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Journal of International Commerce & Economics

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Journal of International Commerce and Economics

Measuring Shifts in Brazil's Trade Using International Input-Output Tables

Web Version:
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Abstract

In this paper, we use information from the World Input-Output Database (WIOD) and a method for decomposing the value-added contributions of each country in international trade flows to measure shifts in Brazil's exports between 1995 and 2009. The database allows us to separate gross trade flows into intermediate and final products and to trace Brazil's value added to the country of final use. Over the fifteen year period covered by WIOD, there was a shift in Brazil's exports of intermediate and final goods away from services and other manufactured products toward greater specialization in the country's traditional areas of comparative advantage, agricultural and mineral products. There was also a shift in Brazil's exports toward East Asia and developing countries and away from the European Union and the United States. However, the redirection of Brazil's exports to East Asia does not reflect a significant shift in the ultimate destination of Brazil's value added from its traditional markets. According to our calculations of trade in value added, Brazil's exports of intermediate goods and services to East Asia have been increasingly incorporated into East Asia's exports to the United States and the European Union.

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[1] This article is the result of the ongoing professional research of ITC staff and is solely meant to represent the opinions and professional research of the authors. It is not meant to represent in any way the views of the U.S. International Trade Commission or any of its individual Commissioners. Please direct all correspondence to David Riker, Office of Economics, U.S. International Trade Commission, 500 E Street, SW, Washington, DC 20436, or by email to *David.Riker@usitc.gov.*

INTRODUCTION

In this article, we use information from the World Input-Output Database (WIOD) and a method for calculating the value added of each country in international trade flows to examine shifts in Brazil's exports between 1995 and 2009. This rich data set separates trade in intermediate products from trade in final products. With this additional information, we calculate the value-added components of Brazil's output and trade flows. We examine trends in the data, establish a set of stylized facts, and document patterns in Brazil's trade flows.

Overall, we find that during the fifteen years for which WIOD provides data, Brazil's exports shifted toward greater specialization in the country's traditional areas of comparative advantage: agricultural and mineral products. At the same time, the exports shifted toward East Asia and developing countries. However, the redirection of Brazil's exports to East Asia does not reflect a significant shift in the ultimate destination of Brazil's value added from its traditional export markets. According to our calculations of trade in value added, Brazil's exports to East Asia have been increasingly incorporated into East Asia's exports to the United States and the European Union.

Our analysis contributes to a small but growing literature on how Brazil participates in global value chains.[2] It is closest to the branch of the literature that takes the macroeconomic approach, such as Chen (2012).[3] Chen's study examines sector-level trade flows between 2000 and 2010. It finds that Brazil is the least trade-dependent of the emerging BRIC countries, and that its export growth has been dominated by resource-based manufactures and primary products.

The article is organized into the following sections. Section 2 introduces key economic concepts relevant to this analysis. Section 3 provides details about WIOD and discusses its strengths and limitations. Section 4 describes the method that we used to calculate Brazil's exports of value added. Sections 5 and 6 document the shifts in Brazil's exports across products and destination markets. Finally, Section 7 offers concluding remarks.

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[2] The term *global value chain* describes the international staging of vertically integrated production: final products are the result of a series of production stages, and the final and intermediate stages can be located in different countries and connected by international trade.

[3] A second branch of the literature focuses more narrowly on the specific firms and industries. Examples of this microeconomic approach include Filho et al. (2006) in Brazil's metalworking industry, Gomes (2006) in Brazil's fresh fruit industry, and Strachman and Pupin (2011) in Brazil's sugar and alcohol sectors.

ECONOMIC CONCEPTS

In our analysis of the shift in Brazil's exports, we distinguish between final products and intermediate products. Final products are goods and services that are consumed or are invested as capital goods. Intermediate products are goods and services that are used in the production of downstream products, including final products and other intermediates.

Gross exports are a traditional measure of a country's trade flows. Gross exports are defined as the total value of all of the goods and services that the country sells to foreign nationals. They include the value of any intermediates that are used in production, even if these intermediates are imported from another country. A common criticism of gross exports as a measure of trade is that it overstates the value that a country contributes to its exports.[4]

To address this issue, economists have developed methods and data sets to better estimate the value that a country contributes to international trade flows. Exports of value added is defined as the value of a country's factors of production that is incorporated into goods and services that are ultimately consumed or invested as capital in another country.

The easiest way to explain the difference between gross exports and exports of value added is to use a hypothetical numerical example. Suppose that Brazil produces an intermediate mineral product valued at $10 million and exports the product to China. In China, this intermediate import is used to produce $15 million in final products by adding $5 million in Chinese value. The final product is then exported from China to the United States, where it is consumed.

As a result of this series of international trades, China's gross exports to the United States are $15 million, but its exports of value added to the United States are $5 million. Brazil's gross exports to China are $10 million, but this $10 million is consumed in the United States, so it is classified as a Brazilian export of value added to the United States. This simple example illustrates the distinction between the gross and value-added measures of exports when some of the value of the final product is exported more than once (from Brazil to China, then from China to the United States). It also illustrates the distinction between direct exports and indirect exports. Brazil is exporting $10 million of the mineral product directly to China, and Brazil is exporting the same $10 million of the mineral product indirectly to the United States by way of China. The value that originated in Brazil enters consumption in the United States, though there is no direct trade between the two countries in the example.

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[4] Koopman, Wang, and Wei (2014) discuss this issue and a related concern about "double counting" in gross exports.

DATA SOURCES

Our calculations of exports of value added are based on the international input-output (IIO) tables in the recently published WIOD.[5] An IIO table reports how the output of each sector in each country is distributed across intermediate and final uses in different countries. The WIOD tables also provide information on the direct value added in each sector in each country. The tables are disaggregated into 35 sectors and 40 countries, including Brazil, plus an aggregate of the Rest of the World. We compare data for the first and final years that are available in WIOD, 1995 and 2009.[6] In order to simplify our graphical analysis of the data below, we combine the WIOD sectors into four product groups (agriculture and food products, mining and petroleum products, other manufactures, and services), and we combine the WIOD countries other than Brazil into four destination regions (the United States, the European Union, East Asia, and the Rest of the World). Table 1 lists the WIOD sectors and countries that are included in each of these product groups and regions.

The WIOD IIO table is valuable because it is comprehensive: it covers all global trade and all of the sectors in each country's national income accounts, and it disaggregates inter-industry and international shipments by use. However, it is important to keep in mind that the trade data by use are not based on direct observations. The IIO tables, like many national economic statistics, are approximations that are constructed by allocating aggregate values across sectors and uses.

TABLE 1 Aggregation of WIOD Sectors and Countries

Product Groups	WIOD Sectors Included
Agriculture and Food Products	Agriculture, Hunting, Forestry and Fishing; Food, Beverages and Tobacco
Mining and Petroleum Products	Mining and Quarrying; Coke, Refined Petroleum and Nuclear Fuel
Other Manufacturing	Textiles and Textile Products; Leather, Leather Products, and Footwear; Wood and Products of Wood and Cork; Pulp, Paper, Paper Products, Printing and Publishing; Chemicals and Chemical Products; Rubber and Plastics; Other Non-Metallic Mineral Products; Basic Metals and Fabricated Metal; Machinery NEC; Electrical and Optical Equipment; Transport Equipment; Manufacturing NEC
Services	All Other WIOD sectors

[5] Timmer et al. (2012) explains how this database was constructed. The data are publicly available online at *www.wiod.org*.

[6] These years represent the starting and ending dates of the data available in WIOD. However, 2009 may not be a representative year due to the global recession. It will be informative to extend the analysis as the data become available for subsequent years.

TABLE 1 Aggregation of WIOD Sectors and Countries (cont'd)

Regions	WIOD Countries Included
United States	United States
European Union	Austria; Belgium; Bulgaria; Cyprus; Czech Republic; Denmark; Estonia; Finland; France; Great Britain; Germany; Greece; Hungary; Ireland; Italy; Latvia; Lithuania; Luxembourg; Malta; Netherlands; Poland; Portugal; Romania; Slovakia; Slovenia; Spain; Sweden
East Asia	China; Japan; Korea; Taiwan
Rest of the World	Australia; Canada; India; Indonesia; Mexico; Russia; Turkey; WIOD's Rest of World aggregated

CALCULATING EXPORTS OF VALUE ADDED

We calculate the exports of value added based on the WIOD IIO tables and a methodology developed in Johnson and Noguera (2012), Powers (2012), and Koopman, Wang, and Wei (2014). First, we used the tables to calculate the direct value added in the final stage of production of each sector in each country. We repeated this calculation of value added for the imported and domestic intermediate products that were used in this final stage of production, and then for the intermediate products that were used in each prior stage of production, until the full value of the final products was allocated among all of the countries of origin. The Appendix provides a technical description of these calculations. In the remaining sections, we present the results of these calculations.

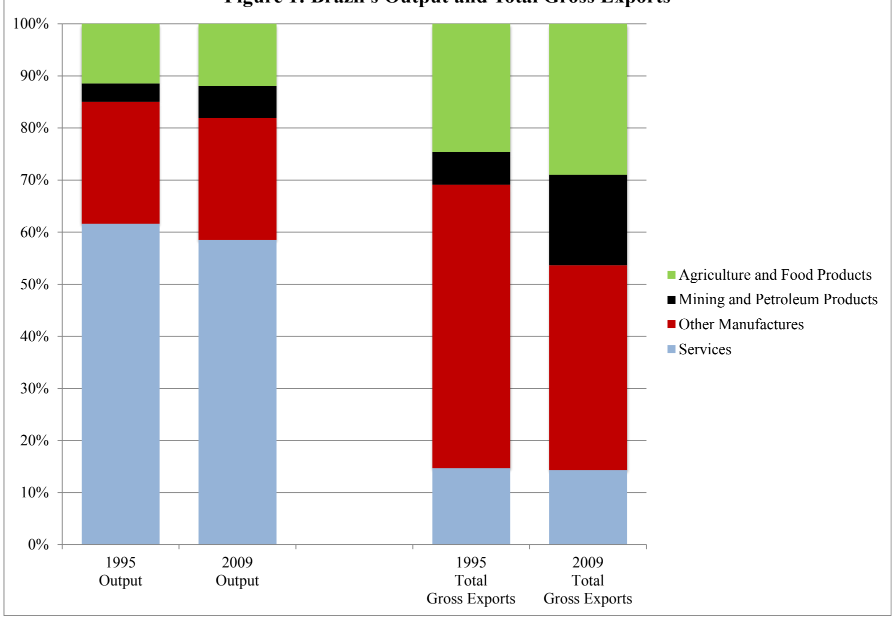
SHIFTS IN THE PRODUCT SHARE OF EXPORTS

The data from the WIOD suggests that the Brazilian economy has increased its participation in global trade over the fifteen-year period, and the types of products exported have shifted as well. Table 2 and figure 1 report WIOD-based estimates of the value of Brazil's output and gross exports for the four product groups in 1995 and 2009 (in 2009 U.S. dollars). According to the WIOD data, Brazil exported 4.4 percent of its output in 1995, and this share rose to 6.3 percent by 2009. Additionally, there were modest changes in the product shares of Brazil's output but more significant shifts in the product shares of the country's gross exports. Mining and petroleum products rose as a share of Brazil's output (from 3.6 to 6.1 percent) and as a share of Brazil's exports (from 6.3 to 17.4 percent). There was also a significant increase in the share of agriculture and food products in gross exports (from 24.6 to 29.0 percent) and a decline in the share of the other manufactures product group exports, but there was little change in the two groups' shares of total output. There were only small changes in the output and export shares of services.

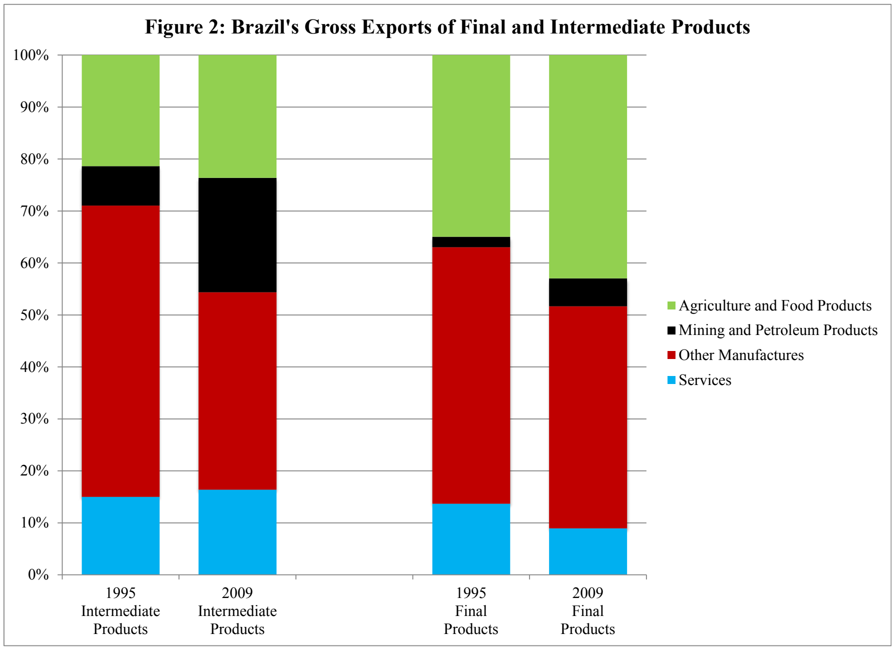
TABLE 2 Brazil's Output and Gross Exports by Sector

Output (Billions of 2009 US Dollars)	**Agriculture and Food Products**	**Mining and Petroleum Products**	**Other Manufactures**	**Services**
Value in 1995	193.9	60.1	395.7	1,043.1
Value in 2009	337.9	172.9	661.1	1,650.4
Average Annual Growth Rate	5.0	12.5	4.5	3.9
Gross Exports of Intermediate Products (Millions of 2009 US Dollars)	**Agriculture and Food Products**	**Mining and Petroleum Products**	**Other Manufactures**	**Services**
Value in 1995	12.2	4.3	31.9	8.5
Value in 2009	30.2	28.2	48.6	20.9
Average Annual Growth Rate	9.88	36.65	3.48	9.68
Gross Exports of Final Products (Millions of 2009 US Dollars)	**Agriculture and Food Products**	**Mining and Petroleum Products**	**Other Manufactures**	**Services**
Value in 1995	6.3	0.4	8.9	2.5
Value in 2009	21.1	2.6	21.0	4.4
Average Annual Growth Rate	15.7	41.6	9.1	5.2

Figure 1: Brazil's Output and Total Gross Exports



The growing importance of Brazil's exports of intermediate mining and petroleum products becomes more apparent as we further disaggregate the gross export data into exports of intermediate and final products (figure 2).[7] The largest gains in product shares were in the country's exports of intermediate mining and petroleum products (from 7.6 to 22.0 percent) and its exports of final agriculture and food products (from 35.0 to 42.7 percent). The largest declines in product shares were in Brazil's exports of intermediate and final manufactures.



SHIFTS IN THE REGIONAL SHARE OF EXPORTS

There were also large shifts in the regional shares of Brazil's exports over the fifteen years. Table 3 reports the shifts in the shares of the four destination regions for Brazil's gross exports and its exports of value added.[8] The combined share of the European Union and the United States declined according to both of these measures, while the combined share of East Asia and the Rest of the World rose. The largest shift was in Brazil's gross exports of final products: the share exported to the United States declined by 15.1 percentage points and the share exported to the European Union declined by 10.1 percentage points. In contrast, the share exported to

[7] Overall, intermediate products account for approximately three-fourths of Brazil's gross exports.

[8] The export values in this table are aggregates of the four product groups.

the Rest of the World countries rose by 26.2 percentage points.[9] This reflects the higher growth rates in the final expenditures in the Rest of the World.[10]

TABLE 3 Regional Shares of Brazil's Gross and Value-Added Exports

Gross Exports Final Goods and Services	European Union	United States	East Asia	Rest of the World
Percentage in 1995	34.15	23.69	7.97	34.18
Percentage in 2009	24.05	8.63	6.91	60.40
Percentage Point Change	-10.10	-15.06	-1.06	+26.22
Gross Exports Intermediate Goods and Services	**European Union**	**United States**	**East Asia**	**Rest of the World**
Percentage in 1995	33.70	14.94	12.35	39.00
Percentage in 2009	28.69	10.63	24.59	36.08
Percentage Point Change	-5.01	-4.31	+12.24	-2.92
Value-Added Exports	**European Union**	**United States**	**East Asia**	**Rest of the World**
Percentage in 1995	33.87	18.80	12.04	35.28
Percentage in 2009	27.30	12.81	17.46	42.43
Percentage Point Change	-6.57	-5.99	+5.42	+7.15

Brazil's integration into the upstream part of global value chains has also increased over the period. The share of Brazil's intermediate product exports shipped to East Asia rose by 12.2 percentage points, while the shares of the other three regions declined. This reflects the significant shift in global manufacturing to East Asia during that period, as the region became the preferred assembly location in many global value chains.[11]

When measured in terms of exports of value added, the shifts in the shares of the regions were less dramatic. The Rest of the World countries' share of Brazil's exports of value added rose (reflecting the large increase in gross exports of final products), as did the East Asian share of Brazil's exports of value added (reflecting the increase in East Asia's share of Brazil's gross

[9] Due to the limitations of the country detail in WIOD, the Rest of the World region includes Brazil's trade partners in South America. The trade flows to these countries are not reported separately in WIOD.

[10] Appendix table 1, based on WIOD data, reports that the share of the Rest of the World countries in global final expenditures (outside of Brazil) rose from 20.4 percent in 1995 to 27.1 percent in 2009, while the shares of the other three regions declined.

[11] Appendix table 2, also based on WIOD data, reports that East Asia's share of global manufacturing output (outside of Brazil) rose from 29.5 to 38.0 percent. The measure of manufacturing output in this table includes all of the sectors in the Other Manufactures product group in table 1 as well as the food, beverage, and tobacco sectors and the coke, refined petroleum and nuclear fuel sectors.

exports of intermediate products). However, the magnitude of each of these shifts in shares of value-added exports was smaller than the shift in final exports in the case of the Rest of the World and the shift in intermediate exports in the case of East Asia. This suggests that the redirection of Brazil's exports to East Asia had only a limited effect on the ultimate destination of value added in Brazil. These exports have been increasingly incorporated into East Asia's exports to the United States and the European Union.

Another way to summarize the shifts in Brazil's exports of value added is to examine the path that they traveled to reach consumers in the United States. Table 4 focuses on exports of value added from Brazil that were used to produce final goods and services that were ultimately consumed or were invested as capital goods in the United States. The table reports the shares of Brazil and the four regions. Over the fifteen-year period, the largest decline was in the share of final product exports from Brazil, which declined by 11.8 percentage points. The share of final product exports from East Asia rose by 4.7 percentage points, while the share of domestic final product shipments in the United States rose by 4.4 percentage points.[12] The combined share of the other two regions rose by 2.7 percentage points.

TABLE 4: Value Added in Brazilian Production That is Consumed in the United States

Share of Brazil's Value Added By the Region of Final Stage Production for Final Use in the United States	Percentage in 1995	Percentage in 2009	Percentage Point Change
U.S. Imports from Brazil	30.04	18.29	-11.75
U.S. Domestic Shipments	58.94	63.30	+4.36
U.S. Imports from East Asia	1.90	6.57	+4.67
U.S. Imports from the European Union	2.20	3.09	+0.89
U.S. Imports from the Rest of the World	6.92	8.74	+1.82

CONCLUSION

Over the fifteen years covered by WIOD, Brazil's exports shifted toward mineral and agricultural products and away from services and other manufactured products, further reinforcing the country's traditional areas of comparative advantage. By disaggregating the trade flows into intermediate and final products and then into the value-added contributions of each country of origin, we have been able to document the shifts in Brazil's exports across products and

[12] However, the share from U.S. producers remained much larger.

destination regions.[13] While Brazil's exports shifted to greater specialization in its traditional areas of comparative advantage, they shifted away from Brazil's traditional markets in the United States and European Union. The shift in the share of Brazil's gross exports to East Asia is more than twice the shift in the share of its exports of value added to East Asia.

