ILLINOIS SCIENCE & TECHNOLOGY COALITION

September 2014

The Illinois science and technology roadmap

Full report

In partnership with:
Elsevier
Ocean Tomo

In collaboration with:
Dr. C. Scott Dempwolf,
University of Maryland

The Illinois Science & Technology Coalition (ISTC) is a member-driven, nonprofit organization that harnesses the power of research and innovation to grow the state's economy. Created by the State of Illinois 25 years ago, ISTC drives public-private partnerships among industry, research universities, federal labs, and government to increase research and technology-based investment, talent, awareness, policies, and job growth in Illinois.

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About the partners

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Dr. C. Scott Dempwolf: Scott Dempwolf is Assistant Research Professor in the Urban Studies and Planning Program at the University of Maryland, College Park, and Director of the UMD–Morgan State Center for Economic Development. His research examines relationships between innovation, manufacturing, and economic development in global and regional contexts. Prior to returning to academia, Dr. Dempwolf practiced community and economic development for more than 20 years at the neighborhood, city, county, and regional levels.

Why an Illinois science and technology roadmap?

The Illinois Science & Technology Coalition (ISTC) was created in 1989 by the State of Illinois in recognition of the fact that research, innovation, and entrepreneurship are the lifeblood to driving and enriching the state's economy. Now, 25 years later, ISTC continues to work to fulfill this promise by advancing public-private partnerships that harness Illinois' innovation assets. From galvanizing the community around impact partnerships that strengthen technology commercialization to providing a shared voice to promote policies that support R&D, ISTC is immersed in building a strong ecosystem that links talent and ideas from our world-class research universities, national labs, and industry to improve people's lives and boost our economy.

In particular, ISTC is charged with telling and celebrating the Illinois story, often using data to benchmark our progress as a national innovation leader and uncover opportunities for fruitful collaboration across and within the state's highly diverse sectors. Thus, we embarked on the creation of this first-of-its-kind Illinois science and technology roadmap, developed through a rigorous, data-driven process, to identify targeted, high-potential technology areas to drive new discoveries, product development, and business growth throughout the state.

This effort builds on recent economic development plans from the State of Illinois and City of Chicago and responds specifically to community interest—from research institutions, R&D-based corporations, and policy makers in Springfield and Washington, D.C.—in having a more informed and detailed understanding of Illinois' R&D potential. Utilizing top analysis tools from Elsevier, Ocean Tomo, and Dr. C. Scott Dempwolf at the University of Maryland, the roadmap offers an unprecedented look into technology clusters that represent opportunities, both realized and potential, for innovation to improve business competitiveness and position Illinois as a magnet for top talent in key industries. We expect the roadmap and its underlying analysis to serve as a valuable resource for institutions, industry, and policy makers, making this report a beginning rather than an end to developing strong innovation policy in the state.

As this report demonstrates, Illinois is rich in R&D activity, and we would like to thank all of those in the innovation community who contributed to the development of this effort. We look forward to working with our member and partner organizations to bring together even more researchers, entrepreneurs, and innovators from the community to tap the strengths highlighted in this roadmap.

Mark Harris

President and CEO
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Introduction

Universities and national labs have the power to drive Illinois' 21st-century knowledge economy by infusing talent and technology across a spectrum of industries to create new products, companies, and jobs. According to the state's recently published economic development plan, for every new high-tech position in metro areas, an average of five additional local jobs are created—two in professional fields and three in nonprofessional fields. Given this economic multiplier, fostering research activity within the state is an important priority.

In Illinois, science and technology fields with a high volume of R&D attract nearly $15 billion in federal and private research funding annually, with the majority of this amount—more than $12 billion—made by industry for internal research. Channeling more of this industry investment, which comes mostly from large corporations, to collaborative R&D with universities, research consortia, and collaborations with high-tech small and midsize enterprises (SMEs) is critical to exploiting Illinois' research strengths. These activities in turn increase business competitiveness and boost the creation of scientific and technical jobs. Achieving these goals will require policies and programs that both encourage collaboration and connect and amplify industry, academic, and public investment in early-stage technologies.

This Illinois science and technology roadmap identifies research strengths primed for increased academic-industry collaboration and partnership. This analysis, coupled with the report's concluding recommendations, is aimed at informing policy makers in the Governor's office, Illinois Department of Commerce and Economic Opportunity (DCEO), Illinois General Assembly, and Illinois congressional delegation. With a greater understanding of Illinois' competitive strengths, industry innovation activities, and priorities, the state can be better equipped to facilitate and support effective programs and collaboration, target federal funding opportunities, and position Illinois as a global hub for partnership in the high-impact technology clusters identified in this report.

The opportunity: Illinois' R&D assets

Illinois has a rich history of innovation in science and technology. Over the past two centuries, local researchers have produced groundbreaking innovations that have reshaped industries and improved the quality of life for people around the world. From the invention of the light-emitting diode (LED) in 1962 to the use of laser technology to treat cardiovascular disease in 1986, the state's researchers have been at the vanguard of discovery. More recently, the founding of Mosaic (later Netscape), the first Web browser, and the development of lithium-ion battery technology for the Chevy Volt have made critical contributions to the growth of technology-based industries around the world.

These discoveries were not made in isolation or even by lone inventors. Indeed, as a U.S. leader in science and technology, Illinois also benefits from a well-developed innovation ecosystem. Illinois' world-class universities and research institutions, including unique facilities such as Argonne National Laboratory and Fermi National Accelerator Laboratory, currently pursue large-scale R&D projects in a wide range of fields. In 2012, Illinois academic R&D expenditures exceeded $2.3 billion, with the Chicago metropolitan statistical area (MSA) ranking eighth nationally.[1] According to National Science Foundation data, in 2012 just $97.9 million of these expenditures came from industry partners both in and outside Illinois, indicating significant additional opportunity for the private sector to tap academic research infrastructure and know-how. Research dollars catalyze R&D centers, such as the Illinois Medical District (IMD), that have significant economic impact on their communities. Each year, the IMD provides $2.2 billion in direct wages and $2.3 billion in value-added production of goods and services to the Illinois economy.

Illinois' large and diverse industry base is also a significant driver of research: its investments create new innovations as well as provide the infrastructure and funding necessary to scale and manufacture them. The state's 33 Fortune 500 companies span several sectors, including R&D-intensive aerospace, agriculture, biotechnology, and heavy equipment. In biotechnology, AbbVie, catalyzed by collaborations including with the Argonne Advanced Photon Source, leads Illinois in biopharmaceutical patents. The Baxter-Northwestern alliance has led to many successful outcomes, including the creation of a new anti-depression drug currently being commercialized by Naurex, a university spin-off. In heavy equipment, Deere & Company is helping to lead the creation of the Quad Cities Manufacturing Innovation Hub, which is focused on new metals innovation, process development, and workforce training.

[1] "R&D expenditures by Illinois universities hold steady," *Illinois Innovation Index*, March 31, 2014.

A solid foundation for growth

Several initiatives have helped increase the scale of industry-driven academic research and expanded these engagements. Public-private research consortia and place-based innovation spaces that engage multiple projects and startups have transformed individually sponsored research projects into broader relationships. These approaches enable industry "customers" to solve shared challenges using the expertise and capabilities of both academic institutions and other companies.

Collaboration across institutions and sectors is increasingly vital to unite ideas and disciplines and to drive innovation in new ways. Thanks to such partnerships, Illinois has recently won high-potential federal projects and built consortia to pursue applied-research initiatives, which potentially use public and private funding to launch new Illinois industries. In September 2012, Argonne National Laboratory was selected to lead the Joint Center for Energy Storage Research (JCESR), a five-year, $120 million initiative to develop the next generation of battery technology. Similarly, in February 2014, UI LABS was awarded $70 million to establish the Digital Manufacturing and Design Innovation Institute (DMDII), which will draw on an additional $250 million in private and local funds to reshape how goods are designed and manufactured in the United States. These successes highlight how industry-driven research partnerships can position Illinois to lead the nation in emerging high-tech industries by connecting academic with private sector expertise to take on grand challenges.

Over the past 15 years, Illinois' more than 20 innovation hubs, located at universities and in cities across the state from Rockford to Carbondale, have harnessed approximately $5.3 billion in infrastructure and investment funding, which has supported more than 620 businesses (primarily early-stage startups). Many of these hubs and resulting companies were launched since 2012, meaning that their value has yet to be fully realized. In total, this network has attracted companies from other states and countries and currently supports more than 5,600 direct jobs, representing a significant contribution to the state's economy and a key to our future economic growth and prosperity.

Illinois universities are using such innovation hubs to connect science, engineering, and business strengths and resources across their campuses to launch new technology-based startups. Coupled with innovation funds, centers such as the University of Chicago's Chicago Innovation Exchange, University of Illinois' EnterpriseWorks, and Southern Illinois Research Park serve as engines to create scalable ventures. ISTC reported in its first *University Startup Report* that from 2010 to 2013 Illinois universities spun off 354 startups, of which 283 are still active. Of these companies, 91 were launched based on university research.

Bridging the divide between research and commercialization

Beyond creating public-private partnerships to pursue large-scale federal opportunities that address critical industry challenges, the Illinois science and technology community is directing increased attention toward lowering barriers for engagement between universities and the private sector. The Illinois Corporate–Startup Challenge, for example—an initiative of the Illinois Innovation Council and managed by ISTC—bridges the gap between early-stage startups and Fortune 1000 companies to spur corporate innovation. Notably, of all matches made between these two groups, 40 percent have involved a university spin-off. Other programs focus earlier in the commercialization continuum; for instance, the Illinois Regional Proof of Concept Fund, recently seeded by DCEO and ISTC, supports pre-company stage technologies in testing and validating commercial milestones. These steps de-risk company formation and increase opportunity for investment and corporate partnership. Supported by organizations such as Chicago Innovation Mentors, industry-specific work including iBIO Institute's PROPEL Center and upcoming MATTER, and the state's physical infrastructure, these initiatives create an ecosystem that enables and facilitates commercialization.

Connecting academia with industrial development

An understanding of the innovation pipeline and its participants helps to frame the data and analysis that follows. In short, basic research institutions and industry R&D facilities operate in distinct stages of the innovation pipeline. Academic institutions work to prove concepts at the individual and small scale, while industry requires validation and replication in the thousands or millions for technologies to be viable. Bridging these communities—through technology startups, among other ways—can drive commercialization and tap research talent to feed corporate product development and further advance university research in areas with significant potential. However, Illinois research institutions and industry need greater awareness of collaboration opportunities and additional infrastructure and programs to facilitate interaction.

Thus, this report seeks to highlight areas where existing and emerging research talent and knowledge overlaps with and can support market-driven, scalable industry commercialization efforts. In this way, academic research (technology push) can better connect with relevant industry applications, and industry influence (market pull) can help support the commercialization of promising and relevant STEM research, orienting technology transfer efforts toward the most relevant and commercially viable outcomes.

Fostering the technologies of tomorrow

While Illinois is home to world-class research institutions and a diverse network of innovative companies, a disconnect between these communities—both perceived and real—has prevented the economy from fully harnessing and connecting these assets. Although Illinois' university patent volume is growing rapidly, data highlighted in the *Illinois Innovation Index* revealed that the flow of academic intellectual property (IP) into the private sector lags behind the national average. Indeed, while the state's total number of patents grew at nearly triple the U.S. average from 2008 to 2012 compared with the previous five-year period, patent licenses grew at less than half the U.S. average (Exhibit 1).[2] Bridging this divide in IP attainment and commercialization activity is one way to drive competitiveness for key Illinois industry clusters.

[2] "Illinois technology transfer," *Illinois Innovation Index*, January 12, 2014.

Exhibit 1: **Growth in technology transfer in Illinois[1] and the United States,**
2003–07 vs. 2008–12, percentage change

United States[2]
Illinois

		2003–2007	2008–2012	Total, 2003–2012	Percentage change
Invention disclosures	United States	57,596	68,007	126,603	19.8%
	Illinois	2,775	3,212	5,987	15.7%
Patents issued	United States	11,895	13,859	25,754	16.5%
	Illinois	519	763	1,282	47.0%
Licenses	United States	14,307	15,495	29,802	8.3%
	Illinois	515	536	1,051	4.1%

[1] In this dataset, the University of Illinois, the University of Chicago, and Northwestern University account for almost all academic technology transfer output in the state.
[2] Excluding Illinois.

Source: Association of University Technology Managers (AUTM), ISTC

Accelerating research and commercialization is compounded by the state's diverse economy, which—while resilient—also presents a formidable challenge. Whereas many states can focus their resources on building strong clusters in just a few leading industries, no single industry in Illinois accounts for more than 13 percent of the economy.[3] As a result, universities and industry are rather segmented, making coordination more difficult. To target efforts on collaboration initiatives for high-potential technologies and keep talent and innovation in Illinois, a strategic approach focused on the state's core research strengths is needed.

Our findings constitute a key piece of Illinois' economic development puzzle, to be implemented in tandem with the workforce and business development initiatives outlined in *The Illinois economic development plan* released in July 2014 by DCEO, and World Business Chicago's *Plan for Economic Growth and Jobs*. This report extends the efforts of the ISTC, Illinois Innovation Council, and Illinois Innovation Network—three entities that exist to strengthen the innovation ecosystem and drive partnerships that move technology from the lab to the market.

[3] *Regional perspectives: Illinois economic outlook*, JPMorgan Chase, June 2014.

Additional reading

→ Richard (Chip) Hay, "Academic-corporate collaborations help drive technology commercialization: The Baxter-Northwestern alliance and the success of Naurex," *ISTC Catalyst*, August 2014.

→ *The Illinois economic development plan*, DCEO, July 2014.

→ Adam Pollet, "Innovation hubs drive jobs, entrepreneurship and return of investment across Illinois," *ISTC Catalyst*, April 2014.

→ *Plan for economic growth and jobs*, World Business Chicago, March 2012.

→ "R&D spending: Illinois' industry expenditures and collaboration with higher-education institutions," *Illinois Innovation Index*, October 31, 2013.

Roadmap data and analysis: A first for Illinois

Traditionally, reports on innovation performance have focused on macroeconomic indicators and employment statistics in specific industries. This roadmap is the first in Illinois to focus on technology and research clusters that underscore and cut across industries. It also provides insights into the comparative volume, quality, and connectivity of research in Illinois from early-stage science to more applied innovations downstream. This data-driven analysis informs a set of policy and program recommendations on how Illinois can more effectively take advantage of its identified research strengths.

The roadmap is divided into three sections:

I

Illinois drives knowledge creation in key research disciplines

Part I uses Elsevier data on research publication volume and impact to investigate strengths in Illinois' research productivity as well as Ocean Tomo data on patent quality to evaluate the commercial potential of Illinois patents.

II

Identifying high-potential technology clusters

Part II draws on analysis developed by Dr. C. Scott Dempwolf, University of Maryland, to evaluate the Illinois technology cluster network. Coupling this analysis with an assessment of current development activities and investments in the Illinois technology ecosystem, the report identifies the technologies that are well positioned to support established Illinois industries as well as those that can drive new, high-growth industries.

III

Harnessing roadmap technology cluster opportunities

Part III synthesizes the opportunities and gaps in commercializing innovations in these technology clusters and offers a list of cross-cutting program and policy recommendations intended to serve as a guide for Illinois and federal lawmakers.

For a glossary of terms used frequently throughout this report, see page 96.

Part I
Illinois drives knowledge creation in key research disciplines

Basic research serves as a fundamental driver of innovation and economic development. It improves not only our understanding of the world around us but also our quality of life and economic prosperity, by serving as a foundation for new technologies and products. In the 21st century economy, which thrives on innovations that feed, heal, fuel, and sustain our communities, Illinois' world-class research institutions represent a significant competitive advantage.

This section draws on the data capabilities of our partners, Elsevier and Ocean Tomo, to examine knowledge creation and impact at two early stages of the innovation pipeline: basic research output and intellectual property (IP) commercial potential. Furthermore, we examined indicators of cross-pollination between academia and industry, which is indicative of a mature R&D ecosystem that produces market-driven research with commercial prospects.

Elsevier publication data reveal Illinois' basic research strengths

A highly skilled and specialized talent pool in scientific and technological research disciplines is a vital component to an innovation ecosystem. Such researchers are crucial to innovation because they generate new knowledge that is the de facto starting point for invention and commercialization. Research findings are disseminated through publications that are subsequently cited as foundational knowledge in patents—and both outputs (publications and patent citations) serve as a platform for further innovation and technology development.

To identify areas where Illinois' STEM research pool is strong and where it has growing strengths, we conducted a comparative bibliometric analysis of data provided by Elsevier on publication, and by proxy research, impact in 17 STEM fields from 2008 to 2012.[4] We found that in all 17 STEM disciplines, Illinois performed above the 70th percentile of all U.S. states for publication output, and 13 of 17 disciplines performed above the 60th percentile for publication impact, as measured by Elsevier's field-weighted citation impact (FWCI).[5] In other words, Illinois demonstrates above-average competency across the majority of STEM fields, with several STEM disciplines demonstrating exceptional performance as highlighted in Exhibit 2.

[4] Bibliometrics includes a set of methods, such as citation and content analysis, to quantify the impact of academic literature. This period (2008 to 2012) was selected to ensure a focus on recently published knowledge. Data beyond 2012 was excluded due to incomplete information on impact, which requires several years to be determined with statistically significant accuracy.

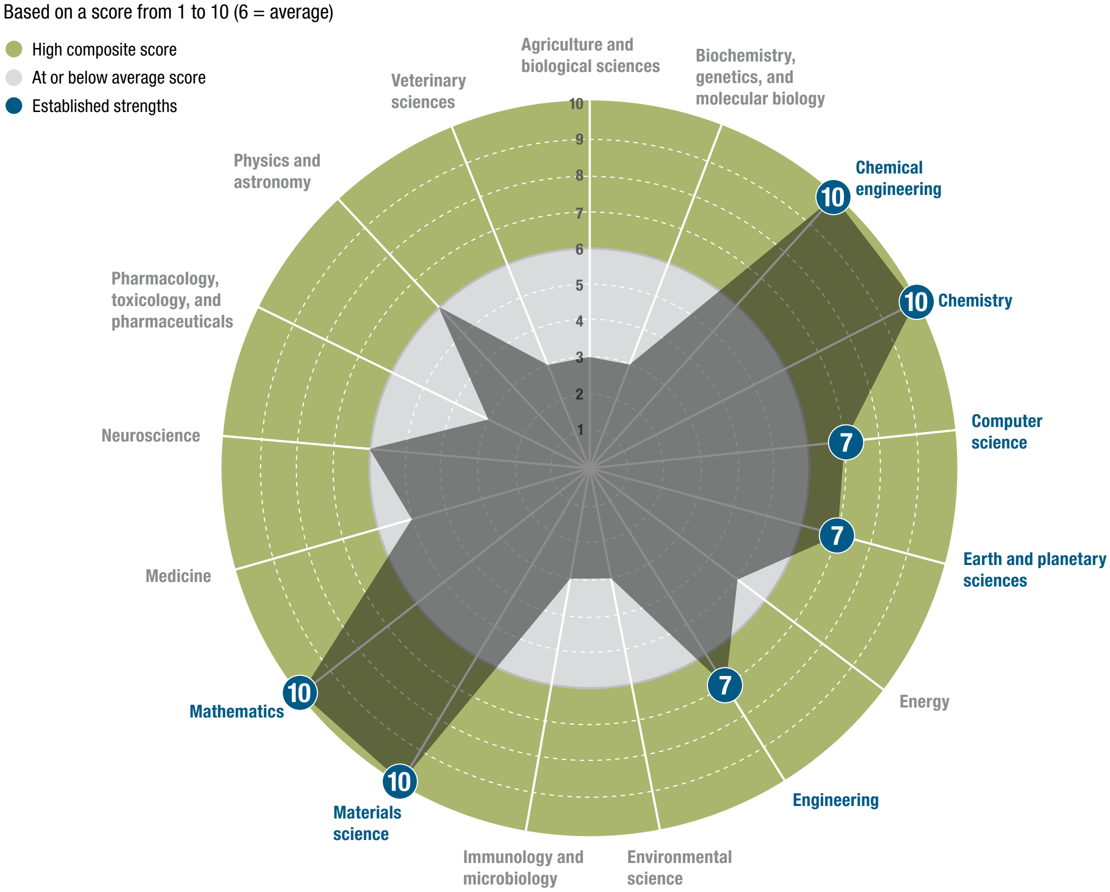
[5] FWCI is an indicator of mean citation impact and compares the actual number of citations received by an article with the expected number of citations for articles of the same document type (article, review, or conference proceeding paper), publication year, and subject field. Where the article is classified in two or more subject fields, the harmonic mean of the actual and expected citation rates is used. The indicator is therefore always defined with reference to a global baseline of 1.0.

Physical and computational sciences lead Illinois' established research strengths

To identify Illinois' established strengths, we created a composite scoring system based on publication output (as measured by publication volume and concentration) and impact (as measured by FWCI) for each discipline. Each metric was assigned a weighted score, and the composite score was calculated using the aggregate performance across these metrics. Publication impact was weighted more heavily than output because it is assumed that highly referenced research is more closely linked than output to such factors as the likelihood of cutting-edge research and top research talent. For each metric, performance was benchmarked against other U.S. states and and, where appropriate, internally among Illinois disciplines. (For more details, see the abridged methodology on page 80.)

Exhibit 2: **Illinois' top established science and technology strengths,** overall composite score

Based on a score from 1 to 10 (6 = average)



Note: Established-strength composite score calculated based on weighted measures of research impact and output, taking into account overall performance and benchmarking against other U.S. states and internally within Illinois. Impact was measured by Elsevier's field-weighted citation impact (FWCI) and output based on publication volume.

Source: Data provided by Elsevier; analysis and composite scores by ISTC

Seven research disciplines in Illinois can be categorized as established strengths based on their composite scores (Exhibit 3). These seven disciplines are differentiators for the Illinois research community due to a combination of high influence (as measured by research impact) and high output (as measured by publication volume and concentration). Illinois' universities and national laboratories excel in the physical and computational sciences, which account for six of the seven established strengths (earth and planetary sciences being the exception). The FWCI for these established strengths, ranging from the 86th to the 98th percentile, demonstrate the leadership position of Illinois' academic institutions in these research disciplines. Cutting-edge research in these fields has innumerable commercial applications, including advanced materials and coatings with applications in the energy, aerospace, and defense industries; next-generation battery and energy storage technologies; and non-silicon electronics that use nano-inks and organic materials to create next generation semiconductors, to name only a few.

Exhibit 3: **Illinois' established strengths in STEM research fields**

	Overall composite score	Impact and output, 2008–12: Elsevier field-weighted citation impact (FWCI)		Output metrics		
		Impact strength (1.0 = U.S. average)	Impact percentile	Publication concentration (1.0 = U.S. average)	Publication volume percentile	Share of U.S. output
Chemical engineering	10	1.2 (+20%)	94th	1.1 (+10%)	88th	6.6%
Chemistry	10	1.1 (+10%)	98th	1.2 (+20%)	90th	7.0%
Materials science	10	1.1 (+10%)	94th	1.1 (+10%)	86th	6.3%
Mathematics	10	1.2 (+20%)	86th	1.1 (+10%)	86th	6.2%
Computer science	7	1.2 (+20%)	92nd	1.0 (0%)	78th	5.6%
Earth and planetary sciences	7	1.4 (+40%)	96th	0.7 (–30%)	76th	4.1%
Engineering	7	1.1 (+10%)	90th	0.9 (–10%)	86th	5.5%

Source: Data provided by Elsevier; analysis and composite scores by ISTC

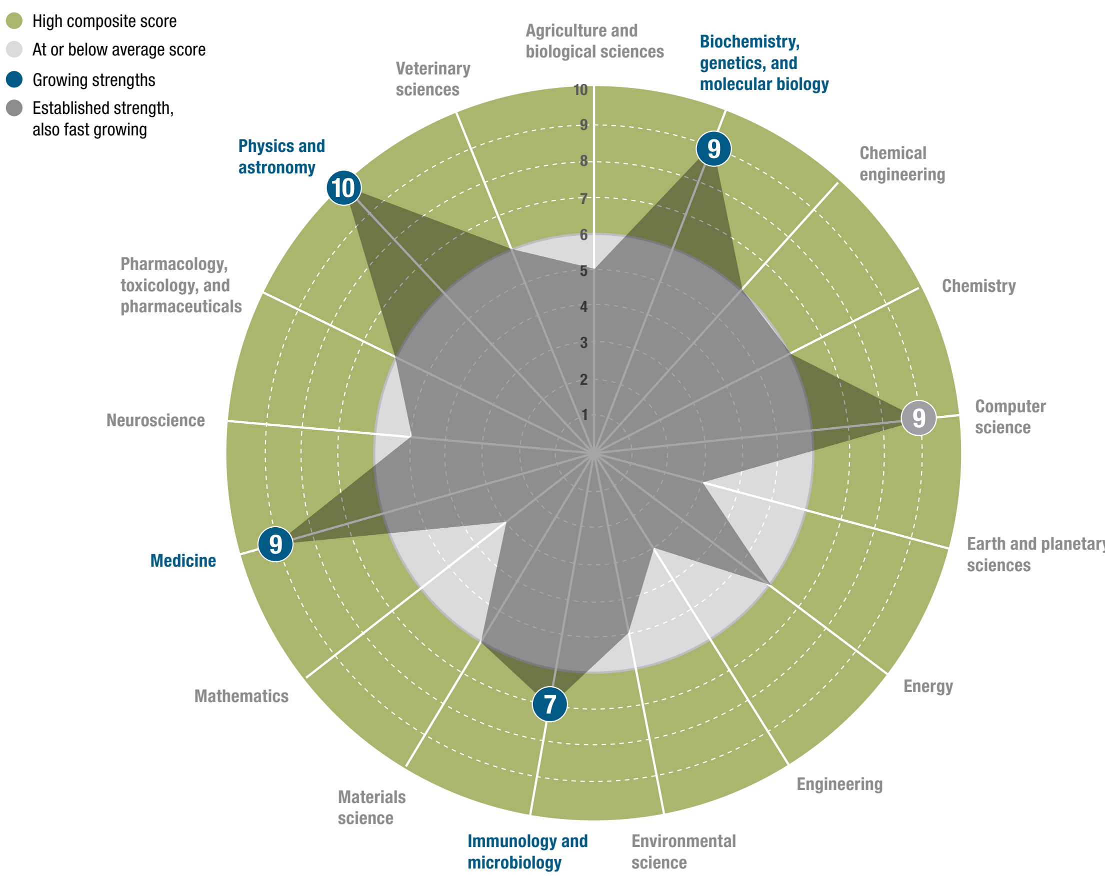
Biomedical and life sciences as well as physics lead growing research strengths

To identify those research fields in Illinois with significant—but not nation-leading—levels of publication impact and output, we developed a growing-strengths composite score based on metrics related to growth in impact and output from 2008 to 2012. Here again we weighted impact as more significant than output. Performance in publication impact and output growth was compared externally against a national average and internally against an Illinois average.[6] If a discipline that was already identified as an established strength also displayed high growth, it was counted only as an established strength. Our analysis determined that four research fields can be considered growing strengths in Illinois (Exhibit 4).

[6]The growing-strengths composite score is a weighted index based on compound annual growth rates in volume and impact per discipline. For more details, refer to the abridged methodology on page 80.)

Exhibit 4: **Illinois' top growing science and technology strengths,** overall composite score

Based on a score from 1 to 10 (6 = average)



Note: Growing-strength composite score calculated based on weighted measures of growth in research impact and output, taking into account overall performance and benchmarking against other U.S. states and internally within Illinois.

Source: Data provided by Elsevier; analysis and composite scores by ISTC

In addition, computer science, which was included in the established-strengths group described above—also demonstrated strong growth—indicating this field may become a major Illinois strength if this trend continues.

