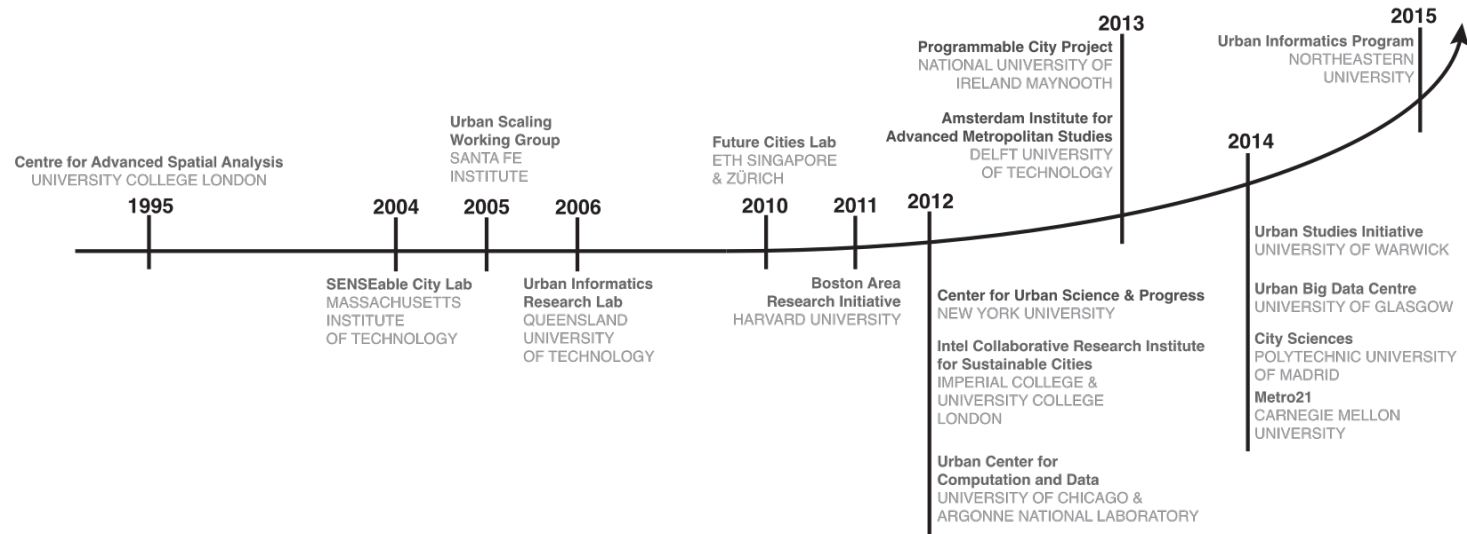# MAKING SENSE OF THE NEW URBAN SCIENCE

The world's leading universities have embarked on a building boom for urban research.

What does it mean for the future of cities?

2013

Programmable City Project
NATIONAL UNIVERSITY OF
IRELAND MAYNOOTH

2015

Urban Informatics Program
NORTHEASTERN
UNIVERSITY

Urban Scaling
Working Group
SANTA FE
INSTITUTE

Future Cities Lab
ETH SINGAPORE
& ZÜRICH

Amsterdam Institute for
Advanced Metropolitan Studies
DELFT UNIVERSITY
OF TECHNOLOGY

Centre for Advanced Spatial Analysis
UNIVERSITY COLLEGE LONDON

2014

1995   **2004**   **2005**   **2006**   **2010**   **2011**   **2012**

Urban Studies Initiative
UNIVERSITY OF WARWICK

SENSEable City Lab
MASSACHUSETTS
INSTITUTE
OF TECHNOLOGY

Urban Informatics
Research Lab
QUEENSLAND
UNIVERSITY
OF TECHNOLOGY

Boston Area
Research Initiative
HARVARD UNIVERSITY

Center for Urban Science & Progress
NEW YORK UNIVERSITY

Urban Big Data Centre
UNIVERSITY OF GLASGOW

City Sciences
POLYTECHNIC UNIVERSITY
OF MADRID

Intel Collaborative Research Institute
for Sustainable Cities
IMPERIAL COLLEGE &
UNIVERSITY COLLEGE
LONDON

Metro21
CARNEGIE MELLON
UNIVERSITY

Urban Center for
Computation and Data
UNIVERSITY OF CHICAGO &
ARGONNE NATIONAL LABORATORY

NYU | WAGNER
rudin
center
for transportation policy & management

Data&Society RESEARCH INSTITUTE

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Diagrams by Alissa Chisholm

July 2015

Executive Summary

We are living in the age of cities. It is an urgent time, and an uncertain one. Never before have human beings built so much with such haste. Yet we understand so little about how our urban world grows — and sometimes — declines.

To meet this challenge, the world's universities have set out to plug this knowledge gap, and establish a *new science of cities*. This report is an initial attempt to understand the collective scope and impact of this movement. What does this new science seek to achieve? Who are its practitioners? What questions are they pursuing? What methods do they use? What are they learning? How might their discoveries shape our shared urban destiny?

By 2030, $2.5 Billion Will Be Invested In Urban Science and Informatics Research…

Since 2005, more than a dozen new labs, departments and schools have been launched with a common purpose - to pursue deeply quantitative and computational approaches to understanding the city.

While today these efforts are small and disconnected, they are growing and linking up, creating a global community of applied scientific and engineering research. If present trends continue, by 2030, new urban science institutions could connect thousands of researchers and students, and represent more than $2.5 billion in current and future investment.[1]

…To Address Key Obstacles to Sustainable, Resilient, Smart Urbanization…

The subjects of urban science address the full range of questions about the city that have puzzled us for centuries. From fundamental theoretical questions — why do cities grow? — to more pragmatic challenges, such as mapping the flow of energy across interconnected infrastructure networks, no aspect of urban dynamics is being left unaddressed.

The stakes of this enterprise are high. Cities stand as both the main cause of, and the best solution to, most of humanity's pressing problems - from climate change to migration to resource scarcity. The new urban science that may emerge from these efforts could transform our civilization, and our planet.

… Through Knowledge Transfer to the Public Sector

But success is not assured. Not since the urban social crises of the 1960s have universities so actively worked to put the city at the center of research. But we should heed the experience of that earlier generation, which largely failed to realize its own ambitions for harnessing computer- and data-driven approaches to urban improvement. The methodological and institutional challenges that stymied those efforts are still present. If anything, as the stakes are so much greater now, they may be even more intractable than before. This is where the greatest push is needed to demonstrate the tangible potential of urban science in the 21st century.

1. The New Urban Science

Since the earliest days of city-building, scientists and engineers have sought to rationalize the chaotic nature of urbanization. During the rapid industrial boom of the 19th century, when city planning first emerged as a distinct intellectual movement and field, science and engineering delivered tangible benefits — the improvement of public health through sewer construction drew on civil engineering know-how. Architecture provided a basis for rethinking the provision of more affordable and comfortable housing in overcrowded cities.

But, then as now, some of the most profound new scientific ideas about cities came from non-traditional directions. Influential British town planner Patrick Geddes was trained as an evolutionary biologist long before he began to work on urban social problems in the 1890s. Geddes' intellectual background led him to see the city was less as an industrial machine — as many of his peers imagined — and more of a great organism splayed out across an entire metropolitan region. And he was intrigued by the potential usefulness of the then (relatively) new quantitative science of sociology for designing reforms. In one fell swoop, he hoped to reintroduce the importance of the environment as a factor in the evolution of civilization, and to make sociology a tool for social change.[2]

But science has also served less noble goals. While do-gooders like Geddes used science to inspire and inform study of the city, perhaps more often, scientific ideas were used to justify urban interventions decided by less objective means. For instance, in the 1930s, the battles to claim American city streets was largely fought with rhetoric arguing for a more rational, scientific approach to planning. The pseudoscientific profession of "traffic engineering" was created to establish the car's legitimacy and create a seemingly objective, modernist rationale to deny other uses of city streets.[3]

Fast-forward to the 1960s, and as two trends collided in the United States — the social crisis caused by the automobile-enabled abandonment of central cities, and the widespread introduction of computers in U.S. universities — leaders once agains turned to science for insight on cities. "I propose that we focus all the techniques and talents within our society on the crisis of the American city", wrote President Lyndon Johnson in 1967. "[C]reating a safe, happy city is a greater challenge than a trip to the moon…", reflected the group of scientists invited to meet the president's challenge at Wood's Hole, Massachusetts that summer, the city's "problems, nevertheless, can be attacked in the same logical way that we have gone about exploring the universe."[4]

