The Indiana University Pervasive Technology Institute at 20: Two decades of success and counting

Craig A. Stewart, Executive Director, IU PTI https://orcid.org/0000-0003-2423-9019

Von Welch, Director, Center for Applied Cybersecurity Research, Associate Director, IU PTI https://orcid.org/0000-0002-5896-7789

Thomas G. Doak, Director, National Center for Genome Analysis Support, Associate Director, IU PTI https://orcid.org/0000-0001-5487-553X

Therese Miller, Program Director, Research Technologies, Associate Director and Finance Officer, IU PTI https://orcid.org/0000-0002-4862-4897

Beth Plale, the Michael A. and Laurie Burns McRobbie Bicentennial Professor of Computer Engineering, Luddy School of Informatics, Computing, and Engineering, Director, Data to Insight Center, and Associate Director, IU PTI https://orcid.org/0000-0003-2164-8132

Marlon Pierce, Director, Cyberinfrastructure Integration Research Center, Associate Director, IU PTI, https://orcid.org/0000-0002-9582-5712

David Y. Hancock, Director, Advanced Cyberinfrastructure, Research Technologies https://orcid.org/0000-0001-8082-8980

Robert Henschel, Director, Research Software and Solutions, Research Technologies https://orcid.org/ 0000-0003-2289-9398

John A. Walsh, Director, HathiTrust Research Center, Associate Professor, Luddy School of Informatics, Computing, and Engineering, Associate Director, IU PTI https://orcid.org/0000-0002-1824-210X

Matthew R. Link, AVP, Research Technologies, University Information Technology Services, Associate Director, IU PTI https://orcid.org/0000-0002-7764-9110

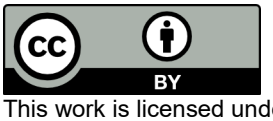
Winona Snapp-Childs, Manager, Collaboration and Engagement Support Group https://orcid.org/000-0003-4354-7092

Harmony Jankowski, Editor, Research Technologies, IU PTI https://orcid.org/0000-0002-7774-1435

Indiana University

IU PTI Technical Report PTI-TR19-001
January 3, 2019 and Revised 22 September 2020

Please cite as: Stewart, C.A., Welch, V., Doak, T.G., Miller, T., Plale, B., Pierce, M., Walsh, J.A., Link, M.R., Snapp-Childs, W., & Jankowski, H. (2019). *The Pervasive Technology Institute at 20: Two decades of success and counting*. (IU PTI Technical Report PTI-TR19-001). Indiana University. Retrieved from http://hdl.handle.net/2022/22607



PERVASIVE TECHNOLOGY INSTITUTE
INDIANA UNIVERSITY

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1. Executive Summary

In 1997, Myles Brand, Indiana University's 14th President, challenged the university to become "a leader [in higher education], in absolute terms, in the use and application of information technology." The Indiana University Pervasive Technology Institute (IU PTI) has been one of IU's most significant responses to President Brand's challenge. In its first 20 years, IU PTI's accomplishments have strengthened IU, the state of Indiana, and the nation. This report captures these accomplishments.

IU PTI's mission is to ***transform*** *innovations in cyberinfrastructure, computer science, informatics, and information technology into robust tools enabling new breakthroughs in research, scholarship, and artistic creation;* ***deliver*** *such tools and support their use in academic and private-sector contexts;* ***aid*** *economic growth in the State of Indiana; and* ***strengthen*** *Indiana's 21st century workforce.* IU PTI acts locally, regionally, and nationally through its leadership, resources, and services, aligning with its motto: ***Accelerating innovation through advanced computing.***

IU PTI has evolved into a large and vital collaborative organization through its pursuit of six objectives:

1) **Creation and dissemination of knowledge:** IU PTI has contributed directly to 1,301 peer-reviewed scientific publications, a tally that excludes the many publications enabled by IU PTI innovations. IU PTI is similarly committed to broad dissemination of scientific knowledge and organizes funding for *Science Node*, a free publication with over 140,000 readers.
2) **Development and deployment of advanced computing infrastructure:**
   a. IU PTI has transformed technology innovations from proofs-of-concept to widely used R&D tools in academia and research, and has created 72 such major services (hardware, software, consulting) to accelerate discovery within the broad research community.
   b. IU PTI has created and deployed new software tools, releasing 73 open-source software packages.
3) **Commercialization of Indiana University-developed technology**: IU PTI has cultivated a total of eleven startup companies, with four of these continuing today as significant business successes.
4) **Economic growth of Indiana:** IU PTI has enhanced the growth of Indiana's economy. Grant awards to IU PTI supported 862 person years of full-time employment within IU and, according to standard economic metrics, an estimated 2,100 job years within Indiana.
5) **STEM workforce development:** IU PTI has stimulated interest in STEM fields through outreach events ranging from robot programming camps to displays at national and international conferences.
6) **Stimulation of IU's innovation pipeline**: IU PTI has stimulated IU's innovation pipeline by fostering new centers and areas of excellence. IU PTI has grown from three to a total of seven centers, with two labs being incubated toward center status.

IU PTI's successes encompass four broad themes: creating knowledge, creating tools, developing people, and enhancing the economy. These successes have been supported by extramural funding, including $123,624,974 in public grant awards and $12,702,779 in private funding, for a total of over $136 million dollars to IU.

IU PTI's researchers exert national and international influence by sitting on advisory boards for federal funding agencies, founding research community organizations, and producing internationally distinguished scholarship while also responding to needs expressed by IU researchers. IU PTI influences university, state, and national priorities by pointing out new research directions gleaned from the insight, technical expertise, and imagination of its leaders and researchers.

The research landscape evolves continuously as new research tools and needs, emerge. The COVID-19 pandemic has illuminated the utility of computational simulations to many new researchers, and they have revealed new and exciting needs. These and many other challenges ensure that IU PTI will persist for another 20 years of *accelerating innovation through advanced computing.*

2. Introduction

In 1997, Myles Brand, Indiana University's 14th president, challenged the university to become "a leader [among institutions of higher education], in absolute terms, in the use and application of information technology."[1] The Indiana University Pervasive Technology Institute (IU PTI), initially called the Pervasive Technology Labs (PTL), was founded in 1999 to help IU achieve this goal. PTL was initiated through a $30M grant from the Lilly Endowment to IU, called "The Indiana Pervasive Computing RESearch Initiative – IPCRES."[2] The official start date of that grant award was September 22, 1999. Of that initial $30M, half went to fund the startup of PTL, and half to fund growth of the then-nascent IU School of Informatics (now the Luddy School of Informatics, Computing, and Engineering). Second-round funding of $15M in 2008 led to IU PTI's current structure. At the time of the 2008 award, President Michael A. McRobbie praised IU PTI's inception, noting that "creating the Pervasive Technology Institute is the logical next step to securing our position of leadership in the information technology field and will serve as a catalyst to our efforts to expand all of our research enterprises within the university and state."

IU PTI excels in research in computing, and in supporting computing resources for research, scholarship, and the arts. Collectively, the range of hardware, software, and human resources within the purview of IU PTI's expertise is now commonly referred to as "cyberinfrastructure"—a word popularized but never fully explained by the National Science Foundation. IU PTI created the now standard definition: "Cyberinfrastructure consists of computing systems, data storage systems, advanced instruments and data repositories, visualization environments, and people, all linked together by software and high-performance networks to improve research productivity and enable breakthroughs not otherwise possible."[3] IU PTI's mission, within and beyond IU, is to create cyberinfrastructure and enable innovation through it.

An inherently collaborative organization, IU PTI draws talent from across traditional disciplinary boundaries and pools it within the generative environments of its centers. In essence, IU PTI was created to enable IU to respond to its own needs, and to those of the state and nation, more rapidly than might otherwise be possible within traditional academic structures. IU PTI has done that by working with the Luddy School of Informatics, Computing, and Engineering (Luddy); the Maurer School of Law; the Kelly School of Business; and the College of Arts and Sciences. Collaboration with IU PTI has aided all of those academic units, but particularly Luddy. Luddy has, in its history, been the academic responsibility center at the helm of three grant awards in excess of $10M (FutureGrid, Jetstream, and Jetstream2 advanced distributed/cloud computing systems). These three systems were all led by PTI-affiliated principal investigators, and these three together represent three out of a total of just fifteen federal grant awards to IU Bloomington for research projects in excess of $10M. (A fourth grant proposal in excess of $10M was led by OVPIT but not affiliated with IU PTI). Such large projects are important because of their scope and national impact. At the university level, IU PTI has played an important role supporting

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[1] Dunn, J. Michael, & McRobbie, Michael. (1998). *Information technology strategic plan: Architecture for the 21st century.* Indiana University. http://hdl.handle.net/2022/471

[2] The primary authors of the initial grant proposal were Michael A. McRobbie; Karen Adams, director, Communications and Planning, Office of the Vice President for Information Technology; Dennis Gannon, then-professor of computer science at IU; and Gerald Bernbom, then-special assistant to Vice President McRobbie. Gustav Meglicki, technical advisor to VP McRobbie, and Craig Stewart, then-acting director, Research and Academic Computing, played peripheral roles in the proposal preparation.

[3] NSF Advisory Committee for Cyberinfrastructure Task Force on Campus Bridging. *Final Report*. March 2011. Available from: https://vdocuments.us/download/national-science-foundation-advisory-committee-for-cyberinfrastructuretask-force-on-campus-bridging-final-report-march-2011 cites Stewart, C.A., S. Simms, B. Plale, M. Link, D. Hancock and G. Fox. What is Cyberinfrastructure? In: Proceedings of SIGUCCS 2010. Norfolk, VA, 24-27 Oct, 2010 in its definitional work around the word "cyberinfrastructure."

two of IU's "Grand Challenge" projects: the "Precision Health Initiative" and the "Prepared for Environmental Change" initiative. Perhaps the most striking example of IU PTI's ability to respond quickly and with talent amassed from across IU has been its involvement in national and international responses to the COVID-19 pandemic. At a time of international crisis, IU PTI proved ready and able to aid the nation.

Through its affiliation with the Research Technologies (RT) Division of University Information Technology Services (UITS), IU PTI offers significant computational, storage, and visualization cyberinfrastructure resources, as well as services that do not readily fall under the umbrella of supercomputing. IU PTI is a peerless organization; there is no other organization quite like it.

This document summarizes IU PTI's accomplishments over the first 20 years of its existence and describes its current activities. Audiences for this document include:

- the IU community, so that it can leverage IU PTI's personnel and capabilities;
- lawmakers, business leaders, and the public within Indiana;
- leaders in the private sector—particularly leaders of IT firms nationally, and manufacturing and IT firms with a strong presence in Indiana—so that they can take advantage of collaborations with IU PTI and understand the value IU PTI adds to the state's economy;
- members of the national scientific community and program officers at federal funding agencies, so that they become more aware of the breadth and impact of IU PTI's activity;
- undergraduate students, so that they can consider enrolling at IU for graduate study; and
- highly skilled IT and cyberinfrastructure professionals, so that they may consider IU as a potential employer.

The document includes the following sections:

- *Section 3. IU PTI structure and function: A collaborative, interdisciplinary organization*. This section describes the mission, context, and functions of IU PTI.
- *Section 4. Metrics of IU PTI's success at IU and beyond*. This section includes tallies of IU PTI's most important metrics of success for its first 20 years (September 22, 1999–September 22, 2019).
- *Section 5. Outcomes of IU PTI activities (2015-2020).* This section offers key exemplars of IU PTI's activities that demonstrate the importance and impact of its six primary objectives, focusing on major activities since the last comprehensive report of PTI activities.[4]
- *Section 6. Highlights of our 21st year.* This section includes many of the exciting items that emerged as we wrapped up our 20th year, including the Jetstream2 system and IU PTI's role in understanding and fighting the COVID-19 pandemic.
- *Section 7. Centers and their accomplishments*. This section presents narratives of each center's research program during IU PTI's first 20 years.
- *Section 8. Conclusion and a look forward.*

3. IU PTI structure and function: A collaborative, interdisciplinary organization

> *The mission of the Indiana University Pervasive Technology Institute (IU PTI) is to transform new innovations in cyberinfrastructure, computer science, and information technology into robust tools enabling breakthroughs in research, scholarship, and artistic creation; deliver such tools and support their use at academic institutions and in*

[4] Please see McRobbie, Michael A. *Final Report to the Lilly Endowment, Inc.* Indiana University Pervasive Technology Institute. (2014). Available from: http://hdl.handle.net/2022/19787

the private sector; accelerate the growth of the Indiana economy; and help build Indiana's 21st century workforce.

The word "pervasive" in the name Indiana University Pervasive Technology Institute reflects the foundational importance of computer science, informatics, cyberinfrastructure, and information technology research to academic and industrial activities today. IU PTI's mission expresses its diverse local, regional, and national roles. To express the essence of IU PTI's activities efficiently, it has also adopted the following motto: *Accelerating innovation through advanced computing*.

IU PTI's distinctive structure was designed to enable its persistence over time while it remains responsive to the needs of various communities. IU PTI consists of a core, with support and organizing functions, and a set of affiliated centers. Each center is, in turn, a collaborative organization involving participants from multiple disciplines. The solutions to many important problems often require collaboration across academic disciplinary boundaries. Within Indiana University, IU PTI enables such collaboration, fostering rapid responses to the needs of academia, society, industry, and business.

IU PTI is led by an executive director. Each of the directors of IU PTI-affiliated centers have the title of associate director, indicating their role in IU PTI's leadership and governance. Center directors may also, at their discretion, appoint leaders within their centers with the title of assistant director, IU PTI.

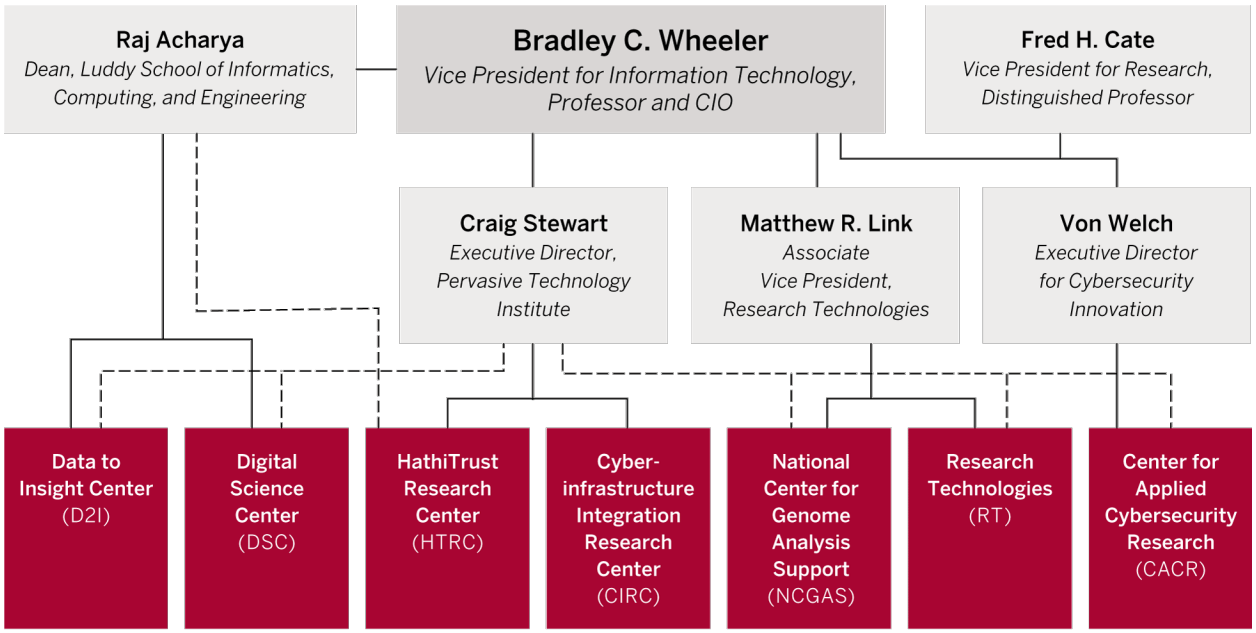

Figure 1. **Organizational structure of PTI as of September 2019.**

IU PTI's unusual positioning within IU's overall organization is critical to its success. IU PTI reports to the Office of the Vice President for Information Technology (OVPIT), where it originated as an effort led by then-Vice President Michael A. McRobbie. IU PTI is, however, a collaboration across many administrative and academic boundaries within IU, and enjoys partnerships with the following units:

- **Luddy School of Informatics, Computing, and Engineering** provides the primary affiliation for three of the current IU PTI centers, and supports IU PTI through salary, support for faculty members, space, and F&A return agreements for Luddy-led centers.
- **Maurer School of Law** has had strong ties with CACR since its inception in 2001 under its founding director, Professor of Law Fred Cate.

- **Kelley School of Business** has strong ties with CACR and also plays an important role in many research projects across IU PTI involving economic development and systems analysis.
- **The College of Arts and Sciences** is home to faculty leaders involved in the National Center for Genome Analysis Support, and to a large group of faculty collaborators who work with IU PTI to define challenging problems, help develop solutions, and put those solutions to work creating new discoveries.
- **IU Libraries** has had strong ties with the HathiTrust Research Center.

