A View of Global Science and Technology: Letter Report

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A View of Global S&T Based on Activities of the Board on Global Science and Technology: Letter Report

Committee on Going Global: Lessons Learned from International Meetings on Science and Technology

Board on Global Science and Technology
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Division on Engineering and Physical Sciences

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Board on Global Science and Technology
Chair
Dr. Ruth David, President and CEO, Analytic Services, Inc
Director
Dr. William O. Berry

500 Fifth Street, NW
Washington, DC 20001
Phone: 202 334 2424
Fax: 202 334 1667
www.nationalacademies.org

December 5, 2011

Melissa Flagg, Ph.D.
Director, Technical Intelligence
OSD AT&L/ASD(R&E)/PD
Pentagon Room 3C855A

Dear Dr. Flagg,

On behalf of the Committee on Going Global: Lessons Learned from International Meetings on Science and Technology, I am pleased to submit the following letter report that describes the 2009-2011 activities of the Board on Global Science and Technology and provides an initial characterization of the global S&T landscape that the Board can use as a roadmap to develop future activities.

BGST met five times between November 2009 and May 2011. Board meetings were devoted to (1) identifying national security implications of the globalization of S&T, (2) building a baseline understanding of current indicators for the U.S. posture with regard to the evolving global S&T landscape, and (3) developing a BGST engagement strategy.

This letter portion of the report summarizes activities of the board in its first year, and also describes some existing approaches to identifying and/or benchmarking emerging technologies globally. Appendices A.1-2 include the names and affiliations of the committee that prepared this letter report and the names and affiliations of the Board on Global Science and Technology. Appendix B acknowledges the reviewers of the letter report. Appendix C describes the two workshops that BGST held during its first program year. Appendices D.1-3 include three experimental examples by BGST members of a qualitative approach to benchmarking. The topics are metamaterials, advanced computing, and synthetic biology, respectively. Appendix E includes brief descriptions of programs that are part of the National Academies complex, with which BGST has cooperated.

The statement of task for this letter report follows:

> The Board on Global Science and Technology (BGST) was established in 2009 to provide policymakers a sustained view of the impact of the globalization of science and

> technology (S&T) on U.S. national security and economic policies.[1] An ad hoc committee of the board will produce a fast-track letter report that provides a characterization of the global S&T landscape that can be used as a roadmap[2] to develop future activities. The committee will gather information from relevant work from throughout the National Academies, including relevant NRC, NAE and NAS reports, BGST meetings, and from the two workshops on emerging technologies convened by BGST in the past year: "Shifting Power: Smart Energy Grid 2020" (August 2010) and "Realizing the Value from 'Big Data' " (February-March 2011).

The National Security Implications of the Globalization of S&T

For many decades, U.S. technological leadership provided a solid foundation for both national security and economic competitiveness. That foundation is eroding. It is increasingly apparent that future U.S. S&T investment strategy must be informed by a comprehensive understanding of the global S&T environment.

In its 1995 report *Allocating Federal Funds for Science and Technology*, the NRC recommended that:

> "The President and Congress should ensure that the Federal Science and Technology budget is sufficient to allow the United States to achieve preeminence in a select number of fields and to perform at a world-class level in the other major fields."[3]

The most recent Quadrennial Defense Review (QDR) observed that:

> As global research and development (R&D) investment increases, it is proving increasingly difficult for the United States to maintain a competitive advantage across the entire spectrum of defense technologies…. The Department will consider the scope and potential benefits of an R&D strategy that prioritizes those areas where it is vital to maintain a technological advantage.[4]

Planning guidance issued by the Secretary of Defense in April 2011 identified the following priority S&T investment areas:

(1) **Data to Decisions** – science and applications to reduce the cycle time and manpower requirements for analysis and use of large data sets.

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[1] The sponsor did not seek input on economic policy during the first program year. BGST plans to investigate economic issues related to the globalization of emerging technologies as it expands its sponsor base.

[2] The experimental activities that the Board conducted during its first program year have shown the complexity of creating a roadmap of global S&T—even for creating the Board's own activity plan. The Board has decided that it would best to base any future roadmap on information that is collected from activities over a multi-year period.

[3] National Research Council. 199. *Allocating Federal Funds for Science and Technology*. Washington, DC: National Academies Press, p. 14.

[4] U.S. Department of Defense. 2010. *Quadrennial Defense Review Report*. Washington, DC: Government Printing Office, pp. 94-95.

(2) **Engineered Resilient Systems** – engineering concepts, science, and design tools to protect against malicious compromise of weapon systems and to develop agile manufacturing for trusted and assured defense systems.
(3) **Cyber Science and Technology** – science & technology for efficient, effective cyber capabilities across the spectrum of joint operations.
(4) **Electronic Warfare / Electronic Protection** – new concepts and technology to protect systems and extend capabilities across the electro-magnetic spectrum.
(5) **Counter weapons of Mass Destruction (WMD)** – advances in DoD's ability to locate, secure, monitor, tag, track, interdict, eliminate and attribute WMD weapons and materials.
(6) **Autonomy** – science & technology to achieve autonomous systems that reliably and safely accomplish complex tasks, in all environments.
(7) **Human Systems** – science & technology to enhance human-machine interfaces to increase productivity and effectiveness across a broad range of missions.[5]

An investment strategy implied by the documents cited above requires an understanding of the global S&T landscape at a granular level not provided by current S&T indicators. It requires ongoing field/sub-field-level benchmarking to ascertain not only the current U.S. position relative to other nations but also to identify the trends and accelerators that help forecast future positions. To maintain technological advantage in the priority S&T investment areas, DoD must not only focus its investment portfolio, but also ensure that its investments are informed by an awareness of research around the world.

An effective and efficient DoD S&T investment strategy thus requires not only ongoing benchmarking at a granular level, but also sustained engagement and collaboration with other nations in order to more fully understand the nation-specific cultural factors that shape trends and accelerate (or impede) progress.

A Baseline Understanding of S&T Indicators

Science has always been a global endeavor but the 20th century birth of the Internet, which enabled a host of subsequent technological advances, created an inflection point in the evolution of the global S&T landscape. Today the 21st century scientific enterprise is more geographically distributed and more interdependent than ever before.[6]

Whereas advances in S&T have long fueled the pace of globalization; now globalization is accelerating the pace of advances in S&T. The physical borders that define national sovereignty pose minimal barriers to the flow of information or ideas and do little to impede the coalescence of global networks among inventors and innovators. A recent NRC report on the S&T strategies of six countries observed that "[t]he increased access to information has transformed the 1950s'

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[5] Secretary of Defense Memorandum, April 19, 2011. OSD 02073-11. Available online at http://www.acq.osd.mil/chieftechnologist/publications/docs/OSD%2002073-11.pdf. Last accessed August 3, 2011.

[6] See, for example, a report on the increasing globalization of science, The Royal Society. 2011. *Knowledge, Networks and Nations: Global Scientific Collaboration in the 21st Century*. (Hereafter *Knowledge, Networks and Nations*.) London, United Kingdom: Elsevier, p. 5.

paradigm of 'control and isolation' of information for innovation control into the current one of 'engagement and partnerships' between innovators for innovation creation."[7]

While the globalization of S&T has become a commonplace notion, there does not yet exist a widely-accepted set of standards for understanding its extent or significance. Traditional measures (e.g.,, Science and Engineering Indicators published by the National Science Board[8]) are limited in both timeliness and granularity, providing a retrospective picture derived from statistical analysis of available data. While valuable, such indicators provide little insight at the sub-field level within major disciplines and in emerging interdisciplinary research domains—both of which are of vital importance in informing research investment strategies.

Analysis of published papers in peer-reviewed journals provides some improvement in both granularity and timeliness, but, as noted in *Knowledge, Networks and Nations*, a report of the Royal Society, "[i]t is clear that bibliometric data alone do not fully capture the dynamics of the changing scientific landscape."[9] Contributing issues include the fact that "[r]egional, national and local journals in the non-English-speaking parts of the world are often not recognised and, as a consequence, journals, conferences and scientific papers from some countries are not well represented by abstracting services."[10] In addition, "grey literature",[11] provides "potentially valuable contributions to the global stock of knowledge, but they are not accounted for in traditional assessments of research output."[12]

Yet by and large, U.S. science policy is still based on traditional measures. These were very instructive for a world with a single S&T leader, but are insufficient for characterizing the growing global S&T environment. For example, An NRC committee that examined international benchmarking in 2000

> acknowledged that quantitative indicators commonly used to assess research programs—for example, dollars spent, papers cited, and numbers of scientists supported—are useful information but noted that by themselves they are inadequate indicators of leadership, both because quantitative information is often difficult to obtain or compare across national borders and because it often illuminates only a portion of the research process.[13]

In this study, *Experiments in International Benchmarking of US Research Fields*, the committee employed a variety of assessment methods, including: "the 'virtual congress';[14] citation analysis; journal-publication analysis; quantitative data analysis (for example, numbers of

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[7] National Research Council. 2010. *S&T Strategies of Six Countries: Implications for the United States*. (Hereafter *S&T Strategies of Six Countries*.) Washington, DC: National Academies Press, p. 1.

[8] See www.nsf.gov/statistics/.

[9] *Knowledge, Networks and Nations*, p. 23.

[10] Ibid.

[11] The term "grey literature" refers to non-peer-reviewed publications. *Knowledge, Networks and Nations*, p. 23.

[12] Ibid.

[13] National Research Council. 2000. *Experiments in International Benchmarking of US Research Fields*. (Hereafter *International Benchmarking*.) Washington, DC: National Academies Press, p. 6.

[14] The "virtual congress" methodology involved asking panels to organize an imaginary international conference to which they would invite the "'best of the best'" researchers from particular subfields and sub-subfields, from anywhere in the world. The purpose of the exercise was to depict the current and future position of the United States relative to other countries in a particular area of science. Ibid., p. 15.

graduate students, degrees, and employment status); prize analysis; and international-congress speakers."[15] Experiments were conducted by assembling panels of experts to conduct assessments in specific fields and results were compared across the assessment methodologies. The analysis made clear that current leadership does not ensure sustained leadership.[16] It therefore is important to understand the underlying factors that enable or impede research and development.

In conducting the experiments described above, the *International Benchmarking* report noted the need for foreign and industry representation on the panels to ensure objectivity:

> . . . at least one-third of panel members should be non-US researchers. An additional one-third should be a combination of researchers in industry and in related fields who use the results of research. In the experience of the panels, that mix of perspectives, including especially the representatives of research-intensive industries, was essential for understanding not only the scholarly and technical achievements of researchers, but also the broader importance of those achievements to social and economic objectives."[17]

In 2005 the NRC empanelled a committee to use the benchmarking approach described in the 2000 report to assess the position of U.S. chemical engineering relative to research in other regions of the world.[18] Slightly fewer than 25% of the committee members were from outside the United States; they represented academia, industry and the federal government. The committee used a mix of quantitative and qualitative evaluation tools[19] recommended in the earlier report and found that the mix yielded consistently robust results.[20] Their Virtual World Congress, composed of 276 "organizers,"[21] resulted in a proposed speakers list of 2,997 speakers (1,897—or 63%—of who were American) and a list of "hot topics" from nine sub-fields of chemical engineering. Further experimentation with this methodology may yield a cost-effective way to maintain an ongoing and dynamic understanding of both the composition and geographical distribution of S&T leadership at a granular level.