The thinking was that computerized, data-driven methods for management, planning and policymaking that had revolutionized national defense during the Cold War could simply be transplanted over to the civilian side of government.[5] The newly established Department of Housing and Urban Development (HUD) became a strong advocate of this approach and eagerly supported many research-policy partnerships focused on computer simulation of urban policy.[6]

Unfortunately, reality did not meet the high expectations of the urban scientists of the 1960s. The disillusionment that ensued from these early efforts to understand cities scientifically is well-documented. Some were simply boondoggles, such as a computer simulation developed in Pittsburgh which was abandoned soon after it was built, when it became clear that the cost of collecting of the data required to run it was prohibitive.[7] Others, such as the New York City-RAND Institute's response time model developed for the New York City Fire Department had catastrophic consequences - in this case a wave of poorly-chosen station closings that led to an

outbreak of fires that ultimately displaced an estimated 250,000 people.[8]

Meanwhile, demand for such tools was on the wane, as the Nixon administration pulled back the federal government's interventionist urban policy agenda and urban planning itself turned away from the solution-driven, technocratic style of the past to a more advocacy-driven activist approach.[9]

A Renaissance

The disappointments of that first wave of computer-intensive approaches to urban study in the 1960s are difficult to understate. In 1973, planning scholar Douglass Lee published his infamous treatise, "Requiem for Large-Scale Models", in the *Journal of the American Institute of Planners*. The article's purpose was, as the author put it, "to evaluate the fundamental flaws… and to examine the planning context in which the models, like dinosaurs, collapsed rather than evolved."[10] For decades, aspiring scholars turned in other directions, and embraced other methods.

In the intervening four decades, however, many of the challenges that these efforts sought to address remain. Our understanding of fundamental processes of urbanization is extremely limited and fragmented. Geoffrey West, a theoretical physicist at the Santa Fe Institute, argues that "we desperately need a serious scientific theory of cities. And scientific theory means *quantifiable* -- relying on underlying generic principles that can be made into a predictive framework."[11] Without this knowledge, we are imagining future cities as if we think the Earth is the center of the universe, and it's surface is flat.

A new generation of scholars is responding to this challenge. And in the meantime, thanks to the painstaking work of a small group of researchers who continued to developed theories, tools and methods for computer-based analysis of cities in the intervening years, the seeds of a renaissance in urban science have been sown. Today, increasingly abundant data, computing power, and analytical tools are available to test out new ideas about how cities work.

What Constitutes Urban Science?

The problem, however, is that this rapid influx of new ideas and new talent, much of it housed in entirely new places, is challenging our definition of what urban science actually is. This is not an easy question, so its best approached through several lenses.

Lens 1: Science vs. Design

The first lens is the tension between science and design that underlies any discussion of this question. Traditional methods of urban inquiry often stress an inductive, bottom-up approach to understanding the city through field work, site visits, and surveys. The goal is to focus on individual places as unique entities. This method, while effective at sensitizing students to urban conditions, is often counter-productive to understanding the general processes that make cities what they are. In the view of one group of scholars, "[a] more critical review of the evidence on urbanization as a process and not on cities as places could lead to systemic solutions that address the whole rather than separate components."[12]

The deductive, scientific approach, in contrast, aims to explain the world through universal laws. The detail is a red herring. As Geoffrey West argues, "we all know that every city is unique. That's all we talk about when we talk about cities, those things that make New York different from L.A., or Tokyo different from Albuquerque. But focusing on those differences misses the point.

Sure, there are differences, but different from *what*? We've found the *what*."[13] To their credit, traditionalists would retort that these new critics are guilty of hubris — that cities in their entirety are too complex and rapidly changing to really be fully understood.

Lens 2: New Ideas From Strange Places

A second starting point for scoping this emerging movement is to look at who is shaping it. Who are the new urban scientists?

Urban research has always thrived at the intersection of multiple disciplines. In the early days of urban planning in the late 19th century, urban planning emerged from interactions amongst experts in civil engineering and architecture, medicine and public health, sociology and (like Geddes) occasionally biology. In the 1960s, many urban research programs re-organized themselves under the rubric of 'urban studies' drawing even more broadly on social sciences from economics, geography, history, political science and sociology.

Perhaps, even if only in their sheer numbers, the most significant new arrival to the urban research community are the physicists, who have not traditionally engaged in the study of cities in any substantial form. These scientists, who have tackled some of our most challenging scientific problems, are bringing their experience, powerful new theories and analytical tools to bear on the complexity of urbanization. Geoffrey West and Luis Bettencourt, who have pioneered research on urban scaling at the Santa Fe Institute, spent the earlier part of their careers at Los Alamos National Laboratory. At Harvard University, 20-year old astrophysics prodigy Henry Lin and department chair Abraham Loeb mathematically derived Zipf's Law, which explains why there are more small cities than large ones — by applying techniques used to explain the size distribution of stars in galaxies.[14],[15]

If it seems odd that an astrophysicist might simply see a city as a different kind of star, it isn't the first time that ideas from star-watching have upended our understanding of our societies here on Earth. In the 1830s, Adolphe Quetelet repurposed the then-new science of probability and statistics, which had been extensively developed in astronomy, to measure human populations. Foreshadowing MIT professor Alex 'Sandy' Pentland's own appropriation of the term in his 2015 book of the same name, Quetelet dubbed the practice *social physics*, a name stolen from fellow scientist Auguste Comte. Comte's revenge was simple — in turn, he coined the far more durable term *sociology* which is still widely used today.

Urban researchers like to think they work on very large scales, but their ambitions are humbled by galaxy-watchers; they also purport to pay attention to detail, and the nuances of place. But other physical scientists are probing new ground in the structure of the very small urban world. For instance, researchers at MIT's Concrete Sustainability Hub describe cities using the mathematics of crystals. By noting that conventional approaches to measuring urban heat island effects rely on a single population or building density variable, they point out "[T]he striking resemblance between urban environments and molecular structure of materials", which "allows us to leverage common methods from statistical physics to reduce the complexity of urban systems to a universal set of dimensionless measures". Some cities mimic crystals, they find, with "distinct periodic Geometries" (Chicago and New York) — others mimic liquids (Boston and Los Angeles), with "more sporadic and chaotic distributions."[16]

While they have not advanced as aggressively as physical scientists, the biological scientists are beginning to engage cities as sustainability surges to the forefront of policy and planning agendas,

elevating their importance. For instance, the head of ETH's Future Cities Lab in Singapore — arguably the largest urban science center by far — is a plant ecologist who started his career in a rainforest! Peter Edwards was the dean of environmental sciences at ETH and saw the lab as an opportunity to advance the agenda he had helped craft as coordinator of the Alliance for Global Sustainability over many years previously.

While physical scientists may bring new ideas that transform our thinking about the city at both the very large and the very small scale, it may be in the biological realm that the best new notions about the human scale lie. As Edwards explains:

> *The thing I know about rainforests is they are sustainable and they are highly decentralized — they have multiple redundancy systems in them. That's exactly the kind of industrial system we need… moving from a zoned sort of city, which depend on large centralized services… to a highly decentralized system with much more interconnection between the individual buildings so that they function together to regulate the urban environment in a way that is not done at present.[17]*

To envision a smart city infrastructure in the form of a rainforest canopy requires, well, a rainforest scientist. Engaging with biology may also carry other unanticipated benefits - the field has been overrun in recent decades by physicists and computer scientists, spawning the sub disciplines of biophysics and bioinformatics, but without disassembling itself entirely. As a field encountering powerful and disruptive new ideas from the outside, biology — long seen as 'soft' itself — may be a model of intellectual resilience for urbanists to learn from.

Finally, the great strides being made in mapping the human brain are informing every aspect of urban research, with often very practical applications for urban professionals. One project at the University of Waterloo uses advanced brain scanning techniques to measure how people perceive and navigate complex urban environments. "Participants are placed into highly immersive simulations of city spaces using sophisticated head-mounted displays and precise motion tracking. They are able to walk freely through photo-realistic simulations of urban spaces that are replete with depth, colour, and motion. We can monitor their gaze and their movements along with their physiology using a set of unobtrusive sensors while they do so." Such studies "give us a set of powerful methods by which to predict the psychological effects of an urban design before anything is built."[18]

Lens 3: The Computational Juggernaut

Theories grafted from physics and biology are already starting to reshape the foundations of urban thinking. But in an age defined by digital technology, ideas and innovations from information and computer science will open up previously unthinkable lines of inquiry. Perhaps the only trend more powerful than global urbanization itself is Moore's Law, which continues to drive an exponentially increasing abundance of computing power and digital data about the world.

