The Materialization of Digital Information and the Digital Economy

Knowledge Synthesis Report

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Executive Summary

This report addresses the socioeconomic implications of an important and potentially far-reaching phenomenon emerging in digital media: the increasing movement of previously digital resources and techniques into the physical environment.

Digital/material convergence. We are witness to a burgeoning movement towards the materialization of digital information; increasingly, people are able to simultaneously make and share both things and knowledge through newly conceived digitally mediated practices.

‘3D Printing’ as lead indicator. Industrial rapid prototyping technologies are becoming more compact and available at lower price points, making in-house fabrication accessible to individuals and small businesses. The push for ubiquity is not driven by large industry, but rather by grassroots ‘Maker’ communities that define a growing subculture around this and other digital desktop fabrication (DDF) technologies.

Existing scholarship. Currently, the majority of scholarship in the area of DDF / 3D printing comes from engineering and the sciences, or is cross-disciplinary in nature. Our research expands what little exists in the way of focused social science and humanities research in this area.

Research & observations. Using research methods that blend hands-on engagement with ethnographic techniques, a workshop was held in which participants explored 3D printing processes. Follow-up interviews were held with participants. From coding and analysis of transcripts from the workshop and interviews, key themes emerged: materiality; design crowdsourcing; legal issues; changing industries.

Emerging Phenomena & Digital Economy Implications

1. Novel spaces for fabrication. Homes, schools and small businesses have the potential to become ‘micro factories’. New online communities are forming that make the outsourcing of 3D printing more accessible, streamlined, entrepreneurial and interactive. New ‘co-creation’ platforms encourage participation. Online user-generated repositories provide free 3D models.

2. Citizen empowerment. Newly developing tools and spaces for digital fabrication are empowering more citizens to make things, which can be seen as a form of political and social activism.

3. The evolving consumer. Today, consumers increasingly seek out individualized experiences. Responding customization practices are producer driven, but are also
increasingly “prosumer” driven, examples being “mass customization”, “co-creation”, and “lead user innovation”. Consumer attitudes are shifting away from the notion of material production as an experts-only profit-making enterprise, to a view of making and modifying products as experiential learning.

4. **New conceptions of labour.** “Peer production” is migrating from digital production to physical. As Makers use web-based networks, they must rely on faculties of the ‘knowledge worker’ to succeed. There is the misconception that 3D printing, through automation, eliminates labour; we argue instead that work is displaced, distributed and embedded within technological systems. Tensions are arising around culturally understood boundaries between digital and material forms of labour.

5. **Unlocking latent entrepreneurship.** 3D printing, in combination with above phenomena are opening new channels for ‘amateur inventors’ to move designs from conception to market reality. The case study of the Glif, an adaptor that connects an iPhone to a standard tripod, is presented to illustrate.

**Implications for Canadian Economic Strategy**

1. **Infrastructure.** Strong and wide-reaching digital networks are needed to support the use, connectivity and growth of emerging novel spaces for fabrication. Also needed is physical network infrastructure that supports efficient transport and shipping of raw materials used and physical products generated by making technologies.

2. **Literacy.** DDF technologies such as 3D printing demand greater fluency with 3D digital content. Those who work in hand production will increasingly use digital skills and knowledge, while those working digitally may find themselves confronting issues materiality as digital content is increasingly transformed to physical form.

3. **Legislation.** The ability of digital/material representations to be shared with great fluidly gives rise to potential legal issues, including: liability and consumer safety; circumvention of various forms of physical prohibition; debate around intellectual property and “fair use”.

4. **Initiatives.** In forming policy, “digital media” cannot be considered as a separate and distinct “sector” within the economy; rather, digitally-mediated creative work is integrated in highly specific ways into a wide array of production practices, and increasingly, this includes production of material things.

**Conclusion.** This work is only just beginning. DDF is not merely a new tool or apparatus, but constitutes a new mode of material engagement that both productively and problematically recombines knowledge work, craft, and design in novel ways. Bringing together a number of important socio-technical developments that are meaningful for a variety of social science and humanities fields, there remains the need for additional, on-going research in this area.
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Introduction

This report addresses an important and potentially far-reaching phenomenon emerging in
digital media, namely: the increasing movement of previously digital resources and techniques
into the physical environment. A blurring of the ‘divide between bits and atoms’ is occurring
that holds the potential to greatly transform current relations between companies and
consumers and to redefine how both individuals and collectives participate in digital economies
and also in larger cultural, social and political life.

Digital / Material Convergence

We are witness to a burgeoning movement towards the materialization of digital information
that encompasses and crosses multiple areas, including recent innovations in ubiquitous and
physical computing, open-source hardware, and digital manufacturing, in concert with ongoing
advances in social networking and online communities. In the spirit of other forms of media
convergence as argued by Jenkins (2006), emerging are previously unseen combinations
between digital and physical production that encourage unprecedented control over material
and symbolic landscapes. Increasingly, groups possessing various levels of technical expertise
are able to simultaneously make and share both things (“material”) and knowledge
(“immaterial”) through newly conceived digitally mediated practices. Such developments may
prove profoundly transformative for traditional production-consumption relationships and
current separations between experts and lay populations.

Activity of this kind is not entirely new; people have been making things themselves and
exchanging information about shared interests throughout history. Now further empowered by
the Internet, today’s so-called “Maker” communities are thriving and becoming increasingly
visible. Also known for modes of engagement such as hacking, tinkering, and do-it-yourself
(DIY), this group has turned its attention to the physical aspects of digital culture - appropriating
hardware and experimenting with self-made devices as an alternative to purchasing
commercial versions of those products. Moreover, the combination of online tutorials, access
to electronic components and new fabrication technologies make it possible to design, develop
and manufacture a variety of physical artefacts such as functional and/or decorative objects,
interactive devices and customized computers that previously required large scale
manufacturing equipment and investment.