Now that we have documented these shifts in Brazil's trade flows, the next step is to investigate the underlying economic causes of these shifts. We leave that for future research.

[13] It is also possible to analyze flows of value added on the import side, though that has not been the focus of this paper. The foreign share of value added in Brazil's output measures the share of Brazil's costs of production that accrue to factors of production in other countries through the purchase of imported intermediate products. Appendix table 3 reports the foreign shares of the value added in each of the product groups. The other manufactures group recorded the largest increase in share. Its foreign share of value added rose from 9.7 percent in 1995 to 13.1 percent in 2009. The foreign share of value added rose in the agriculture and food products group and in the services group but declined slightly in the mining and petroleum products group. On average across the four product groups, the foreign share of value added in Brazil's output rose from 5.5 percent in 1995 to 7.4 percent in 2009. In comparison, the foreign share of value added in the output of the East Asian countries was higher and increased more: it rose from 7.3 percent in 1995 to 16.2 percent in 2009.

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APPENDIX

This technical appendix describes the method for calculating a country's exports of value added using the WIOD IIO tables. The tables report how the output of each sector in each country is allocated across many alternative uses, including use as an intermediate input in each sector in the same country, as exports to other countries, and as final goods or services in private consumption, government consumption, and capital formation in each country. WIOD provides estimates of the intermediate use columns of the table, which are represented by the *NC* by *NC* matrix *A*. *N* represents the number of sectors, and *C* represents the number of countries. The *NC* by *C* matrix *X* represents the value of output in each sector and country in a year. Given these definitions, the value of output in each sector and country is the sum of its intermediate uses, *AX*, and its final uses.

$$X = AX + F \tag{1}$$

The *NC* by *N* matrix represents *F* the final use in each country of the output of each sector and country. Equation (2) is the solution for *X*.

$$X = (I - A)^{-1} F \tag{2}$$

The matrix *I* is an *NC* by *NC* identity matrix. $(I\text{-}A)^{-1}$ is commonly called Leontief's Inverse. The matrix *X* is converted into a measure of the value added in each country of origin in the final use category of the destination country by multiplying by a *C* by *NC* matrix *V* that contains the shares of direct value added in the output of the sectors in each country. Equation (3) focuses specifically on value added that enters final use in destination country *d*.

$$M_d = V(I - A)^{-1} F_d \tag{3}$$

The *C* by 1 vector M_d is the direct and indirect value added of each country in the final use of goods and services in country *d*, and the *NC* by 1 vector F_d is the final use expenditures of country *d*. The vector M_d includes domestic shipments of value added in the final use expenditures of country *d* as well as exports of value added from other countries to country *d*.

APPENDIX TABLES

APPENDIX TABLE 1 Regional Share of Final Expenditures Outside of Brazil

Regional Share of Final Expenditures	Percentage in 1995	Percentage in 2009	Percentage Point Change
East Asia	23.71	19.31	-4.40
European Union	30.21	28.08	-2.13
United States	25.72	25.53	-0.19
Rest of the World	20.37	27.07	+6.70

APPENDIX TABLE 2 Regional Share of Manufacturing Output Outside of Brazil

Regional Share of Manufacturing Output	Percentage in 1995	Percentage in 2009	Percentage Point Change
East Asia	29.52	38.03	+8.51
European Union	30.24	24.78	-5.46
United States	20.81	14.56	-6.25
Rest of the World	19.42	22.62	+3.20

APPENDIX TABLE 3 Foreign Share of Value Added in Brazil's Output

Foreign Share of Value Added in Brazil's Output	Percentage in 1995	Percentage in 2009	Percentage Point Change
Agriculture and Food Products	5.28	7.54	+2.26
Mining and Petroleum Products	14.84	13.45	-1.39
Other Manufactures	9.70	13.11	+3.41
Services	3.35	4.51	+1.16

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U.S. International Trade Commission's High-Technology Roundtable: Discussion Summary

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April 2014

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Abstract

On July 16, 2013, the U.S. International Trade Commission (USITC) hosted its third annual roundtable discussion on high-technology trade issues. Representatives from industry, government, and think-tanks shared their views on a number of high-technology (high-tech) trade issues.

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INTRODUCTION

The USITC's high-tech trade roundtable provides a forum for discussions with industry, government, and academic participants that enhances the USITC's understanding of current and potential issues in high-tech trade. Advanced manufacturing and U.S. competitiveness were covered during the first part of the roundtable; standards as non-tariff measures (NTMs) were addressed in the second part. Several major issues were discussed, including key factors driving U.S. competitiveness in advanced manufacturing, different national systems and approaches to support innovation in advanced manufacturing, challenges in operating under different national standards, and the use of standards as NTMs. A summary of this discussion follows.

ADVANCED MANUFACTURING AND U.S. COMPETITIVENESS

Key Factors of Competition

Four different key factors driving U.S. advanced manufacturing competitiveness were identified: funding and finance, infrastructure, education and labor force, and government initiatives and programs.

Funding and finance

Participants noted that the U.S. market has historically been an excellent place to acquire financing for new innovations. However some actors in U.S. manufacturing who are attempting to upgrade or develop new technologies have funding difficulties due to the temporary nature of government funding and support measures. Participants observed that the main industries which draw venture capital (VC) funding in the high-tech manufacturing sector right now are information technology, biomedical, and various advanced manufacturing technologies like additive manufacturing. One participant mentioned that cell phone applications are a major recipient of VC funding. Participants involved in the production of medical devices noted VC firms are less willing to invest in their industry because of the length and the uncertain outcome of the government's product approval process. Some participants stressed that a decline in the amount of government funding for universities and research institutes is a possible constraint for U.S. advanced manufacturing innovation.

Infrastructure

Participants emphasized that high-tech infrastructure, such as smart grids, will become more important as advanced manufacturing continues to progress. One participant noted that using current technologies such as smart meters, IT sensors, and intelligent process controls, many industries could save 15-30 percent of their energy costs.

Education and labor force

Roundtable participants noted that, while advanced manufacturing may eventually decrease overall labor demand, there is actually strong demand now. It was stressed that the skill gap between the type of worker needed and the type of worker available is a major impediment to U.S. competitiveness. Two broad groups of skilled workers are in demand: those educated at the university level in science, technology, engineering, and mathematics (STEM), as well as workers with education in mechanical and technical skills (such as welders). Several participants argued that the U.S. education system needs to encourage students to pursue STEM and other technical degrees, both at the secondary and tertiary levels, in order to meet demand for manufacturing labor in the future.

Government programs and initiatives

Attendees highlighted several positive areas of U.S. government support for the high-tech industry: openness in research and development (R&D), accessible regulatory development processes, and internet communications. They also mentioned that spillovers from U.S. defense spending on R&D are another driver of innovation. Participants discussed areas in which U.S. government support could be implemented or improved. Some participants mentioned the need for a permanent R&D tax credit as well as more R&D funding. Participants stressed the importance of the predictability of these policies, as uncertainty and temporary policies impede firms' ability to make long-term investment decisions. Relatively strict regulations and lengthy approval processes were also cited as barriers for U.S. advanced manufacturing, especially in the medical devices industry. In general, participants agreed that government programs and initiatives had major effects on U.S. innovation. However, a few participants argued that the main driver of innovation in the United States is the business environment. Key features of the U.S. business environment that are beneficial to innovation include productivity gains from a deep U.S. services industry, an ability to quickly change business structures to take advantage of new technologies, and a variety of physical and virtual research and design clusters.

Open-Market Model vs. Directed-Funding Approach

Participants engaged in a debate on the merits of different national models for driving innovation. This discussion centered around two major models: open-market, in which innovation funding is undirected and concentrated in the research phase, and directed-funding, in which innovation funding is targeted at specific industries chosen by the government and is concentrated in both the research and the application phases. Participants noted that while the directed-funding approach can lead to faster development of the industries receiving benefits, the open-market approach is preferable because: (1) specific targeting of certain industries generally causes no substantial benefit while dramatically increasing the cost of failures, (2) directed-funding often is accompanied by centralization and policies that favor targeted or local industries, and (3) the broad availability of funding and transparency in the open-market approach helps drive major innovations in areas where they may not be expected.

Different Government Support Approaches

Attendees observed that developed countries are more likely to follow the open-market approach, while developing countries often use the directed-funding model. Participants noted it is more challenging to operate in developing markets because of a less open business environment and heavy policy preferences for domestically produced goods. Several participants suggested that the U.S. government and firms could encourage a more competitive and open environment in developing countries through deeper engagement with local firms and policy officials, listening to local perspectives, and sharing their best practices and expertise with local firms.

STANDARDS

Current Trade Agreement Negotiations

The discussion started with a short briefing on the progress of the Transatlantic Trade and Investment Partnership (TTIP) and Trans-Pacific Partnership (TPP) negotiations in regards to harmonization of standards. Participants emphasized the importance of including language ensuring an open and transparent standards development process. Most participants also noted that harmonization of standards is in the best interests of all parties involved in the negotiations. They suggested that working with businesses to harmonize standards could help the negotiation process, as many businesses operate in multiple markets and would greatly benefit from harmonized standards. As a specific example, one participant noted that the adoption of harmonized standards in electronic products would significantly expand EU-U.S. trade. Contrary to this, a few participants commented that large firms can deal with up to two systems of standards without facing major challenges, as long as they are well developed and enforced.

Development of International Standards

Some participants stated that the adoption of international standards provides significant benefits to global and regional trade by lowering costs. Trade agreements such as TTIP and TPP will help to accelerate the development of harmonized international standards. Most expressed the need for more business involvement in developing new standards, by adopting a framework in which standards originate from industry best practices. The pharmaceutical, insurance, and chemical industries were all mentioned as cases in which business rather than government actors are driving the development of international standards. Other participants reported upcoming workshops to help give the private sector more input in standards development in the TTIP negotiations.

Standards as NTMs

Participants mentioned a variety of ways in which standards are used as NTMs. Two major barriers mentioned were local sourcing and compulsory licensing requirements. Industry participants pointed to these as major concerns in countries where intellectual property rights are less strongly protected. Other standards-related barriers mentioned included limited transparency in standards development, few opportunities to provide input on international standards compared to domestic standards, and countries taking a long time to adopt international standards. Many participants pointed toward the Brazilian, Russian, Chinese, and Indian markets as examples of where these barriers are an issue. Some participants noted efforts are being made by firms and organizations operating in China to open up the standards development process. Attendees also discussed how small and medium enterprises (SMEs) are negatively affected by standards and other NTMs to a greater extent than larger firms. SMEs generally do not have a strong voice in the development of international standards because they are often too immersed in day-to-day operations and lack the time and resources to assert their perspectives. While greater access to information and communications technology as well as more flexible and open standards can mitigate these effects to a certain extent, a concentrated effort by organizations and governments is needed to insure that SMEs are included in the development of international standards.

FINAL COMMENTS

Participants at the high-tech roundtable discussed ways in which the competitiveness of U.S. advanced manufacturing could be improved, debated the merits of different government approaches to supporting innovation, and described the importance of business involvement in standards development as well as the use and effects of standards on trade. They advocated for more collaboration between industry and government, sharing of best practices across industries and geographies, improved infrastructure and educational systems, and increased transparency in government initiatives and international standards setting. Other issues mentioned but not covered in detail included the possible effect of new financial regulations on the private sector’s funding of innovation, effects of the U.S. export control system for defense-related and dual-use goods and technologies limiting spillover from defense R&D spending, and how the lack of a U.S. territorial tax system impacts exports.

LIST OF EXTERNAL PARTICIPANTS AT THE USITC'S HIGH-TECHNOLOGY TRADE ROUNDTABLE HELD ON JULY 16th, 2013

Thomas Campbell	Associate Director Institute for Critical Technology and Applied Science Research Associate Professor Virginia Tech
Linda Dempsey	Vice President of International Economic Affairs National Association of Manufacturers
Ed Gresser	Director at ProgressiveEconomy GlobalWorks Foundation
Kathryn Hauser	Principal Somerset Partners LLP
Ralph Ives	Executive Vice President of Global Strategy and Analysis AdvaMed
Justin Koester	Senior International Relations Specialist Medtronic
Welby Leaman	Trade Counsel House Ways and Means Committee
Bill Morin	Director of Government Affairs Applied Materials
Ken Salaets	Director of Global Policy Information Technology Industry Council
Fran Schrotter	Senior Vice President and Chief Operating Officer American National Standards Institute
Neena Shenai	Trade Counsel House Ways and Means Committee
Jennifer Stradtman	Director of Technical Barriers to Trade Office of the United States Trade Representative
Craig Updyke	Manager of Trade and Commercial Affairs National Electrical Manufacturers Association
Jeff Weiss	Senior Advisor for Standards and Global Regulatory Policy Office of the Secretary Department of Commerce
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Who Financed Recent U.S. Trade Deficits?

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Abstract

Some popular and academic economic explanations of the U.S. trade deficit since 1998 emphasize U.S. private borrowing or foreign private interest in investing in the United States. This paper shows basic U.S. government data that demonstrate that foreign governments have been major financers of the U.S. trade deficit in the 2000s. In this light, it considers several explanations of recent U.S. trade deficits to see if they match these basic data.

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[1] This article represents solely the views of the author and not the views of the United States International Trade Commission or any of its individual Commissioners. This paper should be cited as the work of the author only, and not as an official Commission document. The author thanks Harold Brown and the JICE referees for their contributions. All errors are the author's. Please direct all correspondence to John Benedetto, Office of Economics, U.S. International Trade Commission, 500 E Street, SW, Washington, DC 20436, or by email to *John.Benedetto@usitc.gov.*

INTRODUCTION

The United States ran large and persistent trade deficits over 1998–2012. Many modern U.S. trade economists tend to attribute the causes of trade (and current account) deficits to macroeconomic factors such as differential savings rates in domestic and foreign markets. On the basis of this differential savings rate explanation, some economists and other commentators have portrayed the U.S. trade deficit in the 2000s as due to an "ant and grasshopper" story[2] in which the grasshopper (American consumers, or in some versions, the U.S. government[3]) went on a borrowing binge while the ants (workers in other countries) worked hard and saved. Alternatively, other economists and commentators argue that foreigners' craving for U.S. dollars and U.S. dollar assets, due to their desire to invest in the innovative U.S. economy, explains the U.S. trade deficit.

Basic data from the U.S. Department of Commerce's Bureau of Economic Analysis (BEA) and the U.S. Department of the Treasury (Treasury) cast doubt on the idea that either an "ant and grasshopper" story or private-market foreign investment alone accounts for the massive U.S. trade deficits (and corresponding U.S. capital account surpluses) of 1998–2012. Instead, these data show that foreign governments accounted for an unprecedented level of financing[4] of the U.S. current account deficit. Thus, any explanation of U.S. trade deficits over 1998–2012 either must include a large role for foreign government financing, or find that such foreign government financing was performing the same role as private foreign financing would have.

This paper also considers other explanations for the U.S. current account deficit in light of these basic data.

U.S. CURRENT ACCOUNT DEFICITS, 1998-2012

A nation's trade balance (exports minus imports) is usually the largest single component of its current account balance, which also measures investment returns and unilateral transfers in and out of the nation's economy. In recent U.S. economic history, the trade deficit is the largest component of its current account deficit, and so the two terms are virtually synonymous. If one wishes to lower the U.S. current account deficit substantially, one will most likely need to lower the U.S. trade deficit substantially.

The United States began running large current account deficits (as a share of U.S. gross domestic product, or GDP) in the 1980s. Those deficits shrank somewhat in the late 1980s and early

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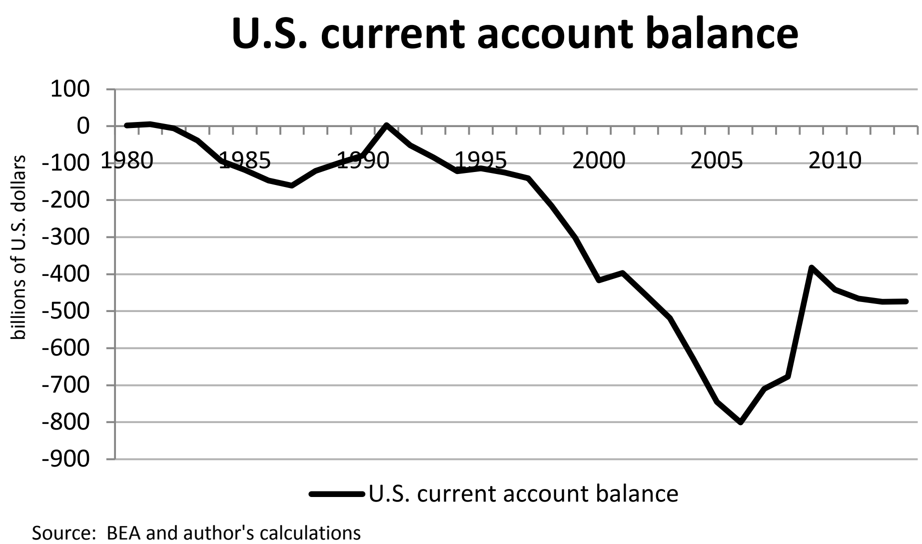
[2] "The Ant and the Grasshopper" is one of Aesop's fables, and the relevant portions are summarized below.

[3] See, for example, Riley, "Federal Spending and the Trade Deficit," July 2011.

[4] As will be discussed later, Borio and Disyatat propose defining financing differently than it is often defined in the economics literature on current account deficits. This author is referring to the more common use of the term for the purposes of this paper, while discussing Borio and Disyatat's alternate definition later. See Borio and Disyatat, "Global Imbalances and the Financial Crisis," May 2011.

1990s as the U.S. economy weakened, but grew again in the late 1990s and remained high until the economic collapse of 2009. With the onset of the modest recovery, current account deficits have returned almost to the levels of the 1980s, at somewhat less than 3 percent of GDP (figure 1).

