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STRATEGIC FORESIGHT REPORT

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STRATEGIC FORESIGHT INITIATIVE

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Could 3D Printing Change the World?

Technologies, Potential, and Implications of Additive Manufacturing

Transformative technologies are the stuff of history. The steam engine, the light bulb, atomic energy, the microchip—to name a few—unalterably changed our world. Such breakthroughs often take decades from initial invention to changing the way we do things and their potential impact can be nearly unimaginable early in the process. It is doubtful that even Tim Berners-Lee in his wildest dreams imagined what the World Wide Web would do to our global "operating system" when he invented it 20 years ago.

Now another new technology is gaining traction that may change the world. 3D Printing/Additive Manufacturing (AM) is a revolutionary emerging technology that could up-end the last two centuries of approaches to design and manufacturing with profound geopolitical, economic, social, demographic, environmental, and security implications.

As explained in this brief, AM builds products layer-by-layer—additively—rather than by subtracting material from a larger piece of material like cutting out a landing gear from a block of titanium—that is, "subtractive" manufacturing. This seemingly small distinction—adding rather than subtracting—means everything.

- Assembly lines and supply chains can be reduced or eliminated for many products. The final product—or large pieces of a final product like a car—can be produced by AM in one process unlike conventional manufacturing in which hundreds or thousands of parts are assembled. And those parts are often shipped from dozens of factories from around the world—factories which may have in turn assembled their parts from parts supplied by other factories.

THE STRATEGIC FORESIGHT INITIATIVE

The Strategic Foresight Initiative seeks to enhance understanding of the potential impact and policy implications of long-term global trends, disruptive change, and strategic shocks. The Initiative publishes articles, blogs, and reports and convenes workshops that bring together policymakers, academic and think tank specialists, and business leaders to analyze long-term threats and challenges ranging from climate change, water and food shortages, and resource scarcities to the impact of urbanization and new technologies. It also analyzes how these trends interact with social, political, economic, and security factors, often to produce disruptive changes to the global strategic environment affecting all nations. The Initiative provides a hub for an expanding international community of global trends experts that seeks to enhance public policy making in the United States and other key countries. The Initiative has been working with the US National Intelligence Council for the last six years on preparation of its long-term trends reports, including Global Trends 2025: A Transformed World, and the upcoming Global Trends 2030 report that will be released in late 2012.

- Designs, not products, would move around the world as digital files to be printed anywhere by any printer that can meet the design parameters. The Internet first eliminated distance as a factor in moving information and now AM eliminates it for the material world. Just as a written document can be emailed as a PDF and printed in 2D, an "STL" design file can be sent instantly to the other side of the planet via the Internet and printed in 3D.

- Products could be printed on demand without the need to build-up inventories of new products and spare parts.
- A given manufacturing facility would be capable of printing a huge range of types of products without retooling—and each printing could be customized without additional cost.
- Production and distribution of material products could begin to be de-globalized as production is brought closer to the consumer.
- Manufacturing could be pulled away from "manufacturing platforms" like China back to the countries where the products are consumed, reducing global economic imbalances as export countries' surpluses are reduced and importing countries' reliance on imports shrink.
- The carbon footprint of manufacturing and transport as well as overall energy use in manufacturing could be reduced substantially and thus global "resource productivity" greatly enhanced and carbon emissions reduced.
- Reduced need for labor in manufacturing could be politically destabilizing in some economies while others, especially aging societies, might benefit from the ability to produce more goods with fewer people while reducing reliance on imports.
- The United States, the current leader in AM technology, could experience a renaissance in innovation, design, IP exports, and manufacturing, enhancing its relative economic strength and geopolitical influence.

The following article, co-authored with three of the top AM researchers in the United States, provides a brief technical introduction to AM and then addresses some of the above geopolitical, economic and environmental implications.

—Banning Garrett

Background

AM offers a new paradigm for engineering design and manufacturing which will have profound geopolitical, economic, demographic, environmental and security implications. AM is perhaps at the point of the earliest development of personal computers or at the beginnings of the Internet and World Wide Web. In those previous cases, there was little if any sense of the game-changing impact and ubiquity of these emerging technologies fifteen to twenty years in the future. But the Internet and PC examples enable us to foresee a significant potential for this new technology, even if only rough outlines of that disruptive future can be sketched at this point. AM could prove to have as profound an impact on the manufacturing world as the PC and the Internet on the information world. It could also provide a step forward in environmental protection and resource productivity. Here we discuss the state of the art, promises, limitations, and policy implications to AM, including how the ability to locally print almost any object could profoundly affect the course of the global economy.

I. Additive Manufacturing Basics

Traditional manufacturing has fueled the industrial revolution that has enabled our world today, yet it contains inherent limitations that point to the need for new approaches. Manufacturing comes from the French word for "made by hand." This etymological origin is no longer appropriate to describe the state of today's modern manufacturing technologies, however. Casting, forming, molding, and machining are complex processes that involve tooling, machinery, computers, and robots. Similar to a child cutting a folded piece of paper to create a snowflake, these technologies are "subtractive" techniques, in which objects are created through the subtraction of material from a workpiece. Final products are limited by the capabilities of the tools used in the manufacturing processes.

By contrast, AM is a group of emerging technologies that create objects from the bottom-up by adding material one cross-sectional layer at a time.[1] Revisiting the childhood analogy, this is conceptually similar to creating an object using building blocks or Legos®. The generalized steps of AM technologies are shown in Figure 1.

1 3D Printing is actually a subset of Additive Manufacturing. ASTM International defines Additive Manufacturing as the "process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies." [Standard Terminology for Additive Manufacturing Technologies, ASTM F2792-10, June 2010.]