This intersection of cities and computing has spawned an area of urban science widely described as *urban informatics*. Literally, merging the Oxford English definitions for these two terms yields a working meaning: 'the collection, classification, storage, retrieval, and dissemination of recorded knowledge of, relating to, characteristic of, or constituting a city'.[19] But is this is too limiting? As Foth explains, urban informatics is:

> *an emerging field populated by researchers and practitioners at the intersection of people, place and technology with a focus on cities, locative media and mobile technology. It is interdisciplinary in that it combines members of three broad academic communities: the social (media studies, communication studies, cultural studies, etc.), the urban (urban studies,*

urban planning, architecture, etc.), and the technical (computer science, software design, human-computer interaction, etc.), as well as the three linking cross sections of urban sociology, urban computing, and social computing.

What concerns us here is Foth's 'technical' academic community and its manifestations in the urban computing and social computing realms. For this aspect of urban informatics is a key platform for the work of other scientists studying cities. One need merely look at the most provocative recent work done by physicists, for example — such as Bettencourt and West's studies of urban scaling — behind which is a data aggregation effort that would have been infeasible just a few years ago. Detailed statistics on infrastructure grids, demographics, economic output, etc. over many different geographic units were analyzed to derive the final, elegant equations. The work of Marc Barthelemy and Rémi Louf drew on street network data from 131 cities contained in the Open Street Maps repository to derive four archetypical urban grid structures.[20]

Easy access to such massive urban data sets allows new urban science to validate theoretical suppositions about the city at an ever-increasing rate and level of detail. When they can work directly with cities that are harvesting data, scientific impact can increase by an order of magnitude — for instance, researchers at NYU's Center for Urban Science and Progress now routinely work with New York City taxi trip datasets possessing billions of elements. In the near future, as they begin analyzing data generate from 'smart city' and 'living laboratory' facilities designed from initiation to collect data, the volume of information will be unprecedented in science. For instance, the amount of data produced by one proposed smart city of 200,000 persons would exceed that of the Large Hadron Collider (currently the world's most prolific scientific apparatus) ten- to

twenty-fold. Our cities may be destined to become urban observatories, which like like their astronomical counterparts, serve as lenses to experimentally validate our grand ideas about the social universe.

Mapping the Boom

Applying these lenses — the tension between science and design, the sources of new scientific ideas about cities, and the growing abundance of computation and data — how should we define the scope of urban science?

We should note we are not the first to raise this question. In a recent survey of 'big data and urban science', Batty defined the scope of "centres which have an established presence" as " a cluster of 4 or more significant individuals working in the domain of computer applications to cities". He identified the following categories of centers:

- established and emerging centers identified with urban informatics and science,

- GIS labs (geographic information systems) with a strong urban science component,

- centers focusing on urban simulation,

- digital media centers that focus on the urban realm,

- computer science labs that focus on urban mobility,

- complexity research centers with a focus on urban science.

The resulting survey identified more than 40 centers worldwide.[21]

In our view, this survey is too extensive in that it spans far beyond the emerging core of researchers who are actively corresponding and collaborating as a peer group that would self-

identify with the 'new urban science' label. We choose to focus instead on the most novel approaches to the study of cities, that break from or represent significant advances in analytical capability over existing research institutions and talent. Our criteria for inclusion include:

- **Newness -** organizations that are less than ten years old (with one notable exception),

- **Data-Enabled -** a mission characterized by deeply quantitive approach to research,

- **Externally Curious -** draw heavily on talent and leadership from physical and information sciences,

- **Probing -** are substantially committed to the deployment of new scientific instruments to collect data about cities.

—-

Our survey is selective, but the scope of investment and activity in urban science it covers is breathtaking. Already, new institutions are outpacing traditional ones. For instance, in just its third year of operation, NYU's Center for Urban Science and Progress will award more master's degrees than MIT's Department of Urban Studies and Planning.

But the question remains - why invest now? Why are research universities rediscovering the city today? And why create new institutions instead of trying to work within the old ones?

There are both push and pull dynamics at work.

The push comes from simple curiosity. Cities are probably the most complex phenomena human scientists will ever encounter - trying to predict and shape them is so much more vastly complex as

to be impossible. According to Luis Bettencourt of the Santa Fe Institute "detailed urban planning is computationally intractable."[22] But that doesn't seem to be stopping some of the brightest minds of our generation from taking a crack at some piece of the puzzle.

The pull of course comes from the ongoing process of urbanization. As economist Paul Romer has argued, the 21st century will see the complete urbanization of the global population and the establishment of a global system of cities that our descendants will inhabit for centuries to come. As intertwined as this process is with climate change, human development, and geopolitics, it has become a powerful motivator for researchers in many fields.

A third factor is the institutional context. Higher education is now an urban phenomenon because of changes in teaching and the university's new role in economic development. Universities will be a key hub of an urban planet, which means this urban science boom may be here to stay.

Table 1. Key Centers of the New Urban Science

Host Institution	Center	Year Established	Current Director	Director's Primary Academic Field
University College London	Centre for Advanced Spatial Analysis	1995	Andrew Hudson-Smith	Urban simulation
MIT	SENSEable City Laboratory	2004	Carlo Ratti	Architecture, civil engineering
Santa Fe Insitute	Santa Fe Institute Cities, scaling and sustainability project	2005	Luis Bettencourt	Physics
Queensland University of Technology	Urban Informatics Research Lab	2006	Marcus Foth	Communication & Media
ETH	Future Cities Lab Singapore	2010	Peter Edwards	Plant ecology
Harvard University	Boston Area Research Initiative	2011	Robert Sampson	Sociology
Imperial College, University College London	Intel Collaborative Research Institute for Sustainable Connected Cities	2012	Duncan Wilson	Artificial intelligence
New York University	Center for Urban Science and Progress	2012	Stephen Koonin	Physics
University of Chicago	Center for Urban Computation and Data	2012	Charlie Catlett	Computer science
National University of Ireland Maynooth	Programmable City Project	2013	Rob Kitchin	Geography
Delft University of Technology, Wageningen University	Amsterdam Institute for Advanced Metropolitan Solutions	2014	N/A	N/A

Figure 1. The Urban Science Boom*

- Student enrollment
- Faculty and research staff
- Operating budget ($m/yr)
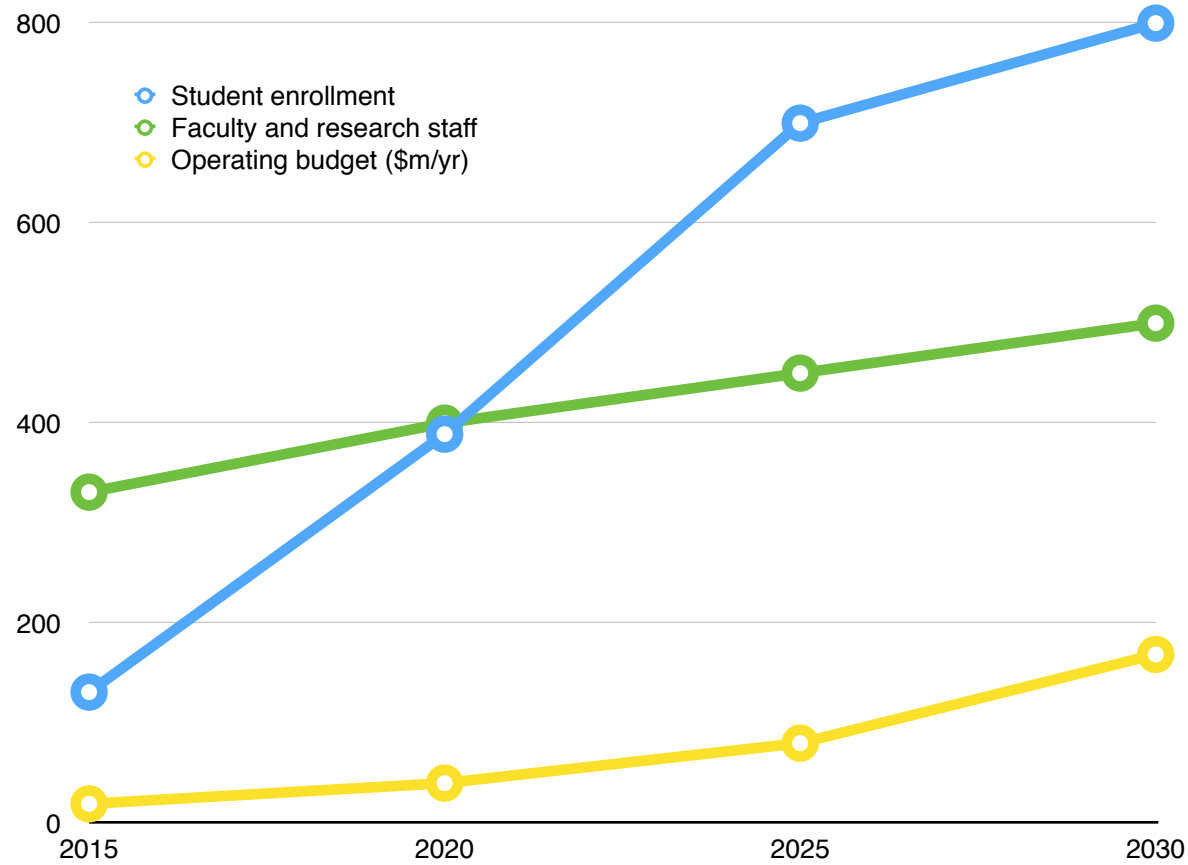
*All 2020-2030 staffing and enrollment figures are author's projections based on reported 2015 staffing and enrollment levels. Budget projections for 2020-2030 and 2015 estimates are based on a confidential sample of 2015 budgets.