FIGURE 1: The U.S. current account balance, as a percent of U.S. GDP



For most of U.S. history, U.S. trade was far more balanced than it is now. The United States ran nearly balanced trade until the 1980s, with only a brief period during 1942–1947 in which the United States ran large trade surpluses. In U.S. postwar history, trade overall was usually a small percentage of GDP, and the U.S. current account was roughly balanced, until approximately the late 1970s.[5]

During the more recent period of high and persistent U.S. current account deficits, many U.S. economists and commentators have offered the following two explanations for U.S. current account or trade deficits. Underlying both claims is the belief that trade deficits are not caused by

[5] The United States ran small trade deficits (usually less than 1 percent of gross national product) for the first half of the 19th century. Those deficits became surpluses in the last decades of the 19th century. In the 20th century, the United States ran trade surpluses of under 2 percent from 1929 to 1941. It then ran a trade surplus of over 3 percent of GDP from 1942–1947. The surplus fell to under 3 three percent of GDP in 1948 and 1949, and after 1950, remained under 1.6 percent of GDP, generally dwindling until it became a small deficit in the 1970s. USDOC, BEA, *Survey of Current Business*, July 1954 and August 1974, Lipsey, Robert. "U.S. Foreign Trade and the Balance of Payments, 1800-1913," and author's calculations.

microeconomic factors, such as tariff rates or industrial competitiveness, but rather by international capital flows.[6]

First, some commentators have argued that U.S. trade deficits mostly reflect what this paper will refer to as an "ant and grasshopper" story in which the U.S. trade deficit is largely a symptom of low U.S. savings and high foreign savings.[7] In this sense, the United States resembles Aesop's grasshopper while foreign countries are the thrifty ants. For example, economist Gregory Mankiw has stated:

> *My view is that the trade deficit is not a problem in itself but is a symptom of a problem. The problem is low national saving. Given that national saving is low, I am not eager for the trade deficit to disappear, because that would mean that domestic investment would need to fall to the low level of national saving. But I do think it would be good if the trade deficit were to disappear accompanied by an increase in national saving.*[8]

Similarly, Laurence Kotlikoff argues that trade deficits only reflect a problem insofar as they reflect inadequate national savings, but may otherwise reflect investment flows that are positive for a nation's long-term growth.[9] Other commentators, such as Stephen Roach of Morgan Stanley Asia and Yukon Huang of the Carnegie Endowment, have tied the U.S. trade deficit to increased U.S. consumption independent of Chinese (among other trading partners') policies, just as they assert that China's large trade surplus is due to high Chinese saving, without always explaining which sectors (households, businesses, and government) account for what share of that saving.[10]

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[6] A summary of this point of view is contained in Daniel Griswold's 1998 piece "America's Maligned and Misunderstood Trade Deficit." In addition to other points, Griswold returns to the writings of Adam Smith and David Hume to argue against concerns over trade deficits, connecting recent periods of shrinking U.S. trade deficits to U.S. recessions. Griswold's arguments are also based on the work of trade economist Douglas Irwin—e.g., Irwin's 1996 publication for the American Enterprise Institute, *Three Simple Principles of Trade Policy.* Also see the statement by the San Francisco Federal Reserve that "by the national income identity . . ., a trade deficit is caused by a change in national saving or investment or both." Federal Reserve Bank of San Francisco, "Is the U.S. Trade Deficit a Problem?" June 2007. Some of these commentators (e.g., Griswold and Irwin) have also posited that, whatever the reasons, trade deficits do not matter (an issue beyond the scope of this paper). This point of view contrasts with the traditional Keynesian view that trade deficits represent a loss of aggregate demand. See Palley, "Explaining Global Imbalances," November 2011.

[7] At some level, this kind of argument may just be a restatement of an accounting identity, as Ian Fletcher argues. See Fletcher, "The Fiscal Cliff and the Trade Deficit," November 2012.

[8] Mankiw, "Is the U.S. Trade Deficit a Problem?" March 31, 2006.

[9] Kotlikoff, "Trade Deficits Are a Problem If," 2011.

[10] See Crawshaw, "Roach: U.S. Should Save, China Spend," November 2008; Roach, "America's Renminbi Fixation," April 2012. There is also an economics literature that attempts to explain China's trade surplus as a product of factors other than the fact that the Chinese government simply not allowing foreign exchange to recirculate freely, as it does not. Those interested in this literature can see a summary at Trachtman, "Understanding China's Trade Surplus," 2012, or an example at Wen, "Explaining China's Trade Imbalance Puzzle," 2011.

In some versions of the "ant and grasshopper" view, trade policy (the setting of tariffs and quotas) is also described as having little role in increasing U.S. trade deficits. For example, in 1996, economist Douglas Irwin wrote that "the United States may have a relatively open market and foreign markets may be more closed, but these facts would not manifest themselves in the trade balance."[11]

In a second explanation offered for high U.S. trade deficits, other commentators have argued that U.S. trade deficits have reflected foreign beliefs that the United States is (or was) a great place to invest, in part due to high U.S. growth rates. Under this argument, the U.S. trade deficit is a positive indicator that foreigners wish to invest their money in one of the most innovative and productive economies in the world. For example, in 1998, Dan Griswold of the Cato Institute stated that "trade deficits may even be good news for the economy because they signal global investor confidence in the United States and rising purchasing power among domestic consumers."[12] Thus, according to this explanation, the United States should happily accept this investment.[13]

FOUR POINTS FROM BASIC DATA THAT ADDRESS THESE THEORIES

Basic U.S. government data cast some doubt on both the "ant and grasshopper" story and the "foreigners love U.S. investment opportunities" story as complete explanations for the large U.S. trade deficits over 1998–2012. U.S. government data make it possible to examine who was buying U.S. assets in the period and what was the minimum being bought by foreign governments. The data show that foreign governments—not just foreign private buyers—were substantial buyers of U.S. assets over 2002–2012. The large increase in foreign government buying of U.S. assets in 2002 suggests that a complete explanation of the recent U.S. trade deficit should give substantial weight to the shift in the activities of non-market actors, i.e., governments that may not be financing U.S. projects solely for the return on investment.[14] The "ant and grasshopper" and "foreigners love U.S. investment opportunities" stories may capture part of the reason for U.S. trade deficits, but they may also not give adequate emphasis to the role of foreign governments.

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[11] Irwin, *Three Simple Principles of Trade Policy,* 1996.

[12] Griswold, "America's Maligned and Misunderstood Trade Deficit," 1998. See also the Kotlikoff analysis noted earlier ("Trade Deficits Are a Problem If," 2011).

[13] Palley discusses other ways that some U.S. economists have downplayed concern over U.S. trade deficits, attributing U.S. trade deficits to, for example, the allegedly faster U.S. rates of technological innovation during the late 1990s and early 2000s. Palley, "Explaining Global Imbalances," November 2011.

[14] Treasuries are bought in a market, but the foreign government buyers are non-market actors, i.e., their motivations may not be market motives.

Four major data and interpretive points illustrate the large role foreign governments have played in financing recent U.S. trade deficits.

Point 1: Foreigners Were Significant Financers of the Growth in U.S. Government Debt in the 2000s

One portion of total U.S. debt is held by the federal government.[15] Some argue that, because the majority of the federal government debt is held by U.S. citizens, foreign and international holdings of U.S. government debt are not significant. For example, National Public Radio (NPR) put on its website a graph showing the breakdown of who owns U.S. government debt, with foreigners only owning approximately one-third of such debt.[16]

However, these arguments and presentations obscure the fact that a large part of U.S. government debt has long been held by U.S. citizens. Thus, the current level of U.S. government debt starts from a base of high domestic ownership. During the growth in the U.S. current account deficit after 2001, however, foreign and international sources were the buyers of over 40 percent of the net increase in U.S. government debt.

Table 1 shows total foreign ownership of U.S. Treasury securities from 1989–2012. Numbers for each year are cumulative. As can be seen from the table, as of December 1993, foreign and international sources owned about 14 percent of U.S. Treasury securities outstanding. By December 2012, foreign and international sources owned over 33 percent of U.S. Treasury securities outstanding. For this cumulative change to occur, foreign and international sources needed to be larger buyers of U.S. Treasuries after 1993 than prior to that year. As can be seen in the table 1, the largest change in relative foreign purchases of U.S. Treasuries occurred between December 2001 and December 2012, a period in which foreign and international sources purchased over 43 percent of all U.S. Treasury securities issued.

Table 1, however, only shows that foreign and international sources were major buyers of U.S. government debt, and not whether those foreign and international sources were governments or private citizens. According to other U.S. Treasury data, as of January 2014, foreign governments accounted for over 71 percent of total foreign holdings of U.S. Treasury securities, making foreign governments likely responsible for a large share of the increasing foreign and international interest in U.S. government debt.[17]

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15 Total U.S. debt would also include household and business debts.

16 Bui, "Everyone the U.S. Government Owes Money To," October 2013. NPR is using data from the General Accounting Office (GAO).

17 U.S. Treasury "Major Foreign Holders of U.S. Treasury Securities," (accessed May 2014) and author's calculations.

TABLE 1 Total foreign and international ownership of Treasury securities during 1993–2012

Year	Total Public Debt	Owned by foreign and international[1]	Percent foreign and international
	Billions of dollars		*Percent*
1993	4,536	650	14.3
1994	4,800	667	13.9
1995	4,989	835	16.7
1996	5,323	1,102	20.7
1997	5,502	1,242	22.6
1998	5,614	1,279	22.8
1999	5,776	1,269	22.0
2000	5,662	1,034	18.3
2001	5,943	1,051	17.7
2002	6,406	1,247	19.5
2003	6,998	1,523	21.8
2004	7,596	1,849	24.3
2005	8,170	2,034	24.9
2006	8,680	2,103	24.2
2007	9,229	2,353	25.5
2008	10,700	3,077	28.8
2009	12,311	3,685	29.9
2010	14,025	4,454	31.8
2011	15,223	5,007	32.9
2012	16,433	5,574	33.9
Difference, 2012 and 2001	10,489	4,523	43.1

[1]"Foreign and international" is the heading used by the Treasury in the source data. It likely reflects that the Treasury does not know with complete certainty whether certain holdings are from certain countries, as will be discussed further below in the text.

Source: U.S. Department of the Treasury, Ownership of Federal Securities, 1999, 2004, 2009, and 2013, and author's calculations.

Point 2: Foreign Government Holdings of U.S. Government Debt Are Likely Even Higher Than the Data Show

Data on foreign government holdings of U.S. government debt are almost certainly a minimum rather than an exact measure. In particular, data for one of the largest holders of U.S. Treasury debt, China, may be underestimated.

As of June 2012, China held over $3.2 trillion in total foreign exchange reserves, and it is likely that roughly two-thirds of those holdings are in U.S. dollars. (The exact percentage is not known except by the Government of China. However, in 2010, *Chinadaily* reported that the IMF estimated that 61 percent of China's 2010 currency reserves were in U.S.-dollar assets, while calculations based on U.S. Treasury data yielded an estimate of 66 percent.)[18] These estimates would yield Chinese holdings of U.S. dollars well above the level of Chinese holdings of U.S. Treasuries reported by the U.S. Treasury. This discrepancy means that China is either holding dollars in other forms and/or that the Treasury data are not capturing all of China's holdings.

Treasury data on how much U.S. government debt that China holds is likely a minimum, and the actual level could be much higher. Economist Brad Setser, before joining Treasury, noted in 2009 that "[t]he US only tracks the initial sale of a bond to an investor abroad. Subsequent sales never [enter] into the TIC [Treasury] data, though they are often picked up in the annual survey."[19] For example, if a U.K. (or Caribbean, or Swiss, or Belgian, etc.) bank purchased Treasuries for the Chinese government, that purchase might be recorded in U.S. Treasury data as a U.K. purchase, rather than a Chinese purchase.

In June 2011, Reuters reported that Treasury investigations had found that China had been buying more U.S. debt than it had disclosed.[20] Additionally, in 2012, Reuters reported that China was now purchasing Treasury debt as a primary dealer, a category previously reserved for select U.S.-based banks.[21] It is quite possible then, that there is underreporting of Chinese holdings (due to the results of the Treasury investigation), and China's importance as a buyer should not be underestimated (due to China's status as a primary dealer).

These first two sections have shown that foreign governments were substantial purchasers of U.S. government debt in recent years. As noted above, however, Treasury debt only shows us what is happening with U.S. government debt, and not how total U.S. government and private debt is financed. The next section will show how the entire U.S. current account deficit, including both U.S. government and U.S. private debt, is financed by both foreign private and foreign government sources.

Point 3: Foreign Governments Were Substantial Buyers of U.S. Assets

Foreign governments finance a large part of the U.S. current account deficit. In the U.S. international transaction data, there are usually higher foreign private investment flows than foreign government investment flows into the United States. However, focusing on just these levels would obscure the fact that there are also high U.S. private investment flows into foreign countries,[22] while the U.S. government has tended not to have large investments overseas. For

[18] See Bloomberg, "China Quarterly Reserves Have First Decline," January 2012; Ming, "US Debt in China's Forex Reserves Worrisome," May 2011.

[19] Setser, "I Am Pretty Sure China Didn't Sell Treasuries in April," June 2009.

[20] Flitter, "U.S. Caught China Buying More Debt than Disclosed," June 2011.

[21] Flitter, "U.S. Lets China Bypass Wall Street for Treasury Orders," May 2012.

[22] This type of misleading analysis will be seen in Borio and Disyatat, "Global Imbalances and the Financial Crisis," May 2011, below.

the current account deficit, what matters is not just the level of investment inflow, but rather the net investment flows, i.e., U.S. investment outflows net of foreign investment inflows.[23]

By looking at U.S. and foreign net investment flows, the role of foreign government investments as a large financer of the U.S. trade deficit becomes clear. While there are large foreign private inflows into the United States, these flows are often cancelled out, at least in part, by large U.S. private investment outflows. What has allowed the U.S. current account deficit to remain large is the difference between large foreign government inflows and usually small U.S. government outflows.

Using BEA data on international transactions, we can identify how much U.S. private and U.S. government investment went overseas as well as how much foreign private and foreign government investment flowed into the United States. Table 2 shows how net private and net government assets finance the U.S. current account deficit. As can be seen, net government assets (foreign government assets in the United States less U.S. government assets overseas) financed a substantial portion of the U.S. current account deficit in the 2000s, and continued to do so after the Great Recession. During and after the recession, the U.S. government engaged, for the first time during the period shown (1993-2012), in large purchases of overseas assets, perhaps contributing to the outlier values in 2008 and 2009.[24]

Overall, the numbers in table 2 lead to the following fact about the U.S. current account deficit over 2003 to 2012: during this period, 70 percent of the U.S. current account deficit was accounted for by the difference in net holdings between U.S. and foreign government holdings. Even if one were only to look at the period 2003 to 2007 (perhaps to avoid the extraordinary swaps that took place in 2008 and 2009), over 55 percent of the U.S. current account deficit was accounted for by the difference in net holdings between U.S. and foreign government holdings.

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[23] In the international transaction data, these investment flows show up in the financial account, not the current account. However, as discussed earlier, this paper is examining the U.S. current account deficit from the point of view of how it is financed.

[24] This analysis extends analysis from Labonte, "Financing the U.S. Trade Deficit," June 2009.

TABLE 2 Components of U.S. Current Account Deficit from 1993-2012

Year	Current account balance	Net private transactions	Net government transactions	Discrepancy[1]	Net government transactions / current account deficit
	billions of dollars				*percent*
1993	-84.8	9.2	73.5	-2.1	86.6
1994	-121.6	79.7	34.6	-7.3	28.5
1995	-113.6	-16.3	120.6	-9.3	106.2
1996	-124.8	2.1	121.0	-1.6	97.0
1997	-140.7	200.9	20.0	80.1	14.2
1998	-215.1	94.1	-12.7	-133.7	-5.9
1999	-300.8	183.1	32.0	-85.6	10.7
2000	-416.3	436.2	44.0	63.8	10.6
2001	-396.7	377.6	33.5	14.4	8.4
2002	-457.8	387.9	119.3	49.4	26.1
2003	-518.7	252.8	276.0	10.1	53.2
2004	-629.3	130.1	393.2	-106.0	62.5
2005	-739.8	421.8	239.6	-78.4	32.4
2006	-798.5	283.8	480.2	-34.5	60.1
2007	-713.4	152.4	503.4	-57.6	70.6
2008	-681.3	743.3	1,089.1	1,151.1	159.8
2009	-381.6	-783.2	-8.8	-1,173.6	-2.3
2010	-449.5	20.0	392.6	-36.9	87.3
2011	-457.7	382.4	373.4	298.1	81.6
2012	-440.4	-28.4	313.1	-155.7	71.1

[1] Net private transactions plus net government transactions should equal the current account balance, but may not due to issues such as statistical discrepancies. In most years, these discrepancies would likely not change the analysis. In 2008, 2009, 2011, and 2012, there are large discrepancies. These large discrepancies may be due to Federal Reserve swaps conducted in those years. This use of the word "discrepancy" is not the same as that used by BEA when providing an explanation of its published data.

Source: BEA, and author's calculations.

Point 4: Foreign Government Currency Reserves Grew Dramatically in the 2000s

Foreign government currency reserves grew dramatically in the 2000s, and beyond normal historical levels. Table 3 shows the change in total reserves for selected[25] nations between 2000 and 2012, both in levels and as a percent of GDP. As can be seen, U.S. reserves did rise as a percent of

[25] These countries were selected to provide examples of some large U.S. trading partners in Europe, Asia, and South America.

GDP, but from one low level to another low level, and remained below the other countries' ratio of reserves to GDP in 2000. Meanwhile, other countries' governments increased their reserves not only in absolute terms but also in large amounts relative to the size of their national economies. These increases were far larger for the selected Asian countries, as well as Brazil, than for the selected European countries, with the exception of Switzerland.

TABLE 3 Total reserves for selected countries, 2000 and 2012

Country or reporting area	Total Reserves, 2000	Total Reserves, 2012
	Billions of dollars (percent of GDP)	
Brazil	33.0 (5.1)	373.2 (16.6)
China	171.7 (14.3)	3,387.5 (41.2)
France	63.7 (4.8)	184.5 (7.1)
Germany	87.5 (4.6)	248.9 (7.3)
Hong Kong	107.6 (62.7)	317.4 (120.6)
Japan	361.6 (7.6)	1,268.1 (21.3)
Korea	96.3 (18.0)	327.7 (29.0)
Switzerland	53.6 (20.1)	531.3 (84.2)
United States	128.4 (1.3)	574.3 (3.5)

Source: World Bank website, and author's calculations.

Based on the data presented in tables 2 and 3, it is highly likely that increased purchases of U.S. dollars played a large role in these increases in foreign governments' reserves. If so, then these increases in foreign governments' reserves are likely an important factor in understanding U.S. current account deficits in the 2000–2012 period. As the Congressional Research Service has noted, "[i]f… a government requires exporters to sell their dollars to the government at a fixed exchange rate, and that government invests the dollars in U.S. securities rather than allowing businesses and consumers to use the dollars to buy American exports, then this combination of government intervention in currency markets plus exchange controls can increase the size of the U.S. trade deficit."[26] While this description may only apply to China in the above table, China's increase in its foreign currency reserves was the single largest. Nonetheless, even though

[26] Hornbeck, "Trade Primer," January 2013.

other countries might not exercise such control over exchange rates, their interventions might be large enough, and with enough control over foreign exchange, to have a similar effect.[27]

Analysis

Both in terms of purchases of U.S. Treasuries, and at the level of all investment in the United States, foreign governments have been large financers of U.S. debts. Compared with U.S. government investment overseas, foreign investment in the United States has played a large role in financing the U.S. trade deficits since 1998. This foreign government interest in the U.S. market likely stems from a general desire of foreign governments to increase their currency reserves over the last decade or so.

Thus, the important question becomes why did foreign governments choose to increase their currency reserves? One possible explanation is that foreign governments were acting entirely the way market actors would, and that had foreign governments not purchased the U.S. assets that they did, private foreigners would have done so. If so, then there may not be much significance to the foreign government role here. One needs to accept such a hypothesis in order to believe the "ant and grasshopper" or the "foreigners love U.S. investment opportunities" explanations as principal explanations for the U.S. trade deficits of the 2000s.

If one does not accept that foreign governments were acting in the same way as private foreign investors would, then a very large share of the financing of U.S. trade deficits has come from sources with potentially non-market motives. Explanations that focus only on the profligacy of U.S. consumers ("ant and grasshopper" stories) or on a market-based desire by foreign investors to invest in the United States likely fail to explain perhaps the single-largest source of financing for the U.S. current account deficit.

This paper will now examine several other explanations for the U.S. trade deficit in light of the above data.

OTHER EXPLANATIONS

The U.S. Dollar as Reserve Currency

In the 1960s, economist Robert Triffin showed that a nation that has its currency used as an international reserve currency will need to run a trade deficit.[28] Under Triffin's theory, the U.S.

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[27] See, for example, Bergsten and Gagnon, who provide analysis alleging that several nations, including but not limited to China, "intervene aggressively to keep their currencies undervalued and thus to unfairly maintain current account surpluses." Bergsten and Gagnon, "Currency Manipulation, the US Economy, and the Global Economic Order," December 2012.