Figure 1. Generalized Additive Manufacturing Process.

The AM process begins with a 3D model of the object, usually created by computer-aided design (CAD) software or a scan of an existing artifact. Specialized software slices this model into cross-sectional layers, creating a computer file that is sent to the AM machine. The AM machine then creates the object by forming each layer via the selective placement (or forming) of material. Think of an inkjet printer that goes back over and over the page, adding layers of material on top of each other until the original works are 3D objects.

There are several AM processes that are differentiated by the manner in which they create each layer. One technique known as "Fused Filament Fabrication"—see Figure 2—involves extruding thermoplastic or wax material through heated nozzles to create a part's cross sections.[2] Filament feedstock is guided by a roller into a liquefier that is heated to a temperature above the filament's melting point. The material is then able to flow freely through the nozzle. When the material reaches the substrate, it cools and hardens. Once the layer is complete, the build platform is lowered one layer-thickness by the Z-stage and deposition of the next layer begins. A secondary sacrificial material may also be deposited (and later removed) in order to support the construction of overhanging geometries.

Other AM technologies use different techniques for creating each layer. These range from jetting a binder into a polymeric powder (3D Printing), using a UV (ultraviolet) laser to harden a photosensitive polymer (Stereolithography), to using a laser to selectively melt metal or polymeric powder (Laser Sintering).Moreover, recent developments in the synthesis of end-use products allow for increasing numbers of materials to be used simultaneously. Think of an inkjet printer with six color cartridges printing simultaneously—but with different materials such as various metals, plastics, and ceramics in each cartridge.

AM offers distinct advantages. First, as a result of the additive approach, AM processes are capable of building complex geometries that cannot be fabricated by any other means; thus, AM offers the utmost geometrical freedom in engineering design. Consequently, new opportunities exist for design in industries as diverse as automotive, aerospace, and bio-engineering. Second, it is possible with AM to create functional parts without the need for assembly, saving both production time and cost. Finally, AM offers reduced waste; minimal use of harmful chemicals, such as

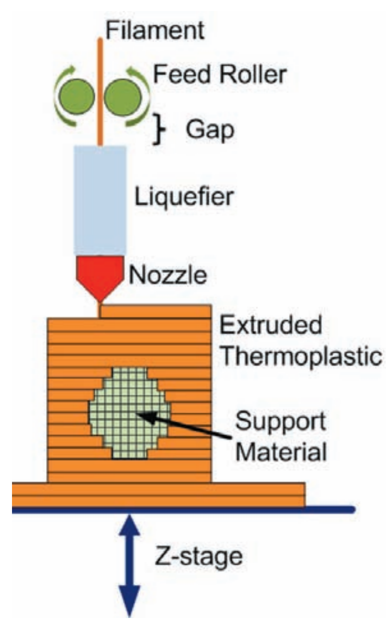

Figure 2. Fused Filament Fabrication.

2 S. S. Crump, "Apparatus and Method for Creating Three-Dimensional Objects," USA Patent, 1989.

etching and cleaning solutions; and the possibility to use recycled materials.

Thus, with recent developments in the synthesis of end-use products from multiple materials (including metals, plastics, ceramics, etc.) and its inherent environmentally-friendly nature, AM has emerged as a transformative technology in innovation-based manufacturing.

II. *Status Quo* of Additive Manufacturing

Initially, AM was referred to as "rapid prototyping," and was primarily used to quickly fabricate conceptual models of new products for form and fit evaluation.[3] An architect could design a new building on a computer and print out a 3D model to show a client or further refine the design. An automotive engineer could design and print a prototype front facia to a vehicle. As material properties and process repeatability improved, AM technologies' use has evolved from solely creating prototypes, to creating parts for functional testing, to creating tooling for injection molding and sand casting, and finally, to directly producing end-use parts. In 2009, Wohlers reported that 16% of AM process use was for direct part production, 21% for functional models, and 23% for tooling and metal casting patterns.[4]

Industrial success stories of using AM for part production include:

- *Automobile components:* While AM is not yet suitable for mass production, it is increasingly used to create components for high-end, specialized automobiles. For example, engine parts for Formula 1 race cars have been fabricated using direct metal laser sintering.
- *Aircraft components:* Low-volume production found in the aerospace industry makes it another market primed for disruption from AM. While the parts resulting from direct metal AM processes are still not quite at critical components grade, there exist many instances of AM parts being used in aircraft. One example is an environmental control system duct on the F-18. The complexity offered by AM enabled the redesign of the assembly, and reduced the number of parts involved from sixteen to just one. Whereas the traditionally manufactured assembly must have its design tailored to fit the capabilities of the machine tools used to produce the part, the AM part is built precisely to fulfill its function.
- *Custom orthodontics:* Align Technology, Inc. uses AM to create clear, custom braces for hundreds of thousands of patients across the globe. Specifically, stereolithography is used to fabricate molds from 3D scan data of each patient's dental impressions. FDA-approved polymer is then cast into the molds to create the braces.
- *Custom hearing aids:* Siemens and Phonak apply laser sintering to quickly fabricate custom hearing aids. Based on 3D scans of impressions of the ear canal, the resulting hearing aid fits perfectly in the patient's ear and is almost hidden from view.

