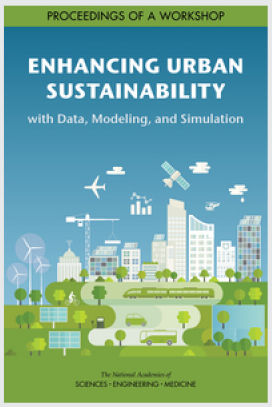

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ENHANCING URBAN SUSTAINABILITY

with Data, Modeling, and Simulation

PROCEEDINGS OF A WORKSHOP

Linda Casola, *Rapporteur*

Board on Mathematical Sciences and Analytics

Committee on Applied and Theoretical Statistics

Board on Energy and Environmental Systems

Computer Science and Telecommunications Board

Division on Engineering and Physical Sciences

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Acknowledgment of Reviewers

This Proceedings of a Workshop was reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise. The purpose of this independent review is to provide candid and critical comments that will assist the National Academies of Sciences, Engineering, and Medicine in making each published proceedings as sound as possible and to ensure that it meets the institutional standards for quality, objectivity, evidence, and responsiveness to the charge. The review comments and draft manuscript remain confidential to protect the integrity of the process.

We thank the following individuals for their review of this proceedings:

Elena Craft, Environmental Defense Fund,
Auroop R. Ganguly, Northeastern University,
Peter Kareiva, NAS,[1] University of California, Los Angeles, and
Joseph A. Langsam, University of Maryland, College Park.

Although the reviewers listed above provided many constructive comments and suggestions, they were not asked to endorse the content of the proceedings nor did they see the final draft before its release. The review of this proceedings was overseen by Andrew Solow, Woods Hole Oceanographic Institution. He was responsible for making certain that an independent examination of this proceedings was carried out in accordance with the standards of the National Academies and that all review comments were carefully considered. Responsibility for the final content rests entirely with the rapporteur and the National Academies.

[1] Member, National Academy of Sciences.

Contents

1

Introduction

With funding from the George and Cynthia Mitchell Endowment for Sustainability Sciences at the National Academies of Sciences, Engineering, and Medicine, the Board on Mathematical Sciences and Analytics, in collaboration with the Board on Energy and Environmental Systems and the Computer Science and Telecommunications Board, convened a workshop on January 30–31, 2019, in Washington, D.C., to explore the frontiers of mathematics and data science needs for sustainable urban communities.[1] The workshop strengthened the emerging interdisciplinary network of practitioners, business leaders, government officials, nonprofit stakeholders, academics, and policy makers using data, modeling, and simulation for urban and community sustainability, and addressed common challenges that the community faces in using data, modeling, and simulation for sustainability (see Appendix A for the workshop agenda). Approximately 80 people attended the workshop, with an additional 800 participating online (see Appendix B). The workshop's statement of task appears in Box 1.1.

This proceedings is a factual summary of what occurred at the workshop. The workshop planning committee's role was limited to organizing and convening the workshop (see Appendix C for biographical information on the members of the planning committee). The views expressed in this proceedings are those of the individual workshop participants and

[1] Urban sustainability is the long-term social, environmental, and economic vitality and viability of the city.

Box 1.1
Statement of Task

A National Academies of Sciences, Engineering, and Medicine-appointed ad hoc committee will plan and organize a workshop to explore the frontiers of big data, modeling, and simulation in urban sustainability. This workshop will bring together leading urban sustainability researchers, data scientists, statisticians, computer scientists, mathematicians, and other stakeholders to

- highlight urban sustainability research efforts and programs under way, including research into air quality, water management, waste disposal, and social equity;
- discuss challenges and opportunities to applying big data, modeling, and simulation to advance urban sustainability research;
- discuss promising urban sustainability research questions that improved use of big data, modeling, and simulation can help address; and
- explore relevant case studies of organizations, sectors, or application domains that have addressed similar big data, modeling, and simulation issues, and discuss how these experiences can help advance data-driven urban sustainability science in the future.

do not necessarily represent the views of the participants as a whole, the planning committee, or the National Academies of Sciences, Engineering, and Medicine.

WORKSHOP OVERVIEW

Katherine Bennett Ensor, Rice University
Aniruddha Dasgupta, World Resources Institute

Katherine Bennett Ensor, Rice University, welcomed participants to the workshop and thanked the George and Cynthia Mitchell Endowment for Sustainable Sciences for its support. She explained that tremendous advancements in science and technology over the past several decades could be applied to cities and urban infrastructure. Aniruddha Dasgupta, World Resources Institute, described the workshop as an opportunity to connect the data, modeling, and urban sustainability communities to enable better decision making related to sustainability. He commented that building, management, and consumption in cities are not currently

planned and operated in a way that will produce desired outcomes for the climate, economic productivity, and human welfare. Appropriate use of data could change the ways in which cities are managed and services are provided as well as allow citizens to co-create solutions to city problems and hold their leaders accountable. He asserted that more than 50 percent of the world's population currently lives in cities, and this number will increase in the future; channeling the data revolution to improve the sustainability of cities is imperative.

2

Framing the Problem

WHY IS THIS WORKSHOP IMPORTANT?

Intelligent Climate Adaptation and Resilient Engineering for Urban Sustainability

Auroop R. Ganguly, Northeastern University

Auroop R. Ganguly, Northeastern University, provided an academic perspective of urban sustainability. He said that there is a clear and present need for pathways to urban sustainability, including economic development, social progress, and environmental motivators as key indicators. To highlight issues of risk and resilience quantification, he shared examples of climate risk management frameworks from the Intergovernmental Panel on Climate Change, the emerging resilience paradigm (see Ganguly, Bhatia, and Flynn, 2018), and a recent report[1] to support climate action in the United States. While natural climate variability is beyond human control, greenhouse gas emissions and land use change, for instance, are partly within human control. Even hazards such as Hurricane Katrina may not turn into disasters if vulnerability (e.g., the levee that broke) and exposure (e.g., human habitations below sea level) are managed. To do

[1] For more information about the national climate assessments, see www.climateassessment.org, accessed April 29, 2019.

this, Ganguly suggested that cities integrate consequence management with longer-term adaptation and urban mitigation plans.

Ganguly also discussed the resilience of interdependent systems to stresses and disruptions. Cities need to evaluate how reliably, quickly, and effectively they can recover from natural disasters (i.e., by restoring critical lifelines such as communications, power, transportation, water, and financial services) as well as consider how to maintain overall levels of functionality through graceful degradation. He emphasized that cities should use disruptions as an opportunity to improve their systems rather than just aiming to restore their systems to their original state. He described the value of designing and incentivizing a virtuous cycle of risk and resilience for cities. For example, sea level rise and other indicators of change could be used to assess the value and risk of more systematic recovery approaches (in this case, potentially using a network-topology-based approach). An important part of this is eliminating the cycle of disincentives (e.g., more funds tend to be available for disaster relief than for preparedness efforts) that can stagnate technology development and increase outdated practices (Ganguly et al., 2018). He stressed the need for financial incentives to achieve these goals.

Ganguly suggested that the scope of "urban" should move beyond city boundaries to consider the larger connected ecosystem in which cities exist. Urban impacts can carry across regional, national, and international borders and can include interrelated infrastructures and supply chains. However, few governance structures can look at these mega-regions holistically. Large-scale coupled natural-engineered-human systems can also pose unique challenges. As an example of the interconnected nature of infrastructures, a surge in agricultural water demands in India from a heat wave and delayed monsoons in 2012 led to large groundwater withdrawals, partly as an unintended consequence of price incentives given to farmers. This caused increased stress on the power grid and a massive blackout, which then downed the rail service.

A specific challenge is managing the risks of urban heat on public health. Urban planners could reduce urban heat intensities through decisions about open spaces, bodies of water, and use of green roofs, while the impacts of urban heat islands could be managed through cooling centers, public health facilities, early warning systems, and community education and resilience-building exercises. Ganguly reiterated the value of thinking about consequence management and mitigation when thinking about development pathways (e.g., how to help senior citizens in disadvantaged areas access emergency facilities during a heat wave). Other urban challenges relate to coastal infrastructures and ecosystems as well as the food-energy-water nexus. To maintain urban services—such as buildings, bridges, the power grid, transportation systems, and means

of communication—the gap between the science that is currently understood and the skills or knowledge available to inform engineering and policy needs to be closed, he asserted.

Ganguly presented a selection of novel approaches to connecting science and policy. The Next Generation Digital Earth, which includes a vision for augmented images of city structures and simulations of urban systems, aims to create a digital replica of real systems. Interlinked data systems, physics-guided data science, hybrid physics and data science approaches, and physics-guided uncertainty quantification can all inform decision making. Entrepreneurship and partnerships among private, public, government, and intergovernmental entities can help build communities around these issues. Together, these efforts can enable better understanding of different lifelines, capabilities, kinds of data and ways of processing them, and types of threats, he concluded.

Connecting Research with Civic Action

Jeanne Holm, City of Los Angeles

Jeanne Holm, City of Los Angeles, provided a city government perspective of urban sustainability, emphasizing that connecting academic research and civic action is key to making change. She noted the importance of using varied learning modalities to educate the next generation around data science tools. Cities should be efficient, effective, safe, resilient, and innovative, and data and technologies should be used to create a city ecosystem that benefits its citizens equitably, Holm continued.

Holm explained that the city of Los Angeles is the 20th largest economy in the world—4 million people living in 500 square miles—which brings both great opportunities and challenges. She suggested that technology provides an opportunity to bring people together to decrease the high inequity in Los Angeles County. She emphasized that data-driven approaches could lead to new policies that impact outcomes. A number of innovative projects are under way in the city of Los Angeles, with the support of its tech-focused and data-driven current mayor, Eric Garcetti. In any city, Holm continued, data come from many different sources, including sensors, satellites, and airborne instruments. Smart cities, such as Los Angeles, have sensors on garbage trucks, street sweepers, streetlights, vehicles, and even animals.

Holm and her team are working to understand which of these data could be used to help make better decisions for the city as well as how to make those data interoperable to drive action. She explained that the city's approach utilizes many technologies, such as artificial intelligence, predictive analytics, personal assistants, machine learning, Internet of

Things, blockchain, gamification, virtual and augmented reality, and open data ecosystems; all of this is possible only with participation from everyone in the city's ecosystem (e.g., the mayor, businesses, the city council, employees, universities, global partners, and the citizens).

Holm reiterated the value of connecting with academic institutions and research organizations to understand which data will create better actions and outcomes for citizens and to activate citizen scientists. Data interoperability, standardization, provenance, and authenticity are important to enabling these partnerships. She noted that as modeling and simulation are becoming more widespread, it is important to give citizens an opportunity to co-create their future, especially through storytelling. Although futuristic films such as *Blade Runner* present a dystopian perspective, Holm reminded participants that it is their choice as to whether a dystopian or utopian future is created.

She explained that the city of Los Angeles owes much of its success to formalized partnerships. For example, the Data Science Federation[2] involves data science professors and students from 17 universities and colleges in California and Arizona who work with city departments on specific data challenges. This program allows members of the next generation, who are often excited to make a difference in their communities, to understand the power of government service and to explore potential career opportunities. The city of Los Angeles also works with the national Code for America;[3] its local organization, Hack for LA,[4] connects citizens' ideas for their communities with academic research and formal data. The LA CyberLab[5] partners with more than 500 businesses, the majority of which were started by immigrants, to help them understand cybersecurity vulnerabilities. There is also an effort to encourage citizen scientists to collect data for the city by playing augmented reality games, such as Agents of Discovery, that allow them to explore city parks. Another partnership, SmartAirLA,[6] works to address public health issues that arise from air pollution at the Port of Los Angeles: global positioning system smart inhalers are issued to people who live near the port, and they generate heat maps identifying where people had a difficult time

[2] For more information about the Data Science Federation, see https://dsf.lacity.org, accessed March 12, 2019.

[3] For more information about Code for America, see https://www.codeforamerica.org, accessed March 12, 2019.

[4] For more information about Hack for LA, see https://www.hackforla.org, accessed April 16, 2019.

[5] For more information about the LA CyberLab, see https://www.lacyberlab.org, accessed March 12, 2019.

[6] For more information about SmartAirLA, see https://www.smartairla.org, accessed March 12, 2019.

breathing. This helps asthma sufferers avoid high-risk areas and reduce their number of attacks.

City data are also collected from the public via MyLA311,[7] an app and call line established for people to report city problems. All of this information is shared on an open data portal and with transportation organizations (e.g., Waze[8]) so that people are aware of and can avoid unsafe areas. ShakeAlertLA[9] is an earthquake early warning system developed in partnership with the U.S. Geological Survey (USGS). Sensors detect when the ground shaking begins and send a signal in 1.8 seconds to the more than 470,000 people who have downloaded the app to let them know how severe the shaking will be at their location. Holm noted that the city invested in federal government work, such as with USGS to build out the earthquake early warning sensor network, because of its value for the citizens of the city of Los Angeles. She added that mayors from more than 400 North American cities have signed a pledge (led by Mayor Garcetti, who chairs Climate Mayors) to take action on climate, and the city of Los Angeles, in particular, has a plan based on the United Nations' Sustainable Development Goals,[10] which it hopes to achieve in time for the 2028 Olympic Games.

The Policy and Planning Perspective

Bill Fulton, Rice University

Bill Fulton, Rice University, provided a policy and planning perspective of urban sustainability and focused on ways that data can be used to improve how municipal governments function. He described a municipal government as a series of operational departments, each with a particular goal and task. It is difficult for these departments to share data in a meaningful way because they have collected data for their own purposes, for

[7] For more information about MyLA311, see https://www.lacity.org/myla311, accessed March 12, 2019.

[8] For more information about Waze, see https://www.waze.com, accessed March 12, 2019.

[9] For more information about ShakeAlertLA, see https://www.shakealert.org, accessed March 12, 2019.

[10] The Sustainable Development Goals are as follows: no poverty; zero hunger; good health and well-being; quality education; gender equality; clear water and sanitation; affordable and clean energy; decent work and economic growth; industry, innovation, and infrastructure; reduced inequalities; sustainable cities and communities; responsible production and consumption; climate action; life below water; life on land; peace, justice, and strong institutions; and partnerships for the goals. For more information about these goals, see United Nations, "About the Sustainable Development Goals," https://www.un.org/sustainabledevelopment/sustainable-development-goals, accessed March 4, 2019.

their own uses, and in their own ways. He added that many municipal governments in the United States are located in small cities and lack analytical capabilities—they are often largely motivated by budget analyses and their impact on operations. Operational data are relatively rare, and although some police departments are sophisticated in the way that they use data, such a practice is fairly atypical, he continued. Municipal government departments are becoming overwhelmed by the abundance of available data. Fulton noted that most city governments are not currently set up to facilitate the use of that amount of data, thus missing opportunities to use data to improve the functioning of the city.

Fulton said that it is crucial to think about how to make data-driven decision making attractive to people who have the power to create political change. First, it is important to pay attention to what can be measured and how, as well as whether the right entities are being measured (i.e., for sustainability as opposed to operations and function). Second, it is necessary for the people who are running municipal governments to understand that investing in data sciences is valuable. Data can then be used in a more efficient, more cost-effective way with the people already on staff. Third, governments need to embed data-driven approaches in their operations so that they become part of the landscape of city management. Fulton explained that change is happening in cities with tech-savvy mayors, but operations should not be dependent on tech-savvy top-level leadership. Fourth, he continued, it is important for municipal governments to understand the value of partnerships, especially with academic institutions—it is impossible for any single municipal government to accomplish such vast change, especially in terms of developing analytic capabilities, without partners. He acknowledged that it can be difficult to initiate partnerships but reiterated that it is essential for progress and is the best way to engage with current data privacy problems.

DISCUSSION

Katherine Bennett Ensor, Rice University, Moderator
Auroop R. Ganguly, Northeastern University
Jeanne Holm, City of Los Angeles
Bill Fulton, Rice University

Data Sharing and Security

Ulrike Passe, Iowa State University, asked the panelists how to prevent dystopian views of the impact of data, models, prediction, and analysis on society and how to ensure that infrastructure remains secure. Holm responded that this question is essential to understanding the provenance

of data and to ensuring that data remain accessible and available at all times to the people who need them. It is also important to understand the challenges of modeling based on those data, including inferences and biases. Katherine Bennett Ensor, Rice University, acknowledged that data security and access are crucial and said that the Kinder Institute[11] is creating the Urban Data Platform,[12] which is a library of past and current data about the Houston area. She added that archiving data (and thus having a record of data provenance) is as important as collecting real-time data; such pursuits are opportunities for city–university partnerships. Ganguly wondered if there is a way to expand the archiving and sharing initiatives that are occurring within cities, as Ensor described, across networks of cities so that more data sets are available to more people.