The recognition of the limitations of traditional indicators has propelled BGST since its first meeting to seek new ways to characterize the global S&T landscape. In a November 2009 discussion with BGST, Dr. Robert Atkinson, President of the Information Technology and Innovation Foundation (ITIF), presented results from the ITIF's February 2009 report, *The Atlantic Century: Benchmarking EU and U.S. Innovation and Competitiveness*, which showed U.S. innovation capacity and performance relative to other nations. The report considered the following 16 indicators:

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[15] See *International Benchmarking*, pp. 14-17.

[16] *International Benchmarking*. Attachment 2: Appendix B.

[17] Ibid., p. 23.

[18] National Research Council. 2007. *International Benchmarking of U.S. Chemical Engineering Research Competitiveness*. Washington, DC: National Academies Press.

[19] Ibid., pp. 33-35.

[20] The committee's chief finding was that "The United States is presently, and is expected to remain, among the world's leaders in all subareas of chemical engineering research, with clear leadership in several subareas. U.S. leadership in some classical and emerging subareas will be strongly challenged." Ibid., p. 7.

[21] The term "organizers" refers to the 276 survey responses that the committee received.

- **Human capital**: higher education attainment in the population ages 25 to 34 years; and number of science and technology researchers per 1,000 employed.
- **Innovation capacity**: business investment in research and development; government investment in R&D; and the number and quality of academic publications.
- **Entrepreneurship**: venture capital investment; and new firms.
- **Information technology (IT) infrastructure**: e-government; broadband telecommunications; and corporate investment in IT.
- **Economic policy**: effective marginal corporate tax rates.
- **Economic performance**: trade balance; foreign direct investment inflows; real GDP per working-age adult; and GDP per hour worked (productivity).[22]

Dr. Atkinson noted that while the United States ranked 6th overall in innovation and competitiveness, it ranked last among 40 nations in terms of improving its innovation capacity and competitive position over the prior decade. In a 2011 update report, ITIF ranked the United States 43rd out of 44 nations in terms of improving its innovation capacity in spite of improvement in absolute rank from 6th to 4th.[23] The 2011 report also indicates that, although the United States ranked 8th and 5th in government and business R&D investment respectively, its rate of change in these categories ranked 28th and 27th relative to other nations analyzed. Other important indicators include rate of change rankings of 39th in researchers and 44th in publications for the United States.[24]

A May 2011 BGST discussion with Dr. Dan Mote, chair of the NRC Committee on Global Science and Technology Strategies and Their Effect on U.S. National Security, provided insights regarding S&T investment approaches adopted by other nations. The committee was tasked to examine the S&T strategies of Japan, Brazil, Russia, India, China, and Singapore and to evaluate the implication of S&T strategy differences to U.S. national security strategy. Dr. Mote presented highlights from the committee's report, *S&T Strategies of Six Countries: Implications for the United States*. The study committee observed that:

> The best indicators of progress toward achieving national goals are country specific and must reflect both traditional and nontraditional factors. Traditional indicators are quantitative measures of S&T investment, activity, and outcomes such as patents per capita, S&T investment as a percentage of gross domestic product, the fraction of national research expenditures made by industry, and the number of start-up companies…Nontraditional indicators emerging from cultural contexts are country specific. They are essential to understanding each country's S&T innovation environment and especially to predicting its future change…. No single set of common

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[22] Robert D. Atkinson and Scott M. Andes. 2009. *The Atlantic Century: Benchmarking EU & U.S. Innovation and Competitiveness.* Washington DC: The Information Technology and Innovation Foundation, p. 3. Also available at http://www.itif.org/files/2009-atlantic-century.pdf. Last accessed August 3, 2011.

[23] *The Atlantic Century II: Benchmarking EU & U.S. Innovation and Competitiveness*, Robert D. Atkinson and Scott M. Andes, p. 9. The Information Technology and Innovation Foundation. July 2011. http://www.itif.org/publications/atlantic-century-ii-benchmarking-eu-us-innovation-and-competitiveness. Last accessed August 3, 2011.

[24] Ibid., p. 11.

> indicators was found by the committee to provide a complete assessment of progress toward goals for all countries.[25]

The importance of nontraditional factors was further corroborated by the committee's observation that: "the S&T innovation environments of the more successful countries posses both top-down (i.e., led by government) and bottom-up (i.e., led by individuals and organizations) drivers of change."[26]

The *S&T Strategies of Six Countries* study also noted the need for nation-specific indicators to augment measures such as patents, publications, degrees awarded, and S&T budgets, to "better monitor, track, and quantify S&T development in other countries and the United States in the future."[27]

The potential value of nation-specific indicators is suggested in Figure 1, which visualizes changes in one aspect of the global S&T landscape over time: the geographic distribution of highly cited research publications in autonomous systems in 2005 and 2010.[28] In addition to a near doubling of the total number of research publications, strong growth can be seen in multiple "hot spots" around the world, including Beijing, Tianjin, and Changsha which show 2.6, 3, and 4-fold increases in publications, respectively. Why some "hot spots" disappear while others flatten or grow over time is an important question for the U.S. S&T enterprise, as well as for U.S. economic and national security. For example, it can help U.S. policymakers understand where centers of excellence in particular technologies may be developing around the world, which in turn may point to the need to find other indicators that can help clarify the U.S. position in a particular technology relative to other countries.

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[25] *S&T Strategies of Six Countrie*s, pp. 2-3.

[26] Ibid., p. 3.

[27] Ibid., p. 12.

[28] "Autonomous systems" is a subject area related to the S&T priorities listed in Secretary of Defense, Robert M. Gates memo of April 19, 2011. See pp. 2-3 above. According to the 2007 DD(R&E) Strategic Plan, autonomous systems technologies are defined as:

> Autonomous systems technologies enable unmanned systems to sense, perceive, analyze, plan, decide, and act, in order to identify and achieve their goals. The systems include communication and interaction with humans and/or other unmanned systems. Unmanned systems in the air, on the ground, and at sea perform their functions with ever increasing capabilities and technological sophistication using autonomy/teaming, human system integration, power, communications, sensors, mobility, planning/C2, processing, and diagnostics and prognostics. All of these technologies are critical to system level capabilities.

See http://www.dod.gov/ddre/doc/Strategic_Plan_Final.pdf. Last accessed October 25, 2011.

For a discussion on autonomous systems, see the PowerPoint presentation by Dr. Bobby Junker on "Autonomy S&T Priority Steering Council" at http://www.dtic.mil/ndia/2011SET/Junker.pdf. Last accessed August 17, 2011.

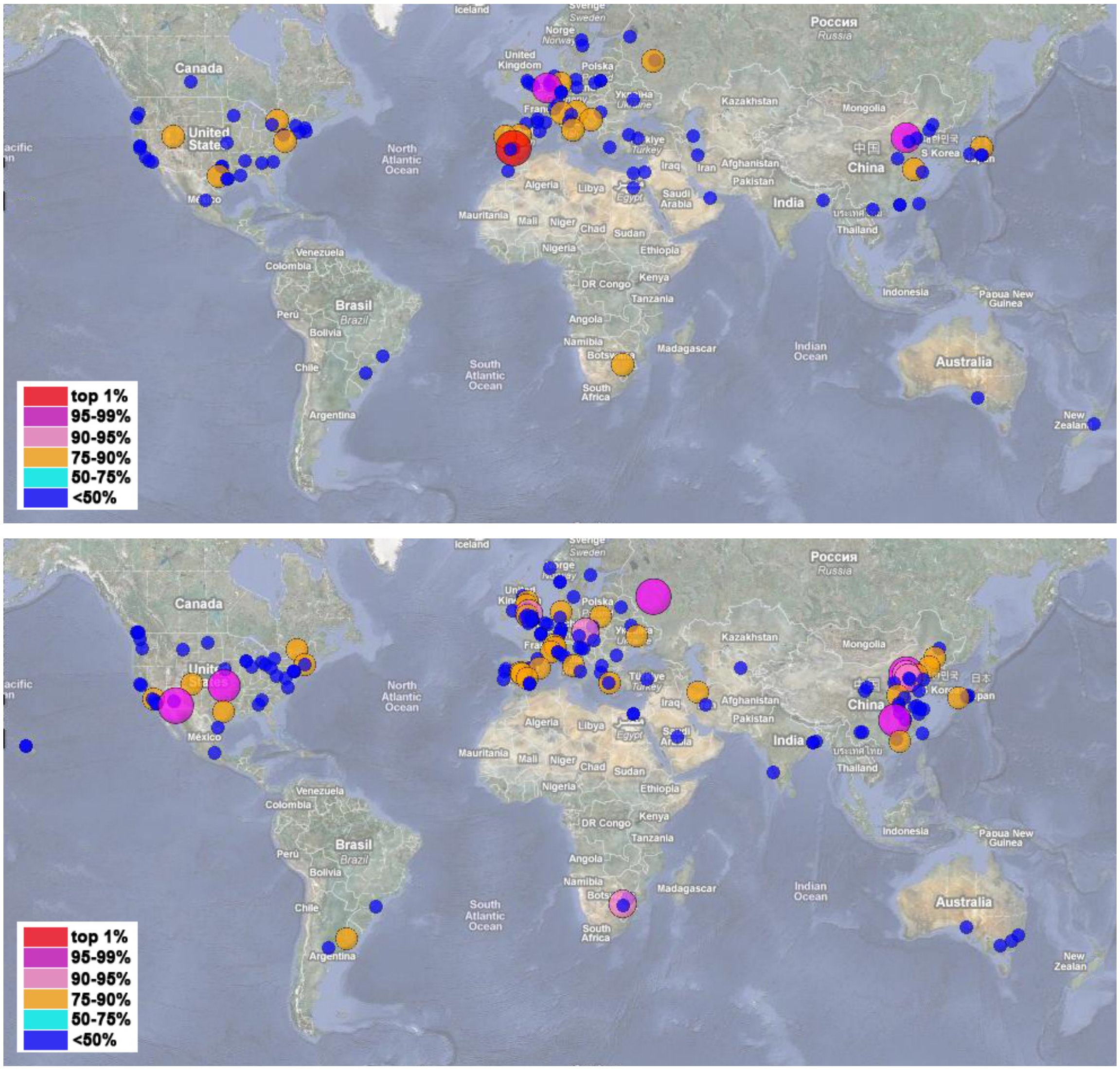

Figure 1: Mapping the geographic distribution of highly cited "autonomous systems" research publications in 2005 (top) and 2010 (bottom). The location of each circle on the map represents the geographic area ("hot spot") where one or more researchers is based. The size of the circle represents the number of publications generated in that area, and the color of the circles represents the number of publications relative to other "hot spots" shown on the map.[29] The term "autonomous systems" has more than one meaning, and the SciVerse Scopus search for highly cited publications on this topic could have counted articles that use other definitions. This can be seen as a limitation of the illustrative approach described here.