IU PTI was designed to be able to react quickly to important university, state, and national needs through its capabilities to collaborate and work across organizational boundaries within IU. IU PTI is an organization that spans five major subunits of IU through collaboration and partnership. IU PTI operates on the philosophy that credit, unlike matter and energy, is a non-conserved property. One does not have less of it as a result of sharing it. This approach fosters a highly collaborative atmosphere—a foundational element of IU PTI's success. This philosophy breeds collaboration among centers with highly diverse foci and fosters partnerships within the IU, state, national, and international research communities. IU PTI, as an organization, is intended to persist over time while individual centers are expected to form, stay active for a period, and disband when they no longer provide practical benefit to the university or nation.

PTI's major objectives

IU PTI pursues the following six major objectives:

1) **IU PTI creates and disseminates knowledge.**
   a. IU PTI creates knowledge, invents technology, and engages in research and development.
   b. IU PTI supports the creation of knowledge, the invention of technology, and research, scholarship, and creativity.
   c. IU PTI disseminates knowledge through support for conferences and meetings in the sciences, humanities, and arts,[5] and support for the online publication *Science Node.*

2) **IU PTI develops and deploys advanced computing infrastructure.**
   a. IU PTI transforms technology innovations from proofs-of-concept to widely used R&D tools in academia and research, bridging the gap between computer science and informatics research and products usable by IU and national research, humanities, and artistic communities. This competence is the source of much of IU PTI's funding success, as the institute is often tasked with developing services into production-quality software and/or hardware, and then delivering and supporting those services. This work benefits the Indiana University community in several ways, including:
      - Inventors of technology, tools, and services receive assistance transforming their inventions into the most useful and meaningful versions possible.
      - The IU research, scholarly, and artistic communities benefit from earlier access to innovations and services developed at IU than their peers and competitors at other institutions.
   b. IU PTI creates and deploys new software tools, releasing most of these tools as open-source software so that they may easily be adopted by the U.S. national research community.

3) **IU PTI leads and supports the commercialization of IU-developed technology.**

[5] One of Indiana University's Bicentennial Strategic Plan metrics includes the number of academic conferences held at Indiana University that brings scholars from other institutions to IU. https://strategicplan.Indiana University.edu/plan/faculty.html#priority2

a. When appropriate, IU PTI becomes directly involved in technology transfer to the private sector. This involves creating startup companies led by IU PTI-affiliated faculty and staff, and licensing innovations created by IU PTI.

4) IU PTI enhances the growth of Indiana's economy.

a. IU PTI aids Indiana's economic growth by consulting with and providing resources to private-sector entities. Some services are provided at no cost (through collaboration) to entities in Indiana, as part of IU's mission to enhance life in its home state.
b. IU PTI attracts talented, technically adept staff to Indiana, and keeps them happily employed within IU. Part of IU PTI's attractiveness as an employer is its collaborative nature and the importance of the challenges it pursues; it also enjoys a well-earned reputation for winning grants and contracts and for providing long-term funding for staff employed through such extramural funding. In addition to their intellectual contributions, these highly skilled staff members contribute to Indiana's workforce and tax base, spending money from their salaries in Indiana—money that originates primarily from federal funding agencies and that, in the absence of IU PTI, would likely go to a different state.

5) IU PTI aids the development of a strong STEM workforce in Indiana.

a. IU PTI aids the development of a strong 21st century science, technology, engineering, and mathematics (STEM) workforce in Indiana and the U.S., drawn as much as possible from native-born Hoosiers and others who adopt Indiana as their home. Though IU PTI does not offer any for-credit courses within Indiana University, it arranges frequent non-credit training activities within the university, ranging from an hour to a few days in length. IU PTI also provides frequent outreach activities designed to interest young people in STEM careers, such as the annual Robot Camp offered each summer.[6]

6) IU PTI stimulates IU's innovation pipeline.

a. IU PTI fosters new centers and areas of excellence within Indiana University. IU PTI often serves an incubating function, helping new projects and initiatives grow into labs and, eventually, into full-fledged IU PTI centers.
b. IU PTI provides for the ongoing support and continuity of centers, sometimes through efforts such as routine delivery of support for grant writing, and sometimes by providing exceptional assistance to centers or labs that encounter periods of challenge in funding continuity.

[redacted]*IU PTI's role within IU and its research, development, and delivery agenda*

IU PTI plays a critical role in Indiana University's overall strategy of leadership in information technology, computer science, advanced cyberinfrastructure, and high performance computing. Just as a stool rests solidly on three legs, Indiana University's strategy in information technology, advanced computing, and cyberinfrastructure rests on three essential strengths:

1) Outstanding basic research in computer science, informatics, and engineering. These activities are led by Indiana University faculty, primarily from the Luddy School of Informatics, Computing, and Engineering, as well as the Maurer School of Law, the College of Arts and Sciences, the Kelley School of Business, and the Purdue School of Engineering and Technology at IUPUI.
2) Ground-breaking research, development, and delivery functions that transform innovations into significant tools, aiding research, scholarly, and artistic communities within and beyond Indiana

[6] UITS at Indiana University. (2015). *Ready, Set, Robots! Camp*. Available from https://www.youtube.com/watch?v=zWh9hWf0rBM&feature=youtu.be&list=PLqi-7yMgvZy8xB64_0-O7PId_uzTFy9PO

University, and bolstering Indiana's economy in the process. These activities are the focus of IU PTI.

3) Exceptional cyberinfrastructure and staff to support it. These activities are led by the Research Technologies Division of University Information Technology Services, and by UITS generally, in activities beyond collaboration with IU PTI.

IU PTI enables a positive feedback loop in which the needs of Indiana University artists, scholars, clinicians, engineers, scientists, and researchers drive the IU PTI research agenda. IU PTI then transforms computer science, informatics, and cyberinfrastructure innovations into high-quality, robust tools usable by IU, national, and international research communities. IU PTI's research agenda is also influenced by U.S. federal funding priorities, and IU PTI, in turn, influences U.S. national research priorities through its actions and its colleagues' work. Due to proximity and collegial communication, IU PTI creates a competitive advantage for IU researchers in that innovations made here are used here first, before they are discovered and widely adopted by other institutions. By supporting research interests in this way, IU PTI adds value to Indiana University, the State of Indiana, and the United States.

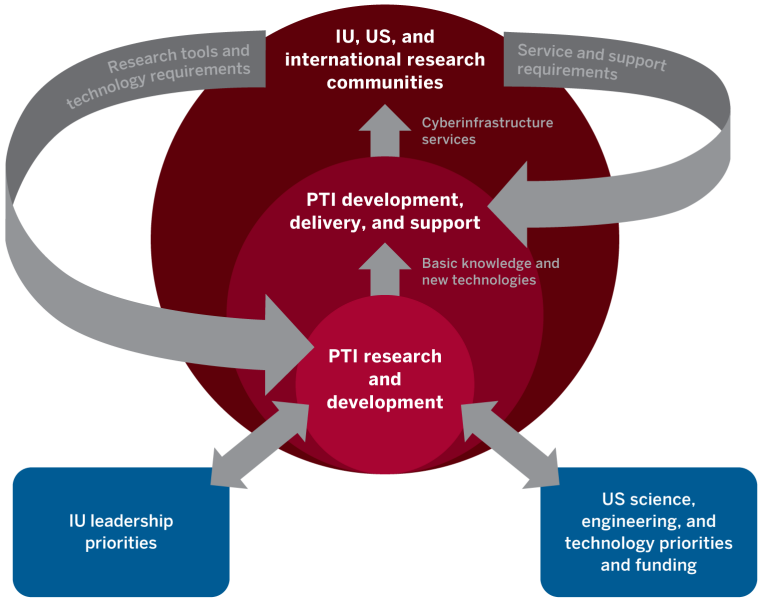

Figure 2. IU PTI's research and services activities: what drives IU PTI's activities, and how IU PTI drives Indiana University capabilities and national agendas.

This positive feedback loop that IU PTI creates is part of how IU PTI has developed over time. IU PTI uses a virtuous, positive reinforcement cycle, as depicted below:

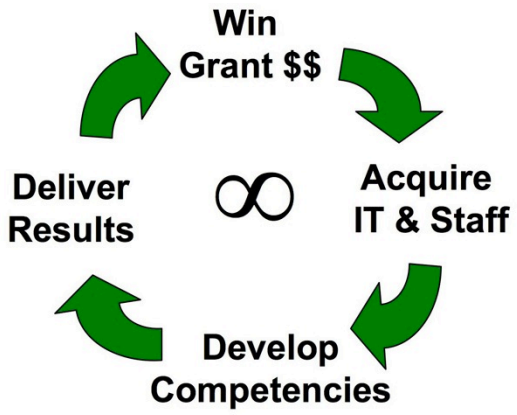

Figure 3. The virtuous cycle of competing for and winning extramural funding, developing competencies, and delivering results that IU PTI has demonstrated for more than 20 years. Adapted from a figure created by former VP for IT Bradley C. Wheeler.

IU PTI's activities are made possible by external (so-called "extramural") funding. Less than 20% of IU PTI's budget comes from IU. The remaining 80% is primarily grant awards from federal research funding agencies, with smaller amounts from private charitable trusts, private companies, and grants and contracts with the State of Indiana. IU PTI pursues grant funding related to cyberinfrastructure when it aligns with IU's strategic goals, and when the following criteria are met:

- The work is of high value to funding agencies (federal and otherwise), and abides by policies. In other words, someone is willing to pay for it, and it is not classified.
- Indiana University has relevant faculty who can serve as intellectual leaders.
- Indiana University employs experts who can do the technical research and development work.
- The grant does not compete with tenured or tenure-track faculty, when IU PTI staff who are not tenured or tenure-track faculty lead the grant proposal.

One of IU PTI's most important functions involves shepherding the innovations developed via this virtuous cycle into widely used tools. Each week, new academic papers and software releases herald the creation of a new prototype for a piece of software or cyberinfrastructure service. Most of these fulfill interesting and innovative functions, but few ever enjoy a useful life extending beyond the publication of an academic paper or perhaps the depositing of the prototype's code in a code repository. The difficult path from initial success as an idea to success as a widely used product is often referred to as "the valley of death." Many ideas enter; few survive the climb up the other side. However, there are really two valleys of death: conversion of a new idea and new product from "proof of concept" into a tool used within research and development communities, and conversion from a widely used research and development tool to a consumer product. IU PTI plays an integral role in creating new technologies and guiding them from proof of concept into widely used R&D tools. IU PTI sometimes, but less commonly, helps commercialize new technologies.

4. Metrics of IU PTI's success at Indiana University and beyond

In the report to the Lilly Endowment summarizing IU PTI's accomplishments through its second round of funding,[7] Indiana University offered a highly positive assessment of IU PTI's value and success. This section updates and expands on prior reports. Some of IU PTI's key metrics are summarized in Tables 1 and 2. These metrics show the outcomes of 20 years of effort from September 22, 1999 through the end of September 2019. To give a sense of IU PTI's current activity levels, operating on an ongoing basis long after startup funding from the Lilly Endowment ended, totals for FY2019 (July 1, 2018–June 30, 2019—the last full fiscal year before PTI's 20th anniversary) are included.

Table 1. Key metrics of accomplishment for IU PTI.

Metric	Total from inception to end of September 2020	Reference
1. IU PTI creates and disseminates knowledge.		
Projects leading to Nobel Prizes supported by IU PTI	3	

[7] McRobbie, M.A. (2014). *Final Report to Lilly Endowment Inc.* Indiana University Pervasive Technology Institute. https://scholarworks.Indiana University.edu/dspace/handle/2022/19787

PTI technical publications	1506 total; 1301 peer reviewed	https://bibbase.org/service/mendeley/42d295c0-0737-38d6-8b43-508cab6ea85d
Datasets published	177	http://hdl.handle.net/2022/25793
Other digital products (not counting open-source software or presentations)	8	http://hdl.handle.net/2022/25793
“Best Paper” awards	11 Best Papers, 1 Best Student Paper, 3 Best Paper finalists	
Major national and international group awards	4 SCxy Challenge awards, 1 SCxy honorable mention (counting predecessors to PTI that were later involved in PTI), 1 SCxy Student Cluster Competition award, IUanyWare, Campus Technology for Jetstream	
Conferences led / hosted	52	
2. IU PTI develops and deploys advanced computing infrastructure.		
PTI grant and contract total from federal sources	$123,624,974	
PTI grant and contract total from non-federal sources	$12,702,779	
Total grants and contracts for PTI	$136,327,753	
Major services offered (e.g., visualization services, online computing tools, science gateways, major computing systems)	72	
Open-source software titles created	73	
3. IU PTI leads and supports the commercialization of IU-developed technology.		
Patents awarded to PTI-affiliated staff or faculty	12	
Number of commercial licenses executed	5	
Startup companies created by someone affiliated with PTI	11	
4. IU PTI enhances the growth of Indiana’s economy.		
Startup companies in which PTL and PTI made an investment as an Angel Investor	2	
Major collaborations with businesses operating in Indiana (including international businesses with a significant presence in Indiana)	9	
Major collaborations with international businesses that do not have a major presence in Indiana	3	
Person years of employment created directly within PTI / Indiana University (actual grant headcount)	862.8 (full-time equivalents)	

Job years of employment in the State of Indiana created as a side effect of PTI grant awards, as estimated by the IMPLAN methodology	2100	
5. IU PTI aids the development of a strong STEM workforce in Indiana.		
Students receiving Ph.D. degree (who worked in or were supported by an IU PTI-affiliated center)	73	
Students who received a Ph.D. and went on to tenure-track faculty positions	22	
Total readership of *Science Node* (www.sciencenode,org), a free electronic publication about computing and science	143,866	
6. IU PTI stimulates IU's innovation pipeline.		
Total number of new centers created or newly brought into affiliation with PTI since organization into centers and labs in 2008	4	
Total number of new labs created or newly brought into affiliation with IU PTI since organization into centers and labs in 2008	2	

Note: These metrics include accomplishments of individuals, labs, and centers while they were formally affiliated with PTL or IU PTI.
*These numbers are underestimated, as these statistics were not counted reliably prior to 2011.

A list of IU PTI's technical publications is available online.[8] Counts for each publication type are presented below in Table 2. A detailed timeline of IU PTI's major accomplishments is also available online.[9]

Table 2. Technical publications by IU PTI-affiliated individuals from 1999–2019.

Metric	Total published
Journal articles, peer reviewed	503
Conference proceedings, peer reviewed	740
Book chapters	58
Subtotal peer-reviewed publications	*1301*
Technical reports (most self-published through IU ScholarWorks, IU's digital online repository)	205
Total technical publications	***1506***

To give a sense of IU PTI's scale and the evolution of its size over time, IU PTI's predecessor—the section of UITS focused on research computing—employed only 24 people the year before Michael A. McRobbie arrived as Indiana University's first vice president for information technology and chief information officer. As of the end of FY2020 (30 June 2019), there were a total of 121 FTEs working in IU PTI-affiliated centers. Sixty-seven FTEs were funded with university monies (most of these in research technology). Within IU PTI, a total of 54 FTEs were supported by external contracts and grants.

[8] https://bibbase.org/service/mendeley/42d295c0-0737-38d6-8b43-508cab6ea85d
[9] pti.iu.edu/about/timeline

5. Outcomes of IU PTI activities (2015–2020)

The facts and figures in Table 2 present a highly positive picture of IU PTI's activities and accomplishments in research and development. But there is much more to IU PTI than just counts of publications and events and dollars of grant awards. Earlier reports have summarized the activities of the PTL up to 2007[10] and through the end of funding from the Lilly Endowment in 2014.[11] These reports are well worth reading. This report emphasizes activities since 2014, but begins with exemplars from the early years of PTI that proved fundamental to its long-term success. Other key activities from the earlier years of existing PTI-affiliated centers, as well as summaries of the activities of labs and centers created by PTL and PTI that have been closed, are presented in section 7.

[redacted] *Early successes*

5.1.1. Data-centric computing

Data-centric computing has been a focus area for IU PTI from almost the beginning, starting with the success of a project called Linked Environments for Atmospheric Discovery (LEAD). LEAD was a system for analyzing and predicting tornado paths. This project was led by University of Oklahoma Professor Kelvin Drogemeier and involved PTL Science Director Dennis Gannon and Professor Beth Plale.

The LEAD project demonstrated the power of a data-centric approach to using supercomputers for solutions to real-world problems. This project was the starting point for three of IU PTI's current centers:

- The Data to Insight Center, led to this day by Professor Beth Plale, focuses on the creation of data-centric scientific concepts and tools.
- The Cyberinfrastructure Integration Research Center, led by Dr. Marlon Pierce, has taken the concept of science gateways developed by Professors Plale and Gannon and created a whole suite of software tools and computational environments based on it.
- The HathiTrust Research Center focuses on data-centric approaches to humanities scholarship, and itself sprang from a data science project led by the Data to Insight Center.

5.1.2. Concept-centered approaches to cybersecurity

CACR is one of the oldest IU PTI-affiliated centers; that affiliation, however, came well after the center was created. CACR was founded in 2001 by then-VP Michael A. McRobbie, with Law Professor Fred Cate as director. Consistent with Professor Cate's expertise, CACR in its early days focused on policy and privacy. Cate was very well known for his privacy work in particular and was frequently called upon to offer his expertise on such issues in Washington, D.C. Other cybersecurity centers have focused on technology first, assuming that the solutions to cybersecurity problems lie in technological approaches. CACR has always focused on principles and policies in the belief that security policy and privacy concerns should drive technological development. That approach has enabled CACR to grow into one of the nation's most significant centers for cybersecurity policy and technology.