Deborah Goodings, George Mason University, commented on the importance of data repositories. She wondered what type of national organization could host a large data repository into which many cities upload their data to be curated, anonymized, and made available. Fulton said that a university could host such a repository as long as it is tied to the university's infrastructure and not to an individual professor's research project. Passe added that land-grant universities should be a part of this conversation because they have the capacity to be in every county in their respective states. Holm explained that some data archiving is available through data.gov/cities, and Ganguly said that national laboratories as well as open access platforms, such as Oasis,[13] have an interest in this issue. Ensor championed the value of open data and suggested that published data be held to the same standards as published papers in terms of product ownership and legitimacy. She added that because it is important to understand the data that drive decisions, it is necessary to build infrastructure for transparency and reproducibility.

Jerry Miller, Science for Decisions, referenced the National Academies' report *Pathways to Urban Sustainability: Challenges and Opportunities for the United States* (NASEM, 2016) and noted that data access remains a major barrier for small cities. Given the data that are currently available for operations in the urban setting, he asked the panelists how to develop data pipelines that will support decision making decades into the future. Fulton used the example of sensors to show that the *presence* of data is not synonymous with the *value* of data. He emphasized the need to be strategic about which data are valuable in helping to achieve sustainability

[11] For more information about the Kinder Institute, see https://kinder.rice.edu, accessed March 12, 2019.

[12] For more information about the Urban Data Platform, see https://kinder.rice.edu/urban-data-platform, accessed March 12, 2019.

[13] For more information about Oasis, see https://www.oasis-open.org, accessed March 12, 2019.

goals. Holm added that part of the challenge is incentivizing cities to act and to share their data when each city has its own motivation. The city of Los Angeles has a strategic plan for sustainability and a strategic plan for resiliency, both of which are action oriented and connected to the United Nations' Sustainable Development Goals. She emphasized that all cities have to prepare and would benefit from data-driven planning, even if what they are preparing for is much smaller in scale than the Olympic Games. She encouraged partnerships between data scientists and philanthropic organizations to help actualize research in a city space. In response to a question from Ensor about how such programs are sustained once the philanthropic organization steps out, Holm said that program sustainability should be built into the city budget process. Fulton added that city managers are driven by budget, so it is essential to show a return on investment for any program.

Partnerships for Sustainability

Roland Gamache, George Washington University, asked how a university could act to broker partnerships with cities beyond the jurisdiction of an established city–university partnership. Ganguly described organizations such as the Thriving Earth Exchange of the American Geophysical Union[14] that are trying to match stakeholders with smaller, lower-resource cities. He referenced Northeastern University's Global Resilience Institute[15] as well as the Boston Area Research Initiative[16] as other innovative programs. Holm added that standards organizations such as the International Organization for Standardization[17] and the World Wide Web Consortium[18] are working to create new schema around data to improve searches. Ganguly also noted that openly available data could be used to solve issues of importance to these cities and that sensors are becoming more affordable.

Fred Abousleman, Oregon Cascades West Council of Governments, mentioned that developing partnerships can be difficult and wondered how to make information more accessible both nationwide and at the local level. He emphasized that the problem is not a lack of data or resources

[14] For more information about the Thriving Earth Exchange of the American Geophysical Union, see https://thrivingearthexchange.org, accessed March 12, 2019.

[15] For more information about the Global Resilience Institute, see https://globalresilience.northeastern.edu, accessed March 12, 2019.

[16] For more information about the Boston Area Research Initiative, see https://www.northeastern.edu/csshresearch/bostonarearesearchinitiative, accessed March 12, 2019.

[17] For more information about the International Organization for Standardization, see https://www.iso.org/home.html, accessed March 12, 2019.

[18] For more information about the World Wide Web Consortium, see https://www.w3.org, accessed March 12, 2019.

but rather a lack of excitement and a fear of high costs. Because cities have so many different approaches, it is difficult to identify a sustainable path forward. Fulton agreed that the presence of these varied approaches is a hindrance right now. However, in time, he believes that a level of standardization will arise, which will make things less expensive and easier for smaller jurisdictions. For now, he suggested leveraging available university and philanthropy capacity as well as any local assets—pooling the cost reduces the burden and increases the return. Holm said that one must always be able to show a cost–benefit for the city; a small up-front investment with a university partner could change the dynamic around a city problem. For example, investing in predictive analytics to try to prevent homelessness through the offering of additional services can provide clear return on investment for a city, Holm explained. Ganguly asserted that there are incentives for those in academia to engage in this type of work.

Chibuzo Okoro, Georgetown University, asked about incentives for communities to create more engagement for data gathering. Holm replied that communities have amazing opportunities for citizen scientists. She referenced the Federal Citizen Science and Crowdsourcing Toolkit,[19] which is open to the public and connects citizen science efforts to scientific research (i.e., citizens gather data that can be converted to help scientists and ultimately lead to government action). Ensor said that there is an ongoing conversation about the best ways to integrate this seemingly haphazard information with more measured information, taking into account sampling biases that might be present.

Aniruddha Dasgupta, World Resources Institute, referenced previous commentary from the panelists about the value of city–university partnerships and wondered how to make such partnerships work with nations that are newly industrialized or are in the process of industrializing (referred to as the Global South). He also asked how to help smaller cities make the political point that scientific capabilities are needed for decision making. Fulton explained that U.S. cities are motivated to make the most of their often-limited budgets. This can present impediments for partnerships with academic institutions, especially because incentives do not always exist for tenure-track faculty to engage in these real-world problems. Ganguly said that there are creative ways to get around this lack of incentive structure. In response to Dasgupta's questions about the Global South, he shared his experiences traveling with U.S. students to India to learn about solving problems from physical infrastructure and natural systems perspectives. Lessons learned include thinking about technological benefits in a sociopolitical context to make improvements

[19] For more information about the Federal Citizen Science and Crowdsourcing Toolkit, see https://www.citizenscience.gov/toolkit/#, accessed March 12, 2019.

for a city. Holm briefly discussed working with local governments in the Global South to create open data portals and to partner with local universities to inform and drive change in their communities and foster transparency in government. Audience member David Rabinowitz noted that many cities have universities with students who want to do projects in data analysis, but such projects become unsustainable after the students leave. He and Ensor proposed that this could be a great opportunity for industry involvement to sustain the work.

Best Practices and Lessons Learned

Justin Smith, U.S. Census Bureau, asked how to motivate smaller cities (i.e., fewer than 100,000 residents) to invest in data and data science. Fulton responded that small cities with large universities have great opportunities to improve their use of data analytics. Regional planning agencies are another potential vehicle to pool resources, he continued. Holm added that Los Angeles County partnered with the Southern California Association of Governments and now has data science federation projects in a number of the county's other 88 cities, which prompts cities with resources to share the wealth. She mentioned Code for America, the Metropolitan Information Exchange,[20] and the FUSE Corps[21] as other programs that work to bridge these resource gaps. She also proposed that federal organizations such as the U.S. Census Bureau, which excels in data anonymization and management, could help cities to become more data literate.

Brian Wee, Neptune and Company, Inc., suggested providing exemplars of how other cities have used data to solve particular problems. Fulton agreed that shared learning is crucial—for example, the MetroLab Network[22] presents a series of use cases on its website of how universities and cities worked together to solve problems. He suggested that local government organizations (e.g., the U.S. Conference of Mayors and the National League of Cities) identify successful use cases, publicize them, and create a learning community so that cities know what other cities are doing to succeed.

Sallie Keller, University of Virginia, mentioned that in order to have successful partnerships, research has to unfold at a pace that is often

[20] For more information about the Metropolitan Information Exchange, see http://www.mixcio.org, accessed March 12, 2019.

[21] For more information about the FUSE Corps, see https://fusecorps.org/about, accessed March 12, 2019.

[22] For more information about the MetroLab Network, see https://metrolabnetwork.org, accessed March 12, 2019.

much faster than a university's capability. She wondered how to create units within universities that can deliver results to their city partners in a timely fashion. Holm agreed that time is of the essence, so the Data Science Federation projects are completed within 10–12 weeks.

The Future of Urban Sustainability

Ensor said that it is crucial to look toward the future when thinking about sustainability. Ganguly noted that, even with modern modeling and data capabilities, it might not be easy to address resilience for plausible futures, especially given changing conditions and complex uncertainties. Holm commented on the power of predictive analytics: ideas about a future that would be desirable for communities are based on an ability to understand the past and the present. Diverse voices are needed to help visualize and shape cities, she continued. She said that the tools exist; the challenge is in identifying which problems to address. Donald Wuebbles, University of Illinois, noted that people recognize the need to develop new tools to translate science into action.

3

Advances in Data, Modeling, and Simulation

DATA, MODELING, AND SIMULATION

Key Questions

David Maier, Portland State University, Moderator

Moderator David Maier, Portland State University, explained that speakers would discuss recent advances in technology related to the use of big data, modeling, and simulation that might be useful for urban sustainability. He presented the following key questions as a guide for the discussion:

- What advances have been made in data, modeling, and simulation for air and water quality, network analysis and mobility, and traffic modeling?
- What is the state of the art in data, modeling, and simulation from each expert's research area (both their work and the best work in the field)?
- How will advances in data, modeling, and simulation inform the work of cities and make an impact on urban sustainability problems?

Advances in Data, Modeling, and Simulation

Elena Craft, Environmental Defense Fund

Elena Craft, Environmental Defense Fund (EDF), described EDF as a U.S.-based nongovernmental organization of scientists, social scientists, and economists working on science-informed policy advocacy. One distinguishing factor of EDF is that it works directly with companies on their environmental problems.

Craft highlighted a number of ways in which EDF is involved with big data, including its initiative on methane. She described methane as more devastating to the climate than carbon dioxide because of its ability to absorb heat. It is essential to understand methane emissions in order to mitigate climate pollution. EDF began a 5-year, $20 million collaborative project with researchers from 40 institutions who studied the links in the oil and gas supply chain to identify leaks. Thirty-five peer-reviewed papers emerged from this project, each demonstrating that methane emissions were significantly higher than previously estimated, with a leak rate of approximately 4 percent. The results of this study were used as the foundation for the methane rules that went into effect during the Obama administration, Craft said. As part of this project, EDF and Google coordinated a data collection campaign to find methane leaks across the country. Sensors were placed on top of Google Street View cars to measure methane, and then maps of methane leaks across various U.S. cities were published. More leaks were found in older cities with older pipelines and transmission lines; newer cities with better infrastructure had fewer leaks. This work enabled EDF to help local utilities prioritize which leaks to address.

Craft explained that because that campaign was successful, EDF decided to outfit the Google Street View cars in Oakland, California, with an array of instruments that could measure particulate matter, ozone, nitrous oxide, nitrogen dioxide, black carbon, and ultrafine particles. EDF then partnered with Kaiser Research Group to discern health impacts at the neighborhood level. This method does not predict individual risk, but it shows the value of making this information available to residents, who can identify locations they visit on the maps and determine whether there is increased health risk from pollution. For example, this community now uses these maps for their proposals to secure funding through the California legislation AB 617, which enables some cap and trade proceeds to go toward reducing emissions in hot spot and environmental justice areas.

After this work in Oakland, EDF began integrating this systematic review and mobilization in Houston and London, with the goal of

providing more information to city planners, health departments, and advocacy groups to aid in the development of action plans to mitigate environmental pollution. Houston is now participating in a pilot program in which the measurement instruments are placed on vehicles in the city's fleet instead of on Google Street View vehicles. The data being gathered could be used to identify potential pollution hot spots in the city. Houston's public health department could then use these data to prioritize a mobile health unit to take additional measurements, information from which could be used during a future permit hearing for a refinery, for example. Craft emphasized the value of having this type of information at hand to make better decisions. Eventually, the process could be automated so that a person at a public health department could look at real-time data on a dashboard. EDF continues to try to find ways to better integrate with existing systems, disaster response teams, and public health policy representatives.

Public Health and Simulation for Supporting Urban Sustainability

Bryan Lewis, University of Virginia

Bryan Lewis, University of Virginia, explained that public health is essential both for urban living and for urban sustainability. Sanitation services, disease control, and strategies for cleaner food enable humans to survive and thrive in dense cities. He noted that open data and increased data sharing, in addition to increased computational power, allow for models to be more sophisticated and for real-world processes to be represented with fidelity. The use of machine learning, deep learning, and natural language processing tools for integrating data can also support decision making around public health issues and inform public health policy. Disease forecasting, course of action analyses, and modeling of complex disasters aim to capture and represent massively interdependent systems in simulation, which is safer and more cost-effective than running disaster experiments in the real world. Data analyses can help address many urban problems, although it is important to consider how to translate this information for governance purposes, he continued.

Lewis shared a few examples of how disease forecasting can be used to improve public health in cities. The Centers for Disease Control and Prevention sponsors an annual challenge to forecast the flu. Public health departments could use these data to determine appropriate hospital staffing levels to better prepare for flu outbreaks. Environmental niche models can generate warning signals about which locations residents should avoid in order to prevent illness. Forecasting for vector-borne diseases, such as Zika, is particularly challenging given the complex system of the

viruses and vectors, as well as the weather and human components. Forecasting for the Ebola virus is also difficult given that poor and sporadic data exist, yet rapid decision making to deploy support is crucial.

An important tool that is increasingly employed is a synthetic representation of an urban system (see Figure 3.1). Myriad data sources are synthesized to gain a robust representation of the population, which can be used to coordinate data analysis systems and assess options for mitigating impacts of disasters or devising policies for the real world.

Lewis described another project, which focuses on optimizing national resiliency, particularly during pandemics when medical supplies can be scarce. To be better prepared and have improved responses, it is possible to simulate pandemics, use real-time forecasting to estimate future deficits, explore the impact of policies, and determine how medical resources could be maintained, shared, or distributed during pandemics.

In another example, Lewis talked about National Planning Scenario Number One[1] and discussed how modeling of complex disasters can help understand actions that could be taken to improve the resilience of a population (see Figure 3.2). Data about people and places are fused, multiple simulation modules interact, and experiments are designed to explore policies and response plans that would enable people to make better decisions during such events. From these experiments, it is possible to learn whether cities need better messaging and better education or infrastructure improvements. The representation shows that with such improvements, individuals could interpret conditions and make better decisions based on improved communications during a disaster. The next step is to consider how this could be integrated into the policy-making process.

In closing, Lewis emphasized that simulation technologies are essential for urban sustainability and described three new areas of study for public health:

1. Model-guided machine learning (i.e., mechanistic models that guide statistical approaches) shows promise for extending the use of simulation.
2. Virtual reality is now more affordable and approachable, enables collaborative work on problem solving, and improves the potential for analysis and exploration of complicated data sets.
3. Engineering capabilities could help restructure governance and management to enable more efficient administration of communities.

[1] For more information about National Planning Scenario Number One, see https://www.fema.gov/national-planning-frameworks, accessed March 12, 2019.

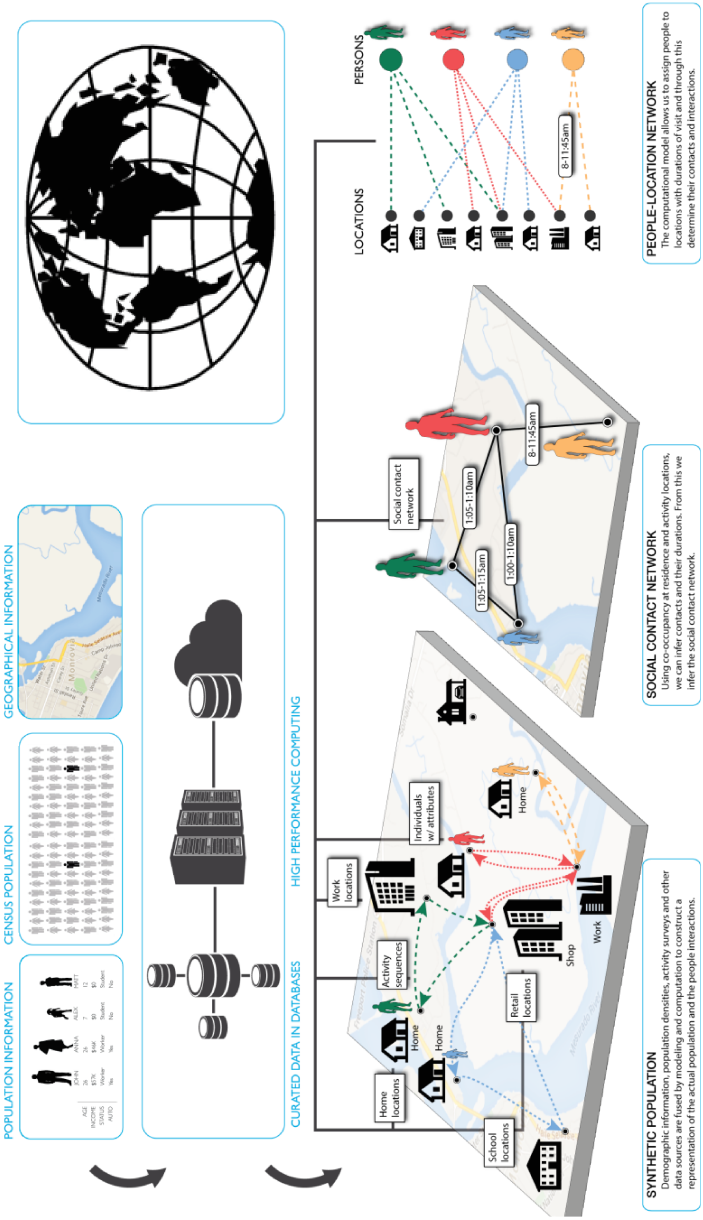

FIGURE 3.1 A synthetic representation of an urban system can be particularly useful in preparing for disasters or in developing new policy. SOURCE: Bryan Lewis, University of Virginia, presentation to the workshop, January 30, 2019, with credit to Henning Mortveit, Ph.D.

