The Impact of Industrial Physics on the U.S. Economy

A Report on the Contributions Physics Makes to U.S. Industry
by the American Physical Society

January 2019

ABOUT APS

Founded in 1899 to advance and diffuse the knowledge of physics, the American Physical Society (APS) is now the nation's leading organization of physicists with approximately 55,000 members in academia, national laboratories and industry. APS has long played an active role in the federal government, industry, and academia, including through studies and reports such as this one. This report was overseen by the APS Industrial Physics Advisory Board, which provides guidance to APS on how best to support industrial physics.

AUTHORSHIP

The American Physical Society has sole responsibility for the contents of this report, and the questions, findings, and recommendations within.

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Availability

A limited number of printed copies of this report are available free of charge by contacting the American Physical Society at Industrial.physics@aps.org. An electronic copy of the report is available free of charge at https://www.aps.org/programs/industrial/impact-economy.cfm

Background

The American Physical Society (APS) is the largest physics membership society in the United States and supports physicists in academia, industry, national laboratories, private research organizations, and other institutions. APS serves its members by:

- Serving as the leading voice for physics and an authoritative source of physics information for the advancement of physics and the benefit of humanity;
- Providing effective programs in support of the physics community and the conduct of physics;
- Collaborating with national scientific societies for the advancement of science, science education, and the science community;
- Disseminating the results of physics research through high-quality publications and expert meetings;
- Cooperating with international physics societies to promote physics, support physicists worldwide, and foster international collaboration; and
- Promoting an active, engaged, and diverse membership and supporting activities of its units and members.

In 2014, APS in conjunction with its Forum on Industrial and Applied Physics (FIAP) held a workshop on National Issues in Industrial Physics: Challenges and Opportunities (1) that explored the issues associated with maintaining U.S. leadership in industrial physics. One of the recommendations of that workshop was to prepare a report on the "Impact of U.S. Industrial Physics." In response to that request and in partnership with the American Institute of Physics, a federation of physical science societies, APS asked the APS Industrial Physics Advisory Board to organize such a study and to issue its findings in a publicly available report, which is contained herein.

The fascinating findings of the study show that an estimated 12.6% of the U.S. economy can be ascribed directly to the practice of industrial physics.

Economic studies such as this involve a number of assumptions as laid out in the report, but the data confirm what we inherently know from our knowledge of modern physics—that since the end of World War II, physics discoveries of the 20th century have been transformed by industrial physicists into incredible products and services. Examples include consumer electronics, personal computers, cell phones, GPS, MRI scanners, digital everything, and the Information Revolution that makes life today virtually unrecognizable to someone who lived 70 years ago. The flow of physics into industry is neither stopping, nor even slowing down as new disruptive products and services continue to emerge.

This report on the Impact of Industrial Physics on the U.S. Economy clarifies the structure of industrial physics, quantifies the contributions of industrial physics, and helps us understand that the entire physics community—industry, academia, government, and physics societies—must continue to support industrial physics so it has a healthy future. We welcome your comments and questions, which should be addressed to Industrial.physics@aps.org.

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Acknowledgments

Assembling the resources for a study such as this one requires significant planning and commitment. As mentioned in the Background to this Report, the idea for a study of the importance of industrial physics to the U.S. economy first was mentioned at the APS/FIAP *Workshop on National Issues in Industrial Physics* held in 2014.

One other recommendation of that Workshop was that APS form an Industrial Physics Advisory Board that would provide APS with input on how best to serve the industrial physics community and implement the Workshop Report. In the summer of 2016, the Industrial Physics Advisory Board decided that the time had come to do the economic study and set up a subcommittee (Study Subcommittee) to oversee the effort, including raising the needed funds. At the same time, the American Institute of Physics (AIP), a federation of physics societies, began a program to fund projects important to the physics community at large. As a result, APS applied for a grant from AIP and was awarded funding in the fall of 2016. Additional funds were obtained from a number of firms and APS itself as listed below.

Upon receiving the award, the Study Subcommittee, chaired by John Rumble Jr. began working with the APS Industrial Fellow, Steven Lambert, to choose an economic analysis organization to assemble the needed economic data. TEConomy Partners LLC of Columbus, Ohio, was selected and work began in the middle of 2017.

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Executive Summary

Industrial physics is a major contributor to the economic well-being of the United States and makes its contribution in four major ways:

- The direct hire of college-trained physicists of all degrees
- Physics as an essential element in the training of scientists and engineers who work in industry
- The use of physical principles in the technology that creates products and services
- The emergence of new physics that drives disruptive changes to the economy

The American Physical Society, with support from the American Institute of Physics, recently sponsored an in-depth analysis of the impact of industrial physics on the U.S. economy. The major findings are given in the box on the right and detailed in this report.

In one way, the size of the impact is not surprising given the increasingly technological nature of our economy. For example, since 1946, industries such as computer hardware and software, semiconductor and sensor manufacturing, and consumer electronics, have grown dramatically and are major economic drivers today. These industries are the direct result of the exciting physics discoveries of the 20th century being transformed into products and services by industrial physicists and other scientists and engineers well-versed in physics.

This impact is anticipated to grow even larger in the future, and it is incumbent upon industry, academia, government, and physics professional societies to recognize the importance of nurturing industrial physics by training the next generation of industrial physicists, increasing the quality of physics training to non-physicists, and fully supporting industrial physicists as they pursue their careers. In addition, 21st-century industry will need new physics and a better understanding of our physical world, a goal that requires the United States to maintain its world leadership in physics R&D.

Industrial physics directly produced an estimated **12.6%** of the U.S. GDP in 2016, or about **$2.3 trillion**.

Direct employment related to industrial physics was about **11,500,000 people** in 2016, which accounts for 6% of total U.S. employment.

U.S. exports by physics-based sectors are about $1.1 trillion (2016), which is approximately 20% of the value added (GDP) by those sectors.

In the period 2003 to 2016, approximately **70,000 degreed physicists** joined the industry

Between 2010 and 2016, over **340,000 patents** with the classification of physics were received by U.S. companies

In 2015, U.S. physics-based companies made **internal R&D investments** of over **$150 billion**.

Including indirect and induced contributions, industrial physics contributed approximately **30%** of the U.S. GDP in 2016, or about **$5.5 trillion**.

Between 1966 and 2016, the ***value added*** (**GDP**) in physics-based sectors of U.S. industry grew by a **factor of 22.** At the same time, the GDP grew by a factor of about 4 (both in 2016 constant dollars).

Introduction

The science of physics provides us with an understanding of our physical world and how it operates. Since 1687, when Isaac Newton presented the first formulation of his three basic laws of motion, physics has yielded an increasingly rich set of principles, solidly based on experiments and theory, that not only explains how our world and the universe operate, but also allows us to transform that knowledge into technology, products, and services that impact us daily in countless ways. Indeed, our world is continuously being reshaped by new advances in physics that lead to new technology, with most of these impacts derived from the use of physics in industry.

This report attempts to provide quantitative answers to the specific question: **How does industrial physics impact the economy of the United States?**

Posing the question this way allows us to consider the four major ways that physics contributes to the economy through:

- The direct hire of college-trained physicists of all degrees
- Physics as an essential element in the training of scientists and engineers who work in industry
- The use of physical principles in the technology that creates products and services
- The emergence of new physics that drives disruptive changes to the economy

Using time-proven economic analysis methodology and an understanding of how industry uses physics, we provide concrete data on the creation of jobs, the impact on U.S. economic activity, and the impact on tax receipts in the period from just after World War II to the present day (2016). We present evidence of the creativity that physics brings to industry and the economy, as well as draw conclusions on why this has happened.

We note at the start that our analysis is based on a number of assumptions that are subject to uncertainty. Even if the details of our methodology are modified, the conclusion remains that industrial physics exerts a significant and essential impact on the U.S. economy.

Industrial Physics!

As described above, industrial physics is practiced by more than just trained physicists. Industrial physics involves application of physics knowledge and principles to the design and manufacture of products and services. These principles include understanding of cause and effect in the physical world; harnessing light, force, and energy productively; and creating materials from the nano-scale to the mega-scale.

The number of jobs in physics-based sectors of the U.S. economy in 2016 was estimated to be about 11,500,000. The number of people working in industry classified as physicists by the Bureau of Labor Statistics occupational classification system (2) was estimated to be only 7,630, which of course vastly underestimates the number of degreed physicists working in industry, given that over 70,000 degreed physicists went into industry over a 13-year period, most of whom have titles other than physicist.

It is important to note that this report looks at all aspects of industrial physics contributions, not just those people who are classified as industrial physicists. Many physicists are employed in industry with titles such as engineer and scientist (e.g. materials scientist), even though they continue to do physics-related work.

Major Impacts of Industrial Physics on the U.S. Economy

Exports

$ 1.1 trillion, 20% of value added (GDP) produced by U.S. physics-based companies (2016)

Direct Employment

11,500,000 people directly involved in U.S. physics-based companies, almost 6% of total U.S. employment (2016)

GDP Growth 1966–2016

Physics-based sectors grew by factor of 22 compared to overall growth by factor of 4

Value Added (GDP)

Industrial physics directly contributed $ 2.3 trillion to the U.S. economy in 2016—12.6% of the GDP

New Industrial Physicists

70,000 degreed physicists joined industry (2003–2016)

R&D Investments

$ 150 billion internal R&D (2015) made by U.S. physics-based companies

Patents

340,000 physics patents granted to U.S. companies (2010–2016)

Total Employment

45 million people have jobs in the U.S. economy due to industrial physics (2016)

Overview of Results

Industrial physics is a major contributor to the economic well-being of the United States. A few statistics suffice to demonstrate this:

- Industrial physics contributes approximately 12.6% **of value added** to the U.S. economy in 2016, about **$2.3 trillion**.
- **Direct employment** related to industrial physics was about **11,500,000 people** in 2016, which accounts for almost 6% of total U.S. employment.
- Adding in indirect and induced employment (defined below), the **total U.S. employment** attributable to industrial physics is about **45 million persons**, just slightly less than a quarter (23.6%) of the U.S. workforce.
- **U.S. exports** by physics-based sectors are about **$1.1 trillion** (2016), which is approximately 20% of the value added (GDP) produced by those sectors.
- In the period 2003 to 2016, approximately **70,000 degreed physicists** joined industry, over 58% of total physics graduates.
- Between 2010 and 2016, over **340,000 patents** with the classification of physics were granted to U.S. companies.
- In 2015, U.S. physics-based companies made **internal R&D investments** of over **$150 billion.**
- Between 1966 and 2016, the **value added** (contribution to GDP) in the physics-based sectors of the U.S. economy grew by a **factor of 22**. At the same time, the GDP grew by a factor of about 4 (both in 2016 constant dollars).

This high impact reflects the strong influence technology has in today's economy, an influence likely to grow in the future. This report is structured as follows:

- General description of the methodology
- Total jobs and economic impact attributable to physics-based sectors in 2016
- Value added (GDP) of physics-based sectors
- Gross output (turnover) of physics-based sectors
- Industrial physics as a driver for manufacturing
- Industrial physics as a driver of productivity
- Physics-based exports
- Emergent physics-based industry as a positive disruptive force in the U.S. economy
- Industrial physics as a continuing catalyst for future growth
- Entrepreneurship in physics
- New industrial physicists

Throughout the report, examples are given of instances in which industrial physics has made significant and, in most cases, positive disruptive contributions to the U.S. economy.

Table 1. The Impact of industrial physics on the U.S. Economy (2016)

Impact Type (2016 data)	Employment	Labor Income (in Trillions)	Value Added* (in Trillions)
Direct contribution	**11,500,000**	**$1.2**	**$2.3**
Direct (Share of Total U.S.)	6.0%	10.9%	12.6%
Total contribution	**45,100,000**	**$3.1**	**$5.5**
Total (Share of Total U.S.)	23.6%	28.2%	29.8%
Total U.S.	**191,300,000**	**$11.3**	**$18.6**

** See definitions in Annex 2*

Precision Agriculture, Ride-Hailing Services, and Golf — Thanks GPS!

Finding a ride on a car service, using a distance finder to hit a golf shot close to the hole, getting directions to a restaurant, and farming by precision agriculture all rely on GPS (global positioning service) technology. GPS is based on fundamental physics work done in the late 1940s by Isidor Rabi and Norman Ramsey that led to atomic clocks. The first commercial atomic clocks appeared in 1956; the first commercial GPS device, which was developed by Gary Burrell and Ming Kao (photo right) in Lenexa, Kansas, went on sale in 1989. While today's applications might have been conceived decades ago, even the most optimistic predictor did not imagine how much we rely on GPS in our everyday lives.

This progression from fundamental physics research to industrial physicists using these principles to create products to those products having large economic impacts is an illustration of an unanticipated disruptive technology. In December 2012, a Boston Consulting Group study commissioned by Google (3) estimated that the U.S. geospatial industry has an impact on the U.S. economy that is 15 to 20 times the size of the geospatial industry, an industry that generated approximately $73 billion in revenues in 2011 and is made up of at least 500,000 high-wage jobs.

A more recent (2015) study for the National Space-Based Positioning, Navigation and Timing Advisory Board (4) estimated benefits in the U.S. for 2013 as shown below.

The next time you use a ride-hailing service, such as Uber™ or Lyft™, thank the industrial physicists who made it happen!

GPS Application Category	Estimated Range of Benefits in U.S ($ Billions) (4)
Precision agriculture - grain	10.0-17.7
Earthmoving with machine guidance in construction	2.2-7.7
Surveying	9.8-13.4
Air Transportation	.12-.17
Rail Transportation - positive Train Control	.01-.10
Maritime Transportation - nautical charts, etc.	.11-.26
Fleet Vehicle Telematics	7.6-16.3
Consumer Location-based Services - vehicles - willingness to pay	4.7-6.3
Consumer Location-based Services - vehicles - value of time	9.9-31.4
Total	**37-74**

General Description of Methodology

Introduction of Methodology

The analysis of the economic impact of industrial physics on the U.S. economy has four basic steps:

- Definition of industrial physics
- Identification of the industrial sectors of the U.S. economy reliant on industrial physics
- Estimation of the impact for each sector reliant on industrial physics
- Application of an economic model to determine the GDP and other economic data for each impacted sector

In this section, an overview of each step is given. Annex 2 contains a more detailed discussion of these steps and the assumptions that were made. The large size of the impact of industrial physics on the U.S. economy may seem surprising at first. Some reflection, however, of the enormous consequences of using new and old physical principles to develop industrial products and services should help convince the reader of the validity of the impact. The sidebars and anecdotes included in this report should aid that reflection.

As detailed in Annex 2, there is considerable uncertainty in much of this analysis, perhaps as much as a factor of + 2. Nevertheless, the impact is still very significant for all economic categories analyzed. Given the increasingly scientific and technological basis for emerging industrial products and services, that impact should remain as high, if not higher, in the foreseeable future.

Definition of Industrial Physics

Industrial Physics is a synergistic combination of people, education, and scientific principles that catalyzes the technological products and services that drive today's U.S. economy. Some of the contributions are obvious, but many others, though more subtle, are equally impactful. To provide a quantitative assessment of the impact of industrial physics, one can define four different ways industrial physics contributes to the U.S. economy:

- Physicists with degrees (B.A./B.S., M.A./M.S., and Ph.D.) in physics who work in industry as researchers, product designers, managers, research directors, and entrepreneurs
- Engineers, chemists, materials scientists, technicians, and other scientists and technical people that employ experimental and theoretical physical principles in their professions
- Use of fundamental physical principles to conceptualize, design, and manufacture physical products and systems, including understanding their use and impact; fundamental physical principles are the laws governing the electronic, nuclear, mechanical, electrical, magnetic, acoustic, heat, and radiation behavior of physical substances
- Emerging knowledge of new physical principles that lead to innovative and new products and services, such as quantum information, nanotechnology, personalized medicine, and autonomous transportation

Identification of the Industrial Sectors of the U.S. Economy Reliant on Industrial Physics

The second step in performing the economic analyses is to identify sectors of the U.S. economy that rely on industrial physics, as defined above, as the basis for their products and services using two criteria:

- Sectors having a significant number of scientific and technical jobs requiring physics training, which include:
  - People with or without physics degrees, working in jobs readily identified as physicists, and
  - People who have significant physics education as part of a professional degree or qualification.
- Sectors whose products and services directly rely on development and production of technologies based on:
  - Use of known physics principles, or
  - Innovation deriving from new or emerging physics knowledge.