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[10] McRobbie, M.A., Adams, K., Baker, M. P., Fox, G., Gannon, D., Heiland, R., Lumsdaine, A., McMullen, D., Miller, T., Siefert-Herron, D., Stewart, C., Wallace, S., Pierce, M., & Travis, G. *Pervasive Technology Labs Program Report 2007*. Report to the Lilly Endowment. (2007). Available from: http://hdl.handle.net/2022/3210

[11] This report outlines the maturation of the IU Pervasive Technology Institute from the end of the name and structure of the "Pervasive Technology Labs" to the point that IU PTI was able to sustain itself with just a small amount of ongoing support from IU.

5.1.3. Creation of new cyberinfrastructure systems and resources

In 1997, Indiana University had its first display at the prestigious IEEE/ACM Supercomputing Conference (more explanation of this conference is in section 14.2). The university was not yet well known for advanced computing, and one of the questions commonly posed to representatives at the display booth was, "Why does IU have a display at this conference?" No one asks that anymore. IU's climb to prominence was fueled by collaboration between RT and IU PTI faculty, though there was no formal tie between RT and PTL prior to 2005. Key highlights in IU's rise to prominence in advanced computing include:

- *Supercomputers and high performance computing clusters.* RT services include designing and implementing supercomputers used by IU and the national research community, including:
    - The first university-owned 1 teraFLOPS (trillion floating point operations per second) supercomputer in the U.S. (2001). The IBM-manufactured "Research SP" was capable of one trillion mathematical operations per second. This system was one of the first IU systems to be made available to the U.S. research computing community, as part of IU's engagement in TeraGrid (discussed on page 24). Led by RT, this system's development benefitted from the involvement of PTL's initial science director, Dennis Gannon.
    - The AVIDD cluster (Analysis and Visualization of Instrument-Driven Data), which was the first distributed Linux cluster to achieve more than 1 teraFLOPS on the LinPack benchmark program (2003). AVIDD was made possible by a grant award from the National Science Foundation. Like the Research SP above, AVIDD was made available to the national research community as part of IU's involvement in TeraGrid. AVIDD was developed, implemented, and led by Craig Stewart with the deep involvement of IU PTI-affiliated faculty members Dennis Gannon and Beth Plale, as well as affiliated computer science faculty member Randy Bramley.
    - Big Red, IU's best-ranked supercomputer ever on the Top500 list, which lists the world's 500 fastest supercomputers. Unveiled in 2006, it was the original of the "Big Red" family. This 20.5 teraFLOPS system debuted at position number 23 on the Top 500 list. While IU has had many systems on many of these prestigious twice-a-year listings, no IU supercomputer has ever been higher on that list than the original Big Red. Big Red was also available to the national research community via TeraGrid, and was for a considerable amount of time the fastest systems part of TeraGrid in running the important molecular simulation program NAMD. Many breakthroughs in the understanding of cell function were made by researchers across the U.S. running simulations with NAMD on Big Red. Big Red was developed under the leadership of Craig Stewart, who was COO of PTL and led RT at the time, in partnership with IU PTI-affiliated faculty member Andrew Lumsdaine.
    - Big Red II, the first university-owned 1 petaFLOPS supercomputer in the U.S. (2013). A petaFLOPS is a quadrillion mathematical operations per second, equal to1000 teraFLOPS. Big Red II was the beginning of the very successful partnership between Cray Inc., known as "America's supercomputer company," and IU. The architecture of Big Red II was developed primarily by RT leaders Matt Link and David Y. Hancock, with important input from IU PTI-affiliated leader Thomas Sterling.
- *Advanced storage systems.* RT has also been a leader in advanced storage systems.
    - *Tape storage systems.* IU was one of the first universities to install a major tape storage system operated with the very secure High Performance Storage System (HPSS) in 1999. HPSS was designed for use at a classified U.S. nuclear weapons lab. IU installed one tape library in Bloomington in 1999 and another in Indianapolis in 2001. RT then wrote code enabling the two different tape storage systems to "mirror" each other. IU was the first university in the world to use this approach, ensuring that IU's research data was stored

in duplicate, 50 miles apart. IU's official digital archive, IU ScholarWorks, depends on RT's tape storage system for its data storage. Like several of IU's storage systems, the Scholarly Data Archive (as this tape storage system is known) was made available for use by the U.S. research community through TeraGrid.

- *Disk-based systems.* IU leadership in disk-based storage systems began in 2005 with a grant award from the NSF. IU built one of the fastest massive disk-based data storage systems in the U.S. based on the high performance, open-source disk storage software Lustre. It was the fastest and most widely used disk storage system ever connected to the TeraGrid. IU has operated one or more local storage systems based on the high performance Lustre system ever since. RT has also played a lead role in national and international leadership of the Lustre file system project, including two periods with IU storage expert Stephen Simms serving as the group's chairperson. IU PTI-affiliated faculty members Beth Plale and Denis Gannon were both involved in the conceptualization of this project.

5.1.4. High performance software tools

Supercomputers are only useful when they remain fast while running software. This requires more than just hardware; rather, it takes innovation and excellence in software implementation. High performance software systems have, like data-centric computing, been a hallmark of IU PTI since its inception. Key faculty members affiliated with IU PTI and working in this area have included Geoffrey C. Fox, Andrew Lumsdaine, Thomas Sterling, and D. Martin Swany.

One early example of high performance software from Fox's lab is the NaradaBrokering system. NaradaBrokering was a content distribution infrastructure for web-based applications that enabled the development of secure, failure-resilient, web-based systems. The concepts behind NaradaBrokering are still used today in web-based distributed computing systems and in supercomputers.

Graph problems are a vast category in mathematics and computing. Everything from website interconnectedness to the processing of big data can be expressed as a graph problem. IU PTI has been involved in developing software for graph processing and related high performance computing tools from its earliest days. Notable software developments include:

- The BOOST graph library was an early and important contribution to high performance computing software. Created under the leadership of Open Systems Lab/CREST Director Andrew Lumsdaine, the BOOST graph library was, for many years, one of the best performing and most widely used software tools for solving graph problems.
- HPX – High Performance Parallax – was a runtime system developed by former CREST Director Thomas Sterling, perhaps best known as the father of Beowulf computing clusters, and for designing the architecture used in the world's fastest supercomputers for more than a decade. HPX was a software system that inherently incorporated ideas from graph libraries.

Digital Science Center Director Geoffrey Fox has most recently been an international leader in the creation of software that integrates big data tools with high performance supercomputer tools. Additionally, several exciting contributions from IU PTI in the area of high performance computing have come from the innovations of Luddy School Professor D. Martin Swany, affiliated with D2I, who has developed performance tools to enhance software used in anything from wide area networks to individual supercomputers.

All in all, high performance software has been a focus of:

- Digital Science Center (DSC)
- Center for Research in Extreme Scale Technologies (CREST)

- Research Technologies (RT)
- Data to Insight Center (D2I)

[redacted]*IU PTI accomplishments, with a focus on 2014–2020*

5.2.1. IU PTI creates and disseminates knowledge.

IU PTI has created thousands of peer-reviewed scientific papers, technical reports, and datasets, and has supported many types of scholarly research. A few important examples of knowledge created and disseminated by IU PTI include:

- *Security from first principles.* All too often in the history of cybersecurity, experts have thought of the problem as being one of taking an existing system and securing it against bad actors. In the book *Security from First Principles*, Center for Applied Cybersecurity Research experts Craig Jackson, Scott Russell, and Susan Sons explain tools and techniques that allow software engineers to build software from the first comment line to finished code in ways that lead to inherently well-secured software. This concept is revolutionizing cybersecurity today.[12]
- *FAIR data.* FAIR refers to a critical concept in production of data and other digital assets expressing that they should be "Findable, Accessible, Interoperable, and Reusable." IU PTI has advanced the development of specific tools that implement FAIR data policies. In Washington D.C., D2I director Beth Plale led the development of data policies and guidance for creating reusable data for the NSF, work that will impact open research in the U.S. for years to come.
- *Big data and high performance computing*. Money is being poured into "Big Data" style computing, yet often without incorporating well-known techniques of HPC computing. At the same time, HPC computing must incorporate new techniques developed in the Big Data world or risk falling into irrelevance. The Digital Science Center, led by Director Geoffrey C. Fox, has emerged as an intellectual leader in creating knowledge maps that link HPC and big data software, and in developing software and software libraries that integrate tools from HPC and Big Data approaches into large-scale computing.
- *Return on investment (ROI) analysis of advanced cyberinfrastructure.* It has been an article of faith at IU for more than half a century that IU's investments in cyberinfrastructure accelerate research and development. IU PTI has emerged as the national leader in the analysis of return on investment in advanced computing. These analyses show conclusively that IU's investment in on-premise facilities is highly cost effective. Systems such as the Big Red series of supercomputers enable analyses not easily performed in cloud systems, and at a cost much lower than would be paid for cloud systems. Similarly, the IU PTI Jetstream cloud system provides straightforward interactive computing tools at a price much lower than commercial cloud services.

Within these areas of expertise, IU PTI has both exerted influence on and been influenced by national research needs. Security from first principles and big data/high performance computing are areas in which IU has responded to clear research community needs. In the case of FAIR data, IU has helped define a need and influenced the federal government to identify this area as a need. It then became one of the U.S. institutions best positioned to help meet that need. IU PTI's involvement in ROI research was initially a result of a request for work on this specific topic from the U.S. federal government that grew into another area of national leadership for IU PTI.

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[12] Jackson, C., Russell, S., & Sons, S. 2017. *Security from First Principles*. O'Reilly Media, Inc. ISBN: 9781491996904.

Producing new knowledge is important, but that knowledge must be transmitted and put to use in order to be meaningful. Scientific, technical, scholarly, and artistic conferences are a way to transmit information, build communities, and aid in the transformation of new inventions into practical tools. Tens of thousands of people have been made aware of IU and its capabilities as a result of IU PTI leadership at conferences. Hosting conferences is also a way to attract people to IU as faculty members, staff, and students. IU PTI has led and/or hosted a total of 47 conferences, serving constituencies from local to international. Three examples of such conferences include:

- *The I-Light Conference.* In the early 21st century, IU was at the forefront of networking research and development, and implemented its own network. Indiana University and Purdue University received state funding to develop a high-speed network that connected the Purdue–West Lafayette, Indiana University Purdue University–Indianapolis, and Indiana University–Bloomington campuses, and connected them to the Internet2 national high-speed network that travelled through Chicago. In 2002,[13] 2004,[14] and 2005,[15] IU and Purdue universities hosted a statewide "I-Light Conference" to share information about how best to use this network capability, and to describe research advances and accomplishments made possible by this network funded by a special state appropriation. Proceedings of this conference remain available online and provide examples of just how far ahead of the rest of the nation Indiana was in its use of advanced networks.
- *PRAGMA 27*. Hosted by the Data to Insight Center and IU PTI October 15–17, 2014, PRAGMA (Pacific Rim Applications and Grid Middleware Assembly) is a major conference on grid computing and big data management. Beth Plale served as general chair and host, bringing this distinguished international conference to IU Bloomington.
- *Galaxy Community Conference.*[16] Galaxy is one of the most important and most widely used bioinformatics workflow tools in existence. Galaxy enables biologists to string together a set of different programs in order to analyze and understand the results of genetic and genomic research projects. Galaxy is specifically designed to be easy for biologists to use and to make analyses easily replicable. The Galaxy Community Conference draws together hundreds of researchers each year to talk about their research with Galaxy, new tools they have developed for Galaxy, and new features they would like to have. IU PTI bid and won the right to host the GCC 2016 conference specifically with the idea that it would be a great way to bring many exciting biological research talks to IU, while at the same time building excitement within the Galaxy user community about using the new Jetstream cloud system. It worked. To this day, Jetstream supports a larger percentage of allocations for biological research projects than any other system allocated through XSEDE.

Within Indiana University, IU PTI staff and affiliated faculty members collaborate with others within the university community, making new technologies available to IU before they are released to the larger U.S. research community and described in academic publications. Some recent examples of IU PTI's role in supporting major research initiatives at IU include:

- *Indiana University Grand Challenge: Precision Health.* The IU Precision Health Grand Challenge Initiative is, quite simply, saving lives. Through this initiative, doctors have developed the most effective treatment in existence for "triple negative" breast cancer—a cancer that

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[13] G. Moore & C.A. Stewart. (eds.). (2002). *I-Light Applications Workshop 2002 Proceedings.* Indiana University. http://hdl.handle.net/2022/14002

[14] C.A. Stewart, G. Moore, & E. Wernert (eds.). (2004) *I-Light Symposium 2004 Proceedings.* Indiana University. http://hdl.handle.net/2022/13999

[15] E.A. Wernert, G.R. Bertoline, & G.S. Moore (eds). (2005). *I-Light: A Network for Collaboration Between Indiana University and Purdue University.* Indiana University. http://hdl.handle.net/2022/435

[16] Please see https://gcc16.sched.com and https://rna-seqblog.com/the-2016-galaxy-community-conference-gcc2016/

disproportionately affects Black women and has a particularly poor prognosis. IU PTI's cyberinfrastructure and support enables advances in the many foci of the Precision Health Grand Challenge Initiative, including cancer, Alzheimer's, and diabetes, and has helped find new immunotherapeutic treatment for cancer and tools for diagnosing and understanding Alzheimer's. The largest U.S. consortium studying Alzheimer's depends on IU's supercomputers and storage facilities as the core of its research enterprise.

- *Indiana University Grand Challenge: Prepared for Environmental Change.* The global environment is changing. One can argue about the causes and strategize about ways to decrease the impact of humans on the global environment, but we must also prepare for these changes as an imminent reality. Current predictions suggest that central Indiana may, in 50 years, have a climate similar to that of northern Texas. The Prepared for Environmental Change Grand Challenge focuses on education and information dissemination to decrease the impact of humans on the global environment. Research associated with the challenge also focuses on developing specific strategies that will prevent loss of species critical to ecosystem function in Indiana and the Midwest, and helping humans in Indiana prepare for and adapt to changes in the environment that will affect all aspects of life.
- *HathiTrust Research Analytics.* IU PTI took on the role of leading the HathiTrust Research Center (HTRC), a multi-state collaboration, and since then has made the copyrighted material of the Google Books project available to the nation as a production service, increased the total number of volumes available for analysis to 17 million, created new tools, and enabled critical new insights in humanities scholarship, particularly in studies of literature and history. HTRC is particularly proud to have played a role supporting the massive text search that has enabled scholars to find, amplify, and reveal the voices of Black women who lived in the U.S. in the 1800s. HathiTrust Research Analytics is a combination of software tools and a dedicated and highly specialized hardware platform. This center and its national services emerged from what was initially a research idea within D2I.
- *3-D digitization and 3D.* IU PTI supports 3D scanning, immersive visualizations, and 3D printing technology in use at IU. IU's distinctive collection of high-resolution scanning devices allows users to capture objects in minute detail, including the "Old Oaken Bucket," anatomical parts of songbirds, the Showalter Fountain, and entire buildings. Staff at the Research Technologies Advanced Visualization Lab have, for example, digitized the entire IU Cinema inside and out. This allows the re-representation of 3D objects in immersive visualization and in 3D prints—blowing things up to review fine details or creating "shrunken" replicas of large structures. 3D printing also creates the opportunities for new forms of artistic creation, such as the 3D sculpture pictured in Figure 4, made by IU Associate Professor Nicole Jacquard.

Figure 4. Sculpture constructed with a 3-D printer by IU Professor Nicole Jacquard

In all of these cases, IU PTI participates in identifying and responding to the needs faced by IU researchers, and then invents technologies that solve problems for them. In the process, IU PTI solves problems for researchers throughout the world.

IU PTI's engagement in the research community also extends beyond its work with IU researchers. In fact, IU PTI frequently engages at the state and national level by providing services, engaging in and informing national research directions and priorities, offering services and education, and otherwise participating in the fabric of the national research community.

The IU PTI-affiliated Center for Applied Cybersecurity Research (CACR) was selected by the State of Indiana to provide services to secure the 2020 election. CACR's team of experts helped prepare election officials in all 92 Indiana counties for potential cybersecurity incidents that might occur around the 2020 general election and beyond. At the 2020 Election Administrator's Conference, the CACR team led a half-day boot camp that included tabletop exercises in dealing with cybersecurity incidents. The boot camp was made possible through a grant from Indiana Secretary of State Connie Lawson.

IU PTI, largely through CACR, contributes to state and national cybersecurity in several other ways:

- CACR helps secure the U.S.'s cyber-borders by assisting U.S. defense departments through engagement with the Crane Naval Surface Warfare Center, serving as a Department of Homeland Security-certified Center of Excellence in Cybersecurity, and training volunteers in the National Guard.
- CACR leads an annual NSF Cybersecurity Summit, which is one of the means by which the largest and most important NSF-funded research projects learn about and share best practices related to cybersecurity.
- CACR leads the Research Security Operations Center (ResearchSOC). ResearchSOC is unique as the only organization with the mission to provide operational cybersecurity services to NSF-funded facilities and projects while at the same time seeking to further research in cybersecurity. Funded by a $5M award from the NSF, ResearchSOC helps make scientific computing resistant to cyberattacks and helps secure the validity of U.S. scientific research.

