

The Importance of Research Universities

**With Examples of their Functional Role
and Impacts Within the State of Indiana**



Prepared by: TEconomy Partners LLC

Prepared for: BioCrossroads

Report Authors: Simon Tripp, Ryan Helwig and Dylan Yetter

Each problem that I solved became a rule which served afterwards to solve other problems.

- Rene Descartes (1596-1650)
"Discours de la Methode"

Contents

Executive Summary	ES-1
Indiana’s Research Universities	ES-2
A History of Performance, But Challenges Ahead	ES-5
Recommendations for Indiana	ES-6
Chapter I: Introduction to the Report and the Role of the Research University.....	1
A. Introduction.....	1
B. The Importance of Research	1
C. Research as an Engine of the U.S. and Individual State Economies	5
D. The Structure and Function of Universities	7
E. Indiana’s Research Universities	8
F. Organization of this Report.....	10
Chapter II: Functional Impact Domains of Research Universities.....	11
A. The Functional Activities of Universities and Examples from Indiana	12
B. Research University Functions in Advanced Economic Development.....	28
Chapter III: Social/Private and Market/Non-Market Returns to Research Universities.....	33
A. The Structure of University Returns	33
B. Motivations and Drivers for Research at Research Universities and the Benefits Derived.....	37
Chapter IV: Research at Signature Research Universities	41
A. The Structure of Disciplines, Scientific Fields, and Domains of Inquiry	43
B. Pathways to Innovations: The Role of Diverse Areas of Research Resulting in Industries and Innovations	50
C. Indiana’s Research Universities: Areas of Research Specialization	53
Chapter V: University Life Sciences Research	63
A. Life Sciences: On the Frontlines of Scientific Advancement	65
B. The Indiana Life Sciences Research Environment	66
C. Research in Life Sciences: Examples and Case Studies	69
Chapter VI: The Changing Environment of Academic Research	77
A. Financial Challenges and Tensions.....	78
B. Communications Challenges and Tensions	80
C. Educational Challenges and Tensions.....	83
D. Political and Socio-Cultural Challenges and Tensions	86
E. Academic Structural Challenges and Tensions.....	89
F. Other Challenges and Tensions	90
G. Enhancing the Impacts of Research Universities in Indiana.....	92
Appendices	99



Prologue

Over the past few years, BioCrossroads has published a number of studies to better understand the factors that make Indiana so important in the life sciences, evaluating progress in terms of capital, workforce, and measures of innovation. The larger metrics are readily understood for this sector, a sector that provides one in every ten Hoosier jobs, 20 percent of all tax revenues, and several billions of dollars in annual R&D expenditures by our life sciences industrial partners. Our research universities—Indiana University, Purdue University and University of Notre Dame—each play an equally critical role conducting premier research, attracting signature talent, leveraging federal grant funding, and transacting licensing and technology transfer. Because the role of the research university is so multifaceted, we engaged TEconomy Partners to provide an overview and assessment of these functions, taking into account ongoing trends and to highlight observations that could become recommendations for further study and action.

To organize the many functions of the research universities, we divided the framework of this report into four major areas: knowledge expansion and innovation; economic development; the enhanced capabilities of human capital; and societal well-being and quality of life. TEconomy conducted interviews with representatives of the universities, augmented by data sourced from Bureau of Labor Statistics, Indiana's Department of Workforce Development, U.S. Department of Education, and the Association of University Technology Managers, among others, as well as articles appearing in *The Economist*, *Nature*, *The Times*, and *US News and World Reports*, and published studies including those by Lynne Zucker and Michael Darby, the National Research Council, National Science Foundation, and many others. Assembling these data within the context of national and global trends impacting research, the report includes authoritative and timely observations for further study and action.

The report's findings are significant. And they remind us that not only are these institutions grounded and linked to our earliest days as a state, but also, they represent critical components within our economic ecosystem to produce talent, anchor our communities, and participate in innovation for the future prosperity of Indiana, and indeed, our country. With an annual combined enrollment of 132,000 in 2016, it is not surprising that in aggregate, the living alumni base for all Indiana research universities now exceeds 1.44 million persons—a figure equivalent to 1 in every 5 Hoosiers, or one to fill every seat at the Indianapolis Motor Speedway 3.5 times over. Their annual research expenditures total almost \$1.3 billion and they operate eight research parks across our state. From Purdue's agricultural extension services to Indiana University's excellence in music and the arts and Notre Dame's focus on service—each university interacts with the state and their surrounding communities in ways both large and small. Even so, they also operate on a world-stage, and each is recognized within the top 150 best institutions in the world, and boasts alumni and faculty who have achieved the highest recognition, including members of the National Academy of Sciences, World Food Prize recipients, and Nobel Prize winners.

These research institutions are vital and dynamic contributors and represent cornerstones of our state's identity and its economy—yet, enhancements can be made. This report identified five areas for further review and activity while recognizing that no single metric or measure of performance can capture the impact of Indiana's research universities. These areas include: improving external federal research funding competitiveness; enhancing university connectivity to collaborative commercial research opportunities; leveraging universities and other institutional anchors for talent attraction and retention; improving performance on key technology transfer metrics; and exploring new collaborative opportunities for research universities and industry that draw more on dominant areas of research strengths shared

across the universities. In fact, there are already programs underway to address these areas. From the launch of the Indiana Biosciences Research Institute, which connects our world-leading life sciences corporate community to our research universities and includes funding from the State of Indiana, to the recently announced \$52 million partnership between Eli Lilly and Company and Purdue, to the recent grant from Lilly Endowment to Indiana University to attract and retain talent at the Medical School, to the University of Notre Dame's decision to establish and recruit a Vice Provost for Innovation and double the size of its incubation facilities for start-ups, each of these developments underscores the commitment of our stakeholders and their willingness to work together. But over the long term, we will need to continue to do more. Our state has celebrated its first 200 years, and now our universities are preparing it for the next 200.

This report is important and timely. And certainly, it is appropriate here to thank those whose efforts have made it possible: through a generous grant to the CICP Foundation on behalf of BioCrossroads, the Lilly Endowment provided the essential funding; the many members of Indiana's research universities who contributed information and participated in interviews; my colleague Nora Doherty, who led this project for BioCrossroads; and our consultants at TEconomy Partners, who know both Indiana and the life sciences sector well, and have drawn on their substantial expertise to provide a helpful and comprehensive study.

Sincerely,

A handwritten signature in black ink, appearing to read "David L. Johnson". The signature is fluid and cursive, with a large initial "D" and "J".

David L. Johnson

President and CEO, BioCrossroads

September 2017



300 North Meridian Street, Suite 950
Indianapolis, IN 46204

By:

TEconomy Partners, LLC

Simon Tripp, *Principal and Senior Director*
Ryan Helwig, *Principal and Project Director*
Dylan Yetter, *Research Analyst*

BioCrossroads

David Johnson, *President and CEO*
Nora Doherty, *Vice President*

With thanks to:

Indiana University

Bill Stephan, *VP Engagement*
Jay Hess, *Dean of the School of Medicine and VP for University Clinical Affairs*
Fred Cate, *VP for Research*

Purdue University

Marietta Harrison, *Special Advisor, Strategic Initiatives*
Suresh Garimella, *Exec. VP for Research and Partnerships*
Jeff Bolin, *Assoc. VP for Research*
David McKinnis, *Special Advisor, Office of Corporate and Global Partnerships*
Bo Beaulieu, *Director, Purdue Center for Regional Development, Assistant Director, Extension Community Development Program*
Vic Lechtenberg, *retired, Professor, Dean of Agriculture, Vice Provost for Engagement, Director Center for Regional Development*
Cynthia Sequin, *Assistant Vice President, Marketing and Communications for Purdue Research Foundation and Purdue Research Park*

University of Notre Dame

Tom Burish, *Provost*
Bob Bernhardt, *VP for Research*
Bryan Ritchie, *VP and Associate Provost for Innovation*
Mary Galvin, *Dean of Science*
Peter Kilpatrick, *Dean of Engineering*
John Affleck-Graves, *Executive VP*

Supported by a grant from:

Lilly Endowment Inc.

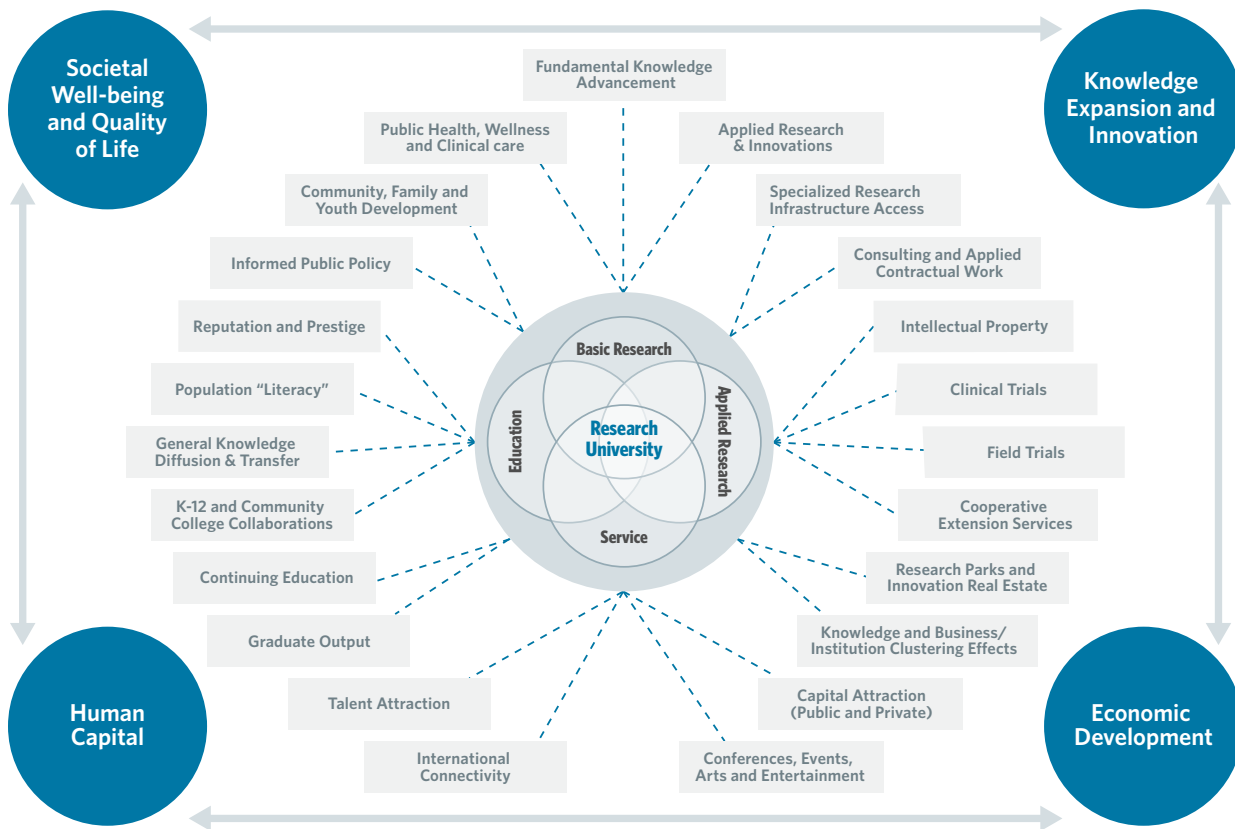
Executive Summary

There are so many reasons to take pride in the United States – our freedoms, our democracy, and our economic leadership among them. In addition to these, and contributing to them, one of the most notable points-of-pride is the U.S. portfolio of world-class academic institutions, with our nation dominating the global rankings of top universities. Indeed, although the U.S. is home to only 4.3% of the world’s population, 43% of the world’s top 100 universities¹ are located in the U.S. America’s signature research universities are a national asset of great historic and current significance and, as discussed herein, in the future their importance will come even more to the forefront in our increasingly knowledge-driven, innovation-based economy.

The crucial role research universities play in advancing society and the economy is wide-ranging — in Indiana, as well as nationwide. It is therefore highly important for national and state leaders to have a thorough and shared understanding of the functional benefits generated by these institutions. Research universities provide diverse benefits that are distributed across two dozen functional impact areas (Figure ES-1) that positively influence four primary impact domains:

- Knowledge expansion and innovation
- Economic development
- Enhanced capabilities of human capital
- Societal well-being and quality of life.

Figure ES-1: The Functional Impacts of Research Universities



Source: TEconomy Partners, LLC.

¹ Average number of US universities (43) in the top 100 calculated as the average of the rankings from four leading world university ranking systems: QS ranking U.S. = 32 of top 100; Times ranking U.S. = 41 of top 100; US News ranking U.S. = 51 of top 100; Shanghai ranking U.S. = 49 of top 100.

This report examines the role of research universities and their contribution to the American R&D ecosystem. Specific illustrative examples from Indiana’s research universities underscore the multi-faceted activities and impacts that research universities bring as unique drivers of innovation and regional prosperity.

It is evident that the future of the United States (and Indiana) is very much tied to the performance of a complex research ecosystem – one in which research universities serve a series of unique and crucial functions. In turn, these functions provide robust returns across social and private dimensions, and market and non-market dimensions that justify both public and private investment in American research universities.

Indiana’s Research Universities

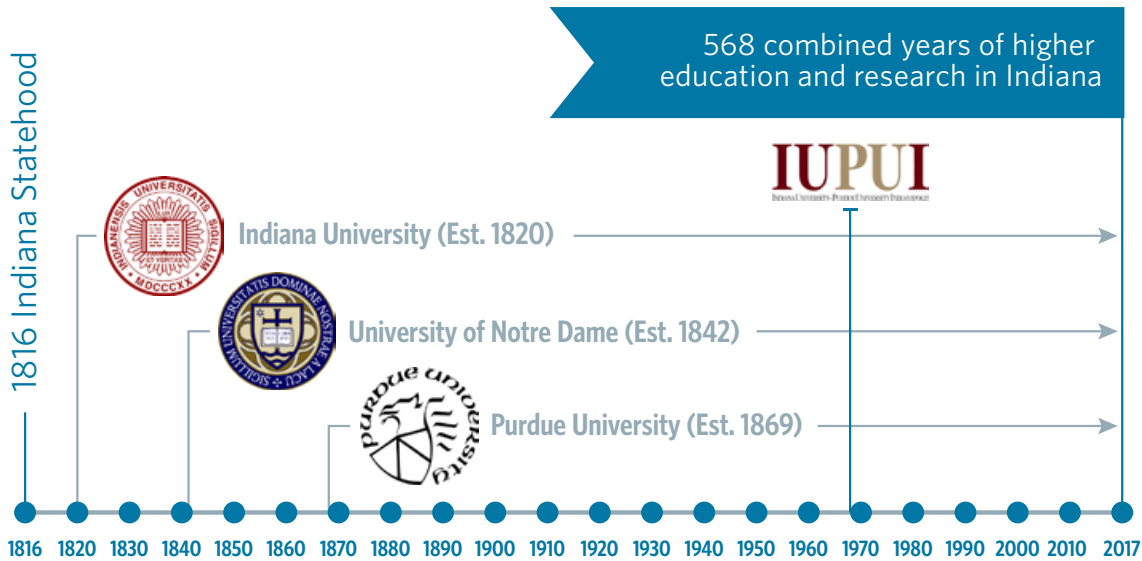
Indiana is well-served by its prestigious and high-performing research universities: Indiana University, Purdue University, and the University of Notre Dame. Spanning the full spectrum of basic and applied inquiry, these institutions demonstrate a substantial diversity of quantifiable areas of specialized research focus. Multiple fields in physical sciences (especially physics and chemistry), life sciences (fundamental, biomedical, and agricultural), formal sciences (mathematics and logic), and engineering represent particularly notable and sizeable areas of comparative strength in Indiana research output. This diversity of research competencies holds promise for advancement in Indiana not only along individual disciplinary lines, but also for advancing modern transdisciplinary approaches to complex challenges and opportunities.

As shown on Figure ES-2, Indiana’s major research universities have contributed to Indiana’s society and economy from the state’s earliest beginnings.

Academic Research and the R&D Ecosystem

- Public and private research, and university and industry research do not exist in separate vacuums. Rather, they are each part of a complementary, holistic research ecosystem that achieves results for the economy, for society, and for individuals through robust symbiotic relationships and knowledge interactions.
- Policymakers, research funders, research organizations, and other key stakeholders must recognize that all parts of the ecosystem serve a function, and that emphasizing one type of research performing entity or one type of research (such as applied over basic) at the expense of another has the potential to create a destructive imbalance in the system.
- The nature of academic research is evolving. Academic disciplines form the foundation of the research ecosystem in terms of thematically bounded fields-of study. While this disciplinary model has served society well, the complexity of science, and an expanding recognition of the complexity of grand challenges and the frontiers of science are producing an increasing emphasis towards transdisciplinary, team-science oriented research.
- The increasing complexity of the frontiers of research particularly favors major research universities, as they have the diversity of disciplines, skills, perspectives, and facilities to undertake transdisciplinary inquiry.
- The concept of an R&D ecosystem, with disciplinary interactions and transdisciplinarity as an emerging theme, is important to understand in terms of both societal and economic development. Particularly from the latter perspective, technologies, useful commercial products, and innovations in commercial practices and other human endeavors rarely, if ever, form solely out of the work of one company or individual innovator (even though that may seem to be the case). Rather, as shown in this report, they are the result of the integration of previous fundamental and applied research and knowledge advancements. Therefore, attention must be paid to the entire system (the research ecosystem) that supports and enables innovation, knowledge expansion, and knowledge exchange.

Figure ES-2: Indiana's Research Universities



Source: TEconomy Partners, LLC.

The impact of these three Indiana universities extends across the full range of functional impact domains shown in Figure ES-1, and multiple examples are highlighted throughout the report.

Indiana's Research Universities: Highlights in Perspective

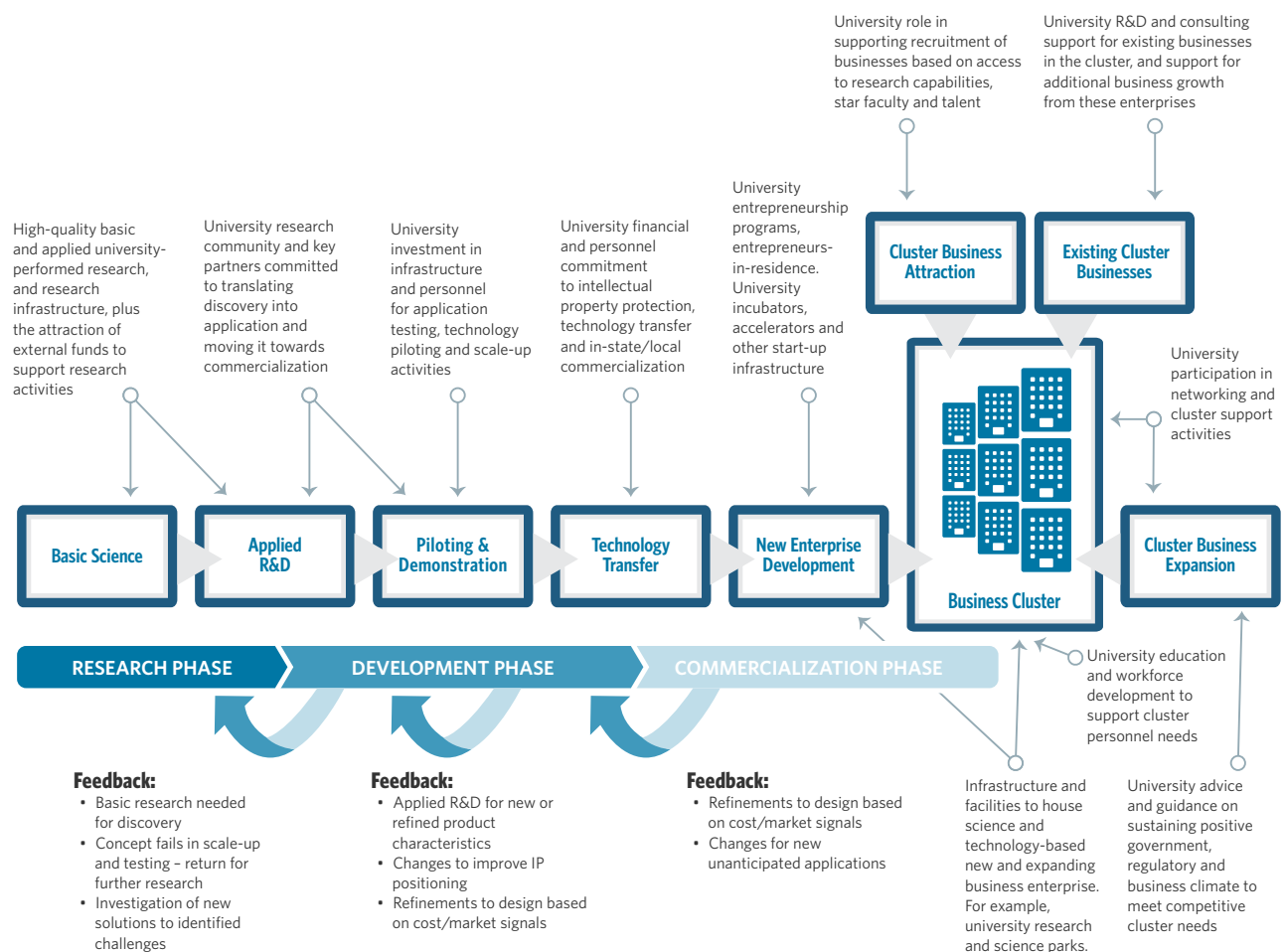
- The Times "World University Rankings" ranks 980 leading universities world-wide across teaching, research, international outlook, reputation, and more. All of Indiana's major research universities rank in the top 150 (the top quintile).
- Twenty Nobel Prize winners have been associated with Indiana's research universities, either as long-term faculty, temporary faculty or post-docs, or as students. The universities are home to 73 faculty that have been elected to the National Academies of Sciences, Engineering, or Medicine, considered one of the highest professional honors. Purdue University has been affiliated with three recipients of the prestigious World Food Prize. Compared with neighboring states including Illinois, Michigan, and Ohio, Indiana's concentrations of what might be referred to as "star talent" within its research universities are competitive. Relative to its base of research expenditures, Indiana has a slightly higher concentration of Nobel Laureates compared with Ohio and Michigan though these three states are well below Illinois' concentration given the large number of Nobel Prize recipients from the University of Chicago. Indiana's concentration of National Academies Members lies in the middle of this group, essentially the same as for Michigan, above Ohio, though behind Illinois.
- For the fall of 2016, the universities' combined enrollment exceeded 132,000 – enough to fill every seat in Lucas Oil Stadium (which holds 70,000 people) almost two times over.
- The research expenditures of Purdue University (\$558.6 million), Indiana University (\$544.2 million), and Notre Dame (\$191 million) total almost \$1.3 billion. Combined, these direct research expenditures exceed the direct annual economic impact of the Indianapolis Motor Speedway on the state by more than four times. Total academic research expenditures in Indiana are well below those for some of its neighbors, with Illinois, Michigan, and Ohio universities each exceeding \$2 billion in spending annually. However, on a per capita basis, Indiana's levels of research are much more competitive. Indiana's academic R&D spending reached \$200 per resident in 2015, lower than for Michigan (\$235 per resident), but exceeding that for Illinois and Ohio, which both measured \$186.
- Between 2012 and 2016, Indiana institutions produced 59,115 academic publications. Led by Purdue University (22,704 publications) and Indiana University (21,217 publications) almost equally, Indiana institutions produced 2.9% of all U.S. academic publications despite the state comprising only 2.1% of the total U.S. population. Indiana is clearly "punching above its weight" in terms of its academic research output.
- Compared to all U.S. universities, Purdue University ranks in the top quintile in U.S. invention disclosures, patents issued, and start-up companies formed per \$10 million in research expenditures.
- Indiana's research universities operate eight research parks across the state of Indiana and are each engaged in the new 16 Tech innovation district development in Indianapolis.

Indiana's Research Universities: Highlights in Perspective (cont.)

- A key destination for visitors, Indiana University contributes to tourism being the third largest industry in the region, employing 4,000 personnel and hosting over 3 million visitors per year.
- In the most recent year, Purdue's statewide Extension service had 323,500 direct contacts with those it serves, and provided 11,524 structured educational programming events. The online information resources of Extension were accessed over 31 million times at the Purdue Extension website.
- The universities are proactive in reaching out to enhance the pre-college education and engagement for Indiana's youth. For example, IU offers 69 different pre-college programs, and Purdue and Notre Dame are likewise engaged in similar activities. In both rural and urban settings, Purdue's 4-H programming reached over 61,000 youth in the most recent year via 4-H club programs across the state.
- The living alumni base of Indiana's signature research universities exceeds 1.44 million, or enough to fill the entire Indianapolis Motor Speedway 3.5 times.

Indiana's research universities play a very important role in the state's economic development, especially in the highly competitive arena of science-based and technology-based economic development. The functional benefits of the universities to Indiana's economic development extend across the full spectrum of the economic development ecosystem in the state, as shown in Figure ES-3:

Figure ES-3: The Modern Economic Development Ecosystem and the Integral Role of Indiana's Research Universities



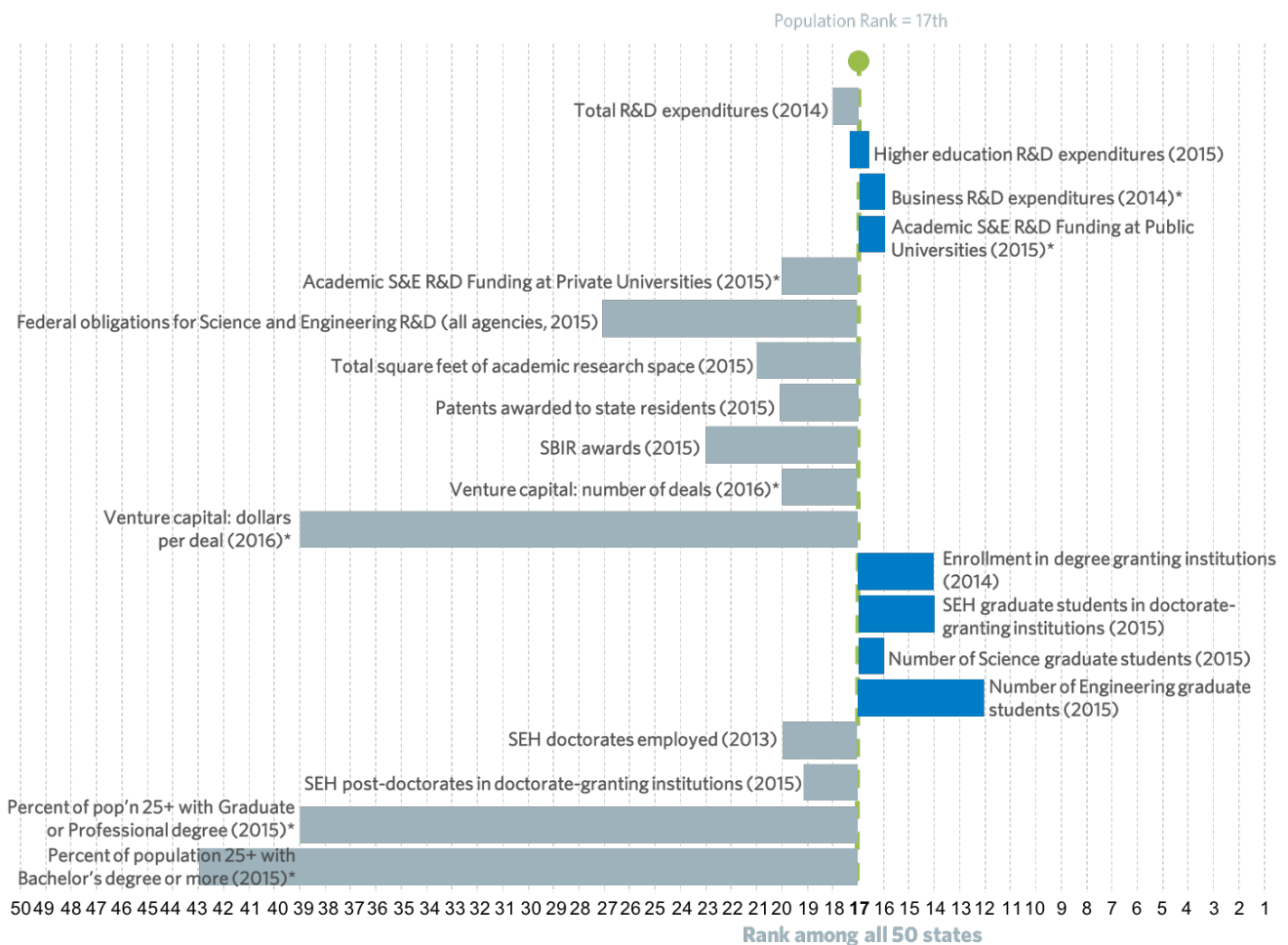
Long-term, sustained university commitment to R&D and to providing key support for activities across the technology-based economic development ecosystem

Source: TEconomy Partners, LLC

While Indiana’s signature research universities have a diverse and far-reaching impact across the socioeconomic spectrum in the state, it would be a mistake to conclude that such impacts cannot be enhanced further or improvements made to the higher-education, university-driven research ecosystem in the state of Indiana. Considerable room exists for improving the relative performance of the universities across a range of metrics.

Figure ES-4 provides a dashboard of 19 metrics largely, but not exclusively, drawn from published National Science Foundation statistics. To illustrate Indiana’s relative position, the green-dashed vertical line sets a baseline position for Indiana in terms of its rank in population among states (17th). Each metric used is itself a rank for Indiana on that metric, and shows that on 12 of the 19 metrics, Indiana is underperforming relative to its population rank.

Figure ES-4: Academic R&D and Associated Metrics for Indiana



Source: National Science Foundation except for those marked * which are sourced from <http://www.stats.indiana.edu/sip/>

In terms of total higher education R&D expenditures, at 17th, Indiana is right where the state rank would suggest it should be, and the state is moderately outperforming its expected rank in terms of both business R&D and academic science, and engineering R&D funding at public universities. Enrollment in Indiana higher education institutions is also a strong point with Indiana well ranked in:

- Number of engineering graduate students (12th)
- Total enrollment in degree granting institutions (14th)

- Science, engineering, and health graduate students in doctorate-granting institutions (14th)
- Number of science graduate students (16th).

However, across Indiana's relative performance on all other measures, issues can be seen. While Indiana higher education institutions are enrolling a larger than expected number of students (especially in STEM disciplines), as a whole, actual higher education attainment figures for the Indiana population are low. The state ranks 43rd in the percent of the population with a Bachelor's degree or higher, and 39th for percent of population with a graduate or professional degree.

Indiana is also underperforming in attracting its fair-share of important federal funding for science and engineering R&D (ranking 27th), and probably related to this is a similar underperformance in terms of innovation output and certain surrogate commercialization metrics (such as in SBIR and Venture Capital awards). In terms of patents (a proxy measure for innovation), Indiana is ranked 20th; it is 23rd in SBIR awards; and 20th in number of VC deals (and these VC funding events are funded low in comparison to other states, with Indiana ranked 39th in VC dollars per deal).

Life Sciences at Indiana's Research Universities

In terms of expanding the frontiers of science, technology, and new knowledge generation, analysis on the speculation of new academic journals illustrates that life sciences are the leader by a considerable margin. 73% (almost three out of every four) of new journals created globally are in areas classified as life sciences. Among these, medicine and health lead the pack followed by agriculture and environmental/natural resource sciences.

In terms of university R&D across the U.S., life sciences research is the largest macro-level field, and with almost \$603 million in research expenditures, Indiana has a considerable volume of research being undertaken in life sciences. At 46% of total R&D spending, life sciences represent a very important area of focus for university research in Indiana. This share of life sciences research in Indiana, however, is below the national average of 58%. Balancing this below-average research expenditure share, Indiana's research universities are more concentrated in their R&D activities in engineering (21% vs. 16% nationally), physical sciences (8% vs. 7%), computer science (4% vs. 3%), and social sciences (6% vs. 3%).

Further, life sciences research in Indiana has a rich history, with multiple groundbreaking discoveries recognized globally for their impact (and highlighted herein), including the role of researchers at Indiana University in curing testicular cancer; Purdue-developed Striga resistant sorghum varieties have been transformational for African farmers and their communities; and Purdue's foundational work in the development of next-generation biofuels. A strong legacy of life science impacts continues in Indiana across the basic and applied spectrum of university research and in diverse domains spanning human biomedical, veterinary, agricultural, and industrial applications of life sciences. It should be noted, however, that life sciences do not stand on their own - they are supported by and intersect with physical sciences, formal sciences, social sciences, and applied research in engineering, data sciences, and other disciplines. In other words, life science progress benefits from having robust core competencies in Indiana across a diverse base of academic disciplines and fields of inquiry. TEconomy's analysis of research publications and their relative concentrations in Indiana by field, and irrespective of a specific research university, revealed notable areas of research strengths in physics—including contributions across seven specialized sub-disciplines and major participation by all of the research universities—and in engineering, primarily at Purdue. Coupled with the aforementioned R&D expenditure activity and strengths in these diverse discipline, these findings highlight the opportunities for collaborations with and in the life sciences to leverage additional science and engineering strengths for transdisciplinary life science innovation involving physics and engineering (including for medical device innovation), computer sciences (including bioinformatics), analytical chemistry, and others.

A History of Performance, But Challenges Ahead

While research universities represent individual communities of faculty and research professionals with extremely broad skills and interests, they work within a research ecosystem that is very much influenced by funding and the priorities of external funding agencies. As such, funding organizations wield great influence over the system in terms of sustaining it economically, but also in terms of acting somewhat as a rudder steering the ship. Without sustained commitment to research and research funding (including the full spectrum of basic and applied/translational research inquiry) by public sources as well as private, it is evident that the fuel tank for the U.S. knowledge economy, and the economies of individual states such as Indiana, would slowly be drained.

In the face of growing global competition in research, and in the competition for the skilled human-capital that powers research, the United States is starting to backslide. For various reasons, investment in research is being constrained, and the net effect will be a diminution of the comparative performance of American social and economic systems. In “Rising Above the Gathering Storm, Revisited” (2010) the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine collectively examined, in depth, what is at risk by allowing an erosion of research and higher education to occur in the U.S. TEconomy’s work leads us to concur with the Rising Above the Gathering Storm Committee when they concluded:

In the face of so many daunting near-term challenges, U.S. government and industry are letting the crucial strategic issues of U.S. competitiveness slip below the surface... Without a renewed effort to bolster the foundations of our competitiveness, we can expect to lose our privileged position. [Over five years] the unanimous view of the authors is that our nation’s outlook has worsened [and is at] a tipping point. Addressing America’s competitiveness challenge will require many years if not decades; however, the requisite federal funding of much of that effort is about to terminate. “Rising Above the Gathering Storm, Revisited” is a wake-up call. To reverse the foreboding outlook will require a sustained commitment by both individual citizens and government officials—at all levels.

TEconomy notes that while it may seem that research universities are stable institutions (part of an institutional structure and tradition dating back centuries), the pace of change in today’s society and economy, and in technologies and global competition, is creating tidal forces that will impact the future of U.S. research universities. The double threats posed by reductions in both federal and state level funding for research universities, working in concert with increasing levels of investment by our global competition, undermine our ability to maintain our preeminent status.

Recommendations for Indiana

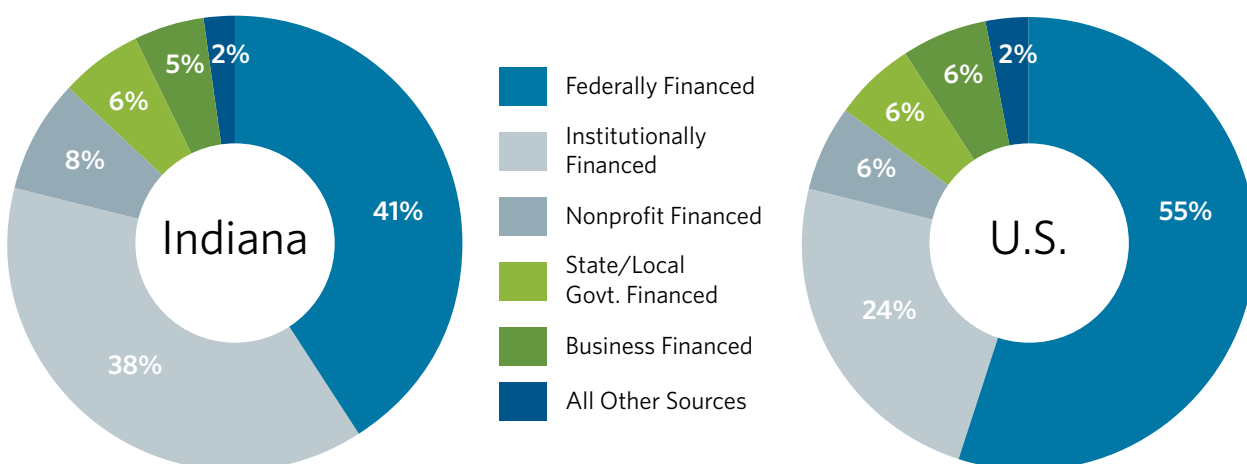
Across the societal fabric and economy of the state, Indiana’s signature research universities have diverse and far-reaching impacts. However, it would be a mistake to conclude that such impacts cannot be enhanced further or improvements made in support of Indiana’s higher-education, university-driven research ecosystem.

While this report is focused primarily on an assessment of the impact of research universities within the state of Indiana, the findings of this project do lead to some preliminary recommendations for consideration and additional study. These recommendations are primarily focused towards:

- **Improving external federal research funding competitiveness.** In 2015, federal research funding, as a share of all R&D funding sources at Indiana’s research universities, comprised 41% of total university research, compared with 55% as the national average (Figure ES-5). Indiana universities are relying more on “institutional funding” (such as endowment funds, gifts, and cross-subsidization from clinical revenues) as a source for R&D activities, while other sources of funding are generally in line with national average shares. Overall, in terms of federal obligations for science and engineering R&D (ranked 27th), the higher education community in Indiana is underperforming relative to the State’s population rank (17th). Indiana’s lagging performance in capturing federal

research funding is worth examining in greater depth, and will be studied further to better understand funding flows and the dynamics behind why this is occurring.

Figure ES-5: Sources of Funding for University R&D Expenditures, Indiana vs. U.S., 2015



Source: National Science Foundation, Higher Education Research and Development Survey.

- Enhancing university connectivity to collaborative commercial research opportunities.** At U.S. universities, business financed research comprises 6% of R&D funding, whereas in Indiana, it stands somewhat lower at 5%. While currently a relatively minor component of university research funding in the U.S., the opportunity to engage with industry more can have significant research dollars attached to it. The move towards more “open innovation”, reductions in industries’ internal R&D initiatives, and the high degree of complexity in advanced technological R&D (which often requires transdisciplinary expertise to advance) each represent trends favoring more contract research and collaborative industry/university research engagement. In July 2017, Eli Lilly and Company announced a \$52 million; 5-year strategic research collaboration with Purdue University that dramatically illustrates the significant opportunities for enhanced research funding that may come via industry engagement.
- Better leveraging research universities and other institutional anchors for talent attraction and retention.** Current, multi-faceted efforts to attract top talent to Indiana, which include a newly established research anchor (Indiana Bioscience Research Institute); a major strategic place making effort (16 Tech); and targeted investments in both talent recruitment and development, must continue and should, in fact, be advanced further. In addition, economic development in the state needs to focus on development and attraction of enterprise with a high demand for university graduates. Currently the state’s workforce ranks 43rd in “percent of population 25+ with Bachelor’s degree or more” and 39th in “percent of population 25+ with Graduate or Professional degree”, despite ranking 17th in terms of population among the 50 states.
- Improving performance in intellectual property and technology commercialization.** There is considerable variability in recent performance of Indiana’s research universities across five key measures tracked by the Association of University Technology Managers (AUTM, Table ES-1). In terms of U.S. invention disclosures, patents issued, and start-ups formed per \$10 million in research expenditures, Purdue University performs well, ranking in the top quintile of U.S. universities. On these same metrics, Indiana University is generally in the third quintile, while Notre Dame’s ranking ranges between the second and fourth quintiles depending on metric.

Table ES-1: Intellectual Property and Technology Transfer at Indiana’s Research Universities by Quintile, 2015

	Licenses Executed per Patent	per \$10M in Research Expenditures				
		Licenses Executed	Licensing Income	Invention Disclosures	U.S. Patents Issued	Start-Ups Formed
Indiana University	4th	4th	2nd	3rd	3rd	4th
Purdue University	5th	5th	3rd	1st	1st	1st
Univ. of Notre Dame	4th	3rd	4th	3rd	2nd	4th

Source: TEconomy analysis of AUTM survey data.

- Exploring new collaborative opportunities for Indiana’s research universities and industry** that draw more heavily on dominant areas of research strengths that are shared across the universities in fields such as physics, chemistry, computer science and mathematics (in combination with robust strengths in engineering and life sciences). Drawing upon the capabilities of multiple institutions (both shared and complementary), and multiple disciplines, could lead to unique combinations of competencies enabling the pursuit of novel innovations in inherently transdisciplinary areas such as bioinformatics, precision agriculture, functional imaging, medical devices and cyber-physical systems.
- Recognizing that no single metric or measures of performance can capture the impact of Indiana’s research universities**, and that rather their full range of multifaceted impacts on Indiana’s societal and economic well-being (as shown on Figure ES-1) should be consistently communicated, considered and celebrated. This will assure the work of the universities is always recognized in a holistic context.

The data and position of Indiana presented in Figure ES-4 also suggest that the state of Indiana needs to concentrate on building its technology-based economic development profile to increase its base of innovative tech companies (through new business start-ups, expansions and business attraction) to provide higher demand for personnel with higher education credentials. Relative to the size of the state, Indiana’s current population is relatively under-educated – yet the university systems see relatively robust enrollment in STEM disciplines. These data suggest that the current make-up of the Indiana economy presents relatively limited opportunities for baccalaureate graduates, including those in STEM disciplines, and many of those educated from Indiana’s signature research universities are leaving the state to find employment commensurate with their qualifications elsewhere.

Chapter I: Introduction to the Report and the Role of the Research University

A. Introduction

In this report, we will discuss the services universities provide to society. In particular, the report will examine the role of research universities and their contribution to the socioeconomic, R&D-powered ecosystem in the U.S. Using Indiana's research universities as the basis of in-depth discussion, this report seeks to:

- Explain university research in the context of the full-range of functions served by universities in modern society, emphasizing that research is one component, albeit a critically important one, in the multi-faceted mission of our leading higher education institutions;
- Profile the structure of modern university-based research, academic disciplines, and the expanding importance of transdisciplinary inquiry;
- Elucidate the functional benefits of the university and of university research in terms of both private and social returns – both monetary and non-monetary;
- Discuss the changing environment for university research funding and structural changes taking place in academe resulting from technological, political, and societal trends;
- Spur a mutual understanding and appreciation of the importance of Indiana's universities and university-based research in all its forms among policy makers, university officials and faculty, economic developers, students, research funders, commercial enterprise, and other key economic and societal stakeholders.

