Urban Science: Integrated Theory from the First Cities to Sustainable Metropolises

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Preface

Urban science seeks to understand the fundamental processes that drive, shape and sustain cities and urbanization. It is a multi/transdisciplinary approach involving concepts, methods and research from the social, natural, engineering and computational sciences, along with the humanities. This report is intended to convey the current "state of the art" in *urban science* while also clearly indicating how urban science builds upon and complements (but does not replace) prior work on cities and urbanization in many other disciplines. The report does not aim at a fully comprehensive synopsis of work done under the rubric of "urban science" but it does aim to convey what makes urban science different from discipline-based examinations of cities and urbanization. It also highlights novel insights generated by the inherently multidisciplinary inquiry that urban science exemplifies. The authors of the report are all based in academic or research institutions but several of them are close to practice by virtue of collaboration with NGOs and community groups and engagement with policy. The authors also represent different academic disciplines and varied traditions of scientific inquiry. The report is meant to facilitate, and hopefully also provoke, discussion among the many stakeholders for whom a scientifically based, empirically rich, and historically deep understanding of cities and urbanization is not only intellectually compelling but also socially urgent and ethically pressing. We believe that the innovative scholarship constituting urban science can importantly provide scientific leadership to support meeting the urgent challenges of global sustainable development.

1. Introduction

There are many species in which individuals interact prosocially with close relatives, but humans are unusual in the scale and scope of complex social interactions with non-kin. This has led to fluid, open-ended, and collective organizations that solve common issues of energy acquisition, conflict management, sharing and exchange of material goods, and information processing through varying degrees of cooperation. These organizations—when maintained for the benefit of groups—have been essential for our species' success, marking who we are collectively in uniquely powerful ways. Many technological innovations and social transformations have characterized the rapid growth of our species over its relatively short history, culminating in our current position as the makers (or breakers) of the Anthropocene. From an evolutionary perspective, cities are a very recent phenomenon. Their appearance in the archaeological record coincides with the advent of increasingly sedentary, agricultural, bureaucratic, and politically asymmetrical societies. The social, economic, and political importance of cities as foci of human social interactions, innovation, and productivity has steadily increased over time up to the present and can be expected to continue to do so at least for the next few decades.

The urbanization process that arguably began around 10,000 years ago will soon be complete and *Homo Sapiens Sapiens* will be mostly an urban species. Urban areas have become the principal driver of most social, institutional and technological innovations. Cities are also the focus of the solutions to our most pressing challenges, requiring sustainable solutions for continued improvement in the human condition. Our success in addressing the related challenges of adaptation to climate change, sustainability, poverty alleviation, and shared prosperity will be largely determined by what happens in cities. Rapid urbanization in the developing world will have increasingly dominant effects on conditions across the globe.

Here, we argue that a strengthened scientific understanding of the *fundamental processes* by which cities operate and urbanizing societies grow, is not only possible but necessary if we are to solve the challenges and leverage the opportunities of our time. Whether one focuses on the origin of the first cities, the role of urbanization in socioeconomic development, how the Industrial Revolution lead to the first urbanized nations, or the present time when the world has become a "planet of cities," it is apparent that a set of intertwined transformations in how people live, use space, and produce goods and services can be understood through the lens of urbanization.

Technological and social developments have combined (intentionally but also as unintended consequences) to generate unprecedented amounts of data concerning what people (as individuals and in organizations) do when they agglomerate in cities. To some, this "big data" revolution, often associated with the notion of "smart cities," holds the promise of more effective urban management. However, experience has reminded us that data—even enormous amounts—without associated theory to interrogate and make sense of it, do not generate predictive insights (Shutters 2018, West 2017). While the "urban big data" phenomenon was capturing the imagination of urbanists and city managers, another intellectual movement, which we refer to as *Urban Science*, was taking shape, itself the result of a confluence of several analytical trajectories (Batty 2013). A significant realization is that the city is itself an important "unit of analysis" (as Paul Romer recently argued):

> "The urban environment that humans are so busily creating is many things: a biological environment, a social environment, a built environment, a market environment, a business environment, and a political environment. It includes not only the versions of these environments that exist inside a single city, but also those that are emerging from the interaction between cities. Our understanding of the urban environment will draw on existing academic disciplines, but it will also develop its own abstractions and insights." (Romer 2013)