Source: Board on Global Science and Technology.[30]

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[29] Here, there is little difference between circle color and circle size due to the relatively small size of the N used to generate these maps.

[30] A detailed description of the methodology used to generate these graphs, including freely available software, is available at http://www.leydesdorff.net/mapping_excellence/index.htm (Last accessed July 26, 2011). The mapping tutorial can also be found in Bornmann L, Leydesdorff L, Walch-Solimena C, et al. 2011. "Mapping excellence in the geography of science: An approach based on Scopus data." *Journal of Informetrics* 5(4):537-546. Bibliometric data were collected via SciVerse Scopus with the following search restrictions: Title/Abstract/Keywords exact phrase="autonomous systems"; Document Type=Article; Publication Year=2005 or 2010.

It is the goal of the Board to apply these complex, but more representative, kinds of indicators to understanding the implications of the globalization of S&T for U.S. national security.

BGST's Engagement Strategy: A Continuing Experiment

The Board is experimenting with various ways to develop new qualitative metrics that will demonstrate the significance of the evolving global S&T landscape for policymakers. During its first program year, the Board held two workshops that were highly interdisciplinary and forward looking; the second one included participants from nine countries and four continents. The Board has developed a professional networking site and questionnaires to engage participants before meetings and to keep them involved afterward. The Board is also developing a data-gathering tool that takes an interdisciplinary approach to obtain situational awareness in diverse areas of emerging science and technology.

Data-intensive Science

For its initial exploration, the Board sought an over-arching theme that would (1) lead to topics of broad interest and applicability; (2) be sufficiently focused to motivate the development of sustainable, international networks; (3) yield ongoing insights into the trends and accelerators shaping the global S&T landscape. An important consideration in topic selection and in the development of a collaborative methodology for sustained engagement was the notion of "what's in it for them" (i.e. what would motivate researchers from the United States and elsewhere to stay engaged in such a network).

BGST chose the opportunities and challenges of data-intensive science. This selection was informed by discussions with Dan Reed (Corporate Vice President, Microsoft Corporation) and Alexander Szalay (Alumni Centennial Professor Department of Physics and Astronomy, The Johns Hopkins University), both of whom were contributing authors to The Fourth Paradigm: Data-Intensive Scientific Discovery.[31] These discussions made clear that the topic was broadly applicable, spanning a range of scientific disciplines as well as a diverse array of problem domains of global importance. Selection of the data-intensive science topic was further motivated by its relevance to DoD's priority S&T investment areas. The topic is directly linked to the DoD priority S&T investment area #1 (Data to Decisions) and plays an enabling role in several of the other priority areas due to its link to sensors, simulations, and other computationally-intensive applications.

The Board derived additional insights on data-intensive science from a discussion with Randal E. Bryant (University Professor of Computer Science and Dean, School of Computer Science at Carnegie Mellon University) on the topic of "Data Intensive Scalable Computing: Its Role in

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[31] Tony Hey, Stewart Tansley, and Kristin Tolle, eds. 2009. *The Fourth Paradigm: Data-Intensive Scientific Discovery*. Redmond, WA: Microsoft Research.

Scientific Research," who made a compelling case for the need for computational infrastructures that:[32]

- Focus on Data: Terabytes, not tera-FLOPS;
- Problem-Centric Programming: Platform-independent expression of data parallelism;
- Interactive Access: From simple queries to massive computations; and
- Robust Fault Tolerance: Component failures are handled as routine events.

A recent BGST discussion with Ben Shneiderman, University of Maryland, on the topic of "Visual Analytics Science and Technology for Collaborative Knowledge Discovery" further illustrated both the challenges and the opportunities inherent in data-intensive science. Key lessons from this presentation included not only the need for awareness of advances in the field of visual analytics, but also the potential value of using such tools to more efficiently explore and more effectively describe the complex and dynamic nature of the global S&T landscape.

Data-intensive science is rich in that it affords exploration from multiple perspectives. Board-sponsored activities to date include two meetings, each thematically focused on big data, but with different structural approaches. The first meeting brought together a multi-disciplinary group of researchers and practitioners around a common problem—"Data Analytics & the Smart Energy Grid 2020." The second meeting, co-sponsored by Singapore's Agency for Science, Technology and Research (A*STAR)[33] also engaged a multi-disciplinary group but addressed a problem spanning multiple domains—"Realizing the Value from Big Data" (see Appendix C for descriptions of these workshops).

Building a Professional Network

The Board created an interactive website (using Ning) as a multi-party, international communication tool for the global S&T community involved in emerging science areas. To date it has been used primarily by participants in BGST workshops. As a continuation of this experiment, the Board plans to explore its use as a tool to create a continuing discussion on qualitative and quantitative assessments of emerging global S&T areas.

The BGST Template

The Board created a template to gather experts' assessments of the global S&T landscape in selected emerging S&T domains that contribute to the DoD priority S&T investment areas. The template is intended to provide a multi-faceted yet brief snapshot of a particular subject area from several viewpoints: technology, international players, national security implications, future problems/avenues of exploration, and significant publications. To date, this experimental template has been tested only by BGST members. We believe that it can be a unique qualitative data-gathering tool because its diverse questions can yield insights into how researchers perceive their field within a global context. Thus, we plan to continue to experiment with this template by involving experts beyond the BGST's current areas of expertise.   Appendix D includes applications of the template by three BGST members in three areas of emerging S&T, respectively: metamaterials, computing performance and synthetic biology.

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[32] See this PowerPoint presentation at http://sites.nationalacademies.org/xpedio/groups/pgasite/documents/webpage/pga_056621.pdf.

[33] For additional information on A*STAR, see http://www.a-star.edu.sg/.

Leveraging Expertise Throughout the National Academies
BGST has worked with a number of units throughout the National Academies with subject area expertise and /or international S&T interests to take advantage of the expertise in other programs. Appendix E lists several of the programs that BGST has or intends to work with to bolster a collective understanding of global science and technology.

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For the near future the BGST will continue to experiment with various ways of assessing the global S&T landscape in emerging areas, including use of the Ning site and the template assessment tool. However, the main focus will involve another experiment—using NRC study committees with a fast-track study format to assess the trends in global S&T in a specific technical domain of interest to the DoD. The goal is to have a report completed in six months of the first committee meeting. The first study being undertaken is a fast-track assessment of Global Approaches to Advanced Computing.

Sincerely,

Ruth A. David

Ruth David, Ph.D.
Chair, BGST
President and CEO, Analytic Services Inc.

Appendix A.1

Committee on Going Global: Lessons Learned from International Meetings on Science and Technology

Ruth David, *Chair*
President and CEO
Analytic Services Inc.
Arlington, VA

Jeffrey M. Bradshaw
Senior Research Scientist
Florida Institute for Human and Machine Cognition (IHMC)
Pensacola, FL

Dianne Chong
Vice President of Materials and Process Planning in the Boeing Engineering, Operations &Technology Organization
The Boeing Corporation
Bellevue, WA

Nan Marie Jokerst[34]
J.A. Jones Distinguished Professor of Electrical and Computer Engineering, and Professor of Electrical and Computer Engineering
Duke University
Durham, NC

Bernard Meyerson
Vice President for Strategic Alliances and Chief Technology Officer, Systems and Technology Group
International Business Machines
Yorktown Heights, NY

Staff
William O. Berry, Study Director
Ethan N. Chiang, Program Officer
Neeraj P. Gorkhaly, Research Associate
Patricia S. Wrightson, Senior Program Officer

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[34] Dr. Nan Marie Jokerst resigned from the committee on August 19, 2011, due to time constraints.

Appendix A.2

Board on Global Science and Technology

Member Affiliations

Ruth David, *Chair* (NAE)
President and CEO, Analytic Services, Inc.
Arlington, VA

Jeffrey Bradshaw
Senior Research Scientist, Florida Institute for Human and Machine Cognition
Pensacola, FL

Dianne Chong
Vice President,
Assembly, Factory and Support Technologies Engineering, Operations & Technology
The Boeing Company
Bellevue, WA

Jared Cohon
President, Carnegie Mellon University
Pittsburgh, PA

Eric C. Haseltine
President and Marketing Director
Haseltine Partners, LLC
Washington, DC

John Hennessy (NAS/NAE)
President, Stanford University
Stanford, CA

Nan Marie Jokerst
Professor, Department of Electrical and Computer Engineering
Duke University
Durham, NC

Peter Kolchinsky
Managing Director, RA Capital Management, LLC
Boston, MA

Bernard Meyerson, IBM Fellow (NAE)
VP, Innovation
IBM Corp. HQ
Yorktown Heights, NY

Neela Patel
Director, External Research, Global Pharmaceutical R&D
Abbott Laboratories
Belmont, CA

Dan Reed
Corporate Vice President, Technology Strategy and Policy
Microsoft Corp.
Redmond, WA

Staff
William O. Berry, Director
Ethan N. Chiang, Program Officer
Neeraj P. Gorkhaly, Research Associate
Patricia S. Wrightson, Associate Director

Appendix B

Acknowledgments

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the National Research Council's Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process.

We wish to thank the following individuals for their review of this report: Mildred Dresselhaus, Massachusetts Institute of Technology; John Gannon, BAE Systems; Michael Lesk, Rutgers University; Lyle Schwartz, University of Maryland; James Valdes, U.S. Army; and Yannis Yortsos, University of Southern California.

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations, nor did they see the final draft of the report before its release. The review of this report was overseen by Samuel Fuller**.** Appointed by the National Research Council, he was responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

Appendix C

Meetings on Data-Intensive Science

Shifting Power: Data Analytics & the Smart Energy Grid 2020[35]

August 23-24, 2010
Microsoft Corporate Campus
Redmond, Washington

This meeting assembled an invited group of scientists and engineers from major research universities, private industry, and government to discuss the impact of large and distributed datasets, together with the associated computational challenges, on the smart energy grid. The smart grid focus was selected in part due to the growing international interest in this subject and in part because the issues can be abstracted to other application domains (e.g., real time analysis of streaming sensor data is broadly applicable). This meeting was U.S.-centric, with nominal international representation. The subject did, however, provide a valuable "use case" for discussing issues directly linked to DoD's priority S&T investment areas, as multiple participants noted that monitoring of international smart grid initiatives may yield useful insights regarding trends and accelerators that will shape the S&T landscape in areas of interest to DoD. Discussions throughout the two days centered on issues relating to decision making from multiple stakeholder perspectives—ranging from design optimization to operational control at various levels of the grid to individual consumer decisions enabled by "smart" meters. Topics discussed included the need for real time and predictive analytics together with better visualization techniques to inform decisions, additional grid management complexities stemming from distributed decision-making, and a spectrum of data management challenges (ownership, retention, access, privacy, etc.). In discussing research pathways to underpin smart grid initiatives, several participants noted the need to fuse data across disciplines as well as across time and space. All of these issues address research related to DoD's "Data to Decisions" investment area.

Many participants noted the need for a 'smart grid' that is self-healing, i.e., able to identify and react to system disturbances and take actions to correct them with little or no human interaction. They emphasized that the smart grid would need to be resilient to human-induced and natural disasters, resisting attacks on its physical and computerized infrastructure. Achievement of these attributes would depend on further research in areas including "Engineered Resilient Systems," "Autonomy," "Electronic Protection," and "Cyber Science & Technology."

