moving as commons-based 3D printing, this is an unavoidable limitation. I aim to address these issues by defining a precise empirical scope, core theoretical concepts, a geographically diverse sample of Fab Labs, and variation in my types of analysis.

There are also more specific critiques from the perspective of using the IAD to study knowledge commons. Madison, Frischmann, and Strandburg (2010), Frischmann, Madison, and Strandburg (2014), and Cole (2014) agree that the IAD framework should include an extra feedback arrow between an action arena and resource characteristics. This allows for knowledge resources to be created by the same actors that access and use the resources, unlike in natural resource commons. Relatedly, Cole (2014) states that the dynamics of knowledge commons environments compels the researcher to reconsider the term ‘exogenous variables’ on the left side of the diagram. Cole (2014) explains, ‘Because of the recursive nature of the framework – feedback from outcomes of action situations effects, either directly or mediated through evaluative criteria, resource attributes, community attributes, and rules-in-use – [exogenous variables] are endogenised within the framework’ (p. 59). Cole suggests the terms ‘initial conditions’ or ‘entry conditions’ as more appropriate to conceptualise what precedes a particular action situation.

This perspective is appropriate for thinking through the highly dynamic action arenas of Fab Labs as production commons. Clearly, endogenous feedback is an important conceptual feature of thinking through access to and production of knowledge in a Fab Lab. However, my study of Fab Labs does not capture change over time, and is primarily concerned with access to knowledge. While I recognise the inherent dynamics of my empirical context, I must apply the IAD to more limited data. For this reason in Chapters 4-6 I keep the original IAD framework diagram with the label of ‘exogenous variables’ and simple feedback mechanisms as specified by Ostrom (2005). While I note its conceptual limitations, it is an appropriate analytical device for my research question and data sources.

My study of the Ultimaker community in Chapter 7 allows the dynamics of endogenous change to be addressed. However, the Ultimaker community is only one part of the overlapping layers of commons communities that influence the operational activities of Fab Labs. A more full analysis of change over time in these communities, in addition to a longitudinal study of Fab Labs at the operational level, would be needed to fully address the above critique.

3.4.5 Data validity, reliability, and generalisability

Here I discuss issues related to the data in this research as a whole, with more of an emphasis on the qualitative data and conceptual integration within the IAD framework. Because of the specific nature of regression techniques used with the Ultimaker dataset, I give detailed attention to issues of quantitative data validity in Chapter 7. I draw attention to weaknesses stemming from the data gathered, as well as ways that my analysis addresses certain drawbacks. More attention is given in Chapter 8 to research limitations.

Data validity is first important to assess. As described by Silverman (2005), validity is a measure of truth and thereby confidence in one's findings. I address this in two main ways. By using the IAD and multitier framework I explicitly include in my analysis a large set of variables that may or may not be strongly related to my outcome of interest. In designing and analysing my interviews, all of the variables listed in Appendix I were taken into account. My main findings, therefore, are based on strong relationships repeatedly described by my interview subjects. Other relationships that were described less repeatedly are noted and discussed in each chapter section. Thus, my research design attempts to achieve 'an integrated precise model that comprehensively describes a specific phenomenon, instead of a simple correlational statement about antecedent and consequent conditions' (Silverman, 2005, p. 21, quoting Mehan, 1979).

One must also address data reliability. As stated by Hammersley (1992, p. 67), 'Reliability refers to the degree of consistency with which instances are assigned to the same category by different observers or by the same observer on different occasions'. I address this point through my research design in the following two ways. First, by way of the nested categorisation of variables within the IAD framework, I am able to obtain an extensive set that minimises reliance on my own categorical inferences (Silverman, 2005). Second, I follow the tradition of careful use of a shared language for describing one's research framework and variables of interest in commons research. This has led to commons researchers being able to engage with each other's empirical contexts that are highly diverse in nature. In adapting the IAD to study 3D printing in the commons, my aim is to allow the reader to understand how each variable considered is related to more general, theorised categories of variables that many scholars have taken into account in their respective commons research. This allows my findings to be more thoroughly related to existing scholarship, and my theoretical contributions to be more accurately assessed.

Lastly, I consider generalisability of this research. The IAD framework is explicitly designed to enable meta-analysis, and indeed grew out of meta-analytical studies of diverse commons environments. Given that I take into account differences in resources and property regimes, community attributes, and nested levels of rules-in-use, the findings presented here can be used as a starting point for inquiry into other commons environments. However, the complexity introduced by layers of resources and their corresponding property regimes signal a corresponding increased risk in generalising. Overall, the area of knowledge commons scholarship is in need of context-specific empirical analysis. This is even more acute in commons settings that interrelate physical and digital resources.

4 RESOURCES IN THE COMMONS

4.1 Introduction

Fab Labs, framed as action arenas for the purpose of analysis, are physical spaces governed by common-property regimes, and are linked with open access digital commons communities. The chapter explores how digital and physical characteristics of 3D printing resources in use relate to access to knowledge about the resources from the perspective of Fab Lab members. As explained in section 3.3.4, I assume that access to knowledge about materials from the perspective of Fab Lab users represents this knowledge being part of the commons.

4.1.1 Guiding question

The main question that guides this chapter is as follows:

What resource characteristics influence whether knowledge about materials enters the commons?

I address this question as follows. To begin, I describe the common-property regime of a Fab Lab, noting specific types of property rights in use. I then discuss 3D printers as technologies within Fab Lab property regimes. By using the typology of goods, one notices that 3D printers are systems that interrelate physical and digital resources that come with varying characteristics. I then analyse the property regimes that govern these types of goods. Second, by employing the distinction between resource facility and flow, it becomes clear that while flows of 3D printing materials are governed within the Fab Lab common-property regime, facilities where materials are made are external. This boundary contrasts to open source hardware, software, and firmware, often produced and governed within a Fab Lab common-property regime or open access commons. I use these analytical tools to explain barriers and enabling factors behind access to knowledge about materials. As a final part of this chapter analysis, I investigate two main sources of disruption to the boundary between facility and flow when it comes to 3D printing materials: these are the use of waste, and the proximity to raw materials. Both subjects have important implications for knowledge about materials entering the commons.

4.1.2 Theoretical concepts

The main theoretical concepts that guide this chapter are (1), a basic typology of goods in a Fab Lab, where common-pool resources are distinguished from public goods, private goods, and toll or club goods; (2), the distinction between common-property and open access regimes; and (3), the distinction between facilities and flows for physical resources, and facilities, artefacts, and content for information resources. These theoretical concepts provide a basis from which to assess the relationship between resource characteristics and knowledge about materials entering the commons.

Figure 4.1 introduces the basic typology of goods formulated by Elinor and Vincent Ostrom (1977):

Figure 4.1: Basic Types of Goods

		SUBTRACTABILITY	
		Low	*High*
EXCLUSION	*Difficult*	**Public Goods**	**Common-Pool Resources**
	Easy	**Toll or Club Goods**	**Private Goods**

Source: Adapted from E. Ostrom and V. Ostrom (1977, p. 12).

Public goods offer benefits that are non-subtractable and are hard to exclude from others; ‘peace’ is a given example (Ostrom, 2005). Common-pool resources, by contrast, are subtractable yet hard to exclude from others, with an example being a forest or fishery. Toll of club goods are non-subtractable while being easy to exclude others from, such as a golf course. Private goods are both subtractable and easy to exclude others from, such as a car piece of cake. This table frames subtractability and exclusion as two ‘attributes of the biophysical and material world being acted upon or transformed’ in action situations (Ostrom, 2005, p. 22). These biophysical attributes are pre-institutional: as Ostrom (2005) states, ‘What actions are physically possible, what outcomes can be produced, how actions are linked to outcomes, and what is contained in the actors’ information sets are affected by the world being acted upon in a situation’ (p. 22).

4.2 Resources in a Fab Lab

4.2.1 Standard inventory

All Fab Labs are organised around a core set of digital fabrication tools. This generally includes a laser cutter and CNC milling machine, one or more 3D printers, mould making tools, a precision milling machine for making circuit boards, and programming tools for making embedded processors[28]. Although this is considered a common set of tools shared by all Fab Labs, the set of tools that Fab Labs have is often locally adapted, and in response to the needs of the community it serves.

Although Fab Labs ascribe to a basic set of software, hardware, and material capabilities, there is no obvious restriction on the variety of tools or materials a Fab Lab may acquire and use. As shown in Figure 3.6, I find that Fab Lab inventories seem to form in response to their community's situation and needs, as well as responding to the dynamics of new machines and materials. One Fab Lab member articulates the thinking that drives inventory choices:

> *We started with a standard Fab Lab…it's super useful for us, this standard laboratory. But of course our goal is how to connect it with our local situation. We need to search, we need to look, this is not previous knowledge, we have to discover it in the interactions with people and citizens. In this laboratory for example I don't know really what would be the best machines or the best instruments and tools, but we are in this process to experiment and to see what really we need.*

In other Fab Labs the inventory is more tightly controlled and monitored. Therefore, in framing Fab Labs as action arenas, it is important to note that there is adherence to a common set of tools across all Fab Labs, although there is some local variation in inventory according to place and purpose (see Figure 3.6 for details).
In this study I focus on the use of 3D printing systems in Fab Labs. 3D printers are prototypical digital fabrication machines, where a computer controls the fabrication of physical objects. Even though emphasis is placed on the use of open source tools in

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[28] See suggested inventory list: http://fab.cba.mit.edu/about/fab/inv.html

the inventory list, open and proprietary tools most often coexist. There is no prescribed inventory of materials for 3D printing systems. This means that for 3D printing in particular, characteristics about materials in use cannot be accounted for by looking at the Fab Lab inventory.

4.2.2 3D Printers in a Fab Lab

3D printers are among the most widespread tools in Fab Labs. One Fab Lab member explains the use of 3D printers as a flexible tool for fabrication:

> *The interesting difference with 3D printers is that there is no tooling cost. You can make batches of different products in 'x' amount, which means you don't have to carry any stock really…[This] makes it very ideal as a base of the pyramid technology…if you can make things locally then you're not paying the cost of transport. The cost of transport in rural environments is massive [and] very unreliable.*

This quote appropriately frames why 3D printers are being disseminated so widely, and why they are becoming widespread in developing countries.

One must set 3D printing systems within the context of their use among the wider set of digital fabrication tools in the Fab Lab. One member explains:

> *Most people use 3D printers for making objects. In the Fab Lab, we [also] use 3D printers for making models for using resin and making composites. You see, people outside of this knowledge see the tools as tools. We see the tools as part of a whole set of tools. And we learn that you use tools in combination to achieve what you want.*

This observation is important, as it changes one's view of 3D printing in a Fab Lab. The following quote from a Fab Lab member continues in a similar vein, describing the use of 3D printers as one tool among a set of integrated machine capabilities in a Lab:

> *Each of these pieces of equipment [in the Fab Lab] has its place: [when] you combine the different pieces of equipment that are available, you optimize the means to manufacture…I don't think that the 3D printer is a Swiss army knife of the Fab Lab, but it does allow particular types of construction…[3D printers] are part of the toolbox.*

The importance of viewing 3D printers as integrated into a larger set of digital fabrication tools lies in the integration between digital and physical resources. In a Fab Lab, tools are selected on the basis of digital interfaces, their ability to integrate with one another digitally. From a practical standpoint, this opens up the potential to fabricate more complex products as users can coordinate the making of their design across different machines.

3D printing materials are typically a type of Acrylonitrile Butadiene Styrene (ABS) or Polylactic Acid (PLA) plastic filament (a spool of plastic wire that feeds into the heated nozzle of the 3D printer). These are the generic plastics used across all low cost FDM 3D printers. The following quote from a Fab Lab member puts the current landscape of 3D printing materials in perspective:

> *It's early days of materials. The explosion of 3D printing was to do with a particular type of method being opened. So everyone started with PLA and ABS but after a year or two of that, we suddenly see the emergence of new materials that give quality, flexibility, different colours.*

This new range of materials is being tested and experimented with in various Fab Labs. The range of materials present most often depends on whether users bring in new materials. In answer to the question of what materials are present in the Lab, one Fab Lab member states,

> *Oh, we do with what we have in our hands. If some visitors come and want to give us some material, they can.*

This means that the range of materials often depends on what is available in the surrounding community. In general, Fab Lab members can bring in, access, use, extract, and decide on materials resources.

4.2.3 Categorising types of goods

I now turn to categorising different types of resources in a 3D printing system. Whilst Figure 4.1 illustrates the classic typology developed by Vincent and Elinor Ostrom (1977), Figure 4.2 adds in institutional attributes that affect the way these goods are used in practice.

Figure 4.2: Typology of Goods in a Fab Lab

		SUBTRACTABILITY	
		Low	*High*
EXCLUSION	*Difficult*	**Public Goods** Open source software Open source firmware Open source hardware designs	**Common-Pool Resources** 3D printer hardware 3D printing materials
	Easy	**Toll or Club Goods** Machine time Proprietary software Proprietary firmware Proprietary hardware designs	**Private Goods** Individual’s 3D printed objects

Source: Adapted from E. Ostrom and V. Ostrom (1977, p. 12).

One can see that 3D printers in Fab Labs are a mix of public goods, common-pool resources, toll and private goods. This is a combination of biophysical attributes, as well as institutional rules-in-use. For example, 3D printers that are 'open source' usually are made with hardware designs, software, and firmware that are hard to exclude others from because of their open source licensing. Closed-source, or proprietary 3D printers involve hardware designs, firmware and software that are toll goods, meaning they can be excludable but are not subtractable. For both open source and closed source 3D printers, materials and physical hardware components in use in a Fab Lab can be categorised as common-pool resources or private property, depending on ownership. This categorisation is a matter of degree. As Hess and Ostrom (2003) maintain, such divisions between types of goods is at best a useful heuristic. Many grey areas exist, and categorisation is mutable.

4.3 Governing Physical and Digital Resources

It is important in any commons analysis to differentiate between the characteristics of the governance regime, and the characteristics of the resources being governed. This is because the category of the good being studied can change according to types of property rights. For example, open source software resulted from an innovation in licensing that made it possible for software to become a public good rather than a toll good. 'Copyleft' can be understood as a common-property regime determining the rules of use (Schweik, 2007), and in doing so, altering the category of the good itself.

Here I describe the nature of common-property regime governing Fab Labs and then introduce how this relates to the types of goods being governed. I introduce variation in property rights present for different resource in use: access, extraction, management, exclusion, and alienation (Hess & Ostrom, 2003). In particular, I focus on property rights present for resource flows versus resource facilities. I then examine the different dilemmas that arise from the perspective of Fab Lab members when using these resources. I find this clarifies observable differences in the governance of physical and digital resource.

4.3.1 Fab Labs as common-property regimes

The Fab Lab charter[29] is a document describing the general ethos and rules of Fab Labs. The full document can be found in Appendix II. Members of the Fab Foundation and individual Fab Labs originally wrote this in 2004. This document acts as a check for new Fab Labs seeking to join the network. Although there is no sanction for not following the charter, Fab Labs who do not ascribe to its rules are not generally included in the curated list of Fab Labs, managed by the Fab Foundation. Three particular rules of community use are important to note here:

1. Fab labs are available as a community resource, offering open access for individuals as well as scheduled access for programs;
2. Designs and processes developed in Fab Labs can be protected and sold however an inventor chooses, but should remain available for individuals to use and learn from; and,

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[29] http://fab.cba.mit.edu/about/charter/

3. Commercial activities can be prototyped and incubated in a fab lab, but they must not conflict with other uses, they should grow beyond rather than within the lab, and they are expected to benefit the inventors, labs, and networks that contribute to their success.

The rules relate to many of the five categories of property rights identified by Schlager and Ostrom (1992) as being important for commons analysis: access, extraction, exclusion, and alienation. To understand these rules in use, it is important to reflect on them from the perspective of Fab Lab members.

Fab Lab users often express the rule of open access to the community as the need for users to learn about the tools themselves rather than out-sourcing a project to another member. A Fab Lab member explains:

> *Under the Fab charter, talking about rules, as loose as it is, it says anybody should be able to come in to any Fab Lab and use it…we want that…So they come in, [and] a lot of them say 'I have this idea please make it for me'. And I say 'well it doesn't work that way, you have to do it yourself…if you can't, you have to pay us to do it'.*

This quote makes it clear that although the Fab Lab is open access, the human resources available for making things is scarce. As a consequence, along with a rule of access comes a rule of responsibility for one's own work.

Closely related is the rule to contribute and help out other members of the lab. As stated in rule number 2 from the Fab Charter, there is a general rule about sharing and contribution to the community. One Fab Lab member describes this rule being explained to newcomers to the Lab:

> *Every time we meet somebody, we tell them that all this is great, this is fantastic, you can have all this for free, but…you pay with your willingness to tell other people about how stuff works.*

Again, there is the reference made to access in exchange for a commitment. While the first quote states a commitment to self-sufficiency, the second is a commitment to helping others in the community.

Exceptions to these rules of open access and commitment are often made for businesses. Many Fab Labs take orders from businesses, making prototypes for them in exchange for payment. One Fab Lab member explains:

> *If we have someone who works only for [a] company, we can teach them how to use the machine. [Or] we can do [the project] for them, [but] it's more expensive: you pay the price of the machine and you pay people who do the designs. It's not the goal of the Fab Lab to do this, but we can get some funding like this.*

This is clearly an exception to the commitment to self-sufficiency, yet is compensated by payment. The second rule, relating to the availability and use of designs produced in a Fab Lab, is ambiguous. The ambiguity comes from the Fab Lab charter rule statement that the 'designs and processes can be protected and sold however an inventor chooses, but should remain available for individuals to use and learn from'. Clearly, if an inventor patents a design developed in a Fab Lab, it runs counter to the idea of being available for the use and learning benefit of others. This is where an exception for business users is often made. Many businesses sign Non-Disclosure Agreements (NDAs) with Fab Labs so their designs and processes will be protected. In exchange, these businesses usually pay for the service of using a Fab Lab like a commercial prototyping facility.

The third rule cited here from the Fab Lab charter directly relates to the regulation of business use in the Lab commons. A Fab Lab member explains how this rule works in practice.

> *We have this rule…you can start the business within the Fab Lab, [and] your businesses [can] grow out of the Fab Lab, but you cannot depend on the Fab Lab for your business. If you wanted to start a 3D printing [company], you cannot say 'I'm going to print everything in the Fab Lab and occupy the 3D printer'. You're not supposed to occupy the machines only for your business…They [must] buy their own to start their own business.*

Again, the issue of scarce resources can be seen as the underlying rationale. A business cannot 'occupy' the Fab Lab's machines. Logically, this accompanies the rule of open access that allows entrepreneurs to incubate and develop their ideas, without overextending the capacity of the Fab Lab to provide services for others.

Overall, I find that these rules of community use and appropriation are generally adhered to. Very few people complained of community members or businesses exploiting the resources held in common. The distinction between community users and business users may suggest a hierarchy of rules. This is carefully managed. Fab Lab rules are clearly designed to balance inclusion with reciprocity. If a business uses the Fab Lab's machines for private gain (not community gain), it pays for the use of the machine. A community member does not need to pay for the machine, yet he or she is expected to 'pay' in their willingness to share knowledge with others. Although community and business members have differential terms of access and use, Fab Labs on the whole are governed as common-property regimes. I now look at how this common-property regime interacts with 3D printing materials in a Fab Lab.

4.3.2 Governance of types of resources in a Fab Lab

Although rules pertaining to the governance of digital and physical resources are not are not set down in the Fab Lab charter, interviewees expressed a general set of rules for the use of physical resources. These are, (a) if community members bring their own materials, they don't need to pay for any fee of usage; (b) if community members use materials supplied by the Fab Lab, then they pay for the amount they use, and (c), businesses pay for both materials (unless they supply their own) and machine time. I found no variation in Fab Labs applying these rules.

As such, Fab Lab members typically possess the property rights of access, extraction, management, and exclusion over physical resources. For example: Fab Lab members may access materials in a Fab Lab, extract them for the purpose of personal projects, help with the management of inventory, and contribute to exclusion of certain types of members based on their intended use of materials in the Fab Lab (for example, if the user does not respect the rules of the charter). Regarding *alienation*, Fab Lab members do not have the right to sell or lease management or exclusion rights regarding 3D printing materials. The presence of the first four rights, but not the fifth, is the mark of a common-property regime (Hess & Ostrom, 2003). These characteristics of the common-property regime were found to be sufficiently general to all Fab Labs studied. Thus one can usefully categorise 3D printing materials in use in a Fab Lab as common-pool resources.

Digital resources are governed differently due to their underlying nature. If open source, they are public goods that are both non-subtractable and non-excludable. As such, their rules of use are not specific to Fab Lab common-property regimes, instead involving rules associated with open source licensing and the wider set of norms in their respective use and development communities[30]. If the digital resource is proprietary, such as with some types of 3D printing software, the resource is governed as a toll good. The individual Fab Lab, or in some cases the Fab Foundation[31], purchases or negotiates a license of use from the private company offering the software. However, for 3D printing overall there is a greater interest and emphasis on using open source digital resources. For this reason, when referring to digital resources in a Fab Lab, I primarily frame them as public goods.

4.3.3 Digital and physical resource dilemmas

Differences between digital resources like open source 3D printing software and hardware designs, and physical resources such as 3D printing plastics, are very much understood by the Fab Lab members. For example, a Fab Lab member articulates the idea of subtractability as a core difference between information and physical resources as follows:

> *Access to the know-how to make something is very different to the access to that something. It's the source code, the idea that can be transferred. We're really talking about knowledge transfer versus material transfer. I can close and restrict access to an idea. [But] I*

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[30] While open source communities intersect with Fab Lab communities, the rules and norms associated with open source software, hardware, and firmware communities are beyond the scope of this analysis. Chapters 6 and 7 do provide further context on open source 3D printer use and development.

[31] In 2015 The Fab Foundation negotiated a free license with Solidworks for any Fab Lab using the modeling software.

> *think the idea shouldn't be under a kind of false scarcity, or an imposed scarcity. The materials are scarce. So in that sense, it's not imposed, it's real scarcity. That can be measured…organised, managed.*

The well-understood common resources dilemmas of overuse of physical resources, and under-provision of information resources, emerge from this passage. The Fab Lab member goes on to explain how different dilemmas of resource use emerge with the advent of digital fabrication in a community commons:

> *The open source or collaborative economy was born out of the sharing of software. So now we're talking about the sharing of hardware or the sharing of designs - designs to be then made into products. When openness, open to use, turns into a material thing, we've got a slightly different deal because those materials are finite, they're often resources which have issues of scarcity, and it touches the real material economy. For us…we can think of the [Fab] Lab as a commons, as a place for everyone to investigate, to use. But what we don't want to engage with is the tragedy of the commons, where it's overused, where there's depletion. You get overuse and overshoot. So I think yes, we must have open access to information. But be intelligent about our resource use. I don't think they're mutually exclusive, [rather] different aspects.*

These views express the importance of considering the different types of goods and the ways they are governed. They also underline the need to pay attention how digital and physical resources are related in the process of digital fabrication, and the corresponding dilemmas of resource use that emerge.

Although one can theoretically differentiate between types of goods in use in Fab Labs, and their regimes of governance, *in practice* the boundaries between categories are often less clear. By definition, digital fabrication is a hybrid of types of goods. It is interesting to note that Fab Lab members also grapple with definitions of resources and property rights. One Fab Lab explores this in the following passage by using a forest as an example:

> *A resource is only a resource once you've defined it as such. Which is ownership of that thing - we could call it collective ownership. But, is a…tree a resource? Well it is once we've decided to make use of it…This is what we do, as a species, as animals, we make use of the things around us. But then is biodiversity a resource? I would like to think of the forest as a library, as an information library and the biodiversity in it as the resource system. So if you take out one component of that and say that's the most valuable thing and I'm going to use all of that, are you then depleting the rest of the resource which is the living system as a whole?*

One can see that this member is contending with the definition of a forest as containing physical as well as information resources. The passage also draws attention to the dilemma of how the use of physical resources can have an impact on information resources from the same resource system: while information is non-subtractable and trees are subtractable, both types of resources can be drawn from a biodiverse forest, and are thus interdependent.

4.3.4 Physical resources: distinguishing between resource system and flow

To clarify the dilemmas articulated in the last section, it is useful to distinguish between governance of the units of materials present in a Fab Lab, and the governance of the system within which those units are produced. In traditional commons theory, scholars distinguish between the governance of resource flows and resource systems to help analyse common-pool resource dilemmas. Often, scholars find that the root of common-pool resource dilemmas is in the different regimes of governance operating upon the resource flows versus resource system (Hess & Ostrom, 2003). For example, control of a forest or lake resource may be in the hands of a government or a private corporation, while the flow of logged trees or fish may be used as a commons by local communities. Such as disjunction between the governance of facility and flow is often linked to issues of exploitation based on the lack of information that centralised actors have about local flows known to the community (Ostrom, 2005).

My study offers to extend this core idea by looking at how the exclusion of resource systems that produce 3D printing materials impacts how Fab Lab users access knowledge about materials for productive purposes in the Fab Lab common-property regime. Although the most common 3D printing materials are synthetic plastics, rather than natural resources such as forests or fisheries, they can be treated as common-pool resources within the context of a Fab Lab, and as such, the analytical device of distinguishing between resource system and resource units can be applied.

3D printing plastics are made from crude oil or natural gas that are carbon-based, or a type of starch such as corn or potato that is biologically based. Polymerisation is an industrial process that takes monomers (molecules chemically processed from crude oil, natural gas, or starch), and transforms them into polymer resins (macromolecular chains of monomers), through chemical reactions. For FDM 3D printing, these pellets are then processed into long strands of filament. Filament companies often buy raw plastic pellets that are colourless and have specific base properties that can be added to with chemicals to produce properties specific to 3D printing extrusion processes. These are additives such as dyes, plasticizers (e.g. solvents that increase flexibility of the polymer resin), and other specialised chemicals. The high capital cost involved in such production processes means that high economies of scale characterise the plastics industry. As a result, large, private industrial companies dominate the production of primary resources for 3D printing.

In sum, while acting under a common-property regime, users of Fab Labs have the rights to access, extract, and govern the provision and use of 3D printing materials present in the Fab Lab. Yet Fab Labs contain flows of material units, not resource systems where the materials are produced. Although the flow of resource units is common property, the facility that produces these units (e.g. a plastics manufacturing plant), is external to the Fab Lab's common-property regime.

4.3.5 Digital resources: distinguishing between resource facility, artefact, and content

The governance of 3D printing materials, as physical resources, can be contrasted with the governance of information resources, such as open source software and hardware designs. For analysis of information goods in the digital domain, Hess and Ostrom (2006) note that the simple distinction between resource facility and resource flow needs to be expanded. They introduce a threefold distinction between:

- Facility: the resource system that stores artefacts and the information they contain and make them available, such as optical fibres, wireless routers, bandwidth, computer workstations, and databases[32];

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[32] Note the ambiguity here in categorising a database as an artefact and/or a facility. Databases can contain simply information content and ideas. They can also store other artefacts such as webpages. This dual role is noted in Hess and Ostrom (2006).

- Artefact: discreet, observable flow units from an information facility such as a web page, database, or computer file; and,
- Content: non-physical content of artefacts such as thoughts, design ideas, diagrams that may or may not be protected by Intellectual Property rights.

With respect to Fab Labs, information facilities, artefacts, and content can be seen to intersect with and be included in Fab Lab common-property regimes. A Fab Lab will commonly own information facilities such as computer workstations and wireless routers, used to produce artefacts such as software code, or CAD files for hardware designs. The content within these artefacts (designs, thoughts and ideas) are often licensed formally under creative commons, GNU or copyleft, and are often shared within the Fab Lab community.

Comparing physical and digital resources, the following observation can be made: while both information and physical resource units are governed under a Fab Lab's common-property regime, governance over the *production* of those resource units differs. Physical resource systems are not part of a Fab Lab's common-property regime, many important information resource facilities are.

I now turn to analysing how Fab Lab users access and use knowledge of materials. As will be discussed, the exclusion of resource systems governing the production of physical materials from a Fab Lab's common-property regime has interesting implications for access to and use of knowledge about these materials.

4.3.6 Impact on access to knowledge about materials in the commons

Many Fab Lab members express the realisation that resource production facilities for making 3D printing materials are not within the control of their communities. As one Fab Lab member articulates,

> *Hard core capitalism is all about control…If you're going to be unique in what you bring to the market, you also need to control the materials. So there's big incentives for lots of people to get exclusive access to materials, knowledge of materials, processing them.*

Fab Lab members commonly express lack of information as a lack of control. Referring to companies that make 3D printing filament, another Fab Lab member explains:

> *These people have their own patented way of producing a plastic. The way of making PLA is, for example, well known. Okay, you've made PLA, now you've got to somehow turn it into granules that can be shipped. And all the little processes that form those granules, and rehydrate those granules so they flow in the machine, they're all proprietary. We don't have any control over them.*

The reality that the companies that make 3D printing materials are generally not part any common-property regime proves important for access to knowledge from the perspective of Fab Lab users. The following statement from a Fab Lab member illustrates:

> *Printing material is very out of control. Most of what we use is [bought] from Amazon, from China, from somewhere outside of [the*

> *country]. It's anarchy. [When] we buy this material from Amazon and open it, [there is] no information.*

A complete lack of information about materials sources for 3D printing is not necessarily the case. One Fab Lab member expresses a more varied picture of information about materials coming into the Lab:

> *Usually [Fab Lab users] know where they got [material] from…If they don't bring the specs, you can look it up. Most resellers or manufacturers provide some information, but a lot comes with experimenting. So for this standard ABS and PLA stuff, it's pretty easy, it's settled and the quality of the materials is quite consistent. But for the new stuff that comes out, nobody really knows and it's a lot of trial and error.*

This quote shows that there are ways that users access behavioural knowledge about material properties through use and experimentation. More explicit information, such as chemical composition or material properties, may not be disclosed. In this way, certain types of knowledge about materials are out of the control of users.

There are often reasons why companies that control the production of 3D printing materials would not want to allow users access to certain types of information. One Fab Lab member responds to the question of whether knowledge about making 3D printing materials can be accessed:

> *No, it's out of our hands. People who compound the colours, for example, have their own method of doing that. The extrusion people are not very keen on sharing the secrets of exactly how they maintain this very high quality.*

Quite apparently, users of 3D printing materials in a Fab Lab are not privy to the ways the material is produced, and its designed behavioural parameters. In a statement referring to fellow users of a Fab Lab, another member states, 'if the material is a raw material, they know everything about it'. This is critical, for knowledge about raw materials relates to the resource systems where the raw materials are first processed; that is, the private companies removed from a Fab Lab's common property regime.