Several intellectual developments have animated the efforts to develop a transdisciplinary, theoretically rich and empirically robust understanding of urbanization as one of the major drivers of human development. Among these is the revival of Jane Jacobs' view of the city as an instance of "organized complexity" (Jacobs 1961), awareness about the centrality of social networks in channeling and structuring human sociality (together with the flowering of work on network theory), and the feasibility of conducting truly comparative investigations of urban systems across locations and eras. (Here we adopt the convention that transdisciplinary research crosses disciplinary boundaries and integrates distinct domains of knowledge, generating novel insights, in a manner that goes beyond bringing together or combining existing units of knowledge.) While definitions of scientific enterprises can become straightjackets for the imagination, the following statement by Batty (2019: 998) neatly captures what makes *urban science* distinct from and irreducible to any of the extant research traditions on the urban:

> "City science is often called 'urban science', in this context referring to theories of the urban system that provide analogies to flows of energy and information but not particularly in the physical domain. Urban science deals with the structure and functioning of cities, and the generic laws that seem to govern cities everywhere insofar as they can be articulated…Urban science in this portrayal does not mean the technology of constructing cities, or of the materials and energy flows that determine its rudimentary functioning. It means here a science of human behaviour as it applies to cities… This is not the science of the physics of buildings or energy flows in cities (although it clearly relates in part to some of these aspects), it is the science of people flows, flows of goods, and the flow of information and ideas and the extent to which all these can be generalised over city size and scale."

Whereas Batty's proposal originates from the fields of urban spatial geography, a parallel proposal for a (new) science of cities from the discipline of physics is offered by Marc Barthelemy (2017). He proposes an interdisciplinary strategy using ideas and tools from statistical physics, of disordered systems, quantitative geography, and spatial economics. Key to this strategy is the extraction from data of generalizable facts that go beyond historical or geographical aspects of cities. These empirical results can then support the construction of models with a minimal number of microscale ingredients leading to emergent collective behavior consistent with data (Barthelemy 2017: 2).

These juxtaposed proposals from a geographer and a physicist highlight a basic tension in current urban science between approaches from the social sciences and those from the natural sciences (Solecki et al. 2013). Most social scientists are uncomfortable working with a small number of first-principles variables as often proposed by physicists working on cities (e.g., West

2017). Nevertheless, much social science research on cities and urban phenomena uses quantitative methods and a scientific epistemology (e.g., Batty 2013, Glaeser 2011, Massey and Denton 1989, Sampson 2012). Most physical scientists now addressing cities have moved beyond earlier work that proposed to understand urbanism without consideration of the large body of social science research on social patterns, economics, and political processes. (Not surprisingly, the earlier work by natural scientists turned urbanists generated considerable annoyance among social scientists.)

We believe that the time is ripe for a targeted integration of the social and physical sciences of cities and urbanism. In this effort, formal theory is crucial. We take a general stance that views *urban science* as dealing with the behavior of agglomerated humans in settlements that can vary greatly in size and density (thus we are somewhat relaxed when it comes to defining the "city"). We hasten to clarify that urban science is not synonymous with "urban analytics" or "urban informatics," and that urban science is different from "smart cities." Urban analytics is a collection of tools used to analyze and map "urban big data" (generated by social media, crowd sourcing and sensor networks) and is closely related, conceptually and methodologically, to geographic information systems (GIS) and spatial statistics (Singleton et al. 2019). Urban analytics is to urban science as data analytics and applied statistics are to science in general (Tukey 1962).

In many ways the research landscape remains unchanged since the NSF sponsored a workshop in 1998 on urban sustainability:

> "…geographers (and others), dissuaded in part by the political cacophony surrounding the debate, have largely neglected the challenge of conceptualizing the interrelationships among social, economic, political, and environmental processes, a challenge simultaneously posed by the scale of predicted urbanization and by the idea of sustainability. Existing structures of knowledge creation and compartmentalization in academia exacerbate this silence. Scholars of urban processes affecting first-world cities rarely interact with scholars of third-world cities. Theories of third-world urban processes rarely inform current theorizing about first-world cities. Neither group has a strong tradition of embracing environmental or ecological concerns. Urban scholars investigating global–local linkages focus primarily within the economic sphere and neglect environmental impacts and questions of ecological sustainability. Scholars focusing on environmental processes (including researchers examining global environmental change and political ecologists) have almost completely disregarded the urban. The barriers separating these distinct areas of research—first- and third world urban processes and environmental processes—have grown to be sturdy and quite impermeable." (Hanson and Lake 2000: 1-2)