The U.S. Office of Management and Budget, with support from the U.S. Bureau of the Census, issues the North American Industry Classification System (NAICS) (5) listing of all segments of the U.S. economy. The 2012 classification includes 312 four-digit NAICS codes, each representing an industry sector. In developing a quantitative approach, the 2016 U.S. Bureau of Labor Statistics (BLS) Occupational Employment Statistics (6) (7) and U.S. Census of Employment and Wages (8) were used as the basis for measuring industrial physics employment.

Occupational employment codes were selected to define occupations using physics-based knowledge including physicists, physical scientists, engineers, technicians, and computer and information research scientists. Using this set of physics-based occupations, the analysis identified a wide range of U.S. industries that rely on varying levels of physics-based knowledge, leading to the selection of 79 four-digit NAICS codes that satisfy the criteria defined above (Table A-4 in Annex 2). Of these, 23 sectors contributed about 80% of the impact as shown in Table A-1 in Annex 2. These sectors include electric power, aerospace, computers, and semiconductors.

Estimation of the Impact for Each Sector Reliant on Industrial Physics

By their nature, the manufacturing and service industries employ many more operations, administrative, or production workers than scientists or engineers. Yet the foundations of these sectors would not exist without the contributions of science and engineering to their R&D, and product and process development. **Hence, an industry sector may be totally reliant on scientists and engineers, yet its employment structure only includes a small percentage of such workers.** This context becomes the crux of our approach to estimating the economic contribution of industrial physics to a particular industry sector.

A sector with 10% or more employees trained in physics-based knowledge has 100% of its economic output counted as a contribution. No contribution is counted if fewer than 2% of employees are trained in physics, with a sliding scale in between. The economic impact can be scaled up or down by adjusting these factors. Each industry sector is assigned a contribution on the sliding scale. Annex 2 has additional discussion of this assumption. We believe our approach provides a more objective estimation basis than "simple" assignment.

While in some sense this algorithm is arbitrary, our thesis is that physics knowledge and discoveries used in industry provide the foundation for those industries. In essence, this approach uses people trained in physics to determine which industries are based on physics discoveries. Two similar studies done in Italy (9) and the United Kingdom (10) took a slightly different approach and used the judgment of physics experts to assign a percentage contribution on an industry segment by industry segment basis.

Application of an Economic Model to Determine the GDP and Other Data for Each Impacted Sector

The final step of estimating GDP impact and other data is done using one of the many commercially available economic analysis packages. This study used IMPLAN (11). IMPLAN was developed by the U.S. government in the 1970s and became available to the private sector in 1991. It is updated regularly and is used by many organizations for a wide variety of economic studies because of the completeness of its data, its full representation of the U.S. economy, and its ease of use. IMPLAN allows assessment of employment, labor income, contribution to GDP, revenue, and productivity (value-added or gross output per employee) for the selected industry sectors.

Value Added and Gross Output

The two primary ways to quantify the economic activity of a country are to calculate the **value added** and the **gross output** of the economy.

Gross output, sometimes also referred to as "Turnover" is the total value of goods and services produced by an industry.

Value added is the difference between gross output and intermediate inputs and represents the value of labor and capital used in producing gross output. **Intermediate inputs** are the foreign and domestically produced goods and services used up by an industry in the process of producing its gross output. The sum of **value added** across all industries is equal to **gross domestic product (GDP)** for the economy.

A simple example illustrates how these two concepts are related. A steel producer buys iron ore and coal to make steel and sells the steel to a number of different customers. An auto maker buys steel to produce an automobile. In addition, it buys aluminum, plastics, tires, and other items that are needed to make a complete car. In this case, the steel maker's ***gross output*** is the revenue earned from all sales of the steel. Similarly, the auto maker's ***gross output*** is the revenue earned from its automobile sales. Intermediate inputs are calculated as the cost of iron ore, coal, and equipment for the steel maker, and the cost of steel, aluminum, plastics, and other items for the automaker. **Value added** for both is the difference between revenue earned and the cost of intermediate inputs.

Because gross output includes sales to other industries, it can be duplicative in nature. In this example, total gross output double counts the value from steel used to make automobiles by including it both in the output of the steel maker and in the output of the automobile sold by the automaker. By contrast, an industry's **value added** is defined as the total revenue from an industry's production **less** the cost of inputs purchased from other industries and eliminates this duplication. In this case, the cost of steel (and other inputs) is subtracted from the auto maker's revenue when calculating value added.

Gross domestic product (or **value added**) by industry and ***gross output*** by industry are both tabulated in the Industry Economic Accounts by the U.S. Bureau of Economic Analysis (BEA) (11), and both sets of statistics provide important insights into an industry's contribution to the overall economy. IMPLAN allows calculation of both value added and gross output on an industry and NAICS code basis, enabling the analyses presented below to be done in an efficient but rigorous manner.

In the following sections, the tables and figures quantify the size and impact of physics-based economic activity in the U.S. economy. Detailed data for the period 2010 to 2016 are based upon IMPLAN estimations. Later, longer time series data for the period 1946 to 2016 are developed using direct BEA data (12).

Total Jobs and Economic Impact Attributable to Physics-Based Sectors in 2016

Table 2 provides a breakdown of employment, labor income, value added, and gross output for physics-based sectors in the U.S. economy in 2016. The total contributions are broken into three standard types (13).

Direct: Impact that directly results from physics-based activity

Indirect: Impact that supports direct activity, e.g., inputs from suppliers, etc.

Induced: Impact from workforce of direct and indirect sectors spending their incomes in the economy, e.g., buying homes, retail and service purchases

Total: The sum of direct, indirect, and induced impacts

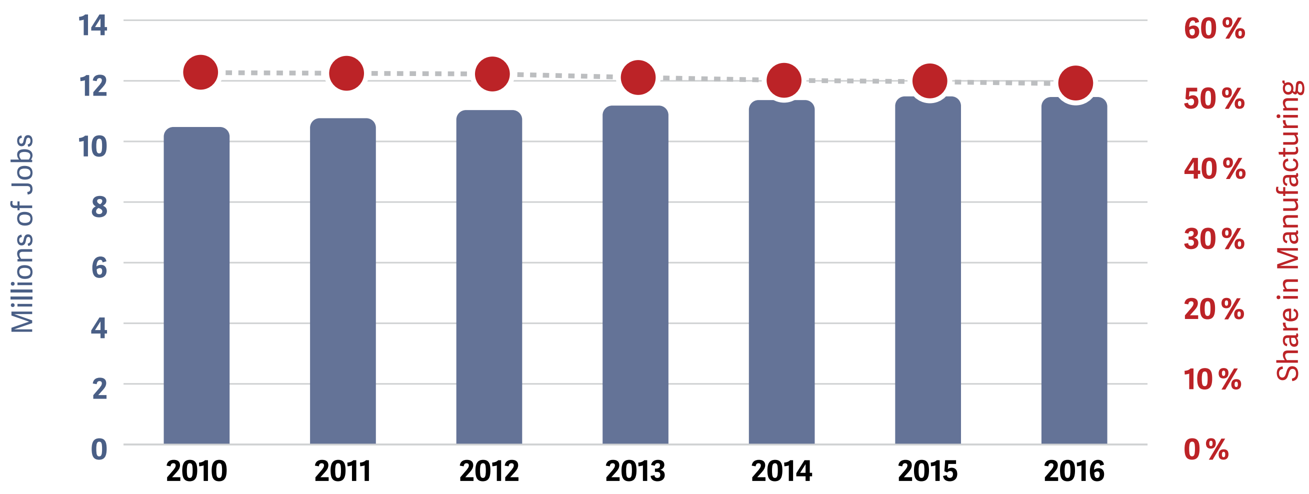
Employment (job) and tax revenue data come from databases maintained by the U.S. Bureau of Labor Statistics (6) (7) and the U.S. Census of Employment and Wages (14). The multiplier in Table 2 is the ratio of the total impact category to the impact of the direct category (13). Since 2010, **direct employment** in industry due to physics has grown almost continuously (Figure 1). Manufacturing accounts for about 50% of **total employment** in physics-based sectors (Figure 1) in the period 2010 to 2016.

Note that the numbers in Table 2 have been rounded off and may not add exactly.

Table 2. Employment, Labor Income, Value Added, and Gross Output for Physics-Based Sectors in the U.S. Economy in 2016

Impact Type	Employment	Labor Income (in Trillions)	Value Added (in Trillions)	Gross Output (in Trillions)
Direct physics-based jobs	11,500,000	\$1.2	\$2.3	\$6.1
Direct jobs as share of U.S. total	6.0%	10.9%	12.6%	18.4%
Indirect physics-based jobs	14,400,000	\$0.99	\$1.5	\$3.1
Induced physics-based jobs	19,300,000	\$0.95	\$1.6	\$2.9
Total physics-based jobs	45,100,000	\$3.2	\$5.5	\$12.2
Total as share of U.S. total	23.6%	28.2%	29.8%	36.3%
Multiplier (Total/Direct)	*3.93*	*2.58*	*2.36*	*1.97*
U.S. total	191,300,000	\$11.257	\$18.577	\$33.567

Figure 1. Estimate of Physics-Based Direct Employment and Share in Manufacturing (2010–2016)



It is important to realize that the estimated 11,500,000 jobs in physics-based sectors of the U.S. economy in 2016 are not the actual number of physicists or physical scientists working (see sidebar "Industrial Physics!" on page 4). As was described, the number of people employed in physics-based sectors is based on the following parameters:

- The number of industrial physicists, which includes people with or without physics degrees, working in jobs readily identified as physicists
- The number of jobs based on industrial physics, which includes:
    - People who have taken multiple physics courses to obtain a professional degree or qualification, including certain engineering occupations and other physical scientists
    - People who work on the development and production of technologies based on applying known physics principles
    - People who work on the development and production of technologies based on new physics innovation

Throughout this report, the term ***"physics-based"*** refers to this definition.

The small decline in physics-based direct employment from 2015 to 2016 is driven by job losses across a variety of sectors, but most significantly across the full spectrum of oil & gas extraction, including oil & gas machinery. The declines in this particular space were actually significantly larger (loss of approx. 75K jobs). These and the larger overall declines were partially offset due to significant growth in some sectors primarily in the consulting, computer systems/design, scientific R&D, and headquarters sectors (approx. 90K jobs). The interplay of employment gains and losses across sectors is typical on a year-to-year basis and not confined to this one period (2015 to 2016).

Value Added of Physics-Based Sectors

In 2016, the direct **value added** by physics-based sectors was $2.3 trillion out of the U.S. Gross Domestic Product (GDP) of $18.6 trillion. This 12.6% contribution to the GDP reflects the increasingly technological make-up of our economy.

In a broader view, the total **value added** includes the value of labor and capital used in producing direct value. This was $5.5 trillion added by physics-based sectors in 2016, or 29.8% of U.S. GDP.

One should ask if these numbers are surprising and the answer should be no. The perspective that must be kept is that the physics-based contribution consists of both very direct contributions, such as modern electronic gadgets, GPS devices, and MRI (magnetic resonance imaging) and induced contributions such as the Information Revolution, which simply could not have happened without industrial physics.

Some of the physics-based contribution is part of the great increases in productivity that happened in the century from 1870 to 1970, as described by Robert Gordon in his book The Rise and Fall of American Growth (15). Yet many of the productivity increases have come about from totally disruptive technology based on the application of 20th-century physics to products and services by industrial physics. Measures of disruptive technology are discussed later in this report, but their existence must be mentioned to account for the multi-trillion-dollar impact industrial physics has on our economy.

Figure 2 shows the contributions to **value added** due to physics-based **direct employment** (bars) and the share of that contribution (dots) of the **total** amount of the **value added** (GDP) in the U.S. economy for the years 2010 to 2016. Figure 3 shows the same data for the physics-based **total employment** for the same period.

It is instructive to look at the share of the total U.S. **value added** by various sectors and compare them to the share contributed by physics-based direct employment. Figure 4 provides such a comparison for 2016. The $2.3 trillion due to the physics-based direct employment is 12.6% of the total $18.6 trillion GDP in 2016.

Other sectors, especially those related to services, are not included in this comparison, so the total contributions shown do not add up to 100%. All manufacturing, not just physics-based manufacturing, are included for comparison as well as key component sectors of the economy. The physics-based contribution includes both manufacturing and non-manufacturing components while manufacturing contains both physics-based and non-physics-based contributions.

Figure 2. Estimated Value Added (GDP) Due to Physics-Based Direct Employment (2010–2016)

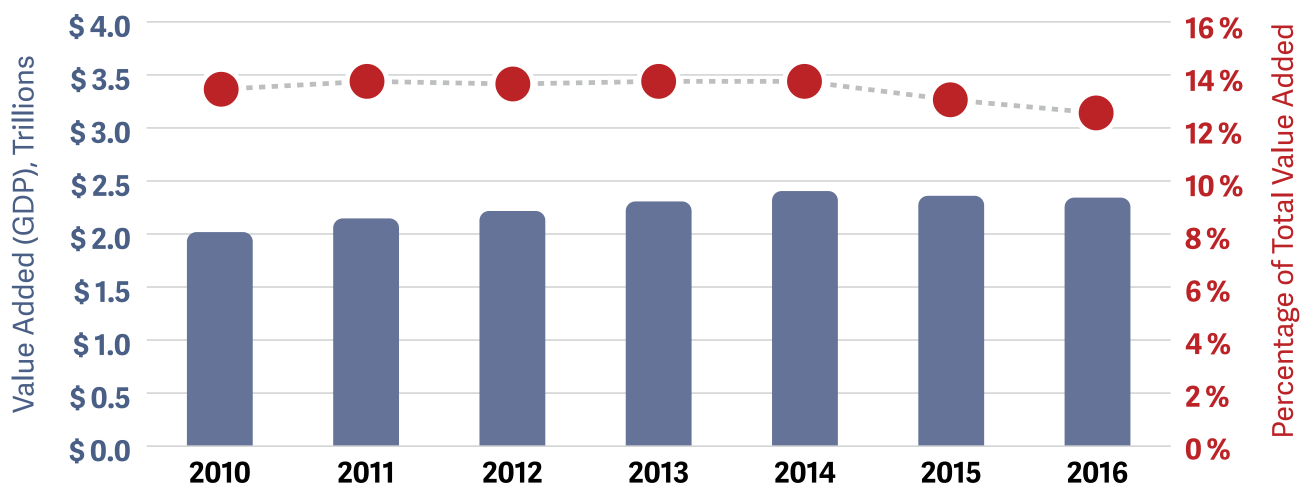


Figure 3. Estimated Value Added (GDP) Due to Physics-Based Total Employment (2010–2016)