The life sciences demonstrate the highest growth in both the growth of publication FWCI impact and publication output from 2008 to 2012. Although Illinois' output in the life science disciplines has a lower impact percentile than those disciplines included in the established strengths section above, the FWCI for life sciences research is still at or above the U.S. average of 1.0, with the exception of pharmacology. At the same time, output in life science disciplines, including biochemistry, immunology, and medicine, is also the fastest growing (Exhibit 5).

Exhibit 5: **Illinois' fast-growing strengths in STEM research fields**

	Overall composite score	Impact and output, 2008–12							
		Elsevier field-weighted citation impact (FWCI)				Output metrics			
		Impact strength (1.0 = U.S. average)	Impact percentile	Impact growth rate: U.S. average	Impact growth rate: Illinois	Publication volume	Share of US output	Compound annual growth rate: U.S. average	Compound annual growth rate: Illinois
Physics and astronomy	10	1.1 (+10%)	68th	–1.1%	2.1%	21,336	7.5%	3.5%	5.9%
Biochemistry, genetics, and molecular biology	9	1.1 (+10%)	61st	–1.8%	3.1%	22,316	5.6%	4.6%	5.3%
Medicine	9	1.2 (+20%)	53rd	–2.2%	–0.2%	44,633	5.8%	5.3%	5.9%
Immunology and microbiology	7	1.1 (+10%)	67th	–2.3%	1.3%	4,557	5.0%	0.4%	–1.0%

Note: If a discipline that was already identified as an established strength also displayed high growth, it was counted as an established strength, not a growing strength, to avoid confusion between the two categorizations.

Source: Data provided by Elsevier; analysis and composite scores by ISTC

At the discipline level, the life sciences were found to be moderate but growing as measured by publication impact and output. However, the life sciences demonstrated strong recent performance at the subdiscipline level; 6 of Illinois' top 20 research subdisciplines by FWCI were in biomedical and life science fields.[7] Developmental neuroscience ranked highest among all disciplines based on FWCI; 5 clinical research fields also scored highly (Exhibit 6).

[7]Elsevier evaluated a total of 304 subdisciplines.

Exhibit 6: **Top 20 subdisciplines by Elsevier field-weighted citation impact (FWCI)**

Medicine and life sciences (shaded)

Subdiscipline	Impact strength (1.0 = U.S. average)
Neuroscience: Developmental neuroscience	**1.93** (+93%)
Medicine: Critical care and intensive care medicine	**1.88** (+88%)
Computer science: Computer vision and pattern recognition	**1.78** (+78%)
Mathematics: Numerical analysis	**1.75** (+75%)
Physics and astronomy: Astronomy and astrophysics	**1.75** (+75%)
Earth and planetary sciences: Space and planetary science	**1.71** (+71%)
Medicine: Dermatology	**1.50** (+50%)
Earth and planetary sciences: Economic geology	**1.50** (+50%)
Medicine: Epidemiology	**1.50** (+50%)
Medicine: Geriatrics and gerontology	**1.47** (+47%)
Computer science: Artificial intelligence	**1.47** (+47%)
Agricultural and biological sciences: Forestry	**1.47** (+47%)
Chemical engineering: Fluid flow and transfer processes	**1.46** (+46%)
Earth and planetary sciences: Geochemistry and petrology	**1.46** (+46%)
Engineering: Aerospace engineering	**1.44** (+44%)
Medicine: Microbiology (medical)	**1.39** (+39%)
Computer science: Information systems	**1.38** (+38%)
Engineering: Mechanics of materials	**1.35** (+35%)
Energy: Renewable energy, sustainability, and the environment	**1.34** (+34%)
Mathematics: Mathematical physics	**1.34** (+34%)

Source: Data provided by Elsevier

Academic-industry collaboration yields higher productivity

Academic and industry research build off each other and contribute complementary knowledge, tools, and facilities to move ideas from the lab bench to the marketplace. As research-intensive industries such as life sciences rely more heavily on external research and intellectual property to drive product development, engaging with academic research institutions during the basic research process is vital to align the push of technology out of the lab with the pull of companies and markets.

To determine the degree to which industry utilizes academic talent and publications, we evaluated patent citation as well as academic-industry coauthorship data, which denotes publications with at least one academic and one industry researcher contributing to the work. Researchers across all disciplines who coauthored papers with industry published nearly double the number of publications annually (7.17) compared with those who published with academic institutions (3.77). Patent citations refer to research publications as foundational knowledge in patent applications. This analysis helped to gauge each academic discipline's current contribution to corporate R&D as well as the degree to which industry priorities are informing academic research.

Chemical engineering, chemistry, and materials science (the top established research strengths) again fair strongly by these measures: coauthorship and patent citation index outputs far exceed the national average, suggesting that industry identifies significant value in Illinois research outcomes in these areas. For both chemical engineering and materials science, the patent citation index is 1.4, indicating that Illinois' share of patent citations in these disciplines is 40 percent above the national average. These figures suggest that local research in chemical engineering and materials science makes an outsized contribution to intellectual property creation and commercialization compared with other evaluated states. Consistent with these figures, we note that local researchers in chemistry, chemical engineering, and materials science are 50 to 150 percent more likely to be coauthoring with industry, suggesting that innovative companies are using this research and are closely connected with Illinois universities. Despite this observation, physical science research—which includes chemistry and materials science—only receives 3 percent of industry-sponsored research, highlighting the need to connect large industry with universities more actively around these disciplines in Illinois.[8]

Levels of academic-industry publication coauthorship among the state's life sciences disciplines (many of which are categorized as growing strengths) are slightly above the national average, indicating the existing role these disciplines play in supporting downstream commercialization activities (Exhibit 7). Although coauthorship levels with industry are moderate for most life sciences disciplines, medicine is a clear exception, with coauthorship levels 40 percent above the national average. This observation is not surprising

[8] "Academic–corporate collaborations help drive technology commercialization: The Baxter–Northwestern Alliance and the success of Naurex," *ISTC Catalyst*, August 2014.

Exhibit 7: **Connection with industry,** 2008–12

		Publication academic-industry coauthorship index[1] (1.0 = U.S. average)	Share of publications with university-industry coauthors	Patent citation index[2] (1.0 = U.S. average)
Established strengths[3]	**Chemical engineering**	**2.5** (+150%)	**28%**	**1.4** (+40%)
	Chemistry	**2.1** (+110%)	**27%**	**1.2** (+20%)
	Materials science	**1.5** (+50%)	**28%**	**1.4** (+40%)
	Mathematics	**0.5** (–50%)	**27%**	**1.0** (+10%)
	Computer science	**0.5** (–50%)	**30%**	**1.0** (0%)
	Earth and planetary sciences	**0.3** (–70%)	**28%**	**0.3** (–70%)
	Engineering	**1.1** (+10%)	**26%**	**1.2** (+20%)
Growing strengths[3]	**Physics and astronomy**	**1.1** (+10%)	**25%**	**1.3** (+10%)
	Biochemistry, genetics and molecular biology	**1.1** (+20%)	**20%**	**0.9** (+10%)
	Medicine	**1.4** (+10%)	**18%**	**0.9** (+20%)
	Immunology and microbiology	**0.9** (+20%)	**24%**	**0.9** (+10%)

[1]Coauthorship index: Measures the number of publications coauthored by academic and industry researchers indexed to the national average.
[2]Patent citation index: Measures a discipline's share of all patent citations to Illinois research and indexes it to the national average.
[3]As established through ISTC analysis of Elsevier data.

Source: Data provided by Elsevier

given that medical sciences are the single largest recipient of industry research funding at Illinois universities. In total, life sciences account for more than 75 percent of all industry-funded university research in Illinois, and nearly two-thirds of this is for research in the medical sciences.[9] Patent citation levels in Illinois' life sciences disciplines are also moderate, ranging from 80 to 90 percent of the national average.[10] These results reveal an opportunity for industry to capitalize on Illinois' growing strengths by engaging earlier in life sciences research.

Also notable, Illinois patent citations are growing in two physical sciences; energy and physics. Nationwide, almost 10 percent of all patents citing energy research refer to Illinois publications.[11] We also found a significant number of patent citations of Illinois research for materials science output, which accounted for 8 percent of all patent citations referring to materials science research, followed by chemical engineering (7.8 percent) and physics (7.4 percent). These results further suggest that Illinois' research in the physical sciences plays an especially strong role in industry commercialization efforts.

[9] Discipline definitions pertaining to this data are based on National Science Foundation (NSF) classifications, which may differ from Elsevier disciplinary definitions.

[10] Elsevier analysis—data not shown. Given the strength of the physical sciences in Illinois, fields in the life sciences have a lower relative concentration of patent citations within the state. However, this result is due more to the predominance of the physical sciences than any particular weakness in life sciences patent citations. For instance, in both medicine and biochemistry, more than 5 percent of all patents citing research in these disciplines refer to Illinois research. For the physical sciences, the share of all patent citations ranged from approximately 6 to 9 percent of all citations.

[11] Elsevier analysis—data not shown.

Fermilab: Using basic research to propel innovation and commercialization

The collaboration between Batavia-based Fermi National Accelerator Laboratory (Fermilab) and Naperville-based Tezzaron Semiconductors is one example of how basic research can propel cutting-edge industrial innovation and commercialization in Illinois. Tezzaron engineers are working closely with Fermilab scientists—who have unique equipment and expertise in making detectors to track particles emitted in high-energy collisions—to build prototypes and eventually commercialize new 3D computer chips. These chips have the potential to significantly increase the memory of electronic devices such as cameras and cell phones, and improve the speed of information processors.

The unique expertise and equipment at Fermilab can play a crucial role in helping high-tech industry solve some of its most complex technological challenges. At the new Illinois Accelerator Research Center (IARC)—currently under construction at Fermilab and funded in part by a grant from the State of Illinois—scientists and engineers from Fermilab, Argonne, and Illinois universities will work side by side with industrial partners to research and develop breakthroughs in accelerator science and translate them into applications for the nation's health, wealth, and security. These partnerships will position Illinois to become the world leader in accelerator research, development, and commercialization and attract more businesses like Tezzaron.

Ocean Tomo patent data identifies commercial potential in Illinois universities and companies

While basic science serves as the foundation of human knowledge and a stepping-stone to innovation and technology commercialization, steps to intellectual property (IP) creation such as disclosures and patents are key stages on the path to product development. Such IP can then be validated and scaled to determine if laboratory findings can be replicated thousands and millions of times in a commercial setting for profit.

To identify Illinois' IP strengths in STEM fields, we applied a rigorous gating process, comparing Illinois' total patenting output and relative quality for industry and academic institutions based on the Ocean Tomo Ratings™ (OTR™) system with that of 17 leading innovation states. First, we quantified the commercialization potential of Illinois' STEM patents.[12] We then further narrowed the group by selecting those patent classes with an average OTR™ that was at least one standard deviation above the average patent OTR™ score and a volume count that was no less than 1.2 times the Illinois average (65) across all patent classes. The aggregate patent output of the 17 states in the sample group constituted 68 percent of the total national patent output from 2009 to 2013. Thus, this sample represents a selection of the most innovation-intensive states as measured by patent volume and quality of patents.[13] For more information, see the abridged methodology on page 80.

Patent analysis determines ten high-potential patent classes

This rigorous gating process highlighted a total of ten high-potential patent classes. As a group, these patent areas represent the technology fields and applications where Illinois companies and universities have strength and demonstrate a critical mass of activity. In particular, the number of high quality patents (defined as those with OTR™ of 135 or above) provides insights into patent classes with potential for licensing and commercialization (Exhibit 8).[14] We also define a commercialization potential index (CPI) to benchmark Illinois' high-quality patent production in a given patent class versus that for the 17 state comparator group.[15]

[12] The OTR™ system employs a regression model to calculate a raw probability score for a patent. Raw scores represent the simple probability that a patent will be maintained for the full statutory term—an attribute that in one study has been found to correlate with the probability of licensing or commercialization of the patent and its underlying technology. For convenience, these raw scores are mathematically adjusted to provide a normalized mean or nominal expected score of 100, dubbed the OTR™ score. Thus, a score of 100 on the OTR™ scale generally corresponds to an expected normal or median quality (average expected maintenance rate).

[13] An average of 3.8 OTR™ points above the mean for all patents.

[14] The OTR™ system is used to evaluate the likelihood of a patent being maintained by the owner. One study (www.oceantomo.com/system/files/OTRatings_Brochure_Final.pdf) indicates that this rating system provided "strong predictors of commercialization rates" based on a correlation between OTR™ and licensing and commercialization rates. ISTC uses an OTR™ of 135 and above to define high-quality patents when calculating this index but does not attribute a particular OTR™ to a specific likelihood of commercialization.

[15] The CPI benchmarks the proportion of Illinois high-quality patents (defined by this report as patents with an OTR™ score of 135) in a given UPSC class against the sample average. A CPI of 1.0 represents a proportion of high-quality patents equal to the sample average in that patent class.

Exhibit 8: **Illinois' high-potential patent classes,** 2009–2013

Technology group	Technology patent class	Average Illinois OTR™ patent score (compared with the sample average)	Number of patents (number of OTR™ 135 and above)[1]	Commercialization potential index (CPI)[2] (1.0 = comparator state sample average)
Chemistry and advanced materials	**Compositions**	126.4 — +12.9 better than average	**73** (27)	**1.6** (+60%)
	Coating processes	122.7 — +4.8 better than average	**120** (49)	**1.6** (+60%)
	Compositions: Coatings and plastics	121.9 — +6.9 better than average	**86** (29)	**1.3** (+30%)
	Catalysts (petrochemicals)	115.4 — +1.4 better than average	**103** (27)	**1.2** (+20%)
Energy	**Chemistry: Electrical current producing apparatus**	122.4 — +3.7 better than average	**117** (36)	**1.2** (+20%)
Biomedical and biotechnological	**Analytical and immunological testing** (medical devices and drug discovery)	129.5 — +9.1 better than average	**89** (38)	**1.3** (+30%)
	Molecular biology and microbiology	118.9 — –0.6 lower than average	**449** (141)	**1.0** (0%)
	Biopharmaceuticals[3]	116.5 — –0.7 lower than average	**328** (93)	**0.9** (–10%)
Computer hardware and software	**Electrical computers and digital processing systems: Multicomputer data transferring**	117.9 — +0.4 better than average	**468** (110)	**1.1** (+10%)
	Optics: Measuring and testing	117.5 — +6.5 better than average	**114** (22)	**1.1** (+10%)

[1] Patents with a score of 135 or higher were determined to be high quality. These patents represent the 85th percentile and above of all patents. Ocean Tomo awards A or A+ grades to patents at or above the 85th percentile.

[2] Using the OTR™ system, we developed a commercialization potential index (CPI) of Illinois' patents. This indicator benchmarks Illinois' proportion of high-quality patents—defined to be patents with OTR™ score greater than or equal to 135—in a given U.S. Patent Classification (USPC) class to the proportion in the comparator state group. For a more complete description of the CPI methodology, please refer to the abridged methodology on page 80.

[3] Refers only to USPC 424. USPC 514 patents, also classified as drug, bio-affecting and body treating compositions, have an average 104.5 OTR™, 0.4. points above the sample average, across a total output of 592 patents for the period covered. This brings Illinois' total output in biopharmaceutical patents (USPC 424 and 514) to 900 for the period from 2009 to 2013.

Source: Data provided by Ocean Tomo; analysis by ISTC

Chemistry and advanced materials

Compositions

Biotechnological innovations for water remediation, gasification, and biosolvents account for a sizable share of all compositions patents. In Illinois, top innovations in compositions are driven by Northwestern University and Cabot Microelectronics. The University of Illinois at Urbana–Champaign also contributes to patenting in this class. Key Illinois specialty chemicals companies include Nalco Chemical Company, Hallstar Innovations, INEOS Bio, and Vertec Biosolvents.

Coating processes

Cutting-edge innovations in coating processes are driven by nanotechnology discoveries at Northwestern University with additional innovations by UOP. Northern Illinois University, University of Chicago, and University of Illinois at Urbana–Champaign also contribute to patenting in this class, and Abbott Laboratories is a key innovator in coating processes in the area of medical devices.

Compositions: Coatings and plastics

Innovations in this class are driven by Nalco and USG for specialty uses in the construction and industrial processes industries. Environmentally friendly chemical innovations are also a significant component and primarily driven by Videojet Technologies and Unlimited Finishes. Universities do not display significant activity in this area.

Catalysts

Innovation in catalyst technologies is applied in the petrochemical industry for gas and oil refining. Illinois has several leading industry innovators in catalyst technologies, led by AMCOL, INEOS, and UOP. Out-of-state giants such as BP and Chevron often tap Illinois inventors as well. Non-industry patenting is led by Argonne, with additional contributions by Southern Illinois University and the University of Illinois at Urbana–Champaign.

Energy

Chemistry: Electrical current producing apparatus

Argonne National Laboratory is the principal driver of local innovations in this field, joined by the Illinois Institute of Technology, Northwestern University, and University of Illinois at Urbana–Champaign. Motorola Mobility is the chief locally based industrial innovator with a focus on battery research for electronic applications. Additional industrial innovation is driven by out-of-state companies working with innovators based in Illinois, suggesting that the state's research and talent has the potential to be further directed toward the Illinois energy storage innovation cluster.

Biomedical and biotechnological

Analytical and immunological testing

Principal innovators in this area include Abbott Laboratories in medical devices, Nalco in biotechnological applications, and Northwestern University, the University of Chicago, and University of Illinois at Chicago and at Urbana–Champaign, which focus on sensor innovations with applications in medical devices and diagnostics. As with innovations in energy storage, patenting in this area is characterized by substantial collaboration between innovators and out-of-state companies, primarily in medical devices.

Molecular biology and microbiology

Another area of very high patent output, molecular biology and microbiology (also known as biotechnological) patenting is driven by a diverse group of companies—including Abbott, ADM, AgriGenomics, Baxter, Fermlogic, Pierce Protein Technology, and Valent BioSciences—with applications of biological organisms in agri-sciences, biofuels, biosolvents, and reagents for biopharmaceuticals. Industrial innovation is complemented by intense university innovation, pointing to biotechnology as a particularly well-aligned area between industry and university expertise in Illinois.

Biopharmaceuticals

Biopharmaceutical innovations display one of the highest volumes among all patent classes in Illinois. This innovation is driven by AbbVie and Illinois' major research universities.

Computer hardware and software

Electrical computers and digital processing systems: Multicomputer transferring systems

Industry is the primary driver of innovation in this area, led by Caterpillar, Cleversafe, Motorola Solutions, and Motorola Mobility. Among universities, the Illinois Institute of Technology and Northwestern University are the main academic contributors. Most innovations by local inventors are assigned to out-of-state software companies such as IBM, Intel, and Microsoft.

Optics: Measuring and testing

Optics patenting is divided into specialty industrial applications by Abbott, Boeing, Caterpillar, Cummins-Allison, Motorola Mobility, and Panduit, as well as innovations by local universities and national laboratories. University patenting is focused on cutting-edge optics such as measuring and testing using nanophotonic inventions with applications in a variety of industries, predominantly but not exclusively in the biomedical field.

A comparison of university and industry patent performance

Increasing the development and utilization of academic IP is one motivation for this report. By both enhancing visibility of university technology and promoting company input in university research and commercialization activities, Illinois can create more opportunities for researchers to discover market needs and develop products with high commercialization potential.[16]

The majority of university patents across the country are concentrated in technologies broadly related to biomedical and biotechnological applications, chemicals and advanced materials, semiconductors, specialty electronics, and—in Illinois' case—also battery and energy storage technologies. We selected technology groups[17] that had above-average output (29 patents) for the five-year period from 2009 to 2013 and a commercial potential index of at least 1.0. This analysis enabled us to identify the technology areas where a combination of high volume and high-quality patents suggested Illinois university IP is most likely to yield a significant impact. CPI provides particularly strong insights about Illinois universities' comparative advantages.

Biomedical and biotechnological university patents, followed by chemistry-related patents, display the greatest potential based on total volume of high-quality patents. Federal funding tends to finance high-impact biomedical research related to diseases such cancer and diabetes. Consequently, university biopharmaceuticals patents are especially well positioned to have market potential. We found that in Illinois, just over a fifth (21 percent) of university biopharmaceutical and biotechnology patents are of high quality; among patents in this group, a total of 56 inventions scored a minimum of 135 OTR™ or in the 85th percentile and above. This concentration of high-quality patents is approximately 40 percent higher than the average across all patent classes. The share of Illinois university pharmaceutical patents was also 3 percent higher compared with Illinois' industry share. These findings support the increased emphasis on developing mechanisms to more effectively connect Illinois' biomedical research community with commercialization partners (Exhibit 9).

[16] Due to the smaller sample size, individual patent classes were grouped into technology subgroups based on a concordance and taxonomy developed by Bronwyn Hall et. al. For a concordance of patent classes to broader technology groups, see Bronwyn H. Hall, Adam B. Jaffe, and Manuel Trajtenberg, *The NBER patent citation data file: Lessons, insights and methodological tools*, National Bureau of Economic Research, pp. 41-42, 2001.

[17] While Illinois patenting has demonstrated exceptional growth over the past decade, licensing has grown at only half the national rate. For more information, see Q4 2013 issue of the *Illinois Innovation Index*.

Exhibit 9: **University patent strengths,** 2009–2013

Technology group	Total university patents: All patents in group	Total university patents: OTR™ 135 and above patents[1]	**Share of group OTR™ 135 and above,** percent	**Commercialization potential index (CPI)**[2] (1.0 = sample average)
Drug and medical: **Biopharmaceuticals**	156	35	22.4%	1.5 (+50%)
Chemicals: **Miscellaneous**[2]	116	21	18.1%	1.2 (+20%)
Drug and medical: **Biotechology**	109	21	19.3%	1.3 (+30%)
Electrical and electric: **Semiconductor devices**	66	18	27.3%	1.8 (+80%)
Electrical and electric: **Measuring and testing**	61	10	16.4%	1.1 (+10%)
Electrical and electric: **Power systems**	60	9	15.0%	1.0 (0%)
Chemicals: **Organic compounds**	49	9	18.4%	1.2 (+20%)
Chemicals: **Coatings**	31	9	29.0%	1.9 (+90%)

[1] Patents with OTR™ greater than or equal to 135 represent approximately the 85th percentile or above in patent quality.
[2] Using the OTR™ system, we developed a commercialization potential index (CPI) of Illinois' patents. For a more complete description of the CPI methodology, please refer to the abridged methodology section on page 80.
[3] The miscellaneous category includes those chemicals that do not fall under other chemical patent classes, which are: agriculture, food, textiles; coatings; organic compounds; gas; and resins.

Source: Data provided by Ocean Tomo; analysis by ISTC

Although university and industry patenting diverge in some technology groups, several areas display alignment based on patenting output, including coatings, biopharmaceuticals, biotechnology, measuring and testing, and power systems (such as batteries and energy storage). From an economic development perspective, patent classes with more potential "wins," measured here by OTR™ scores greater than 135, offer particularly substantial opportunity for further development and industry collaboration. Drugs and medical technologies and chemical technologies demonstrate the most viable opportunities based on this measure.

Part II

Identifying high-potential technology clusters

Building on Part I of this report, which identified research strengths and IP areas with strong commercial potential, Part II identifies Illinois technology cluster where increased academic-industry collaboration could drive economic growth. Analyzing where these opportunities align with community activity and investment provides insights into the supporting programs and policies that could yield significant impact on business competitiveness and talent attraction. To identify technology clusters that can drive industries through research and commercialization partnerships, Part II integrates technology cluster network analysis, which evaluates network strengths and highlights R&D collaboration opportunities, with data from Part I on research productivity. For each cluster, quantitative data analysis is enriched through a discussion of existing activity and investment to capture the most current developments that may not be reflected in patent and grants data.

The importance of cluster strategy

Cluster strategy—which examines geographic concentrations of related companies, organizations, and institutions in a specific field—has emerged as a critical component of economic development efforts across the country, particularly in technology-based economic development due to the alignment of multiple, diverse organizations needed for innovations to reach the market. The primary benefit of identifying clusters of synergistic organizations across industry, workforce, and R&D is the ability to design targeted economic development policy focused on leveraging existing assets and investments. The predominant approach to cluster analysis emphasizes industries, and for good reason: the Harvard Cluster Mapping Project has shown that industries require integration of complementary technology, talent, and suppliers to thrive.

The Rockford Area Aerospace Network (RAAN) presents one example of an industry cluster. RAAN consists of more than 200 companies across the aerospace supply chain and focuses on workforce development, technology innovation, and business development to capitalize on dramatic growth in Illinois' aerospace industry. Formed in partnership with institutions such as Northern Illinois University and catalyzed in 2011 by funding from the U.S. Economic Development Association's Jobs and Innovation Accelerator Challenge, this organized cluster has created or retained more than 4,000 jobs so far and is considered a national model for industry-based clusters.

DCEO's EDP industry clusters identified in 2014

- **Advanced materials**
- **Agribusiness, food processing, and technology**
- **Biomedical/biotechnical**
- **Clean energy**
- **Information technology and telecommunications**
- **Machinery and fabricated metal products manufacturing**
- **Transportation and logistics**

In July 2014, DCEO's economic development plan (EDP) identified seven industry clusters that are primed for growth and job creation in Illinois. These seven clusters were chosen based on a rigorous analysis of key metrics such as projected employment growth, location quotient, and wages paid by industry.[18]

[18]This analysis was led by the Center for Governmental Studies at Northern Illinois University. For more information, see "Identifying high-potential clusters," *The Illinois economic development plan*, Department of Commerce and Economic Opportunity (DCEO), July 2014.

Focusing on technology clusters to drive industry competitiveness

To expand on the work of DCEO and other organizations, this roadmap examines technology clusters,[19] which cut across sectors and connect research productivity with entrepreneurs, investors, demonstration facilities, and industry collaborators focused on commercializing new technologies. Technology clusters present a more granular perspective, allowing us to pinpoint specific technology areas that can benefit from targeted economic development interventions to drive innovation and competitiveness in one or more industries. In addition, this approach identifies emerging strengths where research activity is strong but industry presence or connectivity is lacking.

The SBA-funded smart grid cluster, which promotes business growth and entrepreneurial activity in efficient power transmission and storage throughout the Midwest, is one example of an Illinois technology cluster. Spearheaded by the Illinois Institute of Technology (IIT), the cluster provides business development services to startup companies and connects inventors with a variety of resources, including power grid test beds supported by Illinois utilities Ameren and ComEd and funding and support from entities such as the Clean Energy Trust and Energy Foundry.

Identifying Illinois' technology clusters

To identify technology areas that align with Illinois' research and IP capabilities, we focused on technology networks with significant potential for increased academic–industry collaboration that can harness talent and ideas in order to access public and private funding opportunities and support Illinois business competitiveness in large and growing markets. Commercialization and production of these underlying technologies also present significant opportunity for Illinois to lead disruptive, emerging industries.

The development of the Illinois technology cluster network model in collaboration with Dr. C. Scott Dempwolf, the director of the University of Maryland–Morgan State Joint Center for Economic Development at the University of Maryland, was central to this effort. The Illinois technology cluster network model provides a snapshot of where innovation occurs in the state and what companies and institutions are the drivers. The model maps more than 16,700 institutions, companies, and inventors that participated in research and commercialization activities in Illinois from January 2010 to March 2014. The network demonstrates more than 90,000 unique connections based on cluster network analysis of core datasets and others samples.[20] The model provides insights into a given community's organization and

For more information, see the abridged methodology on page 80.

[19] We focus on technology clusters rather than industry clusters, which tend to be broader and anchored in North American Industry Classification System (NAICS) data. This report defines technology clusters as networks of research and development activity that exhibit expertise and connections related to specific types of innovations (for instance, nanotechnology, polymers, biopharmaceuticals) that may have applications across multiple industries.