2. The New Global Infrastructure for Urban Research

In this section we present a survey of the new research organizations leading the development of new urban science. We examine the factors leading to their establishment, and the sources of intellectual energy and financial support. The purpose is to provide an overview of the evolution of the movement as seen through the establishment of new research organizations, and share insights into the motivations and aspirations of its key leaders.

Figure 2. Timeline of New Urban Science Institutions
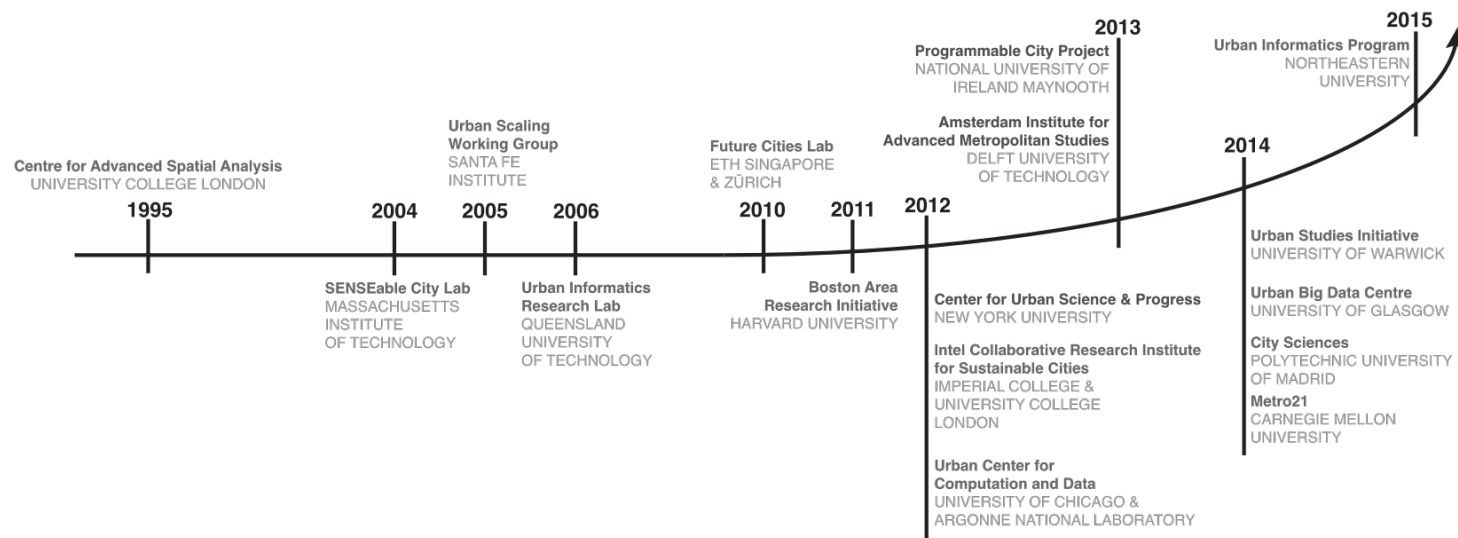
From Geographic Information Science to Urban Science

Founded almost two decades ago in **1995**, the **Centre for Advanced Spatial Analysis** (CASA) at University College London fails our 'newness' filter. Yet it is a logical starting point for our exploration of the new urban science for three other important reasons.

First, CASA's founder and long-time director Michael Batty is unique among leaders in the organizations in this study in that his career spans from the first wave of interest in urban science and computer-based analysis of cities in the 1960s to the present urban science movement. Second, Batty is the author of *The New Science of Cities* (MIT Press, 2014) which has become a standard textbook in urban modeling and simulation. Finally, over its nearly 20 years in existence, CASA has developed a strong series of partnerships with the Greater London Authority, most notably Transport for London, one of the GLA's three main units. It also works closely with the Future Cities Catapult, a nationally funded research organization to develop urban simulations for licensing and export. CASA's success with these partnerships suggests some of the positive benefits that other urban science institutions may deliver in the the future.

CASA is also important because while it maintained strong ties to traditional urban research communities, it remains at the forefront of computationally-advanced methods of urban research, despite the urban science boom. That is to say, CASA has quite nimbly adapted to the shifting landscape of urban science from a narrow specialization to an ever-broadening field of inquiry. Comparing its website in 1998, when CASA's focus was on the application of computation to geospatial analysis, its goal was:

…to develop emerging computer technologies in several disciplines which deal with geography, space, location and the built environment. The kinds of computation involved cover geographic information systems (GIS), computer-aided architectural design, spatial analysis and simulation and methodologies of planning and decision support.[23]

Today, the group's website casts a far broader ambition, stating:

CASA's focus is to be at the forefront of what is one of the grand challenges of 21st Century science: to build a science of cities from a multidisciplinary base… Our vision is to be central to this new science…[24]

As Batty explains, CASA was "[e]stablished as a GIS centre with strong urban focus" but is "now orientated towards simulation, spatial data and visualization."[25].

Clear evidence of CASA's ambition is the launch in 2014 of a Master of Science in Smart Cities degree program. In some ways CASA could be seen as having ceded a market opportunity for the kinds of large-scale education programs in urban informatics that we will see later at NYU's Center for Urban Science and Progress. But in many ways it is the grandfather of them all - demonstrating that computationally demanding urban research can be combined with education and strong partnerships with government to create capacity for the creation of actionable knowledge that benefits its host city.

Centre for Advanced Spatial Analysis

Full-time faculty and research staff	8
Post-doctoral researchers	15
Graduate student enrollment (current)	55
Graduate student enrollment (projected)	70

Degrees offered: MSc in Smart Cities and Urban Analytics, MRes in Advanced Spatial Analysis and Visualization

Where Urban Design Meets Technology Development

Not surprisingly, the Massachusetts Institute of Technology is home to more than one research group taking heavily quantitative and computational approaches to the study of cities. These include the City Science Initiative at the Media Lab, the Human Mobility and Networks Lab in the Department of Civil and Environmental Engineering, and the Center for Advanced Urbanism in the Department of Urban Studies and Planning. But the **SENSEable City Laboratory**, formed in **2004,** sets the course for urban science at one of the world's greatest engineering universities. But ironically, SENSEable stands alone in this survey as the only organization created within an existing school of urban planning. It thrives at the interface of these two cultures - led by Carlo Ratti, an architect who cut his teeth early on picking apart algorithmic flaws in the popular space syntax technique of computerized urban spatial analysis.[26]

Whereas CASA was setup to push the limits of a very specific set of computer tools for a narrow range of planning applications, SENSEable has always cast its net wide, playfully engaging any number of emerging technologies with urban implications very early in their life cycle. As the lab's website bombastically describes the opportunity:

> *The real-time city is now real! The increasing deployment of sensors and hand-held electronics in recent years is allowing a new approach to the study of the built environment. The way we describe and understand cities is being radically transformed - alongside the tools we use to design them and impact on their physical structure.[27]*

And as its name implies, of particular interest to the lab are technologies for sensing the material world and the novel kinds of interactions they can enable with the city.

cThis style of inquiry has created a body of work that is a hybrid of research and design experimentation through a fairly agnostic selection of projects. These range from rich graphic visualizations of population movements in cities gleaned from mobile phone location records collected by carriers (Real Time Rome, 2006) to visualizations of flows of trash through the "disposal chain" collected by cheap throwaway sensors (Trash_Track, 2009). More recently, the group has explored the potential beneficial applications of robots and unmanned aerial vehicles in urban space. For instance, in 2013, the lab developed a drone dubbed SkyCall that, paired with a smart phone app, could hover overhead to guide visitors through an unfamiliar city.[28] Ratti's architectural background has also led to several substantial built works. The Digital Water Pavillon, an interactive, programmable water sculpture in Zaragoza, Spain that combines technology, architectural and urban design. The Future Food District, designed for retailer COOP Italia, interweaves digital information about food production into a supermarket setting.