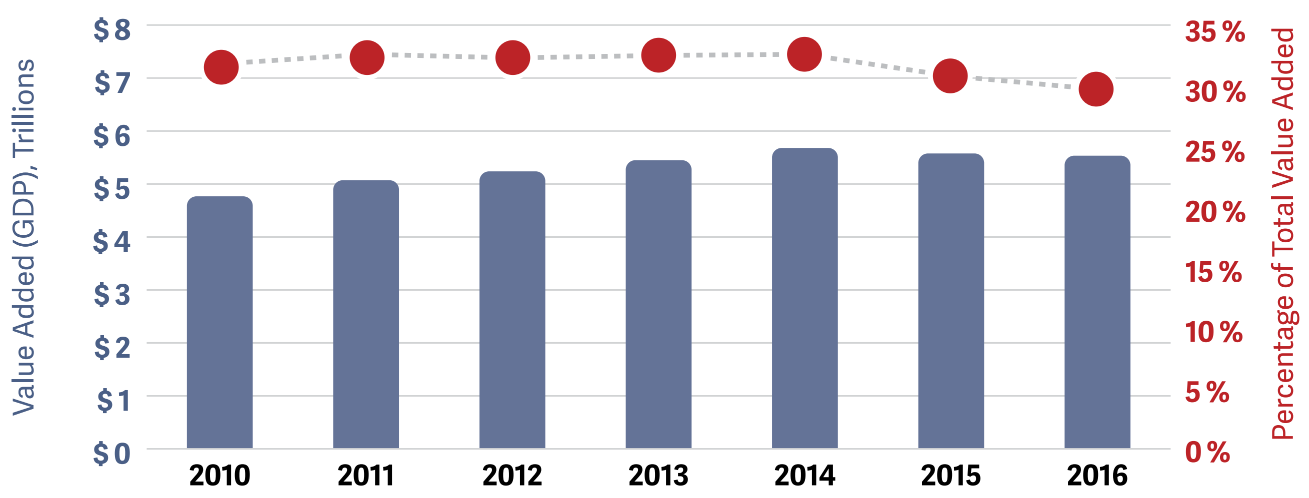
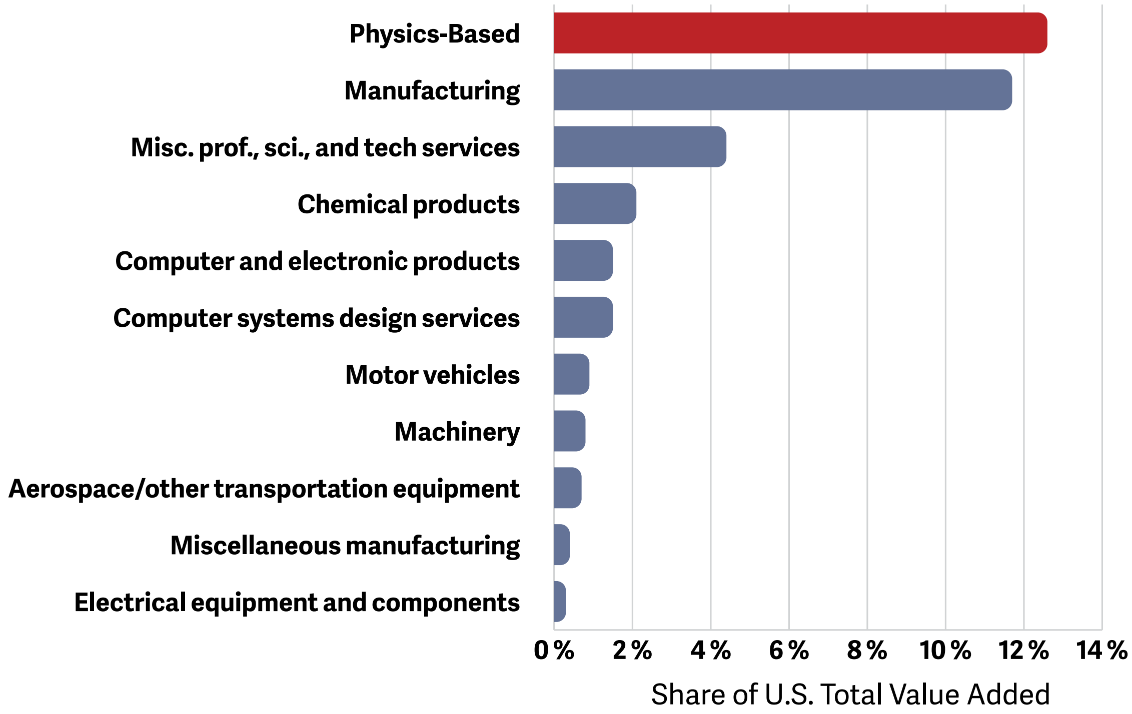


Figure 4. Share of Total U.S. Value Added (GDP), Comparison of Various Sectors with the Physics-Based Direct Employment Contribution (2016)



Gross Output of Physics-Based Sectors

In this section, data are presented on the physics-based share of U.S. economic activity as measured by **gross output** for direct physics employment and total physics-related employment. As noted before, the **gross output** provides an estimate of the amount of total economic transactions taking place in the economy.

In 2016, the **gross output** attributed to physics-based direct employment is estimated to be an impressive **$6.1 trillion**; while the corresponding gross output due to total physics-based employment is about **$12.2 trillion**.

Gross output is sometimes called Turnover as it reflects the amount of economic value "turned over" in an economy during all phases of producing final goods. For example, gross output captures the activity associated with producing iron ore (all the direct, indirect, and induced activity), then the same quantities during iron and steel production, and then again in the manufacture of a product such as an automobile.

Figure 5 shows data for the **gross output** of the U.S. economy in the period 2010 to 2016 attributable to physics-based **direct** employment (bars) and its share of the **total gross output** of the U.S. economy (dots).

Data are given in Figure 6 on the estimated share of the **gross output** of the U.S. economy in the period 2010 to 2016 attributable to physics-based **total** employment (bars) and its share of the **total gross output** of the U.S. economy (dots).

It can be seen that the share of the total U.S. gross output due to physics-based **direct** employment stays around 20%, while the share for **total** physics-based employment is around 40%. It is possible that the slight declines for percentage of total gross output shown for 2015 and 2016 in Figures 5 and 6 are a reflection that the total U.S. economy was finally recovering from the Great Recession of 2008-2009. In that case, during the initial years of recovery, physics-based industrial sectors were more resistant to the effects of the Great Recession and thus less affected by the decline than other sectors, such as construction, retail, and service.

The size of the contribution of physics-based sectors to the total gross output (turnover) is a reflection that physicists and physics are used in all stages of creating products and services. Using our previous example of transforming iron ore to automobiles, the individual steps use physics in many ways, from measuring temperatures to determining the purity of materials to ascertaining the smoothness of an auto finish.

Figure 5. Estimated Gross Output (Turnover) Due to Physics-Based Direct Employment (2010–2016)

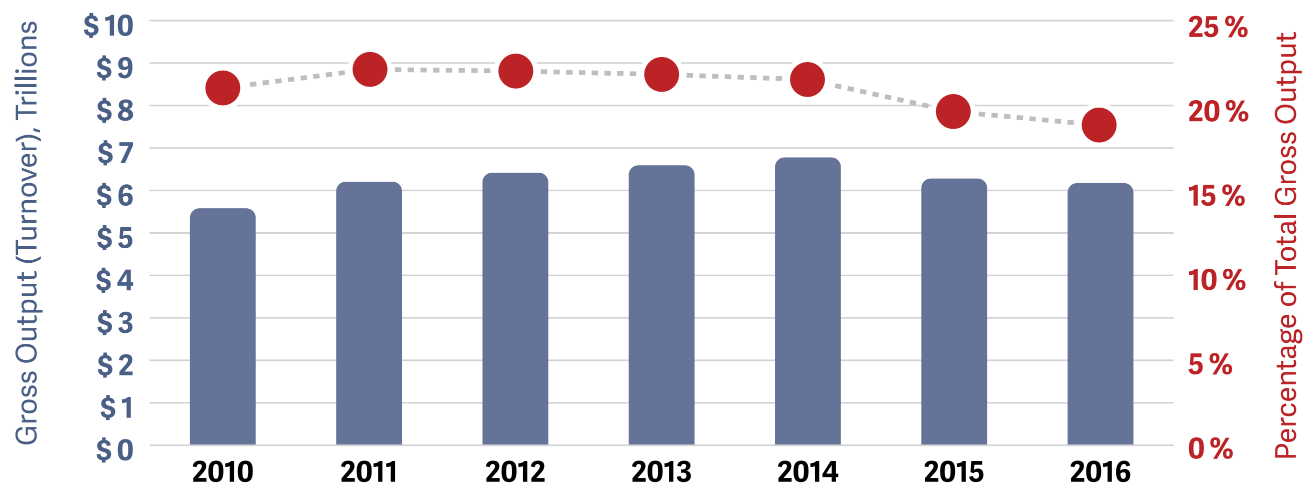
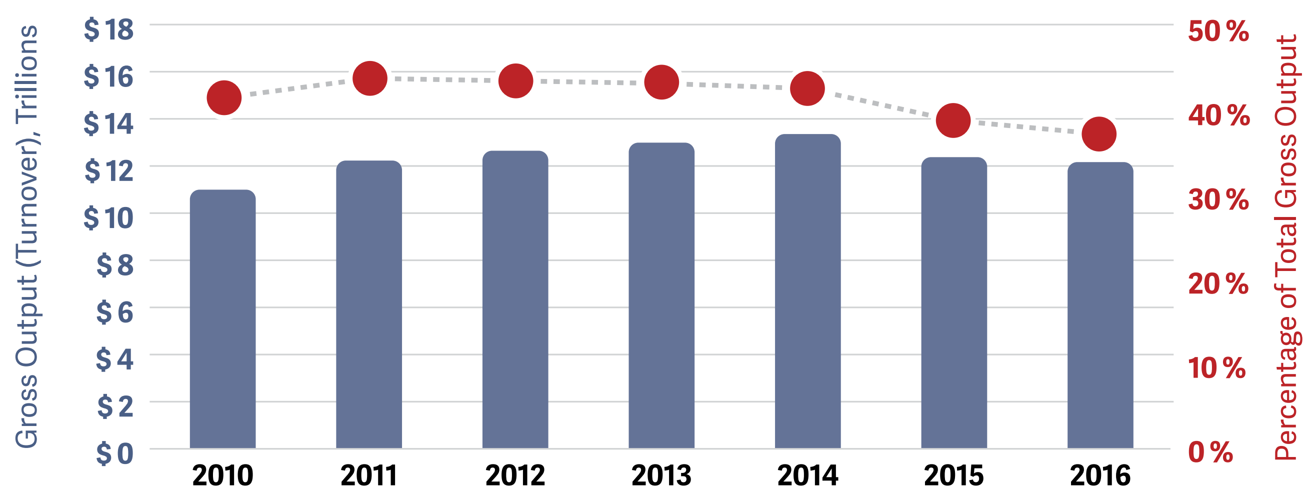


Figure 6. Estimated Gross Output (Turnover) Due to Physics-Based Total Employment (2010–2016)



Dick Tracy©, Cell Phones, Electric Cars, and Batteries

In 1983, when the first mobile phone went on sale costing almost $4000 and weighing 2.5 pounds with 30 minutes of power, we were a far cry from Dick Tracy's© vision of wearable electronics. Now, fewer than 35 years later, we are there. While much of that progress has been due to advances in integrated circuitry (also thanks to industrial physicists), innovative batteries have also made this possible.

The first portable energy sources came about in the mid-1800s to help power telegraph lines. Later battery innovations led to flashlights, mobile electric toys, and car starters. In the 1950s, the alkaline battery came on the scene and quickly dominated the market with a wide variety of shapes, sizes, and capacities. More recently nickel-metal hydride batteries were developed to provide more, longer lasting power, as required by power tools and early electric cars. Newer lithium-ion batteries now power our laptop computers and cell phones as well as advanced electric cars. The battery market in 2020 is estimated to be on the order of $17 billion annually (16).

While the basic physics of batteries has remained unchanged—with electrons flowing from the anode to the cathode through a conducting media—physics research has long been key in the progression from short-lived, unstable devices to today's long-lasting powerful batteries to tomorrow's polymer- and nano-based batteries.

Industrial physicists today are building batteries with innovative new characteristics and functionalities, including miniaturization, high power densities, flexibility, fast recharge times, and greater current densities.

Possibly, in the foreseeable future, we will all be wearing our Dick Tracy© watches while driving our electric cars thanks to these innovations.

Industrial Physics as a Driver for Manufacturing

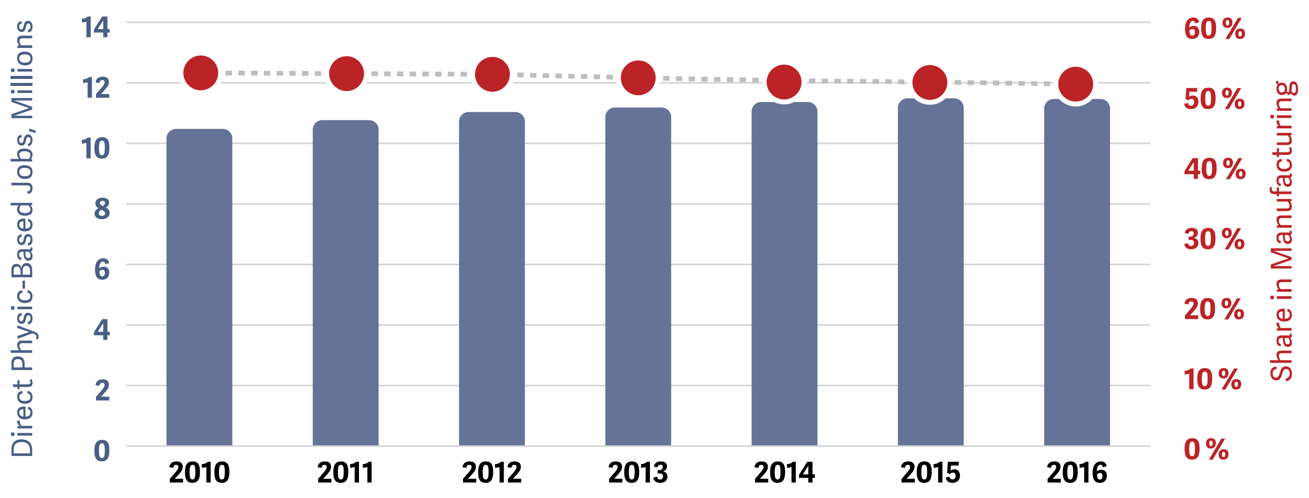
Modern manufacturing is data driven, computer controlled, and sensor reliant. The quality, tolerances, functionalities, and innovation that characterize manufacturing today owe a great debt to industrial physics.

Manufacturing accounts for about one-half of all industrial physics activity (dots), and millions of manufacturing jobs are physics-based (bars) as shown in Figure 7. Over the past seven years, the percentage has remained nearly constant, with minor fluctuations.

The steps in introducing a new product are similar regardless of the type of product being manufactured. A design must be validated, and a process to produce the new product must be established. Equipment must be designed or bought, installed, and made to function properly. During the actual manufacturing event, the process must be monitored and controlled through a variety of sensors. Problems when identified must be fixed. All these steps require skills that call upon the physics training and knowledge of professionals and technicians, and in many cases, such as semiconductor manufacturing, degreed physicists actually carry out these functions.

Manufacturing will become more automated in the future due to the increased availability and capability of robots. Industrial physicists will continue to play essential roles in developing new processes, applying new knowledge and materials, and using a wealth of data to improve output. Thus, the impact of industrial physics should remain the same or grow as most automation is ultimately driven by physics.

Figure 7. Estimate of Physics-Based Direct Employment and Share in Manufacturing (2010–2016)



Industrial Physics as a Driver of Productivity

The growth of an economy is dependent not only on the growth of the population and capital but also on increasing productivity. Producing more products and services with the same or fewer resources is the basis for productivity improvements. Technology improvements, many fostered by industrial physics, have long played a role in increasing the productivity of the U.S. economy. Productivity is defined as the amount of **value added (GDP) per employee**. The productivity of employees in physics-based industries for the period 2010 to 2016 is shown for **value added** (in red bars) in Figure 8. The amount of **gross output** (in blue bars) **per employee** for the same period is shown in the same figure for comparison. Given that the direct employment in the physics-based sectors is about constant over time, the fluctuation in productivity reflects the fluctuation in the total gross output (turnover) in the period, which varies sector by sector.

A comparison of the **gross output per employee** in physics-based direct employment to other sectors is given in Figure 9. The physics-based direct employees have about 2.37 times the productivity of the average private sector employee.