[20] The data used in this model includes patent applications, patents granted, federal research grants data including SBIR and STTR awards, and proprietary sponsored-research data provided by Illinois universities and national laboratories.

can highlight new potential connection opportunities based on areas of existing technology activity and collaboration.[21]

Analysis of the Illinois technology cluster network revealed numerous technology areas with significant existing innovation activity and collaboration and substantial opportunity for new partnerships to expand R&D impact and economic development. For this report, we elaborate on six high-potential technology clusters selected based on the following criteria:

- → **Significant opportunity for academic–industry partnership**
- → **Strong research productivity and IP commercial potential based on Part I data analysis**
- → **Ability to support competitiveness for one or more key Illinois industries**
- → **Existing public and/or private technology cluster development activity and investment**
- → **Significant addressable market for the technology**
- → **Notable research and commercialization funding opportunities (including from federal sources)**

Through this approach, we focused on six high-potential technology clusters—advanced materials: alloys, advanced materials: polymers, batteries and energy storage, biofuels and biomass-derived products, medical biotechnology, and nanotechnology and analyzed opportunities for new collaborations and initiatives to strengthen connectivity and maximize research outcomes and commercialization.

[21] Opportunity ties were modeled based on similarity in patent class and subclass output and semantic keyword matches in patent and grants data. For additional information on the technology cluster network model developed for this report, refer to the abridged methodology. A full methodology can be found at www.illinoisinnovation.com/science-technology-roadmap.

Exhibit 10: **Technology clusters can drive competitiveness in key Illinois industries**

	DCEO economic development plan industries						
Roadmap technology clusters	Advanced materials	Agribusiness, food processing, and technology	Biomedical/ biotechnical	Clean energy	IT and telecommunications	Machinery and fabricated metal products mfg	Transportation and logistics
Advanced materials: Alloys	●	●	●	●	●	●	●
Advanced materials: Polymers	●	●	●	●	●	●	●
Batteries and energy storage	●	●	●	●	●	●	●
Biofuels and biomass-derived products	●	●		●		●	●
Medical biotechnology			●				
Nanotechnology	●	●	●	●	●	●	●

Advanced materials

Research in materials science underpins innovation in every high-tech industry. High-performance materials and even biomaterials are critical for aerospace and defense applications; and new chemistries are needed for energy storage, flexible electronics, and biopharmaceuticals and diagnostics. The Deloitte report: Reigniting growth—Advanced materials systems, estimated that the global end market for advanced materials would grow from $2 trillion in 2012 to more than $4 trillion by 2020.

More than 19,000 manufacturing companies, many focused on the design and production of materials-based products such as metals and plastics, stand to benefit greatly from new advanced materials development. In 2012, University of Illinois' Business and Industry Services (UI BIS) organization conducted a survey of 142 companies and found that access to new materials was the number two priority (behind online training) for driving competitiveness and profitability.

Illinois' undisputed strength in materials science offers a competitive advantage that can be harnessed to seed new high-tech materials companies and enable new-product development that will meet the growing demand for specialty materials by the largest industries. As the data presented in Part I show, Illinois' research and intellectual property creation in materials science and related disciplines such as chemistry and chemical engineering is virtually unmatched in quality and volume of output.

Aligning Illinois research and commercialization efforts with federal initiatives creates opportunity to increase advanced materials research and support Illinois industry through access to new markets or increased competitiveness. The federal government's Materials Genome Initiative (MGI), for example, aims to double the pace of advanced materials discovery, qualification, manufacture, and commercialization by developing computational and experimental tools and building collaboration networks.[22] To position the United States as a global leader in this market and promote competitiveness of U.S. manufacturers through the utilization of advanced materials, MGI has invested more than $250 million since 2011 in R&D and innovation infrastructure.

Illinois' universities and industry have already used their combined strengths in the chemical and material sciences to benefit from MGI initiatives. The $25 million Center for Hierarchical Materials Design (CHiMaD) is a center of excellence for advanced materials research sponsored by the National Institute for Standards and Technology. The center focuses on developing the next generation of computational tools, databases, and experimental techniques in order to accelerate the design of novel materials and their integration into industry. By connecting leading researchers from Northwestern University, Argonne,

[22] For more information, see "Fact sheet: The materials genome initiative – Three years of progress," White House Office of Science and Technology Policy, June 19, 2014."

the Computational Institute at University of Chicago, and the expertise of Evanston-based QuesTek Innovations, CHiMaD supports the testing, demonstration, qualification, and manufacturing of advanced materials discoveries in alloys and polymers in Illinois.

Illinois' unparalleled high-performance computing facilities are key to achieving MGI goals. The White House recently announced that the Materials Data Facility Pilot will include multi-petabyte storage environments at the National Center for Supercomputing Applications (NCSA) at Argonne and UIUC and will rely on the Globus research data management service at University of Chicago.[23] In addition, advanced modeling and simulation capabilities developed in Illinois are helping manufacturers optimize their materials selection before developing physical prototypes. This capability is being rolled out across Illinois and nationally through the UI LABS' $320 million Digital Manufacturing and Design Innovation Institute (DMDII), which has more than 40 industry partners, and the Illinois Manufacturing Lab. These recent wins underscore how Illinois' combination of strengths in materials and computational sciences gives Illinois the state a competitive advantage in becoming the center of advanced materials innovation, with an emphasis in two areas—allows and polymers.

[23]This facility, a pilot program of the National Data Service (NDS), will function as a repository where scientists can store and share materials research data produced by both simulations and experiments.

Alloys and metals

Cluster performance

Research
Illinois' core research strengths are anchored in chemical and material sciences, with direct applications in new alloy and metal powder innovations (an average research impact 24 percent above the average).

Commercial potential
Although patents related to metallurgical manufacturing processes exhibit below-average commercial potential compared with the sample group, related patent classes with a more direct application to new-materials development such as compositions and coatings are significantly above average.

Cluster development
Illinois research institutions have substantial opportunities to use partnerships in metals and alloys innovation to support important Illinois industries, including aerospace, automotive, and heavy equipment, and secure federal funding for commercialization through the SBIR and STTR programs.

New metals and alloys technologies play a critical role in the evolution of products for high-performance design and manufacturing industries. Due to the importance of new material advances in the development of novel products across multiple industries, innovations in alloys address the needs of multibillion-dollar markets. Breakthroughs in metal powders are also critical in positioning Illinois to take advantage of growing and disruptive industries such as additive manufacturing—or 3-D printing—which is expected to grow from a $2.2 billion market in 2016 to an almost $11 billion market by 2021.[24]

In the Chicago metropolitan statistical area alone, there are 3,700 companies in the metals industry and its associated supply chain. These companies, with collective revenues in excess of $30 billion, employ more than 100,000 people.[25] Metals fabrication and utilization of new alloys and metal coatings are key to manufacturing industries around the state, including aerospace, automotive manufacturing, biotechnology, and heavy equipment. Regional innovation and economic development initiatives such as the Chicago Metro Metals Consortium, the Quad Cities Manufacturing Innovation Hub, and the Rockford Area Aerospace Network all include innovation and research that focuses on the development and integration of alloys and metals to address design and production needs.

Large manufacturers tend to rely on external academic and private R&D partners to develop new metals and alloys (see sidebar, "Company spotlight: QuesTek Innovations," on page 33). A metal's capacity must undergo extensive testing and qualification to verify that it can perform in a variety of environments and that it can be manufactured at scale with consistent properties. As a result, prolonged testing can often extend commercialization periods to as long as two decades. In addition, companies need prototyping and demonstration facilities to scale and validate new metals and alloys developed through academic collaborations. Once materials are qualified, manufacturers must undertake additional efforts and workforce training to select appropriate alloys for design and production.

Joint partnerships with industry, universities, and federal research facilities to support testing and qualification of new alloys are therefore integral to the commercialization of this research. Illinois' growing infrastructure that supports these commercialization activities encompasses both basic and applied research on alloys development and metals and multi-materials manufacturing. CHiMaD utilizes NIST funding to connect expertise and assets at Argonne, Northwestern, and University of Chicago to tackle alloys and new materials challenges. In addition, the Quad City Manufacturing Lab (QCML) and the NIU Rapid Optimization of Commercial Knowledge (ROCK) program in Rockford pilot and commercialize new alloys and composite materials.

[24] *The search for creative destruction*, Goldman Sachs, August 2013.
[25] "Investing in manufacturing community partnerships," Chicago Metro Metal Consortium Manufacturing Community, n.d.

Alloys and metals cluster analysis findings

Analysis of the Illinois technology cluster network model reveals that the metals and alloys research cluster consists of a distributed network of research institutions, materials innovation companies, and OEMs (see alloys and metals cluster map on page 34). The wide fan of green ties originating from the universities and national labs indicates significant opportunity for collaboration with OEMs, including Boeing, Caterpillar, Deere & Company, Honeywell, and Illinois Tool Works, across a diverse group of industries ranging from transportation and heavy equipment manufacturing to packaging, energy, defense, and even surgical tools. Potential connections are also observed with metals and alloys development companies such as Cristal Metals and QuesTek Innovations.

The analysis found 151 institutions involved in alloys and metallurgical R&D in Illinois. These research institutions and companies have the potential for 4,395 collaboration opportunities, with 46 percent involving at least one academic institution. With 1,726 unique pairings, the cluster shows a potential multiplex percentage of 61 percent, indicating that more than half of potential organizational pairings have multiple connection points based on complementary research activities. A connectivity index of 0.79 also points to a network that does not adapt easily to new collaborations but has existing networks to build on.

Company spotlight

QuesTek Innovations

A completed hook shank for the T-45 landing gear using QuesTek's ICME-designed Ferrium M54 steel, which was supported by Navy funding. The company was able to get M54 qualified to be used on demanding landing-gear applications within seven years.

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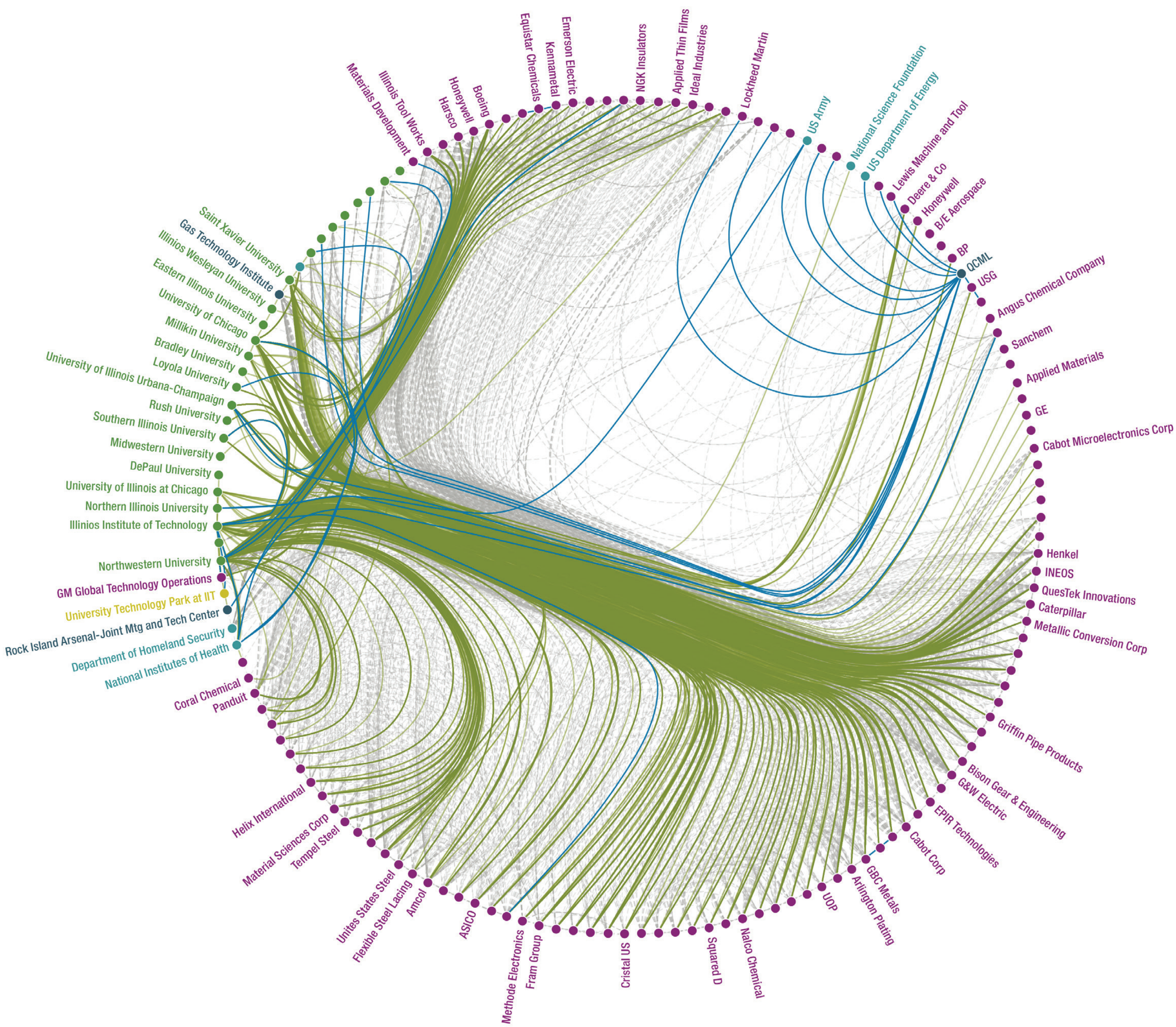
Founded by a team of Northwestern University materials science engineers in 1999, QuesTek Innovations has proved itself as a global leader in the field of integrated computational materials engineering (ICME). Using ICME and a proprietary method registered as Materials by Design®, QuesTek's team has demonstrated that high-performance steels and other alloys can be developed twice as fast (in 5 to 10 years) as conventional methods (usually 10 to 20 years or longer). In doing so, QuesTek considerably accelerates the development of novel alloys, enabling customers from a range of industries to reduce the cost of testing and deploying new alloys by millions of dollars. QuesTek's innovative methods have earned the company a unique role as an industrial partner on the ChiMaD consortium, which strengthens the company's position at the forefront of innovation in materials engineering while enabling Illinois to capitalize on new advances in alloy engineering. Several of its advanced high-performance Ferrium® steels are being or have been qualified for demanding aerospace applications such as landing gear, helicopter rotor shafts, and helicopter transmission gear, replacing steels that have been used for decades. QuesTek has been awarded funding to design new alloys specifically tailored for additive-manufacturing processes—a potential growth area in the future.

Additional opportunity: Facilitating and nurturing strong relationships and exchanges among universities and the state's high-tech metals companies is critical to retaining and harnessing local innovations. QuesTek exemplifies a successful model of mutual support that can strengthen the economic competitiveness of local innovative businesses and enable universities to compete more effectively for federal funding, which is increasingly tied to commercialization goals. Both outcomes serve to bring more research dollars and employment to Illinois.

Alloys and metals cluster map

Existing connection
Potential connection to Illinois academic institutions
Potential company-to-company connection

Company/For profit
University
National laboratory
Federal funding agency
Independent research institution
Ecosystem player



Source: Created by Dr. C. Scott Dempwolf (University of Maryland) and ISTC using NodeXL

Alloys and metals collaboration scorecard

Metrics

Organizations (companies and research institutions) **151**	Unique potential connections **1,726**
Total potential connections **4,395**	Percentage of connections linked to academic institutions **46%**
Multiplex percentage (share of pairs with multiple potential connections) **61%** Illinois average is **43%**	Connectivity index (measure of cluster integration) **0.79** Optimal for innovation: **0.4–0.7**[3]

Illinois impact

Relevant industries from state economic development plan[1]

Advanced materials

Agribusiness, food processing, and technology

Biomedical and biotechnical

Clean energy

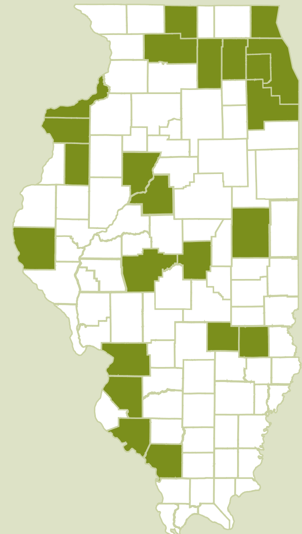
Information technology and telecommunications

Machinery and fabricated metals product manufacturing

Transportation and logistics

Leading counties[2]

Champaign, **Cook**, **DeKalb**, **DuPage**, **Effingham**, **Hancock**, **Jackson**, **Jasper**, **Kane**, **Lake**, **Macon**, **Madison**, **Mercer**, **Ogle**, **Peoria**, **Randolph**, **Rock Island**, **Sangamon**, **St. Clair**, **Tazewell**, **Warren**, **Will**, **Winnebago**



Research impact

as measured by field-weighted citation impact (FWCI)[4]

Leading research areas	FWCI (average = 1.0)
Metals and alloys	**1.24** (+24%)
Surface coatings and films	**1.04** (+4%)

Related patent strengths

as measured by OTR™[5]

Leading patent classes	OTR™ (average = 100)
Metal treatment	**111.1**
Specialized metallurgical processes, compositions for use therein, consolidated metal powder compositions, and loose metal particulate mixtures	**111.0**

Community[2]

Key research institutions

Argonne National Laboratory

Illinois Institute of Technology

Northern Illinois University

Northwestern University

University of Illinois at Urbana–Champaign

Notable companies

Original equipment manufacturers

Caterpillar

Deere & Company

Illinois Tool Works

Alloy developers

Cristal Metals

QuesTek Innovations

UOP

Federal funders

Department of Defense

Department of Energy

Department of Homeland Security

National Science Foundation

National Institute of Standards and Technology

National Institutes of Health

[1] *The Illinois economic development plan*, Department of Commerce and Economic Opportunity (DCEO), July 2014.

[2] Innovation activity measured based on datasets used to create the Illinois technology cluster network model.

[3] A connectivity index below 0.4 indicates a lack of cluster integration. A value above 0.7 suggests an increasingly insular community with more limited assimilation of new ideas and partnerships.

[4] The U.S. average FWCI is 1.0; therefore, a score of 1.5 indicates Illinois research publication strength is 50 percent above the national average.

[5] The OTR™ system employs a regression model to determine the probability that a patent will be maintained—an indication of patent quality.

Related research strengths

In the field of metals and alloys research Illinois' impact is 24 percent above the average, making it one of the strongest subfields within material science. Relevant research and patenting are driven in large part by Northwestern University's leadership in metallurgy and metal treatment research. For applied end of metals and multimaterial manufacturing, on the whole Illinois' innovation quality is moderate and may benefit from increased access to specialized applied research facilities such as CHiMaD, QCML, and NIU Surface coatings and films on the other hand demonstrate above-average impact.

Promising technical areas

Additive manufacturing. Quickly emerging as an alternative to traditional manufacturing processes, additive manufacturing of metals uses lasers and materials deposition equipment to layer metal powders in any configuration. This method accelerates prototyping and increases design configuration flexibility. Universities and research institutions play an important role in the validation and adoption of new applications of this technology by industry (see sidebar, "Industry collaboration spotlight: Quad City Manufacturing Lab," on this page). Gaining an early foothold in this industry through the development and production of specialized metal powders and the expansion of applied additive-manufacturing facilities positions Illinois companies to grow as this emerging industry continues to expand.

Integrated computational materials engineering (ICME). ICME uses sophisticated software for multiscale materials modeling to capture and test the properties and performance of new materials. This virtual testing drastically reduces the time and cost involved in testing new materials. Illinois is poised to be a leader in ICME thanks to CHiMaD and Materials Data Facility Pilot at the National Center for Supercomputing Applications (NCSA). In conjunction with these resources, the NCSA Private Sector Partnership and the Argonne Leadership Computing Facility provide additional infrastructure that can make high-performance computing power available to OEMs and their suppliers to accelerate materials development and utilization.

Industry collaboration spotlight

Quad City Manufacturing Lab

A 3-D-printed demonstration of a nuclear reactor component made with a superalloy for a project with Lockheed Martin and the Department of Energy (DOE).

Located on the Rock Island Arsenal and operated by Western Illinois University, the Quad City Manufacturing Lab (QCML) performs research, development, and small-scale manufacturing of new metals and alloys. This center of excellence enables additive manufacturing by developing new processes and materials including titanium alloys, aluminum alloys, steel alloys, superalloys, metal matrix composites, and other advanced materials. Partnerships with other metals research initiatives, such as the Northern Illinois University Rapid Optimization of Commercial Knowledge (ROCK) program, integrate expertise from across the region to support materials development for aerospace, defense manufacturing, and heavy equipment. Global and regional manufacturers—including Caterpillar, Deere & Company, GE, Lockheed Martin, and United Technologies—tap QCML metals and additive-manufacturing capabilities.

Additional opportunities: The planned Quad Cities Manufacturing Innovation Hub, which will focus on the region's metal and multimaterials industry, will help small and midsize manufacturers and their workforce to integrate new materials and technologies such as those developed by QCML into their production processes. By networking QCML and the Quad Cities Manufacturing Innovation Hub with other regional manufacturing initiatives through UI LABS' Digital Manufacturing and Design Innovation Institute (DMDII) and the Illinois Manufacturing Lab, Illinois can promote the dissemination of new metals innovations across the state's manufacturing base.

Supporting the alloys and metals innovation cluster

Illinois is still in the early stages of developing a robust infrastructure focused on new materials, in particular advanced metal and alloys commercialization. However, recent wins for large-scale, federally funded research and R&D facilities confirm Illinois' potential to become a hub for new metals and alloys innovation. Given the quality of related research and size and impact of Illinois metals manufacturers (both suppliers and OEMs), alloys innovation and commercialization could have a significant impact on the state's economy. To realize this potential, Illinois should pursue the following goals:

1. Seed new testing and qualifying facilities. Applied research capabilities along the QCML model could be used to expand materials qualification for 3-D printing of metal and address additional alloys production processes including casting, forging, and advanced machining.

2. Use Illinois leadership in federal manufacturing initiatives to harness new technologies from national innovation network. DMDII's position as the central node for the federal National Network for Manufacturing Innovation could support links to the America Makes additive-manufacturing hub in Youngstown and the new lightweight metals developed by the Detroit-based hub. These connections would provide Illinois manufacturers with the knowledge and tools to integrate new metals and alloys into their parts and products.

3. Expand workforce training in ICME through facilities at the DMDII, Illinois Manufacturing Lab, and Illinois computing facilities. The creation of a unique talent pool of experts will provide local cluster companies with capabilities to develop and utilize new alloys. Entrepreneurs applying ICME will also be more competitive for SBIR awards through the Department of Defense and NSF, which support the application of computing techniques to accelerate the development of advanced materials.

4. Harness the dissemination of new alloys and metals to Illinois companies and and military facilities such as the Rock Island Arsenal Joint Manufacturing and Technology Center to increase the number and competitiveness of certified suppliers to the Department of Defense, a multibillion dollar industry where Illinois has historically lagged behind other states despite its extensive industrial base of companies in metals manufacturing.

Polymers

Polymers are substances composed of large molecules used to create materials that combine flexibility, durability, and, in more recent years, even self-healing properties. Polymers can be naturally occurring—such as DNA and proteins—or they can be produced synthetically to form polymeric materials with properties that do not occur naturally. Discoveries in polymers research help to develop new materials used in applications such as next-generation flexible electronics, heat and light conduction, quantum computing, and transformative technologies for food processing and packaging.

Synthetic-polymer production represents a strong alignment between Illinois research strengths and the needs of local industry. The state boasts one of the most formidable research capacities in polymers in the nation, driven by the Materials Science and Engineering Department at Northwestern University, the Department of Chemistry and Biochemistry and Center for Friction Studies at Southern Illinois University, the recently opened Institute for Molecular Engineering (IME) at the University of Chicago, the Center of Excellence in Polymer Science and Engineering at IIT, and Departments of Chemistry and Materials Science and Engineering at UIUC. New Initiatives, such as the $25 million Center for Hierarchical Materials Design, are reinforcing Illinois' strengths in advanced materials by combining materials science and chemistry with computational expertise to drive new materials research and innovation in polymers. This unparalleled research base is augmented by a substantial chemicals manufacturing industry. Large companies such as Amcol, Honeywell, Molex, Nalco, and UOP are joined by early-stage companies such as Autonomic Materials (AMI), Elevance Renewable Sciences, and Polyera, which were founded on university research.

As an indication of the immense economic potential of commercializing advanced polymer materials, in 2011 and 2012 Elevance Renewable Sciences raised a total of more than $200 million in venture capital funding—Illinois' largest round of venture capital funding over the past decade. Its growth would not have been possible without the combination of executive expertise from the existing chemicals industry in Illinois and the cutting-edge university research at the core of Elevance's innovations.

Cluster performance

Research
Illinois provides leadership in polymer-related disciplines such as chemistry, chemical engineering, and materials science, all of which score above the 90th percentile in publication impact.

Commercial potential
Patent classes related to polymers include compositions patents—the highest commercial potential of any patent class in Illinois—as well as other patenting strengths significantly above the comparator state average in quality.

Cluster development
Analysis found potential connections to a wide range of large manufacturers in the state as well as cutting-edge startups that are commercializing advanced materials or related products.

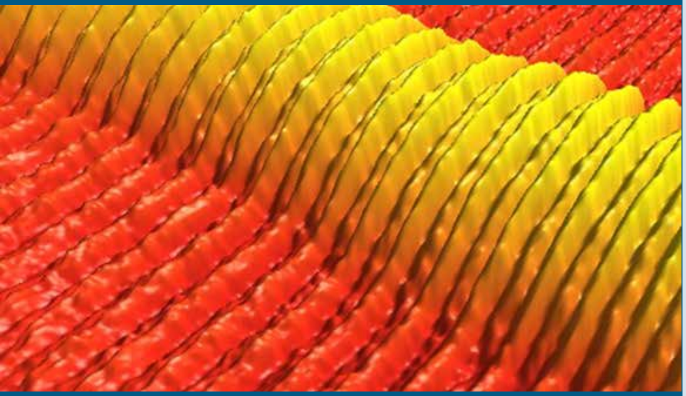
Polymers cluster analysis findings

An analysis of the potential connections between Illinois' research universities and industry (green ties) reveals opportunities in both organic and synthetic polymers (see polymers cluster map on page 40). Focusing on ties more likely to be associated with polymeric materials, we see a pattern of alignment between academic research in polymers, a diverse manufacturing industry, and startups commercializing innovations in materials technology. Multiple potential touch points suggest opportunities to harness university research through collaboration with large Illinois-based manufacturers, including Amcol, Elevance Renewable Sciences, Molex, Nalco, Panduit, Parker Heneffin, UOP, and USG. Other companies with demonstrated innovation activity in Illinois include 3M, BP, and Siemens. Opportunities for collaboration that can accelerate startup commercialization efforts are also pronounced, including 10x Technologies, Applied Thin Films, Nanosphere, and Polyera.

The polymers cluster network exhibits a particularly vibrant opportunity for increased collaboration. Approximately 96 organizations currently work in polymers, and 4,112 potential connections can be modeled based on available research and patent data. Up to 49 percent of potential connections link back to the academic institutions. This pattern of potential research collaborations reflects the broad spectrum of applications of Illinois' university research in materials and polymers in the context of the state's diverse manufacturing base: The network exhibits a high degree of concentration, with 87 percent of potential connections between pairs with more than one connection and a clustering coefficient of 0.79—indicative of a network characterized by strong organization but a slightly inward, closed view.