We find that the future of Indiana (and the United States) is very much tied to the performance of a complex research ecosystem – an ecosystem in which research universities serve a series of unique and absolutely crucial functions. Further, we find that Indiana is well-served by its prestigious and high-performing research universities. In considering the future, we also find that elements of the research ecosystem are threatened by external forces and trends that risk eroding the foundations of American research leadership – and that research universities must be provided with strategic support and assistance to ensure they continue to provide a robust competitive advantage for democratic, social, and economic progress.

B. The Importance of Research

Through the applied curiosity of humankind, society has advanced. Inquisitive by nature, our human desire to “know”, “to explain”, and to “understand” has given rise to inquiry ranging from simple childhood questions to the formal structure of academic disciplines and great institutions designed to further the pursuit of discovery and knowledge.

While humans as a species are inquisitive, it is not a universal-given that human society will leverage this natural inquisitiveness to advance our species beyond relatively primitive states. In selected spatial pockets across the globe –the Amazon, the Sahel, and New Guinea for example, there are places where societal and technological progress has arrested in its earliest forms. However, where education and the pursuit of knowledge have been formalized in societal structures, the true potential for human curiosity and ingenuity has been advanced. While formal knowledge pursuit is recorded in the history of most global civilizations (for example, ancient China, the Middle East, Greece, and Rome), the formalization within an institutionalized community of a “university” is a European invention. Generally accepted as the first university,

Where education and the pursuit of knowledge have been formalized in societal structures, the true potential for human curiosity and ingenuity has been advanced.

the University of Bologna in Italy was founded in 1088, and the word “university” is derived from the Latin “*universitas*”, meaning a number of persons (masters and their apprentices) associated into one body such as a society, company, or guild. “*Universitas*” was originally employed to denote any community or corporation regarded under its

collective aspect.”² As these institutions became more formalized as a home of exclusively academic scholarship and instruction, the name university began to specifically denote a body devoted to learning and education. As noted by the Encyclopedia Britannica, “in the course of time, probably towards the latter part of the 14th century, the term began to be used by itself, with the exclusive meaning of a community of teachers and scholars whose corporate existence had been recognized and sanctioned by civil or ecclesiastical authority or by both.”³

Since their early establishment, research has been a component of the work of universities. The term research (which is derived from the Middle French “*recherche*”, which translates as “to go about seeking”) first appears in common use in the late 1500’s, and we now benefit from considerably more than a half-millennium of the structured and formalized pursuit of research and scholarship in the western tradition. Globally, this university structure has become the de facto norm for an institution in which advanced research and higher education combine. However, the university is not, of course, the only environment in which formal research occurs. For example, research is also undertaken in commercial enterprise, within government national laboratories, and within free-standing research institutes. The university is, however, a unique community in which research and higher education combine. And thus, universities are not only performers of research, but serve as the crucially important training ground for researchers moving into all other research-performing organizations.

Research is obviously important because it increases the stock of human knowledge upon which economic, social, and technological progress depends. Today, research-based knowledge has become the driving force of national progress in what is often termed the “knowledge economy”, but in actuality, research is the glue that ties society and the economy together, and underpins almost all productive human activity. If we consider most any significant aspect of our economy or society, the role of research in empowering functionality and progress is clearly evident – for example in:

What is “Research?”

The Merriam-Webster Dictionary defines research as:

1: *careful or diligent search*

2: *studious inquiry or examination; especially:*

investigation or experimentation aimed at the discovery and interpretation of facts, revision of accepted theories or laws in the light of new facts, or practical application of such new or revised theories or laws

3: *the collecting of information about a particular subject.*

² *Encyclopedia Britannica, Eleventh (Public Domain) Edition*

³ *Ibid*

- **Agriculture** - where research produces high yield crops, crop protection technologies, precision agricultural equipment, livestock veterinary medicines, and downstream value-added processing technologies.

- **Healthcare** - where research brings us new medicines, diagnostics, medical devices, vaccines, and other tools that have dramatically increased average human longevity.

- **Manufacturing** - where automated process controls, robotics, inventory management systems, logistics systems, computer-aided design (and now additive manufacturing) have transformed the factory floor.

- **Finance** - where advanced analytical techniques, financial models, computer-based trading, actuarial systems, and other specialized tools and systems are applied to model, control, and facilitate the movement and momentum of wealth.

- **Governance** - where research in social sciences, political science, law, economics and other fields provides the knowledge required to inform and drive policies, regulations, management of the economy, and law and order in a civil society.

Total education spending in the U.S. comprised 6.1% of GDP in 2013 (\$1.02 trillion). Higher education spending comprised 2.6% of GDP (\$0.43 trillion), or 42.6% of total education spending in 2013.

OECD, Education at a Glance 2016

CONCLUSION: Research increases the stock of human knowledge upon which economic, social and technological progress depends. Research-based knowledge has become the driving force of national progress in the “knowledge economy”, but it is broader than that - serving to underpin almost all productive human activity.

As evidenced in the above examples, research may also produce both private and social returns. Research that leads to better governance, rule of law, improved public health, enhanced food security, etc. is providing social returns. Research generating a patented technology, improving the productivity of a production process, or developing a new financial instrument provides private returns to those inventing and using the research-based tool or knowledge for monetary or personal gain. In many cases, research leads to both forms of return at the same time. For example, the development of a vaccine for an infectious disease provides private monetary returns to the vaccine developer and social returns through enhanced public health. Research on research itself finds that both types of returns motivate investment in research, and that the rate of social return to R&D exceeds the rate of private return (although both are strong).⁴ Despite our large national investment in research, analysis shows that “a conservative estimate indicates that optimal investment in research is more than four times actual investment.”⁵

The robust levels of social return on research underpin the core rationale for public investment in research. Indeed, without public support for university-based research, a wide-ranging and important suite of research topics would go unaddressed. This goes to the root of a second distinction in examining returns to research – that of market versus non-market returns. Research may produce one, or the other, or both, and this condition may vary over time. Consider the following example:

Market and Non-Market Returns to Research: The Laser Example

With his paper on the photoelectric effect, Albert Einstein lit the spark igniting the field of quantum mechanics. As noted by Robert Forward “*Einstein showed that light does not consist of continuous waves, nor of small, hard particles. Instead, it exists as bundles of wave energy called photons. Each photon has an energy that corresponds to the frequency of the waves in the bundle. The higher the frequency (the bluer the color), the greater the energy carried by that bundle.*”⁶

Einstein’s discovery (which earned him a Nobel Prize) is an example of basic research which at the time of its discovery did not have any application and thus had only non-market returns. It explained a physical phenomenon, but did not have an immediate application in terms of goods in the marketplace. Over time, however, widespread applications of this fundamental discovery have been derived.

Again, as noted by Forward, “*although Einstein did not invent the laser, his work laid the foundation. It was Einstein who pointed out that stimulated emission of radiation could occur. All it took to invent the laser was for someone to find the right kind of atoms and to add reflecting mirrors to help the stimulated emission along. Remember, the acronym LASER means Light Amplification by (using Einstein’s ideas about) Stimulated Emission of Radiation.*”⁷

Today the laser is most definitely a technology with robust market returns. Lasers see wide-ranging application in scientific instruments, surgical tools, cutting and welding devices, range-finding equipment, optical electronics, and lighting, to name just a few. Indeed, at the time of the writing of this report – the activity of writing itself is being facilitated by lasers: 1) the laser used in the mouse tethered to the computer running MS-Word, and 2) the lasers used in the fiber optic link to the Internet facilitating rapid access to information and rapid communications between co-authors.

Because so much important research is non-market (focused on phenomena or subject matter without an immediate line-of-sight to a market application) or focused toward the generation of social returns (benefiting society overall, but perhaps not able to realize private returns to investment), the public sector plays a critically important funding function in the R&D ecosystem. Further, because of the speculative nature of early fundamental research, because of the long time-horizons involved in the performance of much basic inquiry, because of the risk of experiment failures, but most

4 Charles I. Jones and John C. Williams. 1997. “Measuring the Social Returns of R&D.” Federal Reserve Bank Publication. Accessed online at: <https://www.federalreserve.gov/pubs/feds/1997/199712/199712pap.pdf>

5 *Ibid*

6 Robert L. Forward. 1979. “Einstein’s Legacy.” Originally published in *Omni Magazine*, March 1979. Accessed online at: <http://laserstars.org/history/einstein.html>

7 *Ibid*

importantly because of the lack of immediate line-of-sight to a market, private sector investment in basic science is relatively scarce, and almost non-existent in social science and other fields focused almost exclusively on social returns. As noted by Luke Georghiou in a paper for the European Commission:

These arguments help to underpin the core rationale for public support for R&D, that the social rate of return exceeds the private rate of return. In consequence, without government intervention, market and system failures would mean that valuable research would not be performed by companies.⁸

The market/non-market and social/private return characteristics of research are explored further in Chapter II, and their implications for research funding and research performance considered.

CONCLUSION: Research has both private and social returns, and research shows that social returns exceed private returns. Because of high social returns on research, public investment is very much required.

C. Research as an Engine of the U.S. and Individual State Economies

For the United States and for an individual state such as Indiana, public interest is served by research that addresses needs and challenges in society and within the economy. Both basic and applied research (distinguished and discussed further in Chapter III) contribute to both steady and punctuated progress in realizing solutions to challenges, and to realizing opportunities for improving society, individual welfare, economic performance, governmental efficiencies, etc. Market and non-market and social and private returns to research each play a role in sustaining and advancing the nation and the state. Because they provide wide-ranging benefits, research universities play the most holistic and central role in the R&D ecosystem that exists within the state. For example:

- Lan, Katrenko and Burnett note that “Research plays a key role in defining a region’s future economic prosperity. From Silicon Valley to Silicon Alley in New York, the Research Triangle in North Carolina to Kendall Square in Boston/Cambridge, there are countless examples over the past several decades of how research drives innovation, attracts jobs, and fosters economic growth.”⁹ Research universities are key engines in each of these geographies.
- “Universities attract and train talented students in the latest technologies. As urban studies theorist Richard Florida and others note, an increasingly mobile creative class makes it more important to attract and retain talented students and future knowledge workers”.¹⁰ A robust research university profile is central, particularly in the attraction and support of graduate students and the enterprises and organizations that employ them.

“A recent study of (living) Massachusetts Institute of Technology alumni found that those alumni have started more than 25,800 active companies that “employ 3.3 million people and generate annual world revenues of nearly \$2 trillion.” Of those 25,800 companies, 6,900 are headquartered in Massachusetts and generate worldwide sales of about \$164 million. Likewise, a similar study of Stanford University alumni found that those alumni have created 18,000 firms that are headquartered in California, generating annual worldwide sales of about \$1.27 trillion.”

George Lan, Sophia Katrenko and Jennifer Burnett. 2015. “America’s Knowledge Economy: A State-by-State review.” http://www.csg.org/programs/knowledgeeconomy/Elsevier_Report_2015.pdf

⁸ Luke Georghiou. 2015. “Value of research.” Policy Paper by the Research, Innovation and Science Policy Experts (RISE) for the European Commission. Published June 2015. EUR 27367EN. Accessed online at: https://ec.europa.eu/research/innovation-union/pdf/expert-groups/rise/georghiou-value_research.pdf

⁹ George Lan, Sophia Katrenko and Jennifer Burnett. 2015. “America’s Knowledge Economy: A State-by-State Review.” Published by Elsevier and the Council of State Governments, June 2015. Accessed online at: http://www.csg.org/programs/knowledgeeconomy/Elsevier_Report_2015.pdf

¹⁰ *Ibid*

"The broad label "knowledge economy" covers a wide array of activities and interpretations. At least three lines of research fall under this umbrella. The oldest approach... focuses on the rise of new science-based industries and their role in social and economic change. Some analysts include professional services and other information-rich industries such as publishing in this category, noting the marked growth in employment in these sectors of the economy over the past three decades....A core idea unifying this strand of work is the centrality of theoretical knowledge as a source of innovation. With some stretching, the new growth theory in economics could be included here as this work stresses the importance of knowledge in economic growth, noting that discoveries differ from other inputs because they are non-rivalrous and fuel further innovation."

Walter W. Powell and Kaisa Snellman. 2004. "The Knowledge Economy." *Annu. Rev. Sociol.* 2004. 30:199–220

- Leveraging funding from the federal government, state governments, foundations, and other sources, universities perform the early stage, non-commercial research necessary to build a platform upon which later market applications, new industry sectors, and productivity-enhancing innovations for existing industry may develop. As Mariana Mazzucato notes "From the Internet to biotech and even shale gas, the US state has been the key driver of innovation led growth—willing to invest in the most uncertain phase of the innovation cycle and let business hop on for the easier ride down the way."¹¹
- In addition to fundamental research, universities perform applied and translational research in science, engineering, and other disciplines that can result in the transfer of technologies and innovations to existing local industry or spur the start-up of new entrepreneurial ventures to bring original innovations to market.

- University faculty and researchers transfer knowledge, knowhow, processes and technologies to benefit local communities, industry sectors, or individual organizations or businesses. Via publishing, via consulting and contractual research relationships and, in Purdue University's case (as a Land-grant university) via a formal

Indiana's "Advanced Industries"

In 2015, 14.3% of Indiana's 2.55 million private sector employees worked in Advanced Industries (as defined by Brookings Institution). This exceeds the 10.9% of American private sector workers employed in Advanced Industries across the country. In other words, Indiana's economy is more advanced and more dependent on technology-oriented and science-oriented business than is average for the nation.

We analyzed Indiana's Advanced Industries employment to determine which industries are both sizable and highly concentrated within the state. The location quotient (LQ) compares the concentration of employment at the state level with the concentration of that same industry at the national level. A location quotient of 1.20 or greater is considered "high". This indicates that employment in a given industry is at least 20% greater in Indiana than for the nation. The following list shows these highly concentrated, specialized advanced industries in Indiana (that each comprises at least 2,500 employees):

- Power generation and supply
- Petroleum and coal products manufacturing
- Pharmaceutical and medicine manufacturing
- Other nonmetallic mineral products
- Iron and steel mills and ferroalloy mfg.
- Alumina and aluminum production
- Foundries
- Turbine and power transmission equipment mfg.
- Other general-purpose machinery manufacturing
- Electric lighting equipment manufacturing
- Motor vehicle manufacturing
- Motor vehicle body and trailer manufacturing
- Motor vehicle parts manufacturing
- Medical equipment and supplies manufacturing
- Other miscellaneous manufacturing

TEconomy analysis of Bureau of Labor Statistics, Quarterly Census of Employment and Wages (QCEW) data from IMPLAN.

¹¹ Mariana Mazzucato. 2010. "The Entrepreneurial State: Debunking Public vs. Private Sector Myths." Anthem Press.

Extension service, research universities actively disseminate information and innovations to those in society who can put new knowledge and technology to use.

From the perspective of research as a driver of state economic growth, researchers at the Brookings Institution note the centrality of R&D to U.S. progress that is rooted in America's "Advanced Industries" – a set of industries characterized by "deep involvement with technology research and development and STEM (science, technology, engineering, and math) workers."¹² Advanced Industries encompass 50 industries "ranging from manufacturing industries such as auto making and aerospace to energy industries such as oil and gas extraction to high-tech services such as computer software and computer system design, including for health applications."¹³ Brookings notes that "These industries encompass the nation's "tech" sector at its broadest and most consequential. Their dynamism is going to be a central component of any future revitalized U.S. economy. As such, these industries encompass the country's best shot at supporting innovative, inclusive, and sustainable growth."¹⁴ Indiana also has strengths in technology services and associated business sectors, but the state's core strengths still derive first and foremost from its legacy as a maker and manufacturer of things.

What is critically important to note is that these advanced industries benefit from the R&D occurring inside research universities just as they depend on their own corporate R&D. They also depend on the education of advanced scientists, engineers, business management professionals, creative designers, etc. educated within the research university ecosystem. It should also be observed that in many cases, the celebrated products of industry – products viewed as being on the cutting edge of innovation, such as the iPhone – actually represent industry playing an integrative role using innovations and technologies that were developed outside of the company, usually at universities or national labs using public funding (in the case of the iPhone, for example, thin-film displays, lithium batteries, voice recognition technologies, GPS, multi-touch surfaces, etc.) – this is discussed further in Chapter III.

CONCLUSION: The U.S. and individual state economies are not the sole result of private-sector investment – rather they are the result of the operation of a long-standing and symbiotic ecosystem of public and private, academic, institutional and industrial R&D performers interacting with each other and progressively leveraging knowledge built by others. And, research having high social returns may never have engaged industry at all. Commercial markets are not perfect in meeting the full needs of society and individuals. Ergo, if you want a successful economy and society, there must be both public and private sector R&D activity and funding.

¹² Mark Muro, Jonathan Rothwell, Scott Andes; Kenan Fikri and Siddharth Kulkarni. "America's Advanced Industries: What They Are, Where They Are, and Why They Matter." Accessed online at: <https://www.brookings.edu/research/americas-advanced-industries-what-they-are-where-they-are-and-why-they-matter/>

¹³ *Ibid*

¹⁴ *Ibid*

D. The Structure and Function of Universities

As discussed above, universities play a highly important role in America's R&D ecosystem – both as performers of research and as the educators of the skilled human capital required to integrate advanced knowledge into society and commerce. Researchers in industry know how to perform research because they learned the scientific method and were trained in the performance of research while at university. They carry with them the knowledge, skills, perspectives, and social networks established during their university education. Industry can perform and absorb research because of the skills imparted by a university education to key employees.

“Previous studies have touted both the short- and long-term benefits of increasing investments in research and development. In an environment in which all stakeholders increasingly demand more accountability for the risks they take, particularly when it comes to public dollars, states and universities do not want simply to invest more money. State leaders are adopting strategies to identify in which areas to invest their limited resources most effectively. Moreover, while public officials should not be dissuaded from investing in moon shots—areas with long-time horizons for maturity—policymakers need to be sure they are choosing the right moon shots, those that build on a state’s existing strengths and critical mass of expertise. Once states’ comparative research advantages have been identified, it is imperative that policymakers and stakeholders around the country receive that information. It is important that local universities, businesses, government agencies, not-for-profit incubators and economic development organizations recognize what they are doing best to collaborate and coordinate on maximizing those advantages.”

George Lan, Sophia Katrenko and Jennifer Burnett. 2015. “America’s Knowledge Economy: A State-by-State Review.”

It would be a mistake, however, to consider universities only as places for research and higher education. Universities such as Indiana University, Purdue University, and Notre Dame serve highly diverse functions in society. Whether we have attended university or not, we each carry a unique impression or perspective of universities. For some, a university may be viewed as the home of advanced cutting-edge research, while others may see universities as a place for celebrating state traditions and athletic achievements. Parents hope universities are a safe haven where their sons or daughters can mature and take their first steps towards independence; while others see the university as a key means of imparting tangible jobs skills and professional qualifications. And for many, the core university mission is teaching students “how to analyze and think independently”, while others see universities purely as a training ground for practical work skills. Living close to a university, residents may view the institution as a source of culture, arts, entertainment, and educational enrichment, while to others it may be a source of annoyance in terms of traffic and occasional anti-social behavior. And in some cases, the overarching

power of association with academic institutions can be such that individual states and regions draw their identity and external recognition from their universities. Consider, for example, how Harvard and MIT exert positive influence and prestige on Boston and Massachusetts, and the awareness of Indiana that is raised domestically and internationally by the high profile of Notre Dame, Purdue, and Indiana University. Indeed, there are both tangible and intangible benefits afforded by the presence of universities and the diverse functional impacts they generate.

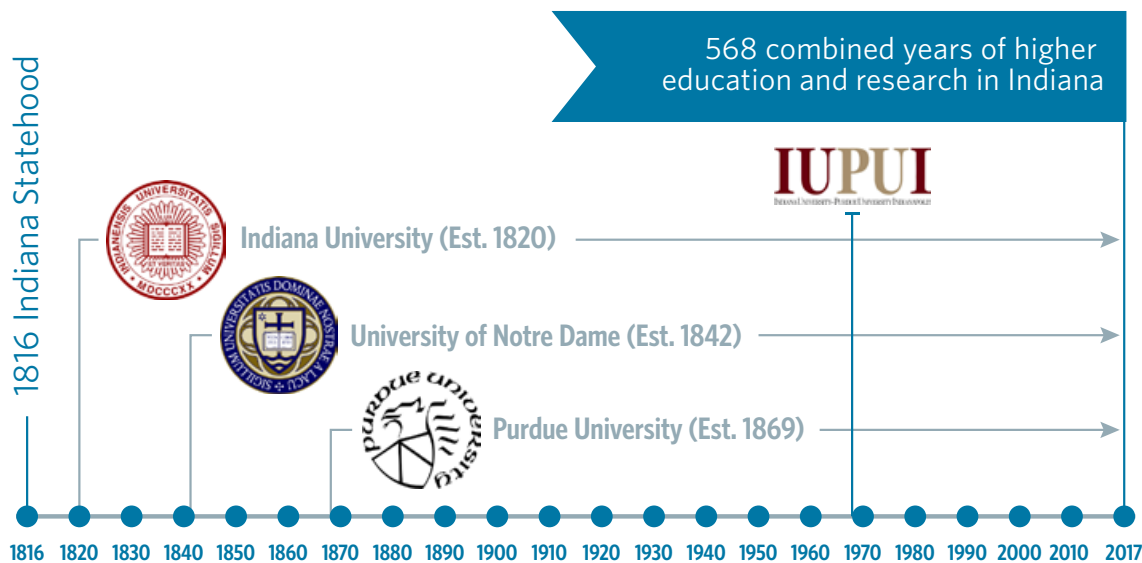
While we may each have differing perspectives on what a university is, their role is so crucial in society that there is much to be gained from seeking to reach a shared understanding of their full-range of functional contributions to individuals, to society and to the economy. Universities are certainly not one-dimensional entities (indeed the very name “university” illustrates they are not). And if we allow our perspective or attention to only be drawn to one aspect of these institutions (whether that be basic research, applied research, education, public service, or some other function) we run the risk of downplaying important institutional aspects that contribute to the university being (very much) more than simply the sum of its individual parts. In other words, the multi-faceted mission of research universities must be fully understood and appreciated in order to guide policies, regulations, funding changes, or other activities that may positively or negatively impact their critical functions. In order to help promote this understanding, BioCrossroads commissioned TEconomy Partners to undertake this report on the importance and functionality of research universities, and to provide examples of the role played by Indiana’s research universities in the economy, society, and quality-of-life in Indiana.

CONCLUSION: The role of research universities in advancing society and the economy is multi-faceted and highly important. In fact, this importance is so high, it is crucial for national and state leaders and decision makers to have a thorough and shared understanding of the functional benefits generated by these institutions.

E. Indiana's Research Universities

From the state's earliest beginnings, research universities have contributed to Indiana's society and economy. Established just four years after the granting of statehood, Indiana University will celebrate its bicentennial in 2020. Notre Dame was founded in 1842, while Purdue University was established in 1869 as Indiana's Land-grant University under the visionary Morrill Act of 1862. In 1969, the Indianapolis-based programs of Indiana University and Purdue University joined to create Indiana's urban research university, IUPUI. Together, Indiana's signature research universities have 568 years of contribution to the social, intellectual, and economic fabric of Indiana.

Figure 1: Indiana's Research Universities.



Source: TEconomy Partners, LLC.

In the fall of 2016, these four institutions had a combined student body (including undergraduate and graduate students) totaling over 132,000 students—enough to fill all the seats in Lucas Oil Stadium (which holds 70,000 people) almost two-times over. National Science Foundation (NSF) data for 2015 show that the total research expenditures of Purdue University (\$558.6 million), Indiana University (\$544.2 million), and Notre Dame (\$191 million), combined reach almost \$1.3 billion, and these direct research expenditures exceed the direct annual economic impact of the Indianapolis Motor Speedway on the state by more than four times.

Clearly, Indiana's research universities are a key economic engine for Indiana, but they also serve to provide a snapshot of the critical role that universities play across the nation. Comprising both public and private research universities, and a comprehensive range of academic research inquiry across all disciplines and fields of inquiry, Indiana stands as a robust case study for an examination of the multifaceted roles that U.S. research universities play in our nation.

F. Organization of this Report

In the chapters that follow, consideration is given to the full-range of impacts and benefits to society and the economy derived by the activities of major research universities. The report seeks to provide a well-rounded and systematic review of university functions and provide a specific focus on the role of research and research universities in advancing our national and state interests.

In Chapter II, we provide an overview of the wide-ranging functional impact areas of research universities, serving to place the research mission within the overall institutional context.

Chapter III examines the nature of research university impacts on social/private and monetary/non-monetary dimensions, and key drivers in performance of academic research.

Chapter IV returns the discussion solely to academic research, profiling the nature of research as performed within signature research universities such as Indiana University, Purdue, and Notre Dame.

Chapter V further narrows the discussion into consideration of the dynamic and expanding world of university life sciences research – an area of research that is advancing at a rapid pace, has profound implications for human life and the sustainability of our planet and, for those universities that excel at it, represents a vast frontier of economic opportunity.

Chapter VI provides an overview of the changing conditions and forces that are impacting signature research universities. This includes consideration of the challenges and threats to American leadership in university research related to observations of current trends. Some preliminary recommendations are made in relation to enhancing benefits from research universities in Indiana.

All knowledge is useful; every part of this complex system of nature is connected with every other. Nothing is isolated. The discovery of to-day, which appears unconnected with any useful process, may, in the course of a few years, become the fruitful source of a thousand inventions.

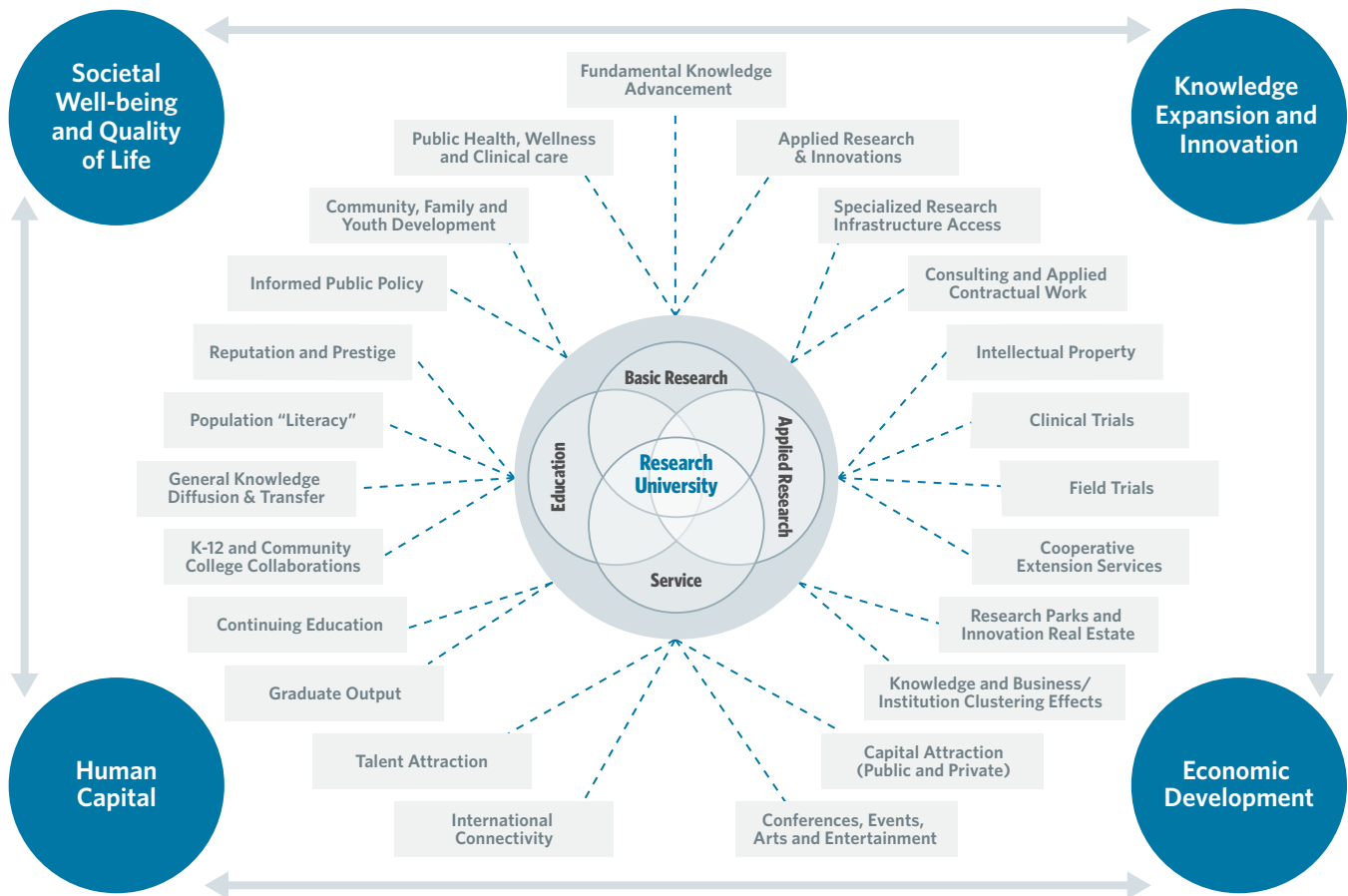
- Joseph Henry (1852)

Chapter II: Functional Impact Domains of Research Universities

As referenced in Chapter I, major research universities serve a diverse range of functions that provide both private and social, and market and non-market returns. In terms of promoting full recognition of the multi-faceted mission and benefits of university presence in localities, regions, and states, understanding the full-range of functional impacts generated by universities is vitally important.

TEconomy has enjoyed the privilege of working with universities, state and federal government agencies, and economic development organizations across the nation and internationally in examining the impacts of academic institutions, and developing strategies to further advance these impacts. In combination with a review of the literature, this experience has enabled TEconomy to develop an illustrative model for discussing university functional impacts, as seen in Figure 2.

Figure 2: The Functional Impacts of Research Universities



Source: TEconomy Partners, LLC.

At the heart of this representation are three primary mission cores: 1) research (incorporating both basic and applied research, and the continuum of research therein); 2) education, and 3) service. Individual functional outputs and impacts radiate from these cores - ultimately supporting four primary impact domains: A) knowledge expansion and innovation; B) economic development; C) the enhanced capabilities of human capital, and D) societal well-being and quality of life. This model was shared with, and reviewed by, Indiana's research university leadership, and feedback

received confirmed it to be a valid model representation of the multi-faceted functional roles of research universities and their benefits.

A. The Functional Activities of Universities and Examples from Indiana

In terms of the relative effect of each functional activity on social or private returns, or market/non-market benefits, it should be noted that no weighting is placed on elements in Figure 2. Indeed, where the principle focus is on the R&D function of universities, it is beyond the scope of this study to provide relative measures of the benefits afforded by each university function. However, we have no doubt it would be the case that there is considerable variability between universities regarding their relative emphasis on each functional impact area. Interesting follow-on research could be produced that would examine the feasibility of developing characterization schemata for relative higher education institution types based on this model, but such is not attempted herein.

Below, a description of each identified functional impact activity area is provided (starting from the top of the diagram and proceeding in a clockwise direction), as well as context around why it matters for Indiana, and examples of many activity areas specific to Indiana’s research universities.

1. Fundamental Knowledge Advancement

The pursuit of knowledge is one of a university’s oldest functions and universities are a primary location of activities which advance our understanding of the processes that govern human society and the natural world. The university is home to both basic and applied research, the former being research activities undertaken for the sake of knowledge itself, and the latter directed towards having tangible impacts on a problem of concern or identified opportunity or need. Both types of research, as well as other forms of creative and collaborative discovery at universities, expand our knowledge of an array of important topics. The primary output of university research typically, but not exclusively, takes the form of academic publications.

Research Publishing in Indiana

Academic publications are one of the main metrics by which institutions of higher learning and their academic departments are evaluated. Between 2012 and 2016, Indiana produced 59,115 academic publications. Led by Purdue University (22,704 publications) and Indiana University (21,217 publications) almost equally, **Indiana institutions produced 2.9% of all U.S. academic publications despite the state comprising only 2.1% of the total U.S. population.** Indiana can thus be seen to be “punching above its weight” in terms of its academic research output.

2. Applied Research and Innovation

Universities are home to intensive applied research—research focused on developing technologies, solutions, or processes with practical application to observed opportunities and needs. Applied research takes many forms and includes work as diverse as the development of improved agricultural crops, discovery of new pharmaceutical molecules, design of novel medical devices, engineering of innovative new materials, development of software algorithms, design of virtual reality systems, researching approaches to combatting drug addiction, and measuring coastline erosion (to name just a few areas of study). Applied research deals with solving practical problems and typically employs empirical methodologies.

Applied university research and innovation also brings numerous benefits to the state where the university is located, and these activities often create and set in motion a virtuous cycle where the benefits of innovation multiply. In addition, applied research requires intensive expertise and talent in key scientific and technological fields, access to specialized facilities and equipment, and research funding and support. These ingredients themselves have economic impacts extending throughout the state or region in which they operate. Combined, Indiana’s research universities spend more than \$1.3 billion annually in R&D activities and pursuits, and this spending on both basic and applied

research is an economic boon for the state, with each \$1 million in scientific research spending expected to generate 7.8 jobs throughout the state economy.¹⁵ In Indiana, these research activities have attracted corporate partners including both Indiana-based companies (e.g. Rolls Royce and Cummins at Purdue and Eli Lilly and Company at Indiana University) as well as out-of-state companies (Ford Motor Co. working with Purdue, for example).

One example of this kind of applied research partnership has just been announced between Eli Lilly and Company and Purdue: a strategic collaboration in life sciences research. The five-year agreement includes \$52 million in funding from Eli Lilly with initial research focused on developing improved delivery of injectable medicines and developing predictive clinical models, and this agreement represents Purdue's largest strategic collaboration with a single company.

3. Specialized Research Infrastructure Access

The concentration of research activities at universities generates significant funding for specialized technologies and the equipment necessary for sophisticated analysis—infrastructure that is key to the production of quality scientific discovery within the university. The critical mass of researcher knowledge and specialized research infrastructure also encourages the collaboration of universities and other institutions, allowing industry partners to team with universities for the use of expensive and advanced equipment that a business may not have the financial or technical knowledge to acquire and use on its own. This type of relationship facilitates knowledge and technology transfer between universities and business, which carries substantial economic and scientific benefits.

For research and educational partnering opportunities, Indiana companies are partnering with the state's research universities around their unique facilities and specialized research infrastructure. From an economic development and attraction perspective, these capabilities matter for Indiana as companies are able to conveniently access facilities in a cost-effective manner, and look within the state for partnerships rather than extending themselves further abroad. For example, Rolls Royce's Research and Technology Division, based in Indianapolis, need look no further than West Lafayette for specialized facilities to conduct its jet propulsion research (see below).

In other cases, companies and institutions are attracted to Indiana by specialized infrastructure, which can provide further economic development opportunities. In 2016, NASA moved its Advanced Noise Control Fan facility to the University of Notre Dame where it is currently being commissioned by the Notre Dame Turbomachinery Laboratory (see below) at its on-campus facilities to study the acoustics of jet engines.

Just a few examples of the many specialized infrastructure and facilities developed and maintained by Indiana's research universities include:

- **The Notre Dame Turbomachinery Laboratory (NDTL)** is a new, 28,000 square foot facility in South Bend's Ignition Park focused on research, testing, and workforce development for a wide range of applications that involve turbomachinery technology. The facility, which includes 41 full-time employees and works with 7 PhD candidates, is designed to enhance the development path for new gas turbine engine technologies, and allow for a rapid transition to production. NDTL's capabilities include computational software for structural and fluid-flow analysis; a dedicated, large-scale HPC cluster; and shaft powers from 700 to 12,000 horse power, all in a secured, export-controlled environment. NDTL is looking to form new relationships with government and industry to advance the development of commercial and military aircraft, power plants, and the oil and gas industries.
- **Purdue Research Park Aerospace District.** Building on a rich legacy in aerospace technology development, and complementing the academic strengths of Purdue's School of Aeronautics and Astronautics is a significant facilities infrastructure for applied research and training at the Purdue Research Park Aerospace District, a 980-acre flagship for public and private R&D to advance innovation. Although still under development, plans for the

¹⁵ Based on TEconomy analysis of IMPLAN's Input/Output model for Indiana.

District include collaborative R&D opportunities for private companies adjacent to existing assets such as the Purdue University Airport, Purdue Aviation, the Niswonger Aviation Technology Building, and the Maurice Zucrow Laboratories for rocket and jet propulsion research. Purdue's excellence in aerospace research and education has led to numerous industry partnerships including a \$33 million research partnership with Rolls Royce announced in 2016, and this R&D program will work to create next-generation aircraft propulsion systems. Rolls Royce's Research and Technology division is located in Indianapolis, and the company employs nearly 600 Purdue alumni, and this exciting partnership is strengthening the University's contribution to the Indiana economy.

- **Indiana University's Genomics and Bioinformatics Core Facility (GBCF)** hosts state-of-the-art technology to provide genomics-related experiments and bioinformatics analysis. Research applications include metagenomics/genetics, population genomics, transcriptomics, and epigenomics in a 1,500 square-foot genomics facility with specialized equipment including sequencers, a bioanalyzer, a "GeneChip" system, fluorometer, and high-intensity acoustic shearing equipment. The computing facilities include high-performance hardware and computational resources for large-scale data storage, access, and management. Complementing the facilities and technical equipment, the GBCF hosts and conducts bioinformatics training through seminars workshops, and customized consulting on bioinformatics problems.

4. Consulting and Applied Contractual Work

Many university researchers are afforded the opportunity to seek consulting or applied contractual work with government and private organizations looking to utilize their expertise in a given area. This symbiotic relationship functions as a key source of knowledge transfer between the university and other institutions – university researchers can provide knowledge and services that other institutions do not have the capacity to discover on their own, facilitating faster development of new products and services. In addition, these opportunities also offer significant economic benefits and can increase the reputation of the university expert, as well as strengthen the relationship between the university and other institutions.

The Indiana Business Research Center (IBRC) within Indiana University's Kelley School of Business plays a vital role in providing and interpreting economic data and other information needed by the state's business, government, and non-profit organizations. Dating back to 1925, IBRC maintains databases and expertise on a number of areas including income, employment, taxes, industry sectors, education, demographics, and many others. The Center also conducts original research when existing data are not available or sufficient.

To help them make informed decisions, the IU Public Policy Institute provides objective, expert research and analysis on a variety of issues that affect companies and other organizations across Indiana. The multidisciplinary institute is within the IU School of Public and Environmental Affairs (SPEA) and offers a range of services and analysis in varied research areas that include: economic development, tax and finance, criminal justice, public safety, housing and community development, and land use and the environment.

Consulting and applied contractual work through Purdue's Center for Regional Development assists regions across Indiana, the U.S., and beyond to advance new ideas, initiatives, and strategies that contribute to regional innovation, collaboration, and economic development. The Center partners with public, private, nonprofit, and philanthropic organizations to help identify and enhance key regional innovation drivers through, among other services, advanced data support systems to drive sound economic development decisions and strategies.

5. Intellectual Property and Technology Commercialization

University research often results in the development of innovations, technologies, creative works, or other physical “works of the mind” that have market value. Intellectual property (IP) law grants the inventors exclusive rights to the use of their invention for a limited time period. When innovations with potential commercial value are made, research universities will usually require faculty to file an “invention disclosure”. The university technology transfer and licensing office will evaluate the disclosure for potential value and decide whether to pursue the process of filing for patent or other formal IP protection. University IP has formed the basis for a large base of U.S. start-up businesses. The most recent (2015) Association of University Technology Managers (AUTM) survey of U.S. universities found that respondent institutions recorded 25,313 invention disclosures, filed 15,953 new U.S. patent applications, and were issued 6,680 U.S. patents. University IP was the basis for 1,012 new startup businesses formed, with more than 72% of the new businesses remaining in the institution’s home state.

Indiana’s University Technology Transfer Highlights

Compared to all U.S. universities, Purdue University ranks in the top quintile in U.S. invention disclosures, patents issued, and start-ups formed per \$10 million in research expenditures. Indiana University ranks in the second quintile in licensing income generated, and the University of Notre Dame ranks in the second quintile in U.S. patents issued. Indiana’s research universities rank in the third quintile or lower in licenses executed per \$10 million in research expenditures and licenses executed per patent held.

TEconomy analysis of Association of University Technology Managers (AUTM) data

Table 1: Intellectual Property and Technology Transfer at Indiana’s Research Universities by Quintile, 2015

	Licenses Executed per Patent	per \$10M in Research Expenditures				
		Licenses Executed	Licensing Income	Invention Disclosures	U.S. Patents Issued	Start-Ups Formed
Indiana University	4th	4th	2nd	3rd	3rd	4th
Purdue University	5th	5th	3rd	1st	1st	1st
Univ. of Notre Dame	4th	3rd	4th	3rd	2nd	4th

Source: TEconomy analysis of AUTM survey data.

Through an increasing emphasis on entrepreneurship, Indiana’s research universities are promoting student-led and technology-focused business formation. Designed to directly apply core business disciplines to a startup environment, Notre Dame offers a professional master’s degree in entrepreneurship. The University’s ESTEEM program, which stands for “Engineering, Science & Technology Entrepreneurship Excellence Master’s”, is an intensive, 11-month program for students with a science, engineering, or math background to learn not only about entrepreneurship, but also about the commercialization of innovative science, engineering, and technology discoveries. The ESTEEM program happens during real-time startup development and concludes with a Capstone Thesis which includes a business plan, a financial model, and a marketing strategy for an early-stage discovery or invention.

6. Clinical Studies and Trials

Universities, especially (but not exclusively) those with a college of medicine (e.g. Indiana University) will make practical discoveries and innovations that show promise as clinical products¹⁶. These may be vaccines, diagnostics, drugs, or medical devices and each will need to be evaluated through clinical studies and trials for efficacy and safety before they can move to practical application in the market, treating patients. An institution such as Indiana University, with its infrastructure and university hospital and health system, provides an ideal testing ground for clinical products. Early stage animal models can be used to establish efficacy and safety prior to the trial advancing to further testing with human subjects, and the patient access provided by the university hospital system and associated clinical practice facilitates trial management and subject recruitment. In addition to conducting trials on innovations made by university faculty or

personnel, universities may also participate in industry trials. The benefits of conducting clinical trials are many: procuring income from industry trials; providing a pathway to advancing university IP towards commercialization and, most importantly, giving patients with challenging health conditions access to new treatments, therapies, and medical devices.