We are of the view that *urban science* has become a well-defined field which is now addressing the two main challenges identified by Hanson and Lake. And it is doing so by examining a shared set of phenomena across many disciplines, building upon much that has already been learned while developing common theoretical ideas, identifying underlying principles and deploying analytical methods for understanding cities and urbanization across the globe and across history. While much has been accomplished already, much remains to be done. Here, we attempt a brief overview of how insights from several fields have recently come together methodologically and in terms of new theory to make sense of the processes by which cities operate and grow.

2. Unifying Perspectives

At least since the late 19th century the study of different aspects of cities has been pursued independently by multiple disciplines. As a result, little progress has been made in the analytical articulation of diverse urban phenomena. For example, the study of city and social transformation through deep time was the realm of archaeologists and historians, while the spatial organization and city size statistics of urban systems were left to geographers, demographers and regional scientists; the economic productivity of cities to urban economists; the infrastructural systems of cities to civil engineers; and land uses to city planners. Sociologists have historically studied neighborhoods, race and segregation, and sometimes crime, while social psychologists have been concerned with cognitive constraints and adaptive social behavior. These perspectives do touch of course, but they have rarely constrained one another in the service of building a consistent and common body of knowledge.

Another dimension of the multiplicity of approaches to studying cities deals with the study of *urban systems* from around the world and across time. In the 19th and 20th centuries, early in the study of cities, empirical data was overwhelmingly more available for cities in Europe and North America. Today this picture is very different, allowing us to study cities all around the world in quantitative comparative ways. New archaeological methods are adding great time depth by generating quantitative data on long trajectories of past urbanism around the world. High-precision remote sensing methods, particularly LiDAR, are used in conjunction with new survey methods to increase greatly the amount of ancient urban data available (e.g., Canuto et al. 2018). These broader comparative possibilities demand the unification and extrapolation of theoretical frameworks originally developed for certain places and times. For example, how do ideas of innovation and economic growth developed in the context of manufacturing industrial districts apply to today's industries and their spatial clustering? How may concepts of neighborhood effects, developed in the context of strong racial segregation in US cities, apply to Asian cities? Or how do ideas of regional organization in a system of cities developed in the 19th century for agricultural landscapes still apply given completely different regional economies and transport systems?

Despite these well-known examples it is still common in the literature to see models transplanted from original contexts and applied to more generalized situations without a deeper understanding of why they may or may not apply. A scientific understanding of cities must be able to explain on a much more fundamental level phenomena like the presence and persistence of neighborhoods, agglomeration and scaling effects, and urban hierarchies beyond models tied to specific settings. By now an extensive set of insights into the causes and consequences of humans agglomerating into groups—from Hunter/Gatherer bands into permanent settlements and then into cities—have been accumulated and they provide conceptual and empirical underpinnings upon which to build a *science of cities*. These insights have jointly provided robust foundations for the development of "science of cities" (and urban science has begun to integrate them); what are they?

1. The study of urbanization confronts the seemingly innocuous question of how to define a *city*. Definitions must follow from theory, and specifically via principles of what a city is and how it operates, i.e., they should be *functional* definitions (Bettencourt and Lobo 2016). The functional in "functional city" refers to the various functions which individuals and organizations can perform and fulfill facilitated by agglomeration (Mumford 1937, 1961).

2. Wirth (1938) proposed that a city is a permanent settlement of heterogeneous individuals living and working at high population densities; he famously described "urbanism as a way of life"—a condition of socioeconomic interdependence among specializing individuals. This concept extends from large cities to small towns so long as they are integrated in a common urban system. More recently, Richard Sennett (1977:39) suggested that "a city is a human settlement where strangers are likely to meet." Architectural historian Spiro Kostof (1991: 37) observed that "cities are places where a certain energized crowding of people takes place," and the urban economist Edward Glaeser (2011: p.6) describes cities as "the absence of physical space between people and companies. They are proximity, density, closeness." For Batty and Ferguson (2011: 753) "…cities are dense agglomerations where, historically, people have come together to trade and engage in diverse social relationships. In abstract generalization, they are considered points in space where the friction of distance that restricts our ability to relate to one another is minimized." A textbook, and minimalist, definition (O'Sullivan 2011) defines cities as geographical areas with a concentration of individuals and activities higher relative to the surrounding area. All these characterizations of what a city is illustrate the general notion that the essence of urbanism is not physical space per se, but the frequent and intense social interactions ("mixing") among a diversity of individuals, occupations and organizations embedded in each space