Industry collaboration spotlight

University of Chicago's Institute of Molecular Engineering (IME)

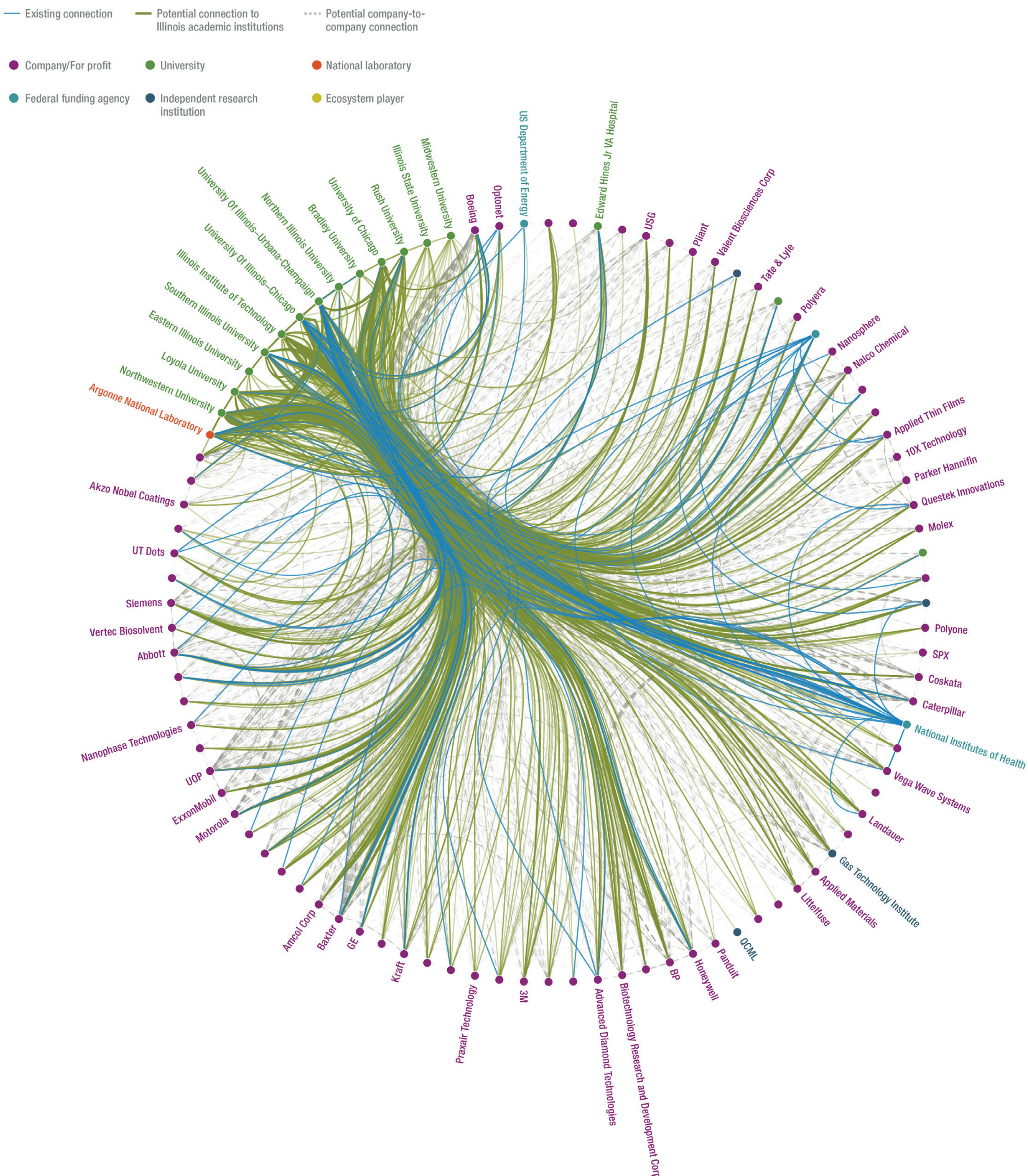


This atomic force microscope image shows directed self-assembly of a printed line of block copolymer on a template prepared by photolithography.

Solutions to some of the world's most pressing challenges in energy, health, and production of new devices will require discoveries at the molecular level and new advanced materials with unique properties. Created in 2011, the University of Chicago's Institute of Molecular Engineering (IME) ushers in a new era of interdisciplinary molecular research and an intensified effort around translating discoveries from across the university's scientific departments including through industry partnerships. Organized around several research themes and in conjunction with new commercialization mechanisms led by the Chicago Innovation Exchange (CIE), IME researchers and collaborators use molecular engineering to address high-impact societal issues. One focus is using nanopatterning and nanolithography to improve the understanding of self-assembled nanostructures and materials that could reduce manufacturing costs and enable a new generation of electronic, medical, and mechanical devices.

Additional opportunity: IME represents one example of multidisciplinary research initiatives with application to new materials and polymeric materials development. Increased connections between these centers and Illinois companies will harness the documented research strengths of Illinois institutions to develop and validate new polymers, providing an advantage for local companies and serving as a magnet for business attraction.

Polymers cluster map



Source: Created by Dr. C. Scott Dempwolf (University of Maryland) and ISTC using NodeXL

Polymers collaboration scorecard

Metrics

Organizations (companies and research institutions) **96**	Unique potential connections **553**
Total potential connections **4,112**	Percentage of connections linked to academic institutions **49%**
Multiplex percentage (share of pairs with multiple potential connections) **87%** Illinois average is **43%**	Connectivity index (measure of cluster integration) **0.79** Optimal for innovation: **0.4–0.7**[3]

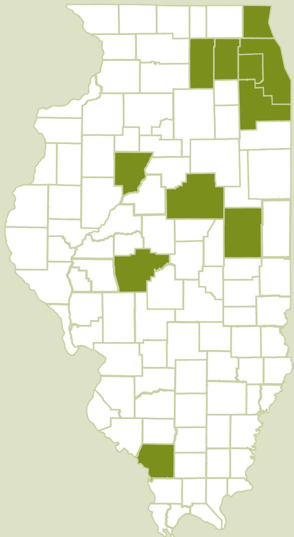
Illinois impact

Relevant industries from state economic development plan[1]

- **Advanced materials**
- **Agribusiness, food processing, and technology**
- **Biomedical and biotechnical**
- **Clean energy**
- **Information technology and telecommunications**
- **Machinery and fabricated metals product manufacturing**
- **Transportation and logistics**

Leading counties[2]

- **Champaign**
- **Cook**
- **DeKalb**
- **DuPage**
- **Jackson**
- **Kane**
- **Lake**
- **McLean**
- **Peoria**
- **Sangamon**
- **Will**



Research impact
as measured by field-weighted citation impact (FWCI)[4]

Leading research areas	FWCI (average = 1.0)
Inorganic chemistry	**1.46** (+46%)
Ceramics and composites	**1.27** (+27%)
Surface coatings and films	**1.26** (+26%)
Materials chemistry	**1.15** (+15%)
Polymers and plastics	**1.02** (+2%)

Related patent strengths
as measured by OTR™ 5

Leading patent classes	OTR™ (average = 100)
Compositions	**126.4**
Coatings	**122.7**
Compositions: coating or plastic	**121.9**
Chemistry of inorganic compounds	**115.1**
Resins	**114.1**

Community[2]

Key research institutions

- **Illinois Institute of Technology**
- **Northwestern University**
- **Southern Illinois University**
- **University of Chicago**
- **University of Illinois at Urbana–Champaign**

Federal funders

- **Department of Defense**
- **Department of Energy**
- **National Institute of Standards and Technology**
- **National Science Foundation**

Notable companies

- **Boeing**
- **BP**
- **Elevance Renewable Sciences**
- **Polyera**
- **UOP**

[1] *The Illinois economic development plan*, Department of Commerce and Economic Opportunity (DCEO), July 2014.
[2] Innovation activity measured based on datasets used to create the Illinois technology cluster network model.
[3] A connectivity index below 0.4 indicates a lack of cluster integration. A value above 0.7 suggests an increasingly insular community with more limited assimilation of new ideas and partnerships.
[4] The U.S. average FWCI is 1.0; therefore, a score of 1.5 indicates Illinois research publication strength is 50 percent above the national average.
[5] The OTR™ system employs a regression model to determine the probability that a patent will be maintained—an indication of patent quality.

Related research strengths

Data analyzed in Part I of this report demonstrated that Illinois' core research strengths are anchored in exceptional performance in chemistry, chemical engineering, and materials science, all of which are at the core of basic research in polymers. In addition, several subfields with a close link to polymers exhibited exceptional quality, including inorganic chemistry, ceramics and composites, surface coatings and films, and materials chemistry (see polymers scorecard on page 41).

In patenting and commercial potential, we found that polymer-related patenting by both universities and industry exhibited the highest quality of all patent classes in Illinois, with compositions and compositions: coating or plastic patents scoring an average of 12.6 and 6.9 points, respectively, above the OTR™ average of 17 comparator states. The commercialization potential of related patents was 30 to 60 percent above the sample average.[26] Patent commercial potential in other classes related to polymers, including coatings, resins, and inorganic compounds, also showed outstanding quality (see scorecard).

Promising technical areas

Pathways for polymer commercialization can be broadly classified into two categories. Joint development builds upon sponsored research between university and industry and requires a large manufacturing capacity to fully demonstrate the technology. Alternatively, commercialization can also advance through startups focused on proving new synthetic methods or developing polymer platform technologies. Recent research and commercialization successes in Illinois indicate two technical areas of particular promise:

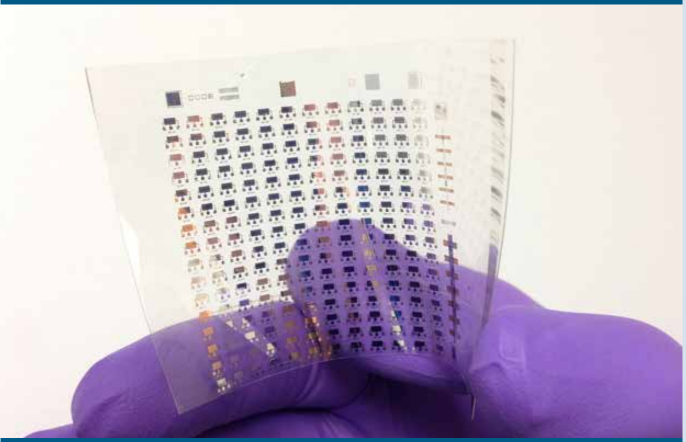
Self-healing polymers. Still a nascent platform technology, self-healing polymers refer to polymeric materials modeled after processes in plants (biomimetic) and other organic matter that can partly regenerate after damage. Pioneered by researchers at the University of Illinois at Urbana–Champaign, self-healing polymers technology has transformative implications in aerospace, electronics, and even medicine. AMI, based at the EnterpriseWorks incubator at UIUC's research park, represents one recent commercialization success in self-healing polymer technology. Founded by UIUC researchers who discovered ways to create self-healing coatings, AMI's innovations address the needs of the large market for corrosion resistant coatings and structural composites. In 2011, AMI announced that it had also successfully applied self-healing technology to electronic circuits with major efficiency implications for the semiconductor industry.

Electricity-conducting polymers and composites. Polymers and organic composites capable of electric conductivity are transforming the future of electronics. Next-generation semiconductors and electronics will be printed on flexible and dissolvable organic and synthetic materials. Some of the world's leading researchers and commercialization efforts in flexible electronics are based in Illinois, with leadership from Northwestern University and UIUC. (To read about the work of one of UIUC's leading nanotechnology innovators, see sidebar, "Innovator spotlight: Dr. John Rogers," on page 72.)

[26]For more information, see the abridged methodology on page 80.

Company spotlight

Polyera



A flexible microprocessor chip printed on a polymeric material developed by Skokie-based Polyera.

Polyera is at the forefront of a revolution in flexible microelectronic components made possible by novel, polymeric, electricity-conducting materials originally discovered at Northwestern University. In Polyera's Chicago facilities, its scientists—chemists, materials scientists, and physicists—are commercializing new materials for flexible transistors and developing new manufacturing processes in printing and photolithography to enable the production of flexible electronics scalable. Polyera's technology has multiple applications, including two of the world's fastest growing markets: mobile technology and the Internet of Things. Since its founding in 2006, Polyera has grown to more than 50 employees and established a global presence.

Additional opportunity: Polyera's success exemplifies how Illinois' industry-leading research and talent pool in the chemical and materials sciences can serve as the basis for new ventures to develop disruptive technologies. Retaining and scaling similar polymeric materials ventures can be supported by access to advanced materials incubation and testing, through either stand-alone facilities near academic institutions or access to university expertise and infrastructure.

Supporting the polymers innovation cluster

Illinois is at the epicenter of research in polymer platform technologies that have the potential to revolutionize entire industries and create new ones. Retaining this research in Illinois by expanding opportunities for testing and development will need to be a critical goal of economic development strategies focused on advanced materials commercialization. In addition, Illinois' diverse industrial base and strength in specialty chemicals manufacturing offer rich opportunities for collaborative research and joint development projects between leading university research and Illinois industry. Illinois policies and programs related to polymers should seek to achieve the following goals:

1. Establish specialized testing and demonstration facilities where polymer entrepreneurs can share expertise and work with industry partners on feasibility testing and joint development related to polymer innovations.

2. Extend access to university polymer research facilities beyond the academic community to include small businesses and corporate researchers from Illinois' chemicals industry and beyond.

Batteries and energy storage

Cluster performance

Research
Illinois research shows strengths related to batteries and energy storage including energy and power technology, energy, and electrochemistry. Almost 10 percent of energy patents nationwide cite Illinois publications as foundational knowledge.

Commercial potential
Illinois companies demonstrate high commercial potential in patents in power systems and chemical energy production.

Cluster development
Illinois has a strong battery research community with potential to better integrate with industry end users.

The wide array of applications for battery technology—from cell phones and electric vehicles to power transmission and storage—has created immense demand for new designs that provide high capacity, longevity, and quick charging. As a result, the potential market for innovations in batteries and energy storage is large and expanding rapidly. The McKinsey Global Institute, for example, pegged energy storage as one of the top 12 economically disruptive technology areas in the coming years.[27]

Illinois research institutions actively collaborate and engage industry to develop advanced energy storage technologies. The state's flagship Joint Center Energy Storage Research (JCESR), which was established with funding from the U.S. Department of Energy (DOE) and is led by Argonne National Laboratory, has become a hub for academia and industry. In addition, organizations such as Energy Foundry, Illinois Smart Grid Regional Innovation Cluster, and Clean Energy Trust have attracted private and public (state and federal) funding to create a nascent but growing startup ecosystem that supports companies coming out of academic institutions (both universities and national labs). These battery startups have a vibrant customer base in Illinois who can not only purchase the end products but also partner on the technology development. Many anchor Illinois corporations from heavy equipment to hardware to retail are pursuing more efficient, lower-cost battery and energy storage options—a need demonstrated through the Illinois Corporate–Startup Challenge, which paired Fortune 500 companies with several battery and energy storage startups based on industry-identified technology demand.

Batteries and energy storage cluster analysis findings

Our analysis of the battery and energy storage network in Illinois revealed a technology cluster centered on a core of academic research and a small contingent of battery design companies with strong potential to plug into a broad end-user base. Realizing this opportunity will require both increased collaboration within the existing battery design and materials subclusters and greater connectivity to companies with commercialization capacity that will benefit from partnering to support energy storage research.

Green ties in the cluster map on page 46 show the many potential connections between academic institutions and the industry organizations that can support research and commercialization, including strong potential ties to end users such as John Deere and Motorola (Illinois Corporate–Startup Challenge participants) as well as materials innovators such as UOP and battery manufacturers such as Navitas. Gray ties show additional

[27] *Disruptive technologies: Advances that will transform life, business, and the global economy*, McKinsey Global Institute, May 2013.

opportunities for materials companies to partner with end users.[28] Notably, companies who are part of the Rockford aerospace cluster—including B/E Aerospace, GE, Hamilton Sundstrand (UTC Aerospace), and Honeywell—have many potential connections to academic institutions.

The Illinois technology cluster network model identified potential research collaborations that connect federal funding agencies, academic institutions (universities and national labs), and small companies. Specifically, we identified a total of 117 institutions with 1,061 unique possible pairings and 4,447 total collaboration opportunities, with 76 percent of institutions displaying multiple collaboration touch points to a given partner; given Illinois' average of 43 percent having multiple collaboration opportunities, this three-quarters share indicates strong alignment on technology interests among those in the energy storage field. Notably, 13 percent of these opportunities link to academic institutions that can help translate basic electrochemistry and materials research into prototypes and products.

[28] In an effort to make the visualization of each technology cluster easier to follow and to emphasize the potential for further connectivity within clusters, existing ties such such inventor and some sponsored research ties are not shown. The model does not include proprietary industry data such as technology licensing and joint development agreements.

Company spotlight

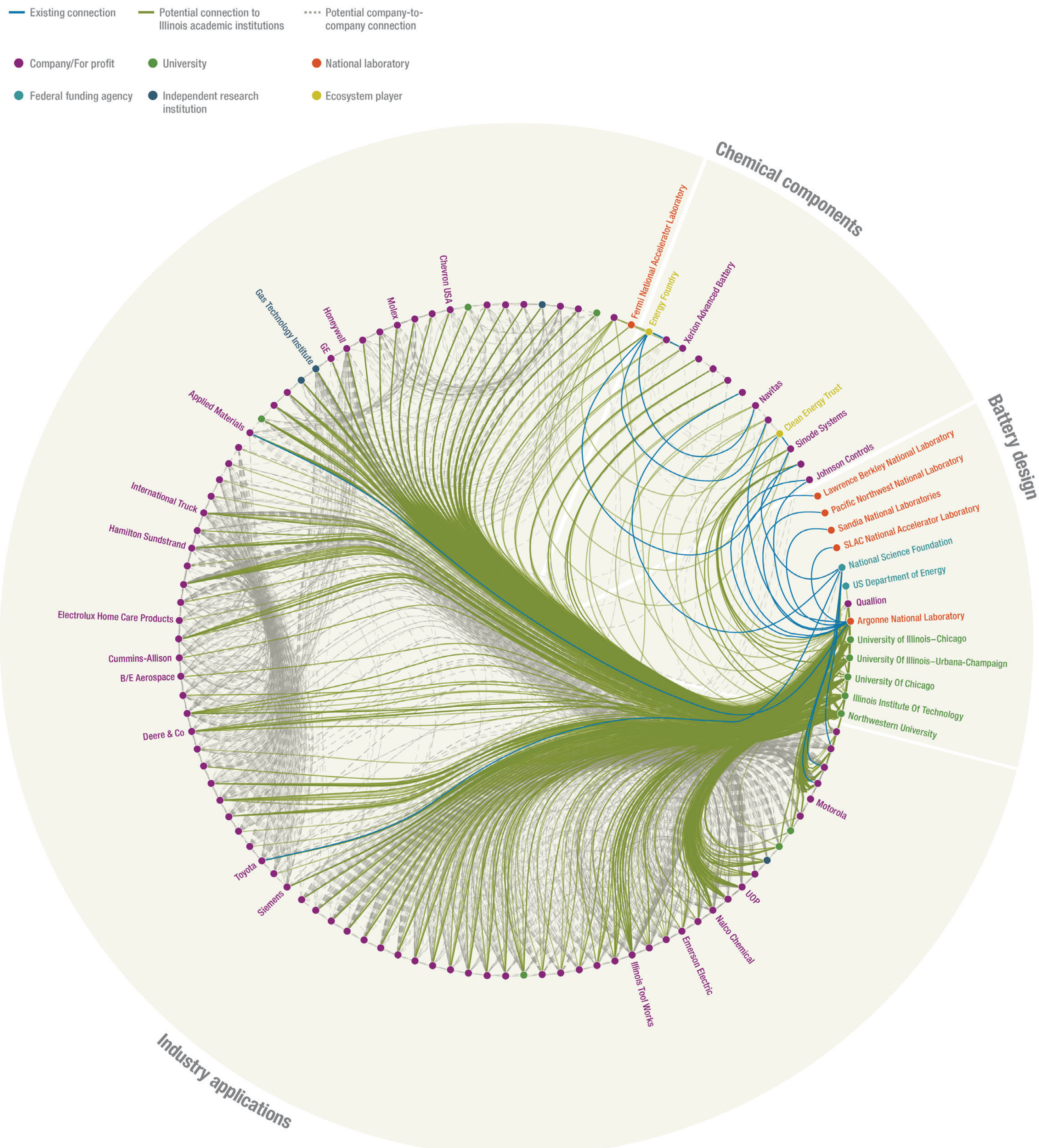
SiNode Systems

The SiNode Systems team showcasing early prototypes of their graphene-based anode battery solution.

With the goal of developing a longer-lasting lithium-ion battery, SiNode Systems is an advanced materials startup seeking to commercialize a new graphene-based anode. Based on IP initially developed via collaboration between Argonne National Laboratory and Northwestern University, SiNode was launched through the Northwestern NUvention Energy course. The company has grown through broad support and investment from the Illinois battery technology ecosystem, including investment and business development assistance from Energy Foundry, Illinois Smart Grid Regional Innovation Cluster, and Clean Energy Trust. Housed at the Illinois Institute of Technology's University Technology Park, SiNode has received numerous awards, including SBIR Phase I and 2 grants, along with top prizes at the U.S. Department of Energy (DOE) and Rice business plan competitions. As a participant in the Illinois Corporate–Startup Challenge, SiNode connected with Motorola Mobility, which has mentored the company, shared technology, and provided sponsorship to attend the Mobile World Congress in Barcelona.

Additional opportunity: As with many Illinois battery innovators, SiNode's technology is currently in the prototype phase and thus requires access to capital and customers to further develop and validate their product. Access to Illinois' rich talent and high-tech R&D facilities, like those at Argonne, would also accelerate the company's growth. Additionally, scaling production is challenging given intellectual property considerations with foreign battery manufacturers who dominate the market, highlighting the need to foster increased battery manufacturing activity in the U.S.

Batteries and energy storage cluster map



Source: Created by Dr. C. Scott Dempwolf (University of Maryland) and ISTC using NodeXL

Batteries and energy storage collaboration scorecard

Metrics

Organizations (companies and research institutions) **117**	Unique potential connections **1,061**
Total potential connections **4,447**	Percentage of connections linked to academic institutions **13%**
Multiplex percentage (share of pairs with multiple potential connections) **76%** Illinois average is **43%**	Connectivity index (measure of cluster integration) **0.61** Optimal for innovation: **0.4–0.7**[3]

Illinois impact

Relevant industries from state economic development plan[1]

Advanced materials

Agribusiness, food production, and technology

Biomedical/ biotechnical

Clean energy

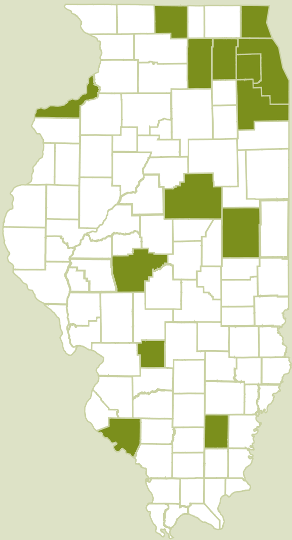
Information technology and telecommunications

Transportation and logistics

Machinery and fabricated metals product manufacturing

Leading counties[2]

Bond
Champaign
Cook
DeKalb
DuPage
Hamilton
Kane
Lake
McLean
Randolph
Rock Island
Sangamon
Will
Winnebago



Research impact

as measured by field-weighted citation impact (FWCI)[4]

Leading research areas	FWCI (average = 1.0)
Catalysts	**1.62** (+62%)
Electrochemistry	**1.25** (+25%)

Related patent strengths

as measured by OTR™[5]

Leading patent classes	OTR™ (average = 100)
Chemistry: Electrical current producing apparatus, product, and process	**122.4**
Electricity: Measuring and testing	**108.6**
Electricity: Battery or capacitor charging or discharging	**105.2**

Community[2]

Key research institutions

Argonne National Laboratory

Energy Frontier Research Centers—Northwestern and Argonne

Gas Technology Institute

Illinois Institute of Technology

Joint Center Energy Storage Research (JCESR)—Argonne, Northwestern, The University of Chicago, UIC, UIUC

Northern Illinois University

Northwestern University

Southern Illinois University

University of Illinois at Urbana-Champaign

Federal funders

Department of Energy

Department of Defense

National Science Foundation

Small Business Administration

Notable companies

Applied Materials, Inc.

GE

Honeywell

John Deere

Molex

Motorola Mobility

Navitas

[1] *The Illinois economic development plan*, Department of Commerce and Economic Opportunity (DCEO), July 2014.
[2] Innovation activity measured based on datasets used to create the Illinois technology cluster network model.
[3] A connectivity index below 0.4 indicates a lack of cluster integration. A value above 0.7 suggests an increasingly insular community with more limited assimilation of new ideas and partnerships.
[4] The U.S. average FWCI is 1.0; therefore, a score of 1.5 indicates Illinois research publication strength is 50 percent above the national average.
[5] The OTR™ system employs a regression model to determine the probability that a patent will be maintained—an indication of patent quality.

Related research strengths

Illinois is well positioned to be a leader in batteries and energy storage innovation. We found that chemistry and materials science research, including that related to batteries, are among the strongest STEM research fields in Illinois. Leading fields include chemistry research in catalysis and electrochemistry, which perform 62 and 25 percent above average in research publication impact, respectively, as measured by Elsevier's field-weighted citation impact (FWCI).[29]

Illinois' energy-related publications were cited in almost 10 percent of all energy patents nationwide—a figure that reinforces the value that inventors place on Illinois energy research. Illinois also demonstrates strong performance in energy patenting; Illinois inventor patents have an average Ocean Tomo Ratings™ (OTR™) score of 122.4, 3.7 points above the comparator state average for electrochemical-producing apparatuses.[30] Two other areas of Illinois' patenting related to battery production—electricity: measuring and testing as well as battery or capacitor charging and discharging—each demonstrating above average performance.

Unrealized collaboration opportunities

The Illinois batteries and energy storage cluster is led by three main types of stakeholders:

R&D institutions. Rooted in the JCESR collaboration network, this category includes major Illinois universities and national labs.

Component materials developers. Promising Illinois companies include startups SiNode Systems (see sidebar, "Company spotlight: SiNode Systems," on page 45), Xerion Advanced Battery Corporation, and battery maker Navitas.

End users. Consistent with cross-cutting demand for battery technologies, our analysis indicates potential ties to diverse industry applications such as aerospace, automotive and heavy equipment, healthcare, commercial buildings, and consumer electronics.

For this nascent and growing cluster, platforms such as JCESR are positioned to help realize these potential ties. Through JCESR, companies such as Applied Materials, Dow Chemical, and Johnson Controls are actively partnering with academic institutions to support battery materials and electrochemistry development. Better integration of battery and component materials designers will facilitate market-driven innovation and provide access to end-user customers who can help develop and pilot new materials.

[29] For more information on FWCI and how it measures research publication impact, see abridged methodology on page 80.

[30] For more information on OTR™ and the comparator state sample, see abridged methodology on page 80.

Promising opportunities

Illinois has made significant contributions to the development of the batteries and energy storage technology, including Argonne's work on the battery design for the Chevy Volt (see sidebar, "Industry partnership spotlight: Argonne[en dash]General Motors collaboration on Chevy Volt battery," on page 50). Three technical areas provide opportunity for the state to lead new markets:

Lightweight, high-capacity vehicle batteries. Illinois institutions have received federal funding to support the development of more advanced vehicle batteries. In August 2013, the Illinois Institute of Technology (IIT) was awarded $3.4 million from the US Department of Energy's (DOE) Advanced Research Projects Agency to increase the capacity and range of electric automobiles.[31] In August 2014, DOE directed $55 million to support 31 research projects, with Argonne receiving $2 million.[32]

Energy storage for power grids. Companies, institutions, and communities are exploring ways to harness renewable energy to augment the traditional power grid. The Shedd Aquarium has identified a critical reliability need for, and is in negotiations to procure, grid-scale energy storage to augment and ultimately replace its current back-up generation. This system will provide a one-megawatt energy storage system to improve the reliability of its solar panels and enable its participation in the retail energy markets, providing access to additional revenue. Such demonstration projects help create new markets for battery innovations.

Battery manufacturing. Existing overseas battery manufacturing limits innovation due to IP considerations and diminishes economic benefit domestically. Tesla has announced plans to ramp up domestic manufacturing through the new "gigafactory" in Nevada and its supply chain. Illinois is positioned to be a key part of Tesla's supply chain given the state's recent innovations, high-skilled talent, and manufacturing capabilities that can be focused on battery production with new infrastructure and training.