Lacking knowledge of 3D printing materials can have significant impact for fabricating objects. The importance of accessing deeper levels of material processing and production knowledge is evident in the following quote by a Fab Lab member:

> *[If] the material is a raw material they know everything about it. If you don't know the types of plastics, you can't work with plastic. This is how it is. You have to understand the material to be able to work with it. So the more you know about the material, the more you'll work on it. The more you know, the more you experiment.*

Access to full knowledge about materials is linked to activity in a positive feedback loop: 'the more you know about the material, the more you'll work on it. The more you know, the more you experiment'. A lack of knowledge from the exclusion of resource systems imposes a restriction on experimentation and therefore, access to knowledge in the Fab Lab commons community.

From the views expressed here, one can see that access to, and control over, resource systems related to 3D printing materials is limited from the perspective of Fab Lab users. Information gets even more remote when users buy materials through online marketplaces rather than directly from materials suppliers. By contrast, Fab Lab communities do govern the flows of material used in the Lab. There is a marked difference between the governance of flows and facilities with respect to the Fab Lab’s common-property regime.

This finding is intriguing from the perspective of much of common-pool resource scholarship. Hess and Ostrom (2003) observe, ‘It is frequently the case that the resource system is jointly owned, while the resource units withdrawn from the system are individually owned by appropriators’ (p. 121). This applies to common-pool resources such as fisheries and forests. In the case of 3D printing materials in Fab Labs, however, one sees an alternative outcome: here, the resource system is privately governed, while the units are governed under a common-property regime. As such, there are no apparent dilemmas of over-extraction of 3D printing materials as common resources in a Fab Lab, given their rules of access, extraction, management, and exclusion. Yet, there is an apparent lack of knowledge within these common-property regimes about the resource in flow.

The main implication of the exclusion of resource systems producing 3D printing materials from a common-property regime is lack of knowledge, specifically *knowledge about materials*. In answer to my main research question, I find that the exclusion of material production systems is an important barrier to accessing knowledge about materials in the commons. I now explore how users are disrupting the boundary of the common-property regime when it comes to knowledge about materials.

4.4 Sources of Disruption

One main reason explaining why the production of materials remains largely outside of the common-property regimes of Fab Labs, leading to a lack of access to knowledge, is that large economies of scale dominate the production of plastic polymers for 3D printing filament. This means that large companies control the supply of materials, and can, therefore, control the knowledge associated with the materials through patents and trade secrets.

However, many Fab Lab users do not accept that materials need be excluded from the commons. One Fab Lab member articulates the concern about materials well:

> *When we think about what is happening in our labs…a question remains at the core: the materials, what are the materials, where are they coming from, all of the resources we are using. We are talking about personal fabrication but maybe we also have to think about personal material production - how to make it. In a typical project in a Fab Lab we spend a lot of material and we don't know where these materials are going. So how could we develop not only personal fabrication, but personal material production and personal recycling systems?*

The question of what the materials are and where they are coming from leads the Fab Lab member to think about how and where these materials are made. This introduces the main ideas of this section: how the separation between resource flow and resource system is being disrupted in important ways, leading to new access to knowledge about materials. I find this is taking place through the use of waste as well as proximity to material facilities.

4.4.1 Waste as a common-pool resource

The use of waste for 3D printing materials seems to be disrupting the exclusion of resource production systems from Fab Lab common-property regimes. Three main characteristics of waste explain this. First, waste is almost universally accessible. For Fab Labs that are resource constrained, waste is a cheap and available source of material for digital fabrication. One Fab Lab member explains:

> *With really poor communities that are far away, they're starting to see what they need, and that's why they said, okay we have a lot of garbage, what can we do with it? That's the way they started.*

Waste is even accessible within the Fab Lab. Speaking about waste produced by a Fab Lab, one member states: 'Because there's a lot of waste, trash that comes out…we really need to start thinking about how we turn those outputs back into inputs'.

The second characteristic is about access to material *value* at an appropriate level of community organisation. Many Fab Lab members see waste as a valuable resource for the Fab Lab. Recognising the value of turning waste materials into new materials, one Fab Lab member remarks, 'We need to set up a structure for recycling materials in order to produce new materials'. Another Fab Lab member articulates the value of local 3D printing from waste in a globalised economy where value does not currently accumulate at a local community level:

> *The global demand for recyclable plastic far exceeds the supply. So internationally there are massive demands for recyclable polymers…I suspect that at the base of the pyramid where recycling is going on, what is happening is plastic is being collected very cheaply and then*

> *it's being moved upstream to a point where it can be shipped back into the global manufacturing process. China is a massive buyer of industrial quantities of recyclable plastic…So the value is taken away from the point of which plastic is gathered. And then more value is added in a production process that takes place somewhere else. Then the value added product is shipped back into the very place that the waste came from. What 3D printing does is it actually enables local production to take place at a scale that makes sense, at a cost which makes sense even in the poorest of countries. You're able to put the manufacturing process right up next to the source of the raw material, and right up next to the potential buyers of the finished goods. So that's why it's an interesting technology.*

In this quote lies a direct challenge to the idea that resource production systems are by definition excluded from Fab Lab common-property regimes. By turning this waste into a resource locally, value can be added at a local level.

A third characteristic is access to information about waste materials. In recycling, information can be generated when waste is processed and tested. One Fab Lab member explains the making of new 3D printing filament from recycled materials: 'The materials are proprietary but for [new] filaments we are studying recycled materials'. Making a similar point, another Fab Lab member states 'We must be looking at…our waste as a material library'. It should be kept in mind that there are particular issues with accessing information from waste. These will be discussed in the following section.

There are numerous examples of how Fab Lab communities are using local waste as a resource. The type of waste in use is most often a function of what is freely available. One Fab Lab member comments, 'we have a lot of dumps of e-waste, so you get a lot of e-waste for projects'. This particular Fab Lab is fabricating

3D printers from e-waste. Another Fab Lab member describes turning Polyethylene Terephthalate (PET) plastic from soda bottles into 3D printing filament:

> *[The Fab Lab] makes the whole community wash their own PET and categorise it by colour so…the PET is already clean and ready to start making filament. They're working with the filament to make it [in] a grade that you can actually sell…The whole idea is to start selling this filament to all the Fab Labs so we're actually working with [materials] that we're recycling.*

As a ubiquitous waste product, PET plastic is readily available around this community.

In order to turn waste plastic into filament, particular machines are being developed. One Fab Lab member states:

> *There's some absolutely wonderful technologies out there that allow us to reuse plastics for example…I'm thinking of the filamaker*[33] *and the filabot*[34] *which chop up thermoplastics to then extrude them into filament again to remake products.*

Waste materials, in effect, are a supply of new materials, with the supply of raw inputs and the technologies needed to transform them controlled by the Lab community. These examples all point to the disruptive potential of waste: bringing resource production systems, where flows of materials are generated, within the governance regime of the Fab Lab commons.

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[33] See http://filamaker.eu

[34] See http://www.filabot.com

Although there is widespread interest in waste, and increasingly technologies are being developed to transform it into a usable resource, many barriers remain. Broadly, these barriers have to do with the technology to deal with numerous waste materials, the quality of the materials produced, and access to knowledge about the raw waste material itself.

Although materials such as PET and other thermoplastics can be processed into 3D printing filament, there are numerous sources of waste that still lack a viable low-cost recycling solution. The following statement by a Fab Lab member explains this well:

> *It's actually quite difficult to recycle materials that have been produced through some fairly complex chemical industrial processes…the processes required to undertake that recycling are quite complex and expensive.*

The Fab Lab member goes on to explain:

> *What we need to do is to find ways in which we can broaden the range of materials we can recycle at an appropriate level of technology. How do you take that $100 million recycling plant and scale it down? I think that's the critical thing.*

The issue of technological cost and sophistication is closely linked with the quality of the resulting resource such as recycled 3D printing filament. While melting or grinding the waste and extruding it into new filament may be mechanically possible, the resulting properties of the filament may be problematic for use in high quality fabrication. The following quote by a Fab Lab member illustrates how the use of recycled waste for 3D printing is an active learning process:

> *We just showed it was possible to put all this different kinds of waste through the printer…we discovered what works and what doesn't… Now that we're moving on to really selling products, quality control becomes much more important.*

Even though there are barriers in terms of quality, the learning that comes from working with local sources of waste and turning it into 3D printing filament is most certainly enabling access to knowledge about materials in Fab Labs. Furthermore, as illustrated by the following quote, it is important to note that industrial quality may not be the necessary standard for all fabricated objects. One Fab Lab member explains,

> *[Assessing quality] depends if you're going create a prototype, if it's going to be a test thing or [a final product]. A lot of 3D prints don't have a very long lifetime, and half of them they fail, so why not print those with recycled material? And then the final one you can print with the best quality material.*

This quote highlights the contingency of material quality. In effect, quality is dependent on the use of the material.

Quality control is often a direct result of a much broader issue with waste: lack of knowledge about composition and behaviour. If these properties are not known, it is difficult to ensure that a particular quality filament results from the recycling process. Although the contingency of quality on the intended use of the material implies that sometimes the user may not need to know, there are nonetheless significant issues that remain. One Fab Lab member describes the concerns that must accompany the production of 3D printing materials with waste:

> *[At the] industry they have to have certifications…if we're going to sell the filament, a father is going to print some toys with it for his kids, and the kid is going to put it in his mouth, we're really looking at compliancy certifications to make sure that we know what's in the filaments.*

This statement frames the particular dangers that could result when information about waste materials is unknown. Another Fab Lab user articulates this issue in more detail:

> *Computer monitors, which are made from ABS, are sprayed inside to prevent or reduce the impact of heat has on the monitor. Now I don't know what that spray is. I sure don't know [what happens] when you try to turn a monitor case into pellets and then try to turn it into filament. But my guess is if the monitor is being sprayed with some chemicals there's going to be some toxicity associated with it. So as the interest in recycling polymers for 3D printing grows, in situations where, for example, plastics are treated, it will become more and more important for it to be very evident and visible that the treatment has taken place and for there to be clear guidelines are to what materials can be used for their recyclability.*

These views make it is clear that using waste does not fully address the issue of knowledge that is excluded from the common-property regime; indeed, knowledge can be obscured further as the link to the original supplier is lost. Because waste was initially produced as a private material good, much of the knowledge of composition and behaviour is hidden from those who appropriate the material after it is thrown out.

However, waste remains attractive given ease of access to material value at the level of the community. Partial knowledge benefits come from recycling and testing processes. It is, however, misleading to think of waste as fully within the control of a Fab Lab's common property regime from a knowledge perspective. I now look at the second source of disruption: efforts to create *new* materials within Fab Lab common-property regimes.

4.4.2 The disruptive influence of resource proximity

As explored, plastic production is highly industrialised. However, there are an increasing amount of smaller companies starting to produce filament from base polymers, creating their own recipe for tailored 3D printing markets. A Fab Lab member describes why choosing to buy filament from local suppliers is preferable:

> *At a certain point we started buying cheaper 3D filaments, the Chinese stuff that's mass-produced, shipped everywhere. And we started having even more problems because the filament thickness is not the same. It goes from 3 to 2.8 to 3.1 mm. So we end up buying it from Ultimaker or a local guy who has it made [here], we know where it comes from - just does not have the issue.*

The statement 'we know where it comes from' underlines the importance of having more knowledge about materials in use. Quality and cost drivers are also cited in the following example where a Fab Lab member describes an emerging relationship with a new local filament producer:

> *You can buy printing material from MakerBot, but it's expensive. So we buy from 4 to 5 different web shops, and now we also work with a local manufacturer of filaments. They were setting up their machine and developing materials over the past 6 months. And now the quality is pretty good. So we actually now plan to start selling that filament. And it's cool because you can get custom colours or things pretty quickly.*

In this statement one sees a mix of other motivations for bringing a step in the chain of material processing closer to the Lab. Quality and cost are factored into the decision. Yet there is also the attraction of being able to 'get custom colours', giving Fab Lab users a new level of control over the 3D printing filament they use.

A third example highlights the benefits of local sources in different way. Coming from a highly professional Fab Lab, serving primarily an entrepreneurial and business-minded community, one Fab Lab member describes the relationship to a local filament producer:

> *In terms of recycling, it's very easy. The person who makes the material comes to your lab and delivers the stuff, and you just give them a bag with trash and they can recycle it. You can always use a percentage of old filament for the new.*

The terms of this relationship are stated as simple and profitable. The local material producer has an incentive to collect waste filament from the Fab Lab because the material characteristics are known. Increasing knowledge about materials in a local area can benefit both material producers and consumers.

Although there are an increasing number of local filament producers, I found no evidence of Fab Labs manufacturing base polymers for 3D printing filament. The reasons given are the cost, patented knowledge, and technological sophistication associated with polymer production.

Despite these barriers, there are clear examples of Fab Lab users making interventions into particular steps of materials processing in order to shape materials for local use. The separation between different steps in the process of producing materials seems to allow such interventions. In the quote below, a Fab Lab member describes being teamed up with students who had access to plastic pellets from a local polymer manufacturer:

> *I saw [the students'] extrusion machine and I was like, you can make filament with that machine! And actually what they were doing, they were extruding foil [from plastic pellets]…I was like, can you ask this guy from the workshop whether you have a cylinder extrusion nozzle for it? Now I'll please start extruding filament instead of foil.*

This particular project did not stop with changing the nozzle. Rather, the Fab Lab sourced a different type of raw plastic pellet from the company for the purpose of filament extrusion. The Fab Lab member explains:

> *We changed the pellets. First we were using the pellets made for foil extrusion which means that it didn't really flow well [in the 3D printers]. Later we tried pellets that are meant for injection moulding. [These] will drop easier or will get more fluid when it warms. So that's what we had to find out.*

This story exemplifies how decomposing the plastics processing chain can allow local actors to intervene and tailor a material for local use. In this case, Fab Lab actors took a base polymer intended for injection moulding and extruded it into 3D printing filament. Although the composition of the base polymers is still not known by Fab Lab actors, intervention further back in the chain of material processing results in access to *more* knowledge about the material being used in commons-based 3D printing. These can be thought of as efforts that bring knowledge of materials closer to a Fab Lab's common-property regime.

This particular story is also is an example of the partnerships that can be created when Fab Labs are close to the facilities where materials are being produced. The polymer producer, the school doing experiments, and the Fab Lab with 3D printing tools were all in the same locality. The proximity to local partners greatly enabled connections to be made.

Fab Lab members are beginning to experiment with creating new raw materials for 3D printing, although the result is thus far rudimentary. Experimentation with new materials often seems paired with local natural materials; that is, materials not derived from synthetic chemicals. One member states, 'We have many different [types of] algae. And we are experimenting now how to create our own plastics'. Partnerships between 'Biohacker Labs[35]' and Fab Labs are resulting in new attention to materials that can be 'grown' with the help of living organisms using biosynthesis techniques. It is important to note that these efforts to produce and synthesise new materials are highly experimental, and are far from the idea of providing a viable resource system for materials production within Fab Labs.

However, for this research it is important to pay attention to the underlying rationales for why Fab Labs are experimenting with making raw materials from natural sources. Primarily, it seems that knowledge is acquired by proximity to

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[35] See http://diybio.org

natural resource systems. The following quote from a Fab Lab member illustrates this:

> *[The Fab Lab is] essentially surrounded by a very large pine forest.... The upper canopy of the forest is pine, and then you have oak below that.... We are interested in seeing how we can use those pines in an intelligent way. So we're looking to refract and distil the [pine] resin into its different chemical components. Some of those we've realized are photo-sensitive, photo-reactive.... [We] bring it back to the Fab Lab and we can then print with those in terms of stereolithography [3D printing]. It's quite exciting...we can even have wood filament that goes through a 3D printer.*

This quote clearly communicates the knowledge of local resource systems, and the ways that this knowledge can be used for production. Fab Labs are found in a diversity of locations around the world. Therefore, the resource systems that Fab Labs are proximate to vary widely. The following quote from a Fab Lab member explains how knowledge comes from proximity to a variety of natural resources:

> *[What material is used] depends how people understand this material. For example, you see a lot of cultures, they work with wood. And they love the wood, and they know all types of wood, like Europe because they have trees. We don't have the trees so we don't know anything about wood...we've never been exposed to different types. We know chemicals because we have a lot of oil that we can extract chemicals from.*

In this Fab Lab, the fact that users were more comfortable working with oil than wood is related to the proximity of the particular type of resource system. The example of oil as a local resource system is also interesting. Given its use as an international staple of industrial production, one can forget that it comes from specific locations: locality can still matter in terms of knowledge of and familiarity with such resource systems.

These views support the idea that being close to facilities where materials are produced can increases the likelihood of access to knowledge about materials in commons-based 3D printing. However, abundance can be a disincentive for learning and experimentation. In answer to the question of whether 3D printing filament is made in the Fab Lab to accompany printers that are made there, one Fab Lab member exclaims:

> *'I cannot make everything, I wish!' I get free filament all the time. Filament producers come to me and say, test this, test this! I have tons of filament I haven't tested. Filament is not a problem for us right now.*

This quote signals an inverse relationship between abundance of materials from outside of the Fab Lab, and the interest in making materials. This is even as knowledge is being accessed through the testing of filament. Knowledge of materials is, therefore, a graduated concept: one can have *partial knowledge,* and interestingly, that partial knowledge may be a disincentive to acquire more in some cases.

In sum, Fab Lab members are clearly starting to disrupt the boundary between resource flow and resource system when it comes to material resources. This is happening through intervening at particular points in materials processing, as well as nascent attempts to create new materials from natural resources. In both cases, proximity to a resource production system seems to help enable knowledge about 3D printing materials entering the Fab Lab commons.

4.4.3 Use of digital resources

At a time when digital fabrication technologies are changing and disseminating so quickly, it is extremely difficult to state with any certainty the influence of digital facilities, artefacts, and ideas on physical resource systems and flows. Given this, some Fab Lab members frame the use of digital facilities as disruptive to physical resource systems in interesting ways. Two main examples of this are the ways digital technologies can influence the management of knowledge about physical materials, and disclosure of information about physical resource systems.

The Fab Lab itself is a digital facility, storing and providing access to information artefacts and content. By storing and providing access to knowledge about resource systems, it becomes possible to manage physical resource systems in new ways. Relating back to the example of the pine forest for sourcing resin for 3D printing, one Fab Lab member explains:

> *We don't want to overuse the resources we have. So if we are looking to design a solution, we must design material factors into whatever [technology] we are engaging with…. Maybe we also design a tap for the resin that comes out that monitors the tree and allows us to only take as much as we can from that tree whilst it still lives.*

This provides an example of using information facilities such as data monitoring devices to better control a resource system in use. Another Fab Lab member looks at how simply disclosing information through the use of digital facilities, artefacts, and content be used to impact resource systems in a locality:

> *Open knowledge can have disruptive possibilities. Just making a map of your town [with] all the hardware stores and carpenter shops selling material…map those communities and communicate those opportunities: that's open knowledge.*

Although the example given is a simple disclosing of the locations of local stores selling materials, one should recall how the proximity to a resource facility was associated with knowledge and engagement in the process of creating local materials. It is important to note the role of information-based technologies in facilitating such engagement.

In Fab Labs, the sophistication of digital fabrication technologies means that information facilities, artefacts and content are interacting heavily with physical resources in use. Yet at present, the disruptive potential of information facilities, artefacts, and content to physical resource systems seems mainly conceptual, and my findings are limited to the examples above. For example, there were no cases of Fab Labs disseminating open source designs that contained sensitive information about the recipes for proprietary plastics. For now, it seems like the use of information facilities, artefacts, and content in Fab Labs leaves the exclusion of physical resource facilities relatively untouched.

4.5 Summary

In this chapter I have explored how a lack of governance over material production systems impacts the ability of Fab Lab members to gain access to knowledge about materials for commons-based 3D printing. Unlike physical flows that are common-pool resources, Fab Lab members do not have the right to access, extract from, or manage resource production systems. Many Fab Lab members struggle with a lack of information about materials brought into the Fab Lab, and as a result, knowledge about materials often remains excluded from the commons. I find that the exclusion of physical resource systems from Fab Lab common-property regimes is a key barrier to accessing knowledge of materials for commons-based 3D printing.

As an interesting comparison, one can look at the location of digital resource facilities, artefacts and content of 3D printing hardware and software in relation to the Fab Lab's common-property regime. For open source hardware designs and software, Fab Labs can act as the information producing facility, as well as intersect with larger open source communities producing artefacts and content. This observation is central to my analysis in Chapter 6, where the relationship between the open design of 3D printing systems and access to knowledge about materials is explored. Rephrased, the open sourcing of digital resources has led to facilities that produce resource units being located within the boundaries of common-property regimes.

The exclusion of physical resource systems from Fab Labs can be linked to some interesting disruptive activities regarding 3D printing materials. Some Fab Labs are turning waste into resources in knowledge-intensive ways. Whilst waste can be accessed, used, and managed within a Fab Lab's common-property regime, the lack of information about waste is a considerable barrier to its effective use. One must take account for the fact that waste began its life as a private good, and knowledge is therefore subject to private property rights. Just because waste facilities can now be governed within the commons, knowledge about the materials is still difficult to access due to the parts of its lifecycle governed by private actors.

A second example of disruption is local proximity of a Fab Lab to the process of producing materials. Even in the highly industrialised process of polymer plastics, local companies and some Fab Labs are intervening in latter stages of processing, tailoring raw plastic pellets for local 3D printing uses. Although primary polymer manufacturing remains excluded from the commons, these efforts are contributing to more knowledge about materials entering the commons.

At present, there seem to be limited ways that digital facilities, artefacts, and content in a Fab Lab are impacting physical resource systems. Examples include increased monitoring and management capabilities, and the influence of disclosing information about physical resource systems as knowledge in the commons.

This concludes my study of how the nature of resources relates to knowledge about 3D printing materials entering the commons. In Chapter 5 I turn to examining the community factors that may enable or prevent knowledge about materials entering the commons.

5 COMMUNITY ATTRIBUTES: INFLUENCES AND INTERACTIONS

5.1 Introduction

In this chapter I discuss the community attributes of Fab Labs. My aim is to explore how particular attributes may enable or inhibit knowledge about materials entering the commons. I begin with an analysis of users of Fab Labs, including user purpose, and attributes that relate to accessing knowledge about materials. I explore the influence of financial resources of a Fab Lab, and the level of collaboration between members, between a Fab Lab and its community, and between Fab Labs. My aim is to uncover patterns in how some attributes may be more or less linked to knowledge about materials entering the commons.

I then analyse particular norms operating at the community level. These are the norms of openness, local production, resource sustainability, and knowledge documentation. Among other affects, I find these norms can help explain why Fab Lab members act in a way to disrupt the exclusion of physical resource production systems, discussed in the previous chapter, as well as why many do not.

5.1.1 Guiding question

The question guiding this chapter is as follows:

> *What attributes of the community influence whether knowledge about materials enters the commons?*

5.1.2 Theoretical concepts

The theoretical foundations of this chapter are twofold. First, I build on prior scholarship that considers the importance of characteristics of the community in analysing community-based production models (Schweik, 2007; David & Shapiro, 2008; von Hippel & von Krogh, 2003). Here I consider the community attributes of: (a) type of users and purpose of the Fab Lab; (b) financial resources of the Fab Lab community; (c), levels of collaboration within and between Fab Labs and other related commons-based digital fabrication communities.

Second, I follow Ostrom and Crawford (2005) in employing the concepts of community norms for a set of people with particular attributes within the confines of certain conditions. Here, norms are particular sets of actions and outcomes that are permitted, obliged, or forbidden, for Fab Lab members engaging in 3D printing. I explore the norms of openness, local production, resource sustainability, and knowledge documentation.

5.2 Users and Community Purpose

First, I describe characteristics of Fab Lab users, their purpose, and their interest in experimentation. In particular, I ask whether different user types tend to experiment with materials more than others. This is motivated by the link between access to knowledge and learning by doing (Foray, 2004). I then describe the roles Fab Labs play in their communities: as social meeting places, as educational hubs, and as providers of business services.

5.2.1 User purposes

Exploring why Fab Labs are valued from the perspective of users helps explain the activities taking place. The purpose of Fab Labs for a given user varies widely. A single Fab Lab user can also have multiple purposes. However, there are common threads. Within and between Fab Labs, common purposes of users are: (1) personal fabrication, (2) stimulating local economic development, and (3) educational empowerment. These differing purposes explain much of the activities that take place, the types of users in Fab Labs, and relate to roles Fab Labs have in their communities. I take each type of 'purpose' and discuss how it relates to activities and users.

First there is the purpose of providing users with tools for personal fabrication, or making to serve an individual purpose. There is a widespread belief in the Fab Lab community of the importance of individual creativity, innovation, and quite simply, making things. Speaking of fellow users, one Fab Lab member states,

> *At the end [of their time in a Fab Lab they] go home with a real tangible product, something they're proud of, something that defines them. That's what they're looking for.*

Personal fabrication is also viewed as being in the best interests of wider society. One Fab Lab member explains this relationship:

> *To have a collaborative economy, we must open access first of all. So in terms of personal fabrication, it's the liberty to be able to design and make something, or adapt something, to your need. Being able to do that, respond to your need, in a demand led way, is*

> *hugely empowering. It is a capacity. It's a capability. So we must open up the field to everyone to then be able to learn from their differences, to have a wider hot bed of innovation. It's the idea of going from the head or the peak of production and ideas, to the tail, the long tail of everybody, where most of the needs and the demands are.*

This quote emphasises that a collaborative and innovative economy is best served by allowing individuals to express themselves through making things. Individual 'liberty' to make things builds collective 'capacity' for innovation. This philosophy explains a large amount of the activity that goes on in Fab Labs. Most Fab Lab members relate that the most common purpose for the Fab Lab is helping individuals fulfil their own purposes.

Interestingly, the focus on individual fabrication does not seem to come at the cost of a connected community. Far from being seen to undermine the community, the emphasis on personal fabrication is celebrated, and is viewed as community strength. One Fab Lab member articulates this:

> *I believe that the ideas of the many are a more fertile environment than the control of a few. So in my perspective, I would open the playing field up to all to benefit from the ideas of the many.*

As the above quotes state, there is a widespread belief that individual differences can enhance learning and innovation for the wider community.

Referencing the types of users a Fab Lab brings together, the following quote from a Fab Lab member reflects builds on this idea of individual knowledge giving rise to collective benefit:

> *[Users] bring different types of knowledge. We get carpenters and they bring the knowledge of materials. We have users of electronics, and they bring knowledge about programming micro controllers. Then we have artists bringing ideas when they are designing and we teach them digital fabrication.*

This is key to understanding Fab Labs as community commons: one should not assume that 'community' means engaging in collective projects. Rather, Fab Labs are collections of individuals with differing knowledge and personal goals who nevertheless generate value as a community through their heterogeneous knowledge contributions.

The idea of heterogeneous actor motivations for use of and contribution to commons resonates with David and Shapiro's (2008) findings in open source software communities. In the context of Fab Labs, heterogeneous motivations give rise to heterogeneous types of social connectivity. This is where the empirical context of Fab Labs contributes an important angle into commons-based and peer production models. It offers a view into the creation of communities based on interpersonal connections, as well as use and contribution to common resources. In Fab Labs, interpersonal connections are often created *because of* heterogeneity because quite simply, users with different skillsets are useful to one another. The following Fab Lab member, speaking of the way that community can be generated, illustrates this point:

> *One of the important things of this Fab Lab is that this space is for people, so it's not like you need to have a master plan and you go there and you execute it. Very often beautiful things happen spontaneously. So you go there with a vague idea of what you find interesting. And you start doing your thing, and could talk to so*

> *many people and you get so much cross-pollination of minds and ideas and then a new thing emerges.*

Articulated here, the community seems to be an emergent entity based on commonly held ideas, of which the importance of personal fabrication is one. Personal fabrication is thus not held in opposition to the community, but rather is framed as the necessary root of inspiration that a community grows from.

A second commonly stated purpose is that of local economic development. For some, this can be motivated by larger inequalities. One Fab Lab member states:

> *I think digital manufacturing will improve the lives of the kind of 3 billion people that have been left behind in the global kind of economic growth…Material wealth is an issue of distribution.*

Addressing inequality through access to digital fabrication resonates with many, particularly in developing countries. Some Fab Lab members frame development aims within their more immediate context, as many Fab Labs are founded in communities that aim to revive their local economy. From the user perspective, gaining job skills, accessing retraining opportunities, and creating entrepreneurial opportunities are often stated aims. Unsurprisingly, this rationale goes hand in hand with incubating and engaging local businesses, a core activity that can serve as an aim unto itself as well as an instrumental way to economically sustain the Fab Lab.

Third, a common purpose behind users engaging with Fab Labs is education for its own sake. Many Fab Labs are affiliated with, or housed in, formal or informal academic organisations. The influence of organisational affiliation will be returned to subsequently. For many Fab Labs educational goals are paramount. A focus on education changes radically the idea of what output a Fab Lab should be producing. One member in a very student-focused Fab Lab explains:

> *Today there are people that make very useful things: it is not people who use 3D printers. Right now they are not practical tools, not yet. But tomorrow if a school of girls and boys know how to print, in 10 years, 20 years, they will print things they will sell, so we are in the beginning. Maybe we [as adults] are too old to find a solution, but if you educate, they will find this solution.*

For these student users, their purpose is simply to learn and gain educational empowerment. One can see that a longer-term view is created from this when it comes to measuring the relevant output of tools like 3D printers. As opposed to value connected to economic development, or even to producing personal fabrication projects, 3D printers, and Fab Labs by extension, can by simply for educational purposes.

5.2.2 Users and experimentation

Given that Fab Labs require open community access, service a wide range of public and commercial interests, and exhibit considerable geographic diversity, it is unsurprising that there is a large variety in types of Fab Lab users. Given this, it is possible to identify main user types that broadly are associated with experimental activities in the Lab.

One Fab Lab member explains the relationship between user type and experimentation as follows:

> *[Experimentation] depends a bit on the users. There are some people who come for making stuff, and when they made it, then it's finished. So they only want to learn what they need to learn to achieve that. Then there are others that more or less come to the place to learn like students. We have a couple of interns from different universities. They are not designers who have a project to finish, but they find the place interesting because they want to learn about the technology and they keep on going. They always set new goals to learn new stuff.*

This quote suggests that students are a group that are likely to learn and experiment. Adding to this, another member states, 'It's good to experiment with another material that…the company can sell, like a new material from, designed by, or investigated by a student.

Although it seems intuitive that students would be highly experimental and learning-oriented, other Fab Lab members point out that students coming into a Fab Lab are often constrained by project goals and deadlines set by their school or university. The following quote from a Fab Lab member provides an extreme example of the impact of this:

> *Things [in the Fab Lab] have to be standardised…. If you're going to bring kids into a Fab Lab, they're coming for a field trip for like an hour and a half in groups of 10. And every kid has to print a design and they have to come out with something in their hand…it's very constrained.*

These quotes show that even as an identified user type, students show considerable variation in the ways they use Fab Labs.