One particularly important component of IU PTI's service to the nation is its influence on national research priorities, as depicted in Figure 2. Some of this influence is exerted by participation in and leadership of government agencies and government advisory committees. IU PTI-affiliated faculty and staff have often served in positions of national leadership in academic associations and organizations, conferences, workshops, and advisory committees to federal agencies. A few IU PTI-affiliated individuals have testified before congressional committees or served as temporary employees of federal funding agencies. Several IU PTI-affiliated faculty have been recognized for the distinction of their service and intellectual achievement by being named members of national academies, winning major honorary awards, best paper awards, and being awarded distinguished or endowed professorships at IU.

By demonstrating new technologies and breakthrough computing innovations, especially at national and international conferences, IU PTI continues to influence the national research community and federal research priorities. This occurs in many venues, but perhaps most importantly and most consistently in the International Conference for High Performance Computing, Networking, Storage, and Analysis (SCxy series). IU PTI collaborates with other Indiana University entities (for example, the Luddy School and GlobalNOC) to display their computer science, informatics, cyberinfrastructure, and cybersecurity innovations at the annual conference. This conference serves as a testbed for development and demonstration of new technologies through various challenge competitions. IU has won a total of four such events—as far as we know, more than any other advanced computing center, apart from the initial four NSF-funded supercomputer centers. SCxy also gives IU faculty and staff the opportunity to network with colleagues from other institutions working on projects such as the NSF-funded Jetstream or NCGAS. IU benefits from its participation in this conference and also contributes strongly to its management and execution. RT Associate Vice President Matt Link was elected to serve on the SCxy steering committee—

the top-level organizing body for this conference—for several years. Link is the only member of the IU community to serve at this level of the SCxy organizational structure.

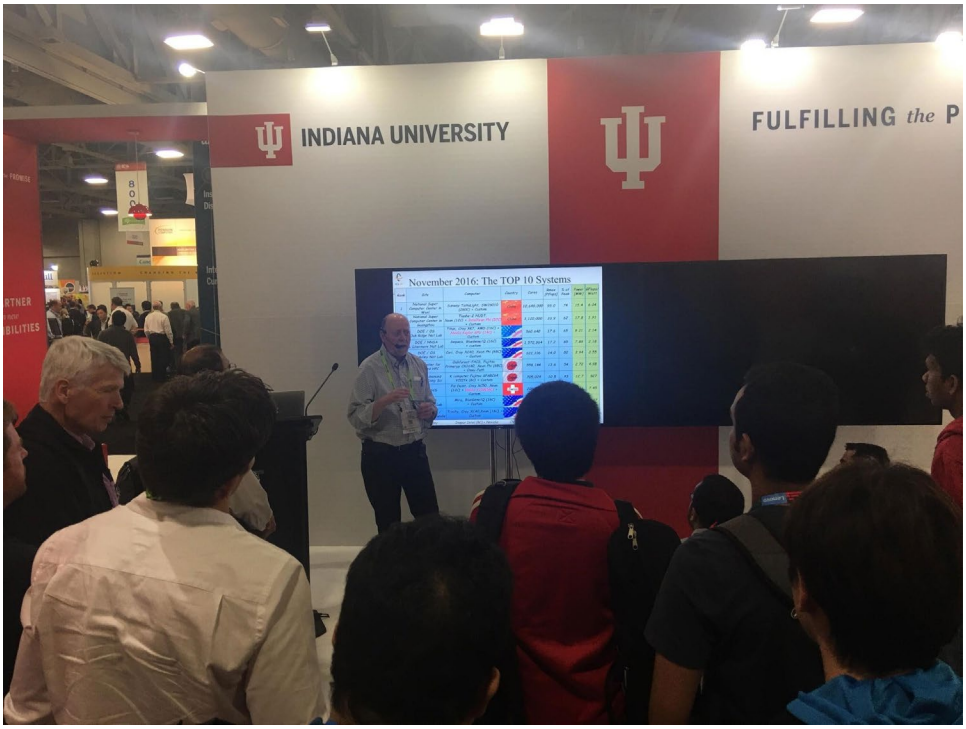

Figure 5. World-renowned supercomputer expert Jack Dongerra gives a presentation at the Indiana University booth on opening night of SC16. The crowd spilled out into the aisles and neighboring booths.

IU PTI's leadership and competence to lead national agendas is evident in its success in receiving federal funding to offer services to the U.S. research community. Many of the services mentioned earlier are offered by IU PTI via federal funding, which has a number of important benefits for IU and for the nation. Often these services are prototyped and demonstrated at national and international conferences, such as the SCxy series. As mentioned before, IU PTI pursues grant funding when its leaders believe that it is the organization within the U.S. best qualified to design and deliver a particular service. Our unusually high success rate in having proposals funded shows that we are often right. The nation is therefore served by some of the best experts available in the country—including our IU colleagues. On top of that, such federal funding creates a critical mass of expertise available within IU. As a matter of policy, IU provides funding for at least 10% of the salary of each IU PTI-affiliated staff member, so all of the expertise we bring to IU has at least a small amount of time funded by IU and allocated to serving the IU community.

IU PTI is unique among U.S. advanced computing centers in its commitment to national and global education through leadership of an international free publication called *Science Node* (sciencenode.org). IU PTI organizes the fundraising for this innovative and popular e-publication. *Science Node* is read by nearly 150,000 people, and offers reliable, engaging journalism about new scientific and technological breakthroughs made possible by advanced computing technology. *Science Node* is operated by the Information Technology Communications Office (ITCO) in the Office of the VP for Information Technology, and operates with journalistic independence under the guidance of an external advisory board. Because of that, *Science Node* is trusted as an authentic and accurate conveyer of excellent science journalism. IU PTI-affiliated centers and the IU GlobalNOC contribute roughly one-third of the funding for *Science Node*. The remaining two-thirds is provided by underwriting from colleges and universities throughout the U.S. and European Union. *Science Node's* readership includes students, young

professionals, and seasoned university experts; its ever-growing base of readers accesses *Science Node* content via Twitter, LinkedIn, Facebook, an email newsletter, and a constantly updated web page. It is the only free publication that focuses so directly on the role of advanced computing technology in innovation.

5.2.2. IU PTI develops and deploys advanced computing infrastructure

Through IU PTI's success in winning grant and contract money, it often creates new technologies or transforms existing proofs of concept into widely used and robust research and development tools. IU PTI has brought more than $136M in grant money to IU, including two grants of more than $10M. Both accomplishments, within the context of IU, and of higher education generally, are simply exceptional and represent expertise in creating ideas, explaining their importance to funding agencies, and carrying out funded research so that the virtuous cycle of obtaining federal funding, using it well, and pursuing innovative directions for federally funded research persists.

Examples of new technologies transformed into widely used research and development tools include:

- *Science gateways.* Science gateways are web interfaces and middleware that enable straightforward interaction for researchers with complex suites of software running on multiple advanced supercomputers and data resources. Science gateways tie together diverse cyberinfrastructure systems in ways that appear straightforward from the users' standpoint. In the area of Science gateways, IU PTI has both invented a new technology and nurtured it to the point of becoming a widely used tool. Cyberinfrastructure Integration Research Center leaders Marlon Pierce and Suresh Marru are Apache Foundation Fellows (the only people in IU PTI with this distinction) and the primary architects of the Apache Airavata software. Apache Airavata, one of the most widely used open-source science gateway frameworks in existence, is responsible for dozens of science gateways in use in science and engineering applications. Many of these are hosted by IU on its cloud systems, while many others are operated by other universities, government research labs, and private manufacturing firms. As computing moves increasingly to interactive analyses, including advanced engineering in the private sector and defense-related design, Apache Airavata offers the unusual capabilities of supporting highly secure computations and features that enable recording and replaying interactive analyses.
- *Workflows for genome analysis.* Gone are the days when analysis of genomic information involved running one or two software packages. Today, genomic analysis involves putting together multiple software packages, piping data from one to another, adjusting parameters and options, and then reanalyzing to obtain a rich understanding of the wonder that is life on this planet. The National Center for Genome Analysis Support (NCGAS) has emerged as a leader in the curation of "best-of-breed" software and assembly of tools into workflows designed to enable new insights from biological research. In the process, NCGAS has enabled the assembly of the genomes or transcriptomes (the full suite of RNA sequences assembled from the expression of DNA) for organisms of economic importance, from the white pine to crustaceans at the base of the oceanic food chain, and from common animals like salamanders to endangered species found only in one small part of the Colorado River basin.
- *New tools for programming new hardware.* The use of graphical processor units (GPUs) has transformed the hardware design and processing capabilities of supercomputers worldwide. In the U.S., exascale computers, which are capable of a thousand quadrillion mathematical calculations per second, are created with designs that depend on tens of thousands of GPUs. They are, however, quite difficult to program. OpenACC, with IU PTI's aid through RT, has become one of the standard programming tools to develop scientific applications that use GPUs effectively.
- *Software Assurance Marketplace (SWAMP).* The Software Assurance Marketplace is a suite of tools and a service that enable U.S. researchers to create secure, hack-resistant scientific software. SWAMP, which operates as a combination software tool and platform for software, checks for

vulnerabilities in scientific software. One can easily upload software to a SWAMP instance running in the cloud and have those software packages evaluated automatically, or one can download "SWAMP in a box" and run it locally. SWAMP protects U.S. scientific software, data, and results from bad actors.

In most of the above areas, IU researchers function as exemplars of world-class research leaders. IU PTI works to discover their needs, create proofs of concept to solve problems, and propose that the government make large-scale investments that serve national needs. OpenACC is the exception, where IU PTI involved itself in a public-private consortium and then led an activity that involves little federal investment and yet benefits the U.S. greatly.

IU PTI has also been a long-time leader in creating open-source software, and in improving open-source software released by others. To date, IU PTI has released new or improved versions of a total of 73 software titles.[17] Notable tools include a suite of software packages for management of data provenance, a number of programming and communication suites, and a large suite of bioinformatics software. For example, Trinity is the most widely used software package in existence for assembling sequences of RNA. It produces excellent biological results, but its authors were primarily biologists, not software engineers. Software performance experts from RT, under the leadership of Director Robert Henschel, rewrote important pieces of the software without changing the results it produced and made it run eight times faster than it had previously. This meant a change from "one day to the next" in getting results to "results back multiple times in a working day," drastically altering how biologists could interact with their data.

IU PTI also operates hardware resources, software systems, and dedicated hardware/software environments designed to support particular functions. Throughout its existence, IU PTI has hosted a total of 68 major services, ranging from visualization systems to specialized software tools running on dedicated hardware. Thousands of students and visitors have seen compelling scientific and artistic works displayed on advanced visualization environments created by IU.

Many of PTI's notable major services have arisen from the collaboration of two or more centers on one project. The following examples illustrate the powerful cooperation among centers. Collaborative relationships within IU PTI facilitate the creation of a whole that is more than the sum of its parts.

- *FutureGrid.* A distributed set of heterogeneous high performance computing clusters and small supercomputers used to develop and test new software, FutureGrid was a breakthrough for IU PTI as its first individual grant award with a budget over $10M. It was also IU's first grant award for what the National Science Foundation calls "Track 2" systems: systems that are made available as a resource to the national research community and allocated and supported by XSEDE. FutureGrid, a collaboration between DSC and RT, provided resources for many important grid and cloud computers, and innovations created through FutureGrid were active from 2010 through 2015. The project was led by Geoffrey C. Fox, but the preparation of the proposal and implementation of systems in four different physical locations would not have been successful without RT's deep engagement.
- *Jetstream.* Perhaps IU PTI's most significant contribution to advanced computing hardware systems, Jetstream is the first NSF-funded cloud system for support of science and engineering research. Initially led by PTI Executive Director Craig Stewart, and continued under the leadership of Principal Investigator David Y. Hancock since 2017, Jetstream was IU PTI's second grant award for more than $10M. Funded initially at just over $10M in 2015, Jetstream remains

[17] In prior reports, IU PTI has listed a tally of titles and different versions of the same title. In this report, we have chosen to list simply titles. For example, the CREST / Open System Lab software called the "Boost Graph Library" represents one title but dozens of releases.

active today. Additional NSF funding has brought the total federal investment in this system to nearly $15M. In the last half-decade, Jetstream has had an immediate impact on the national research community, as thousands of researchers have used this accessible, intuitive cloud system. Jetstream has been particularly important in fostering biological, earth science, and climate research in the U.S. Jetstream operates with the same philosophies and principles as commercial cloud systems—always on, continual improvement—but unlike commercial cloud systems, Jetstream was designed to serve research and educational purposes. Cloud computing is now a widely accessible tool for the NSF and the U.S. open research community thanks to Jetstream. Jetstream was led by RT, but its success has depended upon collaborations with NCGAS, CIRC, and CACR.

- *XSEDE and its predecessor, the TeraGrid.* The "eXtreme Science and Engineering Discovery Environment" is a goofy name for a tremendously important national resource. One of the most important national computing, storage, and support resources, XSEDE is *the* national advanced computing administration and support service for the NSF. It is the latest instance of four decades of NSF-funded delivery of the nation's most advanced cyberinfrastructure in existence. Beginning with TeraGrid in 2003, the NSF moved from a model of independent centers to a single administration and support organization. Since then, the NSF has funded one organization to be a front door to the many advanced computation, data analysis, and visualization systems it funds for the national research community. IU became a service provider as part of the TeraGrid in 2004. TeraGrid evolved into XSEDE in 2011, and IU PTI has played a role in these critically important national services. IU PTI has also played integral roles in the other major services made available to the nation via XSEDE: the experimental FutureGrid system in 2010, efforts in science gateways and national cyberinfrastructure (CI) integration since 2011, and most significantly the Jetstream cloud system starting in 2016. No U.S. unclassified organization has had a larger overall impact on advanced CI-enabled research in the U.S. than XSEDE, and IU has provided its expertise in the service of U.S. global competitiveness. Tens of thousands of researchers and students have used NSF-funded systems and services with the aid and participation of CIRC, DSC, CACR, and RT.
- *Open Science Grid*. OSG was in many ways the complement to TeraGrid and XSEDE. OSG was a national grid of computers focused on high throughput computing (HTC) rather than high performance computing (HPC) (supercomputers and clusters). OSG was designed in large part to analyze data created by the Large Hadron Collider. RT and CACR were involved in OSG from the predecessors of the OSG projects that began in 1999 up to the writing of this report.
- *Support for research leading to Nobel Prizes.* Through its involvement in TeraGrid, XSEDE, and the OSG, IU has been involved in projects that facilitated research leading to three Nobel Prizes:
    - The 2013 Prize for Physics, awarded jointly to Englert and Higgs for predicting the Higgs boson (analysis done via the OSG)
    - The 2013 Prize for Chemistry, awarded to Karplus, Levitt, and Warshel for the development of multi-scale models for complex chemical systems (software development and analysis supported by TeraGrid and XSEDE)
    - The 2017 Prize for Physics awarded jointly to Weiss, Thorne, and Barish for directly detecting gravitational waves (software development and analysis supported by TeraGrid and XSEDE)
- *Science gateways by the dozen.* CIRC, RT, and CACR offer dozens of such tools for use by local, national, and international audiences. Key services include:
    - *Science Gateway Community Institute (SGCI).* SGCI is funded by the NSF to support and foster the growth of the science gateways community. SGCI is one of just three grant awards for centers called "NSF Scientific Software Innovation Institutes." Through SGCI, CIRC provides technical consulting and support services for science gateways.

These services have supported the creation or enhancement of more than 50 science gateways.

- *Science gateway cybersecurity.* Custos, a collaboration between CACR and CIRC, will integrate and deliver a major security capability needed to operate science gateways. CACR provides cybersecurity consulting and input on best practices for this NSF-funded project, bringing together CIRC's unique expertise in science gateways and CACR's excellence in cybersecurity.
- *Science Gateways Platform as a Service (SciGaP).* As a result of a major grant award from the NSF, CIRC and collaborating organizations at other universities provide a computing environment on which researchers can operate "turnkey" (configure and use) science gateways for use by the science community. As with most such projects, CACR provides security analysis and monitoring.
- *Jetstream as a science gateway host.* Many science gateways are hosted on Jetstream, the majority of which are built in CIRC's Apache Airavata software. Tens of thousands of people use these gateways.