The meeting participants were selected for their expertise directly relating to some aspect of the myriad smart energy grid initiatives. Some of the BGST members who participated in the meeting observed that an unintended consequence of this selection was a tendency to focus on issues—particularly in the policy realm—that were specific to the smart energy grid application. As a result, in structuring its next meeting, BGST chose to invite participants who were working in multiple problem domains.

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[35] A brief summary of this meeting can be found at http://sites.nationalacademies.org/xpedio/groups/pgasite/documents/webpage/pga_062054.pdf.

Realizing the Value from Big Data[36]

February 28-March 2, 2011
Institute for Infocomm Research (I^2R) of Singapore's Agency for Science, Technology, and Research (A*STAR)
Fusionopolis, Singapore

This meeting convened bioinformatics scientists and environmental scientists together with computational/data scientists, who were asked to identify computational and policy roadblocks that prevent their disciplines from fully extracting value from "big data." Bioinformatics and environmental sciences were selected not only because both are data-rich applications, but also because the underlying research challenges are inherently international. Invited participants were selected jointly with principals from Singapore's I^2R,[37] which hosted the meeting, and were drawn from research organizations in Australia, China, England, Hong Kong, Japan, Korea, the Netherlands, Portugal, Singapore, and the United States. Discussions during the meeting reflected broad international interest in the subject, but also exposed difficulties inherent to communications across problem domains as well as across cultural contexts.

A central theme centered on challenges stemming from researchers' needs to find and use "big data" captured or generated by others; many participants generally agreed that improvements in this area would enhance the efficiency of their own research. Issues ranged from researchers' inability to find and access relevant datasets to an inability to make sense of the data, given access. While some barriers derived from policy (e.g., ownership, privacy), other impediments were related to the absence of standards for metadata that could enable search engines to find relevant datasets and also help researchers understand the provenance and meaning of the data. Participants working in small groups were asked to identify specific initiatives that might mitigate key barriers; suggestions ranged from the development of common abstractions that could be reused across domains, to the notion of a standardized Internet protocol that would facilitate identification and location of "big data" of interest to a research team.

Participants also discussed challenges related to the management and exploration of "big data," e.g., the importance of common infrastructures to share the cost burden associated with "big data"; efficient processes and incentives to motivate researchers to share data; and common tools to facilitate mining and exploration of complex datasets. Participants expressed differing opinions on the definition of "big data"; some viewed it as a matter of size, while others associated it with complexity. Disciplinary differences arose, too. Most computer scientists voiced a desire to perform research at a level of abstraction above that valued by domain scientists working on specific problems (e.g., many computer scientists wanted to be seen as "enablers" rather than "plumbers"). Many participants expressed the view that a "principal investigator-centric" funding model is not well-matched to "big data" problems, as a multi-disciplinary collaborative environment is needed.

Participants at this meeting identified a diverse array of issues—most of which were common to all nations represented—that today limit their abilities to fully extract value from 'big data.'

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[36] A brief summary of this meeting can be found at http://sites.nationalacademies.org/xpedio/groups/pgasite/documents/webpage/pga_062988.pdf.
[37] For information on the Institute for Infocomm Research, see http://www.i2r.a-star.edu.sg/.

Many expressed the view that a number of the barriers mentioned would require international remedies to enable researchers and practitioners to tackle the big problems that cross national borders (e.g., environment, health, and, increasingly, security). Other participants noted the relevance of issues on “big data” to DoD’s “Data to Decisions” investment area, since the data required to inform decisions is increasingly heterogeneous, and drawn from disparate sources that are distributed over both space and time.

Appendix D

Assessments of Three Areas of Emerging S&T

The following three assessments, each written by a member of BGST, constitute an experimental qualitative, multi-dimensional view of the global landscape in three areas of emerging S&T—metamaterials, computing performance and synthetic biology, respectively. They are based on a template that was created by BGST. The template is intended to provide a multi-faceted yet brief snapshot of a particular subject area from several viewpoints: technology, international players, national security implications, future problems/avenues of exploration, and significant publications. The views expressed in these assessments belong exclusively to the authors and do not necessarily represent the views of the Committee on Going Global, the Board on Global Science and Technology, or the National Academies.

Appendix D.1

Metamaterials

Nan Marie Jokerst
Duke University

I. Keywords

Metamaterials (MMs), transformation optics, negative refractive index materials, engineered materials, cloaking, superlenses; Plasmonics and nanophotonics are related areas. Some types of metamaterials: photonic MMs, acoustic MMs, tunable MMs, switchable MMs, bi-isotropic and bianisotropic MMs, chiral MMs, resonator MMs.

II. Issue

Metamaterials are engineered materials designed to interact with and control waves (e.g., electromagnetic, acoustic waves). MMs are artificially structured materials that are periodic, with feature sizes that are less than or equal to 1/10 the size of the wavelength to be controlled. When the wave enters the metamaterial, it interacts with the structure, and the wave can be manipulated. MMs can be used to create materials with a designed permittivity (electrical) and/or permeability (magnetic), thus realizing material properties that do not occur in nature—such as negative index of refraction materials. Transformation optics has created a design toolset for wave media that can utilize MMs.

III. National Security Relevance/Importance

Metamaterials expand the design space for electromagnetic and acoustic materials, and enable far greater manipulation of waves. Areas of impact include: imaging (particularly infrared, visible in the longer term), tailored emissivity of surfaces, optical systems (e.g., superlenses), nonlinear optics (high EM fields in small volume), telecommunication photonics (e.g., 2D waveguide structures), antennas, sensors, power transmission, and solar cells. This is a field that is growing rapidly across the world. MMs have a potential impact on Engineered Resilient

Systems, Electronic Warfare/Electronic Protection, Counter WMD, Autonomy, and Human Systems.[38]

IV. "Metamaterials" Researchers with High Citation and Publication Counts

The following is a list of lead authors of the most highly cited papers published between 2005-2011 (October 2011) containing the terms "metamaterials" in the title, abstract, or keywords, according to SciVerse Scopus.[39]

> Pendry JB (Imperial College, U.K.); Schurig D (North Carolina State University, U.S.A.); Leonhardt U (University of Saint Andrews, Scotland); Shalaev VM (Purdue University, U.S.A.); Cai W (Geballe Laboratory for Advanced Materials, U.S.A.); Zhang SD (University of Birmingham, U.K.); Valentine J (Vanderbilt University, U.S.A.); Smith DR (Duke University, U.S.A.); and Soukoulis CM (Iowa State University).

The following is a list of the most highly published authors between 2005-2011 (October 2011) containing the terms "metamaterials" in the title, abstract, or keywords, according to SciVerse Scopus.[40] The number of citations is indicated in parentheses.

> (81) Eleftheriades GV, University of Toronto, Canada; (63) Alu A, University of Texas at Austin, U.S.A.; (63) Ozbay E, Bilkent University, Turkey; (63) Bonache J, Universitat Autonoma de Barcelona, Spain; (61) Soukoulis CM, Iowa State University; (57) Martin F, Universitat Autonoma de Barcelona, Spain; (56) Kivshar YS, Australian National University, Australia; (56) Engheta N, University of Pennsylvania, U.S.A.; (56) Cui TJ, Southeast University, China; (56) Padilla WJ (Boston College, U.S.A.).

V. Background/Historical Synopsis

Sir John Pendry and David R. Smith are viewed as the early innovators in MMs. Victor Veselago predicted negative index of refraction in 1967; Pendry developed two structures, one that controlled microwave permeability, and one that controlled microwave permittivity, in the late 1990s; and Smith demonstrated negative refractive index in 2000. Cloaking was theorized by Pendry and Smith, and demonstrated by Smith in 2006. Transformation optics design tools for MMs were developed in 2006 by Pendry and Smith. MMs have expanded to THz, infrared, and visible wavelengths. As the wavelength decreases, the feature size of the artificial structures also decreases. Thus, for infrared and visible wavelengths, nanofeatures must be patterned to realize MMs. Losses for metals typically used in MMs at longer wavelengths are "lossy" in the visible. Thus, visible and shorter wavelength MMs are challenging to produce.

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[38] Defense priorities as described in the S&T Priorities for FY 2013-2017 Planning Document, April 19, 2011.

[39] Methodology: SciVerse Scopus. Search term: TITLE-ABS-KEY="metamaterials," 2005-Oct 2011, sorted by citation count (excluded Shevchenko et al. *Nature* 439(7072):55-59, 2006). Lead authors from the top 10 most cited publications are listed. This list may include more than 10 people when publications have an equivalent number of citations. See references below.

[40] Methodology: SciVerse Scopus. Search term: TITLE-ABS-KEY="metamaterials," 2005-Oct 2011, sorted by publication count. The top 10 most published researchers are listed. This list may include more than 10 people when multiple researchers have equivalent numbers of publications.

VI. Future Options/Avenues of Exploration

Metamaterials can be considered generalized composite materials. The potential impact of MMs can be understood by considering glass or carbon fiber composites—artificially structured media that are often stronger and lighter weight than conventional materials—which have revolutionized structural and mechanical engineering. MMs have the potential to likewise impact waves such as electromagnetic and acoustic waves. MMs have an emerging suite of tools and techniques that provide guidance and precise design methods for electromagnetic, acoustic, and other types of materials that control wave phenomena. MMs are also currently demonstrating highly graded index of refraction materials. The impact and relevance to DoD and national security is not yet realized, but could be transformational. Areas to watch include:

Metamaterial Design – Design techniques for arriving at a homogenized description of an otherwise inhomogeneous collection of objects. The techniques for metamaterial design have been refined over the past decade, but techniques continue to evolve and should be monitored for emerging capabilities that will drive innovation and realization of practical structures.

Metamaterials Fabrication – Once designed, physical metamaterial implementations must be found that enable the conceived designs. Not all metamaterial theoretical designs translate to practical implementation. There is a necessary step of coordinating theory and simulation of metamaterials with available dielectrics and metals, as well as fabrication and manufacturing techniques; realization of structures often requires innovation, experimentation, and iteration.

