

3D Printing

Economic and Public Policy Implications



Maureen Kilkenny

3D PRINTING

- ECONOMIC AND PUBLIC POLICY IMPLICATIONS

Maureen Kilkenny



NÄRINGSPOLITISKT
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Förord

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Näringspolitiskt forums sjätte rapport beskriver globala ekonomiska effekter av 3D-printing, tekniken och framtida användningsområden samt belyser frågor som: Vad är 3D-printing? Hur utvecklas tekniken? Innebär 3D-printing en "tredje industriell revolution"? Vilka är möjligheterna och riskerna? Hur påverkar 3D-printing lokaliseringen av ekonomisk aktivitet? Vilka policyimplikationer följer?

3D-printing är en revolutionerande teknologi som har möjliggjort tillverkning som vi tidigare inte kunde föreställa oss. Genom kraften som finns i IT och internet kan nu användare och konsumenter vara sina egna producenter. Tekniken minimerar spill, sparar resurser och återanvänder material. Precis som med alla revolutionerande innovationer utmanas företag att anpassa sig eller använda sig av tekniken. Revolutionerande innovationer introduceras aldrig utan ett visst motstånd men på sikt, med hjälp av forskning, utveckling och utbildning, kan 3D-printing innebära stora vinster för samhället.

Rapporten är författad av Maureen Kilkeny, Senior Fellow vid National Center for Food and Agricultural Policy, USA. Författaren svarar för de slutsatser och den analys som presenteras. Ekonomiskt stöd har bl a erhållits från PwC.

Stockholm i januari 2014

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Innehåll

FÖRORD	3
SAMMANFATTNING	7
INTRODUCTION	11
1. WHAT IS “3D PRINTING”?	13
1.1 HOW 3D PRINTING DEVELOPED	14
1.2 HOW IT WORKS	15
2. ECONOMIC IMPLICATIONS	19
2.1 OPPORTUNITIES FOR CONSUMERS	19
2.3 THE THIRD INDUSTRIAL REVOLUTION?	22
2.4 EFFECTS ON THE LOCATION OF ECONOMIC ACTIVITY	23
3. POLICY IMPLICATIONS	29
3.1 INTELLECTUAL PROPERTY POLICY	31
3.2 RESEARCH	33
3.3 ECONOMIC DEVELOPMENT SPENDING ON ADDITIVE MANUFACTURING	38
3.4 EDUCATION	38
SUMMARY	42
ABOUT THE AUTHOR	42
REFERENCES	43

Sammanfattning

3D-printing är en revolutionerande teknologi som har möjliggjort tillverkning som vi tidigare inte kunde föreställa oss. Genom kraften som finns i IT och internet kan nu användare och konsumenterna vara sina egna producenter. Tekniken minimerar spill, sparar resurser och återanvänder material. Precis som med alla revolutionerande innovationer utmanas företag att anpassa sig eller att använda sig av tekniken. Revolutionerande innovationer introduceras aldrig utan ett visst motstånd men på sikt, med hjälp av forskning, utveckling och utbildning, kan 3D-printing innebära stora vinster för samhället.

3D-printing: Ekonomiska och politiska implikationer

Rapporten kartlägger ekonomiska effekter av 3D-printing och associerade policyförändringar. Diskussionen rör sig kring frågor som: Vad är 3D-printing? Hur utvecklas tekniken? Innebär 3D-printing en "tredje industriell revolution"? Vilka är möjligheterna och riskerna? Hur påverkar detta lokaliseringen av ekonomisk aktivitet? Vilka policyimplikationer följer?

Rapporten refererar till dokument och videos som beskriver 3D-printingsteknologin och branschen. Dessa finns tillgängliga online. Genom att applicera ekonomisk teori förutses möjliga effekter av 3D-printing för olika sektorer, skala och lokalisering av ekonomiska aktiviteter. Rapporten samlar även åsikter från experter som har specialiserat sig på 3D-printing och lyfter fram exempel på bra offentliga initiativ för att stärka konkurrens, uppmuntra innovation och säkerställa kompetens inom 3D-sektorn.

Vad är 3D-printing?

3D-printing är det folkliga namnet för *additiv tillverkning*, en teknologi genom vilken solida objekt tillverkas genom deponering och/eller sammansättning av material, lager för lager.

Tills nu har främst *subtraherande tillverkningsmetoder*, så som formgjutning, bearbetning, beskärning etc, använts för att tillverka objekt (och delar av objekt). Den metoden inkluderar även sammansättning för att färdigställa en produkt. I 3D-framtiden kommer väldigt komplexa objekt att kunna tillverkas, direkt och redan sammansatta, med additiv tillverkning.

Det finns nu ett urval av additiva tillverkningsmetoder för industriella såväl som individuella användare. Industrier har använt additiv tillverkning för att tillverka termoplastiska prototyper i ett par årtionden. Nu finns små, billiga 3D-skrivare för hemmabruk som kan tillverka plastföremål med egen design.

Dagens additiva tillverkningsplattformar och verktyg kan, utöver plastföremål, producera allt som görs med subtraherande processer och mer därtill. Additiva tillverkare kan producera objekt av metall, glas, keramik, ätbara ingredienser, cellulosa eller papper, levande celler, mänsklig vävnad, och många andra material. De kan tillverka enkla eller komplexa slutprodukter, exakta och detaljerade på en nanoskala. 3D-skrivare kan även tillverka ytterligare 3D-skrivare (t ex RepRap). Även om de flesta 3D-skrivare enbart använder ett material så har forskare nyligen utvecklat teknologi för att tillverka produkter av en kombination av material.

Hur det fungerar

Den grundläggande idén om 3D-printing kan förklaras genom en analogi. Tänk på en bläckstråleskrivare som kopplas till en dator för att producera utskrifter från datafiler. I likhet med att skriva ut ett dokument kräver en 3D-skrivare (1) en datafil, (2) ett "bläck", (3) en "bläckstråle" och (4) en yta där lagren av "bläck" hamnar för att skriva ut ett objekt.

För 3D-printing är den första datafilen som krävs en virtuell "ritning" av objektet som ska tillverkas. Denna kan skapas antingen genom designmjukvara (computer aided design – CAD) såsom "Google SketchUp" (gratis online) eller genom att skanna av ett föremål och på så sätt skapa 3D-bilden digitalt. Den andra sortens datafil som krävs skapas ur den digitala ritningen. Mjukvara definierar oändligt smala digitala tvärsnitt eller lager av det virtuellt uppritade föremålet och dokumenterar tvärsnittet i ett *.stl-format. *.stl-filen innehåller en guide till det digitala tvärsnittet som behövs för att skriva ut varje lager av det objekt som tillverkas.

Möjligheter för konsumenter

3D-printing erbjuder helt nya ekonomiska möjligheter för både företag och konsumenter. Genom att använda billiga konsumentanpassade 3D-skrivare kan individer skapa och tillverka helt nya saker med egen design, kopiera existerande föremål som de kunde ha köpt och ersätta saker som inte längre finns tillgängliga. Möjligheten att tillverka saker med egen design och möjligheten att tillverka ersättningar för sådant som inte längre finns tillgängligt är helt nya nyttor. 3D-printing möjliggör prisvärd och helt individanpassad design. Det uppmuntrar individuell kreativitet och innovation och möjliggör ersättning av föremål och delar av föremål som inte längre tillverkas eller finns i lager. Dessa nyttor är lika revolutionerande som de utlovade möjligheterna med persondatorer och universell internetuppkoppling.

Forskning har visat att det är ekonomiskt för konsumenter att äga och använda en konsumentanpassad 3D-skrivare. Wittbrodt, et al. (2013) beräknade konsumentkostnaden för att köpa en RepRap 3D-skrivare, det termoplastiska råmaterialet och alternativkostnaden för konsumentens tid som krävs för tillverkning hemma med RepRap 3D-skrivaren. Med antagandet att ett hushåll producerade 20 specifika produkter på ett år, uppskattade de "intjänade kostnader genom uteblivet köp" till

mellan \$300 och \$2000 per år, en återbetalningstid mellan fyra månader och två år och en avkastning på investeringarna på mellan 40 % och 200 %. Således är redan 3D-printing ett ekonomiskt attraktivt alternativ till att köpa massproducerade varor. Ytterligare teknologisk utveckling kommer bara att öka dess dragningskraft.

Möjligheter för producenter

Tillverkare utvecklade 3D-printing/additiv tillverkning av goda skäl. Genom additiva tekniker skapades vinster genom reduktion av tiden fram till marknadsintroduktion (snabba prototyper), från lägre produktionskostnader (lite spill och snabb reparation), minskade monteringskostnader (eftersom invecklade produkter kan skrivas ut färdigmonterade) och reducerade lagerkostnader (eftersom produkter kan produceras vid efterfrågan). Additiv tillverkning gör det möjligt att producera komplexa, färdigmonterade objekt som inte kan tillverkas på annat sätt. Tekniken sparar även in på arbetskraft och materialanvändning.

3D-printing har även framhållits som sporren för en tredje industriell revolution eftersom tekniken gör det möjligt att producera småskaligt, med större flexibilitet och mindre arbetskraft med bibehållen eller ökad ekonomisk vinst. Cirkeln är nästan sluten, trenden går från massproduktion till en mer individanpassad produktion och detta kan innebära att en del av jobben inom produktionssektorn återvänder till länder som sedan länge i huvudsak förlagt produktion i länder där det är billigare.

Effekter på lokalisering av ekonomisk aktivitet

Effekterna av additiv tillverkning/3D-printing på lokalisering av ekonomisk aktivitet följer teknologins särskiljande drag. Dessa kan sammanfattas som följer:

Väldigt låga hinder för marknadstillträde: 3D-skrivare kostar mellan \$300–\$300,000 USD.

Flexibilitet: En maskin kan producera produkter med obegränsad variation.

Effektivitet: Väldigt lågt råmaterialsvin, mindre monteringsarbete per produkt.