Beyond the more well-recognized research and innovation breakthroughs that are improving and saving lives, clinical trials themselves generate economic

Clinical Trials in Indiana

As of the close of 2016, there were 2,158 active clinical trials recruiting in Indiana. In terms of only “investigator-led” clinical trials, where faculty or clinicians with one of Indiana’s research universities are the lead investigator, 181 were at Indiana University (including the IU School of Medicine) and 27 at Purdue University.

returns at the site level. In a 2015 study for PhRMA, Battelle’s Technology Partnership Practice examined the economic impacts for state economies associated with hosting and conducting biopharmaceutical industry-sponsored clinical trials.¹⁷ While not limited to those conducted solely at research universities, the study found these clinical trials provide a major boost to state economies via a number of activities specific to sites including investigator fees and expenses, patient recruitment costs, general trial procedures, purchase and shipment of materials, efficacy assessments, lab fees and procedures, site-based IT and data management, and the expenses of Contract Research Organization’s (CRO) facilitating the studies. For 2013, Indiana was among the top 20 states in the number of active trials with 1,111 and nearly 20,000 patients enrolled, and a total estimated economic impact of \$442 million within the state.

7. Field Trials

Just as medical products need to be tested for efficacy, so do novel plant varieties and cultivars developed for agricultural use. With an expanding global population and limited agronomic land stocks, it is imperative that agricultural researchers improve the intrinsic yield of crops or reduce yield losses in crops caused by damaging abiotic and biotic stressors. Universities, especially those in America’s unique system of Land-grant universities (which includes Purdue) are on the front lines in research focused on improving agricultural productivity and the quality of agricultural output. Using laboratory bench research, greenhouses, and field trials at university research stations and cooperating farms, universities are able to test their agricultural innovations and advance the very best products through to application in American farming, forestry, and associated green industries.

Purdue University has a strong track record of developing and testing crop varieties and cultivars well-suited to the specific growing environments across Indiana. Plant Variety Protection Certificate data, maintained by USDA, show Purdue to be particularly active in development in the major crops of wheat and soybean.

¹⁶ IU School of Medicine Data are generally reported under an Indiana University classification.

¹⁷ Battelle Technology Partnership Practice, “Biopharmaceutical Industry-Sponsored Clinical Trials: Impact on State Economies,” prepared for the Pharmaceutical Research and Manufacturers of America (PhRMA), March 2015.

8. Cooperative Extension Services

Land-grant universities address the core mission of service through cooperative extension. In effect, extension services are purpose-designed to disseminate and distribute the many impact benefits described in this list to rural, urban, and economically disadvantaged communities. State-based cooperative extension services are crucial in supporting agricultural processes, environmental concerns, and the health and well-being of families, youth, farmers, and other community members. Primary functions of cooperative extension programs include translation of research findings to practical applications, health and nutrition education (including leadership in the national SNAP-Education program), response and relief for emergencies and natural disasters, youth education and development (incorporating 4-H), and community and economic development.

Purdue Extension's activities in Indiana are extensive and robust; in 2016, Extension had 323,500 direct contacts with those it serves, and provided 11,524 structured educational programming events.¹⁸ Plus the online information resources of Extension were accessed over 31 million times at the Purdue Extension website.¹⁹

9. Research Parks and Innovation Real Estate

Many research universities have developed and operate research parks and other real estate developments (such as business incubators, accelerators, maker spaces, or innovation districts) designed to encourage and facilitate commercialization of research discoveries and collaborative work with innovative, research-driven companies. The Association of University Research Parks notes that a research park comprises a master-planned property designed for research and commercialization, and these developments have several positive impact advantages including: facilitating close R&D and commercialization partnerships between universities and companies; encouraging the growth of new companies; translating university discoveries into commercial opportunities, and being drivers of technology-led economic development.²⁰ Battelle notes that "university research parks are a successful way to advance innovation and create economic growth in regions across North America."²¹

Purdue University has been a leader in research park development, operating multiple parks in Indiana (Table 2), and moving forward with innovation district projects. Both Indiana University and Notre Dame also have research park developments, and Indiana's research universities are collaborating in the Indianapolis 16 Tech innovation district development project.

Purdue Cooperative Extension

Purdue Extension's activities in Indiana are large and extensive – with Extension in 2016 having 323,500 direct contacts with those it serves, and providing 11,524 structured educational programming events. The online information resources of Extension were accessed over 31 million times at the Purdue Extension website.

¹⁸ Purdue Extension. "2016 Annual Report." Accessed online at: <https://extension.purdue.edu/annualreport/>

¹⁹ *Ibid*

²⁰ <http://www.aurp.net/what-is-a-research-park>

²¹ Battelle Technology Partnership Practice. 2012. "Driving Regional Innovation and Growth." Published by the Association of University Research Parks. Accessed online at: https://aurp.memberclicks.net/assets/documents/aurp_battellereportv2.pdf

Table 2: Indiana’s University Research Parks and Innovation Districts

Park or Innovation District	Notes
Purdue Research Park of West Lafayette	Opened in 2005, this is Indiana’s first designated certified technology park. It comprises 725 acres and hosts 100+ companies with 3,200 total employees.
Purdue Research Park of Indianapolis	Opened in 2009, this Purdue park also has Certified Technology Park status. It comprises 400 acres and hosts 75 companies with 1,500 total employees.
Purdue Research Park of Northwest Indiana	Located in Merrillville and the site of the Purdue Technology Center
Purdue Research Park of Southeast Indiana	Located in New Albany. Has a total size of 44 acres.
Purdue Research Park Aerospace District	Located in West Lafayette, comprising 980 acres.
Purdue Innovation District	New project for a planned innovation district to be located adjacent to the Purdue campus in West Lafayette. Will comprise “live-play-work” environment with innovation space, housing, retail outlets, and public spaces.
Indiana University Technology Park	Located at the Bloomington campus of Indiana University
Innovation Park at Notre Dame	Opened in 2009, Innovation Park in South Bend is comprised of 29 companies.
16 Tech	New project to create a Planned Innovation District, located in Indianapolis. Anticipated to comprise an urban live-play-work environment with innovation space, housing, retail outlets, and public spaces. Both IU and Purdue are planning a shared innovation presence at the site.

10. Knowledge and Business Clustering Effects

According to *The Economist*, “clustering is the phenomenon whereby firms from the same industry gather together in close proximity.”²² Clustering brings with it several business advantages including shared supply chains, talent and knowledge bases, and supporting infrastructure. *The Economist* further notes that “modern high-tech clusters often gather round prestigious universities on whose research they can piggyback. Silicon Valley is near Stanford University, for example, and similar high-tech clusters are gathered around MIT near Boston in the United States and around Cambridge University in Britain.”²³

Advanced Industry Clusters in Indiana

Indiana is home to notable clusters of industry in:

- Advanced manufacturing across sectors such as aerospace and automotive
- Biomedical technologies with distinctive clusters in medical devices and biopharmaceuticals
- Agricultural biosciences

Each of these clusters has strong ties to research occurring in Indiana’s research universities.

Research at other colleges and universities play a vital, multi-faceted role in supporting and advancing industry clusters. Arguably the most critical ingredient to high-functioning, knowledge-driven industry clusters, talent development is the primary role of postsecondary institutions. Both on their own and in partnership with the private sector, research universities are advancing innovation, and technology-based economic development programs are typically designed around the interface between university R&D core competencies and related industry clusters.

²² *The Economist*. August 24th 2009. “Clustering”. Accessed online at: <http://www.economist.com/node/14292202>

²³ *Ibid*

Indiana's industry strengths and clusters are interrelated with those niche strengths, capabilities, and concentrations of knowledge at its research universities. The Indiana University School of Medicine and its related talent base, facilities, and research activities and infrastructure provide a highly complementary anchor for the state's biomedical innovation in both medical device manufacturing and biopharmaceuticals. The Indiana Clinical and Translational Sciences Institute (CTSI) is a statewide collaboration of Indiana University, Purdue University, and the University of Notre Dame, as well as public and private partnerships, focused on the translation of scientific discoveries in the lab into clinical trials and new patient treatments in Indiana and elsewhere. The Indiana CTSI is one of 61 such Institutes nationally, established through an award from the NIH and supplemented by funding from the state, the three universities, and public and private partnerships. The CTSI provides a partnering vehicle with the private sector and has brought together the research universities in collaborations with Indiana-based Eli Lilly and Company and Cook Group, as well as healthcare institutions such as Eskenazi Health.

Among its partnership efforts is the Strategic Pharma-Academic Research Consortium Funding Program (SPARC), which the Indiana CTSI spearheaded and now leads. The consortium involves three other NIH-funded CTSA's - Ohio State University, Northwestern University, and The Washington University - and its industry partners include Eli Lilly and Co. and Takeda

Purdue University's Renowned Strengths in Aerospace Engineering Research, Education, and Industry Partnerships

Purdue's deep and illustrious history in aerospace research and education includes numerous points of pride including:

- The nation's first airmail delivery originated by hot air balloon in Lafayette in 1859;
- Purdue graduates set altitude records in 1911 and 1956, which were ultimately surpassed by graduates Neal Armstrong and Eugene Cernan's flights to the moon;
- In 1930, Purdue was the first U.S. university to offer college credits for flight training;
- In 1934, the University was the first to open a college-owned airport;
- The University employed Amelia Earhart as a "Counselor on Careers for Women" and provided funds to support her fateful around-the-world voyage;
- The University has produced the most aerospace engineering degrees in the nation during the past ten years;
- Twenty-three Purdue alumni have been selected as astronauts and more than one-third of all of NASA's manned space missions have included at least one Purdue graduate as a crew member including both the first and last men to step foot on the moon.

This excellence in aerospace continues today within the School of Aeronautics and Astronautics which is educating the next generation of engineers in the design and operation of numerous aircraft, missiles, and space vehicles with a consistent emphasis on R&D.

Complementing the academic strengths of the University in these fields is a significant facilities infrastructure for applied research and training at the Purdue Research Park Aerospace District, a 980-acre flagship campus for public and private R&D to advance innovation. Plans for the District, which is still under development, include collaborative R&D opportunities for private companies adjacent to existing assets such as the Purdue University Airport, Purdue Aviation, the Niswonger Aviation Technology Building, and the Maurice Zucrow Laboratories for rocket and jet propulsion research.

Purdue's excellence in aerospace research and education has led to numerous industry partnerships including a \$33 million research partnership with Rolls Royce announced in 2016. The R&D program will work to create next-generation aircraft propulsion systems. Rolls Royce's Research and Technology division is located in Indianapolis, and the company employs nearly 600 Purdue alumni. The new agreement is strengthening the University's contribution to the Indiana economy.

"Research and development in jet engines is an important objective for Rolls-Royce as we strive to create jet engines that are more energy-efficient and can perform even more effectively. Purdue has always been a great partner with Rolls-Royce and I am confident that our collaborative research will result in strong long-term advances in jet engine development."

- Phil Burkholder, President of Rolls-Royce Defense Aerospace, North America

Pharmaceuticals International Inc. The first grants from SPARC provided over \$1.9 million to advance research on autoimmune disease at several medical research universities across the Midwest. Another Indiana CTSI public-private partnership effort is with Covance for a Phase I clinical trials unit.

Purdue's position as a land-grant institution and its corresponding strengths in agricultural research and talent development provide a critical anchor and driver of the state's leadership in the agricultural biosciences. To that end, Purdue and Dow AgroSciences (based in Indianapolis) have formed a partnership with Dow, occupying research and office space, as well as a research greenhouse in the Purdue Research Park and its researchers collaborating with Purdue faculty at its Colleges of Agriculture and Science.

An additional catalyst for biosciences cluster development is the new Indiana Biosciences Research Institute (IBRI). Established in 2012, the non-profit IBRI was designed by industry but is intended, in part, to create collaborative bridges to Indiana's research universities. The state of Indiana and its leading life sciences companies, academic research universities and medical schools, and philanthropic community saw the need for better health solutions in the local and global community and called for the creation of IBRI. The Institute leverages the depth and breadth of the varied, complementary R&D activities occurring in Indiana, and in particular, the industry and academic expertise in nutrition science, genetics and genomics, biochemistry, endocrinology, novel delivery systems, and therapeutic approaches, to deliver important answers to metabolic disease. IBRI's mission is to "become the leading industry-inspired applied research institute in the discovery and development of innovative solutions to improve health, initially targeting diabetes, metabolic disease, and poor nutrition."²⁴

Finally, IBRI is intentionally designed to advance discoveries by breaking down traditional barriers to research that encourages collaboration across both industries and scientific disciplines. This includes leveraging and sharing assets and resources, utilizing a flexible business model across multiple funding sources, and attracting world-class talent. The Institute also encourages academic collaborations and talent connections by allowing a "shared" talent approach where academic researchers can have IBRI and university privileges at the same time.

11. Capital Attraction and Formation

Business capital is attracted to commercial concepts showing strong viability for success and, as noted above, proximity to and relationships with a research university that can enhance viability – providing access to ideas and innovations, specialized equipment and real estate, and human capital. In addition, multiple universities and states have been able to (individually or in collaboration) form pools of pre-seed, seed, and proof-of-concept funding which allow them to progress new business development to a point where private sector risk capital is attracted to co-invest. The large alumni base of major research universities can also provide access to high net worth individuals willing to prioritize investments in their alma mater's entrepreneurial ventures.

Over the last decade plus, both Purdue University and Indiana University have taken important steps to improve their capabilities to commercialize university technologies through modest investments combined with management assistance in technology assessment, market analysis, and business planning. University sources of innovation capital in Indiana include Purdue's Emerging Innovation Fund and Trask Funds, and Indiana University's Innovate Indiana Fund.

- Purdue's Emerging Innovations Fund, managed by the Purdue Research Foundation Office of Technology Commercialization was established in 2008 to provide resources to early-stage companies to advance commercialization. Funds are invested on a competitive basis in the form of a loan with equity participation, with the fund designed to be self-sustaining.

²⁴ See: <http://www.indianabiosciences.org/about/>.

- The Trask Innovation Fund (TIF), managed by the Purdue Research Foundation, is a University development mechanism designed to assist faculty in commercializing disclosed technologies. The objective of the TIF is to support short-term projects with financing up to \$50,000 for a 6-month period to enhance the commercial value of the University's intellectual property. An Advisory Council advises on the awarding of funds.
- The Innovate Indiana Fund partners with IU-connected companies to provide funding, guidance, and a world-class network. The \$10 million fund is designed to provide equity capital to high-potential companies with a strong university association. The University is leveraging the IIF to create a culture of entrepreneurship, to harness talent, and to strengthen Indiana's economy.

Founded in 2012, the IrishAngels investing group is focused on advancing startup growth through early-stage investing in companies in which a founder, board member, or active investor is a student, graduate, parent, or faculty member at the University of Notre Dame. This angel investment organization includes more than 170 members with startup or finance backgrounds that span a variety of sectors, and that leverages the wide-reaching network associated with Notre Dame.

12. Conferences, Events, Arts and Entertainment

As discussed elsewhere in this section, universities are major centers of innovation and creativity. They also offer platforms for dissemination of research findings and displays of artistic achievement, including academic conferences and lectures, and performances of live theater, music, and art. Participants and featured presenters are drawn from inside and outside the campus community, providing opportunities for enrichment and exposure to new ideas.

University sporting and athletics events also represent major visitor attractions, and provide research and educational opportunities in disciplines such as athletics training, sports management, and sports medicine. The degree to which a major university serves as a focal point for area tourism is highlighted in statistics from the Bloomington Convention and Visitors Bureau, which reports that tourism is the third largest industry in the region, employing 4,000 personnel and hosting over 3 million visitors per year.²⁵

The Jacobs School of Music at Indiana University-Bloomington is one of the largest and most acclaimed of its kind. Dating back to 1921, the School has more than 1,600 students representing musical performers, scholars, and music educators, all influencing music performance and education around the world. Ranked first by *U.S. News and World Report* and *The Chronicle of Higher Education* in vocal performance, the School has also been ranked the top program in America by *Classical Singer*. In addition, the School offers more than 1,100 performances each year including performing up to seven fully staged operas. The excellence in the performing arts at Indiana University extends to performances and support for the arts all across Indiana, enriching the lives of Hoosiers by sharing and advancing arts and culture in the state.

Indiana University and Bloomington Visitors

The degree to which a major university serves as a focal point for area tourism is highlighted in statistics from the Bloomington Convention and Visitors Bureau, which reports that tourism is the third largest industry in the region, employing 4,000 personnel and hosting over 3 million visitors per year.

²⁵ Bloomington Indiana Convention and Visitors Bureau. Bloomington/Monroe County Fact Sheet. Accessed online: at <http://www.iub.edu/~iubphys/resources/FactSheet.pdf>

13. International Connectivity

Universities facilitate international collaboration, dissemination of information, and talent exchange. And now more than ever, international interconnectedness is more possible due to the relative ease of travel and digital distribution of research findings. Plus, study abroad programs and hiring of international faculty further facilitates skill and knowledge transfer. Additionally, there are now over 1 million international students studying in U.S. universities, which provides faculty and students with exposure to an abundance of ideas from other cultures.²⁶

Purdue continues to be a top destination for international students. According to the Institute of International Education, the University has the third-largest number of international students among all U.S. public colleges and universities.²⁷ Among both public and private institutions, Purdue ranks seventh. The University leverages this status to promote cross-cultural exchanges, and sees the presence of students from more than 120 nations as an enriching experience for all of its students. Indiana is ranked 10th among all states in terms of the largest population of international students and Indiana University is ranked 16th among all institutions.

U.S. universities can also serve as attraction points for overseas inward investment to the U.S., particularly those having research park developments. For example, at Purdue, the university research parks host major international companies including Rolls Royce and Novo Nordisk. Internationally located alumni of U.S. universities also form a valuable network of individuals knowledgeable about their alma mater, and the community and state where it is located.

14. Talent Attraction (and Retention)

University prestige and reputation make talent attraction another important function of universities. In areas surrounding the university, research, teaching, and administrative openings provide an important pathway for increases in socioeconomic status and occupational prestige. In addition, university towns are generally considered desirable places to live because of the arts, culture, sports, and other university-related amenities in the community. Generally viewed as diverse, welcoming to outsiders, home to good school districts, protected in property values by university-driven demand, etc. college and university towns are attractive to high skill individuals.

Indiana's high quality public and private institutions of higher education are a valuable resource to the state, and one that sets Indiana apart from other states in their attraction of students (and potential future workforce) into Indiana. As previously mentioned, students from across the U.S. and around the world come to Indiana to study and to earn their degree and in turn, this influx of students increases the talent pool that can be retained to grow Indiana's economy. In terms of the percentage of all undergraduate students who attend school in Indiana from out of state, Indiana ranks in the middle (of all states); in 2014, 24 percent of undergraduates were from out of state, ranking Indiana 22nd among all states. However, if one ranks states by the sheer size of this out-of-state cohort, Indiana ranks 11th, with the migration of undergraduate students into Indiana totaling 16,583 in the fall of 2014.²⁸ Analysis among individual institutions for the 2013-14 academic year shows Indiana University-Bloomington having the third-highest number of out-of-state undergraduate students among all 4-year schools nationwide with at least 2,000 students, and Purdue University having the third-highest number of first-year foreign undergraduate students.²⁹

²⁶ <https://www.iie.org/en/Research-and-Insights/Open-Doors#.WCXddS0rKUn>

²⁷ <https://www.purdue.edu/newsroom/releases/2015/Q4/purdue-ranks-3rd-for-largest-international-student-population-at-public-universities.html>

²⁸ U.S. Department of Education, National Center for Education Statistics, Integrated Postsecondary Education Data System (IPEDS), Spring 2015, Fall Enrollment component. Accessed via the Digest of Education Statistics. Data represent residence and migration of all first-time degree/certificate-seeking undergraduates in degree-granting postsecondary institutions in Fall 2014. Student in-migrant totals include foreign students.

²⁹ Institute of Education Sciences, U.S. Department of Education, analysis developed and presented by Valore Books, see http://www.valorebooks.com/visualizing-college-out-of-state?pd=_.

Many of these students, both native Hoosiers and their out-of-state counterparts, then remain in Indiana and form the foundation of the high-tech workforce. Among graduates from 2009 to 2013 across all of Indiana’s public colleges and universities (which excludes Notre Dame):³⁰

- 33 percent of in-state biological science graduates, and 6 percent of out-of-state graduates were employed in Indiana in 2014;
- 38 percent of in-state engineering graduates and 6 percent of out-of-state graduates were employed in Indiana in 2014;
- 49 percent of in-state computer and information sciences graduates and 5 percent of out-of-state graduates were employed in Indiana in 2014;
- More than 60 percent of in-state healthcare-related graduates and nearly 10 percent of out-of-state graduates were employed in Indiana in 2014.

15. Graduate Output

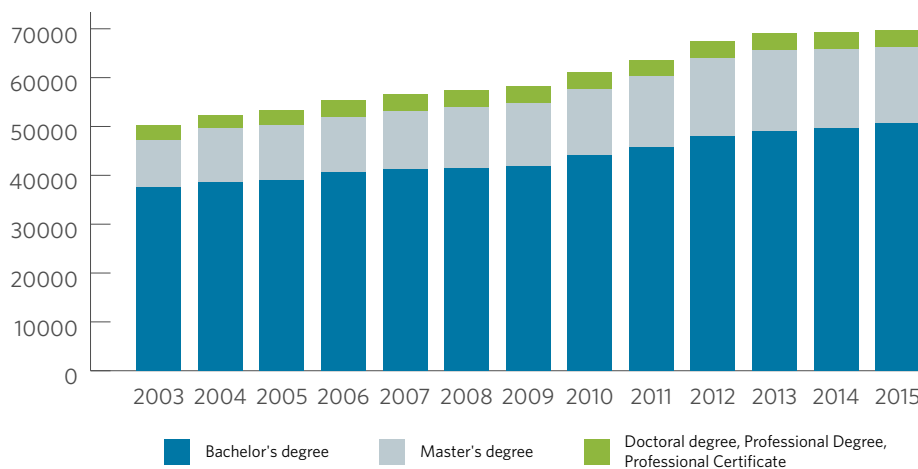
Alongside research, the principal output of research universities is higher education. Education of undergraduates, masters, PhD candidates, and professional degree students provides a constant annual flow of available human capital to employers. Higher education brings both private returns to the student (in terms of skills, capabilities, and enhanced job and income prospects) and social returns in areas such as enhanced labor productivity, increased innovation capability, and reduced social costs generally found to be associated with higher education (such as reduced levels of crime and improved health). In a knowledge-based economy, it is clear that human capital becomes the most valuable form of capital – and it is universities that are at the forefront of producing this crucial capital asset.

Higher Education Enrollment in Indiana

In fall 2014, 436,327 people were enrolled in degree-granting postsecondary institutions in Indiana (6.62% of Indiana’s total population). This is a slightly larger proportion enrolled than for the U.S. as a whole, which had 20,207,369 fall enrollees in 2014 (6.34% of the total U.S. population).

In 2015, Indiana’s colleges and universities graduated nearly 70,000 students, in degree programs at the bachelor’s level and above, representing a 39 percent increase from approximately 50,000 in 2003 (Figure 3).

Figure 3: Annual Number of Graduates from Four-year and Postgraduate Study at Indiana Higher Education Institutions, by Degree Level



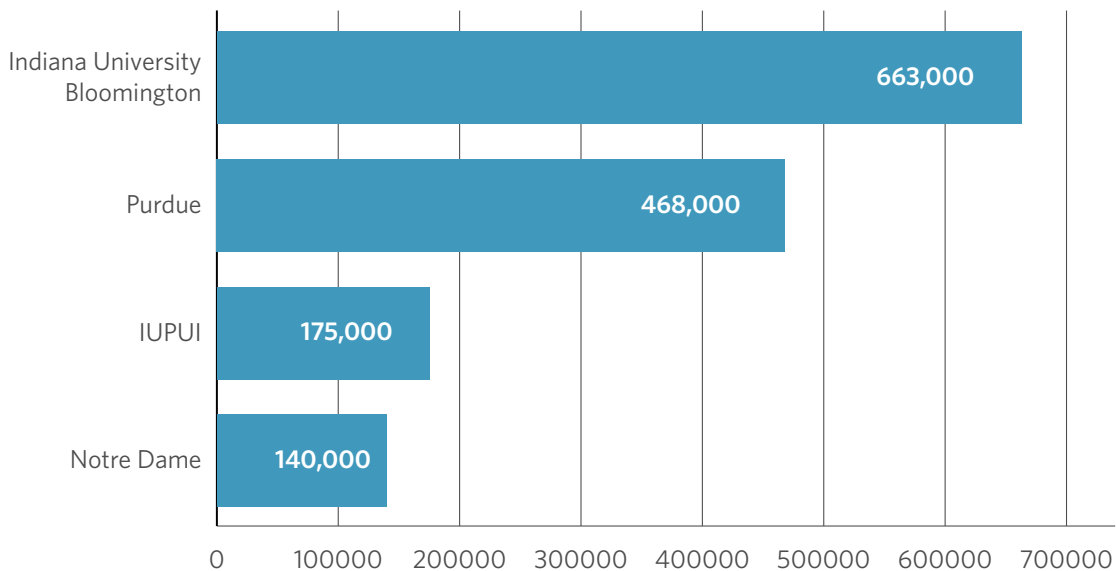
Source: TEconomy analysis of National Center for Education Statistics, Integrated Postsecondary Education Data System.

³⁰ Based on analysis of data provided by the Indiana Network of Knowledge (INK) via the Indiana Department of Workforce Development. Note some graduate and employment totals are suppressed by INK due to limited sample sizes and to maintain confidentiality.

Whether or not they currently live in Indiana, this significant volume of graduate “output” ultimately translates into very large alumni populations and networks with a meaningful connection to Indiana and their specific institution. As in the case of the aforementioned IrishAngels investing group, alumni networks often mobilize on a group level to act in the interests of those associated with their alma mater. On an individual level, an active alumni network can translate into job opportunities or a welcoming introduction to a new city.

Estimates of living alumni from Indiana’s four research universities are presented in Figure 4 below. When summed, the living alumni of these four universities totals more than 1.44 million. For perspective, Lucas Oil stadium holds 70,000, which would need to be filled over 20 times over in order to accommodate a homecoming for these alumni.

Figure 4: Estimates of Living Alumni for Indiana’s Four Research Universities



Source: alumni data provided by individual institutions

16. Continuing Education

Universities are the predominant providers of post-secondary education in the U.S. In addition to two-year, four-year, and post-baccalaureate programs, universities offer a range of opportunities for adult learners. Typically comprised of part-time enrollees, continuing education programs provide credit-granting or non-credit courses designed to develop knowledge and enhance skills, and can be undertaken for vocational or personal reasons. Universities are therefore a stable source of personal and professional development to members of the community. University-based continuing

education in areas such as the professional practice of medicine, nursing, law, architecture, engineering, and agronomy benefits society by assuring professionals serving the community are up-to-date in their skills, best practices, and current practice recommendations.

Indiana’s Research Universities and Indiana’s Human Capital

Large public research universities, such as Indiana University and Purdue University, tend to have a particularly strong impact in terms of alumni remaining in the state. Purdue University, for example, has 468,000 living alumni in the U.S. of which 44% currently reside in Indiana.

Through its Lifelong Learning program, Indiana University has hosted local adult learners for more than 45 years in Bloomington. The non-credit program is designed for adults in the greater Bloomington–Monroe County community (and beyond), and allows them to access the

knowledge, research, and facilities at IU, and serves as a key outreach component of IU Bloomington's broader mission to contribute to the community.

17. K-12 and Community College Collaborations

Across the full spectrum of educational opportunities, universities play an important role. University research conducted in education, pedagogy, educational technologies, etc. provides direct input into the development of curricula and teaching methodologies impacting the K-12 education community. In addition, universities are providing undergraduate and graduate level training of teachers and school administrators. Major state universities, such as Purdue and Indiana University, will also be closely engaged with community colleges in curriculum development, and the management of student transfers from two-year to four-year programs. Universities in Indiana also offer pre-college programs, with summer school and other offerings providing K-12 students with opportunities to

engage in arts programs, sports programs, and a range of for-credit and non-credit educational opportunities. In this regard, the range of opportunities provided by Indiana's research universities is extremely diverse. For example, Indiana University lists 69 different pre-college programs, covering diverse areas such as journalism, foreign languages, dance, music, biology, business studies, mathematics, theater, and a range of sports. Similarly, Purdue offers a broad range of programs, and is home to the Indiana 4-H program which engages over 61,000 youth in 4-H club programs across the state in both rural and urban settings. Purdue offers additional youth programs in engineering, science, mathematics, technology and sports. Finally, Notre Dame also has an active summer scholars program for precollege youth.

In 2017, Purdue University is launching the Purdue Polytechnic High School in Indianapolis. Created and developed through the leadership of Purdue and the City of Indianapolis, the charter school is focused on providing an educational experience that prepares students for college and careers in high-tech and STEM-related fields. Utilizing approaches such as learning by doing and experiential learning, the school is designed to help better serve underrepresented and underserved students in these STEM fields.

18. General Knowledge Diffusion & Transfer

Through a large number of formal and informal channels, universities facilitate knowledge diffusion and transfer. In general education areas and degree-specific information, undergraduate courses and programs emphasize academic growth, while graduate students and faculty publish and present academic findings to other researchers, governments, businesses, the press, and the general population. Campuses also offer a range of presentations, lectures, and non-credit courses which focus on both academic and personal development topics. The general public, in addition to having access to some of the aforementioned resources, is also the target of outreach programs through print and online publications, public health initiatives, and cooperative extension services.

Youth and Pre-College Programs in Indiana's Research Universities

Indiana University lists 69 different pre-college programs covering diverse areas such as journalism, foreign languages, dance, music, biology, business studies, mathematics, theater, and a range of sports. Similarly, **Purdue** offers a broad range of programs, and is home to the Indiana 4-H program which engages over 61,000 youth in 4-H club programs across the state in rural and urban settings. Additional Purdue programs for youth are offered in engineering, science, mathematics, technology and sports. **Notre Dame** also has an active summer scholars program for precollege youth.

Extension Public Information Access

Purdue University Extension provides access to a wealth of online information to support personal development and learning, with almost 31 million visits recorded to the Extension website in 2016.

19. Population “Literacy”

In the broadest sense of the term, literacy is crucial for a functioning knowledge economy and a democracy. The future holds significant challenges for the U.S., and an educated, literate populace is required to exercise rational voting and civic engagement that will assure decision makers address our challenges with logic and care. Providing an objective source of information and advice, universities enhance population literacy in areas as diverse as health, technology, public policy, environmental sustainability, and community management.

Purdue University extension provides access to a wealth of online information to support personal development and learning, with almost 31 million visits recorded to the Extension website in 2016.³¹ Student, faculty and staff volunteers at Indiana’s research universities are also actively engaged in fundamental adult and youth literacy work within the state.

20. Reputation and Prestige

Historically, major research universities have been viewed as prestigious organizations. Excellence in research, education, the arts, athletics, and other areas bolsters the prestige of the university and increases the reputation of the communities and home states of these institutions. Additionally, decades of social science research demonstrate that university professors enjoy high occupational prestige.

Indiana benefits from the presence of well-recognized, globally influential research universities. Within *The Times* “World University Rankings”, which ranks 980 leading universities world-wide, each of Indiana’s major research universities ranks in the top 150 (the top quintile) with Purdue at 70th, Notre Dame at 143rd and Indiana University at 150th.³²

Indiana’s Research Universities are Globally Prominent

The Times “World University Rankings” ranks 980 leading universities world-wide across teaching, research, international outlook, reputation, and more. All of Indiana’s major research universities rank in the top 150 (the top quintile).

The prestige of research universities, including in Indiana, acts as a major attractor for “star” research talent into a state or region, as well as all the innovative capacity, research grants, and teams associated with that individual. In addition, these top researchers can have an outsized impact in the formation of new companies and even new industries. A well-known study by Zucker, Darby, and Brewer demonstrated the associated connection between top scientists and the founding of biotechnology firms over more than a decade.³³ The study found that “at least for this high-tech industry, the growth and location of intellectual human capital was the principal determinant of the growth and location of the industry itself.” And the authors conclude that “our results provide new insight into the role of research universities and their top scientists as central to the formation of new high-tech industries spawned by scientific breakthroughs.” Therefore, this role as talent attractor has the potential to birth new companies and even new sectors, and thus must be leveraged not only for education and basic research purposes, but even further for the economic potential of star faculty.

Table 3 below summarizes counts of what many would consider to be “star” faculty affiliated with Indiana’s research universities across the following awards and recognitions:

- Members of the National Academies. According to the National Academies: “Election to the National Academy of Sciences, National Academy of Engineering, or National Academy of Medicine is considered one of the

31 Purdue Extension. “2016 Annual Report.” Accessed online at: <https://extension.purdue.edu/annualreport/>

32 World University Rankings 2016-2017. Accessed online at: https://www.timeshighereducation.com/world-university-rankings/2017/world-ranking#!/page/0/length/25/sort_by/rank/sort_order/asc/cols/stats

33 Zucker, Lynne; Michael Darby; Marilyn Brewer, “Intellectual Human Capital and the Birth of U.S. Biotechnology Enterprises,” *The American Economic Review*, March 1998, pages 290-306.

highest professional honors among scientists, engineers, and health professionals. Each year, new members are elected by current members based on outstanding achievement and commitment to service.”³⁴

- The Nobel Prize is a set of international awards bestowed annually across several disciplines that recognize academic, cultural, or scientific advances. The prizes are awarded in chemistry, literature, peace, physics, physiology or medicine, and economic sciences.
- Considered the Nobel Prize of food and agriculture, the World Food Prize is the world’s foremost honor that recognizes the achievements by individuals in advancing human development through the improvement of the quality, quantity, or availability of food in the world. The annual award recognizes contributions in a whole range of fields from plant, animal, and soil science to food science, to social organization and poverty elimination.

Table 3: “Star” Talent Affiliated with Indiana’s Research Universities

Institution	National Academies Members (Living)	Nobel Prize Winners ³⁵	World Food Prizes ³⁶
Indiana University	42	9	--
Purdue University	29	10	3
University of Notre Dame	2	1	--

Source: Information provided by the individual institutions.

Compared with neighboring states including Illinois, Michigan, and Ohio, Indiana’s concentrations of “star talent” within its research universities are competitive. Relative to its base of research expenditures, Indiana has a slightly higher concentration of Nobel Laureates compared with Ohio and Michigan though these three states are well below Illinois’ concentration given the large number of Nobel Prize recipients from the University of Chicago. Indiana’s concentration of National Academies Members lies in the middle of this group, essentially the same as for Michigan, above Ohio, though behind Illinois.

21. Informed Public Policy

Academic research is vital to the proposal and assessment of informed public policy initiatives. Government agencies often do not conduct their own in-depth research into key social and political issues governed by policy – rather top academic researchers are called upon to offer their insights into how policy can best serve the needs of the public. University research need not evaluate policy directly to

The Need for University Research Focused on Improving Well-being and Quality of Life

“While the United States provides its people with many opportunities, and represents the largest and most diverse economy among nations, there is no hiding the fact that it is also a country where tens of millions of residents face significant problems and challenges. Over 45 million Americans presently live in poverty, and U.S. life expectancy is just 42nd among all nations. Almost 79 million Americans are obese, and more than 117 million residents have one or more chronic health conditions. Over 87 million people in the nation are worried about having enough money each month to pay their regular monthly bills, and 17.6 million U.S. households are food insecure. We have the highest incarceration rate of any nation, and, if presented with this report, more than 32 million adult Americans would be unable to read it because they are illiterate.”

Battelle. 2015. “Analysis of the Value of Family & Consumer Sciences Extension in the North Central Region.”

³⁴ See: <http://www.nationalacademies.org/memarea/>.

³⁵ Nobel Prize information comes from summary table for the universities maintained on Wikipedia at https://en.wikipedia.org/wiki/List_of_Nobel_laureates_by_university_affiliation. It includes Nobel laureates who may have been faculty at the university, previous visiting faculty or post-docs, and alumni of the subject university.

³⁶ Two were awarded the World Food Prize while at Purdue University for work they did at Purdue, and one is an alumnus.

inform the general discourse around a topic of interest. The ongoing body of research across all disciplines can be utilized to form appropriate policy responses to key issues, and in Indiana, this important societal role is well acknowledged. Indiana University operates the IU Public Policy Institute, with faculty and staff performing research and providing public policy guidance and assistance in: economic development; tax and finance; public safety; criminal justice; housing and community development; and land use and the environment. In 2016, Indiana University-Bloomington was ranked the top U.S. graduate school in Public Affairs by U.S. News and World Report. Public policy is also the subject of research and education at Purdue and Notre Dame.

22. Community, Family and Youth Development

In their communities and states, universities function as central actors. As such, they often serve as a resource to community members and state residents with no formal connection to the university infrastructure. Universities provide public spaces for civic groups and community arts and entertainment projects, and they advocate for community issues. Outreach programs promote family stability, positive parenting practices, and children's educational attainment. In addition, cooperative extension services run by Land-grant universities offer numerous programs designed to address these issues including 4-H, which promotes youth development as well as family and consumer sciences education.

In 2001, The University of Notre Dame began an off-campus educational initiative in partnership with Northeast Neighborhood residents in South Bend called the Robinson Community Learning Center (RCLC). The Center, which serves residents through educational programming and as a gathering place, draws in an estimated 600 participants each week, and hundreds of student volunteers from Notre Dame are matched one-to-one with local children through the Center's tutoring program. The Center also provides a high-quality technology center, and offers classes that include: basic computing, financial literacy, entrepreneurship, advanced skills, and English as a New Language (ENL), which includes a preschool for ENL students. The RCLC staff is part of the Office of Public Affairs at Notre Dame, with programs overseen by an advisory board that includes residents, partners, Notre Dame faculty and staff, and students.

23. Public Health, Wellness and Clinical Care

By applying research findings and best practices, universities offer a range of important public health programs designed to support the health and well-being of community members. Some health services are offered primarily for the benefit of students, faculty, and staff, including on-site clinics specializing in mental health counseling, sex education, and basic physical health services. Universities also offer non-credit education opportunities in public health issues and perform outreach services to community members through clinics, presentations, and online resources.

Indiana's research universities are engaged in a full spectrum of research and service activities in public health, wellness, and clinical care – ranging from SNAP-Ed, nutrition, and health guidance performed by Purdue Extension through to population health and public health research at IUPUI's Fairbanks School of Public Health, and into specialized provision of advanced clinical healthcare services and the Indiana University School of Medicine and Indiana University Health (which operates 15 hospitals with total personnel exceeding 30,000).

As shown above, the functional activities of research universities engender a very broad range of positive impacts and matter greatly to Indiana. And as noted in Chapter I, impacts can be segmented into those having private and/or social returns and impacts having market or non-market returns, which will be considered in Chapter III.

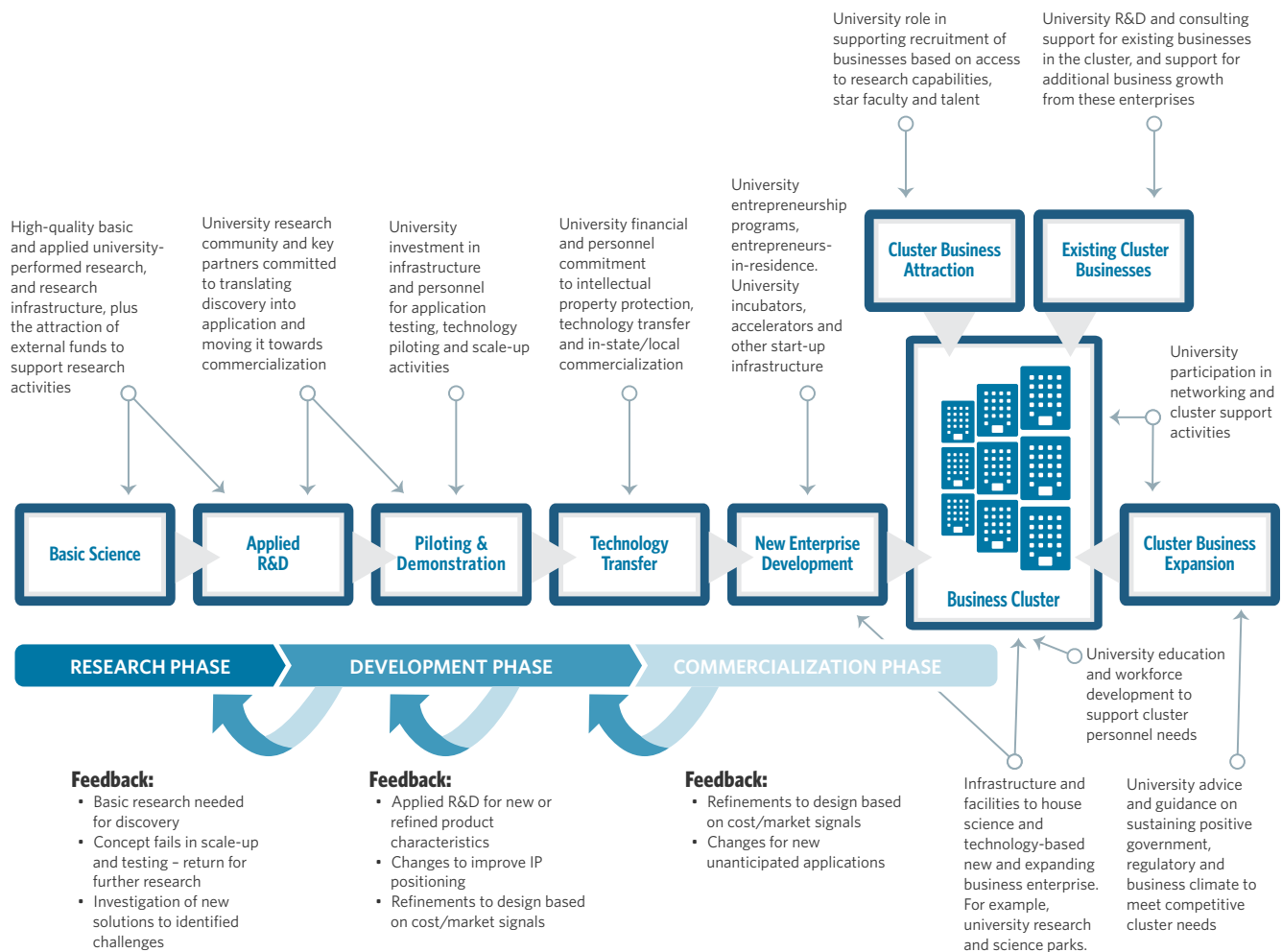
B. Research University Functions in Advanced Economic Development

The TEconomy model of the functional impacts of research universities (Figure 1) highlights four primary impact domains:

- Knowledge expansion and innovation
- Economic development
- Enhanced capabilities of human capital, and
- Societal well-being and quality of life

The economic development domain of research universities (which also draws substance from and is supported by each of the other three domains) clearly holds great importance in modern developed economies that are increasingly driven by technological innovation and the deployment of highly educated, skilled human capital. Sustaining economic progress in the face of intense global competition mandates that a state or region maintain a complete and robust economic development ecosystem. As Figure 5 illustrates, research universities serve critically important functions across each component of a modern economic development ecosystem, and are integral to success in advanced technology-based economic development that is at the forefront of creating high-wage, family sustaining jobs.