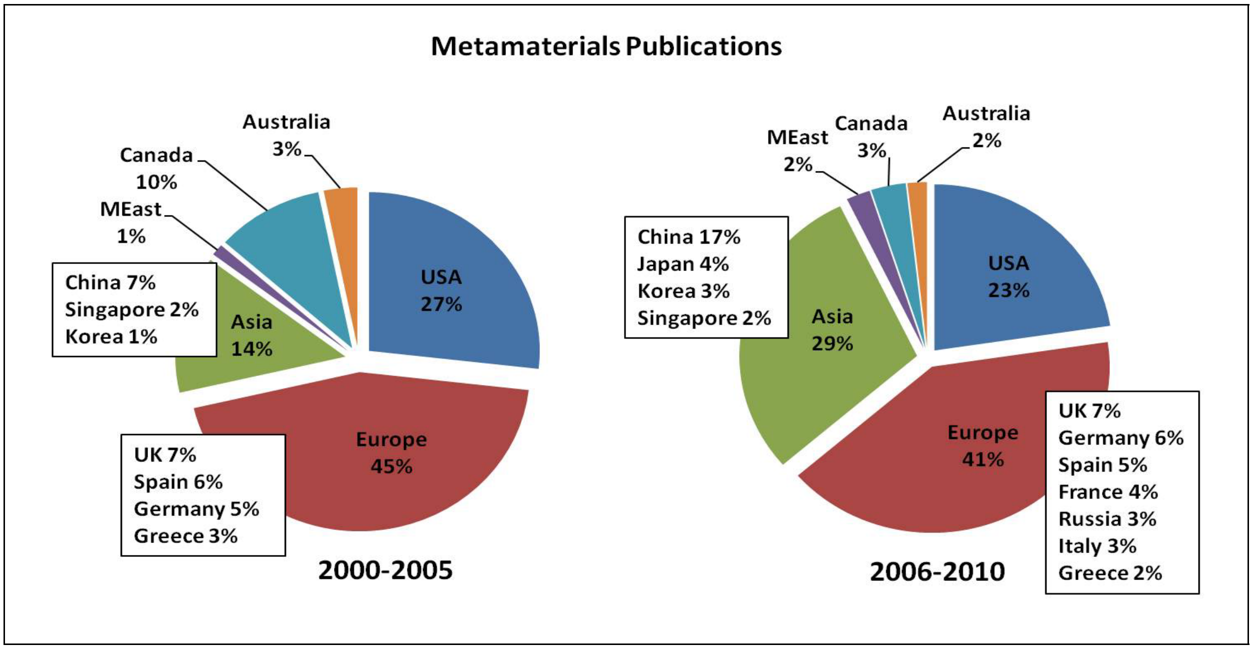
Metamaterial Integration into Devices – The successful development of devices requires an in-depth evaluation of existing technology. Entry points for metamaterial structures and components into existing technologies can be subtle, and require the fusion of traditional engineering methods with emerging metamaterial designs and structures.
MMs face a number of technical challenges, including narrow band operation and polarization sensitivity (more complex designs may address these), as well as losses and small feature sizes (both particularly at optical and shorter wavelengths).

MMs also face a number of more non-technical issues: (1) A broadened definition of MMs by those in related fields who seek funding (e.g., photonic crystals and frequency selective surfaces); (2) Unrealistic short term expectations; (3) The potential to impair U.S. innovation and research through classification of MM research in the U.S.A.; (4) Highly competitive worldwide research, with heavy funding levels abroad.

At microwave and radio frequencies, MM manufacturing technologies are better understood, and the transition to applications is critical. The teaming of MM experts with industrial and DoD system designers is crucial, as the latter have knowledge of system needs and can help to identify areas where MM structures and devices can have an impact. In the THz, radar, infrared, and optical regimes, basic research is necessary into dielectric materials, conductors, structures, and manufacturing methods. Innovations in materials and structures will optimally be led by interactions between MM theorists, materials engineers, and fabrication researchers. Early interaction of these researchers with the component and systems communities will identify the critical aspects for MMs for each application (e.g., does loss matter?).

VII. Snapshot of Global Landscape

Metamaterials is a rapidly evolving, highly competitive field worldwide. This is demonstrated in the pie charts below, which show the distribution (by country) of the top 10% most cited "metamaterials" papers published between 2000-2005 (left) and 2006-2010 (right).[41] While the U.S. and European share of metamaterials publications declined by 4% between the two time periods shown (2000-2005 and 2006-2010), Asia's % of publications doubled. In particular, Japan, which was not even on the chart between 2000-2005, increased its % of publications to 4% and China's percentage of publications dramatically increased from 7% to 17%.



VIII. References

The following is a list of the most highly cited papers published between 2005-2011 (October 2011) containing the terms "metamaterials" in the title, abstract, or keywords. The number of citations is listed to the right.

- Pendry JB, Schurig D, and Smith DR. 2006. "Controlling electromagnetic fields." *Science* 312(5718):1880-1782. 1530 citations.
- Schurig D, Mock JJ, Justice BJ, et al. 2006. "Metamaterial electromagnetic cloak at microwave frequencies." *Science* 314(5801):977-980. 1261 citations.
- Leonhardt U. 2006. "Optical conformal mapping." *Science* 312(5781):1777-1780. 857 citations.
- Shalaev VM, Cai WS, Chettiar UK, et al. 2005. "Negative index of refraction in optical metamaterials." *Optics Letters* 30(24):3356-3358. 720 citations.

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[41] Methodology: SciVerse Scopus. Search term: TITLE-ABS-KEY="metamaterials" for 2000-2005 (601 total publications) and 2006-2010 (6063 total publications), data by country.

- Shalaev VM. 2007. “Optical negative-index metamaterials.” *Nature Photonics* 1(1):41-48. 629 citations.
- Cai WS, Chettiar UK, Kildishev AV, et al. 2007. “Optical cloaking with metamaterials.” *Nature Photonics* 1(4):224-227. 461 citations.
- Zhang S, Fan W, Panoiu NC, et al. 2005. ”Experimental Demonstration of Near-Infrared Negative-Index Metamaterials.” *Physical Review Letters* 95(13):137404. 407 citations.
- Valentine J, Zhang S, Zentgraf T, et al. 2008. “Three-dimensional optical metamaterial with a negative refractive index.” *Nature* 455(7211):376-379. 365 citations.
- Soukoulis CM, S Linden. M Wegener. 2007. “Negative refractive index at optical wavelengths.” *Science* 315(5808):47-49. 318 citations.
- Chen HT, Padilla WJ, Zide JMO, et al. 2006. “Active terahertz metamaterials devices.” *Nature* 444:597-600. 308 citations.

Appendix D.2

Computing Performance
Bernard Meyerson
IBM Corporation

I. Keywords
Semiconductors; power density; device scaling; 3D integration; multicore; parallel processing; compiler tuning; quantum computing; hybrid materials; autonomic dispatch; algorithmic workloads; generic accelerators; CMOS evolution; optical integration

II. Issue
A discontinuity of great significance is looming for the semiconductor industry. For the past five decades the United States—and ultimately the global semiconductor community—based much of its progress in information technology (IT) on a sustained evolution of silicon technology. There were countless predictions as to when silicon technology might "run out of gas," but most such predictions were predicated on an inability to manufacture a given generation of devices due to a perceived, but incorrect, limitation in the ability to define the device lithographically. The impending discontinuity stems from true physical limitations. At the present rate, there are roughly three generations of silicon technology left before lateral dimensions on a silicon chip progress below the onset dimension for quantum mechanical behaviors ***in silicon itself***, essentially terminating progress in silicon technology as we know it today.

III. National Security Relevance/Importance
Information technologies are integral to every aspect of national security, supporting both operational advantage and economic prosperity. The nation that leads in exploitation of IT to translate "data-to-decisions" will have a decisive advantage in operational agility.

IV. Researchers with High Citation and Publication Counts

"Semiconductors and 3D Integration" Researchers: High Citation Counts
The following is a list of lead authors of the most highly cited papers published between 2005-2011 (October 2011) containing the term "Semiconductors and 3D integration" in the title, abstract, or keywords, according to SciVerse Scopus.[42]

> Kikuchi H (University of Tokyo, Japan); Beica R (Semitool Incorporated, U.S.A.); Gagnard X (STMicroelectronics SA, France); Ramm P (Fraunhofer Institute for Assembly and Packaging Technologies for Microsystems, Germany); Pozder S (Freescale Semiconductor, U.S.A.); Loh GH (Georgia Institute of Technology, U.S.A.); Zhang X (State Grid, China); Crnogorac F (Stanford University, U.S.A.); List S (The Research Triangle Park, U.S.A.); and Lee SW (Konkuk University, South Korea).

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[42] Methodology: SciVerse Scopus. Search term: TITLE-ABS-KEY="Semiconductors and 3D integration," 2005-Oct 2011, sorted by citation count (excluded Kastalsky et al. *Nuclear Instruments and Methods in Physics Research, Section A* 565(2):650-656 and Suga T, *ECS Transactions* 3(6):155-163). See references, below. Lead authors from the top 10 most cited publications are listed. This list may include more than 10 people when publications have an equivalent number of citations.

"Multicore" Researchers: High Citation Counts

The following is a list of lead authors of the most highly cited papers published between 2005-2011 (October 2011) containing the term "Multicore" in the title, abstract, or keywords, according to SciVerse Scopus.[43]

> Vlasov Y (IBM Corporation, U.S.A.); Kistler M (Pacific Northwest National Laboratory, U.S.A.); Gschwind M (IBM Corporation, U.S.A.); Hill MD (University of Illinois, U.S.A.); Hoskote Y (Intel, U.S.A.); Wentzlaff D (MIT, U.S.A.); Owens JD (University of California-Davis, U.S.A); Che S (University of Virginia, U.S.A.); Geer D (Freelance Technology, U.S.A.); and Donald J (Princeton University, U.S.A.).

"Power Density and Microprocessors" Researchers: High Citation Counts

The following is a list of lead authors of the most highly cited papers published between 2005-2011 (October 2011) containing the terms "Power Density and Microprocessors" in the title, abstract, or keywords, according to SciVerse Scopus.[44]

> Haensch W (IBM Corp., U.S.A.); Donald J (Princeton University, U.S.A.); Pop E (University of Illinois at Urbana-Champaign); Sankaranarayanan K (Ohio State University, U.S.A.); Mahajan R (Intel Corporation, U.S.A.); Schelling PK (University of Central Florida, U.S.A.); Zhou J (Third Military Medical University, China); Chaparro P (Intel Barcelona Research Center, Spain); Puttaswamy K (Intel, U.S.A.); and Colgan EG (Intel Corporation, U.S.A.).

"Semiconductors and 3D Integration" Researchers: High Publication Counts

The following is a list of the most highly published authors between 2005-2011 (October 2011) containing the terms "Semiconductors and 3D Integration" in the title, abstract, or keywords, according to SciVerse Scopus.[45] The number of citations is indicated in parentheses.

> (4) Beica R, Semitool Incorporated U.S.A.; (3) Kikuchi H, University of Tokyo, Japan; (3) Yamada Y, High Energy Accelerator Research Organization, Japan; (3) Fukushima T, Tohoku University, Japan; (3) Koyanagi M, Tohoku University, Japan; (3) Sharbono C, Semitool Incorporated, U.S.A.; (2) Ritzdorf T, Applied Materials Incorporated, U.S.A.; (2) La Manna A, Interuniversity Micro-Electronics Center at Leuven, Belgium; (2) Beyne E,

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[43] Methodology: SciVerse Scopus. Search term: TITLE-ABS-KEY="Multicore," 2005-Oct 2011, sorted by citation count (excluded Kumacheva et al. *Journal of the American Chemical Society*. 127(22):8058-8063, 2005 and Olson et al. *Journal of Computational Chemistry* 31(2): 455-461, 2010). See references, below. Lead authors from the top 10 most cited publications are listed. This list may include more than 10 people when publications have an equivalent number of citations.

[44] Methodology: SciVerse Scopus. Search term: TITLE-ABS-KEY="Power Density and Microprocessors," 2005-Oct 2011, sorted by citation count. See references, below. Lead authors from the top 10 most cited publications are listed. This list may include more than 10 people when publications have an equivalent number of citations.