[28] See, for example, description in Palley, "Explaining Global Imbalances," November 2011.

dollar's function as a reserve currency certainly could explain in general why the United States runs persistent and large trade deficits.

Nonetheless, the U.S. dollar's status as a reserve currency does not explain why foreign governments acquired much larger reserves in 2012 than they had before 1998. Nor does it explain why U.S. current account deficits have been persistently large since 1998. U.S. trade deficits never cracked three percent of GDP in the 1960s or 1970s, and did so only briefly in the 1980s. In all these decades, the U.S. dollar was a reserve currency. Why did U.S. trade deficits only grow to be nearly 3 percent of U.S. GDP, or more, in the 1980s, and remain persistently at or above that level after 1998?[29]

Bernanke's "Savings Glut"

In 2005, Federal Reserve Chairman Ben Bernanke put forward another possible explanation for the U.S. current account deficit. He described a "savings glut" in some parts of the world that helped foster current account deficits in other parts of the world, including the United States. He attributed the "savings glut" in part to the desire of developing nations hit by the Asian financial crisis to channel their local savings into large reserves in anticipation of a future crisis.[30]

The data above do not directly address the savings glut hypothesis, but are consistent with it. However, Bernanke's suggestions for reducing the savings glut focus on improving and liberalizing flawed financial systems in developing nations. In this sense, the savings glut story may morph into a variant of the "ant and grasshopper" story, albeit perhaps with some policy recommendations for the ants as well. Of more concern, other economists have attempted to discuss the savings glut in terms of too much savings in emerging markets because of inadequate safety nets.[31] Such an explanation potentially takes the focus off of foreign governments' savings, and explains it with a reference to private savings. This paper suggests that whatever the explanation for any savings glut, a key point to remember is that a large portion of any "savings glut" is the net savings of other countries' governments. Thus, explaining a "savings glut" requires explaining foreign governments' behavior.

Borio and Disyatat: Look at Gross Flows

On the other hand, in a May 2011 paper, Bank of International Settlements (BIS) economists Borio and Disyatat argue that international current account imbalances were not likely a cause of the 2008 global financial crisis.[32] While this author is not assessing the causes of the global

[29] Palley also offers other reasons for skepticism about the reserve currency hypothesis. Palley, "Explaining Global Imbalances," November 2011.

[30] Bernanke, "The Global Saving Glut and the U.S. Current Account Deficit," March 2005.

[31] For example, Mendoza, "Financial integration, financial deepness and global imbalances," as cited in Borio and Disyatat, "Global Imbalances and the Financial Crisis," May 2011.

[32] Borio and Disyatat, "Global Imbalances and the Financial Crisis," May 2011.

financial crisis here, Borio and Disyatat's paper does contain several analytical points on the U.S. current account deficit that are problematic, or prone to potential misinterpretation, and worth discussing here.

Borio and Disyatat argue that since U.S. financial inflows and outflows are very large relative to official (and even nonofficial) U.S. financial flows from emerging economies, it is doubtful that those latter flows played much of a role in "determining financial flows into the United States." The authors are defining financing as the use of specific, available funds for a particular expenditure. Their definition of financing is likely a more accurate use of the term than the one that economists typically use when discussing current account deficits, i.e., as national savings less national investment. Thus, based on this terminology change, they argue that attributing the current account balance to net foreign investment is "arbitrary."

In considering current account deficits only, this argument is misleading. Even if one accepts Borio and Disyatat's terminology change, it is still a simple fact of accounting that if the large net foreign government buying of U.S. assets had not happened, and all other flows had stayed the same, the U.S. current account deficit would have been much lower. In other words, had foreign governments bought U.S. assets at the levels that the U.S. government bought foreign assets over much of recent history, and foreign private investors had not compensated, then the United States would have run a much smaller current account deficit.

Perhaps Borio and Disyatat would respond that the same analysis holds if any large private actor would have chosen not to make an investment. It would, but then the authors would need to show why such a choice is relevant. Differences in two countries' trade relationships that are due to one country's government engaging in policies to generate such a difference are qualitatively different than subtracting one private actor's actions. In other words, the difference between governmental net flows was a large portion of the U.S. current account deficit in the 2000s, and changing the terminology cannot change that fact.

A second problematic analysis in Borio and Disyatat is that they argue that, since some trade deficit countries have acquired large financial reserves, the relationship between reserve levels, currency, and current account deficits is empirically weak. This analysis is not correct. A trade deficit nation can acquire large reserves in preventing its currency from appreciating even more; the fact that its current account balance is negative while it acquires reserves does not mean the acquisition of reserves had no impact on its current account balance.

Moreover, as previously discussed, these foreign government acquisitions are not insignificant simply because they are small relative to total private flows. Perhaps because they are addressing a somewhat different question, Borio and Disyatat downplay or ignore that U.S. private financial outflows often balance private financial inflows better than government flows do. As the earlier charts and tables show, foreign government net purchases are large in comparison with both the U.S. economy and the economies of many of the countries that engage in such purchases. Thus, it is difficult to imagine that the decisions foreign governments are making are insignificant.

Interestingly, Borio and Disyatat also note that foreign governments' currency "accumulation may reflect the wish to resist the appreciation of the currency, when the authorities face strong foreign demand for domestic currency assets, manifested in gross capital inflows." This may or may not be true. Nonetheless, foreign government resistance to the currency appreciation that private sector flows are pushing is likely to have an impact on the U.S. current account balance.

Importantly, Borio and Disyatat are to a great extent addressing issues outside the scope of this paper, such as whether Bernanke's "savings glut" in emerging markets was a major contributor to the financial crisis. The authors do acknowledge elsewhere in their paper that large foreign official inflows could have had an effect on the U.S. economy.

Reaction to the Asian Crisis, or Other Preparation for Financial Failure

Dean Baker (along with Jared Bernstein) has argued that recent reserve growth is due to the failure of the International Monetary Fund (IMF) in the late 1990s during the Asian crisis.[33] This explanation is consistent with the data. It sounds similar to Bernanke's but leads to a different policy prescription, i.e., that the U.S. government should work to ensure that the IMF does not handle future financial crises the way that it handled the East Asian crisis. Importantly, Baker's explanation keeps a significant focus on the activities of foreign governments as financers of the U.S. trade deficit, a focus that fits the data shown above.

Similarly, Aizenman and Lee create a distinction between what they call traditional currency interventions to create an export advantage ("monetary mercantilism") and large reserve hoardings in order to prepare for potential financial failures after policies to promote loans to domestic producers ("financial mercantilism").[34] They state that financial mercantilism is not always damaging to trading partners' economies, and posit their belief that Asian governments' large-scale "international reserves hoarding" is due to financial mercantilism rather than monetary mercantilism. Their belief is based on their statement that keeping currencies undervalued for a long period of time would be difficult, and based on a limited selection of economic work that posits that many Asian currencies (including that of China) were not much undervalued. Their work would appear to be contradicted by the findings of Bergsten and Gagnon.[35]

Also in contrast to Aizenman and Lee, Palley argues that the large scale of Asian governments' currency acquisitions is in excess of anything needed to avoid another episode of capital flight.[36] Even if the only motivation were to avoid the kind of difficulty that Asian nations found themselves in in 1997, though, building a large hard currency reserve for economic emergencies

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[33] Baker and Bernstein, *Getting Back to Full Employment*, 2013.

[34] Aizenman and Lee, "Financial Versus Monetary Mercantilism," December 2006.

[35] Bergsten and Gagnon, "Currency Manipulation, the US Economy, and the Global Economic Order," December 2012.

[36] Palley, "Explaining Global Imbalances," November 2011.

sounds very similar to the types of mercantilist motives that Adam Smith decried in his Wealth of Nations.[37] In that sense, perhaps Baker's argument should be considered under the category of the larger class of potentially mercantilist reasons why many foreign governments acquired so many U.S. assets over 1998–2012.

It is also worth noting that Asian currencies appreciated, and their trade surpluses with the United States shrank, in the early to mid-1990s.[38] It is possible that policymakers in some of these nations may have attributed part of any economic or financial problem their nations experienced in the 1990s to the shrinkage of their trade surpluses with the United States and/or the earlier appreciation of their currencies against the dollar.

Foreign Governments Acquiring Dollar Reserves to Maintain a Trade Surplus with the United States

Another possible explanation for the increase in foreign governments' reserves is that foreign governments were acting to keep their trade balance with the United States larger than it would be without their intervention. For example, economists at the Peterson Institute of International Economics (PIIE) have presented work describing some foreign governments as engaged in currency reserve acquisitions in order to maintain trade surpluses.[39] Such explanations are also consistent with the basic government data described above.

For example, looking at the data in table 2 above, net foreign private flows financed most of the U.S. current account deficit over 1997 to 2002. However, perhaps in the wake of the fall of the U.S. stock market after 2000, net foreign private flows fell over 2000 to 2004. Around 2002, foreign governments stepped into the breach and allowed the U.S. current account deficit to remain large even though foreign private investors were showing less relative interest in the United States. One possible explanation for this increase, consistent with the work of Bergsten and Gagnon, is that foreign governments did not wish to allow their trade surpluses with the United States to diminish. It should be noted that, whatever the motivation for these foreign government acquisitions, the acquisitions were in no way forced on these foreign governments.

[37] See Smith, *Wealth of Nations*, 1776, book IV, chapter 1. Smith criticizes "the mercantile system" as one in which national policies work to increase reserves of money (in Smith's case, gold and silver) by running trade surpluses, rather than focusing on what Smith describes as the true economic wealth of a nation, i.e., all of its productive potential.

[38] For example, both Japan and Korea ran large current account surpluses in the mid-1980s. Their currencies both appreciated against the dollar until the early 1990s (Korea) or mid-1990s (Japan), and both countries' current account surpluses shrank substantially. See data from the Federal Reserve Bank of St. Louis and the International Monetary Fund.

[39] See Bergsten and Gagnon, "Currency Manipulation, the U.S. Economy, and the Global Economic Order," December 2012.

CONCLUSION

Foreign governments invested in U.S. assets at record levels in the 2000s, far beyond the traditional levels of reserve growth, and at high levels relative both to their own economies and to the U.S. economy. These investments have sometimes been a replacement for foreign private investment (e.g., during 2002–04 and in 2012) and have sometimes merely remained flat while foreign private investment rose. But they have never substantially declined, except very briefly in 2009.

From these facts, one must either conclude that foreign governments are acting in exactly the same way as other private foreign investors would or that without foreign government purchases of U.S. securities, the U.S. current account deficit would have been lower, perhaps even substantially lower. Whatever the reason, foreign governments have played a large role in recent U.S. trade deficits. Thus, any explanation of why there have been large recent U.S. trade deficits must provide ample explanation of foreign government actions.

This paper has presented some basic U.S. and international data that show that foreign government actions are important contributors to the U.S. current account deficit of 1998 to the present. It then has suggested that any explanations of recent U.S. current account deficits must be consistent with this reality, and has examined several explanations through the prism of this reality.

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Additive Manufacturing Technology: Potential Implications for U.S. Manufacturing Competitiveness

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Abstract

This article explores the development and application of additive manufacturing as well as initiatives in the United States and other countries to advance it. It also examines the technology's effect on firm and industry production activities, as well as the potential implications for U.S. manufacturing competitiveness focused in three industries. It concludes that the most significant factors affecting the potential of additive manufacturing to contribute to U.S. competitiveness are developing standards, improving the selection and affordability of materials, and increasing the accuracy and reliability of equipment and processes.

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INTRODUCTION

Additive manufacturing, or three-dimensional (3-D) printing, is receiving unprecedented attention. Additive manufacturing is a suite of emerging technologies that fabricates three-dimensional objects directly from digital models through an additive process, typically by depositing and "curing in place" successive layers of polymers, ceramics, or metals.[2] Unlike traditional manufacturing processes involving subtraction (e.g., cutting and shearing) and forming (e.g., stamping, bending, and molding), additive manufacturing joins materials together to build products. The number of articles published on this nascent industry rose from about 1,600 in 2011 to 16,000 in 2012.[3] The additive manufacturing market, consisting of all additively manufactured products and services worldwide, shows equally impressive growth: it rose from $1.7 billion in 2011 to $2.2 billion in 2012, by 28.6 percent.[4] Evolving and fluid, additive manufacturing technology is shaping the future of product development and manufacturing.

This article addresses three questions about additive manufacturing. First, how is this rapidly evolving technology being applied? Second, will its growth prompt changes in firm and industry production activities? Third, what are the potential implications for U.S. competitiveness in manufacturing processes and the economy? The article draws on the experiences of three industries that are thus far among the top users of additive manufacturing: automotive, medical, and aerospace.[5] It examines how additive manufacturing is used in these industries. The article also reviews the dynamics that affect wider deployment of additive manufacturing, such as technological challenges, new innovations, and industry and government initiatives to facilitate its use. It concludes that the most significant factors affecting the potential of additive manufacturing to contribute to U.S. competitiveness are developing standards, improving the selection and affordability of input materials, and increasing the accuracy and reliability of equipment and processes.[6]

Originally conceived as a way to make prototypes,[7] additive manufacturing has improved to the extent that it is increasingly used to deliver final products.[8] Recent improvements include enhancements of the speed and performance of additive manufacturing machinery, an expanding range of input materials, and falling prices for both machinery and materials. These

[2] USDOE, "Advanced Manufacturing: Pursuing the Promises," August 2012, 1.

[3] Wohlers, "Additive Manufacturing," June 2013, 67–73.

[4] Park, "Unsurprisingly, Wohlers," May 24, 2013, 1.

[5] For the purposes of this article, "automotive" is used interchangeably with "motor vehicle," and "medical" encompasses "dental."

[6] Sealy, "Additive Manufacturing as a Disruptive Technology," 2012, 92.

[7] Rapid prototyping and additive manufacturing differ according to product characteristics. While prototypes are used to show special product properties or functions during the product development phase, additive manufacturing also delivers final products.

[8] Approximately 28 percent of additively manufactured parts are final products. Wohlers, "Additive Manufacturing," June 2013, 7–12. Desktop computers and industrial lasers have facilitated advancements in additive manufacturing.

advancements are likely to inspire further adoption of additive manufacturing in the United States and around the world in coming years.

Additive manufacturing provides an important opportunity to advance the U.S. manufacturing industry, which has the largest research and development (R&D) expenditure for manufacturing overall of any country.[9] Though barriers to production with the technology exist, unique capabilities make additive manufacturing processes superior to conventional manufacturing for some products. These capabilities include constructing previously impossible geometries, such as pyramidal lattice truss structures with hollow trusses,[10] and significantly reducing material waste by building layer by layer and using only the material necessary.[11] Firms that employ additive manufacturing are beginning to achieve benefits such as increasing supply chain efficiencies; reducing time to market; moving from mass production to mass customization; and sustaining the environment.[12] As a result, the technology is receiving attention in policy as well as manufacturing circles. President Obama extolled additive manufacturing in his 2012 State of the Union address, stating it could "revolutionize the way we make almost everything."[13]

OVERVIEW OF TECHNOLOGY

Process

Additive manufacturing begins with computer-aided design (CAD) modeling software that takes a series of digital images of a design or object and sends descriptions of them to a professional-grade industrial machine. The machine uses the descriptions as blueprints to create the item by adding material layer-upon-layer. Layers, which are measured in microns, are added by the hundreds or thousands until a three-dimensional object emerges. Raw materials may be in the form of a liquid, powder, or sheet and are typically plastics and other polymers,[14] metals, or ceramics.

[9] OECD, Structural Analysis Database (accessed September 24, 2013).

[10] Queheillalt and Wadley, "Pyramidal Lattice Truss Structures," 2005, 132–37; A truss that resembles latticework because of diagonal placement of members connecting the upper and lower chords.

[11] Subtractive manufacturing processes such as machining take raw material and remove and shape it into the desired final form. In some cases, over 90 percent of a billet of raw material may be removed before the product is finished. Campbell and Slotwinski, "Metrology for Additive Manufacturing," 2013, 154.

[12] Matthews International Corporation representative, interview by author, March 5, 2014.

[13] White House, "State of the Union Address," January 24, 2012.

[14] A polymer is a chemical compound made of small molecules that are arranged in a simple repeating structure to form a larger molecule. Merriam-Webster Dictionary website, *http://www.merriam-webster.com/dictionary/polymer* (accessed May 21, 2014). Examples of polymers often used in additive manufacturing are polycarbonate and high-density polyethylene.

The numerous additive manufacturing processes differ according to the materials and methods of patterning and fusing layers they employ. Major processes include material extrusion,[15] material jetting,[16] binder jetting,[17] sheet lamination[18] vat photopolymerization,[19] powder bed fusion,[20] and directed energy deposition.[21] Some of these melt or soften material to produce the layers, while others cure liquid materials using different sophisticated technologies.[22] An image of selective laser sintering, an additive manufacturing process that is a type of powder bed fusion, appears below (box 1) as an example.

Thirty-one manufacturers from around the world produced professional-grade industrial additive manufacturing machines in 2011, compared to 32 in 2010 and 35 in 2009. In 2010 and 2011, 9 of these companies sold more than 100 machines each. Firms that produce additive manufacturing machines range from those that produce and sell fewer than 10 per year, to those that sell hundreds of machines per year.[23]

The United States leads in the production and sales of professional-grade industrial additive manufacturing machines, with 35,753 units sold between 1998 and 2011. Israel and Germany made 4,556 and 3,980 units, respectively, during the same period. Powder bed fusion and binder jetting are the most common processes used by leading vendors, more of whom (70 percent) use metal than any other material.[24] Table 1 presents several leading vendors that manufacture machines, an overview of processes and applications, and the most frequently used materials for each process.

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[15] Material extrusion is the selective dispensation of material through a nozzle or orifice. Wohlers, *Wohlers Report 2012*, 2012, 68.

[16] Material jetting is the selective deposition of droplets of build material via ink-jet print head nozzles. Wohlers, *Wohlers Report 2012*, 2012, 68.

[17] Binder jetting is the selective deposition of a liquid bonding agent through ink-jet print head nozzles to join powder materials. Wohlers, *Wohlers Report 2012*, 2012, 68.

[18] Sheet lamination involves bonding sheets of material together. Wohlers, *Wohlers Report 2012*, 68.

[19] Vat photopolymerization is selective curing of liquid photopolymer (light-sensitive polymer) in a vat via light-activated polymerization. Wohlers, *Wohlers Report 2012*, 2012, 68.

[20] Powder bed fusion is selective fusing of powder bed regions via thermal energy. Wohlers, *Wohlers Report 2012*, 2012, 68.

[21] Directed energy deposition is simultaneous fusion and deposition of material. Wohlers, *Wohlers Report 2012*, 2012, 68.

[22] A list of process category names and definitions which the ASTM International Committee F42 on Additive Manufacturing Technologies approved in January 2012 appears in the appendix; Additive manufacturing machines range in size from desktop models, which weigh just a few pounds, to an Objet-Stratysys model, which measures 9 feet x 6.7 feet x 5.5 feet and weighs 6,325 pounds.

[23] Wohlers, *Wohlers Report 2012*, 2012, 83.

[24] Wohlers, *Wohlers Report 2012*, 2012, 74, 82.