3. The observation that the size of a human spatial agglomeration is both a cause and an effect of technological and cultural development has become widely accepted within anthropology (Feinman 2011). The complex cultural and technological systems that humans develop do not stem simply from individual cognition but from distributed knowledge maintained in social networks, with larger-sized groups maintaining larger accumulations of such knowledge (Henrich 2015). There is a long-standing recognition (in economics, sociology and anthropology) that population size is a determinant of many socio-economic features of human settlements (Carneiro 2000, Johnson and Earle 2000, Nordbeck 1971).

4. The realization that individuals' behaviors and performance are crucially influenced by those with whom they interact is a fundamental sociological insight (Granovetter 1973, Watts 2004). More recently, the realization that economic behavior is explicitly mediated by social interactions has seeped into economics (Easley and Kleinberg 2010, Jackson 2014). Storper and Venables (2004) identify four properties of spatially proximate social interactions that promote increasing benefits for the people and activities involved: cities provide effective communications; they generate trust and incentives in relationships; they help in screening and socializing; and they involve personal stimulation and motivation.

5. The "non-rivalry of knowledge" (i.e., multiple individuals can use the same idea or bit of knowledge simultaneously as the use of this knowledge cannot be controlled by a single individual or entity) encourages the generation of new ideas from the combination of existing knowledge, a process facilitated by larger-sized groups, thereby making scale a determinant of innovation and output (Jones and Romer 2010, Lee 1988, Simon 1986). The crucial role cities have played in the generation of innovations—intellectual and material, cultural and political, institutional and organizational—is well documented (e.g., Bairoch 1988, Hall 1998). The realization that economic growth hinges on the flow and exchange of ideas naturally leads to recognition of the social role of urban centers in furthering intellectual cross-fertilization

(Lucas 1988). There is a strong tendency for inventions to emanate more frequently from larger cities (Bettencourt et al. 2007b).

6. Cities concentrate and generate "creative" occupations (those occupations requiring high levels of training, creative thinking, the manipulation of information and the creation of knowledge—the set of occupations including science, engineering, arts, culture, entertainment and the knowledge-based professions of management, finance, law, healthcare and education (Florida 2002a,b). An important distinction, for understanding urban economic development, is that between educational attainment, i.e., human capital, and occupations, i.e., bundles of skills (Florida et al. 2008)

7. Cities around the world and throughout history vary tremendously in size, form, and economic and political contexts. Nevertheless, there are coarse-grained empirical regularities that are well documented. Urban "universals" include: neighborhood organization (Christaller 1966, Lösch 1954, Mumford 1954, Smith 2010); social inequality (Kohler and Smith 2018, Massey and Denton 1989, Piketty 2014); non-linear agglomeration effects (Marshall 1890); interdependence reflected in a division of knowledge and labor (Smith 1778); regularities in the relative distribution of city sizes and other "laws of geography"—i.e., allometric relationships between areal extent and population size, gravity-Tobler models, Gibrat's Law, and Zipf's Law (Auerbach 1913, Gibrat 1931, Stewart 1947, Zipf 1949).

8. The spatial division of cities into *neighborhoods* or districts may very well be one of the few continuously universal characteristics of urban life, dating from ancient cities up through contemporary urban areas (Kearns and Parkinson 2001, Park 1915, Park et al. 1925, Smith 2010). The neighborhood is the physically embedded social construct through which urban residents experience the defining zeitgeist of their city-living: dense social networks and face-to-face encounters. Much of urban life is structured by and around such neighborhoods, and as a result they have received a lot of attention from urban sociologists (Chaskin 1997, Hoyt 1939, Sampson 2012, Small 2009, Wilson 2012a). Neighborhoods are the setting for social interactions among residents, that are not limited to family members or close friends (Brower 2011, Mellander et al. 2017, Sampson et al. 2002, Suttles 1972). Neighborhood characteristics affect the activities, conditions, and life courses of their residents, and these "neighborhood effects" are crucial for understanding cities. The fundamental nature of neighborhoods is shown by the fact that where neighborhoods are not created by authorities or developers, they inevitably develop through local generative processes (Smith et al. 2015).