SENSEable's model stands out for its focus on producing usable prototypes, a reflection of MIT's engineering culture, where the urge to 'demo or die' is a deeply shared value. While SENSEable has produced peer-reviewed scientific papers, these are not considered its most important output. Just as important are spin-offs like Superpedestrian, which commercialized the 2009 Copenhagen Wheel project, an electrically-propelled wheel that can be retrofitted to any standard bicycle. Finally, SENSEable has leveraged considerable industry funding, borrowing the corporate consortium model pioneered by the MIT Media Lab.

SENSEable City Laboratory

Full-time faculty and research staff	5
Post-doctoral researchers	25

Taking the Synoptic Point of View

The urge to see the city from on high in its entirety — or *synoptically* — is one of the oldest yearnings of urban planners. In the early 1900s, Patrick Geddes undertook painstaking efforts to develop 'regional surveys', holistic catalogs of the human and natural environment of a city and its surrounds. In doing so, he reflected on the words of Aristotle, writing:

> *[Aristotle] urged that our view be truly synoptic, a word which had not then become abstract, but was vividly concrete, as its make-up shows : a seeing of the city, and this as a whole ; like Athens from its Acropolis, like city and Acropolis together the real Athens from Lycabettos and from Piraeus, from hill-top and from sea. Large views in the abstract, Aristotle knew and thus compressedly said, depend upon large views in the concrete.[29]*

Through the transformative era of aerial photography, to our present reality of desktop satellite imagery, this urge leaves few untouched.[30]

Few are intrigued by the challenge of synoptic urban sensing as the physical scientists who have joined the urban science movement. And few have embraced the opportunity as aggressively as New York University's **Center for Urban Science and Progress** (CUSP), which opened in **2012**. Under the direction of Steven Koonin, a nuclear theorist whose career has led him to Cal Tech, BP and the U.S. Energy Department, CUSP launched its flagship research project, the Urban Observatory. The Urban Observatory has one goal — to move urban science beyond merely analyzing the exhaust data of cities, and start developing massive new scientific instruments to collect novel data about the city.

In its first instantiation, the Urban Observatory is quite modest - taking the form of an 8-megapixel camera mounted atop the Metrotech office complex in downtown Brooklyn where CUSP is located. Every ten seconds, the camera takes a photograph of the Manhattan skyline. In the future, the vision is to expand the apparatus with a multi-spectral array of instruments — infrared, ultraviolet, etc.

The Urban Observatory's version of 'synoptic urban sensing', as Koonin describes it, is at once a hornet's nest of privacy concerns and a boon for research. On the cautionary side, instruments like the one deployed at CUSP can potentially capture the activities of millions of people simultaneously, at frequent intervals, over very long periods of time. For instance, the Urban Observatory's consumer-grade camera is sensitive enough to identify the reflected light signature of individual television programs. As a precaution against this kind of analysis, CUSP deliberately down-samples the resolution of video footage collected before storing it.

But the social value of synoptic urban sensing is equally clear. The data collected by the Urban Observatory could be an unrivaled source of insight into heat loss and other energy performance characteristics of buildings — at a speed, cost and level of detail never before possible. It could be an indispensable tool to meet the city's ambitious goal of reducing carbon emissions by 80% by 2050.

In today's urban science, a synoptic view of the city is within reach, but many will ask if the costs and benefits are well-matched.

Center for Urban Science and Progress

Full-time faculty and research staff	12
Post-doctoral researchers	3
Graduate student enrollment (current)	67
Graduate student enrollment (projected)	247

Degrees offered: Masters in Applied Urban Science & Informatics, PhD in Urban Science

In Search of Ground Truth

In remote sensing, the concept of 'ground truth' describes data collected in the field corroborate what synoptic sensing has picked up up from afar. This is the focus of the Array of Things project, the flagship research project of the University of Chicago's **Urban Center for Computation and Data**, launched in **2012** by Charlie Catlett, a computer scientist. While CUSP's Urban Observatory watches from on high, in downtown Chicago the Array of Things is seeking ground truth in the smart city.

Catlett became interested in cities during a sabbatical from his work at Argonne National Laboratory, and got intrigued by the resonance between frameworks for urban architecture and computing architecture. The idea behind the Array of Things is to create a general purpose platform for instrumenting the city at an intimate scale through "a network of interactive, modular sensor boxes around Chicago collecting real-time data on the city's environment, infrastructure, and activity for research and public use."[31]

The relationship between the public and the data it generates is an explicit part of the deal citizens make with the Array of Things. As the project website explains:

> *What if a light pole told you to watch out for an icy patch of sidewalk ahead? What if an app told you the most populated route for a late-night walk to the El station by yourself? What if you could get weather and air quality information block-by-block, instead of city-by-city?*

Compare this to the Urban Observatory, whose public benefits are indirect (reductions in future greenhouse gas emissions through a new enforcement mechanism) and realized at an uncertain point in the future (whenever new building codes are written, built to, and enforced).

One lingering question is, which kind of sensing is more invasive of citizens' privacy? The eye in the sky, or the watcher at the corner? While it sounds equally ominous, at least citizens might notice the watcher at the corner - they can watch it, watching them. And there is the possibility that it could play a connective social role, like Jane Jacobs' "self-appointed public character", the old busybody at the corner who keeps an eye on everyone, but also keeps the social fabric together.

UCCD also strikes a different note in the kind of organization it's trying to build. While groups like CUSP have assembled a sizable standing staff of faculty, administrators, and research staff, UCCD is more of an impromptu ensemble that pulls together people and funding for each project from a network that includes universities, Catlett's alma mater Argonne National Lab, private firms and non-governmental organizations. It's a style of collaboration Catlett brings from Argonne, where this more fluid model is used to form both research teams and after-hours jazz ensembles (Catlett plays drums and guitar himself).

Urban Center for Computation and Data

Full-time faculty and research staff	2
Post-doctoral researchers	1
Institutional partnerships	45+

A Corporate Collaborative

More than any other corporation, chip giant Intel has placed a big bet on urban informatics and urban science research, setting up the Intel Corporation in the Intel Collaborative Research Institute for Sustainable Connected Cities (hereafter ICRI) in London in 2012.

The company's collaborative research organization model was pioneered in the 1990s at UC-Berkeley, the University of Washington and Cambridge University. For ICRI, the structure consists of equal partnerships with two universities - Imperial College and University College London. Intel's initial commitment of $1.6m (£1m) annually for three years was matched by $400,000 (£250,000) from each of the universities, for a total core investment of $2m (£1.5m) per year to support academic research. Executive staff are supported separately by Intel, with the goal of making the center self-sustaining after five years.

With its existing R&D concentrated in Silicon Valley and Israel, London is an interesting choice for Intel — whose R&D presence in the British Isles has for many years been concentrated in Dublin, Ireland. But as Duncan Wilson, the group's director explains, a confluence of smart city initiatives surrounding the 2012 Olympic Games caught the company's attention. (Wilson himself an interesting choice as well - he was one of the co-founders of the highly-regarded foresight group at engineering giant Arup).

ICRI's work has focused, like others, on deploying research capacity. It is under contract with the Future Cities Catapult Centre, the UK-government's London-based smart cities accelerator, to deliver a "London Living Lab" sensor testbed for research and development of new urban products and services. Already, the group has launched five neighborhood-scale sensor deployments throughout London. To support future research, in the first 18 months, Wilson reports that an additional $3.4m in research funding from UK and EU sources has been secured.

Intel's interest is clearly self-serving — the company wants to push university research that might have an impact on its business in the future. But how does corporate involvement in academic work influence the research agenda? And are there larger public benefits?

According to Wilson, the academics drive the agenda. Intel personnel fill two of the groups six board seats, with the rest held by two principal investigators from each of the partner universities. Priorities are, he argues, more heavily influenced by partners in government like the Greater London Authority and government-backed NGOs like the Future Cities Catapult. But as Wilson explains, Intel is looking to understand better the vertical market opportunities within the broader smart cities and urban informatics landscape, and get more specific about the R&D agenda needed to unlock them. Ultimately, ICRI's success will be measured by "by how many things have been developed in those ICRIs and actually get pulled into the business," he says. That the Intel 'lablets' of the 1990s were shuttered for failure to live up to that standard is a lesson of both the company's focus and its willingness to try again even where it has failed before in collaborative ventures with universities.