TABLE 1 Leading industrial additive manufacturing machine vendors, 1988-2011

Vendors/Production Sites	Processes/Applications	Materials
3D Systemsa (US, AUS, NED, ITA)	Binder jetting, material jetting, vat photopolymerization, powder bed fusion	Plastic, polymer, metal
Beijing Tiertime (CH)	Material extrusion	Polymer
DWS (ITA)	Vat photopolymerization	Polymer
Envisiontec (GER, US)	Vat photopolymerization , material extrusion	Biomaterial, ceramic, polymer
EOS (GER)	Powder bed fusion	Ceramic, metal, polymer
ExOnea (US, GER, JPN)	Binder jetting	Ceramic, polymer, metal
Objetb (ISR, US, GER, Asia)	Material jetting	Biomaterial, polymer
Solidscape (US)	Material jetting	Plastic
Stratasys[a, b] (US, GER, IND)	Material extrusion	Polymer
Z Corp. (US)	Powder bed fusion	Plastic, metal

Sources: Wohlers, *Wohlers Report 2012*, 2012, 135, 136; "Introduction to Additive Manufacturing," Ceramic Industry, December 2012.

[a] Stratysys acquired Solidscape in 2011, and merged with Objet in 2012; 3D Systems acquired Z Corp. in 2012.

[b] Also fabricates parts.

Additive manufacturing offers industry a range of unique possibilities. The technology makes it possible, for example, to produce viable three-dimensional objects of virtually any complex geometry without significantly increasing the cost of the parts.[25] Additive manufacturing also has the potential to transform the rules of design by reducing—and perhaps even eliminating—the constraints of molds and dies.[26] Major industrial sectors additively manufacture parts ranging from visual aids to patterns for metal casting. Due to the speed and efficiency with which additive manufacturing can produce prototypes and parts,[27] the technology will have the greatest impact on products that require high customization, have complex designs, and are made in small quantities.[28]

However, additive manufacturing is not yet suitable for mass production. Inherent limitations in the processes include lengthy build time: for example, additive manufacturing processes are capable of creating a 1.5 inch cube per hour, on average, while an injection molding machine can produce several similar parts in under a minute. Current additive manufacturing technologies

[25] Georgia Institute of Technology Representative, interview by author, June 25, 2013.

[26] Wohlers, *Wohlers Report 2012*, 2012, 183. When machine tooling is not needed and the restrictions of design for manufacture and assembly are eliminated, the possibilities for design are limited only by the available tools and a designer's imagination.

[27] Vacari, "3D Printing Industry," April 19, 2013, 3.

[28] In traditional manufacturing, the prototype, tooling, and setup processes are too time-consuming and expensive to profitably produce small volumes.

are unlikely to be able to create parts as quickly as molding technologies.[29] Other limitations include the size of the objects that can be made, and the cost and size of the machines and materials used.[30]

U.S. Additive Manufacturing Market and Major Industrial Sectors

The United States has several advantages in manufacturing in general, and in additive manufacturing in particular. For example, U.S. R&D spending for total manufacturing in 2011 was $415.0 billion, the highest among the countries for which Structural Analysis (STAN) data from the Organisation for Economic Co-operation and Development are available.[31] Additionally, the technology was predominantly developed in the United States, where several leading producers of additive manufacturing machines, including Stratasys and 3D Systems, are based. In 2011, the United States accounted for 38.3 percent of the cumulative installed industrial additive manufacturing systems (figure 1).[32] The same year, the United States accounted for 64 percent of all industrial additive manufacturing systems sold worldwide.[33]

FIGURE 1 Cumulative additive manufacturing machines, installed by country, 1988-2011, (percent of global total)

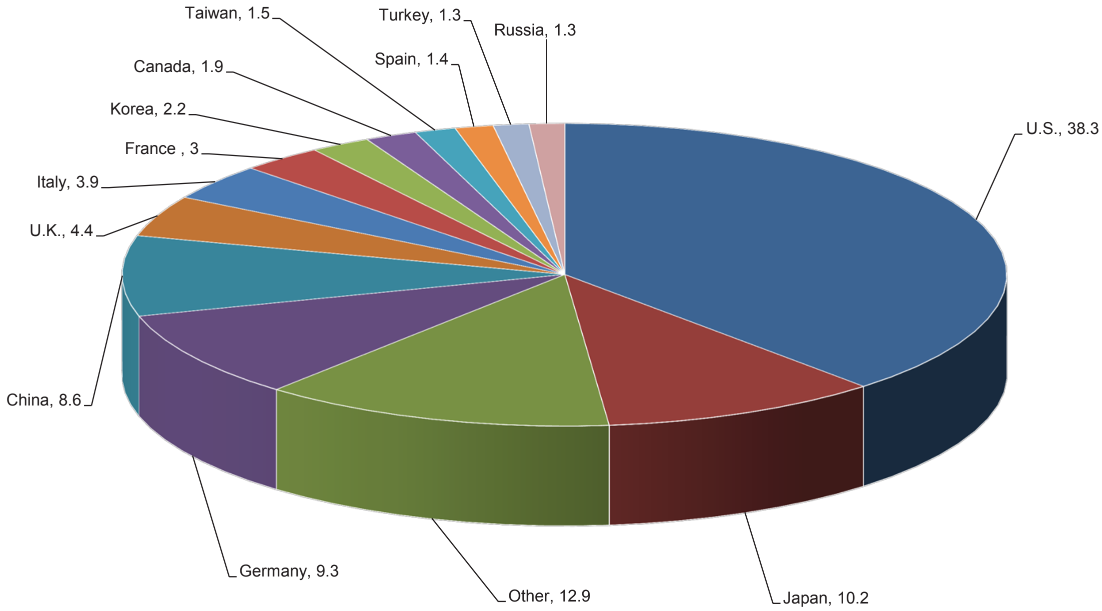
[29] Campbell et al., "Could 3D Printing Change the World?," October 2011, 6. If production is decentralized, then hundreds of thousands of units of a product may be produced at multiple locations that are near the source of demand, rather than at one location.

[30] Plastic materials for additive manufacturing can be 10 to 50 times as expensive as plastic materials for injection molding.

[31] OECD, Structural Analysis Database (accessed September 24, 2013).

[32] Wohlers, *Wohlers Report 2012*, 2012, 133.

[33] Other countries with significant stocks of industrial additive manufacturing machines include Japan (10.2 percent of global total), Germany (9.3 percent), and China (8.6 percent). Wohlers, *Wohlers Report 2012*, 2012, 18.



Source: Wohlers, *Wohlers Report 2012*, 2012, 20.

Leading sectors in this field, based on revenue for all additive manufacturing products and services in 2011,[34] include automotive (19.5 percent), medical (15.1 percent), and aerospace (12.1 percent) (figure 2).[35]

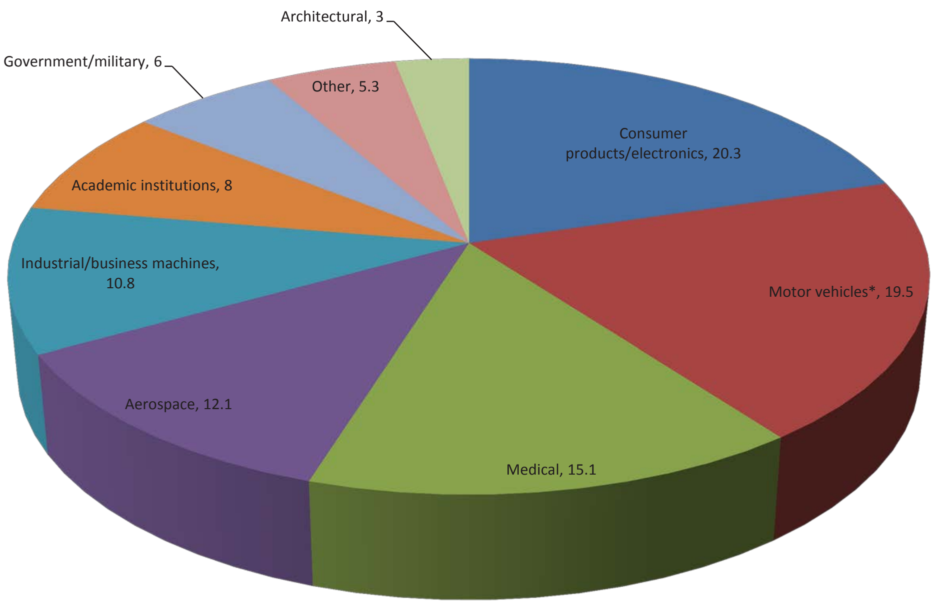
Information to show how broadly additive manufacturing is being deployed in the U.S. manufacturing base, and, in what specific sectors, is not yet available. However, data from the U.S. Department of Commerce show that goods using additive manufacturing methods represent less than a fraction of 1 percent of their relevant industry subsectors, implying abundant potential for growth (table 2).[36]

FIGURE 2 Industries served and approximate revenues (by percent) for additive manufacturing, 2011

[34] This paper focuses on the second-, third-, and fourth-largest sectors because they are relatively distinct. It does not address the single largest sector, consumer products and electronics, because it is too varied and diffuse to discuss comparably. Approximately 20.3 percent of additive manufacturing is within consumer products and electronics. Wohlers, *Wohlers Report 2012*, 2012, 18.

[35] Wohlers, *Wohlers Report 2012*, 2012, 18.

[36] Thomas, *Economics of the U.S. Additive Manufacturing Industry* (prepublication draft), June 2013, 38.



Source: Wohlers, *Wohlers Report 2012*, 2012, 20.

Automotive

The automotive industry has used additive manufacturing to make tool prototypes and small custom parts with short production runs (in the hundreds) for decades. It is increasingly applying the technology to metals, with a focus on aluminum alloys, to construct lightweight vehicles. Additive manufacturing shipments for the U.S. automotive industry were valued at $48 billion in 2011. As noted earlier, approximately 19.5 percent of additive manufacturing occurs within the automotive industry, with additive manufacturing shipments estimated to be less than 0.05 percent of total U.S. automotive shipments.[37]

An example of an early adopter within the industry is Ford Motor Company, which has been using the technology to develop prototype parts for test vehicles since the 1980s. With industrial-grade machines that cost as much as $1 million each, Ford engineers have produced prototypes of cylinder heads, brake rotors, and rear axles in less time than traditional manufacturing would require. The company reports that use of the technology saves, on average, one month of production time when creating a casting for a prototype of a complex cylinder engine head that includes multiple ports, ducts, passages, and valves to manage fuel and air flow.[38]

[37] Thomas, *Economics of the U.S. Additive Manufacturing Industry* (prepublication draft) June 2013.

[38] Boulton, “Barbie, Auto Parts Hot Off the Press,” June 6, 2013, B5.

TABLE 2 U.S. Additive manufacturing (AM) shipments, 2011

Category	Relevant industry NAICS codes	Shipments of US-made AM products (billion $)[a]	Total industry shipments (billion $)	AM share of total industry shipments (percent)[b]
Motor vehicles	3361, 3362, 3363	0.048	445.3	0.01
Aerospace	336411, 336412, 336413	0.030	157.7	0.02
Industrial/business machines	333	0.027	365.7	0.01
Medical/dental	3391	0.037	89.5	0.04
Government/military	336414, 336415, 336419, 336992	0.015	32.8	0.05
Architectural	3323	0.074	72.2	0.01
Consumer products/ electronics, academic institutions, and other	All others within NAICS	0.083	895.7	0.01
Total	332 through 339	$.25	$2,058.9	0.01

Source: Thomas, Economics of the U.S. Additive Manufacturing Industry (prepublication draft), June 2013.

[a] These values are calculated assuming that the percent of total additive manufacturing made products for each industry is the same for the U.S. as it is globally. It is also assumes that the U.S. share of AM systems sold is equal to the share of revenue for AM products.

[b] If rounded to "1" right of decimal.

Note: Numbers may not add up to total due to rounding.

*Note: For the purposes of this article, motor vehicles and automotive are used interchangeably.

**Note: The primary additive manufacturing market consists of all products and services directly associated with additive manufacturing processes, worldwide.

Additive manufacturing for automotive parts is also showing increasing potential. For instance, Daimler AG recently funded the development of the X Line 1000R System, a laser fusing machine with a large build volume[39] that uses powdered metals to additively manufacture components for vehicles and engines. The machine, which was introduced at the Euromold Trade Show in November 2012, has a build chamber of 23.6 inches x 15.7 inches x 19.7 inches and a layer thickness of 20 to 100 microns. The new machine has a high-powered laser in the kilowatt range, enabling as much as 10 times more productivity than standard laser fusing machines used in additive manufacturing.[40]

Automotive companies are applying additive manufacturing to an expanding range of parts, including engines and vehicle bodies. An extreme example is KOR EcoLogic's Urbee, 60 percent of which will be additively manufactured. The frame, chassis and engine will be conventionally manufactured from metal.[41] In March 2013, KOR EcoLogic announced that it is collaborating

[39] Build volume refers to the external dimensions.

[40] Brooks, "Auto Giant Harnesses New Super-scale Laser," November 15, 2012, 7.

[41] Sharma, Ananya, "Interaction with Jim Kor," January 24, 2014.

with Stratasys, Ltd., a maker of additive manufacturing equipment, to produce the Urbee 2, a road-ready, fuel-efficient car.[42] The two-passenger vehicle will be able to travel 70 miles per hour on the freeway, and use a biofuel such as ethanol.[43]

When additive manufacturing can produce larger components, the automotive industry will likely adopt the technology more broadly. Like the aerospace industry, as discussed later, the automotive industry has high demands for performance and weight reduction that additive manufacturing can help to address.

Medical

The medical industry is another leading user of additive manufacturing. Additive manufacturing is being used to create customized medical devices that closely replicate the human form. Approximately 15.1 percent of U.S. additive manufacturing takes place within this industry, with additive manufacturing shipments estimated to be $37.2 million—again, less than 0.05 percent—of medical and dental manufacturing.[44] It is the dominant technology for manufacturing customized in-the-ear hearing aids, which have dramatically increased patient comfort. Additive manufacturing has also been used worldwide to create approximately 30,000 prosthetic limbs, more than half a million dental implants, and countless other devices.[45] Shipments for U.S. manufacturing of medical and dental products amounted to $89.5 billion in 2011.[46]

One of the most well-known applications of additive manufacturing is InvisAlign orthodontics. Align Technology, Inc. uses stereolithography, a form of vat polymerization, to custom-make a series of clear plastic aligners that correct malocclusions[47] and straighten teeth without the use of metal or ceramic braces and wires. Patients wear sequential liners, which they change about every two weeks, until treatment is complete. In 2012, Align Technology shipped 363,540 cases of aligners and, as of March 2013, had trained more than 78,000 dentists and orthodontists worldwide to use the technology to fabricate products on-site.[48]

In recent years, scientists have devised a means of using a patient's cells to additively manufacture skin tissue and an array of other human body parts. In February 2013, doctors at Weill Cornell Medical College and biomedical engineers at Cornell University announced that they had used additive manufacturing and injectable gels made of live cells to build a facsimile of a human ear.[49] According to one industry expert, "the ability to manufacture living human tissue for medical research and clinical practice has the potential to reshape the future of medicine."[50]

42 Owano, "Kor Ecologic," February 28, 2013, 1.
43 Owano, "Kor Ecologic," February 28, 2013, 1.
44 Wohlers, *Wohlers Report 2012*, 2012, 18.
45 Campbell, Bourell, and Gibson, "Additive Manufacturing," 2012, 258.
46 Thomas, *Economics of the U.S. Additive Manufacturing Industry* (prepublication draft), June 2013.
47 A malocclusion is a misalignment of teeth or incorrect relation between the teeth of the two dental arches.
48 MarketWired, "Align Technology Announces," April 18, 2013, 1.
49 Prototype Today, "3D Printer Creates Ear Using Injectable Gels," February 28, 2013.
50 Keith Murphy Selko, CEO at Organovo, *IndustryWeek*, "The Next Wave of Manufacturing," June 6, 2013, 3.

The pharmaceutical industry is also applying the technology. For example, additively fabricating a single custom-made daily pill for each patient eliminates the need to keep track of multiple medications. Identification markings on the pill can eliminate the confusion and uncertainty of conventional medicines.[51]

While there are no formal projections of future use, experts anticipate new machines and new processes will expand applications, particularly in orthopedic implants.[52]

Aerospace

Additive manufacturing holds significant potential for the aerospace industry, which requires parts that are lightweight, strong, and geometrically complex—and typically produced in small quantities. Total (both traditional and additive) manufacturing shipments in the U.S. aerospace industry were estimated at $157.7 billion in 2011. Aerospace accounts for approximately 12.1 percent of additive manufacturing, with the total shipments estimated to be $29.8 million, or less than 0.05 percent of the U.S. aerospace industry.[53]

Aerospace firms are increasingly turning to the technology to reduce the costs of developing models and prototypes and of creating components. In a constant effort to reduce aircraft weight,[54] the industry is developing a growing proportion of its parts from titanium, plastic, and other lightweight materials. Many of these materials are costly, and additive manufacturing can make it possible to keep the amount used to a minimum. Aircraft landing gear, for example, can be additively manufactured from titanium layer by layer—rather than cut from a titanium block—thereby greatly reducing material waste and costs.[55] In addition, additive manufacturing uses these materials to create parts in geometries that may not be possible with conventional manufacturing. It can also significantly reduce the waste generated in producing the materials themselves, as well as in manufacturing and using the components.[56]

The increasing breadth and sophistication of these applications are, in turn, driving needs for improvements in process control, materials, and inspection to ensure safety.[57] Boeing, Inc., for example, has additively manufactured more than 200 different parts for 10 aircraft platforms.[58] Boeing has also used roughly 20,000 additively manufactured parts in military and commercial

[51] Lipson, "Frontiers in Additive Manufacturing," Spring 2012, 1.

[52] BoneZone, "The Future of Additive Manufacturing," March 5, 2013.

[53] Wohlers, *Wohlers Report 2012*, 2012, 18.

[54] Rucks, "What Automakers Can Learn from Boeing's Culture," March 28, 2012.

[55] Lyons, "Additive Manufacturing in Aerospace," September 19, 2011, 2; Campbell et al., "Could 3DPrinting Change the World?," October 2011, 1; Campbell and Slotwinski, "Metrology for Additive Manufacturing," 2013, 154. Traditional manufacturing and subassembly of 16 parts, plus glue, of an air duct for an F-18 fighter jet is additively manufactured into a component. It is also optimized for air flow efficiencies.

[56] A reduction of one kilogram in the weight of an airliner saves about $3,000 annually in fuel and reduces carbon emissions. Additive manufacturing could help build greener aircraft—especially if all of the 1,000 or so titanium parts in an aircraft could be printed. *Economist*, "3D Printing," February 14, 2011, 19.

[57] Lyons, "Additive Manufacturing in Aerospace," September 19, 2011, 9.