Figure 5: The Modern Economic Development Ecosystem and the Integral Role of Research Universities



Long-term, sustained university commitment to R&D and to providing key support for activities across the technology-based economic development ecosystem

Source: TEconomy Partners, LLC

Each element of an advanced economic development ecosystem sees research universities engaged in primary or secondary activities crucial to the function of the ecosystem. Chief among these areas are:

- **Basic Research.** Providing the curiosity-driven inquiry that empowers new discoveries, basic research can lead to the development of novel knowledge or innovation breakthroughs that may then have application to improving or powering downstream economic activity. Basic research can also lead to fundamental innovations that may drive the development of new industries.
- **Applied Research.** The bed-rock of technology-based economic development progress. As attested to by the clusters of companies formed around Stanford University, MIT, the University of California San Diego, University of Texas at Austin, Carnegie Mellon University, Purdue University and many others, applied research leverages the knowledge and specialized research infrastructure of universities to solve real-world challenges and derive economic growth from commercialization of applied innovations. Applied research may be funded by federal or other external grants, but it may also be performed on a contract basis for, or in collaboration with, regional industries that need to find solutions to challenges and improve their products.

- **Piloting and Demonstration.**
Most new technologies have to be advanced through a piloting and demonstration phase in which the innovations stemming from basic and applied research are evaluated through proof-of-concept and testing at a pilot scale. Research universities have invested in the specialized scientific infrastructure and facilities and often pilot-scale technologies needed to advance technologies through testing and onwards into the early stages of commercialization. Universities do this with their own discoveries, but also serve an important role in providing industry with access to the specialized university infrastructure required to test and pilot new technologies and process improvements.

- **Technology Transfer.**
Intellectual property refers to creations of the mind such as: technological

The Role of the University in Regional Economic Development: The University of Notre Dame and the Regional Development Authority for North Central Indiana Capture Regional Cities Award

The Indiana Regional Cities Initiative, created by then-Governor Pence, aims to bring Indiana communities together with the goal of attracting and retaining talented Hoosiers. In 2015, the initiative attracted seven Indiana regions to collaborate around bold strategic regional development plans that included over 420 distinct projects designed to advance the goals of Regional Cities. Phase 1 of the Initiative awarded \$126 million in \$42 million tranches of matching funds to support the development plans of three winning regions.

The initiative provided a new opportunity for Indiana counties to work together to think regionally, and to craft a coordinated economic development plan that could serve varied geographies and constituents. Notre Dame played a vital role in advancing the regional plan as a “neutral” party and effective convener among the varied political and government players that often compete for economic development opportunities in North Central Indiana. As an anchor institution in the region, Notre Dame has a vested interest in promoting regional economic development.

One of the three major Regional Cities grants was awarded to the North Central Indiana team, recognizing the effective regional collaboration across the region representing 22 cities and towns in Elkhart, Marshall, and St. Joseph counties. The region, through its Innovate Indiana Plan, has implemented economic development projects that have thus far generated \$390 million in investments, representing a 10:1 match.

“Regional Cities has already led our communities to collaborate in unprecedented ways and going forward, our responsibility is to further galvanize this newfound regionalism, as we work together to create a vibrant, thriving economy in all of the South Bend-Elkhart region.”

- John Affleck-Graves, Executive Vice President of the University of Notre Dame and member of the Regional Development Authority for the North Central Region of Indiana.

inventions; literary and artistic works; designs; and symbols, names and images used in commerce. Within research universities, intellectual property (especially tangible scientific and technological innovations) is identified through internal Invention Disclosures that are then evaluated for commercial potential in terms of deciding whether to pursue formal legal protections, typically in the form of a patent. Purdue University, for example, is in the top performing quintile in terms of university invention disclosures and patents awarded. The value of intellectual property for regional and state economic development is realized when the innovation is: sold or licensed to a regional industry for commercialization (where it may form a new product line or improve existing products or processes, thereby increasing competitiveness); sold or licensed to external companies (with revenues then flowing to the university to support further R&D and tech transfer activity); or sold or licensed to a new business formed in the state to realize the commercial potential embodied in the innovation. Research universities operate technology transfer offices to evaluate inventions, and file for intellectual property protections.

- **New Enterprise Development.** In multiple ways, research universities facilitate the start-up of new business enterprise. Faculty, staff, and student innovations may be commercialized, and universities facilitate that process by providing access to IP and via: entrepreneurship development and advisory services; facilitating and providing access to early stage pre-seed and seed capital; providing access to university infrastructure and resources on favorable terms to the start-up; and providing access to university-operated business incubators, accelerators or research park space. Some universities provide faculty-leave programs to encourage engagement in start-ups, and some universities also invest directly in university start-ups, taking an equity position or providing other financing options.
- **Industry Attraction and Expansion.** Both in terms of providing access to skilled, highly-educated human capital, and in terms of being hubs for accessing technology, science and technology infrastructure, and specialized assets, universities are key attractors for firms across multiple sectors. Universities also are important research collaborators for existing industry, providing opportunities for collaborative industry R&D and technical consulting services, and many industries cluster near universities to become part of robust tacit knowledge and innovation networks.

Because of the core role research universities play in technology-based economic development and cluster-based economic development, states and regions across the nation are increasingly grounding their economic development strategies around the objectively identified R&D core competencies of their universities. This economic development phenomenon works to align R&D core competencies with established or emerging industry clusters able to leverage them in application areas with an observable line-of-sight to significant markets with strong growth potential. Indiana has been one of the states in the forefront of this movement with the Central Indiana Corporate Partnership and other stakeholders identifying university and industry core competencies in life sciences, agriculture, energy, manufacturing, and logistics around which focused economic development initiatives and collaborations have formed.

CONCLUSION: Research universities serve a critically important role in supporting the operations of modern economic development ecosystems. University activities in R&D, education, technology transfer, new business development, and support for existing and inward investor companies are strong contributors to the formation and successful operation of a comprehensive technology-based economic development ecosystem. This leads to expanding regional wealth and the creation of high-paying jobs associated with established and emerging advanced industry sectors.

The medieval university looked backwards; it professed to be a storehouse of old knowledge. The modern university looks forward, and is a factory of new knowledge.

- Thomas Henry Huxley.

Chapter III: Social/Private and Market/ Non-Market Returns to Research Universities

A. The Structure of University Returns

As shown in Chapter II, research universities bring a wide range of high-value functions to the world, the nation, individual states, regions, and communities. University functions generate benefits that can be broadly classified as:

- **Social or Private:** Impacts that accrue to the benefit of society or the economy as a whole, or to specific sub-populations or groups (for example, enhanced public health or economic growth) vs. impacts that accrue to the benefit of individuals (for example personal longevity or enhanced earning potential from having a graduate degree).
- **Market or Non-Market:** With market benefits being those that have monetary value associated with them vs. non-market being impacts that are not primarily monetary in nature.

In an October 2013 paper, the UK Government's Department for Business Innovation and Skills (BIS) examined the private/social and market/non-market returns of higher education.³⁷ The BIS authors note that "the report covers only benefits from HE [Higher Education] participation, so that benefits arising from research exploitation, spin-off companies, export earnings through international student fees and spending, and other aspects of HE are not included." Despite the focus on education, and not research, the BIS report provides a useful "two-way taxonomy of benefits, with individual/society as one dimension and market/non-market (or wider) benefits as the other."³⁸

Figure 6 recreates the key quadrant graphic from the UK BIS report serving to summarize key benefits of higher education observed in the BIS team's review of data and the research literature.

³⁷ Department for Business Innovation and Skills. 2013. "The Benefits of Higher Education Participation for Individuals and Society: key findings and reports." October 2013, BIS Research Paper No. 146.

³⁸ *Ibid*

Figure 6: “The Quadrants.” The market and wider benefits of higher education to individuals and society³⁹



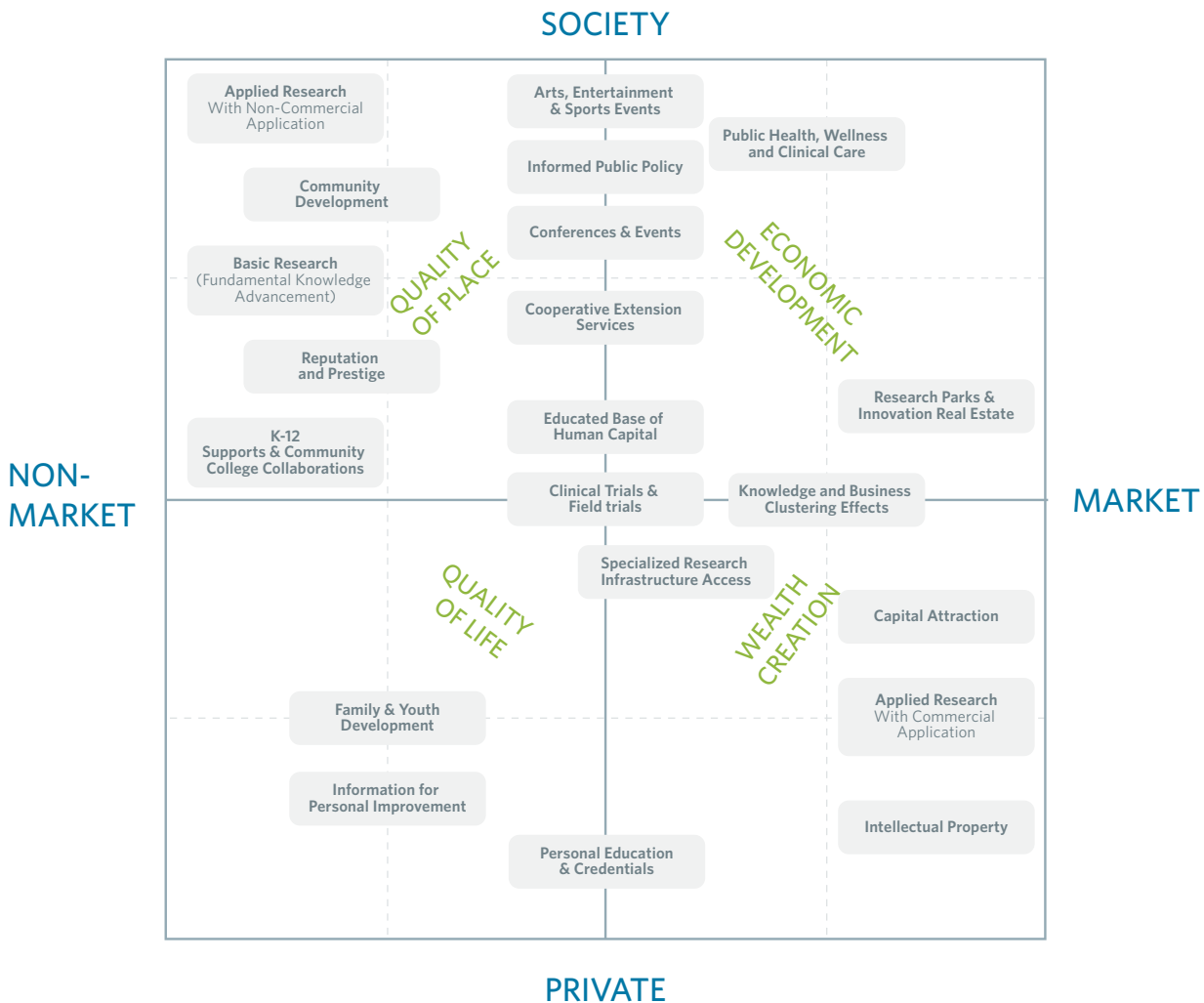
A similar two-way taxonomy of benefits can be deployed in summarizing the full scope of benefits provided by research universities overall as identified in Figure 1 and discussed in Chapter II (i.e. not just in terms of higher education). Figure 7 does this, providing a subjective placement of each TEconomy identified university function on a quadrant graphic, and it is evident that many of the functions provided by research universities carry multi-faceted aspects that are a fit to multiple quadrants. Overall, it is clear that research universities have equally robust impacts on the market and non-market dimension. Social benefits predominate on the social/private dimension except in relation to the commercialization of research findings and consultations (whereby benefits are largely to be realized by private investors) and private returns to the education earned by graduates. As noted in Chapter I, **the significant base of non-market impacts provides a strong argument for why public investment in research universities should be a high priority, as does the pathway through the basic-to-applied research realm that may result in commercializable innovations that will benefit national, state, and local economic development.**

³⁹ Graphic adapted from the Department for business Innovation and Skills. (UK) 2013. “The Benefits of Higher Education Participation for Individuals and Society: key findings and reports.” October 2013, BIS Research Paper No. 146.

It is also evident that each of the quadrants can be distinguished with a descriptive title that captures most of the impact themes contained therein -- namely:

- Non-Market/Social = University impacts on **Quality of Place**
- Non-Market/Private = University impacts on **Quality of Life**
- Market/Social = **Economic Development**
- Market/Private = **Wealth Generation**.

Figure 7: Quadrant Placement of Research University Functional Impacts.



Source: TEconomy Partners, LLC

CONCLUSION: Investment in research universities produces both social and private returns, and market and non-market returns. Placing functional impacts on a four-quadrant grid with social/private and market/non-market impact axes shows robust benefits in terms of economic development and growth, wealth creation, individual quality of life, and quality-of-place (especially at a state/regional level). Social returns are strong, again illustrating the importance of and return on public investment in research universities.

Investment in American research universities provides a wide-ranging and substantial portfolio of benefits for society, for the economy, and for individuals. A review of each of the functional impacts shown on Figure 7 reveals the fingerprints of research across most of these impact areas. Research is providing benefits to the overall economy, and in the generation of wealth to invest in new venture formation and business growth. Research is also improving the quality of American society and the quality of life realized by individual Americans. **These benefits of research present a strong argument for ongoing support for research and, as noted earlier in this report, the public rate of return is so strong that significantly enhanced levels of public investment would be very much justified.** The previously cited work of Luke Georghiou supports this conclusion noting that:

Numerous studies have addressed the rate of return on public investment in research by tracing the linkages between research and innovations in the market across a variety of industries. The methodologies individually raise some questions but the strong consensus is that the rate of return is high. According to most studies, the overall value generated by public research is between three and eight times the initial investment over the entire life cycle of the effects. When calculated in terms of annual rates of return, the median values are in the range between 20% and 50%. Other studies have investigated the proportion of innovations which could not have been introduced without the contribution of public research and again have found a high share, typically between 20% and 75%.⁴⁰

Research also indicates that academic research and industrial research do not occur in respective vacuums, but rather, there is considerable complementarity between public and private R&D. Analysis conducted by Jeaumotte and Pain, reported in Georghiou⁴¹, examined research in 20 OECD countries across a 20-year time period, and concluded that there is “clear complementarity between public sector R&D and business sector R&D, with public sector R&D influencing business R&D at the level of the economy as well as being reflected in patenting.” Georghiou further notes:

Another dimension of complementarity between investment in research and private sector R&D arises from the attraction it exerts for internationally mobile R&D, a “crowding-in” effect. Factors such as the prospect of high quality collaborators, recruitment opportunities and technology transfer infrastructure feature variously in such studies. All sources of evidence point to a central contribution from research to economic growth. However, they also emphasise that this contribution only is realised when certain framework conditions apply. Excellence in research is one such condition, the existence of effective channels for knowledge flows and mobility of people is a second and a high absorptive capacity in industry (or other users) is a third.⁴²

CONCLUSION: Public and private research, and university and industry research, do not exist in separate vacuums. They are part of a complementary holistic research ecosystem that achieves results for the economy, for society and for individuals through symbiotic relationships and knowledge interactions.

⁴⁰ Luke Georghiou. 2015. “Value of research.” Policy Paper by the Research, Innovation and Science Policy Experts (RISE) for the European Commission. Published June 2015. EUR 27367EN. Accessed online at: https://ec.europa.eu/research/innovation-union/pdf/expert-groups/riase/georghiou-value_research.pdf

⁴¹ Ibid

⁴² Ibid

B. Motivations and Drivers for Research at Research Universities and the Benefits Derived

In examining the role of research universities in society, it is informative to consider the motivations and drivers influencing the undertaking of university research activity. Put another way, the question would be “why is academic research performed?”

A simple model is to consider research driven from two different perspectives or directions that we can call “academic push” and “challenge pull.” Academic push represents research that extends the knowledge of an academic discipline – working to investigate basic or applied research questions. This can include, but be not limited to, blue sky, free-ranging research driven by academic curiosity. Challenge pull represents externally-oriented challenges, needs, and questions brought to the university community for the purpose of researching solutions. Table 4 provides a summary of multiple motivations for performance of research under this two-part model, and the broad spectrum of motivations has implications when considering the operations of the university research ecosystem.

Table 4: Examples of Motivations and Drivers for Performing Research

Academic Push – Drivers and Motivations	Challenge Pull – Drivers and Motivations
<ul style="list-style-type: none"> ▪ Expand boundaries and knowledge of an academic discipline. ▪ Investigate fundamental questions. ▪ Generate publications to meet promotion, tenure, and career development expectations. ▪ Graduate student research to meet requirements for degree (e.g. thesis or dissertation) ▪ Faculty seeking research funding to sustain graduate students and their financial support. ▪ Production of intellectual property and value realized from it. 	<ul style="list-style-type: none"> ▪ Societal and scientific grand challenges. ▪ Federal funding agency priorities. ▪ Calls for proposals by foundations, agencies, non-profits, and other organizations. ▪ Applied questions posed by industry consortia and individual companies. ▪ External research requiring access to university instrumentation, facilities, and associated expertise.

Funding agencies wield significant influence over the research environment through setting thematic priorities for their funding. Because the vast majority of university-performed research is funded by external organizations (e.g. federal, state, foundation, and industry sponsored research), these funders can exert directional influence on research by specifying priorities that will be given preference in review of proposals. Some examples serve to illustrate this:

- The National Institute for Food and Agriculture (NIFA) has prioritized six National Challenge Areas and is also influenced by six Priority Areas designated by Congress in the 2014 Farm Bill.
- Under the National Institutes of Health (NIH), individual Institutes have a series of designated priority areas given preference in research. In addition, the NIH Roadmap Initiative and the NIH Clinical and Translational Science Awards (CTSAs), of which Indiana has received one, have emphasized research proposals focused on accelerating translational research, whereby basic research findings are accelerated from the “bench to the bedside”.
- Large philanthropies and foundations, such as the Bill and Melinda Gates Foundation, express priorities for their funding such as improving the status of the world’s poor, combatting global infectious diseases, and improving educational attainment, for example. In Indiana, the Lilly Endowment has a strategic, city- (Indianapolis) and state-focused set of priority causes it funds via grant awards that include religion, education, and community

development. The Endowment has funded major projects and initiatives at Indiana's research universities including grants/donations to expand advanced technology infrastructure, to promote intellectual capital across Indiana, and to fund scholarships for Hoosiers.

- State government agencies may often create funds to support university research, or joint university-industry research, geared towards supporting the growth of identified industry clusters – seeking to drive technology-based economic development.
- Many non-profit funding organizations, especially in relation to human health and medical conditions, are specifically geared to support research in a narrow-band of focused inquiry often around an individual disease or medical condition.

An illustrative example of a federal agency guiding research proposals towards priorities can be seen in this statement by the NIH National Institute of Mental Health (NIMH):

NIMH has highlighted several cross-cutting themes in the Strategic Plan which investigators are strongly encouraged to consider in proposed studies, including the Research Domain Criteria (RDoC) project, the Brain Research through Advancing Innovative Neurotechnologies (BRAIN) Initiative, and the Institute's experimental therapeutics approach, in which 'targets' refer to hypothesized mechanisms of action and their ability to modify disease, behavior, or functional outcomes, and in which the underlying assumption is that modification of the target will result in improvement of symptoms, behavior, or functional outcomes. Equally important cross-cutting themes include the role of the environment, prevention through early intervention, consideration of sex as a biological variable, mental health disparities, and the importance of maintaining a global perspective on mental health.⁴³

Funding priorities of agencies can also influence the structure of research performance and encourage collaborations and transdisciplinarity. For example, the Engineering Research Centers (ERC) program of the National Science Foundation (NSF) specifically awards significant grants which “operate at the interface between the discovery-driven culture of science and the innovation-driven culture of engineering. They provide a venue where industry can work with faculty and students on resolving long-range challenges, producing the knowledge needed for steady advances in technology and their speedy transition to the marketplace.”⁴⁴

Universities themselves will often facilitate academic push initiatives, particularly for younger, early-career faculty. Using funds from endowments, gifts, and from the university general operating funds, universities may operate internal grant award programs that allow early-career faculty to build their research portfolio, develop their reputation in a line of inquiry, and improve their resume and competitiveness for acquiring external grants. Land-grant universities (including Purdue) also have the advantage of receiving “capacity funds” from USDA-NIFA which are formula-based funds that have considerable flexibility for allocation to faculty research. Universities with a major clinical practice element in their academic medical centers can also cross-subsidize research with funds from clinical revenues – again providing flexibility to pursue research independent of external funding source priorities.

The prevalence of funding in one area versus another will exert gravity on the academic research community towards large-scale funding. This exertion is particularly evident in the proportion of overall research funding in the United States that is applied towards medical research, where a high percentage of U.S. research funding is presently directed. Funding availability and priorities exert considerable force on the structure, function, and direction of academic disciplines.

⁴³ NIMH. *Strategic Research Priorities Overview*. 2016. Accessed online at: <https://www.nimh.nih.gov/about/strategic-planning-reports/strategic-research-priorities/index.shtml>

⁴⁴ <http://erc-assoc.org/>

U.S. University R&D Funding in Perspective

The volume of R&D activity performed at U.S. academic institutions is extremely large – projected to see \$75.2 billion in 2017 R&D funding. This is second only to industry funding in terms of scale. Table 5, from R&D Magazine’s 2017 Global R&D Funding Forecast, shows the federal government as the largest source of funding for academic research (\$38.5 billion, or 51.2%), followed by self-funding by academic institutions themselves (via endowments, gifts or cross-subsidization from sources such as clinical revenues) at \$19 billion (25.3%), other government sources (typically state government, but not exclusively) at \$7 billion (9.3%), non-profits (such as foundations) at \$5.5 billion (7.3%) and industry at \$5.2 billion (6.9%).

Table 5: 2017 Global R&D Funding Forecast: U.S. R&D Source/Performer Matrix⁴⁵

Funding Source ↓	R&D Performer					
	Federal Gov't	Industry	Academia	FFRDC (Gov't)	Non-profit	Total
Federal Gov't	\$43.2	\$30.0	\$38.5	\$15.5	\$6.0	\$133.2
Industry		\$336.8	\$5.2	\$3.6	\$2.1	\$347.7
Academia			\$19.0	\$0.3		\$19.3
Other Gov't			\$7.0			\$7.0
Non-profit			\$5.5	\$0.1	\$14.7	\$20.3
Total	\$43.2	\$366.8	\$75.2	\$19.5	\$22.8	\$527.5

Compared with the national average for all U.S. universities (Figure 8), Indiana’s university R&D expenditures are financed to a lesser degree by the federal government. In 2015, federal funds (as a share of all sources) were 41 percent for Indiana compared with the national average of 55 percent, and Indiana institutions are relying more on institutional funding (such as endowment funds, gifts, and cross-subsidization from clinical revenues) as a source for R&D activities. Other sources of funding are generally in line with national average shares.

Underlying this overall composition, however, are varying funding structures across the numerous fields for which NSF surveys. In Indiana, numerous academic fields have a relatively high concentration of federal funding relative to the national average including disciplines such as:

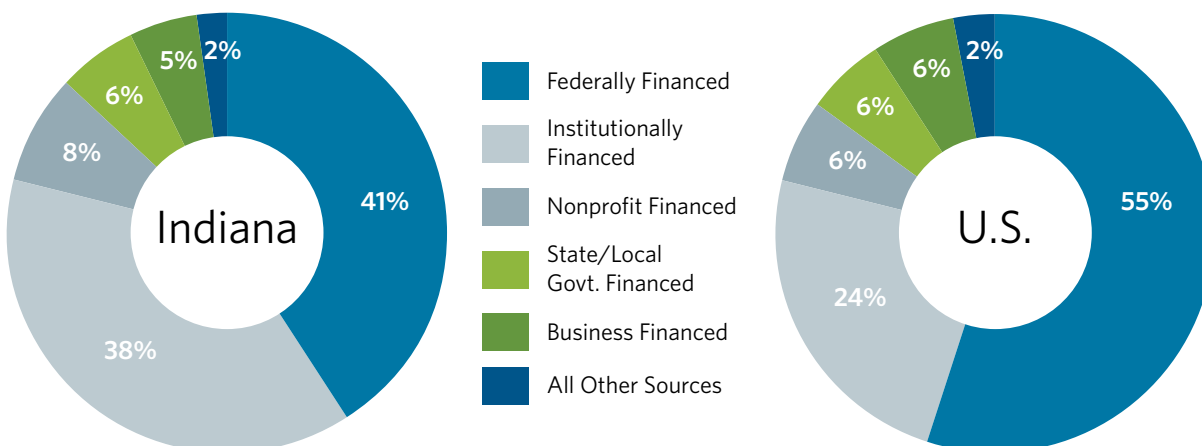
- Aeronautical and Astronautical Engineering
- Business and Management
- Political Science

Other disciplines in Indiana are highly concentrated in their R&D funding by industry, including:

- Agricultural Sciences
- Chemistry
- Computer Sciences
- Electrical Engineering
- Mathematical Sciences
- Mechanical Engineering

⁴⁵ R&D Magazine. "2017 Global R&D Funding Forecast." Accessed online at: http://digital.rdmag.com/researchanddevelopment/2017_global_r_d_funding_forecast?pg=1#pg1

Figure 8: Sources of Funding for University R&D Expenditures, Indiana vs. U.S., 2015



Source: National Science Foundation, Higher Education Research and Development Survey.

CONCLUSION: While universities represent individual communities of faculty and research professionals, with extremely broad skills and interests, they work within a research ecosystem that is very much influenced by funding and the priorities of external funding agencies.

No man is an island entire of itself; every man is a piece of the continent, a part of the main...

**- John Donne
1624. MEDITATION XVII.
Devotions upon Emergent Occasions**

Chapter IV: Research at Signature Research Universities

University research and higher education have a long-standing tradition of being conducted under the structure of academic disciplines which comprise thematically bounded fields-of-study. A detailed understanding of the structure of a university cannot be achieved without recognition of disciplines and their power. Defined not only by their field of study, disciplines are also defined by their tradition and history of inquiry, a collective understanding of what constitutes “new knowledge” in the field, and generally accepted practices that define how research questions are posed, data collected, and results interpreted. Disciplines are also characterized by having their own knowledge networks, comprising publishing outlets (academic journals) and academic conferences. Traditionally, universities organize disciplines under individual academic departments, which, in turn, are organized into related colleges (for example, departments of electrical engineering, civil engineering, and mechanical engineering all under an overall college of engineering structure).

A university is a collection of individual faculty scholars who have a degree of intellectual freedom to pursue their interests (within the bounds of research funding realities, as discussed in the previous chapter). From a research perspective, the disciplinary structure of universities has the advantage of exerting a *de facto* set of standards and rigor upon faculty and other scholars in the performance of research in their disciplinary domain. The accepted model of peer review for senior academic journals in each discipline provides a robust level of quality control without overly stifling creativity and novel approaches to work. Similarly, presentations at academic conferences expose researchers to reactions, critique, and questions regarding their work that both serve as a check on quality and provide input to lines of further inquiry.

This disciplinary structure of academe is long-established and carries with it substantial advantages (see sidebar). It is not, however, a perfect system and there are disadvantages associated with it. A core challenge of this traditional structure for modern research occurs in interdisciplinary or transdisciplinary⁴⁶ research inquiry domains, where the boundaries of disciplines become blurred or individual scholars need to interact in teams comprised of multiple disciplines where members have different traditions, modes of inquiry, communications protocols, and promotional structures. As noted by Simon Tripp in a report for the State of North Carolina and North Carolina State University:

“The tradition at universities across the United States is for the academy to be partitioned into distinct colleges and departments in a system of independent and distinct academic disciplines. This traditional model concentrates faculty, and their students, into relatively inward looking siloes of inquiry focused on the specialized content of their discipline. Judging by the advancements made in science, engineering, social science, the humanities, arts, and other areas of university academic research the model has been a success. Humankind has advanced in knowledge, fundamental scientific understanding, and technological development upon the back of this traditional academic structure – used not only in the United States, but almost universally worldwide in higher education systems. It is a system particularly well-suited to the training of the next generation of academicians through the close mentorship of faculty in their discipline and to supporting evaluation of faculty for advancement through the judgment of their peers. The system serves to create tight-knit communities of academic inquiry.”

Simon Tripp. 2015. “North Carolina Plant Science Initiative: Governance White Paper.”

North Carolina State University

⁴⁶ While the terms multi-disciplinary, inter-disciplinary and trans-disciplinary have separate meanings, the colloquial use of these terms is often interchangeable. TEconomy uses the term “interdisciplinary” throughout this report to refer to an environment of science in which multiple scientist/faculty work together on a common team to advance a research initiative, and an environment in which these faculty may come from multiple academic colleges, departments, and individual academic disciplines. An article in *Science*, by Elizabeth Pain, provides a description of the semantic differences in terms, noting that: “Multi- (or pluri-) and interdisciplinary research are often used interchangeably, but originally they referred to different approaches. When experts from different fields work together on a common subject within the boundaries of their own discipline, they are said to adopt a multidisciplinary approach. However, if they stick to these boundaries they may reach a point where the project cannot progress any further. They will then have to bring themselves to the fringes of their own fields to form new concepts and ideas--and create a whole new, interdisciplinary field. A transdisciplinary team is an interdisciplinary team whose members have developed sufficient trust and mutual confidence to transcend disciplinary boundaries and adopt a more holistic approach.” http://sciencecareers.sciencemag.org/career_magazine/previous_issues/articles/2003_01_03/nodoi.16570029665485298080

While there are certainly advantages to the traditional academic department model, there is increasing recognition that many of the leading challenges and questions in academic inquiry are of a level of complexity that any one discipline lacks the scope of inquiry required to adequately address the challenge. Often comprising challenges that are multidimensional and systemic, many grand challenges require the application of interdisciplinary team science. There are many varieties of such challenges, for example:

Discovery Park at Purdue University: Interdisciplinary Approaches to Solving Global Challenges

The global grand challenges facing societies today are highly complex and require the attention and focus of the world's best scientists and thought leaders across numerous disciplines. Recognizing the need to break down the silos so ingrained within traditional university structures, Purdue University has developed Discovery Park, a 40-acre complex on the edge of Purdue's main campus to integrate scientists across disciplines in a collaborative research environment. Collaborative teams at Discovery Park include not only academics, but also policy makers and business leaders coming together to address major challenges.

Discovery Park is addressing and leveraging the powerful convergence of disciplines and technologies in an effort to address global challenges by bringing together the deep strengths well established at Purdue across the "strategic themes" of STEM, Advanced Instrumentation, Nanotechnology, Social and Behavioral Sciences, Big Data/Simulation/Cybersecurity, Entrepreneurship, and Complex Systems. In uniting these disciplines within some of the most advanced facilities on any university campus, the strengths are designed to propel solutions to challenges in global health, global sustainability, and global security.

- *Understanding and modeling the potential physical and biosphere impacts of global climate change: requiring expert input from climatologists, physicists, geographers, oceanographers, mathematicians, hydrologists, soil scientists, plant scientists, botanists, zoologists, and environmental scientists (to name just a few).*
- *Approaches to geriatric medicine and end-of-life care requiring the management of complex interactions of clinical symptoms (including biochemical, neurological, endocrine, immune, and psychological status) together with ethics, public health, social work, and other disciplines.*
- *The development of advanced prostheses for amputees and assistive devices for the disabled that integrate neuroscience, biophysics, materials science, electrical engineering, mechanical engineering, computer science, and rehabilitation medicine.⁴⁷*

While the complexity of many academic research questions is promoting a growth in multi-disciplinary approaches, it is still the case that the majority of work in academic research falls under the rubric of individual academic disciplines. Purdue University, however, is in the vanguard of developing new physical and organizational academic structures to facilitate multi-disciplinary research (see sidebar). Similarly, Indiana University is promoting multi-disciplinary

research through its \$300 million Grand Challenges Program, launched in 2015. The most recent investment by Indiana University is called "Prepared for Environmental Change", investing \$55 million to help "Indiana develop actionable solutions that prepare businesses, farmers, communities, and individual Hoosiers for the effects of ongoing environmental change."⁴⁸ Notre Dame is similarly focusing their research resources strategically to address global challenges in rare and neglected diseases, for example (see further discussion on page 74 in Chapter V).

CONCLUSION: Academic disciplines form the foundation of the research ecosystem in terms of thematically bounded fields of study. This disciplinary model has served society well, but the complexity of science and an expanding recognition of the complexity of grand challenges is producing an increasing emphasis towards transdisciplinary, team-science oriented research.

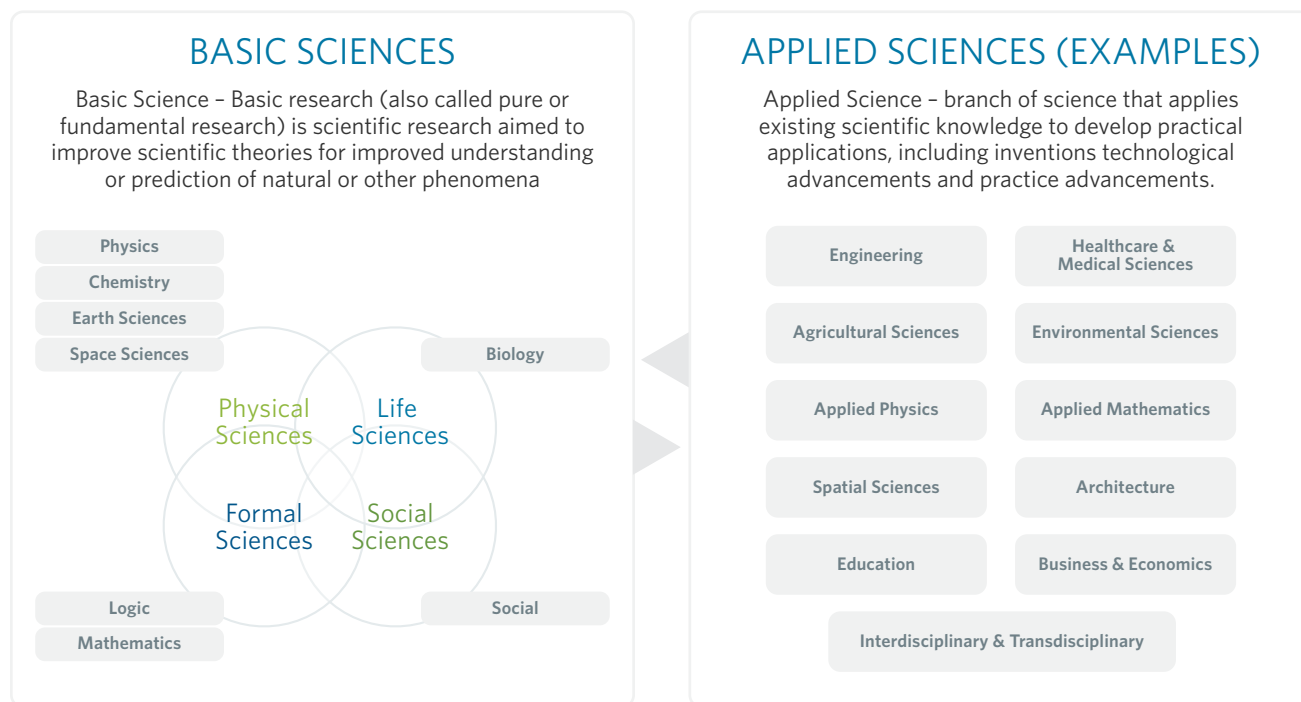
⁴⁷ Simon Tripp. 2015. "North Carolina Plant Science Initiative: Governance White Paper." Battelle Technology Partnership Practice for North Carolina State University and the State of North Carolina. March 2015.

⁴⁸ Indiana University Press Kit. "Grand Challenge – Prepared for Environmental Change." Accessed online at: <https://news.iu.edu/media-kits/IUGrandChallengesPressKit.pdf>

A. The Structure of Disciplines, Scientific Fields, and Domains of Inquiry

Explaining the content, focus, structure, and pedagogy of each academic discipline is beyond the scope of this report; however, it is informative to provide an overview of the general structure of scientific disciplines given their overall dominance in research funding and research performance. A useful, albeit imperfect, view of the domains of scientific research and associated disciplines is provided in Figure 9, in which TEconomy uses a simple taxonomy that divides these into basic and applied science fields. The work in basic sciences can be viewed as forming the foundation upon which the content of applied work is built. While this appears to depict a linear research continuum – moving from left to right, from basic discovery to applied research application – the reality is that the line between is actually rather blurred and that ideas for basic research inquiry are often identified during the performance of applied research. In other words, it is not one way: basic and applied research forms a two-way street.

Figure 9: Depiction of Basic and Applied Science Domains and Disciplines



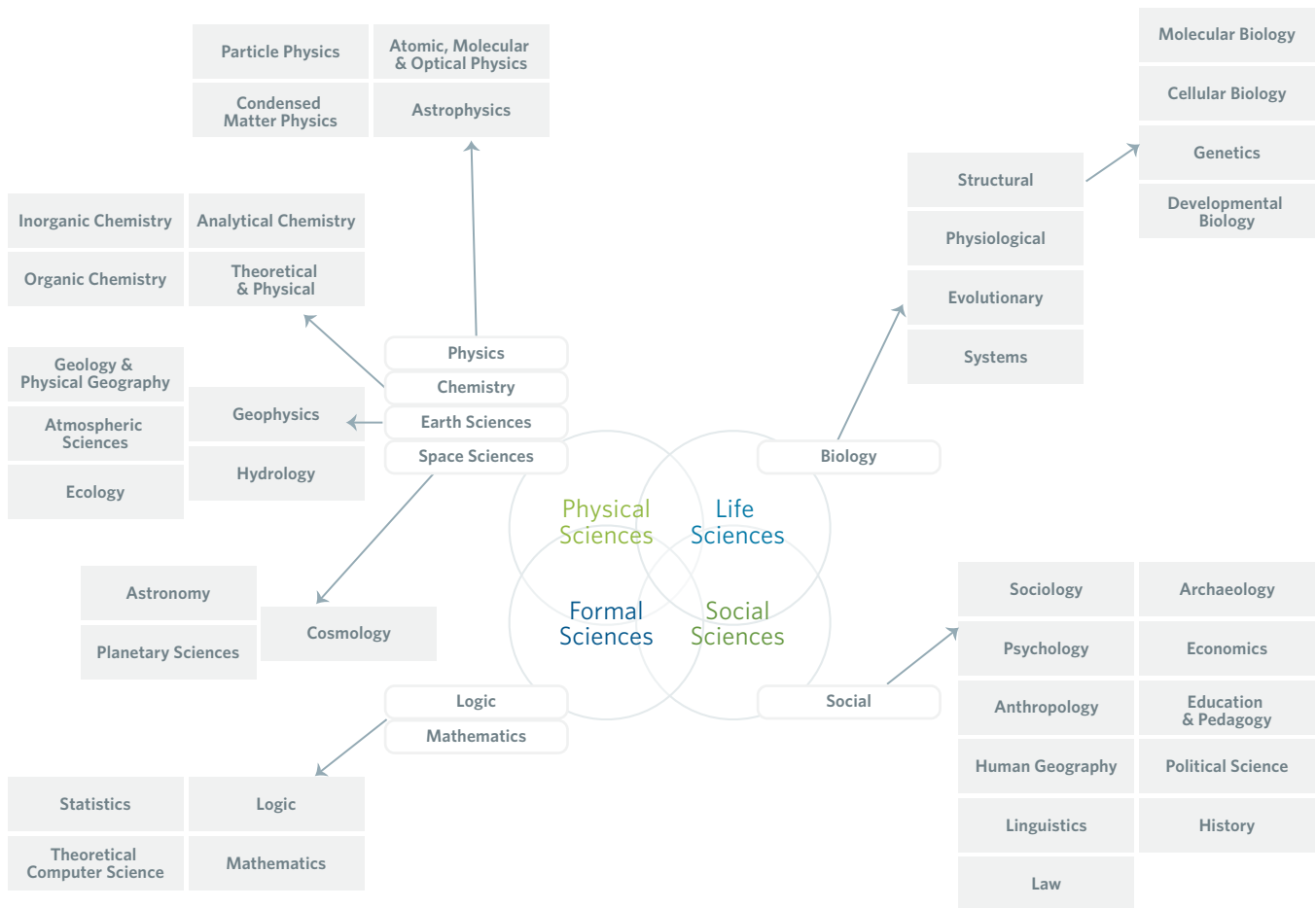
Source: TEconomy Partners, LLC.

As Figure 9 shows, the basic sciences are structured under four principle categories: physical sciences; life sciences; formal sciences; and social sciences. These are deliberately depicted in a Venn diagram because fundamental knowledge in one category may be leveraged for discovery within another, for example:

- Basic knowledge from physics used in understanding bio-physics processes in biology.
- Fundamental mathematical principles being used in mathematical modeling of physics phenomena.

In Figure 9, basic sciences are simplified for illustrative purposes, but they actually break-out further into disciplines and sub-disciplines in a more detailed taxonomy, as show in Figure 10:

Figure 10: Depiction of Basic and Applied Science Domains and Disciplines



Source: TEconomy Partners, LLC.

Physical Sciences and Life Sciences are sometimes classified together under the term “Natural Sciences”, providing macro-level taxonomy of:

- **Natural Sciences.** The branch of science that seeks to explain and predict nature’s phenomena, based on empirical evidence. In natural science, hypotheses must be verified scientifically to be regarded as scientific theory or a physical law. Peer review and repeatability of findings are amongst the criteria and methods used to advance work to the level of theories. Natural science can be broken into two main branches: biology and physical sciences.
- **Formal Sciences** – Comprising branches of knowledge that are concerned with formal systems such as: logic, mathematics, theoretical computer science, information theory, game theory, systems theory, decision theory, statistics, and certain aspects of linguistics. Unlike other sciences, the formal sciences are not concerned with the validity of theories based on observations in the real world, but instead with the properties of formal systems based on definitions and rules.
- **Social Sciences** – Comprising the study of people in society and how they relate to one another and to the group to which they belong. The scientific method is utilized in many social sciences, albeit adapted to the needs of the social construct being studied. Individual branches of social science address different components of society and social structures, e.g. sociology, psychology, economics, political science, history, or anthropology.

As noted above, it may be useful to depict research as either “basic” or “applied” in a simple classification scheme, but in reality, the fields and disciplines of science, and academic research overall, interact with one another to form a research ecosystem. Discoveries in one area influence another, and a basic discovery may, initially,

have no practical application only later to lead to very profound and wide-ranging applications. Research into an applied area, such as agricultural crop improvement, may uncover multiple plant viruses that spur basic research to uncover their microbiome and mechanisms of plant-microbe symbiosis. Applied research in the development of devices and scientific instruments is useful in enabling and powering basic experiments. In actuality, **what exists is a massive cocktail or mélange of theories, knowledge, and constructs (operating in a complex research ecosystem) that build-upon one another, inform one another, and make possible a constant advance in the boundaries of human progress.**

A basic discovery may initially have no practical application only later to lead to very profound and wide-ranging applications.