Intel Collaborative Research Institute for Sustainable and Connected Cities

Full-time faculty and research staff	7
Post-doctoral researchers	6

Theorizing Complexity in the Connected City

Without theory, the boundless streams of data our cities now produce may do little to advance our understanding of the bigger picture of urban evolution. Nowhere is this fundamental challenge being addressed more directly than in high desert of the American Southwest, where a handful of the world's brightest physical theorists at the **Santa Fe Institute's (SFI) Cities, scaling and sustainability** research effort have been exploring the links between complexity science and cities since **2005**.

SFI's explorations of cities date to the late 1990s when Geoffrey West, a researcher at Los Alamos National Laboratory, got interested in the role of size in biology. It had been known since Max Kleiber's studies in the 1930s that as organisms grew larger, their metabolism slowed by a predicable and constant rate. A few years later, the study of scaling in biology was given a name — *allometry*. But while earlier work had merely induced these laws from observations, West and colleagues deduced them from first principles about the nature of organisms and metabolic processes themselves.

With this toolkit in hand, West moved down the street to the freewheeling Santa Fe Institute where he served as president from 2005–2009. It was not long before they began to apply it to connected complex systems of all kinds. According to West:

> *We conjectured that… highly complex self-sustaining systems — whether they are cells, organisms, ecosystems, cities, or corporations — require close integration of many constituent units that require an efficient supply of nutrients and the disposal of waste products… "the key lies in the generic mathematical properties of networks." [32]*

The implications for cities were stunning, because they turned out to be a very different sort of network than an animal body or a corporation, which both stagnate and decline as they expand. But for cities, "with every doubling of city size… socioeconomic quantities — the good, the bad, and the ugly — increase by approximately 15% per person with a concomitant 15% savings on all city infrastructure-related costs." Think of it as a divine gratuity, bestowed upon cities as they are fruitful and multiply.

West saw the breakthrough in scaling as an essential step in developing a true science of cities, as it had been in other fields:

> *Over the past 50 years, scaling arguments have led to a deeper understanding of the dynamics of tipping points and phase transitions (how, for example, liquids freeze into solids), chaotic phenomena (the mythical flapping of a butterfly's wings in Brazil stimulating a hurricane in Florida), the discovery of quarks (the building blocks of matter), the unification of the fundamental forces of nature, and the evolution of the universe after the Big Bang. [33]*

As SFI's work on urban scaling has continued, led by Luis Bettencourt, it has proven surprisingly robust. It has described the evolution of pre-Colombian settlements in Mexico based on archaeological survey data as well as it does our own cities using mobile phone network records.

Ironically, for all its insight into the nature of urbanization, SFI is perhaps the furthest removed from an actual megacity. But in January 2015, the group announced the creation of a joint research program with Arizona State University, the ASU-SFI Center for Biosocial Complex Systems which will study scaling and innovation in cities. This center represents SFI's first formal collaboration with a university since its establishment over three decades ago.[34]

Santa Fe Institute

Investigators and collaborators   10

The Policy Shop

Home to more than 250,000 students, the Boston metropolitan area is perhaps the world's largest concentration of higher education. And as one of the one of the nation's oldest central cities, and one of its oldest universities, it is not surprising that the two joined forces in **2011** to launch the **Boston Area Research Initiative** (BARI), based at Harvard University's Radcliffe Institute.

Boston is no stranger to research-policy collaborations between university and government. The city was one of the most aggressively re-developed during the post-War era, and served as something of a guinea pig for urban policy ideas in the 1950s and 1960s. Boston's universities were actively engaged in both monitoring as well as designing some of the best and the worst of the schemes imposed on the city's neighborhoods as it struggled with deindustrialization, segregation, and crime.

Today, however, the city is thriving, driven by a resurgent wave of largely university-enabled economic growth, and research-policy collaboration aims primarily to improve quality of life and ensure that the city's gains are evenly distributed. To this end, Harvard's effort was the brainchild of three university scholars —Rob Sampson, Chris Winship and David Luberoff.

BARI has two mandates. First, the BARI research team would conduct cutting edge research. Second, it would conduct matchmaking between public sector "clients" and graduate students in the region, for whom it would support in collaborative research efforts with government. In the process, BARI's work has become more data-focused than originally intended, as - much like the other centers we're looked at - data has presented itself as an abundant resource to be exploited in the pursuit of applied urban research, particularly for young researchers looking to make a name for

themselves. Government has found value in the work as well - student researchers have delivered visualizations and analysis of 311 and 911 call records with far greater precision than the city's own analysts. The focus on data is creating a virtuous circle of value creation - student work has helped build a data library for BARI, which in turn supports development of a collaborative research community. One student project built off of Boston Police Department bicycle accident data that was shared to DataVerse, a site hosted by Harvard's Institute for Quantitative Social Science, and has been used by over 11,000 people.

BARI's strengths lie in its close working relationship with policymakers and staff in government. As Dan O'Brien, BARI's director of research explained, convincing policymakers that academics can deliver tangible benefits (as well as convincing researchers that its worth their time to talk to policymakers and that there is good science to be done), works best when collaborators are "climbing the ladders together", building relationships that allow researchers and their partners in government to grow together, and develop trust and understanding over time that can span across changes in political leadership.

Boston Area Research Initiative

Full-time faculty and research staff   3
Post-doctoral researchers   1

A Skunkworks for A Smart City

Like many other global financial centers, Amsterdam's city leaders found themselves in early 2009 facing a serious strategic question - how could they diversify the local economy away from banking in the wake of the global financial crisis? Amsterdam was a major telecommunications hub, and in 2013 it made Wired UK's 2013 list of "Europe's Hottest Startup Capitals."[35] By 2014, the city's smart city campaign earned it the number two spot among 30 global cities for 'technology readiness' in scorecard compiled by PwC.[36] City leaders wondered - could Amsterdam turn the business of building and running cities of the future into an export industry?

By 2013 the city's plans were taking shape. A solicitation for proposals to setup a new applied technology research institute was issued. The winning proposal, to establish an **Amsterdam Institute for Advanced Metropolitan Solutions** (AMS) in **2014,** featured a team led by the Delft University of Technology (the largest and oldest engineering school in the Netherlands), Wageningen University (a leader in life sciences), and MIT's Center for Advanced Urbanism.

The university's vision and road map for AMS is ambitious and unique in a number of ways. First, it is focused on tough and long-range engineering efforts, not the easily scalable, high-yield informatics research that characterizes so many urban informatics groups. AMS plans to take on tough civil, mechanical, and biological engineering challenges in urban food, water, waste, transportation and energy systems - there is much less emphasis on the underlying informatics challenges. Second, its educational program is orthogonal to the specialized degrees of schools like CUSP - in contrast to CUSP's MSc in applied urban science and urban informatics, AMS will offer a MSc in Metropolitan Solutions, "an interdisciplinary field that resides around improving the quality and sustainability of living in the city and its surroundings". Third, AMS has a substantial financial commitment from the city of Amsterdam, which will provide $175m (€150m) over ten years. Finally, citizens are considered from the outset as part of the strategy. "AMS will not just study cities and their citizens; it will mobilize them," states the center's proposal in no uncertain terms — by far the strongest language about the role citizens from any of the centers surveyed here.

AMS has an ambitious road map, with some 100-150 researchers at full buildout, following a ten-year path to self-sufficiency. Most cities have policy think tanks, some have urban research centers that directly support government — none have an engineering skunkworks like this.

Amsterdam Institute for Advanced Metropolitan Solutions

Full-time faculty and research staff (projected, 2025) 100-150
Graduate student enrollment (projected, 2025)   200-250
Degrees offered: MSc in Metropolitan Solutions

Engineering Utopia

"I believe the world is ecological," says Peter Edwards, the director of the **Future Cities Laboratory,** (FCL) based in the city-state of Singapore. While we've seen urban science and informatics pushed forward elsewhere by physical and information scientists, Edwards spent much of his early career tramping around the rainforests of Papua New Guinea, later rising to become the dean of environmental sciences at ETH, the Swiss engineering university that launched FCL in **2010**.