[45] Methodology: SciVerse Scopus. Search term: TITLE-ABS-KEY="Semiconductors and 3D integration," 2005-Oct 2011, sorted by publication count. The top 10 most published researchers are listed. This list may include more than 10 people when multiple researchers have equivalent numbers of publications.

Interuniversity Micro-Electronics Center at Leuven, Belgium; (2) Klumpp A, Fraunhofer EMFT, Germany; (2) Reichl H, Technical University of Berlin, Germany; (2) Tanaka T, Tohoku University, Japan; (2) Ruhmer K, SUSS MicroTec, U.S.A.; (2) Cassidy C, Queen's University Belfast, U.K.; (2) Lu JQ, Rensselaer Polytechnic Institute, U.S.A.; (2) Siblerud P, Semitool Incorporated, U.S.A.; (2) Koppitsch G, Austriamicrosystems AG, Austria; (2) Clavelier L, CEA LETI, France; (2) Liang J, Ningxia University, China; and (2) Stucchi M, Interuniversity Micro-Electronics Center at Leuven, Belgium.

"Multicore" Researchers: High Publication Count

The following is a list of the most highly published authors between 2005-2011 (October 2011) containing the term "Multicore" in the title, abstract, or keywords, according to SciVerse Scopus.[46] The number of citations is indicated in parentheses.

(29) Mahlke S, University of Michigan Ann Arbor, U.S.A.; (21) Ayguade E, Centro Nacional de Supercomputacion, Spain; (19) Bader DA, Georgia Institute of Technology, U.S.A.; (18) Fedorova A, Simon Fraser University, Canada; (18) Agarwal A, MIT, U.S.A.; (18) Kandemir M, Pennsylvania State University, U.S.A.; (17) Merritt R, EE Times, U.S.A.; (17) Benini L, Sveuciliste U Zagrebu, Croatia; (16) Dongarra J, University of Manchester, U.K.; and (16) Anderson JH, University of North Carolina at Chapel Hill, U.S.A.

"Power Density and Microprocessors" Researchers: High Publication Count

The following is a list of the most highly published authors between 2005-2011 (October 2011) containing the terms "Power Density and Microprocessors" in the title, abstract, or keywords, according to SciVerse Scopus.[47] The number of citations is indicated in parentheses.

(6) Dick RP, University of Michigan Ann Arbor, U.S.A.; (5) Shang L, University of Colorado at Boulder, U.S.A.; (5) Atienza D, Universidad Complutense de Madrid, Spain; (4) Brunschwiler T, IBM Research, U.S.A.; (4) Chrysler GM, Intel Corporation, U.S.A.; (4) Ismail Y, Northwestern University, U.S.A.; (4) Garinto D, Indonesian Power Electronics Center, Indonesia; (4) Mahajan R, Intel Corporation, U.S.A.; (3) Chiu CP, IEEE, U.S.A.; (3) Liu P, Zhengzhou University, China; (3) Tan SXD, Chinese Academy of Sciences, China; (3) Bezama RJ, IBM, U.S.A.; (3) Skadron K, University of Virginia, U.S.A.; (3) Memik SO, Northwestern University, U.S.A.; (3) Ku JC, Samsung Electronics, U.S.A.; (3) Wu W, Capital Medical University, China; (3) Mukherjee R, IEEE, U.S.A.; (3) Jin L, NVIDIA, U.S.A.; (3) Goodson KE, Stanford University, U.S.A.; (3) Lee FC, Virginia Tech, U.S.A.; (3) Sauciuc I, Intel, U.S.A.; (3) Wakil J, IBM, U.S.A.; (3) Mahajan RV, Intel, U.S.A.; (3) Prasher R, Arizona State University, U.S.A.; (3) Yang J, Amgen Incorporated, U.S.A.; (3) Sun J, Virginia Tech, U.S.A.; (3) Gu Z, East China University of

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[46] Methodology: SciVerse Scopus. Search term: TITLE-ABS-KEY="Multicore," 2005-October 2011, sorted by publication count. The top 10 most published researchers are listed. This list may include more than 10 people when multiple researchers have equivalent numbers of publications.

[47] Methodology: SciVerse Scopus. Search term: TITLE-ABS-KEY="Power Density and Microprocessors," 2005-October 2011, sorted by publication count. The top 10 most published researchers are listed. This list may include more than 10 people when multiple researchers have equivalent numbers of publications.

Science and Technology, China; (3) Zhu C, Queen's University, Canada; (3) Li H, National University of Singapore, Singapore; and (3) Krishnan S, AT&T Laboratories, U.S.A.

V. Background/Historical Synopsis

The historical drivers of progress in the semiconductor industry were a combination of two fundamentals, Moore's Law, and Classical Scaling. According to "Moore's Law,"[48] silicon technology density must double every 18 months in order to maintain technical and financial viability across the semiconductor industry. This anticipation has proved essentially correct over a six order magnitude range in device densities and a four decade long period of semiconductor achievements.

Additionally, it was understood that the power density of semiconductor technology must be maintained as approximately a constant. This requires halving the power of each component on the chip in exact synchrony with the halving of its area. For the better part of four decades, the entire industry has relied on R.H. Dennard's[49] formulaic approach to achieve constant power density while scaling (shrinking) silicon technology. However, this is only a temporary solution and is ultimately subject to the limits of physical laws.

From its inception, Information Technology was based upon high performance devices known as homo-junction bipolar transistors. While incremental shrinking, both laterally and vertically, of these devices resulted in enhanced performance, physical limitations—for example, increased device leakage due to band to band tunneling—eventually rendered them obsolete. In fact, no systems exist today, nor have there been for almost two decades, based upon bipolar transistors.

Approximately a decade ago, bipolar technology's successor, CMOS, began to approach a similar set of physical limits. This heralded the end of classical device scaling after being practiced for many decades, ushering in an era of exponentially increasing device complexity as various material and structural "tricks" were implemented to address the inability to further shrink transistors without disastrous outcomes. Despite small gains, these "tricks" have only delayed the inevitable.

VI. Future Options/Avenues of Exploration

Summarized below are three potential areas of investment:

- <u>3D Integration</u>: We must enable the tight coupling of logic, memory, and optical links in 3D "bricks" if we are to compensate for loss of ability to further conduct planar technology shrinks at the chip level. This may not drive cost down, but provides performance gains via minimized signal path dimensions. Dramatic improvements in optical link cost-performance and integration are required to fully execute this strategy.

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[48] Gordon Moore. 1965. "Cramming more components onto Integrated Circuits." *Electronics* 38:114-117.

[49] Robert H. Dennard, Fritz H. Gaensslen, Hwa-Nien Yu, V. Leo Rideout, Ernest Bassous, and Andre R. LeBlanc. 1974. "Design of Ion Implanted MOSFET's with Very Small Dimensions," *IEEE Journal of Solid State Circuits* 9:(5)256-268.

- Multi-Core Software Optimization: Current trends toward massive core counts are ineffectual as a long term strategy in the absence of software able to provide performance advantages linear in core count. This remains a fertile area for further research, as it is unclear to what extent one can further drive system throughput in this manner.

- Intelligent Software: To date, compiler tuning, as one example, is essentially a manual undertaking by our best and brightest computer science experts. An area of exploration is to exploit "intelligent" software, which upon analysis of a given application's characteristics, halts and recompiles code to best match software to the available hardware. Autonomic real time tuning of operation, if rendered as effective as manual tuning, is a viable avenue to extract significant performance gains, and opens the door to countless other autonomic software functions.

Other relevant areas include quantum computing,[50] hybrid materials, and autonomic dispatch mechanisms[51] for algorithmic workloads to generic accelerators.

VII. Snapshot of Global Landscape

Homogeneous 3D integration is well known globally from broad use in flash memory designs to add density by stacking chips, but heterogeneous integration of computing "blocks" with logic, memory, and optical I/O is not practiced yet. A similar common global practice is the development of software to leverage multi-core chips and systems, with applications for systems aimed at High Performance Computing. China and Japan recently announced that software of this class was one enabler of performance records. There is little, if any, global work in the field of self-optimizing software, where "smart" compilation and recompilation, are leveraged to boost system capabilities in real time.

Abortive first attempts at semi-automatic variants have been made, providing software tools enabling the porting of algorithms from central processing units to highly parallel hardware accelerators such as FPGA's and/or GPU's, but overall this field is in its infancy. Future efforts will likely focus on finding new means to drive IT performance as classical means—such as raw technology performance—approach the end of their life.

There are many discussions regarding the use of silicon nano-wires, carbon based graphene devices, quantum computing, and all manner of alternatives, but the hard reality is that to compete with silicon, any new technology must achieve integration levels exceeding 10 billion devices. Since no such successor appears on the horizon at present, the question of how one must drive the performance of Information Technology going forward is paramount.

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[50] Quantum computing is defined as utilizing quantum mechanical phenomena (e.g., superposition and entanglement) rather than traditional transistors and digital logic to perform operations on data.

[51] Autonomic dispatch mechanisms are highly adaptable and dynamic processes that map messages to a specific sequence of code at runtime (as opposed to other phases of a program's lifecycle such as compile, link, or lead time). They can similarly dispatch instructions to auxiliary capabilities within a system such as accelerators without need for human intervention/setup.

VIII. References

The following is a list of the most highly cited papers published between 2005-2011 (October 2011) containing the terms “Semiconductor” and “3D Integration” in the title, abstract, or keywords. The number of citations of each article is listed to the right.

- Kikuchi H, Yamada Y, Ali AM, et al. 2008. “Tungsten through-silicon via technology for three-dimensional LSIs.” *Japanese Journal of Applied Physics* 47(4)Part 2:2801-2806. 18 citations.
- Beica R, Sharbono C, and Ritzdorf T. 2008. “Through silicon via copper electrodeposition for 3D integration.” *Proceedings—Electronic Components and Technology Conference*, art no. 4550031:577-583. 14 citations.
- Gagnard X and Mourier T. 2010. “Through silicon via: From the CMOS imager sensor wafer level package to the 3D integration.” *Microelectronic Engineering* 87(3):470-476. 11 citations.
- Ramm P, Wolf MJ, Klumpp A, et al. 2008. “Through silicon via technology –processes and reliability for wafer-level 3D system integration.” *Proceedings—Electronic Components and Technology Conference*, art no. 4550074:841-846. 10 citations.
- Pozder S, Chatterjee R, Jain R, et al. 2007. “Progress of 3D integration technologies and 3D interconnects.” *Proceedings of the IEEE 2007 International Interconnect Technology Conference—Digest of Technical Papers, art no.* 4263705:213-215. 9 citations.
- Loh GH. 2009. “Extending the effectiveness of 3D-stacked DRAM caches with an adaptive multi-queue policy.” *Proceedings of the Annual International Symposium on Microarchitecture, MICRO* pp 201-212. 7 citations.
- Zhang X, Kumar A, Zhang QX, et al. 2009. “Application of piezoresistive stress sensors in ultra thin device handling and characterization.” *Sensors and Actuators, A: Physical* 156(1):2-7. 6 citations.
- Beica R, Siblerud P, Sharbono C, et al. 2008. “Advanced metallization for 3D integration.” *10th Electronics Packaging Technology Conference, EPTC 2008*, art no 4763436:212-218. 6 citations.
- Kikuchi H, Yamada Y, Kijima H, et al. 2006. “Deep-trench etching for chip-to-chip three-dimensional integration technology.” *Japanese Journal of Applied Physics, Part 1: Regular Papers and Short Notes and Review Papers* 45(4B):3024-3029. 6 citations.
- Cronogorac F, Witte DJ, Xia Q, et al. 2007. “Nano-graphoepitaxy of semiconductors for 3D integration.” *Microelectronic Engineering* 84(5-8):891-894. 5 citations.
- List S, Bamal M, Stucchi M, et al. 2006. “A global view of interconnects.” *Microelectronic Engineering* 83(11-12):2200-2207. 5 citations.
- Lee SW and Bashir R. 2005. “Dielectrophoresis and chemically mediated directed self-assembly of micrometer-scale three-terminal metal oxide semiconductor field-effect transistors.” *Advanced Materials* 17(22):2671-2677. 5 citations.