Several other important services operated by IU PTI are primarily the result of the efforts of a single center, including:

- *Secure systems.* In 2005, IU was the first U.S. university to have alignment with HIPAA (the Health Insurance Portability and Accountability Act) as the "default" for all its storage and computation systems, which means that IU's advanced cyberinfrastructure can be used to analyze and understand identifiable patient data. Very few universities provide this as a general capability even today, and IU biomedical research has been greatly enhanced and accelerated as a result. The initial push for HIPAA alignment was the result of an important collaboration between RT and the IU School of Medicine, in which IU ran the data repository for an international collaboration studying fetal alcohol spectrum disorder (FASD). That project, funded by the NIH with Craig Stewart as the PI, required IU's system to be HIPAA aligned to carry out the essential analyses required to enable better analysis of FASD.
- *Visualization systems.* The RT Advanced Visualization Lab (AVL) promotes and supports the innovative application of visual technologies to enhance IU's research, education, creative activity, and community outreach missions. Systems implemented and supported by the AVL include:
  - *IQ-Walls.* These large-format, ultra-resolution displays for visualization and collaboration were developed and designed by AVL staff and offer modestly priced and extremely high-resolution display facilities.
  - *IQ-Tables.* These 65-inch multi-touch monitors can be reconfigured into table, drafting table, or landscape mode for exhibitions and multi-user engagement.
  - *Experimental virtual and augmented reality systems.* These include a suite of cutting-edge VR and AR technologies, including the Programmable Immersive Peripheral Environmental System (PIPES) mixed-reality interface systems. By way of example, users of the PIPES system can walk through a 3D rendering of an ancient Roman garden, feel the warmth of the sun on their face, feel the breeze in the air, and smell fresh flowers.

  Systems obtained from commercial manufacturers and implemented at IU by AVL include:
  - *CAVE and BARCO Virtual Reality Theatre.* The CAVE was the first widely used 3D immersive stereoscopic virtual reality system. So named in part because it was a "walk-in" size facility, IU was one of the first universities to have this advanced VR system. IU's 10'-cubed CAVE system was a highlight of visualization activities at IU for many years, and was visited by many notables, including, in the days before IU PTI began, former USSR leader Mikhail Gorbachev. The CAVE was superseded in 2000 with a BARCO Virtual Reality Theatre on the IUPUI campus.

    - *Science on a Sphere.* This spherical display was developed by NOAA for presenting scientific and informational visualizations, and creating dynamic visual experiences.
- *Operation IceBridge*. Active from 2009 to2019, Operation IceBridge sought to provide a highly accurate yearly picture of Arctic and Antarctic sea ice, ice sheets, and ice shelves in order to track their behavior and enable future predictions. In collaboration with the University of Kansas's Center for Remote Sensing of Ice Sheets and IU Research Technologies, the project collected and processed hundreds of terabytes of data amassed as the team flew over the ice in Greenland and Antarctica. The mission used naval P-3 and DC-8 planes equipped with multiple radar systems and an IU-designed flying supercomputer called the Forward Observer to map surface snow accumulation, the thickness of the snow on top of the sea ice, and the terrain under the ice. Through Forward Observer, the research team was able to get a preliminary look at data as it was collected, making it possible for the team to make adjustments while still in flight.
- *Parallax Execution Model and HPX.* Professor Thomas Sterling and his colleagues created the Parallax Model of Parallel Computing Execution, the goal of which is to address the key challenges of efficiency, scalability, sustained performance, and power consumption with respect to the limitations of conventional programming practices. The Parallax model was realized in the HPX high performance parallax software developed by CREST. A full version of HPX-5 software was released in 2015 at the SC15 conference in Austin, Texas.[18] While the U.S. Department of Energy ultimately did not select HPX as a key component in the U.S. exascale computing project, the Parallax model and HPX were influential in the design and development of software for exascale systems. This project was led by CREST during its heyday at IU.
- *Trusted CI: leading the NSF cybersecurity ecosystem.* Now in its seventh year of service, Trusted CI has been at the forefront of the NSF community in building a set of technical, policy, and cultural best practices to ensure the security of that infrastructure and the trustworthy nature of the science it produces. Trusted CI has provided security and security review services for more than 260 NSF projects since its inception in 2012, and over 300 hours of training to the community in 2019. CACR's ongoing leadership in protecting more than $7B in NSF-funded research was confirmed this past year with a $12.5M grant extension for the NSF Cybersecurity Center of Excellence (Trusted CI) for expansion of its activities. CACR is the lead organization for Trusted CI, in collaboration with the National Center for Supercomputing Applications, the Pittsburgh Supercomputing Center, Internet2, Lawrence Berkeley National Laboratory (Berkeley Lab), and the University of Wisconsin–Madison.

The list above offers examples of influence moving in two directions: national research needs influencing IU PTI's priorities, and IU PTI's priorities influencing the national research agenda. IU PTI has often helped define needs and proposed solutions that aid U.S. research. In some cases, such as Operation Icebridge, IU PTI was able to propose and implement novel solutions to high-priority national challenges that were otherwise unsolved by other research institutions.

5.2.3. IU PTI leads and supports the commercialization of IU-developed technology.

One of the original arguments for creating the initial set of Pervasive Technology Labs, and then for the transformation of PTL into IU PTI, was the aid and support that PTL and IU PTI provided to the Indiana economy. One aspect of IU PTI's support for Indiana's economy while also supporting Indiana University itself is IU PTI's involvement in commercialization of technology invented at IU. A few key examples of such commercialization efforts include:

- *A new company created and then bought by Facebook.* IU PTI's most successful involvement in a spin-off company must be regarded as the success of Ryan Newton's company

[18] https://itnews.iu.edu/articles/2015/indiana-university-announces-hpx-5-version-2.0-runtime-system-release-.php

Cloudseal. Conceived while Newton was affiliated with CREST, Cloudseal was created through a Small Business Innovation Research grant award, and was not yet a year old before it was purchased by Facebook.

- *Self-driving technology helping to power autonomous lawnmowers.* The Advanced Network Management Lab participated in an autonomous vehicle competition run in 2004 by the Defense Advanced Research Projects Agency. The initial challenge was to create a self-driving vehicle that could navigate a large obstacle course in the desert of the western U.S. A consortium of Indiana organizations worked together to create a self-driving version of a Jeep under the name IndyRobotics LLC. The IndyRobotics entry didn't win, but its self-driving software was picked up by an Indianapolis company that created and manufactured self-driving lawnmowers. That company was bought by MTD—the parent company of Cub Cadet, Troy-Bilt, Columbia, Yard Machines, and other brands, and so inventions by IU PTI have facilitated major innovations in lawnmower products used across the U.S. and also sold internationally.
- *Bloomington-based analytics company, Chalklabs.* Chalklabs LLC is a small company in Bloomington, IN, started by students of IU Professor and PTL Fellow Katy Boerner. Chalklabs remains a successful and profitable business, providing data analytics and reporting services to researchers and companies in Bloomington and across the U.S.
- *Radical new processors for supercomputers.* The work of Professor Thomas Sterling continues on in the private sector as well as the public sector. Simultac LLC is designing a radically new type of processor for potential use in everything from low-power sensor devices to exascale computers. In some ways, what Simultac proposes to do is create a second revolution in computer processors, like the one started by RISC processors in the 1990s. Simultac LLC has received two rounds of federal funding to develop its innovative technologies.

Throughout its 20-year history IU PTI has honed its skills in successfully moving its inventions into the private sector to benefit IU, the State of Indiana, and the U.S.

5.2.4. IU PTI enhances the growth of Indiana's economy.

IU PTI's contributions to the Indiana economy extend well beyond the commercialization of IU inventions. President McRobbie always lists IU's roles as research, education, and service to the State of Indiana (and, by extension, the U.S. and the worldwide community). Such activities are important whether or not they lead directly to income for IU. Often activities to support and advance Indiana's economy do not; rather, they are ways for IU to give back to Indiana.

One of IU PTI's most immediate impacts on the Indiana economy is job creation. IU PTI attracts talented, technically adept staff to Indiana, and keeps them happily employed and funded through competitive grants and contracts brought into Indiana from outside the state. Over the first 20 years of IU PTI's existence, grant funding has contributed 862 person years[19] of employment to the Indiana University payroll. These employees live, shop, and pay taxes in Indiana.

We can also estimate the indirect effects of grant and contract money brought to Indiana through the IMPLAN methodology. IMPLAN estimates the number of jobs created through activities such as spending within communities of grant-funded staff, like those working for IU PTI.[20] IMPLAN is the

[19] This is an exact figure based on how many people have been employed with grant funds by IU PTI since 1999.

[20] The IMPLAN regional impact multiplier system (http://www.implan.com) estimates the total number of jobs created directly and indirectly as a result of grant income. It estimates, for example, how many jobs in the private sector of a given region are created as a result of having more customers in that region hired directly by out-of-state

standard tool used by economic planners across the U.S. to estimate the impact of grants, contracts, and other government investments. Using the IMPLAN methodology, we estimate that IU PTI's collective efforts have created a total of 2,100 years of employment in central Indiana since 1999.

IU PTI also offers direct support to companies located in Indiana and to national and international companies that have a major presence in Indiana. IU PTI has engaged in 11 partnerships with Indiana businesses of various sizes that were sufficiently involved that a contract, MOU, or nondisclosure agreement about the partnership was executed. Key examples include:

- *Aiding the high-tech manufacturing industries of Indiana.* The Virtual, Verification, Validation, & Visualization Institute (V4I) is a private-public partnership led by the Rolls Royce offices in Indianapolis. It aims to identify private-sector problems in computer-enabled engineering and apply public-sector solutions to those problems. IU PTI, and CIRC in particular, has aided V4I's development while also leveraging its relationship with V4I to obtain federal funding for commercialization of IU PTI-developed science gateway technology.
- *Open-source tools used by private firms in Indiana.* Many open-source software tools created and distributed by IU PTI also support research and development in the private sector. Several Indiana industrial concerns make use of IU PTI-created open-source software, making good on the state's investment in IU and IU PTI. For example, the pharmaceutical companies located in Indiana have for many years made use of bioinformatics software distributed by IU.[21]
- *Research contracts with software companies.* Microsoft awarded IU PTI a contract of just over $1M for a project aiming to understand the roadblocks to adoption of commercial cloud technology in research, and how to overcome those obstacles.
- *Helping Cummins Inc. make its diesel engines more efficient.* IU PTI maintains significant engagement with the international diesel manufacturer Cummins Inc., based in Columbus, IN. RT, in particular, aided Cummins in streamlining its workflows for combustion simulations in diesel engines, helping Cummins make more efficient diesel engines that release fewer pollutants into the air.

5.2.5. IU PTI aids the development of a strong STEM workforce in Indiana.

An excellent and capable STEM workforce is essential to U.S. global competitiveness. IU PTI aids Indiana and the nation in employing and developing such a workforce. One way IU PTI does this is, of course, by employing a world-class STEM workforce itself, and by leading IU in the employment of a diverse workforce.

IU PTI helps develop a strong 21st century workforce in Indiana through educational experiences that begin in Hoosier elementary schools and extend through postdoctoral education. To cultivate a high-tech adult workforce, one must begin by sparking children's interest in technology. One must also spark parents' interest in encouraging their children to pursue careers in STEM. IU PTI has offered thousands of outreach and educational events attended by people of all ages. Annual events like camps are part of that effort; talks, tours, demonstrations at the state fair, displays at state parks, and other avenues round out IU PTI's bid to encourage Hoosiers to pursue careers in STEM.

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funding. One has to make a few assumptions to estimate full-time-equivalent (FTE) jobs created in Indiana from IU PTI's grant successes. First, not all of the grant funds obtained by IU PTI stay inside the State of Indiana; purchases of computing hardware, for example, typically involve sending money to vendors outside the state. Subcontracts on multi-party grant awards may also send grant funds out of state. Thus, we assume that one-third of the grant funds awarded to IU PTI have stayed within Indiana. We also assume that one FTE is equivalent to four of the "jobs" that IMPLAN estimates to have been created per unit of external funding.

[21] Note that one of these companies, Eli Lilly and Company, has no direct relationship with the Lilly Endowment Inc. The Lilly Endowment was created by the first-generation offspring of Dr. Eli Lilly as a trust to advance the quality of life in Indiana and has, since its inception, operated independently of the pharmaceutical company.

Some of IU PTI's activities are focused specifically on young people. A few examples of IU PTI programs designed to interest people in STEM fields and the importance of technology include:

Figure 6. The Ready, Set, Robots! Challenge allows campers the opportunity to show off the programming skills they have learned.

- *Ready, Set, Robots!* In 2005, IU PTI initiated a summer camp called Ready, Set, Robots!,[22] and has held it every year since. As part of this camp, junior high and high school students learn computer programming, problem-solving skills, critical thinking, and teamwork. Students also gain public speaking experience, respect for equipment and facilities, and insight into working "green" in IU Bloomington's LEED-certified Cyberinfrastructure Building.
- *Security Matters Cybercamps.* Since 2016, CACR has run a day camp for kids focusing on all things cybersecurity. Security Matters Cybercamps help teach kids safe computing practices from the start while also introducing them to technology and associated careers.

IU PTI's leadership in education continues on through the college experience at IU. Students in many disciplines who are on their way to professional careers participate in IU PTI's Research Experience for Undergraduates (REU) programs. Direct involvement in authentic research is one of the best ways to interest young people in science generally and in cyberinfrastructure for scientific research in particular. The Jetstream REU program led by Dr. Winona Snapp-Childs, manager of RT's Collaboration, Engagement, and Support Group, has been particularly successful in this regard. Since 2017, the program has engaged 21 undergraduates in projects that capitalize on IU's leadership in fields like bioinformatics, cybersecurity, data visualization, and advanced media. Each year, the program culminates in submission to a national conference, and some students have been recognized with prestigious awards, including Best Paper and Best Poster awards. Several participants in REU programs have reported that the program was integral in prompting them to enroll in graduate study, and some of those in computer science. Jetstream

[22] UITS at Indiana University. (2015). *Ready, Set, Robots! Camp*. Available from https://www.youtube.com/watch?v=zWh9hWf0rBM&feature=youtu.be&list=PLqi-7yMgvZy8xB64_0-O7PId_uzTFy9PO

itself has been an important contributor to STEM education. Jetstream has served more than six times as many students as any of the other similar-sized NSF-funded computing resources.

The faculty and staff affiliated with IU PTI also teach courses at IU and supervise students who receive master's and doctorate degrees, particularly in the Luddy School of Informatics, Computing, and Engineering. As one example, CIRC's Marlon Pierce and Suresh Marru co-instruct the course "Applied Distributed Systems," which is offered through the Luddy School to graduate computer science students as a special topics course. The course has been offered at least once per year since 2016 and has been taken by more than 125 students.

A Ph.D. represents the highest level of mastery within most disciplines, and is the highest degree conferred at most research universities. People who earn a Ph.D. not only master what is known in a particular field, but also make important original contributions to research in that field. Throughout its first 20 years, IU PTI has supported and, in many cases, supervised a total of 73 graduate students who have been awarded a Ph.D. IU PTI also helps recruit people to the U.S. for advanced education and training. Graduate education is one way that IU PTI has attracted international talent to come to and stay in the U.S. Many of the graduate students getting degrees from IU with the support of IU PTI have remained in the U.S., strengthening the U.S. STEM workforce.

IU PTI's outreach efforts reach thousands of people per year, many in Indiana, and it has engaged hundreds of students through education and REU programs. Through these efforts, IU PTI keeps Indiana and the natio, abreast of Indiana University's research efforts, and encourages Indiana youth to consider STEM disciplines as college majors and career choices.

5.2.6. IU PTI stimulates IU's innovation pipeline.

IU PTI began as three centers: the Data to Insight Center, the Digital Science Center, and the Center for Applied Cybersecurity Research. It grew to four in 2009 with the Research Technologies Division of UITS. It has since grown to its current seven centers and two labs by creating new centers, sometimes from scratch, but more often by nurturing the growth of single-leader labs into large, multi-leader centers. The current total reflects the creation of these new centers and the closure of one:

- The HathiTrust Research Center (HTRC) started out as a research project within the Data to Insight Center. The initial question was, "How can we create a secure repository containing the millions of books from the Google book project that allows researchers to do text analysis and extract data about the texts without retrieving contents of books (and violating copyright laws)?" From this began the nascent service to support digital humanities research within the Data to Insight center, and the evolution of HTRC into a significant center in its own right.
- The National Center for Genome Analysis Support (NCGAS) started off as one bioinformatics specialist, an idea, and a grant proposal funded by the NSF. With such a start, NCGAS simply sprang into existence and has expanded to its current nationwide reach.
- The Center for Research in Extreme Scale Computing (CREST) was promoted from its status as a lab within the Digital Science Center with the recruitment of Professor Thomas Sterling. CREST was, for a time, a great success for IU, bringing more than $20M in grant funding to the university and creating many important innovations in computer science. CREST was disbanded (as explained elsewhere in this document) in 2018.
- The Cyberinfrastructure Integration Research Center (CIRC) was created in an unusual way: the promotion of what had been a management group within RT into its own center.

IU PTI continues to foster innovation and incubate new research organizations within IU, such as the recently created Crisis Technologies Innovation Lab (CTIL) and the eLearning Research and Practice

Lab. When it comes time to disband a center or lab, IU PTI facilitates the process while also providing employment continuity for technical staff.

These many IU PTI-affiliated centers offer services directly to the IU community at no cost to users through funding provided within IU from OVPIT, the Luddy School, the Office of the Vice President for Research, the Office of the Vice Provost for Research, and the IU Libraries. That is, through IU PTI, the IU community has access to a group of professionals so good that they are the top experts serving the nation with services deemed critical by federal agencies such as the National Science Foundation, Department of Homeland Security, Department of Defense, and the Department of Energy. Such services aid the IU community generally in developing new areas of expertise and intellectual accomplishment.