The first thing to note about FCL is that it is *big* — it consists of over a hundred faculty and post-doctoral researchers housed in Singapore working on nine topics within the overall research framework of "urban metabolism". According to a course text:

This framework helps us consider the city as a complex system that calibrates, manages and configures various stocks and flows of resources, such as energy, water, capital, people, space and information. Guided by principles of sustainability, we seek to encourage circular flows of such resources…[37]

Such thinking, very much at the vanguard of sustainability research when the lab was initially proposed to the Singaporean government in the late 2000s, presents an ambitious framework for engineering research.

But, as they do, things seem to have shifted as the lab's work has progressed. The urban systems approach was always meant to be directly supported by the second linchpin of the group's approach - an overarching focus on computer modeling and simulation as an integrative toolkit for urban research and engineering. Simulations are seen as a focal point for data capture, analysis and visualization to enable collaboration with stakeholders such as investors, public officials, researchers and citizens.

But as the Future Cities Lab shifts into its second five-year push, in many ways the simulation is moving to the forefront as the research product itself. The center's "value lab", an immersive simulation studio where researchers and Singaporean officials work together on 'what-if?' explorations, has proven very effective. It's a lesson not lost on Edwards, who argues that FCL's experience is is indicative of the fundamental winds driving the new urban science are in fact widely shared across the globe:

It's becoming more and more evident that that way you look at a city has just changed over the last five years. My guess is [the other new urban science centers] are all in the same situation. It wasn't that they sat down and said 'We're going to take a new view of cities.' This is simply something which has happened to them, because of the opportunities of the data and computing power.

To encounter such a well-resourced group, so far into its investigations, still grappling with the epistemological implications of the onslaught of urban data is at once both promising and troubling — promising in that it shows the expanding frontier of work that needs to be done, and the clear need for the research capacity coming online; troubling in that it shows how easily even the most prepared researchers may be dazzled by data.

Future Cities Laboratory

Full-time faculty and research staff   123

An Expanding Constellation of Urban Science

The urban science and informatics landscape is evolving rapidly. New centers are being launched at universities around the world on an ongoing basis. Here we briefly highlight a handful of additional notable centers. These organizations fall into three broad categories: emerging organizations similar to those profiled in the preceding section, urban science groups forming within existing urban research departments, and what might be called reflective practice groups largely focusing on critical perspectives on urban science.

Other Emerging Organizations

UCCD and CUSP launched in 2012, inspiring a wave of universities around the world to quickly mobilize similar programs. The University of Glasgow's Urban Big Data Centre was created in 2014 with the help of a grant from the European Commission. The Polytechnic University of Madrid established its City Sciences Group in the summer of 2014 as an accelerated master's degree program. The spring of 2015, saw new "smart cities" programs announced at two major universities in the southeastern United States - the University of Miami and the University of Alabama.[38] Given the market opportunity and the focus of even the biggest players like CUSP on their home city, we expect this trend to continue, as universities experiment with low-cost, potentially high-yield degree program launches in urban science and informatics, where compared to a field like bioscience, capital investment is minimal and spin-up time is very short.

Urban Science Within Existing Academic Units

While these centers highlight a new strategy for advancing heavily quantitative and computational study of cities through the establishment of new, focused centers, there is also a considerable amount of such work being done within existing departments - both by traditional urban studies and planning faculty, as well as computer scientists and natural scientists. The first "Urban Big Data" conference convened at the University of Illinois at Chicago in 2014 and was almost exclusively attended by scholars from existing departments - having little research results yet to show, the new urban science institutions were barely represented.[39] Several other examples of urban science being carved into inside existing academic departments are the University of Warwick's Institute for the Science of Cities, Northeastern University's Urban Informatics program, and the Metro21 initiative at Carnegie-Mellon University.

Reflective Urban Science

A final category of research organizations —while not engaged in the kind of data-intensive empirical research that characterizes the majority of urban science and informatics — play a crucial role in examining the social and ethical dilemmas involved. These include groups such as he National University of Ireland's Programmable City project and the Queensland University of Technology's Urban Informatics Research Lab (which arguably coined the term "urban informatics" in the 2008 *Handbook of Urban Informatics*).

The curious thing about these reflective urban science groups is why they are not more directly integrated into the mainstream institutions being established elsewhere. Clearly, there is a disciplinary and perhaps ideological and cultural chasm to cross between social scientist and engineer, but it's clear there is much to be gained from the exchange - in terms of more balanced and sophisticated approaches to risk, regulation, and ethics on the one hand, and access to funding, resources and real world test cases on the other.

Analysis

What can we learn from this survey of the emerging urban research infrastructure of urban science and urban informatics? In this section, we summarize common characteristics and assets, and the most notable unique elements among the centers within four main areas of activity: research, collaboration, finance and education.

Research Frameworks

Research is the primary purpose driving investment in the expansion of urban science and informatics at universities around the world. Yet there are a wide range of approaches to defining research agendas, staffing and executing research, and disseminating results. We see at least three general approaches that have emerged:

Ad Hoc

The SENSEable City Lab at MIT embodies this approach - much of its work involves rapid engagement and experimentation with emerging hobbyist and consumer technologies such as personal drones and gestural video game controllers. These tools, when they exhibit promising characteristics for interacting in urban settings, are repurposed to inexpensively develop novel urban sensing projects.. The lab tends to pursue many small projects in parallel, with graduate students leading the bulk of the work.

Big Science

The Center for Urban Science and Progress has committed itself to a handful of flagship projects such as the Urban Observatory, a multi-decade sensor deployment at the Hudson Yards development project in Manhattan, and a massive data repository hosted on behalf of the City of New York. These efforts require researchers, support staff, and specialized administrative personnel such as a Chief Privacy Officer (to develop and monitor compliance with protocols for use of research data provided by external partners) to be supported over an extended period of time. This amalgamation of people, facilities, instruments and infrastructure very much embodies a 'big science' approach to building a research enterprise, with a national government as the only likely source of sustainable funding at the level required.

Ensemble

The Urban Center for Computation and Data takes yet a third approach, combining elements of the previous two. Leveraging both an agile project-based approach, but also bringing to bear the substantial resources of both the University of Chicago and Argonne National Laboratory, it is as director Charlie Catlett describes it, "an impromptu ensemble". But rather than keep projects in-house, either run by students on a shoestring or the largesse of big science, the model aspires to outsource much of the key roles and work to partner organizations in a distributed collaboration.

These three approaches reflect different strategies for impact and funding, but they also highlight key differences in research style deployed by group leaders from different disciplines. SENSEable's Ratti, an architect working in an urban planning department, favors projects that combine research *and* design. CUSP, led by the physicist Koonin, is focused on building substantial new scientific instrumentation to vastly improve study of the city. Writing to his colleagues in the newsletter of the American Physical Society, Koonin described how cities could be measured like galaxies using the Urban Observatory's imaging capabilities:

Processing nighttime images (with well-known astronomical analysis techniques such as image registration, source identification (think of the individual windows as variable stars), color analysis, time series analysis and statistical procedures, is yielding aggregate patterns of temporal variation.[40]

The implication - in its third or fourth iteration a decade from now, the Urban Observatory will basically be a Hubble Space Telescope — only pointed at the Earth

Finally, many computer scientists like UCCD director Charlie Catlett are focused on building tools — sensing platforms, data warehouses, algorithms for analyzing data, and APIs - that support the work of a larger urban research community. They seem to work on some combination of desires: to work with their hands, to push new technologies to and past their engineering limits, and to invent things that can help others and improve their communities. While computer science has shed its once-marginalized status in the scientific establishment, in some ways it still tends to produce more unconventional kinds of research practice.

Models for Collaboration

The style of research in each organization has a powerful influence on how it collaborates with outsiders. But every organization must address collaboration somehow - the city is too vast, complex and dynamic a research topic for any one institution to carry out alone.

The most important partner for any urban science organization is with its host city government. That's because unlike traditional urban research groups, whose faculty and students increasingly have turned their attention to the rapidly urbanizing parts of the developing world, these new organizations have largely kept their real-world

research very close at hand. Again these relationships map across a spectrum:

- BARI's efforts to provide basic analytical capabilities to Boston and smaller suburban municipal governments within the context of more advanced research-based investigations.

- AMS's intention to develop a close working relationship with Amsterdam and serve as a skunkworks and consultancy on the most pressing challenges.

- CUSP and FCL's data warehousing functions — they are amassing larger and more well-curated collections of data about their host cities than any single entity in city government.