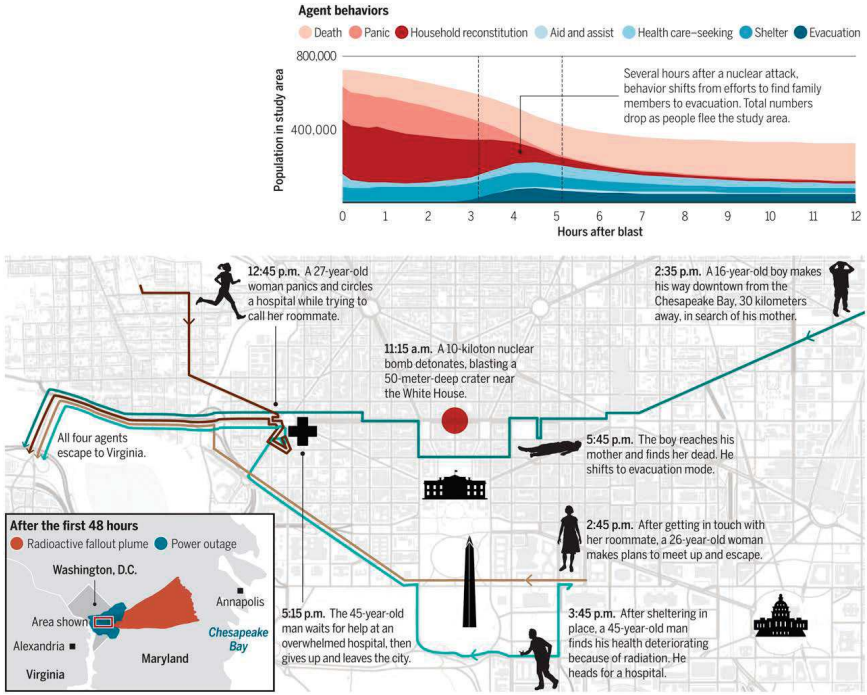

FIGURE 3.2 Modeling can be used to improve a city's resilience to complex disasters. For a hypothetical situation of an unannounced detonation of a nuclear bomb, Lewis's team examined the 72 hours following the event and the possible impact on affected people and places, in terms of communications, power, transportation, and health infrastructure. SOURCE: From M.M. Waldrop, 2018, Free agents, *Science* 360(6385):144–147. Reprinted with permission from the American Association for the Advancement of Science.

C2SMART: Data-Driven Transportation Modeling and Simulation

Kaan Ozbay, New York University

Kaan Ozbay, New York University, emphasized the importance of transportation systems in cities and provided an overview of uses of simulation for transportation systems. Ozbay's C2SMART University Transportation Center[2] works on modeling, simulation, and data-driven

[2] For more information about the C2SMART University Transportation Center, see http://c2smart.engineering.nyu.edu, accessed March 12, 2019.

solutions for transportation. The two types of models he most often uses are activity travel behavioral models (e.g., how people make their decisions about travel, from both user and provider perspectives) and traffic flow/control models (e.g., how outcomes affect congestion, safety, and other externalities such as emissions and noise). He emphasized that modeling is rapidly evolving with the increased availability of open source data.

Ozbay explained that many types of traffic models exist, including macroscopic (i.e., fluid flow approximation of individual cars), microscopic (i.e., car-level traffic dynamics), mesoscopic (i.e., a hybrid between micro and macro models), and agent-based (i.e., individual driving and decision-making dynamics). Which model is chosen depends on the problem in need of a solution. Types of use cases for simulation and modeling include (1) proof of concept studies for evaluations where analytic models are very simplistic; (2) deployment decision support, which helps to understand the impacts of a scenario on a population and its existing infrastructure (often using the open source MATSim[3] and SUMO[4] models); and (3) real-time decision support for traffic operations and control.

Ozbay provided highlights of work at the C2SMART University Transportation Center, including a study on using autonomous buses to improve capacity in the Lincoln Tunnel that demonstrated that autonomous vehicle technologies could dramatically improve traffic flow. The C2SMART University Transportation Center is also working on macroscopic modeling and agent-based demand modeling to predict how to evacuate a large city and improve its resilience during a disaster (see Figure 3.3). He noted that data sets that were unavailable only 5 or 10 years ago—such as taxi trip data, subway data, and socioeconomic data—are now readily available. These data sets are used to build, validate, and calibrate evacuation models.

Another project involves using commercial models for large-scale simulations of disruptions. Simulation modeling was used for long-term construction planning for a highly congested, dense urban network (the New Jersey Turnpike) and to make decisions about which lanes to close, and when, based on levels of reasonable disruption. The C2SMART University Transportation Center is also engaged in work with modeling and simulation of connected vehicles in an effort to support the New York City Department of Transportation's work in that area.

Ozbay described the value of open source tools such as MATSim, an agent-based modeling tool being used in research on redesigning citywide

[3] For more information about MATSim, see https://matsim.org, accessed March 12, 2019.

[4] For more information about SUMO, see https://sumo.dlr.de/userdoc/Tools/Main.html, accessed March 12, 2019.

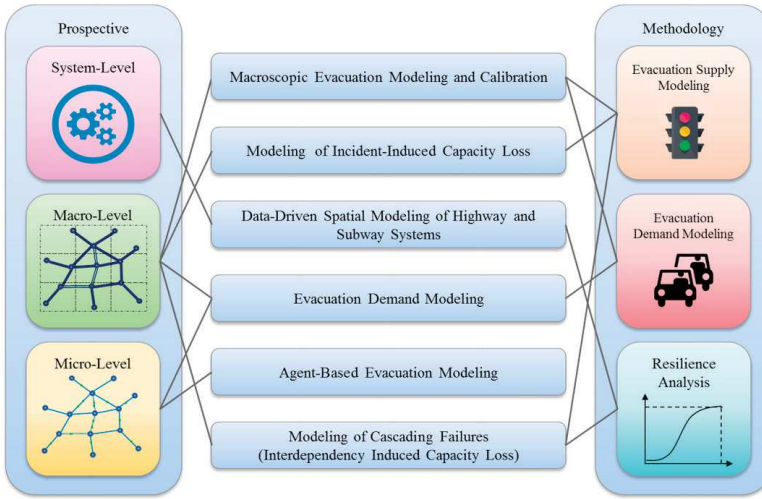

FIGURE 3.3 Various new modeling techniques can help New York City to predict evacuation patterns during a disaster as well as to improve resilience. SOURCE: Kaan Ozbay, New York University, presentation to the workshop, January 30, 2019.

bus systems and in hurricane evacuation planning. Another open source tool, SUMO, can simulate pedestrians and traffic signals, which makes it possible to understand things at a microscopic level. With all of these innovations, Ozbay continued, an urban data observatory (i.e., warehouse) is needed to incorporate these data and use them in conjunction with various kinds of simulation and decision-making tools.

Ozbay summarized priority research areas in transportation modeling and simulation:

- Open source modeling tools, which are key to innovation in the transportation sector;
- Large and detailed data-driven models, which allow better calibration and validation;
- Multiscale models;
- Integrated models (e.g., traffic, climate, communication);
- Online calibration and learning using real-world data from probe vehicles and the Internet of Things; and
- Online and real-time use of simulation models for real-time decision making for traffic control, traffic safety, evacuation operations, and fleet optimization.

He concluded by mentioning the value of virtual/augmented reality for traffic simulations and noted that it is important to consider how simulations will be used as well as how to validate and calibrate models. He warned that simulations can become too computationally complex and can be misused or overused, so simulation should not be used for all types of transportation problems.

Discussion

Fred Abousleman, Oregon Cascades West Council of Governments, said that although massive modeling and simulation efforts have been funded for more than 20 years, he wondered whether the technologies were straightforward enough for local practitioners to use. It is difficult for smaller cities to make decisions about potential investments when the state of the art is changing so quickly. Lewis noted that tools are increasingly available and simulation costs have decreased, so it is easier to deploy technology, iterate solutions, and address problems more quickly. He suggested that there is a need for improved communication with local practitioners so that academic researchers better understand what their problems are and how they might be able to help. Ozbay acknowledged that it takes time for information to diffuse, but open source tools serve as evidence of the growing body of research.

Deborah Goodings, George Mason University, asked what specific changes have been made for people managing hurricane evacuations. Ozbay asserted that evacuations are likely still operating in the same way that they were 20 years ago because models are not being well used in decision making. Goodings wondered why taxpayers should continue to invest when there are no visible outcomes. Ozbay commented that even if progress is slow, there is still value in the work. He suggested that technologies be made open source to increase access instead of relying on commercial developers. Goodings emphasized that this community is responsible for taking action that could lead to real change.

INNOVATION IN GEOSPATIAL DATA SOURCES AND SPATIOTEMPORAL ANALYSIS

Hurricane Harvey: A Real-Time Role for Data Scientists

Katherine Bennett Ensor, Rice University, Moderator

Katherine Bennett Ensor, Rice University, explained that Hurricane Harvey demonstrated a real-time role for data scientists—the Urban Data Platform mentioned in Chapter 2 contains the only existing archive of

Hurricane Harvey data. She emphasized the strength of statistics and data science research and resources in this project, which built on the strength of existing long-term collaborations and was aided by university support (both financially and through recognition).

Ensor's team also engaged in the redrawing of Houston's floodplains. Her team was able to show the dramatic change in land cover over a 21-year period as a result of increased urbanization in Houston. This information will be fed into floodplain models, which are complex physics-based models. Her team then asked the following questions: Have extreme precipitation trends shifted over the past century? How are these changes in precipitation, land cover, and floodplain models related spatially? She explained that this is a challenging data science problem, and the solution has to match the level of the problem. She said that her team had to model the 3-day rain event of Hurricane Harvey using extreme value modeling. These models are difficult to fit, she continued, and require a lot of statistical thinking to generate relevant information. She highlighted the great science that enables spatiotemporal modeling of extremes in rare events. She added that there have been tremendous advances in the past 10 years in spatiotemporal modeling for both big and small data and with hierarchical models that allow relatively easy integration of complex data and process structures. Transparent machine learning models are being used more often, as are dictionary-based machine learning models. She said that it is critical to understand the questions that data address, the dependence structure of data, the uncertainty associated with a scenario or decision, and the reproducibility of results.

Big Data and Urban Science: Advancing Sustainability with High-Resolution Spatiotemporal Data and Data-Driven Modeling

Constantine Kontokosta, New York University

Constantine Kontokosta, New York University, explained that his work uses large-scale, high-resolution geospatial data to build data-driven models that address specific problems in urban operations, policy, and planning, particularly in sustainability and resilience. Urban scientists are excited to learn about the complex dynamics of a city using simulations with the "digital exhaust" of a city and citizen-generated data.

He shared some of his work from the Quantified Community at Lower Manhattan,[5] which provides opportunities for situational intelligence and for using a variety of data sets (e.g., from credit card transactions, call data

[5] For more information about the Quantified Community, see http://www.urbanintelligencelab.org/quantified-community, accessed March 12, 2019.

records, Wi-Fi probe requests, global positioning systems from sanitation trucks, and 911 incident data) to understand how humans and the physical environment of the city interrelate. These complex interactions are at the heart of urban planning.

Kontokosta's laboratory is focused on understanding the pulse of New York City and modeling these dynamics, with a clear consideration for and understanding of the city's socioeconomic and political realities. Computing with heterogeneous data sources is key to the laboratory's work, as is understanding both data bias and algorithmic bias. It focuses on translational research, working hand in hand with city agencies, industries, and nonprofit organizations to inform decision making and policy. A persistent challenge is how to integrate and process the diverse massive data sets and how to target the appropriate problems to address.

Kontokosta categorized urban big data in three ways: (1) organic data flows (e.g., administrative records and social media), (2) sensors (e.g., data from mobile phones), and (3) novel technologies (e.g., light detection and ranging, and aerial imagery). A sample is used to understand an entire population, which requires an understanding of spatial and temporal dynamic data. Kontokosta said that cities are beginning to think about problems in terms of operations, policy, and planning. Because operations do not involve long legislative processes or citizen engagement, and are thus relatively straightforward optimization problems, most previous work has been focused in that space.

To work with city data, data integration along spatiotemporal dimensions as well as across sectors and domains is necessary. Kontokosta's team developed a data-mining algorithm that retrieves data from 40 city agencies and other data sources for place-based studies (see Figure 3.4).

He described breaking through the different silos of sectors as another challenge. New York City's DataBridge is a data repository for all of the city agencies to archive their data each night. However, it is difficult to retrieve the data and to integrate data across the city's geographic and operational divisions.

Kontokosta described two projects that highlight the use of high-resolution, larger-scale data in the urban space. The first focuses on climate modeling and the leading role cities play in reducing energy use. Approximately two-thirds of carbon emissions in New York City come from buildings, but the transportation network has to be considered as well. New York City has a goal of reducing carbon emissions by 80 percent by 2050; after setting this goal, New York City began measuring, benchmarking, analyzing, and evaluating progress. Large buildings are required by law to report how much energy they use, and Kontokosta's team has built an interactive online visualization tool that makes it easier to access, analyze, and compare these data. He mentioned that this platform could be used

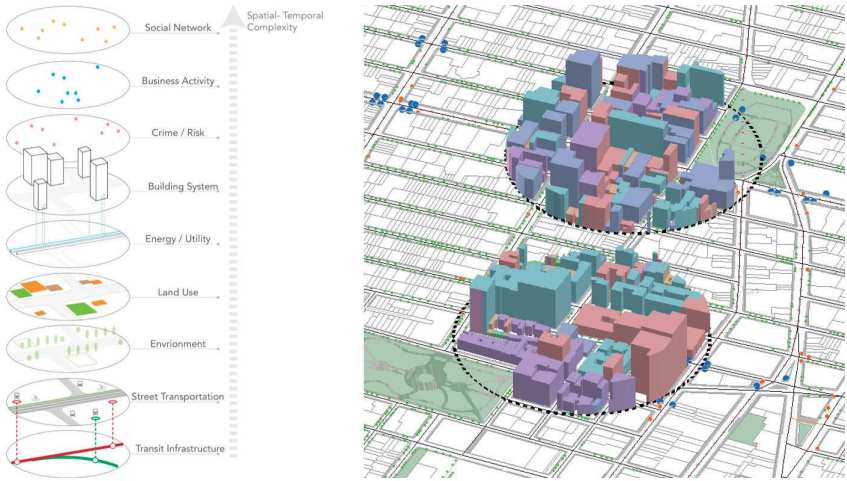

FIGURE 3.4 Data integration along spatiotemporal dimensions as well as across sectors and domains. SOURCE: Reprinted from *Landscape and Urban Planning*, 180, Y. Lai and C.E. Kontokosta, Quantifying place: Analyzing the drivers of pedestrian activity in dense urban environments, 166–178, 2018, with permission from Elsevier.

in any city. His team, supported by a United Nations project, next built a high spatiotemporal resolution of carbon emissions across New York City and estimated the emissions from every building in the city and all traffic routes and vehicles across the city. This can be used to better understand hot spot locations and the patterns of energy dynamics across the city, which helps to target policies appropriately.

The next project he discussed focused on using geospatial data to understand mobility and behavior. Wi-Fi probe requests in New York reveal information about the way people move throughout the city. The goal of the project was to develop a real-time census and understand how many people are in any part of the city at any given time and segment them by behavior (e.g., into categories of resident, worker, or visitor). These models were validated against both census data and ground truth data (i.e., pedestrian counts on the street). His team is now working with the Fire Department of New York and other organizations, who want to better understand real-time populations. Kontokosta referenced Hurricane Harvey as an event from which geolocation data (i.e., from mobile phones) revealed information about a city's evacuation, emergency response, and recovery. However, he emphasized that collecting this type of information highlights privacy concerns in using high-resolution data as well as the importance of data ethics and governance in the use of such data.

In closing, Kontokosta observed that there are limitations to the application of data-driven methods. Data access and management are nontrivial problems, and he discussed the challenges of developing standardized ontologies that work across domains and cities. There are also questions about privacy, the line between surveillance and observation, and bias in data. To illuminate this final point, he talked about a project to de-bias citizen-generated 311 complaint data in New York City to develop more fair and equitable service and resource allocation models. Some important questions remain in the path toward urban sustainability: What urban data are available and what urban data are needed? What models and methods work best for pattern and anomaly detection in different environments? What applications are possible for cities to use to meet their goals?