Snabb tillverkning av enstaka produkter: från design till färdig produkt inom timmar snarare än månader; reparationer på plats inom timmar snarare än veckor eller månader; behovet av att montera komplicerade produkter minskar eller elimineras helt.

Billig tillverkning av enstaka produkter: kostnad = vikt och ”komplicerat är gratis”.

Relativt dyr massproduktion: Ingen eller liten intern skalavkastning.

Överlägsen kvalitet: Lättare, starkare, detaljerat på nano-skala, individanpassat.

Väldigt låga logistik- och transportkostnader: Tillverkning vid behov vid användnings- eller konsumtionsstället. Detta innebär inget produktlager eller frakt (materiallagring och fraktkostnader kommer dock att bestå).

Open source: Design och mjukvara finns tillgängligt gratis på internet. De ekonomiska effekterna på omfattning, skala och lokalisering av ekonomisk aktivitet, arbetstillfällen och handel kan dras av från dessa utmärkande drag.

Policyeffekter

Många av de vinster och kostnader som associeras med framväxten av additiv tillverkning speglas av förändringar i marknadspriser. Det skulle kunna tolkas som att det inte finns ett behov av ny policy men det finns vissa områden där policyöversyn för 3D-printing är motiverat. Dessa områden är immaterialrätt, forskning och utbildning. Det finns en risk att etablerade företag kommer att försöka utöka immateriella rättigheter för att slippa anpassa sig. Detta skulle innebära lägre innovation än optimalt. Det finns utrymme och möjlighet att uppmuntra mer forskning och utveckling än marknaden stödjer och det finns ett behov av att erbjuda ytterligare utbildning för att förbereda våra arbetsplatser och arbetstagare för de nya verksamhetsområden som möjliggörs genom 3D-printing.

Introduction

An iPhone case, a hearing aid, a section of the landing gear for an Airbus, a hamburger patty, an exotic dancer's gown...what do these things have in common? They were all made by 3D printers.

This is a report about implications of "3D printing" for the mix and location of economic activity and the associated public policy challenges. It addresses these questions: What is 3D printing? How is it being developed? What are the opportunities and threats? Is this really the "third industrial revolution"? How might it affect the location of economic activity? What are the implications for public policy?

The report references documents and videos that are also available online to describe 3D printing technology and industry. Economic theory is applied to predict the possible implications of 3D printing for the sectoral mix, scales, and locations of economic activity. The opinions of pundits specializing in 3D printing and intellectual property protection are also summarized. Exemplary public initiatives in various countries to enhance competition, encourage innovation, and train people for 3D work and marketplaces are highlighted.

What is “3D printing”?

3D printing is the popular name for *additive manufacturing*, a technology by which solid objects are fabricated by the deposition and/or fusing of material, layer by layer.

Until now, *subtractive manufacturing* techniques such as die casting, tooling, cutting, etc., have been used to make things (and parts of things). Parts are also assembled to produce finished items. In the 3D future, even very complex objects will be fabricated all at once, already assembled, using additive manufacturing (Fachot, 2011).

There are now a variety of additive manufacturing techniques for industrial use and for consumer use. Industries have been using additive manufacturing to fabricate thermoplastic prototypes for a couple of decades. Consumers can now obtain low-cost, counter-top-sized 3D printer ‘appliances’ they can use at home to fabricate plastic items of their own design.

Today’s industrial additive manufacturing platforms and tools can produce not only plastic prototypes, but anything made using subtractive processes, as well as some things that could not have been made before. Additive manufacturers can fabricate in metal, glass, ceramic, edible ingredients, cellulose or paper, living cells, human tissue, and many other materials. They can make simple or complex final products, precise and detailed at the nanoscale. 3D printers can even fabricate more 3D printers (e.g., RepRap). Although most 3D printers fabricate in just one medium, recently researchers have developed the technology to fabricate products from combinations of materials as well (Vaezi, et al, 2013; and Stratasys, at http://www.stratasys.com/~media/Main/Secure/White%20Papers/~Rebranded/SSYS_WP_10_reasons_multi-material_3d_printing_is_better.pdf).

1.1 How 3D Printing Developed

The basic technology was developed in the early 1980s in research laboratories in the United States, Europe, and Japan for industrial use. Charles Hull, the American co-founder, executive vice president and chief technology officer of 3D Systems, is generally credited as the inventor. In 1984 he patented a "system for generating three-dimensional objects by creating a cross-sectional pattern of the object to be formed" (Hull, 1984).

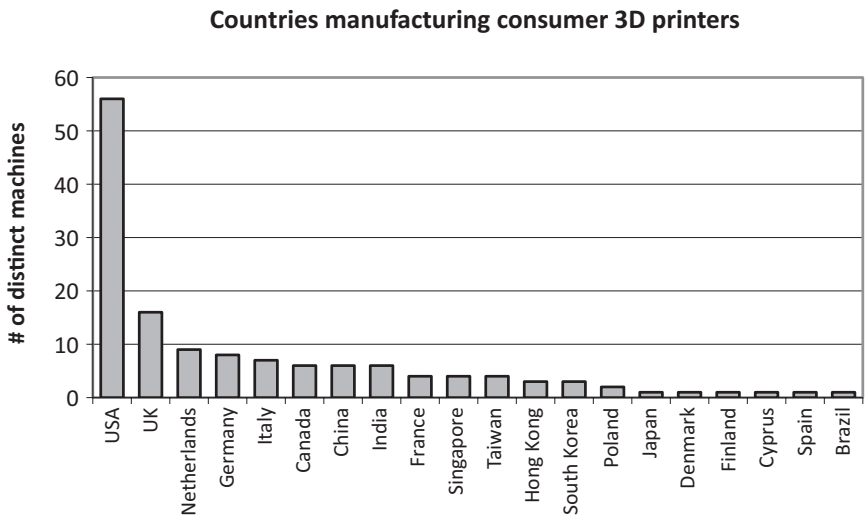
As noted earlier, although 3D printing was originally employed to create prototypes, the technology is now used around the world to produce final products as well. Additive manufacturing techniques are now employed by auto and aerospace manufacturers, appliance repairmen, prosthetic suppliers, medical researchers, artists, architects, clothiers, food manufacturers, utility companies and other industries. Professional designers as well as individual enthusiasts contribute open-source product designs. All types of "makers" are pushing the development of 3D printing hardware and software.

Industry drives the majority of the demand for 3D printing. Medical device, hearing aid, implant, and prosthetic producers have embraced the technology (Excell and Nathan, 2010). The aerospace and automotive industries alone accounted for 20% of the 3D printing industry's multi-billion dollar revenue in 2011 (King, 2012). The retail market for consumer appliance-type 3D printers is tiny in comparison. The New York Times (September, 2013) reported that 68,000 consumer appliance-type 3D printers have been sold. Competition in that market, however, has grown rapidly since the first patents expired in the late 1990s. Prices have fallen dramatically, and explosive growth is anticipated as more key patents expire (Mims, 2013).

In 2009 Makerbot® 3D printer appliances sold for about \$22,000 USD. In the four years since, the retail price of a Makerbot® has fallen to one-tenth (~\$2,200), and competitors' 3D printers are available for as low as \$300 USD (3ders.org). In June 2013 The Economist magazine reported that since they were introduced in 2009, over 22,000 Makerbot® 3D printers for consumer use had been sold. Half of those have been sold in the latest year alone.

Young startup firms in the United States currently lead the world in the design, manufacture, and sales of 3D printers for consumer use (3ders.org). Yet, as of autumn 2013, at least 76 distinct companies manufacture and sell retail consumer 3D printers for small businesses, hobbyists, and households. Located in at least 21 countries around the world (Figure 1), these companies include the makers of RepRap® 3D printers that can replicate themselves; the Dutch supplier of the Ultimaker® 3D printer, the South Carolina USA firm 3D Systems where the inventor Charles Hull is an executive VP, and the US + Israeli firm Stratasys. Stratasys commercialized Scott Crumb's fused deposition modeling invention. It has also recently acquired the leading consumer 3D printer maker, MakerBot Industries of Brooklyn, New York.

FIGURE 1. Producers of Consumer 3D Printers around the World



Source: Data source: <http://www.3ders.org/pricecompare/3dprinters/?o=Manufacturer> (as of 9/2013)

1.2 How it works

The basic idea of 3D printing may be explained by analogy to its namesake. Think of the inkjet printer that people connect to their computers to produce printed pages from computer files. Analogous to printing a document, to produce an object a 3D printer requires (1) a data file, (2) an “ink,” (3) an “inkjet,” and (4) a surface upon which to layer the ‘ink.’

In 3D printing the first data file required is a virtual ‘blueprint’ of the object to be fabricated. This can be created either using computer aided design (CAD) software, such as “Google SketchUp” (free online) or by scanning the item and digitally recording the 3D image. The second type of data file required is generated from that virtual blueprint. Software defines infinitesimally thin digital cross-sections or layers of the virtually blueprinted item, and records the cross-sections in an *.stl format file. The *.stl data file containing the digital cross-sections guides the printing of each layer of the object to be fabricated.

A variety of “inks” and associated “inkjet” 3D printing processes exist today. Table 1 summarizes the major technologies in use as of August, 2013: the mode or method, the name of the process, acronym, and the types of “ink” or material that the system “prints.” The most common FDM and SLS processes are described subsequently in more detail.

Fused deposition modeling (FDM) is the technique applied by most customer appliance-style 3D printers. FDM was developed by Scott Crump in the late 1980s and commercialized by Stratasys in 1990. Thermoplastic, usually in filament form,

is melted in a nozzle head and extruded in layers as thin as 0.0125 mm (12.5 micrometers). It hardens immediately after extrusion. Thermoplastics such as polylactic acid (PLA), acrylonitrile butadiene styrene (ABS), polycarbonate (PC), or high density polyethylene (HDPE), as well as recycled plastics can be used.