The following is a list of the most highly cited papers published between 2005-2011 (October 2011) containing the terms “Multicore” in the title, abstract, or keywords. The number of citations is listed to the right.

- Vlasov Y, Green W, and Xia F. 2008. “High-throughput silicon nanophotonic wavelength-insensitive switch for on-chip optical networks.” *Nature Photonics* 2(4):242-246. 141 citations.
- Kistler M, Perrone M, and Petrini F. 2006. “Cell multiprocessor communication network: Built for speed.” *IEEE Micro* 26(3):10-23. 139 citations.
- Gschwind M, Hofstee HP, Flachs B, et al. 2006. Synergistic processing in Cell's multicore architecture.” *IEEE Micro* 26(2):10-24. 137 citations.
- Hill MD and Marty MR. 2008. “Amdahl’s law in the multicore era.” *Computer* 41(7):33. 124 citations.
- Hoskote Y, Vangal S, Singh A, et al. 2007. “A 5-GHz mesh interconnect for a teraflop processor.” *IEEE Micro* 27(5):15-61. 120 citations.
- Wentzlaff D, Griffin P, Hoffman H, et al. 2007. “On-chip interconnection architecture of the tile processor.” *IEEE Micro* 27(5):15-31. 117 citations.
- Owens JD, Dally WJ, HO R, et al. 2007. “Research challenges for on-chip interconnection networks.” *IEEE Micro* 27(5):96-108. 116 citations.
- Che S, Boyer M, Meng J, et al. 2008. “A performance study of general-purpose applications on graphics processors using CUDA.” *Journal of Parallel and Distributed Computing* 68(10):1370-1380. 102 citations.
- Geer D. 2005. “Industry trends: Chip makers turn to multicore processors.” *Computer* 38(5):11-13. 97 citations.
- Donald J and Martonosi M. 2006. “Techniques for multicore thermal management: Classification and new exploration.” *Proceedings—International Symposium on Computer Architecture 2006*, art no. 1635942, pp. 78-88. 89 citations.

The following is a list of the most highly cited papers published between 2005-2011 (October 2011) containing the phrases “Power Density” and “Microprocessor” in the title, abstract, or keywords. The number of citations is listed to the right.

- Haensch W, Nowak EJ, Dennard RH, et al. 2006. “Silicon CMOS devices beyond scaling.” *IBM Journal of Research and Development* 50(4-5):339-361. 102 citations.
- Donald J and Martonosi M. 2006. “Techniques for multicore thermal management: Classification and new exploration.” *Proceeding—International Symposium on Computer Architecture 2006*, art no. 1635942, pp. 78-88. 89 citations.
- Pop E, Singha S, and Goodson KE. 2006. “Heat generation and transport in nanometer-scale transistors.” *Proceedings of the IEEE* 94(8):1587-1601. 78 citations.
- Sankaranarayanan K, Velusamy S, Stan M, et al. 2005. “A case for thermal-aware floorplanning at the microarchitectural level.” *Journal of Instruction-Level Parallelism* 7, 16p. 53 citations.
- Schelling PK, Shi L, and Goodson KE. 2005. “Managing heat for electronics.” *Materials Today* 8(6):30-35. 41 citations.
- Mahajan R, Chiu CP, and Chrysler G. 2006. “Cooling a microprocessor chip.” *Proceedings of the IEEE* 94(8):1476-1486. 41 citations.

- Zhou J, Xu M, Sun J, et al. 2005. “A self-driven soft-switching regulator for future microprocessors.” *IEEE Transactions on Power Electronics* 20(4):806-814. 40 citations.
- Chaparro P, Gonzales J, Magklis G, et al. 2007. “Understanding the thermal implications of multicore architectures.” *IEEE Transactions on parallel and Distributed Systems* 18(8):1055-1065. 35 citations.
- Puttaswamy K and Loh GH. 2007. “Thermal herding: Microarchitecture techniques for controlling hotspots in high-performance 3D-integrated processors.” *Proceedings—International Symposium on High-Performance Computer Architecture*, art no. 4147660: pp. 193-204. 34 citations.
- Colgan EG, Furman B, Gaynes M, et al. 2007. “A practical implementation of silicon microchannel coolers for high power chips.” *IEEE Transactions on Components and Packaging Technologies* 30(2):218-225. 31 citations.

Appendix D.3

Synthetic Biology

Neela Patel

Abbott Laboratories

I. Keywords

Synthetic biology, synthetic genomes, synthetic biology engineering, Do-It-Yourself (DIY) biology/biopunks, biohacking, genetic engineering

II. Issue

Synthetic biology, as defined within this document, ultimately aims to make a complete DNA blueprint for an organism de novo. Currently, our understanding of the biology prevents achievement of the goal e.g.,, control of gene expression and of protein synthesis are still being explored on a single gene basis and are poorly understood on a genome basis. However, major technical advances in the speed and associated cost of DNA synthesis and sequencing, and decreases in the cost of molecular biology equipment have resulted in two parallel and sometimes intertwined research communities manipulating genes in small numbers (genetic engineering) and attempting to do so on larger scales (synthetic biology). Scientists within the research institute community have promoted engagement by youth through iGEM and other means, and have indirectly enabled Do-It-Yourself communities by the publication of large numbers of gene sequences from a variety of organisms. Synthetic biology may be understood to encompass incorporation of non-canonical amino acids, or building completely abiotic systems; however, these variations all rest upon foundations of manipulating DNA as described throughout this document.

III. National Security Relevance/Importance

Genetic engineering and synthetic biology may pose threats and opportunities for national security. From a threat perspective, the DIY movement, while espousing ethical, curiosity-driven goals, has the potential to enable individuals interested in bioterrorism to make life-threatening toxins, viruses, and bacteria with relative ease. In the future, as synthetic biology matures, the permutations become greater and the risk higher. Vendors are currently self-regulating and screen requests for suspicious requests; in 2007, Blue Heron Biotech reportedly received and denied requests for synthesis of a toxin and part of the smallpox genome.[52] Alternately, genetic engineering has already resulted in life-saving medications beginning with insulin production in E. coli through monoclonal antibodies, and biosensors for arsenic and other toxins. On the economic security side, synthesis of petrochemical replacements is proceeding via synthetic biology (energy security) and technology applications for synthetic biology may create new industries which cannot yet be specified.

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[52] Bhattacharjee Y. 2007. DNA synthesis. Gene-synthesis companies join forces to self-regulate. *Science* 22(316):5832-1682.

IV. "Synthetic Biology" Researchers with High Citation and Publication Counts

"Synthetic Biology" Researchers: High Citation Count

The following is a list of lead authors of the most highly cited papers published between 2005-2011 (October 2011) containing the term "Synthetic Biology" in the title, abstract, or keywords, according to SciVerse Scopus.[53]

> Glass JI (J Craig Venter Institute, U.S.A.); Benner SA (Foundation for Applied Molecular Evolution, U.S.A.); Andrianantoandro E (Princeton University, U.S.A.); Stricker J (University of California, San Diego, U.S.A.); Sprinzak D (California Institute of Technology, U.S.A.); Li JWH (University of Alberta, Canada); Bhattacharyya R (University of California, San Francisco, U.S.A.); Alper H (University of Texas at Austin, U.S.A.); Posfai G (Biological Research Center, Hungary); and Hung PJ (CellASIC Corporation, U.S.A.).

"Synthetic Biology" Researchers: High Publication Count

The following is a list of the most highly published authors between 2005-2011 (October 2011) containing the term "Synthetic Biology" in the title, abstract, or keywords, according to SciVerse Scopus.[54] The number of citations is indicated in parentheses.

> (23) Fussenegger M, University of Basel, Switzerland; (14) Weber W, Swiss Federal Institute of Technology Zurich, Switzerland; (14) Weiss R, Columbia University, U.S.A.; (14) Benner SA, Foundation for Applied Molecular Evolution, U.S.A.; (12) Collins JJ, Boston University, U.S.A.; (12) Jaramillo A, Ecole Polytechnique-Palaiseau, France; (11) Keasling JD, University of Missouri-Columbia, U.S.A.; (11) You L, Duke University, U.S.A.; (10) Zhang YHP, Virginia Tech, U.S.A.; and (10) Krasnogor N, Universita degli Studi di Catania, Italy.

V. Background/Historical Synopsis

Synthetic biology is a logical next step building on genetic engineering by attempting to make gene-encoding and gene-controlling DNA segments into building blocks to be used as a "parts" kit. The first example of commercially applied genetic engineering was the production of insulin by bacteria in 1979.[55] Subsequently, the molecular biology tools of DNA synthesis, sequencing, and replication were used for a variety of purposes from the production of enzymes for dying and for softening blue jeans (Genencor), to medicines (biotech and most pharma companies),[56] to bacteria for bioremediation. Beginning in 1989, the Human Genome Project spurred the

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[53] Methodology: SciVerse Scopus. Search term: TITLE-ABS-KEY="synthetic biology," 2005-October 2011, sorted by citation count. See references, below. Lead authors from the top 10 most cited publications are listed. This list may include more than 10 people when publications have an equivalent number of citations.

[54] Methodology: SciVerse Scopus. Search term: TITLE-ABS-KEY="synthetic biology," 2005-October 2011, sorted by publication count. The top 10 most published researchers are listed. This list may include more than 10 people when multiple researchers have equivalent numbers of publications.

[55] Goeddel DV, Kleid DG, Bolivar F, et al. 1979. Expression in Escherichia coli of chemically synthesized genes for human insulin. *Proceedings of the National Academy of Sciences of the United States of America* 76(1):106-110.