Satellite Imagery for Urban Sustainability

Rhiannan Price, DigitalGlobe

Rhiannan Price, DigitalGlobe, explained that DigitalGlobe, founded in 1992, is one of the leading satellite imagery providers in the industry. DigitalGlobe has a repository of nearly 20 years of very-high-resolution satellite imagery spanning the world. Its sensors are collecting 3 million square kilometers of imagery at sub-meter resolutions every day. In addition to resolution, spectral and other properties that cannot be seen with the human eye are important. Near infrared and shortwave infrared present exciting opportunities for cities in particular. Price showed a 30 cm image over a port from space to demonstrate just how much detail can be extracted from satellite imagery. These images can then be used to create digital elevation models.

Price explained that although DigitalGlobe has global coverage, it also images thousands of urban areas consistently, updating the areas annually. DigitalGlobe creates imagery-based maps that are between 30 cm and 50 cm resolution (see Figure 3.5). This means that cities will have regular high-resolution snapshots that could support a variety of use cases, including evidencing deforestation; analyzing watershed, traffic, and land use; responding to disaster; and monitoring large gatherings of people. Price believes that all 17 of the United Nations' Sustainable Development Goals can be supported either directly or indirectly by remote sensing.

Price described the baseline and tipping and cueing process. This process involves using high-resolution base maps to inform where information will continue to be collected and where it is necessary to distill a signal from noise. DigitalGlobe has been working with various cities to create common geospatial information layers.

FIGURE 3.5 An example of DigitalGlobe's satellite imagery of San Francisco, which could be used to create digital elevation models. SOURCE: Rhiannan Price, DigitalGlobe, presentation to the workshop, January 30, 2019. © 2019 Maxar Technologies.

DigitalGlobe partnered with PSMA Australia to map the continent using satellite imagery, machine learning, and crowdsourcing. Every address in Australia was attributed with more than 40 different pieces of information, creating a large corpus of open geoinformation. This project demonstrated how diverse stakeholders could collaborate on urban sustainability. With all of this information, DigitalGlobe was able to create a data cube, co-registering the data so that they are interoperable and reveal more insights. Another example of tipping and cueing relates to disaster response. In 2017, DigitalGlobe used imagery to identify where a fire in California was burning most intensely, which was used to inform first responders. Tipping and cueing can also be used for damage assessment after a disaster. Before and after images can be useful for change detection as well as for monitoring and risk assessment, especially for infrastructure such as dams. Price emphasized that DigitalGlobe can provide actionable information that provides a common operating picture to coordinate efforts across the private and public sectors.

Price's final point was about collaboration and acceleration. Partnerships are crucial to achieve goals, and crowdsourcing (e.g., citizens extracting information from satellite imagery) enables accelerated progress. Crowdsourcing tools can be tailored depending on the use case or the features desired from the imagery, help people think about their world spatially, provide actionable information, and begin to close the gap of

the digital divide. DigitalGlobe also leverages artificial intelligence to extract information accurately from large sets of imagery. She encouraged participants to embrace open imagery and open data and leverage them to achieve goals. Price said that there is an opportunity to accelerate this work by creating a "data collaborative" around urban sustainability and spurring machine learning, crowdsourcing, and other mechanisms to extract information.

Discussion

Andrews Simmons, Resilience.io/Ecological Sequestration Trust, asked Kontokosta about his work across domains. Kontokosta observed that although individual research teams are doing well with data integration, there is room for improvement collectively. Nonlinear causalities offer exciting opportunities to view interactions of different systems. He added that there are a number of interesting studies at the intersection of public health, data science, and urban planning that can be done with domain integration. Ensor cautioned about overinterpreting what the data show.

Ensor asked Price how DigitalGlobe deals with privacy. Price replied that in the high-resolution space, it is important to consider how the data are being disseminated and communicated. While she emphasized that DigitalGlobe works closely with its partners to discuss licensing and usage, it is ultimately the responsibility of the partner to ensure that people's privacy is maintained. DigitalGlobe is heavily regulated by the U.S. government and the International Trafficking and Arms Regulations.

Elizabeth Zeitler, National Academies of Sciences, Engineering, and Medicine, noted that geospatial data come from cities, researchers, and members of the public. She wondered about Kontokosta's and Price's experiences with data accessibility and transparency as well as community members' interest in the data and models. Kontokosta responded that much appropriate skepticism exists among city agencies and community organizations regarding work with large-scale geospatial data and machine learning algorithms. Having a conversation about transparency is important because it ties into all of the other questions about privacy, trust, and expectations for local government. He suggested finding the right use case, working closely with the partners to understand their needs, and delivering a solution that can be applied and implemented by the partners.

Seth Schultz, Urban Breakthroughs, asked if satellite imagery is being used to predict where urbanization is going to occur. Price said that DigitalGlobe has done informal settlement mapping in the Global South. Another project in Chile used call detail records and satellite imagery to

understand how travel safety is different for men and women and what that means for urban sustainability and policies. Price noted that a better repository is needed to share all of this work, increase collaboration, and move away from siloed research efforts. Kontokosta added that his team works in data-rich environments and looks for generalizability of an approach rather than generalizability of results.

PRIVATIZATION OF DATA AND DATA PRIVACY: TWO SIDES OF ONE COIN

Aniruddha Dasgupta, World Resources Institute, Moderator

Following Kontokosta's discussion of localized data and Price's discussion of massive geospatial data, Aniruddha Dasgupta, World Resources Institute, explained that the next step is to discuss how all of this work produces public goods or helps make decisions for the public good. The discussion that followed centered on how to manage the data governance process as data and data science evolve and as privacy concerns increase.

Comments on Privatization of Data and Data Privacy: Two Sides of One Coin

John L. Eltinge, U.S. Census Bureau

John L. Eltinge, U.S. Census Bureau, described the interface of urban sustainability with statistical methodology and technology. Turning the vision of big data into practical reality requires taking a nuanced assessment of statistical information products and services as a form of public good. It is important to reevaluate the traditional questions used to determine the value of public goods (based on a balanced assessment of quality, risk, and cost) with an added consideration for privacy and confidentiality.

Eltinge cited a standard definition of "public goods," which is distinct from the broader concept "for the good of the public." Public goods are *nonexclusive* (i.e., everyone can use them) and *nonrivalrous* (i.e., if someone else uses them, the value is not reduced). Examples of public goods include public roadways, free national parks, clean air, and even some information products and services provided by governmental statistical agencies. Because standard market mechanisms can be problematic for the production and provision of public goods, it is necessary to reevaluate resource allocation for statistical information products and services.

Eltinge mentioned that within the context summarized above, the literature on public goods also sheds light on issues related to privacy and privatization. He outlined five classes of questions pertaining to public goods and private rights, and he emphasized that there are no easy answers for any of these questions:

1. *Why are you producing this public good? What are the goals?* Goals for statistical products can be characterized in terms of traditional statistical inference. These goals generally relate to one or more of the following: description, association, prediction, causality, or outright control. Some statements of "sustainable development goals," and related indicators explored in this workshop, appear to reflect interest in statements of "outright control," which can involve a very heavy lift in inferential rigor and data quality.
2. *How good is the information? How do customary measures of information quality align with risk, cost, and value?* Some measures of quality are quantitative (e.g., accuracy) and others are qualitative (e.g., relevance, timeliness, granularity, comparability, coherence, accessibility).
3. *Who benefits from production of the good or service?* Stakeholder standing and related use cases play important roles in expectations for quality. In addition, it is important to determine whether a given group of stakeholders has specific formal or implicit rights to a given set of data products, at a given level of quality.
4. *Who controls and how?* For example, who frames—and then makes—the very difficult judgment calls about trade-offs among multiple dimensions of privacy, data quality, risk, and cost, at both broad policy levels and at more specific technical levels? Transparent multiway communication in these governance areas can be crucial to the reduction of information asymmetries and improvement of efficiency. Eltinge referenced *Principles and Practices for a Federal Statistical Agency* (NRC, 2013) as a good distillation of many of the underlying issues.
5. *Who pays for the good or service? How much is paid and what is the transfer mechanism?* Costs are often measured through cash expenditures but also include burden on the data provider and several additional intangible or difficult-to-measure dimensions of resource requirements. Privacy rights for data sources and intellectual property rights for some data sources and intermediaries are examples of important intangibles.

In closing, Eltinge suggested that when thinking about privacy and privatization, it can be useful to frame some questions in the context of the

public goods literature. One should also consider the interface of public goods and private rights, which naturally involve complex trade-offs. He emphasized that clarifying what is known and unknown relating to those five classes of questions could help, as does communicating clearly and respectfully with stakeholders.

Privatization of Data and Data Privacy: Local Data Flows

Sallie Keller, University of Virginia

Sallie Keller, University of Virginia, discussed privatization of data and data privacy at local levels and provided the following definitions relating to her understanding of privacy:

- *Privacy* refers to the amount of personal information individuals allow others to access about them.
- *Confidentiality* is the process that data producers and researchers follow to keep individuals' data private.
- *Security* applies to data storage and transport.
- *Privatization* of data is the collection, aggregation, and (re)processing of personal data to sell to consumers.

She suggested that the data pipeline begin with data discovery instead of data acquisition, because so much is gained from learning about and using new data sources when working to solve problems (see Figure 3.6).

To illuminate this point, Keller described a research problem about affordable housing. Data sources included designed data, administrative data, opportunity data, and procedural data, all of which provide different challenges with respect to privacy, confidentiality, security, and privatization. The discovery to find local housing data revealed more than 50 different potential data sources, including commercial, local, and state sources. This data discovery exercise illustrated that there is an abundance of housing data available and that the data discovery process is essential as a first step to solving a problem creatively or answering a research question. She emphasized that the data science steps to discover, profile, prepare, link, and explore data sources are not trivial. Statistical sciences provide the methods to integrate different units of analysis over time and space.

Keller noted that it is important to think about one's purpose in using data when considering the role of informed consent. For example, policy-focused analyses are very different from case management. The

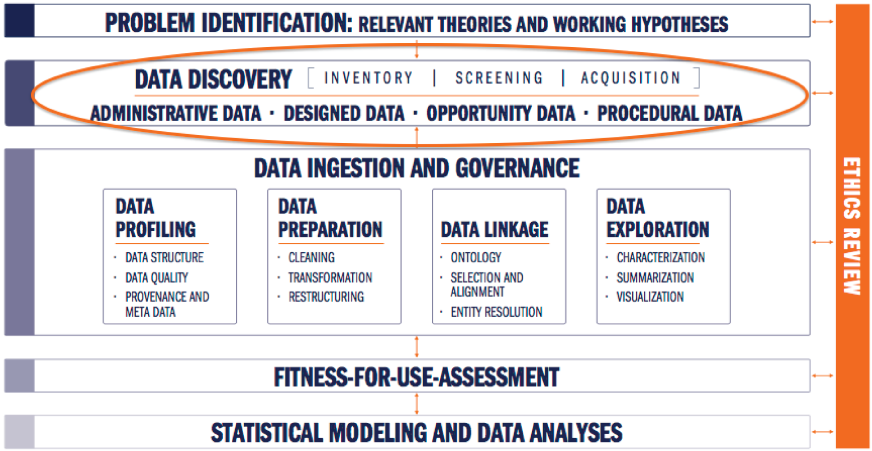

FIGURE 3.6 A visual representation of the data science framework. SOURCE: Sallie Keller, University of Virginia, presentation to the workshop, January 30, 2019.

Commission on Evidence-Based Policymaking (2017, p. 24) explained the following:

> Access to data held by the government should occur only in service to the public interest. Decisions about allowing data access must be calibrated according to a project's potential public benefits, the sensitivity of a particular data set, and any risk that allowing access could pose to confidentiality. Access can and should be restricted to eligible individuals who demonstrate an understanding of their obligations for data stewardship.

She described these standards as similar to those set by institutional review boards (IRBs). The IRB principles govern the collection and use of data on human subjects or the use of archival data. Keller encouraged individuals who may be engaging with the ethical dimensions of data science research to take IRB training. She also shared a number of instances when it makes sense to waive informed consent, as detailed in the Federal Policy for the Protection of Human Subjects:

- The research involves no more than minimal risk to the subjects;
- The research could not practicably be carried out without the requested waiver or alteration;
- If the research involves using identifiable private information or identifiable biospecimens, the research could not practicably be carried out without using such information or biospecimens in an identifiable format;

- The waiver or alteration will not adversely affect the rights and welfare of the subjects; and
- Whenever appropriate, the subjects or legally authorized representatives will be provided with additional pertinent information after participation.[6]

For agencies, Keller continued, the Privacy Act of 1974[7] states that records can be used by researchers but only for statistical purposes. She reiterated that these rules apply to policy analyses, not to case management. Data sharing agreements with local governments have similar guidelines about the role of research for the public good. She shared a cautionary note about responsible analyses, using an example from Amazon's expansion of Prime same-day delivery. Even though the algorithms did not use race as a factor, there were social biases in the data that led the algorithms to recommend that white neighborhoods receive same-day Prime delivery services and black neighborhoods do not.

Keller suggested that the Community Principles on Ethical Data Sharing (Data for Democracy, 2017) should be exercised continuously. She summarized these principles as follows:

- *Fairness*. Understand, mitigate, and communicate the presence of bias in both data practice and consumption.
- *Benefit*. Set people before data and be responsible for maximizing social benefit and minimizing harm.
- *Openness*. Practice humility and openness. Transparent practices, community engagement, and responsible communications are an integral part of data ethics.
- *Reliability*. Ensure that every effort is made to glean a complete understanding of what is contained within data, where it came from, and how it was created.

Keller concluded by commenting that the data revolution is changing the focus of the privacy discussion from the masking and suppression of data to maintain confidentiality to building trust, policy, and governance around data practices; this is in itself a revolution in both data and society (see Keller, Shipp, and Schroeder, 2016).

[6] *Federal Register* Vol. 82, No. 12 45 CFR 46.101(l), as amended June 19, 2018.

[7] For more information about the Privacy Act of 1974, see https://www.justice.gov/opcl/privacy-act-1974, accessed March 12, 2019.

Privacy Considerations for Integrated Data Efforts

Michael Hawes, U.S. Department of Education

Michael Hawes, U.S. Department of Education, discussed privacy considerations for integrated data efforts, why it is difficult to acquire data, and how people can acquire data more easily. Hawes said that he is both a privacy regulator and an advocate for data-driven decision making, so he works to find ways to protect student privacy while still enabling data analyses that have the potential to improve students' educational experiences and outcomes. Noting that people sometimes incorrectly use the terms privacy, confidentiality, and security synonymously, he provided a series of definitions. Building on a *Random House Dictionary* definition, Hawes described "privacy" as protecting individuals from unreasonable intrusion or disturbance into their private lives or affairs. He added that components of privacy could include information privacy, bodily privacy (e.g., airport scanners and wearables), territorial privacy (e.g., entering one's home without permission or collecting geospatial data), and communications privacy (e.g., mobile phones and eavesdropping). He said that "confidentiality" is a component of privacy, but it relates to protecting access to the information itself and keeping that information private. He described confidentiality in terms of appropriate data *access* and privacy as appropriate data *use*. "Security" relates to the systems on which data are hosted, and it protects the confidentiality, integrity, and availability of data.

Hawes explained that new data sources raise new privacy concerns relating to data access and sharing, data release, and transparency. He observed that it has become more difficult to obtain data, owing to recent proliferation of state and local privacy laws, improved agency awareness of existing legal requirements, greater scrutiny of agency data practices, and changes in agency risk tolerance. Strategies to navigate these challenges include knowing the relevant laws, practicing data minimization and use limitation, understanding and building a relationship with the data provider, and being transparent and explaining the value of the work. Data re-identification has become a major concern, causing many agencies to enhance their privacy rules for publishing data. To confront these challenges, Hawes suggested understanding the underlying methodological options and their differing impacts on data quality, discussing protection methodology requirements during the acquisition process and being ready to propose alternatives, and remembering to consider the cumulative impact of data releases on re-identifiability. He concluded by emphasizing that transparency is a key component of privacy; a lack of transparency can derail worthwhile data initiatives. To increase transparency, Hawes suggested proactively explaining data practices, soliciting

feedback from the community, and articulating the value of a project in tangible terms that relate to the data subjects. Hawes urged people who are interested in education data or data governance to visit the U.S. Department of Education Student Privacy website[8] for resources.

Discussion

Dasgupta noted that each time a person "accepts" terms to use an app, that person has given up some of his or her privacy rights. However, the boundary between private use and public use of data is not always clear. He asked how to protect privacy while still working with data for greater public good. Hawes said that this is particularly complicated in education because schools collect a lot of information about students as part of providing an education. School administrators have to evaluate levels of risk and determine what uses of those data are appropriate. Because the parents and students do not decide if the use is appropriate, transparency is especially important. With transparent practices, parents and students have an opportunity to raise concerns and be part of the decision-making process. Keller noted that confidentiality practices have historically been built around bits of information. Instead, a paradigm shift from protecting data to protecting the *use of the data* is necessary. She emphasized that it is not possible to protect the privacy of individuals when all of their data are so readily available. She mentioned that those who work with medical data have made more progress in embracing this paradigm shift than those who work with social data. Eltinge said that a high degree of transparency is essential and that data providers should communicate clearly with decision makers. He suggested identifying critical use cases to start the conversation about privacy, risks, trade-offs, and value and added that formal legislation often responds to shifting social norms.