This report focuses on the socioeconomic implications of these new fabrication technologies
that are becoming increasingly integrated in to the process of making, particularly at the level
of the individual and micro organization. As forecasted by Gershenfeld (2005), technologies
such as computer numerically controlled (CNC) mills, laser cutters and engravers, as well as ‘3D
printers’ that were once the exclusive domain of large industry are now migrating from the
factory to the desktop. While it has largely been tech-savvy design, art and Maker communities
that have embraced such resources, broader interest is gaining momentum. If we look at how readily other forms of digital development such as document publishing, digital photo manipulation and website creation moved from expert to lay populations, it can be expected that a similar move will occur with digitally designed and physically manufactured media as well. Indicative of the increasing porosity between the digital and the material, a revolution in \textit{desktop digital fabrication} (DDF) is underway.

\textbf{3D Printing as Lead Indicator}

For this study, we chose one particular form of desktop digital fabrication technology, 3D printing, to gain more focused views into the wider phenomenon of the materialization of digital information. This choice was made in part because of the very noticeable groundswell of developments and discussion surrounding this technology in recent years. Additionally, as will be discussed in coming sections, our ongoing research work in Critical Making employs 3D printing technology for both hands-on experimentation and ethnographic research. Moreover, the very concept of ‘3D printing’ seems to capture the popular imagination and speak optimistically of the future; ‘2D’ paper printers have occupied such a common space in our technocultural landscape throughout the past few decades that the prospect of similar machines entering daily life and producing functional objects on demand is particularly poignant.

To place 3D printing technology in context, it must be acknowledged that computers have been used in manufacturing since the 1960s in the form of ‘rapid prototyping’ tools for large industry (Gebhardt, 2003). Priced in the order of hundreds of thousands of dollars CDN, such industrial machines have been used to fabricate prototypes of products and parts to test their feasibility prior to mass-production, utilizing processes that include stereo lithography, selective laser sintering, and fused layer modeling. In general, industrial rapid prototyping processes are characterized as either ‘additive’ (building up material to make an object) or ‘subtractive’ (removing or cutting away material to make an object). The principle behind the majority of the additive processes, including 3D printing, involves layerization: ‘slicing’ digital models into horizontal layers and building the object up one layer at a time, much like contours of a terrain model or making a clay coil pot (Figure 1). In recent years, industrial rapid prototyping machines such as those by Stratasys (stratasys.com) have become more compact and available at lower price points (within the tens of thousands of dollars CDN), making in-house fabrication accessible to enterprises such as major industrial designers, small-run manufacturers, research labs and architectural firms.

Given the roots of digital fabrication in industrial manufacturing, one might assume that the gradual migration of these technologies from the factory to the desktop is the result of product development and marketing driven by the corporate interests in capturing broader market share. While this effort is certainly underway, progress has been slow; major electronics retailers like Best Buy still do not include 3D printers alongside other consumer technologies such as gaming consoles, digital cameras and mobile phones. The more notable push towards widespread adoption of 3D printing is, in fact, occurring at the much more grassroots level of
Maker subculture, which as mentioned previously has turned its attention to appropriating technological hardware and experimenting with self-made devices. The technologies of industrial rapid prototyping (and in particular, the relatively simple principle of layerization) has been and remains a natural target for Makers, in part because people who enjoy making their own technological things would, somewhat understandably, be enamored with the idea of making devices that would, themselves, make things. Personal explorations in building DIY CNC machines have proliferated, proportionate to advancements in personal computers and programmable microprocessors, as well as the increasing availability of mechanical components such as stepper motors (often recovered from discarded consumer electronics such as inkjet printers and scanners).

Exemplifying the spirit of such DIY CNC experimentation, RepRap (reprap.org) is a seminal UK-based project that is committed to the ongoing development of an extremely affordable (less than five hundred dollars CDN), open-source 3D printer designed to be self-replicating, or at least capable of printing all of its own key structural components. Like open-source software, RepRaps are freely available to ‘anyone’ – anyone, that is, with enough know-how and drive to put one together. Successful assembly of a RepRap has been characterized as “nontrivial”: requiring local sourcing of often elusive hardware, extensive wiring and soldering of electronic components, as well as a employing a decent working knowledge of software code. While enough RepRaps have been made worldwide to earn the project a measured degree of success, it remains the domain of a niche community of Makers who possess considerable technical expertise.

Yet the real value of the RepRap, as seen with other open-source initiatives, lies in the manner in which developments become appropriated and modified to suit alternative needs and
visions. Many hackers have appropriated RepRap electronics to make customized Cartesian fabrication robots, and perhaps the most well known of these is the MakerBot (makerbot.com). Capitalizing upon the intellectual and physical resources borne of the RepRap project, MakerBot Industries is a small company started by a team of self-described hackers in Brooklyn, New York that manufactures and markets affordable (around $1200 CDN), open-source 3d printer kits (Figure 2). In keeping with their affiliations to Maker sensibilities, these 3D printers are sold as prefabricated kits that require final assembly by the user: a form of “DIY-lite”. While a certain comfort level with manipulating both electronic and mechanical parts is required to assemble one, the Makerbot has nevertheless made 3D printing far more accessible than the RepRap. Akin to Ikea furniture, customers order a flat-packed MakerBot kit shipped to their door then put it together themselves as an “enjoyable activity” that one or two people can accomplish over a weekend. Though still far from mainstream, the increasing attention MakerBot is garnering in the popular press (http://blog.makerbot.com/category/in-the-news/) indicates that awareness of and interest in 3D printing by the general public is on the rise.

![Figure 2: MakerBot 3D printer (www.makerbot.com).](image)

While it is posited here that the current interest and activity surrounding 3D printing is largely driven by and attributable to the grassroots open-source efforts of Maker subculture, corporations are also actively seeking market share. Hewlett Packard recently joined with Stratasys to put the HP brand name behind a line of 3D printers priced at around $20 000 CDN, still just above the reach of the home market. Currently, it appears that the most ‘consumer-ready’ commercial 3D printer on offer is the UP! (pp3dp.com), a machine that also uses RepRap electronics but is mass-produced in China and sold online as a proprietary, closed-source, plug-
and-play device. Priced at about $2500 CDN and dropping, the UP! represents the closest competitor to the MakerBot in terms of widespread adoption. Regardless, it seems inevitable that a proprietary mass-produced 3D printer (whether the UP! or an HP) will, in the foreseeable future, eventually undercut, outperform and outsell the MakerBot and other similar open-source projects. The effects that this milestone will bring to the currently vigorous culture of tinkering, hacking and DIY in this area remains to be seen.