[56] Lee SY, Kim HU, Park JH, et al. 2009. Metabolic engineering of microorganizsms: general strategies and drug production. *Drug Discovery Today* 14(1-2):78-88.

evolution of faster and cheaper sequencing technologies; DNA synthesis technologies followed a similar path. Today, relatively long (1 kilobase pair) DNA sequences can be ordered commercially for <$0.35/base pair, compared to short sequences (30-50 bp) sequences at a cost of $25/bp 10 years ago. Similarly, sequencing costs have dropped from ~$0.25/bp to $0.00000317/bp.[57] Community labs and even garage labs are now relatively inexpensive to furnish with second-hand basic molecular biology equipment, thanks to the high level of churn within the biotech/pharma industry. In the late 1990s, scientists with engineering backgrounds such as Randy Rettberg began to view DNA segments as building blocks for making new things and have been pushing the field towards the goal with BioBricks and BioFab. Despite the hoopla surrounding the May 2010 publication by Gibson et al of an artificially synthesized 1.08 mbp M. mycoides genome,[58] the absence of fundamental understanding of control of gene and protein expression on a genome/organismal level poses a key impediment to the development of synthetic biology. From the physical engineering side, challenges remain to accurately assemble large numbers of DNA segments in the desired order, and once assembled, to faithfully replicate them.

VI. Future Options/Avenues of Exploration

While the full promise (and threat) of synthetic biology will require a deep understanding of networks, pathways, and chromatin structure and function, commercial applications will be enabled with intermediate stage tools such as the ability to co-express moderate numbers of proteins in bacteria. Today genetic engineering techniques are commonplace in the pharma/biotech and cleantech sectors which use individual gene scale approaches. Closer to synthetic biology, co-expression of multiple enzymes for production of biofuels, for example, is under way. Current levels of technology and equipment are also sufficient for biohackers and for potential bioterrorists to make bacteria that express particular proteins. Genome scale synthetic biology will require overcoming several barriers. While no single robust normative method has emerged for the concatenation and replication of large DNA segments, multiple techniques are being developed and tested.[59] Genome scale experiments in bacteria lie in the distant future, with genome scale experiments in eukaryotes even farther off due to the complexity of gene regulation in higher organisms. Synthetic biology on a designed genome scale will require large scale experiments and analysis to build foundational knowledge of control of gene expression. Today experiments are conducted on single genes or small numbers; robotics and software to allow larger scale explorations are in development. Some of the more provocative methods to circumvent the issues facing de novo design are partially directed genome scale mutation and selection[60] and the development of libraries of well-characterized DNA segments (so called BioBricks) to be used in the manner of Legos. The latter still suffers from the limitation of not knowing how multiple segments will interact both at the DNA level as well as protein expression levels. Research in the area of systems biology will eventually yield insights which may be

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[57] Baker M. 2011. " Synthetic genomes: The next step for the synthetic genome." *Nature* 473(7347):405-408.

[58] Gibson DG, Glass JI, Lartigue C, et al. 2010. "Creation of a bacterial cell controlled by a chemically synthesized genome." *Science* 329(5987):52-56.

[59] Ellis T, Adie T, Baldwin. 2011. "GSDNA Assembly for synthetic biology: from parts to pathways and beyond." *Integrative Biology* (Cambridge). February 8;3(2):109-118.

[60] Wang HH, Isaacs FJ, Carr PA, Sun ZZ, Xu G, Forest CR, Church GM. 2009. "Programming cells by multiplex genome engineering and accelerated evolution." *Nature* 460(7257):894-898.

applied to synthetic biology. However, systems biology is itself an emerging area and may lag behind our abilities in synthetic biology.

VII. Snapshot of Global Landscape

While true "synthetic biology" currently requires the scale and technical prowess embedded in conventional research labs (i.e., government funded), basic genetic engineering is rapidly becoming available to those outside the realm of large research labs via the DIY/ biohacker movement. For synthetic biology, while the United States (in particular MIT, Harvard, Stanford), is currently in a leadership position, ex-U.S. institutes are now on par with them (e.g., ICL, London), and the next generation of scientists is appearing throughout the world as evidenced by the origin of teams entering and winning the iGEM contest for undergraduates. From 2004-2010, countries of origin included Brazil, Peru, Columbia, Panama; Canada, the United States, and Mexico; China, Japan, Singapore, Australia, and New Zealand; South Africa, India; all Western European countries and some eastern European countries. The Grand Prize winning teams over the past five years have come from Slovenia (three times), Bejing, and Cambridge. To date, it appears that the DIY movement has nodes throughout North America and Europe, with a scattering of sites in Australia and New Zealand. It is unclear whether the movement will be able to spread into other parts of the world. Currently, the same infrastructure challenges that slow S&T generally in the developing world would also prevent the DIY movement from taking root there—poor roads, erratic mail delivery, limited electricity, access to the sequences available on the Internet, and so forth. Rather, scientists in those countries are likely to be working within universities where some of the challenges are addressed systemically. In countries where S&T are on the rise within political systems that tightly control access to information such as China, it would be surprising if a DIY movement could emerge as there would be significant impediments to self-organizing via the internet and to obtaining equipment and reagents without state detection. Both the evolution of synthetic biology worldwide and the promulgation of genetic engineering throughout western societies are worth monitoring. At the 5th annual Synthetic Biology conference held in June 2011 at Stanford (SB5.O, sponsored by the BioBricks Foundation), U.S. government representatives included Theresa Good (NSF), Alicia Jackson (DARPA), and Linda Chrisey (ONR). Previous meetings of SB were held in Berkeley (CA, U.S.A.), Hong Kong, and Zurich.

VIII. References

The following is a list of the most highly cited papers published between 2005-2011 (October 2011) containing the terms "Synthetic Biology" in the title, abstract, or keywords. The number of citations of each article is listed to the right.

- Glass JI, Assad-Garcia N, Alperovich N, et al. 2006. "Essential genes of a minimal bacterium." *Proceedings of the National Academy of Sciences of the United States of America* 103(2):425-430. 234 citations.
- Benner SA and Sismour AM. 2005. "Synthetic biology." *Nature Reviews Genetics* 6(7):533-543. 198 citations.
- Andrianantoandro E, Basu S, Karig DK, et al. 2006. "Synthetic biology: New engineering rules for an emerging discipline." *Molecular Systems Biology* 2, art no. msb4100073:2006.0028. 175 citations.

- Sprinzak D and Elowitz MB. 2005. “Reconstruction of genetic circuits.” *Nature* 438(7067):443-448. 160 citations.
- Stricker J, Cookson S, Bennett MR, et al. 2008. “A fast, robust and tunable synthetic gene oscillator.” *Nature* 456(7221):516-519. 160 citations.
- Li JW-H and Vederas JC. 2009. “Drug discovery and natural products: End of an era or an endless frontier?” *Science* 325(5937):161-165. 147 citations.
- Bhattacharyya RP, Remenyi A, Yeh BJ, et al. 2006. “Domains, motifs, and scaffolds: The role of modular interactions in the evolution and wiring of cell signaling circuits.” *Annual Review of Biochemistry* 75:655-680. 136 citations.
- Alper H, Fischer C, Nevoigt E, et al. 2005. “Tuning genetic control through promoter engineering.” *Proceedings of the National Academy of Sciences of the United States of America* 102(36):12678-12683. 123 citations.
- Posfai G, Plunkett III G., Feher T, et al. 2006. “Emergent properties of reduced-genome Escherichia coli.” *Science* 312(5776):1044-1046. 121 citations.

Appendix E

National Academies' Activities with Relevance to BGST

The following summarizes programs at the National Academies that BGST has worked with or intends to work with to bolster a collective understanding of global science and technology.

The **Computer Science and Telecommunications Board** (CSTB) focuses on the nexus between information technology and public policy. Its reports have addressed the major issues of the day related to information technology—from electronic voting to export controls, from health care informatics to cryptography. BGST worked with CSTB staff to develop its workshops in 2010 and 2011. Currently, CSTB staff is working closely with BGST to develop the fast-track study on a global assessment of the future of computing performance.

The **Board on Mathematical Sciences and Their Applications** (BMSA) has four current themes: the responsible and effective use of computational modeling, massive data, risk analysis and new directions for the mathematical sciences. BMSA has worked with BGST to develop the 2011 BGST workshop, "Realizing the Value from Big Data." The Board director, Scott Weidman, was the co-rapporteur for the report, *Steps Toward Large-Scale Data Integration in the Sciences: Summary of a Workshop*, a study that informed the 2011 workshop.

The mission of the **Board on Data Research and Information** (BRDI) "is to improve the stewardship, policy, and use of digital data and information for science and the broader society."[61] BRDI helped to identify participants of both workshops and BRDI's director, Paul Uhlir, helped to develop the surveys that BGST sent to participants of the Singapore meeting prior to the workshop. BRDI constitutes the U.S. representative to the Council on Data for Science and Technology, or CODATA. The mission of CODATA "is to strengthen international science for the benefit of society by promoting improved scientific and technical data management and use."

Due to its focus on energy supply and demand technologies and systems, BGST worked with the **Board on Energy and Environmental Sciences** (BEES) to identify participants for the 2011 workshop, "Data Analytics and the Smart Energy Grid 2020." Other subject areas of interest to BEES include the environmental consequences of energy-related activities; fuels production, energy conversion, transmission, and use; and related issues in national security and defense.

The National Academy of Science's **Kavli Frontiers of Science** symposia bring together outstanding young scientists to discuss advances and opportunities in a broad range of disciplines, including astronomy, astrophysics, atmospheric science, biology, biomedicine, chemistry, computer science, earth sciences, genetics, material sciences, mathematical sciences, neurosciences, pharmacology, and physics. Annual Kavli Frontiers symposia are held for young scientists in the U.S. and bilateral symposia have included young researchers in the United Kingdom, Germany, France, Japan, China, Indonesia, and India. Participants include leading researchers from academic, industrial, and federal laboratories.

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[61] See http://sites.nationalacademies.org/PGA/brdi/.

The Frontiers of Engineering[62] program brings together emerging engineering leaders (ages 30-45) from industry, academia, and government labs to discuss pioneering technical work and leading edge research in various engineering fields and industry sectors. The goal of these meetings is to introduce these outstanding engineers to each other, and to facilitate collaboration in engineering, the transfer of new techniques and approaches across fields, and establishment of contacts among the next generation of engineering leaders. There are four Frontiers of Engineering (FOE) meetings every year: the U.S. Frontiers of Engineering Symposium held each year and a rotating schedule of FOE meetings with Germany, Japan, India, China, and the European Union. Examples from past symposia include visualization for design and display, nanotechnology, advanced materials, robotics, simulation in manufacturing, energy and the environment, optics, intelligent transportation systems, MEMS, design research, bioengineering, counter-terrorism technologies, and quantum computing.

The Committee on Comparative National Innovation Policies: Best Practice for the 21st Century was established in 2005 by the Board on Science, Technology, and Economic Policy (STEP)[63] to compare U.S. innovation policies with selected innovation programs in other countries, particularly national technology development and innovation programs designed to support research on new technologies, enhance the commercial return on national research, and facilitate the production of globally competitive products. The study includes a review of the goals, concept, structure, operation, funding levels, and evaluation of foreign programs that are similar to major U.S. programs, e.g.,, innovation awards, S&T parks, and consortia. To date the committee has produced summaries of symposia on innovation in India, Belgium, Japan, China, and the United States, as well as a volume on S&T research parks. A final report will be issued in 2012.

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[62] For more information on the Frontiers of Engineering, see http://www.naefrontiers.org/.

[63] For more information on STEP, see http://sites.nationalacademies.org/PGA/step/.