9. There is a long history of quantitative models in urban economics, economic geography, and regional science that trace the origin and persistence of population agglomeration to the advantages of concentrating human populations in space after accounting for associated costs (Isard 1956, Fujita et al., 1999). These are sometimes referred to as *agglomeration effects*, and they constitute the foundational concepts for explaining the formation and persistence of cities everywhere (Duranton and Puga 2004, Storper 2013).

10. The prevalent interpretation of urban areas, or functional cities, in contemporary urban studies is thus of a spatial object whose outlines contain daily flows of people, goods and information within one or more adjacent residential centers (Pumain 2000). How much distance can be

covered in a day is strongly dictated by available technologies and infrastructure, as well as the availability of fuels sources and their costs.

11. Cities can be seen as the absence of physical space among individuals, households and businesses—that is, cities are ultimately about proximity facilitating interaction among people. Thus transportation costs, more generally the cost of moving in physical space (influenced largely by technology), is one of the most important determinants of urban form and scale (Glaeser 2011). The pronounced decrease in transportation costs experienced in the 20th century had two major consequences for cities. First, it allowed cities to change their locations once proximity to natural resources or geographically facilitated transport routes became less dominant as locational attractors. Second, lowered transportation costs affected urban form: the internal combustion engine (automobiles and buses) and public transportation systems made possible urban sprawl, eliminated the need for a single city center, and created the suburbs (Glaeser and Kohlhase 2004).

12. Enough work has been done in spatial and urban economics, regional science and economic geography to justify the identification of "five axioms of urban economics" that provide a foundation for economics models of locational choice (O'Sullivan 2011): (a) location-specific costs and benefits balance to generate a locational equilibrium; (b) self-reinforcing effects induce concentration of activities and individuals; (c) externalities are prevalent in the costs and benefits experienced by individuals in cities; (d) production is subject to economies of scale, which in turn engenders specialization and favors agglomeration; and (e) competition generates zero economic profit—meaning that total revenue balances total economic cost, including the opportunity costs of all inputs. While the language of these axioms seems tailored to modern market economies, they can be generalized to represent canonical micro-level foundations equally applying to ancient and pre-modern urban experiences.

13. The development and performance of individual cities are greatly affected by the properties of the hierarchical networks linking individual cities into urban systems. Goods, people and information flow through these networks. Central place theory is one of the earliest analytical frameworks in urban geography that sought to explain the number, size and location of settlements (cities) in a system. Introduced in 1933 by Walter Christaller it was further developed by Edgar Hoover and Allan Pred (Christaller 1966, Hoover 1948, Pred 1977). In central place theory larger settlements provide goods and services to smaller settlements with larger settlements specializing in activities not found in the smaller ones. Recent elaborations of this framework highlight the role of larger cities as sources of invention and innovations which then spread throughout the system.

3. The Study of Cities Needs Theory

There have been articulate calls for the development of an "urban science"—see, for example, Acuto et al. (2018a,b), Alberti (2017), Barthelemy (2017), Batty (2013, 2018), Bettencourt and West (2010), Haila (2008), Kennedy (2011), Kotokosta (2018), PCAST (2016), Pumain (1997, 2018), Ramaswami et al. (2012), Solecki et al. (2013), Vandecasteele et al. (2019), Wilson (2012b). There were earlier appeals to integrate different strands of urban research into a coherent viewpoint—e.g., Berry's argument in favor of using systems theory as unifying general framework for studying cities (Berry 1964)—or to "bring closer together" assumptions and generalizations about urbanization made by different social sciences—for example, the 1965 report *The Study of Urbanization* sponsored by the Committee on Urbanization of the Social Science Research Council (Hauser and Schnore 1965). These various disputations did not sufficiently highlight the role of theory in the development and use of an urban science. Furthermore they have not described what type of disciplinary integration is needed for urban science to be "more than the sum of its disciplinary parts". Why is theory important? And what does it do?