Existing Scholarship

The majority of current scholarship on 3D printing and related technologies relates to engineering or scientific aspects of these developments. Examples include Balk & Campbell, 2004; Burton, 2005; Sells & Bowyer, 2006; Hopkinson, Hague, & Dickens, 2006; Hague, Tuck, Campbell, Ruffo, Dickens, & Wohlers, 2007. There is still little in the way of social science and humanities scholarship that specifically refers to 3D printing. What does exist tends to be cross-disciplinary works that blend industry interest, computing and engineering knowledge, as well as social themes; here, issues of intellectual property, questions of design methods and processes, and possible business possibilities and outcomes are blended. A prototypical work in this regard is Neil Gershenfeld’s monograph Fab: The Coming Revolution on Your Desktop - From personal computers to personal fabrication (2005). Published by Basic Books for popular audiences, Gershenfeld’s text contextualizes DDF within a longer history of computing, provides details as to various current and upcoming technologies, and predicts future socio-technical developments. More recent works have somewhat narrower scope, but are equally cross-disciplinary. Examples that address IP include Bradshaw, Brower and Haufe (2010) as well as Weinberg (2010). Others focus on implications for design and designers (Duffy & Keen, 2006; Simpson, Siddique, & Jian, 2006; Campbell, De Beer, Barnard, Booyesen, Truscott, Cain, et. al, 2007; Lunar Design, 2008). And many address possible ramifications for the manufacturing industry, mass customization in particular (Baumberger, 2005; Chin, 2005; The Manufacturer US, 2006; Koren & Barhak, 2007). Our research extends from this work by providing a more detailed and nuanced examination of DDF and 3D printing through interviews and observations.

Research & Observations

To help us gain insight into the perceptions, attitudes and connections surrounding a technology such as 3D printing, we employed a method termed Critical Making (criticalmaking.com), developed and practiced by P.I. Matt Ratto in his lab at the University of Toronto. The primary aim of Critical Making (like other forms of STS and HCI research) is to connect technological systems and practices to critical scholarship and ideas. However, where our method finds distinction is that we also engage collective hands-on experimentation (making), the results of which serve as “cultural probes” (Gaver & Pacenti, 1999) that help open conceptual channels of discourse to augment traditional ethnographic practices. Key to Critical Making are therefore collaborative meetings, sessions or workshops, where participants are encouraged to physically engage, experiment with and discuss pertinent aspects of technologies in question.
For this study, an evening workshop addressing the possibilities of 3D printing and desktop digital fabrication was held at the University of Toronto’s Faculty of Information. Of the 25 participants, most were professionals who work with digital media in their daily practices and were drawn from a group known as DDIMIT (Designing Digital Media for the Internet of Things) consortium. Funded by the Ontario Media Development Corporation, this collective was formed by Matt Ratto in conjunction with the University of Toronto’s Knowledge Media Design Institute to connect university researchers, non-profit associations, digital media content creators and related businesses to collaborate on projects concerning “Internet of Things”, a burgeoning area that intersects with the materialization of information framed in this report.

Throughout the session (Figure 3), participants explored online crowdsourced repositories of 3D models (described later in more detail), designed their own 3D objects using free software, and printed these objects on a professional-quality 3D printer located in the Critical Making Lab. The functional or aesthetic merit of the actual objects made by participants, in this case custom pendants (Figure 4), were not the end goal or even the focus of the workshop. Rather, as stated earlier, the artifacts (and moreover, the process of learning how to make them using 3D printing and related systems) were used to open channels for conceptual exploration, reflection and criticism.

These Critical Making processes (both physical and intellectual) were captured in two ways. First, the workshop itself, including discussions both informal (solving problems, clarifying unclear points) as well as formal (opening presentation and wrap-up discussion), was captured in audiovisual recordings as well as field notes. Second, follow-up interviews were conducted with willing participants in the weeks following, to dive deeper in to their personal thoughts and response to their experience 3D printing that the workshop may have stimulated. The analysis of this material is still ongoing using a grounded theory coding approach (Charmaz, 2006). The following are our initial observations, with some excerpts from the interviews.

The workshop session provided a shared experience that provided context for scheduled interviews. These unstructured interviews took place within one month of the workshop, lasted for approximately one hour each, and were transcribed and anonymized. Distinct themes have emerged from our initial coding process. Respondents emphasized the materiality of 3D printing, finding it to be both a possible problem as well as a solution to a variety of issues. Not surprisingly given that many of them self-identified as designers, the role of the designer and the possible transformation of design practice was also a theme. Finally, the ramifications for design and manufacturing and related political and legal issues (such as IP) was also a theme.

Materiality

It's sort of the same as when Styrofoam came out. You know, can you picture a world without Styrofoam now? (Nelson, cultural sector)

It's more on the fringes of design right now, but we're starting to see more hand-crafted furniture; hand-crafted wood furniture is starting to make a
comeback, as kind of a reaction against the 80s/90s disposable mentality regarding products. (Mark, industrial design)

My perspective on the 3d printing... I didn't actually print my object at the workshop, because, you know, I didn't need the physical object - I actually really like the digital sphere, where I can have all kinds of stuff, without having to carry it around with me. (Ron, e-business consultant)

The hands-on nature of the workshop highlighted the material qualities of 3D printing, the particular aesthetic quality of fabricated objects, as well as their environmental ramifications. In the quote above, Nelson, for example, predicts a world where such 3D printed things are as ubiquitous as styrofoam, and wonders about the ramifications of this. Mark compares 3D printing and hand-crafted design and in doing so articulates his anxiety about how widespread access to desktop fabrication technologies may increase the ‘disposable object’ mentality. Similarly, Ron focuses on how the virtual object he created at the workshop was enough - he liked its virtual form without needing a physical version.

These quotes reveal some deep ambiguities as to the possibilities of desktop fabrication. On one hand, there is a sense that the technology creates the potential for novel commercial and cultural expression, and that this potential will have widespread impact. On the other hand, desktop fabrication is also seen as having negative ramifications, as increasing our already existing ‘throw-away’ culture. Such ambiguities also demonstrate an insecurity that many designers feel about their role in society. They worry about the objects they are creating and whether or not they are trivial. This concern is exacerbated by a sense that design is becoming an increasingly mainstream activity.