The focus on host cities stems quite logically from several unique aspects of *data-intensive* research-policy collaborations. First, it eases the access to and cost of acquiring and transferring data. For instance, CUSP's unique close data-sharing arrangement with New York City means that it *already has* most of the data it will ever want in its archive, ready for use at a moment's notice. Secondly, a close long-term relationship with many, frequent encounters provides a deeper understanding of the context of how data is produced, processed, manipulated and interpreted by various stakeholders. Third, the aggregation of data about a single place allows researchers to be less opportunistic (e.g. conducting a particular study on a topic simply because the data becomes available) and more free to pursue questions of particular scientific or public interest. Finally, the advantage of accumulating a track record of data-sharing experiences with the host city allows makes it more politically expensive for a city to withdraw from collaborations with academics.

Financing Schemes

Historically, funding for urban research has surged from one crisis to the next, with periods of boom and bust as social and political priorities wax and wane, driving resources to or away from urban programs in any particular national context. But because the urban science and informatics movement rides multiple tides - the growing interest in big data in business as well as government, the rapid pace of global urbanization, and the need to re-engineer existing cities and infrastructure to be more sustainable and resilient - the organizations in this survey are pursuing a variety of public and private funding models. These include:

University Endowment

The Boston Area Research Initiative (BARI), is funded by the Radcliffe Institute for Advanced Study which was created in 1999 when Harvard's former women's college was merged into the larger university. The Institute draws its financial support from the university's endowment investment proceeds.

Industry Sponsorship

As part of the MIT Media Lab, City Science is supported by an industry consortium model. Currently, some 80-plus organizations including many corporations provide a substantial portion of the lab's $45-million-plus annual operating budget.

Tuition

NYU's Center for Urban Science and Progress appears to be ultimately intended to be supported largely through tuition. With projected enrollment of some 500 full-time students annually in the early 2020s, CUSP could theoretically generate as much as $35 million annually in tuition revenue.

Corporate Seed Funding

The Intel Collaborative Research Institute for Sustainable and Connected Cities is supported by three years of funding committed by the company and its two university partners, with £1m (approximately $1.5m in 2015) from Intel and £250,000 each from Imperial College and University College London. Additional funding for year 4 and 5 will be authorized, and the organization is intended to be self-sustained through external funding beyond that date.

Clearly, no single model for funding urban science and informatics is dominant. In each institutional context, we see available resources mobilized to meet research priorities. The business model for each center is a creature of potential research funding pipelines and supplemental revenue-generating activities that each center can support.

Education Programs

Not all of the organizations surveyed actively engage in education, and there is little similarity in approaches to education among those that do (with the notable exception of the UK-based centers). At groups like UCCD, BARI, SFI and SENSEable City Lab, the only training that takes place is in the form of postdoctoral research work that serves as a kind of faculty-in-training apprenticeship for recent PhDs. The next step up is groups like QUT's Urban Informatics Research Lab which focus solely on a handful of doctoral students working on their own highly specialized research.

At the other end of the spectrum are institutions largely focused on producing degrees, usually on an accelerated timetable. CUSP for instance, grants a Masters in Applied Urban Science and Informatics which can be completed in just under one year for approximately $50,000 in tuition and fees. The Polytechnic University of Madrid's City Science degree program is similar in duration, though at €17,900 considerably less costly to students.

In the middle are a number of institutions - mostly based in the UK, such as CASA, Warwick's Institute for the Science of Cities, and Glasgow's Urban Big Data Centre - that strike a balance between graduate education and research. These centers operate more traditional 2-years masters degree programs as well as doctoral programs, while also engaging in substantial externally-funded multi-year research.

3. Sustaining the Movement

This survey has outlined a new movement in urban research, empowered by rapidly advancing capabilities and falling costs for collecting and analyzing vast amounts of data about cities. The goal of this exercise is twofold: to hold a mirror to this emerging field so that it might evaluate itself, its identity, and its collective ambitions; but also to present it to the outside world to inform dialogue about how to link it to existing research networks and real-world systems of government.

While it has accomplished a great deal in less than a decade, this movement is at a fragile moment in its infancy. If present trends continue, by 2030 this network of global universities could invest a projected $2.5 billion in new centers to pursue this agenda. There is great promise that this effort will produce new knowledge about urbanization at just the moment in human history it is most needed for good decision-making. But success is not guaranteed and many challenges remain.

The Near Term

The last two years have witnessed an interesting inflection point in the broader smart cities movement with which urban science and informatics shares much common DNA. The early promises of rapid market growth and return on public investment made by technology vendors during the post-financial crisis stimulus wave have proven elusive. Yet at the same time, a slew of new consumer-focused companies are making great strides developing smart city products and services.

As the hype bubble around big data cools in the coming years as well, we might expect a period of reckoning for the wave of urban science and informatics groups launched in the last five years. It could go either way, though — in the quest for quick results, some institutions might simply double-down on high-yield, rapidly scalable informatics research and dial back messier, more expensive work on big physical engineering systems. Meanwhile, some very basic challenges need to be addressed, as CUSP's Koonin argues - "figuring out what urban science is, is a meta-goal of CUSP", and the field needs to be put on a solid academic footing with a journal and conferences.

But even as new urban science institutions reset their own expectations, the infusion of new talent from disparate disciplines is likely to shake up and disrupt the research community in highly positive ways. We will likely see more unprecedented and novel ideas for instrumentation, and radical approaches to analysis that unlock subjects of research deemed too costly to even consider previously. For instance, sibling computer scientists Enrique and Vanessa Frías-Martínez have mapped clandestine nightlife districts in cities using geotagged Twitter messages. The resulting land use maps can inform planners about shifting or non-conforming uses at a greatly reduced cost, and be updated in real-time.[41]

The Long Payoff

In the short run, few observers expect either a transformation in our understanding of the city, or a massive social impact of this knowledge through its application in government. But looking 15-25 years out, expectations could rise considerably.

While much of the focus today is on the growing abundance of data, and the rapid expansion of raw computational horsepower for processing data, the actual underlying science - algorithms for discovering patterns, models for simulating real-world systems, etc. — has been dramatically improving as well, by some accounts even more rapidly. We cannot overlook the concurrent advances in algorithms for data analysis, linking of data, and data visualization that are even more important than the volume of data itself.[42]

But even these substantial undercurrents will take time to accumulate into a classic Kuhnian 'paradigm shift', in which an entire scientific framework is tossed out in favor of one that does a better job explaining away the annoying anomalies of the old. As Nigel Thrift, the urban geographer who heads the University of Warwick struggles to explain the process in metaphorical terms - it may be 10-15 years before we have aggregated enough urban data that it begins to "swirl", another decade before "big statistical models start cracking". The notion being simply that an almost infinite array of data on almost any urban phenomenon will be at a researcher's hand, cross-referenceble with anything else.

The Role of Funders: Three Future Challenges

We are at a pivotal moment in urban science and informatics - amidst a new generation of institutions there are already signs of distress. For the field to flourish in the coming decades three key challenges must be met.

First, urban science research institutions need paths to long-term financial viability. Research funding is materializing far more slowly than than the scope of challenges. Public funding is abundant in some quarters of the world, but it is not clear how these funds will be replaced when policy priorities inevitably shift — as they often do on urban issues. Institutions need to band together to articulate a shared agenda and the importance and impact of their nascent field. Urban science is drawing energy from many areas that funders in government and the philanthropic community have supported - the quantitative revolution in social science, civic technology, and sustainability. Cities provide a vital lab for those fields. The linkages must be supported in both directions.

The second challenge is developing mechanisms for accelerating the transfer of new knowledge and technology from urban science and informatics to city governments where it can improve the lives of billions. But as we have seen in fields such as biomedicine, applied research that involves complex institutions, public policy and large populations is painstakingly slow. There is an urgent need for research and experimentation in mechanisms that address the institutional challenges to harnessing the fruits of this research. But currently, there is a disconnect between efforts to overhaul government use of technology and what's happening in the halls of urban science.

The third challenge is preparing for a variety of futures. We don't yet know how this movement will evolve, but it will continue in some form. In a future publication we will examine four possible scenarios of the future of urban science - an overrun of established disciplines, integration with them, a boom and bust cycle, or a deepening scientific maze. Funders need to be prepared to help these organizations anticipate and strategize for resilience in these, and many other, possible futures.

Notes

[1] Author's calculation of total aggregate investment through 2030 amongst the centers surveyed in this study based on published financial information, staffing levels, and selected confidential disclosures collected January-May 2015.

[2] Munshi, Indra. 2000. "Patrick Geddes: Sociologist, Environmentalist and Town Planner." *Economic and Political Weekly.* 35 (6): 485–91.

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[4] Torrey, Volta. 1967. *Science and the City.* (U.S. Department of Housing and Urban Development: Washington, D.C.).

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