Figure 8. Estimated Physics-Based per Employee (Productivity) for Physics-Based Direct Employment (2010–2016)

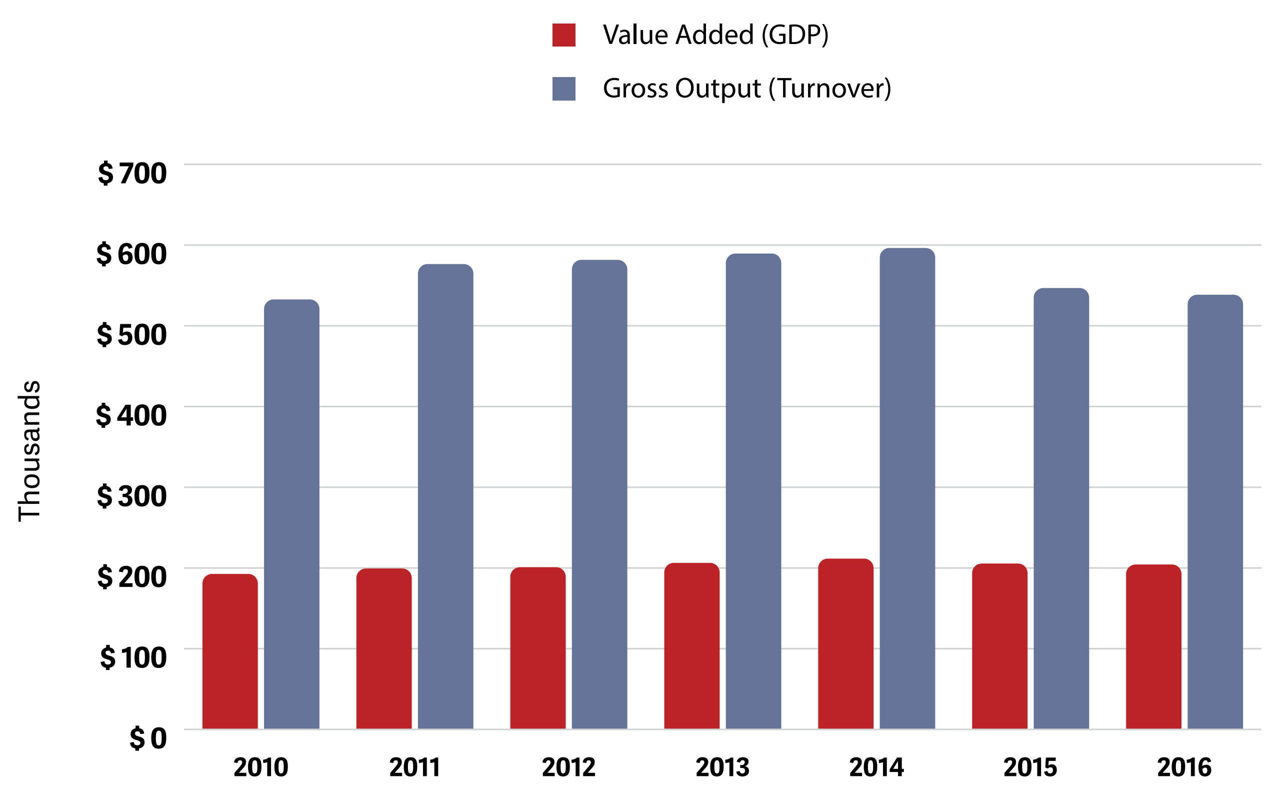
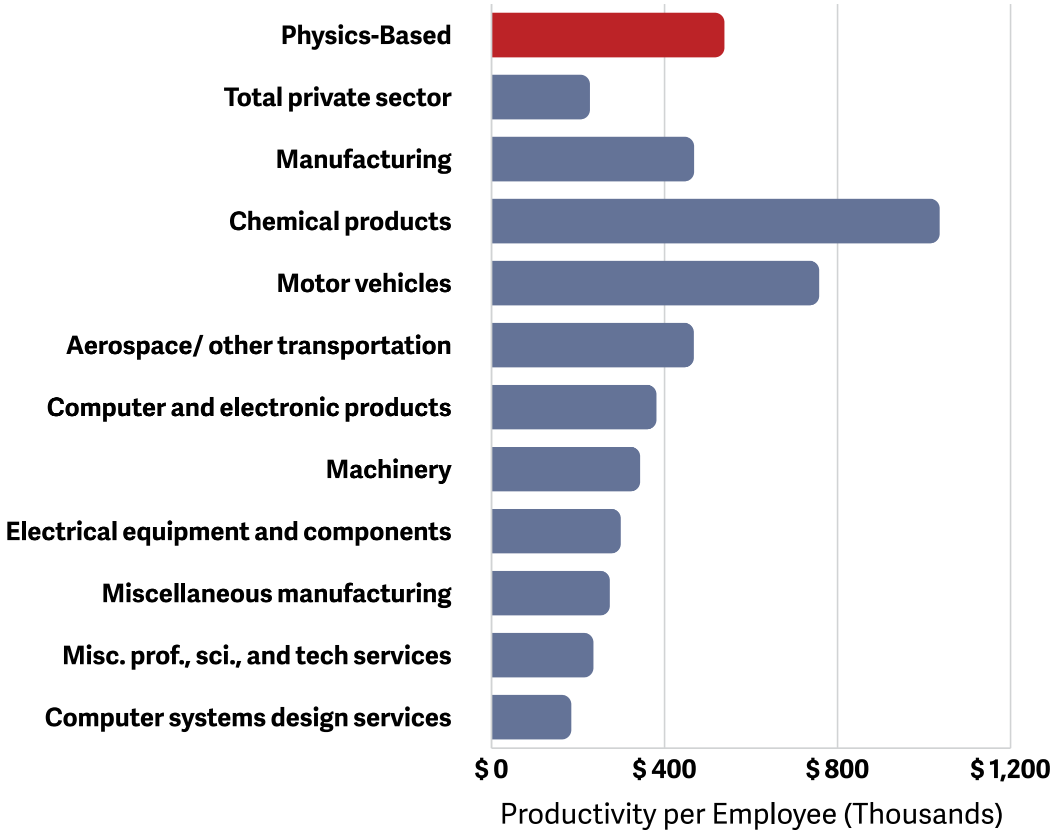


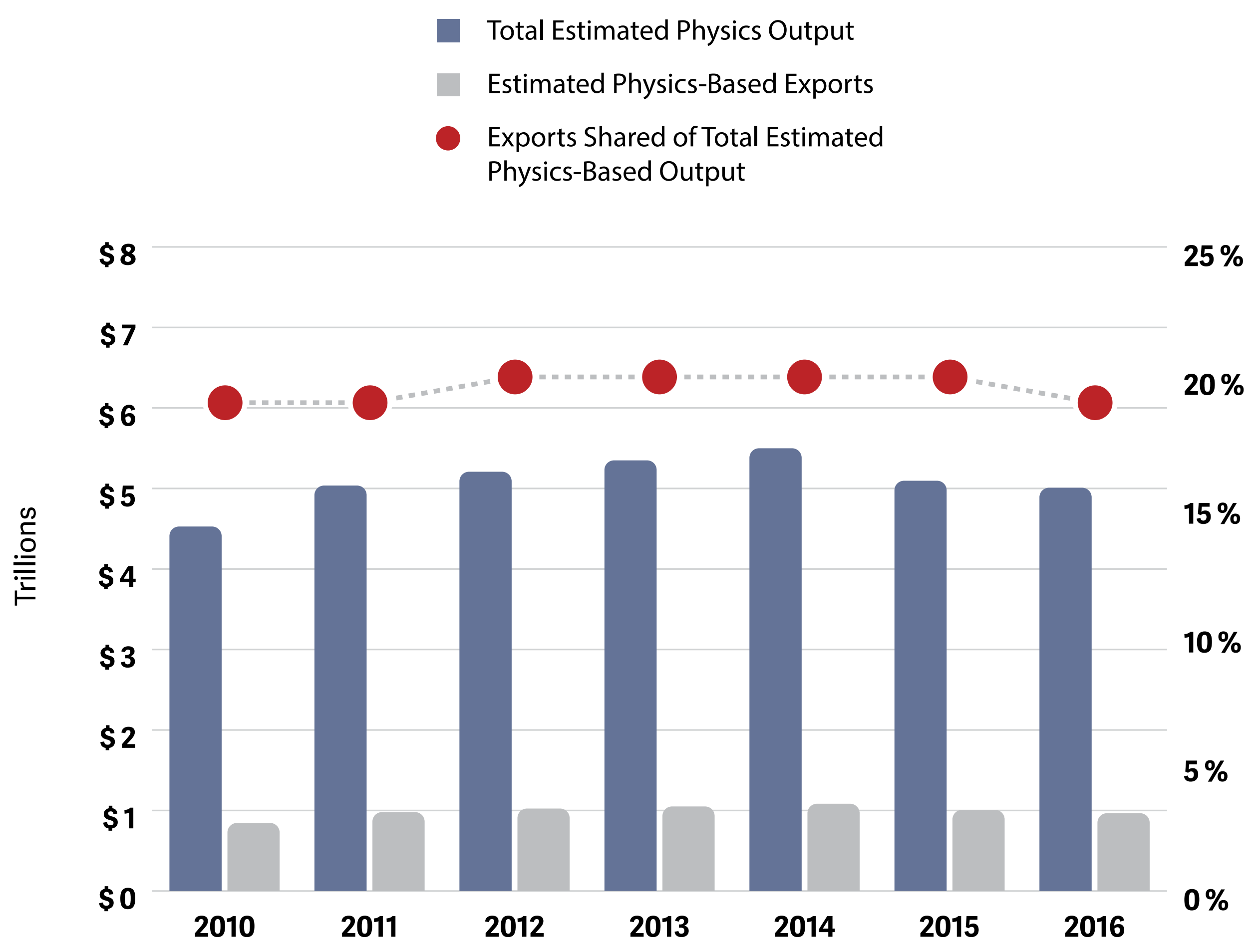
Figure 9. Estimated Productivity (Gross Output (Turnover) per Employee), Physics-Based (Direct Employees) and Comparisons Sectors (2016)



Physics-Based Exports

The impact of physics-based sectors on U.S. trade is huge, about $1 trillion a year in exports since 2010 (gray bars in Figure 10) with approximately 20% of the total **value added** (GDP) (blue bars in Figure 10) of the physics-based industrial sectors (16). The percentage of physics-based exports as a share of the total physics-based output (dots in Figure 10) has remained relatively constant at about 20% in the period 2010 to 2016. High-value, physics-based exported products include semiconductor chips, medical imaging equipment, and advanced commercial and defense aircraft.

Figure 10. Estimate of Total Physics-Based Value Added (GDP) and Physics-Based Exports as Shared Total Physics Value Added



Yoda, Clouds, Hard Drives, and Big Data

Contrary to popular opinion, a yottabyte of data was not named for Yoda of Star Wars© fame. Yotta is the largest prefix in the metric system and refers to a quantity of 1000^8 or 10^{24}. Today the amount of data stored in the "Cloud" is said to be approaching a yottabyte, even though actually measuring the amount of data seems an impossible task. This amount of data, unimaginable just 20 years ago, requires an equally unimaginable amount of disk space. Yet today's hard disk drives accomplish this feat.

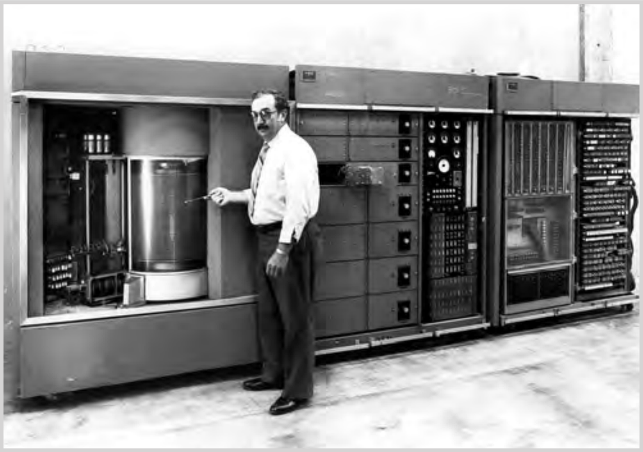
Hard drive disks with a complex magnetic coating are used to store data written and read by "heads" that zip across the disk surface to access various data tracks. Invented by IBM and first sold in 1956, hard disk drives generate annual revenue of more than $20 billion and have stayed at the forefront as an economical storage solution due to relentless innovation. Industrial physicists have played a key role in commercializing fundamental discoveries such as precise tunnel junctions for reading data, exquisitely controlled deposition of thin layers, and sealing helium into drives to reduce power dissipation and turbulence. The physics behind today's hard disk drives is fascinating.

- Highest areal density shipping today (2018) is approximately 1.1 terabytes/in^2, which requires about 550,000 tracks per inch. For comparison, about 500 tracks would fit on the edge of a piece of paper!
- The spacing between the reading head and the disk itself is fewer than 10 nanometers, barely larger than the size of a few heavy atoms.
- Each bit of data is stored in a magnetized area with dimensions of 10s of nanometers.

Lower capacity applications are transitioning to flash memory, solid-state devices that have higher cost today but are faster and more mechanically robust. Flash memory also has benefited from an infusion of physics innovation that will empower the storage industry as demand continues to explode.

The impact of these powerful hard drives goes far beyond their physical marvels. The hard drives enable the millions of servers used by the major search engines and cloud service providers to dispense answers to millions of questions a minute and also enable Big Data and artificial intelligence (AI) research that is transforming our understanding of how diseases spread and how the universe was formed. The largest of these companies are in fact some of the most valuable companies in the world, an accomplishment achieved in fewer than twenty years for some of them.

A yottabyte is a lot of data, and a company worth $100 billion is equally impressive. Both are realities because of hard disk drives powered by a stream of innovative and brilliant physicists and physics.



Emergent Physics-Based Industry as a Positive Disruptive Force

The infusion of physicists and physics knowledge into industry during the 20th century has been an amazing catalyst for U.S. economic growth. As has been illustrated in the tables, graphs, and sidebars to this report, entire industries arising from innovations in physics now employ millions of people and provide hundreds of billions of dollars of value added and gross output to our economy annually. The ICT (Information and Communication Technology) Revolution has been driven by physics. Consumer electronics— everything from television to cell phones to digital music devices—rest upon our understanding and controlling of the physical properties of silicon. One clear way to see this impact is to look at the indexed growth (in constant 2016 dollars relative to the first year of the period) of physics-based sectors in the years following World War II—1947 to 2016. Figure 11 shows the explosive growth of various physics-based sectors during that period. The first 30 years of that period (1946 – 1976) show an increase of 4 to 9 times in **gross output (turnover)**, and the next 40 years (1976 – 2016) show indexed growth of at least 10 times in every segment. The same accelerated indexed growth was reflected in **value added (GDP)**, as shown in Figure 12 for the period 1966 to 2016.

What about Chemistry, Materials Science, and Engineering?

Are physicists being too aggressive in claiming many of the advances in science and technology? In some respects, no; and in other respects, yes.

No, because it is legitimate to recognize that the explosive increase in knowledge of the physical laws governing the behavior of matter and systems is fundamental to advances in the other sciences and engineering. Specifically, quantum mechanics, solid-state physics, non-linear optics, advanced physics facilities such as light sources and accelerators, and modern electronics have transformed all science and engineering. It is not just the development of the physical theory that has been so important, but the fact that physics is taught to virtually every physical scientist and engineer. This physics training ensures their research and development is based on sound physical principles and broadens the impact of non-linear optics, modern electronics, quantum mechanics, and other advanced physics. Modern chemistry relies on these physics concepts.

It is clearly possible to analyze the impact on the U.S. economy of industrial chemistry and industrial engineering and find quite large contributions from those sectors. Probably if all such contributions were added up, they would total more than 100%, but that is not really relevant.

Our perspective, as would be the same perspective from other disciplines, is to try to calculate the total economic impact of physics in industry. We would also argue that including the impact of physics education and the use of physical principles allows a fuller estimation of the total impact physics has on industry and the economy. That is our definition of industrial physics.