**Design Crowdsourcing**

The one thing I think I had almost a visceral reaction to was the one comment that was made (and it's probably because I'm a designer) but the idea that this is heralding “the end of good design”. I just thought that was a load of baloney. Because, you know, my friend might have a really good pair of scissors, but that doesn't mean I'm going to let her cut my hair! (Megan, industrial design)

I can understand that perspective, and I can understand being defensive, but I don't think that just having 3D printing devalues craftsmanship. I don't think you can just magically replace old ways of doing things... there could be craftsmanship inherent in something that has been digitally modelled... after it comes out of the printer, it's still not perfect. [How we engage with it] can be very creative and very time consuming; it's just a different way of doing things. (Holly, industrial design)

Because many of the workshop participants were industrial designers, there was much discussion around 3D printing posing a threat to their areas of expertise. Here, Megan downplays the technological novelty of 3D printing diminishing the quality of good design
through democratization and crowdsourcing, stressing instead that it is a ‘tool’ like any other (what scissors are to hair). Holly saw that 3D printing, though commonly regarded as an ‘automated process’, does not replace design skill and craftsmanship, but rather transfers various forms of expertise to different areas, such as modelling effectively to achieve high quality 3D prints.

Legal Issues

IP is really hard. I've published about a dozen software patents, but I don't agree with them, so it's a weird place to be... We have a whole culture of kids growing up who have no concept of intellectual property. They take stuff of the web, and mix and mash it together, upload it to YouTube, and that's just the way things work. The tools are available, it's easy to do, and they're actually creating new things and new value, but not legally allowed to... Policy always lags what's actually happening in the world. (Ron, e-business consultant)

Like with small snap connectors, there's patents all around that sort of stuff... but all of a sudden, with 3d printing, you could just print one for free... It's a hard question; it's hard to say what will become of it. It definitely would be a threat, for lack of a better term. (Mark, industrial designer)

Intellectual property and other legal issues were not widely addressed during the workshop session. Despite the above quotes, participants were unsure how fabricated objects might participate in current IP regimes. Like Ron, many acknowledged a shift in cultural conceptions of property, seeing the ‘mash-up’ culture of the web as creating new kinds of value. However, most also understood how current owners of IP might see desktop fabrication as a threat. Mark’s quote provides an example of this. Certainly, more thinking and research needs to be done in this area.

Changing Industries

I think that if designers are flexible, and you move your company in certain ways, people will still need you. Just maybe not in ways that you think that they will... I don't think that people's jobs will be lost, and that people will stop needing designers or design-type people in the world; they just need to adapt to meet the needs of clients - present yourself with different values and offer different things. (Holly, industrial design)

Right now, alot of the bigger projects we send out to get prototyped. Which is really good too, because they are able to update their machines; it's their business, so they should always have the latest and the greatest. But, as costs go down, I think those types of companies are probably going to have to find a new model. (Megan, industrial design)
If you're talking about creating rapid prototyping objects for sale, are things like those amazing light fixtures that look like sponges or foam, with undercuts galore, enclosed areas, that you could never mold using injection molding processes. I think that is where, from a consumer perspective, it could actually take off. But otherwise, you just can't beat 5 cents a part by a chinese manufacturer. (Megan, industrial design)

These comments point to an awareness among the group that as 3D printing gains adoption, the structure and practice of affected small and medium sized businesses will be transformed. As Holly observes, as more of their clients obtain and use 3D printers, designers may have to adjust their practices around such developments, rather than resist them. Megan also sees that the rapid evolution of digital fabrication will put increased pressure on companies who provide outsourcing of rapid prototyping services to innovate rather than become obsolete. However, Megan was less optimistic about changes to existing industry practices in the near future; while she could see niche markets for 3D printed products, the entrenched infrastructures and economic efficiencies of injection molding will be difficult to ‘break’.

**Workshop Wrap-up Session**

The week following the workshop, we met in the lab to reflect upon and discuss our impressions of the session and our observations of participants. From the many threads that were drawn out, two were found to be particularly resonant. One was tension around the ways in which 3D printing potentially reframes existing notions of work involved in making things, and the potential “trivialization” of both “design” and “objects” that might result. As one observer noted, “There seemed to be the suggestion that if you break your cup from Ikea, and you go to your 3D printer to replace it, that replacement cup is more trivial than the IKea cup...” It is notable, however, that ‘ease’ of effort in replacing a cup implied by this statement somewhat contradicts the visible difficulty that most participants experienced during the tutorial in navigating the tools provided in order to successfully print a pendant of their own.

Another thread that was quite evident from comments expressed during the session discussion was that of ‘futurism’ - and more specifically, what the impending ubiquity of desktop 3D printing will mean for consumer culture. One observer remarked on “how intuitive it was to talk about the economic aspect of it... but when you think about it, it's not necessarily an economic subject.” This sense, that the changes that may occur are not just technical but equally social and economic in nature provides the frame to contextualize the results from our environmental scan.
Figure 3: Critical Making tutorial guide exploring 3D printing processes.

Figure 4: Samples of pendants 3D printed by Crtical Making workshop participants.
Emerging Phenomena & Digital Economy Implications

In this section we identify key emerging phenomena related to 3D printing (and digital desktop fabrication more generally) mined largely from our environmental scan and discuss the ways in which these phenomena implicate the structure of digital economies, both currently and in the future.

1. Novel Spaces for Fabrication

The current developments in 3D printing and DDF technologies are opening novel ‘spaces’ for fabrication to occur. For example, as 3D printers drop in both size and price, they are becoming more common in homes, schools, and small businesses, potentially transforming those spaces into micro ‘factories’.

The spaces are also virtual. New online virtual communities (Rheingold, 1993) and network forums (Turner, 2006) are being established that make the outsourcing of 3D printing more accessible, streamlined, entrepreneurial and interactive. The two most prominent examples are Shapeways (shapeways.com), which is focused on 3D printing, and Ponoko (ponoko.com) that began as a laser cutting hub, but has recently expanded to include 3D printing as well as open-source electronic hardware. Resembling hybrids of online machine shop and social network, sites such as these bring together thousands of Makers worldwide to share a virtual version of the collective studio or workshop space, a typology held dear within the social histories of craft, art and design. In these collaborative spaces, users make, showcase, share and sell their creations while interacting with and learning from others. If recent major expansions by both companies are any indication, this model of the ‘virtual collective studio’ will continue to grow.