Ensor asked if there are (or should be) practical rules for republishing geospatial information. Keller thought that it would be useful to develop such rules to build more trust around the use of data. Dasgupta expressed skepticism about cities having systems in place and capabilities to manage and protect data, especially given the pace at which solutions and innovations are occurring. He wondered what could be done in the regulatory space to keep up with these infrastructure changes in cities. Hawes suggested a focus not only in the regulatory space but also in the technology space. Technologies such as secure multiparty computation offer a way to leverage disparate data that may have different regulatory

[8] The U.S. Department of Education Student Privacy website is https://studentprivacy.ed.gov, accessed March 12, 2019.

privacy protections. Eltinge noted that new technologies can both benefit and harm society; however, harmful experiences can be mitigated by technological, regulatory, or societal buffers. In-depth exploration of relationships among inferential goals, methodology, and disclosure risk can offer insights on ways to reduce the likelihood and impact of substantial negative outcomes. Keller added, and Hawes agreed, that data misuse should always be punished or exposed in some way.

DATA USE EXPERIENCES ACROSS CITIES

Data Access and Innovation for Cities

Amanda Eichel, Global Covenant of Mayors for Climate and Energy

Amanda Eichel, Global Covenant of Mayors for Climate and Energy, described the Global Covenant of Mayors for Climate and Energy as an alliance of more than 9,000 cities (more than 7,000 of which are in Europe) that have agreed to take on climate change consistent with the Paris Climate Agreement targets. Eichel expects that more cities would join this initiative if they had additional resources to support implementation. The Global Covenant of Mayors helps ambitious cities that are not data rich to gain resources so that they can take action. The Global Covenant of Mayors creates a space in which all of its partners can work together to support these cities. It also focuses on vertical alignment, in which national governments work in partnership with local governments. The Global Covenant of Mayors is also essentially a data platform, making city data publicly available in a transparent and consistent way.

Cities have different tools available to them to take action (e.g., some can influence policy, some are policy implementers, and some are partners who set the stage for others to move things forward). The pathways to move from ambition to implementation are complex, making it difficult for many of the cities to scale their processes. Eichel explained that the Global Covenant of Mayors has thus started an initiative on research and innovation. Cities need support from partners in national and regional governments, academia, business, and civil society across three pillars: science and research, innovation and technology, and city-level data access. Three core initiatives are supported by the Global Covenant of Mayors and then deployed through regional covenants:

1. *Data4Cities*. This initiative develops a new reporting standard as well as creates a database and website to open up access to data for cities to support climate action planning.

2. *Innovate4Cities*. This initiative provides a research and innovation agenda to catalyze the scientific advances necessary to better equip cities with the intelligence and tools to take even more ambitious climate action. The initiative's call to action includes advocating to national governments for commitments to specific, targeted funding; developing partnerships with the private sector; building a more consistent research agenda among city networks; and engaging with the research and academic communities.[9]
3. *Invest4Cities*. This initiative aims to raise $800 million for technical assistance and credit enhancement financing as well as to pilot an effort to vertically integrate investment plans.

Eichel explained how to think about the flow of data in the city reporting space through a series of steps: (1) data gathering and analysis (to understand what is happening on the ground); (2) reporting (three platforms are available); (3) data management (a consolidated global database is being created to bring reporting from the three platforms together to make information available to the public and create more knowledge and insight); (4) auditing (ensuring that the reporting is consistent with what happens on the ground) and badging to recognize progress; and (5) data sharing and public access.

Eichel said that many cities do not have the data they need to meet these commitments, so the Global Covenant of Mayors launched a partnership with Google to share data with cities; the goal is to improve decision making around transportation and buildings. She noted that there are still privacy issues to be discussed in this partnership. The Global Covenant of Mayors also has a partnership with the World Resources Institute (WRI) to create a national data portal for cities.

Response to Data Access and Innovation for Cities

Jessica Seddon, World Resources Institute, Discussant

Jessica Seddon, WRI, observed that the Global Covenant of Mayors' initiatives demonstrate effective ways to bring new data to bear on increasingly urgent and complex problems. Seddon explained that the WRI Ross Center for Sustainable Cities works mostly in the Global South with lower-information cities (i.e., cities without historic investment in statistical systems and national data) that are facing problems for which

[9] For more information about the Innovate4Cities initiative, see https://www.globalcovenantofmayors.org/participate/innovate4cities, accessed March 12, 2019.

they need data. WRI also helps cities figure out how to use data that are outside of the public sector (e.g., remote sensing, citizen science, data generated by local universities, data from the private sector, activities data), and it works on issues related to air quality, flood modeling, land use change detection, and informal settlements.

Seddon emphasized the following points:

- *You can lead a horse to water, but you can't make it drink*. City use of data is multifaceted. Individual adopters can implement specific changes, but systematic use of data within the broader bureaucratic processes (e.g., procurement, public investment planning, zoning, assessment of use of land, use of resources, and optimization of transport systems) is a substantial hurdle that often depends on the city structure. Many city systems are optimized around efficiency but not necessarily resiliency, and a change in institutional design (as opposed to a change in the data) is needed.
- *The sovereign barrier exists*. Once a city decides to use analysis that is based on data *not* from a concerted public investment in collection and analysis, a supply chain risk develops. Good precedents for being able to manage this risk and remain sustainable over time do not yet exist.

Discussion

Dasgupta asked how data are being used by the governments and mayors of data-poor cities who are partnered with the Global Covenant of Mayors. Eichel responded that of the nearly 2,000 cities outside of Europe, 30 percent have a climate action plan that they have begun to implement. The barrier for the remaining 70 percent is access to data, which will hopefully be alleviated by the new partnership with WRI. The Data4Cities and Innnovate4Cities initiatives could automate a process for cities so that a sufficient data inventory becomes something they can access and use to take action. Ultimately, the Global Covenant of Mayors hopes to automate a scenario planning or policy scenario planning process for cities.

Caetano de Campos Lopes, Citizens' Climate Lobby, noted that information to benchmark return on investment is not available at the local level, and he wondered if there are any ongoing projects to address this issue. Eichel said that through its city network partners, the Global Covenant of Mayors is investing many resources in research around the benefits of taking action on climate change, including assessing the economic benefits, payback, jobs created, and health benefits of specific interventions. She agreed that information on return on investment is a

top priority. De Campos Lopes also asked Seddon about her opinion on the treatment of Scope 3 emissions in the Greenhouse Gas Protocol for Cities.[10] Seddon said that WRI should have included Scope 3, and she confirmed that it is a top item on a future agenda for the report.

Price asked whether there is an opportunity for data-poor cities to leapfrog with technology advances or if there are systemic barriers in the way. Eichel commented that there is interest and ambition from various cities, and her organization would be interested in a partnership to figure out how to use those technologies. Seddon added that although the opportunity to leapfrog exists, it will not happen if concerns about the sanctity of the data supply chain, the incentives to manipulate or increase the cost of data, and the sustainability and consistency of metadata over time are not addressed. To enable leapfrogging, the gap between private-sector and public-sector data services must be bridged. Eichel wondered at what point data are sufficient to empower cities to take action at scale quickly while balancing precision.

Anu Ramaswami, University of Minnesota, suggested that stakeholders consider lessons, simplifications, and insights that can be drawn from work in certain cities and applied to others. Seddon agreed that science-based targets are important and that an increasing number of methods are available, although it is difficult to collect information in a consistent way. Keller asked whether there are linkages between city and state plans. Eichel confirmed that the Global Covenant of Mayors is still working on coordination between state and local actors. She added that this vertical integration is a challenge in both directions, especially at the global level when each country's entities have different levels of control.

[10] The Greenhouse Gas Protocol for Cities is a standard and set of tools to measure greenhouse gas emissions, build emissions reduction goals and strategies, and track progress comprehensively. Scope 3 emissions refers to the emissions from the upstream and downstream supply chain for a city, outside of Scope 1 (i.e., direct emissions within the city) and Scope 2 (i.e., emissions from the generation of energy that is imported into a city). The website for the Greenhouse Gas Protocol for Cities is https://ghgprotocol.org/greenhouse-gas-protocol-accounting-reporting-standard-cities, accessed April 4, 2019.

4

Challenges and Opportunities for Cities

URBAN THEORY TO UNDERSTAND CITY CHALLENGES AND OPPORTUNITIES

Luís Bettencourt, University of Chicago

Luís Bettencourt, University of Chicago, spoke about the state of urban theory—the science of cities that provides the framework for understanding data and modeling. Urban theory relies on a convergence of ideas from geography, economics, sociology, and engineering, with newer contributions from data and comparative analysis across cities, to understand the human experience with scientific rigor. Bettencourt directs the Mansueto Institute for Urban Innovation at the University of Chicago,[1] where he tries to triangulate concepts and methods from ecology, evolution, and the natural sciences with emerging perspectives from the social, political, and economic sciences and new empirical evidence.

Bettencourt showed participants an image from Apollo 8 in 1968, which changed people's perspectives about the state of the Earth and is credited with the beginning of the environmental movement, when sustainability entered mainstream public consciousness. He pointed out that such a global perspective was both compelling and paralyzing, because it is difficult to know why and from where challenges to the global

[1] For more information about the Mansueto Institute for Urban Innovation, see https://miurban.uchicago.edu, accessed March 13, 2019.

environment are arising. Aerial photographs and satellite images of India, Beijing, and Hong Kong demonstrate that air quality, diversity, transportation, information, and continual change present ongoing challenges and opportunities within cities. Bettencourt argued that a new focus on cities—as demographic, economic, and information centers where consumption and innovation occur—is making it possible to generate a more scientific understanding of human societies and their relationship to Earth's natural environments and to initiate policies with more traction. He stressed that cities are ultimately about people (and their societal interactions) whose needs could be better understood by looking at cities from the ground up instead of from the sky. This new perspective defines the challenge of the science and practice of urban planning and policy.

Bettencourt presented the United Nations Habitat's new declaration for what urban policy should be by 2030, a "New Urban Agenda."[2] It asks for an approach to urban planning that is about people-centered cities, and people's rights to the cities, which are inclusive and sustainable from an environmental perspective. This vision comes from the larger framework of the United Nations' 17 Sustainable Development Goals. Goal number 11, in particular, focuses on sustainable development in cities, targeting housing, transportation, sustainable planning, culture, resilience, pollution and health, and green public spaces. Although he noted the challenge in trying to achieve these goals, he expressed his encouragement at the worldwide mobilization for this systemic process. He described this as an example of an approach toward global policy and mentioned that similar attempts to drive policy are being echoed in almost every American city. For example, he described the city of Los Angeles's plan, Sustainable City pLAn,[3] which aims to integrate quantitative goals to create a cleaner environment, a stronger economy, and a more equitable community.

Against a backdrop of aspirational policy, it is necessary to create a fundamental knowledge about cities and urbanization that can guide these changes at the necessary scope and speed, Bettencourt continued. These difficulties are illustrated by questions such as the following: What does it mean to create a good city? Why are cities growing so fast? What can cities deliver for human societies? He explained that a societal transformation related to communication and information technology lies ahead and that universal urbanization is occurring along with the digital technologies revolution. Data computing and comparative analysis enable the practice of urban science and urban analytics and present new ways

[2] For more information about the United Nations' plan, see http://nua.unhabitat.org, accessed March 12, 2019.

[3] For more information about the Sustainable City pLAn, see http://plan.lamayor.org, accessed March 12, 2019.

to deal with data and problems such as urban logistics. However, a challenge remains in how to use this information to better understand how cities work fundamentally.

Bettencourt showed a three-dimensional model of Chicago, noting that Google Earth (and other technology companies) now has similar models for all North American cities. Such models help researchers to think about how the physical environment of a city works and to understand how the built environment is changing. He added that in the next few years, everything will be known about the built environment; researchers must be asking how these data can be used. Other images and measurements from satellites and sensors can measure every tree in a city, for example, or can be used to improve air quality and manage urban heat islands. He emphasized that these types of innovations are a result of the ability to feed ambient data into simulations and real-time analyses. He provided an example of a map of spatial mixing in Chicago that was derived from mobile phone data; he mentioned that this work shows the data's potential for surveillance and ability to identify a city's equity issues (see Figure 4.1) in terms of the urban amenities, spaces, and communities available to someone living in a specific neighborhood.

Simply providing the data of people's movements and the built environment is not science; the objective is to understand why people move, and making sense of cities requires a particular type of theoretical knowledge. Although a city is a physical infrastructure, it is really about people's socioeconomic interactions and information—the goal is to have generalizable knowledge that can be used to understand multiple cities. Bettencourt emphasized that cities, at their essence, are socioeconomic networks of people and organizations concentrated in space and time. Many researchers are presently aiming to redefine the foundations of social science from this richer and more unifying perspective, based on better empirical evidence and with a renewed focus on human cognition and behavior in complex urban environments.

Bettencourt described four critical scales of urban theory: urban systems (i.e., nations made up of many cities), cities, neighborhoods, and individuals (see Figure 4.2). The scales in between relate to how a city is put together as a network, scaling agglomeration effects and neighborhood effects. Urban theory takes in all of these scales, explains their articulation, and begins to understand how they are interrelated.

Bettencourt explained that all models of economic geography rely on the notion of the city as a bound state in space (i.e., a spatial equilibrium). The classical Alonso model of the monocentric city represents the simplest instantiation of these ideas as a balance between a net income (including consumption costs) that an individual makes from his or her interactions in the city as well as land rents and commuting costs. He noted a trade-off

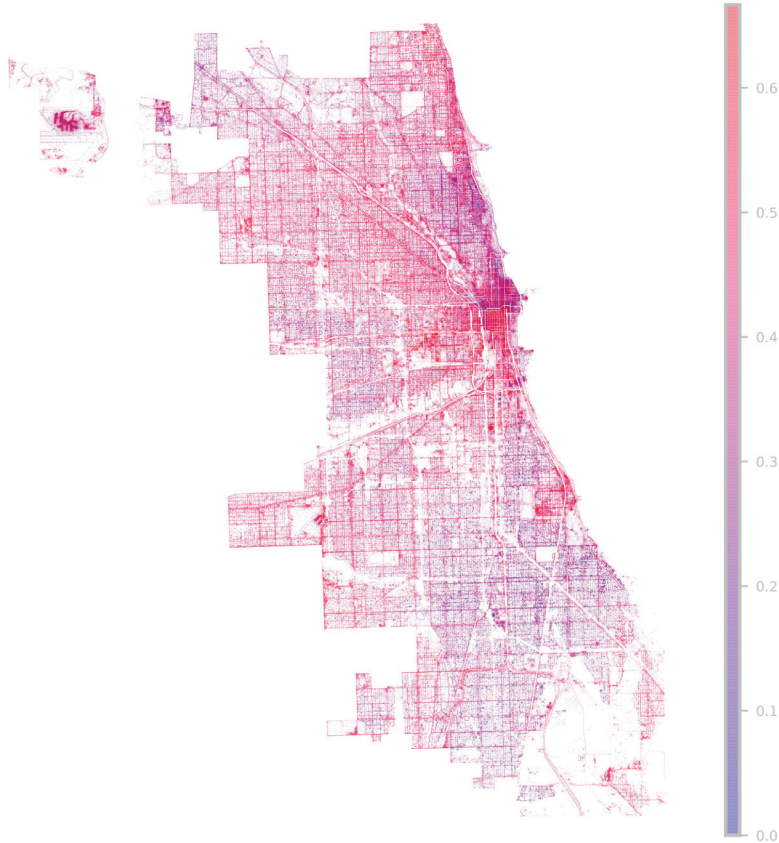

FIGURE 4.1 A map of spatial mixing in Chicago generated with individuals' mobile phone data. The hue denotes the likelihood of two individuals at a location being of different race or ethnicity (i.e., black, white, or Hispanic), while the intensity scales with the log of the number of people who frequent that location. This is calculated at a resolution of 10 m. SOURCE: James Saxon, University of Chicago.

between these spatialized costs (e.g., an individual would pay higher rent to live in a city than in a suburb, but then in a suburb one might have to pay to commute to the city for work). The model assumes a continuum in terms of managing rents and commuting costs, gives a spatial limit to the city, and defines functional urban areas (i.e., the systems in which people live and work together, known in the United States as metropolitan areas). It follows from elaborations of these models that cities express strong network effects, which relate the outcomes of socioeconomic variables nonlinearly to measures of city size, such as population. For example, the

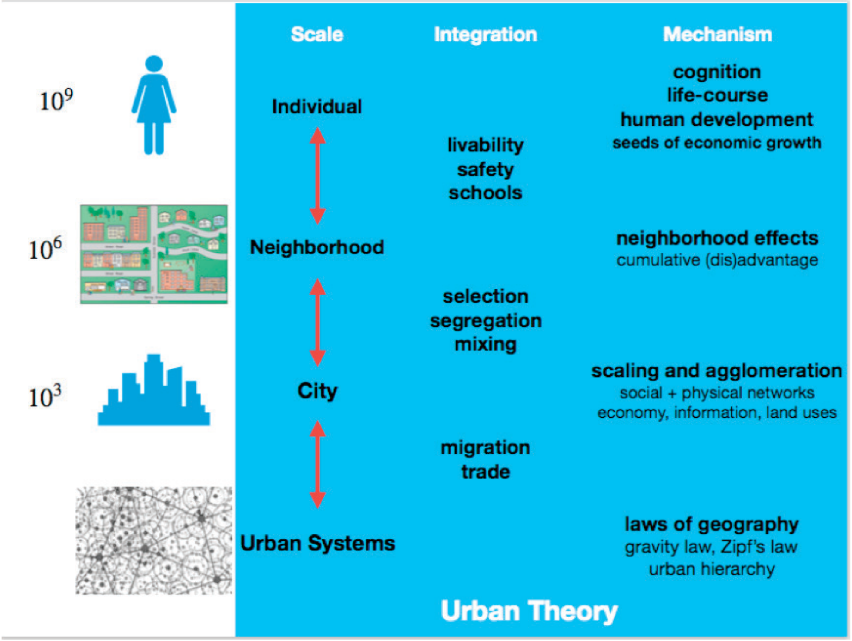

FIGURE 4.2 The scales of urban theory. SOURCE: Luís Bettencourt, University of Chicago, presentation to the workshop, January 31, 2019.

volume of infrastructure in a city is not proportional to its population: as cities become larger, there is less area of infrastructure per person but simultaneously an increase in gross domestic product per person and many other socioeconomic outputs that result from human interactions. Bettencourt continued by noting that the density of people within cities, both in terms of space and time, promotes diverse interactions that can be measured in relation to production, consumption, and crime, for example. Increasing density can help manage the physical, social, and economic aspects of a city, but such density has to be made livable for residents via more developed urban systems and institutions. He explained that housing is often not affordable in large cities because land surface decreases per capita on average with city size (because of higher densities) and incomes increase. This leads to a rapid increase in land rents (i.e., costs per unit time and area) with city size—faster than incomes. The antidote is either sprawl, with severe congestion and energy costs, or greater building heights and more sophisticated infrastructure (Washington, D.C., is an example of a city in which such construction is prohibited).