Figure 11. Indexed Growth (Constant 2016 $) in Gross Output (Turnover) of Physics-Based Sectors (1947–2016)

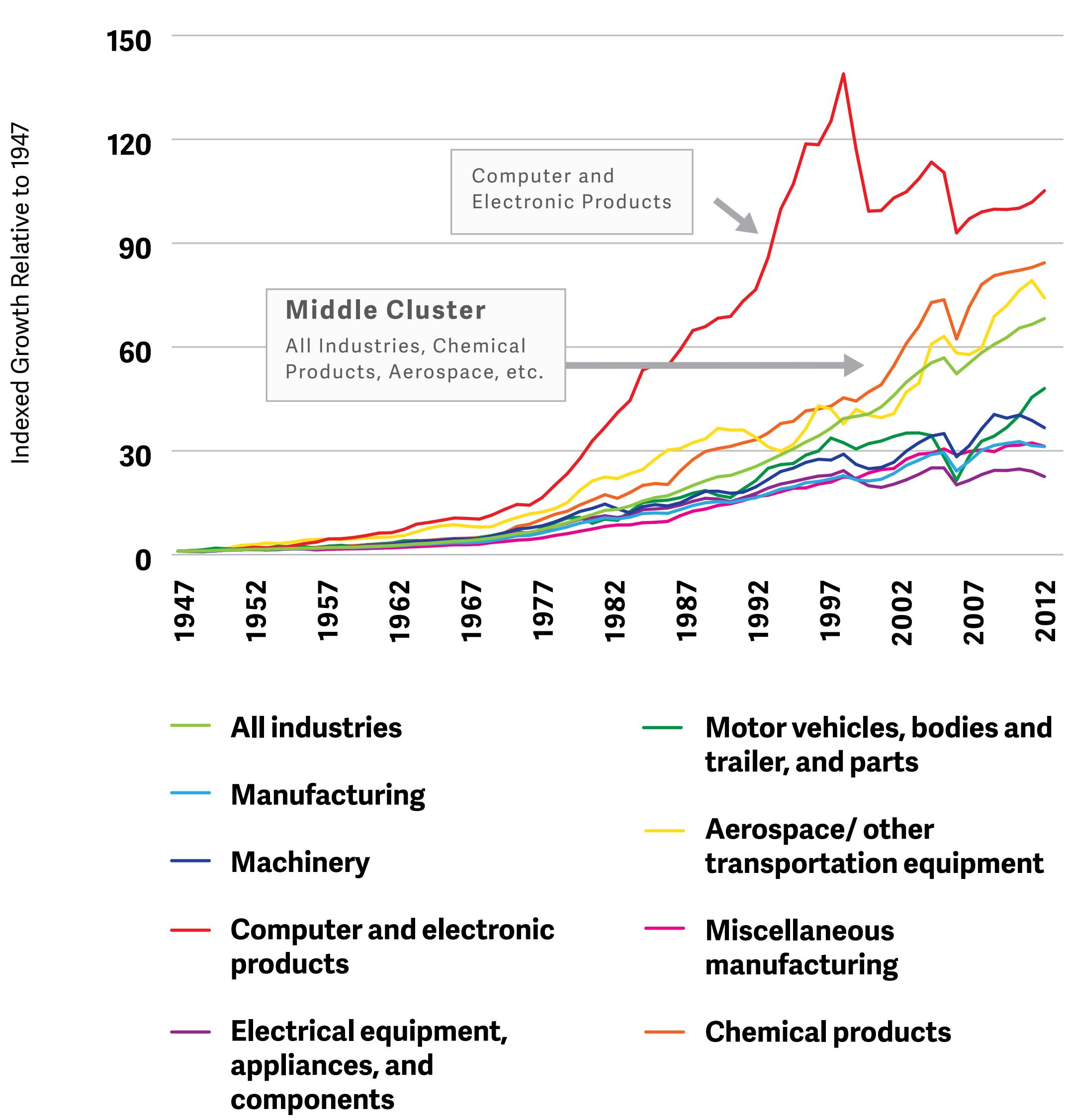
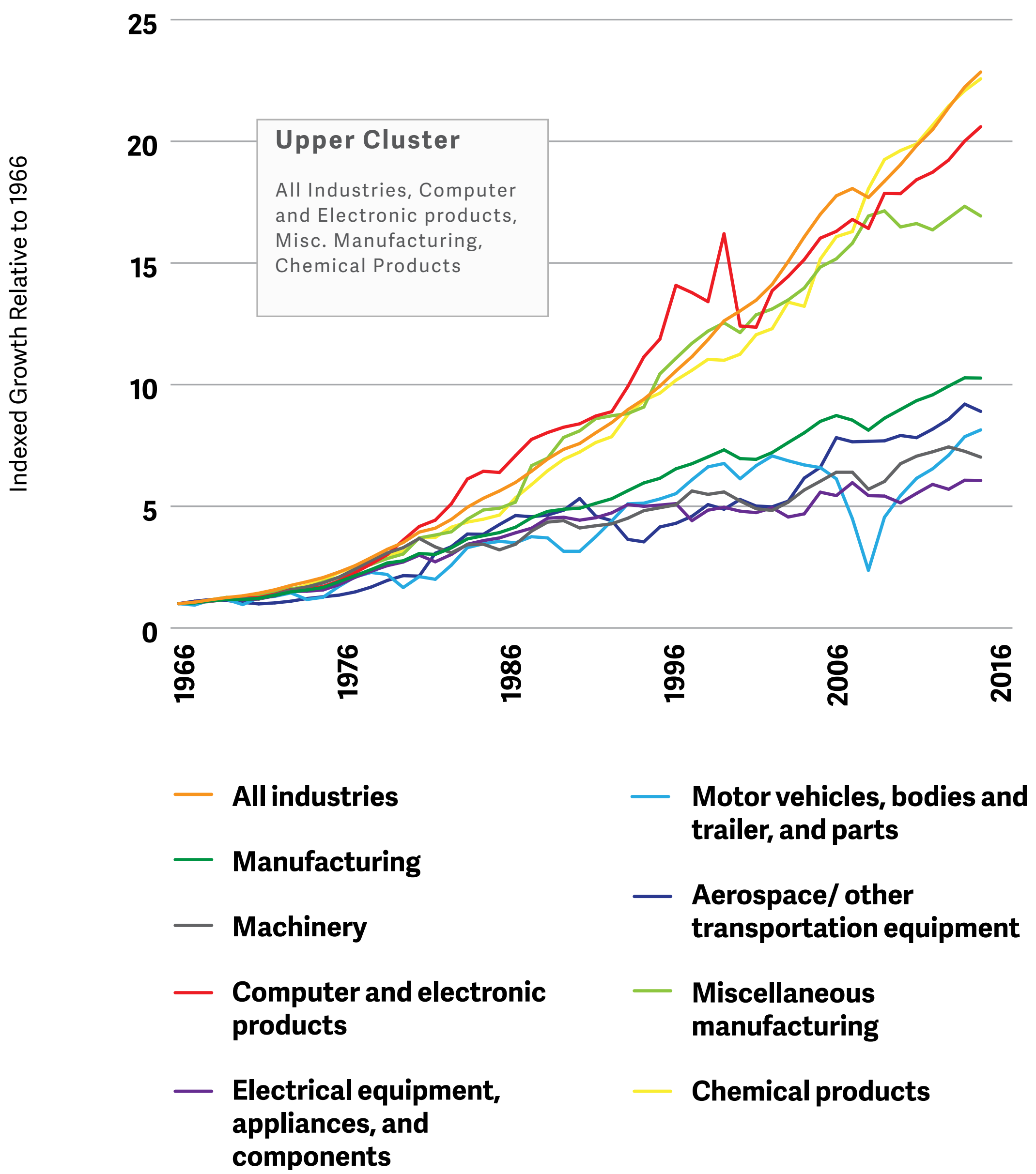


Figure 12. Indexed Growth (Constant 2016 $) of Value Added in Physics-Based Sectors (1966-2016)



Another way to see industrial physics as being positively disruptive to the U.S. economy is to look at how the productivity in two heavily physics-based sectors has outpaced the general growth of productivity in all private sector industries. Figure 13 displays the growth in terms of **value added (GDP)** for the period 1946 to 2016, and Figure 14 displays the growth of productivity in terms of **gross output (turnover)**.

For both economic measures, the physics-based industries grew by over 300% compared to only a 200% increase for all private sector industries.

Between 1986 and 1996, productivity greatly accelerated in overall advanced manufacturing, and especially in the computers and electronics sectors. These two sectors are proxies for physics-based industries as both sectors began to take advantage of automation.

Not only did these sectors bring entirely new contributions to the economy as a whole, productivity gains over time in these emerging sectors provided additional growth.

Figure 13. Value Added (GDP) per Worker (Productivity) in Emerging Physics-Based Industries

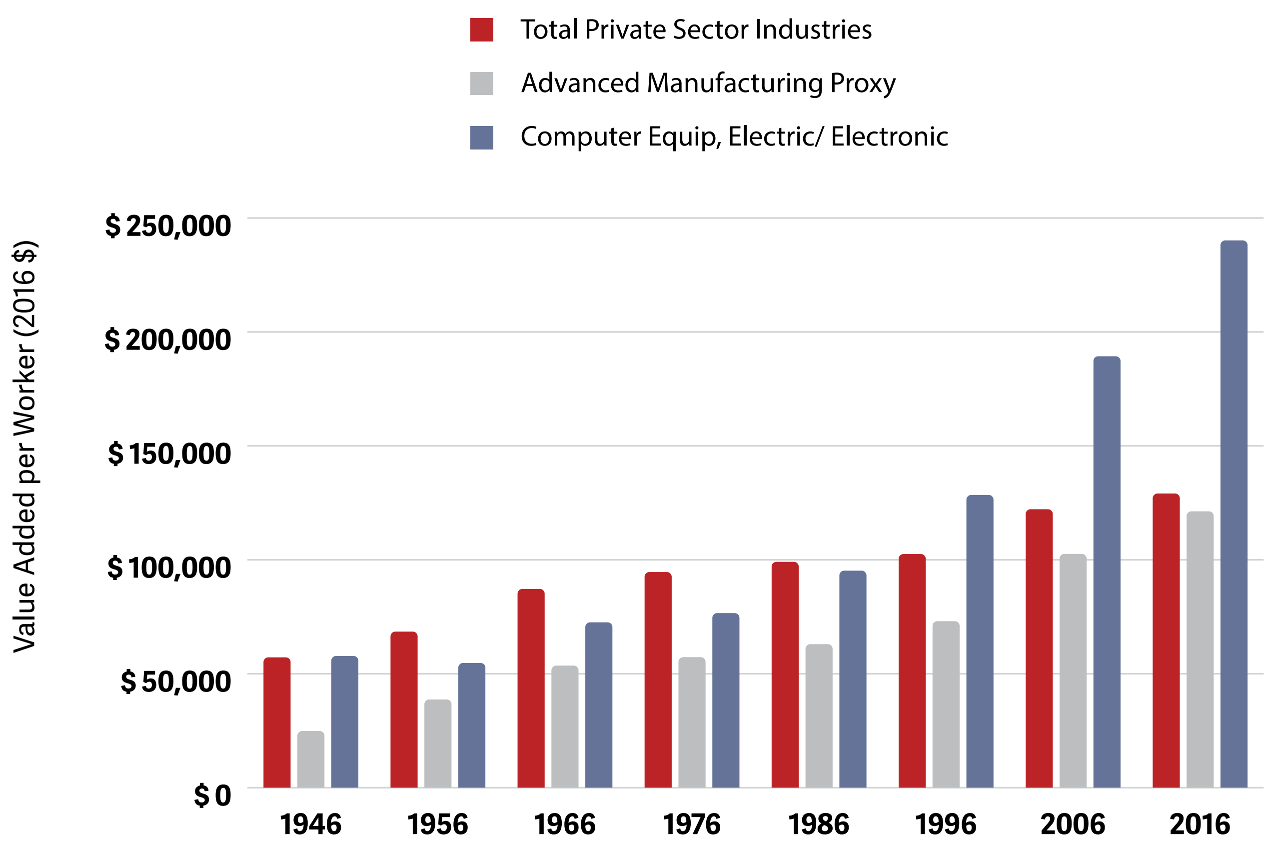
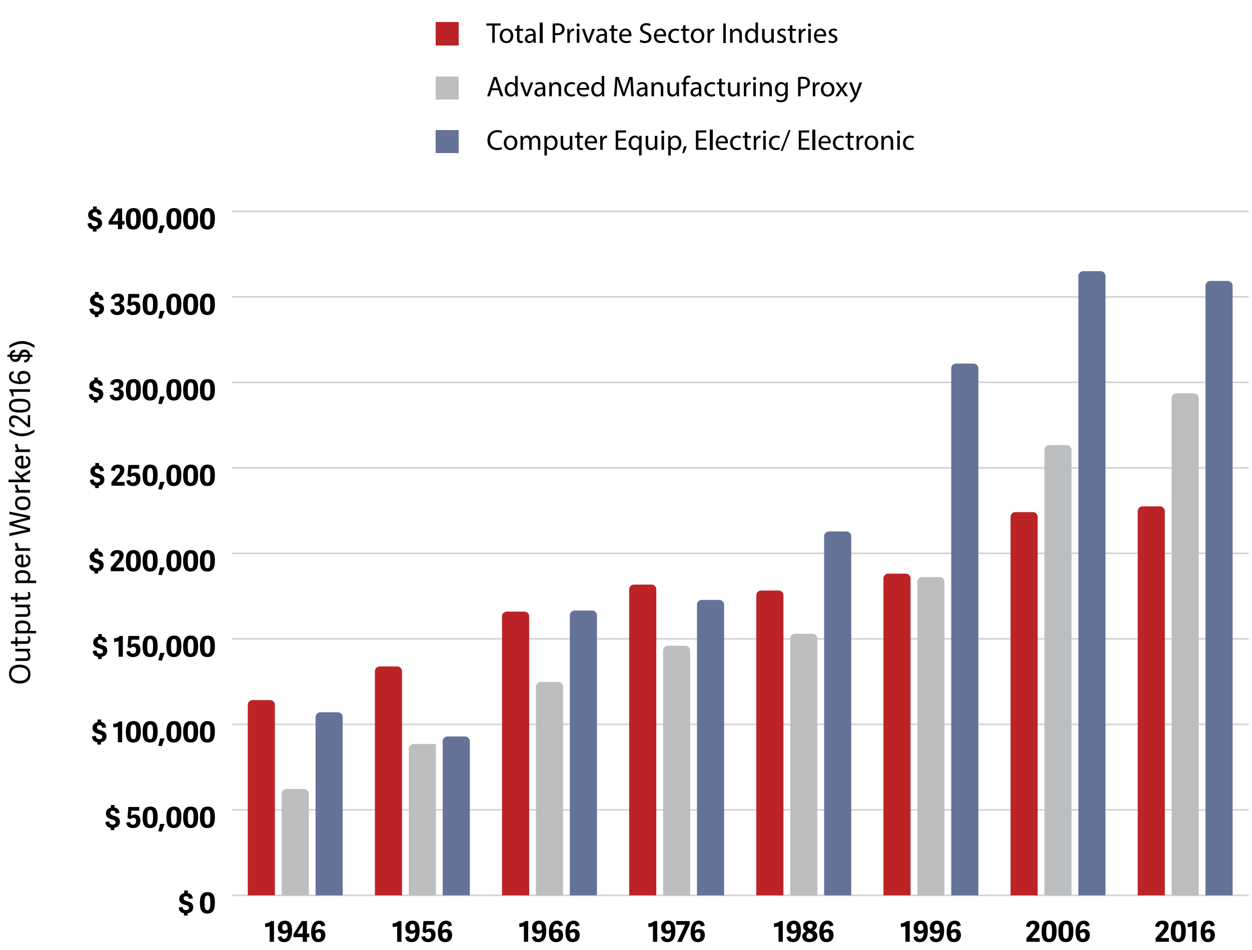


Figure 14. Gross Output (Turnover) per Worker (Productivity) in Emerging Physics-Based Industries



Industrial Physics as a Continuing Catalyst for Future Growth

Industrial physics continues to inject growth into the U.S. economy in many ways, including the infusion of new ideas, new equipment and measuring devices, and new people. It is difficult to predict exactly which technologies might be disruptive, but the sidebar on entrepreneurship identifies several possibilities. Here we provide some measures of the power of industrial physics to grow the U.S. economy in the future, including:

- R&D investment
- Patents
- Entrepreneurship
- New industrial physicists

The continued strength of the U.S. Industrial Physics Enterprise is reflected in the data and stories that follow. Maintaining that strength over the long-term is a challenge—not only for industry itself, but also for academia that educates student for physics degrees as well as other science and engineering degrees, for government funding agencies that support basic and applied physics research as well as highly sophisticated user facilities, and for the physics community as a whole—in recognizing that our economy and society rely on physics for products and services that enhance our lives in countless ways.

Annex 1 displays industrial physics as a system and the various relationships that provide a continuing catalyst for future growth.

R&D Investments

New ideas and new devices result from research and development (R&D) investments. Figure 15 shows estimated physics-based R&D investments for several industrial sectors, indicating company-funded (internal) investments and external investments, including the government (17). In 2015, the total internal investment was about $150 billion, an impressive figure. Much of the external investment is from the U.S. government through several agencies including the National Science Foundation, the Department of Energy, the Department of Defense, NASA, and the National Institutes of Health. A key difference between the internal and external investments is that much of the external investment is focused on fundamental physics research as well as large physics instrumentation. These big projects include intense light and neutron sources that in many cases allow industry to do experiments no one company could afford.