Web-based networks and digital fabrication technologies are also enabling studios to be more inclusive and participatory. While there are countless choices available in 3D modeling software (several of them free), the steep learning curve presents a formidable barrier to entry for the general population. To enable a greater number of users to interactively customize digital objects without the use of 3D modeling software, Shapeways, Ponoko, Studio:Ludens (studioludens.com) and others leverage ‘co-creation’ interfaces through which objects are tailored to a set of preferences, parameters, sketches or other input uploaded by the individual. The use of digital fabrication distinguishes these emerging forms of co-creation from other forms of mass customization (discussed later) by treating the user less as a ‘customer’ and more as a member of the studio, encouraging creative input beyond merely selecting from preset features in a drop-down menu. Rather, users interactively define attributes such as shape, proportion, eccentricity and porosity that are not only aesthetic, but may also imbue the object with personal meaning (Figure 5).

With more citizens accessing 3D printing, there exists a corresponding need for printable digital content, and this has given rise to online resources supporting the availability of 3D models. For example, Thingiverse (thingiverse.com), created by the team at Makerbot, is a user-generated online database of free, ready-to-print models that has established itself as a ‘go-to’ place to
both search for and share digital objects. Google has also established a user-generated “3D Warehouse” of models as a complement Google’s family of products that includes SketchUp, a free modelling program billed for ease of use. Developments such as these raise both possibilities and questions. While the concept of “wiki” (thanks largely to Wikipedia) is now a cultural norm, the term remains strongly associated with the sharing of digital information and knowledge. Yet because of the ease of movement between digital and physical representations enabled by digital fabrication, repositories such as Thingiverse and Google 3D Warehouse have the potential to become, effectively, ‘wikis’ of physical things – a concept certainly not yet within the sphere of widespread cultural acceptance. Also, the linking of the Google 3D Warehouse to the location-based capabilities of Google Earth and Google Maps has already resulted in ‘geographically correct’ virtual representations of many buildings and structures. Yet with the increasing interest in smaller object representations encouraged by desktop 3D fabrication, extending the geo-capabilities of 3D Warehouse to its hypothetical limits opens the remarkable possibility of collaborative construction and maintenance of a more complete virtual world, not just at the level of cities, streets and buildings, but also inclusive of the everyday things contained within.

Figure 5: Co-creation option offered by Shapeways (http://www.shapeways.com/creator/about).

2. Citizen Empowerment

The novel spaces for fabrication described above are opening new opportunities for citizen empowerment. Individuals are afforded digital tools, either through affordable 3D printing hardware or streamlined outsourcing, to engage with the act of making directly. Furthermore, this engagement does not typically occur in isolation; rather, digital media also provides the means for sharing the experience of making with others, through both receipt and dissemination of resources.
In our environmental scan, we found that current uses of 3D printing seem to empower people in several distinct ways, including: fashioning custom tools to accomplish specific tasks (Figure 6); extending or connecting disparate forms, systems or structures (Figure 7); visualizing problems that are difficult to picture virtually (Figure 8); expressing their aesthetic taste, individualism, community affiliation or ‘brand’ (Figure 9); and of course, having fun by making their own toys (Figure 10).

We posit that such activities can constitute alternative forms of civic engagement, akin to explicit political forms such as protest or voting. Physical space and objects are expressions of their making and are ultimately manifestations of ideologies, so the act of creating alternative or personalized physical instantiations of those things is to engage with those ideologies, whether consciously or not. While this level of exchange is well established within the doctrines of the fields of art, architecture and design, and also within self-aware Maker communities, the novel spaces for expression and exchange afforded by desktop fabrication are helping to expand opportunities for material forms of civic engagement to the general population.

There are, of course, limits to the extent of these forms of citizen empowerment. Currently, the maximum size of objects that may be 3D printed by popular means is currently at the scale of the handheld (Shapeways specifies its build limit as 49 x 39 x 20 cm; the MakerBot at 96 x 108 x 115 mm), and though larger sizes are available through industrial shops, the cost becomes prohibitively high. This means that someone interested in making their own car bumper, for example, would need to seek out more traditional methods of production such as hand-laid fiberglass. This is not to say that her DIY process would not be digitally mediated (she would likely turn to a site like Instructables.com or the myriad of auto forums for resources); however, she is excluded from the spaces of citizen empowerment that 3D printing currently affords.

Figure 6: Using 3D printing to fashion custom tools to accomplish a specific task. Image courtesy of Mark Ungrin, University of Toronto.
Figure 7: Using 3D printing to extend or connect disparate forms, systems or structures (http://blog.makerbot.com/2010/09/13/duplo-brick-train-track-adapter-by-zydac/).

Figure 8: Using 3D printing to visualize problems that are difficult to picture virtually. Levitation illusion (http://www.thingiverse.com/thing:4246)
Figure 9: Using 3D printing to express aesthetic taste, individualism, community affiliation or ‘brand’ (http://www.shapeways.com/gallery).

Figure 10: Using 3D printing to make ones own toys (http://www.shapeways.com/model/79999/fat_frankie_6cm_.html?gid=mg).
3. The Evolving Consumer

The new forms of citizen empowerment enabled by 3D printing described above are occurring alongside notable shifts in consumer behavior. In the contemporary digital economy, consumers increasingly seek out individualized experiences and expect that products be tailored to their specific needs, wants, contexts and tastes. One illustration of this is what Lessig (2008) terms “Little Brother”, the practice of major online businesses such as Amazon, iTunes and Google to surreptitiously collect data on the buying behavior of their customers and then suggest products and display advertising targeted to that profile. Consumers are now accustomed to individual attention, and the challenge for producers is adequately satisfying that demand.

In terms of manufacturing, Von Hippel (2005) analyzes the shift toward individualized consumerism in terms of the gaps that occur when users’ needs for a technology or product are far more heterogeneous than can be adequately satisfied through mass production. There are multiple ways in which producers can fill this gap. One is, of course, the ‘bespoke’ mode of customization, now reserved for highly specialized and often elitist items. Alternatively, the manufacturer may allow consumers to select from various options late in the production phase, which is common for such features as car color or a condominium’s interior finishes.