IU PTI has contributed to the growth of new areas of excellence for IU in many ways over its two decades, most recently and most specifically in the areas of artificial intelligence (AI) and hypersonic defense technology. While AI is hardly a new area of computer science research, having begun in the 1950s, it has recently increased as a priority for research and investment. IU PTI-affiliated faculty in the Luddy School are deeply involved in the new Indiana University Artificial Intelligence Institute, particularly D2I Director Beth Plale and DSC Director Geoffrey Fox. CACR Director Von Welch is leading efforts to integrate AI techniques into cybersecurity, and RT is providing new advanced computing systems designed to support AI tool development and AI application use.

IU PTI plays a critical role in IU's capacity-building in engineering and defense-related activities. The first two chairpersons of the Department of Intelligent Systems Engineering were DSC Director Geoffrey C. Fox and D2I Associate Director Martin Swany. Hypersonic weapons defense is a new area of focus for IU, IU PTI, and the Luddy School Department of Intelligent Systems Engineering. These weapons, which travel at more than five times the speed of sound, are highly destabilizing. During the Cuban Missile Crisis of 1962, the U.S. and USSR had more than a week to deescalate a life-threatening situation. By contrast, a hypersonic weapon launched from a submarine could wipe out any U.S. city in under 20 minutes. The impact of such capabilities is obvious, and the U.S. must develop its ability to defend against such weapons. With funding support from the Luddy School and IU PTI, IU is working to compete for grants and contracts related to hypersonic defense. This capacity-building has been going on under the leadership of IU Bloomington Vice Provost for Research Jeff Zaleski, and will likely continue for months more before IU receives its first contract or grant in this area. Still, this capacity-building is essential if IU is to be involved in protecting against hypersonic weapons. IU PTI has emerged as IU's top asset in development of technologies relevant to hypersonic weapons defense efforts.

In a more general sense, IU PTI provides a number of central services that enable each center to maximize its productivity. These services include:

- *Pre-award support for grant preparation.* Perhaps IU PTI's most critical service to its centers and labs is its support of grant preparation through editing assistance, budget assistance, and critical reading and evaluation of draft proposals. As a result, IU PTI has an unusually high success rate with its proposal submissions.
- *Education, outreach, and training activity support.* IU PTI, the Office of the VP for Information Technology, and the Luddy School of Informatics, Computing, and Engineering have staff who support education, outreach, and training events. When an individual center, a lab, a group of centers, or IU PTI as a whole wishes to put on an event, there are people available to help plan and put on such an event.
- *Public relations, publicity, state and federal relations, and reporting.* Communicating about what IU PTI does is a critical part of its sustainability. IU PTI staff and IU staff generally provide expertise and assistance in these important communication roles, ensuring that IU PTI messaging is effective, clear, accurate, meets the highest ethical standards, and is well within all relevant legal regulations.

- *Branding.* IU PTI has, after 20 years, earned a national reputation for excellence among the advanced research computing community. The name connotes IU PTI's reputation for being prudent and effective at accomplishing its goals. New centers and labs automatically inherit this reputational advantage, even though those new labs and centers might only be a year old.[23] This has been demonstrated time and again to increase attention given by the national research community and government to the innovations we create, and to aid the competitiveness of individual researchers, labs, and centers affiliated with IU PTI when competing for grant and contract funds.

Beyond supporting centers and labs, IU PTI has also supported accomplishment and promotion of its affiliated faculty. Certainly each of the following promotions would have occurred without IU PTI's existence, but support and facilities from IU PTI have, we believe, accelerated the advancement of many of its affiliated personnel, such as:

- The Luddy School of Informatics, Computing, and Engineering has two faculty members at the "Distinguished" rank. Geoffrey C. Fox was recruited to IU to become one of the initial leaders of IU PTI and rose from full professor to be the Luddy School's first-ever distinguished professor.
- Katy Boerner arrived at IU as an assistant professor, and has since risen to distinguished professor and been named the Victor H. Yngve Distinguished Professor of Engineering and Information Science. Early on, Boerner received financial support as a fellow of the Pervasive Technology Labs.
- Beth Plale arrived at IU as an assistant professor and was promoted to full professor as of the time she took partial leave from IU to serve as a staff member and policy expert at the National Science Foundation.
- Associate Professor Judy Qiu Fox came to IU as a postdoctoral fellow and rose through the ranks to professional staff member, assistant professor, and then associate professor with tenure.

A promise kept

In his letter submitting IU's proposal for second-round funding, IU President Michael A. McRobbie wrote that in 50 years we might look back and see the creation of IU PTI as one of the critical turning points in the development of high-tech research at Indiana University. Twenty years on, IU PTI can claim an important role in the evolution of Indiana University as a high-tech university. IU PTI's impact ranges from its grant success, funding expansion of the local high-tech workforce, value to the Indiana economy, and increasingly direct value to the IU community.

IU PTI and IU can claim that a promise made in 2008 is now a promise kept. In the 2008 proposal to the Lilly Endowment, IU committed that at the end of the second round of financial funding for IU PTI, it would be maintained on the basis of external grants and contracts and a small amount of IU support. IU PTI has more than been sustained; rather, it has thrived and expanded its scale and its effect carefully and prudently. The promise to the Lilly Endowment has, indeed, been kept.

6. Highlights of our 21st year

Thus far we have focused exclusively on activities and accomplishments of our first two decades. However, as we were wrapping up our 20th year, there were projects afoot that were so exciting that we just couldn't keep ourselves from writing about them here. Among other things, the story of Jetstream is

[23] In the movie *The Princess Bride*, one of the main characters, the Dread Pirate Roberts, turns out to be less a person than a brand name. The role is handed down from person to person so each new "Dread Pirate Roberts" inherits the reputational advantage created by their predecessors. IU PTI's brand name functions a bit like that.

simply not complete without talking about Jetstream2. Plus, we're all a little tired of report writing, and no one was enthused about the idea of writing an annual report for Fiscal Year 2020 independent of the present report. So in this section we present highlights of the first few months of our 21st year, followed by updates to those metrics that have changed since the day of our 20th anniversary on September 22, 2019. Highlights of the activities of particular centers and labs are provided in Section 7.

- *COVID-19 response.* IU PTI has proven its capability to react quickly to local, regional, and national needs with its involvement in the fight against the COVID-19 virus. Prominent among IU PTI's engagements in this fight are:
    - IU PTI was a charter member of an organization called the U.S. COVID-19 HPC Consortium[24] – a public-private collaboration bringing together dozens of supercomputers and cloud systems with a total of more than 600 petaFLOPS of processing capability to support research in the fight against COVID-19. Jetstream is among the systems being used in "rapid response" research related to this fight.
    - The DSC created and operated the software used on supercomputers of the Pittsburgh Supercomputing Center to run overnight predictions and simulations of the spread of COVID-19 under different scenarios, helping to inform public health recommendations for fighting COVID-19.
    - DSC Director Geoffrey Fox and Associate Director Judy Qiu Fox are part of a newly funded collaboration called the Global Pervasive Computational Epidemiology project. This project, funded by the NSF, aims to develop new strategies for controlling epidemic outbreaks, supporting real-time decisions and analysis during epidemics.
    - The eLearning Research and Practice Lab received significant grant support to lead a survey of all undergraduates and instructors across several universities. The results of this "Mega-Study of COVID-19 Impact in Higher Education"[25] are already published and guiding the response of IU and many other institutions of higher education nationally in responding to the COVID-19 pandemic.
    - The Crisis Technology Innovation Lab has created and is operating regional and national dashboards to inform the public and civil protection officials in understanding and reacting to the COVID-19 pandemic.
    - NCGAS offers consultations to medical scientists, biologists, and bioinformaticians who are involved in COVID-19 research.
    - RT offered critical support to IU in the early weeks of pandemic response, as all IU students were sent home to take their classes remotely in March of 2020:
        - RT's Windows-oriented virtualization service IUanyWare was expanded to enable students and researchers working remotely to use software otherwise available to them only on campus. Secure exams were also offered via IUanyWare.
        - RT made all statistical and mathematical software licensed by IU available to students free of charge from April to June 2020 to help with learning from home.
- *Jetstream2.* IU PTI has been awarded a grant from the National Science Foundation to deploy Jetstream2, an 8 petaFLOPS distributed cloud computing system to support on-demand research, artificial intelligence, and enhanced large-scale data analyses for the nation. This is an award with an initial budget of $10M. The structure of this award is designed to fund Jetstream2 as a national service for a decade with a 10-year budget that should easily exceed $30M. In the press release about this exciting project, Principal Investigator David Y. Hancock stated, "We intend Jetstream2 to be a democratizing force within the NSF ecosystem, allowing researchers and educators access to cutting-edge resources regardless of project scale." Jetstream2 will continue

[24] https://covid19-hpc-consortium.org
[25] https://osf.io/n7k69/wiki/home/

to focus on the life sciences research, education, and earth sciences research that characterized the original Jetstream system. In addition, this system is designed to support interactive use of AI software and the development of new AI tools. "AI for everyone" is one of the themes of Jetstream2. Jetstream's focus on AI is in part informed by the development of IU's new Artificial Intelligence Institute, and will in turn offer IU researchers and the AI Institute computing resources to support and further their research. Jetstream2 will keep IU on the map of national services for the next decade with clarity and certainty for potential users, and with security of roles and funding for the dedicated staff who make the Jetstream program so effective. Jetstream2 is a first for IU: the first time that IU PTI has received major national funding for a larger cyberinfrastructure system based on the success of a first award for a smaller system. This is *exactly* what the largest supercomputer centers in the US have done decade after decade to stay at the cutting edge of the nation's research community. Jetstream2 is led by PI Hancock and Research Technologies, and includes involvement from CIRC, CACR, and the Office of the Executive Director of IU PTI.

- *A major jump in the readership of Science Node. Science Node* experienced a major jump in its subscriptions during the spring of 2020—adding more than 143,866 new readers. One reason for this was tremendous early coverage of how advanced computing was enabling the U.S and the worldwide community to react to and fight the COVID-19 pandemic. Another is the publication's long-running series on female leaders in advanced computing, and how they arrived in careers in computing and places of prominence in the field.
- *Formal participation in hypersonics research and development.* Thanks to IU PTI leadership, IU became one of the founding members of the Military-Academic Center for Hypersonics (MACH). MACH is a consortium of universities in Indiana and in several other states that pursues research and development to help protect U.S. citizens form the danger of hypersonic weapons. IU PTI has within the MACH collaboration a particularly close relationship with the University of Notre Dame, which has some of the fastest nonclassified wind tunnel facilities in the country. IU PTI is aiding researchers at Notre Dame in analyzing data from their wind tunnels.
- *Support for cancer research.* IU PTI has formalized an agreement to host a computer cluster for the not-for-profit organization Cancer Computer.[26] IU PTI will provide facilities and support for this international effort to find cures for many types of cancer.
- *Incubation efforts continue.* Luddy School professor Dr. Martin Swany and CACR Director Von Welch have proposed the creation of a Systems Assurance and Integrity Lab (SAIL). This relationship is modeled on the IU PTI lab concept and allows the two organizations to benefit from their complementary cybersecurity skills in outreach and grant competitiveness. Once approved, this will mark the addition of the third new lab affiliated with IU PTI in two years.
- *IU's first engineering baccalaureates.* IU PTI has played an essential role in the creation of IU's engineering program. At spring graduation in 2020, the first recipients of an undergraduate degree in engineering received their diplomas from the Luddy School.
- *Rectifying the effects of systemic discrimination.* In response to national, statewide, and local events, IU PTI has engaged in an open discussion of what we can do to help bring an end to the effects of systemic racism and discrimination of all kinds in the U.S. A particular focus is what has been successful in the past in increasing the diversity of the IU PTI workforce and what we can do to expand that success in the future.
- *IU recognition of IU PTI and its affiliated centers.* Indiana University has a policy on approval of the words "Institute" and "Center" in the titles of organizations, and a classification system for such entities. "University level" is the highest such level, indicating impact and importance to IU as a whole. IU PTI is now recognized as a university-level institute. CACR is recognized as a

[26] https://www.cancercomputer.com

university-level center. NCGAS is now recognized as a Bloomington campus center – "campus level" being the second highest level of importance within IU's classification system.

Another highlight relevant to IU PTI is the appointment in the spring of 2020 of Dennis Groth as Dean of the Luddy School of Informatics, Computing, and Engineering. Together with newly appointed Finance Director Jill Piedmont, and longstanding Luddy leaders Associate Dean for Research Kay Connelly and Erik Stolterman, the 2020 Luddy School leadership team is instigating a new era in deepened collaborations with IU PTI. This has included commitment to create new IU PTI-affiliated centers and the codification of a memorandum of understanding that establishes consistent approaches to distribution of funds, which has the impact of facilitating collaborative research activities.

Metrics in some areas have not changed since the 20th anniversary of PTI in September of 2019. A few have. The few metrics updated to the end of FY2020 (June 30, 2020) follow in Table 3.

Table 3. Key metrics of accomplishment for the Indiana University Pervasive Technology Institute up to the end of fiscal year 2020—most of our 21st year of existence.

Metric	Total from inception to end of June 2020
Creation of products	
PTI technical publications	1506 total; 1301 peer-reviewed
Datasets published [27,28]	179
Major services (added Big Red 3[29])	72
Community leadership and service	
Grant successes	
PTI grant and contract total from federal sources to date	$131,449,586
PTI grant and contract total from non-federal sources to date	$11,064,747
Total grants and contracts for IU PTI	$142,514,333
Impact on employment in Indiana	
Person years of employment created directly within IU PTI / Indiana University (actual grant headcount)	917 FTE person years
Job years of employment in the State of Indiana created as a side effect of IU PTI grant awards as estimated by the IMPLAN methodology	2,195 job years
Science Node readers	143,866

As of the end of FY2020 (30 June 2019), there were a total of 121 FTEs working in IU PTI-affiliated centers, 67 of which were funded with university monies (most of these in RT). Within IU PTI, a total of 54 FTEs were supported by external contracts and grants as of the end of FY2019. In Figure 7, RT is shown separately from the other IU PTI centers because it has such a significant set of responsibilities to IU funded by institutional monies. Of the grant- and contract-supported staff in RT, most are engaged in

[27]Costa, C.M., J.A. Wernert, D.F. McMullen, C.A. Stewart, P.D. Blood, R. Sinkovits, S. Mehringer, R. Knepper, G. Rogers. 2020. Dataset: XSEDE Return on Investment Data and Analysis (July 2014 to August 2019). http://hdl.handle.net/2022/25407

[28] Ping, R. and T. Miller. 2020. Dataset: Indiana University Pervasive Technology Institute Education, Outreach, and Training Events through 20th Anniversary (22 September 2019). http://hdl.handle.net/2022/25793

[29] https://kb.iu.edu/d/aoku

collaborative projects that involve one of the IU PTI centers or which were obtained with the aid of IU PTI in some fashion.

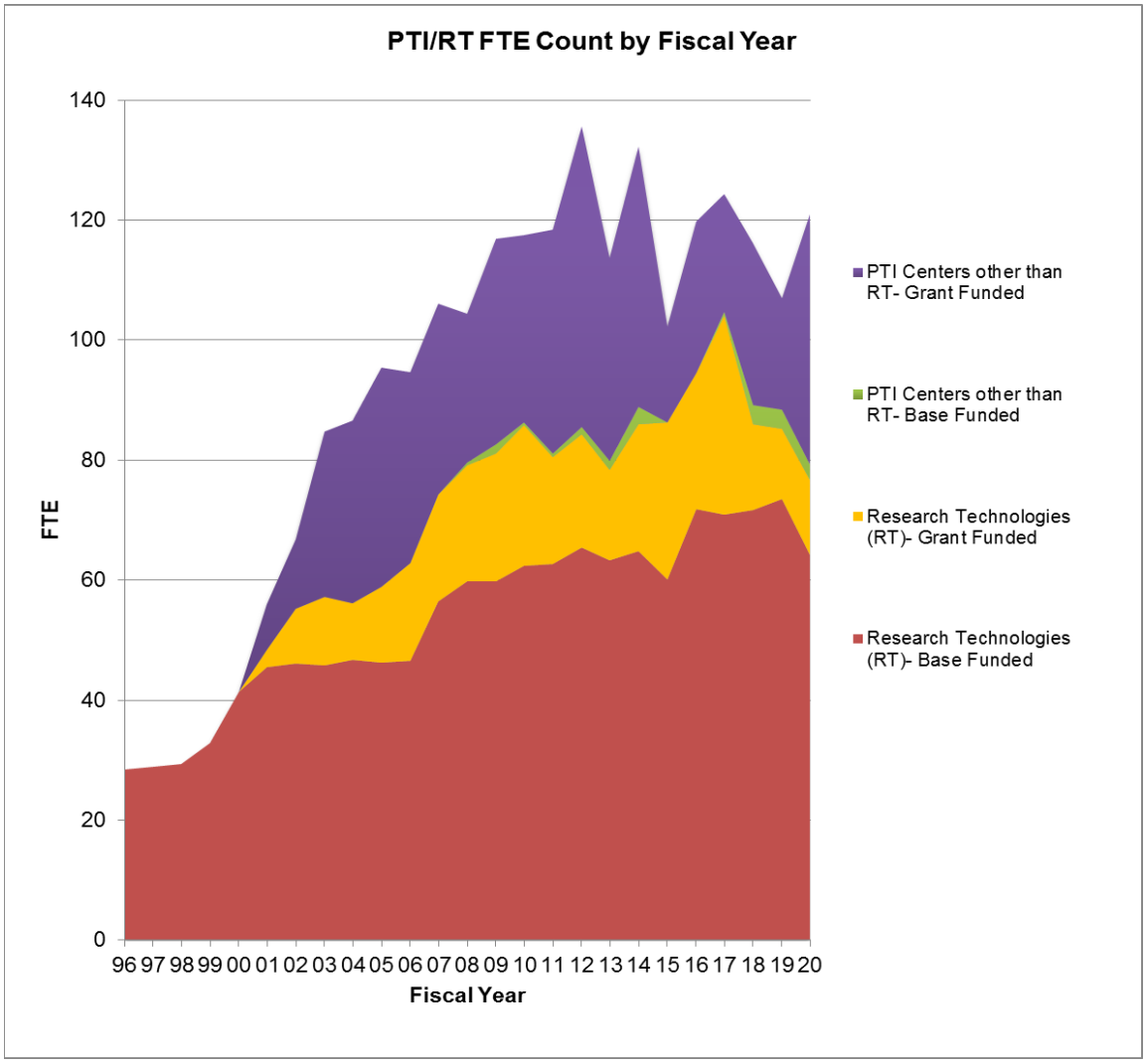

Figure 7. Personnel and funding for the Pervasive Technology Institute showing base-funded and grant-funded staff as of June 30, 2020

7. Centers and their accomplishments

This report has been focused on the aggregate accomplishments of IU PTI as a whole, but at the end of the day, its accomplishments happen at the level of centers or of multiple centers working together. It is not possible to summarize IU PTI's work without giving due credit to the various centers. Rather than focus on quantitative tallies of papers or grant proposals, the narratives below focus on the qualitative character of the research programs of each center or lab. These narratives begin with those centers active as of IU PTI's 20th anniversary, followed by a summary of the activities of labs and centers that have come and gone.