Patents

A second measure of the growth potential of industrial physics is patents. Patents are a direct result of industrial innovation, and aggressive patent registration is indicative of a robust industry sector. Cooperative Patent Classification Class G (CPC G) represents physics-based patents. This patent classification system is far from perfect, both excluding some physics-based work and including patents that do not rely on physics. This database, however, is a useful indicator of patent trends in industrial physics.

U.S. companies were granted over 340,000 physics-related patents from 2010 to 2017, more than 25% of the total number of patents granted to U.S. companies in the period (18). Table 3 shows the top 20 U.S. companies receiving CPC G patents between 2010 and 2017 (18). These patents are highly cited, with an average of more than four citations per patent. The ranking of these U.S. companies with respect to the number of CPC G patents and overall CPC patents is also given, together with the proportion of each company's patents that are CPC G patents.

Table 4 gives data for CPC G and total patents (all CPCs) awarded by the U.S. Patent and Trademark Office between 2010 and 2017 (18). Data for all years 2010-2017 are plotted in Figure 16 and show substantial growth in patents during these years. Companies continue to invest in research and development that leads to physics-based patents. For both the United States and all assignees, more than 25% of all patents are Class G for all these years, showing the tremendous importance of protecting new physics-based knowledge that enables technology development.

The range of companies seeking and being awarded patents is quite large and is an indication of the importance of industrial physics in the long-range planning of our largest companies. With new devices relying on a combination of nano-scale electronics, highly sensitive sensors, and complex artificial intelligence software, industrial physics is crucial to future competitiveness.

Figure 15. Physics-Related R&D Investment in Different Industrial Sectors (2015)

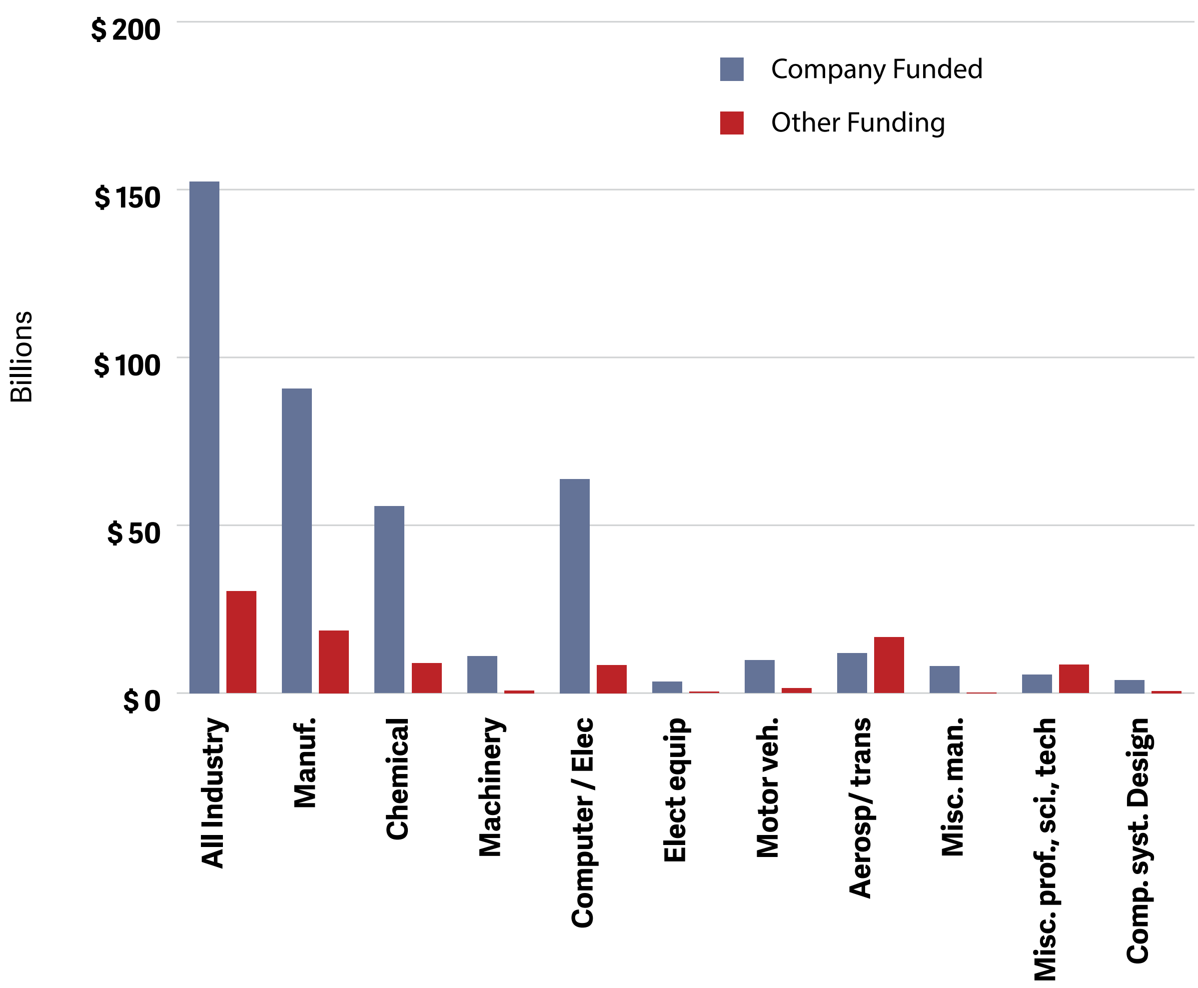


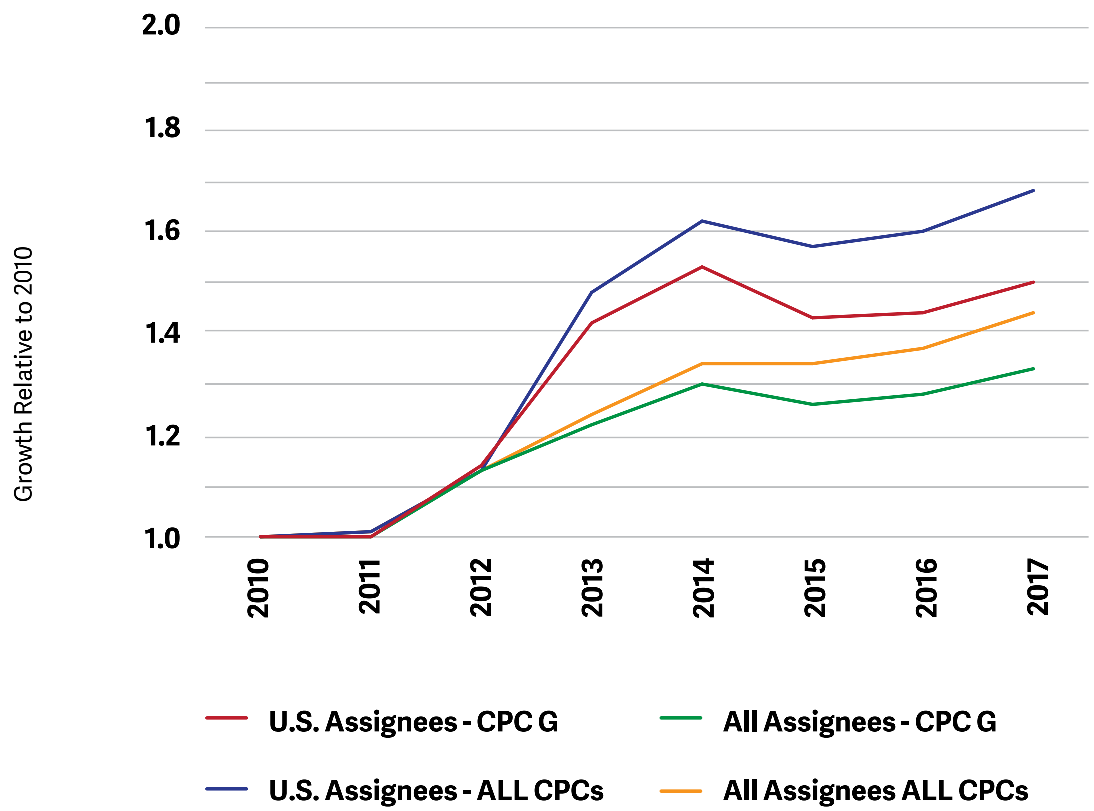
Table 3. Physics-Related U.S. Patents Granted to the Top 20 U.S. Companies (2010-2017)

Assignee [CPC G]	U.S. Patents CPC G	Cited by	Rank CPC G	All CPC Patents	Rank Total	CPC G Share
IBM	37,044	101,835	1	56,538	1	66%
MICROSOFT	14,507	85,274	2	23,102	2	63%
GOOGLE	9,871	60,600	5	15,507	5	64%
INTEL	7,213	18,638	6	15,693	4	46%
APPLE	6,645	46,311	9	14,177	6	47%
HEWLETT PACKARD	5,190	22,349	12	10,677	8	49%
ORACLE	4,849	23,716	14	6,209	19	78%
AMAZON	4,033	24,441	20	6,679	17	60%
QUALCOMM	3,708	13,229	23	15,972	3	23%
XEROX	3,318	8,198	25	6,758	16	49%
MICRON TECHNOLOGY	3,309	10,329	26	7,476	12	44%
EMC	3,118	19,885	28	3,952	24	79%
GENERAL ELECTRIC	2,837	8,538	29	13,049	7	22%
HONEYWELL	2,742	14,223	30	6,173	20	44%
SEAGATE TECHNOLOGY	2,526	8,373	33	3,041	34	83%
TEXAS INSTRUMENTS	2,375	5,675	34	6,582	18	36%
AT & T	2,276	10,234	35	10,259	9	22%
BOEING	2,270	7,337	36	6,911	15	33%
ADOBE SYSTEMS	2,054	12,913	38	2,680	39	77%
IGT RENO NEV (US)	1,990	18,472	40	2,107	48	94%
Top 20 U.S. Companies US CPC G (Physics) Patents	**121,875**	**520,570**		**233,542**		

Table 4. Physics-Related and Total Patents Awarded in the United States (2010-2017)

Patent Trend Data	2010	2011	2013	2015	2017	Total
U.S. Assignees - CPC G	32,625	32,637	46,168	46,719	49,022	341,175
All Assignees - CPC G	66,951	67,049	81,800	84,204	88,753	636,689
U.S. Assignees - ALL CPCs	109,218	110,793	161,873	171,739	183,434	1,211,634
All Assignees - ALL CPCs	244,664	248,107	303,659	326,971	352,587	2,414,964

Figure 16. Indexed Growth in Physics Patents (CPC G and All CPCs), 2010-2017



Entrepreneurship

Another view of the robustness of the contribution of industrial physics to future U.S. economic growth is provided by examining the entrepreneurial aspects of physics-based sectors. Table 5 gives the number of registered businesses in the 79 NAICS4 code sectors of the U.S. economy in 2016 previously identified as physics-based as well as the increase from 2010 to 2016 both in terms of total growth as well as Annualized Average Growth Rate (AAGR) (14).

Even though the U.S. economy was experiencing problems, especially at the beginning of this period, 8.0% total growth for all physics-based industry sectors indicates the substantial entrepreneurial spirit of industrial physicists. Except for the motor vehicle industry sector, all sectors showed some growth.

The sidebar on entrepreneurial physics ventures describes some specific successful examples, including cases where industrial physics is the enabler of traditional technologies such as measurement and electronics as well as emerging crossover fields in health, biology, advanced materials, and quantum computing.

Table 5. Number of Registered Businesses in Physics-Based Sectors in the United States at the Start of the Year (2010 -2016)

Industry Sector	2016	Growth 2010-2016	AAGR 2010-2016
All physics-based industry	9,716,618	8.0%	1.3%
Manufacturing	343,695	0.3%	0.1%
Chemical products	17,545	9.4%	1.6%
Machinery	29,940	1.5%	0.3%
Computer and electronic products	19,570	4.2%	0.7%
Electrical equipment and components	7,974	8.7%	1.5%
Motor vehicles	8,251	-1.7%	-0.3%
Aerospace/other transportation equipment	6,477	6.2%	1.0%
Miscellaneous manufacturing	31,909	1.8%	0.3%
Misc. prof., sci., and tech services	727,113	15.6%	2.6%
Computer systems design services	247,801	22.4%	3.7%

Entrepreneurship in Physics

Physicists have long been interested in industry and many of today's largest companies have roots in creating innovative products and services from newly discovered and commercialized physics. Even Albert Einstein along with Leo Szilard, patented a design for a refrigeration unit with no moving parts. It should be noted no consumer products ever resulted from this invention, although prototypes were built.

Below are examples of some entrepreneurial companies started by physicists: large, small, old, new. They all share a common trait: That new physics can create an innovative and disruptive industry. No endorsement is meant by the mention of these specific companies except that they reflect the importance of physics in industry.

The J.A. Woollam Company of Lincoln, Nebraska, was started in 1987 and now employs over 50 scientists and engineers to produce spectroscopic ellipsometers. These handcrafted instruments measure properties of thin films, which are critical in semiconductors and other applications.

QuantTera is a small and entrepreneurial company founded in Phoenix, Arizona, in 2005. QuantTera focuses on microelectronics and has received patents for transistor and transistor laser technology with direct application in wireless and telecommunications devices.

Industrial Measurement Systems, Inc. of Aurora, Illinois, produces complex measuring instruments for use in manufacturing control and quality assurance. Since 1994, the company has developed several patented devices using ultrasound and optical techniques and has received three SBIR awards from NASA.

American Magnetics, Inc. (AMI), a veteran owned company in Oak Ridge, Tennessee, has been a manufacturer of superconducting magnet systems and cryogenic equipment for over 45 years. Founded in 1968, AMI has become a world leader in supplying turn-key cryogen-free, and liquid helium-based superconducting magnet systems with literally thousands of magnets in the field.

Asylum Research started in 1999 to build atomic force microscopes (AFM) for materials and bioscience applications. The company grew tremendously and was purchased in 2012 by Oxford Instruments. They continue to operate out of their Santa Barbara, California location.

Intel was started in 1968 in Santa Clara, California, as a small company focused on semiconductors. In 2017 Intel had $63 billion in revenue and is an example of a highly successful entrepreneurial venture.

CREATV MicroTech creates medical physics products using high-aspect-ratio microfabrication and ultra-sensitive bio-detection technology they have developed with applications for innovative blood tests and biomarkers for early detection of cancer. The company was founded in 1999 and is located in Rockville, Maryland.

Rigetti Computing, founded in 2013 by Chad Rigetti, and based in Berkeley and Fremont, California, is focused on building high-performance computers using quantum chip technology. They currently have over 50 U.S. patent applications on file, with many more in process.

New Industrial Physicists

The United States remains a leader in quality physics education and attracts students from all over the world, especially for graduate degrees. These newly prepared physics graduates, with bachelor's, master's, and doctorate degrees, are primarily employed in industry. The infusion of this new talent provides a capable workforce to replace retiring workers, and also brings new physics thinking and research techniques that are crucial in developing new technology and equipment.

Table 6 gives data on the number of exiting physics degree graduates in the period 2003 to 2016 as well as an estimate of those entering industry (19) (20) (21). In this period of 14 years, we estimate over 70,000 new physicists became industrial physicists. It should be noted that many have titles without the term "physicist," but their physics training and skills acquired in school are the basis for their success throughout their careers.