III. The Future of Additive Manufacturing

Recent reports and developments suggest that AM development is gaining momentum and could be reaching a take-off point within the next decade. Hints of the future in a recent *Economist,* cover story, "Print me a Stradivarius," captured imaginations throughout the policy world.[5] A 2010 Ganter report[6] identified 3D Printing as transformational technology in the Technology Trigger phase of the Hype Cycle[7] (*i.e.*, only 5-10 years from mass adoption). While those involved in AM research might argue that it instead is emerging from a "Trough of Disillusionment" towards a "Slope of Enlightenment," two recent significant advances have ignited broad interest in AM:

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3 Conceptually, AM has existed since the time of raised relief maps, in which 3D terrain is approximated by stacking 2D layers. AM technology first emerged in 1977, when Swainson suggested a method of creating 3D objects directly by using two electromagnetic radiation beams and a sensitive polymer that solidifies in the presence of the beam. This method is considered to be the ancestor of modern stereolithography. Over the past four decades, AM techniques have further evolved. Researchers in the domains of mechanical engineering and materials science have focused on improving old and creating new techniques, as well as developing novel materials.

4 Terry Wohlers, *Wohlers Report 2009*, ISBN 0-9754429-5-3.

5 "Print me a Stradivarius," *The Economist*, February 10, 2011.

6 Jackie Fenn, "Emerging Technology Hype Cycle 2010: What's Hot and What's Not," **http://www.gartner.com/it/content/1395600/1395613/august_4_whats_hot_hype_2010_jfenn.pdf**, accessed July 2011.

7 Jackie Fenn, "Mastering the Hype Cycle: How to Choose the Right Innovation at the Right Time," Harvard Business School Press, Cambridge, MA, 2008.

- *Direct Metal AM:* Significant improvements in the direct additive manufacture of metal components have been made in the past five years. Engineers are now able to fabricate fully-functional components from titanium and various steel alloys featuring material properties that are equivalent to their traditionally manufactured counterparts. As these technologies continue to improve, we will witness greater industrial adoption of AM for the creation of end use artifacts.
- *Desktop-scale 3D Printers:* As direct metal AM is breaking longstanding technology acceptance barrier related to materials, the recent emergence of desktop-scale 3D printers is eliminating cost barriers.[8] Thanks to expiring intellectual property and the open-source (and crowd-source) nature of these projects, AM technology can now be purchased for around $1,000. Because of this low price point, interest in 3D Printing has skyrocketed as more and more hobbyists are able to interact with a technology that, in the past, was relegated to large design and manufacturing firms. This has democratized manufacturing, thus resembling the early stages of the *Apple I*'s impact on personal computing.

Thus, the 3D printing revolution is occurring at both the high end and the low end, and converging toward the middle. One end of the technology spectrum involves expensive high-powered energy sources and complex scanning algorithms. The other end is focused on reducing the complexity and cost of a well-established AM process to bring the technology to the masses. Major advances will continue to be made in both directions in the next five years. "Direct metal" processes will continue to advance as process control and our understanding of fundamental metallurgy improves. These cutting-edge technologies will gain broader acceptance and use in industrial applications as the necessary design and manufacturing standards emerge. On the other hand, the quality and complexity of parts created by the desktop-machines will continue to improve while the cost declines. These systems will also see broader dissemination in the next 5 years—first through school classrooms and then into homes. While these two technical paths will continue to develop separately—with seemingly opposing end goals—we can expect to see a convergence, in the form of a small-scale direct metal 3D printer, in the next few decades.

IV. The Additive Manufacturing Advantage

Additive manufacturing offers a number of benefits over traditional manufacturing techniques (*e.g.*, injection molding, casting, stamping, machining):

- *Increased part complexity:* An immediately apparent benefit is the ability to create complex shapes that cannot be produced by any other means. For example, curving internal cooling channels can be integrated into components. Fundamentally, AM processes allow designers to selectively place material only where it is needed. Taking inspiration from nature (*e.g.*, coral, wood, bone), designers can now create cellular materials–strong and stiff structures that are also lightweight (*e.g.*, Figure 3).
- *Digital design and manufacturing:* All AM processes create physical parts directly from a standardized digital file (.STL), which is a representation of a three-dimensional solid model. These computer-controlled processes require a low level of operator expertise and reduce the amount of human interaction needed to create an object. In fact, the processes often operate unmonitored. This allows for overnight builds and dramatically decreases the time to produce products—thus reducing the time between design iterations. Furthermore, creating the part directly from the computer model ensures that the created part precisely represents the designer's intent and thus reduces inaccuracies found in traditional manufacturing processes.
- *Complexity is free:* In metal casting and injection molding, a new product requires a new mold in which to cast the part. In machining, several tool changes are needed to create the finished product. However, AM is a "single tool" process—no matter the desired geometry, there is no need to change

8 MakerBot CEO and Founder Bre Pettis recently appeared on the "Colbert Report" demonstrating the "Thing-O-Matic." **http://www.colbertnation.com/full-episodes/wed-june-8-2011-bre-pettis**. See the MakerBot printing Colbert's head: **http://www.youtube.com/watch?v=H5aeJNpmW5s**, accessed July 2011.

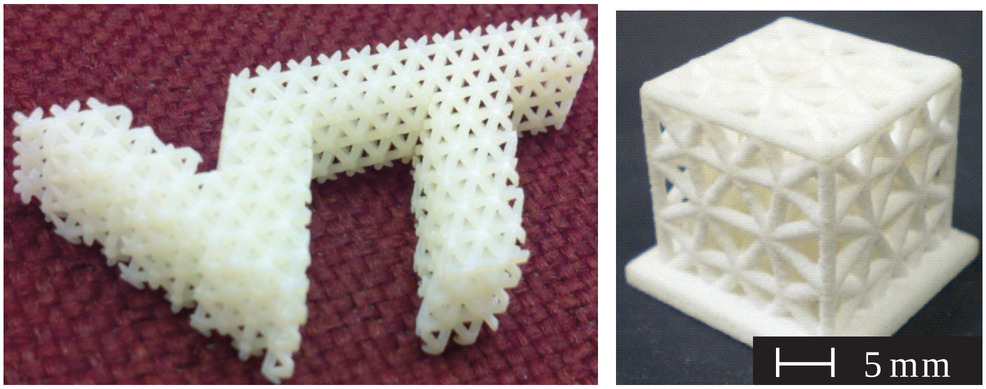

Figure 3. Examples of cellular materials produced by Additive Manufacturing (VT=Virginia Tech).

any aspect of the process. This, in effect, makes shape complexity free—there is no additional cost or lead time between making an object complex or simple. As such, AM processes are excellent for creating customized, complex geometries. Returning to the custom orthodontics application: the AM process is capable of building dozens of unique molds in a single batch run, printing many sets of teeth molds at the same time. This type of customization cannot be economically offered by any traditional manufacturing process.