Currently active centers

The Center for Applied Cyberinfrastructure Research (CACR). Under Welch's leadership, CACR has developed an international reputation for leadership in cybersecurity theory and practice, with a focus on first principles of cybersecurity, security of scientific applications and data, and collaborations with federal defense agencies. Designated as a Center of Excellence by the Departments of Homeland Security and Defense, CACR has achieved an important IU objective of ongoing cooperative agreements with the Crane Naval Surface Warfare Center, located south of Bloomington, IN. CACR is currently advising the State of Indiana regarding cybersecurity for the 2020 elections. Most recently, CACR has been named a university-level center and now reports jointly to the Vice President for Research. As part of this change, CACR Director Von Welch was promoted and now reports jointly to the Vice President for Information Technology and the Vice President for Research. A clear success story, CACR has achieved a position of singular national leadership, prestige, and accomplishment under the leadership of Von Welch and aided by its affiliation with IU PTI.

The Digital Science Center (DSC). DSC is the oldest of the current centers, starting as the "Community Grids Lab" when Dr. Geoffrey Fox first arrived at IU as PTL's new lab director. The Community Grids Lab evolved into the Digital Science Center in 2008 with the integration of Andrew Lumsdaine's Open Science Lab, the creation of Judy Qiu Fox's SALSA Lab (Service Aggregated Linked Sequential Activities), and the affiliation of the CNets Lab of Professor Fil Menczer. Today, affiliated faculty include Director Geoffrey Fox, Assistant Director and Associate Professor Judy Qiu Fox, leading AI expert David Crandall, and Adjunct Associate Professor Gregor von Laszewski. DSC has been the most prolific of all IU PTI-affiliated centers regarding production of scientific papers, graduation of PhD students, and creation of new concepts. DSC has been particularly prolific in generating and demonstrating new concepts in grid and distributed computing. From message-based web interaction systems to integration of big data and high performance computing, DSC has been at the forefront of inventions that are subsequently widely adopted in computer science and in practical, everyday computing applications. Today, DSC is at the forefront of efforts to bring together high performance computing and big data/cloud computing to aid advances in AI.

DSC holds distinctions within IU PTI, the university, and the world. DSC Director Geoffrey C. Fox was PI of the NSF FutureGrid grant award to IU PTI—the first grant award in excess of $10M and an innovative distributed system for developing grid and cloud software. Fox was the first faculty member in the Luddy School of Informatics, Computing, and Engineering to be promoted to the rank of distinguished professor. He was also the inaugural chair of the Department of Intelligent Systems Engineering. Lastly, he has been awarded one of the two most prestigious awards given to anyone affiliated with IU PTI: the 2019 IEEE-ACM Ken Kennedy Award recognizing his contributions to computer science and HPC.

The Data to Insight Center (D2I). The Data to Insight Center is run by Professor Beth Plale, who came to IU as an Assistant Professor in 2001. D2I was established as an IU PTI-affiliated center, with Dr. Plale as IU PTI's science director, as part of IU PTI's formation. D2I is directly responsible for three widely used concepts in computer science and its applications:

- *Science gateways.* Science gateways are web front-ends linked to complex middleware that allow the orchestration of complicated analysis and simulation tasks across high-speed networks using many supercomputers simultaneously. The most powerful initial demonstration of this important concept was a system called LEAD—Linked Environments for Atmospheric Discovery—a system for analysis and prediction of tornado paths. This project, led by University of Oklahoma Professor Kelvin Drogemaier (now director of the White House Office of Science and Technology Policy) and involving PTL Science Director Dennis Gannon, was a critical "proof of concept" leading to the widespread use of science gateways today.

- *Tools for FAIR data.* One of the critical concepts in data science today is "FAIR," which holds that data should be "findable, accessible, interoperable, and reusable." D2I was creating tools for FAIR data before FAIR was cool, and remains one of the most important sources of software and concepts about FAIR data in the U.S.
- *Data capsules and non-consumptive research.* Professor Plale invented the concept of "non-consumptive research," which is the research and analysis of texts retrieved as research results that do not include enough copyrighted material that a researcher could reassemble and "consume" it as a written work. This and the creation of secure data capsules led to the foundational concepts and services of the HathiTrust Research Center. HTRC was created initially as a project within, and then a subunit of, D2I, and since 2019 has been an independent center.

D2I is a leader in developing new concepts in computer science, data science, and integration that have led directly to tools now used widely in the sciences and humanities. D2I is so far also the only IU PTI-affiliated center to develop and spin off a new center. As of the writing of this report, Professor Plale spends much of her time working at the NSF doing policy analysis and creation related to data policy and public access. Dr. Martin Swany has aligned his activities with D2I and focuses on advanced computing and communications related to scientific and practical applications, including the detection of and defense against hypersonic weapons.

National Center for Genome Analysis Support (NCGAS). Led by Dr. Sheri Sanders, NCGAS was created at the suggestion of a federal funding agency program officer, who pointed out to Craig Stewart the tremendous national need for expert bioinformatics software support and consulting. NCGAS's mission is to "...enable the biological research community of the U.S. to analyze, understand, and make use of the vast amount of genomic information now available. NCGAS focuses particularly on transcriptome- and genome-level assembly, phylogenetics, metagenomics, transcriptomics, and community genomics." Started in 2011 with funding from the BIO directorate of the National Science Foundation, NCGAS has offered consulting services to researchers in 44 U.S. states and Puerto Rico. NCGAS distributes hundreds of different software titles in the area of bioinformatics and genome analysis. As of 2020, NCGAS supports 315 versions of 215 software packages across IU clusters, XSEDE Jetstream, and XSEDE Bridges. In the last nine years, NCGAS has held 165 training and outreach events, serving more than 6,500 researchers through free training.

One of NCGAS's important services involves interacting with clients throughout the U.S. NCGAS serves a large number of researchers and students from EPSCoR states, which receive little funding from the NSF relative to other states. Through its funding from the NSF, NCGAS has been instrumental in enhancing research and expanding possibilities for discovery throughout the U.S. NCGAS is also unique among IU PTI-affiliated centers in that the majority of its funding comes from the NSF BIO directorate. NCGAS has also been involved in a variety of research activities funded by the National Institutes of Health, and at this point has received funding to participate in more projects funded by the NIH than any other IU PTI-affiliated center.

Cyberinfrastructure Integration Research Center (CIRC). CIRC's mission is to "accelerate research, discovery and collaboration through the creation, integration, and operation of user-centric cyberinfrastructure that benefits scientific communities." CIRC traces its roots back to the hiring of its current director, Dr. Marlon Pierce, by Professor Geoffrey Fox at DSC, where Pierce was instrumental in developing middleware to realize the potential of the concept of science gateways. At DSC, Pierce developed his own subgroup, which eventually moved as a management unit into RT. Pierce's group, originally called the Science Gateways Research Center, became an IU PTI-affiliated center reporting to the IU PTI executive director. The group's initial focus was on expanding tools for and use of science gateways, which are designed to help communities of researchers use high performance computing resources and advanced cyberinfrastructures to pursue common scientific goals. Its portfolio expanded to

include responsibility for IU PTI's work in campus bridging, which includes the bridging of campuses to larger-scale research ecosystems, and bridging within campuses, between centrally managed research computing facilities and those who use them. CIRC, in collaboration with D2I, is also working with the Research Data Alliance to develop digital object architecture implementations that make scientific data easier to find and more accessible, interoperable, and reusable (FAIR). CIRC leads within XSEDE in its implementation of and support for science gateways and campus bridging, and also is a co-lead in a national effort called the Science Gateways Platform as a service (SciGaP) project. Today, CIRC supports the operation of more than 40 science gateways, and is also a leader in the open-source software community. Apache Airavata—the open-source software behind CIRC's science gateways—is an official Apache Foundation project, and Marlon Pierce and Suresh Marru were the first two people at IU named Apache Fellows.

HathiTrust Research Center (HTRC). HTRC is IU PTI's most critical and valuable service to the U.S. humanities community. HTRC is also unique within PTI in that it is a fully fledged center that spun off from another IU PTI-affiliated center (D2I). The mission of the HTRC is to provide infrastructure, tools, and services to support text data mining of the HathiTrust corpus, a collection of more than 17 million volumes, of which more than 11 million are still protected by copyright. The primary operational foundation for HTRC's activities has been funding from HathiTrust, a membership organization operated by the University of Michigan and comprising 160 dues-paying colleges, universities, and libraries throughout the U.S. HTRC was initiated in 2011 with a grant award from HathiTrust to the University of Illinois Urbana-Champaign and Indiana University. In 2019, the partnership was restructured slightly, with IU taking on the role of lead institution in the partnership.

HTRC has enabled unprecedented and interesting research in the humanities, ranging from analyses of Hoosier native son Kurt Vonnegut's works to the analysis of the experience of Black women in 19th century America. The latter example illustrates the power of the HTRC and the data capsule approach for exploring the experience of a group of people who were not allowed to read or write, as was done by Nicole M. Brown in a pathbreaking analysis and explication of voices otherwise hidden.

Research Technologies (RT). "One of these things is not like the others," and RT is the odd center out, with more operational responsibility and funding related to service to IU than the rest of IU PTI.

RT services include designing and implementing supercomputers used by IU and the national research community, including:

- the first university-owned 1 teraFLOPS supercomputer in the U.S. (2001)
- the first distributed Linux cluster to achieve more than 1 teraFLOPS on the LINPAC benchmark program (2003), made possible by the NSF-funded AVIDD award
- the first university-owned 1 petaFLOPS supercomputer in the U.S. (2013)
- the first NSF-funded cloud system for general research use for the national research community: Jetstream, funded in 2015 and put into operation in 2016.

RT has also collaborated with faculty of the Luddy School and its predecessors, and has won a total of four different "Challenge" awards at the IEEE/ACM SCxy conference.

RT has been a leader in advanced storage systems, operating one or more local storage systems based on the high performance Lustre system since 2005, while also staying involved in national and international leadership of the Lustre file system project. RT's leadership in storage extends back even farther than that, as IU was one of the first universities to install a major tape storage system operated with the very secure High Performance Storage System (HPSS). IU, in fact, wrote code that enabled two different tape storage systems to mirror each other, and was the first university in the world to use this method, with a

system in Indianapolis mirroring the one in Bloomington to provide the best possible data security. IU's official digital archive, IU ScholarWorks, depends on RT's tape storage system for its data storage.

In 2005, RT also led the way for IU to be the first U.S. university to have alignment with HIPAA (the Health Insurance Portability and Accountability Act) as the "default" for all IU storage and computation systems. This means that IU's advanced cyberinfrastructure can be used to analyze and understand identifiable patient data. Very few universities provide this as a general capability even today, and IU biomedical research has been greatly enhanced and accelerated as a result.

Additionally, RT has been a leader and innovator in terms of developing and delivering visualization services. The RT Advanced Visualization Lab (AVL) promotes and supports the innovative application of visual technologies to enhance IU's research, education, creative activity, and community outreach missions. The majority of AVL technologies are installed in accessible campus spaces, such as lobbies, workspaces, and Student Technology Centers (STCs); additional and more experimental technologies are accessible in centrally located AVL spaces, including labs at IU Bloomington and IUPUI. The AVL also provides expert consulting services, training opportunities, and learning resources related to visualization.

AVL distributed systems include:

- Large-format, ultra-resolution displays for visualization and collaboration (IQ-Walls). These systems, developed and designed by staff of the AVL, offer modestly priced and extremely high-resolution display facilities.
- Virtual reality classrooms and laboratories for teaching and individual exploration
- A suite of cutting-edge VR and AR technologies, including the PIPES (Programmable Immersive Peripheral Environmental System) mixed-reality interface system
- A spherical display developed by NOAA (Science on a Sphere) for presenting scientific and informational visualizations, and creating dynamic visual experiences
- 65-inch multi-touch monitors (IQ Tables) that can be reconfigured into table, drafting table, or landscape mode for exhibitions and multi-user engagement

RT has been a leader in software, as well. RT offers programming assistance and very often dedicates staff to support particular major research projects, including two of IU's three "Grand Challenge" projects. RT also contributes storage and computational resources to these challenges.

While the other IU PTI centers largely function as traditional research and development labs, RT's difference lies in its size, its base of university funding, and its commitment to providing services to the IU community. RT has always had a headcount far greater than that of the other IU PTI centers and labs combined, and for that reason, care has been taken to ensure that RT does not exert too much influence over IU PTI's direction. At the same time, there have been moments when IU PTI's (or PTL's) future hung by a thread, and RT budgets and personnel were critical to its survival. Similarly, the most productive phase of IU PTI's history (when the number of grants, funding totals, and national influence were at their highest) have been during peaks in collaboration between RT and Luddy School faculty. IU PTI's emergence as a national power in cyberinfrastructure and RT's national prominence depend upon the intellectual contributions of Luddy faculty and other staff affiliated with PTI. For example, RT now has an entire management group that develops and supports software for management of data from high-output instruments. These software environments were modeled after and based on concepts originally developed by CIRC under Director Marlon Pierce.

Office of the Executive Director and its predecessors. The IU PTI executive directors, and prior science irectors, have always engaged in a research program of their own specification and usually with extramural funding obtained by these leaders. Founding Science Director Dennis Gannon was

foundational in establishing PTL and IU as leaders in high performance computing and grid computing, and was personally a lynchpin in PTL and RT's early success in becoming part of the NSF-funded TeraGrid. As science director, Beth Plale put a great deal of focus on data-centric computing and led the creation of one of the most crucial reports ever produced by IU PTI—the final report about PTL and PTI activities submitted to the Lilly Endowment at the end of the Lilly grant that created PTI in 2014. Professor Plale was also instrumental in shaping the governance structure. The Office of the Executive Director was created as a distinct group in 2017 after a cancer diagnosis resulted in splitting Stewart's responsibilities three ways: Matthew R. Link became acting AVP of Research Technologies, David Y. Hancock became acting principal investigator for Jetstream, and Von Welch took over temporarily as acting executive director of PTI. The new roles for Link and Hancock soon became permanent, and, as his health improved, Stewart relieved Welch and resumed responsibility as executive director.

The Office of the Executive Director now leads the following activities in three major projects and one operational group:

- *XSEDE*. The Office of the Executive Director is responsible for overall management of IU's subcontract for XSEDE—the eXtreme Science and Engineering Discovery Environment.
- *Return on investment in cyberinfrastructure.* Stewart has carved a niche in U.S. cyberinfrastructure research related to analysis of return on investment in cyberinfrastructure and in facilitating the adoption of cloud technologies. He and his colleagues lead several related projects all designed to quantitatively and qualitatively assess the return to academic institutions on their investment in cyberinfrastructure. IU PTI is now the leading producer of peer-reviewed reports on ROI analyses of cyberinfrastructure investments in the U.S.
- *Humans Advancing Research in the Cloud.* This project looks at obstacles to adoption of cloud computing in research and seeks to find ways to overcome them.
- *Cyberinfrastructure Assessment and Evaluation (CAE).* The CAE group, led by Julie Wernert, assesses cyberinfrastructure locally at IU and nationally through XSEDE, as well as several other grant-funded cyberinfrastructure projects at IU and other institutions. CAE also manages assessment of multiple national and international conferences. Assessment is becoming a critical aspect of all grant-funded projects, and CAE supports itself almost entirely on grant subcontracts.