Table 6. Number of Graduating Physicists (2003–2016) and Estimates of the Number Entering Industry

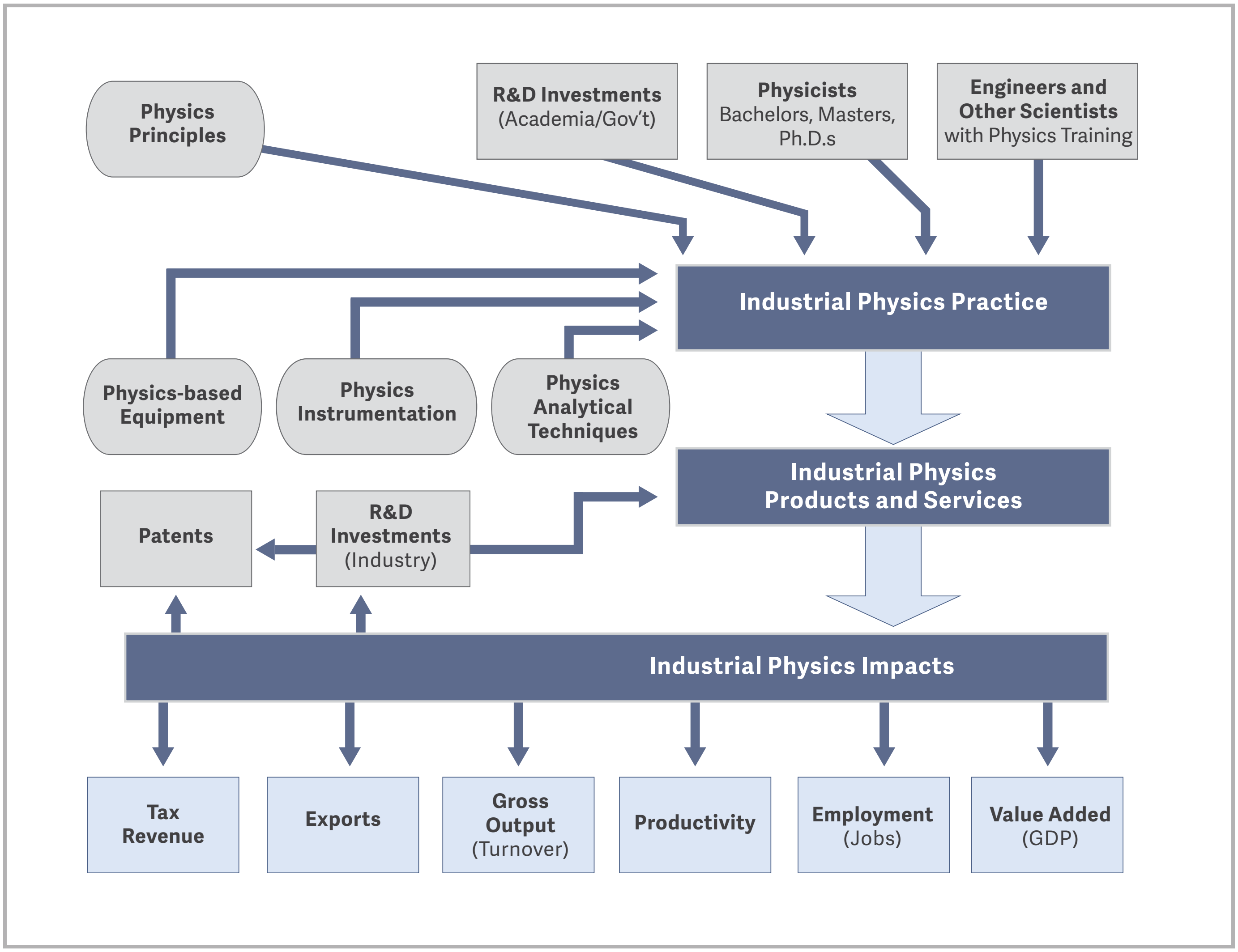
Year	B.S.	Exiting M.S.	Ph.D.'s	Total Physics Degrees	Entering Industry (est.)
2003	4,553	672	1,106	6,331	**3,679**
2004	4,965	716	1,090	6,771	**3,946**
2005	5,113	798	1,244	7,155	**4,155**
2006	5,373	799	1,380	7,552	**4,381**
2007	5,755	824	1,460	8,039	**4,667**
2008	5,767	790	1,499	8,056	**4,676**
2009	5,908	838	1,554	8,300	**4,814**
2010	6,017	794	1,558	8,369	**4,859**
2011	6,296	735	1,688	8,719	**5,062**
2012	6,778	801	1,762	9,341	**5,428**
2013	7,329	801	1,743	9,873	**5,755**
2014	7,526	870	1,803	10,199	**5,941**
2015	8,081	891	1,860	10,832	**6,319**
2016	8,440	940	1,819	11,199	**6,543**
TOTAL				120,736	**70,224**
% Entering Industry (est.)	61%	53%	49%		**58%**

Annex 1 Industrial Physics as a System

The term Industrial Physics defines an integrated system that involves industry, academia, and government as partially sketched in the diagram below (Figure A-1). The system consists of people, organizations, ideas, products and services, economic value, and intellectual property rights.

In the main sections of this report, we have addressed many of the individual components of the system and, to some extent, showed how they interact and affect each other. The ultimate aim of a company is to make money, and they do that through the products and services they sell at a profit. In today's world, those products and services are increasingly based on science and technology. Thus, industrial physics as a system plays a critical role in helping companies to achieve their goal: profits.

Figure A-1. Industrial Physics as a System



Annex 2 Methodology and Assumptions

In this Annex, we expand on the methodology and assumptions used in obtaining and analyzing the data used in making this report.

The goal of the report is to identify the contribution industrial physics makes to the U.S. economy, both at the present time and over the decades. The value in such an analysis is many-fold and includes the following:

- Understanding how large the contribution is
- Understanding how it has changed over the recent and longer past
- Given the size of the impact, what are the trends physics policymakers should be aware of
- What can and should be done to maintain the contribution and impact in the future

Consequently, it is important that the methodology used and the assumptions made are reasonable so that policy makers can have confidence that the data are believable.

It is our belief that while minor changes, based on personal preferences, could be made to the methodology and assumptions, those changes would only alter the data at the fringes and the basic results and conclusions would remain the same.

Setting Up the Analytical Strategy

In establishing an initial strategy to determine the economic impact of industrial physics on the U.S. economy, three basic questions were identified as critical, as shown in Figure A-2:

1. How to identify which sectors of the U.S. economy are dependent on industrial physics?
2. How to estimate the portion of each sector's operations (e.g., employment, output, etc.) that should be attributed to industrial physics?
3. Which measures are suitable to demonstrate the economic impact of industrial physics in each sector and on the U.S. economy as a whole?

Our methods for answering these questions are summarized below the solid line in the boxes in Figure A-2.

Identifying Relevant Industrial Sectors

Answering the first question is relatively straightforward. The U.S. Office of Management and Budget (with support from the U.S. Bureau of the Census) issues the North American Industry Classification System (NAICS) (2) capturing all segments of the U.S. economy in a hierarchical scheme. For the purposes of this effort, the 2012 classification was used and the analysis was developed using the four-digit NAICS (NAICS4) (5) level of specification, which includes 312 industry sectors.

We then made the assumption that the identification and size of the physics-based sectors in the U.S. economy could be determined by making two estimates:

1. The number of industrial physicists, which includes people with or without physics degrees, doing work in jobs readily identified as physicists
2. The number of jobs based on industrial physics, which includes:
    - People who have taken multiple physics courses as part of a professional degree or qualification
    - People who work on the development and production of technologies based on applying known physics principles
    - People who work on the development and production of technologies based on new physics innovation

In developing a quantitative approach, the 2016 U.S. Bureau of Labor Statistics (BLS) Occupational Employment Statistics (12) were used to identify and define the industrial physics sectors, through the use of specific occupational codes.

The use of physicists and other physical science codes were expanded to include occupations that use physics-based knowledge, including engineering, engineering technicians, plus one IT occupation. This analysis identified the wide range of U.S. industries that are based on physics knowledge. The top 30 contributors (88% of physics-based value added) are shown in Table A-1, and the complete list of sectors deemed to be physics based is in Table A-4.

Estimating the Economic Attribution to Industrial Physics

There is no standard methodology for the second step, and we began with the working definition of industrial physics, as described above. By the nature of any "scientific" input into a manufacturing or service industry, many more operations, administrative, or production workers will be employed in these industries than scientists or engineers. Yet, the foundation of these sectors would not exist without the contributions of the scientists and engineers to their R&D, product development, and process development. Hence, an industry sector may be totally reliant on science and engineering, yet its employment structure only includes a small percentage of physics-based workers. This context becomes the crux of our approach to estimating the economic contribution of industrial physics to a particular industry sector.

A sector with 10% or more employees trained in physics-based knowledge has 100% of its economic output counted as a contribution. No contribution is counted if fewer than 2% of employees are trained in physics, with a sliding scale in between. It is possible to scale the economic impact up or down by adjusting these factors. The physics-based workforce contribution was determined from 2016 BLS data, and those same proportions were used when estimating physics-based economic outputs for all years of the IMPLAN data.

While this algorithm is somewhat arbitrary, our thesis is that physics knowledge and discoveries used in industry provide the foundation for those industries. In essence, this approach uses people trained in physics as an objective indicator for industries relying on people trained in physics and industries based on physics discoveries. Two similar studies done in Italy (9) and the United Kingdom (10) took a slightly different and more subjective approach that used the judgment of physics experts to assign a percentage contribution on an industry segment by industry segment basis.

As stated in the body of this report, we believe our approach provides a more objective estimation basis than a "simple" assignment. The objectivity, of course, is not complete, and different parameters in our algorithms could be used, with slightly different results as shown in Table A-3. The calculated variation of ±33% does not significantly affect our assertions that industrial physics makes major contributions to the U.S. economy.

One can ask if the present definition of industrial physics overestimates its contributions and diminishes the contribution of sectors such as chemistry or electrical engineering. It is certainly possible for other fields to perform the same kind of economic analysis as presented in this report, with the result that when adding the value of all contributions there would be considerable overlap. Our assumption is not that other disciplines make no contribution to economic activity except through industrial physics. Instead, it is that industrial physics is a necessary catalyst for the success of other disciplines. Physics as the theoretical and experimental science that provides our understanding of electronic, nuclear, mechanical, electrical, magnetic, acoustic, heat, and radiation behavior of physical substances makes science and engineering possible.

Additional insight on this subject can be seen by consideration of the contribution of industrial physics to different levels of the Technical Readiness Level (TRL) methodology (22), which was originally developed for assessment of space technology, and has now been extended to other technological fields. A discussion of TRL is beyond the scope of this report, but it can be assumed that industrial physics makes a substantive contribution to TRL level 1 (basic research), level 2 (applied research), and level 3 (proof of concept).

Table A-1. Top 30 Physics-Based Sectors

NAICS4	U.S. Bureau of Labor Statistics Occupational Employment Data			IMPLAN Estimated 2016 ($B)			
	NAICS4 Description	Physics-Based Users	Physicists	Gross Output		Value Added	
				Total	Physics-Based	Total	Physics-Based
2211	Electric Power Generation, Transmission and Distribution	13.4%	0.5%	$551.8	$551.8	$227.9	$227.9
3254	Pharmaceutical and Medicine Manufacturing	14.5%	6.0%	$426.8	$426.8	$178.2	$178.2
3241	Petroleum and Coal Products Manufacturing	13.1%	1.8%	$449.6	$449.6	$154.4	$154.4
5413	Architectural, Engineering, and Related Services	34.0%	2.2%	$254.5	$254.5	$139.2	$139.2
5511	Management of Companies and Enterprises	3.0%	0.3%	$574.3	$170.2	$362.5	$107.4
3364	Aerospace Product and Parts Manufacturing	20.3%	0.1%	$316.5	$316.5	$104.3	$104.3
5417	Scientific Research and Development Services	18.7%	4.7%	$178.5	$178.5	$93.2	$93.2
3344	Semiconductor and Other Electronic Component Mfg.	25.6%	0.1%	$170.4	$170.4	$88.5	$88.5
3341	Computer and Peripheral Equipment Manufacturing	16.1%	0.0%	$197.8	$197.8	$86.2	$86.2
2111	Oil and Gas Extraction	15.9%	4.0%	$220.7	$220.7	$84.5	$84.5
3345	Navigational, Measuring, Electromedical, and Control Instruments Manufacturing	16.5%	0.4%	$170.7	$170.7	$79.4	$79.4
5415	Computer Systems Design and Related Services	3.1%	0.0%	$370.0	$116.5	$245.1	$77.2
3251	Basic Chemical Manufacturing	15.4%	3.4%	$424.1	$424.1	$72.9	$72.9
5416	Management, Scientific, and Technical Consulting Services	5.6%	2.2%	$195.2	$109.9	$123.8	$69.7
5172	Wireless Telecommunications Carriers (except Satellite)	6.6%	0.0%	$249.9	$164.2	$98.4	$64.6
3363	Motor Vehicle Parts Manufacturing	7.7%	0.0%	$309.1	$238.0	$77.6	$59.7
5171	Wired Telecommunications Carriers	3.6%	0.0%	$278.4	$99.6	$146.0	$52.2
3391	Medical Equipment and Supplies Manufacturing	8.0%	0.3%	$121.6	$96.7	$55.9	$44.5
3361	Motor Vehicle Manufacturing	4.9%	0.0%	$371.9	$182.4	$69.7	$34.2
3339	Other General Purpose Machinery Manufacturing	9.4%	0.0%	$99.8	$93.8	$33.0	$31.0
3331	Agriculture, Construction, and Mining Machinery Mfg.	8.5%	0.2%	$137.8	$117.6	$35.7	$30.4
3252	Resin, Synthetic Rubber, & Artificial Synthetic Fibers & Filaments Manufacturing	14.5%	2.3%	$133.3	$133.3	$23.7	$23.7
3256	Soap, Cleaning Compound, and Toilet Preparation Mfg.	6.0%	2.1%	$101.0	$61.0	$39.1	$23.6
2131	Support Activities for Mining	4.1%	0.5%	$75.2	$31.1	$55.6	$23.0
3329	Other Fabricated Metal Product Manufacturing	6.1%	0.1%	$86.4	$53.1	$34.8	$21.4
3261	Plastics Product Manufacturing	3.3%	0.1%	$200.4	$66.4	$60.8	$20.2
3342	Communications Equipment Manufacturing	18.8%	0.0%	$45.4	$45.4	$19.8	$19.8
2212	Natural Gas Distribution	6.2%	0.2%	$92.4	$57.6	$31.2	$19.5
3353	Electrical Equipment Manufacturing	13.1%	0.0%	$53.6	$53.6	$19.0	$19.0
3359	Other Electrical Equipment and Component Mfg.	9.1%	0.1%	$54.5	$49.4	$17.8	$16.1

Figure A-2. Diagram of Methodology Used to Perform Economic Analysis.

Step 1: How to identify which sectors of the U.S. economy are dependent on industrial physics?

Four-digit NAICS (NAICS4) (4) level of specification, which includes 312 industry sectors

Step 2: How to estimate the portion of each sector's operations (e.g., employment, output, etc.) that should be attributed to industrial physics?

A sector with 10% or more employees trained in physics-based knowledge has 100% of its economic output counted as a contribution. No contribution is counted if fewer than 2% of employees are trained in physics, with a sliding scale in between, resulting in selection of 79 sectors.

Step 3: Which measures are suitable to demonstrate the economic impact of industrial physics in each sector and on the U.S. economy as a whole?

Value Added (GDP), Gross Output, and Employment using data from IMPLAN and government economic databases

Impact Type (2016 data)	**Employment**	**Labor Income** (in Trillions)	**Value Added** (in Trillions)
Direct Contribution	**11,500,000**	**$1.2**	**$2.3**
Direct (Share of Total U.S.)	6.0%	10.9%	12.6%
Total Contribution	**45,100,000**	**$3.1**	**$5.5**
Total (Share of Total U.S.)	23.6%	28.2%	29.8%

Which Measures to Use to Determine Economic Impact: Value Added, Gross Output, and Employment

The two primary ways to quantify the economic activity of a country are to calculate the **value added** and the **gross output** to the economy.

Gross output is the total value of goods and services produced by an industry.

Value added is the difference between gross output and intermediate inputs and represents the value of labor and capital used in producing gross output. **Intermediate inputs** are the foreign and domestically produced goods and services used up by an industry in the process of producing its gross output. The sum of **value added** across all industries is equal to **gross domestic product** (GDP) for the economy.

GDP (or ***value added***) by industry and ***gross output*** by industry are both published as part of U.S. Bureau of Economic Analysis' (BEA) Industry Economic Accounts (23) and both sets of statistics provide important insights into an industry's contribution to the overall economy.