Compared to fabricating single objects using traditional manufacturing techniques, the process is very fast-- which is why it is called ‘rapid prototyping.’ It currently takes about half a day to 3D print an item about the size of a loaf of bread. However, the size of the item that can be fabricated is limited by the size of the 3D printer, typically under ~60cm3.

Table 1. Additive Manufacturing technologies

Mode	Technology	Acronym	thermoplastic	photopolymer	edible materials	biological cells	titanium alloys	cobalt-chrome alloys	stainless steel	aluminum	eutectic alloys	metal, nec	cermanic
Extrusion	Fused deposition modeling	FDM	X		X	X					X		
Fusing powder or granules	Selective laser sinte- ring	SLS	X				X	X	X	X		X	X
	Direct metal laser sintering	DMLS					X	X	X	X		X	
Fusing gel	Stereolit- hography	SLA		X									
Melting wire in a vacuum	Electron Beam Free Form Fa- brication	EBF3					X	X	X	X		X	
	Electron beam melting	EBM					X						

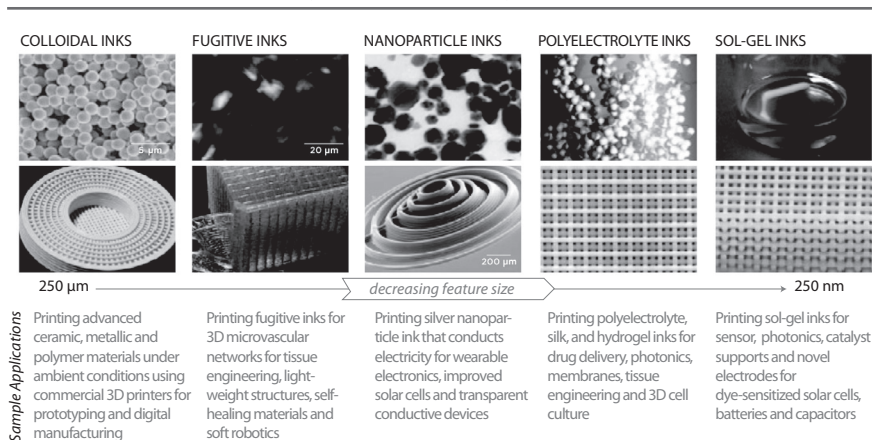
Among the hundreds of videos available online, these short videos provide particularly nice introductions to fused deposition modeling (FDM) 3D printing:

1) “Introduction to 3D Printers: The Promise and Pitfalls of Desktop Manufacturing” March 27, 2013 <http://youtu.be/hTCIO0oLP8> (~28 minutes), and

2) “Will 3D Printing Change the World?” Feb 28, 2013 by PBS Digital Studios, <http://youtu.be/X5AZzOw7FwA> (~7 minutes)

Other types of “inks” used in industrial 3D printing not listed in Table 1 are summarized in Figure 2, excerpted from the 2012 report “3D Printing and the Future of Manufacturing” by Vivek Srinivasan and Jarrod Bassan (2012) for the Computer Sciences Corporation.

FIGURE 2. Custom “inks” designed for 3D printing



Source: http://assets1.csc.com/innovation/downloads/LEF_20123DPrinting.pdf

The technique widely used by industry to fabricate metal objects involves the selective fusing of powdered metal. The main technologies are selective laser sintering (SLS) and direct metal laser sintering (DMLS). In SLS, a thin layer of powdered metal is laid on a platform. A laser beam is applied to fuse the areas of the powder layer comprising a single cross-section of the object. For each subsequent cross-section, another layer of powdered metal is deposited and another round of laser sintering is applied, repeating until the object is complete.

Selective Laser Sintering (SLS) was developed and patented by Dr. Carl Deckard and Dr. Joseph Beaman at the University of Texas at Austin (Deckard, 1989), with funding from the United States Department of Defense Advanced Research Projects Agency (DARPA).

This online video provides a nice introduction to industrial 3D printing with metal and other materials: “Ready for Printing – 3D Printing at Siemens” July 29, 2013 (~7 minutes) <http://youtu.be/VyEgbyNg0Q8>.

Economic Implications

2.1 Opportunities for Consumers

3D printing offers unprecedented economic opportunities for both businesses and consumers. Consider the benefits to consumers. Using low-cost consumer appliance-type 3D printers individuals can create and fabricate entirely new things of their own design, replicate versions of existing items they could have purchased, and replace things that are no longer available. The opportunity to make items of one's own design and the opportunity to fabricate out-of-stock replacements are unprecedented benefits. 3D printing enables affordable and completely individualized customization. It encourages individual creativity and innovation. It makes it possible to replace discontinued or out-of-stock items or parts. Those benefits are as revolutionary as the benefits promised by personal computers and universal internet access.

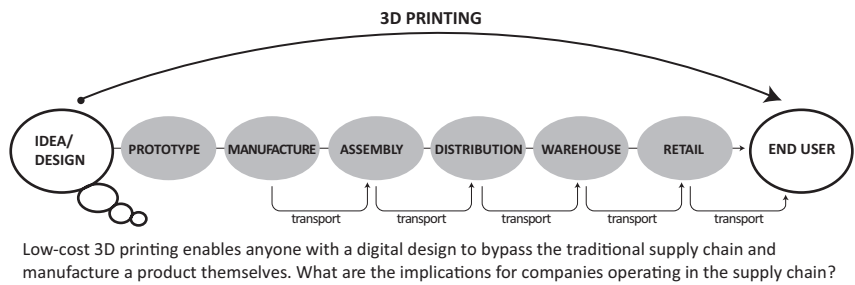
In this online video a Swedish man shows the variety of things he's made with his 3D printer: "One Year with My 3D Printer – Super Hobbyist Demo & Details" Dec 18, 2012 <http://youtu.be/HDdGUEetvHY> (~8 minutes)

Research has shown that owning and operating a consumer appliance-type 3D printer is also economical (good value) for consumers. Wittbrodt, et al. (2013) prepared a life-cycle analysis of home 3D printing to determine its economic viability. They calculated the consumer costs of purchasing a RepRap® 3D printer, the thermo-plastic feedstock, and the opportunity cost of the consumer's time to fabricate various items for the home using the RepRap® 3D printer. Assuming that a household would fabricate just 20 typical products a year, they estimated "avoided purchase cost savings" of \$300 to \$2000 per year, a payback time between four months to two years, and a return on the investment of 40% to 200%. Thus 3D printing is already an economically attractive alternative to purchasing mass-produced items. Further technological progress will increase its attractiveness.

Not everyone wants to make their own things. But a significant portion may. For example, Retro Company, a specialty retailer of reproduction antique home furnishings (door handles, lanterns, etc) estimates that 60% of its customers will have the capacity to 3D print their own alternatives to their products by the year 2020 (reported by Srinivasan and Bassan, 2012). The rapid growth in the numbers of consumer appliance-type 3D printer purchases since 2009 also indicates the potential size of the portion who want to be “makers”.

Obviously, because of the low cost of 3D printing, anyone anywhere can become a “manufacturer.” As Bre Pettis, CEO of Makerbot in Pettis (2012) pointed out, ‘customers can become manufacturers’ (Figure 3, from Srinivasan and Bassan, 2012). Established manufacturers will be challenged by that competition to both adopt additive manufacturing on their own shop floors and to develop new business models to retain clients.

FIGURE 3. Consumers as Manufacturers



Source: http://assets1.csc.com/innovation/downloads/LEF_20123DPrinting.pdf

2.2 Opportunities for Producers

Manufacturers developed 3D printing/additive manufacturing for good reasons. Using additive techniques they benefit from the reductions in time to market (rapid prototyping), from production cost reductions (low waste and rapid repair), reduced assembly costs (because complex items can be printed already assembled), and reduced inventory costs (because items can be produced on demand). Additive manufacturing allows them to produce complex, preassembled items that cannot be fabricated any other way. It is also labor and material conserving:

“...Able to build models of mind-boggling geometrical complexity from scratch, they dispense with tooling costs. Plus, there’s very little waste. While traditional ‘subtractive’ manufacturing processes often remove up to 95 per cent of the raw material to arrive at a finished component, additive machines only use

the material they need to make the part. "This technology is almost as close to Nirvana as you're ever going to get." (Prof Richard Hague, AMRG)
"...Even without changing the component at all, additive-layer manufacturing (ALM) means that you're extracting 26 times less material out of the ground to make it," said Johns. And this isn't just a matter of material saving. John Piper, engineering consultant on the Bloodhound Supersonic Car project, which has been working with Johns' team, outlined some of the other benefits. 'Machining starts with a block of aluminium or titanium,' he said. 'There's a huge investment in the process to make that billet: heat-treating it, rolling it, reheating it, cutting it up and bringing it to the machine. Add the issue of making the tooling and you're looking at very significant process input, even before you start machining. And with conventional machining, most of that expensively produced material gets chucked into the swarf bucket.'"

Both excerpts from Excell and Nathan (2010) <http://www.theengineer.co.uk/in-depth/the-big-story/the-rise-of-additive-manufacturing/1002560.article#ixzz2gPELdsOi>

Perhaps the biggest change that additive manufacturing might engender is in the way that engineers work. According to Chris Turner, additive manufacturing engineer at the European Aeronautic Defence and Space Company (EADS) Innovation Works Centre for Additive Layer Manufacturing (CALM) near Bristol, it "restores the link between designer and manufacturer that dates back to the days of the industrial revolution and the very first factories" (Excell and Nathan, 2010).