While the above forms of customization are consumer-oriented but producer-driven, emerging modes of customization are decidedly consumer-driven (Mowatt, 2005). The “prosumer” (Ritzer & Jurgenson, 2010; Tapscott, 2008) is a model that puts the consumer at the centre of product innovation and has been exerted most visibly on digital products such as software and gaming. Now, aided by DDF, prosumer modes of production are traversing from the digital to the material. “Mass customization” describes the approach of employing industrial rapid prototyping technologies, not just for test pieces, but to manufacture end products with customer-specified features. A current example is NIKEiD (nikeid.nike.com), Nike’s website that allows users to ‘build’ custom shoes with individualized color combinations and personal text insignia (‘iD’). This form of manufacturing is thus able to introduce elements of bespoke tailoring to products normally associated with mass production, but at mitigated price points due to economies of scale. “Co-creation” platforms, discussed earlier, are also variants of mass customization that afford prosumers the opportunity to interactively personalize products in such a way that encourages users to feel more like ‘designers’ of objects rather than passive recipients.

Another prosumer model is that of “lead user innovation” (Von Hippel, 2005), whereby consumers modify mass produced products after purchase to suit their own preferences through hacking and tinkering. Although initially resistant, manufacturers are increasingly willing to release their products with this end in mind, reaping the benefits of increased appeal among DIY consumers as well as gathering ‘free’ ideas generated in the resulting modifications. As discussed earlier, 3D printing is empowering people to fabricate things that serve as viable alternatives to purchasing mass produced consumer goods. Therefore, as personal rapid
prototyping technologies such as 3D printing, scanning and modelling become more accessible, “lead user innovators” will be even more empowered to alter, reverse engineer, and design their own products. This will continue to challenge the viability of traditional modes of production and commercialization to fully satisfy an increasingly atomized consumer base.

Finally, one way that this evolving notion of the ‘consumer as product innovator’ will trouble manufacturers is that the motivation behind many lead user innovators is not necessarily financial. For many, the choice to either “innovate or buy” is not simply a matter of cost-effectiveness (Von Hippel, 2005). Rather, there are alternative rewards that people derive from taking on challenges such as reverse-engineering an appliance or developing their own carrying case for their smart phone. Many DIYers report that they are driven less by financial interests than more by intangible benefits such as opportunities to learn, apply creativity, and share knowledge (Kuznetov & Paulos, 2010). While the implications of nonmonetary gain on the digital economy will be discussed in coming sections, what is notable here is that these developments reflect a shift in consumer attitude away from the notion of material production as an experts-only profit-making enterprise, to a view of making and modifying as experiential learning (a notion that runs parallel to our research work in Critical Making). Through making, consumerism may gain greater awareness of the ideas and issues surrounding production processes - knowledge that is not only intrinsically beneficial, but may also encourage more “Made in Canada” products in the marketplace.

4. New Conceptions of Labour

As the lines between digital and physical production become increasingly blurred, so too do conceptions of labour surrounding them. Questions arise as to what different forms of ‘work’ required to make physical things through digital means, whether that work is skilled or unskilled, and what forms of value are created and exchanged.

As digital information becomes increasingly materialized, established modes of digital production are migrating to the physical realm as well. “Commons-based peer production” (Benkler, 2006), enabled by digital networks, has proven transformative in the digital realm by introducing modes of production of large projects (Linux, Wikipedia, etc.) based on collaboration and the widely distributed contributions by many, as opposed to mass production from a centralized source. In a previous section we described novel spaces for fabrication, all of which are built on the peer production model and rely on user-generated content. As more Makers turn to web-based networks in their making process, they must increasingly rely on faculties more closely associated with the (so-called) ‘knowledge worker’ to deftly navigate and reap full benefit from those spaces. This may include effective information seeking, documenting and presenting projects through digital photographs or CAD renderings, describing work in writing (that strikes the correct ‘tone’), and being wary of the authenticity of digital representation by others. Such skills have not necessarily been a substantial part of Making cultures in the past, which may have been more reliant upon face-to-face interactions (Sennett, 2008).
Many people laud the precision, intricacy and fineness of detail exhibited by a 3D printed object and often express delight that such a thing could be produced “automatically”, without having to do any “work”. This, we believe, is a misconception of digitally mediated practices such as 3D printing. When comparing the labour and expertise involved in making an object by 3D printing versus making the same object by hand, it is incomplete to account only for effort exerted by the maker exclusively at that particular place and time. The process of creating the digital 3D model of that object (whether done visually, haptically or parametrically) requires skilled work, particularly to achieve the standards of “printability” (http://www.shapeways.com/tutorials/things-to-keep-in-mind) demanded of current file formats (STL and Collada). Second, while it is true that actually executing a 3D print turns much of the in-situ effort of materialization over to a machine, the machine itself is the manifestation of knowledge, skills and labour involved in its design, manufacture and maintenance. The 3D printer as a ‘tool’ tends to dissolve and replace certain forms of effort, so long as it operates smoothly, as intended. However, as any MakerBot owner will tell you, when the tool breaks down or behaves in unexpected ways, specialized work is required to return it to its “unproblematic” state (Knorr-Cetina, ). In the most broad framework, to account for the labour involved in making a 3D printed object, one must consider the entire sphere of effort that was exerted by an object’s making, as distributed over space and time as that may be.

The changing notions of labour around DDF have resulted in tensions between newer forms of digitally mediated craftsmanship and ‘traditional’ craft practices. These tensions became very visible recently in a forum debate on Etsy (etsy.com), the online craft marketplace similar in concept to Shapeways and Ponoko but dedicated to “handmade” and “vintage” goods. As was reported by Turner (2010) on Ponoko:

“I think it is time that laser cut products be taken out of the handmade category,” declared a wood worker in the Etsy forums last month. What followed were 37 pages worth of debate on what qualifies as ‘handmade’.

...The handmade movement was never about the rejection of machines. It was about the rejection of mass-production. Unfortunately, the term mass-production became synonymous with ‘machine-made’.