- *Instant production on a global scale:* The representation of physical artifacts with a digital file enables rapid global distribution of products, thus potentially transforming product distribution much in the same way the MP3 did for music. The digital file can be sent to any printer anywhere that can manufacture any product within the design parameters of the file—*i.e.*, which can print the size, resolution, and materials called for in the file.
- *Waste reduction:* AM processes are inherently "green." Since material is added layer by layer, only the material needed for the part is used in production. There is virtually zero waste. This lies in stark contrast to traditional subtractive manufacturing processes, such as machining, where the desired part is carved out of a stock billet—often resulting in much of the final product leaving behind wasted material chips (that are often coated in oily cutting fluid).

V. Additive Manufacturing Limitations

While AM technologies offer critical advantages over traditional manufacturing processes, there are inherent limitations in the processes that keep them from being a panacea for every manufacturing problem. In their current embodiments, AM processes are limited for mass production purposes. On average, AM processes are capable of creating a 1.5 inch cube in about an hour. An injection molding machine, on the other hand, is capable of making several similar parts in under a minute. While AM

	Is AM *more* or *less* green than traditional manufacturing?
+	Reduces material waste and scrap
+	Limits the amount of energy used
+	More efficient use of raw materials
+	Minimal harmful (*e.g.*, etching) chemicals needed
+	Environmentally friendly product designs possible
+	Changes to design streamlined
+	Carbon footprint of a given product reduced (via reduced waste and need for global shipping)
-	But can it use recyclable materials?
-	What about environment, health and safety (EHS) issues, especially with nanomaterials?

processes will continue to increase in speed, it is unlikely they will ever be able create parts as fast as molding technologies. The bottleneck lies in the fundamental physics of the processes—it is not possible to scan a laser (and cure material, and recoat each layer) at a speed comparable to that of injection molding.

Nevertheless, this limitation is only valid for the production of several thousand of a common part. Since tooling must be created for each unique part one wishes to injection mold, AM is the preferred process when custom parts, or low-volume production runs, are needed. Moreover, if production is decentralized, then "mass production" of hundreds of thousands of a given product may be done by producing thousands on one hundred printers that are near the source of demand around the world rather than at one factory producing hundreds of thousands of the same item. Also, the same printers producing thousands of each item can be instantly reprogrammed to produce different products as demanded.

Another sign that AM is in the "*Apple I* stage" is the need for better materials to use in printing and greater uniformity in production quality. Most AM processes use proprietary polymers that are not well characterized, and are weaker than their traditionally manufactured counterparts. Also, in some AM processes, part strength is not uniform—due to the layer-by-layer fabrication process, parts are often weaker in the direction of the build. Finally, AM process repeatability is in need of improvement; parts made on different machines can often have varying properties.[9]

VI. Additive Manufacturing Could Leverage Other Scientific Breakthroughs

Much has been written about the promises of the on-going convergence of technical disciplines, especially the so-called NBIC (nanotechnology, biotechnology, information technology, and cognitive sciences). "Revolutionary advances at the interfaces between previously separate fields of science and technology are ready to create key NBIC transforming tools (nano-, bio, info-, and cognitive based technologies), including scientific instruments, analytical methodologies, and radically new material systems. The innovative momentum in these interdisciplinary areas must not be lost but harnessed to accelerate unification of the disciplines."[10] However, as in any technology, manufacturing must be advanced for the products that the NBIC researchers develop. AM may offer a novel new means toward the incorporation of NBIC technologies into prototype and finished products. Moreover, such an interdisciplinary approach could offer even greater design flexibility and higher part quality within AM-produced components.

Modern AM techniques use materials such as liquid, solid, and powder polymers; powder metals; and ceramics. Individual material options are thus limited to thermoplastics, elastomers, ferrous metals (steel alloys), non-ferrous metals (*e.g.*, aluminum, bronze, Co-Cr and Ti), and some ceramics (*e.g.*, SiO_2, TiO_2). New composites with other materials may offer greater opportunities to extend the present limitations of materials in AM.

The marriage of AM and nanomaterials offers a particularly intriguing avenue for perhaps overcoming some of the fundamental materials and design limitations that presently stymie AM engineers and designers. Nanotechnology offers a novel approach for AM with its potential to both complement existing techniques and create wholly new nanocomposites. The National Nanotechnology Initiative defines it as "the understanding and control of matter at the nanoscale, at dimensions between approximately 1 and 100 nanometers, where unique phenomena enable novel applications."[11] When shrinking the size scale from the macroscale to the nanoscale, or bulk to molecule, materials can change their fundamental properties. At the nanoscale, objects can exhibit unique optical, thermal, and electrochemical properties that differ from the properties of the bulk material or molecules. These properties strongly depend on the size and the shape of nanostructures. There are also a wide variety of nanomaterials, including carbon nanotubes (CNTs), nanowires (NW), buckyballs, graphene, metal nanoparticles (NPs), and quantum dots (QD). These materials possess unique characteristics that allow

9 Of course, the same can also be said for traditional manufacturing. One of the authors (T.C.) once witnessed a US automobile assembly plant worker pounding a front bumper onto a car with a hammer she brought from home. When asked why she was doing that, she replied, "Because the part doesn't fit!" When he told his superior back in Detroit, the superior stated, "That's great! She's being innovative; we don't need to change anything in our design then."