[58] Boeing.com, "Boeing Launches New Manufacturing Venture," September 3, 2002.

aircraft, including 32 different components for its 787 Dreamliner planes.[59] General Electric, the world's largest supplier of jet engines, is preparing to additively manufacture a fuel nozzle for use in thousands of jet engines.[60] These nozzles are 25 percent lighter and as much as five times more durable than the existing model, which is welded from 20 different parts.[61] General Electric reports that it may additively manufacture up to half of the parts in its energy turbines and aircraft engines in 10 years.[62]

Aurora Flight Sciences, in partnership with Stratasys, Ltd., fabricated and flew a 62-inch wingspan aircraft with a wing composed entirely of additive manufactured components. The wing was designed by Aurora and manufactured by Stratasys utilizing fused deposition modeling 3D printers.[63] Aurora anticipates additively manufacturing small, unmanned aerial vehicles—both military and civilian—in five years.[64] In a public-private venture, the National Air and Space Administration (NASA) and Pratt & Whitney Rocketdyne (PWR) jointly produced an additively manufactured rocket engine injector. A rocket engine injector is one of the most critical and expensive engine components in a launch vehicle, and typically takes up to a year to conventionally manufacture. The NASA-PWR team was able to additively manufacture it in four months while reducing costs by 70 percent.[65]

Despite these advances, limits on the size of goods produced by additive manufacturing have likely constrained adoption of this technology in the aerospace industry. Issues with materials, accuracy, surface finish, and certification standards have further limited its use.[66]

Beyond these aerospace/medical/automotive uses, additive manufacturing has applications in many other industries, ranging in size from miniature instrumentation to large structures such as the earth boring drills used in oil exploration. The applications are so broad that they cannot be easily classified, but several are seen on a recurring basis, such as specialized manufacturing fixtures and tools, power generation equipment, robotics, heat exchangers, and thermal controls.[67]

The Potential Benefits of Additive Manufacturing

Additive manufacturing competitively produces low-volume, customized, and intricate goods because it enables inexpensive design of prototypes and parts. Additional levels of product complexity do not add costs to production beyond the design stage, because once the design is set, complex layering is no more expensive than if you were to layer a cube or a sphere. In traditional

59 Freedman, "Layer by Layer," December 19, 2011.

60 LaMonica, "10 Breakthrough Technologies 2013," April 23, 2013, 2.

61 Davidson, "3-D Printing Could Remake U.S. Manufacturing," June 10, 2013, 3.

62 Davidson, "3-D Printing Could Remake U.S. Manufacturing," June 10, 2013, 3.

63 Industry representative, interview by author, July 15, 2013.

64 Industry representative, interview by author, July 15, 2013.

65 Engineering.com, "3D Printed Rocket Blasts Off," July 15, 2013.

66 Industry representative, interview by author, July 11, 2013.

67 Castle Island, "Additive Manufacturing: What RP Will Be," n.d. (accessed May 1, 2014).

manufacturing, by contrast, the prototype, tooling, and setup processes can be too time-consuming and expensive to profitably produce small volumes. In addition to these advances, additive manufacturing technology is fostering innovation and transforming how some companies produce and deliver goods and services. Firms are beginning to employ additive manufacturing as a tool to achieve objectives such as increasing supply chain efficiencies; reducing time to market; moving from mass production to mass customization; and sustaining the environment.

Supply Chain Efficiencies

Additive manufacturing has the potential to reduce the costs of storing, moving, and distributing raw materials, mid-process parts, and end-usable parts. The ability to produce parts on demand without the need for tooling and setup could become a basis for new solutions in supply chain management. Ed Morris, director of America Makes, the federally-funded initiative set up to define and promote the future of the industry, reports that "you don't have to have the finished product stacked on shelves or stacked in warehouses anymore. . . . Whenever you need a product, you just make it. And that collapses the supply chain down to its simplest parts, adding new efficiencies to the system."[68] As noted, General Electric is now additively manufacturing hollow fuel nozzles for aircraft that it previously manufactured in pieces and assembled later. The company has thus reduced the product's supply chain.

Reducing Time to Market

Time to market is expected to shrink in additive manufacturing applications due to shorter design and prototyping cycles, more predictable factory loads, and the elimination of tooling and factory setup times for new products. The freedom to design and redesign prototypes and parts without slowing down or adding to production costs enables a more fluid product development process. Similarly, the ability of machines to read CAD files improves planning: machines know the time and material requirements necessary to build a part before it is on the machine, and can track and measure volume and capacity at any moment.[69] For example, General Motors used additive manufacturing to significantly redesign models for the 2014 Chevrolet Malibu at a much lower cost than for its previous clay sculpting processes.[70] The company reports the technology was particularly useful for updates to the new Malibu's floor console, which features a pair of integrated smartphone holders for driver and passenger. The redesigned console also weighs less, which contributes to the car's improved fuel efficiency.[71]

Mass Customization

Additive manufacturing's ability to employ multiple designs on the same machine could enable the manufacturing industry to move from mass production in factories to mass customization

[68] Hessman, "3D Printing the Supply Chain," July 15, 2013, 2.

[69] Wohlers, *Wohlers Report 2012*, 2012, 13.

[70] Brooke, "Chevrolet Uses Rapid Prototyping," June 11, 2013.

[71] Brooke, "Chevrolet Uses Rapid Prototyping," June 11, 2013.

with distributed manufacturing.[72] Using materials ranging from plastic to titanium to human cells, additive manufacturing creates intricate products of a near-infinite variety that can be made to exact customer specifications.

Bespoke Products, a division of 3D Systems, additively manufactures custom-designed prosthetic human body parts, such as legs. The company builds models of complete legs that have sophisticated features such as body symmetry, locking knees, and flexing ankles. During the development process, customers select from a range of options for customizing their product. The additively manufactured legs cost $5,000 to $6,000 each, and have features that are not available in existing prosthetic legs, which can cost up to $60,000.[73]

Environmental Sustainability
Additive manufacturing could become a multifaceted tool for mitigating environmental impact by replacing many of the casting, molding, and other manufacturing processes that consume significant amounts of energy and produce hazardous industrial waste. The technology also imposes few constraints on product design, enabling previously separate parts to be consolidated into a single object with increased functionality while reducing the amount of energy and natural resources required to operate it. The U.S. Department of Energy reports that energy savings of 50 percent or more can be realized in applications where additive manufacturing is competitive.[74]

PRESENT TRENDS

Numerous, multifaceted dynamics are shaping additive manufacturing. As users demand more from the technology, developers are investing in increasingly advanced processes and materials. Indeed, many industry experts see additive manufacturing as a way of providing high-value, high-margin parts and products that has a potential for explosive growth. Others, however, point to weaknesses in the technology that they argue will continue to challenge development and adoption of additive manufacturing for the foreseeable future.

Drivers to Development and Adoption

A mix of market forces and technologies are driving development and adoption of additive manufacturing. Three of the most significant ones are mass customization, new and improved processes and products, and government initiatives.

[72] Distributed manufacturing, also known as distributed production and local manufacturing, is a coordinated networkof geographically dispersed manufacturing facilities.

[73] Sorrell, "Bespoke Innovations Makes Beautiful, Custom Prosthetic Legs," December 22, 2010, 1.

[74] USDOE, "Additive Manufacturing: Pursuing the Promises," August 2012, 2.

Mass Customization

Mass customization is a significant driver—as well as a result—of additive manufacturing.[75] In response to increasingly fragmented markets that value individualization, manufacturers across industries are using innovative manufacturing techniques and technology to both mass-produce and individually customize products.[76] In the automotive industry, additive manufacturing enables companies to quickly and distinctively design cars, and rapidly customize them. Ford Motor Company allows its customers to "build" certain aspects of a vehicle by choosing from a palette of online additively manufactured options, such as body side cladding.[77] BMW North America also provides the option to customize several of its vehicles.[78] Customers can choose from a wide variety of additively manufactured features, including trims and inlays.

The medical device industry is similarly using the technology to build customized implants and devices. The Walter Reed National Military Medical Center uses the technology to produce customized cranial plates and cutting guides for bone grafts that are less expensive than existing alternatives and better matched to the patient.[79] Additionally, 95 percent of the world's custom "in the ear" hearing aids are additively manufactured.[80]

Additive manufacturing offers numerous advantages for mass customization. Flexibility, speed, and the ability to build objects directly make it an attractive alternative to conventional machining, forging, molding, and casting of customized parts. However, business models are only now catching up with the movement toward greater mass customization. Companies are still determining how to capture individual or group customer requirements, how much input customers will have in the design process, and which parts of the product will add the most value to the customer when customized. Given the trend, the reciprocal relationship between additive manufacturing and mass customization will likely accelerate.[81]

New and Improved Processes and Products

As noted, advances are occurring in basic areas, such as manufacturing machines, and in more applied areas, such as nanotechnology.[82] Below are several of the most significant developments in additive manufacturing processes and the end products they create, as identified by the Institute for Defense Analysis.

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[75] IBISWorld, *3D Printer Manufacturing Market Research Report*, December 2012, 23.

[76] The Manufacturer, "Additive Manufacturing," January 2012, 7.

[77] Industry representative, interview by author, July 11, 2013. Body side cladding is a protective composite paneling that covers the lower part of the doors and fenders around the wheels.

[78] BMW North America website, "Build your Own," *http://www.bmwusa.com/* (accessed July 8, 2013).

[79] Scott et al., "Additive Manufacturing," March 2012, 10.

[80] Glass, "Pitch Perfect: The Quest to Create," November 9, 2012; Maxey, "3D Printing for the Hearing Impaired," January 4, 2013.

[81] Wohlers, *Wohlers Report 2012*, 2012, 187.

[82] Campbell and Ivanova, "3D Printing for the Hearing Impaired" August 2013, 8, 119-120.

Incorporating Energy and Electronics

Advances are being made in additively manufacturing conformal electronics.[83] Robotic dispensing systems could apply conformal coating to printed circuit boards to protect them against moisture, dust, chemicals, and extreme temperatures. The systems would be able to create a repeatable coating thickness and a precise coverage area that provides superior quality and reduces costs. While no commercially available additive manufacturing process currently produces conformal electronics, the concept has been demonstrated in a joint project between Sandia National Laboratory and the University of Texas at El Paso.[84] In addition, researchers at Cornell University have additively manufactured parts that embed electronics, such as conductors and zinc batteries.[85]

Creating New Structures

Additive manufacturing enables the creation of structures with distinct advantages over traditionally manufactured ones: they are more complex, have greater geometric freedom, and are more capable of performing multiple functions. The technology allows for characteristics such as nonlinear holes and re-entrant features on complex parts with little—if any—addition to cost.[86] It also enables structures, such as honeycombs and lattices for the interiors of parts, which have significant benefits: maintaining the requisite strength and stiffness while being considerably lighter than conventionally manufactured counterparts. Researchers at the Lawrence Livermore National Laboratory of the U.S. Department of Energy are additively manufacturing combinations of materials in new ways and creating materials with properties not found in nature that will further innovation and design capabilities.[87]

Three-Dimensional Scanning

New three-dimensional scanners and processing software options are expanding opportunities for designing and additively manufacturing prototypes and parts. New algorithms, for example, are able to transform relatively crude scans into quality three-dimensional surface mapping.[88] These developments hold great potential for fields such as robotics and human-computer interaction.[89]

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[83] In conformal electronics, protective material is applied to electronic circuitry.

[84] De Beer, "Additive Manufacturing: Turning Mind into Matter," May 31, 2013, 17.

[85] Scott et al., "Additive Manufacturing," March 2012, 8.

[86] Federation of European Screen Printers Associations, "3D Printing, Additive Manufacturing and Drivers for Adoption," October 2012, 9.

[87] Lawrence Livermore National Laboratory, "Additive Manufacturing: 3D Printing Metal Parts and Novel Materials," n.d. (accessed December 3, 2013).

[88] Scott et al., "Additive Manufacturing," March 2012, 10.

[89] Newcombe, "KinectFusion: Real-Time Dense Surface Mapping and Tracking," March 2011, 9.

Bioprinting

Advances in custom medical implants and devices are driving demand for additive manufacturing. As discussed, the Walter Reed National Military Medical Center has successfully produced and implanted porous cranial plates and cutting guides for bone grafts that are less expensive than existing alternatives and better matched with the patient.[90] Progress has also been made in additively manufacturing soft tissue and organs such as kidneys.[91] Heart valves and small veins have also been made, but are not yet ready for implementation.[92]

Government Initiatives and Public-Private Partnerships

As part of an effort to strengthen productivity and competitiveness in manufacturing, national governments around the world have launched several initiatives to promote additive manufacturing. China, Singapore, and Germany are investing heavily in the technology (box 2). The White House Office of Science and Technology has formed an interagency working group, and numerous federal organizations, such as the Department of Commerce, the National Science Foundation, and the Department of Energy, have programs to advance the technology. For example, engineers at the National Institute of Standards and Technology (NIST) are working to enhance additive manufacturing equipment and process metrology; process optimization and control; advanced sensor systems; materials characterization; data formats; and standards development.[93]

The U.S. federal government is also working with private industry and academic institutions to further advance additive manufacturing. NIST awards grants to improve additive manufacturing; it provided $7.4 million of funding in 2013.[94] The National Science Foundation has programs to educate students, workers, and enterprises about additive manufacturing. It also awards grants to improve the technology. The Department of Energy Advanced Manufacturing Office partners with industry, small businesses, and other stakeholders to identify and invest in additive manufacturing technologies. With the Oak Ridge National Laboratory, it has a program to develop advanced materials; implement advanced controls; and explore next-generation systems to overcome technology barriers for additive manufacturing. One project involves the development of large-scale, high-deposition-rate additive machining centers.[95]

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90 Scott et al., "Additive Manufacturing," March 2012, 11.

91 BioPortfolio, "Additive Manufacturing Techniques for Producing Tissue," July 22, 2013.

92 Levy, "A Fully Functional 3-D Printed Heart," April 15, 2014.

93 Slotwinski, "Additive Manufacturing at NIST," March 9, 2013, 2.

94 Bello, "NIST Awards $7.4 Million in Grants for Additive Manufacturing Research," September 2013 (accessed October 8, 2013).

95 Dehoff, "Thinking Beyond Today," July 11, 2013.

BOX 2 Initiatives in Other Countries

Industrialized economies, and a few developing ones, are working to develop and apply additive manufacturing, and thus strengthen productivity and competitiveness.

China, Singapore, and some countries in Europe have committed hundreds of millions of dollars to develop and commercialize additive manufacturing. China, for example, has been investing in additive manufacturing since the early 1990s, and the Chinese government is pledging 1.5 billion yuan ($245 million) to a seven-year project to advance development of the technology.a The Asian Manufacturing Association,[a] Beijing-funded trade group, is promoting wider integration of additive manufacturing by establishing 10 innovation institutes, each starting with a $3.3 million injection of investment.[b] A company in Hefei, Anhui Province, is investing 750 million yuan ($125 million), indicating that Chinese business is eager to explore the technology.[c]

Singapore is investing $500 million in additive manufacturing over the next five years.[d] The Singaporean government is dedicating significant funding to specific programs to help engineers define and use next-generation manufacturing technologies, and to explore the potential of building a new additive manufacturing industry ecosystem.[e]

There are also numerous efforts to further additive manufacturing in Europe. One initiative is the Direct Manufacturing Research Center at the University of Paderborn in Germany. Established in 2008, this institution is a leading research center for additive manufacturing, with funds from the German state of North Rhine-Westphalia and member companies. Research has thus far focused on improving the processes for laser sintering/melting technology for metal and plastic powder, as well as establishing industry requirements for materials, training, and standards development.[f] In October 2012, the UK government announced grants for collaborative research and development projects in additive manufacturing. The grants will be awarded through an open competition managed by the Technology Strategy Board, the Engineering and Physical Sciences Research Council, and the Economic and Social Research Council.[g]

[a] Brooke, "China Flexes Muscles," June 27, 2013.
[b] Brooke, "China Flexes Muscles," June 27, 2013.
[c] With the exception of Japan, additive manufacturing started much later in Asia than in the United States and Europe. Asia has largely caught up with the rest of the world; however, most industrial machines there are bought by product development companies to assist in early product development rather than final goods. Brooke, "China Flexes Muscles," June 27, 2013.
[d] Brooke, "Singapore to Invest," March 27, 2013.
[e] Brooke, "Singapore to Invest," March 27, 2013.
[f] Direct Manufacturing Research Center website, http://dmrc.uni-paderborn.de/about-dmrc (accessed July 5, 2013).
[g] The Engineer, "£7m Funding for UK Additive Manufacturing Projects," October 23, 2012.

America Makes, formerly the National Additive Manufacturing Innovation Institute (NAMII)—a public-private partnership with member organizations from government, industry, and academia—is a particularly robust additive manufacturing program.[96] America Makes is the flagship of 15 manufacturing institutes developed by the National Network for Manufacturing Innovation, a billion-dollar initiative to strengthen U.S. manufacturing and competitiveness.[97] The stated mission of America Makes is "to accelerate additive manufacturing technologies to the U.S. manufacturing sector and increase domestic manufacturing competitiveness."[98] It is promoting the technology by:

- establishing a collaborative network for sharing information and research;
- facilitating the development and application of efficient additive manufacturing technologies; and
- developing a workforce that can adapt to the changing requirements of additive manufacturing technologies and practices.[99]

America Makes is the first national program dedicated to additive manufacturing. It was launched in 2013 with $90 million in funding: $30 million from the federal government and the rest from the business and nonprofit sectors. The 20 projects underway range from basic research about how polymers and other materials will react during the heating and deposition process to work on more industrial applications, such as developing a lower-cost, high-temperature process for working with thermoplastics to make air and space vehicle components.[100]

Industry is taking steps to facilitate the development of additive manufacturing.[101] EWI, a nonprofit engineering and technology resource organization, launched the Additive Manufacturing Consortium (AMC) in 2010. The AMC is a diverse group of practitioners and stakeholders working to "accelerate the innovation in additive manufacturing technologies to move them into the mainstream of manufacturing technology from their present emerging position."[102] Stratasys, Ltd. is working with the Oak Ridge National Laboratory to develop fused deposition

[96] In January 2013, the Brookings-Rockefeller Project on State and Metropolitan Innovation put NAMII on its annual "Top 10 State and Metropolitan Innovations to Watch" list, recognizing its potential to create jobs, grow regional economies, and boost global competitiveness.

[97] America Makes website, *https://americamakes.us/* (accessed June 13, 2013).

[98] America Makes website, *https://americamakes.us/* (accessed June 20, 2013).

[99] America Makes website, *https://americamakes.us/* (accessed June 13, 2013).

[100] America Makes website, *https://americamakes.us/* (accessed June 20, 2013).

[101] The United States dominated basic research for additive manufacturing through the late 1990s, when public funding decreased. Today, Europe, especially Germany, dominates applied research in the technology. Industry representative, interview by author, July 15, 2013.

[102] EWI is a member organization which develops and applies manufacturing technology innovation within the manufacturing industry. EWI, Additive Manufacturing Consortium website, *http://ewi.org/additive-manufacturing-consortium* (accessed June 20, 2013).

modeling[103] and make it a mainstream manufacturing practice.[104] Firms are also partnering with academia to promote additive manufacturing. Jet engine manufacturer Aerojet Rocketdyne, for example, is collaborating with the University of Connecticut to create one of the country's most state-of-the-art additive manufacturing facilities. Over the next five years, Aerojet Rocketdyne will invest $9 million in the development of powder-based additive manufacturing technologies.[105] These and other efforts aim to accelerate U.S. development and application of additive manufacturing technology and will likely help strengthen U.S. competitiveness.

Challenges to Development and Adoption

Several fundamental challenges must be addressed to achieve widespread use of additive manufacturing and to realize its potential economic benefits. Among the most significant challenges are developing standards, improving the selection and affordability of materials, and increasing the reliability and accuracy of equipment and processes.[106]

Standards Development

Developing standards is critical to increasing diffusion and adoption of the technology.[107] Standards would provide a foundation for creating products that conform to certain specifications and are compatible with products provided by different suppliers seeking the same quality, performance, and interchangeability.[108] Additive manufacturing standards would also ensure the safety, reliability, and quality of processes and products. Because there are currently only a handful of additive manufacturing standards, companies conduct their own testing to ensure integrity of the equipment, processes, and products.[109] Costly and time-consuming, testing deters wider application of additive manufacturing, underscoring the need to develop standards from design to part build to operation. A standard is needed, for example, for software compatibility and communication across additive manufacturing machines. Instead of a standard format for electronic blueprints that allows CAD programs to talk to each other, there are a number of proprietary and ad hoc formats that do not work well together, slowing and limiting production.[110]

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103 Fused deposition modeling heats thermoplastic material to a semi-liquid state and extrudes it according to computer-controlled paths. The resulting parts are unrivaled in mechanical, thermal, and chemical strength.

104 Grimm, "Stratasys and Oak Ridge," July 7, 2012.

105 Photonics.com, "Pratt & Whitney Opens Additive Manufacturing Center," April 11, 2013; Aerojet Rocketdyne acquired Pratt & Whitney Rocketdyne in June 2013.