The ability to customize products is not just a boon to do-it-yourself 'makers.' Additive manufacturing enables zero-cost product line switching and individualization also by producers. The cost savings have been particularly valuable to medical supply companies:

"...Reeves claimed that the biggest spur for adoption of the technology in the medical world is not customisation, but economics. 'Most of the interest in using metal-based additives for implants is currently for affordable healthcare,' he said. 'For instance, the traditional manufacturing process for an acetabular cup [the socket of the hip joint] is a drop forging that is CNC machined and then has a coating put on it for the bone to grow in to the coating. With additive, because we're building in particles, we can change the density and make the surface of the implant porous so you don't have to go through a secondary downstream ceramic operation. It's a lot cheaper.'" (Excell and Nathan, 2010)
<http://www.theengineer.co.uk/in-depth/the-big-story/the-rise-of-additive-manufacturing/1002560.article#ixzz2gPDWf83i>

Additive manufacturing/3D printing promises unprecedented benefits for consumers and businesses. There are infinite opportunities for further invention and innovation.

The things we make, the way we make them, the people who make them, and where they are made will change. How revolutionary might the changes be?

2.3 The Third Industrial Revolution?

In the 19th century the first industrial revolution followed the introduction of mechanical power to replace human or animal power. The concomitant dramatic increase in productivity led to significant changes in the mix, increases in the scale of productive activity, and improved quality of life. It enabled urbanization, empowered a rising middle-class, changed the established social order, altered the pattern and level of commerce and world trade, accelerated resource use, impacted on environmental quality, and so on. The second industrial revolution followed the introduction of assembly-line production in the early 20th century. The concomitant dramatic increase in productivity fueled even more urbanization, grew the working class, inspired new workplace and social relations, led to significant market widening and deepening, further extended human longevity and improved our quality of life, and continued to affect commerce and world trade.

Before the two industrial revolutions, nine in ten people lived on the land and farmed. Ten percent lived in cities, where they fabricated tools for farming, building, warfare, transport, and daily life. By the turn of the 21st century the rural and urban portions had switched. Today eight of ten live in cities. Less than one in ten farms, and less than two in ten fabricate things. Two-thirds to three quarters of people today work at providing services to other people, in both rural and urban areas.

Mass production manufacturing occurs where the factor of production used relatively intensively – labour – is relatively abundant, such as China. Today's geography of manufacturing continues to exemplify the location pattern hypothesized by the neoclassical economic theory of international specialization and trade known as the “factor proportions” model. According to the ‘factor proportions’ model, countries tend to specialize in and export the goods that employ their relatively abundant factors relatively intensively. Where factors of production are relatively more abundant, they are less expensive. Thus the locations implied by the factor proportions model also tend to maximize profit; abstracting from the costs of transporting input materials and products to markets. Furthermore, because different factors of product are important over the life of a product, also called the “product cycle,” and because locations are relatively abundant in different factors, industries tend to relocate as they age.

For example, in the U.S., personal computers were first invented where the innovators happened to live: in South Dakota, Texas, California, or Massachusetts, ... The start-ups did not stay where they were ‘born.’ They opened R&D labs where the venture capital they needed at the time was (is) relatively abundant: high-income metropolitan areas like what became: “Silicon Valley.” Next, they opened the early production facilities in nearby nonmetropolitan areas, because although it required

more floor space, they still needed engineers, designers, and skilled labour, and those factors are relatively abundant there. Finally, for products that survived to maturity, commodity mass production relocated to Asia, because that is where regular workers are relatively abundant. Furthermore, it minimizes transport costs to the fastest growing markets, both because Asian markets are huge and growing, and also because water-borne transport is 100 times cheaper than overland.

How might 3D printing affect this pattern? 3D printing has been touted as the impetus for a third industrial revolution:

“As manufacturing goes digital, a third great change is now gathering pace. It will allow things to be made economically in much smaller numbers, more flexibly and with a much lower input of labour, thanks to new materials, completely new processes such as 3D printing, easy-to-use robots and new collaborative manufacturing services available online. The wheel is almost coming full circle, turning away from mass manufacturing and towards much more individualised production. And that in turn could bring some of the jobs back to rich countries that long ago lost them to the emerging world.” Excerpted from A Third Industrial Revolution, Special report: Manufacturing and Innovation, The Economist April 21, 2012.

There is no doubt that 3D printing is productivity-enhancing. There is also no doubt that it will enable further market widening, by which we mean it will enable the production of entirely new things—such as prosthetic limbs, nano-scale detailed items, and complex structures that cannot even be made any other way. Less obvious are the likely effects of 3D printing on urbanization and trade.

2.4 Effects on the Location of Economic Activity

The effects of additive manufacturing/3D printing on the location of economic activity follow from the salient features of the technology. These can be summarized as follows (see also Srinivasan and Bassan, 2012):

Very low entry barriers: 3D printers cost \$300 – \$300,000 USD

Flexible: one machine can produce unlimited varieties of products

Efficient: very low raw material waste, less assembly labor per item

Rapid single item production: from design to fabricated item in hours rather than months; repairs conducted in-place in hours rather than weeks or months; the need to assemble even complex items reduced or avoided altogether

Inexpensive single item production: cost=weight, and “complexity is free”

Relatively expensive mass production: few or no internal returns to scale

Superior quality: lighter, stronger, detailed to nano-scale precision, individualized

Very low logistics and transport costs: fabrication on demand at the place of use or consumption means no need for inventories, product storage or shipping (material storage and shipping costs, however, will remain)

Open source: designs and software are freely available on the internet

The economic implications for the scope, scale, mix and locations of sectoral economic activity, employment, and trade can be deduced from these key characteristics.

Given these characteristics, spatial economic theory (as well as the neoclassical theory of international trade discussed earlier) suggests at least two competing hypotheses about how 3D printing will affect the location, scale, and mix of regional economic activity. The first follows from classic economic geography, which posits that the within-country spatial patterns of population and employment are driven by businesses choosing locations and scales that minimize transport costs and maximize returns to (internal) scale. (An internal scale economy is the reduction in per unit costs as expenses are spread over more and more units of output of an establishment or a firm.)

From this perspective, the low sunk costs of additive manufacturing/3D printing and the trend increase in transport costs (fuel costs) will lead over time to within-region spatial dispersion of goods production at smaller scale. For example, even TVs and refrigerators might be made-to-order using additive manufacturing hubs in each community, from recycled metals and materials.

Furthermore, because of the product-line flexibility of additive manufacturing, these small hubs will supply a wide variety of consumer durables and nondurables where customers reside and recyclable or raw materials are available, at the scales appropriate to their local markets. Spatially dispersed, small scale additive manufacturing minimizes transport costs at the expense of few, if any, foregone returns to scale. This means that there will be fewer large manufacturing establishments, and many more much smaller ones (see also Anderson, 2012). Goods producing firms that operate spatially dispersed, smaller scale additive manufacturing establishments may profit more than firms that do not.

Thus, classic economic geography is the logic behind the claims in the New York Times (Vance, 2010) and the April 2012 Economist article (excerpted above) that 3D printing “could bring some of the jobs back to rich countries that long ago lost them to the emerging world.” The powerful ‘re-shoring’ forces will also have significant implications for regional labor markets and employment by occupation. There would be an increase in the number of additive manufacturing/goods producing and 3D renovation and repair jobs, as well as material recycling jobs, notably also in the less accessible and lower population density (rural) regions of developed as well as developing countries (Pearce, et al 2010). There will also be a decrease in the number of jobs in traditional/subtractive manufacturing, warehousing, trucking and transport, and retailing industries.

Srinivasan and Bassan’s (2012) summary of the effects of 3D printing on various economic sectors is shown in Figure 4 below, excerpted from their online report.

FIGURE 4. Sectoral Impacts of 3D printing

	1990- 2000s	2010 and beyond		2030 +
DEFENSE & AEROSPACE	weight reduction on aircraft	entire aircraft wings printed	3D printers for use in outer space and on battle-fields	entire aircraft printed
	niche and low volume parts			self-healing military vehicles
AUTOMOTIVE	rapid design & prototyping	light-weight & specialist components in some vehicles		innovative vehicles enabled by 3D printing
	after-market customization & vehicle restoration		crowd-sourced vehicle design & manufacture	
HEALTHCARE	prosthetics, dental & bone implants medicine	medical instruments	3D printed tissue and simple organs for transplants	nano-scale
	hearing aids	pharmaceuticals production		complex 3D printed organs
CONSUMER & RETAIL	novelty items	customized products	innovative in-store experiences & marketing	co-creation with customers
		popular DIY & “maker” communities		Grandparents buy 3D printers for themselves
GENERAL MANUFACTURING	rapid prototyping & product design	innovative products with 3D printed components		retooling & reskilling
	low volume specialist manufacturing	3D printed embedded electronics	3D printing coexists with traditional mnf	rows of 3D printers on factory floors
SUPPLY CHAIN	printing bureaus serve niche markets	recycling used for feedstocks	off-shoring is challenged	reorganized business models
		rising demand for powdered titanium & other feedstocks		direct supply: ship the design, not the product
GENERAL ECONOMY	intellectual property issues debated	Boom of start-ups enabled by 3D printing		capital real-locates to new industries
	crowd-funding models perfected		adjustment of commodity values due to changing demand patterns	

Source: Figure 24 in Srinivasan and Bassan (2012)

The alternative or competing hypothesis about how 3D printing will affect the location, scale, and mix of economic activity across space derives from more recent economic geography theories of *agglomeration externalities*. An ‘agglomeration externality’ is the effect on business revenues or costs due to the numbers or variety

of other businesses and people in the same place. The effects are labeled “externalities” because they are not consequences of choices made internally by the business itself (other than the business’s choice of location).

This theory posits that the geographic concentration of economic activity is productive and profitable. Indeed, if not, why would businesses and people willingly pay such high city rents? Large concentrations of diverse businesses host multiple alternatives for firms and workers, and thus lowers adjustment costs and risks for both. Higher density also means lower-cost matching between employees and employers, increased opportunities to exchange ideas and learn from others, thus encouraging innovation; and lowers the costs of shopping by customers. (See the 2009 World Development Report by The World Bank for more about agglomeration economies.) Furthermore, local competition weeds out low productivity, high-cost businesses. The existence of beneficial agglomeration economies rationalizes more spatial concentration of economic activity and population than the concentration that merely minimizes transport costs while maximizing internal returns to scale.