10 Bainbridge, W.S. (Ed.) (2006), "Managing Nano-Bio-Info-Cogno Innovations," Converging Technologies in Society, Springer.

11 **http://www.nano.gov**, accessed July 2011.

applications in areas such as sensing, separations, plasmonics, catalysis, nanoelectronics, therapeutics, and biological imaging and diagnostics.

Ivanova, *et al.*, recently performed a literature review of AM combined with nanomaterials.[12] Table 1 provides a summary of those findings. There are many opportunities in the marriage of AM and nanotechnology, but also significant technical and scientific challenges. The addition of metal nanoparticles generally decreases sintering temperatures, improves part density, and decreases shrinkage and distortion of printed parts. Metal nanoparticles embedded into polymer materials can also provide improved electrical conductivity in fabricated objects. Incorporation of carbon nanotubes in printing media offers a potential route to improving mechanical properties of the final parts and to increasing electrical and thermal conductivities. The addition of carbon nanotubes in bio-scaffolds can yield excellent enhancement of cell proliferation. Adding semiconductor and ceramic nanoparticles to printing media can lead to improvements in mechanical properties of the final parts. Ceramic nanoparticles can be effectively used for bone tissue engineering. Table 2 details the challenges in the application of nanomaterials to AM. Each of the AM methods described has its own inherent limitations when nanoparticles are applied with the respective printing media. In short, while the convergence of Nanotechnology with AM holds promise, much research remains.

Similarly, the convergence of AM with bioengineering technologies could further escalate AM's promise. In the past decade, significant advances have been made in using AM to "print" tissue scaffolds—biocompatible materials that, when implanted into the body and integrated with biological cells, assist in the regeneration of tissue. The geometric freedom offered by AM allows for the creation of scaffolds that are optimized to encourage cellular growth, while maintaining strength. In addition, recent advances have been made in direct printing of human tissue. These "bio-printers" could eventually permit the routine printing of replacement organs for transplant.[13]

At the Wake Forest School of Medicine, researchers are developing organ and tissue printing systems. "Researchers at the Wake Forest Institute for Regenerative Medicine have developed a way to use modified ink-jet technology to build heart, bone and blood vessel tissues in the lab. By using ink-jet technology, we are able to arrange multiple cell types and other tissue components into pre-determined locations with high precision. Various cell types are placed in the wells of a sterilized ink cartridge and a printer is programmed to arrange the cells in a pre-determined order."[14] As this technology advances,

Material	Effect
Metal Nanoparticles	Decrease in sintering temperature Improved density Decrease shrinkage and distortion Provide electrical conductivity
Carbon Nanomaterials	Increase in tensile and fracture stress Parts more brittle Rough final surfaces Decrease in density Significantly improved thermal and electrical conductivity Increase in cell proliferation rate
Ceramics and Semiconductor nanomaterials	Increase in tensile strength and modulus Parts stiffer but more brittle (silica) Enhanced sintering characteristics (Alumina)

Table 1. Summary of published literature of AM with nanomaterials.

12 O. Ivanova, C. Williams, T. Campbell (2011), "Additive Manufacturing with Nanotechnology—State of the Art, Challenges, and Promises," *Progress in Materials Science*, invitation to submit article, in writing.

13 "Printing Body Parts: Making a Bit of Me," *The Economist*, February 18, 2010.

14 "Using Ink-Jet Technology to Print Organs and Tissue," **http://www.wakehealth.edu/Research/WFIRM/Our-Story/Inside-the-Lab/Bioprinting.htm**, accessed July 2011.

Challenge	Possible Solutions
Agglomeration of nanomaterial in printing media	Proper functionalization with organic linker molecules
Cure depth can be affected by the presence of nanomaterials (Stereolithography)	Need to find suitable material for a given wavelength of the UV light source
Nozzle clogging (3DP and Extrusion methods)	Determine ideal composition with high concentration of nanomaterial that could flow freely through the nozzles
Porosity of final parts printed using nanomaterials is higher compared to parts printed without nanomaterials (Laser Sintering)	Synthesis of core-shell structures (the core is nanomaterial, the shell is printing material) can improve density of final parts

Table 2. Challenges in the use of nanomaterials in AM processes.

doctors may reach the point that a patient could have their own cells harvested and then a full replacement organ directly printed in the lab. Organ rejection would thus be obviated, since the patient's own cells would be used. Such procedures would revolutionize organ transplantation procedures.

VII. Additive Manufacturing as a Disruptive Technology

Although AM processes have been available on the market for over three decades, we are only now starting to see their more widespread adoption—*cf.*, Figure 4. Spurred, in part, by the reduction of cost and the development of direct metal technologies, we are able to visualize a disruption in the manner in which products are designed and manufactured. With the ability to efficiently manufacture custom goods, it is possible that local manufacturing could start making a return to the United States—*cf.*, Figure 5. Thus, AM could dramatically reduce costs (both monetary and environmental) related to production, packaging, distribution, and overseas transportation. AM technology also enables the design, and efficient manufacture, of personalized products, and could drive the transition from mass production to mass customization, in which each item produced is customized for the user at little or no additional production cost.