Other types of users are more clearly defined in their activities. Upon answering a question about experimenting with 3D printers in the Lab, one Fab Lab member stated: ‘honestly I haven’t investigated it. I’m an industrial designer by background and more interested in getting things that work and not getting caught up in that level of detail’. Although industrial designers and other professionals may already have a high level of knowledge about materials, this quote does not suggest that new knowledge comes from experimental engagement in the Fab Lab.

By contrast, artists as a user group are widely known to be experimental. One Fab Lab member describes this group in the Fab Lab:

> *In the arts, they’re doing a lot of experimentation…. They want to come up with a better material. For example, the pottery, they’re trying now to put it in the 3D printer. Print dishes and stuff like this.*

Other groups of users are technology hobbyists. One Fab Lab member articulates the goal of developing technology through experimentation as follows:

> *I want to convince these companies, ‘Look, get your machine here and we are going to use your machine, we’re going to break your machine, and you’re going to better [be able to] improve it, you’re going to learn from it, and maybe even some company [will] come out of this [Fab Lab], [and] they will buy your machine in the future.*

In this quote the Fab Lab member is expressing a pure interest in using and improving technology. The specific ways Fab Lab members are experimenting with and modifying 3D printing technology will be explored in detail in Chapter 6.

The following statement from a Fab Lab member illustrates how this interest in experimenting with technology for its own sake translates to experimenting with materials:

> *People who are really experimenting with materials, it's because they have this vision not only to consume technology, more to develop technology…connected with your local resources.*

A slightly different motivation comes from wanting to develop the technology as well as prolong the useful life of 3D printers. One Fab Lab member describes the project of altering an out-dated 3D printing system in order to make it useful for the Fab Lab:

> *The project itself is to take our existing machinery we've got and increase the functionality…Really trying to get how we can push the bounds of its capabilities beyond what it was originally designed for and the manufactures would like to support so we can get more use out of it and prolong its life but also because it's a shame to throw it out…it's about extending its life as well as making it more useful to us…. If you have these closed source devices and then the manufacturer releases version 2.0 or whatever and stops supporting the old one, what do you do with that? Especially because there's no documentation around it and they've given up on it. It really puts the ball in your court. It's a nice driving factor, the onus is on us to do something about that. And this is not a one off occurrence – there are heaps of people that even have these exact printers and are in the same situation, and with technology in general there's that 18 month lifecycle that does tend to happen in a lot of products, so extending the life beyond what the manufactures intended is hugely beneficial.*

In this passage it is clear to see the interest in keeping a machine in use, for the pure interest in pushing technological capabilities. One can also see the principled attraction of countering an industrial logic of built-in obsolescence with local skills and competence to keep the particular machine in use. This is a hallmark of users driven by a love of technology, and can often lead such users to access knowledge of materials as a consequence of their technical experiments with 3D printing systems.

A different motivation that relates to access to knowledge about materials is the value of experimenting as an end unto itself. As one member puts it, some Fab Lab users simply ‘like to make something new and find not just a new material, but an application that is different from the usual’. This often is related to the close relationship between making things and play. One member explains that ‘a lot of this Fab Lab movement has come out of Hackerspaces, Makerspaces…people are makers and they want to play with things’. The way this value is expressed is evident in the following quote from a Fab Lab member, describing other members in the Fab Lab:

> *So then they brought materials back to the lab. And then they start experimenting. Lots of trying to find different opportunities and methodologies, doing a lot of stupid things that all the experts know already, but that you don’t know, that you have not done. And all those stupid things [are] really interesting.*

Another Fab Lab member explains that play is natural, and should be celebrated:

> *How is it possible in the natural world all these animals learn by playing, and then we created this school system that bans*

> *play…[that] separates learning from playing whereas the true power is combining. So play in the lab. Laser-cut a cucumber and see what happens.*

This statement communicates the idea of creativity, play, and experimentation as natural parts of being human. When it comes to experimentation and access to knowledge about materials, one must allow for the playful involvement of all types of users.

Overall, understanding user type and purpose is important as some user types seem more likely to experiment with and access knowledge about materials more than others. In general, students experiment unless tasked with restrictive learning outcomes. Technology hobbyists are interested in technological advancement, and another group simply wants to play. This adds to the study of who participates in the commons on what basis (Schweik, 2007; David & Shapiro, 2008; von Hippel & von Krogh, 2003). In sum, the different orientations of user groups in Fab Labs may influence how knowledge of materials enters the commons.

5.2.3 Fab Lab community roles and purpose

Closely related to user purpose is the role Fab Labs have in communities. Together, they provide a frame for understanding what Fab Labs are, what they do, and whom they serve.

Although there are a multitude of community roles, I find three most common. First, Fab Labs act as a social meeting place for their community; second, Fab Labs are community educational hubs; and third, they are a provider of business services for their community. One can see that these correspond closely to the purposes of users of Fab Labs, although the details of these roles in the community are not quite captured by the previous section. Here I place the Fab Lab in the context of its service to the wider community beyond the Fab Lab itself.

To begin, one of the most common roles Fab Labs have is the simple provision of space for community members to interact. One Fab Lab member states that users simply ‘come to the FabLab to socialise, to meet new people, to talk with the people, to share ideas’. Another Fab Lab member states that Fab Labs are places where people can ‘talk in the same language’. A third Fab Lab member states that a ‘Fab Lab is a kind of space that people can really see each other and see your project and give you some feedback and interact with people. It’s about people and the community.’ These quotes underline the centrality of community to the very idea of what a Fab Lab is. One Fab Lab member sums this up by saying,

> *People from Fab Lab communities seem to feel they have a sense of responsibility for their community environment in which they’re working and are responsible for looking at ways to improve that.*

As an educational hub, Fab Labs often bring in school groups and work within the formal educational system. Showing the use of this, one member says that ‘teachers are coming to the lab and they are happy because [they] change our knowledge into good teaching material.’ Fab Labs also play a strong role for informal community learning. The following quote from a Fab Lab member explains this formal and community educational role in a rurally isolated Fab Lab:

> *What we are doing is bringing Fab Labs to educational systems, Fab Labs to schools, and also getting a big portion of the community to come into the lab…. We have around 6,000 of the population that is visiting every month. And what we bring is work[ing] in a*

> *collaborative way…Because we are so isolated, we know that we need to collaborate with the rest of the world.*

Education is not just a service to students. Rather, Fab Labs can become hubs of community learning where formal and informal education takes place.

The third clear role is the Fab Lab as a business hub for entrepreneurs and businesses. Some Fab Labs are designed to serve the professional business market by providing an incubator and co-working space. Some enable significant ties to the surrounding business community: as one member states, 'We have some partners, [who do] crowd funding for start-ups…there is an ecosystem [that] we want to build inside the Fab Lab'.

A Fab Lab with a strong community role as a business hub often attracts a distinct group of users. For example, one such Fab Lab attracts mainly 'creative professionals: engineers, architects, programmers'. However, one should not overstate the commercial role of Fab Labs. Even in Labs that orient strongly towards business professionals, there is a gap between traditional manufacturing production and how businesses use a Fab Lab. A member from a highly business oriented Fab Lab explains that the tools are not usually industrial grade machines: 'For every machine you have in the Fab Lab…there are 2 or 3 steps to an industrial level'. As described by a member, this changes the business model of the Fab Lab:

> *If you're buying a machine for production, you want to make it work as much as possible. And if you buy it for prototyping, you want to make it accessible to as many people as possible…The Fab Labs have the tools for visualising or materialising ideas, but they are not meant or constructed to produce consumer grade products.*

When businesses want to go into production, they need commercial services. The reason for production *not* taking place in a Fab Lab can also be a simple matter of limited resources. One Fab Lab member explains:

> *Say if you create something nice that's laser cut, then you want to make a thousand of it. I don't really want to do it in my lab because then the laser cutter is busy for a week and that means no one else can use it.*

Although they do not have industrial capabilities, the value of Fab Labs to business must be understood within a wider context. Businesses typically use Fab Labs to incubate and prototype their ideas. This is a significant role for the wider business environment. One member explains that 'around these labs where the ideas come from, there's an ecosystem growing of more professional providers'. The Fab Lab can be a knowledge hub at the centre of an ecosystem of commercial capabilities that takes a new idea and develops it further.

Although these community roles are distinct, they are most often combined in a single Fab Lab: Fab Labs are simultaneously social meeting spaces, educational hubs, and business hubs. One Fab Lab member articulates this synthesis of community roles:

> *[Most] Fab Labs have some source of funding that's not really interested in the revenue that you make from renting out the machines, but that's interested in the ideas and the intellectual property or whatever comes out of the community that works there. We don't really make our money renting our machines. But we learn so much from the community that by now, it works quite well to do consulting and service jobs and that's much more profitable to us. So*

> *we have the lab, we can gather some knowledge, and when we condense it we can offer it to someone else. If a university is interested in a Fab Lab, it's because it helps their students make better ideas. That's why it's important that it's cheap and accessible because if you exclude too many people, then you don't have the pool of talent that you want to have.*

In this quote one can see articulated that one of the most important goals shared by Fab Labs is providing knowledge for the local community. This knowledge comes from the social space that encourages a wide 'pool of talent', as well as a place where students can make 'better ideas', and businesses can benefit from the Fab Lab's services and collective community knowledge.

The purposes of Fab Labs and their community roles are certainly more diverse than detailed here. The purposes and community roles discussed here are the most general and widespread, and appropriately set up the context of Fab Labs as action arenas.

5.2.4 Fab Lab purpose and experimentation

Experimentation links to the overall purpose of the Fab Lab. Fab Labs go to great lengths to make possible the means to experiment with tools in the Fab Lab to as many people as possible. One Fab Lab experimenting with many materials likens experimentation in the Fab Lab to cooking:

> *Gastronomy is so close to what we want to do because you can experiment with different materials and you can see what is happening…for example…when you put some kind of power or energy, or you mix with different things.*

The choice of metaphor here is intentional and significant: the idea of cooking is meant to be widely appealing, and not just to a specialist knowledge group.

Building on this theme, many Fab Labs demonstrate that experimentation and creativity should not be associated with only certain types of users. The following quote from a Fab Lab member states this:

> *[People] have this thing that they're not creative, right. That's completely wrong. That's a misconception I think. They just don't have the time. They work too much. And they don't have abundance…So when you don't have abundance, you don't have time to create. If you're in a company where you're being pushed around, you're not going to be creative. So people that complain about [being creative], it's because [of] uniforms that are tied to the neck. Give them some free time. You'll see creativity.*

The value that a Fab Lab places on learning is important for the community fostering this type of creative experimentation. One Fab Lab member clearly articulates the high value given to experimentation within as a Fab Lab community:

> *As a manager of the Fab Lab, we buy certain things. But if there is a group of people who want to experiment on something, they can bring it to the lab. They can experiment over there, everybody is watching, learning from them. Maybe it explodes, maybe something happens, we're going to have fun.*

Other Fab Labs do not allow such open experiments, often because experimentation is time intensive, with no assured outcome. Without direct control over the production of materials, any means of disruption is difficult and time intensive. The following quote from a Fab Lab member illustrates:

> *When you want to experiment with a new filament…you need so much time! Because you've got to try something: it doesn't work. Other settings: you lose 2 days just printing a small object to know if it worked. And most people who come in, they don't want to use 2 days, they want to use 1 hour and leave with the object.*

There is an oft-cited tension between time given to material experimentation and the want of users to make products quickly and easily. The time given to learning in a Fab Lab is thus an important factor in users accessing knowledge about materials.

Given the lack of knowledge about upstream industrial material production within Fab Labs, investing in ways to bring materials within the control of the Fab Lab's common-property regime is not only time intensive but requires considerable investment in learning. One Fab Lab member explains the process of creating 3D printing filament from recycled waste in the Lab:

> *For the 3D printer, we're looking to see whether we can get thermoplastics, which is what's being recycled. [In the Fab Lab] they're extruding it and chopping it into pellets…And now the question is, because it's recycled, all these plastics have been picked and cleaned, and from the materials perspective…does it flow continuously and so on? So there are measurements that we can make [and with] the Melt Flow Index as we call it, we are able to see, does it satisfy? And if it doesn't then we're going have to go back and see how can we make it work.*

The amount of iterative learning in this process is clearly considerable. Another Fab Lab member with experience of turning waste into 3D printing filament explains what is needed:

> *There's a whole bunch of learning that needs to come together. At a very practical level, there's stuff around the design of the equipment. There's a piece that's knowing which materials can be recycled and which lend themselves to being feedstock and how you push that envelope to enable a broader range of materials to be used.*

As a final part of this section, I examine the relationship between the financial resources of the community, and access to knowledge about materials due to experimentation. I particularly investigate how the need to be resourceful relates to accessing new knowledge about materials in the commons.

One Fab Lab member describes how the availability of financial resources relates to choices of materials across different Fab Labs:

> *[Types of materials used] depends extremely on the context of the lab…In a western lab, we use what we can buy. And in a developing country Fab Lab, you use what you can get.*

The lack of financial means may restrict the use of commercial high quality 3D printing materials, yet it may also result in high levels of experimentation with local material sources for the purpose of 3D printing. One member states that students in the lab are making 3D printing filament from waste plastic 'because they are not rich.' In another Fab Lab where waste PET plastic is being turned into a 3D printing filament intended for sale, a member states, 'They're not [just] experimenting, they actually need it to find a way to eat.' Regardless of intent, the outcomes of these initiatives are often a significant increase in access to knowledge about materials for Fab Lab members. In general, I find that a lower the level of financial resources of a Fab Lab community often relates to experimenting with materials by consequence of needing to be resourceful, and choosing open 3D printing systems because of cost.

Overall, I emphasise that gaining access to knowledge about materials in Fab Labs is time intensive and requires a significant investment in learning. For some Fab Labs, this learning process is part of the role and purpose of the Fab Lab, or is a consequence of being financially constrained. Yet if Fab Lab members are not interested, it is difficult to overcome the lack of knowledge about materials that the exclusion of physical resource production systems introduces.

5.3 Impact of Collaboration

I now look at how openness to experimentation and knowledge sharing relate to collaboration within and between Fab Lab communities. As stated by Madison, Frischmann, and Strandburg (2010), the study of communities should examine how a 'particular community is accessible to and interconnected with related context, institutions, and social practices' (p. 696). By itself, the strength of community ties and openness to knowledge sharing seems to link to the level of experimentation in a Fab Lab. As experimentation is often linked to increased to acquiring new knowledge about materials, it is worth noting the particular ways that community collaboration plays a role in encouraging experimentation in Fab Labs.

In general, I find community collaboration to be associated with three main themes. First, many users contributing rich and varied knowledge; second, an environment that encourages open knowledge sharing; and third, high levels of collaboration with other commons-based digital fabrication communities.

5.3.1 Contributions of users

The following passage is useful for understanding the relationship between individual user knowledge and community collaboration. A Fab Lab member, in describing a project of hacking a closed source 3D printer, states:

> *We've already got some of the materials we need for testing. Certainly with these things there's iterations, a bit of trial and error so we don't necessarily have to hit it bang on first time. We've put out this hack we're doing as a community event so if people are really interested in changing 3D printers they can come along and see…So that's the true value to me, doing something that's really useful as well as getting people interested in what we're doing.*

This quote connects the importance of community collaboration to experimentation with materials. Community engagement and knowledge about materials are stated as expected, and important, outcomes.

The richness of knowledge brought by individuals does not necessarily mean that community members have to be highly trained engineers or software developers. For example, in a Fab Lab in an extremely poor country with comparatively few resources, high levels of experimentation with materials can flourish. A member of a Fab Lab that fits this description explains their view of access to knowledge in a Fab Lab:

> *You don't need to bring knowledge. If you are a community of 30 people everyone teach the others what they know.... We have a community of 30 persons, who have each 30 [sets of] knowledge.*

Another member of a Fab Lab describes the contributions of community members as follows:

> *That's the very potential of collaboration, because nobody is an expert in everything. So [if] there's a lack of material knowledge and insight…then you have the programming guy working together with the artist together with a material expert, and together they can come much further than if they do stuff on their own.*

A vital dimension explaining collaboration is time spent in the Fab Lab. The member of a highly collaborative and experimental Fab Lab states:

> *[Relationships] develop over time, and there are groups now…like the Musketeers as we call them, they know everything. The gurus. There are the people who are the 3D print guys. They love 3D printers, nothing else. And there are the people who like mechanical stuff…and everyone is challenging everyone.*

Thus it is the collaboration between different types of users, with different knowledge and interests, over time that can lead to new knowledge being accessed and produced in a Fab Lab.

5.3.2 The Fab Lab environment

When there is a rich base of knowledge in the community, the design of how the Fab Lab is used can also enable collaboration. As one Fab Lab member states, 'When the conditions are there, collaboration does emerge'. One of these conditions is the model of providing open hours for the public, as required by the Fab Lab charter. One Fab Lab member details this:

> *You really have to connect people to each other. It happens during open hours when people can just walk in, use the machines for free. And because then they will have to wait to use the machine they will meet our people, and say 'Oh what are you doing? Oh that's nice, I'm doing this'. So that is where collaboration can start…Every Friday afternoon we are having free space that is not only focusing on production but more on projects. And then other people come into the lab as well, so then there is more collaborative spirit. But the other hours during the week, we just rent our machines. So then people do not get to meet other people, because they rent the machine for production. And so they are alone with me and the interns.*

A Fab Lab member explains the combination between individual experimentation and knowledge sharing as follows:

> *[Individually] they investigate each material. But many times they exchange opinions. And many times they look at what the other is doing and they try if that material they are using can help. So in this way they are collaborating a lot of the times. I mean, it's very open. It's completely open.*

In this way, collaboration becomes a core challenge for many directors and managers of Fab Labs. One Fab Lab member states this as follows:

> *It's true, sometimes some people, they only want to print something, and they will not use the community. So this is our goal, to teach, to tell them, there is this community, and this is also a big challenge.*

Importantly, knowledge sharing need not take place in the physical Fab Lab space. A member from a highly collaborative Fab Lab explains, 'We have a mailing list…and this is very nice because it's amazing when someone poses a very technical question, there is always someone to respond'.

Yet not all Fab Labs use such collaborative methods. On the other end of the spectrum, many Fab Labs have users that are highly individual in their approach to fabrication. One Fab Lab member states:

> *Most projects are really driven by the interests of the single person that wants to achieve some goal. We started a couple of projects ourselves where we brought people together…There was one guy who wanted to build something for drones and he needed an electronic engineer, so I pointed him towards another one. And then they co-developed that…but most people do their own stuff.*

This is a common theme with Fab Labs. One Fab Lab member expresses this as their loss:

> *People do what they want. We encourage them to share if they want. For example, if a start-up came, if they don't say anything, they don't get benefits from the community.*

The community, although emphasised by many, may not feature as an important reason for why many members use the Fab Lab.

5.3.3 Collaboration between Fab Labs and their communities

A final dimension of collaboration is the relationships between other communities engaged in the commons-based digital fabrication. This is often other Fab Labs, especially in countries where many are in close proximity. In the following passage, one Fab Lab member describes how Fab Labs with different levels of emphasis on experimentation work in concert with one another:

> *We have other Fab Labs where they take all those [experimental] detours…but our process is so focused on getting a good idea, screening it, getting it validated, getting it commercialised. The thing is that we need it to work. So the people who come, it is people with ideas they want to do something with, it's not just exploring how can you cut a [material]. We don't care because…we also source the knowledge from the other Fab Lab. We know about [their] experiments so we're like super users in this environment so that makes us easy to shortcut the knowledge sharing.*

This Fab Lab member describes how this relationship works in detail:

> *[The other] Fab Lab close by - they do a lot of experiments. They have a machine park which never works so they will eventually come to us. People from that Fab Lab call us, [and say] 'could we borrow [something], I know I called you yesterday as well'. [I say] 'Okay and what has happened now?' [They say] 'we have tried something and it went wrong'. We don't have those very deep dive geeks deeply into open source software or exploring all that can be done with 3D*

> *printing…But we know where they are. We know exactly where they are. They are in a basement and we know exactly which basement.*

These two quotes illustrate how collaboration between different Fab Labs with different purposes can be of benefit for both communities. In this case, a highly experimental Fab Lab developed a symbiotic relationship with a more professional Fab Lab, each making up for the other's weakness with their respective strengths. This pushes one to think of access to knowledge about materials being fostered by collaborations between Fab Labs in a local area.

Fab Labs can also have strong community ties with other communities broadly organised around commons-based digital fabrication. Examples are Hackerspaces, Makerspaces, Tech Shops, and general 'tech hubs'. Although slightly different user groups, organisational structures, and technologies define each model, they all provide services as community-based digital fabrication hubs. One Fab Lab member describes the benefits of linking into these other communities:

> *There's the link or the potential for links between Fab Labs, Hackerspaces, and the Tech Hubs that are springing up…which are much more software focused. There's been historically a delineation [where] the Fab Lab is kind of like the engineering shop and the tech hub is where the software geeks hang out. But now I think people are looking at ways of bringing those communities together, because clearly that's a logical thing to do.*

Although specific links will vary from place to place, depending on the interest and existence of these communities as proximate to one another, collaboration can enhance the overall pool of accessible knowledge for commons-based 3D printing.

5.4 Community Norms

I follow Ostrom and Crawford (2005) in employing the concept of community norms as particular sets of actions and outcomes that are permitted, obliged, or forbidden, for a set of people with particular attributes within the confines of certain conditions. Here I explore four norms I find important to the Fab Lab community: the norms of openness, local production, resource sustainability, and knowledge documentation. These are found to have a particular influence on access to knowledge about materials.

5.4.1 Norm of openness

I define the norm of 'openness' in relation to theory of knowledge commons. Madison, Frischmann, and Strandburg (2010) state: 'Openness with respect to a community has an internal dimension as well as an external one, as it reflects the degree to which participants in the cultural commons collaborate with one another or otherwise share human capital as well as (or rather than) resources' (p. 696). I explore this in the context of Fab Labs in order to understand how it may relate to access to knowledge about materials.

One aspect of openness as a community is the alignment with open source technologies. One explanatory factor for using open source tools is the values and principled feeling many community members have about open source. For some this norm is expressed as a principle. It is also expressed through the value of belonging to a community of likeminded people. A third reason is for the good it can provide to others in terms of the development of and access to technology. I discuss these ideas as follows.

One Fab Lab member expresses the value of open source in a very personal way:

> *About open design and sharing, I realised, I just really love to share knowledge! More than I love to sell knowledge. Somebody else is real excited they can make it so now I'm even more excited that I made it. And if you're going to sell that thing or sell knowledge of that thing, you're creating artificial scarcity. Much less people have access to this. And in that sense, the potential for you to be impacted on their behalf with their joy of creation is also artificially limited…artificial scarcity, when it comes to knowledge or blueprints or designs, severely restricts our collective intelligence. It's like you're consciously making humankind dumber. Right? It's almost like locking your neurons.*

The language of this statement mirrors that of authors in commons scholarship. Madison, Frischmann, and Strandburg (2010, p. 664) state, 'Copyright and patent laws create artificial but legally sanctioned forms of exclusion, restoring a measure of market control to creators and innovators'.

A principled stance towards open source is often directed at the commercial sector and the model of traditional, proprietary business. One Fab Lab member states:

> *The idea of a single, centralised corporation benefitting and looking to make a profit for its shareholders is a poor model in the first place…We need to look at open source, really challenge the current business model.*

The belief in open source is also manifest in actions against those who try and restrict knowledge. The following statement is from a Fab Lab member describing his response to a company who took an open source design and made it proprietary:

> *This company, they had some open source thing and closed sourced it, a misuse of their license. So I'm trying to hack it. I don't care…I'm going to reverse the software and whatever they kidnap and then we can go back to using the commons.*

The use of the word 'kidnap' is interesting here. It expresses the idea that the company in question is stealing what is rightfully common property. Not only does this communicate an ethic of open source, it also shows a willingness to punish those who compromise this ethic.

Open source is also associated with the value of belonging to a shared community. As one Fab Lab member explains:

> *Because of the Internet and because of the digital commons, there is the ability for us to interact with people remotely and share knowledge because of our value systems. That's what I feel is important in the open hardware movement.*

Sharing the development of software, hardware, and designs brings a level of belonging and commitment to community. For many Fab Lab members who identify with open source communities, value is related to what open source technology can provide for others. One Fab Lab member states:

> *So if you can open source your equipment and your designs to make things, then you've got something that can self-replicate and make a big difference to people…So [if] the open source Fab Lab concept and designs and materials are available for people to either develop locally or make locally, then you've got a system that can really change things fundamentally.*

Being part of a larger community that is 'changing the system' is an important explanatory rationale for the use and development of open source technology in Fab Labs.

Although communities who identify with the value and norms of open source form central parts of Fab Labs, there are important distinctions. Quite certainly, not everyone in a Fab Lab community may identify with open source technology. Responding to the question of whether using open source tools was important to Fab Lab users, one Fab Lab member stated:

> *It is generational. Older people don't [care] about that. Younger people are more interested [and] aware of it. To older people, open source is still just software.*

Rather than being about a norm of open source, openness in the Fab Lab context is often a simple openness to all users who want to share and use a set of tools in a physical space. One Fab Lab member puts this norm of openness well:

> *Culture is very important. It doesn't really matter if you're printing on an open source machine or a closed source machine, most of the time you just want to get the result. We try not to have a fixed ideology of we want this, but we don't want this. We try to create an atmosphere where everybody feels welcome and where change is*

> *encouraged. And I think that's one of the key factors for a successful lab, because if you focus too much on one side, you always exclude the other. And that's not my goal. There are Hackerspaces for example that are very ideological and very hard core open source, and you just don't want to go there if you don't belong to that community. And the same thing goes if it's too commercial.*

Such flexibility in the norm of openness allows Fab Labs to be more inclusive in terms of community members. This explains the overlapping usage of proprietary and open source resources. However, as the Fab Lab is a place of digital fabrication, the norm of open *source* relates highly to the overall openness of the community engaged in commons-based 3D printing. The norm of openness, in terms of a community committed to sharing knowledge, relates indirectly to the sharing of knowledge about materials. That is, if knowledge about materials can be accessed, a norm of openness increases the likelihood that such knowledge will be shared. The more direct influence of open source 3D printing technology on access to knowledge about materials will be examined in Chapter 6.

5.4.2 Norm of local production

In Fab Labs, the benefits of local production are strongly believed in. One Fab Lab member introduces the idea of digital fabrication as local manufacturing as follows:

> *Digital fabrication fundamentally changes the whole world economic model, which is offshoring of production and labour and the resulting disconnect between demand and production…I think we're going to see a move away from big, centralised distribution. And*

> *that applies to everything, from food to energy to education, manufacturing in particular.*

This shift towards local fabrication is partly explained by the flexibility of the tools themselves. As introduced in Chapter 1, 3D printing systems enable smaller scale local production by lowering barriers to entry in fabricating complex physical goods. With 3D printers, anyone can make endlessly varied products with zero cost of retooling. A member states, 'if you want to use stuff locally again, the 3D printer is just a great tool to make a whole variety of stuff'.

Others see digital fabrication as not necessarily supporting localisation. One Fab Lab member explains:

> *Digital fabrication could be used in a lot of different ways. It could help people or it could consolidate corporate power. I'm interested in local economies, communities, being more self-sufficient and less dependent on the whims of global corporations.*

This quote indicates that localisation and self-sufficiency is a question of community norms and values, not a natural outcome of technology use. Another Fab Lab member explicitly states the connection between self-sufficiency, localisation, and resources as follows:

> *Coming back to this idea again of self-sufficiency, that's not to say we're locked off from the rest of the world or unconnected to it, but we're interested in being able to make optimised use of local resources…we are trying to build an ethic…when we're talking about self-sufficiency, we are talking about how to be more local.*

As indicated in this quote, for Fab Lab members the norm of localisation does not run counter to ideas of open connectivity and sharing of ideas.

One Fab Lab member articulates the benefits of digital connectivity with adaption to local materials:

> *I think we want to move from the global, from the inventory sourced from one place to a system where you say – are you able to make this? And I don't care what materials you use, but I would like to advise you to use something local. So they might end up using bamboo, or some kind of plastic because there's a plastic factory next to the lab…. So you might end up with all these different locations coming up with different solutions for the same assignment using different materials.*

Another Fab Lab member underscores the link between local adaptation to physical resource flows and the free flow of ideas:

> *I think that the ideas, when left open, allow for innovation and allow for progress at a faster rate, and allow for adaption to local circumstance, which in our time, is something needed. We need to be thinking fast about how we make things and how we interface with the environment…. So let the ideas be free, and then let's be clever about the way we interact with resources.*

This statement describes the idea that placing value on self-sufficiency may influence Fab Lab efforts to control materials locally under a common-property regime. As discussed in Chapter 4, the use of local resources can result in increased access to knowledge about materials from the perspective of Fab Lab members.

5.4.3 Norm of resource sustainability

A closely related norm is that of resource sustainability, a belief in the value of maintaining the health of natural resource systems. In the views expressed by Fab Lab members, concerns are raised about consumption, waste, and the nature of industrial materials.

Through the personal story of the following Lab member, one can see how digital fabrication interrelates with resources through the lens of sustainability, helping foster a belief in the importance of local manufacturing. The link made is that local manufacturing is important in shifting unsustainable patterns of global consumption and mass manufacturing. The Fab Lab member states:

> *I'm big into the open source movement, gradually realising that [it] applied to hardware as well. I've been working in the resource sustainability arena for about 15 years, mainly in education and research so it was a natural next step. Sustainability is very difficult when you're embedded in a system that supports mass manufacturing and consumerism. So it was interesting for me to see the opportunity here for mass customisation*[36] *and local products and the potential of local manufacturing - manufacturing for people's needs rather than just for a consumption basis. So all of that dovetailed nicely into the sustainability area.*

A sustainability ethic is also driving interest in new materials for 3D printing. A Fab Lab member speaks of experiments with local materials in the following way:

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[36] Mass customisation may seem a paradoxical term. However, the cost of printing a large quantity of customised objects is virtually the same as printing the same quantity of identical objects. This stems from the lack of retooling costs for 3D printing (see Chapter 1). The term mass customisation is associated with the hypothetical of mass adoption of 3D printing as a means of production. This is a hypothetical given that 3D printing cannot presently compete on a cost basis with mass manufacturing technologies for the production of a large range of common goods.

> *I don't think a huge amount of [Fab Lab] materials as yet have been looked at from a sustainability perspective. Natural, or organically produced, or grown materials, or non-toxic materials that can be recycled - there's much work to be done there. I'm very interested in the potential of all the new materials that are emerging. There's materials like the filament that is part wood dust, but then it binds by solvents so we weren't sure if that was a very eco-friendly option. But you know, lignin itself within wood is a good binder, so it's possible.*

Clearly, this sustainability ethic reinforces interest and efforts in producing materials from local, natural sources.

Combined with the norm of localisation, the value placed on sustainability may influence Fab Lab communities in sourcing waste and local natural materials for 3D printing. Given the disruptive affect of these two factors on the exclusion of resource production systems from Fab Lab common-property regimes (discussed in Chapter 4), these community norms may influence increased access to knowledge about materials.