...If people on Etsy have conflicting views about handmade vs digitally fabricated, imagine the confusion of the general public. As the public’s concern about the origin, manufacturing process, and materials of products continues to rise, so will the popularity of handmade goods. It is crucial that digitally fabricated designs be understood with the same positive and respected reputation as the handmade.

...We need a term that focuses not on technology or human touch, but on the individual attention an object receives during its construction. Because it’s with individual attention that today’s maker movement is replacing mass-production. (http://blog.ponoko.com/2010/08/15/missing-the-point-handmade-vs-digitally-fabricated/)
Conflict such as this reveals an increasing ambiguity of the meaning of “craft” caused by increased digital mediation in creating physical things, similar to the contention faced historically by other machine tools that were seen as threats in replacing the ‘authenticity’ of skilled hand work (Hughes & Sinclair, 2010; Sennett, 2008). As digital customization technologies such as 3D printing provide craftspeople more opportunities to serve consumer tastes for goods bearing a unique personal signature, new instantiations and configurations of skill and labour forming around these processes are proving to be disruptive of existing cultural understandings of boundaries, not only between digital/material, but also between “sectors” of work in the contemporary digital economy.

5. Unlocking Latent Entrepreneurship

There exist many ‘amateur inventors’ who harbour innovative ideas for products but find themselves unable to move those designs from conception to market reality. Achieving viable consumer price points for such inventions is typically cost-prohibitive for the individual or micro organization, requiring substantial capital investment to cover steps such as specialized R&D services, industrial rapid prototyping, mass production in large quantities, and corporate distribution. However, new opportunities are emerging for ambitious small-scale inventors to bypass these barriers. With the co-evolution of novel spaces for fabrication, citizen empowerment, the evolving consumer, and new conceptions of labour, there now exists notably greater potential to unlock entrepreneurial ventures that would otherwise lay latent and untapped.

These developments are illustrated by the very recent case study of the “Glif” (Figure 11), a product whose entrance in to the market was made possible in part by 3D printing, while the funding, marketing, manufacturing, and distribution were all enabled to some degree by the emerging dimensions of the digital economy argued previously in this paper.

The Glif was reported in The Economist’s Science and Technology online magazine on October 6, 2010, then with a follow-up piece on November 17, 2010. Two New York industrial designers, Tom Gerhardt and Dan Provost, in their spare time outside of full-time jobs, conceived of an adaptor that allows an iPhone to be mounted to a standard tripod, transforming the shaky handheld smart phone camera into a photography tool suitable for portraiture and time-lapse imagery. This is a prime example of both lead user innovation and ‘extending and connecting disparate systems’ empowered by 3D printing described previously.

While the pair were already familiar with CAD, they leveraged a free beta test version of Rhinoceros 3D (rhino3d.com), illustrating the willingness of a software company to issue their product with the express intention of gathering feedback on desired modifications from testing and appropriation by lead users.

Having developed the design using legally obtained professional-quality software (a hurdle for many who must either purchase licenses or rely on less robust free packages), Gerhardt and
Provost then exploited the *novel space for fabrication* provided by Shapeways, which proved to be convenient, efficient and affordable:

> It took about ten days for Shapeways to "print" each prototype in 3D, and a day later it would be in the designers' hands in New York. Shapeway charges by material volume, so each Glif test cost about $10. They would try out a few variants each time just to meet a $25 minimum (Oct. 6, para. 2)

After the product had been refined to satisfaction through 3D printed prototypes, the pair then obtained an estimate from Protomold (protomold.com), a company that provides “Rapid Injection Molding” services, a process that uses digital fabrication to fast track the making of molds for traditional injection molding (http://www.protomold.com/ProtomoldProcess.aspx). In essence, this form of manufacturing is the application of the principles and techniques of *mass customization* back to manufacturing, with the aim of achieving the high finish quality associated with injection molding but at reduced volume and cost. Factoring the cost of Rapid Injection Molding in their calculations, $10,000 was determined to be the Glif’s initial break-even production figure, based on a retail price of $15 per unit.

Rather than seek this capital from more conventional (centralized) sources such as a bank loan, family loan or credit card, they leveraged *distributed peer production* to raise funds. This was enabled by Kickstarter (kickstarter.com), a website that helps user-uploaded “creative projects” receive crowdsourced financing. On Kickstarter, projects are described in a video “pitch” (as if in a boardroom, though notably less corporate in style) that includes verbal descriptions and visual aids. Posted along with the pitch is the targeted financing amount, of which small portions ($25 to $50) at a time are “pledged” by visitors to the site, in exchange for allotted returns on investment. The pitched project does not go ahead (credit cards are not charged) unless the total financing target is met by a given deadline. In the case of the Glif:

> ...a $20 commitment to the Glif project functions, essentially, as a pre-order for the finished product. For $50, you'll get a 3D printed version right away and a production version later. At $250 you get all that and dinner with the founders in New York City, a video conversation if you can't make it... (Oct. 6, para. 5)

In the first three days, $70,000 was raised; after 30 days, the total reached $137,417, *over thirteen times the initial target*. This unanticipated popularity forced Gerhardt and Provost to scramble and, having met greater economies of scale, switch production from Protomold to more powerful yet conventional injection molding methods. They were also able to outsource packaging (portions of which they had planned to do by hand) to an industrial supplier.

Although the project is still unfolding at the time of writing, to say that the Glif is a success could be an understatement. It is an evocative case study in key concepts implicated by the materialization of digital information as it pertains to the digitally-mediated economy: lead user innovation, extending and connecting disparate systems via 3D printing, using free resources directed to evolving consumers, participating in a novel space for fabrication, using mass
customization strategically, as well as leveraging peer production as a means to financing and marketing. Moreover, perhaps the unlocking of latent entrepreneurship exhibited here is an indicator of things to come, as the digital and the material continue to converge.

![Image](image_url)

**Figure 11:** The Glif, a case study in entrepreneurship empowered by 3D printing (http://www.economist.com/blogs/babbage/2010/10/small-scale_production).