CONCLUSION: Academic disciplines form the foundation of research inquiry and they must be understood in the context of being components of an overarching and complex research ecosystem where advancements in one discipline inform another.

Figure 11 illustrates how time also needs to be a component in a model understanding of academic research.

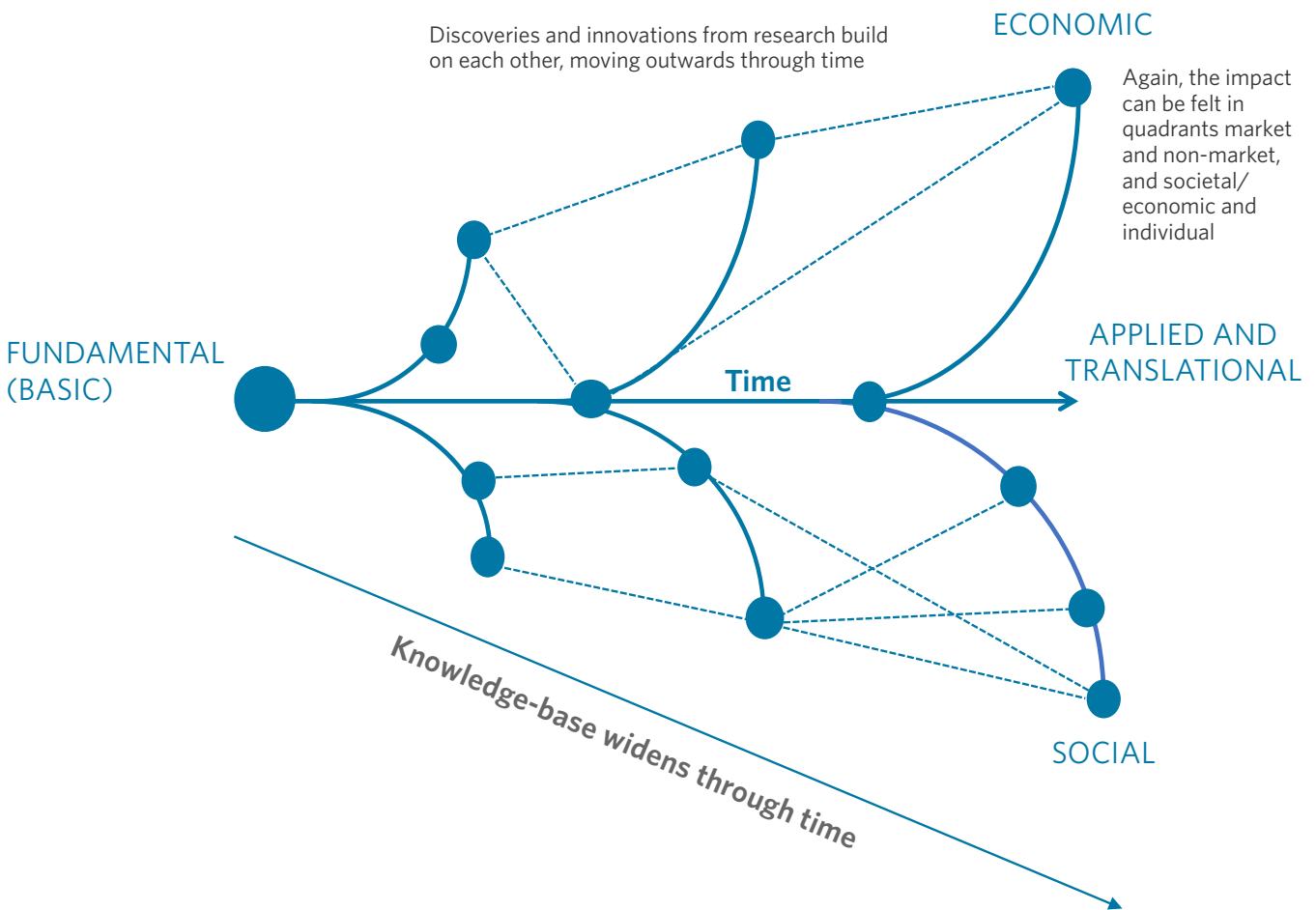
Although a basic science discovery may lead to applied or basic innovations in its own and other disciplines, these innovations then branch out further, intersect and interact over time, expanding our universe of understanding and generating applications. The laser example on page 4 is a prime illustration of this interaction in action. Another example, one local to Indiana, is that of Professor Julius Arthur Nieuwland, at the University of Notre Dame, whose basic research in acetylene chemistry led to him discovering synthetic rubber. Dr. Elmer Bolton, a scientist working with DuPont, attended a lecture by Professor Nieuwland and DuPont subsequently purchased the patent rights from Notre Dame and undertook commercial development of the discovery in collaboration with Professor Nieuwland. The result was the commercialization of neoprene (see sidebar on page 49). Another example of basic science discovery leading to later applications is that of the late Albert Overhauser, a member of the Purdue physics faculty, who discovered what is now known as the Overhauser Effect: the possibility to line up, or polarize, nuclear spins at a much larger scale than previously thought possible. Overhauser’s discovery revolutionized the field of nuclear magnetic resonance, including MRI’s for medical diagnosis. And although he conceived the effect in the early 1950’s, the idea was so unexpected that physics authorities originally rejected it. Later experiments in 1953 by Slichter and Carver demonstrated the effect, leading to it becoming accepted. Along with MRI, the basic discovery of the Overhauser Effect has been used in nuclear magnetic resonance for higher energy physics, chemistry, and biology to determine, for example, the structure of proteins and other molecules.

An original discovery can have an effect similar to that of a pebble thrown into a pond, with ripples of knowledge and application forming and moving outwards through time. But those ripples (waves) can reach the pond’s edge and reflect back again, causing further changes to the surface. The world of science and academic research is effectively akin to a pond in a hailstorm, with constant ripples and waves forming, intersecting, and influencing one another. TEconomy’s Figure 11 illustrates this and

An original discovery can have an effect similar to that of a pebble thrown into a pond, with ripples of knowledge and application forming and moving outwards through time. But those ripples (waves) can reach the pond’s edge and reflect back again, causing further change to the surface. The world of science and academic research is effectively akin to a pond in a hailstorm, with constant ripples and waves forming, intersecting, and influencing one another.

also introduces application classification back into the model in terms of impacts occurring on market (economic) and non-market (social) domains.

Figure 11: Illustration of an Expanding Network of Related Innovations Sparked by Basic Discovery.



Source: TEconomy Partners, LLC.

Recognizing that a linear model of a BASIC-to-APPLIED continuum is imperfect in describing the structure of science, Donald Stokes proposed an alternative model in his 1997 book “Pasteur’s Quadrant: Basic Science and Technological Innovation.” This alternative added an additional dimension to basic and applied science, building a model with “quest for fundamental understanding” on one axis, and “consideration for use” on the other – resulting in four quadrants. Three of the four quadrants bear illustrative names based upon the work of renowned scientists which quite neatly fits within the bounds of that quadrant:

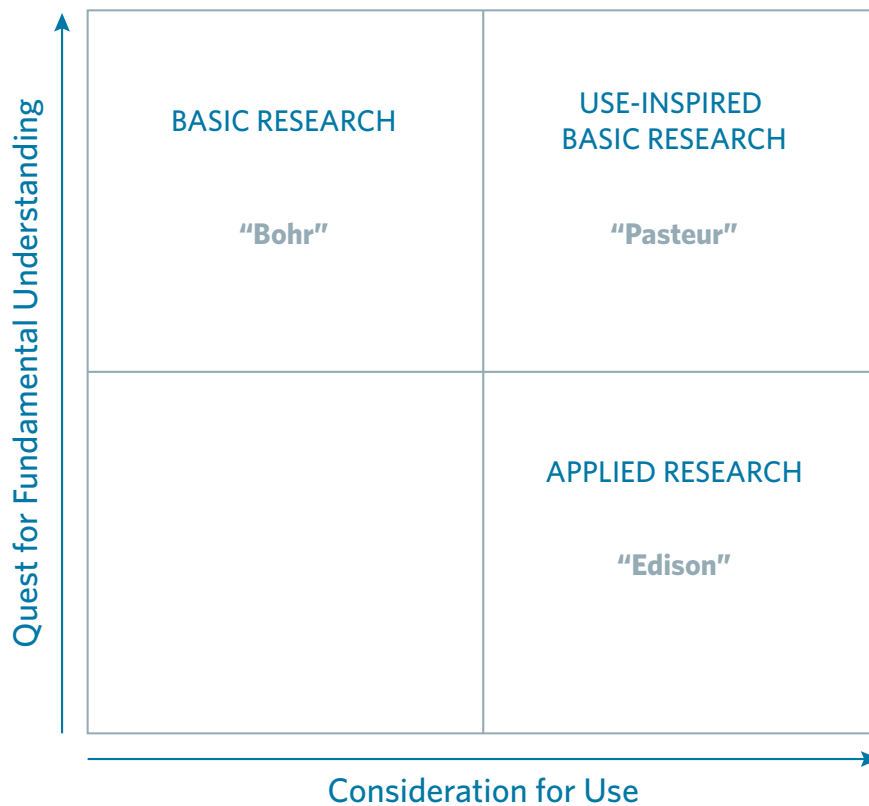
The importance of basic science derives from its contribution to knowledge deeper within the tree of information and, consequently, its greater potential for integration with other facts. In contrast, the importance of translational science lies in its practicality. Hence, we do not view basic and translational science as one being more important than the other but rather as complementary areas of human endeavor, with the important distinction that basic science findings often precede advances in translational science. We also note that observations in translational or applied science can generate new questions for fundamental research, as illustrated from the fact that vaccination preceded the field of immunology. Hence, the epistemological flow is bidirectional, and investments in both types of science are needed.

Ferric C. Fang and Arturo Casadevall. “Lost in Translation—Basic Science in the Era of Translational Research.” *Infect. Immun.* February 2010 vol. 78 no. 2 563-566.

- Bohr’s Quadrant (named after Physicist Niels Bohr) comprising fundamental (basic) science research performed with knowledge as the goal, not application.
- Pasteur’s Quadrant (named after Louis Pasteur the French biologist, microbiologist and chemist whose work uncovered the principles of vaccination, microbial fermentation, and pasteurization) comprising fundamental work performed with an eye to, or inspired by, an application.
- Edison’s Quadrant (named after Thomas Edison) focused on the use of existing scientific knowledge in the pursuit of useful applications and the development of technologies and practical innovations.

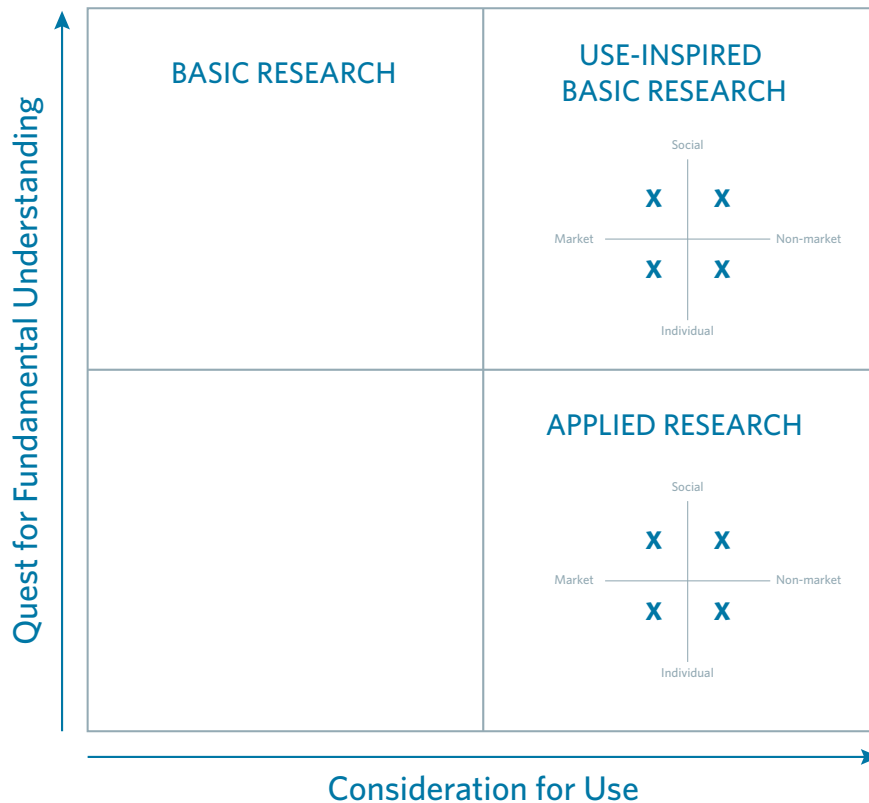
Figure 12 shows the Stokes model, which is generally referred to as “Pasteur’s Quadrant”, and is an extremely valuable contribution to understanding research activity, and helping to move dialog away from an overly simplistic basic/ applied duality model. The model’s key contribution is in providing recognition that while basic research has no direct application or consideration for use by definition (Bohr’s quadrant), it can often be strategically focused in areas where practical applications are anticipated (Pasteur’s quadrant).

Figure 12: Quadrants of Stokes’ Model of Science Inquiry: “Pasteur’s Quadrant”.



TEconomy observes that Stokes’ model (Figure 12) may be further built-upon to include the market/non-market and social/private returns to research discussed in Chapter III, resulting in the model shown in Figure 13. A representative scientist name could probably be found to reside in each of these sub-quadrants (but we will leave that for future research).

Figure 13: Stokes' Model Revised to Incorporate Functional Impact Sub-Quadrants.



Source: TEconomy Partners, LLC.

What figures 9 through 13 illustrate is the challenge of representing something as multifaceted as the world of science and academic research in simple models - when the reality is that they comprise a complex ecosystem of components and interactions, with time as a third dimension. This challenge is referenced in a recent report on the UK science base which notes:

[I]mportant and increasingly cited rationales for policy support are based on addressing system failures. They emphasise the difficulty of drawing simple distinctions between pure and applied research and that the process of moving from pure to applied is not linear but involves interactions between the two. These approaches instead emphasise the interrelationship and complementarity between applied and basic research and the need to foster connections between the private and public sectors to generate effective knowledge exchange and productive iteration between the two sectors. They also emphasise the “two faces” of private sector R&D, first in terms of advancing knowledge and second in enhancing the absorptive capacity of an organisation measured in terms of its ability to access, understand and apply the results of research carried out elsewhere. [F]rom a systems point of view, domestic R&D enhances absorptive capacity and the ability to access, understand and absorb external basic and applied research. Therefore, to capture spillovers requires domestic R&D effort. Domestic pure research is then complementary to domestic applied research, and both may attract “sticky” domestic and inward R&D justifying national support for “pure” research.⁴⁹

The bottom line is that the research environment, operating as an ecosystem, needs policymakers, research funders, research organizations, and other key stakeholders to recognize that all parts of the ecosystem serve a function, and

49 Jonathan Haskel, Alan Hughes and Elif Bascavusoglu-Moreau. 2014. “The Economic Significance of the UK Science Base.” A Report for the Campaign on Science and Engineering (CaSE). Published by CaSE, the University of Cambridge and Imperial College London. Available online at: <http://www.sciencecampaign.org.uk/resource/UKScienceBase.html>

that emphasizing one macro-area at the expense of another may create imbalance in the system. Certainly, a move to deemphasize the funding of basic research in order to grow applied research poses a hazard to the efficient operation of the ecosystem – especially over the long-term. De-emphasizing basic research is akin to farmers eating their seed corn, or investors spending their principal instead of interest.

CONCLUSION: Because the research environment operates as an ecosystem, policymakers, research funders, research organizations and other key stakeholders must recognize that all parts of the ecosystem serve a function, and that emphasizing one macro-area at the expense of another may create imbalance in the system.

In addition to the pitfalls of emphasizing one type of research over another (e.g. applied over basic), setting up systems to measure the impact of research may also have pitfalls in terms of judging certain elements of the ecosystem. As noted by Michael Spence in the Chronicle of Higher Education:

First, impact measurement works against fundamental or basic research due simply to the relevant timescales. This is the scholarly work, about which Australia's top research universities known as the Group of Eight, say "investment in basic research is equivalent to long-term, patient, capital investment that creates new infrastructure and will provide a sustained flow of opportunities well into the future, many of which we cannot yet envisage." For instance, modern computers owe their existence to the pure research in mathematics and quantum physics conducted over a century ago, for which there was no known practical application at the time.⁵⁰

Recognizing the role of all stripes of research in the operation of the economy and society, TEconomy has long used a descriptive illustration of the ecosystem in operation – an ecosystem in which basic and applied research both feed the ecosystem and receive inputs from it (see Figure 5). The model is very much focused on economic development, especially advanced technology-based economic development, but it does serve to illustrate the role of research within an overarching economic and social ecosystem.

What should be absolutely clear is that **without sustained commitment to research, including the full spectrum of basic and applied/translational research inquiry, it is evident that the fuel tank for the U.S. knowledge economy**

Indiana Research Legacies:

The Discovery of Synthetic Rubber at the University of Notre Dame Leading to the Invention of Neoprene by DuPont.

The research discoveries of Julius Arthur Nieuwland, a priest and professor at the University of Notre Dame, represent an excellent example of basic scientific research which ultimately led to a widely-adopted commercial application. Father Nieuwland, C.S.C., PhD, a graduate of Notre Dame himself, taught botany and later, organic chemistry at the University.

In the early 1930s, his expertise and research work with acetylene chemistry led to his discovery of synthetic rubber. Dr. Elmer Bolton, a scientist working with DuPont, attended a lecture by Father Nieuwland and DuPont subsequently purchased the patent rights from Notre Dame and undertook commercial development of the discovery in collaboration with Father Nieuwland. The result was neoprene.

DuPont initially offered the compound commercially branded as "DuPrene," and it was valued for its superiority to rubber, and its resistance to sunlight, abrasion, and extreme temperatures. Uses and applications for Neoprene are wide and varied and include: as an insulator for electrical cable and telephone wiring, gaskets, hoses, corrosion-resistant coatings, a base for adhesives and molded products, rug backings, weather stripping, gloves and face masks, roofing, and many others.

⁵⁰ Michael Spence. 2013. "How Best to Measure the Value of Research." Guest post at the Chronicle of Higher Education website. Accessed online at: <http://www.chronicle.com/blogs/worldwise/how-best-to-measure-the-value-of-research/32765>

would slowly be drained. In a 21st Century economy driven by innovation, it is the case that R&D and intellectual capacity effectively power the economy, just as oil and coal powered the economy that came before.

CONCLUSION: Without sustained commitment to research, including the full spectrum of basic and applied/translational research inquiry, it is evident that the fuel tank for the U.S. knowledge economy, and the economies of individual states such as Indiana, would slowly be drained.

B. Pathways to Innovations: The Role of Diverse Areas of Research Resulting in Industries and Innovations

The understanding of university research as comprising a complex ecosystem of inquiry and actors is particularly relevant when considering the role of academic research as an innovation and economic development engine or a facilitator of the same. It is all

too easy for policymakers or others to view a particularly impactful commercial innovation in a vacuum – as the product solely of a commercializing company, rather than the sum of the constituent discoveries, research

programs, innovations, and technologies that are embodied within it. For example, Apple Inc. is heralded as an innovator and pioneer in smart phones (e.g. the iPhone), and associated applications of the technology, without a full appreciation of the **publicly funded** research, often performed at universities or national laboratories, that actually made the product possible.

It is all too easy for policymakers or others to view a particularly impactful commercial innovation in a vacuum – as the product solely of a commercializing company, rather than the sum of the constituent discoveries, research programs, innovations, and technologies that are embodied within it.

In almost every instance, a successful commercial product is built upon a foundation of knowledge, technologies, and innovations developed elsewhere – including the findings of basic research (much of which may have occurred quite far in the past, but nonetheless are crucial to the functioning of the products).

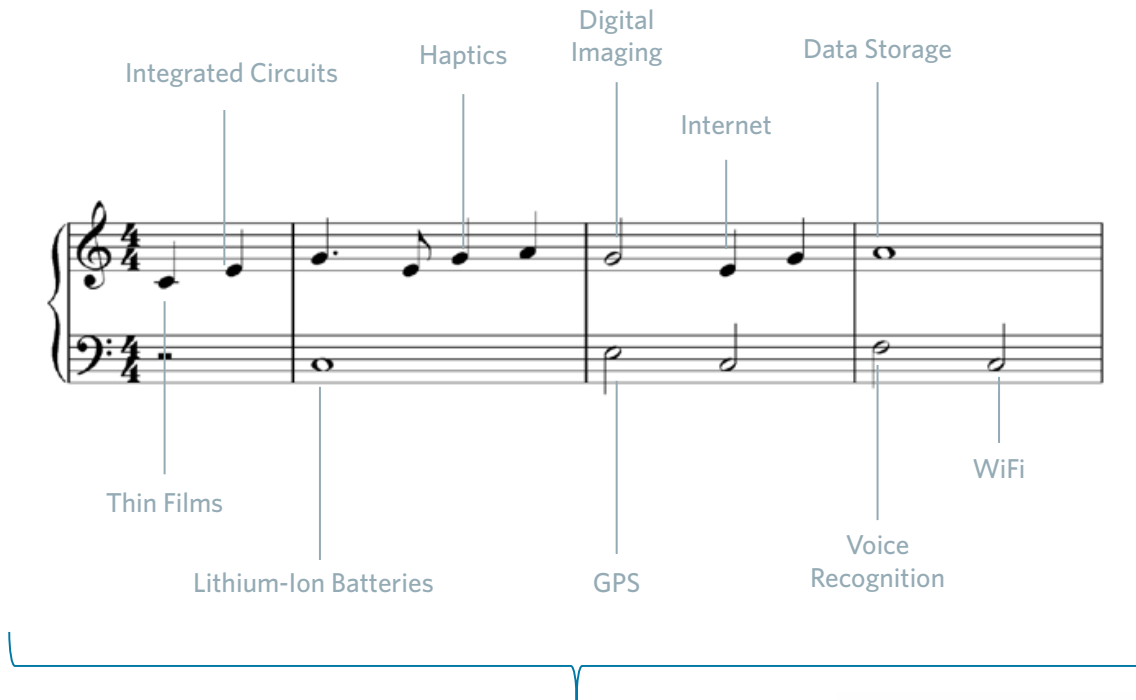
In almost every instance, a successful commercial product is actually built upon a foundation of knowledge, technologies, and innovations developed elsewhere – including the findings of basic research (much of which may have occurred quite far in the past, but nonetheless are crucial to the functioning of the products). Recognizing this history is critical because it

means the support for all kinds and forms of research has importance, and because the integration of work from a diversity of disciplines and fields may be drawn upon in creating things or processes that are useful to humanity and available to solve needs.

An innovation or advancement in practice or some other tangible outcome of applied or translational research is akin to a music composition. Like multiple notes coming together to form a tune, multiple research discoveries are integrated to make something whole, and individual research discoveries come together to form the song, or “end product” (Figure 14):

Figure 14: Integration of Multiple Research Discoveries and Innovations to Produce a Single Product.

A simplified example using the iPhone.



Like notes building upon notes to build a song, research discoveries build upon research discoveries to create novel products and technologies. **The result, in this case = Smart Phone....**



In the example above, it's worth noting that each of the individual elements of the product will themselves have been derived through the application of a suite of fundamental and applied research advancements. For example, haptics: the touch and feel of the click, or sensory feedback, on a touch screen, may have integrated work from basic fields such as chemistry and physics, applied work in electronic engineering, algorithms from software engineering, and insights from psychology and neuroscience. The functionality of lithium batteries is the result of fundamental work in physics, chemistry, and electrical engineering. In fact, lithium batteries are a great example of university-based research incorporated into commercial products, since "John B. Goodenough at the University of Texas at Austin conducted critical research underlying lithium-ion batteries in 1980, with funding mainly from the Department of Energy and the Air Force."⁵¹

51 Association of American Universities. "Federally Funded Research Drives American Innovation"

A Perspective on Curiosity Driven Fundamental Research

The OECD recently defined basic research as that undertaken primarily to acquire new knowledge of the underlying foundations of phenomena without regard for a particular application. Fundamental research should be clearly distinguished from another form of basic research, strategic research, which is primarily aimed at understanding the fundamental basis of an applied ultimate goal. Inevitably there will be arguments over the distinction between fundamental and applied research. For example, the National Research Council of Canada argues that fundamental research in one discipline could easily be construed as applied in a different field. It is true that basic discoveries in one field may represent “applications” of existing knowledge in another field. In practice, fundamental research has led to many important applications that, almost without exception, were not anticipated at the time that the work was undertaken. It is impossible to over-emphasise two aspects of fundamental research that many politicians find hard to believe. Most applications cannot be foreseen; and, the period between a fundamental discovery and eventual applications is often very long compared to the criteria normally used by investors.

Cris dos Remedios. “The Value of Fundamental Research”. July 11, 2013. The International Union for Pure and Applied Biophysics (IUPAB). Accessed online at: <http://iupab.org/publications/value-of-fundamental-research>

CONCLUSION: Technologies, useful commercial products, and innovations in commercial practices and other human endeavors rarely, if ever, form solely out of the work of one company or individual innovator. Rather, they will be the result of the integration of a suite of previous fundamental and applied research and knowledge advancements. Attention has to be paid to the entire system (research ecosystem) that supports and enables innovation.

C. Indiana's Research Universities: Areas of Research Specialization

Research at universities is almost universally undertaken with the goal of publishing research findings within academic journals, conference proceedings, or other generally accepted publishing formats. As such, the most commonly used metric for reviewing and understanding research output is “publications”. With journals and academic publications covering the full spectrum of basic through applied and translational research, bibliometric analysis of publications can provide valuable insight regarding research output by field, by institution, and by individual academic researchers. Accordingly, bibliometric analysis is used herein to turn this chapter on the structure and content of university research to specifically focus on the range of recent academic research occurring at Indiana's research universities.

The academic research output of the United States is understandably huge. Between 2012–2016, a total of 2,075,639 individual publications were generated, as measured by the Clarivate Analytics “Web of Science” (WoS) database.⁵² These data capture the institutional affiliation of each publication's author, and therefore, enable analysis on the academic research output derived from Indiana's research universities, including the use of location quotient (LQ) analysis⁵³ to identify where Indiana's research universities as a group have research specializations versus national normative levels. Research analysts generally consider 1.2 as being the threshold for an LQ indicative of being a regional specialization, where the value 1.0 equals the national normative level for the variable being analyzed.

1. Indiana's Research Universities' Research Specializations as a Collective Group

TEconomy downloaded the data for all U.S. publications and for Indiana's research universities by academic field (which comprises 251 individual academic disciplines, designated by WoS field categories) for 2012 through 2016. The data includes a count of the publications produced by field, with the total being 50,348 individual publications (and the total number of records being higher at 88,345 because certain interdisciplinary publications will be recorded in more than one field classification). Findings are that Indiana demonstrates a broad variety of academic fields that may be defined as “State Specializations” by virtue of them having an LQ greater than or equal to 1.2. Table 6 lists these disciplines, omitting those very small/niche areas that listed less than 50 publications between 2012–2016. Figure 15 provides further insight on these data, illustrating each of the specialized fields for Indiana and the contribution of each Indiana research university in terms of publications volume.

⁵² TEconomy subscribes to Clarivate Analytics “Web of Science” (WoS) as a preferred provider of bibliometric data. The WoS dataset covers more than 33,000 individual journals. Clarivate notes that: “Web of Science is a comprehensive research platform. Journal articles, patents, websites, conference proceedings, Open Access material—all can be accessed through one interface, using a variety of powerful search and analysis tools. Web of Science Core Collection is a painstakingly selected, actively curated database of the journals that researchers themselves have judged to be the most important and useful in their fields”. Accessed online at: <http://clarivate.com/?product=web-of-science>

⁵³ A location quotient (LQ) is a formula derived measure of how concentrated a particular industry, occupation, or activity is in a region or state as compared to the nation. It can reveal areas that are “more”, “the same”, or “less” concentrated in the region in comparison to the national average. The location quotient is a ratio. In the publications analysis herein, the formula is $(X/Y) / (X'/Y')$, where X is the amount of publication in a field in Indiana (e.g., Analytical Chemistry), and Y is the total amount of all academic publishing in Indiana. X/Y therefore is the regional concentration of that asset in Indiana. X' is total U.S. publishing in the subject field and Y' is the total for all publications in the United States. A value of >1.0 identifies areas in which Indiana is more specialized than the national normative level. Usually, regional economists use a threshold of 1.2 as indicative of a field being a “regional specialization”.

Table 6: The Specialized Research Fields of Indiana’s Research Universities. Publication Fields with an Indiana LQ ≥ 1.2

Field	Indiana Location Quotient	Indiana Number of Records
Physics Nuclear	4.28	1043
Physics Particles Fields	4.07	1885
Education Scientific Disciplines	2.49	1023
Engineering Multidisciplinary	2.11	807
Logic	2.06	81
Thermodynamics	2.05	477
Information Science Library Science	1.99	215
Education Educational Research	1.91	853
Agricultural Economics Policy	1.85	80
Mathematics	1.80	1259
Social Sciences Mathematical Methods	1.77	173
Audiology Speech Language Pathology	1.76	232
Computer Science Cybernetics	1.76	152
Spectroscopy	1.75	293
Communication	1.74	98
Astronomy Astrophysics	1.74	1950
Ergonomics	1.73	75
Engineering Manufacturing	1.73	311
Agriculture Dairy Animal Science	1.72	274
Construction Building Technology	1.71	382
Hospitality Leisure Sport Tourism	1.69	75
Linguistics	1.68	153
Psychology Multidisciplinary	1.66	150
Nuclear Science Technology	1.62	376
Physics Multidisciplinary	1.61	852
Mineralogy	1.60	102
Mechanics	1.59	670
Engineering Mechanical	1.56	1406
Chemistry Analytical	1.53	671
Computer Science Software Engineering	1.53	684
Social Sciences Interdisciplinary	1.49	128
Computer Science Interdisciplinary Applications	1.48	952
Crystallography	1.46	152

Field	Indiana Location Quotient	Indiana Number of Records
Physics Atomic Molecular Chemical	1.44	761
Physics Mathematical	1.44	423
Computer Science Information Systems	1.43	1186
Chemistry Inorganic Nuclear	1.42	309
Instruments Instrumentation	1.41	571
Chemistry Organic	1.41	548
Transportation Science Technology	1.41	352
Psychology Experimental	1.40	237
Mathematics Interdisciplinary Applications	1.38	317
Psychology Developmental	1.38	112
Mathematics Applied	1.37	791
Computer Science Hardware Architecture	1.36	652
History Philosophy of Science	1.36	171
Evolutionary Biology	1.35	415
Engineering Civil	1.34	752
Substance Abuse	1.33	251
Anatomy Morphology	1.33	79
Medical Informatics	1.33	229
Engineering Industrial	1.31	286
Imaging Science Photographic Technology	1.30	341
Automation Control Systems	1.29	643
Computer Science Theory Methods	1.26	1294
Robotics	1.26	264
Operations Research Management Science	1.23	408
Agricultural Engineering	1.21	108
Dentistry Oral Surgery Medicine	1.21	323
Engineering Chemical	1.20	578
Behavioral Sciences	1.20	384
Language Linguistics	1.20	55
Religion	1.20	120
		Total = 30,994

Source: TEconomy analysis of Web of Science database.

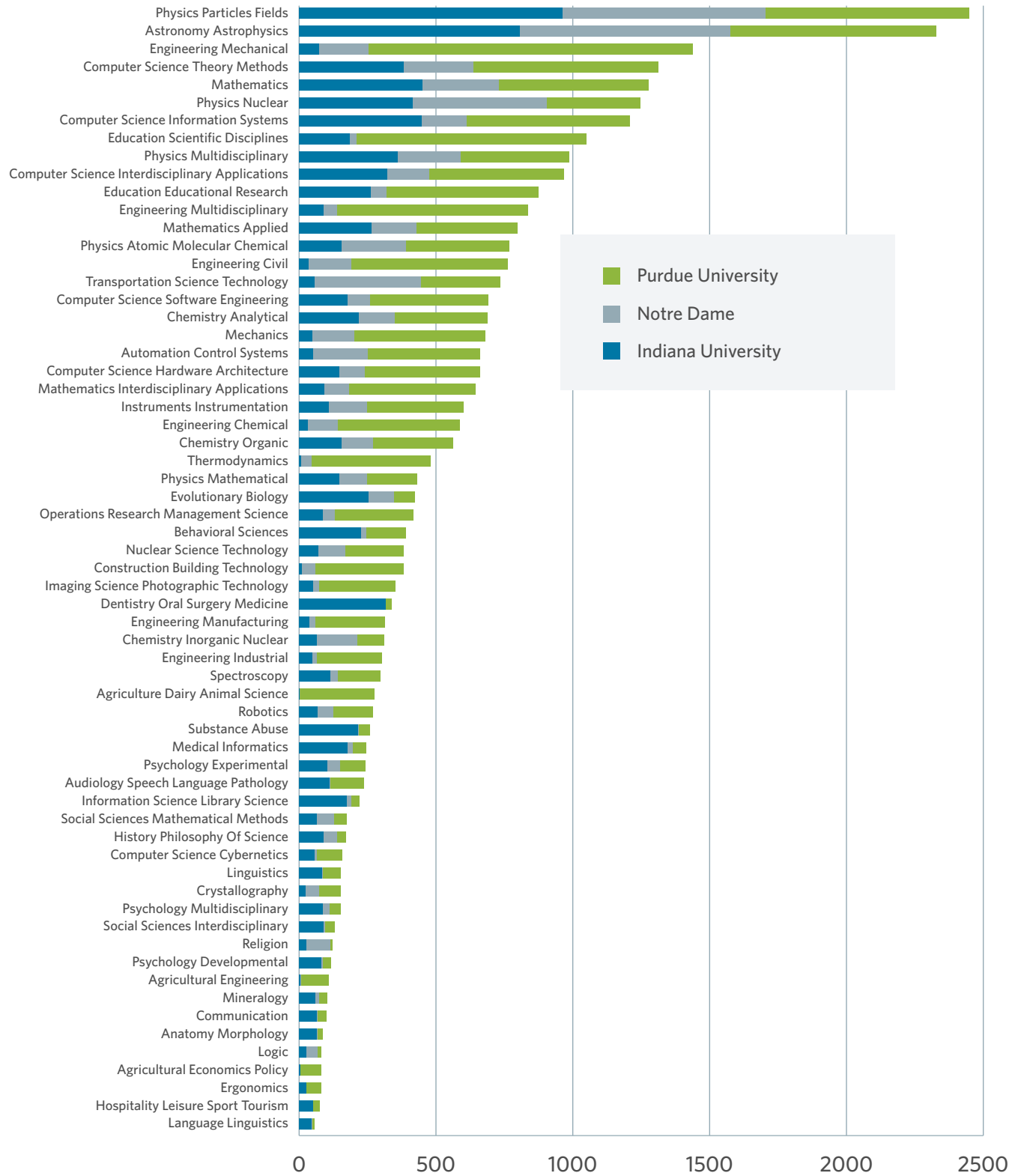
The diversity of research specializations in Indiana's research universities is quite evident, with specialized fields comprising a broad-spectrum of physical sciences, life sciences, formal sciences, social sciences, the humanities, and other fields of inquiry. Some particularly striking areas include (See Figure 15):

- Physics – comprising the largest cluster or specialized research in Indiana, with contributions by seven specialized categories and major participation by all of the research universities:
 - Physics of Particles and Fields
 - Astronomy and Astrophysics
 - Nuclear Physics
 - Multidisciplinary Physics
 - Physics Atomic Molecular Physical
 - Thermodynamics
 - Mathematical Physics

- Engineering (primarily at Purdue) – especially in Mechanical Engineering and Mechanics Multidisciplinary Engineering, Civil Engineering, and Chemical Engineering
 - Formal Sciences – Mathematics and Logic
 - Computer Science
 - Education

In reviewing Figure 15, it is particularly notable how deep Indiana's group of research universities is in basic sciences, especially in terms of basic physical sciences and the formal sciences.

Figure 15: The Specialized Research Fields of Indiana’s Research Universities. Publication Fields with an Indiana LQ ≥ 1.2 . Volume of Publications in Each Field and the Contributory Total for Each Indiana Research University. IUPUI data is included under Indiana University.



Source: TEconomy analysis of Web of Science database.

It is also notable that there are many fields in which the LQ for Indiana resides in the range of >1.0 but <1.2 (Table 7). These fields still have a higher than national average concentration in Indiana, but do not reach the generally accepted 1.2 level of a “regional specialization”. More life sciences disciplines appear in this classification group than in the ≥ 1.2 regionally specialized group of fields. Physics, chemistry/materials science, and electrical and electronic engineering are particularly robust. Overall, 24,624 publication records fall within these fields for 2012–2016.

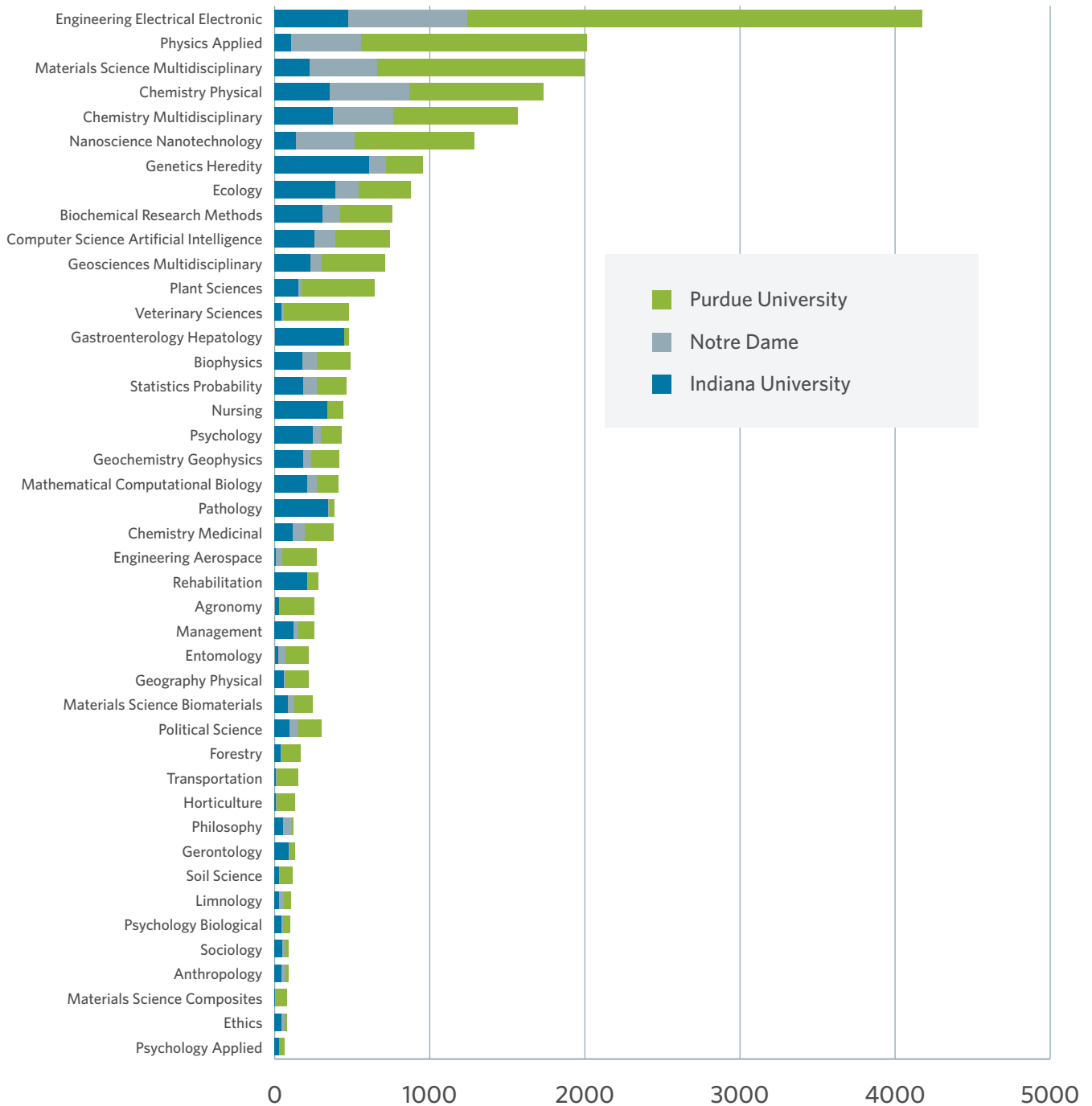
Table 7: Research Fields of Indiana’s Research Universities with Location Quotient between 1.0 and 1.19

Field	Indiana Location Quotient	Indiana Number of Records
Gerontology	1.19	120
Forestry	1.18	168
Nanoscience Nanotechnology	1.17	1250
Psychology Biological	1.17	99
Chemistry Multidisciplinary	1.17	1537
Chemistry Physical	1.17	1695
Philosophy	1.15	122
Sociology	1.15	88
Management	1.15	249
Psychology	1.14	421
Engineering Aerospace	1.14	271
Pathology	1.14	382
Transportation	1.14	152
Limnology	1.13	106
Plant Sciences	1.13	640
Rehabilitation	1.13	271
Materials Science Composites	1.12	80
Mathematical Computational Biology	1.10	390
Gastroenterology Hepatology	1.10	471
Veterinary Sciences	1.10	476
Agronomy	1.10	254
Engineering Electrical Electronic	1.09	4074
Ethics	1.09	76
Physics Applied	1.09	1988
Geography Physical	1.09	216
Statistics Probability	1.09	455
Soil Science	1.07	116
Ecology	1.07	865
Computer Science Artificial Intelligence	1.06	723

Field	Indiana Location Quotient	Indiana Number of Records
Biochemical Research Methods	1.05	726
Psychology Applied	1.04	64
Anthropology	1.04	85
Horticulture	1.03	132
Materials Science Biomaterials	1.03	215
Geochemistry Geophysics	1.03	409
Entomology	1.01	221
Biophysics	1.01	470
Chemistry Medicinal	1.01	366
Materials Science Multidisciplinary	1.01	1950
Geosciences Multidisciplinary	1.00	703
Political Science	1.00	173
Genetics Heredity	1.00	929
Nursing	1.00	426
		Total = 24,624

Source: TEconomy analysis of Web of Science database.

Figure 16: Research Fields of Indiana’s Research Universities with LQ ≥ 1.0 to <1.2 . Volume of Publications in Each Field and the Contributory Total for Each Indiana Research University. IUPUI data is included under Indiana University.



Source: TEconomy analysis of Web of Science database.

The above analysis, in part, has significant utility in terms of identifying areas where Indiana’s research universities as a collective enterprise contribute to research excellence in the state. These may well be target areas for future collaboration because the sum of the research output at the universities gives rise to Indiana having more work taking place in these fields than would be anticipated given national normative levels.

CONCLUSION: Indiana’s research universities demonstrate a broad-variety of research areas that reach the threshold of being “regional specializations.” These span a spectrum of research work across a diverse range of academic disciplines and fields of inquiry. Among these regional specializations, the greatest volume of research output is in fields that are STEM disciplines (science, technology, engineering, and mathematics) representing 92% of specialized field publications. Multiple basic science areas are included in these evident strengths.