5.4.4 Norm of knowledge documentation

Documentation is commonly understood as a key component of learning and accumulation of knowledge over time (Foray, 2004). I explore how knowledge documentation, if present as a community norm, may encourage the accumulation and corresponding potential to access knowledge of materials in Fab Labs.

Much explanatory power is ascribed to the online documentation processes for open software projects. As Schweik (2007) notes in his institutional analysis of open source software communities, 'This kind of infrastructure works in conjunction with established rules-in-use to provide a system or process for new work to be conducted, a system for submissions of new or revised modules to be received, and a system for peer review of these modules for possible inclusion in subsequent releases of the software' (p. 287). I explore whether similar infrastructure exists for hardware and materials knowledge in Fab Labs.

Fab Lab users often refer to GitHub[37] in relation to open software and hardware for 3D printing, as well as the RepRap forum[38] for open hardware knowledge. One Fab Lab member explains,

> *I'm somebody who uses a platform called GitHub a lot. Git is a sharing protocol rather like Dropbox, but it allows you to track the history of design…Mercurial is the one that Fab Labs use, basically just the same thing, it's a distributed version control system. Those are the means for sharing documentation.*

However, there is not an analogous example of online documentation of open knowledge about materials in commons production. In open source software and hardware communities, the structure and function of documentation is core to the success of the model. The need for documentation in the realm of materials is, however, recognised. As one Fab Lab member states,

> *Documentation is really one of the fundamental pillars of the collaborative economy. What is digital fabrication, what is knowledge transfer? It is the heart of collaboration. So we can make new materials, we can look at different inventories for appropriate use, but how are we ever going to learn anything unless we share*

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[37] See https://github.com

[38] See http://forums.reprap.org

> *what we know? And documentation is a big part of that. In fact one of the reasons I came to the Fab Lab in the first place was to set up a platform for sharing.*

The beginnings of thinking about documenting open knowledge linked to materials is articulated in the following quote by a Fab Lab member:

> *Mapping of expertise of knowledge as well as linking that to locality and appropriate technology [is about] being able to have a system that is interoperable. Being restrictive, but being intelligent about the resource use as well, I think is being explored, but only just being touched now.*

Within Fab Lab communities, the emphasis placed on documentation varies widely. This can be explained to some extent by general barriers to open source documentation. One interesting barrier that is cited is the issue of standards. When asked why people struggle to document production in a commons community, one Fab Lab member responded:

> *Standards. The open source summits in New York last year started to work on standards and the open source hardware association started to work on standards. But it's not there yet. So I think the documentation aspect for the open source projects is not there yet.*

If open hardware is seen as challenged by a lack of standards, standards for materials documentation are even more remote. Another barrier seems to be associated with trust in open source communities as articulated by a Fab Lab member:

> *A problem I'll have, when I started to talk to people, some of them [say], 'I'm not sure everyone will be okay to put data on your platform because…even though their project is open source, you will have to really show them you come in peace to document on the platform. So even in open source communities, there are still people who are not okay to give it to anyone, because they don't know what you are going to do with it. Maybe I will send it to a company, you know.*

There are also barriers that seem specific to the user community and activities of Fab Labs. An important dimension is the heterogeneity of user types. One Fab Lab member explains that older users of the Lab are less likely to be interested in documenting their work on online forums:

> *The idea of documenting things well enough to be able to post them isn't real appealing to people who haven't been trained to do it…I think there's a lot of people who maybe didn't grow up with Facebook [who] don't like documenting everything or taking a photo of everything.*

Another Fab Lab member elaborates this theme in the following statement:

> *[In a Fab Lab] you have two movements. One is a kind of hacker-based spirit. And they are really into open source and really into sharing and really into non-profit and non-entrepreneurial projects. And their movement is more 'we want to make stuff' but not to get profit from it. But [with the other movement] entrepreneurship is not bad at all…so these two are like different species. And I know the ones with more entrepreneurship values…they would be afraid to give what they are doing, because they don't know what they could do with it afterwards…So there are really more defensive modes*

> *towards the public…So that sometimes will be a problem [for documentation].*

A different barrier entirely comes from understanding the culture and activities of Fab Labs. One Fab Lab member says:

> *What is interesting to makers in Fab Labs and spaces like that is they want to break the usual barriers between fields and they want to mix stuff. Maybe that's one of the reasons we have so many problems documenting because we have our different backgrounds when we try to work together.*

In addition to referencing the differences between users in a Fab Lab, this quote suggests that there is a problem of documenting knowledge areas that are distinct yet related when it comes to the process of digital fabrication.

Despite barriers, some Labs are trying to formalise knowledge sharing through documentation initiatives. As one Fab Lab member articulates, this seems to relate highly to levels of community collaboration:

> *We do introduction classes for standard processes where we explain about the materials, what the differences are, what the possibilities are. Some people want to try things that we haven't done before. For some things we know they don't work or that they are harmful for the operators. So we have a list of things that you can't do. And then other things where I think it's not a problem, I just let them try. And we have a feedback worksheet. [When] we're trying new materials for example, we gather the information and put it in our official sign for the machine.*

In responding to the question of ‘why document’, Fab Lab members cite the importance of reproducing good ideas and raising the profile of Fab Labs in the community. As stated by a Fab Lab member, collaboration is a main incentive:

> *We now have a wonderful platform that…will make documentation a lot easier. What I really like is we added this functionality so you can add people to your project. So someone can come up to you and say, ‘Wow that’s a cool project, can I help?’ And you can say, ‘Yeah seriously I’ll add you to my project online’. And we can track each other’s work. People can work at home and go back to the website and add stuff. Then their collaborators get an email saying, ‘He added this!’ So really we try to build a tool that’s not only a documentation tool, but it’s going to help people collaborate and it’s also going to help them create a maker profile. So if at a certain point, you need a 3D modeller for your project…you know who has experience 3D modelling. And you contact the guy and you say, ‘Do you want to do a project together?’*

These examples are significant but seem to relate strongly to specific levels of community collaboration, rather than an overall norm of documentation. In general, it is difficult to see any tangible efforts to document materials used in Fab Labs. Upon considering the sharing of knowledge about materials, one Fab Lab member articulated the need for ‘deeper communication if they want to be part of the open innovation process so people can go faster on studying and shaping projects’. In general, Fab Lab members recognised that a more substantial level of documentation was missing, particularly concerning the use of materials.

This is significant given the lack of knowledge about materials in commons-based 3D printing in comparison with knowledge of software and hardware. Whether there may be an interesting relationship between the lack of such documentation, and the widespread use of proprietary 3D printing filament, is in need of further study. Use of documentation platforms of hardware and software in Fab Labs confirms prior studies of open source software communities where ‘group collaboration is supported through web-based communication and version-control systems’ resulting in extensive systems of documentation (Schweik, 2007, p. 287). Without similar infrastructure, commons-based sharing of knowledge of materials lags far behind.

5.5 Summary

To sum up this chapter, community attributes play a major part in influencing how knowledge about materials may enter the commons. Those reviewed here are user type and purpose, as well as the community role and purpose of the Fab Lab; and, collaboration within and between Fab Labs. Community norms of openness, local production, resource sustainability, and knowledge documentation also are analysed.

Given the barriers to physical resource production systems becoming part of Fab Lab common-property regimes (discussed in Chapter 4), the characteristics of the community matter a great deal for the potential to disrupt the exclusion of knowledge about materials. I find a strong emphasis on learning in communities experimenting with new materials, whilst the time intensity of this process is a clear barrier. Indeed, a strong emphasis on experimentation in a Fab Lab relates clearly to accessing knowledge about materials. Users who value and engage in creative experimentation seem more likely to access knowledge about materials. Fab Labs who encourage experimentation foster communities of users who are more likely to bring knowledge about materials into the Fab Lab.

The norms of openness, local production, and resource sustainability reinforce efforts to access knowledge about materials. I find that these are strong beliefs that significantly reinforce efforts to govern physical resource production systems within the common-property regime of the Fab Lab. Fab Lab members are looking around their community for new resources that can enhance their self-sufficiency and improve the environment. These norms act as incentives for members to access knowledge about materials for commons-based 3D printing.

An exception is the presence of widespread and effective knowledge documentation. Although Fab Lab members state the importance of documentation, and its linkages to knowledge sharing and collaboration in Fab Labs, organised and systematic documentation appears limited. Unlike the standards and systems of documentation in open source software and hardware communities, documentation regarding materials is not a significant factor at present. This may inhibit accumulation of knowledge in Fab Labs, affecting general access to knowledge about materials in the commons.

6 TECHNOLOGY DESIGN RULES

6.1 Introduction

In this chapter I explore how design of 3D printing systems may change the capture and use of knowledge of materials by users of the technology. I examine the design rules of 3D printers as technological artefacts, focusing on open and modular design rules. If one is to understand the factors that enable and prevent access to knowledge about materials in the commons, it is essential to consider the mediating role of the technologies in use.

I also analyse the affect of using highly integrated as well as proprietary 3D printing systems. Given these concepts are theoretically conceived of as opposite to highly modular and open designs, I examine their affect on access to knowledge about materials in order to increase confidence in overall findings.

6.1.1 Guiding question

The following question guides the chapter:

What rules-in-use influence whether knowledge about materials enters the commons?

I study two important design characteristics of 3D printing systems: first, whether the 3D printer is open with respect to the design of hardware, software, and firmware; and second, whether the 3D printing system is more or less modular. Using the language of institutional analysis, I frame openness and modularity and as design rules-in-use. I consider how these rules manifest at the operational and collective-action levels, following Ostrom's (2005) framework of nested levels of analysis.

6.1.2 Theoretical concepts

Before using rules as an analytical tool, one must revisit why rules are particularly important for examining access to knowledge. In the words of Crawford and Ostrom (2005, p. 184), rules are generative, having 'information-processing' and 'productive and reproductive capacities'. It is my assumption that modularity and open source 3D printing systems relate to processing certain types of information about fabrication, leading to the production and reproduction of certain types of actions in Fab Labs. The conception of rules as regulators of behaviour is core to this analysis, as is the idea of rules as contestable and changeable according to shared meaning and values. This framing allows me to analytically consider the influence of 3D printing design characteristics in relation to other variables within the IAD research framework.

The theoretical concepts central to this chapter are twofold. First, it is useful to define 3D printing systems as technological artefacts. I employ the concept of a technological artefact as an object or phenomenon adapted to serve human goals and purposes (Simon, 1962). Artefacts are designed, and it is the structure of the artefact itself that can be studied in order to locate the rules of design. Artefacts can be physical and non-physical (Baldwin & Clark, 2000). Books, computers, computer programs, the Internet, and patents are all artefacts (ibid). 3D printing systems are thus technological artefacts that encompass physical hardware and materials, firmware controllers, software, and design files. The characteristics of these components and interfaces will be subsequently elaborated.

Second, I explore how the design rules embedded in technological artefacts can usefully be integrated into the IAD framework as rules-in-use. How rules of open source and modularity in 3D printing systems structure behaviour may be subtle and hidden, but are nonetheless present. They interact with other rules of community use in important ways, such as in promoting experimentation with materials. Guidance for examining modularity as a rule-in-use comes from the theory of modular design rules (Baldwin & Clark, 2000). Open source is a concept linked to modularity in the study of open source software platforms (Langlois & Garzarelli, 2008). Open source must be differentiated from 'open interfaces' associated with a modular system. While the design of *open interfaces* allows coordination in complex modular systems, *open source* refers to the institutional terms of governance of the technological system, allows certain types of contributions and uses. For example, open source as a rule-in-use explicitly rules out extraction of knowledge from the commons and enclosure within private property regimes. One from of punishment that may result from such actions is community sanction.

Scholars of knowledge commons have examined rules-in-use and rules-in-form in terms of access, contribution, and use or extraction of information resources. These works have looked principally at rules that emerge from various collectives of actors that constitute or intersect with the focal community (Contreras, 2014; Madison, 2014; Schweik, 2014). This is analogous to the rules that govern access to materials and machines in a Fab Lab as set by the Fab Lab community and Fab Lab charter. I push the idea of rules-in-use into new territory, by examining the rules embedded in the structure of artefacts: in this case, 3D printing systems. My integration of design rules of technological artefacts with commons theory is a core theoretical contribution. It is meant to provide analytical guidance for a deeper analysis of how digital technologies structure knowledge commons domains, and can aid in theorising boundaries in emergent commons communities.

6.2 Open Source and Modularity as Design Rules-In-Use

In the following section, I discuss the concepts of openness and modularity as design rules important for the study of 3D printing systems. This encompasses a discussion on 3D printing systems as technological artefacts, and establishes design rules associated with technology within the typology of rules employed by institutional analysts in commons theory.

6.2.1 The concept of openness

Open source 3D printers contain integrated digital and physical components, with a corresponding mix of licenses and production arrangements. The diversity of 3D printers in the market, as well as the diversity of open source software, firmware, and hardware designs means that one cannot specify in general what an open source 3D printer is using formal license and institutional definitions. To deal with this complexity, I interpret the concept of open source more expansively in terms of general system *openness*, allowing me to study it as a characteristic of the overall 3D printing system. Thus, when used in reference to 3D printing systems in the following analysis, the term open signifies a more general view of openness from a user's perspective.

To elaborate these broader dimensions, I consider openness as design rule, what Langlois and Garzarelli (2008) call, 'unfettered access to knowledge of the visible design rules of the system' as well as 'the *right* to take advantage of those design rules' (p. 131-132, *emphasis in original*). This definition of openness comes from open source software development, and is fundamentally related to 'the way the intellectual division of labour is organised' (ibid). I adopt this same idea of openness in the context of 3D printing systems.

By scholars in the knowledge commons, openness has been conceptualised in terms of open *knowledge.* Madison, Frischmann, and Strandburg (2010) state in their discussion of the knowledge commons, that:

> *Openness describes our capacity to relate to a resource by accessing and using it. In other words, openness describes the extent to which there are barriers to possession or use. Openness varies according to the costs of surmounting barriers (in terms of money, conditions, or other restrictions) to exploitation. Openness in this sense may encompass joint or shared access to and use of the resource (p. 695).*

Defined in this way, openness can be considered alongside formal legal restrictions such as copyright or patent law, or any restrictions that 'may arise through norms and customs among owners and users and through institutional design' (Madison, Frischmann, & Strandburg, 2010, p. 695). Madison et al. (2010) go on to articulate this as follows:

> *Openness and the sources of control also reflect power and its distribution among potential possessors and users…. Openness is a functional variable that describes the degree to which possession and use of a resource is controlled, and it is a relational variable that describes the structure of relationships among potential resource users (p. 696).*

In a practical sense, Fab Lab members may access knowledge about 3D printers by reading machine instructions, learning from others, or even teaching themselves. This access is conditioned by how closed or open the design rules are made by the original manufacturer. Such actors control the distribution of information and therefore have control over knowledge regarding their 3D printing system. Here, I explore access to knowledge at the operational level; that is, from the perspective of users in Fab Lab communities.

6.2.2 The concept of modular architecture

Product architecture is defined by Ulrich (1995) as 'the arrangement of functional elements, the mapping from functional elements to physical components, and the specification of the interfaces between interacting physical components' (p. 420). Modular product architectures involve 'a one-to-one mapping from functional elements in the function structure to the physical components of the product, and specifies de-coupled interfaces between components' whereas integral architectures are characterized by more complex or tight coupling between product components (ibid, p. 422).

I use Baldwin and Clark's (2003) more elaborate set of conditions of a modular system, developed from the work of Simon (1962) on complex hierarchical systems. They state:

> 1. *A complex system is said to exhibit modularity if its parts operate independently, but still support the functioning of the whole.*
> 2. *Modularity is not an absolute quality…Systems can have different modular structures and different degrees of interdependence between their respective elements.*
> 3. *The different parts of a modular system must be compatible. Compatibility is ensured by design rules that govern the architecture, the interfaces, and the tests of the system.*
> 4. *"Modularising" a system involves specifying its architecture, that is, what its modules are and what each will do; specifying its interfaces, i.e., how the modules will interact; and specifying a set of tests that establish that the modules are compatible and how well each module performs its job (p. 6).*

Baldwin and Clark (2006a) describe the main benefits of modularity as making a system more manageable, organising and enabling parallel work, and encouraging experimentation in discreet modules by making the overall system tolerant to uncertainty. My particular focus is on how modular design relates to the third benefit, experimentation, for it is by way of experimentation that access to knowledge about materials can be gained. Baldwin and Clark (2006) note that modularity can be studied in use, in production, and in design. I primarily focus on modularity in use by exploring how this relates to experimentation with materials in significant ways.

6.2.3 The application of rules-in-use

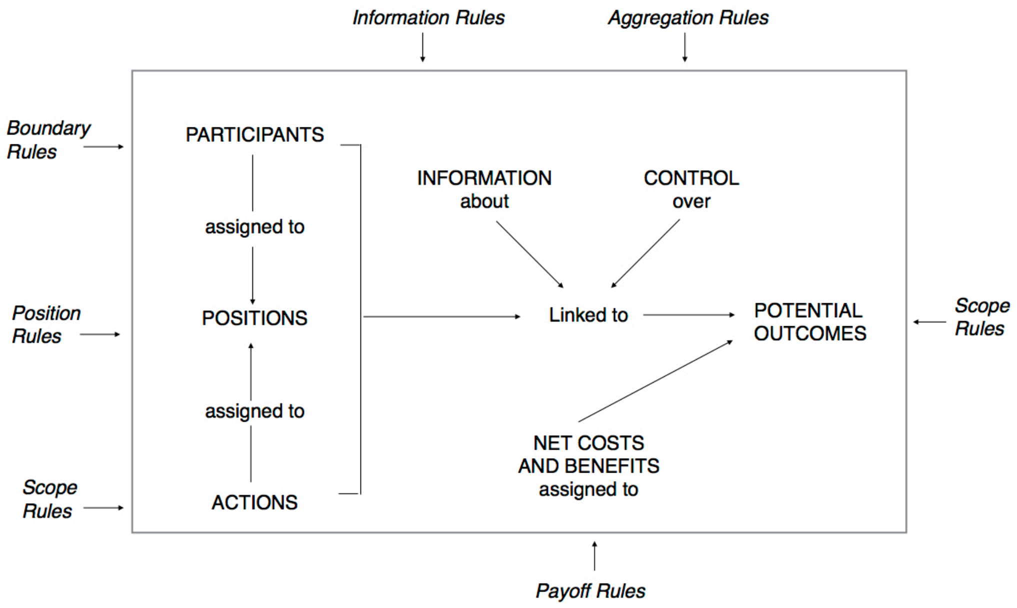
Classifying openness and modularity as rules-in-use involves ‘horizontal’ and ‘vertical’ typologies. In their horizontal typology, Ostrom and Crawford (2005) classify rules-in-use according to their application to working parts of an action situation. Rule types are position rules, boundary rules, choice rules, aggregation rules, information rules, payoff rules, and scope rules (ibid). From many years of research collecting and analysing rules-in-use in various contexts, Ostrom and collaborators find that the specified rule types are found to affect different components of an action situation. I paraphrase these rules explained by Ostrom and Crawford (2005) and Ostrom (1986) as follows:

1. Position rules that specify a set of positions and how many actors hold each one;
2. Boundary rules that specify how actors are to be chosen to enter or leave an action situation;
3. Choice rules that specify which actions can be taken by participants in particular positions;
4. Aggregation rules specify whether a single participant or multiple participants are needed to take a particular action;
5. Information rules that specify channels of communication among actors and what information is available to a given participant about the entire action situation ;
6. Payoff rules that specify how benefits and costs are to be distributed to actors according to actions taken; and,

7. Scope rules that specify the outcomes that could be affected, that is, the set of outcomes included in the analysis.

In institutional analysis, these rule types interact to construct and structure a particular action arena, and the action situations that arise. The following diagram illustrates the elements of an action situation where participants take actions with potential outcomes, affected by information about and control over their situation.

Figure 6.1: Classifying rules in an action situation



Source: adapted from Ostrom and Crawford (2005)

The typology of rules specified by Ostrom and Crawford (2005) can be used to define rules that were listed in Chapter 4 when discussing Fab Labs as common-property regimes. For example, rules of inventory can be understood as Choice Rules, where certain actions are allowed (i.e. what machines are part of a Fab Lab) based on a particular set of conditions (creating a collective capacity for digital fabrication) and attributes that define to whom the rule applies (users of Fab Labs). Rules related to organisational affiliation such as a Fab Lab being part of a university can be understood as Boundary Rules, as they typically involve how actors may enter and exit the action arena of the Fab Lab. The categorisation of these rules is by no means deterministic; rather, such categories act as useful tools to discuss the impact of rules found in Fab Labs on the activities taking place. The typology is also useful when analysing why some rules may affect access to knowledge about materials in a Fab Lab more than others. Given the way each type of rule is linked to a theoretical role in action arenas, the typology may help explain why some rules affect the outcome of interest more than others.

Recalling Figure 3.6, rules can also be understood within a vertical typology of nested levels of analysis. Ostrom (2005) states, ‘All rules are nested in another set of rules that define how the first set of rules can be changed’ (p. 58). These nested sets are operational, collective-choice, and constitutional rules-in-use. In this analysis I focus on the operational level, where participants are constrained by rules of ‘what they must, must not, or may not do’ (ibid) when using a 3D printer. Here, Fab Lab members are constrained by the design of the 3D printer machine when fabricating objects and accessing knowledge about the process of fabrication. Machine capabilities are a function of what machine an individual Fab Lab decides to acquire. I study these choices in order to include an aspect of collective-choice in my analysis. While not directly studied, I acknowledge that other collective-choice rules play a role in structuring operational rules, as in the case of open source hardware and software communities or firms that design a more modular or integrated 3D printer. Further, constitutional-level intellectual property rights structure these production models and by extension, the operational choices of use.

This level is discussed in Chapter 8 on the topic of extending this research topic beyond the current study.

This vertical typology is useful to capture ideas of dynamics in action arenas. If one observes where operational rules come from, and whether collective-choice and constitutional levels reinforce them, increased depth of understanding can add confidence to observed relationships.

6.2.4 Openness and modularity as design rules-in-use

I now turn to categorising the design rules of openness and modularity found in 3D printing systems according to the rule typologies developed for institutional analysis. Figure 6.2 is important for the defining openness and modularity as rules-in-use. Openness in 3D printing systems can be easily be categorised as an Information Rule, where:

> *Information rules affect the level of information available to participants. Information rules authorise channels of information flow among participants, assign the obligation, permission, or prohibition to communicate to participants in positions at particular decision nodes, and the language and form in which communication will take place' (Ostrom & Crawford 2005, p. 206).*

From a user's perspective, openness as an Information Rule means the level of information Fab Lab actors can access about the design and functionality of 3D printing systems.

Modularity as a design rule can be understood as a type of 'aggregation rule', used to 'determine whether a decision of a single participant or of multiple participants is needed prior to an action at a node in a decision process' (Ostrom & Crawford 2005, p. 202). As such, 'Aggregation rules are necessary whenever choice rules assign multiple positions partial control over the same set of action variables' and includes 'who will participate in the choice' and 'how much weight each participant will have relative to others' (ibid, p. 202). To explain the concept of modular design as an aggregation rule, one can see that the ability of an individual Fab Lab member to modify a given component of a 3D printer is partly defined by the number of other components that also need to be modified as a result, a property of the level of overall system modularity. This refers to the concept of modularity-in-use[39]. In the language of institutional analysis, a highly integrated machine means that multiple positions have partial control over the same variable.

In anticipation of the following analysis, a conceptual clarification is needed. It is important to note that the design rules of openness and modularity are not binary. That is, it is misleading to think of 3D printing systems as open/closed or modular/integrated. Rather, the degree of open source and modularity varies among the various components of 3D printing systems, and thus varying degrees of 'strength' in the design rules present. Such variations were not measured systematically, and as such, one should interpret the influence of modularity or openness as having general, rather than specific, effects. My aim is to explore how openness and modularity, as design rules in 3D printing systems, may generally influence access to knowledge about materials in one direction or another.

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[39] The term *modularity-in-use* is differentiated from *modularity-in-design* and *modularity-in-production* by Baldwin and Clark (2000). So as to avoid conceptual confusion with the similar term 'rules-in-use' from institutional analysis, I refer simply to 'modularity' rather than modularity-in-use, although this more precise definition is inferred.

Conceptualising openness and modularity as information rules and aggregation rules, respectively, is useful for theoretical coherence. However, it is worth defining openness and modularity as distinct rules of *technological design.* This helps frame the contribution to the field of knowledge commons, where the role of technology is in need of further analytical development. I thus define openness and modularity as technological design rules-in-use, corresponding to the categories of information and aggregation rules, respectively. As will be discussed in Chapter 8, openness and modularity can help in the theorising of boundaries for participation in the knowledge commons.

6.3 Openness and Access to Knowledge About Materials

In this section I introduce open source 3D printing systems in the wider context of open source communities from the perspective of Fab Lab members. I then explore the way openness as a design rule relates to access to knowledge about materials from the perspective of users. To briefly restate the theoretical premise of this section, I posit that the degree of openness in 3D printing systems has the affect of ruling in or out particular uses of 3D printing systems. I discuss the corresponding impact on access to knowledge about materials in commons-based 3D printing. I include examples of the use and choice of closed source proprietary 3D printing systems in order to explore this question in greater detail and include a level of collective-choice analysis.

6.3.1 Open source 3D printing systems

In general, low cost desktop 3D printers (using FDM processes) can be described as either open source or closed source. As discussed in the previous chapter, an open source system does not include access to material composition and the process of making the material: this information is kept proprietary. By contrast, in open source models software, firmware, and hardware designs constitute shared resources in the knowledge commons.

It important to view open source 3D printers as technology platforms made up of modules produced by multiple communities (see Figure 3.4). Open source 3D printing systems are part of the larger rise of knowledge commons resources linked to distributed Information Communication Technologies (ICTs) (Hess & Ostrom, 2003). A Fab Lab member introduces this by stating:

> *[When] you put something on the Internet, it's almost inevitably public and hackable. And what we've seen since the rise of a socially connected society, we've had to invent terms like open source, and the collaborative creative commons. So I think those are protocols which are reactions to the reality of the Internet, which is intrinsically about sharing.*

For Fab Lab users, the core idea of sharing is often linked to empowerment in having access to the means of digital fabrication. When asked the reason for having open source 3D printing systems, a Fab Lab member responded:

> *Knowledge. Knowledge. It's empowering, to be able to make something such as a 3D printer. It's empowering to be legally able to do so. It's becoming clear that the sharing of knowledge, the sharing of data, the sharing of designs, is empowering. Now I'm not*

> *against more proprietary systems because it allows and has allowed the economy to function. But I think we're living in a different age, where the value of things is different. One of the big statements about open source and design is that we stand on the shoulders of giants. Maybe we could patent a wheel for a car, but did we really design that wheel? Is that an idea we own? Perhaps not, perhaps we've got thousands of years of history to thank. Open source allows us to work at a very free level. I think that's what's interesting, for investigation anyway.*

Open source hardware and software communities are closely related, yet differences in their stage of development are apparent in the following statement by a Fab Lab member:

> *The open source hardware movement is very young, I think very it's a nascent movement and it's nowhere near as big or sophisticated as software which is very much within industry now.*

Despite the relative immaturity compared to open source software, open source hardware underpins a diverse and increasingly sophisticated family of 3D printers. Making 3D printing systems in Fab Labs is now commonplace. In the following quote, a Fab Lab member describes this activity:

> *We have…one [3D printing system] model that was developed in our lab that we are selling now. It's based on the RepRap model and was further developed over the course of the last year…It's [built by] some guys who were working in our lab. We are also offering a workshop once a month where you can build your own printer based on the one they produce.*

Local innovation and rapid experimentation is one of the hallmarks of open source models of software (Langlois & Garzarelli, 2008). From the following statements, is clear that Fab Lab users see the same benefits resulting from the development and use of of open source 3D printing hardware. A Fab Lab member describes this as follows:

> *You improve upon what is already done. So the project can develop much faster because of the distributed research…. If it's open you enable faster development.*

Another Fab Lab member builds on this theme, describing the way in which a large number of users can locally adapt 3D printing systems in the following quote:

> *[O]ne of the principles…is from patterns to details. So you start out on the bigger picture and you look at all of the elements that you want to integrate into your design. And as you place those, then you sort of drill down, down, into the details of the design…In your open source hardware or software, anything when it gets eventually tailored to the end user, it's going to be a very different product in Ireland than it is going be in Australia. So…I see as long as [there is] the open source hardware set of principles and concepts and applications, that application is universal.*

This description calls attention to the underlying modularity of open source development projects, as well as their open source design. This accords with Langlois and Garzarelli's (2008) analysis of the integration of modular design and openness in the peer production of open source software.

It is important to note that 3D printing systems need not be under an open source license to exhibit fast evolving properties. On describing proprietary 3D printers being developed in a hacker culture, one Fab Lab member explained:

> *[They are] brand-less. It's almost like open source but it's not that they are sharing the knowledge, it's that they copy each other so much…And there is a kind of evolution in how they copy. Because the next guy, well he'll change this [system] and copy. And then they have…customisations on top of the patented software.*

While this statement shows that openness in design rules is not a necessary precondition to technological system adaptation and evolution, there is an interesting cost of closing access to knowledge. As one Fab Lab member explains:

> *If it's closed, people…may hack it. But not necessarily take tests to improve or go further.*

This quote supports the idea that access to knowledge does not necessarily mean that knowledge will become part of a commons; that is, a shared resource available to others in a knowledge community. If someone succeeds in hacking a design, they may not contribute to its development for the benefit of others.

In general, one can see that the idea of open source design is not just about accessing and appropriating knowledge for one's own purposes, but contributing to the continued improvement of the technological or knowledge system.

6.3.2 Open source systems in use

I now consider how the use of open source 3D printing systems relates to access to knowledge about materials. I find that Fab Labs with high levels of access to knowledge about their 3D printing systems tend to acquire higher levels of knowledge about materials in use.

In one particular Fab Lab, co-founded by a local designer of 3D printers, a large amount of material knowledge resulted from the development of new open source 3D printers in the Fab Lab. A fellow Fab Lab member relates, 'My colleague is the designer that is making the machine and [has] all the knowledge about the machining'. Together with students in the Fab Lab, this designer experimented with materials in order to develop the machine further. This particular Fab Lab used a stereolithography machine as well as a filament-based machine for large amounts of material experimentation. In the stereolithography machine they '...mix resin with other materials like um hair, wool, and glow in the dark powders in the machine'. In the filament 3D printer they 'did experiments with sugar and salt…different kinds of materials…almost all of them was paste with like cement and like glue, white glue, the normal glue, and then with the powder of plywood, with silicon, and chalk'. Their machine was developed with complete knowledge and control of every component and its interface with materials.