[31] "ARPA-E awards IIT-Argonne team $3.4 million to for breakthrough battery technology," Argonne National Laboratory, August 30, 2013.

[32] "Energy Department invests more than $55 million to advance efficient vehicle technologies," U.S. Department of Energy, August 14, 2014.

Industry partnership spotlight

Argonne–General Motors collaboration on Chevy Volt battery

Materials research and the Advanced Photon Source at Argonne National Laboratory were instrumental in developing new cathode materials currently used in the battery for the Chevy Volt. These materials, which are rich in manganese and lithium, enable a radical leap forward in the cost and performance of lithium-ion batteries, making them cheaper, safer, and longer lasting. This outcome was catalyzed by the US Department of Energy's (DOE) Office of Science investment in an intensive study of lithium-ion batteries at Argonne in the late 1990s and translated through support from DOE's Office of Energy Efficiency and Renewable Energy.

Additional opportunity: Despite the project's success, the secondary economic impact of this work was not fully captured in Illinois. The technology was licensed to Envia Systems, a Silicon Valley company funded in part through a $7 million General Motors investment.[1] BASF, which also licensed Argonne's cathode material research, opened a battery facility in Elyria, Ohio, to manufacture cathode materials.

[1] Lindsay Riddell, "Battery maker Envia Systems charging ahead," *Silicon Valley Business Journal*, March 11, 2011.

The innovative cathode materials for the Chevy Volt battery shown in the photo were developed at Argonne National Laboratory.

Supporting the batteries and energy storage cluster

Illinois' concentration of employment in this industry is only 0.34—a substantially lower concentration level compared with the national average of 1.0—but Illinois has one of the most sophisticated research capabilities in this emerging industry. Our analysis of research and patent impact and output as well as Illinois' existing network reveal a substantial opportunity to promote intensified commercialization and industry development in this area. To build on the state's research foundation and maximize the impact of ongoing activity, Illinois should pursue five strategies:

1. Use the Illinois batteries and energy storage cluster model described in this chapter to identify and convene potential commercialization partners for JCESR and Illinois academic research institutions.

2. Increase connections between startup companies and established firms to Argonne's experts and facilities, IIT's microgrid, and other Illinois research infrastructure.

3. Establish core facilities and test beds for battery startup companies to develop technologies, designs, and products for pilots and consumer testing.

4. Pursue mechanisms to scale and manufacture battery technologies in Illinois coupled with relevant infrastructure and workforce development efforts.

5. Continue to improve supply chain opportunities and promote new applications for residential and commercial markets through demonstration projects.

Biofuels and biomass-derived products

Cluster performance

Research
Illinois research in applied microbiology, biomaterials, bioengineering, and genetics exceeds the national average, indicating research strengths across the research spectrum related to bioenergy and biomass-derived products. University research is complemented by local industry research.

Commercial potential
Illinois patenting in biotechnology--a key driver of biofuels and biomass-derived products--is double the average volume of 17 other leading innovative states. Illinois patent quality in this area is almost two standard deviations above the mean for this same group of states.

Cluster development
A very high degree of multiple potential connections between potential partners suggests strong alignment throughout the research network. A sizable research base of established and growth-stage companies offers extensive opportunity to promote cross-sector collaboration.

Food and energy security are vital to the sustainability and competitiveness of Illinois and the United States. With 76,000 Illinois farms covering 28 million acres (nearly 80 percent of the state's total land area), Illinois has long been a key player in U.S. agricultural production. Each year, Illinois corn is used to produce 678 million gallons of ethanol—more than any other state. Bio-ethanol is then mixed into fuel to reduce cost, improve engine performance, and decrease environmental impact. According to McKinsey research, the biofuels and biomass market accounts for an increasing share of the total energy market; by 2020, the industry is projected to grow to $544 billion from $203 billion in 2008.[33]

While growth in the production of corn crops and other biomass feedstocks translates to an expansion of the raw materials available for biofuels and biomass-derived products, several technical (as well as market access and legal) barriers exist to realizing this cluster's potential. Illinois must embark on concentrated efforts to link researchers with agricultural companies, engine manufacturers, and industry fuel formulators and consumers.

A key to bringing industrial and agricultural biotechnology products, particularly biofuels and biomass-derived products, to market is scaling production capacity from laboratory through pilot and demonstration scale to commercial production. Facilities such as the National Corn-to-Ethanol Research Center (NCERC) at Southern Illinois University–Edwardsville (SIUE)—a unique facility researching and piloting corn ethanol, cellulosic ethanol, and advanced biofuels—provide infrastructure and expertise to help scale laboratory technologies and processes. In January 2015, the University of Illinois will break ground on the Integrated Bioprocessing Research Laboratory (IBRL), a state-of-the-art pilot facility and analytical laboratory. The $25 million, state-funded project will bridge the gap in Illinois between laboratory-scale research and the large-scale capabilities of NCERC.

Increasingly, startups are also bridging this gap between laboratory and production scale. Based on research at the University of Illinois, TetraVitae developed a new process for producing biobutanol, an energy-dense biofuel precursor and commodity chemical feedstock that is normally too toxic for microorganisms to produce at scale. This breakthrough led to the acquisition of TetraVitae's technology platform by Eastman Renewable Materials.

Biofuels and biomass-derived products cluster analysis findings

Our analysis of the biofuels cluster using the Illinois technology cluster network model revealed three groupings where Illinois academic institutions have clear potential ties for collaboration. First, the state has several large, well-established multinational companies with active

[33] "Expertise: Biosystems," Sustainability and Resource Productivity, McKinsey & Company.

research and product lines related to ethanol, biodiesel, and other alternative forms of energy, including Archer Daniels Midland, BP, INEOS, and Tate & Lyle.[34] The second group consists of companies that manufacture equipment related to either the processing of biofuels or the use of biofuels, including Caterpillar, Honeywell, John Deere, and Siemens. The third group, which may represent a primary target for the state's economic development efforts, includes smaller companies and startups such as Activa BioGreen, Coskata, GreatPoint Energy, and others that are commercializing or utilizing new, innovative technologies related to biofuels. Green ties in the cluster map indicate opportunities for each grouping to connect with academic research institutions.

The biofuels and biomass-derived products group has clear potential to be a strong, cohesive technology cluster in Illinois. The alignment between academia and industry as well as the large market potential suggest further development of this cluster will yield significant economic benefits. Previous collaborative efforts—such as that among Archer Daniels Midland, John Deere, and Monsanto to turn feed and crop residue into bioenergy products and higher-value animal feed for ruminants—reinforce the importance of joint R&D in this area and the opportunity for Illinois to become a hub for bioenergy innovation. To help coordinate existing individual activity and investment in this area, the State should promote greater network connectivity among companies in all three constituent groups and increased integration with local universities.

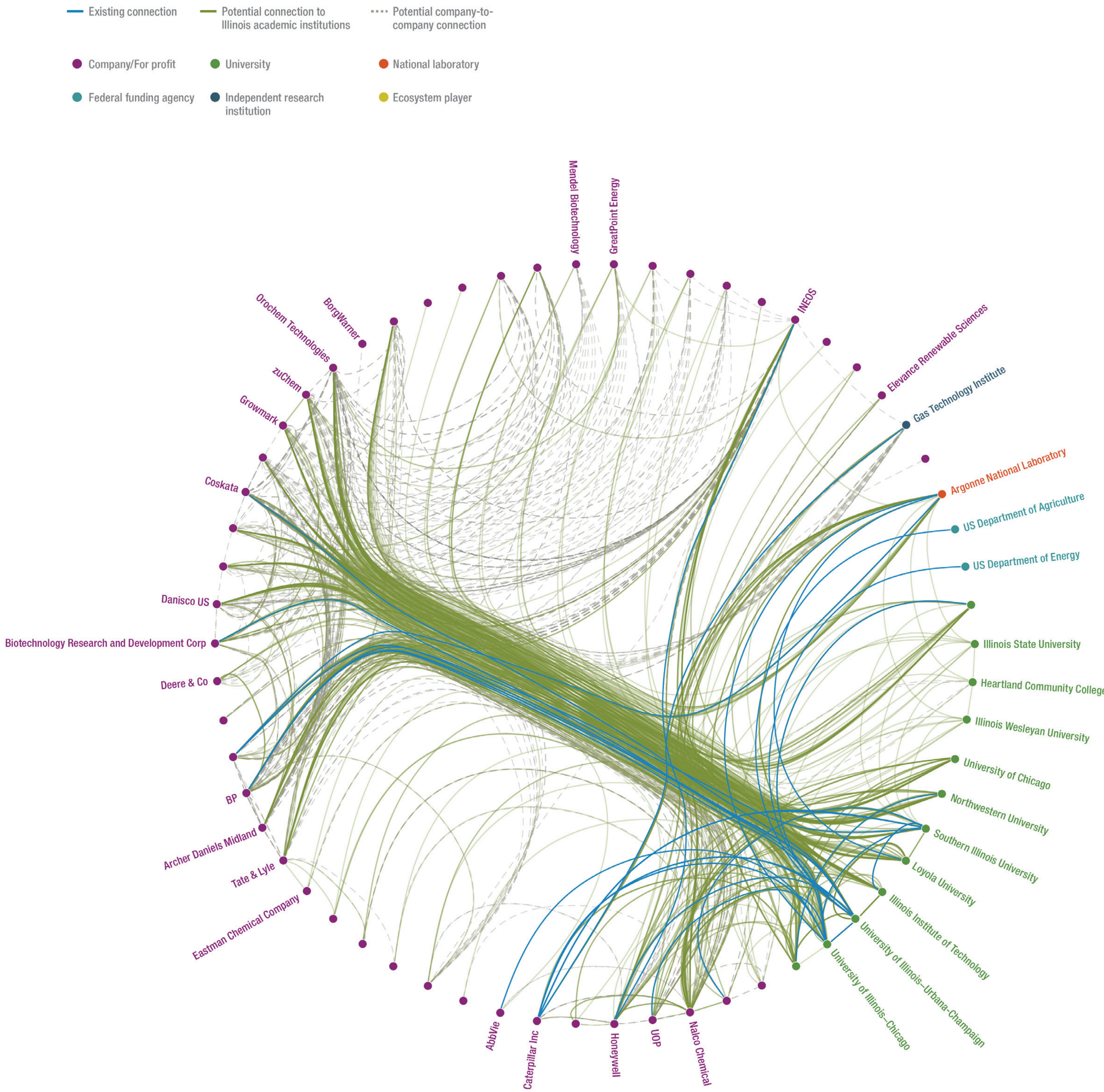
According to analysis of the Illinois technology cluster network model, the community for biofuels and biomass-derived products is smaller than other clusters—it has just 62 organizations—but relatively well organized, with 225 unique points of connections and a connectivity index of 0.56.[35] This number largely reflects organizations focused specifically on biofuels and biomass-derived product technology and process development but does not include companies focused on upstream agricultural research related to increasing biomass yield. Of the 1,483 potential ties in biofuels, 58 percent of connections involve academic research institutions, more than any other clusters examined in the roadmap.

The Illinois technology cluster network model detected limited participation of startup and small companies in biofuels innovation. The cost of scaling biofuels technologies supports this observation. Potential collaborations include academic institutions with companies such as Coskata, a biology-based renewable energy company, and zuChem, a producer of glycochemicals.

[34] Illinois also demonstrates significant activity and industry engagement in biotechnology research and a strong patenting performance by companies such as Monsanto and Syngenta. Since these activities are upstream direct biofuels innovation, not all are captured in the biofuels cluster snapshot.

[35] U.S. average connectivity is 1.0. Analysis based on available (as opposed to exhaustive) data.

Biofuels and biomass-derived products cluster map



Source: Created by Dr. C. Scott Dempwolf (University of Maryland) and ISTC using NodeXL

Biofuels and biomass-derived products collaboration scorecard

Metrics

Organizations (companies and research institutions) **62**	Unique potential connections **225**
Total potential connections **1,483**	Percentage of connections linked to academic institutions **58%**
Multiplex percentage (share of pairs with multiple potential connections) **85%** Illinois average is **43%**	Connectivity index (measure of cluster integration) **0.56** Optimal for innovation: **0.4–0.7**[3]

Illinois impact

Relevant industries from state economic development plan[1]

Advanced materials

Biomedical and biotechnical

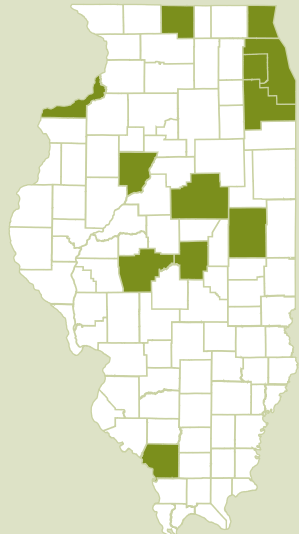
Clean energy

Machinery and fabricated metals product manufacturing

Transportation and logistics

Leading counties[2]

Champaign
Cook
DuPage
Jackson
Lake
Macon
McLean
Peoria
Rock Island
Sangamon
Winnebago
Will



Research impact
as measured by field-weighted citation impact (FWCI)[4]

Leading research areas	FWCI (average = 1.0)
Genetics	**1.23** (+23%)
Bioengineering	**1.21** (+21%)
Biomaterials	**1.13** (+13%)
Applied microbiology and biotechnology	**1.05** (+05%)

Related patent strengths
as measured by OTR™ [5]

Leading patent classes	OTR™ (average = 100)
Chemistry: Molecular biology and microbiology	**118.9**
Multicellular living organisms and unmodified parts thereof and related processes	**117.6**

Community[2]

Key research institutions

Argonne National Laboratory
Loyola University
Northwestern University
Southern Illinois University
University of Illinois at Chicago
University of Illinois at Urbana–Champaign

Federal funders

Department of Energy
Department of Agriculture

Notable companies

Large enterprises
Archer Daniels Midland
BP
INEOS
Tate & Lyle
UOP

Small and medium enterprises
Activa BioGreen
Coskata
Elevance Renewable Sciences
GreatPoint Energy

[1] *The Illinois economic development plan*, Department of Commerce and Economic Opportunity (DCEO), July 2014.
[2] Innovation activity measured based on datasets used to create the Illinois technology cluster network model.
[3] A connectivity index below 0.4 indicates a lack of cluster integration. A value above 0.7 suggests an increasingly insular community with more limited assimilation of new ideas and partnerships.
[4] The U.S. average FWCI is 1.0; therefore, a score of 1.5 indicates Illinois research publication strength is 50 percent above the national average.
[5] The OTR™ system employs a regression model to determine the probability that a patent will be maintained—an indication of patent quality.

Startup spotlight

Thermaquatica

A Process Development Unit (PDU) in the Thermaquatica lab at the Southern Illinois Research Park.

Founded by University of Southern Illinois at Carbondale (SIUC) professor Dr. Ken Anderson, Thermaquatica has developed a process to convert nonpetroleum materials including coal, agricultural waste, and other lignocellulosic materials into chemical feedstock and liquid fuels. Thermaquatica's oxidative hydrothermal dissolution (OHD) process uses only superheated water and oxygen to effect this conversion, eliminating the need for costly and toxic chemicals. Thermaquatica's innovative OHD process has the potential to generate cost-effective liquid fuels, decreasing our dependence on petroleum (foreign and domestic), all in an environmentally friendly way that does not rely on harsh chemicals or solvents or produce carbon dioxide and other noxious gases.

In 2011, the Illinois Clean Coal Institute awarded $950,000 to Thermaquatica in order to construct a multi-kilogram-scale unit for process scale and refinement.[1] The company also received $2 million from Green Power Energy in Australia in 2013 to support further development and ultimately commercial deployment.[2] The company is currently looking to validate the OHD process at pilot scale.

Additional opportunity: As discussed above, a key to biofuel and biomass-derived product commercialization is increasing laboratory production capacity to commercial scale. Without private investment, access to facilities such as NCERC at SIUE is cost prohibitive. By engaging the significant number of Illinois biofuel end users to support scaling and commercialization, companies can have the opportunity to develop technologies to the point where they can capture the potential benefits.

[1] "Thermaquatica partners with Greenpower Energy Limited to develop novel, environmentally friendly coal-to-liquids technology," press release, Southern Illinois University Carbondale Technology Transfer Program, June 1, 2013,

[2] "Greenpower signs agreement to license & fund technology to convert coal to higher value products," press release, Greenpower Energy, May 28, 2013.

Related research strengths

Illinois has a strong agricultural biotechnology research base, an industry engaged in the development of biofuels and biomass-derived products, and several large-scale engine designers such as Caterpillar and John Deere.

Genetics and bioengineering, two disciplines with close ties to biotechnology applications in bioenergy, outpace the national average in publication impact by 23 and 21 percent, respectively, as measured by Elsevier's field-weighted citation impact (FWCI).[36] Biomaterials and applied microbiology research are also among the state's high-impact research areas, further demonstrating Illinois' strength in biotechnology, a core driver of biomass yield and efficient conversion to bioenergy products.

In biotechnology-related patenting, Illinois boasts patent output 2.3 times the national average. This high volume reflects Illinois' and the Midwest's strong agricultural corporations as well as collaboration between Illinois innovators and agricultural companies both in and near Illinois. The combined average quality of Illinois' biotechnology patent classes have a combined Ocean Tomo Ratings™ (OTR™) average of 118.3, indicating the strong commercial viability of related inventions.[37]

[36] For more information on FWCI and how it measures research publication impact, see abridged methodology on page 80.

[37] Our analysis found the comparator state average OTR™ in this field is 100. For more information on OTR™ and the comparator state sample, see abridged methodology on page 80.

Promising opportunities

Given the critical mass of biofuels research and number of industry customers, galvanizing this nascent cluster has strong potential to generate additional markets for Illinois agricultural products. According to the Renewable Fuels Association, Illinois currently has 12 biofuels refineries; efforts to build the Midwest biofuels industry may increase this figure.

Biofuels public-private partnerships. Developing an industry-driven consortium of academic research institutions, biofuels producers, industry consumers, and government will enable stakeholders to coordinate resources and develop common priorities.

Bio-energy small business. Bio-energy startups in Illinois currently lack the same concentrated support that industries like medical technologies and digital technologies enjoy. The success of companies such as TetraVitae and production companies such as zuChem highlight the existing opportunity.

Position Illinois as an aviation biofuels and "bio-jet" hub. Illinois has an opportunity to position itself as a leader in aviation biofuel production, as highlighted in a 2013 report, *Fueling a sustainable future for aviation*, by the Midwest Aviation Sustainable Biofuels Initiative (MASBI)—a partnership between Boeing, Clean Energy Trust, Chicago Department of Aviation, United Airlines, and UOP. Illinois is home to a several OEMs and suppliers of aviation equipment that stand to benefit from increased efficiency and profitability in air travel, building on the reported $6.3 billion spent on jet fuel a year for flights originating in the Midwest. MASBI estimates that replacing just 5 percent of petroleum jet fuel in the region with aviation biofuel would create more than 3,600 jobs and reduce carbon-dioxide emissions by 700,000 tons—representing a significant opportunity for the Illinois biofuels cluster. As foreign countries move to require flights originating in the U.S. to use some percentage of bio-based fuel, Chicago's O'Hare airport has the opportunity to serve as a US "bio-jet" hub.

Industry collaboration spotlight

Energy Biosciences Institute

The University of Illinois Energy Farm, created as part of the Energy Biosciences Institute, is the world's largest outdoor research center devoted to bioenergy crops.

Looking to tackle the grand challenge of transitioning from petroleum-based to biomass-derived fuel, BP launched the $500 million Energy Biosciences Institute (EBI) in 2007 to bring together leading agriculture and biotechnology researchers.[1] The University of Illinois was selected as one of four research institutions to participate in this effort. Bringing together expertise and resources from the College of Agriculture, Consumer, and Environmental Sciences (ACES) and the Institute for Genomic Biology (IGB), the University of Illinois is working with BP scientists to engineer solutions that optimize biomass feedstock production and to develop new processes for producing biofuels. As part of the partnership, IGB created the 320-acre Energy Farm, the world's largest outdoor research center devoted to bioenergy crops.

Additional opportunity: EBI demonstrates the potential for public-private partnerships to pursue ambitious challenges at the nexus of agriculture and energy. Given the number of companies at this nexus in Illinois, creating a coordinated cluster or ecosystem that aligns resources and connects academic and industry researchers would help to position Illinois as a global leader in biofuel research.

[1] "About EBI," Energy Biosciences Institute, accessed August 29, 2014.

Supporting the biofuels and biomass-derived products cluster

Harnessing Illinois' strong agricultural and industrial biotechnology base to drive biofuels and biomass-derived product commercialization requires innovation and partnerships across agricultural sciences, biotechnology, and engineering. Several existing Illinois programs—including the University of Illinois' Center for Advanced BioEnergy Research, the Illinois Sustainable Technology Center, and the Advanced Energy Institute at Southern Illinois University at Carbondale (SIUC)—already reflect this multidisciplinary approach. Biofuels represent a pre-competitive field where large Illinois corporations can work together and with academic institutions to create new tools and technologies to improve scale and yield. To realize the full potential of the biofuels technology cluster, Illinois should pursue four strategies:

1. Build off the University of Illinois' partnership with BP through the EBI to engage Illinois industry in directing biofuels research.

2. Leverage NCERC and the upcoming IBRL facilities to position Illinois as a leader in piloting biofuels technologies and processes at multiple scales through outreach and potential matching funds.

3. Engage Illinois industry that commercializes or utilizes biomass-derived products to support startups and pilot-scale projects—a model that has been used by Ameren and ComEd with power grid technologies.

4. Link Illinois academic institutions with MASBI to support the agriculture research and innovation recommendations from their 2013 aviation biofuels report.

Medical biotechnology

Cluster performance

Research
Medical and life sciences represent one of Illinois' growing research strengths based on publication impact and output. Six of the top 20 research subdisciplines (out of more than 300) fall in this category.

Commercial potential
Biopharmaceutical and other biotechnology patents classes represent some of the highest quality intellectual property for both Illinois companies and universities based on the Ocean Tomo Rating System™. In the past five years, Illinois has produced 900 biopharmaceutical patents, an average growth rate of 27 percent during that time frame.

Cluster development
Technology cluster network model analysis reveals almost 6,500 new collaboration opportunities across academia and industry, including significant new partnership opportunities with industry and agricultural biotechnology expertise.

A 2013 Illinois Biotechnology Industry Organization (iBIO) report, *The economic engine of biotechnology in Illinois*, found that Illinois is the center of a Midwest biotechnology industry cluster, which contributes $98.6 billion in economic output and 369,000 direct and indirect jobs to Illinois. In addition, DCEO's economic development plan reported that four of ten Illinois regions have a specialization in the biomedical and biotechnology industries.[38]

The growing strength of Illinois' medical and life sciences research, large and diverse clinical populations, and the immense economic impact of successful products—combined with the critical mass of startups and industry focused on product development—has led to the launch of numerous efforts to promote biotechnology commercialization. Our analysis indicates a large medical biotechnology research cluster, with significant potential for interaction between its major groups—pharmaceuticals, medical devices, and diagnostics–with notable connection opportunities to industrial and agricultural biotechnology firms.

Medical biotechnology cluster analysis findings

In Part I, our analysis determined that biomedical and life sciences research is a growing strength across Illinois academic institutions; bibliometric data show significant growth in publication volume and impact between 2008 and 2012. Furthermore, 6 of the top 20 research subdisciplines by the Elsevier field-weighted citation impact (FWCI) measure of impact were in the biomedical and life sciences, indicating several existing strengths within the medical biotechnology cluster.

Based on data from Ocean Tomo, we found that biomedical patents secured by Illinois industry and universities demonstrate strong commercial potential. Illinois universities and companies collectively performed favorably compared with leading innovative states in patent potential in biomedical areas, with an exceptionally high performance in analytical and immunological testing related to medical devices and drug discovery.[39] Illinois university patents showed strong commercial potential in biopharmaceuticals and biotechnology—both scored well in the commercial potential index (CPI),[40] exhibiting a CPI 50 percent and 30 percent above the average compared with other Illinois university patents.

Our analysis of the Illinois technology cluster network model identified at least 229 participating organizations with 1,437 unique pairings (78 percent of these pairings demonstrate multiple potential connections) and a calculated 6,498 collaboration opportunities. Overall, 35 percent of these opportunities link to academic institutions.

[38] Specialization indicated by a location quotient (LQ) greater than 1.0.
[39] Based on patent volume and Ocean Tomo Ratings™ (OTR™) score
[40] The commercialization potential index (CPI) benchmarks the proportion of Illinois high-quality patents (defined by this report as patents with an OTR™ score at or above 135) in a given UPSC class against the sample average. A CPI of 1.0 represents a proportion of high-quality patents equal to the sample average in that patent class.

The medical biotechnology cluster consists of four primary areas of research and commercialization:

Pharmaceuticals

The largest group in the cluster, pharmaceuticals features a significant volume of industry-sponsored research with academic institutions. The Illinois technology cluster network model identified local pharmaceutical research and patenting activity at companies such as AbbVie and Takeda. Companies such as Astellas and Hospira were not detected by the Illinois technology cluster network model, likely due to their patenting activity not occurring or being registered in Illinois. Therapeutics is also an area where we see an alignment with small companies: Therapeutic Proteins International manufactures biologics such as recombinant protein therapies, while Vidasym is developing novel vitamin D receptor modulators to treat chronic kidney disease.

Diagnostics

Our network analysis highlighted many potential connections in diagnostics between academia and industry. Abbott—whose work cuts across diagnostics and devices—demonstrates strong academic collaboration potential. PTM Biolabs has commercialized several conjugate antibodies for proteomic testing and diagnostics uses. Nanosphere's Verigene System enables clinicians to identify and treat certain bacteria and viruses that cause complex and costly diseases. And Ohmx developed an electronic detection platform to analyze proteins, molecules, or DNA from small volumes of clinical samples.