From this perspective, additive manufacturing will continue to support the spatial concentration of design, product development, and the large-scale manufacturing employment where a diversity of highly-skilled people, businesses, and private sources of capital already concentrate and interact with higher frequency. For one argument that large scale manufacturing will also be less vulnerable than small or medium-scale to competition from consumers using their own 3D printers, see Easton, 2008. For another, consider this “fact” regarding the “myth” that additive manufacturing (“AM”) will render mass production obsolete, shared by Terry Wohlers and Tim Caffrey (2013):

Myth #7: AM will replace conventional manufacturing. AM has disrupted and forever changed several niche manufacturing applications, including in-the-ear hearing aids, dental restorations, orthopedic implants, orthodontics, and environmental control system ducting for aircraft. However, AM will not displace conventional manufacturing methods for high-volume, low-complexity parts any time soon. Think of common mass-produced items, such as injection-molded stadium seats, trash cans, and disposable drinking cups, or the ubiquitous 12-ounce aluminum beverage containers. These products will continue to be made by conventional methods because it is much faster and more cost-effective to do so. <http://www.sme.org/MEMagazine/~Article.aspx?id=73494#sthash.A36CdUFg.dpuf>

In any event, it is most reasonable to expect a mix of both dispersion and concentration, depending on the sector. As traditional manufacturing reinvests and adopts additive technologies, establishments are likely to become smaller and more ubiquitous. In the USA and China today, for example, mass production establishments are more spatially concentrated than population. In the USA they also currently locate outside metropolitan centers. 3D printing will enable the activities for which

proximity to retail customers is most cost-effective to profitably disperse geographically to match the dispersion of population. In some cases this means manufacturing will move back into cities as well. 3D printing also enables economic activities that are 'footloose' – those for which transport costs are negligible and agglomeration benefits are high– to spatially concentrate. Those activities may also locate in cities.

The geographic dispersion of productive capacity to match the concentration of population will allow for a significant reduction in the shipment of mass-produced manufactured goods. Some employment in logistics and transport industries may become redundant. The pattern of international trade will change. It will be less profitable for a few firms to attempt to continue to supply a global market from a few very large plants (see also Anderson, 2012).

"Advocates of the technology say that by doing away with manual labor, 3-D printing could revamp the economics of manufacturing and revive American industry as creativity and ingenuity replace labor costs as the main concern around a variety of goods. "There is nothing to be gained by going overseas except for higher shipping charges," Mr. Summit said." Vance (2010) The New York Times

In sum, the international division of labor and the pattern of international trade will change, in different ways across sectors. Employment in some activities will further disperse and employment in others will further concentrate geographically. In both cases a disruption of the existing order is unavoidable. This underscores the value of training people and coordinating infrastructure investments to increase a society's ability to successfully adapt as well as to reduce the costs of transition. Cities and manufacturing regions that embrace and prepare for 3D printing will profit, areas that do not may decline.

Policy Implications

Decentralized private decision making, also known as the free market mechanism, leads to socially optimal outcomes in many – but not all – realms of economic activity. In situations where the actions of a firm or person – not signaled or reflected in market prices – imposes benefits or harms on others, society must rely on non-market mechanisms to achieve efficient and optimal outcomes. Public policies are these non-market mechanisms. An example is where the spatial concentration of people and businesses leads to negative outcomes, such as crime or an intensity of pollution that exceeds the local environment’s absorptive capacity. Society learned long ago to cooperate to enforce public safety and to handle municipal waste. The current question is what should be done – if anything – about 3D printing. To answer that question we first consider what the market may fail to do.

Many of the benefits associated with the rise of additive manufacturing are being properly signaled by changes in market prices, implying no need for policy intervention. Many of the costs – the “disruptions” threatening traditional business models (see Srinivasan and Bassan (2012) for an excellent overview) – will also be signaled by changing market prices. Adaptation may be costly, but businesses always know that to survive they must evolve. Box 1, from Srinivasan and Bassan (2012) lists questions businesses can think about to adapt to the emergence of 3D printing.

Box 1. Prepare for the Market Forces Unleashed by 3D printing

Questions for manufacturing firms

To help manufacturing firms grasp the future opportunities and challenges of 3D printing, here are 10 questions to consider. Some may have already been answered and some may be uncomfortable or difficult to answer, but all are relevant.

1. When products can be manufactured with the same ease as walking down the hall to print paper copies, how will you keep your company's business model relevant?
2. What are the business implications of delivering a digital design rather than a physical product to your customers? When your customers do manufacturing instead of you, what are the implications for product quality, product safety (e.g. a product recall) and intellectual property protection?
3. How can your company use 3D printing to improve your end product? Possibilities include consolidating components to reduce maintenance, creating lighter-weight product and leveraging new materials research.
4. In a world of 3D printing, will your customers continue to need large production runs? Even if it is more cost-effective for your company to manufacture large quantities, will your customers demand more frequent changes and upgrades? Has the expected lifetime of your product changed?
5. Is your factory going to become an assembler rather than a manufacturer? A hybrid? What effect will this have on your existing production lines for length, direction, workstations, staffing, storage etc.? How will your inbound logistics processes change to reflect those alterations?
6. What is the new relationship between IT and manufacturing? Between IT and product designer, scientists and engineers? How can IT use 3D printing to enable manufacturing, not overtake it?
7. Where are the opportunities for driving greater customer intimacy, such as customization and co-creation with your end customer? How can you best integrate online buying and mass customization to meet customer needs? What types of technology platforms are required to enable this? Is your company or industry susceptible to open design trends?
8. How will you prepare for new competitors, including new entrants and DIYers? Do the current benefits of 3D printing (low cost, high customization, delivery close to point of use) challenge your existing product line? Do future areas of 3D printing research pose a threat?
9. What organizational factors could prevent (or support) your adoption of 3D printing – for example, operating model, resource allocation, on-shore/off-shore mix, financial model, culture – and how will you address them?
10. Where should your company make capital investments today? What training and education investments are required? What investments should your company avoid?

Source: http://assets1.csc.com/innovation/downloads/LEF_20123DPrinting.pdf

There are, however, some areas where 3D printing has wholly justified implications for public policy. These are intellectual property policies, research, and education.

There is a threat that incumbent firms will seek to expand intellectual property protections to avoid having to adapt. This would mean less innovation than optimal. There are opportunities to encourage more research and development spending than the market alone would support. And there is a need to provide more education than individuals can afford to purchase, to prepare our workplaces and workforces for the new activities made possible by 3D printing.

3.1 Intellectual Property Policy

Until 3D printing, it took years of research and development to introduce an innovation to the market. Under an exclusively free market mechanism, once a new product was introduced, competitors could simply copy the innovation, driving market prices down to the marginal costs of production and leaving no return to compensate the inventors and developers for their investment in R&D. Lacking any reasonable expected return, few would bother to spend the time and money to invent, conduct research, or develop new products. That free market outcome is socially sub-optimal. The market mechanism alone supports too little innovation. That's called a "market failure." To overcome that particular market failure, public policies to protect intellectual property ("IP") have been designed to ensure a return to research and development for a limited period of time. Innovative activity has flourished since IP protections have been in place. More new and useful goods have been developed and supplied at ultimately lower prices.

There are two main types of intellectual property protections: copyrights and patents. (Trademarks are a related practice that inform consumers about the provenance of a product, which may also benefit the owner of the trademark with higher revenues.) Copyrights indicate the ownership of a non-tangible, nonfunctional, artistic creation such as a painting, a short story, a song or piece of music, and so on. Copyright protection is simply asserted at no cost by the creator, and is in force for the life of the creator plus 70 years.

While copyrights protect the creators of intangibles from unlicensed replication, patents protect the creators of tangible items from unlicensed replication. Patents indicate the ownership of the right to reproduce the patented item. In contrast with copyrighting a patent must be applied for. The application process is time-consuming and expensive; the applicant must prove that the creation is unique. Patent protection endures for ten to 25 years, depending on the jurisdiction. During that period the patent holder has the exclusive right to reproduce and sell the patented item (or to sell licenses to others to do so). In that way patent protection ensures a return to new product research and development.

Weinberg (2010) explains how intellectual property laws relate to 3D printing. His motivation is to help ensure citizens' rights to innovate and develop additive manufacturing and 3D printing. The risk is that despite lacking a bona fide 'market failure' rationale, entrenched or incumbent interests may organize to attempt to obtain policies that protect them from having to adapt to the disruptive effects of 3D printing.

This is not an unprecedented risk. Innovations have met similar resistance in the past. Established firms attempted to forestall the commercialization of personal computers, video recording devices, and photocopiers, for example (Weinberg, 2010). The IP policies incumbents might seek would punish rather than reward innovators. Such policies would serve special interests at the expense of society's interests.

To focus on the most likely IP conflicts, Weinberg (2010) first emphasizes the unique strengths of 3D printing for consumers: it enables individual creativity, complete product personalization and customization, and allows consumers to replace discontinued items. In neither case does consumer use of 3D printers threaten either copyright or patent holders. By definition, the creation of an original item implies no intellectual property conflicts.

There is a non-zero but very low probability that an individual might fabricate an item currently under intellectual property protection without license to do so. Weinberg argues that the risk is very low because most functional items –things people would 3D print – are not under either copyrights or patents. Copyrights do not extend to functional items. And because patents are only in force for a limited period of time, there is “an entire universe of products that can be freely replicated in a 3D printer.” Furthermore, patents do not prohibit the copying of individual elements of patented items. A person may 3D print a part or replacement part of a patented item as long as the person legitimately purchased the whole item in the first place.