These effects taken together result in a specific kind of human experience in cities, which has been discussed in sociology and social psychology

but can now be developed theoretically (i.e., with empirical tests). From this perspective, cities can be understood as a social network in which each person has a varied trajectory through the built environment with consequences for information, energy, and resources. An increase in interactions per capita enlarges on average the opportunities for knowledge creation, specialization, and interdependence, he continued. The impacts of a city can be measured in terms of associated social benefits and costs; equity and sustainability in cities can be measured in terms of the properties of specific neighborhoods, where spatial selection is associated with income, race and ethnicity, and education.

Bettencourt began a brief discussion about scientific and data-driven tools for urban planning, such as OpenStreetMap, which maps the built environment. It is possible to identify places that are not connected via streets (i.e., where people will not have access to services) and use that information to create networks for urban planning. During a later discussion, Rhiannan Price, DigitalGlobe, asked whether Bettencourt has observed that governments are hesitant to give OpenStreetMap data credibility in data-poor environments. Bettencourt said that there will always be political resistance to what is happening at the city level, but mapping data can be verified and consequently can be a basis for consensus. He shared his excitement about data from organizations such as DigitalGlobe and OpenStreetMap because these technologies have the potential to allow people to create a desirable future for their cities.

He concluded by explaining that there are many challenges and opportunities for urban science, particularly to enable equal opportunities and economic, sustainable growth in each neighborhood and across the globe. He emphasized that improvements are needed to increase the quality of models for cognition, agency, and institutions in relation to innovation and economic development. He added that a better quantitative understanding of how energy and resource use are connected to value would also be beneficial. Lastly, he emphasized the need to focus on design and planning that starts with an individual but embraces the complexity of the city.

DISCUSSION

Aniruddha Dasgupta, World Resources Institute, noted that cities are trying to connect economic growth, environmental footprint management, and quality of life. He asked how innovations in data science and modeling could help to balance those three entities. Bettencourt responded that more could be known about these processes starting from the bottom up—people, their behaviors, and the physical and economic conditions of the city. Cities change on a daily basis, and this change can

be directed to enable sustainability, economic growth, and more equitable outcomes. However, it is important to be aware of how these processes articulate across time and over various social and spatial scales; otherwise, unintended consequences are possible. Through data and an improved understanding of underlying principles, Bettencourt believes it is possible to comprehend the fundamental ingredients for innovation and economic growth. He added that researchers are beginning to see how the physical, social, and innovation aspects of a city are coming together across scales, starting with people and organizations. Auroop Ganguly, Northeastern University, wondered how to hold policy makers and citizens accountable for their roles in urban sustainability. Bettencourt explained that almost all large cities are setting up quantitative targets for their energy consumption and carbon emissions, and quantitative harmonized standards have now been developed to measure energy expenditures across cities. Responsibility is being taken by cities, and methods are being developed, but questions about the end goal still remain: How much energy should a city use? Would a city use more energy as it becomes greener? What are the social and economic trade-offs?

Audience member David Rabinowitz asked about underlying lifestyle assumptions built into the United Nations' Sustainable Development Goals. Bettencourt replied that cities are open systems that sustain a great diversity of individuals, choices, and lifestyles; understanding cities requires understanding diversity in human behaviors. Anu Ramaswami, University of Minnesota, noted that many policies are aimed at changing the norm and asked if methods exist to detect effective policy outliers. Bettencourt said that both positive and negative exceptions are always defined against a norm and that urban theory reveals what is typical to most cities, while local deviations express some of these contextual factors. Ramaswami asked about the presence of causal loops, and Bettencourt responded that the city's spatial equilibrium (i.e., what happens every day in the city) implies a logic of circular causality so that change tends to happen in virtuous and vicious cycles of self-reinforcing effects. It is possible to see how well cities handle certain problems, but the causality connected to making the city more sustainable depends on the accumulation of effects over time and has historical underpinnings. This shows how human development, economic growth, health, and living conditions are changing systematically over time and makes it possible to compare transformations and extract general trends over time, he continued. Understanding and creating positive self-reinforcing cycles of change in different contexts remains a critical goal, he said. Marjorie Lightman, QED Associates, LLC, said that institutional forces may be antithetical to change, but this political reality is an important part of how to create change. Bettencourt emphasized that politics started in

cities and still happens most naturally in cities, where balancing civic and economic issues with basic livelihoods tends to make politics more open and capable of accommodating change. Ideas for change are typically developed in the civic and nonprofit sectors and then enter the political agenda if judged to garner popular support. He asserted that cities benefit from incubating these ideas, typically through advocacy at the civic-sector level, which could improve innovation, mobilize public opinion on larger scales, and increase the pressure to create change in politics.

5

Identifying Directions for Partnership

Workshop participants divided into three groups, based on their areas of interest and expertise, to discuss specific issues related to urban sustainability. The first group discussed air and water systems; the second group discussed transportation and the physical infrastructure; and the third group discussed sustainable inclusive communities. What follows are brief overviews of presentations given during those sessions, as well as summaries of each group's report-out to the rest of the workshop participants.

THEME 1: AIR AND WATER SYSTEMS

Anu Ramaswami, University of Minnesota, Moderator
Elena Craft, Environmental Defense Fund, Moderator
Katherine Bennett Ensor, Rice University, Moderator

Anu Ramaswami, University of Minnesota, opened this discussion with a brief presentation about how to use both models and data to inform actions in multi-objective systems. She noted that although urban areas directly occupy only approximately 3 percent of land area, they are impacting the planet through large transboundary resource draws (e.g., 70 percent of global greenhouse gas emissions are associated with cities), economic interactions, and trade. Cities seek multiple sustainability outcomes, but there are benefits and trade-offs among these outcomes. This results in an urgent and historic opportunity to act by leveraging social

and technological innovation through partnerships as well as through the adoption of interdisciplinary, multiscale frameworks (see Figure 5.1) based on theories, models, and data (Ramaswami et al., 2018).

Ramaswami also provided a brief overview of the complexity of benefits and trade-offs associated with the food-energy-water nexus in India from an urban systems perspective. While process-based air quality models are well developed for larger-scale air pollution modeling, further finer-scale innovation is needed. She shared examples of cities, such as Denver, that are explicitly creating transboundary environmental and economic models to better reflect relationships between the city and its surrounding and connected areas. To move from science to action, Ramaswami suggested taking a deep dive with a few cities to co-produce knowledge. This could include developing a better understanding of underlying principles and exploring typologies of cities to simplify science and to gain insights. Partnerships between individual cities and broader policy makers could be helpful. She concluded by noting that more data does not necessarily imply more knowledge, insights, or capacity to act; higher-order systems thinking, new models, and innovative co-production skills are needed to address transboundary sustainability.

Elena Craft, Environmental Defense Fund (EDF), presented a case study of Hurricane Harvey as a means to think about improving urban sustainability. She emphasized the value of understanding how to better

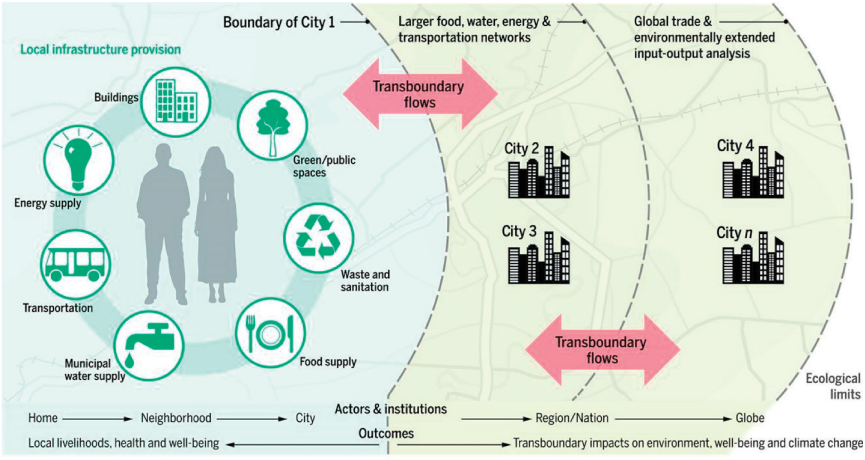

FIGURE 5.1 An interdisciplinary research framework including multiple scales, sectors, objectives, and actors. SOURCE: From A. Ramaswami, A.G. Russell, P.J. Culligan, K. Rahul, and E. Kumar, 2016, Meta-principles for developing smart, sustainable, and healthy cities, *Science* 352(6288):940–943. Reprinted with permission from the American Association for the Advancement of Science.

integrate information (using data, simulation, and models) in order to increase preparedness. Craft explained that in the days following Hurricane Harvey, the Valero refinery reported small amounts of excess benzene emissions, but the Texas Commission on Environmental Quality (TCEQ) did not take any measurements. After the city of Houston received complaints about odor, it partnered with EDF, which arranged for mobile monitoring to be deployed from California to Houston. The measurements of benzene emissions were substantially larger than those reported by Valero, prompting EDF to release an air quality health alert to neighborhoods at risk. Although the Environmental Protection Agency (EPA) took independent measurements, it did not release the information to the public; instead, it released a statement to announce Valero's underreporting. Valero refiled its report, noting that the actual emissions were approximately 300 times as much as initially reported. TCEQ eventually released a summary of EPA's findings more than 1 month after the initial concern was raised by Houston residents.

On the one hand, EDF believed that these concentrations were "at least 10 times higher than health officials deemed safe," Craft explained. On the other hand, TCEQ believed that they "would not expect any adverse effects to occur as a result of exposure to these concentrations," she continued. This was an example of the state environmental agency not providing effective public health protections related to a disaster scenario because the agency did not have enough data to understand the problems. She emphasized the value of using information collected by monitors to protect public health. Better risk management, infrastructure, and sustainability are needed, especially during a disaster, to ensure more effective policies. The Hurricane Harvey Registry[1] is an example of a well-used tool for collecting information on both the hurricane and its impact on Houston.

Based on this small group's discussion of sustainable air and water systems, Ramaswami offered the following summary of suggestions. Focusing on modeling and data within city boundaries does not address opportunities and challenges external to the city. New science and models are needed to address the benefits and trade-offs of the United Nations' Sustainable Development Goals. She added that modeling complex phenomena requires a hierarchical approach (i.e., linking parameter models, process models, and data models), and geolocated data are often insufficient for insight. Shorter time frame forecasting and pollution source apportionments are both important to address air and water systems. New simulation approaches that link movement of people with pollution

[1] The website for the Hurricane Harvey Registry is HarveyRegistry.rice.edu, accessed March 12, 2019.

exposure can be leveraged. Another key component of this discussion was balancing model simplification and transparency with model accuracy.

A cohort model for co-production of data, models, and knowledge among researchers, communities, and practitioners could be useful in supporting smaller cities. Ramaswami said that co-production needs the development of long-term trusted partnerships that can be activated during extreme events. Partnering with larger networks enables the institutionalization and diffusion of knowledge. Data platforms are most effective if they are open, collaborative, nimble, curated, and long-lived, and taxpayer-supported institutional data should be public and incorporate new data sources, according to Ramaswami.

THEME 2: TRANSPORTATION AND PHYSICAL INFRASTRUCTURE

Kaan Ozbay, New York University, Moderator
Auroop R. Ganguly, Northeastern University, Moderator
Christine Ehlig-Economides, University of Houston, Moderator

This discussion began with a brief presentation by Auroop R. Ganguly, Northeastern University. He spoke about systematic ways to use data and modeling for disaster recovery efforts and cautioned about various financial disincentives that can lead to engineering stagnation and outdated best practices. He discussed a variety of novel approaches for harnessing complex data and designing policy, including the Next Generation Digital Earth. The rise of urban technology (e.g., Uber, Lyft, Jupiter,[2] KatRisk,[3] risQ,[4] and One Concern[5]) is also provoking changes in this space. Ganguly encouraged private, public, government, and intergovernmental partnerships to better solve problems with data. Highlighting the importance of frugal innovation and technology transfer, he noted that the United States could learn from more resilient developed nations (e.g., the Netherlands' management of natural-built urban coastal infrastructures and systems) as well as emerging nations (e.g., Brazil, Russia, India, and China, each of which performs tasks under constrained resources).

Christine Ehlig-Economides, University of Houston, later shared highlights of conversations that occurred during this session. She emphasized the value of open and accessible data, open source models, and benchmarking models (perhaps through competitions). Individuals from this

[2] The website for Jupiter is https://jupiterintel.com, accessed March 12, 2019.
[3] The website for KatRisk is http://www.katrisk.com, accessed March 12, 2019.
[4] The website for risQ is https://www.risq.io, accessed March 12, 2019.
[5] The website for One Concern is https://www.oneconcern.com, accessed March 12, 2019.

group discussed how models are used by talking about disasters, such as hurricanes, that can have a huge impact on transportation infrastructure. Models can also be used to address resilience, optimize everyday life, help to envision a more sustainable future, and inform policy. Participants also discussed the risk of policy yielding unintended consequences, no matter the strength of the models, and the importance of bringing together individuals with diverse expertise to develop strategies. Ehlig-Economides echoed the concerns shared earlier in the workshop about privacy and privatization as well as data ownership and the competitive advantage that that might imply. Partners may help fund or enable modeling by opening up otherwise private data. Partners also help modelers by setting priorities for and boundaries on the models, based on defining the intended audience.

THEME 3: SUSTAINABLE INCLUSIVE COMMUNITIES

Bill Fulton, Rice University, Moderator
Aniruddha Dasgupta, World Resources Institute, Moderator
Seth Schultz, Urban Breakthroughs, Moderator

Bill Fulton, Rice University; Aniruddha Dasgupta, World Resources Institute; and Seth Schultz, Urban Breakthroughs, invited participants to discuss topics related to equitable access to data, the use of data to promote equity, the collection of relevant data that can be measured, accountability for decision making, the process of knowledge generation and sharing, the building of interconnected models, and the balance of multiple goals related to job growth, healthy climate, and quality of life.

On behalf of the group, Fulton identified key takeaways from the discussion on sustainable inclusive communities:

- *Equitable access to data and the use of data to achieve equitable outcomes*. Fulton said that there are many different players who are generating data and analysis (e.g., government, universities, nonprofits, and the private sector), but not all of these data and their analyses are accessible to everyone. He raised a question about the role of the private sector and whether it is possible to establish an agreement between the public sector or a university and the private sector to share data that are of mutual benefit.
- *Role of both quantitative and qualitative data in telling stories that convey the fullness of communities and their issues, especially those that are underserved*. Communities are empowered to use data to tell stories about people and their neighborhoods. The National

Neighborhood Indicators Partnership,[6] for example, provides neighborhood-level data for nonprofit organizations and community organizations.