Ultimately, AM has the potential to be as disruptive as the personal computer and the internet. The digitization of physical artifacts allows for global sharing and distribution of designed solutions. It enables crowd-sourced design (and individual fabrication) of physical hardware. It lowers the barriers to manufacturing, and allows everyone to become an entrepreneur.

Of course, with such disruption comes a need for new policy related to intellectual property and "part piracy," perhaps through the development of new digital rights management solutions. In addition, there are legal questions to answer—if everyone is a designer, who is held responsible when their designed part fails? An excellent exposition of the nuances possible within IP law relative to AM can be found in a recent report by Weinberg.[15] Trademarks, copyrights, liability, and patents may all come into play.

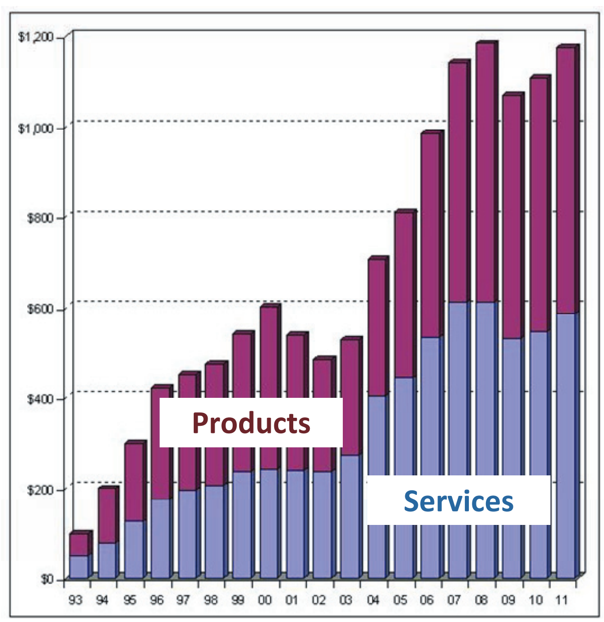

Figure 4. Estimated revenues (in millions of US dollars) for Additive Manufacturing products and services worldwide—**http://wohlersassociates.com/growth2010.htm**, accessed July 2011.

15 M. Weinberg, (November 2010), "It will be awesome if they don't screw it up: 3D printing, intellectual property, and the fight over the next great disruptive technology," Public Knowledge, **http://www.publicknowledge.org/files/docs/3DPrintingPaperPublicKnowledge.pdf**, accessed August 2010.

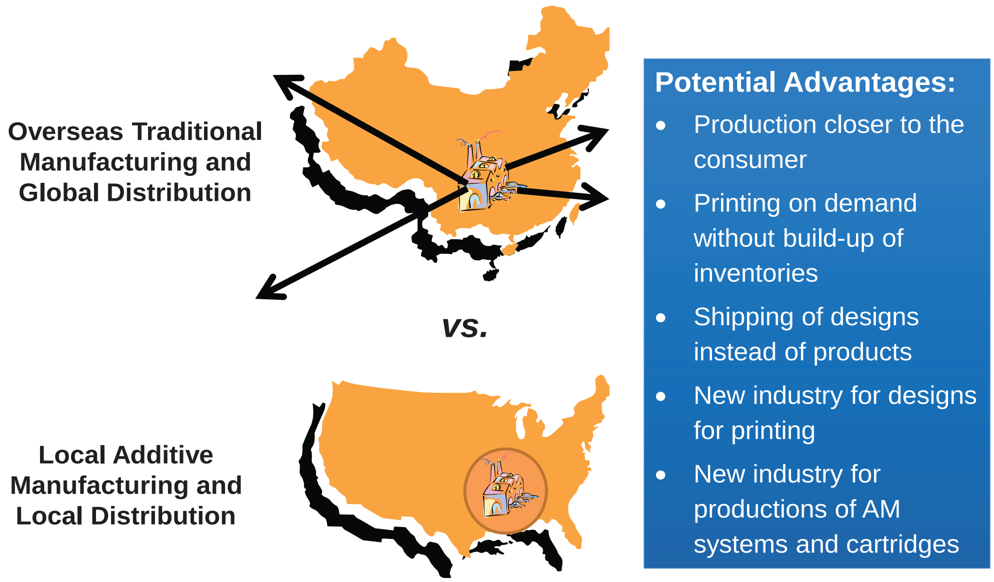

Figure 5. Additive Manufacturing could alter our manufacturing landscape.

VIII. Uncertain Pace of Change Over the Next 20 Years

The pace of development and implementation of AM is, of course, uncertain and likely to vary widely for different types of manufactured products. Many consumer products may be cheaper to mass produce by traditional methods and shipped to points of consumption for a long time. Nevertheless, there will likely be tipping points in various fields of production at which it becomes necessary for manufacturers of a given type of product to change to the new process or lose their competitive edge and risk extinction. This will likely be an uneven process and could take many years longer in some areas than in others. For example, at what point could a product as complex as an iPhone or a jet engine be printed in a single process?

While no one has a proven estimate at this point, the prospect for such a revolution in manufacturing can be foreseen. It seems likely that for such products, the shift will be in spurts as certain parts are increasingly printed and then assembled in a traditional fashion but with far fewer individual parts to assemble; thus, the costs of production could fall significantly and supply chains could be simplified and shortened. There will also be the benefit of needing to print far fewer of a particular product because it is being manufactured closer to the consumer and on-demand—benefits which may more than compensate for the cost-savings of mass production at one plant and global distribution from that production platform. Printing a few thousand iPhones on demand (and with instant updates or different versions for each phone) at a local facility that can manufacture many other products may be far more cost effective than manufacturing ten million identical iPhones in China and shipping them to 180 countries around the world.