Weinberg underscores that copyright protection currently does not extend beyond the design (the intangible attribute) to the tangible item fabricated using a 3D printer. But he cautions that traditional manufacturers and designers threatened by 3D printing will seek to expand design patent and/or copyright protection to functional items, to limit the applicability of the ‘severability test’ (the extent to which ‘form’ is distinct from ‘function’). For example, recently an auto manufacturer attempted to extend design patent protection to functional parts, to prevent competition in the market for replacement auto parts. That lawsuit should fail: a public policy that leads mainly to less being supplied at higher prices is not in society's interests.

Weinberg (2013) explains the “severability test” in more detail in a subsequent article. He also shares his expectations of public policy:

“both the legislature and the courts can take steps to protect innovation. Legislatures can say no when incumbents try to push laws designed to criminalize a new technology. Courts can protect legally defensible, but culturally novel, ways of doing business. After all, it was the [U.S.] Supreme Court’s refusal to hold the creator of the Betamax liable for copyright infringement that gave us VCRs, DVRs, MP3 players, and more.” What’s the Deal with copyright and 3D printing? Michael Weinberg JANUARY 2013, Institute for Emerging Innovation.

It is also possible that patent owners may attempt to prohibit individuals from replicating patented items by suing the manufacturers of 3D printers, hosts of 3D printing hubs, or hosts of internet sites where computer aided designs (CAD) can be acquired

for “contributory infringement.” (An example of “contributory infringement” was the case against Napster, rather than those who actually copied, for enabling individuals to copy music off the internet.) However, as Weinberg (2010) notes, such plaintiffs will not be able to prove that 3D printers and CAD designs do not have any non-IP-infringing uses. Therefore that approach is not a credible threat to 3D printing.

Indeed, United Parcel Service (UPS), a prominent logistics company, is now offering 3D printing as a service in a few of its stores (Sophy, 2013). UPS’s move to facilitate 3D printing activity by small businesses and individuals is noteworthy for at least three reasons. One, it exemplifies the trend towards localized, small scale 3D fabrication hubs hypothesized in the previous section. Two, it is an example of how a logistics business potentially threatened by 3D printing (as the demand for shipping wanes) can adapt its business model to benefit instead. Three, apparently UPS does not fear ‘contributory infringement’ lawsuits either.

3.2 Research

Before discussing the public role in financing research in additive manufacturing, as usual it behooves us to look at the private level of investment in that R&D. There’s a public role if investment is too low. On the one hand, companies making 3D printers have attracted the lion’s share of crowd-funded equity capital. On the other hand:

“3D Systems makes the vast majority of its money selling large printers to companies that want to crank out quick prototypes of parts. Aeronautics and auto companies have been longtime users of this technology. Today so, too, are consumer electronics companies and even orthodontists making custom braces. For all of 2011, 3D Systems reported revenue of \$230.4 million. One chunk (\$137.3 million) came from selling the actual machines, while the second chunk (\$93.1 million) came from selling what amount to proprietary plastics and powders that go into the machines, much as Hewlett-Packard (HPQ) sells toner and ink to its printer customers.

Here’s the rub: 3D Systems spent just \$14.3 million on research and development in 2011. That’s a paltry 6 percent of revenue. Its main rival Stratasys (SSYS) posted 2011 revenue of \$155.9 million and spent \$14.4 million on R&D. [14.4/155.9 = 9%]

Step back and think about these totals for a minute, and you might come away disheartened. 3D printing rightly gets billed as one of the most exciting areas of technology, and it’s simply not receiving the level of investment that you would expect.” Vance, Bloomberg Businessweek (2013).

While some may argue that spending 6-9% of gross revenue on R&D is not too low, most people understand that market spending on research is often lower than

socially optimal because it is prohibitively difficult to charge many of the beneficiaries for the benefits they will enjoy after the innovations are commercialized. In emerging market economies where financial markets are underdeveloped, government remains responsible for industrial investment in research and development. Box 2 is an example from the Peoples Republic of China. Yet others argue that national security issues are at stake. National governments fear losing competitive advantage. Box 3 is an example from Singapore, and Box 4 is an example from the U.K.

Box 2. Chinese Government Invests in 3D Printing Research Institute

Chinese Government Invested 200 million RMB in Setting up 3D Printing Research Institute

The 3D Printing Research Institute of China was launched on August 8th 2013 at Zijin Hightech Zone of the Nanjing city, Jiangsu Province. The Institute is planned to carry out applied 3D printing research and seek for opportunities for its commercialization and industrialization.

The Institute will combine forces of some best Chinese 3D printing research teams from Tsinghua University, Xian Jiaotong University, Northwestern Polytechnic University and Central China University of Science and Technology. Chinese Academy of Engineering Academician Prof. Lu Bingheng will work as the Project Coordinator. Research will focus on 3D printing technology, equipment, materials, applications in various fields including medicine, civil aviation, aerospace technology, automotive industry and biological manufacturing. The aim is to build China's 3D printing leading force and foster a group of companies around the industry.

The institute will be non-profit public research entity with 200 million RMB investments from the government in its first phase.

Source: Posted on August 13, 2013 by NOST China News. Note: 200 million RMB is about 33 million USD.

Box 3. Singapore to Invest \$500m in 3D Printing

Singapore to Invest \$500m in 3D Printing

Over the coming five years, the country will be digging deep to develop the technology, injecting a total of \$500 million (£330.3 million, €390.4 million) into advanced manufacturing techniques in order to maintain its competitiveness with its south-east Asian neighbours.

One of the primary contributing factors in decision-makers' reasons for investing in 3D printing is Singapore's ambition to become the high-tech capital of the Asia-Pacific region.

Included in the investment is a pledge to commence work on "exploring the potential of building a new 3D printing industry ecosystem" in the country.

Moreover, part of the multi-million-dollar cash injection will be steered towards developing training initiatives to help workers and engineers define and utilise next-gen manufacturing technologies.

Source: <http://news.nost.org.cn/2013/08/chinese-government-invested-200-million-rmb-in-setting-up-3d-printing-research-institute/manufacturing/singapore-to-invest-500m-in-3d-printing/>

Box 4. U.K. Invests £14.7mil. in 3D

UK Gov't Gives 14.7m Pounds to 3D Designers

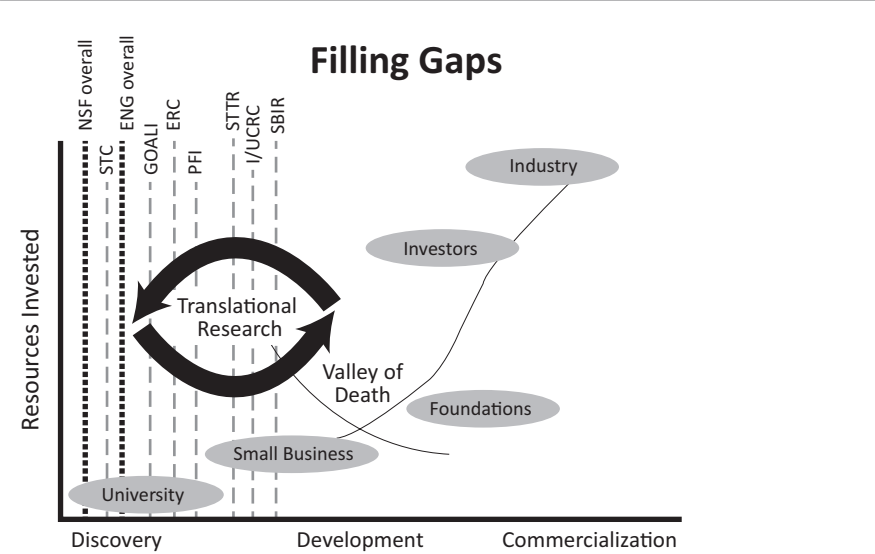
United Kingdom business secretary Vince Cable recently announced that the government will spend a whopping £14.7 million (\$23 million) on enterprising research and development projects that utilize 3D printing technology. Most of the sum, £8.4 million, will come from the UK government. The remaining £6 million and change will come from the private sector, proving that both eager investors and government agencies have faith in the future of 3D printer technology.

Source: Posted by Dabney B. on Wednesday, June 12th, 2013 <http://www.gnomonschool.com/blog/3d-modeling/uk-govt-gives-14-7m-pounds-to-3d-designers#sthash.GBDClvzH.dpuf>

3.2.1 Publicly funded R&D in the USA

As noted, many of the early 3D printing innovators were in the United States. In this section we focus on that country's public policies relevant to 3D printing research, development and technology transfer, simply as a case in point. The National Science Foundation (NSF) funds approximately 20 percent of all federally-supported basic research conducted by colleges and universities in the U.S. As usual, the government agency first investigated the need for non-market intervention. In 2010, the NSF commissioned a study to identify impediments to engineering technology transfer from academia to industry. Peterson (2010) identified three major barriers: insufficient resources; insufficient industry engagement in university research; and lack of talent flow across university–industry boundaries. Consider resources. Both public and private funds are scarce for the development phase between invention and commercialization (Figure 5).