Elinor Ostrom (2009) pointed out that, "without a common framework to organize findings, isolated knowledge does not accumulate"; and echoing Darwin: "Let theory guide your observations" (Ayala 2009:10034). Theory provides falsifiable general explanations of observable phenomena. Whether in sociology, economics, or physics, theory "tells us how to carve a system at the joints," indicating what truly matters (and concomitantly, what matters less or not at all) for understanding the behavior of a particular system (Romer 1996). Theory proposes which processes and properties are central in generating phenomena of interest and which are ancillary. Theoretical frameworks do not seek to explain or address everything noteworthy about a system of phenomenon, nor do they negate the role of contingency. But theory does seek to predict fundamental commonalities, based on observable properties and identified processes.

The particularities of specific episodes of urbanization (such as the one currently underway in Sub-Saharan Africa) will continue to be important—but the particular becomes revelatory when the general is truly understood. Rich historical narratives about individual cities, such as Cronon's (1991) *Nature's Metropolis*, will continue to be indispensable inputs for weaving narratives with broad applicability. As urban science tries to make sense of the deluge of "urban big data", it is particularly important to emphasize the importance of theory. In the words of Geoffrey West (2017:444), the success of big data, "in terms of major discoveries and new ways in which we view the world will depend on the extent to which it is integrated with deeper conceptual thinking and traditional development of theory." And at a time when sophisticated statistical modelling techniques are easily implementable through the use of software packages, we share the warning that better methods can't make up for absent, or mediocre, theory (Smaldino 2019).

Why is a multi/trans-disciplinary, theory-based and empirically rich "science of cities" possible now? The study of cities and urbanization within many distinct disciplines has reached a productive level of methodology, data, and findings. Many methods are shared, such as the use of network models, geographic information systems (GIS), statistics and information theory, population dynamics, dynamical systems, scaling analysis and spatial econometric modeling. In addition, interdisciplinary approaches are now widely appreciated as necessary to integrate and cross-validate hypotheses. Furthermore, the micro-foundations of urban models need not be based on simplistic, non-empirical assumptions about individual-level behavior. Ethnographies, behavioral economics, and anthropology can all help us move beyond postulates or caricatures of how humans behave when they agglomerate, while pointing to essential continuities and commonalities in choices, responses and behaviors. Another impetus for theory building is the growing recognition that various components and scales of urbanism are complex, interconnected, and exceed the explanatory abilities of any single discipline.

What would a theoretically and empirically robust science of cities look like? Advances in other areas of science, especially in biology, have come from a focus on process rather than form. The theory of biological evolution by natural selection is a theory of the process by which "endless forms most beautiful" arise in the biosphere, while Newton's mechanics focuses on how objects move based on just a few generic properties. The explanation of the origins of biodiversity in ecosystems required a theory of evolutionary processes and an understanding of both breeding and natural selection. The advent of public health had to wait for an understanding of contagion processes and vaccines are predicated on the workings of the immune system. Theories of economic growth and human development rely on processes of innovation across scales, whereby learning, changing modes of production and adaptive institutional arrangements create economic value, improve collective efficacy and ultimately support improving livelihoods.

Similarly, a science of cities is not only, or even mainly about, cities per se, but also about the processes which generate and sustain urbanization and urban functions—processes that apply broadly in a range of different contexts. A theoretically grounded science of cities should capture fundamental processes that lie at the core of all human spatial agglomerations, whether these are past or present, agrarian or industrial, in developed economies or developing countries. In the same way that evolution applies to the fossil record as well as living populations, we believe that a good science of cities should apply equally well to settlements known through archaeology and history as to contemporary cities. An empirically robust science of cities should make sense of both cross-sectional variation among cities in a society and across urban systems, and processes of growth and development in specific cities and urban systems over time.

The properties of cities do not generally arise as simple summations of localized human activity. Instead, many of these properties seem to be emergent properties of agglomerated human groups. Thus, a good science of cities needs to focus on identifying and explaining such emergent properties across scales—the ways in which urbanization produces wholes that are greater than the sum of their parts. Urban science should continue building on and integrating methods and concepts that facilitate communication across disciplines, and strive to integrate insights from urban economics, urban sociology, economic geography, urban ecology, anthropology, archaeology and history. Finally, a good science of cities should account for findings in a wide range of fields in an integrated and synthetic way, based on (mathematical) models that specify how the properties at a specific level lead to emergent properties at a higher level of organization.