> **“The convergence of the Internet, digitized music and media players has had dramatic consequences for music copyright. 3D printing technology may have similar implications for artistic copyright, design right, trade marks and patents, but in a rather more diverse legal framework.”**
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> [Bradshaw, *et al.*, (2010), “The intellectual property implications of low-cost 3D printing,” scriptEd, 7(1), 5-31.]

IX. A Global Revolution in Manufacturing Processes?

Additive Manufacturing could transform the manufacturing process in many critical ways, some of which are likely to happen sooner than others and all of which will likely apply to different end products at different paces. But overall, AM will bring production closer to the consumer and thus production at any given point will likely be required in smaller numbers. Moreover, AM will allow for printing on demand without the need to build-up inventories of products. Think e-books compared with paper books, which have to be printed, shipped, stored, and returned (and often shredded) if unsold.

Not only will maintaining large inventories be unnecessary, but maintaining stockpiles of spare parts—or shipping them urgently—will no longer be necessary in many cases. The ability to "print" spare parts could have significant implications for businesses, the military, and consumers. The military especially needs to maintain large inventories of spare parts on ships, foreign bases, and the battle front. Costs could be reduced by deploying printers and materials to make a wide range of spare parts, rather than keeping all the possible spares at or near where they might be needed. The Defense Advanced Research Projects Agency (DARPA) is working on printing technologies, especially for spare parts.[16] Consumers could also have 3D printers at home to manufacture spare parts for household items—for which software designs could be downloaded from the manufacturer.

Manufacturing could be pulled away from "manufacturing platforms" like China and back to the countries where the products are consumed, from the home to other larger but local facilities. A given manufacturing facility would be capable of printing a range of products with minimal retooling. A primary limitation would be the size of the printer necessary to print the item—yet there are companies working on printing small residential buildings and Airbus is developing AM to print entire wings of airplanes. Another limitation is the capability of the printer to use particular materials and resolutions required for the product.

The rise of AM will likely lead to the re-invention of many old products, as well as to extraordinary new innovations. Since AM processes can print virtually anything that can be designed on a computer—thus eliminating the limitations posed by machine tools, stamping and molding—engineers and designers will no longer be limited in their designs because of previous manufacturing technologies. This could lead to better products that competitors will not be able to match without also adopting the new design and manufacturing process.

AM is likely to provide a boost to innovation and could provide a major new impetus to bring manufacturing back to the United States. Printing allows an engineer or designer to "print" her or his ideas immediately to assess the viability of the product and incorporate design changes. Instant incorporation of design changes and product improvement for each printing would allow for the constant updating of products or tailoring of each produced item to meet the needs and specifications of the user. This direct relationship between the designer and the product—a relationship that has been strained by the past 200 years of industrial production methods—will be similar to the relationship between software engineers and their products. As a result, interest in engineering and industrial design could be spurred again, as has happened in the field of computer science and software engineering over the last half century.

X. Advances in Environmental Protection

AM may inadvertently also help achieve some of the most urgent environmental and resource goals facing the international community. The transportation and manufacturing carbon footprint of many products could be reduced as designs, rather than products, are "shipped" around the world. These designs will be digitally transferred to individuals or companies who will then "print" the product nearer to where it is purchased and used. Moreover, the carbon footprint of the final product would be further reduced by scaling back or eliminating complex supply chains of parts produced by dozens if not hundreds of suppliers scattered around the globe. In addition, depending on the complexity of the product build, number of components, and materials involved for a given product, the total energy required for production of final product may also be reduced.

By significantly reducing waste in the manufacturing process, AM also could enhance global "resource productivity"—that is, getting more "product" out of the same quantity of a given resource. This could ease the growing gap between supply and demand for non-renewable resources (*e.g.*, Rare Earth Metals). Since the printing process has almost zero waste compared with "subtractive manufacturing" and other current processes, the same amount of steel, cement, plastic, and other raw materials will lead to more final products, thus conserving precious resources. Moreover, AM could enhance the

16 DARPA's "disruptive manufacturing technologies" program is described at **http://www.darpa.mil/Our_Work/DSO/Programs/Disruptive_Manufacturing_Technologies_(DMT).aspx**, accessed July 2011. DARPA has been supporting the overall development of additive manufacturing processes.

ability to use recycled materials such as plastics and metals, especially for lower end products.

Another source of waste that could be sharply reduced or eliminated is excess or unsold production, as well as the cost of storage of inventory and spare parts. This could diminish the direct monetary cost of maintaining inventory of new products and spare parts. AM could also reduce the use of toxic chemicals used in manufacturing processes. This will reduce the difficulty and expense of disposal of these chemicals, as well as reduce the overall need for their production.

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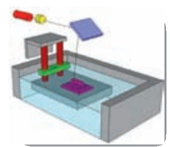
***Localization of economies* through AM could:**

- Reduce global economic imbalances
- Use local materials that are more appropriate for local consumption, including recycled materials
- Force relative decline in powerhouse production nations such as China, Japan and Germany that have built their prosperity and political power on export-led growth



***Innovation-based Manufacturing* through AM could:**

- Shift work-force requirements, with likely reduction in traditional manufacturing jobs
- Change economic power centers toward leaders in design and production of AM systems and in design of products to be printed
- Fuel a renaissance in innovation, design, IP exports, and manufacturing in the U.S., Europe and OECD countries
- Drive developing countries more rapidly toward becoming developed and less dependent on others

XI. Possible Fundamental Shift in the Global Economy

The widespread use of AM could profoundly affect the global economy. Production and distribution of material products could begin to be de-globalized with manufacturing of many goods closer to the consumer and on-demand. This localization of production could potentially reduce global economic imbalances as export countries' surpluses are reduced and importing countries' reliance on imports shrink with a new form of "import substitution" taking hold.