2. Indiana’s Research Universities’ Research Specializations at Individual Institutions

Assessed as a group, the above analysis provides perspective on where Indiana has research specializations as a result of summing the collective work of its research universities. While this provides a useful state crosscutting perspective, each of the institutions is an individual entity, and it is important to understand their individual strengths. To this end, TEconomy performed LQ analysis for each of the research universities (with Indiana University and IUPUI analyzed with data combined). The data reported are at the full-university level, providing analysis for Indiana University (including IUPUI), the University of Notre Dame, and Purdue University. The analysis is reported for academic fields in which the universities had at least 25 publications in the 2012–2016 period of analysis, and the results for this analysis are reported in Appendix A.

CONCLUSION: Examining Indiana’s research universities individually shows strengths that are shared across multiple universities (such as engineering, physics, chemistry, computer science, and mathematics) and strengths that are more focused within individual institutions (biomedical and health related life sciences at Indiana University, and agricultural sciences at Purdue University).

There is an advantage for Indiana in the diversity of disciplines and fields of research that represent university specializations, particularly as science and technology fields become increasingly transdisciplinary – where multiple strengths can intersect and build-upon each other’s knowledge. It is also clear that both basic science and applied science disciplines are well represented across Indiana’s research universities’ specializations.

There is not a discovery in science, however revolutionary, however sparkling with insight, that does not arise out of what went before.

*'If I have seen further than other men,' said Isaac Newton,
'it is because I have stood on the shoulders of giants.'*

- Isaac Asimov

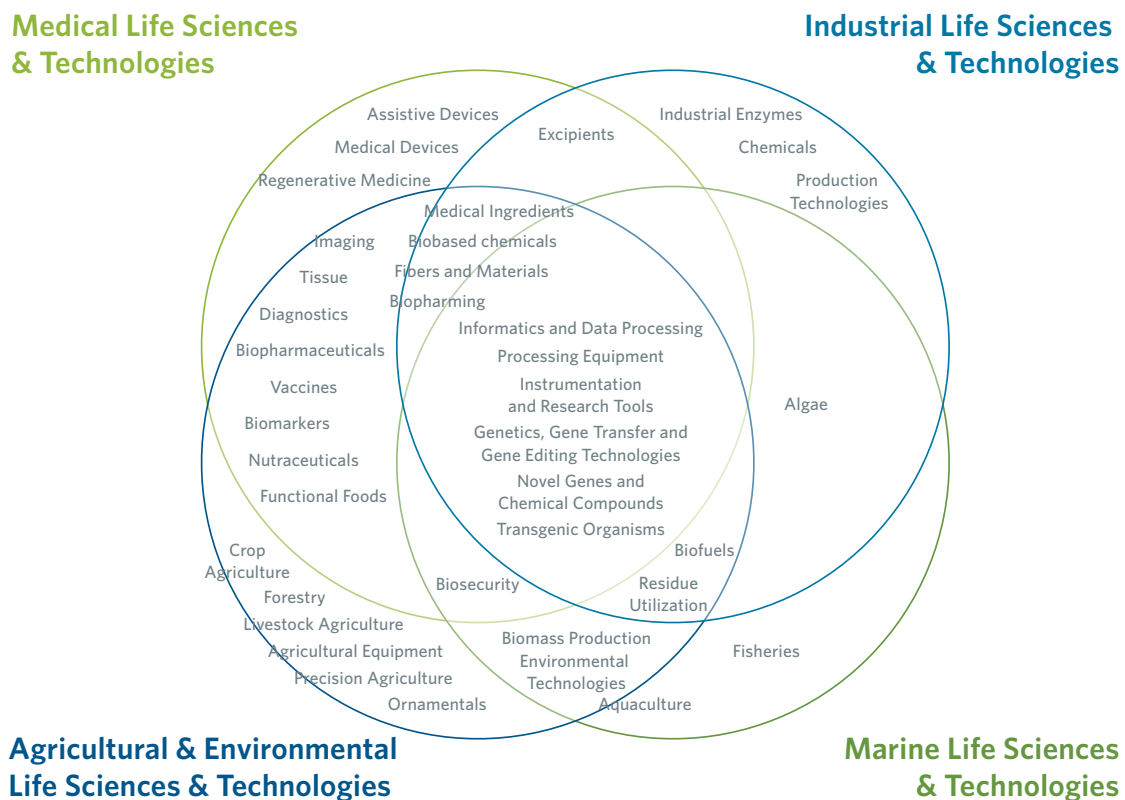
(Adding a Dimension: Seventeen Essays on the History of Science)

Chapter V: University Life Sciences Research

Chapters I through IV have described the critically important and multifaceted roles research universities play in American society and the economy, and profiled the central role of university-performed research across all types and fields of inquiry. By engaging in a highly diverse and complete spectrum of basic and applied research in each key quadrant of the Stokes model, research universities contribute significantly to the fuel that drives national and state progress on both market and non-market dimensions, and social and individual dimensions.

In this chapter, we turn specifically to a review of life sciences research. It may be said that no other area of research so directly impacts the lives of humans as “life sciences” research. As physical organisms, the world of life is what we are and what sustains us. The food that energizes us, our longevity in the face of disease and health conditions, the air we breathe, the operation of the global and local ecosystems and biosphere in which we live, each are the result of life processes. We live in a world of life, and indeed each of us is a walking biological ecosystem—comprising, at latest count, 30 trillion human cells and 40 trillion bacterial cells.⁵⁴ Indeed the opportunities for knowledge expansion, novel products, and technologies from life sciences are extraordinary. The combination of rapid advancements in genomics (and related ‘omic sciences), imaging technologies (providing resolution of life processes to an atomic level), collection and analysis of biological data (bioinformatics), and new discoveries in frontier areas like synthetic biology, gene editing, regenerative medicine, etc. create an unprecedented era for potential innovations across a wide-spectrum of life science applications and domains. Figure 17 serves to illustrate just some of the potential technology and application areas for advancement in life sciences research in the four macro domains of: biomedical, agricultural, industrial, and marine life sciences.

Figure 17: R&D in Life Sciences and Associated Technology Domains



⁵⁴ Tina Hesman Saey. 2016. “Body’s bacteria don’t outnumber human cells so much after all: new calculations suggest roughly equal populations, not 10-to-1 ratio.” *Science News*, January 8th, 2016. Accessed online at: <https://www.sciencenews.org/article/body%E2%80%99s-bacteria-don%E2%80%99t-outnumber-human-cells-so-much-after-all>

The importance and significance of life science in U.S. university research is well documented by the National Science Foundation, which reports that:

Academic R&D spending has long been concentrated in the life sciences, which have received more than half of all academic R&D expenditures for more than three decades. The remainder is distributed across seven broad fields, including computer sciences, environmental sciences, mathematical sciences, physical sciences, psychology, social sciences, and engineering. In 2014, academic R&D in life sciences accounted for 59% of total academic spending in all fields of S&E and a slightly smaller share (56%) of federally supported academic R&D that year. Within life sciences, medical sciences accounted for over one-half of this field's spending (and 32% of total academic R&D), while biological sciences constituted just under one-third of spending in the life sciences (and 18% of total academic R&D). The remainder was spread between agricultural sciences (5% of total academic R&D) and other life sciences—life sciences R&D that could not be classified into one of the subfields. Academic R&D expenditures in medical sciences almost doubled from 1995 to 2004 and then grew more slowly from 2005 to 2011, declining slightly from 2011 to 2014. The sizeable increase from 1995 to 2004 resulted, in part, from a near-doubling of NIH's budget from 1998 to 2003. Similarly, academic R&D expenditures in biological sciences increased by about 80% from 1995 to 2004 and by much less (13%) from 2005 to 2014 after adjusting for inflation; there was also a decline in spending from 2011 to 2014. Spending changes over the two decades were somewhat less dramatic within the smaller life sciences field of agricultural sciences⁵⁵

The NSF also reports that “the nation’s colleges and universities had 211.8 million net assignable square feet (NASF) of research space available at the end of 2013.”⁵⁶ Again, the NSF’s analysis shows life sciences to comprise the largest share of academic institution research space, noting that:

The biological and biomedical sciences constituted the largest share (27.0%, or 57.2 million NASF) of all academic research space in 2013, which is slightly more than the share it held in 2011 (26.6%). This field, along with the agricultural and natural resources sciences, accounted for two-thirds of the 9.6 million in NASF growth from 2011. Research space in the biological and biomedical sciences increased 6.5% (3.5 million NASF) during the 2011-13 period. Space in the agricultural and natural resources sciences increased 10.5% (2.9 million NASF). From 2003 to 2013, research space in biological and biomedical sciences grew 58.9%); this is the only field that increased space in each of the five biennial periods since 2003. The related field of health and clinical sciences was the second largest in 2013, accounting for 17.9% of the total, or 38.0 million NASF. However, this total is slightly lower than the 39.7 million NASF of health and clinical sciences research space in use in 2005 after the near-doubling of the NIH budget from 1998 to 2003. The remaining large fields in 2013 were engineering (15.8%, or 33.5 million NASF); physical sciences (14.5%, or 30.7 million NASF); and agricultural and natural resources (14.4%, or 30.5 million NASF).⁵⁷

CONCLUSION: Life sciences research is the largest macro-level field in terms of university-based R&D. In the most recent NSF survey of U.S. academic institutions, it comprised 59% of total academic R&D spending.

Relative to other academic disciplinary field groupings, life sciences (receiving the largest share of research funding, and having a high proportion of research space dedicated to it) is not surprisingly a leading area of science in terms of scientific discovery and innovation.

⁵⁵ National Science Foundation. “Science and Engineering Indicators 2016.” National Center for Science and Engineering Statistics. Higher Education Research and Development Survey. Accessed online at: <https://www.nsf.gov/statistics/2016/nsb20161/#/report/chapter-5/expenditures-and-funding-for-academic-r-d>

⁵⁶ *Ibid*

⁵⁷ *Ibid*

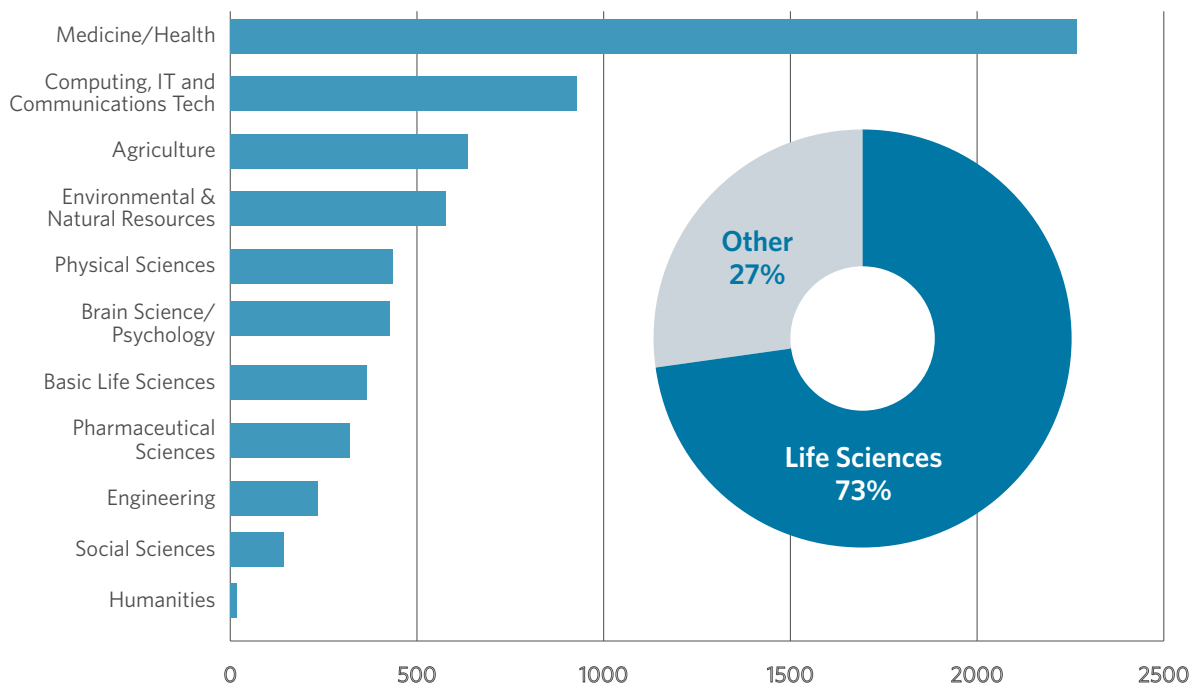
A. Life Sciences: On the Frontlines of Scientific Advancement

In terms of activity on the frontiers of science, the extent to which life sciences leads was revealed in recent research performed by Martin Grueber and Simon Tripp of TEconomy for Flad Architects. Flad, specialists in science and technology buildings, sought to identify the leading edge of sciences and academic research through a concept we called “disciplinary speciation” whereby the leading-edge areas of science reach a critical mass of subject matter around which new academic journals evolve.⁵⁸ For example, the speciation of Bioinformatics as a discipline is relatively new, and is where the disciplines of computer science, statistics, mathematics, and biology combined to create a new transdisciplinary field and generate the speciation of completely new journal titles and entirely new journal mastheads, including (but not limited to): “Bioinformatics”; “Journal of Biomedical Informatics”; “Computers in Biology and Medicine”; “Evolutionary Bioinformatics” and “Briefings in Bioinformatics.” Thus, TEconomy developed the hypothesis that leading “up-and-coming” frontier areas of science could be identified through examining the emergence of completely new journals as disciplinary speciation flags.

Using data contained in the Ulrich Global Serials Directory for a recent 14-year period, Grueber and Tripp identified the development of 7,496 new journals – a volume considerably larger than initially expected (representing an average of 535 completely new journals “speciated” annually, equivalent to an average of almost 1.5 completely new journal mastheads per day). The vast majority of these were in science and engineering disciplines, with only very limited new journal activity in humanities and social sciences. This result likely reflects the increasing complexity and compartmentalization of science, but also to a certain degree, shows the globalization of science and need for foreign language and regionally oriented journals.

For each journal, Grueber and Tripp downloaded the journal title and the journal’s own narrative description of its general subject matter and content goals. Martin Grueber then used the specialized real-text cluster analysis software tool OmniViz™ to identify clusters of similar subject matter. The results of this unique analysis are shown at the most macro level in Figure 18:

Figure 18: OmniViz™ Cluster Analysis of Major Themes in New Journal Speciation (2000-2013)



⁵⁸ This research is unpublished and was sponsored by Flad Architects, a leading architecture firm specializing in science and technology buildings. Reproduced with permission.

As identified through new journal formation, the results of the Grueber and Tripp Disciplinary Speciation Analysis illustrate the dominant nature of life sciences as being on the frontiers of science expansion. Fully **73% (almost three out of every four) new journals created are in areas classified as life sciences.** Among these, medicine and health lead, followed by agriculture and environmental/natural resource sciences.

It is important to note that it is NOT a general trend for academic journals to proliferate at a high rate in all disciplines – because such proliferation is not evident in humanities and social sciences. Rather the intense growth is occurring on the S&E side of the equation and particularly in life sciences.

CONCLUSION: As evidenced in the speciation of new academic journals, life sciences is the leader, by a considerable margin, in terms of expanding the frontiers of science, technology, and new knowledge generation.

B. The Indiana Life Sciences Research Environment

Understanding that research is crucial to economic and social advancement (and that life sciences research is the largest and most dominant among modern research fields) significant useful intelligence can be gained via a state focusing on its performance in life sciences research. Understanding the position of Indiana in life sciences is thus an imperative for understanding where the state stands in a highly dynamic sector of research, economic development, and human progress, and in identifying what it can do to best leverage its core competencies and opportunities in this regard.

Every two years, TEconomy works intensively with the Biotechnology Innovation Organization (BIO) to conduct a state-by-state review of life sciences. The 2016 report shows the importance of the bioscience sector on the U.S. economy, noting that:

U.S. bioscience firms employ 1.66 million people, a figure that includes nearly 147,000 high-paying jobs created since 2001. The average annual wage for a U.S. bioscience worker reached \$94,543 in 2014. These earnings are \$43,000 greater, on average, than the overall U.S. private sector wage of \$51,148.⁵⁹

Indiana is shown by the BIO/TEconomy analysis to be a high performer among states in biosciences, with it noted that:

Indiana's bioscience industry is large, highly specialized, and stands out in its diversity. The state's bioscience companies employed more than 58,000 in 2014 across 1,727 state business establishments. Indiana essentially has a specialized employment concentration in four of the five major subsectors, though the location quotient for bioscience-related distribution comes in just short of the 1.20 specialization threshold. The state is highly specialized in three subsectors—agricultural feedstock and chemicals; drugs and pharmaceuticals; and medical devices. Overall, the industry has grown by 1.4 percent since 2012 with especially large job gains in drugs and pharmaceuticals. Indiana's research universities combine to conduct nearly \$582 million in bioscience-related R&D. Indiana has also been increasing its bioscience patents, which reflect the diversity of the industry with medical devices, agricultural biosciences, biochemistry, and drugs and pharmaceuticals all represented as areas of focus.⁶⁰

Continuing to build life sciences research activity in Indiana is an important state strategy for economic development because it supports significant clusters of economic activity. As shown above, on a statewide basis Indiana has a quantitatively confirmed economic specialization (measured by location quotient) in four out of five major bioscience

59 BIO Website. Summary page on the BIO/TEconomy Report: "The Value of Bioscience Innovation in Growing Jobs and Improving Quality of Life 2016." Accessed online at: <https://www.bio.org/value-bioscience-innovation-growing-jobs-and-improving-quality-life-2016>

60 Ibid

subsectors as tracked by BIO and TEconomy. Indiana also stands out in having metro-areas that have robust location quotients in biosciences. As noted in the BIO/TEconomy report⁶¹ the “Indianapolis-Carmel-Anderson, IN Metropolitan Statistical Area (MSA)” has a specialization in four of five sub-clusters, as does the “Lafayette-West Lafayette, IN MSA”, and it’s worth pointing out that only four other metro areas in the nation share this four out of five classification. The “Bloomington, IN MSA” also is deeply engaged in life sciences, with a specialization in three out of five BIO sub-clusters, as is the “South Bend-Mishawaka, IN-MI MSA Area”, again with three. What is particularly telling in these data is that Indiana’s metro areas demonstrating substantial specialization in life sciences each correspond to the communities that host Indiana’s research universities. The growth of Indiana’s high wage bioscience sector, both within the universities themselves but also in commercial companies and organizations, is very much tied to the activities and presence of the signature research universities in the state.

The degree of life sciences research intensity present at Indiana research universities can, in part, be viewed through the lens of their life sciences research expenditures. The National Science Foundation (NSF) maintains data on total R&D expenditures, by field, for individual U.S. research universities. Each of Indiana’s research universities is included in the latest dataset (which reports 2015 as the most recent data). Table 8 summarizes these data, indicating that of the \$1.32 billion total R&D expenditures of the research universities in Indiana (which includes all institutions), nearly \$603 million (nearly 46%) are spent on life sciences R&D.

Table 8: R&D Expenditures in 2015 and 2014 by Indiana’s Research Universities: All R&D vs. Life Sciences⁶²

University	All R&D Expenditures, 2015 (\$ thousands)	Life Sciences R&D Expenditures, 2015 (\$ thousands)	Percent of All R&D Comprising Life Sciences 2015	All R&D Expenditures, 2014 (\$ thousands)	Life Sciences R&D Expenditures, 2014 (\$ thousands)	Percent of All R&D Comprising Life Sciences 2014
Indiana University, Bloomington	\$485,076	\$323,487	66.7%	\$206,039	\$44,906	21.8%
Indiana University-Purdue University, Indianapolis	\$55,973	\$21,060	37.6%	\$324,261	\$286,761	88.4%
Purdue University	\$558,611	\$223,402	40.0%	\$564,923	\$218,245	38.6%
University of Notre Dame	\$190,954	\$26,987	14.1%	\$182,228	\$24,751	13.6%
All Other Institutions	\$33,210	\$7,677	23.1%	\$31,405	\$6,844	22.1%
TOTAL	\$1,323,824	\$602,613	45.5%	\$1,308,856	\$581,507	44.4%

Source: TEconomy analysis of National Science Foundation, Higher Education R&D Survey.

61 Ibid

62 It should be noted in these data the significant change made by Indiana University and IUPUI in terms of the allocation of research expenditures. In 2014, the majority of life science expenditures were categorized within IUPUI, but for 2015 reporting changed to incorporate the majority of expenditures (including the IU School of Medicine) under Indiana University.

Compared to the nation, it is interesting to note that Indiana’s research universities are actually less concentrated in life sciences R&D than might be expected. It must be understood, however, that this lower relative concentration is impacted by comparative strengths in other research areas including in engineering and other physical sciences that are not included within the life sciences. As such, the bioscience specialization clusters in Indiana shown in the BIO/TEconomy report cannot only be rooted in university employment and output, but also reflect a strong presence of bioscience industry (which is a positive finding). As previously noted, NSF data show 58% of total academic R&D spending to be in life sciences in the U.S. overall, whereas Table 8 shows this percent at 45.5% for Indiana (up from 44.4% in 2014). Nevertheless, at nearly 46%, life sciences as an overall field still represent the largest area of R&D concentration for the collective group of four Indiana institutions. In the case of Purdue, while the university is doing a significant \$223 million in life sciences research, it is doing a similarly robust level of research in engineering (\$194.4 million). The University of Notre Dame also sees a high percentage of its research (35.2%) focused on engineering (\$67.2 million), and does more work in physical sciences (\$39.5 million) than it does in life sciences (\$27 million).

Advances in the biosciences have reshaped all aspects of biomedical development from the way we study medicine, discover and develop therapeutics, and diagnose and treat diseases and medical conditions. Looking ahead, bioscience innovation will continue to shape two important medical revolutions. The first is the rise of genomic-based medicine in which medicine is moving from being an inexact art of detection and treatment to a science of prediction, prevention, and strategic intervention or what is more popularly referred to as “personalized” medicine. The second revolution is regenerative medicine which refers to the use of biotechnology to restore bodily functions, replace failing body components and organs, and address many currently incurable diseases with cell-based therapies.

Advances in biotechnology innovation have also had an enormous transformative impact on many sectors of the economy — from improving and protecting plants that are key to feeding the world to industrial biotechnology applications that are leading to bio-based fuels, chemicals, and products that can protect our environment and herald a new age of sustainable development.

TEconomy/BIO. 2016 “The Value of Bioscience Innovation in Growing Jobs and Improving Quality of Life.”

As transdisciplinary work becomes increasingly important, it is likely to prove to be a competitive strength for Indiana in that it has a demonstrably diverse range of science and engineering strengths (as illustrated by research expenditures). The intersection of physical science disciplines and the life sciences is strong and complementary, and engineering plays an increasingly important role in advancing life science research and applied development. A good example of an opportunity area in this regard is in the agricultural life science space, where engineering, computer science, spatial analysis, sensors, and big data analytics are combining with agronomy and plant sciences to develop new tools, technologies, and processes for precision agriculture. Indeed, based on cross-cutting and interrelated competencies in Indiana in life sciences, physical sciences, and engineering, precision agriculture focused “high tech agriculture” is one of AgriNovus Indiana’s four core platforms for agbioscience development in Indiana.

CONCLUSION: Indiana has a considerable volume of research being undertaken in life science, with almost \$603 million in research expenditures. At nearly 46% of total R&D spending, life sciences represent a very important area of focus for university research in Indiana covering applications in biomedical, agricultural, and industrial bioscience application areas, as well as basic science inquiry.

C. Research in Life Sciences: Examples and Case Studies

The importance of basic research in life sciences is hard to overstate, and the performance of basic and applied/translational research are intimately connected. Indeed, it is probably no coincidence that Stoke’s quadrant for “use inspired basic research” is named after a noted life scientist Louis Pasteur. There are many examples of basic research linkages to profound discoveries and tangible technologies in life sciences that serve to illustrate the connection, and just how important funding for basic science work is to progress in life science fields. For example, as noted by Julie McClure:

An excellent example of the interplay between basic and translational research can be seen in the work done on G-protein-coupled receptors. In the 1970s, fundamental research on signal transduction mechanisms led to the discovery of G proteins. Representative G-protein-coupled receptors were subsequently discovered in studies of hormone action, vision, and other processes. These receptors represent the targets of nearly half of all drugs, which have therapeutic actions across a wide array of human diseases ranging from allergic rhinitis and hypertension to schizophrenia. We’re talking about 40 years of research that now represents a huge slice of the pharmaceutical pie. That’s a story that needs to be told. The initial work behind those therapeutics was not directed toward translation but rather fundamental knowledge. Without that basic knowledge, understanding the action of many drugs and developing assays for drug discovery and development would be essentially impossible.⁶³

Table 9 illustrates just a few examples of this in action:

Table 9: From Basic Science to Pragmatic Innovations – Selected Life Science Examples

Applied Activity or Technology	Exemplary Roots in Basic Research
Chemotherapy treatments	Made possible through basic research elucidating molecular differences in cancer cells. Multiple chemotherapy drugs have been developed using recombinant DNA technology rooted in basic research such as bacterial biochemistry. Determining the structure of DNA alone was a 40-year process of inquiry and discovery.
Diagnostics and treatments for genetic disorders	Fundamental research in the structure of the human genome has led to the identification of genes associated with a range of diseases and disorders. Understanding the genetic code has opened up the molecular path for developing diagnostics and therapeutics.
Biomedical imaging	Multiple biomedical imaging technologies have their roots in fundamental physics inquiry that was performed with absolutely no eye towards biomedical applications. For example, the first scan of a human using MRI was conducted in 1977 but is based on work conducted in 1937 by Isidor I. Rabi at Columbia, who first observed the quantum phenomenon dubbed nuclear magnetic resonance (NMR).
Food Safety	We obviously need to eat, but food used to be a consistent killer before basic science brought us germ theory and an understanding of the impact of microorganisms in disease. Pasteur’s research into the use of heat to sterilize milk revolutionized public health.
Improved Crop Yield	The large-scale increases in crop yield achieved through the 20th and into the 21st century leverage basic science discoveries in plant hybridization, crop genetics, transgenics, biochemistry, and molecular biology.

In the biomedical and health sciences sector, life science research innovations are having a powerful impact on quality and longevity of life. As BIO/TEconomy reports:

⁶³ Julie McClure. 2012. “The value of basic research shouldn’t be lost in translation.” *ASBMB Today*, February 2012. The American Society for Biochemistry and Molecular Biology. Accessed online at: http://www.asbmb.org/asbmbtoday/asbmbtoday_article.aspx?id=15846

Life expectancy in the U.S. has risen steadily from 76.8 years in 2000 to nearly 78.8 years in 2013, while death rates from conditions such as heart disease, stroke, cancer, influenza, and pneumonia are steadily declining. The contributions from the bioscience industry to increasing life expectancy are directly linked – it is estimated that 73% of the increase in recent years is attributable to the use of innovative medical products.⁶⁴

The same report goes on to note that “today, many diagnoses that were once devastating can now be treated as a manageable chronic condition, including:

- *Once an incurable disease, Hepatitis C now has cure rates above 90%.*
- *Since its peak in 1991, the death rate for cancer has fallen by 20%, due in large part to medicines.*
- *Among children born during the last 20 years, it is estimated that vaccination and advances in vaccines will prevent more than 730,000 early deaths in the U.S.*
- *The five-year survival rate for acute lymphocytic leukemia has increased from 41% in the mid- 1970s to 70% between 2005 and 2011.”⁶⁵*

As the case studies below indicate, life science research at research universities in Indiana has been a notable contributor to American biomedical research success and applied advancements in healthcare.

Case Study: University Life Sciences Research in Action in Indiana

Indiana Research Legacies: Indiana University School of Medicine and the “Father of Echocardiography”

Dr. Harvey Feigenbaum, an Indiana University School of Medicine faculty member since 1962, pioneered the use of ultrasound technology in cardiology. An IU-trained M.D., Dr. Feigenbaum experimented with ultrasound machines, realizing he could use them to detect the collection of fluid in the sac that surrounds the heart, a condition known as pericardial effusion. The diagnostic technique he developed was the first reliable and long-lasting application of cardiac ultrasound.

Dr. Feigenbaum, who later became recognized as the “Father of Echocardiography”, taught the first medical school course in echocardiography and has continued to lead research in this field for decades. Echocardiography is the most widely used cardiovascular imaging tool and is used all over the world to assess the size, shape, and condition of the heart. In the U.S. alone, more than 20 million echocardiograms are performed each year.

In 2014, Dr. Feigenbaum was awarded the President’s Medal for Excellence by Indiana University President Michael McRobbie, who notes:

“His discoveries have helped ensure an exceptional quality of life for Hoosiers, and his distinguished career has brought great distinction to the university and the IU School of Medicine.”

⁶⁴ TEconomy Partners. 2016. “The Value of Bioscience Innovation in Growing Jobs and Improving Quality of Life 2016.” Accessed online at: <https://www.bio.org/value-bioscience-innovation-growing-jobs-and-improving-quality-life-2016>

⁶⁵ *Ibid*

Case Study: University Life Sciences Research in Action in Indiana

Indiana Research Legacies: Indiana University School of Medicine and the Cure for Testicular Cancer.

As recently as the early 1970s, the vast majority of men who developed testicular cancer died from the disease. That changed mid-decade with one of the most important developments in oncology occurring at the Indiana University School of Medicine. Dr. Lawrence Einhorn, a medical oncologist with expertise in cancer drug therapies, arrived at Indiana University in 1973. His expertise was to complement the surgical excellence of Dr. John Donohue, who at that time was considered a global leader in surgical care for early-stage testicular cancer and was making progress in saving lives. Drs. Einhorn and Donohue were committed to improving the patient survival rate which at that time, was at a devastatingly low five percent.

Early in his tenure at Indiana University, in 1974, Dr. Einhorn tested a platinum-based drug called Cisplatin. While particularly toxic, this drug was not effective in stopping the growth and spread of most cancers. However, it had shown some promise in disease regression among testicular cancer patients. Einhorn developed an approach to combine Cisplatin with two additional drugs, and the results were “stunning”. After administering the three-drug regimen, patient’s tumors dissolved in a matter of days. Dr. Einhorn’s continued research minimized side-effects of the treatment and cut the duration of therapy from what had been two years down to nine to 12 weeks. Further, as he had developed a model for a curable tumor, the work of Dr. Einhorn advanced that of other oncologists for generations. Today, just 40 plus years later, the odds for men with testicular cancer have flipped, and 95 percent of all patients are cured.

Dr. Donohue continued to advance surgical treatments and together, the two doctors established the reputation of IU’s School of Medicine as the leading institution in testicular cancer research, treatment, and education.

Similarly, the work of Indiana’s universities, especially Purdue University, in agricultural life sciences has resulted in celebrated discoveries and innovation:

Case Study: University Life Sciences Research in Action in Indiana

Indiana Research Legacies: Purdue University Research and the World Food Prize

The World Food Prize is the foremost international honor recognizing the achievements of individuals who have advanced human development by improving the quality, quantity, or availability of food in the world.

Dr. Gebisa Ejeta was the 2009 World Food Prize laureate for his, and his Purdue team’s, work on developing sorghum hybrids resistant to drought and to Striga weed. Known as the greatest threat to food production in Africa, Striga is a parasitic weed that impacts over 40% of the arable land in Africa -devastating the yield and substantially reducing the food supply for 100 million people. In collaboration with Purdue colleague Dr. Larry Butler, Dr. Ejeta’s work at Purdue used the tools of genetics, biochemistry, and agronomy to scientifically unravel the parasitic relationship between Striga and the host sorghum plant. The work resulted in the team identifying genes for Striga resistance and then being able to transfer these genes into high performance sorghum varieties, well-suited to high yield production in the African environment. Achieving yield up to four-times that of local African varieties, the Purdue-developed Striga resistant sorghum varieties have been transformational for African farmers and their communities.

Sorghum is also an increasingly important crop in the United States, and the work of the Purdue team has also resulted in the release of multiple elite sorghum inbred lines for use in U.S. agriculture.

Case Study: University Life Sciences Research in Action in Indiana

Indiana Research Legacies: Purdue University Fundamental Advancements in Biofuels

Dr. Nancy W. Y. Ho received her PhD from Purdue University's Department of Biological Sciences and has enjoyed a long career at Purdue on the faculty of Chemical Engineering.

Dr. Ho's work in DNA techniques to improve industrial organisms has formed the foundation for the recombinant yeasts that make possible the production of cellulosic ethanol via fermentation technology. The work of Dr. Ho and her colleagues in the Purdue Laboratory of Renewable Resources Engineering has had such a widespread impact on the development of next-generation biofuels that in 2016, Dr. Ho was awarded the National Medal of Technology and Innovation in a ceremony at the White House.

Case Study: University Life Sciences Research in Action in Indiana

Indiana Research Legacies: From Basic Chemistry to Blockbuster Drugs

On the faculty of Purdue at the time, Professor of Chemistry Dr. Herbert Brown was the co-recipient of the 1979 Nobel Prize in Chemistry for his work on the fundamental study of boron compounds, and the use of boron- and phosphorus-containing compounds, respectively, as important reagents in organic synthesis.

This research stands as a prime example of how fundamental research can later result in a high impact application of the knowledge generated. In the case of Dr. Brown's work, the reagents he developed were instrumental in the development of both Lipitor and Prozac, blockbuster pharmaceuticals that have both helped millions of patients. Lipitor is used to treat hypercholesterolemia (high cholesterol) and help prevent the cardiovascular complications related to it, while the serotonin reuptake inhibitor (SRI) Prozac has been a successful frontline drug in fighting the psychiatric disorder of depression.

As an interesting aside, the development of Prozac was further facilitated by Indiana University where neuroscientist and faculty member at IUSM, Dr. Paul Stark, led the clinical team at Eli Lilly and Company in the development of Prozac.

The above case studies represent hugely influential discoveries, but they are just a small part of the intense volume of research findings flowing out of Indiana's research universities each year. It is impractical to list all the life sciences work taking place or recently concluded, but some further examples below serve to show the wide-range of basic and applied life sciences research and innovations originating at Indiana's signature research institutions (Table 10):

Table 10: Some Recent Examples of Life Sciences Research in Action at Indiana's Research Universities

Purdue University
<ul style="list-style-type: none">Flavivirus research team at Purdue was first to map the structure of the Zika virus, including a 3-D representation of the virus structure.Zebrafish-based modeling at Purdue is elucidated dosing levels of the herbicide atrazine that would harm embryo development.Research by Purdue sociologists uncovered a link between negative social situations (such as persistent poverty, verbal, or physical abuse, etc.) and the development of physical diseases (such as cancers and cardiovascular disease) later in life.Purdue researchers led the international team to complete the genome sequence for the deer tick (<i>Ixodes scapularis</i>), the vector for transmission of Lyme disease.

Purdue University (cont.)

- Discovery of the first identified gene associated with “hard seededness”, an issue for agricultural seed producers who need predictable, rapidly germinating plant seeds.
- Purdue medicinal chemists are in the field and the lab using ethnopharmacology to identify plant-based chemicals with application as neuroprotection agents in Parkinson’s disease.
- Development of an enzyme inhibitor to block the release of malaria parasites from red blood cells in the host. This led to a new drug to treat malaria, currently in human trials.
- Biochemists at Purdue are developing ways to enrich molecular signatures of cancer to detect the earliest signs of its development.
- Communication with severe, non-verbal autistic children has been accomplished for the first time using tools developed by a multidisciplinary group in speech, language, hearing sciences, and educational studies.

Indiana University

- Indiana University researchers at the medical school discovered the cancer-fighting agent in Tamoxifen.
- Indiana University School of Medicine is home to NIH funded National Centers of Excellence in Alzheimer’s disease, cancer, musculoskeletal diseases, and diabetes.
- The Indiana University School of Medicine is home to the only NIH funded viral vector production facility for clinical grade therapeutics.
- Indiana University research is pioneering a cure for Fanconi Anemia, which results in decreased production of all types of blood cells.
- Indiana University research leadership in traumatic brain injury is performing pioneering work on both combat and sports-related injuries.
- Using large datasets and universal scaling laws, biologists at Indiana University published (in the Proceedings of the National Academy of Sciences) results indicating the Earth may contain nearly 1 trillion species, with only one-thousandth of 1 percent currently identified.
- Indiana University school of medicine was awarded the only national center for developing animal models of Alzheimer’s disease by the NIH in 2016.
- Indiana University School of Medicine’s affiliate Regenstrief Institute is world leader in health informatics research.
- Indiana University houses multiple national collections of biospecimens including most NIH neurodegenerative diseases including Alzheimer’s, Parkinson’s, traumatic brain injury, Komen Foundation breast cancer tissue, and Michael J. Fox foundation Parkinson’s disease samples and others.

The University of Notre Dame

- Researchers at Notre Dame have performed fundamental research resulting in a potential new approach to identifying T-cells and T-cell receptors that may lead to new cancer immunotherapies.
- Researchers at the Notre Dame Center for Rare and Neglected Diseases are making fundamental strides in drug discovery and development for Malaria and Tuberculosis and in rare diseases such as Niemann-Pick Type C (NPC) and MPS-3A. (See case study below).
- Researchers in the Notre Dame Initiative on Advanced Diagnostics and Therapeutics (AD&T) have been developing the analytical tools necessary to bring the tools of precision medicine to practical application, particularly in rapidly advancing ‘omics areas. The AD&T initiative also works together with colleagues at Purdue University and Indiana University in the Indiana Center for Analytical Science and Engineering (ICASE) where they teach joint classes and are developing multi-university research initiatives. Recent conversations have included the Indiana Biosciences Research Institute.
- Investigators with the Notre Dame Environmental Change Initiative are conducting both fundamental and field studies of agricultural run-off and environmental issues due to agricultural herbicides and pesticides. A recent USDA study is measuring the efficacy of cover crops and double ditch methods on farms near Warsaw Indiana for reducing pollutant flow into fresh water streams and lakes.

Case Study: University Life Sciences Research in Action in Indiana

Biomedical Research to Save and Improve Lives: Notre Dame's Focus and Strengths in Rare and Neglected Disease Research

In recent years, The University of Notre Dame has increased its emphasis on biomedical research, expanding its R&D expenditures in biological and medical sciences by 84 percent since 2006, and reaching \$27 million in 2015. While this research covers a number of focus areas, the university stands out in its unique emphasis and strength in research related to rare diseases—defined as those thousands of diseases that, on their own, affect fewer than 200,000 people—as well as “neglected” diseases that afflict billions of people, primarily in the developing world.

“The work of this center to find cures and therapies for those who suffer from rare and neglected diseases aligns perfectly with our institutional goal to use our research capabilities to make a genuine difference in the world.”

Rev. John I. Jenkins, C.S.C., President, University of Notre Dame

In 2009, the University established its Center for Rare and Neglected Diseases (CRND), which in 2014 was endowed via \$10 million in gifts and renamed the Boler-Parseghian Center. The center includes faculty from more than 10 different departments, combining expertise that spans vaccine development and medicinal chemistry, drug delivery platforms, and social development programs and patient outreach.

The Boler-Parseghian Center is focused on the translation of research into technologies, therapeutics, vaccines, and diagnostics related to rare and neglected diseases that improve lives and outcomes for patients. Areas of focus supported by the center include drug discovery and development in infectious diseases such as Malaria and Tuberculosis, and in rare diseases such as Niemann-Pick Type C (NPC) and MPS-3A; and health analytics for tropical diseases.

Recognizing the importance of both biomedical as well as transdisciplinary research collaboration, the center plays a key role in bringing together researchers and capabilities not only from different departments within the University, but also with external partners such as non-profit foundations, other academic institutions, and private industry. CRND has developed partnerships with Eli Lilly & Co., Medicines for Malaria Venture; the Bill and Melinda Gates Foundation; and the NIH, and the center recognizes the need to leverage public-private partnerships involving pharmaceutical partners and national and international agencies to make progress in these areas.

Led by the Warren Center for Drug Discovery, several colleges, centers, and administrative units at Notre Dame have come together as part of the University's partnership with Eli Lilly to create the Notre Dame-Eli Lilly & Co. Faculty Fellowship Program in Drug Discovery. The Fellowship provides a stipend to support a faculty member as a visiting scholar at Eli Lilly, and to learn and experience the drug discovery and development process. For two to three months, the Fellow shadows research scientists and project managers in Lilly's Indianapolis-based chemistry program, and has the opportunity to consult, collaborate, and to promote new connections between researchers at the University and those at Lilly.

CONCLUSION: Life sciences research in Indiana has a rich history, with multiple groundbreaking discoveries recognized globally for their impact. A strong legacy of life science impacts continues in Indiana across the basic and applied spectrum of university research and in diverse domains spanning human biomedical, veterinary, agricultural, and industrial applications of life sciences.

Nothing in life is to be feared, it is only to be understood. Now is the time to understand more, so that we may fear less.