FIGURE 5. NSF funding and the “Valley of Death” funding gap

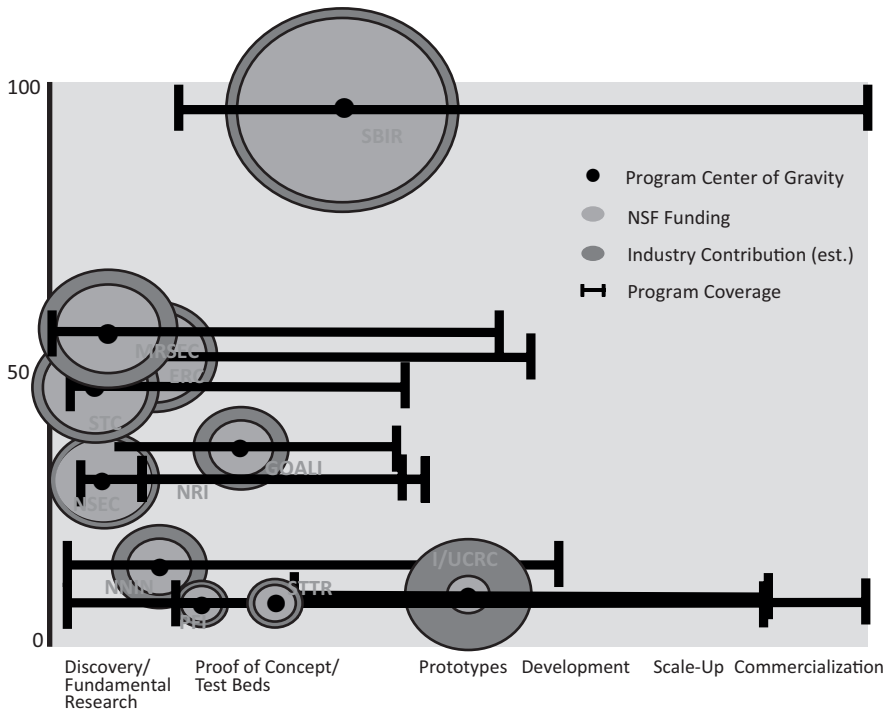


Source: Peterson (2010) “Update to the ENG Advisory Committee” http://www.nsf.gov/attachments/116656/public/AD_Update.pdf

A white paper describes NSF’s role in the “innovation ecosystem” and its plans to reduce these gaps (NSF, 2010). It reviewed five established NSF programs: Engineering Research Centers (ERCs; NSECs, MRSECs, and STCs); Industry/University Cooperative Research centers (I/UCRCs); Grant Opportunities for Academic Liason with Industry (GOALI), Partnerships for Innovation (PFI), and the Small Business Innovation Research (SBIR) and Small Business Technology Transfer (STTR) programs. Specifically, the longstanding Small Business Innovation Research (SBIR) and Small Business Technology Transfer (STTR) programs provide grants to small businesses to enable technological innovation and encourage university–industry collaboration. The STTR program requires an academic partner, thereby increasing the commercial application of academic research. NSF also explicitly links SBIRs with the ERCs and the I/UCRCs as well. These existing programs enhance industry engagement with university research and increase talent flows between universities and industry.

Figure 6 illustrates relative importance of SBIR funding, as well as the extent to which industry funding has leveraged the public funding for Industry/University Cooperative Research Centers (I/UCRCs).

FIGURE 6. NSF and industry partner contributions by innovation phase



Source: Taylor and Pancake (2008) http://www.nsf.gov/oirm/bocomm/meetings/nov_2009/EAC_UIP_report.v4.pdf

Next, the white paper (NSF, 2010) described five pilot activities. (1) The pilot **Industry-defined Fundamental Research** *Industrial Research Institute* convenes its own members, other professional society members, and university partners to examine possible research thrusts to identify those that may be fundamental and might have a transformative economic impact on an industry, to inform the NSF's programs. Proposals for new research directions have been solicited from participants in I/UCRCs. (2) Forty new grants have been provided for **Industry Postdoctoral Fellows** through an award to the American Society for Engineering Education. The costs of the fellowships are shared between industry and the NSF. (3) The pilot program for undergraduate engineering students is the **Innovation Fellows** activity. It supports engineering undergraduate student participation in summer internships in industry and encourages them to enroll in innovation-focused graduate programs. (4) The **Accelerating Innovation Research (AIR)** pilot activity consists of two parts. The first focuses on educating faculty and students to innovate,

by leveraging training for researchers to translate technologically promising NSF-funded discoveries. This has evolved into the current **Building Innovation Capacity** (BIC) program under the PFI umbrella (see http://www.nsf.gov/funding-/pgm_summ.jsp?~pims_id=504708&org=IIP&from=home). The second, the current AIR, leverages university-industry collaborations. It is now also part of the two programs under the PFI umbrella.

The fifth pilot program addresses the barrier of insufficient resources for the phases between discovery and commercialization. (5) **Translational Research in the Academic Community** (TRAC) targets supplemental funding to academic researchers who have had GOALI funding (see above) to begin the translational research. TRAC funds support prototyping, proof-of-concept tests, or scale-up, subsequent to the phases supported by GOALI (see Figure 6).

3.3 Economic Development Spending on Additive Manufacturing

Governments in developed market economies are also targeting additive manufacturing as a regional economic development tactic. For example, all levels of U.S. government are actively promoting it. At the federal level, as part of President Obama's plan to catalyze a nationwide network of 'regional innovation institutes' to support the development of additive manufacturing in the U.S., five federal agencies — the Departments of Defense, Energy, and Commerce, the National Science Foundation (NSF), and the National Aeronautics and Space Agency (NASA) — jointly committed to invest in a pilot institute. After public solicitation of proposals from teams led by non-profit organizations or universities, the Obama Administration awarded an initial \$30 million in federal funding, matched by \$40 million from the winning consortium, to establish the "National Additive Manufacturing Innovation Institute" (NAMII). The consortium includes manufacturing firms, universities, community colleges, and non-profit organizations from the Ohio-Pennsylvania-West Virginia 'Tech Belt.'

States and federal agencies also leverage local efforts. For example, with grant funding of \$77,000 USD a public library in Sacramento, California purchased a consumer 3D printer to be used by individuals and small businesspersons (Marshall, 2013). Most of these efforts have a large educational component.

3.4 Education

Two years ago I attempted to repair the thirty-year-old faucet at the kitchen sink in the home of my octogenarian parents in California. A small plastic part was cracked. The local hardware store could not match it, so they offered the next closest version. The young clerk at the cash register remarked that if the store had a 3D printer he could scan it, correct the crack, and print an exact replacement part. How did he know? He had learned 3D printing in shop class in secondary school in Utah. A hardware store may be able to buy a 3D printer, but it relies on public education to train

the mobile workforce. Industry must communicate the need to include 3D printing in school curricula.

Stratasys, a leading producer of 3D printers in the U.S., has a particularly aggressive education promotion effort. Dozens of case studies are showcased on its website at <http://www.stratasys.com/resources/case-studies/education>. Through its “Extreme Redesign” competition *Stratasys* has also awarded more than \$100,000 in scholarships to innovative students (<http://www.stratasys.com/industries/education/extreme-redesign#sthash-.gBVzhfZc.dpuf>). First place winners get a \$2,500 USD award plus a limited-time demo 3D printer from *Stratasys* for the instructor to use in the classroom. Instructors of top students receive tablet computers for classroom use. Many of these and other classroom efforts are leveraged by funding from federal agency STEM (science, technology, engineering and mathematics) education competitive grant programs.

Makerspace.com is devoted to establishing “Makerspaces” (Box 5) and encouraging “the growth of Maker communities all over the globe” (<http://makerspace.com/makerspace-directory>). The hub of this online community is a collaboration between O’Reilly Media’s Make division, “a technical publisher and conference organizer known for its advocacy of Open Source, the Web and the Maker movement” and Otherlab, “a Clean Tech Do-Tank and developer of next generation algorithmic design tools.” Makerspace offers an impressive array of resources for teachers.

Box 5. Makerspaces

What’s a Makerspace?

A Makerspace is a learning environment rich with possibilities. As new hardware and software tools for making, digital design, and fabrication are emerging, we’re working together — with teachers and community leaders — to place those tools into the hands of a wider audience. We’re building the infrastructure for more kids and adults to connect to a future in which they can personally change, modify or “hack” the physical world, creating things that were nearly impossible to do on their own just a few years ago. Making is about getting hands-on, using these new technologies and basic tools, to do real and personally meaningful work.

We’re enabling new makers — and makers of makers — everywhere to create spaces, find the tools they need, and create the programs for the spaces.

Source: <http://makerspace.com/home-page>

Oriented more explicitly to the artistic and design community, “The Creators Project” launched in 2010, posts video and editorial content online daily, hosts an official *YouTube* Channel, commissions original artwork, and stages global events celebrating “visionary artists across multiple disciplines who are using technology in innovative

ways to push the boundaries of creative expression.” (<http://thecreatorsproject.vice.com/about>) 3D printers are essential in many of the works. *The Creators Project* is collaboratively managed by computer chip maker *Intel* and *VICE*. *VICE* is “the world’s leading youth media company.” One link is an amusing website that showcases various ways 3D printing fails to fabricate the planned objects: <http://thecreatorsproject.vice.com/blog/3d-printed-glitch-art-when-3d-printing-fails> .

Universities are also leading efforts to extend the technology to the general public. Since 1998, Massachusetts Institute of Technology (MIT) physics professor Neil Gershenfeld has taught “How to Make (Almost) Anything.” He also founded a global degree program, the *Fab Academy* that certifies students in building from digital designs (Greenberg, 2008, Gershenfeld, 2012). The MIT’s Center for Bits and Atoms manages the “Fab Lab” outreach effort to promote widespread access to modern means for invention, aiming ultimately to develop programmable molecular *assemblers* (Gershenfeld, 2012) that will be able to make almost anything; Box 6.

Box 6. Selected Fab Lab FAQs

Fab Labs have spread from inner-city Boston to rural India, from South Africa to the North of Norway. Activities in Fab Labs range from technological empowerment to peer-to-peer project-based technical training to local problem-solving to small-scale high-tech business incubation to grass-roots research. Projects being developed and produced in Fab Labs include solar and wind-powered turbines, thin-client computers and wireless data networks, analytical instrumentation for agriculture and healthcare, custom housing, and rapid-prototyping of rapid-prototyping machines.