4. Urban Science Grounded in History

A hallmark of science is the production of generalizable knowledge, which in the case of urban studies necessitates the study of cities and urbanization across time and across locations. A growing body of comparative urban studies highlights fundamental similarities and ephemeral differences (Bairoch 1988, Fletcher 1995, Pumain 2018). It is not hard to see how current urban conditions have grown out of the historical past and specific historical trajectories account for many aspects of individual cities (e.g., Mexico City (Tellman et al. 2018)). The question is whether a theory of general processes by which cities develop in different contexts can be advanced.

We believe that a theory of urbanization is both possible and desirable. As is the case with successful theories across the sciences, urban theory should be expected to predict (post facto and ex ante). Batty (2018) notes that "there has been little effort to figure out an evidence base that discriminates what might be predictable from that which is not." But he adds, "slowly but surely, our knowledge about prediction is growing, and we are beginning to assemble evidence about what kind of routine prediction might be possible." Despite historical contingency and path dependence, the recognition of similar empirical regularities in both contemporary and ancient contexts, exemplified by settlement scaling research, suggests that the fundamental ingredients of these regularities are similar in ancient and modern contexts (Ortman et al. 2014, 2015; Lobo et al. 2019a).

Only through a historical perspective can fundamental processes underlying urbanization be identified while making it possible to discern how technology and culture help shape particular urbanization experiences. Three arguments can be made for the value of knowledge on historical and ancient cities for urban science.

(i) *The urban trajectory argument* focuses on the archaeological and historical records of urban change over centuries and millennia. Economists Rosenthal and Ross (2015) state that "long periods of time are necessary to appreciate that change in a location's economic status is common." Economic historians have shown how the relationship between urbanization and economic growth is shaped largely by institutional forces rather than local, idiosyncratic processes. This conclusion depends on the magnitude of growth rates, which have been very small through history requiring studies of long-term developments over periods of maybe five to ten centuries (Bosker et al. 2008, Jedwab and Vollrach 2015). Such long-term historical data have also revealed the durability of neighborhoods and their characteristics (Behar 2003), and they have the potential to illuminate issues such as the endurance and sustainability of cities over time scales unapproachable by research on cities today. Over shorter time periods, path-dependence is an important channel by which past urban developments influence cities today. In the words of Michael Batty (2001:6350), "Urban settlement structures from much earlier times are persistent to a degree that is extraordinary."

(ii) The *sample size argument* is based on the notion that research on a larger and more varied sample of cities permits scientists to create more reliable generalizations about urban phenomena. Scholars ignorant of the long record of past cities have made numerous faulty generalizations about cities, including the notion that all cities have streets, all cities have markets, all cities exhibit sprawl, and even the notion that important cities must be permanent settlements. Knowledge of past cities is necessary to create a true generalizing science of urban systems.

(iii) The *laboratory argument* notes the value of premodern cities for testing models and hypotheses derived from contemporary urban science in order to distinguish the contingent from the universal in the forms and operations of cities. For example, analyses of Zipfian distributions in the past show that historical (de Ligt 2016) and ancient settlement systems (Drennan and Peterson 2004) exhibit the same approximate size distributions as contemporary urban systems (Eeckhout 2004). Research in settlement scaling has uncovered even more extensive and precise similarities between ancient and contemporary urban systems (Lobo et al. 2019a). This finding not only allows models of contemporary scaling (Bettencourt 2013) to be extended to past urban systems, but it also helps confirm the validity and generalizability of those models (Lobo et al. 2019a). This research counters the common misperception that archaeological and historical data are not useful for the study of economic development because they derive from smaller and simpler societies than those of recent times. We suggest here that, on the contrary, these features are helpful in that they allow one to isolate more readily specific mechanisms of interest and control for confounding factors.

5. Data: More, Better and Newer

As has often been the case in the history of science, the emergence of a new science—in this case urban science—has been animated by the existence of new empirical phenomena: different variables, novel data, and new ways of measuring. The past two decades have seen a veritable explosion in the features and consequences of urban life that can be measured, at the level of individuals, neighborhoods urban areas and urban systems. This "urban big data" phenomenon covers both the social and the ecological, the topological and the economic. The new data on cities today come mainly from three kinds of sources: (i) new methods for analyzing existing data; (ii) new sophisticated methods of generating urban data; and, (iii) data being collected not by the government or commercial operations, but by the grass-roots actions of urbanites themselves.