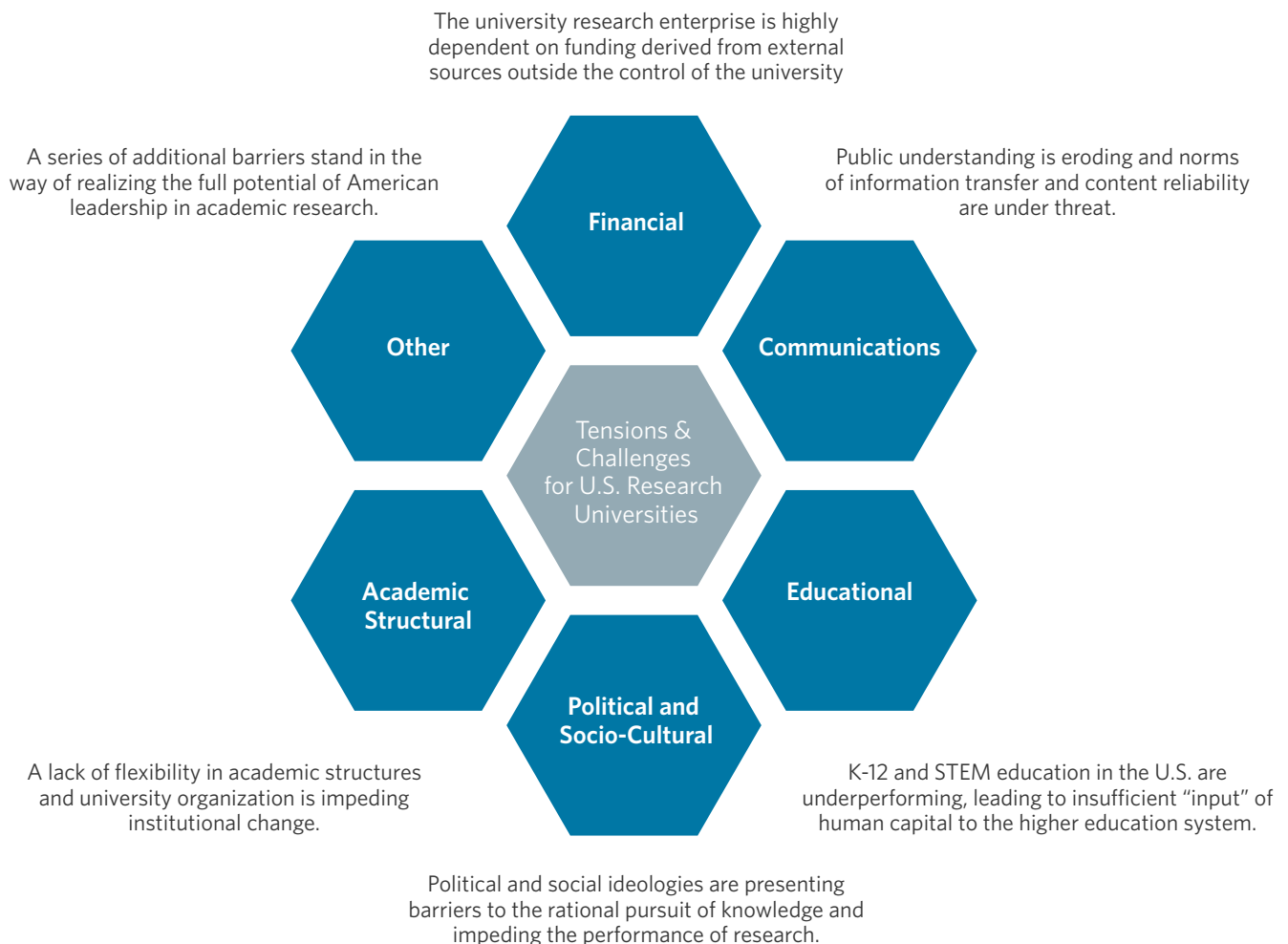
- Marie Curie

Chapter VI: The Changing Environment of Academic Research

Thus far, we have established that research is of crucial importance to the societal and economic advancement of the United States and to individual Americans. Further, we have also established that research universities play a vitally important and multifaceted role in society, the economy, and in the performance of research across the entire research spectrum—basic to applied. Both in terms of performance of research directly, and in terms of training graduates in research methods who may then move into R&D or related positions in commerce, government, and other sectors, university-based research is a core and absolutely necessary component of the U.S. R&D ecosystem. We have also seen that public investment in research yields a particularly high return, and is a necessary component for research focused on multiple social and economic issues. The future performance of the United States across a broad range of economic and social issues and opportunities will be very much impacted by the strength and fortunes of U.S. research universities.

While it may seem that research universities are stable institutions, part of an institutional structure and tradition dating back centuries, the pace of change in today's society and economy, and in technologies and global competitive forces, are creating tidal forces that will impact the future of the U.S. research university. And, there are a series of tensions that our signature research universities are experiencing that if not resolved favorably, represent a serious threat to the standing and future performance of our nation and its individual states. Macro-categories containing many of the key tensions or challenges facing research universities are shown in Figure 19:

Figure 19: Collective Macro-categories of Tensions and Challenges Facing U.S. Research Universities



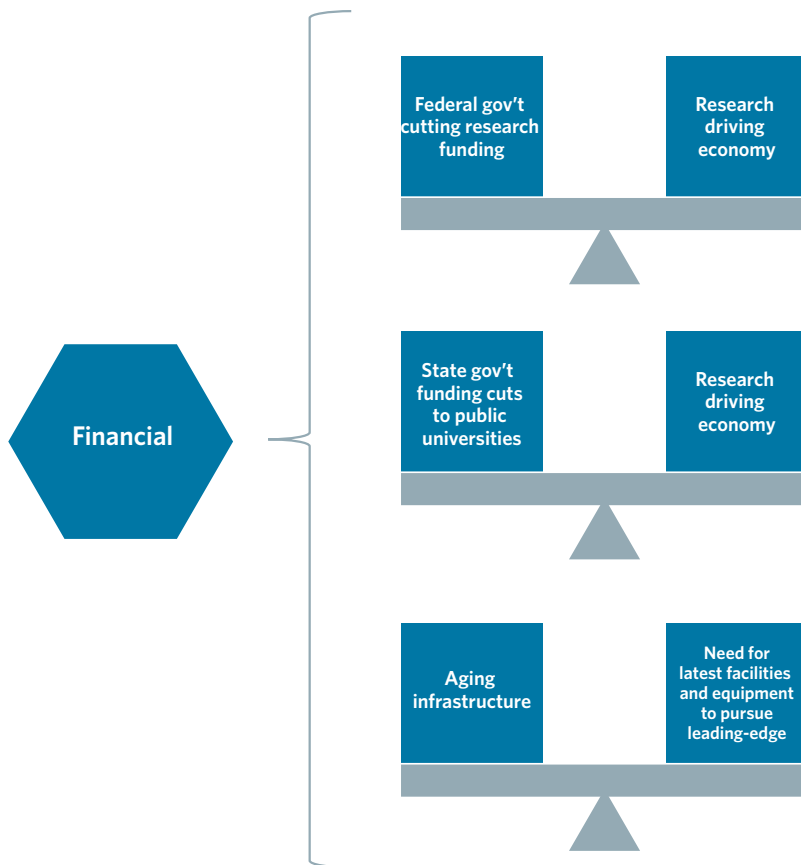
Each of these macro-categories of challenges and tensions are individually a serious threat to our national research leadership. Taken together, as we have shown, they represent an unprecedented threat to institutions that play multifaceted and crucial roles within American society and the economy. Each is considered below:

A. Financial Challenges and Tensions

It's no secret that undertaking research requires both human and financial capital. Funding is necessary to support payroll for university faculty and staff, and to acquire and support operations of the physical infrastructure, instrumentation, and supplies necessary to conduct research. For some time, the United States has sustained the largest single nation expenditure on R&D of all forms, but this position is eroding – as evidenced by successive Global R&D Funding Forecast's which have demonstrated a gradual decline in the percent of global R&D conducted in the U.S. In 2016, the U.S. captured 25.6% of global R&D funding⁶⁶, whereas in 2006, this percentage stood at 32.7%⁶⁷ (showing a decline of 21.7% over the last decade) and China is now nipping at the heels of U.S. R&D (with 20.8% of global R&D projected for 2017). In fact, as a region, Asia has already overtaken North America, with 42.3% R&D funding share, versus 27.8% for North America⁶⁸.

For universities (Figure 20), financial challenges (including to R&D funding) present a series of tensions for our nation and for individual states. Declines in financial support for universities at a state level, in combination with existing and potential cutbacks in federal funding agency budgets, are in direct tension with future progress and economic growth given the importance of R&D to national economic performance.

Figure 20: Examples of Financial Tensions Facing U.S. Research Universities



⁶⁶ R&D Magazine. 2017. "Global R&D Funding Forecast"

⁶⁷ R&D Magazine. 2017. "Global R&D Funding Forecast"

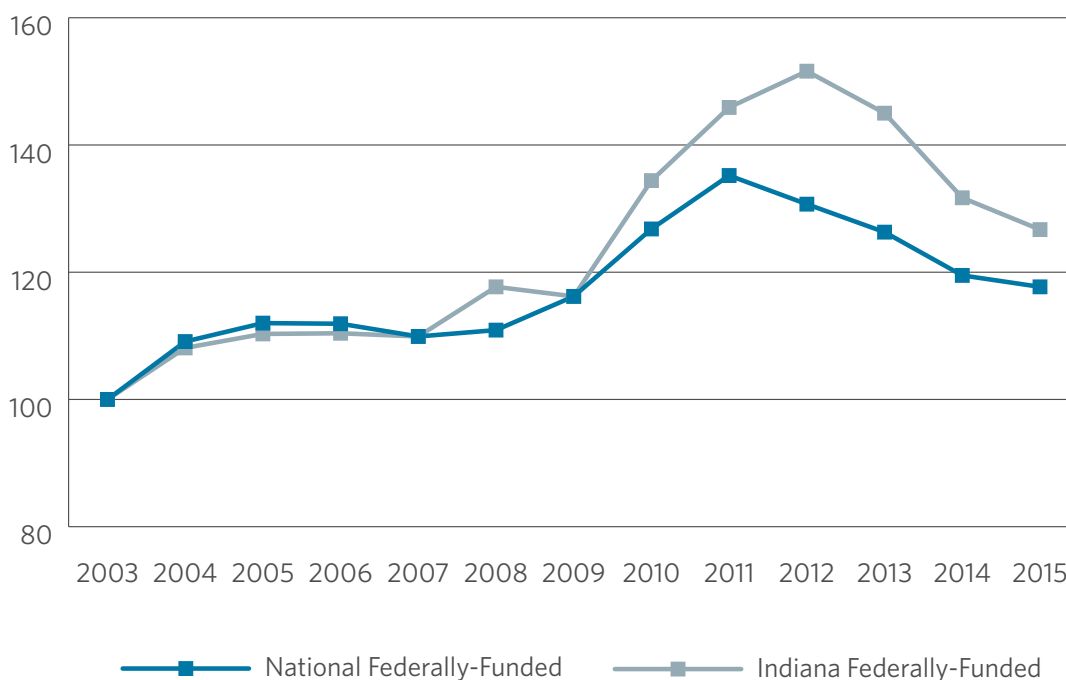
⁶⁸ R&D Magazine. 2017. "Global R&D Funding Forecast"

Restricted budgets at universities restrain the hiring and retention of faculty, limit financial support available for graduate student research and training, and reduce the ability of universities to invest in the facilities and equipment required to pursue leading-edge areas of research. U.S. News reports that:

Federal support for research at America's universities dropped 11 percent from 2011 to 2014 when adjusted for inflation, and these funds make up over half of all university research, according to the National Science Foundation. "This is the longest multiyear decline in federal funding for academic R&D since the beginning of the annually collected data series in FY 1972," the National Science Foundation concluded.⁶⁹

The latest National Science Foundation data confirm that this downward trend has continued in federal R&D funding at universities adjusted for inflation (Figure 21, blue line). Further, this is the trend nationally and is also very much evident in Indiana (Figure 21, grey line), where although significant gains occurred from 2009 through 2012 (likely influenced by the temporary boost of the American Recovery and Reinvestment Act), since 2012, there has been a significant downward trajectory.

Figure 21: University Research Expenditures from Federal Funding (U.S. total and Indiana), Indexed from 2003 baseline and in Constant 2009 Dollars



Source: TEconomy analysis of National Science Foundation, Higher Education R&D Survey; adjusted for inflation by NSF using GDP Implicit Price Deflator and shown in constant 2009 dollars.

As noted elsewhere in this report, federal investment in research is vital to U.S. competitiveness and economic growth as well as technological development, which is one of the main drivers of job creation over the long-term. Continued spending cuts in these areas will likely cause further decline in the dominance of the U.S. in R&D and academic publications. Likewise, the U.S. may become a less desirable destination for top researchers from around the globe looking to live and work in an environment that supports research both economically and ideologically. Federal spending cuts send a signal to the world that American leadership is discounting the importance of research in the nation.

69 Lou Anna K. Simon. 2016. "The Future of America, Forgotten in 2016". U.S. News and World Report. March 18, 2016.

Additionally, states saw revenues plunge as a result of the Great Recession. Recovery has been slow, and despite progress since the recession, nineteen states still collect less tax revenue than at their pre-recession peaks.⁷⁰ These developments make it difficult for state governments to fill the gaps left by changes to federal funding streams. Budget cuts and decreases in tax revenue at the state level are being felt strongly across public research universities. For instance, twenty state governments invested fewer dollars in R&D in 2015 than in 2006, despite total state R&D funding growing by over 100% during that same period⁷¹, and over time, this is likely to increase disparities between high performing and low performing state economies. As in the case of decreased federal funding, reduced state funding carries the risk that a state will become a less desirable destination for top researchers.

B. Communications Challenges and Tensions

Universities, and indeed society as a whole, are also facing a communication problem. Ironically, we live in an economy and society increasingly defined by the importance of knowledge and information, yet we are also seeing a dramatic rise in the impact of disinformation (deliberately misleading information) and misinformation (unintentionally false information). The Internet has helped support the proliferation of vast news and information sources, much of it unrestrained by moderation or traditional editorial standards. Further, social media, the ubiquity of rapid, Web-enabled information access devices, and search engines promote an “instant gratification” mode of acquiring information that is perhaps antithetical to considered and thoughtful inquiry and acquisition of knowledge.

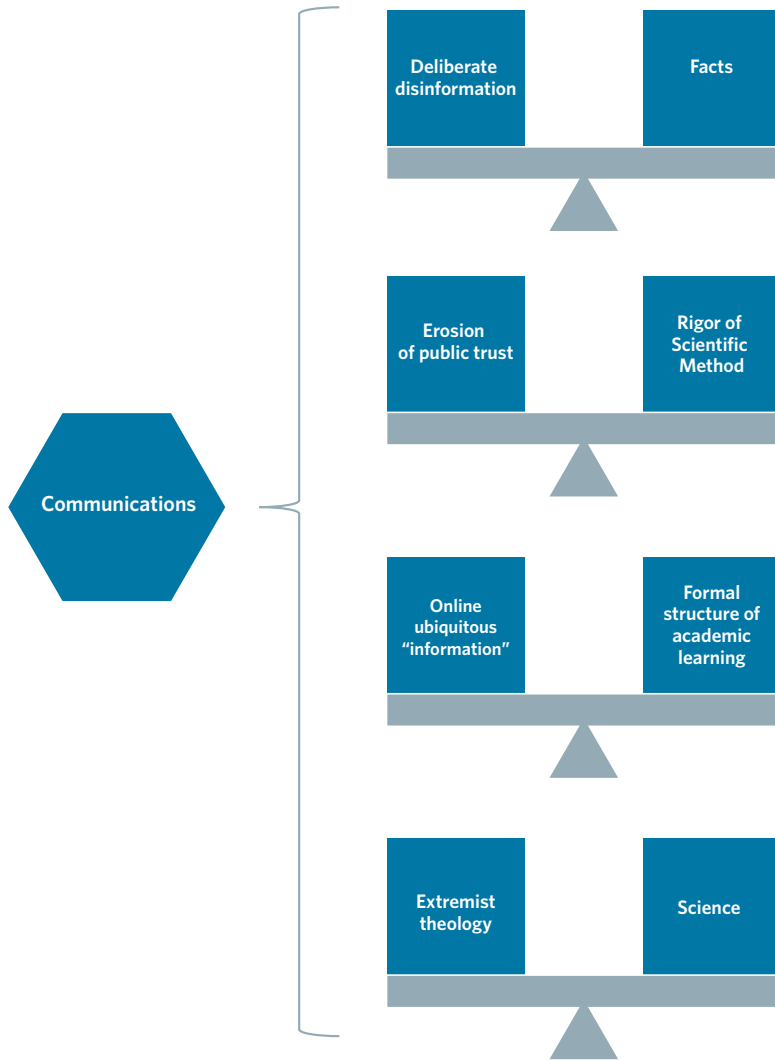
In our relatively recent past, information and accepted knowledge were communicated primarily through the written word in publications subject to editorial review (whether that be a newspaper article, a book, or an academic journal). In addition, knowledge has been transmitted verbally, typically in a structured fashion of a mentor to a mentee, a supervisor to a worker, or a professor to a student, etc. In this past environment, a university held a seemingly unassailable position of trust as a producer and disseminator of knowledge and information. Today, that position is threatened by these other modes of communication.

Just some of the tensions observable in the modern American conversation surrounding science, politics, the environment, and the economy are highlighted in Figure 22, but the implication of these to future progress in our society and economy are extremely serious.

⁷⁰ <http://www.pewtrusts.org/en/multimedia/data-visualizations/2014/fiscal-50#ind0>

⁷¹ <https://www.nsf.gov/statistics/2017/nsf17308/>

Figure 22: Examples of Communication Tensions Facing U.S. Research Universities



Part of the communication challenge being faced is well described by Sociologist Gerard Delanty, who describes the growing phenomenon of the “contestability of knowledge”, noting that:

As knowledge becomes more available, and therefore no longer confined to an institutional space such as the University, it also becomes more contested. Today, in the knowledge society, with knowledge ever more available as a result of mass education and developments in reproduction of culture and communication and as a result of the rise of knowledge professions, it is also paradoxically more and more unreliable and contested. The knowledge society is thus also a 'fragile society'. The university has experienced this in the 'culture wars' over the curriculum, radical multiculturalism and the low culture's critique of the high culture of the academy.⁷²

A 2013 private strategic planning report written by Simon Tripp, Deborah Cummings, and Adrian Roberts at the Battelle Memorial Institute for The Ohio State University scrutinized the wide-range of grand challenges facing the world. Examining the literature on global issues and consulting with many leading scientists and senior government policy advisors globally, the project for Ohio State focused on challenges that had a root or compounding effect on multiple other challenges. Misinformation and disinformation were found to hold a central place in terms of being global grand

72 Gerard Delanty. 2002. “The Governance of Universities: What is the Role of the University in the Knowledge Society?” *The Canadian Journal of Sociology*, Vol. 27, No. 2. (Spring 2002)

challenges themselves and powerful inhibitors of progress on other global challenges. As noted in the Ohio State document:

Misinformation is false or inaccurate information that is spread unintentionally. Disinformation is intentionally false or inaccurate information that is spread deliberately. Both misinformation and disinformation can have significant impact on world opinions and the subsequent global policies. For instance, there is widespread misinformation/disinformation regarding global warming, driven in part by political and economic special interests. One of the goals of misinformation/disinformation appears to be to confuse the average citizen and give the impression that the science behind global warming is weak. This disinformation campaign is at least partly successful; polls (for example, the 2009 Pew/AAAS poll, SI, November/December 2009) show that about half the people in the United States think there is substantial disagreement among scientists, when actually there has been a consensus on this topic for about a decade. The scientific case becomes stronger all the time, but global public acceptance is lagging. Most of the counterarguments don't make scientific sense, or else they are based on information that is obsolete. Another area of global debate in which a significant amount of misinformation/disinformation has been communicated relates to transgenic crops and their impact on food security. The ability to communicate misinformation/disinformation has become increasingly widespread as the use of the Internet has proliferated around the globe.⁷³

Since 2013, the situation has clearly become more challenging, not less. We are seeing compounding evidence that organized disinformation campaigns have been executed by national governments, and that social media and other non-traditional media sources regularly facilitate the proliferation of disinformation and misinformation. Vested commercial interests also engage in self-serving propaganda and in some cases, deliberate disinformation campaigns to attack academic and scientific findings that go against their business interests – facilitated again by rapid access to electronic media. Examples of this in action are relatively easy to find in areas such as:

- Climate science
- GMO crops
- Impacts of fracking
- The relative engagement of different racial groups in crime
- Immigration

As deployed by academe, the very nature of the scientific method means that progress is achieved as gains in knowledge are accumulated and built upon over time. If accumulated academic knowledge is the foundation upon which our societal and economic progress is built, the challenges of communicating research findings to lay audiences, in concert with the disinformation and misinformation proliferation, represent a dangerous undermining of those foundations.

While the vast majority of Americans understand that science has made people's lives better, there still exist significant gaps between the public's opinion and that of scientists with regards to a range of issues.⁷⁴ Insufficient education and STEM education challenges may be partly to blame as a misunderstanding of what scientists actually do leaves room for suspicions of bias that are seldom present. Politicians and political parties and movements have also taken advantage of this situation to advocate for anti- or unscientific policies and these anti-scientific campaigns are usually undertaken for political, ideological, or economic interests. Finally, misinformation and disinformation can have a significant impact on domestic and world opinions and subsequently, national and global policies. These problems seem to exist hand-in-hand with our discussion of ideology as a roadblock to evidence-based policy solutions covered later in this section. In the U.S., these problems have had a particularly strong impact on science policy and

⁷³ Simon Tripp, Deborah Cummings, Adrian Roberts. 2013. "The Ohio State University Discovery Themes: An Evaluation of Global Grand Challenges and Technologies at the Intersection of the Three Discovery Themes." Battelle Technology Partnership Practice. March 2013 (Unpublished).

⁷⁴ <https://www.washingtonpost.com/news/the-fix/wp/2015/01/30/americans-increasing-distrust-of-science-and-not-just-on-climate-change/>

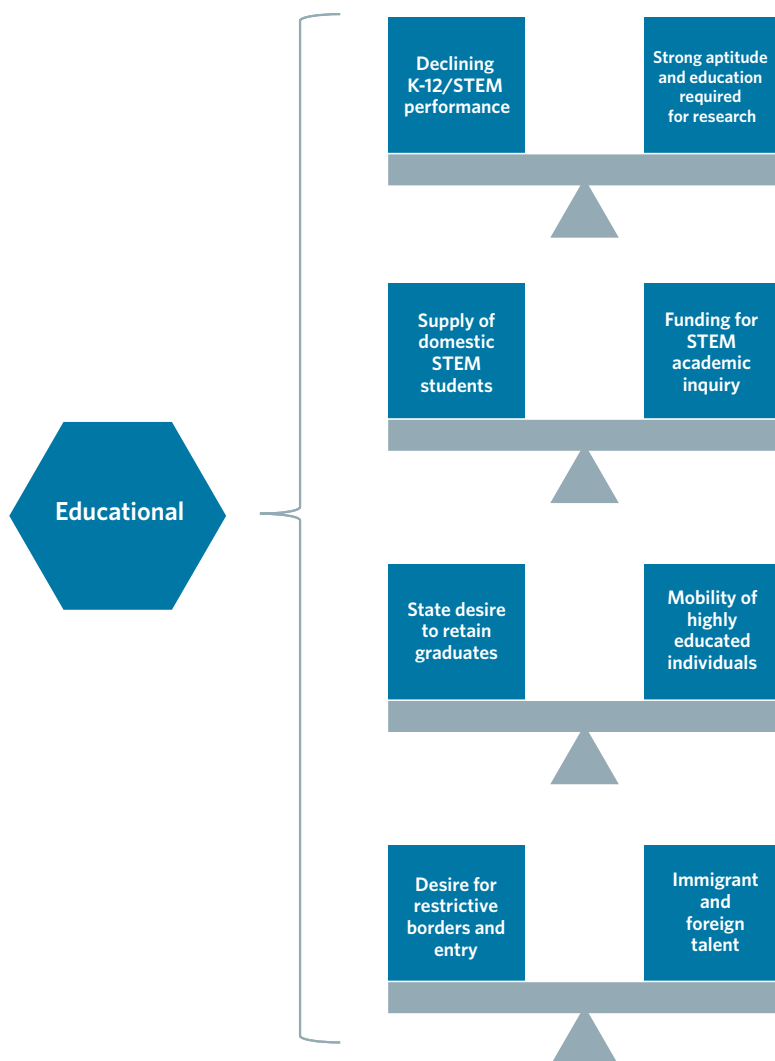
discourse in areas like climate change, genetically modified organisms (GMOs), vaccines, birth control, and education (particularly regarding the theory of evolution), despite near-universal agreement within the scientific community on how each of these processes work.

It is also of concern that social media and other mass communications mechanisms are being used to proactively vilify, shame, or attack faculty for their legitimate academic work. This has occurred from both sides of the political spectrum, with academics attacked for work in areas as diverse as: crop transgenics; women’s studies; climate science; gender studies; and education.

C. Educational Challenges and Tensions

Research is a human endeavor, and the quality of research is, in large part, a function of the quality of the human capital being applied to it. Universities are impacted by a range of education issues including, for example: the quality and numbers of students being produced by the upstream K-12 education system, demand for educational services by foreign students, and state requirements (at public universities) in regard to admission standards and policies. Figure 23 depicts some of these tensions.

Figure 23: Examples of Educational Tensions Facing U.S. Research Universities



A key challenge for our universities (especially research universities that see a core component of their research empowered by high quality graduate students) is our widely acknowledged national underachievement in K-12 education. Some statistics cited in *“Rising Above the Gathering Storm, Revisited”*⁷⁵ illustrate some of the scope of the challenge:

- The United States ranks 20th in high school completion rate among industrialized nations and 16th in college completion rate.
- The World Economic Forum ranks the United States 48th in quality of mathematics and science education.
- In 2000, the number of foreign students studying physical sciences and engineering in the United States graduate schools for the first time surpassed the number of United States students.
- Sixty-nine percent of United States public school students in fifth through eighth grade are taught mathematics by a teacher without a degree or certificate in mathematics.
- Ninety-three percent of United States public school students in fifth through eighth grade are taught physical sciences by a teacher without a degree or certificate in the physical sciences.

The National Center for Education Statistics (NCES) estimates that fewer than half of high school chemistry and physics teachers majored in those subjects, and a quarter of all math teachers do not hold math degrees.⁷⁶ According to OECD analysis of student performance in the Program for International Student Assessment (PISA), the **U.S. ranks 35th in Math and 25th in Science**, in both cases behind Singapore, Hong Kong, Japan, China, Korea, and Western European countries.⁷⁷ Public education is inadequately funded in many areas, and a property tax based funding system for much of our public education makes access to quality STEM training uneven within states. Curriculum standards, which are often set by groups without teaching backgrounds, are subject to political and corporate pressures, resulting in textbooks which ignore or outright reject concepts which are universally accepted by the scientific community.

Given the importance of the science and engineering fields to U.S. economic progress, the lack of emphasis placed on the importance of STEM, and lagging indicators of STEM education achievement make it difficult to produce high quality graduates for STEM fields at the undergraduate and graduate school levels. Due to limited enrollment opportunities, high levels of international interest, and U.S. education disadvantages, many STEM programs at U.S. universities now have a majority of foreign-born students.⁷⁸ Poor STEM performance costs U.S. citizens jobs in top science and technology companies, and foreign-born graduates of advanced STEM programs often take their knowledge and experience back to their home country, which then receives the economic benefits earned from time spent in U.S. higher education.

The American Society of Civil Engineers rankings paint a dire picture for K-12 academic infrastructure in the U.S. School infrastructure received a grade of D+ in the most recent rankings. Underinvestment is a major problem, with an estimated annual gap of \$38 billion. 24% of public school buildings were rated as fair or poor condition. In 2014, thirty-one states provided less school funding per student than they had in 2008.⁷⁹ These findings are key as studies indicate that school infrastructure can have a profound impact on student learning outcomes. A lack of amenities like air conditioning or public health conditions like poor air quality can impact students' academic outcomes and reduce their enthusiasm for learning.⁸⁰

Good infrastructure is vital to the success of academic programs and K-12 teachers are particularly susceptible to the negative impacts of infrastructure. Poor infrastructure can mean students are in environments which have negative effects on health and wellness. For example, teachers not having the tools they need to teach effectively, or teaching

75 National Research Council. 2011. *“Rising Above the Gathering Storm, Revisited: Rapidly Approaching Category 5.”* Washington, DC: The National Academies Press.

76 <https://www.usnews.com/education/blogs/high-school-notes/2011/06/08/many-stem-teachers-dont-hold-certifications>

77 <http://www.businessinsider.com/pisa-worldwide-ranking-of-math-science-reading-skills-2016-12>

78 <https://www.insidehighered.com/news/2013/07/12/new-report-shows-dependence-us-graduate-programs-foreign-students>

79 <http://www.infrastructurereportcard.org/cat-item/schools/>

80 <https://www.usnews.com/opinion/knowledge-bank/2015/06/03/better-school-infrastructure-can-boost-student-learning>

under the added stress of not having the correct number of desks or dealing with buildings in extreme disrepair. Schools with poor infrastructure lack the resources to improve their educational outcomes which in turn, ensure that students from less affluent school districts continue to face an achievement gap compared to children from schools with sufficient resources.

Recent political developments demonstrate that certain segments of the U.S. population and the Executive branch of the federal government seek to restrict the flow of non-Americans across U.S. borders under the stated goal of homeland security and protection for America's workers. And in recent years, these arguments have become more strident, which seems to be impacting the desirability of the U.S. as a destination for travel and for study, and which could have a similar impact on skilled labor migrants.⁸¹ As noted elsewhere in this section, a substantial number of graduate school applicants are foreign-born, but also many faculty positions (especially in STEM disciplines) are held by foreign born faculty. Some U.S. engineering programs have reported declines in foreign-born applicants of up to 30% in 2017 compared to 2016 levels.⁸² Most of the growth in graduate-level enrollment in recent years has been due to foreign-born applicants, so a steep drop in the number of foreign-born applicants does not necessarily mean that there are enough interested and talented U.S. born applicants to meet demand.

Declines in graduate-level enrollment could cause the loss of millions in tuition revenue, impacting engineering and science programs in particular, as well as university-wide expenditures. Science and technology opportunities draw large numbers of foreign-born entrepreneurs and researchers that generate a substantial amount of innovation, and often result in start-up company formation. Policy changes that discourage interest or limit the arrival of highly skilled and educated immigrants threatens to reduce innovation, which will negatively impact the U.S. economy and progress in scientific and technological advancement.

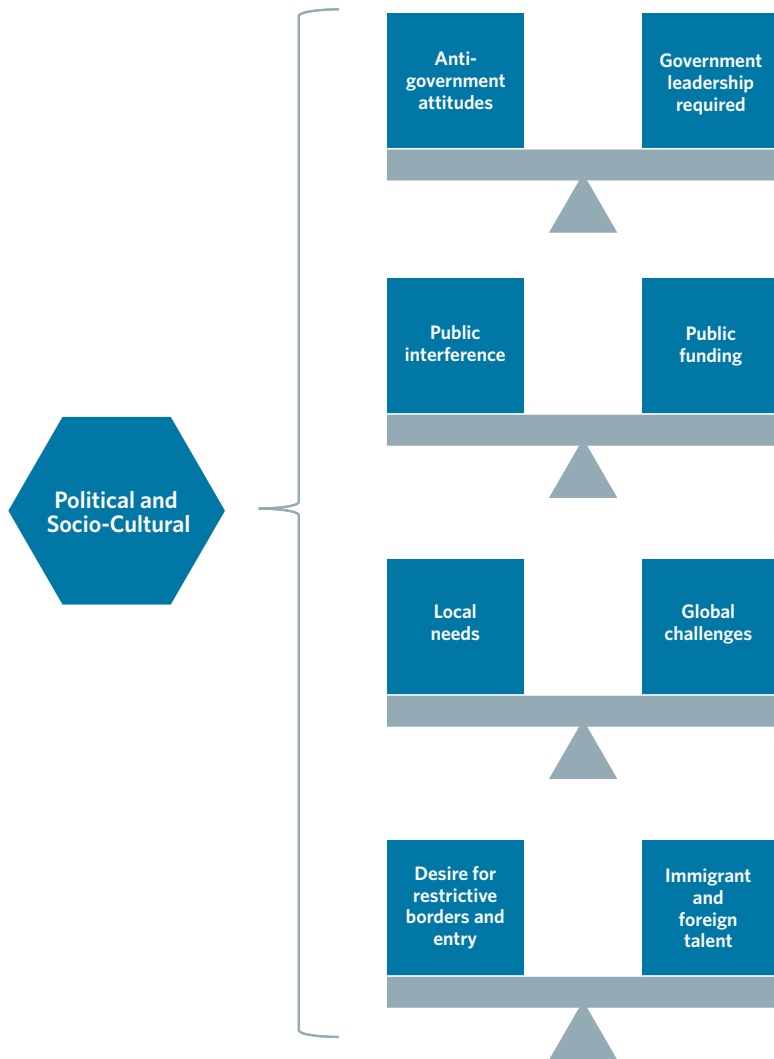
⁸¹ <https://www.nytimes.com/2017/02/20/travel/after-travel-ban-declining-interest-trips-to-united-states.html>

⁸² <https://www.sciencemag.org/news/2017/02/drop-foreign-applicants-worries-us-engineering-schools>

D. Political and Socio-Cultural Challenges and Tensions

Politics and culture have an impact on aspects of each of the previously discussed meta-challenge domains for U.S. research universities. There are also additional dimensions to this challenge category, as depicted on Figure 24:

Figure 24: Examples of Political and Socio-Cultural Tensions Facing U.S. Research Universities



A challenge driven by ideology is the argument that a government can “do no good.” Other related arguments that are relevant to this attitude include the notion that governments just “get in the way” of business, or that the best government is the smallest government, or that only industry needs to do research. While these arguments are not necessarily rooted in logic, their proponents share the same desired outcomes: they generally want government to divest itself of any engagements that might possibly be handled by the private sector, and to substantially reduce regulations, taxes, and other basic functions of governments. As noted elsewhere in this report, investment in basic science is expensive and risky. These efforts do not usually have clear line-of-sight to market opportunities and are therefore not likely to be profitable endeavors for companies. The argument that government can “do no good” falls flat in this case, particularly with regards to science and technology investment because federal research dollars are recognizably integral to the development and dissemination of countless innovations in areas such as communications technologies, medicines and vaccines, plant varieties, and many other commercial innovation domains.

As noted previously in this report, many technological advances we take for granted were facilitated by federal and state funding of university research. Because science advances in ways which cannot be predicted, it is impossible to know whether declines in funding and policy support for basic research will prevent the next significant breakthrough from occurring. We can, however, estimate potential economic costs of not funding scientific research. The Human Genome Project is one such example, and as noted by the National Human Genome Research Institute:

Battelle Technology Partnership Practice estimates that between 1988 and 2010, federal investment in genomic research generated an economic impact of \$796 billion, which is impressive considering that Human Genome Project (HGP) spending between 1990—2003 amounted to \$3.8 billion. This figure equates to a return on investment (ROI) of 141:1 (that is, every \$1 invested by the U.S. government generated \$141 in economic activity). According to the study, Economic Impact of the Human Genome Project, the benefits have been widespread and increasing over time. HGP produced 3.8 million job-years of employment, or one job-year for each \$1,000 invested. Personal income generated by HGP (wages and benefits) exceeded \$244 billion over the time frame, averaging out to \$63,700 income per job-year. Since the HGP's completion in 2003, federal investment in genomic research has actually increased. In 2010 dollars, HGP spending by the National Institutes of Health (NIH) and the Department of Energy (DOE) amounted to \$5.6 billion; for the seven years following, federal genomics spending totaled \$7.2 billion dollars. In 2010 alone, genomics directly supported more than 51,000 jobs, and indirectly supported more than 310,000 jobs, according to the Battelle study. This created \$20 billion in personal income and added \$67 billion to the U.S. economy. The government has even been repaid for its HGP spending. Last year, tax revenues returned to federal, state, and local governments nearly equaled the entire 13-year investment in the HGP. Genomics-enabled industry generated more than \$3.7 billion in federal taxes and \$2.3 billion in U.S. state and local taxes in 2010. Importantly, the scientific and economic benefits of investing in the HGP are growing, the report finds. The impact on medicine, agriculture, energy, and the environment are still in their early stages, with the promise of great things to come.⁸³

As noted by HGP Impact study report authors Simon Tripp and Martin Grueber:⁸⁴

Within the genomics field, there is little doubt among industry and scientific leaders that the Human Genome Project and the Celera sequencing project represented critically important stimuli for the genomics industry's development. In interviewing key leaders in the field for this project, the Battelle research team was told over and over again that the HGP, in particular, empowered the industry's development. Battelle asked the question "Without the HGP, where do you think we might be today in terms of sequencing technologies and associated genomics technologies?" — some typical responses included:

"We would not even be close to where we are today. Would just be doing bits and pieces."

"Would not have advanced practically at all. There has really been a dramatic influence here"

"The industry would not exist. The HGP set up the competitive space that enabled sequencing and genomics companies to grow."

The HGP may be a particularly large example of government funded research paying-off, but it is not atypical. As Chapters II and III illustrate, the world of R&D and the advancements powered by it are part of a research ecosystem, and federally funded research at public and private research universities is a key fuel for the research engine. In the face of this evidence, stating that "government can do no good" or "all research should be in the private sector" is not only naïve, it is destructive to America's future economic and social progress.

⁸³ Jonathan Max Gitlin. 2011. "Calculating the economic impact of the Human Genome Project". Accessed online at: <https://www.genome.gov/27544383/calculating-the-economic-impact-of-the-human-genome-project/>

⁸⁴ Simon Tripp and Martin Grueber. 2011. "Economic Impact of the Human Genome Project." Battelle Memorial Institute, Technology Partnership Practice.

Another political/socio-cultural issue impacting universities relates to public-sector interference in the research process based on religious, ethical, ideological, or other grounds. As noted previously in this report, the size and importance of public sector funding for academic research imposes direction on the research enterprise. And although this influence may have positive or negative ramifications, it should be recognized. Public opinion swaying federal or state lawmakers to legislate on scientific issues has an impact on scientific research funding and the performance of research. For example, in recent years, research universities and their faculty have had to grapple with politicized issues that very much affect their work in areas such as:

- Stem cell research (particularly as it relates to human embryonic stem cell lines)
- Cloning
- Transgenics and genetic modification of organisms
- Climate science
- High energy particle physics (with concerns expressed that the Large Hadron Collider would create a black hole)
- Evolutionary and developmental biology (and the interjection of “Intelligent Design” and “Creationist” theology)
- Political science, where attempts have been made to remove the discipline from NSF funding
- Public health research, where government policy activity blocks, for example, CDC support of research into gun violence.

Universities, most notably public universities, also face understandable state and local desires to focus their work on needs relevant to their home state or region. It is not an unreasonable expectation for state and local funders of public education to desire to see a return on their investment in this manner, but it does create tensions that senior administration of public universities have to account for in terms of:

- Expectations of research relevance to local needs and problems versus global challenges
- Expectations to commercialize research in a manner that favors local commercialization (a local start-up enterprise or transfer of technology to a local company) as opposed to licensing technology to an out of state company
- Expectations for the retention of graduating students in the region or state

TEconomy has generally found both public and private research universities to be very attuned to the needs of their communities and home states, and willing to dedicate significant resources to help their local economies grow and to applying academic expertise and resources towards finding solutions for societal challenges. However, there is a tension between balancing this desire for local relevance and translation with the need to enable full academic freedom and work on major issues, often on a global stage, that contribute to institutional reputation and prestige.

As noted previously, the current political and socio-cultural debate over borders, immigration, visa quotas, etc. is also challenging for major research universities which have substantial international student bodies, international faculty, research relationships overseas, and even international campuses.

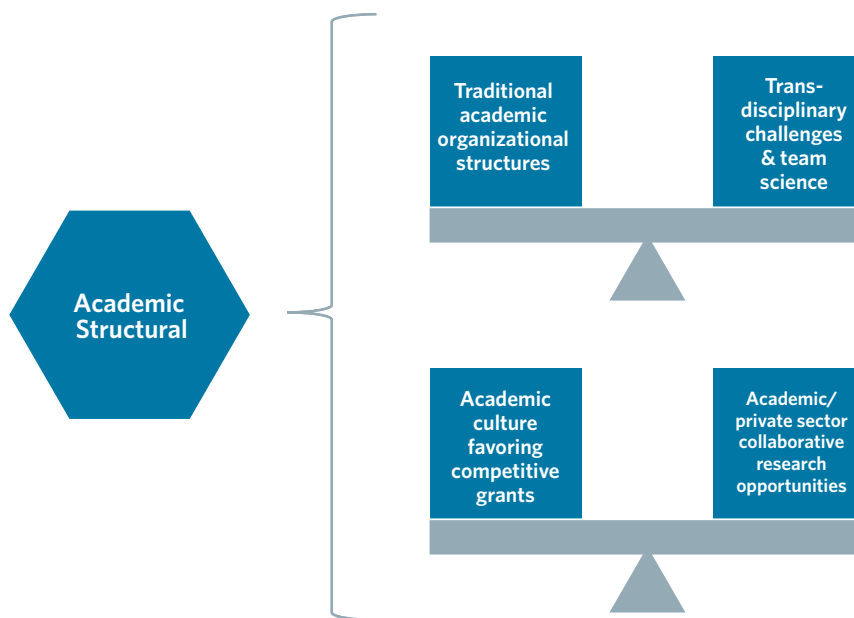
E. Academic Structural Challenges and Tensions

Just as funding source priorities influence the behavior of universities and their faculty, it is also the case that the organizational structure of universities and institutional policies influence behavior. It is beyond the scope of this report to cover the full range of organizational structures deployed in academe, but four principle models have been proposed by Robert Birnbaum:⁸⁵

- **The Collegial Model:** Whereby decisions are not made by a single party but rather result from management by consensus.
- **The Bureaucratic Model:** A process driven model in which the organization is divided into hierarchical layers and departments, each with defined missions and job functions.
- **The Political Model:** Again, this is a hierarchical model but resource allocation tends to occur less by formal policy and more by internal competition and leadership relationships.
- **The Anarchical Model:** Universities with this operational model lack strong central authority, instead granting substantial autonomy to individuals within the organization.

Across these organizational types, there are some observable tensions that appear to be quite consistent (Figure 25). One of these is the power of academic disciplines. Embodied within a university's colleges and departments, they have a silo effect on faculty and their research. With promotion and tenure decisions tending to be highly influenced at the department level, this system is rather inward looking and tends to be relatively inflexible in recognizing the value of work that transcends disciplinary boundaries, or collaborations with faculty from other disciplines. As transdisciplinary research expands in importance (as discussed herein), joint publishing by faculty from different disciplines can result in faculty members being published in journals outside of their primary discipline - which can be an issue in traditional measures of publishing for promotion and tenure considerations. Some academic disciplines do not even place a primary emphasis on journal publications (for example, computer science, where conference proceedings may be considered more important), and so a faculty member say from statistics or psychology, working on a transdisciplinary project in computer science, may find themselves disadvantaged by the nature of the research outlet.

Figure 25: Examples of Academic Structural Tensions Facing U.S. Research Universities



⁸⁵ Robert Birnbaum. 1988. "How Colleges Work: The Cybernetics of Academic Organization and Leadership". San Francisco: Jossey-Bass.

A related issue for transdisciplinary and team science is that relatively large teams of faculty working on a project will generate publications in which there are many co-authors listed (faculty; their multiple graduate students; and other collaborators). Again, in terms judging an individual's work output, this is an issue in promotion and tenure decisions. To illustrate, a recent paper in *Physical Review Letters* set a record by having 5,154 listed authors.⁸⁶ And while this type of “hyperauthorship” is occurring particularly within physical sciences, it also recently occurred in life sciences, with a genomics paper having more than 1,000 authors.⁸⁷ Universities are going to have to rethink evaluation and organizational strategies in light of the expanding team science reality. As noted in *Nature*:

*Research today is rarely a one-person job. Original research papers with a single author are — particularly in the life sciences — a vanishing breed. Partly, the inflation of author numbers on papers has been driven by national research-assessment exercises. Partly, it is the emergence of big and collaborative science, assisted by technology that is changing the research landscape.*⁸⁸

Another tension impacted by institutional structures and culture concerns is that there is a hierarchy of preferences in traditional academe regarding research funding sources. A project funded by a competitive grant from a federal agency such as the NIH, NSF, or NIFA, for example, will have more prestige attached to it than a project funded by a corporation or industry association. Because the careful peer review process of competitive government grants certainly does imply rigor in an accepted research proposal, and the comparatively low acceptance rate for proposals also adds cache to those that are funded, this hierarchy is understandable. However, since the private sector is typically risk averse in the funding of external research, receiving industry funding is also a mark of the quality of a faculty member's work and reputation. Indeed, if the private sector is going to a university for a project, it is because the university contains experts that are considered very much necessary to a project. This hierarchy of importance by funding type presents a challenge, particularly when it is taken to an extreme (observed at some universities by TEconomy) where faculty engaged in commercially sponsored research are viewed by colleagues as “selling out”. Primarily this challenge is more prevalent towards the applied end of the research spectrum, since industry is a quite limited funder of basic research.