Another example of knowledge about materials that can result from development of open source 3D printing hardware comes from a Fab Lab with strong community links to a local 3D printing materials producer. The Fab Lab member describes how this relationship was created:

> *It was really a co-development because it started when the guy who makes the filament came to one of the workshops to build a 3D*

> *printer, because he thought if he's going to produce filament, first he needs to test and he also needs to understand how this works. Then out of that came cooperation for testing the first materials he made and he got a lot of feedback from us like consistency, and colours, and stuff like that. And it just kind of happened naturally.*

In this evolving community relationship, the development of the material itself is linked in part to the use of an open source 3D printer that allows new types of materials to be experimented with. Because the Fab Lab offered open workshops in building 3D printers, the filament producer could gain complete knowledge access of the system design. This type of relationship not only allows access to knowledge of existing materials, but also enables access to knowledge of new materials under development.

By contrast, a Fab Lab member describes why proprietary MakerBot 3D printers are not used in the lab for experimenting with materials:

> *[We] can't replace the pieces [of the MakerBot]. With the MakerBot, the extruder is only 2 millimetres. You have to get the material from MakerBot. You don't do anything. They experiment, they shape the material for you, and they send it to you. No, we need real experimentation.*

In this case, MakerBot as a company is described to be capturing all of the knowledge from experimenting with materials and machine parameters. Referring to such proprietary 3D printing systems, another Fab Lab member captures this lack of knowledge in the simple statement, 'Those printers are black boxes'.

On this point, it is informative to look at MakerBot more closely. The MakerBot 3D printing system grew out of an open source community, with early models made through open source peer production. In 2014, MakerBot became closed source when bought by Stratasys, a large additive manufacturing company. One Fab Lab member explains the impact on the machine design:

> *The newest version of MakerBot that just came out, they really close it off now, so the extruder is sealed and you can't really take it apart, so if it's jammed, you can basically just send it back and get a new one…But the version before is very accessible, you can just disassemble the extruder completely and we already did that a couple of times, it happens when the material gets stuck. With the [new] MakerBot, you have limited options with the software, like also for the settings, how you print, the temperature, speed. With the open source one, you have many more parameters accessible.*

The story of MakerBot underscores the fact that the dividing line between open source and closed source is changeable. The perspective of the Fab Lab member illustrates how changes from open to closed source come with particular implications for access to knowledge from the perspective of the user. When open source, the particular ways the MakerBot system could be understood and modified in order to accommodate material characteristics stands in stark contrast to the reality of the closed system. As stated, if the extruder jams you have to 'just send it back and get a new one'. This is clearly not conducive to gaining access to knowledge about materials, machine parameters, and the interactions between them.

The consequences of not being able to access design rules of 3D printing systems is even more apparent when viewed from the perspective of a Fab Lab member engaging in a project of modifying a proprietary system. The Fab Lab member explains:

> *Whenever you're working with someone else's system, it's really hard to know how the things are going to be compatible with each other especially when you have closed source stuff. There's no documentation on it so there's a bit of trial and error to find out how their system is working so you can then implement something that can mesh with that. That's usually one of the larger barriers. Once we get past that, the software side of things is relatively well established at this point. There's a pretty huge open source community so we're standing on the shoulders of giants in terms of implementing and adjusting for our particular scenario.*

This quote illustrates two important points. First, a lack of knowledge, including documentation, is clearly a barrier to understanding how to modify a proprietary 3D printing system while ensuring overall system compatibility. Second, the quote recalls how modifying 3D printing systems is a function of the contributions of other open source communities. As the Fab Lab member indicates, a lack of knowledge in proprietary 3D printing software systems may be made up for by the existence of solutions in the general open source community that can be tailored for specific use.

This Fab Lab member goes on to explain the reason for gaining knowledge of and control over the design rules of a 3D printing systems as follows:

> *In terms of the material usage [of the closed 3D printer] the manufacturer that supplies them says you have to buy our material to go in our printer so it's a very closed system. In order to open that up you need to have flexibility to deal with a wider range of [materials]…[What] we're after is hacking it just enough so that…we can adjust the temperatures a bit more, deal with some wider filament sizes, cool things down or heat them up faster or slower, because that's going to allow us to work with the local*

> *suppliers so we can use things that are actually produced here rather than shipped in.*

The key relationship articulated is between knowledge of 3D printing design rules, and the potential to use and understand local materials for 3D printing. The benefits of using such local materials is explained by the Fab Lab member as follows:

> *If you use local materials its just awesome in terms of a cost factor, shipping, [and] turnaround times, but there's also the option to do some more experimental stuff so the local producers will also have stuff that they're working on and they'll want people to try out. Being a Fab Lab that's really focused on research and development we're really keen to try out those processes or materials as they come out…it's an obvious choice to try and be involved in that community space where everyone is working together and testing things out and talking to each other, saying 'hey this is what we've found'. So it's hard to be a part of that conversation if you're locked down into what you can actually use.*

A closed source system clearly makes accessing knowledge difficult from the perspective of this Fab Lab member. This story also illustrates how accessing knowledge of the design rules of 3D printing systems can enable access to knowledge about materials at a community level. I now look at how these relationships at the operational level relate to the choice of open source versus closed source machines for individual Fab Labs.

6.3.3 The choice of open source systems

Exploring why Fab Labs choose open source 3D printing systems versus proprietary models helps understand their use at an operational level. For many, the cost of access to goods and services is often at the forefront of concerns for Fab Labs lacking financial resources. Regarding the question of why Fab Labs choose open hardware and software, a Fab Lab member states:

> *We are mostly using [open source software] because we are in a low-income neighbourhood.... We can just tell [our Fab Lab members], okay, go and download it on your own computer and install it.*

Adding to the focus on cost, upon considering the choice of 3D printing systems one Fab Lab member states,

> *The obvious thing about open source is you're not paying for marketing, you're not paying for project development, or anything. But…maybe the downside is that you will actually have to get your hands dirty. But for me, that is the good part of it actually. But some people might think 'oh yeah but I don't know how to do it', and you have to go into a learning process [and] there is a learning curve…But it's cheaper. And we can make it and we like to make it, so that's what we like about it.*

While the choice for buying open source 3D printing systems is clearly motivated by cost, learning is stated as a second factor.

Learning is often connected with the desire to experiment. One Fab Lab member explains the link between open source 3D printing systems and experimentation in the Fab Lab:

> *We have not yet experienced doing experiments with new materials. And that's why we are starting a new Fab Lab…For that FabLab I'm interested in buying the Ultimaker because it seems to be more hackable than the others…It would be able to do more stuff and also to get you into the thinking, 'I can do it also'. With all the capabilities, you would be able to make things outside of the box. So we got this, for what it was not originally meant to do. You can be more innovative.*

Importantly, the choice of an Ultimaker as an open source 3D printing system is based on the potential of using it for 'what it was *not* originally meant to do' (*emphasis added)*. This illustrates the enabling potential of open design rules: those who want to alter the system for their own purposes may access the knowledge necessary and exercise the control needed to do so.

There was one notable exception to this finding, where a Fab Lab member described why some 3D printing systems are used for experimentation with materials rather than others:

> *We have [the] Z-Corp machine. We don't experiment using that because it's very expensive. We have the MakerBot which we killed [through experimenting]. Every couple of months we get a new one, and we kill them over in the lab, and get a new one.*

In this example, both the Z-Corp and MakerBot machines are closed source. The lower cost of replacement explains why the latter are used for experimenting. This quote comes from a member of a Fab Lab with a lot of financial resources, suggesting that, if provided with enough financial means, Fab Labs may allow experimentation on proprietary machines and simply replace them when broken.

When design rules are open source, users can also benefit through the rapid evolution and ability to upgrade components. One Fab Lab member explains:

> *I started with this Dutch brand and buy that one…I like them, so I don't bother with another 3D printer, and because it's open source, the development of the printer goes pretty fast, the software is developing pretty fast, and they are pretty hackable…we can do whatever we want with it because you know how it works, [for example], what to change within the code to make something else.*

The ability to upgrade system components with open source models also relates to the ability to accommodate new materials, as explained by a Fab Lab member:

> *3D printers, you know you can't really recommend one because they change so often…we did buy an Ultimaker because it was based on an open source design…I was interested to see their hacking workshops using different materials or adding different extruders and so forth, it's quite interesting. I've seen now that there are new materials coming along for the standard kind of PLA printers, and that those printers are able to handle these materials, quite exciting, because it means that there's an upgrade path there. They're not just redundant after purchasing them.*

The potential to continue to adapt the machine to new materials is deemed important, especially at a time where more and more materials are coming onto the market.

Given these benefits, it is important to explore the reasons why many Fab Labs choose to purchase and use more proprietary 3D printing systems. One main reason is the number of parameters needed for controlling open source 3D printing systems compared to the ease of proprietary systems. In the following quote, a Fab Lab member explains how the number of options for controlling open source 3D printing systems can be prohibitive to some users:

> *The closed [systems] are most of the time easier to use because there are less options. So if I do an introduction class, [unlike with] an Apple or Windows PC…if you know what you're doing, you can do much more with the Linux operating system. But if you don't know what you're doing, you don't want a million options. You want 10 or 20. And that's enough. And it's the same with the printer. So if you just want to print stuff, the MakerBot is fine and prints reliably, software is very neat, you don't have a hundred buttons but only 10, and you can get very good results. But if you really want to experiment, like change the way that the machine moves or stop in between to do something with the part, or stuff like that, then you need a different software with the way of controlling more.*

Confirming the discussion so far, experimentation is associated with open source systems that come with many possible options. Yet these options are framed as problematic for some users who want reliability and ease of use.

Ease of use is not trivial, especially for newcomers to the technology. One Fab Lab member explains this as follows:

> *I would say [when] 90% of the use cases are standard printing operations, people prefer the MakerBot…You just open the software, put your model in, print, and then it prints. With the open source ones, there are 10 more things you have to do before you start to print. The results are very similar in most cases. When I want to print something, I try to just make it as easy as possible. And only if I want to do something very specific, then I print it on the RepRap.*

It is important to take into account the overall usability of open source 3D printing systems, not just in printing objects, but in maintaining their functionality. One Fab Lab member discusses the costs and benefits of open versus proprietary systems as follows:

> *If you don't know how to fix the [3D printer], you need to have people who help you do so. And this is the problem with all the open source machines. So when I made my own RepRap most of my time I spent in fixing instead of using it. So you need to find the place where you will not only play, you will fix, and you will have enough time. But if it will be a closed system, you will not be able to play. So it needs to be something in between.*

Overall time intensity can thus be a barrier to the choice of using open source 3D printing systems. However, the cost of 'not being able to play' with proprietary systems emphasises the cost of experimenting that comes with the choice.

In general, proprietary systems seem to be the clear choice when it comes to system usability. However, the pace of development in open source 3D printing is challenging this. A Fab Lab member articulates this as follows:

> *MakerBot is really the market leader in consumer printers right now. And I would say they are one iteration ahead of everyone else, in terms of usability and product design. But for example the Ultimaker, the Dutch printer, which is still completely open source, that's also very easy to use by now…it's just the amount of resources you can put into product and software development and usability experts.*

This quote makes an important point: usability depends not on open or close source per se, but on 'the amount of resources you can put into product and software development and usability experts'. This means that the usability of the product is partly a function of the maturity and organisation of the open source community. One Fab Lab member makes this point as follows:

> *Open source is still difficult for a lot of people. It doesn't have the slickness or usability that more proprietary stuff has. So yes it's difficult. Obviously there are pieces of [open source] software that are just as good [as] anything [proprietary]. But on the hardware side, when you're starting a Fab Lab, you want to make sure you've got things that work out of the box initially.*

Here, open source software is described as 'just as good' in usability, while hardware is still behind. This is interesting when 3D printing systems combine components developed by different communities. The debate concerning the quality difference between open and closed source models will evolve along with open source communities. In general, however, Fab Lab members expressed the opinion that proprietary 3D printing systems outperform open source systems when it comes to usability and printing performance at this point in time.

Preferring to enjoy the benefits of both open and closed source systems, many Fab Labs choose to have both open 3D printing systems as well as proprietary systems. One Fab Lab member describes the rationale behind choosing both types:

> *There's two sides to it. One is we want a lab that's easily accessible for as many people as possible so that means in many cases we need to use commercial software and hardware, because they are just easier to use so the entry level is lower. If you have only open source hardware and software, then you exclude quite a few people who might be interested, but they don't want to learn for a week before they start making something, and that's important because the making holds a big part of the fascination. On the other hand, it's very important for the lab, I think, to have a community of people who really know what they are doing, who can really create all the machines and software.*

In addition to stating the importance of having both open and closed source 3D printing systems, the statement notes an interesting cost that comes with open 3D printing systems in relation to access to knowledge about materials. Many Fab Labs consider ease of access to digital fabrication technology as key to future learning taking place. Viewed in this light, the intensive learning involved in using open 3D printing systems can create a higher barrier to entry in terms of basic use of the Fab Lab. This is an important ingredient when accessing the overall impact of openness as a design rule. It must be judged alongside the fact that there is a clear relationship between openness in 3D printing systems and the likelihood of experimenting with and accessing knowledge about materials in commons-based production.

As a final point, the previous quote also shows how the choice between types of 3D printing systems relates to how Fab Labs cater to different user groups with different interests. If both open source and proprietary systems are available in the Fab Lab, the interests of one user group (who want for example to experiment with materials) can be accommodated along with the interests of other users who may be more interested in expedient and reliable output. This relates to the impact of user type, purpose, and collaboration previously discussed in Chapter 5.

6.4 Modularity and Access to Knowledge About Materials

In this section I discuss how levels of modularity in 3D printing systems influences use access to and engagement with types of knowledge. I discuss the implications of use, and the rationales for choosing modular versus more integrated systems from the perspective of Fab Lab users. I discuss a contradictory side of modularity related to the dominance of a particular type of interface relating to materials. I end with a discussion of system interdependencies and their positive relationship to users being able to access knowledge about materials.

6.4.1 Modular systems in use

To understand the degree of modularity present in material extrusion 3D printing systems, the most common type of 3D printer in Fab Labs, one must first understand the components in greater detail. In general, 3D printing systems are composed of hardware, firmware, software, and materials. One Fab Lab member describes the components of a 3D printing system in relation to how they work together:

> *[A] basic understanding of how the 3D printing system works and what the components are: you have this [printer] head and you move it back and forth, up and down. You've got a fourth axis which is your extrusion so you can push filament out fast or slow. That's the guts of the mechanical setup and everything else works on top of that. The layer after that is your [firmware] controller, which is some kind of circuit board, which directly drives those mechanical things, making everything tick. There's sensors that go back to that board and pick up information about the environment and tell it things like if its hit something or how hot it is, and that controller then talks back to the computer and communicates that information. The computer does all of the heavy lifting as far as working out what all of the tool paths would be in order to make this really awesome design. And then you get into your software layers.*

The software layers include Computer Aided Design (CAD) software, and software for slicing the CAD file into thin layers, generating an .STL file that the 3D printer can read. Physical material is extruded from the printing head as directed by the software program, in combination with the firmware controller and mechanical parts. In the following paragraphs Fab Lab members refer to the degree of modularity in 3D printing systems as a whole, exploring the high level modules of hardware, firmware, software, and materials and their respective interfaces. They also speak of the nested hierarchical structure by looking at the sub-modules of hardware such as printer nozzles and the code on firmware controllers. Both levels are important when exploring how modularity in 3D printers affects access to knowledge about materials.

As theoretically stated, the degree of modularity in any artefact can vary considerably. This is certainly the case with 3D printing systems, where variation in the degree of modularity manifests as degrees of inter-module interdependencies. In the following statement, one can see the way that interdependencies between components of a 3D printer present themselves to Fab Lab users. Relating a typical conversation with a new users of 3D printers in a Fab Lab, one member states:

> *Depending on the maker of the filaments, colour plays a role. And then people are flabbergasted. 'I worked with black, now I've put in the white, and it doesn't work. Why?' And I go, 'yes think twice, what has changed? Only the colour. What does the colour imply? What is colour? It's some additive to that material. So are you surprised that this has the potential to require different parameters? Why are you surprised?' But people are surprised!*

Even when only changing the colour of material filament, interdependencies in system parameters must be taken into account (melt point and viscosity are common implications of changes in material used). This quote also demonstrates a core theme of this chapter: how knowledge of materials (in this case, the impact of colour additives on overall functionality) can be revealed through some degree of system modularity (the ability to change the colour of filament and the parameters of the machine). Even though interdependencies in the system must be taken into account, a certain level of modular design in the system is required for a different colour material to be used, and corresponding knowledge to be gained.

When modifying 3D printing system components, the impact of modularity on knowledge of materials can be further elaborated. In the quote below, one Fab

Lab member describes the process of altering a 3D printer in order to allow the use of a new material produced by a local filament company:

> *The key intervention in our particular case is the firmware controller…we need to get in there and put some of our own code on there and widen the temperature range…. Which then means that all of the existing motors and sensors need to work with this new board that we're going to put in so there's a bit of tweaking that's going to go on around there to make those all play nicely with each other. And the layer after that is changing the software side of things on the computer so that now we have the capabilities to work within these different [temperature] ranges. And then the final and hopefully fairly minor thing is we need to make a few mechanical tweaks so the tolerances are a little bit wider so that the wider filament, for example, physically fits down the extrusion part.*

This quote underlines the enabling power of modularity for locally adapting a technological system. The Fab Lab member is able to make a considerable change within a one component (the firmware controller), while intercomponent relationships are not radically affected (only needing 'tweaking' to help them 'play together'). In this example, the firmware controller was altered so that the temperature of extrusion could be varied. If a new material requires a different melt-point, this intervention allows this new material to be used.

Simple modifications to 3D printing systems are also extremely common in Fab Labs and easily exemplify the basic principals of modularity at work. One such simple modification, widely referenced by Fab Lab members in adapting 3D printing systems, is changing the size of the extrusion nozzle.

The diameter of the hole where filament is extruded from the printing head provides a common barrier to material experimentation. If the hole is too small, materials with large particulates jam the extruder. One Fab Lab member explains:

> *[Experimentation] depends on the extruder. If the extruder was meant for two millimetres across, nobody will experiment - how will I get the material inside? If the extruder is big enough for all types of materials it's going to be crazy.*

'Crazy' in this context means high levels of experimentation are expected within the Fab Lab.

The modularity of these 3D printer designs in open source repositories also enables the integration of knowledge from within Fab Lab communities. In the growing community of open source 3D printing systems, large repositories of hardware design files for modifying 3D printers exist. This is often combined with local knowledge. One Fab Lab member explains,

> *We built [the 3D printer] from scratch, but there were some designs floating around at the time on the Internet that we looked at, changed some stuff and then we had our own design.*

In the following quote, a Fab Lab member describes how machines that are made in the Fab Lab are most often used to experiment with different materials:

> *Some other people who experiment a lot, they built up their own [3D printers]. They get only the extruder from China [where] they sell the extruder by itself. They have many extruders and they test*

> *different materials and see what's coming out. It depends on your knowledge: you put it all together.*

This statement clearly relates the degree of modularity with the potential to experiment with materials. If extruders can be bought by themselves in a range of sizes, and made to fit with self-made machines through standardised interfaces, users can experiment with materials. This introduces modularity in design as well as modularity in use (Baldwin & Clark, 2000). Users of 3D printing systems may be part of design communities, where modularity is an important design parameter allowing for local system modifications like extruder nozzles of varying diameters.

Thus far, it is clear that a high degree of system modularity allows users of 3D printers to experiment with and gain access to knowledge about materials. This varies from changing nozzle diameter to altering the firmware code to allow for greater temperature ranges of the material used. Before concluding this section, it is worth considering whether highly integrated machines prevent access to knowledge about materials.

The following statement by a Fab Lab member shows how knowledge about materials can be hidden from a user of a 3D printer due to the tight integration between material and hardware interfaces:

> *It's really difficult, to give people so much to grasp, to have material to understand too. I think that's underestimated, and I think that's also why people are attracted to digital fabrication because there are some things they don't need to think about it in a way. [If you're] a craftsman running a knife through that material, you need to understand it in a different way than…especially [with] these 3D printers…you just press play and this goo comes out the printer.*

This quote makes it clear that a highly integrated machine means there is *no need* to understand the material in use. This does not mean that knowledge is not possible to access and use, only that the machine does not compel the user to do so.

This idea can also be seen with the integration between 3D printing designs and software programs used. One Fab Lab member discusses the impact of Fab Lab members relying on Thingiverse, an online database of 3D printing objects where designs are ready for download and printing:

> *There is a lack of knowledge in 3D design. That is, people are downloading things from Thingiverse or something like that and printing it.*

Importantly, it is not the inaccessibility of 3D printing design knowledge; rather, it is the integrated nature of design with software in 3D printing systems that is identified as linked to a lack of knowledge on the part of the user.

These themes will be further explored in the next section. Having considered the impact of modularity on access to knowledge about materials at the operational level, I now examine the rationale for choosing to acquire modular 3D printing systems in addition to the rationale for acquiring integrated systems.

6.4.2 The choice of modular systems

I find the rationale for acquiring modular 3D printing systems often relates to the range of materials and freedom of use. Modularity is part of the rationale for why Fab Lab members choose some types of 3D printing systems over others. To illustrate this rationale, one Fab Lab member explains how the choice of materials is linked to the type of machine being used:

> *In 3D printing, there are lots of new materials being developed right now. So usually we get a roll or two or sometimes also people bring new material and test it and leave it with us. For example there's a flexible material, called NinjaFlex that only works in the MakerBot because the extruder is built differently from the other machines. And then there's ABS with carbon particles so that it's conductive, and that you need to print in a RepRap because you need a thicker extrusion diameter because these particles would clog the extruder otherwise. So it depends on the material, which machine you want to process it with.*

Here it is clear that a RepRap is the machine of choice when it comes to a filament with unconventional properties (i.e. large particles). On the other hand, MakerBot, a highly integrated machine, is built to work with certain patented materials such as NinjaFlex.

However, the interface between the size of the filament and the printing nozzle across most small filament extrusion printers has become relatively standardised. This is implicit in the following statement by a Fab Lab member:

> *We used to buy the materials from MakerBot, but the nice thing is you don't have to buy it from them - there's nothing stopping you…Basically any filament, you can put in anything you want.*

Filament for extrusion-based systems has become standardised to a particular range of diameters. This means that Fab Labs can use a machine like MakerBot that has been engineered to work with its own filament, while also using other third party filament because of the standardised interface. The Fab Lab member continues this explanation, comparing MakerBot with the Up! printer:

> *Some of the other labs…are running Up!s and they use cartridges. And those, you have to either hack or, you can't just use any filament, you have to buy the cartridges, and that's a stupid system.*

The frustration in this statement is apparent: when using a 3D printing system without a standardised hardware-material interface, the user is limited to buying material from the machine provider. Even though the MakerBot is proprietary, it is still preferable given that it uses a standardised hardware-material interface; this gives the user the option to source a variety of materials.

However, just because a variety of materials can be used by way of standardised interfaces, it does not mean that the result will be as fine a quality as materials engineered to be used in a highly integrated 3D printing system. This accords with theory that states when users require superior performance, integrated systems are chosen (Langlois & Garzarelli 2008, referencing Christensen, 2002).

As the following statement by a Fab Lab member explains, performance and accessibility are high in importance for some Fab Labs:

> *We are not that interested in exploring the capacity of the technology, calibrating and tweaking the temperature and tweaking the velocity of filament and hardware and software. Let everybody else do that. We need a full functioning lab that works all the time. Because we have those inventors coming in [and] we need it to work. We don't have time for experiments…we are fascinated by ideas but not by the toolbox, the machinery…We want the person that has the idea to skim forward and shortcut the whole process going from the idea to the finished product…And that's not [by] calibrating 3D printing.*

The significance of this statement is twofold. First, the rationale for choosing particular 3D printing systems is expediency and reliability, not flexibility of many material options. Second, the member states that ‘exploring the capacity of the technology’ is not of interest. Experiments involving ‘temperature and tweaking the velocity of filament’ are stated as not relevant. Access to knowledge of materials, therefore, is not enabled, and the choice of more integrated 3D printing systems in this Fab Lab is deeply implicated.

6.4.3 The downside of standardised interfaces

There is, however, a contradictory side of modular systems from the perspective of knowledge about materials entering the commons. This is the subtle cost of modularity that has to do with the dominance of material extrusion 3D printing systems.

Baldwin and Clark (2000) state that there are often high fixed costs of establishing visible design rules. In open source peer production models, Langlois and Garzarelli (2008) state that modular systems can become ‘locked-in to a particular system decomposition’ (p. 133). This is because local experimentation within modules is enabled by weak connectivity between modules. When this is the case, these interfaces are less likely to be altered, instead remaining stable while change happens within modules.

3D printing systems designed and developed by commons-based communities have generally followed a particular system design where the interface between hardware and material type has become relatively standardised. As discussed, this can enable experimentation with different filaments that adhere to standard diameters, whereas non-standard interfaces may require a user to buy a material and machine from the same company. However, the range of experimentation between material and machine is necessarily constrained to types of filament. This is emphasised in the words of a Fab Lab member:

> *It's clear right now many limitations associated with 3D printing are a result of the materials used, not just the individual materials, but the opportunity to integrate different types of materials to make composites in an affordable way.*

This general point can be further illustrated by examining how the standardisation of a particular machine-material interface in 3D printing systems risks not exploring other forms of materials with their associated benefits. One Fab Lab member states,

> *I believe that 3D printing is a really good, really interesting tool…but the problem is all the 3D printers I saw here are filament-based…not powder-based. The great advantage of powder-based technology is that you can actually use any material you want. I've seen people…for example using ceramics, using salt, using sugar, using different powders.*

Here the member expresses frustration that the design of filament-based 3D printing systems cannot accommodate other types of material forms. The dominant design parameters of the 3D printer allow only certain types of materials, thereby restricting the types of knowledge about materials that can be accommodated in commons-based 3D printing.

The dominance of material extrusion system design can also have an impact on the use of recycled plastic, a resource that can encourage access to knowledge about materials by virtue of it coming under the control of a Fab Lab common-property regime (see Chapter 4). One Fab Lab member explains how an alternative 3D printing system opens up the potential to use recycled plastic more effectively:

> *You heat [recycled plastic] up when you want to make it into a filament. [This] recycles it twice because it also gets heated again by the printer…. I saw this printer recently that was printing only with pellets…you could instantly feed [recycled plastic] flakes into the machine.*

In this example, a 3D printing system that works with plastic pellets rather than filament is viewed as more appropriate for working with recycled plastic. This is because the recycled plastic needs only to be heated up once (when it is extruded through the print head), rather than twice as in filament-based systems (where the plastic is heated again during the process of making filament). Grinding up waste plastic into pellets does not necessitate heating it up, and as heating degrades the compositional quality of thermoplastics, this system design is deemed preferable from a quality standpoint.

Although there are pellet-based 3D printers on the market, they are far from common. Material extrusion systems have largely adopted the design interface to support filament. This can be a barrier for accessing knowledge about materials that come in forms other than filament, or for using thermoplastic waste as raw materials for new 3D printing material. If material extrusion continues to be a dominant design interface in 3D printing systems, the value of thermoplastic waste as a higher quality resource may remain limited.

6.4.4 The influence of system interdependencies

The way that certain levels of independence between modules in a 3D printing system relate to the potential for users to experiment and acquire new knowledge seems clear. Likewise, the way that a tightly integrated system inhibits access to knowledge by preventing intervention into system parameters is well explained by Fab Lab members. However, this dichotomy underplays the fact that highly modularised 3D printers are not fully decomposable; there are particular interdependencies that are maintained even when a system is highly modularised. To understand the influence of modular design rules, one must take into account the influence of system interdependence together with the influence of independence between system components.

Even a small change in seemingly small part of the 3D printing system can influence the overall function. For example, the diameter of the extrusion nozzle can be highly interrelated with the overall performance of the 3D printer. One Fab Lab member explains, 'What we changed was drilling out the nozzles…you get rougher prints but it also prints faster'. 'Drilling out the nozzles' means enlarging the diameter of the nozzle through which material is extruded. Not only is the final object 'rougher', the speed of printing is also affected.

The complications that arise from changes in one part of a 3D printer causing an unanticipated change in another part of the system are discussed as an issue for designing complex systems (Ethiraj & Levinthal, 2004). From the perspective of 3D printer users, however, there is another important affect: changes across modular interfaces can compel users to engage in a new part of the 3D printing system. A Fab Lab member describes this process of engagement as follows:

> *Take 3D printing…if you want to test a new material, and you know one software, and you realise you can't do what you need to do to test that material with that software, then you need to learn a new software. And then if the extruder jams, then you also need to learn about the hardware. So…it's all connected basically, because digital fabrication involves all these things.*

Quite clearly, the user is compelled to engage with new types of knowledge associated with the 3D printing system by virtue of the interdependence between components. This extends to knowledge about materials. To revisit the example of changing the diameter of the nozzle, one can imagine that the user now must engage with the viscosity of the material (a type of knowledge), as well as the software parameters that set the speed of material extrusion.

In conclusion, the positive influence of system modularity on access to knowledge has two, opposite mechanisms. First, modular independence enables experimentation by allowing the user to intervene in a system parameter without jeopardising overall functionality. Second, the interdependencies that are present can introduce changes that a user must contend with, leading to engagement with different types of knowledge in the process. This latter insight is explored further in Chapter 7.

6.5 Discussion

In this chapter I investigated examples of Fab Lab members using more or less open 3D printing systems, as well as more or less modular systems. I found that openness in 3D printing systems is an enabling force for experimentation with materials and corresponding access to knowledge about materials. However, open 3D printing systems can be difficult to use, creating a barrier to entry for newcomers to learn and acquire knowledge of materials.

I find a clear and positive relationship between the degree of modularity in a 3D printing system and access to knowledge about materials. The ability to alter a system in order to use local materials, the increase in the range of material types possible to use, and the increase in knowledge access to the system's design are key benefits. These underpin the rationales for using modular machines.

An interesting drawback related to knowledge of materials stems from the dominant design interface of material extrusion in 3D printing systems in use in Fab Labs. While modularity may ease entry into commons communities by allowing for distributed participation, boundaries of knowledge may be inadvertently rigid due to the dominance of certain interfaces. One can see this by examining how the dominance of material extrusion reduces the potential of experimenting with different material types. These costs and benefits confirm the analytical use of modularity as a design rule-in-use.

From analysis of user experiences of interdependencies in the architectures of 3D printing systems, there emerges an interesting relationship between the level of system modularity and learning. While a high degree of modularity allows users to experiment locally and thus gain knowledge about system components, including knowledge of materials, system integration can *compel* the user to extend his or her knowledge outside of the bounds of the initial point of system engagement. One general drawback of this analysis of user engagement is the time-dependent nature of the data. This is addressed in the next chapter.