Medical devices

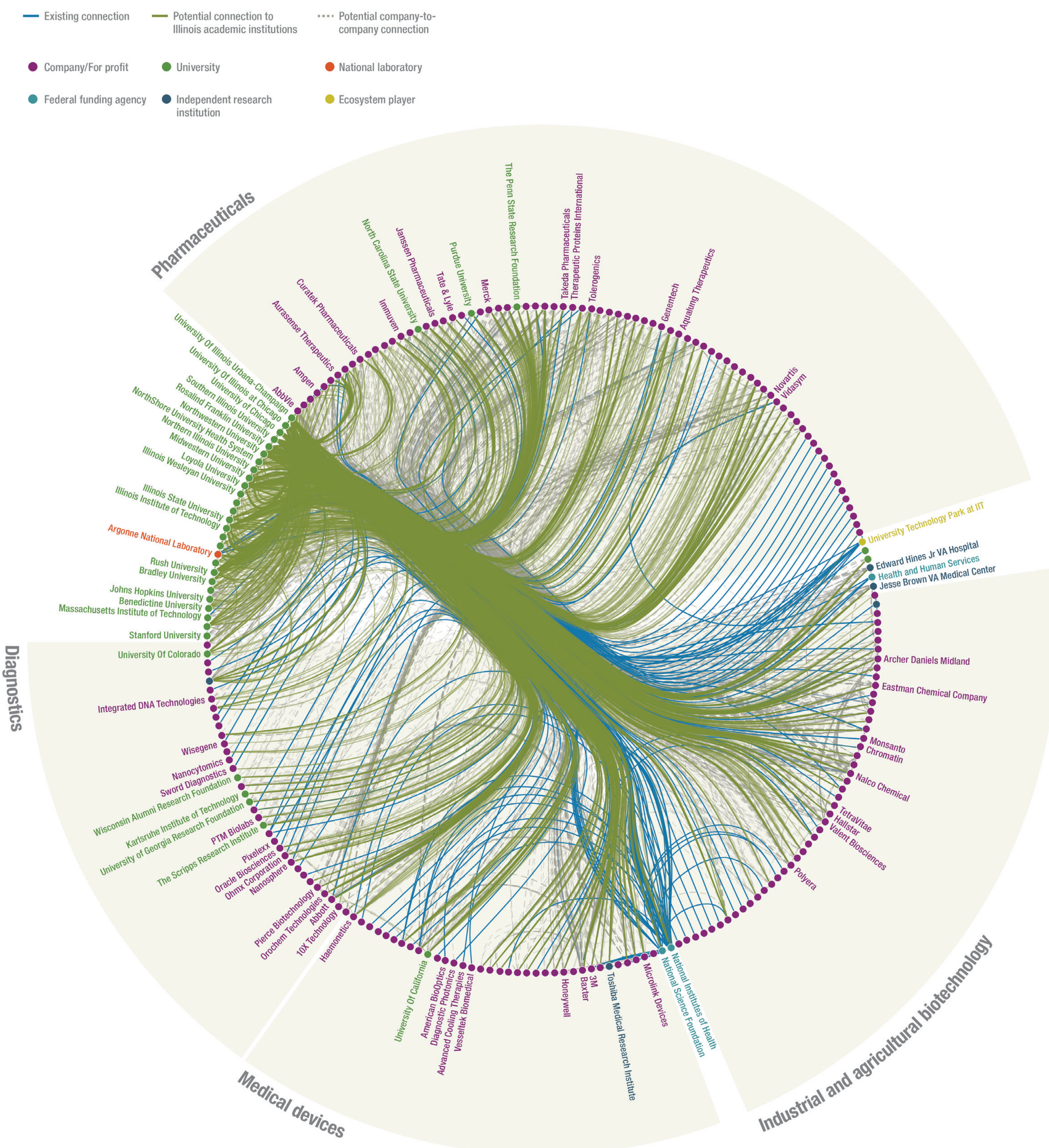
Major Illinois medical device companies include Baxter and Medical Toolworks, the medical products arm of Illinois Tool Works. Illinois' set of smaller companies includes Advanced Cooling Therapy, which developed a patented, disposable medical device that enables cost-effective patient temperature control through an esophageal route. One of Diagnostic Photonics' products, Foresee Imaging System, creates a live view of microtissue structure through a patented technology that creates diffraction-corrected images.

Industrial and agricultural biotechnology

Technology cluster network model analysis also revealed a strong connection between biomedical R&D in Illinois and the industrial and agricultural biotechnology sector. The model highlights the underlying talent and technology that drive this group; companies such as Archer Daniels Midland, Chromatin, Valent Biosciences, and zuChem have potential to create mutually beneficial relationships with Illinois' biomedical community in areas such as bioengineering and fermentation. As an example of this mutual reinforcement, Tate & Lyle (located in the pharmaceuticals subgroup, likely due to strong potential connections to drug manufacturers), maker of food additives and other agricultural and industry chemicals, invests in Cour Pharmaceuticals,[41] whose immune modulating nanoparticles are derived from an FDA-approved, biodegradable polymer.

[41] Cour Pharmaceuticals is not mapped in the medical biotechnology cluster because it licenses technology.

Medical biotechnology cluster map



Source: Created by Dr. C. Scott Dempwolf (University of Maryland) and ISTC using NodeXL

Medical biotechnology collaboration scorecard

Metrics

Organizations (companies and research institutions) **229**	Unique potential connections **1,437**
Total potential connections **6,498**	Percentage of connections linked to academic institutions **35%**
Multiplex percentage (share of pairs with multiple potential connections) **78%** Illinois average is **43%**	Connectivity index (measure of cluster integration) **0.52** Optimal for innovation: **0.4–0.7**[3]

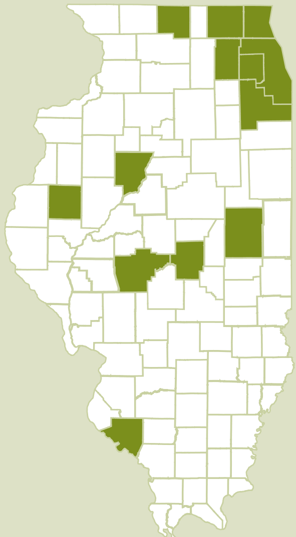
Illinois impact

Relevant industries from state economic development plan[1]

Biomedical and biotechnical

Leading counties[2]

- Champaign
- Cook
- DuPage
- Kane
- Lake
- Macon
- McDonough
- McHenry
- Peoria
- Randolph
- Sangamon
- Will
- Winnebago



Research impact
as measured by field-weighted citation impact (FWCI)[4]

Leading research areas	FWCI (average = 1.0)
Genetics	**1.23** (+23%)
Biochemistry	**1.12** (+12%)
Cancer research	**1.08** (+8%)
Molecular biology	**0.99** (–1%)
Molecular medicine	**0.98** (–2%)

Related patent strengths
as measured by OTR™ [5]

Leading patent classes	OTR™ (average = 100)
Chemistry: analytical and immunological testing	**129.5**
Chemistry: molecular biology and microbiology	**118.9**
Drugs, bio-affecting and body treating compositions	**116.5**
Biopharmaceuticals	**110.4**
Drugs, bio-affecting and body treating compositions	**104.5**

Community[2]

Key research institutions

- Loyola University
- NorthShore University Health System
- Northwestern University
- Rush University Medical Center
- Southern Illinois University
- University of Chicago
- University of Illinois at Chicago
- University of Illinois at Urbana-Champaign

Federal funders

- Department of Health and Human Services
- National Institutes of Health
- National Science Foundation

Notable companies

- Abbott
- AbbVie
- Baxter
- Takeda
- Nanosphere, Inc.

Notable startups

- Advanced Cooling Therapy
- Diagnostic Photonics
- Therapeutic Proteins International
- Vidasym

[1] *The Illinois economic development plan*, Department of Commerce and Economic Opportunity (DCEO), July 2014.
[2] Innovation activity measured based on datasets used to create the Illinois technology cluster network model.
[3] A connectivity index below 0.4 indicates a lack of cluster integration. A value above 0.7 suggests an increasingly insular community with more limited assimilation of new ideas and partnerships.
[4] The U.S. average FWCI is 1.0; therefore, a score of 1.5 indicates Illinois research publication strength is 50 percent above the national average.
[5] The OTR™ system employs a regression model to determine the probability that a patent will be maintained—an indication of patent quality.

Research and commercialization support

Biotechnology research is enabled by infrastructure and support mechanisms for R&D and translational activities that move research discoveries toward commercialized products.

R&D

Biomedical research is a core focus of Illinois research institutions, which received $749 million in funding from the National Institutes of Health (NIH) alone in 2012. In addition, corporate funding for life sciences research at Illinois' universities has been growing in recent years, reaching almost $75 million in 2012 (latest year for which data was available).[42] The state has several established R&D facilities that advance biotechnology research. The Chicago Biomedical Consortium (CBC), supported by the Searle Funds at The Chicago Community Trust, supports the development of research facilities across Illinois institutions and attracts federal funding to perform cutting-edge research to perform cutting-edge research, including $2 million for the NIH-funded Tri-Institutional Center for Chemical Methods and Library Development focused on small molecule drug discovery.

In addition, the Advanced Photon Source at Argonne provides drug discovery capabilities to help universities and companies identify new drug targets and potential therapeutics; AbbVie's Kaletra HIV drug is just one example.

R&D translation support

Over the past several years, the Illinois community has taken several important steps to build connections between universities, hospitals, startups, and industry. These efforts are central to bringing potential partners together and capitalizing on the unrealized connections identified through the Illinois technology cluster analysis. Notable examples include:

Physical spaces such as the University of Illinois HTI proof-of-concept center and MATTER, both of which were catalyzed by state investment.

Startup support programs, including the iBIO Institute PROPEL Center, whose support and training programs have helped biotech companies raise more than $120 million in investment, and Chicago Innovation Mentors, a partnership among Illinois universities and organizations to support new ventures through team-based mentorship.

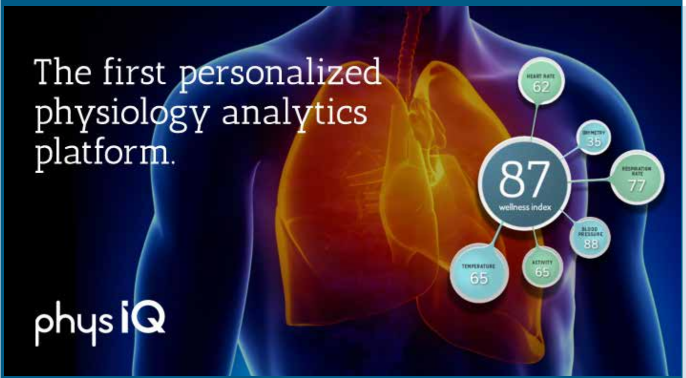
Growth spaces for small companies such as the University of Illinois Research Park, the Illinois Institute of Technology University Technology Park, and the Illinois Science + Technology Park.

Clinical validation and trials through access to the Illinois Medical District (IMD), the largest urban medical district in the United States, and its four hospitals spanning a wide range of patient populations. In addition, several Illinois universities and hospitals, including Loyola University, Northwestern University, the University of Chicago, and the University of Illinois at Chicago, have developed a track record for drug development and validation. Examples include the NIH-funded Northwestern University Clinical and Translational Sciences (NUCATS) Institute and the IMD-led Chicago Area Patient Centered Outcomes Research Network (CAPriCORN).

[42] "Academic-corporate collaborations help drive technology commercialization: the Baxter-Northwestern Alliance and the success of Naurex." *ISTC Catalyst*. August 2012.

Technology transition spotlight

Illinois Regional Proof of Concept Program



PhysIQ has utilized proof-of-concept funding to validate its predictive analytics-based remote patient monitoring system.

Creating startups is a time- and resource-intensive process with inherent risk. Before launching a startup, institutions are well served to keep technologies in the research lab and provide proof-of-concept funding to test commercial milestones to prove their commercial viability. The Illinois Regional Proof of Concept (POC) Fund, managed by IllinoisVENTURES and seeded with support from DCEO and ISTC, is a first-in-Illinois matching program that supports pre–company-stage commercial development for top technologies across Illinois academic institutions. The program is building on the existing and planned efforts of universities and national labs across the state, including the University of Chicago Innovation Fund, which has deployed more than $2 million to more than 30 projects since 2010.

These investments have included $75,000 to PhysIQ (formerly VGBIO), which the company used to validate its predictive analytics-based solution that acquires and analyzes multiple biological signals to reliably identify significant medical abnormalities earlier than current systems; this work led to $4.6 million in Series A funding.[1] The program also takes advantage of synergies between the proof-of-concept funds of these institutions and physical innovation infrastructure, such as the linkage between $10 million UIC Chancellor's Innovation Fund and the 12,000-square foot HTI proof-of-concept center that was made possible through $3.4 million shared state and University of Illinois investment. This investment was instrumental in AbbVie partnering with UIC to access technology and talent located at the university and the broader Illinois Medical District (IMD).

Additional opportunity: To enlarge the pool of viable Illinois biomedical and other startups, the state should expand the Illinois Regional POC Fund and technology maturation funding. This action would help to create new opportunities for Illinois' early-stage medical biotechnology companies while building a technology pipeline for Illinois industry.

[1] "Startup secures $4.6 million, cites university resources," UChicagoTech, August 25, 2014.

Promising opportunities

Within medical biotechnology, four technology areas exemplify opportunity in Illinois:

Drug discovery and diagnostic platforms: Illinois' patent strength in analytical and immunological testing creates a solid foundation for advancement in diagnostics and drug discovery. Furthermore, the presence of several biopharmaceutical companies in Illinois creates opportunities for applied research in these platform technologies, including stem cell models and biomarkers.

Neurological disorders: The White House Brain Research through Advancing Innovative Neurotechnologies (BRAIN) initiative has demonstrated the federal government's prioritization of understanding the causes of neurological diseases like Parkinson's, Alzheimer's, and epilepsy. Elsevier data show that developmental neuroscience demonstrates the highest impact of all Illinois research subdisciplines (more than 300 total) based on FWCI. Coupled with startup and commercialization know-how from companies like AbbVie, Naurex, and Takeda, Illinois is positioned to tap BRAIN initiative funding to improve neurobiology understanding and translate outcomes into new products.

Oncology: Oncology therapies are key product pipelines for Illinois' pharmaceutical companies, including AbbVie, Astellas, Baxter, and Takeda. Expanding industry connections to academic institutions—like the Baxter–Northwestern Alliance and the AbbVie–University of Illinois partnership—will help tap academic talent and facilities to drive innovation in this nearly $100 billion drug market. Furthermore, strong clinical trial partnership opportunities with these companies could be realized through enhanced networking with Illinois' research hospitals, including its two comprehensive cancer centers.

Optical medical devices: Building off the success of American BioOptics and Diagnostic Photonics, Illinois can tap its university strength in optics and image analysis to expand research and commercialization in this market.

Startup spotlight

Naurex launched through Baxter–Northwestern Alliance

Northwestern Professor Joe Moskal (left), founder of Naurex.

Depression affects an estimated 19 million US residents each year, and there is no easy cure. Neurotherapeutics startup Naurex has developed GLYX-13, a novel therapeutic for difficult-to-treat depression that targets brain receptors responsible for learning and memory. GLYX-13, the product of Dr. Joe Moskal's research at Northwestern University, has passed Phase IIb clinical trials and represents an innovative departure from existing antidepressants. It is fast acting—working in a matter of hours—and has no significant toxic side effects. This successful translation of this therapeutic was catalyzed by grant funding from the Baxter–Northwestern Alliance—a partnership created to research new therapeutics, biomedical and device engineering, biomaterials, and drug delivery technologies. After Dr. Moskal's company Naurex licensed GLYX-13, Baxter Ventures later led the company's Series B investments round. To date, Naurex has raised more than $83 million.[1]

Additional opportunity: Naurex's success demonstrates the value of institutional relationships between academic and industry partners. Since an institution's administrative processes are often the barrier to forging such strategic relationships, developing standardized processes and agreements within and across institutions would make Illinois universities more attractive partners—especially when coupled with their strong productivity.

[1] "Careers," Naurex.com.

Supporting the medical biotechnology innovation cluster

Illinois medical biotechnology firms are increasingly engaging in public-private partnerships and university collaborations, including the AbbVie and Baxter examples cited above. To build on the solid and growing research foundation and maximize the impact of ongoing activity in the medical biotechnology cluster, Illinois should focus on the following strategic actions to support commercialization and strengthen ecosystem development:

1. Develop a technology cluster strategy that that aligns state investments and current activities across the community to better coordinate hand-offs between support organizations to create a linked innovation and commercialization funnel and a unified value proposition for Illinois industry.

2. Create academic–industry research collaboration platforms around targeted innovation areas such as drug discovery through opportunities such as the NSF Engineering Research Center program.

3. Promote knowledge transfer and partnerships between biomedical and industrial biotechnology researchers and firms through workshops, joint funding programs, and other opportunities.

4. Explore technology transition support mechanisms with the Chicagoland Biomedical Consortium and other Illinois biotechnology organizations, including:
   - → Expanding the state's proof-of-concept infrastructure to provide gap funding and attract additional federal funding.
   - → Develop a fellowship program for top Ph.D. students and postdoctoral fellows to participate in commercialization activities at one or more Illinois startups, creating new career pathways while providing subsidized expertise.

5. Promote collaboration among institutions on clinical trials to build larger, more attractive patient cohorts for pharmaceutical companies.

Nanotechnology

Cluster performance

Research
Illinois research demonstrates strength in nanotechnology-related fields such as advanced materials, chemistry, and bioengineering.

Commercial potential
The state's companies and research institutions produce high-quality nanotechnology-related patents in the areas of compositions, plastics, coatings, catalysts for the petrochemicals industry, and optical measuring and testing technologies.

Cluster development
Nanotechnology innovation activities and collaboration opportunities center on Illinois nanomaterials, nanoelectronics, and nano-enabled biotechnology startups.

Nanotechnology—the application of concepts from disciplines such as biology, chemistry, materials science, and engineering at dimensions of less than 100 nanometers—has become a critical source of innovation in industries from chemicals and healthcare to automotive and electronics. A recent study by Lux Research cited by the National Science Foundation (NSF) and the National Nanotechnology Coordination Office found that nano-enabled products generated more than $1 trillion in global revenue in 2013—a figure that will more than quadruple by 2018.[43]

The United States currently controls 36 percent of the global nanotechnology market—a share the federal government is working to increase through the National Nanotechnology Initiative. This effort, with funding of nearly $1.8 billion, coordinates the activities of more than 20 federal departments and agencies to support groundbreaking research. To capitalize on this momentum and Illinois' nanotechnology research strength, the *2012 Illinois nanotechnology report: A road map for economic development* lays the initial groundwork for how to connect Illinois' existing research, business development, and training efforts.[44]

Illinois is already home to a robust nanotechnology cluster led by the state's universities and a growing community of startup and commercialization efforts. Catalyzed by federal investments, Illinois academic institutions have an established research infrastructure that drives cutting-edge technology development. These efforts include the Northwestern International Institute for Nanotechnology (see sidebar, "Technology commercialization spotlight: International Institute for Nanotechnology/Illinois Science + Technology Park pipeline," on page 67) as well as the Nano@Illinois initiative, which supports nanotechnology training and research at the University of Illinois at Urbana–Champaign (UIUC) centered on the Center for Nanoscale Science & Technology. (To read about the work of one of UIUC's leading nanotechnology innovators, see sidebar, "Innovator spotlight: Dr. John Rogers," on page 72.) In addition, platforms such as the new University of Chicago's Institute for Molecular Engineering and Chicago Innovation Exchange support the transition of industry-driven research from lab to market.

Nanotechnology cluster analysis findings

The Illinois technology cluster network model uses blue lines to show known research collaborations and funding relationships. Potential ties (green lines) identify strong potential connections between Illinois academic institutions and industry (see nanotechnology cluster map on page 68), with a focus on nanomaterials, nanoelectronics, and nano-enabled biotechnology startups. Notably, several of these startups are connected to tech parks (such

[43] "Nanotechnology update: Corporations up their spending as revenues for nano-enabled products increase," Lux Research, February 17, 2014.

[44] For more information, visit www.istcoalition.org/filebin/pdfs/IL_NanotechnologyReport_Final.pdf.

as the Illinois Science + Technology Park), highlighting the significance of such innovation hubs in enabling the seeding of new high-tech companies and the commercialization of new technologies. Gray ties indicate potential partnerships within the private sector, both within a given nano-enabled technology area (linking small companies with large corporations) and across technology areas (linking companies of all sizes). The number of collaboration opportunities among the latter set indicates strong potential for cross-cutting partnerships between materials, electronics, and biotechnology companies in Illinois.

The network model revealed a nanotechnology cluster centered on university research and startup activity with potential for connections to large corporations. This analysis identified a total of 161 institutions with 542 potential unique connections and 2,449 collaboration opportunities. In all, 77 percent of institutions in this cluster have more than one collaboration possibility, indicating robust institutional partnership possibilities. Notably, 38 percent of these opportunities link to universities and national labs, which can help translate basic chemistry and materials research into prototypes and products. Most potential connections are between companies, suggesting the central role joint development can play in this cluster in advancing the commercialization of early stage nanotechnologies.

Technology commercialization spotlight

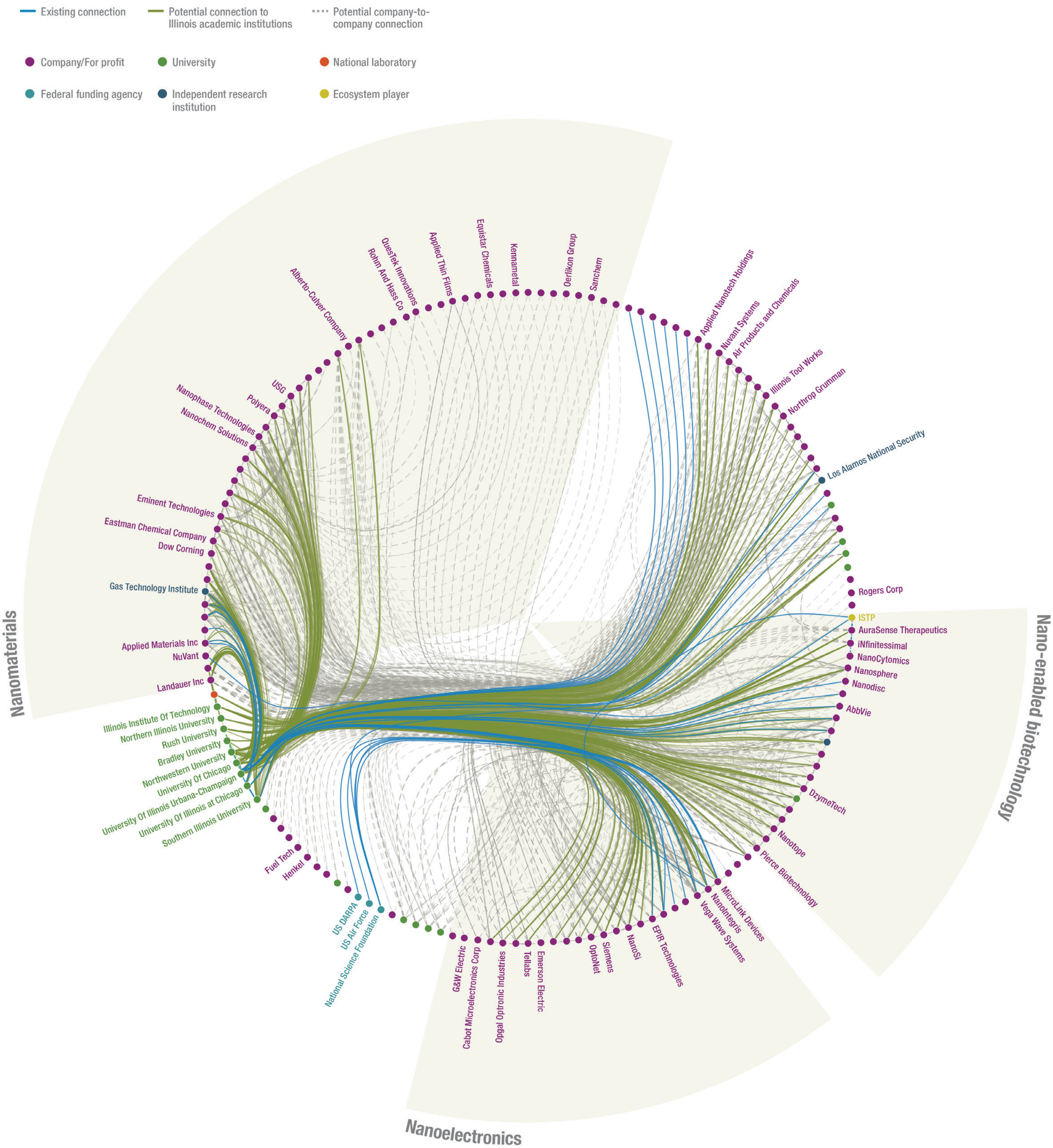
International Institute for Nanotechnology/Illinois Science + Technology Park pipeline

The International Institute for Nanotechnology at Northwestern University; funded in part by $12 million in state support.

The tools that connect researchers with startup support infrastructure—ideas, facilities, and access to partners and customers—is key to translating academic research into tangible products and companies. Uniting more than $600 million in nanotechnology research, educational programs, and critical supporting infrastructure, the International Institute for Nanotechnology (IIN) at Northwestern University has created an innovation ecosystem that efficiently moves technologies from the laboratory to the marketplace. Two of Illinois' leading nanotechnology startups, AuraSense Therapeutics and Nanosphere, were both launched by Northwestern's Chad Mirkin. So far, IIN has commercialized 1,100 new products and services and launched 20 companies based on technologies developed by its researchers—in part due to its proximity to the Illinois Science + Technology Park (ISTP). The construction of ISTP—a 2 million-square foot, state-of-the-art laboratory and office space in nearby Skokie—was itself catalyzed by the strategic alignment of public investment at the local, state, and federal levels. The proximity of the two facilities has been one factor in helping IIN-fostered companies to attract more than $700 million in venture capital to date.

Additional opportunity: Access to skilled workers is one challenge to commercializing and producing nano-enabled technologies. Currently, Ph.D.-level scientists at Northwestern perform technician-level work for IIN due to a lack of available candidates. Building off two state pilot programs—Nanotechnology Employment, Education, and Economic Development Initiative (NE3I) and the Wheeling High School: Introduction to Nanotechnology program—Illinois must develop and scale career pathways that will foster the workforce to fill high-skill, high-wage positions such as those currently in demand at IIN.

Nanotechnology cluster map



Source: Created by Dr. C. Scott Dempwolf (University of Maryland) and ISTC using NodeXL

Nanotechnology collaboration scorecard

Metrics

Organizations (companies and research institutions) **161**	Unique potential connections **542**
Total potential connections **2,499**	Percentage of connections linked to academic institutions **38%**
Multiplex percentage (share of pairs with multiple potential connections) **77%** Illinois average is **43%**	Connectivity index (measure of cluster integration) **0.68** Optimal for innovation: **0.4–0.7**[3]

Illinois impact

Relevant industries from state economic development plan[1]

Advanced materials

Agribusiness, food production, and technology

Biomedical/ biotechnical

Clean energy

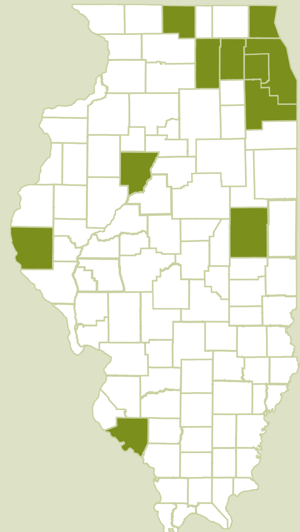
Information technology and tele-communications

Machinery and fabricated metals product manufacturing

Transportation and logistics

Leading counties[2]

Adams
Champaign
Cook
DeKalb
DuPage
Kane
Lake
Peoria
Randolph
Will
Winnebago



Research impact
as measured by field-weighted citation impact (FWCI)[4]

Leading research areas	FWCI (average = 1.0)
Mechanisms of materials	**1.35** (+35%)
Bioengineering	**1.21** (+21%)
Atomic and molecular physics, and optics	**1.20** (+20%)
Colloid and surface chemistry	**1.19** (+19%)
Biomaterials	**1.13** (+13%)

Related patent strengths
as measured by OTR™[5]

Leading patent classes	OTR™ (average = 100)
Compositions	**126.4**
Coating processes	**122.7**
Optics: measuring and testing	**117.5**
Catalysts	**115.4**
Inorganic compounds	**115.1**

Community[2]

Key research institutions

Argonne National Laboratory
Northwestern University
University of Chicago
University of Illinois at Urbana–Champaign

Federal funders

Department of Defense
National Institute of Standards and Technology
National Institutes of Health
National Science Foundation

Notable companies

Advanced Diamond Technologies, Inc.
Applied Thin Films
AuraSense Therapeutics
EPIR Technologies
MicroLink Devices
Nanophase, Inc.

Growth space

Illinois Institute of Technology University Technology Park
Illinois Science + Technology Park
University of Illinois Research Park

[1] *The Illinois economic development plan*, Department of Commerce and Economic Opportunity (DCEO), July 2014.
[2] Innovation activity measured based on datasets used to create the Illinois technology cluster network model.
[3] A connectivity index below 0.4 indicates a lack of cluster integration. A value above 0.7 suggests an increasingly insular community with more limited assimilation of new ideas and partnerships.
[4] The U.S. average FWCI is 1.0; therefore, a score of 1.5 indicates Illinois research publication strength is 50 percent above the national average.
[5] The OTR™ system employs a regression model to determine the probability that a patent will be maintained—an indication of patent quality.