- *Alignment of incentives across all four sectors.* Generally speaking, the government is trying to provide services, university researchers are trying to do work that is rewarded in academia, nonprofits are trying to serve their constituencies, and private-sector players are trying to maximize profits. Aligning goals across these sectors (to the extent possible) is important, although Fulton noted that university research often takes too long to benefit public policy.
- *Feedback loop*. Research should lead to policy that creates action, Fulton explained. It is crucial to identify what will happen if action is not taken and to develop the ability to feed that information back into the research.
- *Assurance of the durability of cross-sector partnerships*. Part of developing partnerships (with either universities or the private sector) means building in resiliency across varying scales of time and levels of engagement. Establishing this durability is especially important to increase city governments' capacity to take advantage of opportunities related to data-driven decision making.

[6] For more information about the National Neighborhood Indicators Partnership, see https://www.neighborhoodindicators.org, accessed March 12, 2019.

6

Reflections and Next Steps

CONCLUDING PANEL DISCUSSION

Aniruddha Dasgupta, World Resources Institute
Jeanne Holm, City of Los Angeles
Sallie Keller, University of Virginia
Katherine Bennett Ensor, Rice University

Partnerships

Katherine Bennett Ensor, Rice University, emphasized that collaborations between researchers and practitioners or between universities and cities are beneficial; the co-creation of data, knowledge, and models produces a shared resource that advances all interested parties. She championed the cohort model for larger communities that span many municipalities or for a network of smaller communities. She added that these partnerships are particularly advantageous when disasters and unusual incidents occur, because a larger team is ready to help face those together. Collaborations can bring in better expertise more quickly for the immediate and long-term recovery from such events.

Jeanne Holm, City of Los Angeles, said that cities have limited bandwidth for partnering with universities. A regional association of governments is a powerful tool that worked well in Los Angeles. Any cohort, federation, or collaborative should encompass more than just universities

(e.g., city colleges, Girls Who Code[1]), and she encouraged people to be creative and inclusive in how they approach collaboration for urban sustainability—for example, through storytelling initiatives, qualitative data gathering, and experiential discussions. It is also valuable to consider students' experiences in cohorts, which can provide good exposure to civil service careers and allow students to apply their education in a meaningful way. She added that it is vital to have a feedback loop connecting theory, policies, actions, and outcomes; this gives information back to the research community to avoid the development of uninformed theories. Holm suggested that the academic perspective move from finding "the shining star of truth" to developing a cycle of learning, iterating, and contributing. She said that although truth can sometimes be found, differences between cities affect how policies are implemented. She stressed that it is vital to think globally and inclusively, following the examples of organizations such as 100 Resilient Cities and the World Resources Institute (WRI). Auroop Ganguly, Northeastern University, agreed with Holm's perspective. He added that there may be unintended consequences of overconfident academic researchers and emphasized the value of the iterative process. Sallie Keller, University of Virginia, underscored that industry and the commercial sector should be a part of any partnership discussion. Community stakeholders should be engaged deeply in data-driven community research and decision making, instead of only being recipients of the academic research and student projects.

Aniruddha Dasgupta, WRI, reiterated the theme of the university–city partnership that was prevalent throughout the workshop. He highlighted the localization of knowledge and expressed his hope that progress that has been made in certain cities can be replicated in other cities. He wondered what incentive structures need to change in academia to recognize practice-oriented work and how cities could develop incentives to learn to work better with academia. Anu Ramaswami, University of Minnesota, proposed that new models be considered to increase the longevity of partnerships, such as the large networks supported by the National Science Foundation. She encouraged participants to be entrepreneurial and to continue to engage universities and cities.

Gyami Shrestha, U.S. Carbon Cycle Science Program (a federal interagency partnership), described her organization's decadal state of the carbon cycle science report, which assessed carbon cycle science across land, air, water, and society in North America. She said that urban sustainability will be attractive for many years and encouraged everyone to consider how to enhance the feedback loop and interactions among

[1] For more information about Girls Who Code, see https://girlswhocode.com, accessed March 12, 2019.

universities, cities, states, federal funders, and international funders. She also suggested that existing funding and activities be leveraged to achieve this common goal (e.g., the National Aeronautics and Space Administration has funded much research on megacities).

Data Access, Ethics, and Privacy Issues

Keller said that improved strategies are needed to distribute information about community resources. It is important that problem solving remains the focus during the data discovery process. She emphasized the value of bridging agency stovepipes through data and exposing people to the wealth of survey and administrative data resources available at local, state, and federal levels as well as Internet-based data. There are not many off-the-shelf products available for data analytics for urban sustainability, but valuable analytics are emerging through the use of sophisticated statistical methods. A body of peer-reviewed research around community problems is also emerging.

Ensor emphasized the value of data archiving and curation; data used to make decisions should be permanently present. Holm advised against reinventing data platforms. Instead, data.gov is an example of an established platform (including 8,000 data sets from cities) that researchers find useful. However, she noted that even this platform is not immune to issues of permanence (e.g., government shutdowns would make this platform inaccessible). She said that maintaining this platform should be considered an essential service. She echoed Keller's assertion that a thorough data discovery is necessary to understand what data are available to address a research question. She emphasized the value of citizen science and crowdsourcing—people with mobile phones and wearable devices are constantly generating data, and she hopes that this work is lifted to a level of rigor in which it can be used in academic research.

Data privacy and ethics are important components of data access. Keller expects that there will be confusion in communities about privacy and whether data can be used for certain circumstances, so more education and conversation about both privacy and ethics are needed. The institutional review board (IRB) structure is well known in parts of academia and industry, but the public and local governments are not necessarily aware of these processes. The IRB framework could help the public to better understand informed consent and privacy, as well as ethical considerations around who is benefiting from a particular analysis. Conversations about ethics and privacy as well as about the value of transparency and reproducibility need to play a prominent role in both partnerships and policy making, Keller asserted.

Dasgupta said that as more data are generated and stored by private entities, ethical issues will continue to arise, especially as those data assets are used publicly. He echoed Keller's suggestion for the generation of rules inspired by IRB standards. Audience member David Rabinowitz questioned what happens with individuals' data. Rather than making data available only for general policy generation, they could be made available to the individuals and perhaps used as motivation to change behavior (e.g., data from utility companies about how much electricity an individual uses as compared to her neighbor). Keller noted the value of this suggestion and added that a different definition of "smart city" is needed: a city is smart if the individuals in a city can access the information they need, when they need it, to improve their lives. As an example, Holm mentioned that through a partnership with Waze, the city of Los Angeles shares information about high traffic-accident injury networks with the app so that it can direct people around potential accident spots. She described this as a highly synergistic way to share information.

Will Angel, NaskMe, asked Holm to elaborate on the successes of such partnerships because, at the city level, larger companies are sometimes reticent to share their data. Holm explained that companies like Waze do not particularly want to share their data, and Los Angeles does not want to access individual data, so there has to be a negotiation with each company (each of which will have a slightly different business model) to try to find the place in which both the city and the company are willing to share information to prevent public harm. She highlighted the National Association of City Transportation Officials as an appropriate place to have this transportation-data-focused conversation about balancing individual companies' interests in protecting data with cities' desire to be better informed by that data. Luís Bettencourt, University of Chicago, said that verification, transparency, and curation become even more important with an increase in available data. It is important to understand which signals can be verified and have the potential to align entities around solutions. The context around data matters, as does integrating data to achieve public good.

Ganguly hoped that people at this workshop would form partnerships, as participants have expertise in data, context, and solutions. He also suggested crowdsourcing efforts based on available data and models that could be built. David Maier, Portland State University, endorsed the idea of coming up with benchmarks with ground truth, both to test the models and to test the sufficiency of data.

Better Decision Making

Ensor asserted that better decisions happen in partnership. Researchers' methods need to align with the problem and the partnership without compromising robustness and validity. She emphasized that decisions in the sustainability framework are multifaceted, which is why a systems approach is essential. Although it is not always possible to arrive at a perfect answer, it is crucial to have a robust answer with a transparent methodology, Ensor continued.

Holm said that from the perspective of a city employee, transparent decision making is enabled by confidence that it is safe to make data available and that cities (or their employees) will not be judged if those data are imperfect. She explained that theories and academic research in cities need to be implemented in a way that civil and public servants do not have to sacrifice their jobs or reputations. She also noted that academic researchers need to articulate how their theories could be actionable and make a difference. Ganguly asked about how academic researchers can best translate information, as some audiences will desire more information than others. Ensor explained that it is important to bring the correct level of science to the conversation, and Holm noted that city employees can have very different backgrounds, so that not all of them are savvy with data or scientific research. She suggested that a chief data/technology officer who could translate back to the political spectrum would be an asset in any city department. Holm said that this is also the best person to reach out to for any conversations about research and action-oriented decision making. Dasgupta commented that being inclusive of different points of view in the data generation and discovery process will provide a multidimensional view of reality and truth, which could lead to multiple valid solutions.

Capability of Cities to Use Data

Dasgupta pointed out that the majority of people in the world do not live in big cities that are capable of using complex data. He reiterated that a gap exists between operational-minded people who run cities with budget optimization in mind and those who use data to make decisions related to issues of sustainability. Holm noted that even when city officials are not tech savvy, most are interested in making better decisions for their residents, businesses, and visitors. Thus, it is important to identify existing political barriers to data-driven decision making and to think about how private-sector funding could offset budgetary constraints. Even though there will be turnover in the positions of elected officials, she explained that city departments will endure (i.e., garbage will always

need to be collected, and buildings will always need to be painted). Staff in those departments might be more willing to try new things, and often there is a political desire to partner with people who can provide data to make better decisions.

Ensor said that new statistical methodologies allow people to work across private databases without having to share the data; this is helpful when the goal is to get to a decision supported by information, not necessarily to hold the data. Keller added that there is a growing body of technology and solutions for issues related to data governance. Maier asked which of the models discussed throughout the workshop could assist cities with operations or short-term decision making. Keller mentioned that Bryan Lewis's work at the University of Virginia relies on nowcasting for real-time decision making. Holm added that from a city government perspective, nowcasting is crucial for emergency management and, more generally, would be useful to understand how to better serve residents. Ensor said that a systems approach to modeling would be more useful for longer-term planning but that nowcasting has value for short-term decisions. She added that a future workshop more specifically about modeling could be useful in addressing this question more deeply.

Ulrike Passe, Iowa State University, explained that as an architect she focuses on the power of design, which is the link between data and decision making. She noted her surprise at how few designers attend meetings on urban sustainability. Keller said that new technologies are emerging to help move from a planner's static view of the city to something more dynamic and to engage people (in all phases and parts of the research) who might be affected by these decisions. Holm emphasized the value of virtual reality because a blueprint is so different from a walk-through of a physical space. If a goal is to design a future city that will elevate its residents' data literacy, then data has to be portrayed in a consumable way. Rabinowitz referred to the Smithsonian Museums' strategy to tell stories with artifacts, and he stressed that the best way to communicate data is through storytelling. Holm agreed and said that it is also important to recognize the data divide and encourage people to understand how data could change their lives for good or bad through the sharing of stories—open source, open data, and open science are all part of achieving data literacy, and GitHub is an example of a platform that makes that achievable.

Keller hypothesized that a conversation at a similar workshop 10 years from now would be very different because these ideas will have been infused in the workforce and in local government. She suggested that communities begin to think now about future data innovations for governance and applications. Ensor highlighted efforts under way at the

K–12 and 2-year college levels, as well as in the National Academies[2] and the American Statistical Association, to improve data literacy. She encouraged striving to overcome the digital divide so that the society of the future is data literate. Holm identified the Computer Science for All initiative,[3] Khan Academy's Hour of Code,[4] and various bootcamps as traditional and nontraditional ways of data science learning that have emerged. She suggested embracing those methods for the students of the future, bringing rigor into conversations about data literacy, and encouraging inclusivity of populations.

Future Work

Michelle Schwalbe, National Academies of Sciences, Engineering, and Medicine, asked how the National Academies could aid in the continuation of these discussions or whether there are other key stakeholders with whom to engage. Ensor suggested resuming the conversation with a series of roundtables that drive both scientist and practitioner inquiry. Keller said that because this workshop's discussion was U.S.-centric, the National Academies could help organize a forum that would better cover the global landscape (i.e., the Global North and Global South)—there is much to be learned at the global level. She also proposed an activity that focuses on the types of city partnerships discussed throughout this workshop. Holm expected that many projects could emerge from this workshop—for example, a marketplace for matchmaking between cities and universities. She hopes that the group can connect and collaborate on projects going forward. Another important topic for further discussion is understanding better ways of accessing data, which might be an area in which the National Academies could facilitate or collaborate.

Keller said that more people and more opportunities are needed to publish the work emerging from partnerships in peer-reviewed literature (instead of only in popular media). Christine Ehlig-Economides, University of Houston, highlighted the need for funding that incentivizes city involvement in partnerships. Bettencourt noted that people from the humanities, social sciences, and policy arenas offer a different approach to

[2] These efforts include the Roundtable on Data Science Postsecondary Education (see www.nas.edu/dsert) and the 2018 report *Data Science for Undergraduates: Opportunities and Options* (see www.nap.edu/25104).

[3] For more information about the Computer Science for All initiative, see https://www.csforall.org, accessed March 12, 2019.

[4] For more information about the Khan Academy's Hour of Code, see https://www.khanacademy.org/hourofcode, accessed March 12, 2019.

data, which should alter perspectives of science, technology, engineering, and mathematics education reform. Dasgupta wondered about strategies to build the National Academies' partnerships with other academies throughout the world. He closed the workshop by thanking participants, noting that society is on the cusp of big changes and expressing his hope that the National Academies would continue this conversation.

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Appendixes

A

Workshop Agenda

Workshop on the Frontiers of Big Data, Modeling, and Simulation in Urban Sustainability

Keck Center of the National Academies
Washington, D.C.

WEDNESDAY, JANUARY 30, 2019

9:00 a.m.	Introduction to the Workshop Katherine Bennett Ensor, Rice University Aniruddha Dasgupta, World Resources Institute

Session I: Framing the Problem

9:15 a.m.	Keynotes: Why Is This Workshop Important? Auroop R. Ganguly, Northeastern University Jeanne Holm, City of Los Angeles Bill Fulton, Rice University
10:15 a.m.	Break

10:30 a.m. Framing Discussion Among Panel and Workshop Participants
Katherine Bennett Ensor, Rice University, *Moderator*
Auroop R. Ganguly, Northeastern University
Jeanne Holm, City of Los Angeles
Bill Fulton, Rice University

11:30 a.m. Lunch

Session II: Advances in Data, Modeling, and Simulation

12:30 p.m. Modeling, Simulation, and Data
David Maier, Portland State University, *Moderator*
Elena Craft, Environmental Defense Fund
Bryan Lewis, University of Virginia
Kaan Ozbay, New York University

1:40 p.m. Innovation in Geospatial Data Sources and Spatiotemporal Analysis
Katherine Bennett Ensor, Rice University, *Moderator*
Constantine Kontokosta, New York University
Rhiannan Price, DigitalGlobe

2:40 p.m. Break

3:00 p.m. Privatization of Data and Data Privacy: Two Sides of One Coin
Aniruddha Dasgupta, World Resources Institute, *Moderator*
John L. Eltinge, U.S. Census Bureau
Sallie Keller, University of Virginia
Michael Hawes, U.S. Department of Education

4:10 p.m. Data Use Experiences Across Cities
Amanda Eichel, Global Covenant of Mayors for Climate and Energy
Jessica Seddon, World Resources Institute, *Discussant*

4:40 p.m. Breakouts Preparing for Day 2 Themes
Theme 1: Air and Water Systems (Keck 100)
Theme 2: Transportation and Physical Infrastructure (Keck 101)
Theme 3: Sustainable Inclusive Communities (Keck 105)

5:10 p.m. Adjourn Day 1

THURSDAY, JANUARY 31, 2019

9:00 a.m.	Urban Theory to Understand City Challenges and Opportunities Luís Bettencourt, University of Chicago
9:40 a.m.	Report Out of Plans Made During Previous Day's Breakouts

Session III: Identifying Directions for Partnership

10:10 a.m.	Theme 1: Air and Water Systems (Keck 100) Anu Ramaswami, University of Minnesota Elena Craft, Environmental Defense Fund Katherine Bennett Ensor, Rice University
10:10 a.m.	Theme 2: Transportation and Physical Infrastructure (Keck 101) Kaan Ozbay, New York University Auroop R. Ganguly, Northeastern University Christine Ehlig-Economides, University of Houston
10:10 a.m.	Theme 3: Sustainable Inclusive Communities (Keck 105) Bill Fulton, Rice University Aniruddha Dasgupta, World Resources Institute Seth Schultz, Urban Breakthroughs
12:20 p.m.	Lunch
12:50 p.m.	Report Back
1:20 p.m.	Concluding Panel Discussion Aniruddha Dasgupta, World Resources Institute Jeanne Holm, City of Los Angeles Sallie Keller, University of Virginia Katherine Bennett Ensor, Rice University
3:00 p.m.	Adjourn Workshop