7 MODULARITY AND ENGAGEMENT IN AN OPEN SOURCE 3D PRINTING COMMUNITY

7.1 Introduction

In this chapter I study commons-based 3D printing from a new perspective. I analyse user activity over time in the online forum for the Ultimaker 3D printer. The Ultimaker 3D Printer is an open source machine that is commonly used in Fab Labs. By studying patterns of user posts, I explore how users are engaging with different types of knowledge associated with the 3D printing system over time. This analysis further illuminates how users engage with types of knowledge associated with 3D printing systems in a commons environment. Findings suggest that learning takes place across types of knowledge associated with digital and physical resources over time.

7.1.1 Guiding question

The findings of Chapter 6, on the role of open and modular system design on access to knowledge about 3D printing materials, can be summarised as follows:

a. Openness as a design rule enables access to knowledge by allowing users to understand and engage with parts of the 3D printing system;
b. Openness as a design rule can be a barrier to engagement if 3D printing systems are difficult to use and confusing to learn;

c. Independence between 3D printer system modules enables access to knowledge by allowing users to experiment with one part of the machine locally; and,

d. Interdependence between 3D printer system modules can affect engagement across interfaces by requiring the user to extend his or her knowledge outside of the bounds of a module.

All of these findings, to some degree, relate to the knowledge of users of 3D printing systems. However, the type of data used to date has a serious limitation when it comes to studying knowledge: it does not allow me to look at change over time. While a user in a Fab Lab may speak about the learning process, and the barriers and enabling factors behind acquiring knowledge, one cannot systematically study it.

My aim in this chapter is to use a different level of analysis to shed light on how users engage with types of knowledge in 3D printing systems over time. The question that guides this chapter is as follows:

> *Do users cross the boundaries between types of knowledge in a commons-based 3D printing community over time?*

To answer this question, I first undertake a descriptive exploration of the Ultimaker community forum, focusing on users and the nature of their contributions. I pay particular attention to how users engage with knowledge associated with the main areas of the user forum: hardware, software, and firmware. I posit the distinction between users who are knowledge ‘specialists’ by posting in only one area, versus users who are ‘generalist’ by way of posting in two or three areas. This categorisation is designed to differentiate users who engage with knowledge associated with either physical hardware or digital software goods, from users who engage with both types of knowledge. I then build a statistical model to test the relationship between the likelihood of being a generalist, where digital and physical knowledge are engaged with, and time spent in the user community. I conclude with a discussion of findings.

7.1.2 Theoretical concepts

The Ultimaker user forum presents an interesting example of peer production (Benkler, 2016). With its open source software, hardware, and firmware components, and distributed user community that aids in the evolution of the 3D printer over time, the Ultimaker organisational model includes the conditions of decentralised problem solving, harnessing of diverse motivations, and the separation of governance and management from property and contract (Benkler, 2016).

I take as a starting point the challenge for studies of peer production in open source communities to extend beyond software (von Hippel & von Krogh, 2003). The Ultimaker forum, with its categories of user postings in hardware, software, and firmware, allows me to explore user engagement with physical and digital knowledge. I adopt the terminology of von Krogh, Spaeth, and Lakhani (2003) in studying specialist and generalist patterns of behaviour in an open source user community. In von Krogh et al.’s (2003) empirical context of an open source software project, being a specialist or generalist means contributing code in one module or more than one modules. I use the terms specialist and generalist to connote engagement in one or more types of knowledge associated with physical or digital goods. This study of the Ultimaker forum thus offers the opportunity to explore the open source phenomenon in terms of an organisational paradigm (David & Shapiro, 2008) beyond software. The wider theoretical contributions in this area will be discussed in Chapter 8.

Furthermore, I employ David and Shapiro's (2008) concept that accumulated experience of users may constitute an important endogenous affect in open source communities. I create a proxy for the concept of learning by studying the posting activity of Ultimaker users in the forum over time. I reflect on the importance of taking into account the level of module interdependence when studying learning across types of knowledge.

7.2 Ultimaker 3D Printers and Fab Labs

To elaborate the place that the Ultimaker user forum has within this research, I first introduce the use of Ultimaker 3D printers from the perspective of Fab Lab users, and then link these empirical contexts using the IAD.

Ultimaker is an open source 3D printer that evolved from the initial open source blueprints of the 'RepRap' 3D Printer. Ultimaker was originally designed in a Fab Lab in the Netherlands[40] in 2011 and has since evolved to be one of the most popular 3D printers on the desktop market. Ultimaker is also the recommended printer on the Fab Lab inventory, making a study of its community a particularly appropriate addition to the study of 3D printing in Fab Labs.

In interviews, Fab Lab users stated why they choose the Ultimaker 3D printer, often citing the positive link between open source systems and

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[40] Ultimaker was first created in ProtoSpace, a Fab Lab in Utrecht. See http://protospace.nl/.

experimentation. A Fab Lab member describes how the choice of Ultimaker is commonly linked to the normative value placed on open source in the following quote:

> *We decide to take the Ultimaker because it's totally open source. And we want to follow this path. So everything we want to do, all the practices we will follow, we want to share with everybody.*

Fab Lab members also voice a practical motivation, linked to the value of control and experimentation for users. Speaking of Ultimaker, one Fab Lab member states:

> *Because it's open source, the development of the printer goes pretty fast, the software is developing pretty fast, and they are pretty hackable. We can do whatever we want with it because you know how it works and what to change within the code to make something else.*

Another Fab Lab member comments explains their choice of Ultimaker in a similar way:

> *We did buy an Ultimaker because it was also based on an open source design, and…I was interested to see their hacking the Ultimaker workshops…potentially using different materials or adding different extruders and so forth, it's quite interesting.*

This quote references workshops run by Ultimaker employees on 'how to hack an Ultimaker'. These have taken place at many events over the course of the printer's development, a strong indicator of the link between experimentation and the Ultimaker design.

Ultimaker is also interesting when it comes to the common trade-off, discussed in Chapter 6, between open source and usability. One Fab Lab member states:

> *Ultimaker, the Dutch printer, which is still completely open source, that's also very easy to use by now.*

This statement is reflective of the overall development of the Ultimaker 3D printer over a number of years. The usability may be understood as partly resulting from its rapid development, helped by its user community, as well the coordinated efforts of the developer community, those employed by the company, Ultimaker. Analysis of the developer community is beyond the scope of this research, given the time needed to collect new data. Yet the significance of the Ultimaker development model for the field of product innovation and competitiveness of open source models is intriguing. Here I focus on the user community, an integral part of the Ultimaker open source model.

7.2.1 Linking action arenas

In the language of institutional analysis, my study of the Ultimaker forum is a way of studying linked action arenas. The Ultimaker user forum is an important example of peer production (Benkler, 2016), where users are encouraged to discuss, contribute to, and, in general, engage with the design and functionality of their Ultimaker. As found in Chapter 6, 3D printing in Fab Labs is partly influenced by the design of those 3D printers. I study the Ultimaker user community as a second level of analysis, conceptualised at the collective-action level, as the community has a role in the development of the 3D printer being used in Fab Labs. While most users in the Ultimaker forum do not necessarily design the printer directly, the forum presents one way for the user community to have feedback into development of the printer over time.

For my purposes specifically, the Ultimaker user community provides a second, aggregate level of analysis where patterns of user contributions on the forum over time can be analysed. This means that links made in qualitative interviews regarding user access and engagement in knowledge associated with parts of the 3D printer can be tested in a new way. That is, one can approach the subject of engagement with types of knowledge by analysing a whole community of users and their individual behaviour in over time.

There are two caveats to my choice of studying the Ultimaker user forum. First, Ultimaker 3D printers are not uniformly present in Fab Labs, although they are a preferred choice on the inventory. Therefore, this chapter should be viewed as studying one important 3D printer in present use in order to add a new level of analysis to the study of knowledge commons communities. Second, this chapter looks more broadly at access to knowledge in a 3D printing system related to physical versus digital components. This includes access to knowledge about materials, but does not single it out as a particular focal point. This is primarily because posts in the Ultimaker user forum that are relevant to knowledge about materials are not differentiated from the main categories of hardware, software, and firmware in the forum structure. This is understandable, as parts of the hardware, software, and firmware, and their interrelations, affect the behaviour of materials in a 3D printer. For example, to change the way the print head lays down material, one can intervene in the electronics of the print arm, or the software code[41]. Therefore, this chapter leaves aside the specificity of studying knowledge about materials, and aims instead to enrich the principal research question by studying how users engage with types of knowledge associated with main areas of the 3D printer over time.

7.3 Characterising the Ultimaker User Forum

The Ultimaker community is a group of users who voluntarily participate in an online community forum. The purpose of the forum is to (a) troubleshoot problems with the printer, (b) offer new ideas for improvement, and (c) find out new ways to modify the Ultimaker machine. Developers of the Ultimaker system, employed by the company, are also present on the forum. This means that they can offer help and support, but also gain new ideas for improving the printer over time.

It is important to note the following distinctive features:

a. The Ultimaker forum is primarily a user community, but also includes developers. Both interact and contribute to the forum's discussion threads.
b. All Ultimaker users have access to the 'source code' of the 3D printer, meaning hardware, software, and firmware. This means any user can contribute their expertise on the basis of the entire design.

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[41] From "Hacking an Ultimaker" workshop by Ultimaker at Fab 11 in Boston, August 2015.

c. Ultimaker is a company that ultimately assembles and releases models of the Ultimaker 3D printer. This means that while users may contribute to the evolution of the machine through the user forum, final control of a new design resides in the hands of Ultimaker developers, those employed by Ultimaker as a company.

d. Due to its open source nature, users may hack or improve their individual machines without a new model being released. While this is anecdotally important, there is no data on individual machine innovations outside of what users choose to post.

It is important to restate that Ultimaker (and indeed any 3D printing system) is a combination of hardware, software, and firmware. Thus my study implicitly involves the study of open source software communities, the communities that adapted the software and firmware (software that is programmed onto hardware) for the purpose of running the Ultimaker 3D printer. The origins of these software and firmware architectures, and the characteristics of their original developer and user communities, are not of direct interest to my research question. This is an area for future research.

7.3.1 Introduction to the data

Data is taken from the open access forum, where each forum post, associated to a unique user ID, was recorded from its founding in October 2011 to the date of collection in March 2015. There are a total of 2,423 unique user IDs in the forum[42]. Although it is reasonable to assume that all users on the forum are users of an Ultimaker 3D printer, it is important to note that being a member in the forum is not obligatory. Indeed, the forum is open to search for non-members, so anyone without a forum membership can browse questions and answers on the forum. Thus the forum should not be taken as representative of the total number of users of Ultimaker 3D printers. Rather, the forum reflects a core community of people[43] who are interested in contributing their time and interacting with other users of Ultimaker 3D printers.

The architecture of the community forum is organised according the basic architecture of the 3D printing system, with hardware, software, and firmware as the main sections of the forum. I call these ‘modules’ of the forum, and use them to denote types of knowledge related to physical and digital goods. Within these modules, there are subject categories, and within these are threads. Each post is part of a specific thread, and therefore nested within this overall structure. Modules, threads, and posts are mutually exclusive, meaning that a post can only be in one category, and each category can only be in one module.

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[42] It is possible that an individual has more than one unique ID. This is not possible to know from the data.

[43] This introduces the possibility of a self-selection bias in the data. While noted, this cannot presently be measured or accounted for.

Table 7.1: Ultimaker Forum Data

Modules (total = 3)	**Hardware**	**Software**	**Firmware**
Categories (total = 12)	1. Assembly 2. Troubleshooting 3. Modifications and hacks	1. Replicator-G 2. CAD 3. Other 4. Cura 5. NetFabb	1. 5D 2. Sprinter 3. Alternatives 4. Marlin
Thread Number (total = 4,301)	2,164	1,944	193
Post Number (total = 38,277)	22,014	14,665	1,598

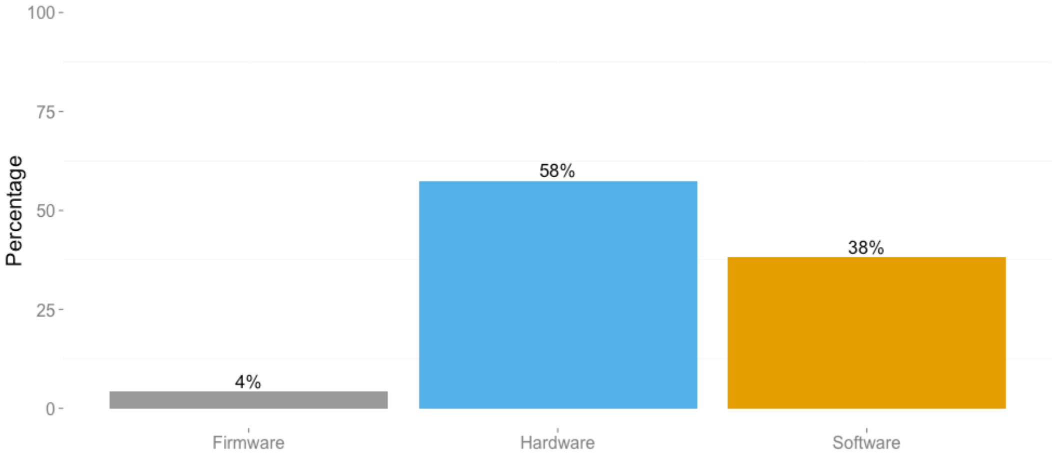
Note: there are 2,423 unique user IDs in the forum.

I list the names of the Categories to provide a basic intuition for the types of activities users are engaging in. For example, it is relatively self-explanatory that users posting in Hardware are engaging in the topic of assembling their 3D printer, troubleshooting its workings, and discussing modifications and ways to hack the printer. The Ultimaker company, given their open source model, actively encourages their users to come up with ways to hack the system and come up with alternative functionality and applications. Software is less self-explanatory, only because the main thread topics, ‘Cura’, and ‘Replicator G’, are the technical names of software packages used by Ultimaker. Replicator-G was the first software Ultimaker ran on, followed by Cura. NetFabb is a 3D printing design software, and CAD is the more general Computer Aided Design file format used across most 3D printers. Firmware, a type of embedded software, is similar, with “Marlin” being the latest firmware, and ‘Sprinter’ and ‘5D’ being older versions.

7.3.2 User posts by module and category

I begin with exploratory data analysis to characterise user behaviour in the forum, before turning to statistical analysis of variable relationships. Figure 7.1 illustrates the percentage differences between posts in hardware, software, or firmware. These basic modules of the 3D printing system are associated with different types of knowledge.

Figure 7.1: Percentage User Posts by Knowledge Type

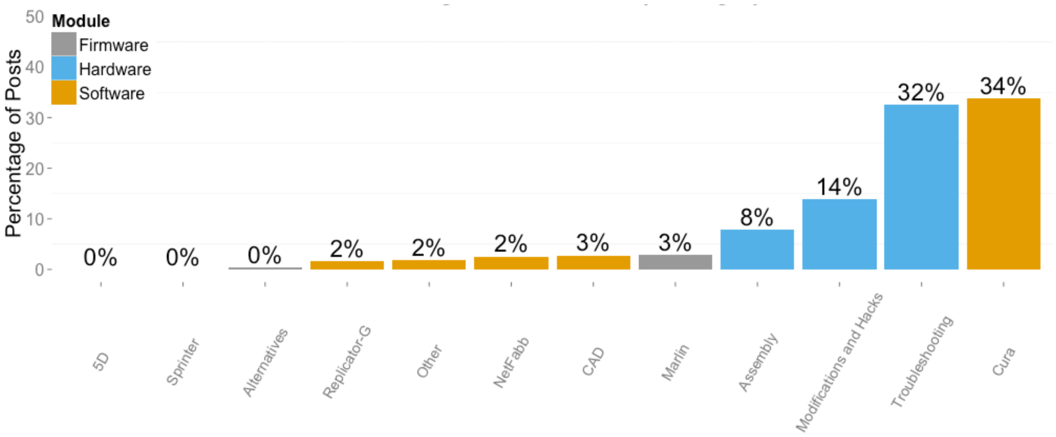


Note: n= 38,227 user posts

As expected, most users engage first with the hardware section of the forum. This makes sense given the first thing one would need to do with a 3D printer is understand how its physical parts function. Furthermore, Ultimaker 1 was sold as a kit that the user needed to assemble upon receiving it. The percentage of posts in firmware is notably low compared to either hardware or software. This is interesting from a knowledge perspective, a subject that will be discussed further in subsequent sections on user activity and patterns of module posting.

To look at such tendencies more closely, I plot the percentage of first posts and overall posts by category

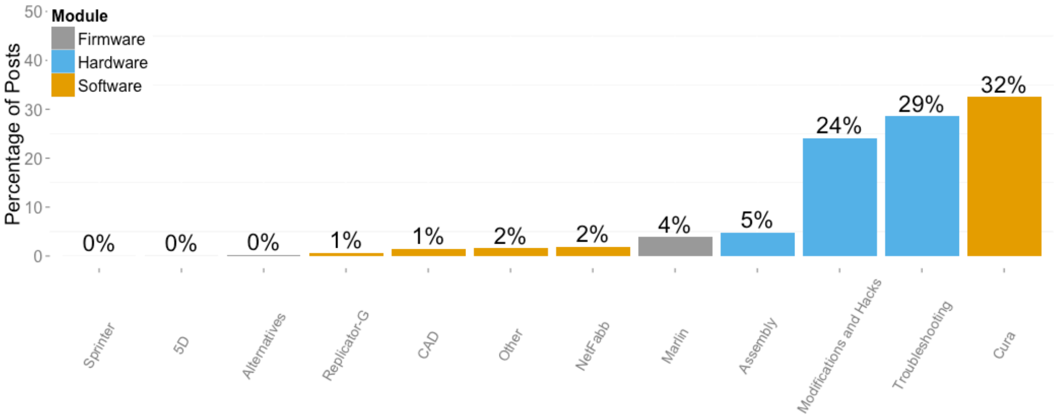
Figure 7.2: Percentage of First Posts by Category



Note: n= 38,227 user posts

Figure 7.2 of user first posts is useful for understanding user motivations upon joining the forum. One sees an expected large number of first posts address assembly of the hardware, followed by troubleshooting. The clear dominance of some categories gives a clear view that many users are first engaging on a need-to-know basis.

Figure 7.3: Percentage of Posts by Category



Note: n= 38,227 user posts

In Figure 7.3, which plots the overall percentage of posts by category (including first and all subsequent posts), we observe that the percentage of posts in Assembly and Troubleshooting categories go down, whereas the percentage in Modifications and Hacks increases. This is intuitive: as users get used to their 3D printer they may be more interested in modifying and hacking it, while at first they are more interested in assembly and troubleshooting.

These plots are also interesting from a knowledge perspective: differences in where users post first may suggest that hardware is more accessible in terms of users new to 3D printing, compared to software and firmware knowledge. Alternatively, a user posting in a module may signify a lack of knowledge in this area, if they are seeking answers to a question. However, in general terms a person usually will want to feel they have some level of knowledge in order to post a public question. Thus, it is logical to assume that those with no knowledge at all may be reading across many modules. Posting introduces a certain level of public engagement and, therefore, I assume that the user has a level of knowledge of the area, however small it is. Given this, it is clear that more research is necessary to understand user motivations, levels of knowledge proficiency, and how this may relate to posting behaviour.

7.3.3 User activity

Before analysing patterns of posting, it is useful to look at the users in greater detail. As of March 2015, the Ultimaker user forum had 2,423 unique user IDs listed[44]. The Ultimaker Forum is set up specifically as a *user* forum, meaning

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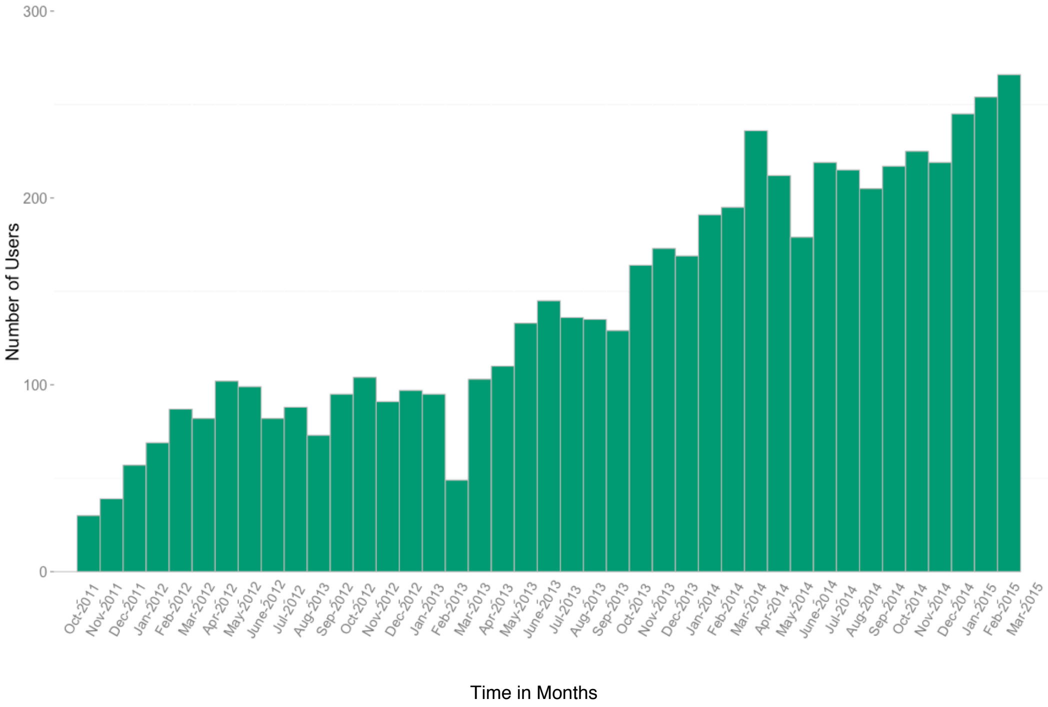
[44] Users could sign up with multiple user names; however, this is deemed unlikely. It is beyond the scope of the data to know whether user IDs are unique to individual persons. We recognise this as an assumption.

that anyone who joins is assumed to be a user of an Ultimaker 3D printer. The following shows the number of users that joined the forum over this time period.

Figure 7.4: New Users Over Time



Note: n= 2,423 users

Figure 7.4 reflects the combined growth in popularity of Ultimaker as a 3D printer[45], the growing use of the forum for users, and the overall rise in popularity of 3D printing over the time period observed. Figure 7.5 illustrates the number of users who post on the forum over time.

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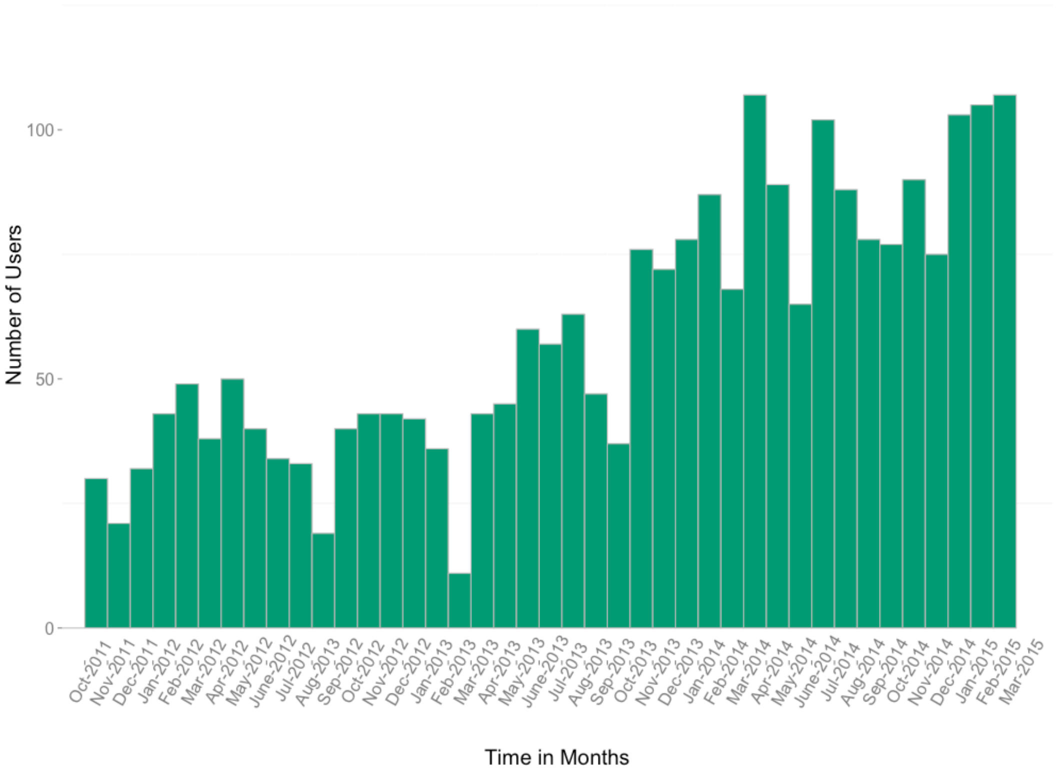
[45] Ultimaker has grown in popularity since its first founding. In 2015 3D Hubs ranked Ultimaker 2 as one of the best printers in their 'Enthusiast' category. Different from the 'Plug-n-Play' category judged by those that work best right out of the box, Enthusiast printers have a combination of ease of use and reliability, easy modifications and upgrades, and active. See https://www.3dhubs.com/best-3d-printer-guide#enthusiast.

Figure 7.5: Number of Users Posting Over Time

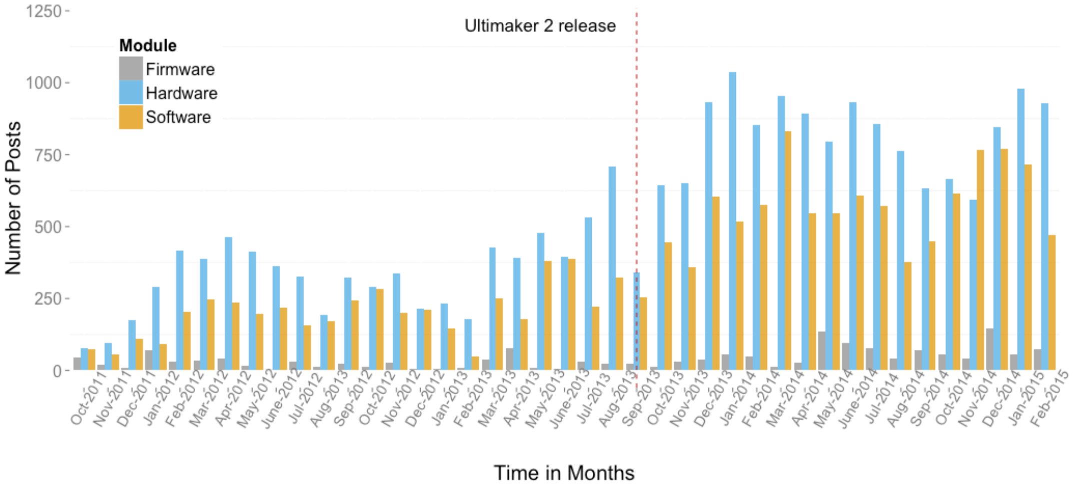


Note: n= 2,423 users

I now explore the structure of user posts by different modules in the forum. My motivating question is how users behave in an open source community with respect to the types of knowledge associated with the structure of the 3D printer. Looking at users posting by module over time gives an important general picture of these trends before building statistical models.

The following figure graphs the number of posts in hardware, software, and firmware over time. Over the time period of the forum, Ultimaker released two versions of their printer: Ultimaker 1 (first sold in May 2011), and Ultimaker 2 (released in September 2013). Although there were changes to software and firmware over the time period observed, there were no new versions of either.

Figure 7.6: Posts by Module Over Time



Note: n= 38,227 user posts

Figure 7.6 shows that the frequency of hardware and software posts generally follow a similar pattern, with hardware consistently showing the greatest number of posts. Posts in firmware, by contrast to the other two modules, does not appear to follow the trend of increasing activity over time as more users enter the forum.

7.4 Patterns of Engagement with Types of Knowledge

I now turn to exploring patterns of posting in parts of the 3D printer associated with types of knowledge from the perspective of users. I associate user posts by module with the type of knowledge a user is engaging with. Posting in software implies engaging with software knowledge, posting in hardware implies engaging with knowledge about hardware, and posting in firmware implies engaging with knowledge about firmware. Although firmware has few posts by comparison to hardware and software, I differentiate it based on the knowledge type associated. It is a particularly technical part of the 3D printing system, consisting of software code written into the hardware that drives the printer. Thus it is interesting to understand engagement in a part of the system that bridges software and hardware in terms of knowledge type.

To look at patterns of knowledge engagement I apply a bipartite network approach to representing the data. A bipartite network consists of two different levels. Here, level 1 is the user, and level 2 the module. Each node at level 1 (that is, each user) is linked to at least one node in level 2. A link between a user and a module signifies that the user was posting at least once in that module during the time period observed[46]. This approach lets me visualise to what extent users post in single modules versus posting in multiple modules.

Figures 7.7-7.10 illustrate active users by module in various yearly timeframes. Active means the user posted at least once in the observed timeframe. Yellow and green nodes signify developers and moderators, respectively. I mark these users to show how developers and moderators predominantly post in all three modules, a behaviour that is controlled for in the statistical models to follow.

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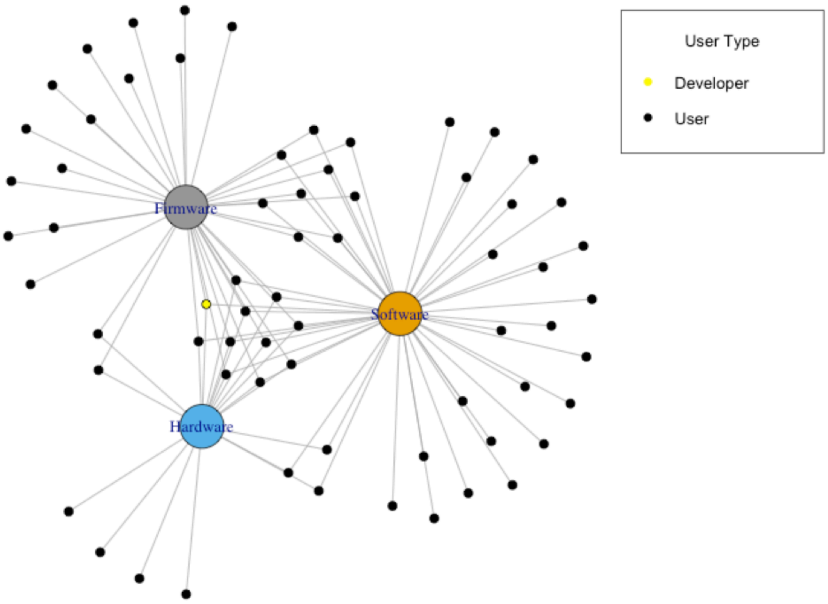
[46] For more detail on bipartite networks, see Wasserman and Faust (1994)

Figure 7.7: Bipartite Network: Users and Modules (2011)



Note: n= 66 active users

For the purpose of explaining Figure 7.8, it is useful to identify parts of the diagram[47]. On the upper left one sees users posting only in firmware. On the bottom left one sees users who are posting only in hardware. Between the firmware and software modules, one sees users who are posting in both. Only three users are posting in just hardware and software, and two users are posting in just firmware and hardware. In the centre of the diagram, there are the group of users who are posting in all three modules[48].