Related research strengths

Stemming from local academic institutions' commitment to developing programs and facilities to drive nanotechnology innovation, Illinois enjoys strengths in nanotechnology-related research disciplines a nd patent areas. Elsevier data reveal a solid basic research foundation for nanotechnology innovation, as demonstrated by Illinois' strengths in fields such as mechanics of materials, bioengineering, atomic and molecular physics and optics, and colloid and surface chemistry.[45] Illinois publications in chemical engineering—a field key to nanotechnology innovation—are cited 40 percent more in patent filings than the national average.[46]

Overall, Illinois nanotechnology patents have an average Ocean Tomo Ratings™ (OTR™) score of 117.5, indicating patents that are significantly more likely to be maintained and used in innovation than the average patent (OTR™ 100). Certain patent classes in which nanotechnology features prominently show an ever higher quality.[47] Patents in optics, an important aspect of nanoelectronics, demonstrate an OTR™ score 6.5 points above the comparator state sample average. Illinois academic institutions are patenting nanotechnological innovations particularly in coatings and biopharmaceuticals, making a key contribution to the high average patent quality in these fields.[48] Driven by research at Argonne, nanotechnology catalysts for petrochemical refining represent another distinct strength with an average OTR of 142, almost 30 OTR™ points above the sample average.[49]

Unrealized collaboration opportunities

Nanotechnology organizations fall into three broad groups that demonstrate significant opportunity for cross-discipline collaboration:

Nanomaterials: Startups such as Nanophase and manufacturers or intermediaries of nanomaterials such as 3M, Honeywell, and Illinois Tool Works.

Nanoelectronics: Startups such as EPIR Technologies as well as established companies such as Cabot Microelectronics, Tellabs, and Vega Wave Systems.

Nano-enabled biotechnology: University spinouts such as AuraSense, iNfinitesimal and Nanocytomics along with large pharmaceutical corporations such as AbbVie and Novartis.[50]

Potential innovation targets include applications of nanomaterials and nanophotonics—areas that align with research and patent strengths identified in Part I—in silicon and next-generation semiconductor technologies and new sensor technologies for clinical and manufacturing settings.

[45] Figures included for the broader groups of which nanotechnology is a subset. The data does not offer outputs specifically on nanotechnology. For more information on Elsevier's data and analysis, see abridged methodology on page 80.

[46] Elsevier data—not shown.

[47] A high OTR™ score does not guarantee high quality/value and vice versa. It only establishes a statistical correlation based on the body of available data. For more information, see abridged methodology on page 80.

[48] See Part I, pages 21-22.

[49] For more information on OTR™ and the comparator state sample, see abridged methodology on page 80.

[50] The Illinois technology cluster network model includes non-Illinois companies who have participated in research and innovation activities with Illinois partners.

Promising opportunities

Illinois has a significant opportunity to build on existing expertise in nanotechnology, evidenced by strong performance by both academia and industry. Among U.S. universities, Northwestern University is a leader in nanotechnology research and commercialization, and the University of Illinois excels on such metrics as facilities and education and research. On the industry side, at least 50 Illinois companies focus on nanotechnology, making Illinois tenth in the country by number of companies using or developing nanotechnology-enabled technologies.[51]

Illinois has already made targeted investments in institutions to support the development of a nano-technology cluster. In 2013, the State partnered with Wheeling High School and the Nanotechnology Employment, Education, and Economic Development Initiative (NE3I) led by Oakton Community College (which collectively reach over 24,000 students) through grants totaling $750,000 to create high-tech training facilities and build career pathways. The initiative's goal is to produce a workforce to fill high-skill, high-wage positions to meet the growing demand at Illinois companies and research facilities.

As the cluster analysis shows, Illinois has a rich community of startups that are commercializing university nanotechnologies. However, given the long development times for nanotechnology products, venture capital funding is often difficult to secure. Illinois' nanotechnology cluster stands to benefit greatly from access to early-stage investment capital and joint development collaborations between established industry and startups. Matching funds or grant application assistance, such as increasing the pool of high-quality SBIR applications, would help amplify the impact of such programs. Promoting increased access to industry that uses or researches nanotechnology will also be necessary.

Furthermore, additional efforts are needed to capture the potential value from Illinois' nanotechnology breakthroughs. In the past several years, high-potential startups, such as Semprius and MC10, have located elsewhere to tap investment and infrastructure. Local leader NanoInk, which had supported 80 high-quality jobs at the Illinois Science + Technology Park (ISTP), went out of business in 2013 when its funding dried up—highlighting challenges in scaling high-potential startups. Promoting joint development work can be critical in proving these technologies at commercial scale.

[51] Not all of the 50 companies are detected in the cluster map due to the types of data being analyzed.

Innovator spotlight

Dr. John Rogers

Ultra-thin silicon sheets developed by Dr. Rogers allow this normally rigid conductive material to be bent and rolled for use in next-generation semiconductors and flexible electronics.

University of Illinois Professor John Rogers uses nanotechnology to create cutting-edge innovations in next-generation semiconductors and flexible electronics. By creating silicon sheets several times thinner than a human hair, Dr. Rogers can shape this normally rigid material into new shapes conducive to myriad applications, including cardiac monitoring sensors and ultra-thin solar cells flexible enough to be rolled into desired shapes or printed on many varieties of surfaces. These discoveries tap the thermal conductivity, electrical performance, and cost efficiency of silicon while offering the flexibility of other, less conductive materials. Dr. Rogers' research is enabled by the interdisciplinary Nano@Illinois initiative, which includes an investment of $160 million in equipment.

Additional opportunities: Dr. Rogers' innovations have been commercialized through startups such as Massachusetts-based MC10 and North Carolina-based Semprius. Additional support mechanisms to build a nanotechnology community in Illinois—especially beyond Chicago—may help to retain more of the commercial value created by Illinois universities. Our technology cluster network analysis revealed that nanotechnology has good potential for cluster integration based on the connectivity index. Therefore, revitalizing platforms such as the Illinois Nanotechnology Collaborative could build integration across organizations and broker joint development projects and public-private partnerships to create the necessary infrastructure and networks and retain more of Illinois' substantial research in nanotechnology.

Supporting the nanotechnology cluster

Building off the ISTC's 2012 Illinois nanotechnology report and the outcomes of the roadmap analysis, three key initiatives would position Illinois to fully harness its nanotechnology research strengths to accelerate sustained startup growth and scale:

1. Establish a proof-of-concept center—or network of centers—to promote the exchange of ideas and mentorship and catalyze joint development between academic and industry, with emphasis on expanding successes to a broader geography.

2. Build connections across nanotechnology facilities in Illinois to provide researchers and entrepreneurs with access to affordable space and a full suite of equipment that would otherwise be cost prohibitive for any one company—and offer access to local industry that can benefit from nanotechnology innovations.

3. Support training programs that build a skilled workforce to help commercialize and manufacture nano-enabled technologies so the economic benefits of Illinois invention are realized here.

Part III
Harnessing roadmap technology cluster opportunities

The data and analysis presented through this Illinois science and technology roadmap provide new understanding of innovation areas primed to spark economic growth through Illinois' R&D and commercialization activity across academia and industry.

The report is intended to advance a more robust dialogue between research institutions, companies, industry organizations, and policy makers to develop stronger innovation policies and programs in the state. With a greater understanding of Illinois' competitive strengths, the state can be better equipped to facilitate and support effective programs and collaboration, target federal funding opportunities, and become a global hub and destination for partnership in the high-impact technology clusters identified in the first two sections of this report.

The technology cluster network analysis in Part II of the roadmap revealed three crosscutting areas where policies and funding can have broad impact: supporting connectivity between industry and academia; assisting high-potential technologies and startups; and providing resources for capital infrastructure needs. To maximize technology development, commercialization, and job growth, programs and resources in these areas will help enable these technology clusters to reach their full potential.

Technology drives Illinois industry

In recent years, long R&D timelines and appreciable risk have moved industry to pursue external partnerships to fill their innovation pipelines. Notable examples include academic collaboration such as the Baxter-Northwestern Alliance and consortia such as the 70-plus companies and universities collaborating on digital manufacturing tools through DMDII. Both models enable companies to accomplish more than they could in-house due to time, cost, or capability limitations. These partnerships create a strong value proposition for companies to support initiatives such as the ones described in each technology cluster as well as the overarching recommendations below.

The role of large Illinois companies such as Caterpillar in Peoria and Deere & Company in the Quad Cities in supporting technology and workforce development initiatives demonstrate the shared value created through industry-driven partnerships. In turn, research institutions help attract and support innovative small business.

Research productivity and connectivity data presented in this report identify opportunities to foster the development of technology clusters that support one or more key Illinois industries. The analysis found 34 connections among the 6 roadmap technology clusters and the 7 industry clusters identified by the DCEO economic development plan. Polymers innovation, for instance, links to all 7 DCEO industry clusters; alloys and batteries and energy storage also cut across all state industry priorities. These Illinois industries employ more than 1.6 million people with an average wage of more than $65,000. More than 430,000 jobs are calculated to be added by 2025.[52]

In addition, roadmap technology clusters represent billions of dollars in market potential, and Illinois' research capacity and strengths position the state to lead related disruptive technology areas. The state's leadership in batteries and nanotechnology research, for instance, position Illinois to be commercialization and manufacturing leaders if the required sup-port is put in place.

High-potential technology clusters

→ **Advanced materials: Alloys**

→ **Advanced materials: Polymers**

→ **Batteries and energy storage**

→ **Biofuels and biomass-derived products**

→ **Medical biotechnology**

→ **Nanotechnology**

[52] Purdue Center for Regional Development and U.S. Bureau of Labor Statistics, *Quarterly Census of Employment and Wages*, 2014; Regional Economic Models, Inc.

Illinois investments in R&D infrastructure and innovation hubs are key assets in tapping Illinois technology clusters to promote competitiveness of established industry and accelerating growth in new, high-tech ones. Industry-specific platforms such as 1871, DMDII, IARC, JCESR, MATTER, and QCML along with regional innovation spaces such as EIGERlab in Rockford and the Illinois Medical District create opportunity to connect innovators with industry partners, provide training, and deliver commercialization support. Such facilities have proved successful in launching startups and attracting industry and investment support.[53] For other technology clusters such as biofuels and polymeric materials, such platforms do not yet exist, revealing a void in facilities and convening power.

As Illinois continues to strengthen existing technology clusters, it will also create new ones such as the digital manufacturing cluster through DMDII, which will connect manufacturing and information technology innovation. The state must work hand in hand with industry and academia to develop policies and funding opportunities to position such research and innovation as the underlying economic engine of Illinois' economy.

To harness state investments in collaboration platforms such as UI LABS and those mentioned above, a systematic approach is needed to form large consortia and partnerships around grand challenges that Illinois academic institutions are uniquely suited to address with a focus on return on investment to industry. Aligning this strategy with initiatives that drive applied research, demonstration and commercialization, and workforce development will foster regional economic competitiveness. Local engagement, driven by each region's strengths in science, technology, and industry identified by this report and DCEO's economic development plan will be critical to each region's economy.

[53] For more information on the innovation hubs and their impact on Illinois' economy, see the introduction of this report on page 3.

Harnessing technology cluster opportunities

To maximize the impact of technology development and commercialization on Illinois' economy—both strong, established industries and disruptive new ones—the state should pursue several policy and programming initiatives that would enable these technology clusters to reach their full potential.

1 Drive connectivity between industry and academia

The roadmap identifies thousands of potential connections between academia and industry centered on technology fields where Illinois' strong research productivity has the potential to drive innovation and competitiveness in one or more industries vital to Illinois' economy. A consistent theme across these technology fields is the need for platforms that academia and industry can use to engage and share expertise and infrastructure.

→ **Establish network of university corporate relations staff.** This network will facilitate and streamline interactions with the private sector and develop best practices in industry engagement, including sponsored research, joint development agreements, and user facility partnerships. The roadmap's technology clusters provide targeted fields to pilot such activities. Involving industry representatives that are seeking these technologies in the network's development will bring the voice of the customer to the process.

→ **Develop technical assistance program.** The roadmap identifies a need for R&D-based companies to access academic facilities and talent. This matching program, coupled with an Illinois shared facility and equipment resource map, will create awareness of available infrastructure and offset costs for innovative companies to:

- Access academic talent to support R&D projects and troubleshoot technical challenges while creating job pathways from our universities to high-tech companies in the state.
- Offset costs of accessing cutting-edge academic research facilities and equipment, which are often too expensive for startups and companies to utilize but vital to developing and commercializing their technologies.

→ **Expand the Illinois Corporate–Startup Challenge.** This program exemplifies the shared value in supporting the competitiveness of large companies through local innovation. Extending this successful program, which bridges innovative technologies and startups with Illinois' Fortune 1000 community, will increase opportunities for corporations to tap innovation from companies coming out of research institutions and help early-stage companies interact with customers to validate their technology and business model and spur expansion.

→ **Develop a network of the state's innovation hubs.** The roadmap provides successful examples of the role innovation hubs play in commercializing technology and developing sustainable startups through access to facilities, training, and mentorship. The hubs are positioned to facilitate research and commercialization partnerships and build connectivity between cluster resources and industry to create an innovation pipeline. Connecting these hubs as their numbers expand and integrating them with university innovation and entrepreneurship expertise and infrastructure will promote the exchange of best practices on operating models and content delivery while also coordinating activities and outreach to maximize impact while minimizing redundancy.

2 Assist high-potential technologies and startups

The roadmap notes examples of Illinois inventions leading to economic development in other regions of the United States. Additional technologies remain in the research lab due to lack of the resources needed to validate and scale them to the point where they become attractive to partners and investors. Providing funding and support will help these technologies grow in Illinois. In addition, increasing the pool of validated technologies will expand access to risk capital and build visibility with industry. These objectives will be advanced by the following recommendations:

→ **Extend proof-of-concept efforts.** With seed funding from DCEO and ISTC, IllinoisVENTURES is developing a regional proof of concept program that supports pre–company stage commercial development for top technologies across Illinois academic institutions. This initiative amplifies university efforts by using matching funds to enable technologies to reach important commercial milestones, and creates visibility with industry and investors for top intellectual property. Increasing funding for the program and enlarging the pool of industry representatives and venture capitalists that serve as evaluators will broaden awareness of top innovations, foster new mentorship and support opportunities, and connect Illinois industry and investors with emerging technologies.

→ **Reestablish the Small Business Innovation Research (SBIR) match.** Restoring funding to the state's lapsed SBIR matching program will accelerate growth for vetted recipients of these federal awards through nondilutive funding, which has fewer restrictions than federal dollars. Previously, the 2007–2008 Illinois Innovation Challenge Grant Program provided flexible funding for high-growth potential companies, including SBIR recipients, that created a 13:1 ratio of federal to state funds.[54]

→ **Develop a PhD startup innovation fellowship program.** Establish a program to harness the technical expertise of Illinois' top talent by helping to subsidize the work of PhDs in validating technologies for commercial applications by early-stage enterprises. This type of initiative would not only expand the technology capacity at startups but also serve as a talent retention strategy to keep this high-skilled workforce in Illinois at local companies.

[54] Data and analysis from ISTC survey of award recipients.

→ **Reduce costs for university-based startups and assist growth stage enterprises.** To encourage the relationship between our universities and the economic potential of innovative new technologies, the state should pursue proactive strategies to reduce or offset the costs of doing business for new or expanding companies that occupy property or land affiliated with a university or using a university-developed technology. Opportunities include costs associated with space usage, taxes, and fees for both early-stage and high-growth small business. In addition, as companies graduate from early phases of commercialization to scalable growth, the state needs to support options for their continued expansion. State capital funds as a business retention tool, for instance, among other resources would help to keep these companies and jobs in Illinois.

3 Ensure resources for capital infrastructure needs

Building alignment between research and industry is made easier by bringing these groups together in a physical space. Many of the successful commercialization efforts reviewed in this report were fostered by state investment in innovation hubs including R&D facilities, incubators, and technology parks. Ongoing, dedicated capital funding to support the three areas below will ensure Illinois' continued leadership in research, innovation, and investment.

→ **Place-based innovation spaces.** Research institutions and communities are both prioritizing place-based innovation to unite technology and business expertise and provide innovators with training and support. These centers, including university research parks, incubators, and other innovation hubs, incubate research into startups and commercialized products. Innovation hubs also provide entry points for industry to technology and talent, such as AbbVie through the HTI center in the Illinois Medical District and the more than 200 aerospace companies in Rockford through EIGERlab.

→ **R&D infrastructure.** Best-in-class research facilities serve as magnets for top talent and federal and industry R&D investments. New ideas and technologies invented through these centers serve as building blocks for the innovation economy in targeted areas (for example, nanotechnology through state investment in the International Institute for Nanotechnology at Northwestern University). State-supported high-performance computing infrastructure such as the BlueWaters system at the National Center for Supercomputing Applications at University of Illinois are differentiators as measured by academic support for industry R&D.

→ **Matching funds for large federal grants and other partnerships.** State capital funds seed public-private partnerships that help transform key Illinois industries. Capital matching funds enable Illinois to seed innovative partnerships and put forward winning bids for high-profile, high-impact, and high-value federal awards by providing needed infrastructure, as well as demonstrating state commitment. Highlights include UI LABS' $320 million DMDII and the $120 million JCESR at Argonne, which have positioned Illinois as flagship centers for the advanced manufacturing and battery technology industries, respectively. The roadmap provides insights into a number of technology areas where Illinois shows particular promise for such opportunities and the potential industry partners that may obtain value through such partnerships. In addition, the report and the underlying data tools offer insights into companies with demonstrated interest in the technologies created by existing platforms such as JCESR, yielding potential commercialization partners for research outcomes. ■

Abridged methodology and glossary

A full methodology is available online at
www.illinoisinnovation.com/science-technology-roadmap

Part I: Illinois drives knowledge creation in key research disciplines

Data sources

Elsevier data

General background on data sources

Scopus is Elsevier's abstract and citation database of peer-reviewed literature, covering 53.3 million documents published in more than 21,900 journals, book series, and conference proceedings by more than 5,000 publishers. Reference lists are captured for 32 million records published from 1996 onward, and an additional 21 million pre-1996 records reach as far back as the publication year 1823.

Scopus coverage is also inclusive across all major research fields, with 6,600 titles in the physical sciences, 6,300 in the health sciences, 4,050 in the life sciences, and 6,350 in the social sciences (the last including some 4,000 arts and humanities–related titles). Covered titles are predominantly serial publications (journals, trade journals, book series, and conference material), but a considerable number of conference papers are also covered from standalone proceedings volumes (a major dissemination mechanism, particularly in the computer sciences).

For this report, a static version of the Scopus database covering the period 1996–2013 inclusive was aggregated by country, region, and subject. Subjects were defined by Scopus' All Science Journal Classification (ASJC) subject areas (see next section for more details).

Titles in Scopus—for example, journal titles associated with publications such as *Science*, *Tetrahedron*, or *New England Journal of Medicine*—are classified under four broad subject clusters: health sciences, life sciences, physical sciences, and social sciences and humanities. These clusters are further divided into 27 major subject areas and 304 minor subject areas (subfields). Titles may belong to more than one subject area or subfield. A team of internal taxonomy experts with subject matter expertise initially categorizes titles, and an independent Scopus Content Advisory Board (see Scopus content selection and advisory board) checks and approves those categorizations.

All records in Scopus (including articles) inherit the categorizations of the titles with which they are associated. For example, the article "Suppression of innate immune pathology by regulatory T cells during influenza A virus infection of immunodeficient mice" (DOI: 10.1128/JVI.01559-10) would be categorized as "Immunology and microbiology" because it was published in the *Journal of Virology*, which was categorized as an "Immunology and microbiology" journal. These subject areas do not necessarily map onto the department, program, or school divisions of a particular institution.

Ocean Tomo data

All raw patent data was provided by Ocean Tomo and is based on official United States Patent and Trademark Office (USPTO) data. Ocean Tomo data includes the Ocean Tomo Ratings™ (OTR™) score.

The OTR™ score is a quantified measure of patent quality—a proxy for value. It is a computer-generated numerical ranking (or score) based on a multivariable regression analysis of several identified predictor variables (patent "metrics") determined to have significant statistical correlation to patent maintenance or mortality rates. Scores are objectively calculated for each patent according to the determined metrics. Raw scores are mathematically adjusted to a nominal expected score of 100. An OTR™ score higher than 100 indicates above-average quality (higher expected maintenance rate), while an OTR™ score lower than 100 indicates below-average quality (lower expected maintenance rate). The OTR™ score provides only part of the equation for determining patent quality and value. Thus, a high OTR™ score does not guarantee high quality and value and vice versa; it only establishes a statistical correlation based on the body of available data.

While OTR™ scores may be predictive of value and commercialization rates, no direct correlation has been established between OTR™ scores and "fair market value" or patent royalty rates. Therefore, care must be exercised not to cast OTR™ scores incorrectly as a surrogate or substitute for value.

See full methodology online at www.illinoisinnovation.com/science-technology-roadmap for normal distribution table of OTR™ scores updated in September 2014.

Rating factors used in OTR™ computation

OTR™ scores are derived from USPTO maintenance fee records using statistical patent survival analysis. The model looks for statistically significant correlations between patent survival (maintenance or abandonment rates) and certain objective attributes or "metrics" revealed by the patent document itself, its prosecution history, and associated public records.

Patents can be comparatively ranked or rated based on these and other objective criteria. The OTR™ system considers more than 50 individual metrics that each have a statistically significant correlation to patent survival rates. For convenience of analysis, reporting metrics are generally categorized in different groups corresponding to various "factors" that contribute to the overall OTR™ score. A brief description of these factors and some of the more relevant metrics is provided below:

Technology. The relative mortality or maintenance rates of similar patents within the same technology space. The technology space is defined as other patents within the same class or patents falling within various, related clusters of technically similar patents. The technology factor considers the relative differences in mortality rates between, for example, patents relating to "hummingbird feeder controllers" (high mortality) and patents relating to "human factor-8 growth hormones" (low mortality). But it does not consider or assess the technical merits of the particular underlying invention in either case.

Prior art. The scope of prior art—which is all publicly available information that could be relevant to a decision on a patent's originality—considered by the patent examiner. Relevant metrics include the number and type of cited prior-art references, the average age of the references, and the number of search fields considered by the examiner in conducting the prior-art search.

Disclosure. Thoroughness of the patent disclosure. Relevant metrics include the number of words contained in the patent specification and the number of figures described.

Claims. Breadth and quality of the claims. Relevant metrics include the number of independent and dependent claims, claim types (method or apparatus, for instance), number of words per claim, and the presence or absence of specific limiting language such as "means" clauses.

Prosecution. Prosecution history of the patent. Relevant metrics include length of pendency, number and type of documents filed, identity of the prosecuting attorney or law firm, and the identity of the primary and assistant examiners.

Ownership. Various factors relating to patent owner (for example, whether private or corporate, a small entity or large entity, foreign or domestic) have been identified as statistically correlated to patent maintenance rates. OTR™ scores are adjusted to ignore ownership factors, meaning that the scores are adjusted to normalize for these factors, such as whether an owner is a large or small company.

Research strengths analysis

Established strengths

The composite scores developed for this report are weighted indices designed to assess the relative quality and growth of research in Illinois of 17 ASJC research fields using metrics of impact and output that compare Illinois' performance against external and internal benchmarks. All analysis and metrics are based on bibliometric data provided by Elsevier.

Bibliometric established strengths composite score

Impact and relative output are both measures of the intensity of research in a given discipline. For the purposes of this index, a combination of high impact and high relative output are needed to make a discipline an established strength compared with other disciplines.

Impact, as measured by a discipline's field-weighted citation impact (FWCI),[55] is weighted more than relative output (as measured by volume of publications) in this index: impact metrics account for 6 out of 10 points, or 60 percent. This scoring distribution reflects the assumption that impact is more likely to be correlated to other outputs associated with innovation such as patents, training of high-quality experts, and collaborative research or consulting for industry.

[55] FWCI is an indicator of mean citation impact and compares the actual number of citations received by an article with the expected number of citations for articles of the same document type (article, review, or conference proceeding paper), publication year, and subject field. Where the article is classified in two or more subject fields, the harmonic mean of the actual and expected citation rates is used. The indicator is therefore always defined with reference to a global baseline of 1.00.

Impact, metrics 1 and 2:
Total points for impact: 6/10

→ Metric 1: Field-weighted citation impact (FWCI) above 0.9
Point maximum: 2

Distinguishes between research impact that for the purposes of this study is considered low (an FWCI of 0.9 or below), and research impact that, at minimum, approximates the national average (less than 0.1 index points or less than 10 percent below the average). This measure is not designed to identify high-impact disciplines. (For high-impact disciplines, see Metric 2, FWCI percentile, below).

→ Metric 2: FWCI percentile
Point maximum: 4

Measures whether output in a given research field is of high quality relative to the U.S. national average and relative to the average impact and quality of other science and technology disciplines in Illinois. The extremely high standard established by this metric is designed to distinguish those research disciplines where Illinois has exceptional research and ensures, even assuming poor output scores, that in combination with Metric 1 (FWCI at or above 0.9), highly rated disciplines in this metric will be at least ranked average in the composite score overall.

Output, metrics 3 through 5:
Total points for output: 4/10

→ Metric 3: Publications volume percentile
Point maximum: 1

Measures the volume of output to determine if the publication output in a certain discipline is high (defined as at or above the top third or above the 67th percentile by publications volume) compared with all other states.

→ Metric 4: High relative output
Point maximum: 2

Attempts to control for the volume of output of Illinois' large research base. Illinois' average share of U.S. publications per research field (5.6 percent) is used as the norm. This metric therefore compares Illinois' share of all U.S. publications for each discipline with Illinois' average share of publications across all research fields.

→ Metric 5: Activity index[56]/high relative concentration
Point maximum: 1

A measure of comparative concentration of output in a given research field. The index score compares a research field's share of all Illinois patents with the field's share of all publications in the United States. The activity index is indicative of the relative "skew" toward or concentration in producing research in a specific field or fields of research.

See full version of methodology online for raw data and scoring system for each metric.

Growing strengths

Bibliometric growing strengths composite score

This model measures the relative rate of growth in 17 ASJC research fields. Impact and relative output are both measures of the intensity of research in a given discipline. Growth in impact and relative output are needed to make a discipline a growing strength compared with other disciplines.

Impact, as measured by a discipline's field-weighted citation impact (FWCI), is weighted more than relative output (as measured by volume of publications) in this index: impact metrics account for 6 out of 10 of all points, or 60 percent. This scoring distribution reflects the assumption that impact is more likely to be correlated to other outputs associated with innovation such as patents, training of high-quality experts, and collaborative research or consulting for industry.

Impact, metrics 1 and 2:

Total points for impact: 6/10

→ Metric 1: FWCI above 0.9
Point maximum: 2

Distinguishes between research impact that for the purposes of this study is considered low (an FWCI of 0.9 or below), and research impact that, at minimum, approximates the national average (less than 0.1 index points or less than 10 percent below the average). This measure is not designed to identify high-impact disciplines. (For high-impact disciplines, see Established strengths, Metric 2, FWCI percentile, on page 84).

For purposes of assessing relative growth strength, a low-impact FWCI (at or below 0.9) was not penalized as in the case of established strengths Metric 1: Field-weighted citation impact above 0.9.

[56]The activity index is defined as a state's share of its total article output across a subject field or fields relative to the national share of articles in the same subject field or fields. For example, in 2012, Illinois published 8.01 percent of its articles in chemistry, while nationally this subject field represents 6.34 percent of all articles published. The activity index for WSU in chemistry in 2012 is therefore 8.01% / 6.34% = 1.26. A value of 1.0 indicates that a state's research activity in a field corresponds exactly with the national average in that field; a value higher than 1.0 implies a greater emphasis while lower than 1.0 suggests a lesser focus.

→ Metric 2: U.S. FWCI CAGR compared with the Illinois FWCI CAGR
Point maximum: 4

Assumes a CAGR measured over a five-year period is sufficient to control for volatility in the growth rate and to indicate a trend. Positive growth over the latest five-year period, or a decrease slower than the national average impact in a given discipline, are strong indicators of research output that is likely to result in an FWCI that will improve or will stay above the national average.