106 Sealy, "Additive Manufacturing as a Disruptive Technology," 2012, 92.

107 Scott et al., "Additive Manufacturing: Status and Opportunities," March 2012, 20.

108 Scott et al., "Additive Manufacturing: Status and Opportunities," March 2012, 20.

109 The adoption of parts made via additive manufacturing processes into critical applications, such as aerospace engine components, is hampered by a lack of consensus (e.g., regarding material properties for additive manufacturing) required for many procurement specifications; the NIST Materials Data Program provides evaluated data on phase equilibria, structure and characterization, and performance properties.

110 Industry representative, interview by author, July 15, 2013.

Another area of additive manufacturing production that would benefit from standards development is material property data generation.[111] Measurement (metrology) capacity, among others, is severely lacking. Experts report that there is a "striking dearth of metrology capabilities for process-structure-property relationships; closed-loop and adaptive control systems; and new sensors for fundamental build properties such as shape and surface finish."[112] They further note critical needs in measuring the raw material inputs, processes, and resulting parts.[113]

All material property data must be robust and comprehensive. In 2009, in response to the need for industry standards, the Society of Manufacturing Engineers and ASTM International (formerly the American Society for Testing Materials) formed Committee F42 on Additive Manufacturing Technologies. The Committee, of which NIST is an executive member, is working to develop standards to:

- allow manufacturers to measure and compare the performance of different additive manufacturing processes and materials;
- specify part-building requirements to give purchasers and suppliers a common set of parameters with which to work, thereby improving vendor relationships;
- help new users adopt additive manufacturing technologies; and
- provide users with uniform procedures for calibrating additive manufacturing machines and testing their performance. [114]

The NIST Engineering Laboratory reports that the additive manufacturing industry has identified many additional needs for standards that will take much effort and time to develop.[115]

Material Selection and Cost

The narrow selection of inputs and uncertain properties of additively manufactured materials present barriers to many industries. This is especially true in aerospace, which needs material that can withstand staggering pressures and temperatures of over 2,000 degrees Fahrenheit.[116]

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[111] Property data summaries are collections of property values derived from surveys of published data. These collections typically focus on either one material or one particular property. Studies of specific materials typically include thermal, mechanical, structural, and chemical properties, while studies of particular properties survey one property across many materials. The property values may be typical, evaluated, or validated. Values described as typical are derived from values for nominally similar materials. Jurrens, "NIST Measurement Science for Additive Manufacturing," March 14, 2013, 7.

[112] Campbell and Slotwinski, "Metrology for Additive Manufacturing," 2013, 164.

[113] Campbell and Slotwinski, "Metrology for Additive Manufacturing," 2013, 163.

[114] Additive Manufacturing Institute, "Manufacturing Engineering," January 5, 2013, 16.

[115] NIST representative, interview by author, June 25, 2013.

[116] Georgia Technical Institute representative, interview by author, June 25, 2013.

Despite recent progress in additive manufacturing material development and characterization,[117] problems remain, including the limited selection of materials, inconsistent production quality, and high costs. As a result, only a fraction of the materials that are used in conventional manufacturing are compatible with additive manufacturing.[118] As noted earlier, the major categories of additive manufacturing materials are plastics and other polymers and metals. There are also diverse filled and composite materials, as well as ceramic and ceramic-metal hybrids.[119] According to NIST, "material requirements are impacted by the need to create feedstock, to be processed successfully by the fabricator coupled with post processing, and to manifest acceptable service qualities."[120]

Most additive manufacturing processes use proprietary polymers that are not well characterized, are often weaker than those used in traditional manufacturing, and can sometimes lack uniform part strength. Parts that have been additively manufactured with metal have physical properties that can be quite different from conventional wrought or cast metals. They may, for example, lack full density, which can compromise fracture toughness and fatigue properties. According to an industry expert, "porosity, or partial delamination, could act as crack initiation sites in the material, which could lead to premature failure of such parts, especially when subjected to cyclic stress conditions."[121]

Although there have been increases in the variety and application of additive manufacturing material inputs and feedstocks, they are still expensive relative to traditional manufacturing materials. For example, powder metals can be 200 times as costly as sheet metal,[122] and photopolymers cost $750–$1,000 per gallon, compared to injection molding material, which costs $1 per pound.[123] While some producers enjoy savings when using additive manufacturing for custom products and low production runs, high material prices continue to be an impediment for many potential producers.

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117 Characterization in materials science refers to the use of external techniques to probe the internal structure and properties of a material (e.g., testing or analyzing a material to visualize its internal structure and gain knowledge about the distribution and interaction of its elements).

118 The most common additive manufacturing materials are metals and plastics and/or polymers. Various filled and composite materials are also used, as well as ceramic and ceramic-metal hybrids. The most common traditional manufacturing materials are metal, ceramics, and polymers. The Library of Manufacturing website, *http://thelibraryofmanufacturing.com* (accessed May 21, 2014).

119 The versatility of what can be made will grow exponentially with the increasing number of primary materials that can be simultaneously mixed and printed. Hybrids are not just mixed materials; they are new kinds of materials with unique properties.

120 Bourell, Leu, and Rosen, *Roadmap for Additive Manufacturing*, 2009, 31.

121 Wohlers, *Wohlers Report 2012*, 2012, 78; Campbell and Slotwinski, "Metrology for Additive Manufacturing," 2013, 167. The layer-wise nature of various additive manufacturing processes can lead to unwanted levels of porosity, especially for processes that involve melting of input materials. Porosity is beneficial for some biomedical implants, but can cause metal aerospace parts to fail.

122 McKinsey Global Institute, *Manufacturing the Future*, 2013, 90.

123 Gordon, "Building Strong but Lightweight," October 1, 2011, 7.

Equipment and Processes

Establishing additive manufacturing as a mainstream technology is, in part, contingent upon overcoming significant constraints in equipment and processes. Limitations such as machine cost and software capability will likely be overcome in the medium term.[124] Indeed, prices of industrial machines are falling, and capabilities of software and scanning devices are improving. Other limitations, however, are less likely to be surmounted soon.[125] The physics of layering and curing, for example, impose limits on process speed. Additionally, the issue of minimum wall thickness[126] is a fundamental restraint that is unlikely to be resolved without significant technological advancement.[127]

The *Roadmap for Additive Manufacturing*,[128] developed by experts in academia, government, and industry, outlines the following technological barriers:

- High costs of machinery and materials in comparison to those used in conventional manufacturing;
- Product fabrication speeds that are significantly slower than mass production processes;[129]
- Inherent tradeoffs between product size, accuracy, and speed (e.g., larger surfaces entail lengthier production times; accelerated production processes may produce parts with unknown and unpredictable properties);
- Significant geometric and property variations between "identical" products built on different machines leading to a lack of repeatability (e.g., use of the same materials and identical CAD files on five different machines could produce five goods with different properties);
- Requirements for highly skilled operators and/or careful periodic tuning, both of which are in short supply and costly;
- Unreliable machinery and inconsistent product quality, particularly with regard to part accuracy and surface finishes;
- Closed architectures, which preclude researchers from making meaningful changes to processing conditions; and
- The lack of hardware and software necessary for simple and effective multi-material deposition.[130]

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124 The average industrial additive manufacturing machine now sells for about $75,000, and some machines cost more than $1 million. McKinsey & Co., *Disruptive Technologies*, 2013, 109.

125 Limitations vary by additive manufacturing technique.

126 Minimum wall thickness is the absolute minimal thickness of a pipe or structure to contain its contents.

127 Deloitte, "TNT Predictions," March 17, 2012, 16.

128 Bourell, Leu, and Rosen, *Roadmap for Additive Manufacturing*, 2009. This document was designed with the goal of developing and articulating a systematic plan for additive manufacturing research for the next 10–12 years. Other sources outlined the same barriers. In 2013, America Makes announced plans to develop a national additive manufacturing roadmap.

129 Rapid prototyping is quicker with additive manufacturing.

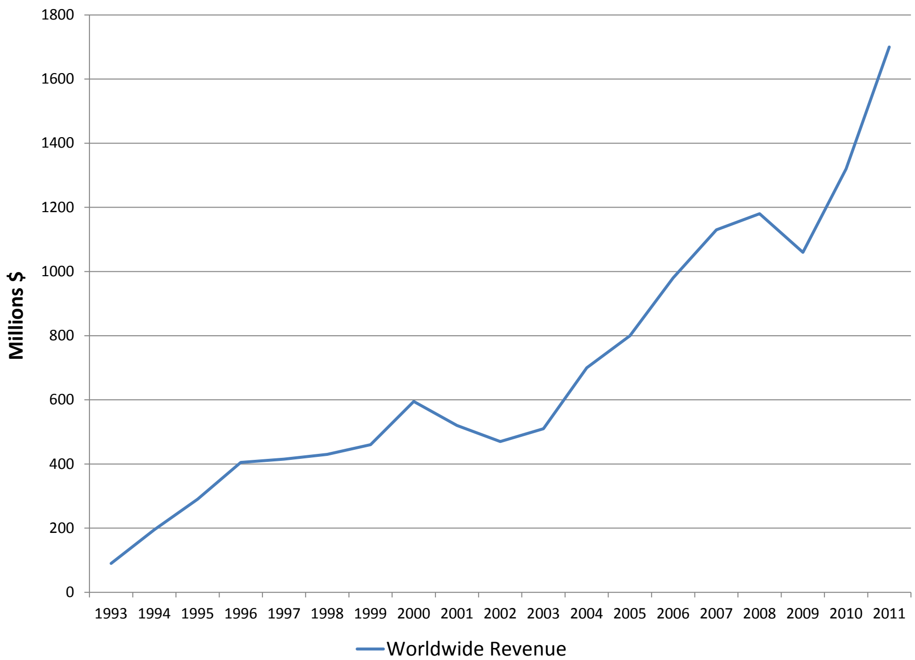
130 Bourell, Leu, and Rosen, *Roadmap for Additive Manufacturing*, 2009, 16.

INDICATORS OF FUTURE GROWTH

Increasing sales, technological advances, new applications, and the expiration of key patents are indicators of likely continuing growth in additive manufacturing. They are also drivers of the market, fueling momentum in investment, development, and applications.

The world market for additive manufacturing equipment and services has steadily and rapidly expanded since the mid-1980s. Wohlers Associates reports that in 15 of the 24 years it has tracked the technology, revenue[131] in the primary additive manufacturing market grew in the double digits and, in 2011, increased an estimated 29.4 percent to $1.7 billion[132] (figure 3). This estimate comprises all products and services directly associated with additive manufacturing processes worldwide.[133] Product revenue of $834 million includes additive manufacturing machines, machine upgrades, materials, and aftermarket products such as third-party software

FIGURE 3 Worldwide revenue for additive manufacturing products and services, 1993–2011



Source: Wohlers, *Wohlers Report 2012*, 2012, 125-127.

[131] Neither category includes secondary processes, such as making castings from this tooling. This market segment grew 25.1 percent, to $1 billion in 2011, up from $836 million in 2010, when it grew 27.3 percent. The combined total for overall additive manufacturing products and services—both primary and secondary markets—was $2.8 billion, an increase of 27.4 percent from $2.2 billion generated in 2010. Wohlers, *Wohlers Report 2012*, 2012, 130.

[132] Wohlers, *Wohlers Report 2012*, 2012, 125.

[133] Wohlers Associates considers and reports the secondary market segment separately.

and lasers.[134] Services revenue includes $642.6 million from parts produced on additive manufacturing machines by service providers, such as replacement components and $236.9 million from machine maintenance contracts and activities such as training, seminars, conferences, contract research, and consulting.[135]

Revenue is expected to continue strong double-digit growth over the next several years, with sales of additive manufacturing products and services likely reaching $3.7 billion worldwide by 2015 and surpassing $6.5 billion by 2019.[136]

The United States leads in the production and sales of professional-grade industrial additive manufacturing machines, accounting for 38 percent of installed machines during 1998–2011 (figure 2). Nearly two-thirds of all the industrial machines sold in 2011 came from U.S. manufacturers.[137] Wohlers Associates reports that annual sales of professional-grade, industrial additive-manufacturing machines will exceed 10,000 units worldwide by 2016.[138] Machines priced in the $5,000–$25,000 range will be responsible for most of this growth.[139] The growth reflects industry developments in and increasing awareness of additive manufacturing.

Advances in Materials

As discussed above, the range of feedstock applications available for use in additive manufacturing pales in comparison to that for traditional manufacturing. Over the past five years, however, significant improvements have occurred in the properties, variety, and quality of the applications for additive manufacturing.[140] It is now possible, for example, to additively manufacture parts in a range of metals that are on par with wrought material and exceed the properties of castings.[141] Among the available metals for additive manufacturing are aluminum alloys, titanium alloys, nickel-based superalloys, and a range of steels. Engineers are able to additively fabricate fully functional components from titanium and various steel alloys, featuring material properties that are equivalent to their traditionally manufactured counterparts. "Direct metal" processes will continue to advance as process control and understanding of fundamental metallurgy for additive manufacturing improves. Recent work at the Fraunhofer Institute for Laser Technology points to the potential for a fourfold increase in printing speeds for metal objects.[142]

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134 Wohlers, *Wohlers Report 2012*, 2012, 126. The average selling price of an industrial additive manufacturing machine was $73,220 in 2011; Wohlers, *Wohlers Report 2012,* 2012, 127.

135 Wohlers, *Wohlers Report 2012,* 2012, 130.

136 Wohlers, *Wohlers Report 2012*, 2012, 131.

137 IBISWorld, "3D Printer Manufacturing Market Research Report," December 2012, 18.

138 Wohlers, *Wohlers Report 2012*, 2012, 131.

139 Wohlers, *Wohlers Report 2012*, 2012, 137.

140 Metals, plastics, and other feedstock require special processing (e.g., polymerization) for use in additive manufacturing.

141 Wohlers, *Wohlers Report 2012*, 2012, 79.

142 McKinsey Global Institute, *Disruptive Technologies*, 2013, 109.

The increase, if achieved, would make additive manufacturing more attractive to a wider range of industries—and more competitive with traditional manufacturing.

The variety and quality of plastic, ceramic, and hybrid materials for additive manufacturing also continues to increase. EOS GmbH recently released three new polymers for its powder bed fusion process. PrimePart and the French chemical company Arkema have begun marketing two nylon-based powders designed for easy processing.[143] Scientists at General Electric Global Research and designers at General Electric Aviation have developed a group of new materials, ceramic matrix composites (CMC). Additively manufactured CMC components outperform the most advanced metallic alloys in gas turbines for jet aircraft.[144] CFM International, a joint venture between General Electric Aviation and France's Snecma, completed designs for a jet engine that includes additively manufactured ceramic matrix composites. CFM plans to build the first engine in 2014, and to test and certify it over the next two years.[145]

As a result of breakthroughs in multi-material additive manufacturing, more complex materials are being produced. The Objet Connex500, for example, additively manufactures up to 14 plastic-like materials in one job run. Rather than being fabricated as separate components and attached one at a time, they are simultaneously fused together. Researchers are developing new materials such as high-temperature polymers integrated with optics gradient materials, in situ sensors,[146] self-assembled single crystals, and continuous-filament composites.[147] The growing number and variety of materials for additive manufacturing increases the range of possible users and applications.

New Design Tools

New design tools specific to additive manufacturing are proliferating. Until recently, inputs into an additive manufacturing machine were limited to a CAD model. Now, input can be generated by a number of means, including medical scan data, entertainment software (as is the case with computer game avatars), and even simple drawing and sketching programs.[148]

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143 Rilsan Invent Natural and Rilsan Invent Black. Wohlers, *Wohlers Report 2012*, 2012, 76.

144 Ceramic matrix composites handle enormous stress and temperatures as high as 2,400 degrees Fahrenheit inside gas turbines and jet engines, and make them much more fuel efficient. CFM estimates that the reduced weight of the additively manufactured components will reduce fuel consumption by about 15 percent—enough to save nearly $1 million per year per airplane, assuming a fuel cost of $2.50 per gallon. Destefani, "Ceramic Matrix Composites Make Inroads in Aerospace," May 14, 2013, 1.

145 GE Reports, "Design Freeze Brings Next-Gen LEAP Engine," May 6, 2013, 2.

146 *In situ* sensors are in constant contact with the medium they are measuring. For example, a spectroscopic sensor detects and categorizes defects, predicts the composition and phase transformation of the medium, and monitors manufacturing quality in real time.

147 Objet Connex website, *http://www.stratasys.com/3d-printers/design-series/precision/objet-connex500* (accessed July 2, 2013).

148 Wohlers, *Wohlers Report 2012*, 2012, 22.

Software and design tools such as Autodesk 123D Suite are becoming increasingly popular.[149] The growing sophistication of the tools will enable production of new, complex designs as well as the analytical techniques to validate the designs before manufacturing.

Future design tools will be created to be intuitive to use. Some, for example, will respond to touch and movement; others will respond to environmental conditions.[150] Co-design and co-creator tools are also emerging and can often be accessed and used on a website. With the advent of more advanced design tools, the benefits of additive manufacturing, such as prototyping, can be more fully realized and may spur new products and innovations.[151]

Expiration of Key Patents

The expiration of early additive manufacturing machinery patents is influencing the development of new machines and applications in the United States and abroad. When the original fused deposition modeling patent expired in 2005, it allowed for the creation of RepRap, a replicating rapid prototyper. RepRap was the first low-cost additive manufacturing machine and it has found great popularity in the open-source community. Today, RepRap is more widely used than any other additive manufacturing system.[152]

The last of the selective laser sintering[153] patents from inventor Dr. Carl Deckard and the University of Texas at Austin expired in June 2014. Wohlers Associates report that plans to produce a more affordable alternative are already underway. They suggest that there will be several new developments based on laser sintering technology by mid-2014.[154] As more patents expire, there will be opportunities to capitalize on the technology and to develop new systems. These new systems will likely provide additional product offerings and increase competition among manufacturers.

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[149] Wohlers, *Wohlers Report 2012*, 2012, 199.

[150] Lipson and Kurman, *Fabricated*, 2013, 221.

[151] Bourell, Leu, and Rosen, *Roadmap for Additive Manufacturing*, 2009, 16.

[152] RepRap website, *http://reprappro.com/about* (accessed July 2, 2013).

[153] Selective laser sintering involves the use of a high-powered laser (for example, a carbon dioxide laser) to fuse small particles of plastic, metal (direct metal laser sintering), ceramic, or glass powders into a mass that has a desired three-dimensional shape.

[154] Wohlers, *Wohlers Report 2012*, 2012, 253. Selective laser sintering can easily make very complex geometries directly from digital CAD data. While it began as a way to build prototype parts early in the design cycle, it is increasingly being used in limited-run manufacturing to produce end-use parts.

POTENTIAL IMPLICATIONS FOR MANUFACTURING COMPETITIVENESS

Additive manufacturing is increasingly used in the automotive, medical, and aerospace industries, but largely remains limited to small-series production within them. While the technology has room to grow and potential to strengthen productivity in many industries, its implications for overall manufacturing competitiveness are less clear. As with any emerging technology, new standards, wider awareness, and a better-developed infrastructure are required to facilitate its use.[155] Further, evolving industry and government policy—as well as the convergence of additive manufacturing with other advancing technologies—will certainly bolster the use of additive manufacturing.