F. Other Challenges and Tensions

Perhaps chief among other challenges facing the U.S. university research enterprise is the rise of international competition in higher education and in research. American research universities receive significant income from international students. Currently, Purdue University, for example, has 9,303 international students, representing 127 nations.⁸⁹ Indiana University reports “just over 7,000” international students,⁹⁰ and Notre Dame reports having 1,400 international students and scholars from over 90 countries.⁹¹ Thus, at the time of writing this report, these three Indiana research universities have a combined international student body totaling over 17,700 students.

Higher education leaders now face a very different set of challenges that necessitate new forms of leadership: for example, a volatile financial environment, the rise of global and international partnerships, greater accountability pressures around college completion and learning outcomes, the need for new business models, opportunities for innovation with technology, and changing demographics. While higher education has under-gone periods of significant change in the enterprise, particularly after World War II when enrollments grew significantly, today's environment is unique in terms of the sheer number of areas that demand change.

Adrianna J. Kezar and Elizabeth M. Holcombe. 2017. Shared Leadership in Higher Education: Important Lessons from Research and Practice. American Council on Education.

⁸⁶ Aad, G. et al. 2015. Combined Measurement of the Higgs Boson Mass in pp Collisions at $\sqrt{s}=7$ and 8 TeV with the ATLAS and CMS Experiments. (ATLAS Collaboration, CMS Collaboration) *Phys. Rev. Lett.* 114, 191803.

⁸⁷ Leung, W. et al. 2015. “Drosophila Muller F Elements Maintain a Distinct Set of Genomic Properties Over 40 Million Years of Evolution.” *G3 Journal - Genes Genomes Genetics* 5, 719–740.

⁸⁸ Liz Allen, Jo Scott, Amy Brand, Marjorie Hlava and Micah Altma. 2014. “Publishing: Credit where credit is due”. *Nature* 508, 312–313.

⁸⁹ <http://www.iss.purdue.edu/>

⁹⁰ <https://ois.iu.edu/about-bloomington/index.html>

⁹¹ <http://international.nd.edu/issa/>

Tending to skew towards enrollment in STEM disciplines, international students have a substantial impact on the performance of R&D at U.S. research universities. Similarly, the tuition, room and board, and fee payments made by international students represent a considerable component of university budgets (and can help cross-subsidize the teaching of domestic students). Given the importance of the international student to U.S. research universities, a rise in high-quality overseas universities competing for these students represents an expanding challenge. In addition to competition from European and Australian universities, an increasing level of competition is being felt from new and expanding Asian universities. China, Hong Kong, Singapore and South Korea have all built high-quality universities, and their research universities have been rising in the primary world university ranking schemes. For example, the closely watched QS Rankings of World Universities placed 13 Asian universities in the Top 100 world universities in their 2008 rankings, with this rising to 23 for the 2017 rankings. By contrast, the USA and Canada dropped in the QS rankings, from 42 in 2008 to 35 in 2017. However, it is interesting to note that the same rise in Asia at the expense of North America is not observable in the other leading universities ranking system published by The Times. What is evident in both ranking schemes, however, is that there is a shift occurring in international competition, and the U.S. cannot rely on being the dominant global force in higher education without sustained investment in quality and research performance.

CONCLUSION: U.S. research universities operate within an increasingly volatile market in which multiple factors (financial, demographic, technological, political, cultural, organizational, etc.) are undergoing significant change. In order to sustain the competitiveness and stability of U.S. research universities, a series of significant tensions have to be addressed. Since the end of WWII, U.S. universities have been a dominant force in global academe, but the foundations upon which these great institutions stand are being increasingly chipped-away by multiple forces, several of which are beyond the control of universities themselves.

TEconomy notes that while it may seem that research universities are stable institutions (part of an institutional structure and tradition dating back centuries), the pace of change in today's society and economy, and in technologies and global competition, are creating tidal forces that will impact the future of U.S. research universities. And the double threats posed by reductions in both federal and state level funding for research universities, working in concert with increasing levels of investment by our global competition, are a direct threat to our position in the world.

The United States, with Indiana a key constituent component, has built an academic research infrastructure and intellectual capacity in its research universities that is the envy of the world. Our national success and future wellbeing is interwoven with the fortunes of these institutions. Cutting back our investment in basic and applied research at universities, at a time when we should rather be doubling-down and investing more, will have substantial negative ramifications for our collective future. Deemphasizing investment in our research institutions is akin to farmers eating their seed corn, or investors spending their principal instead of interest. It is short sighted and ultimately destructive to our national wellbeing and the future prosperity and security of the United States and her people.

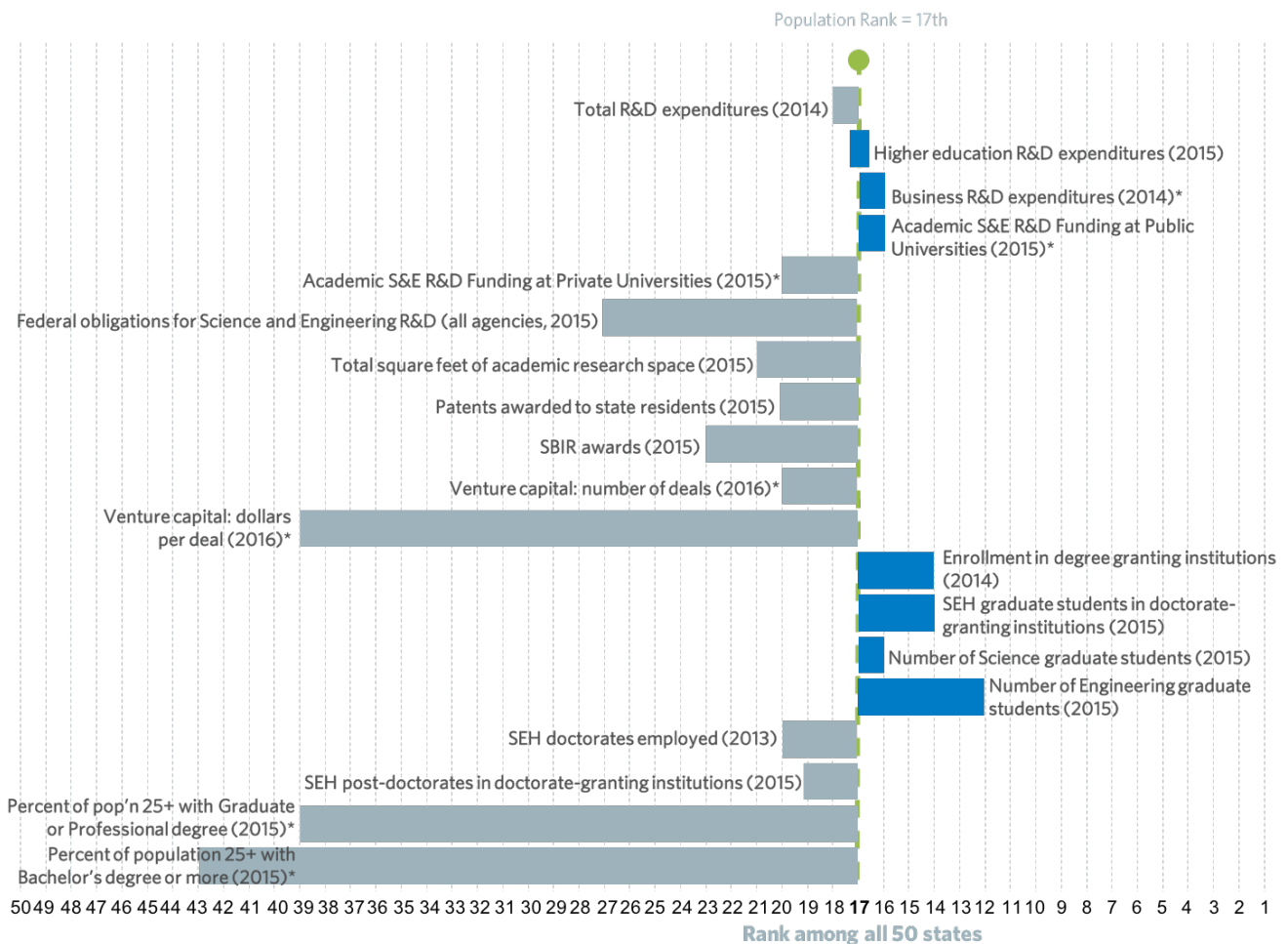
The lesson for individual U.S. states, including Indiana, should be that sustaining investment in signature research universities must be a strategic state priority. There are likely to be winners and losers in the national and global competition for intellectual talent and R&D activity, and those U.S. states that sustain, or preferably grow, their investment in their research universities are making a sound investment in their future place in the world.

G. Enhancing the Impacts of Research Universities in Indiana

While Indiana's signature research universities have a diverse and far-reaching impact across the socioeconomic spectrum in the state, it would be a mistake to conclude that such impacts cannot be enhanced further or improvements made to the higher-education, university-driven research ecosystem in the state of Indiana. Considerable room exists for improving the relative performance of the universities across a range of metrics.

Figure 26 provides a dashboard of 19 metrics largely, but not exclusively, drawn from published National Science Foundation statistics. To illustrate Indiana's relative position, the green-dashed vertical line sets a baseline position for Indiana in terms of its rank in population among states (17th). Each metric used is itself a rank for Indiana on that metric, and shows that on 12 of the 19 metrics, Indiana is underperforming relative to its population rank.

Figure 26: Academic R&D and Associated Metrics for Indiana



Source: National Science Foundation except for those marked * which are sourced from <http://www.stats.indiana.edu/sjp/>

In terms of total higher education R&D expenditures, at 17th, Indiana is right where the state rank would suggest it should be, and the state is moderately outperforming its expected rank in terms of both business R&D and academic science, and engineering R&D funding at public universities. Enrollment in Indiana higher education institutions is also a strong point with Indiana well ranked in:

- Number of engineering graduate students (12th)
- Total enrollment in degree granting institutions (14th)
- Science, engineering, and health graduate students in doctorate-granting institutions (14th)
- Number of science graduate students (16th).

However, across Indiana's relative performance on all other measures, issues can be seen. While Indiana higher education institutions are enrolling a larger than expected number of students (especially in STEM disciplines), as a whole, actual higher education attainment figures for the Indiana population are low. The state ranks 43rd in the percent of the population with a Bachelor's degree or higher, and 39th for percent of population with a graduate or professional degree.

Indiana is also underperforming in attracting its fair-share of important federal funding for science and engineering R&D (ranking 27th), and probably related to this is a similar underperformance in terms of innovation output and certain surrogate commercialization metrics (such as in SBIR and Venture Capital awards). In terms of patents (a proxy measure for innovation), Indiana is ranked 20th; it is 23rd in SBIR awards; and 20th in number of VC deals (and these VC funding events are funded low in comparison to other states, with Indiana ranked 39th in VC dollars per deal).

While focused on assessing the impact of research universities, the findings of this project do lead to some preliminary recommendations for consideration and additional study. These recommendations are primarily focused towards: improving external research funding (particularly from federal sources); enhancing university connectivity to collaborative commercial research opportunities; leveraging research universities and other institutional anchors for talent attraction and retention; and improving performance on key technology transfer metrics where Indiana institutions are currently in the 3rd, 4th or 5th quintile of performance.

1. Increasing Federal Funding for Research

In 2015, federal research funding as a share of all R&D funding sources at Indiana's research universities comprised 41 percent of total university research, compared with the national average of 55 percent, and Indiana institutions are relying more on institutional funding as a source for R&D activities. Other sources of funding are generally in line with national average shares. Figure 26 shows that in terms of federal obligations for science and engineering R&D (ranked 27th), the higher education community in Indiana is underperforming relative to the State's population rank (17th).

Part of the challenge for Indiana in the federally funded research arena relates to university policies that are unsupportive of performing classified R&D for the government. These policies significantly reduce opportunities for federal R&D, especially in physical sciences, engineering, and computer science disciplines that see especially focused funding from the federal defense establishment. As noted by the American Association for the Advancement of Science (AAAS):

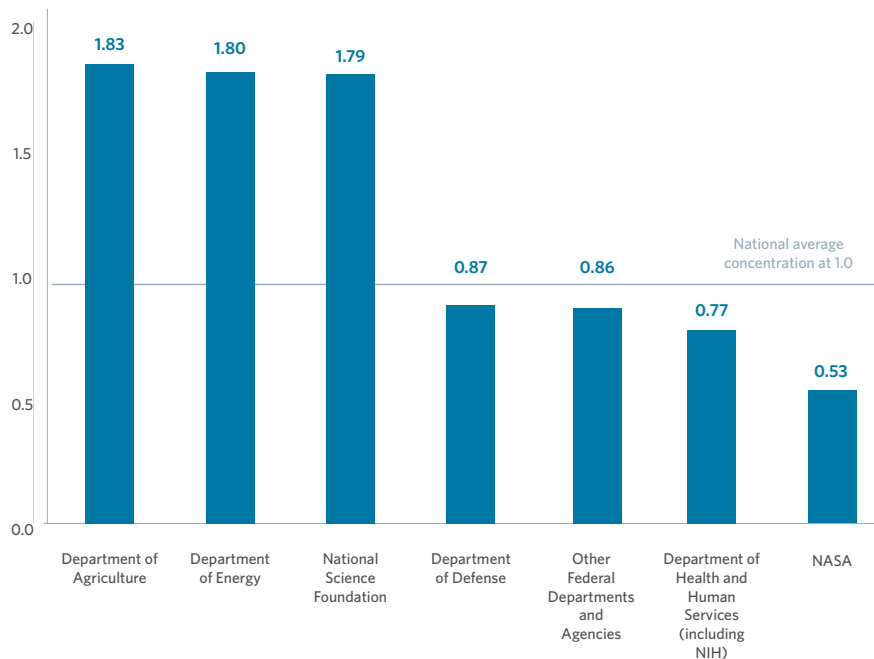
In terms of support for academic R&D, DoD is the third largest federal sponsor behind the Department of Health & Human Services (primarily through the National Institutes of Health) and the National Science Foundation is the largest funder of engineering research at universities, and a top funder of several other disciplines including computer science and life sciences.⁹²

Relative to overall federal funding directed toward universities, Indiana's concentration of DoD research funding is 13 percent below the national average (see Figure 27). This plays out across the key research fields with below-average funding concentrations in nearly all engineering disciplines (except for bioengineering), in computer sciences (65 percent less concentrated), and even in aeronautical and astronautical sciences/engineering (8 percent less concentrated). And while Indiana fares very well in its concentrations of funding from the Departments of Agriculture,

⁹² <https://www.aaas.org/fy16budget/department-defense>

Energy, and the National Science Foundation, the state lags in its relative concentration of funding from Health and Human Services, which includes NIH.

Figure 27: Concentration of Federal Funding by Agency/Department for Indiana University R&D, 2015



Source: TEconomy Partners analysis of NSF, Higher Education R&D Survey.

It should also be noted that increasingly, “unclassified” research is now being considered classified, which translates into lost opportunities for even greater levels of federal funding for Indiana under a “no classified research” academic policy framework. For example, with Purdue University’s robust leadership position in Aerospace Engineering, it is likely that opportunities to bring significant classified federal research programs into the state are being missed. Similarly, research by Battelle for the Southwest Central Indiana region (home to Indiana University-Bloomington) found that the region received quite limited federal defense funding for research despite being home to the Crane Naval Surface Warfare Center.

Defense funding is just part of the federal R&D funding environment, and Indiana’s research universities need to be supported in efforts to increase their competitiveness for attracting federal research grants. As federal funding agency budgets are squeezed, this is becoming increasingly difficult, and the percentage of grant applications accepted for funding dwindles. In such a constrained environment, competitiveness is more likely to be achieved through the recruitment of successful mid-career and “star” faculty who may bring with them significant research grants of their own, and attract around them other high-performing researchers and research teams.

Improving the position of Indiana’s research universities for federal research funding is not easy, but Indiana University has shown it can be done as evidenced by the University’s recent success in improving its rank in National Institutes of Health funding.

2. Enhancing University Connectivity to Collaborative Commercial Research Opportunities

Business financed research at universities comprises 6% of R&D funding at U.S. universities, whereas in Indiana it stands lower, at 5%. While currently a relatively minor component of university research funding in the U.S., the opportunity for increased engagement with industry can have significant research dollars attached to it. The move towards more “open innovation”, reductions in industries’ internal R&D initiatives, and the high degree of complexity in advanced technological R&D (which often requires transdisciplinary expertise to advance) each represent trends favoring more contract research and collaborative industry/university research engagement.

Engaging in commercially funded research may be less favored by faculty, especially tenure track faculty who have not yet achieved tenure, as it generally receives lower prioritization in promotion and tenure decisions versus competitive federal grant awards. However, the increasing challenge of competing for federal awards, versus a trend for companies to engage more in outsourcing of research activities, favors a shift towards competing for more commercial research dollars. Support for enhanced levels of commercial research engagement should be a stated priority for research universities, driven by direction from senior university administration officials, department heads, and tenure committees.

In July 2017, Eli Lilly and Company announced a strategic research collaboration with Purdue University that dramatically illustrates the significant opportunities for enhanced research funding that may come via industry engagement. The new Lilly-Purdue partnership is anticipated to bring up to \$52 million in funding to Purdue over the next five years, with research focused on improving delivery technologies for injectable medicines, and developing “predictive models for clinical success that reduce risks associated with investing in drug development and more effectively predict the outcome of new therapies in humans.”⁹³ As noted by Andrew Dahlem, Ph.D., VP and COO at Lilly, the strategic agreement links Lilly and Purdue in “a commitment to scientific research supporting the global needs of patients” and in addition, strengthens a “shared commitment to attract and retain the top engineering and technology talent in Indiana.”⁹⁴

The University of Notre Dame’s \$36 million Turbomachinery Research and Testing Laboratory at Ignition Park in South Bend also ably demonstrates the types of robust opportunities that exist for university-industry R&D collaborations. Further, this partnership is helping to cement collaborative research relationships with General Electric Corp and Rolls-Royce, and there is now a signed Center of Excellence agreement in place between the Lab and Pratt & Whitney.⁹⁵

State investments to encourage enhanced R&D relationships between universities and industry can help jump-start further activity and may be one option to consider. There are a number of states that have made significant investments over the years in fostering joint university/industry collaboration. For example, since its inception in 2002, the Ohio Third Frontier has spent millions of dollars to catalyze cutting-edge, commercially-relevant research that leads to applied technologies and product innovations that have commercial application within key technology and industry sectors of Ohio. The cornerstone of Ohio’s investments through the Ohio Third Frontier was the Wright Centers of Innovation— large-scale research and technology development centers designed to accelerate the pace of Ohio commercialization. Wright Centers are collaborations among Ohio higher education institutions, nonprofit research organizations, and Ohio companies. The specific technology/research focus of each Center represents areas of competitive differentiation that are unique and sustainable, making them difficult to imitate and overcome by others. OTF funding supported the acquisition of major capital assets to establish each center, as well as initial operating funds for projects and services offered by a center. Oregon has pursued a similar approach with the Oregon BEST program.

In general, it should be noted that per academic researcher, U.S. universities have not stood atop the global rankings for industry funding. Among the Top 20 universities in the world for industry funding per academic, only two are U.S.

⁹³ <https://www.purdue.edu/newsroom/releases/2017/Q3/lilly-and-purdue-university-announce-strategic-research-collaboration.html>

⁹⁴ *Ibid*

⁹⁵ <http://news.nd.edu/news/notre-dame-holds-ribbon-cutting-for-new-turbomachinery-laboratory/>

universities: Duke University and Johns Hopkins University⁹⁶. Given the world class science and technology expertise of U.S. universities and the strong technology industry sectors in the nation, this finding likely illustrates lost opportunities for the U.S. and individual states.

3. Leveraging Research Universities and Other Institutional Anchors for Talent Attraction and Retention

Arguably the most critical ingredient to a thriving innovation ecosystem and economic competitiveness, the prestige of research universities plays a major role in attracting top talent to a state or region. Indiana, which is already closely affiliated with 73 members of the National Academies, has had 20 Nobel Prize winners, and three World Food Prize Laureates, is making progress in attracting talent with an increasing and renewed emphasis across several fronts, including:

- The newly established Indiana Biosciences Research Institute, which represents a key anchor asset and lever for talent attraction with exciting collaborative research opportunities in new facilities that span industry and academia.
- The 16 Tech Innovation District. IBRI sits within another planned asset that will also play its own role in regional talent attraction and retention in Indianapolis, the implementation of the 16 Tech Innovation District. The District is intentionally designed to attract the best talent to collaborate and innovate across a host of advanced industries, all within a vibrant live/work/play, and learn environment that includes modern innovation space alongside retail and housing development, green space, and walking and biking trails.
- In recent years, the Lilly Endowment has been advancing talent attraction with several initiatives. With Indiana University, a grant to enhance the state's position in life sciences research by funding a recruitment strategy for top scientists at the IU School of Medicine. Similarly, in 2009, the Endowment provided funding to Indiana University to advance the generation of new physician-researchers in the form of a MD-PhD program, in addition to recruiting scientists.

These multi-pronged approaches and efforts to advance top talent in Indiana across a newly-established research anchor, a major strategic placemaking effort, and targeted investments in both talent recruitment and development must continue and should, in fact, be advanced further. Critical in the design of these efforts is leveraging the strengths of Indiana, its industry base, and its research institutions and anchors. Much of the activity noted above is focused in the life sciences, where Indiana is among the nation's leaders. By integrating these activities with key areas of strength, these approaches represent best practices for coordinated efforts to advance the talent situation in the state and they should be "normalized", in a sense, to take advantage of the opportunity these institutions represent with respect to talent.

Talent alone does not assure success, for skilled people are mobile, and there needs to be demand for highly educated individuals in the Indiana economy. It should also be noted that the data shown on Figure 24 for the proportion of the State's population with a bachelor's or graduate/professional degree show that Indiana must be lagging the nation, considerably, in terms of generating jobs that require degrees. Since state unemployment is comparatively low, these data must reflect the type of job mix that exists in the State, implying a lower demand for employment in the types of industries and employment activities requiring a higher education. This is likely a sentinel finding for a future at-risk in Indiana, when the U.S. is increasingly moving to a knowledge-based, innovation-driven, high-productivity economy in order to compete on a global stage.

96 Times Higher Education World University Rankings. 2016. "The world's top universities for attracting industry funding." <https://www.timeshighereducation.com/world-university-rankings/funding-for-innovation-ranking-2016>

Indiana’s apparently low comparative employment demand for graduate talent stands in opposition to statistics that show Indiana having a strong ranking in terms of in-state higher education enrollment and graduate output volumes in key areas such as STEM disciplines. The contrast between the demand for and supply of graduate talent in the state suggests that a significant portion of the highly educated human capital generated by Indiana’s universities must be lost to better job opportunities generated outside of Indiana.

The successful recruitment of Salesforce to Indianapolis, with the opening of Salesforce Tower in 2017 illustrates that the state can be competitive in attracting technology-oriented, innovative companies to Indiana. This must continue to be a key focus for state and regional economic development initiatives – leveraging the comparative availability of graduates from Indiana universities to encourage location and growth of companies that have demand for such talent.

4. Improving Technology Transfer Performance

As demonstrated in this report, Indiana’s research universities have a range of academic specializations (as demonstrated by high location quotients) in technological, science, and engineering disciplines. The research within these specialized fields, and others in Indiana, are no doubt producing innovations that have promise for commercialization and new business formation in Indiana.

Data from the Association of University Technology Managers (AUTM) for Indiana University, Purdue University, and the University of Notre Dame (Table 10) demonstrate an unbalanced performance across multiple intellectual property and technology transfer metrics. Strengths are evident in Purdue’s performance on invention disclosures, patents issued, and start-ups formed (where, on each of these metrics, Purdue ranks in the first quintile of U.S. universities). Notre Dame performs well on U.S. patents issued (falling in the second quintile), and Indiana University is in the second quintile in terms of licensing income. On all other metrics, the universities fall in the third, fourth, or even fifth quintiles. Certainly, at both IU and Notre Dame there should be an emphasis placed on increasing the level of invention disclosures as the base upon which the other metrics build, and there is a need to facilitate an enhanced start-up culture at both of these universities given their fourth quintile ranking for “start-up’s formed”.

Table 10: Intellectual Property and Technology Transfer at Indiana’s Research Universities by Quintile, 2015

	Licenses Executed per Patent	per \$10M in Research Expenditures				
		Licenses Executed	Licensing Income	Invention Disclosures	U.S. Patents Issued	Start-Ups Formed
Indiana University	4th	4th	2nd	3rd	3rd	4th
Purdue University	5th	5th	3rd	1st	1st	1st
Univ. of Notre Dame	4th	3rd	4th	3rd	2nd	4th

Source: TEconomy analysis of AUTM survey data.

Comparatively low quintile rankings for licenses executed may be less of a concern (since executed licenses may often be with out-of-state companies), and in Purdue’s case, this may reflect an internal university emphasis on start-ups versus external licensing (which is certainly a favorable policy).

5. Exploring New Collaborative Research Opportunities

Exploring new collaborative opportunities for Indiana’s research universities and industry that draw more heavily on dominant areas of research strengths that are shared across the universities in fields such as physics, chemistry, computer science and mathematics (in combination with robust strengths in engineering and life sciences). Drawing upon the capabilities of multiple institutions (both shared and complementary), and multiple disciplines, could lead to unique combinations of competencies enabling the pursuit of novel innovations in inherently transdisciplinary areas such as bioinformatics, precision agriculture, functional imaging, medical devices and cyber-physical systems.

6. Recognizing that No Single Metric or Measures of Performance Can Capture the Impact of Indiana’s Research Universities

Recognizing that no single metric or measures of performance can capture the impact of Indiana’s research universities, and that rather their full range of multifaceted impacts on Indiana’s societal and economic well-being (as shown in the functional impacts diagram on Figure ES-1 and highlighted throughout Chapter II) should be consistently communicated, considered and celebrated. This will assure the work of the universities is always recognized in a holistic context.

CONCLUSION: While Indiana’s research universities have been shown, within this report, to generate a broad-range of highly positive public and private social and economic benefits across Indiana, there is still room for improvement. Metrics suggest that Indiana institutions need to raise their success rate in terms of securing federal R&D funding, and attention needs to be paid to the downstream commercialization environment into which Indiana research university innovations will flow – especially in terms of access to risk capital for technology ventures.

These data also suggest that the state of Indiana needs to concentrate on building its technology-based economic development profile to increase its base of innovative tech companies (through new business start-ups, expansions and business attraction) to provide higher demand for personnel with higher education credentials. Relative to the size of the state, Indiana’s current population is relatively under-educated – yet the university systems see relatively robust enrollment in STEM disciplines. These data suggest that the current make-up of the Indiana economy presents relatively limited opportunities for baccalaureate graduates, including those in STEM disciplines, and many of those educated from Indiana’s signature research universities are leaving the state to find employment commensurate with their qualifications elsewhere.

A nation which depends upon others for its new basic scientific knowledge will be slow in its industrial progress and weak in its competitive position in world trade, regardless of its mechanical skill.

- Vannevar Bush

A study of history shows that civilizations that abandon the quest for knowledge are doomed to disintegration

- Sir Bernard Lovell

Appendix A:

Specialized Fields of Research at Indiana's Research Universities

A. Indiana University (Including IUPUI)

For 2012—2016, there are 17,836 publication records for Indiana University in the WoS dataset in fields representing **specializations** (those having an LQ ≥ 1.2). With IU having a School of Medicine and the associated academic health center complex, medical, health and life science fields come much more to the fore in this individual research university analysis than when all of Indiana's research universities are analyzed in aggregate. Figure 13 shows the count of IU system publications for the specialized fields.

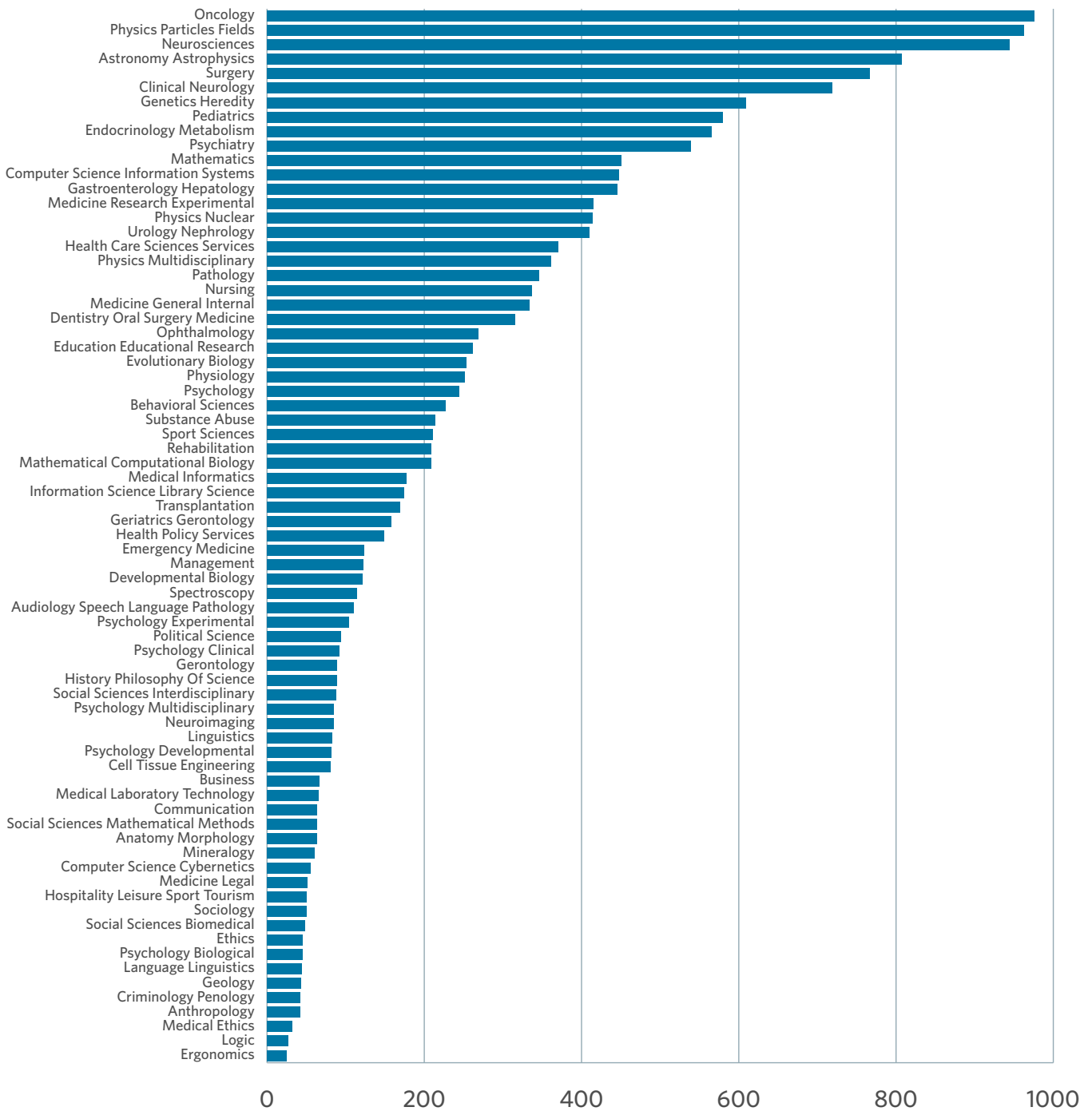
Biomedical research is very much evident, with particular strengths evident in:

- Oncology
- Neurosciences
- Surgery
- Clinical Neurology
- Pediatrics
- Endocrinology and Metabolism
- Psychiatry.

Out of the 17,836 specialized publication records, 12,033 (67.5%) are in life science, health, and associated disciplines.

Physics is also an evident strength at IU, with 2,558 (14.3%) publication records distributed across four individual fields (physics particles fields; astronomy astrophysics; physics nuclear; physics multidisciplinary). Mathematics (451 records) and Computer Science Information Systems (448 records) also show a significant presence.

Figure 13: Indiana University System. Research Fields Qualifying as “Specializations” with LQ>=1.2. Publication Totals by Field for 2012-2016. (Includes Indiana University and IUPUI)



Source: TEconomy analysis of Web of Science database.

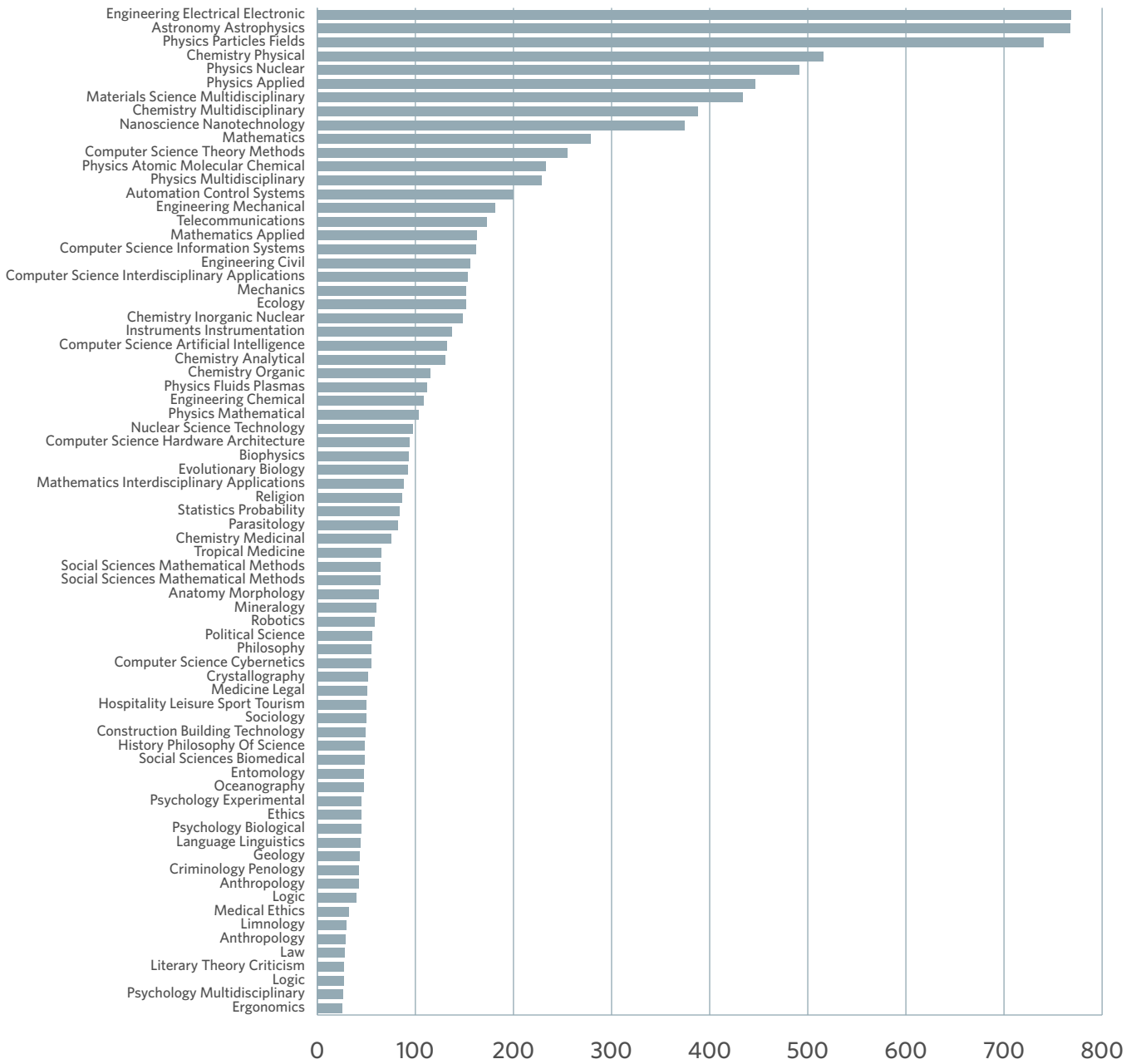
B. The University of Notre Dame

For 2012—2016, there are 9,954 publication records for the University of Notre Dame in the WoS dataset in fields representing specializations (those having an LQ ≥ 1.2). Figure 14 summarizes the data for these specialized research fields at Notre Dame. Areas of evident strength include:

- **Physical sciences** are a clear focus area for research output at Notre Dame, comprising 4,511 (45.3%) with substantial publishing output in the fields of both **physics** and **chemistry**.
- **Engineering** and associated applied technology fields also constitute a substantial focus at Notre Dame, with 2,981 publishing records in specialized fields (29.9%).
- **Computer science** and associated fields with 796 (8%) of the specialized publication records.
- The formal sciences (**mathematics** and **logic**) are also specialized at Notre Dame with 654 records (6.6% of Notre Dame specialized fields).

Some life science and social science disciplines also are in the specialized fields for Notre Dame, however; they have relatively small total counts in comparison to those bulleted above.

Figure 14: University of Notre Dame Research Fields Qualifying as “Specializations” with LQ>=1.2. Publication Totals by Field for 2012-2016.



Source: TEconomy analysis of Web of Science database.

C. Purdue University

For 2012—2016, there are 30,735 publication records for Purdue University in the WoS dataset in fields representing university specializations (those having an LQ ≥ 1.2).

As might be expected for Purdue, among the specialized fields of study at the university, engineering fields represent the largest collective disciplinary group (Figure 15). 11,636 publication records (37.9%) are in engineering areas, with the largest focus in:

- Engineering Electrical Electronic (2,933 records)
- Engineering Mechanical (1,184)
- Nanoscience and Nanotechnology (776)
- Engineering Multidisciplinary (697)
- Engineering Civil (572)
- Energy and Fuels (537)
- Mechanics (480)
- Engineering Chemical (448)
- Thermodynamics (435)
- Computer Science Hardware Architecture (419)
- Automation Control Systems (412)

As seen at both Indiana University and Notre Dame, physics is also a notable strength and focus area for Purdue University. 5,521 records are in physics and associated areas (counting optics under physics), with key fields including:

- Physics Applied (1,462 records)
- Optics (869)
- Astronomy Astrophysics (755)
- Physics Particles and Fields (747)
- Physics Multidisciplinary (395)
- Physics Condensed Matter (392)
- Physics Atomic Molecular Chemical (378)
- Physics Nuclear (341)

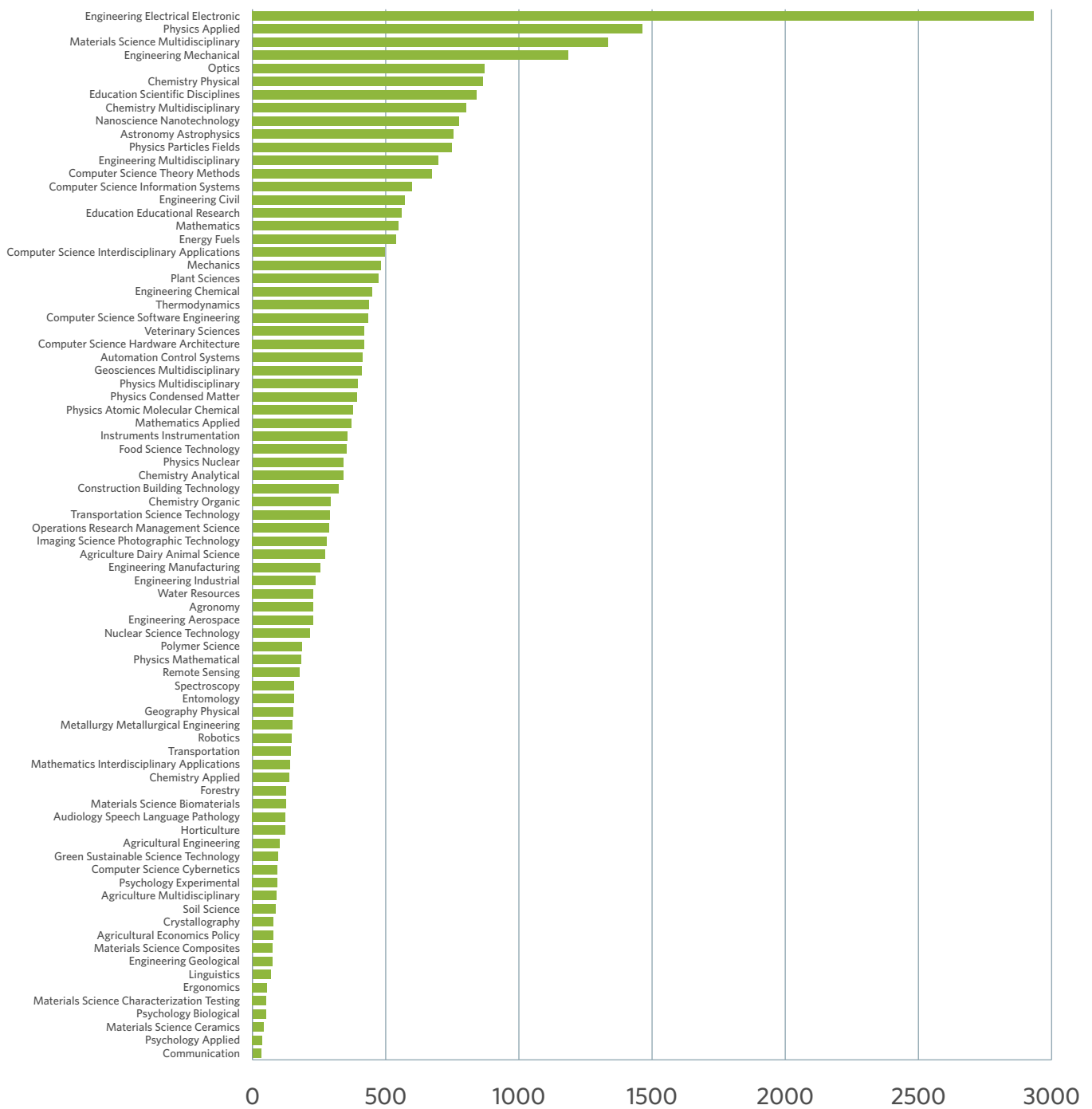
Chemistry and materials science as a combined group is also a notable strength for Purdue, with 4,243 publication records (13.8% of specialized records). The largest areas there are:

- Materials Science Multidisciplinary (1,333)
- Chemistry Physical (863)
- Chemistry Multidisciplinary (801)
- Chemistry Analytical (340)

Purdue also demonstrates specialized publishing in computer sciences and related fields, with 2,710 publication records (8.8%). Also, as Indiana's land-grant university, agriculture and associated fields has a significant group, comprising a combined 1,978 records (6.4%).

Several social science and humanities disciplines also show as specializations, although these tend to have significantly smaller publishing counts than the engineering and physical science disciplines. Representing the formal sciences, three specialized fields of mathematics are represented, totaling 1,057 records (3.4%).

Figure 15: Purdue University Research Fields Qualifying as “Specializations” with LQ>=1.2. Publication Totals by Field for 2012-2016.



Source: TEconomy analysis of Web of Science database