AM will create new industries and professions. Production of printers of all kinds and sophistication is likely to be a new industry with a growing customer base from individual home printers to creation of manufacturing centers, printers in local stores, and government agencies.[17] The shift in global manufacturing to AM processes could potentially involve trillions of dollars in business over the coming decades, including the value of products produced, the value of printers and supplies, and the value of professional services, including product engineering and design—and lawyer fees earned in intellectual property (IP) protection and dispute settlements. Protection of AM IP will likely be a challenge as designs for products potentially can be widely disseminated and identical products produced by compatible printers—replicating the problem with software piracy. Moreover, product design for printing could be a new industry following the pattern of development of the software industry over the last several decades as enthusiastic young engineers and entrepreneurs look to "change the world"—and make their fortunes—by seizing the potential of this new industry. Finally, production and distribution of printer cartridges of all sizes with a wide variety of materials will also likely be a growing industry—and perhaps a major source of profits as it has been in the 2D printing world for Hewlett-Packard and other printer makers.

The developing world could be a major beneficiary of AM production—but also a loser in manufacturing jobs for export industries. Since AM allows products to be designed and printed that are more appropriate for local consumption with local materials, including recycled materials, the developing world could reduce reliance on expensive imports as well as make its own, more appropriate products and reap the profits from this production. But there would also likely be a significant shift in work force requirements, especially a significant reduction in manufacturing and associated jobs.

Aging societies, especially in the developed world, might benefit from AM since it would reduce the need for labor and for imported products as production. This could substantially increase overall productivity of these societies, which would otherwise fall as the ratio of employed to retired shifted toward fewer workers to support more elderly. Some of the health benefits from AM might also lower the cost of health care for the elderly, which, along with pensions, is expected to be a major drag on economic growth in coming decades.

XII. Disruptive Impact on Geopolitics

Trends in the global economy have been critical to perceptions of geopolitics. The shift of wealth and power from West to East over the last decade has been especially

17 "3D printing will be a $5.2 billion market by 2020." **http://money.cnn.com/video/technology/2011/06/02/t_tt_3d_printer_systems.cnnmoney/?source=cnn_bin&hpt=hp_bn3**, accessed July 2011.

pronounced and is expected to continue for the indefinite future and to subsequently shape the geopolitics of the 21st Century.[18] Other trends besides power shifts are also likely to pose great challenges in the coming decades, especially growing scarcities of water, energy, and non-renewable materials in the face of a growing world population, increasing urbanization, and an expanding global middle class making increasing demands on resource consumption.

AM could affect the trajectory of all these trends. Countries like China, Japan and Germany that have built their prosperity and political power on export-led growth, especially of consumer products, could experience a relative decline as more production is shifted to consumer countries and demand for imports falls. It is also possible that companies in one country with superior product design would export the design to their own printing facilities in the target country, thus maintaining profits but reducing the movement of physical goods among countries. The exporting countries would presumably also take advantage of AM to produce for their own people, and countries with large domestic markets such as China, India, Indonesia and Brazil, may successfully transition to an AM economy without reduction in prosperity, despite the loss of export markets and disruptive change in manufacturing processes.

There could be a shift in economic power and prosperity toward leaders in the design and production of printers and in design of products to be printed. The United States in particular could experience a renaissance in innovation, design, IP exports, and manufacturing if it becomes the leader in both production of AM printers and the designs that are most desirable and marketable. Europe and other countries in the Organization for Economic Co-operation and Development (OECD) also could be early benefactors from this manufacturing revolution. Developing countries could more rapidly improve their economic conditions and reduce dependence on producers of manufactured products such as China.

The trend toward increasing competition for resources and even a zero-sum global economy could be slowed or reversed. In addition, international efforts to address environmental challenges, especially climate change, could receive a boost as the cost to take ameliorative or mitigating actions could be reduced.

The impact of AM on manufacturing, the environment, the global economy and geopolitics is likely to occur gradually over several decades. This has been the case with the Internet and personal computers. As noted, the impact of AM could go beyond transforming the manufacturing process and rebalancing the global economy, especially if it contributed to changing the trajectories of some of the most worrisome trends in environmental degradation, resource scarcity and climate change. Perhaps this could be the most important geopolitical impact of additive manufacturing.

AM could have significant implications in security and terrorism:

- Weapons manufacturing could become *easier* –guns, bullets, bombs, etc., could become cheaper and more easily accessible
- Weapons could be much more easily *disguised* (*e.g.*, improvised explosive devices-IEDs-that look identical to non-weapons)
- Terrorists could lose their dependency upon developed countries for their supplies
- Implications will exist for counterfeiting/ anticounterfeiting

XIII. Conclusions

AM is on track to move beyond a mere emerging technology into a truly transformative technology. The ability to locally print almost any designable object would have strong repercussions across our society. It is thus crucial that technologists and policy makers begin a significant dialogue in anticipation of these challenges to our current global economic *status quo*. While the future is certainly hard to predict, prescience and advanced planning are necessary in preparation for the disruptive technology of Additive Manufacturing.

Acknowledgements

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18 Ian Morris (2011) "*Why the West Rules - For Now: The Patterns of History, and What They Reveal About the Future*," Farrar, Straus and Giroux.

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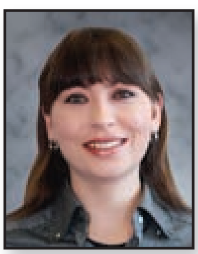

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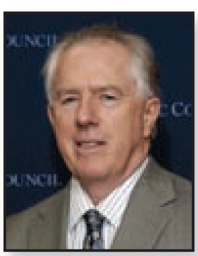

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