Impacts on Manufacturing

It is difficult to predict in detail how additive manufacturing—a technology that is still emerging—will affect individual industries. However, if challenges and barriers noted earlier can be overcome, additive manufacturing has the potential to open the door to myriad new processes and efficiencies. The impacts will initially be limited to a range of customized, small-batch production goods, but there are indications that a paradigm shift has already started. Some likely impacts include:

- reduced material waste in comparison to subtractive methods;
- superior products with complex internal structures that add strength, reduce weight, increase functionality, and are easier to maintain;
- open-design products created by communities of end users; and
- customization as per-unit costs of small production runs (even single items) approach those of long runs.[156]

As additive manufacturing continues to evolve, it will likely result in:

- quicker time to market due to faster design and prototyping cycles as well as the possible elimination of many traditional manufacturing steps such as transportation, tooling, and assembly;
- greater competition, creating a larger variety of products due to lowered barriers to entry; and
- smaller, less costly, and more agile supply chains, especially for low-volume or highly specialized components.[157]

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155 Thomas, *Economics of the U.S. Additive Manufacturing Industry* (prepublication draft), June 2013, 2.

156 CSC, "3D Printing and the Future of Manufacturing," Fall 2012, 21.

157 CSC, "3D Printing and the Future of Manufacturing," Fall 2012, 21.

CONCLUSION

Despite the challenges to further adoption, many experts believe additive manufacturing will significantly change certain production and distribution activities. The Economist predicts the technology will have an impact on manufacturing as profound as modern assembly-line factories did in the 20th century.[158] The McKinsey Global Institute notes that "the technology could usher in a new ecosystem of smaller value chains and new companies providing printable designs on the web, instead of products on the shelf . . . small business will be able to compete with traditional manufacturing, product will never go out of stock, size of batches will become meaningless, and manufacturing will become truly just in time."[159]

The United States is already a leader in the production and use of additive manufacturing. With one of the most innovative and flexible economies in the world, it is also well positioned to further exploit the technology.[160] Additive manufacturing could reduce costs and improve efficiency in manufacturing, which continues to be an important driver of prosperity in the country: manufacturing accounts for 12 percent of U.S. gross domestic product, 70 percent of private R&D spending, 60 percent of exports, and about a third of productivity growth. The establishment of standards and appropriate government and industry policies and initiatives would accelerate development and adoption of the technology. Although the benefits would vary according to industry, the resulting spillover effects would likely enhance the overall productivity and manufacturing competitiveness of the United States.

[158] *Economist*, "Print Me a Stradivarius," April 21, 2012, 17.

[159] Baily, Manyika, and Gupta, "U.S. Productivity Growth: An Optimistic Perspective," Spring 2013, 8.

[160] As noted, among the countries for which OECD STAN data are available, for example, the United States also has the largest R&D expenditure for total manufacturing growth.

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The Economic Implications of Strengthening Intellectual Property Rights in Developing Countries

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Abstract

We survey the recent literature on the economic implications of strengthening intellectual property rights in developing countries. First, we identify the theoretical concepts and empirical methods that are frequently applied to this topic. Then we discuss ten specific economic studies that have addressed this topic in the last ten years. Finally, we identify the most common findings in the literature.

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INTRODUCTION

Intellectual property rights (IPRs) refer to a set of laws and rules that protect the economic value of inventions and artistic creations from imitation by competitors. The most common forms of IPRs are patents, copyrights, trademarks, and trade secrets.[2] IPRs help to motivate and reward creative and innovative efforts, but they can also limit the spread of technological advances and create market power, which can lead to higher prices for consumers. Economic analyses of IPRs focus on this trade-off between incentives for innovation and growth (dynamic efficiency) and competitive pricing (static efficiency). Policymaking in this area involves balancing these conflicting interests.

This tradeoff is even more complicated in the context of international trade and investment. There are often significant differences in IPR regimes across countries, and there is generally a large gap between the strength of IPRs in advanced countries (often referred to in the literature as "the North" because of the historical location of most advanced countries in the Northern Hemisphere) and developing countries (often referred to in the literature as "the South" because of the historical location of many developing countries in the Southern Hemisphere). These differences in IPRs can have a significant impact on international economic activity: they can affect a firm's willingness to transfer technology and to make direct investments across borders, and they can influence international trade flows. There have been attempts to close the North-South gap by strengthening IPRs in the South, like the WTO's Agreement on Trade-Related Aspects of Intellectual Property Rights (TRIPS) negotiated during the Uruguay Round. But these attempts can have economic costs and benefits that are very unevenly distributed between the North and the South.

In the two decades since the signing of TRIPS, the benefits and costs of strengthening IPRs in the South has become an important research topic among academics in the field of international economics. Researchers have developed complex theoretical and econometric models of international trade, foreign direct investment (FDI), and technological innovation, and these models have contributed to the continuing policy debate. For economic theorists, it is challenging to model trade-related IPRs because they involve interrelated economic decisions about international trade, investment, and technology transfer. Their models have been used to predict whether a country will choose to strengthen and reform its IPRs and when countries might benefit economically from strengthening their own IPR regimes. The models have also been used to study the effects of IPRs on wages and economic welfare, FDI, and the form and extent of international technological transfer.

For empirical researchers, the large policy changes that have occurred in developing countries offer opportunities to study and better understand the economic implications of IPRs. The TRIPS reforms have generated many informative "policy experiments" in the data. Recent econometric studies have tried to quantify the effects of changes in IPR protection on patenting,

[2] The issue of trade secrets is not directly addressed in the economic studies that we review, but this issue is discussed in detail in Hall et al. (2014).

research and development (R&D) spending, international royalty and licensing payments, and international trade. This is a challenging area for empirical researchers, for two reasons in particular. First, data on international technology, investment, and services flows are very limited, especially when compared to the data on merchandise trade. Second, IPR policies are often complex and their implementation is usually not transparent.

In this article, we briefly survey the recent literature on the economic implications of strengthening IPRs in developing countries. We review and summarize 10 studies that have been published in leading academic journals or conference volumes in the last decade.[3] The 10 studies are a fairly representative sample of the issues, methods, and findings in the literature. Although several of the studies that we review recommend specific policy alternatives, we are not endorsing one view over another, nor are we offering policy recommendations of our own.

THEORETICAL MODELS: WHY DIFFERENT COUNTRIES VIEW IPRS DIFFERENTLY

In a 2003 article titled "The North's Intellectual Property Rights Standard for the South," Lai and Qiu develop a theoretical model of trade between the North and the South. They estimate the effect on economic welfare of an international agreement to harmonize countries' IPR standards. Assuming that the North has a greater demand for innovative products and a greater capacity for innovation, their model indicates that the North will choose stronger IPRs than the South before an international agreement is negotiated. The introduction of the international agreement strengthens the South's IPRs relative to the North's pre-agreement level, and this increases global welfare; however, the North benefits at the expense of the South. In the North, producers gain from higher profits while consumer prices remain largely unchanged, resulting in net positive welfare effects. In the South, on the other hand, consumer prices rise, resulting in net negative welfare effects. Lai and Qiu conclude that the South would be unwilling to strengthen their IPRs unless they receive some form of compensation. Because the South has a comparative advantage in goods that are not patent-intensive, they suggest that the North offer increased market access as compensation.

Lai and Qiu also model a multi-sector negotiation in which the two countries simultaneously bargain over the strength of IPRs in the South and tariff levels in the North. The bargained outcome is that the South strengthens its IPRs and the North lowers its tariff rates. Higher bargaining power in the South leads to an improved outcome overall, with deeper trade liberalization in the North. Though it is not possible in their model for both parties to benefit from a

[3] Maskus (2012) provides a broader, book-length discussion of the global economics of intellectual property rights. His book includes an introduction to the theoretical concepts and empirical challenges, a detailed survey of recent literature, and a set of policy recommendations. While our brief review covers several of the same articles reviewed in Maskus, it is narrower in scope. We focus specifically on the trade and investment effects of strengthening IPRs in developing countries.

single-issue agreement, the multi-issue agreement results in economic gains for both the North and the South.

Grossman and Lai's 2004 study, "International Protection and Intellectual Property," extends this analysis, focusing again on the incentives that governments have to protect intellectual property when they are open to trade with other countries at very different levels of economic development. Their North-South model is similar to that in Lai and Qiu (2003), but with one key difference: they include in their model the factors determining the resource costs of innovation. Grossman and Lai conclude that the optimal level of IPRs in the absence of trade would not depend on the size of a country's market. However, when the countries trade with each other the relative size of the countries' markets and their relative productivity in innovation do affect the countries' incentives to strengthen their IPRs. Since the North is assumed to have a greater R&D capacity and a larger market, the North has a stronger incentive to protect IPRs.

Grossman and Lai show that there is a level of patent protection that maximizes global economic welfare, and it can be achieved with different combinations of country-level patent protection. However, different policy distributions for IPRs have different implications for welfare in the North and South. Policies that maximize incentives for global research are beneficial for the North but detrimental to the South, and international harmonization of patent policy does not necessarily lead to a globally efficient outcome.

Chen and Puttitnun examine how a developing country's capacity for innovation contributes to the IPR regime that it adopts, in their 2005 article titled "Intellectual Property Rights and Innovation in Developing Countries." Their theoretical model treats the foreign IPR regime and foreign innovation as exogenous and predicts how a country's government will choose its level of IPR protection to maximize domestic social surplus. The model has two sectors, an import sector and a local sector. The import sector has a foreign firm, whose patented technology allows it to produce higher quality products, and a domestic firm that can imitate that technology to a degree determined by the protection of IPRs. The local sector also has two firms, one which can develop technology and one which only imitates this technology. Increased protection of IPRs makes imitation more difficult in both sectors. In the import sector, higher IPRs imply that lower-quality goods will be produced by the domestic firm and that there will be less price competition for the foreign firm, resulting higher prices and a reduction of consumer surplus. However, in the local sector, higher IPRs imply more incentives for innovation. For this reason, there is a tradeoff between the benefits that a country can gain from imitation and those it can gain through domestic innovation. Based on their model, Chen and Puttitanun hypothesize that very poor countries will provide strong protection for IPRs in order to ensure access to foreign technologies; middle-income countries will provide relatively weak protection to facilitate domestic imitation of these foreign technologies; and advanced countries will provide strong protection to benefit their own innovators.

Branstetter and Saggi have made several important contributions to this theoretical literature, including their 2011 article titled "Intellectual Property Rights, Foreign Direct Investment, and Industrial Development." They develop a North-South model of the determinants of innovation, imitation, and FDI. They use the model to examine how the strengthening of IPRs in developing countries impacts their growth, the countries' ability to attract FDI, and the location of multinational production. In the model, there are three types of firms: Northern firms, Northern multinationals and Southern imitators. A strengthening of IPRs in the South raises the cost of imitation while increasing the incentive for FDI by reducing the risk of imitation. However, it also boosts the demand for labor and real wages in the South, as the South becomes a more attractive location for investment. At the same time, it increases the rate of innovation in the North, since shifting multinational production to the South frees up labor for innovation in the North. A rise in the R&D productivity of Northern firms decreases imitation in the South, increases innovation in the North, increases FDI in the South, and increases the shares of production and sales that are controlled by multinational firms.

Regarding the location of production, Branstetter and Saggi conclude that strengthening IPRs in the South increases FDI and consequently the share of Southern production that is undertaken by multinationals. But because imitation is reduced, the profit that must be earned to entice a Northern firm to become a multinational via FDI is lower, and this decreases the value of the foreign affiliate sales of a typical multinational firm relative to the sales of a Northern exporter.

EMPIRICAL STUDIES: THE EFFECTS OF IPR REFORMS ARE COMPLEX

Park and Lippoldt advanced the empirical front in the literature in their 2005 article titled, "International Licensing and Strengthening of Intellectual Property Rights in Developing Countries during the 1990s." Their study examines whether stronger IPRs in developing countries encourage technology transfer through international licensing. They use firm-level data on international licensing and quantitative indexes of patent rights, copyright rights, trademark rights, and enforcement effectiveness in conducting their analysis. Their descriptive statistics show that 32 percent of the international royalties and license fee receipts of the U.S. firms they study come from licensing industrial processes, 30 percent from pre-recorded performances, 20 percent from general use software, and 9 percent from trademarks. Approximately 80 percent of licensing receipts for U.S. parent firms originated in countries where per capita GDP exceeded $18,000 (in 1995 U.S. dollars), and 73 percent of receipts came from affiliated parties.

Park and Lippoldt estimate a model with the licensing receipts of individual firms as the dependent variable and indexes of IPRs as the main independent variables. They estimate the model for a sample of U.S. parent firms for three years (1992, 1995, and 1999). The influence of IPRs varies depending on the type of IPR: patent rights and enforcement effectiveness were significant in most of the specifications, while trademark and copyright protection had only weak influences. The influence of IPRs varied by sector and by the type of property licensed. They found that when U.S. firms were deciding how to transfer technology within a country, stronger IPRs made them more likely to choose international licensing. The coefficients on many of the IPR variables are statistically significant, though they do not explain a large part of the variation in any of the econometric specifications.

Park and Lippoldt also find that developing nations that implemented more extensive patent reforms tended to have more licensing agreements with developed nations. The overall conclusion of their study is that the strengthening of IPRs had a net positive effect on international licensing of technologies between unaffiliated parties in the 1990s.

Branstetter, Fisman, and Foley offer another rigorous analysis of firm-level data in their 2006 article titled "Do Stronger Intellectual Property Rights Increase International Technology Transfer? Empirical Evidence from U.S. Firm-Level Data." They examine the impact of IPR reforms in 16 countries on technology transfer within U.S. multinational firms. Their econometric model uses firm-level and affiliate-level data on royalty payments and country-level data on patents. They find that as reforms occurred, royalty payments to parents and affiliate R&D expenditures increased. They further found that this effect was concentrated among affiliates of parent companies that used U.S. patents extensively before the IPR reforms. Within this group, royalties increased by more than 30 percent. They also find that IPR reforms led to a 23 percent increase in affiliate R&D expenditures in patent-intensive industries. They also examined whether patenting by multinationals increased after IPR reforms. They found that nonresident patent filings grew more rapidly after reform, suggesting that the multinationals transferred new technologies beyond those which had been used, but not patented, prior to reform.

Chaudhuri, Goldberg, and Jia focus more narrowly on the patent-intensive pharmaceutical industry in their 2006 article titled "Estimating the Effects of Global Patent Protection in Pharmaceuticals: A Case Study of Quinolones in India." They examine the effect of patent enforcement on sales of antibiotics in India. Their study addresses the common public health concern that strengthening IPRs in poor countries may reduce consumer access to life-saving medicines. India provides an interesting case study because it has a disease mix that is similar to that of many other developing countries and because it has a large generic pharmaceutical industry. Chaudhuri, Goldberg, and Jia first estimate the price and expenditure elasticities of demand for antibiotics in India, using an econometric model based on product-level data for 1999 and 2000. Then they use the estimated model to calculate the difference in economic welfare if there were patent protection on these products and some domestic substitutes were withdrawn from the Indian market, as a result. They estimate that there would be significant losses in consumer welfare due to higher prices and loss of product variety.[4]

Ivus studies another type of economic effects – the effects of stronger IPRs on the innovating world's exports to developing markets – in her 2010 article titled "Do Stronger Patent Rights Raise High-Tech Exports to the Developing World?" To distinguish between the effects of self-initiated IPR reforms and TRIPS-mandated IPR reforms, Ivus uses data from before and after the signing of the TRIPS agreement and the fact that former colonies of Britain and France

[4] Specifically, they estimate that the prices of foreign patentable antibiotics would be at least 100 percent higher (absent domestic price regulation).

developed strong IPRs before many other countries. She compares the growth rates of exports along two dimensions: former colonies of Britain and France compared to all other countries ("colonies" versus "non-colonies"), and patent-sensitive industries compared to patent-insensitive industries.

Ivus begins by describing the pattern of changes in IPRs in former colonies and non-colonies between 1960 and 2000. The former colonies had stronger IPRs at the time that the TRIPS agreement was signed, apparently as a result of their colonial relations, but the IPRs of the non-colonies changed to a greater extent after the signing of the agreement. Ivus classifies industries as patent-sensitive or patent-insensitive, depending on whether the industries derive their competitive advantage from patented inventions. In her econometric analysis, the dependent variable is export growth rates in the different time periods. These growth rates difference-out country fixed effects associated with the colonial relationships. Using this difference-in-difference measure, Ivus finds that strengthening of IPRs increased exports from the North to the South. She estimates that the dollar value of new exports created by changes in IPRs was about $35 billion per year (in 2000 U.S. dollars), an 8.6 percent increase in the annual value of patent-sensitive trade of the countries in the model.

Arora, Branstetter, and Chatterjee study the effects of patent reform on domestic innovation in the India in their 2011 study titled, "Strong Medicine: the Impact of Patent Reform on the Indian Pharmaceutical Industry." They present an econometric analysis of the effects of Indian patent reforms on the activities of 315 Indian pharmaceutical firms. They find that the reforms had significant positive effects on the stock market values and R&D spending of the firms, especially the most technologically advanced ones. Their study is important because it acknowledges the often overlooked possibility that strengthening IPRs in developing countries can encourage domestic innovation. It provides evidence that this actually occurred in the case of research-intensive Indian pharmaceutical firms.

Most recently, Park estimates the effect of Southern IPRs on Northern R&D expenditures in his 2012 article titled "North-South Models of Intellectual Property Rights: An Empirical Critique." He uses firm-level panel data on R&D carried out by U.S. multinationals and their affiliates in developed countries from the U.S. Direct Investment Abroad Survey published by the U.S. Department of Commerce, Bureau of Economic Analysis, as well as indexes of patent protection in individual countries weighted by market share. Park's model uses R&D investment as a dependent variable, and two measures – the level of domestic patent protection and the level of foreign patent protection – as independent variables. Park disaggregates the measure of foreign patent protection into developed countries and developing countries.

Park's descriptive statistics indicate that most of the U.S. firms in his sample sell to other developed countries. He finds that the levels of patent protection in developing countries are low compared to those of developed countries, and that the levels of domestic patent protection in most developed countries are greater than weighted aggregate patent protection in other countries.

In his econometric analysis, he finds that IPRs in developing countries do not have a significant positive effect on R&D in developed countries. Patent protection in other developed countries, however, is strongly positively correlated with the R&D of U.S. parent firms and their foreign affiliates. Park estimates that the elasticity of the firms' R&D with respect to the strength of patent rights in the foreign countries is 0.92. He finds that the patent rights in all foreign markets combined have a greater quantitative impact than domestic patent rights, reflecting the large size of the global market relative to the domestic market. Several control variables, including the value of sales and the number of R&D employees, are also strongly significant. Tax rates have a negative impact on R&D, but they are only statistically significant for foreign affiliates, suggesting that taxes have only a local influence. Public R&D funding is also statistically significant at the 5 percent level in all specifications.

Overall, Park finds that the protection of IPRs in the South does not have a strong positive influence on R&D in the North, probably because the relatively small economies in the South represent a minor share of the potential market for innovation. Nonetheless, he predicts that this may change in the future, as the markets in the developing countries grow.

CONCLUSIONS

This article has demonstrated that the economics of trade-related IPRs is an active research area with many interesting questions. While the literature continues to advance with the development of richer data sources, most of the questions have not been conclusively answered, and there is a need for further study. However, several preliminary themes find support in the 10 studies we have reviewed.

First, the strengthening of IPRs in the South appears to have little effect on the level of R&D expenditures and the rate of innovation in the North. But it apparently has a positive significant effect on the rate of international technology transfer from the North to the South.

Second, strengthening IPRs in the South has an ambiguous effect on international trade from the North to the South, but has a significant positive effect on FDI in the South. Stronger IPRs can reduce technology imitation and therefore create a market in the South for innovative products exported from the North. On the other hand, strong IPRs can encourage local production through FDI that displaces North-to-South trade in these products.

Third, stronger IPRs in the South usually benefit the North at the expense of the South. However, there are well-defined cases in which stronger IPRs can benefit the South. Stronger IPRs can induce FDI and technology transfer and increase labor demand in the South, and in some cases they can increase innovation in the developing countries.

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