This study used the IMPLAN (11) economic impact model of the U.S. IMPLAN was developed by the U.S. government in the 1970s and became available to the private sector in 1991. In its continually updated form it is used by many organizations for a wide variety of economic studies because of the completeness of its data, its full representation of the U.S. economy, and its ease of use. IMPLAN (8), using underlying data from BEA, the U.S. Bureau of Labor Statistics (BLS), and other federal agencies, allows assessment of employment, labor income, contribution to GDP, revenue, and productivity (value-added or gross output per employee) for the selected industry segments.

Employment (jobs) is the third measure of economic impact and one that is easily visualized by non-economists. The BLS (14) routinely collects and makes available extensive data by economic sector that provides reliable estimates of actual employment as well as labor income and tax revenue associated with that employment.

Uncertainties

As this is a report on the use of industrial physics, it is important that we try to estimate the uncertainties associated with the data presented herein. We have enumerated the sources of uncertainty and made an estimate of its size in Table A-2.

Table A-2. Uncertainty Estimates for Impact of Industrial Physics on the U.S. Economy

	Source	Quality Assessment	Estimated Uncertainty*
Economic data			
Gross output	BEA/IMPLAN	Government-collected survey data and econometric modeling	±5%
Value added	BEA/IMPLAN	Government-collected survey data and econometric modeling	±5%
Employment	BLS	Government-collected survey data (24) (25)	±1%
Patents	USPTO	Patent award and classification statistics compiled by USPTO (26)	±5%
Exports	U.S. Census Bureau	Export data collected by automated fillings except Canada; adoption of automated filing increased export/import data by 20-30% (27)	±2%
Industrial physics impact			
Number of physicists and other occupations using industrial physics	BLS	Employer-reported statistics (24) (25)	±5%
Sectors involved in industrial physics	Best judgment	Sectors selected based on knowledge of U.S. industry, number, and work of industrial physicists	±10%
Amount of impact in a sector	Best judgment	Impact assigned based on knowledge of physics-based industry, and work of industrial physicists	±33%

**These estimates of uncertainty stem from a combination of 1) a literature search on the variability of output and value added (GDP) when BEA makes data revisions over time (<1% typically). Because all output and value added data are in fact "estimations" using econometric modeling, it is difficult to ascertain a more "rigorous" uncertainty level; and 2) IMPLAN often has to make their own estimates or adjustments to their source data to get the full economic model aligned.*

Perhaps the greatest uncertainty in the economic analysis presented is the assumption that a NAICS4 sector with 10% or more employees trained in physics-based knowledge has 100% of its economic output counted as a contribution. For sectors having between 2% and 10% of such employees, a sliding scale from 0% to 100% contribution was computed. For sectors with fewer than 2% of such employees, no contribution was counted.

To test this assumption, the impact of changing the 10% and 2% thresholds was investigated with the following results shown in Table A-3.

Table A-3. Sensitivity of Value Added (GDP) Results to Assumptions about Sector Contributions

With 2% for the lower limit and upper limit of:	Value Added, Trillions $	Percent change from base calculation
5%	2.98	27%
10%	2.35	0%
15%	1.98	-16%
20%	1.60	-32%
With 10% for the upper limit and a lower limit of:		
2%	2.35	0%
3%	2.19	-7%
4%	2.02	-14%

It can be concluded that the sensitivity of the results to this key assumption is in the range of $\pm$ 33%. With a lowest estimate of the impact on the **value added (GDP)** of the U.S. economy being $1.6 trillion, the overall conclusions made in this report do not change.

Table A-4. Complete List of NAICS4 Codes, Descriptions and Value Added Contributions of Physics-Based Sectors

	U.S. Bureau of Labor Statistics Occupational Employment Data			IMPLAN Estimated 2016 ($B)			
		Physics-Based Users	Physicists	Value Added		Cumulative Physics-Based Value Added	
NAICS4	NAICS4 Description			Total	Physics-Based		
2211	Electric Power Generation, Transmission and Distribution	13.4%	0.5%	$227.9	$227.9	$227.9	9.7%
3254	Pharmaceutical and Medicine Manufacturing	14.5%	6.0%	$178.2	$178.2	$406.1	17.3%
3241	Petroleum and Coal Products Manufacturing	13.1%	1.8%	$154.4	$154.4	$560.5	23.9%
5413	Architectural, Engineering, and Related Services	34.0%	2.2%	$139.2	$139.2	$699.6	29.8%
5511	Management of Companies and Enterprises	3.0%	0.3%	$362.5	$107.4	$807.1	34.4%
3364	Aerospace Product and Parts Manufacturing	20.3%	0.1%	$104.3	$104.3	$911.3	38.8%
5417	Scientific Research and Development Services	18.7%	4.7%	$93.2	$93.2	$1,004.5	42.8%
3344	Semiconductor and Other Electronic Component Mfg.	25.6%	0.1%	$88.5	$88.5	$1,093.1	46.6%
3341	Computer and Peripheral Equipment Manufacturing	16.1%	0.0%	$86.2	$86.2	$1,179.2	50.3%
2111	Oil and Gas Extraction	15.9%	4.0%	$84.5	$84.5	$1,263.7	53.9%
3345	Navigational, Measuring, Electromedical, and Control Instruments Manufacturing	16.5%	0.4%	$79.4	$79.4	$1,343.1	57.2%
5415	Computer Systems Design and Related Services	3.1%	0.0%	$245.1	$77.2	$1,420.2	60.5%
3251	Basic Chemical Manufacturing	15.4%	3.4%	$72.9	$72.9	$1,493.1	63.6%
5416	Management, Scientific, and Technical Consulting Services	5.6%	2.2%	$123.8	$69.7	$1,562.9	66.6%
5172	Wireless Telecommunications Carriers (except Satellite)	6.6%	0.0%	$98.4	$64.6	$1,627.5	69.4%
3363	Motor Vehicle Parts Manufacturing	7.7%	0.0%	$77.6	$59.7	$1,687.2	71.9%
5171	Wired Telecommunications Carriers	3.6%	0.0%	$146.0	$52.2	$1,739.5	74.1%
3391	Medical Equipment and Supplies Manufacturing	8.0%	0.3%	$55.9	$44.5	$1,784.0	76.0%
3361	Motor Vehicle Manufacturing	4.9%	0.0%	$69.7	$34.2	$1,818.1	77.5%
3339	Other General Purpose Machinery Manufacturing	9.4%	0.0%	$33.0	$31.0	$1,849.2	78.8%
3331	Agriculture, Construction, and Mining Machinery Mfg.	8.5%	0.2%	$35.7	$30.4	$1,879.6	80.1%
3252	Resin, Synthetic Rubber, & Artificial Synthetic Fibers & Filaments Manufacturing	14.5%	2.3%	$23.7	$23.7	$1,903.3	81.1%
3256	Soap, Cleaning Compound, and Toilet Preparation Mfg.	6.0%	2.1%	$39.1	$23.6	$1,927.0	82.1%
2131	Support Activities for Mining	4.1%	0.5%	$55.6	$23.0	$1,950.0	83.1%
3329	Other Fabricated Metal Product Manufacturing	6.1%	0.1%	$34.8	$21.4	$1,971.3	84.0%
3261	Plastics Product Manufacturing	3.3%	0.1%	$60.8	$20.2	$1,991.5	84.9%
3342	Communications Equipment Manufacturing	18.8%	0.0%	$19.8	$19.8	$2,011.3	85.7%
2212	Natural Gas Distribution	6.2%	0.2%	$31.2	$19.5	$2,030.8	86.6%
3353	Electrical Equipment Manufacturing	13.1%	0.0%	$19.0	$19.0	$2,049.8	87.4%
3359	Other Electrical Equipment and Component Mfg.	9.1%	0.1%	$17.8	$16.1	$2,065.9	88.0%
3336	Engine, Turbine, and Power Transmission Equipment Mfg.	13.1%	0.0%	$16.0	$16.0	$2,081.9	88.7%
3332	Industrial Machinery Manufacturing	13.6%	0.1%	$13.2	$13.2	$2,095.1	89.3%
3255	Paint, Coating, and Adhesive Manufacturing	11.0%	4.6%	$13.0	$13.0	$2,108.1	89.8%
3259	Other Chemical Product and Preparation Manufacturing	8.7%	1.9%	$14.5	$12.6	$2,120.7	90.4%
4862	Pipeline Transportation of Natural Gas	6.9%	0.4%	$17.8	$12.4	$2,133.0	90.9%
3333	Commercial and Service Industry Machinery Mfg.	10.2%	0.1%	$12.2	$12.2	$2,145.2	91.4%
3253	Pesticide, Fertilizer, and Other Agricultural Chemical Mfg.	7.0%	1.1%	$16.0	$11.2	$2,156.4	91.9%

Table A-4. Continued

	U.S. Bureau of Labor Statistics Occupational Employment Data			IMPLAN Estimated 2016 ($B)			
		Physics-Based Users	Physicists	Value Added		Cumulative Physics-Based Value Added	
NAICS4	NAICS4 Description			Total	Physics-Based		
2122	Metal Ore Mining	8.4%	1.3%	$13.3	$11.1	$2,167.5	92.4%
3311	Iron and Steel Mills and Ferroalloy Manufacturing	6.2%	0.1%	$16.5	$10.2	$2,177.7	92.8%
3335	Metalworking Machinery Manufacturing	6.1%	0.0%	$16.5	$10.1	$2,187.8	93.2%
3366	Ship and Boat Building	7.9%	0.0%	$12.7	$10.0	$2,197.8	93.7%
3221	Pulp, Paper, and Paperboard Mills	4.4%	0.1%	$21.3	$9.5	$2,207.3	94.1%
3334	Ventilation, Heating, Air-Conditioning, and Commercial Refrigeration Equipment Manufacturing	6.4%	0.0%	$14.0	$9.0	$2,216.3	94.5%
3327	Machine Shops, Turned Product, Screw, Nut, & Bolt Mfg.	2.4%	0.0%	$30.4	$7.4	$2,223.7	94.8%
3323	Architectural and Structural Metals Manufacturing	2.1%	0.0%	$30.6	$6.6	$2,230.3	95.1%
3262	Rubber Product Manufacturing	4.2%	0.1%	$15.5	$6.4	$2,236.7	95.3%
2121	Coal Mining	2.4%	0.1%	$26.9	$6.4	$2,243.1	95.6%
3352	Household Appliance Manufacturing	6.1%	0.0%	$10.2	$6.3	$2,249.3	95.9%
3399	Other Miscellaneous Manufacturing	2.7%	0.1%	$22.5	$6.2	$2,255.5	96.1%
3314	Nonferrous Metal (except Aluminum) Production and Processing	5.3%	0.4%	$10.7	$5.6	$2,261.1	96.4%
5629	Remediation and Other Waste Management Services	3.2%	0.5%	$17.6	$5.6	$2,266.7	96.6%
3315	Foundries	4.4%	0.0%	$11.6	$5.1	$2,271.8	96.8%
3324	Boiler, Tank, and Shipping Container Manufacturing	4.3%	0.0%	$11.6	$5.1	$2,276.8	97.0%
4861	Pipeline Transportation of Crude Oil	20.4%	2.4%	$4.8	$4.8	$2,281.6	97.2%
5622	Waste Treatment and Disposal	5.1%	1.2%	$8.9	$4.6	$2,286.2	97.4%
3321	Forging and Stamping	4.2%	0.0%	$10.3	$4.4	$2,290.6	97.6%
3343	Audio and Video Equipment Manufacturing	14.6%	0.0%	$3.7	$3.7	$2,294.3	97.8%
4869	Other Pipeline Transportation	14.0%	2.3%	$3.7	$3.7	$2,298.0	97.9%
3351	Electric Lighting Equipment Manufacturing	6.4%	0.0%	$5.8	$3.7	$2,301.7	98.1%
3279	Other Nonmetallic Mineral Product Manufacturing	3.6%	0.2%	$10.2	$3.7	$2,305.4	98.3%
5414	Specialized Design Services	2.9%	0.0%	$12.7	$3.7	$2,309.1	98.4%
3369	Other Transportation Equipment Manufacturing	6.4%	0.0%	$4.8	$3.1	$2,312.2	98.5%
3112	Grain and Oilseed Milling	2.2%	0.0%	$14.3	$3.1	$2,315.3	98.7%
3362	Motor Vehicle Body and Trailer Manufacturing	2.3%	0.0%	$12.9	$3.0	$2,318.3	98.8%
3346	Mfg. and Reproducing Magnetic and Optical Media	15.1%	0.0%	$2.9	$2.9	$2,321.2	98.9%
8112	Electronic & Precision Equipment Repair & Maintenance	2.7%	0.0%	$10.7	$2.9	$2,324.1	99.1%
3313	Alumina and Aluminum Production and Processing	3.6%	0.1%	$7.2	$2.6	$2,326.7	99.2%
3272	Glass and Glass Product Manufacturing	2.8%	0.0%	$9.2	$2.5	$2,329.2	99.3%
3372	Office Furniture (including Fixtures) Manufacturing	2.7%	0.0%	$9.1	$2.4	$2,331.6	99.4%
3312	Steel Product Manufacturing from Purchased Steel	3.0%	0.0%	$7.5	$2.2	$2,333.9	99.5%
3365	Railroad Rolling Stock Manufacturing	7.0%	0.0%	$3.1	$2.2	$2,336.0	99.6%
2213	Water, Sewage and Other Systems	2.5%	0.6%	$8.6	$2.1	$2,338.2	99.7%
3322	Cutlery and Handtool Manufacturing	3.7%	0.0%	$5.5	$2.0	$2,340.2	99.7%
5179	Other Telecommunications	2.3%	0.0%	$7.0	$1.6	$2,341.8	99.8%
3325	Hardware Manufacturing	4.4%	0.0%	$3.3	$1.4	$2,343.2	99.9%
3271	Clay Product and Refractory Manufacturing	3.1%	0.0%	$4.2	$1.3	$2,344.5	99.9%
3326	Spring and Wire Product Manufacturing	2.2%	0.0%	$4.1	$0.9	$2,345.4	100.0%
3133	Textile and Fabric Finishing and Fabric Coating Mills	2.6%	0.3%	$2.9	$0.8	$2,346.2	100.0%
5174	Satellite Telecommunications	5.6%	0.0%	$0.3	$0.2	$2,346.4	100.0%

Complete List of NAICS4 Codes, NAICS Description, and Contributions to Physics-based Sectors

Table A-4 contains the complete List of NAICS4 codes, NAICS description, and contributions to physics-based value added, as expanded from Table A-1. These data were used to compile the tables and graphs in this report. A description of the headings is given below in Table A-4. Note there are 312 NAICS4 codes and only 79 are included here as the others make negligible contributions to the physics-based outputs. The last two columns show the cumulative value added for each industry segment. The gray-shaded rows indicate the 50%, 80%, and 90% cumulative levels for the physics-based value added. Just nine sectors provide over 50% of the physics-based gross output, and 34 sectors provide over 90%. An examination of the sectors within those two categories shows they are the sectors that have physics as a foundation of their technology, products, and services. The anecdotes that are included in the report illustrate the diverse ways that physics and physical principles are critical to such technologies. Based on this analysis, uncertainties in Table A-2 have been assigned.

Table A-5 Legend for Table A-4

NAICS4	The four-digit NAICS4 code for the sector
NAICS4 Description	A description of the sector; they are listed in order of the size of the physics-based contribution to value added
Physics-Based Users	The percentage of employees in the sectors assumed to do work as defined as industrial physics
Physicists	Percentage of employees in the sectors who are classified by BLS as physicists
Value Added–Total	The total value added for the sector
Value Added–Physics-based	The value added in the sector that is physics-based
Cumulative Value Added	The cumulative total of physics-based value added starting with the largest contribution
% Cumulative Value Added	The cumulative percentage of physics-based value added starting with the largest contribution

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The economic statistics and analysis in this report were developed and estimated by TEConomy Partners, LLC. TEConomy is a comprehensive technology-based economic development consulting group whose principals have a 25-year record at the forefront of modern economic development and analytical services, performing research, strategies, and impact analysis for federal agencies, state governments, regions, major communities, research universities, and development consortia across the nation and internationally. TEConomy possesses a unique and extensive understanding of both economic impact analyses and the full range of economic and social benefits attributable to technology development programs, including entrepreneurship, commercialization, STEM education, and other innovation programs. TEConomy understands and appreciates the variations in culture and communications among and between industry, higher education, non-profit organizations, and government, with many in our group having worked in and across these sectors.

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