- Fab Labs share core capabilities, so that people and projects can be shared across them. This currently includes:
- A computer-controlled lasercutter, for press-fit assembly of 3D structures from 2D parts
- A larger (4’x8’) numerically-controlled milling machine, for making furniture- (and house-) sized parts
- A signcutter, to produce printing masks, flexible circuits, and antennas
- A precision (micron resolution) milling machine to make three-dimensional molds and surface-mount circuit boards
- Programming tools for low-cost high-speed embedded processors

These work with components and materials optimized for use in the field, and are controlled with custom software for integrated design, manufacturing, and project management. This inventory is continuously evolving, towards the goal of a Fab Lab being able to make a Fab Lab

Field Fab Labs and digital fabrication research are described in this video: <http://www.principalvoices.com/2007/technology.innovation/video/neil.gershenfeld/>

As mentioned earlier about education and outreach efforts in general, MIT's Fab Lab effort has received considerable funding from U.S. government sources, as much as \$2 million from the NSF alone as of 2008 (Greenberg, 2008). As of today, there are 153 operating Fab Labs and at least 27 planned Fab Labs around the world (Table 2).

Table 2. Fab Labs around the World

<i>country</i>	<i>operating</i>	<i>planned</i>	<i>country</i>	<i>operating</i>	<i>planned</i>
Afghanistan	1		Kenya	2	
Australia	2		Latvia		1
Austria	1		Luxembourg	1	
Belgium	4	1	Mexico		1
Brasil		1	Namibia		1
Canada	2	1	Netherlands	12	2
Chile	1	2	New Zealand	1	
Colombia	1		Norway	2	
Costa Rica	1		Peru	1	
Czech Republic		1	Poland	1	
Egypt	1		Portugal	3	
Ethiopia		1	Russia	2	
Finland	1		Saudi Arabia	1	1
France	9		Scotland	1	
Germany	6	1	South Africa	5	
Ghana	1		Spain	6	2
Greece		1	Suriname	1	
Iceland	3		Switzerland	3	
India	5		Sweden	1	
Indonesia	1		UK & Ire	4	1
Israel	2		United States	61	7
Italy	3	2	total	153	27

Source: <http://fab.cba.mit.edu/about/labs/> accessed 09/08/2013, tabulated by author

Summary

3D printing/additive manufacturing is a revolutionary new technology. With it we are making things we could only imagine before, as individuals, in small workplaces, and in large established companies. It leverages the power of computers and the internet. It enables production at the locations of users and consumers, even allowing consumers to be their own producers. It enables rapid repair and the replacement of discontinued products. It minimizes waste, conserves resources, and recycles material. As with all revolutionary innovations, incumbent firms will be challenged to adopt or adapt. Rather than do so, some firms will attempt to outlaw the open source sharing of designs and the facilitation of do-it-yourself fabrication. Society will benefit if protectionist efforts are not successful. The benefits will be more quickly and more widely enjoyed if governments leverage local and private investments in research, development, and education.

About the Author

Maureen Kilkenney, PhD, is a former professor of Economics, currently a Senior Fellow with the National Center for Food and Agricultural Policy, a virtual think-tank headquartered in Washington, D.C. Google Scholar ranks Maureen among the top ten in the world in her fields of regional science, rural development, banking and finance, and computable general equilibrium modeling (a mathematical technique for analyzing 'what if' economic scenarios). Her twenty-five year academic career consists of a dozen years at Iowa State University, a few years at the University of Colorado and at The Pennsylvania State University, as well as numerous visiting scholar positions at universities around the world, including the Université de Toulouse in France and the Aberystwyth University of Wales in the UK. Her most highly-cited article "Transport Costs and Rural Development" was published in the academic Journal of Regional Science in 1998. In that award-winning article she analyzed the effects of the trade-off between establishment costs (and concomitant economies of scale) and transport costs on the location of economic activity.

References

- 3Ders.org 3D printers list with prices accessed August 15, 2013.
- Anderson, Chris (2012) *Makers: The New Industrial Revolution* Random House Business Books, London, UK.
- Bird, Jane (2012-08-08). "Exploring the 3D printing opportunity". *The Financial Times*
- Deckard, C. (September, 1989) "Method and apparatus for producing parts by selective sintering", U.S. Patent 4,863,538.
- Easton, Thomas A. (November 2008). "The 3D Trainwreck: How 3D Printing Will Shake Up Manufacturing" *Analog* 128 (11): 50–63
- The Economist (April 21, 2012) "A Third Industrial Revolution" Special report: Manufacturing and Innovation.
- The Economist (June 21st 2013) "3D printing: Power shift."
- Excell, Jon, and Stuart Nathan (May 24, 2010) "The rise of additive manufacturing" *The Engineer*; <http://www.theengineer.co.uk/in-depth/the-big-story/the-rise-of-additive-manufacturing/1002560.article#ixzz2gPF8Pezr>
- Fachot, M. (August/September 2011). "The 3D printing manufacturing revolution." *E-Tech*, International Electromechanical Commission (IEC) http://www.iec.ch/etech/2011/etech_0911/ind-3.htm.
- Gershenfeld, Neil (November/December 2012) "How to Make Almost Anything: The Digital Fabrication Revolution" *Foreign Affairs* 91(6).
- Greenberg, Andy (8/13/2008) "The Fab Life" *Forbes* http://www.forbes.com/2008/08/13/diy-innovation-gershenfeld-tech-egang08-cx_ag_0813gershenfeld.html
- Hull, Charles (August 1984) "Apparatus for Production of Three-Dimensional Objects by Stereolithography". US Patent 4575300 A
- King, Rachel (January 12, 2012) "3D Printing Coming to the Manufacturing Space—and Outer Space." *Bloomberg Businessweek* (online).
- Marshall, Kristen (May 14, 2013) "Sacramento Library Offering State-Of-The-Art 3-D Printer Use" *CBS Local* <http://sacramento.cbslocal.com/2013/05/14/sacramento-library-offering-state-of-the-art-3-d-printer-use/>
- Mims, Christopher (July 21, 2013) "3D printing will explode in 2014, thanks to the expiration of key patents" *QUARTZ* <http://qz.com/106483/3d-printing-will-explode-in-2014-thanks-to-the-expiration-of-key-patents/>
- Nathan, Stuart (May 24, 2010) "Building body parts with 3D printing" *The Engineer* <http://www.theengineer.co.uk/in-depth/analysis/building-body-parts-with-3d-printing/1002542.article>
- National Science Foundation (NSF) (2010) "The Role of the National Science Foundation in the Innovation Ecosystem" <http://www.nsf.gov/eng/iip/innovation.pdf>

- Pearce, Joshua M.; et al. (2010) "3-D Printing of Open Source Appropriate Technologies for Self-Directed Sustainable Development" *Journal of Sustainable Development* 3(4):17-29.
- Peterson, Thomas W. (2010) "From the lab bench to the marketplace: Improving technology transfer." Testimony before the Committee on Science and Technology. Subcommittee on Research and Science Education. June 10.
- Pettis, Bre (October 19, 2012) "3D Printing is Bringing the Factory Back to the Individual" *Dezeen Magaine* <http://www.dezeen.com/2012/10/19/3d-printing-is-bringing-the-factory-back-to-the-individual/>
- Sophy, Joshua (August 8, 2013) "UPS Stores Launch 3D Printing for Small Businesses" *Small Business Trends* <http://smallbiztrends.com/2013/08/ups-3d-printing.html>
- Srinivasan, Vivek and Jarrod Bassan (2012) "3D Printing and the Future of Manufacturing" Computer Sciences Corporation (CSC) Leading Edge Forum (LEF) http://assets1.csc.com/innovation/downloads/LEF_20123DPrinting.pdf.
- United States Department of Commerce (August 8, 2012) "Obama Administration Announces New Public-Private Partnership to Support Manufacturing Innovation, Encourage Investment in America" press release.
- Vaezi, Mohammad, Srisit Chianrabutraa, Brian Mellora and Shoufeng Yanga (April, 2013) "Multiple material additive manufacturing – Part 1: a review" *Virtual and Physical Prototyping* 8(1):19-50.
- Vance, Ashlee (September 13, 2010) "3-D Printing Spurs a Manufacturing Revolution" *New York Times* http://www.nytimes.com/2010/09/14/technology/14print.html?pagewanted=all&_r=0
- _____, _____ (February 6, 2013) "A Lack of R&D May Kill the 3D Printing Gold Rush" *Bloomberg Businessweek* <http://www.businessweek.com/articles/2013-02-06/a-lack-of-r-and-d-may-kill-the-3d-printing-gold-rush>
- Wittbrodt, B.T., A.G. Glover, J. Laureto, G.C. Anzalone, D. Oppliger, J.L. Irwin, J.M. Pearce (September 2013) "Life-cycle economic analysis of distributed manufacturing with open-source 3-D printers." *Mechatronics* 23(6):713–726.
- Weinberg, Michael (November, 2010) "It Will Be Awesome if They Don't Screw it Up: 3D Printing" *Public Knowledge* <http://publicknowledge.org/>
- Weinberg, Michael (January, 2013) "What's the Deal with copyright and 3D printing?" http://www.publicknowledge.org/files/What%27s%20the%20Deal%20with%20Copyright_%20Final%20version2.pdf Institute for Emerging Innovation
- Wohlers Associates (2009) *Wohlers Report 2009: State of the Industry Annual Worldwide Progress Report on Additive Manufacturing*, <http://www.wohlersassociates.com/>
- Wohlers, Terry, and Tim Caffrey (June 2013) "Additive Manufacturing: Going Mainstream 2013: Trends, myths, and investments in additive manufacturing" *Manufacturing Engineering Magazine* <http://www.sme.org/MEMagazine/Article.aspx?id=73494#sthash.A36CdUFg.dpuf>
- The World Bank, (2009) *World Development Report 2009: Reshaping Economic Geography* Washington, D.C.

Rapporten *3D-printing – Economic and Public Policy Implications* kartlägger ekonomiska effekter av 3D-printing och associerade policyförändringar, den framväxande tekniken och framtida användningsområden samt belyser den viktiga frågan om vi står inför en industriell 3D-revolution. Rapporten samlar även åsikter från experter som har specialiserat sig på 3D-printing och lyfter fram exempel på offentliga initiativ för att stärka konkurrens, uppmuntra innovation och säkerställa kompetens inom 3D-sektorn.

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