In general, nodes around the periphery of the diagram are posting in only one module, while nodes towards the centre, or core of the diagram are posting in more than one module. Figures 7.9-7.11 also exhibit this core/periphery pattern.

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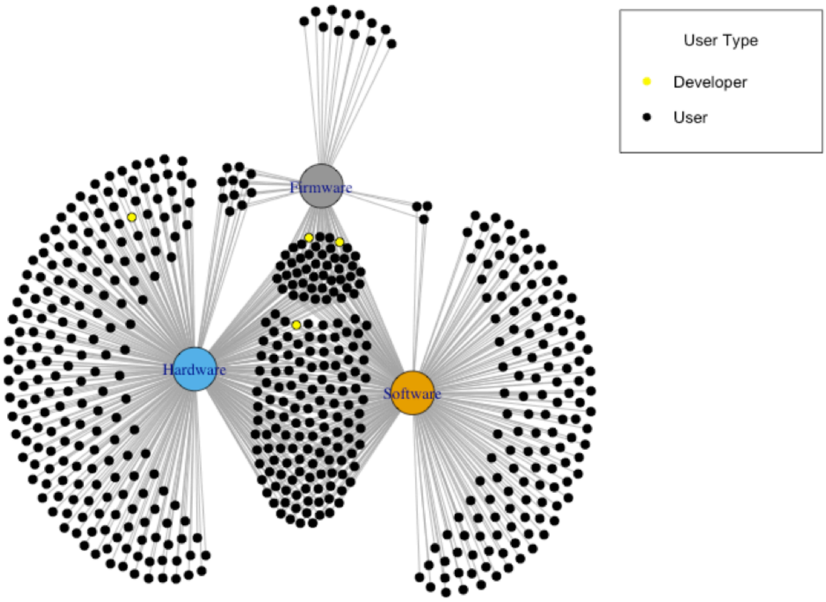
[47] This is not an analytical interpretation, rather an illustrative description of the diagram for the purpose of explanation.

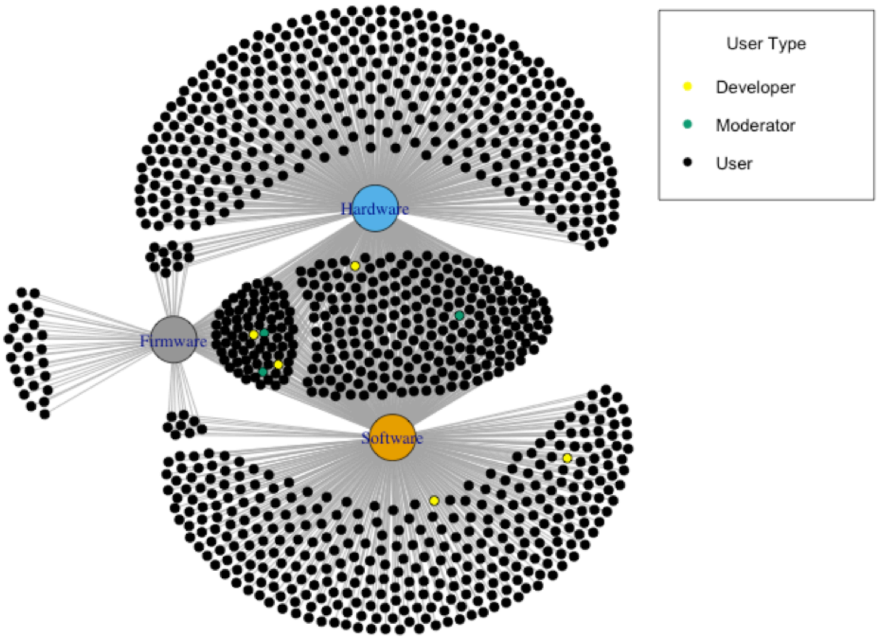
[48] In bipartite graphs nodes of the same category are most often arranged vertically in columns. I choose this alternative layout because it is particularly informative for my analysis.

Figure 7.8: Bipartite Network: Users and Modules (2012)



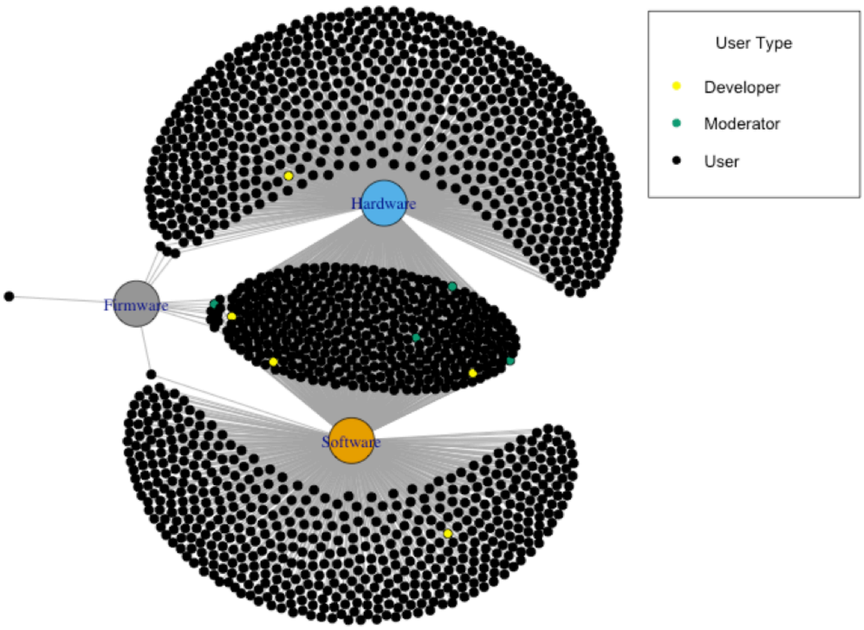
Note: n= 508 active users

Figure 7.9: Bipartite Network: Users and Modules (2013)



Note: n=752 active users

Figure 7.10: Bipartite Network: Users and Modules (2014)



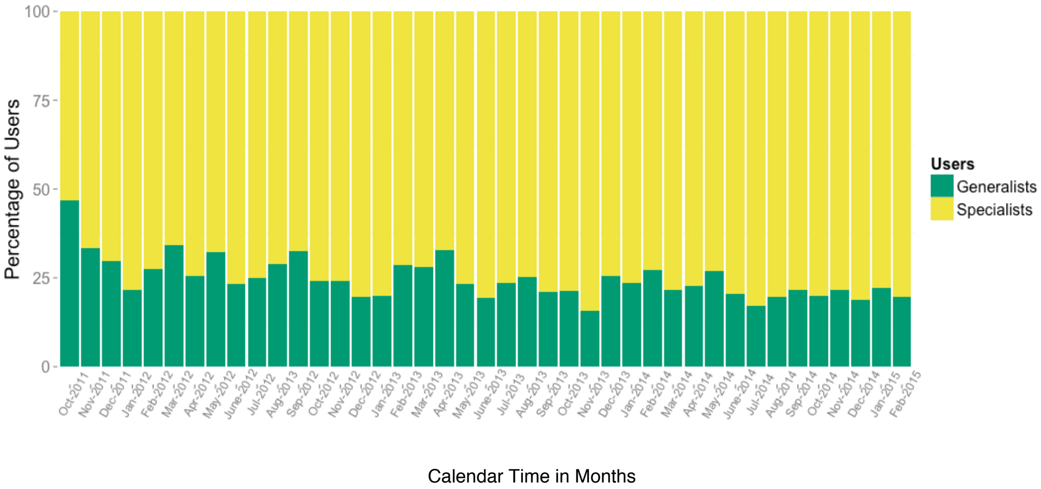
Note: n=1265 active users

7.4.1 Knowledge specialists and generalists

Figures 7.7-7.10 help make the distinction between users who post in one module, and users who post in two or three modules. For this analysis, I call users who post in 1 module 'specialists', and users who post in multiple modules (i.e., two or three modules), 'generalists' from a knowledge perspective. This partially corresponds with von Krogh et al. (2003) in the terminology used to describe user engagement in the modules of an open source software project. As noted, I use the terms to describe users who engage in one or one or more than one type of knowledge. My use of the terms specialist and generalist more properly refers to 'knowledge specialists' versus 'knowledge generalists'. The choice of defining this as a binary category relates to the motivating question of crossing the boundary between knowledge associated with digital versus physical goods. Hardware is a physical good, whereas software is a digital good. Firmware, being software embedded on a hardware chip, occupies a middle ground. The definition of knowledge specialist versus generalist is thus designed to capture user engagement across these boundaries of types of knowledge.

Based on this definition, I now summarise the trend in the number of generalists and specialists over time. Here I use a slightly more fine-grained time window to explain the trend, using monthly rather than yearly time windows used in the network plots. Figure 7.11 illustrates the percentage of generalists versus specialists measured by monthly time windows, from Oct. 2011 when the forum started, until the end of the data window in March 2015.

Figure 7.11: Generalists and Specialists Over Time



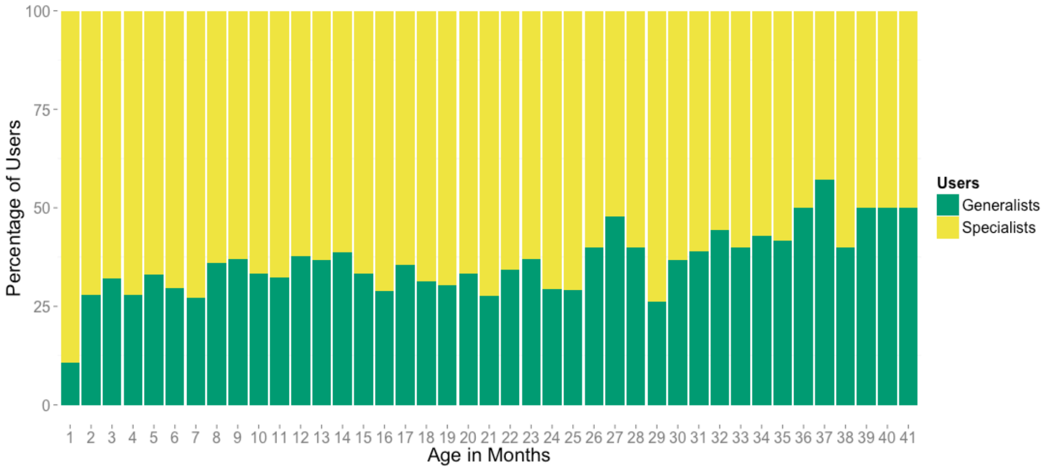
Note: n= 2,423 users

One notes the steady increase in specialists as a percentage of the forum population as time progresses.

It is important to distinguish a user's time in the community from overall calendar time. One can think of time in the community as capturing a measure of experience with one's 3D printer, as well time spent interacting with the user forum.

I call this ‘age in the community’ for the sake of differentiating it from calendar time. Figure 7.12 plots the percentage of generalists versus specialists (out of total users), according to their age in the community. Age is measured in monthly time windows.

Figure 7.12: Generalists and Specialists by Age in the Community



Note: n= 2,423 users

Opposite to the trend shown in Figure 7.11, there is clearly a trend towards more generalists as a percentage of the user community, as age in the community increases.

Based on Figures 7.11 and 7.12 there appears to be two different trends with time. As age in the community increases, the higher the percentage of users who are generalists. However, the proportion of generalists in the community is decreasing over calendar time. I suggest that this difference results from the growth in the user forum, where the number of new users in 2014 is much greater than in 2011 (see Figure 7.4). To effectively distinguish these two trends it is helpful to build a statistical model capturing the differences.

7.5 Statistical Models of Modularity and User Engagement

I now examine whether there is a significant trend towards engaging across modular interfaces the more time is spent in the community. Rephrased, this means analysing whether users have a tendency to become generalists the longer they spend in the user forum. So far I have provided descriptive plots of trends occurring over time in the user community. Here I build a statistical model to apply controls and differentiate the effect of time spent in the community on a user becoming a generalist.

7.5.1 Statistical data overview

Revisiting the main features, the data consists of the posts of 2,423 unique user IDs over the time period of October 2011 (the beginning of the forum) to March 2015 (when data was captured). These users were self-selected, and the dataset captures all activity in the forum relating to hardware, software, and firmware posts. The total number of posts recorded is 38,277.

The variables used in the model are as follows. Measures of time are calendar time (in months), and a user's age in the community (in months). I include a measure of whether each user is a specialist or generalist during each monthly time interval. A basic measure for role in the community captures whether a user is a developer or moderator. A measure of activity level for each user is constructed, to account for the number of posts made during each time interval. I also include a measure of the module of a user's first post. I discuss the construction of these variables in the following sections. Table 7.2 lists descriptive statistics.

Table 7.2: Descriptive Statistics: Users in the Ultimaker Forum 2011-2015

Total User Posts	38,277
User Observations (monthly)	5,814 – Level 1
Unique User IDs	2,423 – Level 2

	N	Mean	SD	Min	Max
Independent variables					
Age in the community (scaled and centred)	5,814	.00	1.00	-.65	4.89
Age in the community (in months)	5,814	4.72	7.22	.00	40.00
Module of First Post (Hardware)	2,423	.57	.50	.00	1.00
Module of First Post (Software)	2,423	.40	.50	.00	1.00
Module of First Post (Firmware)	2,423	.03	.17	.00	1.00
Control variables					
Calendar time (scaled and centred)	5,814	.00	1.00	-2.30	1.35
Calendar time (in months)	5,814	26.17	10.95	1.00	41.00
Activity level of users (scaled and centred)	5,814	.00	1.00	-.38	16.8
Activity level of users (unscaled)	5,814	6.58	14.67	1.00	253.00
Moderator / Developer (coded 1 for Moderator or Developer; 0 otherwise)	2,423	.04	.19	.00	1.00
Dependent Variable					
Generalist / Specialist	5,814	.23	.42	.00	1.00

7.5.2 Dependent variable

The dependent variable in the models is a measure of whether a user is a generalist or specialist. The variable was constructed by measuring whether a user posts in one or more than one module per monthly interval of age in the community. I construct the variable so that I can track a change in user behaviour over time. That is, I do not define a user as a generalist or specialist according to their entire time spent in the forum; rather, I take monthly snapshots of the user behaviour.

For example, if user A posts twice in software during one month of time spent in the community, the user would be a specialist for that time period. If user B posts once in software and once in hardware during a month spent in the community, user B would be a generalist for that time period. However, one must be careful that the time window chosen is not enforcing a false categorisation. If the time interval of days were chosen, then a user posting once a day would be classified as a specialist, even if he or she were posting in different modules. This clearly does not capture the breadth of this user's knowledge base. The aim of choosing a time window is to reflect, as accurately as possible, the level of engagement each user has from a knowledge perspective.

I address this challenge in three ways. First, I choose the time window of months within which to classify someone as being a specialist or generalist, depending on their posting in one or more than one module. The average number of posts for a user within a monthly time frame is 39, with a median value of 18. Even with the lower number 18 (less influenced by high posting users), it is reasonable to assume that a user who is posting every time in the same module within a month is a specialist. Second, in the models that follow, I include a control variable of the activity level of users during each time period. This accounts for users who post only once during the time window. Third, all plots and models to follow have been generated with weeks as time windows to check for robustness.

The generalist/specialist variable is binary variable, with 1 connoting a generalist, and 0 connoting a specialist per month in the community. For the total of 2,243 unique user IDs, there are 5,814 monthly observations of users as generalists or specialists. Overall, 76.9% of these observations are specialists, and 23.1% are generalists.

7.5.3 Independent variables

I begin with the variable, 'age in the community', meaning time spent in the user forum. This is the main explanatory variable of interest. The age variable was constructed by measuring each user's age in the community at monthly intervals, starting from each user's join date, and ending in March 2015. As the previous figures have illustrated, the number of users in the forum has risen considerably over time. In logical terms, this means that some users in the data have had more experience than others with their 3D printer[49].

The age in the community variable included in the model is mean centred and scaled by dividing by its standard deviation. Unscaled, age in the community ranges from 0 to 40 months, meaning the maximum number of months a user has spent in the Ultimaker forum is 40, and the minimum 0. The mean number of months a user has spent in the community is just under 5. In the models to follow, I use the age variable that is centred and scaled for computational reasons related to model convergence. It is expected that age in the community increases the

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[49] While some users may have gained experience prior to participation in the user forum, it is a reasonable assumption that the longer a user has been in the forum, the more experience he or she has.

likelihood of being a generalist. This is based on qualitative interviews, where users of 3D printers in Fab Labs spoke of the need to engage with different parts of the system as they began to use and modify it.

Another independent variable included in the model is the module of first post for each user. Dummy variables are generated to measure whether posting first in any one module, compared to the other two, has a significant affect on the likelihood of being a generalist. I suggest that the types of knowledge a user first engages with may be related to the likelihood that the user has a more general or specialist knowledge base.

7.5.4 Control variables

I include the following variables as controls: activity level, the status of a user as a moderator or developer, and calendar time. Activity level is a measure of the number of posts a given user has per monthly time interval of age. Including activity level (number of posts) per age time interval in the model is thus important for controlling for the effect of users who are posting infrequently. The variable also allows us to control for the effect of high posting users on the general trend. In the statistical models activity level is scaled and centred for computational reasons.

I include a dummy variable for users who are either moderators or developers in the forum. We treat this as a single dummy variable, coded 0 for being a general user, and 1 if the user is a moderator or developer. The categories of moderator and developer are mutually exclusive. The network plots shown in Figures 7.7 – 7.10 show the clear tendency of moderators and developers to be generalists, posting in hardware, software, and firmware. It is also important to control for developers given their different incentives in contributing to the forum.

Developers are employed by Ultimaker, and therefore cannot be treated equally as other users. Moderators are an internal designation, given to users that appear to have high levels of contribution and a more general level of expertise. My primary interest is in the behaviour of general users of in the community. Beyond model controls, I also make sure moderators and developers are not overly influencing the results using appropriate diagnostics.

Lastly I control for calendar time in monthly intervals. Calendar time is the same for every user, ranging from October 2011 – March 2015. By contrast, age in the community is constructed with a different start date for every user. Including calendar time in the model controls for unobserved events in the forum that may affect user behaviour. It also controls for the effect of more users joining towards the end of the observed data.

7.5.5 Statistical model

I modelled the effects of age in the community on the likelihood of being a generalist versus specialist using a hierarchical generalised linear model for binary response data (Snijders & Bosker, 2012). Model choice is motivated by the multilevel nature of the data, and the structure of the dependent variable. Whether a user is observed to be a generalist or specialist status at a given measurement window must be grouped according to unique user IDs to account for interdependence of observations; that is, random intercepts are included for each user ID. Level one of the model constitutes observations of users per age window in the network, totalling 5,814. Level two of the model constitutes unique user IDs, totalling 2,423. I thus model 5,814 observations of 2,423 unique users in the

Ultimaker forum over the period of 2011-2015. Thus I estimate a logistic random intercept model, expressed in the following form:

$$\text{logit}(P_{ij}) = \gamma_0 + \sum_{h=1}^{r} \gamma_h x_{hij} + U_{0j} \tag{7.1}$$

The model expresses the log-odds, or logit of P_{ij}, as a sum of a linear function of explanatory variables. In the model, P_{ij} is the probability of being a generalist for time window i and user j. γ_0 denotes the model intercept; X_{ij} denotes explanatory and control variables for each time window i for user j, summed to r for the number of variables in the model. γ_h denotes the coefficient fit for each variable h to r. We now proceed with fitting the model to the empirical data.

7.5.6 Results

Table 7.3 summarises the results of modelling the effects of age in the Ultimaker community forum on the likelihood of users being generalists or specialists. Also modelled are control variables and the module of a user's first post. I interpret the effect of each variable in the model in turn. Model 1 is a baseline control model, including the variables of calendar time, activity level, moderator/developer dummy, and module of first post. Model 2 tests for the effect of age in the community forum on the likelihood of being a generalist. Model 3 tests for the effect of the module of first post on the likelihood of being a generalist. Model 4 is the full model. Note that the variables of age in the community, calendar time, and activity level are all centred and scaled for computational reasons relating to model convergence.

Table 7.3: Hierarchical Logistic Regression Predicting the Effect of Age in the Ultimaker community on the Likelihood of being a Generalist or Specialist, 2011-2015.

	Model 1		Model 2	
	Coefficient	S.E.	Coefficient	S.E.
Age in the community	-	-	0.238***	(0.063)
Module of First Post				
Hardware Dummy				
Software Dummy	-	-	-	-
Firmware Dummy	-	-	-	-
Calendar time control	-0.306***	(0.056)	-0.416***	(0.064)
Activity level of users	4.468***	(0.193)	4.449***	(0.191)
Moderator/Developer Dummy 1=Moderator or Developer	2.578***	(0.647)	2.375***	(0.632)
Constant	-1.916***	(0.121)	-1.826***	(0.117)
Deviance	3902.3		3888.3	

Note: N= 5,814 observations. Random effects for 2,423 unique user IDs

*p<.05 **p<.01 ***p<.001 (two-tailed tests)

Table 7.3 (Continued)

	Model 3		Model 4	
	Coefficient	S.E.	Coefficient	S.E.
Age in the community	-	-	0.239***	(0.062)
Module of First Post				
Hardware Dummy				
Software Dummy	0.138	(0.136)	0.160	(0.135)
Firmware Dummy	1.050**	(0.337)	1.036**	(0.333)
Calendar time control	-0.300***	(0.056)	-0.409***	(0.064)
Activity level of users	4.476***	(0.192)	4.457***	(0.190)
Moderator/Developer Dummy	2.638***	(0.642)	2.440***	(0.626)
1=Moderator or Developer				
Constant	-1.993***	(0.132)	-1.910***	(0.128)
Deviance	3892.8		3878.5	

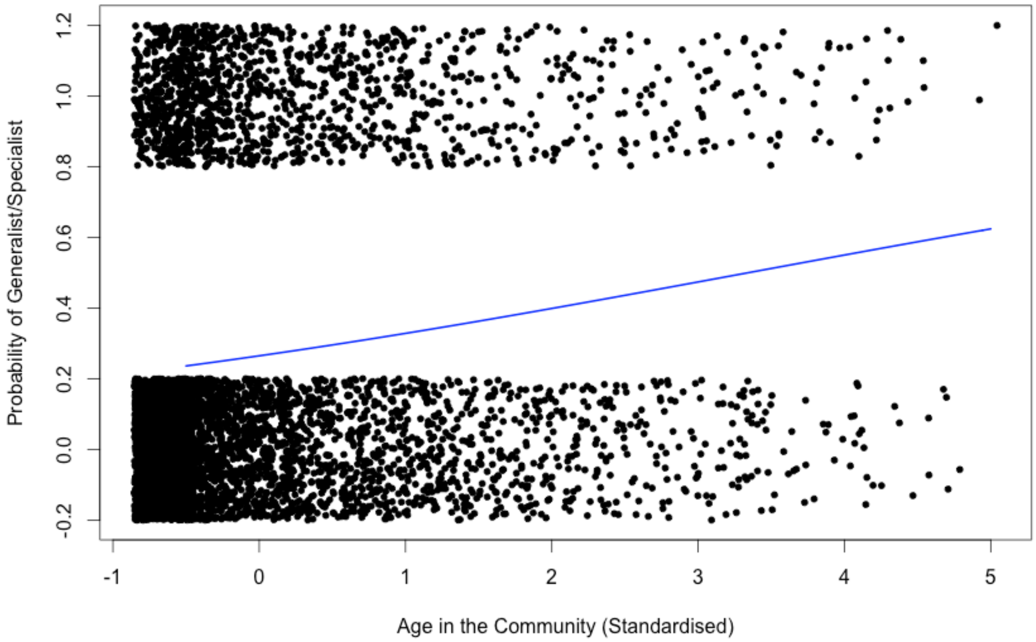
Note: N= 5,814 observations. Random effects for 2,423 unique user IDs

*p<.05 **p<.01 ***p<.001 (two-tailed tests)

From the Model 2 and 4 in Table 7.3, one can see that the coefficient for age in the Ultimaker community forum has a positive significant effect on the likelihood of being a generalist, with a p-value of < 0.001. This means that as age in the community increases, the likelihood of being a generalist increases. The coefficients are expressed as log-odds, or the log of the odds ratio. Therefore, to obtain the odds ratio for the coefficient of age in Model 4, one takes the exponent of 0.239, which equals 1.27. This means that for 1 unit increase in the age variable (1 standard deviation from the mean), the odds of being a generalist increases by 1.27.

Figure 7.13 shows graphically the relationship between age in the Ultimaker community forum and being a generalist/specialist as fit by the full statistical model 4. Each dot represents a measure of a user as either a generalist or a specialist per age interval in the forum. For ease of interpretation I fit a curve by holding other variables in the model at their means.

Figure 7.13: Probability of Generalist/Specialist Given Age in Community



One sees here the positive relationship between age and the likelihood of being a generalist that is expressed in the coefficient of Model 4. This suggests that as age in the forum increases, there is a greater likelihood that users will be generalists versus specialists.

This can be contrasted with calendar time. There is a negative relationship between calendar time and the likelihood of being a generalist, significant at a p-value of <0.001. This means that over time, the proportion of generalists is decreasing. I suggest that the reason that age and calendar time have different directions is because there are more new users joining the forum as time goes on, lowering the proportion of generalists. But as each a user stays in the community, their likelihood of being a generalist increases. The activity level of users is positive and significant at a p-value of <0.001. Likewise is the dummy variable for moderator/developer.

In Model 3 and 4 I include the effect of the module of first post as a predictor of being a generalist, with the base category being hardware. The outcome suggests that if a user posts in firmware first, there is a positive and significant relationship at a p-value of <0.01 to the likelihood of being a generalist. This means that those users who first post in firmware are more likely to be generalists than those who first post in hardware. By contrast, there is not a significant relationship of a first post in software compared with those who first post in hardware (p-value is >0.05).

7.5.7 Diagnostics and model robustness

Several tests were conducted to check for model validity and robustness. Deviance provides an overall measure of model fit. Lower values indicate less unexplained variance in the dependent variable (Snijders & Bosker, 2012). We see from the deviance scores that Model 4 exhibits the best fit. I test for multicollinarity by examining the variance inflation factors. The maximum value was 1.1, suggesting that there is no problematic multicollinarity in the model.

I checked for influential observations by calculating Cook's distance measures. Two observations were potentially problematic. I re-ran the model omitting the influential observations and the main results were not altered. Having checked this, and for reasons of data integrity I choose to keep the observations relating to this individual in the dataset.

I also checked that the results were robust to the time interval chosen by running the models time measured in weeks rather than months. This did not significantly affect the results of the model. I thus choose months based on the rationale that is less sensitive to a low post number per time interval, an issue discussed in 7.53.

7.6 Summary and Discussion of Results

To discuss the contributions of this chapter, I first revisit the guiding research question:

> *Do users cross the boundaries between types of knowledge in a commons-based 3D printing community over time?*

By looking at the descriptive network plots, at any point in time you will see different types of user behaviour, with some users posting only in one module of the forum (hardware, software, or firmware), and some posting in two or three. Can we help to explain what drives this variation in user behaviour? This analysis offers three explanations: (1) initial knowledge base of a user; (2) development of the forum over calendar time; and (3), user time spent in the community.

Concerning the first explanation, regression results of models 3 and 4 show that if a user first engages with firmware, he or she is more likely to be a generalist. Firmware is a technical part of the 3D printer, and it is a fair assumption that a user has considerable knowledge about the system as a whole if he or she is going to engage with that part of the forum. Referring back to Figure 7.7, where the number of posts over time in each module is shown, one sees that unlike hardware and software, the number of posts in firmware stays relatively low, even as more and more users join the forum. This may suggest that firmware is less accessible to users from a knowledge perspective. Given this, it is not surprising that those who post first in firmware are more likely to be generalists and thus post in other modules too. Moreover, it makes sense that some users are broader in their knowledge than others. The control variable for developers and moderators is positive and significant, suggesting that users who are designated as moderators and developers are more likely to be generalists. This accords with the network plots (Figures 7.8-7.11) where developers and moderators were found almost exclusively in the cluster of users posting in all three modules. I suggest that developers and moderators are more likely to have a broad starting base of knowledge about the 3D printing system, and this may correspond to being generalists.

The second explanation concerns the development of the forum over time. One can see from Figure 7.11 that the percentage of users who specialise in the forum rises over time, with the largest percentage being in the most recent time period. This is supported by the regression results, where one sees a negative and significant coefficient for the variable of calendar time. That is, a user is less likely to be a generalist as calendar time increases.

Third and most importantly is the insight into changes in user engagement with knowledge in different modules in the forum over time. From the models summarised in Table 7.3, one can clearly see that the effect of age, or time spent in the community, is positively and significantly correlated with the likelihood of being a generalist. That is, the longer a user spends in the Ultimaker user forum, the more likely he or she is to be posting in two or three modules associated with different knowledge types. At the beginning of the chapter I quoted a Fab Lab user explaining how connectivity between parts of the 3D printer compels one to expand their knowledge, for example, when an intervention in hardware causes a change in software. I suggest that the interdependence between modules of the Ultimaker printer may drive tendencies towards generalist behaviour in the forum as users engage with and learn about their 3D printer over time. Further data is needed to investigate this in detail. In particular, accessing data on the characteristics of forum users would be of great importance.

What is clear, however, is that the posting activity of users changes systematically over time with respect to the modules represented in the user forum. This is an important step towards understanding the effect of 'accumulated experience as an endogenous effect' in open source communities (David & Shapiro, 2008, p. 395). I suggest that user's time in the community forum can be thought of as a proxy for accumulated experience with a 3D printer, as well as experience on the user forum. If understood as such, the finding that experience has an effect on engagement with modules of an integrated system suggests that learning is taking place across knowledge boundaries over time.

In summary, this chapter provides a wider view of user engagement with the types of knowledge associated with 3D printing systems over time. I find evidence for users specialising in one type of knowledge when first joining the Ultimaker community. However, one sees that the longer users are in the community, the more likely they are to engage across types of knowledge associated with hardware, software, and firmware. This is an intriguing starting point for future research, and confirms the proposition that commons-based 3D printing provides an empirical window into the integration of knowledge associated with digital and physical resources.

8 DISCUSSION AND CONCLUSIONS

8.1 Overview

I begin this final chapter with a synthesis of empirical findings as they relate to the guiding research question:

> *What enables or prevents access to knowledge about 3D printing materials entering the commons?*

In Chapters 4-6 I study this question by analysing what enables or prevents Fab Lab members accessing knowledge about materials. In Chapter 7 I introduce the Ultimaker user forum as a complementary level of analysis in order to understand how users engage with different types of knowledge in the commons over time.