Output, metrics 3 through 5:
Total points for output: 4/10

→ Metric 3: Publication volume percentile
Point maximum: 1

Measures whether publication output in a discipline is high (defined as at or above the top third or above the 67th percentile by publications volume) compared with all other states.

→ Metric 4: U.S. publications CAGR compared with Illinois publications CAGR
Point maximum: 2

Measures whether Illinois' output in a given research field is growing faster than the national average rate of growth. This is a measure of strong relative output in a particular discipline. It shows strong growth in the output of a discipline in Illinois that cannot simply be attributed to broader publication dynamics within that discipline.

Greater-than-average growth could potentially be attributed to an increasing number of local researchers in the discipline or to above-average productivity of local researchers.

→ Metric 5: Increase in share of U.S. publications above Illinois' average increase (1.4 percent)
Point maximum: 1

Indicates a particularly strong growth rate in Illinois relative to other research fields

If output in a research field has grown faster than average in Illinois, it may indicate an emerging discipline or an already strong discipline that will continue to be strong in output relative to other research in Illinois.

See full version of methodology online at www.illinoisinnovation.com/science-technology-roadmap for raw data and scoring system for each metric.

Patent strengths analysis

Patent counts and comparative sample

Patent count

This report counts granted, non-expired, utility patents only and throughout. Unless otherwise stated, all counts refer to counts of origination (residence of patent inventor or inventors) rather than counts of assignation (company assignee).[57] The university patent count included only those patents assigned to an Illinois university or national laboratory. In this case, patents were counted at the company assignee level rather than at the inventor count level. (See page 88 for university patent strengths methodology.)

All state-level counts refer to the number of unique patents with at least one inventor from that state. In other words, we did not count the total number of local inventors associated with a patent or patents. Patents were counted at the inventor level rather than the company assignee level to avoid the problem of attributing patents to a state based on company location, which is often different from where the company is located or where the inventor or inventors are located. For instance, Boeing is headquartered in Illinois but few patents assigned to Illinois are connected to Illinois inventors. The large majority of Boeing patents, which would be assigned to Illinois at the patent count level, are attributable to inventors who live outside of Illinois.

Comparative sample

The comparative analysis in this report refers to an aggregate sample of 17 states for the period 2009–2013. This sample was extracted from the Ocean Tomo patent data of more than 4 million patents and represents the 17 states geographically included in the top 10 metropolitan statistical areas (MSAs) by total patent output at the inventor level (see full methodology online at www.illinoisinnovation.com/science-technology-roadmap for patent counts for top 10 MSAs and all 17 associated states; data through 2011). This sample has an average patent score of 103.8 OTR™, 3.8 OTR™ points above the normalized average across all patents. Consequently, the comparative sample used throughout this analysis represents an aggregate patent output above the normalized U.S. average.

Illinois’ patent strengths

Illinois’ top 10 patent classes were identified through a three-step gating process:

Volume: At least above-average patent volume per USPC class in Illinois for the period 2009–2013. The average volume per class for this period was approximately 68 patents.

Quality: Minimum average patent score of OTR™ 115, which is 1.5 standard deviations above the mean across all patents (OTR™ 100). In addition, selected patent classes are no more than 1 point below the sample average in that patent class.

[57] A patent’s “assignee” is the legal entity that has recognized ownership over the patent. In most cases, this legal entity is the company that employs, sponsors, or collaborates with the inventor or inventors of the patent. In a minority of cases, the assignee is a company founded by the inventor. A patent may also have an inventor as sole assignee if the inventor has not formed a legal entity to which the patent is legally assigned.

Commercial potential index (CPI): A CPI score of no less than 0.9. The ISTC's CPI is used to measure the relative commercialization potential of inventions in a given patent subgroup. The CPI compares the percentage of Illinois patents within each patent subgroup with an OTR™ score of 135 or above with the percentage at or above this threshold for the same subgroup in the comparator group.

$$\mathbf{CPI} = [(\#\mathrm{Patents}_{OTR\geq135})^{IL}/(\#\mathrm{Patents}_{Total})^{IL}] / [(\#\mathrm{Patents}_{OTR\geq135})^{Comparator}/(\#\mathrm{Patents}_{Total})^{Comparator}]$$

Patents with an OTR™ score of 135 or above make up approximately the top 15 percent of all patents. Ocean Tomo awards patents at or above the 85th percentile with an A or A+ grade in a grading system from C- (below 5th percentile) through to A+ (above 95th percentile).

The OTR™ score is used to evaluate the likelihood of a patent being maintained by the owner. One study indicates that this rating system provides "strong predictors of commercialization rates" based on a correlation between OTR™ scores and licensing and commercialization rates (see Ocean Tomo Ratings™ systems). According to the study, patents with an OTR™ of 135 have approximately a 20 percent chance of being licensed or commercialized, and rates of licensing and/or commercialization increase with a rise in the OTR™ score. For purposes of this report, ISTC extrapolated from this trend to develop the CPI used in the calculated patent-composite score. ISTC uses an OTR™ score of 135 and above (or patents that score approximately in the 85th percentile or above and are given an "A" grade in the OTR™ system) to define high-quality patents when calculating this index, but does not attribute a particular OTR™ score to a specific likelihood of commercialization.

See full methodology online at www.illinoisinnovation.com/science-technology-roadmap for raw data and additional details.

Illinois' university patent strengths

University patent strengths were selected through a two-step gating process:

Volume: Above-average output in patent technology subgroup (29 or more patents)[57]

Commercial potential: Above-average commercialization potential (CPI ≥ 1.0)

See full methodology online at www.illinoisinnovation.com/science-technology-roadmap for raw data and additional details.

[58] Due to the smaller sample size, individual patent classes were then further grouped into technology subgroups based on a concordance and taxonomy developed by Bronwyn H. Hall, Adam B. Jaffe, and Manual Trajtenberg; for a concordance of patent classes to broader technology groups, see Bronwyn Hall et. al., The NBER patent citation data file: Lessons, insights and methodological tools, National Bureau of Economic Research, working paper number 8498, 2001.

Part II: Identifying high-potential technology clusters

An explanation of social network analysis (SNA)

The Illinois technology cluster network model relies on social network analysis (SNA) to identify, analyze, and represent the six technology clusters featured in this report. SNA analysis focuses on capturing and representing social relationships in terms of individual actors and their ties to other actors in a given field of activity—in this case the innovation process of creating and exchanging new knowledge and technology. Evidence of the relationships involved in the innovation process is drawn from records that pertain to transactions involved in the creation of new knowledge and technology. These are records such as patents, grants, and sponsored research contracts. Innovation networks are simply networks comprised of all of the actors involved in the innovation process and the ties or relationships that connect them. This data is then used to model and measure the innovation networks that can be observed from the underlying data. Selected networks that among other qualities exhibited a large pool of actors and a pronounced university presence were identified as technology clusters and extracted from the data for more in-depth analysis. Readers new to SNA are advised to consult the references cited at the end of this chapter for a broader treatment of basic concepts. Certain key concepts are briefly reviewed here; however, basic knowledge of SNA from these or other sources will enhance the reader's understanding.

One of the first lessons of SNA concerns vocabulary. Certain terms have very precise meanings in network analysis that may not be interchangeable with their meanings in other disciplines or common parlance. For example, *nodes* in network analysis refer to vertices, agents, or actors within the network. Those accustomed to using the term *node* in other ways should take a moment to recognize that any preconceptions they may have regarding this term should be set aside in the context of a discussion on social networks where typically *nodes*, *vertices*, *agents*, and *actors* are used interchangeably. When we talk about a specific node and the other nodes to which it connects, we refer to the node in question as the *ego* and the nodes that are connected to it as *alters*. *Relation* is an SNA term that refers to a collection of similar connections between nodes in the network. *Relationships* or *ties* refer to individual connections between two nodes. Ties may also be referred to as *edges*, *links*, *lines*, or *arcs*. Ties may be *valued*, where the values represent, for example, the value of a research grant. Ties may also be valued or *weighted* to represent multiple ties between two nodes, for example, when two inventors collaborate on more than one patent together. We may also refer to this as the *multiplicity* of relationships, measured by the number of ties between a pair of nodes. Innovation networks include a variety of actors involved in multiple relations. For example, inventors or researchers with multiple ties among them often produce high-impact research or high-value inventions. We may refer to a network in which many dyads have multiple ties as a *multiplex* network.

In SNA, a *dyad* is the smallest possible network and consists of two nodes and a single tie between them. Three actors and the ties between them form a *triad*. Larger groups of connected nodes within the network are referred to by several names, each with specific meaning. Here we will simply refer to them as *subnetworks* or *subgraphs*.

[59]This gives rise to the multi-level *multi-theoretical (MTML)* network model (see Noshir Contractor and Peter R. Monge, "Theories of communication networks," Oxford University Press, 2003).

Collectively, *agents*, *dyads*, *triads*, *subnetworks*, and *whole networks* may be referred to as network levels. Different theories of social interaction and network behavior focus on different levels of interaction. For example, transaction theories may focus more heavily on dyads, while theories of balance and transitivity in relationships focus on triads. For our network models to be grounded in social theory, it is important to recognize that real networks tend to include relationships at multiple levels, and explaining network behavior often involves multiple theories.[1] Network analysis can be a sophisticated, theoretically grounded tool for understanding and affecting an innovation ecosystem and the economy. The important points here are that the interpretation of complex network models is not always simple and straightforward; before implementing network-based strategies, developers should consider possible interactions at multiple levels.

Innovation networks involve multiple levels of organization, and this invokes multiple theories of social interaction to help explain why and how network structure influences particular behaviors or why particular behaviors result in specific network structures. *Network structure* refers to the patterns of nodes and ties, specifically the presence or absence of ties among actors. The strength of existing ties may also be considered in some cases. Network structure may also be referred to as *network topology*.

The key terms and concepts defined and discussed in this section will be useful in moving beyond viewing the innovation network models as just "pretty pictures." Again, readers who wish to become more familiar with social network analysis should consult the references at the end of this chapter.

Building Illinois' technology cluster network model

Innovation networks are extensive and complex. This research focuses on a subset of innovation networks that allow for the integration of multiple relations and data sources and that will permit a focused economic analysis in the future. The networks modeled here do not cover the full spectrum of innovative activities. They are limited to activities and relationships for which data is available. The network model is also open, meaning that new datasets may be added at any time. The innovation network model as it is presently constructed includes data from the following sources: granted patents and patent applications; National Institutes of Health (NIH) research grants; National Science Foundation (NSF) research grants; National Aeronautics and Space Administration (NASA) research grants; Small Business Innovation Research (SBIR) and Small Business Technology Transfer (STTR) research grants; investment; and locally provided data on sponsored research and user facilities. From these data, we may extract nodes and ties comprising several relations.

Patent relation

Disaggregated patent data (from both granted patents and patent applications) is used to identify innovation network fragments. Patent data is inherently "noisy," and there are several valid criticisms concerning the use of patent counts as indicators of innovation.[60] However, this research is focused on the effects of innovation networks, not patents themselves or patent counts, and this distinction avoids the problems identified in those criticisms.

[60] See Zvi Griliches, "Patent statistics as economic indicators: A survey," *Journal of Economic Literature*, vol. 28, pp. 1661–1707, December 1990.

Patents are filed with the U.S. Patent and Trademark Office (USPTO) under the name or names of the inventors and are often *assigned* to another party, typically a firm. Assignment permanently conveys the rights of ownership to the assignee. Individual patent records contain the names of all inventors and their locations, the name of the assignee, patent classification, date of application, abstracts, citations, and much more.[61]

Patents connect inventors to each other, and inventors to assignees.[62] In addition, each inventor is connected to a specific place through residence at the time of the patent application. Locations for many assignees may also be determined through additional patent documentation, and some additional work is required to validate many assignee locations. Ties between inventors and their locations and from assignees to their locations are included in the *location* relation, discussed in the next section.

All ties are non-directional and have a value of 1.0. The ties are considered active from one year prior to one year after the patent application year. This is done to help account for the fact that the relationships existed prior to the patent application event, and that they persist for some time after that event. The data source for this relation is the USPTO.

Location relation

In most conventional statistical analyses, location is treated as an attribute of the individual actors being studied. This permits the exclusive assignment of observations to specific geographic "bins" where those observations may be compared with demographic or economic data for each geographic area. This approach presents a problem when dealing with networks because networks are inherently boundary-spanning. Nodes may not be exclusively assigned to specific "bins" without distorting the network. In these networks, we therefore model locations as ties between individual actors and place nodes. In these network models, the place nodes typically represent counties for U.S. locations and countries for non-U.S. locations. Location ties are typically valued at 1.0, indicating simply that a relationship exists. Nodes may simultaneously have ties to more than one location.

As discussed in the previous section, the location of residence for each inventor at the time of patent application is included in the patent record. Typically, this includes city, state, and country, which for U.S. addresses are used to identify the county of residence. Similarly, assignee locations are converted to U.S. counties for all addresses in the United States. We recode location for two reasons. First, counties are typically the smallest geographic unit for which consistent demographic and economic data is readily available. Second, inventors and assignees are listed by name. Aggregating geography to the county level provides a measure of privacy protection without diminishing the quality of the model.

[61]For example, see the record for patent #7352075. Readers may familiarize themselves with the details of the patent system and patent data at www.uspto.gov/patents/index.jsp.

[62]A patent's "assignee" is the legal entity that has recognized ownership over the patent. In most cases, this legal entity is the company that employs, sponsors, or collaborates with the inventor or inventors of the patent. In a minority of cases, the assignee is a company founded by the inventor. A patent may also have an inventor as sole assignee if the inventor has not formed a legal entity to which the patent is legally assigned.

For each of the other relations described below, available location data is extracted and converted to counties for U.S. locations. For most research grants, the address used for the principal investigators and the grantee institution is the address of the grantee institution—most often a research university. For multicampus institutions, the campus is specified whenever possible. All U.S. addresses are converted to counties.

For locally provided data, the addresses provided are used. All U.S. addresses are converted to counties.

Federally sponsored research relation

Most federal research grants generate similar network structures and thus fall under the same relation. This applies to research other than SBIR/STTR research that is sponsored by NIH, NSF, NASA, and other federal agencies that provide basic and applied research funding to research universities and similar institutions. Data on these federal research grants are obtained from the respective agency websites. Several ties may be extracted from these data:

- Agencies and institutions, which may be valued at the grant amount or as the log of the grant amount
- Research institutions and principal investigators (PIs), which may be valued as 1.0, the grant amount, or the log of the grant amount depending on the type of analysis
- PIs and co-PIs working on the same grant, which are typically valued at 1.0, indicating simply that a relationship exists
- Program managers and their agencies, and program managers and PIs, valued at 1.0, indicating simply that a relationship exists

Research grant data often includes project start and end dates. Ties in this relation exist from one year prior to the start date to one year after the end date.

SBIR/STTR relation

Capital for research and development is often noted as a critical part of the innovation process. The federal SBIR and STTR programs provide grant funding to firms and university researchers to advance the development and commercialization of specific technologies. The SBIR/STTR relation connects federal agencies directly to firms rather than institutions, and therefore SBIR/STTR is treated as a separate relation. Specific ties may include the following:

- Funding agency to firm for both SBIR and STTR grants
- Funding agency to institution for STTR grants
- Firm to institution for STTR grants
- Where PIs are identified, ties between PIs are shown as well as ties between the PIs and their respective firms or institutions

Ties may be valued at the grant amount or as the log of the grant amount, or at 1.0, simply indicating that a relationship exists. SBIR relations are considered active from one year prior to the award year to one year after the award year. Location ties for nodes in this relation are included in the location relation.

Local sponsored research and user facilities relations

ISTC and its partner institutions provided a significant amount of proprietary data on corporate and foundation-sponsored research, user facilities, and intermediaries. Ties under this relation vary according to the data source. In the event that disclosure limitations apply, these ties have indeed informed the structure of the network, but are hidden to maintain confidentiality.

Technology relation: The introduction of weak ties

Whereas the ties in other relations are considered *strong ties,* meaning they represent actual connections identified in the data, ties in the technology relation are considered *weak ties*. In this model, weak ties represent *potential* or *likely* relationships between actors based on similarities in the technology field in which they work. These similarities may be determined in several ways. The first is by patent class *and* subclass. For example, when two firms are assigned different patents with the same class and subclass within the same time period, a weak tie between those firms is generated. A second way to generate weak ties is through keyword matches in semantic searches of patent and research grant abstracts.[63] Working with Elsevier and local subject matter experts, ISTC created keyword lists for each target cluster. These lists were matched with keywords for each abstract, returning documents where there were keyword matches. From the document matches, firm and institutional matches could be made, generating additional technology-based weak ties across all data sources containing abstracts.

Weak ties often have the potential to become strong but do not necessarily imply a strong existing relationship. The actors are likely to know *of* each other. They may belong to the same professional organizations or attend the same conferences or trade shows. Weak ties are non directional and assigned a value of 0.5. The ties are considered active from one year prior to the first patent application to one year after the second patent application. This is done to help account for the fact that the relationships existed prior to the patent application event, and that they persist for some time after that event. The data source for this relation is the USPTO.

Modeling the network

Modeling the network begins with generating all of the actual and potential ties described in the previous sections within our database. For the roadmap, we selected nodes and ties that were active between 2010 and 2014. Multiplex ties are counted and consolidated. A core network is selected by first selecting all

[63] Keyword and semantic search techniques are a new addition to this methodology. While showing great promise in this research, additional work is necessary to refine the semantic search algorithms and reduce the number of "false positive" potential ties. While some false-positive results are expected in this type of matching, the results obtained here required considerable manual effort to remove a large number of false-positive results for the clusters in this report. Work to refine the semantic search methods is ongoing.

nodes with at least one multiplex relationship, then selecting all nodes and ties with connections to that group. These ties are then exported to NodeXL, a free, open-source add-in for Microsoft Excel.[64]

Once imported into NodeXL, a clustering algorithm is run, typically the Clauset Newman Moore algorithm, which is designed to detect communities and reveal overall structure in large networks.[65] This algorithm groups vertices so that the number of ties within each group is optimized compared with the number of ties to vertices in other groups. In other words, vertices that are well connected to each other—meaning that they are either working together or have good potential to work together—form each cluster. After the clusters are identified, a set of metrics is run for each vertex, each group, and the network as a whole. These metrics may be used to evaluate network structure or to set network properties such as vertex size prior to network visualization. Specific metrics reported in the roadmap are discussed in the next section, "Measuring the network."

Network visualization proceeds using one of several layout algorithms. For the roadmap, a circular layout was selected because it is among the easiest for those new to network analysis to understand. All of the vertices are plotted around the circumference of a circle, then the ties between those vertices are plotted in the center of the circle. Other layouts may also be used to convey various types of information about the network, and these are all available in the interactive tool.

Measuring the network

A limited set of descriptive metrics were selected for use in the roadmap. These include:

1. The number of institutions (vertices) and unique ties in the network—simple counts that give a sense of the size of the network or sub network being modeled.

2. The total number of potential (weak) ties in the subnetwork. The subnetworks for the roadmap were dramatically simplified to make them more readable for the report—this means that the majority of ties shown are potential ties. The number of potential ties can also serve as a measure of the size of the network.

3. The percentage of ties that originate or end with institutions, specifically research universities and federal labs. This metric provides a sense of how much opportunity there is for university-industry research collaboration within the cluster.

[64] See www.nodexl.codeplex.com

[65] Aaron Clauset, Christopher Moore, and M.E.J. Newman, "Finding community structure in very large networks," Cornell University Library, 2004.

4. The percentage of dyads in the network characterized by multiplex ties. Since the core network is built around nodes with multiplex ties, this number is expected to be somewhat skewed toward the upper end of the range. Nevertheless, it provides a useful metric that describes the relative level of experience that cluster members have in working together.

5. The last metric is a connectivity index or what is known in the network analysis literature as a clustering coefficient. This is an average measure for each cluster that is a relative indicator of how interconnected each cluster is. Low values, below approximately 0.4, suggest that the cluster may not be connected enough to translate innovation into new production effectively. On the other hand, high values, greater than approximately 0.7, suggest that there may be tendencies toward group-think and path dependency, where the network may have a low capacity for assimilating external interventions such as new ideas and processes.

Glossary

Activity index: A state's share of total article output across subject field(s) relative to the national share of articles in the same subject field(s). For example, in 2012, Illinois published 8.01 percent of its articles in chemistry, while nationally this subject field represents 6.34 percent of all articles published, making Illinois' activity index 1.26.

Article: Unless otherwise indicated, denotes the main type of peer-reviewed document published in journals, encompassing articles, reviews, and conference proceeding papers.

Article output: The number of articles with at least one author from an institution in Illinois (according to the affiliation listed in the authorship byline). All analyses make use of "whole" rather than "fractional" counting: an article representing international collaboration (at least two different countries listed in the authorship byline) is counted once each for every institution listed.

Citation: In an article or patent, a formal reference to earlier work, frequently to other journal articles. A citation is used to credit the originator of an idea or finding and is usually used to indicate that the earlier work supports the claims of the work citing it. The number of citations received by an article from subsequently published articles is a proxy of the quality or importance of the reported research.

Commercial potential index (CPI): A measure of the proportion of Illinois' high-quality patents (defined by this report as patents with an OTR™ score of 135 or higher) in a given United States Patent Classification (USPC) class compared with the sample average. A CPI of 1.0 represents a proportion of high-quality patents equal to the sample average in that patent class.

Compound annual growth rate (CAGR): The year-over-year constant growth rate over a specified period of time.

Connectivity index (or Clustering coefficient): A relative indicator of the interconnectedness of each cluster. Low values, for the purposes of this report below 0.40, suggest that the cluster may not be connected enough to effectively translate innovation into new products. On the other hand, high values, for the purposes of this report above 0.70, suggest that there may be tendencies towards group-think and path dependency, and not enough new ideas could make it into the mix.

Existing connections: All known connections between individuals and organizations, as well as between organizations, known from documentation of research and innovation activities in patent and grants data. See Part II methodology (page 89) for additional information on data sources.

Field-weighted citation impact (FWCI): Developed by Elsevier, an indicator of mean citation impact that compares the actual number of citations received by an article with the expected number of citations for articles of the same document type (article, review, or conference proceeding paper), publication year, and subject field. FWCI is measured according to a global baseline of 1.00.

Industry cluster: A group of organizations involved in the production of similar and related goods and services based on company North American Industry Classification System (NAICS) codes. Industry clusters are usually quantified and expressed in terms of workforce numbers and number of establishments within relevant NAICS codes.

Multiplex percentage: A metric designed specifically for the Illinois technology cluster network. Multiplex percentage is defined as the percentage of total vertices (organizations) connected by multiple edges (connections)—an indication of strong relationships and activity.

Ocean Tomo Ratings (OTR™) system: Employs a regression model to calculate a raw probability score for a patent. Raw scores represent the simple probability that a patent will be maintained for the full statutory term—an attribute that in one study has been found to correlate with the probability of licensing or commercialization of the patent and its underlying technology.

Patent citations: An indicator of the success with which research findings published in journal literature are used to justify the patentability of an invention; this can be seen as a form of academic–industry knowledge exchange.

Potential connections: Projected connections based on research alignments between organizations engaged in research and development activities. For a detailed explanation of the data and assumptions used to model potential ties, see Part II methodology (page 89).

Technology cluster: A grouping of organizations, industry, and research institutions, engaged in R&D on complementary technologies. These clusters cut across industries and are not defined in terms of NAICS codes. Technology cluster magnitude is quantified in terms of the number of existing and potential research ties and number of establishments.

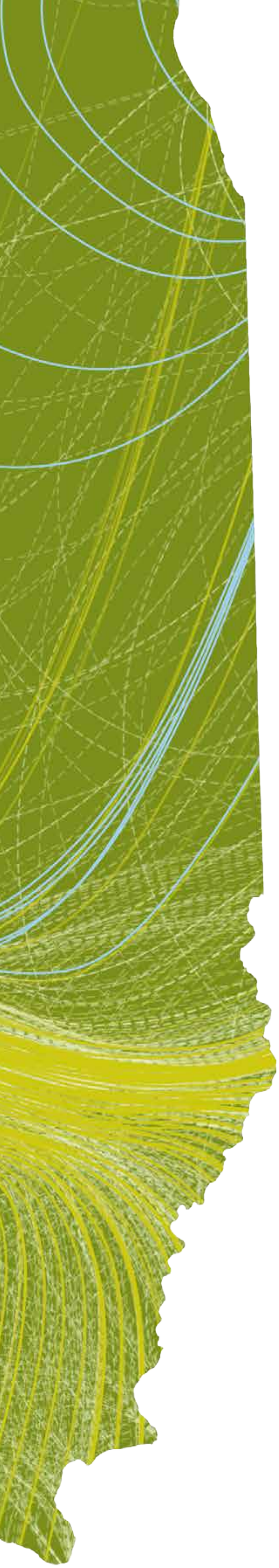
Acknowledgements

This report was developed under the leadership of Mark Harris, president and CEO of the Illinois Science & Technology Coalition and led by Managing Director Jeffrey Margolis and Research Program Manager Lyu Uzunov. Elsevier, especially George Lan, and Ocean Tomo, especially Arijana Karadjuzovic, served as esteemed partners on this project, providing valuable data, analysis, and expertise. Illinois technology cluster analysis was performed by Dr. C. Scott Dempwolf, University of Maryland. Bob Okabe, Managing Director of RPX Group LLC, provided key technology commercialization knowledge and guidance to help analyze and frame report data. Writing, exhibit design, and layout were handled by the staff at Leff Communications, including Scott Leff, Brittany Petersen, Jake Godziejewicz, and Delilah Zak.

The ISTC appreciates the support from its members and partners in conceptualizing and creating the report. The ISTC board of directors provided invaluable guidance and connections to help develop this work. In addition, we appreciate the support of the Illinois Innovation Council, an advisory group to Illinois Governor Pat Quinn that identifies and advances strategies that accelerate innovation, economic growth, and job creation in the state.

We offer special thanks to our university, national laboratory, and industry colleagues who provided data and insights that informed the report analysis and conclusions. In particular, we thank Hans-Peter Bleschek, Lisa Dhar, Brad Edwards, Laura Frerichs, Merle Giles, Joey Mak, Lawrence Schook, and Kimani Toussaint from the University of Illinois; Jeremy Hollis, Maralet Kidra, David Klick, and Mark Krivchenia from the University of Illinois at Chicago; John Flavin, Steve Kron, Alexis Sale, and Alan Thomas from the University of Chicago; Giorgio Bortolotto, Jeff Coney, Kimberly Griffin, Chip Hay, Alicia Löffler, Dragos Visan, and Jay Walsh from Northwestern University; Chris Claxton, George Crabtree, Elizabeth Jordan, and Norman Peterson from Argonne National Laboratory; Robert Kephart and Cherri Schmidt, Fermi National Accelerator Laboratory; Ken Anderson, Jim Garvey, Kyle Harfst, and Amy McMurrow Hunter from Southern Illinois University; Lesley Rigg, Mansour Tahernezadi, and Rita Yusko from Northern Illinois University; David Baker and Sabrina Fesko from the Illinois Institute of Technology; and Robert Kephart and Cherri Schmidt from the Fermi National Accelerator Laboratory. In addition, we thank Neil Kane, Illinois Partners; Barbara Goodman, Illinois Biotechnology Institute; Nancy Sullivan, IllinoisVENTURES; David Cruickshank, ARCH Venture Partners; Marcus Droege and Elena Padilla, Takeda Pharmaceuticals; Vince Kwasniewski; Ray Genellie and Jeff Grabowski, QuesTek Innovations; Eric Faierson, Quad City Manufacturing Lab; Jeremy Adelman and Sara Hochman, Energy Foundry; and Samir Mayekar, SiNode Systems, who each provided subject matter expertise to the analysis and discussion. Sameer Gadkaree provided technical assistance with initial data analysis.

This report was made possible through the financial support of the Illinois Department of Commerce and Economic Opportunity.



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