**Implications for Canadian Economic Strategy**

**1. Infrastructure**

In the previous section we described 3D printing technologies in their current context as well as various novel ‘spaces’ within which digitally-mediated fabrication of material things is flourishing. We also outlined how these developments are encouraging increased citizen involvement in the economy through making, prosumption, and micro entrepreneurship. It is notable that the most prominent platforms in this area have not originated in Canada, but rather in Europe (RepRap, Shapeways, Ponoko) and the United States (MakerBot, Thingiverse, Google). While not yet a leader in the area of digital desktop fabrication, Canada should ensure readiness for increased adoption of such systems, spaces and related practices by having in place a solid foundation of supportive infrastructure. As the use of DDF platforms expand throughout this country (and as Canadian innovations sprout in this area), *strong and wide-reaching digital networks* are needed to support the use, connectivity and growth of novel spaces for fabrication. And also importantly, because these spaces involve transforming raw materials to physical products that also must be distributed and exchanged, *physical network infrastructure* that supports efficient transport and shipping of those goods must also be maintained.
2. Literacy

Given the blurring of the boundaries and changing conceptions around labour and skilled work brought about by the convergence of the digital and material domains, it is vital that the education and training of Canada’s workforce keep ahead of these developments in order to maintain a leadership position in the global digital economy. For example, those who work in areas with strong traditions of hand production (craft, for example) will increasingly find themselves using digital knowledge to navigate network forums and online communities. Also, as desktop digital fabrication technologies such as 3D printing proliferate and spread in to homes, schools and small businesses, greater fluency with 3D digital content will be required. Skills must be developed and maintained for such work as: creating and editing 3D models using the wide array of available CAD software and other methods; reading, editing and converting those models amongst an equally wide variety of file formats; managing 3D content databases effectively and efficiently; checking 3D models for integrity, authenticity and ‘3D printability’. At the same time, those who are accustomed to working exclusively within a digital environment may find themselves, to a greater degree, confronting (often problematic) issues of materiality, mechanics and structural assembly as it becomes more common for the digital content they create to be transformed to physical form.

3. Legislation

As mentioned in our opening, we chose 3D printing as a lead indicator of the wider phenomenon of the materialization of information because it heralds a future of citizen participation through creative and inventive making. However, there are foreseeable frictions that arise alongside this future that will likely require legislative consideration and resolution. We spoke earlier of the possibility of online repositories of user-generated 3D models to develop in to “wikis-of-things”, vast online catalogues of digital object representations (ranging from the everyday to the fantastical) that are continually updated, shared, disseminated, freely downloaded, and (re)produced in material form on a desktop 3D printer. In effect, we may soon live in a world in which everyday objects, as with digital software and other media, are collaboratively created and made available as “open source”.

This ability of digital/material representations to be shared so fluidly gives rise to a number of issues with legal ramifications. One could be liability; if someone downloads, prints and installs a crowdsourced 3D model of a shelving bracket, for example, questions arise as to whether the design had been adequately engineered and tested, and who (if anyone) would be liable for harm or damages resulting from structural failure. Legislation currently abounds in the interest of consumer safety in the marketplace, but as more people use 3D printers to fabricate useful objects in lieu of purchasing them from a ‘known source’, the extent of that safety is brought in to question. There also exists the possibility that 3D printing will be used to purposely to circumvent laws in various ways; for example, though a certain jurisdiction might prohibit the import of a certain type of product (a weapon, for example), 3D printing a digital model of that product after electronically transporting it to the jurisdiction easily bypasses efforts to “keep it
off store shelves”. And finally, charged debate around intellectual property (IP) and “fair use” as it pertains to 3D printing is already taking shape, as examined by Bradshaw, Brower and Haufe (2010) as well as Weinberg (2010). With emerging DDF and 3D scanning technologies, designs for physical things will be increasingly duplicated, reverse-engineered, shared and distributed by users - lawfully or otherwise. The widespread appropriation practices already seen with digital music and video will inevitably migrate from virtual environments to the physical, and the ensuing challenges will require decisive policy that strikes the appropriate balance between freedom and constraint.

4. Initiatives

Through our ongoing research into the socioeconomic consequences of the materialization of digital information brought about by such technologies as DDF and 3D printing, a key theme has emerged that should be considered when designing and implementing public initiatives to support a strong digital economy within Canada. That is, we see that “digital media” cannot be considered as a separate and distinct “sector” within the economy per se; rather, digitally-mediated creative work is integrated in highly specific ways into a wide array of production practices, and increasingly, this includes production of the non-digital. No longer does the term “digital media” automatically imply content that is both produced and consumed exclusively in digital form. As shown in this report, digital information (virtual; electronic; ‘bits’) is becoming increasingly porous with physical representation (material; tactile; ‘atoms’). Thus the notions, assumptions and understandings of what constitutes “digital media” (and for that matter, “information technology”) are thrown in to question and demand broader consideration.

Conclusion

In this report we have highlighted a variety of social and technological innovations associated with digital desktop fabrication. One aspect of DDF is clear - it is not merely a new tool or apparatus, but constitutes a new mode of material engagement that both productively and problematically recombines knowledge work, craft, and design in novel ways. Equally, DDF can be considered a social phenomenon, one in which the crowdsourcing, sharing, and ‘mash-up’ practices that are already mainstream around other digital media forms become instantiated in material artifacts. While such moves entail shifts in how objects are designed, produced and evaluated, also disrupted are the professional roles of designers, the relationships between producers and consumers, and the nature of work itself.

While it is early days, it is clear that with DDF, a wider variety of individuals are going to be more engaged in making and that the role and purpose of traditional manufacturers will ultimately change. As noted above, this vision includes such changes as: making, appropriation and modifying as collaborative acts of alternative modes of consumption and civic engagement, rethinking notions of what constitutes hand-made, machine-made, well-crafted or customized products; individuals and micro organizations taking amateur inventions from conception to final market through newly formed spaces and channels.
Finally, it is important to note the need for additional research in this area. DDF as discussed here brings together a number of important socio-technical developments that are meaningful for a variety of avenues of investigation. New forms of community and community exchange, new types of artistic and cultural expression, transformations of the notion of embodiment and materiality, renewed emphasis on the means of production and the idea of a public good – these are all themes for ongoing social science and humanities research. We will continue to work in this area and hope this report provides some initial economic, social and cultural insight on this emergent phenomenon of the materialization of digital information.
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