Here, after summarising the findings of these empirical chapters, I go on to discuss theoretical contributions that result. This is followed by suggested recommendations for practitioners and policymakers. I conclude by discussing the limitations of this thesis as well as future avenues for research.

8.2 Synthesis of Empirical Findings

In the context of Fab Labs I find there are significant barriers to knowledge about 3D printing materials entering the commons. From a Fab Lab user's perspective, this commonly relates to a lack of knowledge about material properties and behavioural characteristics. In Chapter 4 I discuss a significant barrier that helps explain this: resource systems for material production are primarily located outside of common-property regimes that characterise Fab Labs. Even though flows of physical materials are entering the commons, knowledge may not accompany the flow, remaining in the proprietary control of materials producers. Even though a certain amount of knowledge may be acquired through experimentation, information about the production process, such as chemical composition behavioural characteristics, may not be disclosed to the user. By contrast, the information facilities associated with software and 3D printing hardware designs are located within open access knowledge commons. Fab Lab members are often building their own 3D printers, and modifying open source hardware and software components. The governance of information facilities producing hardware and software artefacts and content within open access regimes helps explain why knowledge is accessible within the commons.

A second barrier to knowledge about materials entering the commons, discussed in Chapter 6, is the level of integration in the design of 3D printing systems. When users do not have sufficient freedom to experiment with different modules of the 3D printer, knowledge associated with materials experimentation is reduced. Highly integrated 3D printers are often proprietary, or closed source. This acts to prevent knowledge about all parts of the system entering the commons.

Factors that enable knowledge of materials to enter the commons are openness and high degrees of modularity in the design of 3D printing systems, and the sourcing of local waste and natural materials for 3D printing. Open source 3D printers allow local experimentation and thus enable access to more knowledge. However, even if a 3D printer is closed source, but highly modular, users can more easily hack or modify the printer, as one component can be altered without causing an unwanted chain reaction. The level of modularity of a 3D printer can thus enable knowledge entering the commons independent of the system being open or and closed source.

Proximity to material producers and material supplies appears to enhance the likelihood that knowledge about these materials enters the Fab Lab. Turning waste into a useable resource also results in knowledge entering the commons, as users experiment with material properties and machine parameters.

A common mechanism explaining how open and modular machines, and local sources of materials are linked knowledge about materials entering the commons is experimentation with materials by users. Experimentation with materials is a type of ‘learning by doing’ (Arrow, 1962). In absence of information producing facilities for 3D printing materials being located within common-property regimes, this type of knowledge acquisition has large explanatory value in understanding how knowledge about materials is entering the commons.

I find that a variety of community attributes affect each of these barriers and enabling factors. Open knowledge is a shared community norm among many Fab Lab members, where the disclosure of technological designs stems from a principled perspective. This leads some Fab Labs to choose open source 3D printers over proprietary models, affecting the potential for experimentation and new knowledge entering the commons. The norms of local production and resource sustainability also influence how Fab Lab members may source and experiment with local materials, potentially resulting in new knowledge entering the commons.

The purpose of individual users and the Fab Lab as a whole also affects the entrance of knowledge into the commons. If Fab Lab members are oriented towards experimentation and learning, rather than expedient production, new knowledge about materials is more likely to be encountered. A Fab Lab does not necessarily need to be oriented towards formal education for the focus on learning to dominate; a mix of community members with varying levels of expertise is found to promote collaboration and knowledge experimentation. Interestingly, a lack of financial resources does not correspond to a lack of new knowledge. On the contrary, members often experiment with materials they find around their community, leading to a greater diversity of knowledge about materials entering the commons.

A final empirical finding comes from data from the Ultimaker user forum, studied in Chapter 7. These data allow me to investigate how users engage with types of knowledge associated with digital and physical resources in a 3D printing system over time. I find evidence to suggest that the accumulated experience of users, measured as time spent in the community, relates to an increased likelihood of engaging with a broader range of knowledge types over time. This is an intriguing finding, and accords with how 3D printer users, in qualitative interviews, expressed the need to understand different parts of the 3D printer by virtue of system interconnectivity. To relate this to the empirical findings already discussed, it is important to explore the dimension of time when considering how types of knowledge may be accessed in the commons. A user may take time to access new types of knowledge about the 3D printer, and through the process of learning, new knowledge related to digital and physical resources may become part of the commons.

8.3 Analytical and Theoretical contributions

In this thesis my aim is to contribute to the theoretical project of evolving the tools needed to study knowledge commons. Whereas the roots of commons theory lie in studying biophysical resource commons, today's networked information economies present examples of new, shared information resources. Theoretical constructs and analytical tools must, therefore, evolve to address these empirical phenomena. As Cole (2014) states, although lessons and research tools from the study of biophysical resource commons can be used to study knowledge commons, a 'systematic study of its own resources, actors, institutions, [and] action situations' is needed (p. 45).

Benkler (2013) describes this project as the need to bring together 'two very different conceptions of the commons: (1) the conception where commons use small-scale production and governance systems that can manage provisioning, congestion, and disinvestment through highly particular and local practices and institutions; and (2) the conception where commons operate as an integral part of open, global, complex modern economies, and for which neither property nor regulation seems perfectly apt…' (p. 1506). This theoretical project is particularly associated with the work of Hess and Ostrom (2003; 2006; 2007a; 2007b), Schweik (2007; 2014), Benkler (2013; 2016), Frischmann, Madison, and Strandburg (2014), and Cole (2014).

Moreover, the challenge is to preserve the nuanced and context-specific approach that marks the Ostrom School of commons research (Benkler, 2013). In keeping with this, I do not attempt to advance knowledge commons theory at the level of theoretical abstraction. Rather, by applying select insights and analytical tools from the study of biophysical resource commons to my specific empirical context of commons-based 3D printing, particular theoretical bridges are revealed based on their use in illuminating my subject of study. After noting the analytical contributions of this research, I describe the specific contributions of this research to knowledge commons theory.

8.3.1 Analytical development

There are three particular ways I build on the analytical tools of commons theory for the purpose of studying commons-based 3D printing. First, to conduct an in depth study of Fab Labs at an operational level I combine the IAD with an adapted multitier framework for analysing complex social and ecological systems (Ostrom, 2007). This enables a thorough study of many variables while keeping within a consistent analytical framework (see Appendix I). Second, I introduce technological design rules as rules-in-use within the IAD framework. This means specifying openness and modularity as types of information and aggregation rules-in-use, respectively. This provides a useful analytical tool for examining the role of technology in knowledge commons.

Third, I frame Fab Labs and the Ultimaker 3D printing community forum as linked action arenas, and draw on the framework of levels of analysis for rules-in-use (see Figure 3.6) in order to conceptualise the correspondence between them. Fab Labs and the Ultimaker user forum may not appear to fit the classical distinction between communities at operational and collective action levels. However, if one views openness and technological architecture of 3D printers as design rules-in-use at the operational level, it becomes important to consider the levels of collective action at which these rules are structured. The design of the Ultimaker, as a 3D printer present in Fab Labs, is thus partly structured by the user forum community. I position this analytical idea as an attempt to take into account overlapping communities in the knowledge commons (see Figure 3.4).

8.3.2 Theoretical contributions: boundaries in the knowledge commons

Frischmann, Madison, and Strandburg (2014) state the need for scholars to appropriately theorise what constitutes openness in the knowledge commons, both in terms of community participation and resources in use. I frame this as a question of theorising boundaries.

My study supports the idea that rules embedded in the design of distributed digital technologies can be constitutive of the boundaries of particular knowledge commons. As such, this study informs the question of how distributed digital technologies alter the production and distribution of knowledge as a resource (Hess & Ostrom, 2003). The main theoretical contribution to the notion of boundaries comes through my exploration of the technological architecture of 3D printing systems as design rules-in-use. By allowing into the commons certain types of information, I find that the openness of 3D printing system design acts as a boundary rule, conditioning types of knowledge included and the terms of participation in commons-based 3D printing. Hacking a proprietary 3D printing system can be understood as disrupting such a boundary, although perspective from Fab Lab members engaged in such tasks highlight the remaining difficulties in accessing complete system knowledge. Importantly, if one component of a 3D printing system is open access, such as software, users have greater incentive and ability to experiment with interconnected components such as hardware and materials. This can also lead to disruption in the boundaries of the knowledge commons pertaining to linked categories of resources. By studying how users continually engage with the openness of technologies, one can envision a way to study the evolution of knowledge commons boundaries over time.

The level of modularity in the architecture of a technological system, when formulated as a rule-in-use, can also be seen to influence access to knowledge in the commons. If a user can easily substitute and alter parts of a 3D printer, there may be more incentive for the user to engage in open source software or hardware knowledge commons. Alternatively, if high levels of modular design lead to lock-in of dominant design interfaces, there may be little incentive to access and produce knowledge about alternative system designs in the commons. In this way, I propose that the design of technological architectures can be a way to study rules-in-use governing incentives around participation in the knowledge commons and boundaries concerning what knowledge is included or excluded.

8.3.3 Knowledge and the nature of resources

One of the most important areas is in adapting the analytical tools of commons theory to new digital commons is dealing appropriately with the underlying nature of resources. As Frischmann, Madison, and Strandburg (2014) theorise, one must understand the natural characteristics of a resource, as well as its social construction, in order to understand how the resource in question may be accessed, used, and produced in a commons community.

My study on knowledge about materials in 3D printing offers a way to explicate the differences between the underlying natures of resources in use. I do so by applying the tools developed for the study of biophysical resource commons including the typology of goods (V. Ostrom & E. Ostrom, 1977) and the distinction between resource system and resource flow (Hess & Ostrom, 2003). I find that applying these tools contributes a level of nuance to the study of knowledge in the commons: while knowledge itself may be nonrival and hard to exclude others from, empirically one sees that access to knowledge in the commons is affected by the nature of the underlying resource it is related to.

To elaborate, I focus on the interactions between types of resources, and the governance of these resources. My study of 3D printing materials in Fab Labs contributes three main ideas. First, my findings support the idea that dilemmas arise from the governance of flows and facilities, as well as the nature of resources (Hess & Ostrom, 2003). I find that significant barriers in accessing knowledge about materials are related to how these physical resources are produced: the proprietary nature of materials production restricts access to knowledge. This introduces an important caution in the general pursuit of theorising knowledge commons when both physical and digital resources are in use. While it may be true that 3D printing as a distributed digital technology may 'change the capture and use of information' (Hess & Ostrom, 2003), I find that information related to different types of resources is differentially altered. Importantly, 3D printing can be viewed as a technology that allows the study of both physical and digital resources. This is just the beginning of such an enterprise: as distributed digital technologies continue to evolve as means of producing physical goods, understanding the interplay between physical and digital resources will become ever more important.

Second, the ways some users of 3D printers are bringing materials production closer to the Fab Lab common-property regime through waste recycling or intervention into plastics production are theoretically significant. These types of disruption haven't been looked at in knowledge commons scholarship, and are suggestive of the avenue of research of entry points into the commons (Hess, 2008).

Again, one must carefully define the nature of the underlying resource so as to see different potential points of entry. This will provide guidance to any analysis of knowledge entering or remaining excluded from the commons.

Third, the finding of how proximity to resource systems enables people to access and produce new knowledge is also interesting. It provides an example of how knowledge as a resource is produced as well as accessed and consumed in the knowledge commons (Madison, Frischmann, & Strandburg, 2010). It supports the idea that local knowledge matters for the governance of resources, a strong theme in commons research (Ostrom, 1990).

8.3.4 Theoretical contributions: studying knowledge commons over time

For knowledge commons, endogenous feedback in the use and production of shared resources is an important area for theoretical development (Frischmann, Madison, & Strandburg, 2014). One aspect of this is the study of learning and engagement in a knowledge community over time. I contribute to this theme by analysing engagement in types of knowledge associated with 3D printing systems. In Chapter 7 I investigate user engagement in knowledge related to hardware, software, and firmware over time in the online Ultimaker user forum. I find that users have a tendency to engage in more types of knowledge associated with the 3D printing system over time, moving from being knowledge specialists to generalists the longer they spend in the community. That is, the longer they are part of the forum, the more they post across boundaries between knowledge associated with digital and physical resources.

This finding has important implications for the literature on peer production. Building on the work of author such as von Krogh, Spaeth, and Lakhani (2003), my findings provoke further work in longitudinal studies of specialist/generalist behaviours as related to knowledge. David and Shapiro (2008), in their study of motivational profiles in FLOSS projects make the point that motives are not only heterogeneous but mutable, ‘subject to changes in accumulated experience, an endogenous effect that raises measurement challenges for observed behaviour’ (p. 395). By studying changes in specialist versus generalist patterns of knowledge engagement in the user forum, this study opens an intriguing avenue for further research with respect to linking knowledge accumulation and patterns of engagement across knowledge types. This idea of accumulated experience resonates with qualitative findings from 3D printer users in a Fab Lab who modify their 3D printer and gain knowledge of different types as a result. This learning appears driven, in particular, by the fact that intervention in one part of the system causes the need to know about changes in another part of the system. This suggests that interdependencies across modular interfaces may constitute one mechanism for endogenous learning in an open source community. Future research is needed to explore this proposition further.

Lastly, my study of the Ultimaker 3D printing community empirically extends the boundaries of what David and Shapiro (2008) call the ‘open-source phenomenon’, specifically in ‘…[the] wider implementation of a new organisational paradigm’ (p. 365-6). In particular, how open source as an organisational model extends beyond the peer production of software is an important empirical question (von Hippel & von Krogh, 2003). The study of the Ultimaker user forum demonstrates how the theory of peer production can be used to analyse user engagement with knowledge of hardware, software, and firmware in open source communities. By their very nature, commons-based 3D printing communities present theoretical opportunities to study access to and production of knowledge about physical and digital resources in the commons.

8.4 Implications for Practitioners and Policymakers

The following provides recommendations for practitioners in digital fabrication communities such as Fab Labs, as well as for policymakers who may influence the development of 3D printing technology through environmental legislation and Intellectual Property regimes.

8.4.1 Practitioner insights

For practitioners involved in digital fabrication communities such as Fab Labs and Makerspaces, there is a need for increased knowledge about materials at a local level. The lack of knowledge about materials, from a Fab Lab perspective, is striking given the benefits of this knowledge for digital fabrication. Although there may be numerous technical difficulties and market barriers, one approach could be to produce materials within Fab Lab common-property regimes, following the example of open source software and hardware movements. These materials are more likely to be accessible in terms of knowledge of material properties and behaviours. The sourcing of waste also creates knowledge benefits, as users go through the process of experimenting with various parameters necessary to create a new material for 3D printing. Examples of this from the research are the use of local pine resin for 3D printing, partnerships created with local materials companies, and the recycling of plastic bottles for 3D printing plastic from the local landfill. Increased standardisation of methods for documenting materials could also help knowledge accumulate (Foray, 2004).

A second area of recommendations for Fab Lab practitioners concerns the choice of 3D printers. The choice of 3D printers relates to how much knowledge Fab Lab users can access and participate in producing. If a Fab Lab wants to enable creative and experimental users to access and produce new knowledge about materials, then open source and highly modular machines are a clear choice. This comes with the caveat that such machines may introduce a steeper learning curve for new users of 3D printers given their additional parameters. This choice may also come at the cost of more reliable prints, which may exclude users who need efficient results. Furthermore, one must take account of individual user learning over time. Here one may observe that a certain level of integration between modules in the 3D printer compels a user to acquire new knowledge, such as learning software programming as well as hardware assembly and firmware electronics.

With the current rate of change in the market, the reasons for choosing open source versus closed source printers will likely change in the years ahead. Given how recent the open source 3D printing movement is, it appears too early to assess the general performance of open versus closed source machines. From the perspective of Fab Lab users at the moment, closed-source machines are said to be more reliable than open source machines. However, Ultimaker, an open source model, is often found by users to perform very reliably. If one takes open source software as a historical precedent, open source hardware may continue to increase in sophistication and reliability. The choice of open or closed source 3D printers also includes the software and firmware that a 3D printer runs on, implying further costs and benefits.

8.4.2 Policy recommendations

Concerning the use of waste materials for local production, Fab Lab users would benefit from environmental policies aimed at disclosing more information about materials in waste streams. Not only would this allow Fab Labs to source and cycle materials more intelligently, it would also avoid potential health impacts from handling unknown chemicals or substances.

A second recommendation concerns corporate disclosure of materials information. While the composition of materials such as 3D printing filament made by companies is often available to industrial customers, individuals and Fab Labs purchasing materials are often not provided with detailed information on composition and behaviour. With limited knowledge available, the potential for innovation and sophisticated use at a local level is curtailed. The need for companies to provide detailed information on materials will only grow as more communities and individuals demand materials for digital fabrication.

The rapid rise of desktop 3D printing opens a further question for policymakers. The numerous and varied models of desktop 3D printers, both open and closed source, is linked to the first expired FDM patents that were open sourced. If one accepts that these open source designs were related to the growth of and variety in the desktop 3D printing market, it raises the question of whether open source activity should be incentivised as a model for stimulating rapid technological development.

8.5 Limitations and Future Research

8.5.1 Limitations

Here I address the limitations in scope, level, and subject of analysis related to answering my research question. Considering scope, my Fab Lab interview data was gathered over a limited amount of time. A longitudinal study of Fab Lab users would be useful for understanding the relative impact of particular barriers or enabling factors to accessing knowledge about materials. A limitation also concerns the particular group I chose as interviewees. Fab Labs are not the only types of digital fabrication communities where commons-based 3D printing takes place. Makerspaces, Hackerspaces, and individuals are also involved with commons-based 3D printing. As such, findings are limited to the experiences and behaviours of Fab Lab users. The exception to this is the study of the Ultimaker community, as users of the forum may or may not be members of a Fab Lab. This widens the scope of the study, although limitations clearly remain.

There are also limitations with the levels of analysis chosen. Although the combination of Fab Lab user interviews and Ultimaker community analysis allows two different levels of analysis to be taken into account, other levels relating to rules-in-use are relevant to my research question. These include decision-making bodies that run or fund individual Fab Labs, as well as other software and hardware communities that, like the Ultimaker community, extend beyond the boundaries of Fab Lab communities. Similar to Ultimaker, these other communities impact the operational level of Fab Labs as action arenas, depending on the tools used and participation by members of Fab Labs.

A lack of analysis at the ‘constitutional level’ understood within the IAD framework is a larger limitation of this work. The intellectual property landscape is a constitutional level of analysis that clearly affects collective-action levels (including the Ultimaker community), as well as operational-level activity in Fab Labs. What may or may not be proprietary or open source at any given point in time has a structural impact. For example, if certain large materials companies patent their process of making 3D printing plastic, this may limit access to knowledge in important ways. This is a limitation in scope of the present research, and is of interest for future study.

Lastly, there are limitations pertaining to the specificity of the subject of my analysis. I choose to study knowledge about materials as a broad category. A limitation is the lack of granularity when it comes to specific brands and types of materials, and the knowledge associated. This is the same for 3D printing systems used in Fab Labs. Although I give some specific attention to the differences between open source and proprietary systems, and brands such as Ultimaker, RepRap, and Makerbot, my research topic would benefit from more in-depth work on specific 3D printing systems and types of materials, hardware, software, and firmware. A related limitation concerning knowledge specificity is the distinction between tacit and explicit knowledge, as well as sensitivity to the various ways knowledge is produced, stored, and accumulated (Foray, 2004). I address this in part by providing context around specific references to knowledge by 3D printer users; nevertheless, a more rigorous treatment of knowledge may allow for more fine-grained insights.

As a concluding note, my analysis is also limited by the outcome variable I chose to study. Access to knowledge about materials from the perspective of Fab Lab users was deemed an appropriate means of assessing whether this knowledge was part of, or entering into, the commons. Yet one could also conceive of different ways to measure whether knowledge about materials is entering the commons. For example, one could analyse online user communities related to open source 3D printing hardware and software and gather data on references to material characteristics. Such studies would involve different research methods, but nonetheless would be highly complementary to the approach taken in this thesis.

8.5.2 Future research

The limitations discussed, as well as my research findings, introduce considerable scope for further research. I choose questions that are intriguing for future work, and present them according to their focus at the operational, collective-action, and constitutional levels of analysis.

At the operational level of analysis one can ask the question of what drives experimentation with materials. The findings from this research offer intriguing examples of Fab Lab users who were disrupting the boundary of Fab Lab common-property regimes that exclude the production of materials by experimenting with recycling waste, working with local material producers, and accessing materials further back in the supply chain. Further detailed research is needed to understand the types of experimentation taking place, the range of knowledge that is being accessed from such experimentation, and the types of incentives driving this activity. Observational methods would be particularly useful to study this, as knowledge documentation is presently limited. Here the approach of science and technology studies may be particularly useful in drawing out the ways that users are enrolling actors in the creation of new actor networks of digital and physical resources.

Related is the further inquiry into how the design of 3D printing systems constrains or enables experimentation. This requires the study of a range of designs of 3D printers, and may become increasingly pertinent as the desktop 3D printing market continues to diversify. A question remains on the lock-in of dominant designs with open source peer production models, and the barriers this may create to experimenting with different forms of materials. An economic history perspective would be important for the study of this question, drawing in the work of Paul David (2007) and the evolution of technology (Ziman, 2000).

Second, at the collective-action level there is the question of comparing different organisational models of producing and governing physical resources in the commons. The phenomenon of open source 3D printing compels researchers to bridge theory of peer production from open source software to the production of physical goods. An in-depth study of the organisational model of peer production behind Ultimaker would be extremely interesting, as would a comparative study with other communities associated with 3D printers such as the RepRap. The IAD framework can provide guidance in this enterprise by providing a framework for investigating and comparing community attributes, rules-in-use, and the nature of the resources being governed.

The concept of shareable goods (Benkler, 2004b) is also a useful framework to analyse the collective infrastructure that the increasingly distributed ownership of 3D printers now represents. There may be opportunities here in studying collective sharing, exchange, and peer production of physical goods. Interesting aspects of this question would involve types of materials and copyright over designs used. While an empirical focus for this type of study is not obvious, highly networked communities such as Fab Labs[50] and individual network platforms such as 3D Hubs may provide a starting point.

Third and finally are questions around the influence of intellectual property regimes on commons-based 3D printing. One question is the role that the open source movement played in catalysing the recent period of rapid technological development in the desktop 3D printing market. A social movement perspective could highlight key differences between communities in terms of values and norms, and the evolving community identities that surround the use of open source models. Such a study could also include a competitive analysis of companies who chose to patent or open source their 3D printing system. This research proposition has considerable implications for how one understands the relationship between IP and technological innovation.

There is also the question of who controls knowledge about 3D printing materials in the wider industrial landscape. This includes intellectual property regimes, and analysis of patents and trade secrets for processing materials as well as chemical recipes. An important factor is material supply chain transparency, as acquiring information may require one to trace back ingredients all the way to the raw material supplier. Related are the incentives to disclose information about materials whether it is material properties or material supply sources. This includes 3D printing system providers who sell materials tailored to their machine, as well as materials production companies who may protect their market advantage by restricting access to information.

Pursuit of these questions will help extend the findings of this research into new areas. As 3D printing is a rapidly evolving technology that is changing flows

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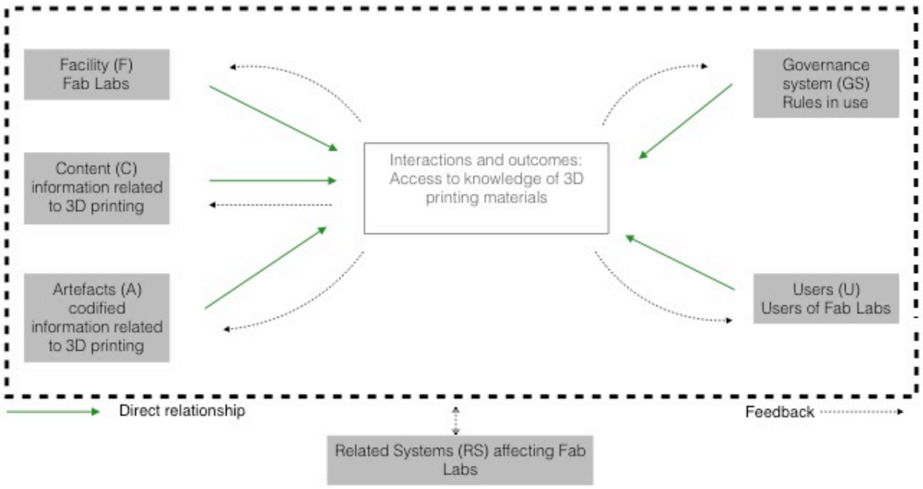
[50] Some members in the Fab Lab network have engaged in collective design initiatives, where a product is designed, modified, and 3D printed by Fab Lab members in multiple locations.

of physical and digital resources in new ways, the on-going potential for advancing commons theory is considerable. My aim is to contribute an important chapter in a larger project of empirical understanding and theoretical advancement.

Appendix I: Variables for Research Design: A Multitier Framework for Analysing 3D Printing in Fab Labs

Adapted from Ostrom (2007)

Level 1



Note: 'Resource Units' in Ostrom's (2007) framework is replaced by 'Content' and 'Artefacts' as recommended for knowledge commons analysis (Hess & Ostrom, 2001)

Level 2

Facility (F): FabLab

F1. Materials

F2. Machines

F3. Software

F4. Personnel

F5. Building facility

Content (C): Production Information

C1. Materials information

C2. Design information

C3. Machine information

C4. Software information

Artefacts (A): Codified production information

A1. Design (CAD)

A2. Software script

A3. Material data sheets

A4. Activity logs

Governance System (GS): Rules in use

GS1. Institutional affiliation

GS2. Funding body

GS3. FabLab Network

GS4. Lab community

Users (U): Users of FabLabs

U1. Type

U2. Use

U3. Outcome/purpose

U4. Collaboration

Related Systems (RS): systems affecting FabLabs

R1. Tech hubs, hacker spaces

R2. Proximate/related Institutions

R3. Market for materials development

R4. Market for machine development

R5. Open software community

R6. Open design CAD community

Level 3

Facility (F): FabLab

F1. Materials

F11. Material type (plastics, metals, wood, other)

F12. Material source (local, MIT, existing supply chain)

F13. Material cost

F14. Open/closed source

F2. Machines

F21. Machine type (associated capabilities)

F22. Machine source (bought, on loan, made in lab)

F23. Open/closed source hardware

F24. Machine cost

F3. Software

F31. Type (performance, level of detail, sophistication)

F32. Source (external, MIT, in-house)

F33. Openness (open-source, patented)

F34. Accessibility (intended use, user interface)

F4. Personnel

F41. Number of facilitating personnel in Lab

F42. Paid/volunteer staff

F43. Expertise and capabilities

F44. Motivation for working

F5. Building facility

F51. Part of another institution/alone

F52. Space for equipment and people

F53. Ambiance/likability

F54. Uniqueness in community

F55. Social facilities (kitchen, social space, facilities)

Content (C): Fabrication Information

C1. Materials information

C11. Material composition

C12. Materials structure

C13. Material behaviour

C2. Design information

C21. Dimensional design

C22. Functional design (how it works)

C23. Integrative design (how it works with other parts)

C3. Machine information

C31. Number and type of parameters (speed, temperature)

C32. Control over parameters (pre-set/not)

C33. Level of precision of control

C4. Software information

C41. Number and type of parameters

C42. Control over parameters

C43. Level of precision of manipulation/visualisation

C44. Integration with other software

Artefacts (A): Codified production information

A1. Design (e.g. CAD)

A11. Source of design (proprietary/open source)

A12. Use of the design (new production/adaptation/direct use)

A2. Software script

A21. Source of script (open source/proprietary)

A22. Ease of access to script

A23. Use of script (modification/contribution to source)

A3. Material data sheets

A31. Source of data sheet (proprietary/open data)

A32. Ease of access to material data sheets

A4. Machine data

A41. Source of machine data (open/proprietary)

A42. Ease of access to machine data

A43. Use of machine data (modification/contribution)

A5. Knowledge recording

A51. Source of knowledge (projects, procedures)

A52. Method of recording (codification, modularity)

A53. Intended use of knowledge

A54. Distribution of knowledge

A55. Volume of knowledge (e.g. frequency of recording)

Users (U): Users of FabLabs

U11. Students

U12. Professionals/community members

U13. Community groups

U14. Individual entrepreneurs (commercial)

U15. Businesses

U2. Use

U21. Time spent

U22. Type of use (design, process, or final product only)

U3. Outcome/purpose

U31. Personal use

U32. Community use
U33. Commercial use

U4. Collaboration
U41. Joint project collaboration
U42. Collaboration on individuals projects

Related Systems (RS): Systems affecting FabLabs
R1. Tech hubs, hacker spaces
R2. Proximate/related Institutions
R3. Market for materials development
R4. Market for machine development
R5. Open software community
R6. Open design CAD community

Governance System (GS): Rules in use
GS1. Institutional affiliation
GS11. Targets and expectations for lab
GS12. Integration with other facilities
GS13. Rules of use for internal/external users to the institution (e.g. students of affiliated university)
GS14. Activities run (courses, outreach)

GS2. Funding body
GS21. Targets and expectations
GS22. Restrictions on provision of funds (amount/time granted)

GS3. FabLab Network
GS31. Inventory rules (machines, materials, software)
GS32. Rules of use for users (allocated days for public)
GS32. Rules of use for fabrication (commercial selling)
GS33. Peer review system for becoming a FabLab

GS4. Lab community
GS41. User engagement policy (commercial/public)
GS42. Safety instructions/procedures
GS43. Method of guiding, assisting, teaching users

GS44. Relationship with local community

GS45. Relationship with regional/global FabLab network

GS46. Relationship with related communities (e.g. hacker spaces)

Appendix II: Fab Lab Charter

Source: Centre for Bits and Atoms, MIT: http://fab.cba.mit.edu/about/charter/

What is a fab lab?

Fab labs are a global network of local labs, enabling invention by providing access to tools for digital fabrication

What's in a fab lab?

Fab labs share an evolving inventory of core capabilities to make (almost) anything, allowing people and projects to be shared

What does the fab lab network provide?

Operational, educational, technical, financial, and logistical assistance beyond what's available within one lab

Who can use a fab lab?

Fab labs are available as a community resource, offering open access for individuals as well as scheduled access for programs

What are your responsibilities?

safety: not hurting people or machines

operations: assisting with cleaning, maintaining, and improving the lab

knowledge: contributing to documentation and instruction

Who owns fab lab inventions?

Designs and processes developed in fab labs can be protected and sold however an inventor chooses, but should remain available for individuals to use and learn from

How can businesses use a fab lab?

Commercial activities can be prototyped and incubated in a fab lab, but they must not conflict with other uses, they should grow beyond rather than within the lab, and they are expected to benefit the inventors, labs, and networks that contribute to their success

draft: October 20, 2012

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