Labs currently being incubated. Right now, there are two labs being "incubated" with the intention to graduate to center status. They were both created in 2019, PTI's 20th year, and are being incubated under the wings of existing centers:

- **eLearning Research and Practice Lab.** Now housed within the D2I center, the eLearning Research and Practice Lab is a link between IU faculty researchers and the systems that store eLearning records, helping to enable systematic and sustained research. The lab leads advances in understanding of students' eLearning behaviors, performance, and outcomes, and their associated social contexts, through cutting-edge research that addresses practical and theoretical questions at the intersection of learning, education, and technology. Its research is collaborative, empowering faculty affiliates to examine student eLearning rigorously and responsibly, and to contribute their insights and expertise to an interdisciplinary research community. Through this work, the lab develops evidence-based practices, interventions, and tools to advance student learning at IU and beyond.
- **Crisis Technology Innovation Lab (CTIL)**. The Crisis Technologies Innovation Lab (CTIL) is a collaboration between the Luddy School of Informatics, Computing, and Engineering and University Information Technology Services (UITS) to accelerate research and practice on the use of next-generation technologies in the front lines of emergency and crisis response. CTIL is affiliated with CIRC. The last decade has seen dramatic growth of technologies that affect society, from data science and machine learning to pervasive devices, social media, and drones. This same decade has also brought major challenges and threats to human well-being and the

economy, including increased severity and frequency of natural disasters, dependency on a fragile technology infrastructure, and demand on first responders. CTIL explores the urgent need for new approaches to using technology to manage crises that are reliable, scalable, and affordable; that can interoperate between emergency professionals and the public; and that can help save lives in a complex, challenging environment.

[redacted]*Labs and centers that were merged or decommissioned*

Advanced Network Management Lab (ANML). ANML was PTL's first lab, and its genesis was IU's leadership deploying and operating[30] the world's most advanced research and education network backbones, including the Internet2 network. ANML combined advances of the IU GlobalNOC with translational research in network management, cyber-threat detection, advanced application-based routing, network traffic characterization, and advanced network protocols, to improve our ability to understand and securely use advanced networks. Some of ANML's more exciting and notable accomplishments include:

- ANML cyber-threat detection activities led to an agreement with the U.S. Air Force to assist the federal government in understanding emerging internationally scoped DDoS activity. ANML assisted in the deployment of DDoS threat detection instrumentation across networks that provide inter-country network traffic.
- Tsunami, a high-speed bulk data transfer protocol that's resilient to network impairments. Tsunami was further developed by Metsähovi Radio Observatory, Finland's only astronomical radio observatory, and used to transfer vLBI radio astronomy data.
- ANML's most widely used contribution is the secure file transfer system Slashtmp. Slashtmp allows users to transfer large files quickly and securely. IU has licensed Slashtmp to several other universities, and itself continues to use Slashtmp to transfer sensitive information safely. Slashtmp has been in service for more than 18 years and is used for data transfer, including critical and protected health information.

Scientific Data Analysis Lab (SDAL). Led by Randy Heiland, SDAL had a straightforward mission: enhance the effectiveness of researchers at IU by offering scientific data analysis and depiction services. It was an important mission, and SDAL produced excellent work. SDAL also did significant work on behalf of nonprofit organizations in the greater Indianapolis area. SDAL's business model plan was to fund itself through obtaining subcontracts on grants to other IU PIs. While this model might have been successful at IU today, it did not work during SDAL's activity, from 2003–2007.

Knowledge Analysis and Projection Lab (KAPLab). Some of the Pervasive Technology Labs focused on developing core technologies; others concentrated on targeted, in-depth application and integration of core technologies to address important real-world needs. The KAPLab, the first externally funded lab affiliated with PTL, was initially charged with developing more efficient electronic warfare maintenance systems for the United States Navy. The objectives were to reduce costs, increase system up-time, and improve military readiness. Working with a research consortium that included IU; the Naval Surface Warfare Center, Crane Division; and Purdue University, the lab developed a knowledge management system to provide dynamic user and situation-aware support for diagnosis and repair processes. The system adapted to ship particulars and to users with varied levels of training and expertise. As a part of an international research collaboration spanning the U.S., Australia, New Zealand, and the United Kingdom, the lab was also active in developing wide area data acquisition and instrument control protocols (the CIMA project) based on semantic web technologies. The result was a system that could describe an instrument completely with respect to measurements so that a remote user or computer could, with proper authorization, access and control an instrument without additional information. These technologies were

[30] Haskett, J. A. 1986. "A History of Academic Computing at Indiana University Bloomington 1940-2000," Bloomington Academic Computing Services, Indiana University. http://hdl.handle.net/2022/14618

used in ecological sensing networks, beamline experiments at the Advanced Photon Source at Argonne National Laboratory, remote astronomy applications, and in laboratory instrument management and control. The KAPLab was active from 2001 to 2008 as part of both PTL and IU PTI, and was decommissioned when Director Rick McMullen, left Indiana University.

Visualization and Interactive Spaces Lab (VIS). VIS leader Pauline Baker was already an international celebrity when she arrived at IU from the University of Illinois Urbana-Champaign, with a textbook on computer graphics that had been translated into more than 20 languages. While at IU, the VIS Lab and Professor Baker worked to advance the field of augmented reality, which combines intuitive physical interaction with advanced (and often stereoscopic) visualization in scientific and educational contexts. The VIS Lab was active from 2002 to 2011 and closed as Dr. Baker prepared for retirement.

Center for Research in Extreme Scale Technologies (CREST). CREST was, in some ways, one of IU PTI's most successful centers, holding the record within IU PTI for the largest amount of grant dollars brought in for software research and development in a single year. CREST grew out of the combination of the Open Systems Lab, led at IU by Professor Andrew Lumsdaine starting in 2001, combined with the research of Thomas Sterling, who moved to IU in 2011. The idea behind CREST was to combine Lumsdaine's work "from the top down" in building high performance parallel computing libraries with Sterling's work "from the bottom up" in building advanced runtime systems. CREST had a real shot at revolutionizing exascale computing in the U.S. CREST and its predecessor, OSL, created the majority of patents granted to investigators affiliated with IU PTI. CREST's end came about in 2018 through the failure of the U.S. exascale initiative to experiment in the area of exascale runtime systems, but the center's impact lives on in the research programs of its affiliated faculty: Thomas Sterling, still at IU and at work developing new processors for exascale computer systems; Andrew Lumsdaine, now at the University of Washington; Ryan Newton, now a group leader at Facebook; Jeremy Siek, one of the intellectual leaders in formal methods in computer science at IU; and Martin Swany, formerly affiliated with CREST and now affiliated with D2I.

Center activities in IU PTI's 21st year

Below are highlights of new activities and accomplishments for individual IU PTI centers between IU PTI's 20th anniversary on September 22, 2019 and the end of fiscal year 2020 (June 2020).

The Center for Applied Cyberinfrastructure Research (CACR).

- CACR launched a service called SecureMyResearch, which provides researchers with consulting and resources to help them protect research data and comply with cybersecurity requirements in grants, contracts, and data use agreements. The service aims to reduce the cybersecurity and compliance burden, helping IU researchers do the world-class research they do best.
- CACR and the IU-led OmniSOC are working together to implement and test new AI software designed to aid in the detection of cybersecurity threats within network traffic.
- CACR's ongoing leadership in protecting the cybersecurity of more than $7B in NSF-funded research was confirmed with a $12.5M grant extension for the NSF Cybersecurity Center of Excellence (Trusted CI) for expansion of its activities.
- CACR's team of experts helped prepare election officials in all 92 Indiana counties for cybersecurity incidents related to the 2020 general election and beyond.
- CACR onboarded its first client, the National Radio Astronomy Observatory. In a first for IU, network data from an NSF facility is now being monitored by IU's OmniSOC, a ResearchSOC partner.
- Through Trusted CI and ResearchSOC, CACR's leadership showed through at PEARC19, July 28–August 1, where CACR staff and collaborators received the PEARC19 Phil Andrews Award

for Most Transformative Contribution for SWIP's publication, *Integrity Protection for Scientific Workflow Data: Motivation and Initial Experiences,* and Trusted CI presented the paper "Trusted CI Experiences in Cybersecurity and Service to Open Science."
- The CACR Principles-based Assessment for Cybersecurity Toolkit (PACT) team delivered their final assessment report in their engagement with the Scripps Institution of Oceanography (SIO) and UC San Diego.
- CACR staff shared their cybersecurity expertise and experience in developing a center of excellence with the $3M Cyberinfrastructure Center of Excellence Pilot.
- CACR provided cybersecurity leadership and served as the CISO to the Open Science Grid (OSG), Institute for Research and Innovation in Software for High Energy Physics (IRIS-HEP), and SWAMP (Software Assurance Marketplace) projects.

Cyberinfrastructure Integration Research Center (CIRC)
- CIRC has been approved as an official reserach center within OVPIT.
- The CIRC-supported SimCCS project for modeling carbon capture and sequestration scenarios was named an R&D100 award winner in two categories.[31]
- CIRC team members are developing a web-based science gateway for both modelers and decision makers in the energy sector that provides access to modeling and simulation codes on high performance computers.
- CIRC is included in the NIH-funded IUSM Alzheimer's Disease Drug Discovery Center, led by Dr. Alan Palkowitz; Dr. Kun Huang leads the bioinformatics core area that includes CIRC. CIRC team members are working with multiple faculty members in the IU School of Medicine and the IUPUI bioinformatics department to develop science gateways to provide software as a service, and in the larger effort to design a comprehensive data management plan for the project.
- CIRC team members are part of the NASA-funded Quantifying Uncertainty and Kinematics of Earthquake Systems (QUAKES) project, led by long-term collaborator Dr. Andrea Donnellan of NASA JPL.
- CIRC team members led thirteen peer-reviewed efforts at PEARC20: seven presentations, two birds-of-a-feather sessions, three posters, and one tutorial.
- The graduate-level computer science special topics course, "Applied Distributed Systems," co-instructed by CIRC's Marlon Pierce and Suresh Marru, had its highest enrollment (57) since it began in 2016.

Data to Insight Center (D2I)
- This spring, D2I Director Beth Plale was named the inaugural Michael A. McRobbie and Laurie Burns McRobbie Bicentennial Professor in Computer Engineering. This endowed professorship will enable Plale to explore her research interests with funding support from the endowment associated with this professorship.
- D2I leadership published a roadmap for D2I research and development activities for the next three to five years.

HathiTrust Research Center (HTRC)
- Local support expanded. IU PTI has funded an additional staff member to work in HTRC and increase knowledge of and support use of HTRC services within the IU humanities community.
- The HathiTrust Digital Library research corpus has been expanded to more than 17 million volumes.

[31] https://www.lanl.gov/discover/news-release-archive/2019/November/1106-rd-100-awards.php

- HTRC released Extracted Features 2.0, a derived dataset consisting of metadata and data elements extracted from volumes in the HathiTrust Digital Library. The dataset is composed of more than 17 million JSON files representing a snapshot of the HathiTrust corpus from February 2020.[32]
- Glen Worthey joined the HathiTrust Research Center as associate director of research support services (based at University of Illinois). Worthey comes to HTRC from Stanford, where he was the digital humanities librarian and founding head of Stanford's Center for Interdisciplinary Digital Research.

National Center for Genome Analysis Support (NCGAS)

- NCGAS has a new director, Dr. Sheri Sanders, and a new suite of collaborations with the Luddy School of Informatics, Computing, and Engineering and the IU Bloomington biology department.
- This spring, NCGAS launched an all-virtual class, "Introduction to R," for bioinformatics that was attended by more than 300 students.

Research Technologies (RT)

- On the day of Indiana University's 200th anniversary (January 20, 2020), the new Big Red 200 supercomputer was dedicated by IU's 18th President Michael A. McRobbie at IU's Bicentennial event. With a processing capability of nearly 10 petabytes, Big Red 200 is full of GPUs and its configuration is optimized to support use of AI in the research and development of new AI tools.
- Also on IU's 200th anniversary, the Office of the VP for Information Technologies unveiled a high-resolution Crystal Wall in the Cyberinfrastructure Building's Wrubel Commons. Implemented and programmed by RT and other OVPIT colleagues, this device is one of the largest curved, mobile crystal light-emitting diode (CLED) displays in the U.S. With a resolution above 4K, this display highlights scientific data and artistic visualizations with stunning clarity and brightness. Nearly 28 feet wide and 10 feet tall, with 108 panels, it enables HPC interaction, video conferencing, and stereoscopic 3D and spatial tracking for virtual reality applications.
- A new supercomputer called Big Red 3 has been put into service to support large-scale CPU-based calculations.
- Recent imaging of the event horizon of the M87 black hole was enabled by the Event Horizon Telescope (a telescope array consisting of a global network of radio telescopes), a large number of scientists, NASA spacecraft, and a variety of computing resources with an increasing portion being done on cloud resources, particularly Jetstream.
- In October, RT hosted two conferences in the same week: the High Performance Storage System (HPSS) User Forum, or HUF19, and the Campus Alliance for Advanced Visualization, or CAAV. As IU PTI Education, Outreach, and Training Manager Robert Ping stated, "Hosting these conferences fits into IU's strategic plan relating to outreach and education. UITS and the Pervasive Technology Institute at IU have become known for bringing user communities together in order to take advantage of expertise and training, share ideas to accelerate IU's supercomputing prowess, and network with folks in the field to stay abreast of current topics."

Office of the Executive Director

- The Humans Advancing Research in the Cloud (HARC) project completed its first phase with publication of work resulting from the Cloud Research Support Engineers' (CRSE) phase one effort, which culminated in a workshop held at PEARC19 at the end of July. All work, papers, and presentations were uploaded to the HARC GitHub site.[33] Fall 2019 saw the project examining alternative pathways forward. Voss was invited to participate in a two-day workshop sponsored by Microsoft for Latin American research universities, presenting a discussion of research in the U.S., its directions toward use of commercial cloud cyberinfrastructure, and the HARC project

[32] https://wiki.htrc.illinois.edu/pages/viewpage.action?pageId=79069329
[33] https://github.com/HARC-PTI

experiences to date. HARC project members also participated in a workshop at Internet2's TechEx conference in New Orleans in December, updating attendees on our findings as well as the experiences of three of our CRSEs. HARC's second phase took on a traditional sub-grant award model and selected four for funding—Arizona State University, Georgia State University, University of Pittsburgh, and University of Notre Dame.[34] HARC continues, with the support of CRSE2 participants, to advance the content and structure of the GitHub community resource, seeking specifically to increase the number of useful cloud tools (reusable code) for various vendors, as well as sharing experiences and other related useful documentation. For the HARC workshop at PEARC20, a call for participation resulted in five papers submitted, a number of invited presentations, and a full-day workshop.[35] The workshop was a joint effort with partners at the National Institutes of Health Science and Technology Research Infrastructure for Discover, Experimentation, and Sustainability (STRIDES).[36]

- IU PTI has continued publication of groundbreaking research related to analysis of return on investment in cyberinfrastructure. We completed an analysis of ROI for federal investment in XSEDE, the national advanced CI organization formally known as the eXtreme Science and Engineering Discovery Environment. We also completed a pathbreaking new analysis of the opinions of IU principal investigators on the importance of IU's advanced cyberinfrastructure to their success in obtaining extramural funding. The answer, in sum, is that it is very important.

8. Conclusion and a look forward

The Indiana University Pervasive Technology Institute began as an idea by then-VP Michael A. McRobbie, backed by Indiana University's innovative spirit and an initial $30M investment from the Lilly Endowment, Inc. IU PTI has matured over nearly 20 years as part of a university-wide effort to achieve a goal set in 1997 by Myles Brand, the 14th President of Indiana University, to make the institution "a leader [among institutions of higher education], in absolute terms, in the use and application of information technology."[37] This goal seemed all but impossible at the time it was first articulated. At present, Indiana University can justifiably claim leadership in this arena.

In 2008, in his letter submitting IU's proposal for second-round funding, IU President Michael A. McRobbie committed that at the end of the funding requested to create the current structure of IU, IU would maintain IU PTI primarily on the basis of external grants and contracts. President McRobbie also wrote that in 50 years, we might look back and see the creation of IU PTI as one of the critical turning points in the development of high-tech research at Indiana University. Twenty years on, IU PTI can certainly claim an important role in the evolution of Indiana University as a high-tech university.

IU's ambition persists today as part of 18th President Michael McRobbie's goal for Indiana University to be one of the great universities of the 21st century. IU PTI has been a major contributor to achievement of these major goals by two of IU's truly great presidents: Myles Brand and Michael. A. McRobbie. IU PTI is regarded as one of the top advanced computing research and development centers in academia, it has done more than just sustain itself. It has thrived and served Indiana University, the State of Indiana, the United States, and the global community in the process. IU PTI has been extremely successful for two decades and remains well positioned for continued success in the coming decades.

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[34] https://itnews.iu.edu/articles/2020/HARC-project-announces-four-awards-.php

[35] https://harc.iu.edu/workshops/pearc20-conference.html

[36] https://datascience.nih.gov/strides

[37] Dunn, J. Michael, & McRobbie, Michael. (1998). *Information technology strategic plan: architecture for the 21st century*. Indiana University. http://hdl.handle.net/2022/471