B

Registered Workshop Participants

Yasser Abdallah, ICFJ
Fred Abousleman, Oregon Cascades West Council of Governments
Jim Abry, Checketts Partners
Akwasi Acheampong, Geomatic Engineering Department
Brian Adair, University of Arizona
Laksono Adhianto, Rice University
Prashanth Adhikari, SAP Concur
Mustapha Adib
Don Adjeroh, West Virginia University
Benjamin Adrian, Senate Energy Committee
Kazir Afolabi, The American University in Cairo, New Cairo, Egypt
Nithin Agarwal, University of Florida
Oforiwaa Pee Agyei-Boakye, University of Pennsylvania
Diaa Ahmed, Utrecht University
Chul Ahn, Read, Dream, and Achieve
Muhammad Ahsan, Afiniti
Bilikis Akindele, Duke Health Technology Solutions—Analytics Center of Excellence
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Hank Allen, Wheaton College
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Shideh Shams Amiri, Drexel University
Tensae Andargachew, New Jersey Institute of Technology
Will Angel, NaskMe
Reuben Aniekwu, ICF
Hassan Anwar, C2 solutions
Anwer Aqil, CAMRIS/United States Agency for International Development
Reginald Archer, Tennessee State University
Ricardo Torres Artavia, Colegio de Medicos y Cirujanos
Hakob Avjyan, General Assembly
Bridget Awosika, Deloitte
Hala Azzam, National Institutes of Health
Gaby Baasch, University of Victoria
Pramita Bagchi, George Mason University
Binulal Balakrishnan, Bell Info
Carmela Balassiano
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Mark Ballard, Oklahoma Center for the Advancement of Science and Technology
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Chuck Banks, Guidehouse, LLP
Yanina Barrera, Harvard University
S. Batterman, University of Michigan
Amber Batts, National Oceanic and Atmospheric Administration
Charles Beck, Synthesis Three
Nora Beck, Chicago Metropolitan Agency for Planning
Emanuel Bendavid, U.S. Census Bureau
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Workshop Planning Committee Biographical Information

ANIRUDDHA DASGUPTA, *Co-Chair*, is the global director of the World Resources Institute (WRI) Ross Center for Sustainable Cities, a program that galvanizes action to help cities grow more sustainably and improve quality of life in developing countries around the world. Mr. Dasgupta guides the Ross Center in developing environmentally, socially, and financially sustainable solutions to improve people's quality of life in developing cities. Mr. Dasgupta leads a team of global experts in sustainable transport, urban development, and building efficiency, as well as in engagement across air quality, low-carbon energy, governance, water risk, and associated areas. He also serves as WRI director of the Coalition for Urban Transitions, Special Initiative of the New Climate Economy, a global partnership of eight economic and policy research institutes, of which WRI is the managing partner. The coalition is a major international initiative to support decision makers in unlocking the power of cities for enhanced national economic, social, and environmental performance, including reducing the risk of climate change. The coalition provides an independent, evidence-based approach for thinking about well-managed urban transitions that ensure the growth of urban areas along with the accompanying processes to maximize benefits for people and the planet. Mr. Dasgupta was previously at the World Bank as director of knowledge and learning, providing leadership and direction in offering knowledge services for development. An urban professional, he has dedicated himself to international development. Mr. Dasgupta has done extensive

operational work in Asia and Eastern Europe as a technical expert centered on community-based development, urban environment, disaster management, solid waste management, water supply, and sanitation. Mr. Dasgupta holds a master's degree in city planning and a master's degree in architecture, both from the Massachusetts Institute of Technology (MIT). His Ph.D. work, at the planning school at MIT, focused on services for the urban poor.

KATHERINE BENNETT ENSOR, *Co-Chair*, is professor of statistics in the George R. Brown School of Engineering and director of the Center for Computational Finance and Economic Systems at Rice University. Dr. Ensor also serves as the faculty lead for the professional science master's program in environmental analysis and decision making. She served as chair of the Department of Statistics from 1999 through 2013. Dr. Ensor develops statistical techniques to answer important questions in science, engineering, and business, with specific focus on the environment, energy, and finance. She is an expert in multivariate time series, categorical data, spatial-temporal, and general stochastic processes. Dr. Ensor is an elected fellow of the American Statistical Association and the American Association for the Advancement of Science (AAAS), and she has been recognized for her leadership, scholarship, service, and mentoring. She holds a B.S.E. (1981) and an M.S. (1982) in mathematics from Arkansas State University and a Ph.D. in statistics from Texas A&M University (1986).

JOHN R. BIRGE is the Jerry W. and Carol Lee Levin Distinguished Service Professor of Operations Management at the University of Chicago, Booth School of Business. Previously, Dr. Birge was dean of the McCormick School of Engineering and Applied Science and professor of industrial engineering and management sciences at Northwestern University. He also served as professor and chair of industrial and operations engineering at the University of Michigan, where he established the Financial Engineering Program. Dr. Birge is currently editor-in-chief of *Operations Research*, former editor-in-chief of *Mathematical Programming, Series B*, and former president of the Institute for Operations Research and the Management Sciences (INFORMS). His honors and awards include the Institute of Industrial Engineers Medallion Award, the INFORMS Fellows Award, the Manufacturing and Service Operations Management Society Distinguished Fellow Award, the Harold W. Kuhn Prize, the George E. Kimball Medal, the William Pierskalla Award, and election to the National Academy of Engineering. Dr. Birge received M.S. and Ph.D. degrees from Stanford University in operations research, and an A.B. in mathematics from Princeton University.

LILIAN CORAL joined the Knight Foundation in September 2017. Ms. Coral is Knight's director of national strategy, where she manages the national portfolio and focuses on the development of the foundation's Smart Cities strategy. She came to Knight from the City of Los Angeles, where she served as chief data officer for Mayor Eric Garcetti. In this role, Ms. Coral led the mayor's directive on Open Data beyond the lens of transparency and toward his vision of a data-driven Los Angeles through the management of the city's Open Data program, the expansion of the use of data science and analytics, and the development of user-centered digital services. Ms. Coral led the development of the GeoHub, a first-of-its-kind data management solution for integrating geospatial information across the City of Los Angeles's 41 departments, and oversaw the publishing of 1,100 city data sets and APIs; the management of five portals of operational and financial data; and the rollout of more than 15 digital services, applications, and public facing dashboards. Prior to joining Mayor Garcetti, Ms. Coral spent 15 years working on a wide range of health and human services issues as an advocate and executive leader, having had the opportunity to work with labor unions, nongovernmental organizations, foundations, and human service agencies at all levels of government to transform the way government uses data and technology to serve its citizens. Ms. Coral has a bachelor's degree in international studies from the University of California, Irvine, and a master's degree in public policy from the University of California, Los Angeles. She is a native of Colombia, from where much of her inspiration for innovation and social justice emerged.

CHRISTINE EHLIG-ECONOMIDES is currently professor and Hugh Roy and Lillie Cranz Cullen Distinguished University Chair at the University of Houston. Dr. Ehlig-Economides held a previous position as professor of petroleum engineering at Texas A&M University in the Albert B. Stevens endowed chair. She founded the Center for Energy, Environment, and Transportation Innovation (CEETI), one of four research centers in the Crisman Institute. Dr. Ehlig-Economides joined Texas A&M to develop research and education in energy engineering to enable the petroleum engineering department to grow and evolve to a broader energy scope. CEETI is currently pursuing research funded by the Texas Department of Transportation and a potential collaboration with the Oak Ridge National Laboratory. Dr. Ehlig-Economides has successfully introduced a freshman-level energy course that was approved for the core curriculum as a natural science elective and an Energy Engineering Certificate program. Dr. Ehlig-Economides worked for Schlumberger for 20 years in a truly global capacity. She has published more than 50 papers, authored two patents, and lectured or consulted in more than 30 countries. Dr. Ehlig-Economides is

internationally recognized for expertise in reservoir engineering, pressure transient analysis, integrated reservoir characterization, complex well design, and production enhancement. She received her Ph.D. in petroleum engineering from Stanford University, her M.S. in chemical engineering from the University of Kansas, and her B.A. in math-science from Rice University. She is also the recipient of the Anthony F. Lucas Gold Medal (2010). Her professional service includes executive editor of the *Society of Petroleum Engineers Formation Evaluation*, 1995–1996; Society of Petroleum Engineers (SPE) Distinguished Lecture, 1997–1998; and numerous posts as chair or member of SPE committees and task forces. She recently co-chaired a steering committee for the Middle East Colloquium in Petroleum Engineering Education, was the program chair for the 2006 SPE Annual Technical Conference and Exhibition, and is currently co-chairing an SPE Talent and Retention Workshop on Dual Career Couples in the petroleum industry. Dr. Ehlig-Economides was a member of the National Academy of Sciences Committee on America's Energy Future.

JEANNE HOLM works at the intersection of innovation, open data, and education. Ms. Holm is the deputy chief information officer of the City of Los Angeles, working on issues ranging from homelessness to predictive analytics. As a senior consultant with the World Bank, she worked with governments throughout the world to build robust open data ecosystems and ensure transparency. She was the evangelist for data.gov for the White House, leading collaboration and building communities with the public, educators, developers, and international and state governments in using open government data. Ms. Holm was the chief knowledge architect at the National Aeronautics and Space Administration (NASA) Jet Propulsion Laboratory, driving innovation through social media, virtual worlds, gaming, and collaborative systems, including the award-winning NASA public portal (www.nasa.gov). She is a fellow of the United Nations International Academy of Astronautics and distinguished instructor at the University of California, Los Angeles; leads several high-tech start-ups; and has more than 130 publications on information systems, knowledge management, and innovation. Ms. Holm's research and courses focus on data science, knowledge management, and civic innovation. Her honors include the NASA Exceptional Service Medal for leadership (twice), top 50 Women in Tech, NASA Achievement Award for her work on the Galileo and Voyager spacecraft, and three Webby awards from the International Academy of Digital Arts and Sciences, and she led NASA to an unprecedented three global Most Admired Knowledge Enterprise awards.

LUCAS JOPPA is Microsoft's first chief environmental scientist, and he oversees AI for Earth, a cross-company program dedicated to deploying

Microsoft's deep investments in AI research and technology in the four key areas of climate change, agriculture, water, and biodiversity conservation. As one of Microsoft's 10 AI Thought Leaders, Dr. Joppa also serves as the company's internal and external focal point on corporate matters pertaining to environmental science and the application of technology to solve sustainability challenges. He serves in an advisory role as a director, adviser, or fellow through the committees and boards of numerous public, private, and nonprofit organizations dedicated to science and technology. Dr. Joppa maintains an active scientific research career and has published more than 100 articles in leading academic journals.

CONSTANTINE KONTOKOSTA is an assistant professor of urban informatics at the New York University (NYU) Center for Urban Science and Progress (CUSP) and the NYU Tandon School of Engineering, Department of Civil and Urban Engineering; the director of the Urban Intelligence Lab; and the deputy director for academics at CUSP. Dr. Kontokosta holds a faculty appointment as visiting professor of computer science at the University of Warwick and is an affiliated faculty member at the Marron Institute for Urban Management. He is also the principal investigator and head of the CUSP Quantified Community research facility, a groundbreaking project under way at three districts in New York City—at the Hudson Yards development in New York City; in Lower Manhattan; and in Red Hook, Brooklyn—that is building sensor-enabled urban neighborhoods to study the impact of the built environment on well-being and human behavior. As one of the first faculty to join CUSP, Dr. Kontokosta is part of the CUSP founding leadership team, setting the center's strategic priorities and leading the design and implementation of its academic programs in urban data science. He serves as faculty engineer-in-residence at the NYU Tech Incubators, where he mentors clean tech and smart city startup companies from early-stage idea refinement to technology demonstration and deployment. Dr. Kontokosta is a 2017 recipient of the National Science Foundation (NSF) CAREER award for his research in urban informatics for smart, sustainable cities. His research lies at the intersection of urban planning, data science, and systems engineering, focusing on using big data and new sensing technologies to better understand the dynamics of physical, environmental, and social systems in the urban environment. Dr. Kontokosta's work has been published in leading academic journals in fields including science, economics, urban policy and planning, and engineering, and he has two forthcoming books, one on data-driven city operations and planning and the other on the subject of big data and urban sustainability. He collaborates with numerous city agencies in the United States and internationally on issues of urban sustainability and resilience policy and planning and city operations, including a multiyear

effort to lead data analysis on building energy efficiency with the New York City Mayor's Office of Sustainability. Dr. Kontokosta's work has been featured in the *Wall Street Journal*, *New York Times*, CNN, NPR, Fast Company, CityLab, *Bloomberg News*, *Financial Times*, *APS Physics*, and the American Society of Civil Engineers' *Civil Engineering Magazine*, among other national and international media outlets. Dr. Kontokosta holds a Ph.D., an M.Phil., and an M.S. in urban planning, specializing in urban economics and econometrics, from Columbia University; an M.S. in real estate finance from New York University; and a B.S.E. in civil engineering systems from the University of Pennsylvania. He is a licensed Professional Engineer, a member of the American Institute of Certified Planners, and a U.S. Green Building Council Leadership in Energy and Environmental Design Accredited Professional, and he has been elected a fellow of the Royal Institution of Chartered Surveyors (RICS). Dr. Kontokosta is a recipient of the IBM Faculty Award, the Google IoT Research Award, the C. Lowell Harriss Fellowship, the U.S. Department of Housing and Urban Development Doctoral Dissertation Award, the Charles Abrams Award, and Teaching Excellence and Outstanding Service Awards at NYU, and has been named a Fulbright senior specialist. In addition, Dr. Kontokosta is an accomplished real estate entrepreneur and has served as vice chair of the Suffolk County Planning Commission and on the boards of the United Nations Environment Programme—Sustainable Building and Climate Initiative and RICS.

DAVID MAIER is Maseeh Professor of Emerging Technologies at Portland State University. Prior to his current position, Dr. Maier was on the faculty at the State University of New York, Stony Brook, and the Oregon Graduate Institute. He has spent extended visits with the National Institute for Research in Computer Science and Automation; the University of Wisconsin, Madison; Microsoft Research; and the National University of Singapore. Dr. Maier is the author of books on relational databases, logic programming, and object-oriented databases, as well as papers on database theory, object-oriented technology, scientific databases, and data streams. He is a recognized expert on the challenges of large-scale data in the sciences. Dr. Maier received an NSF Young Investigator Award in 1984, the 1997 Special Interest Group on Management of Data Innovations Award for his contributions in objects and databases, and a Microsoft Research Outstanding Collaborator Award in 2016. He is also an Association for Computing Machinery (ACM) fellow and an Institute of Electrical and Electronics Engineers (IEEE) senior member. Dr. Maier holds a dual B.A. in mathematics and computer science from the University of Oregon (Honors College, 1974) and a Ph.D. in electrical engineering and computer science from Princeton University (1978).

JOSÉ M.F. MOURA is the Philip and Marsha Dowd University Professor at Carnegie Mellon University (CMU), with the Departments of Electrical and Computer Engineering and, by courtesy, Biomedical Engineering. Dr. Moura is a corresponding member of the Portugal Academy of Science, an IEEE fellow, and a fellow of AAAS. He holds a D.Sc. in electrical engineering and computer science, M.Sc. and E.E. degrees from MIT, and an E.E. degree from Instituto Superior Técnico (IST, Portugal). Dr. Moura was a visiting professor at MIT (1984–1986, 1999–2000, and 2006–2007), a visiting scholar at University of Southern California (summers of 1979–1981), and was on the faculty of IST (Portugal). In the academic year 2013–2014, he was a visiting professor with NYU and CUSP, on sabbatical leave from CMU. Dr. Moura's research interests are in statistical signal and image processing. He is working in the new area of big data and network science, with particular emphasis on distributed decision and inference in networked systems and graph-based data. Research projects include signal processing on graphs and analytics for big data, distributed detection in sensor networks, robust detection and imaging by time reversal, bioimaging, SPIRAL, DSP on Graphs, SMART, and image/video processing. In addition to industrial funding, Dr. Moura's work has been sponsored by several Defense Advanced Research Projects Agency, National Institutes of Health, Office of Naval Research, Army Research Office, Air Force Office of Scientific Research, and NSF grants, as well as several industrial grants. Dr. Moura received the IEEE Signal Processing Society Award for outstanding technical contributions and leadership in signal processing and the IEEE Signal Processing Society Technical Achievement Award for fundamental contributions to statistical signal processing. He is on the board of directors of IEEE and served as IEEE Division IX director (2012–2013). He was president of the IEEE Signal Processing Society (2008–2009) as well as editor-in-chief of *IEEE Transactions on Signal Processing* and acting editor-in-chief for *IEEE Signal Processing Letters*. He was on the editorial board of several journals, including *ACM Transactions on Sensor Networks* and *IEEE Proceedings*. Dr. Moura was on the steering committee of the IEEE International Symposium on Bioimaging and is on the steering committee of the ACM/IEEE International Symposium on Information Processing in Sensor Networks.