(i) Researchers are now able to use *existing* datasets in new ways by finding relationships among well understood variables at the urban scale. As an example, the relationship among changes in population, land use and urban morphology can now be examined at a very fine-grained resolution (using data from LandScan (Bhaduri et al., 2007), LandCast (McKee et al. 2015), and the National Land Cover Data (NLCD, https://www.mrlc.gov/national-land-cover-database-nlcd-2016)). We can use LiDAR to convert building resolution (in the order of meters) into urban "terrain" that can be read by weather models to understand the impact of urban form on urban meteorology (Ching et al., 2018), and the impact of urban meteorology on building energy use (New et al. 2018, Carter et al. 2012). We can use demographic data (US Census, https://www.census.gov/), traffic data (national and local sources) and modeling to inform building energy models of the timing of building occupancy and equipment scheduling (Berres et al. 2019). Watershed and stream locations along with streamflow and allocation standards (USGS, https://www.usgs.gov/) can provide estimates for supply, demand and quality of surface and groundwater for energy, irrigation, livestock, industrial and public supply. Human decision making drives the processes that create these data, and new ways of capturing human activity can be found among social media platforms and electronic copies of newspapers and public documents. Census data are now being analyzed using spatially-explicit global population grids (McKee et al. 2015, Doxsey-Whitfield et al. 2015, Freire et al. 2016).

In the realm of earth observation, the proliferation of sensors, the continuation of long-term satellite records, new methods for data fusion between remote and ancillary datasets, and more readily accessible high-performance computing systems have, together, opened up capabilities for advancing the understanding of urban land and infrastructure systems and their changes over time (Zhu et. al. 2019). Earth observation of urban areas enables comparative and typological urban research, moving beyond the case study paradigm that has been so prominent in urban studies (Seto et al. 2017) to allow for cross-scalar analyses, and a better understanding of the planetary impacts of urban life.

(ii) In the second domain, a wide range of new techniques and technologies have advanced the use of remote sensing for urban science. Sensor platforms of very high spatial resolution have become prolific with the addition of commercial satellite data such as WorldView and Digital Globe (all producing imagery at sub-meter resolutions), PlanetScope (at 5m) and the Copernicus constellation from the European Space Agency, which produce freely-accessible data products at 10m resolution. These new datasets are of sufficient spatial resolution to distinguish built elements within urban areas, enabling the characterization of inter-urban heterogeneity and neighborhood scale land structure. "Within-urban" land patterns are linked to many important social and environmental processes that shape sustainability (Stokes and Seto 2019). Satellite data is limited in the information it alone can provide about urban areas—restricted to land cover and change, land and infrastructure configurations, and physical properties such as "imperviousness" or "greenness." However, when combined with other ancillary, spatially explicit datasets (e.g., census data, cell phone records, social media data, or open-access GIS datasets) the range of urban questions to which they can be applied becomes much more expansive.

Remote sensing (in particular the use of night-time lights data) provides spatially explicit data that have become an essential source of information for the measurement of urban structure, expansion, and energy use (Seto and Christensen 2013, Fragkias, Lobo and Seto 2017). Research on spatial pattern detection has enabled intra-urban analyses across scales, where satellite data provide critical intermediate links for building, block, neighborhood, city, region, nation, and global scale. Key contributions of urban remote sensing include but are not limited to characterization of urban areas, urban land cover changes, and thermal remote sensing of urban climates. The proliferation of new sensors, the availability of satellite data records, joint analysis of Earth observation data with ancillary data sets, widespread availability of high-performance computing facilities, and the increasing use of remote sensing data and methods in urban studies offer new opportunities to generate integrated understanding of an urbanizing planet (Zhu et al. 2019).

In addition to high resolution spatial data, our understanding of urban change has been improved by time-series data over longer periods and at shorter intervals. Multi-decadal archives of nighttime lights (Zhang and Seto 2013), MODIS land cover data (Seto et. al.2011), and even radar data for sensing urban verticality (Frolking et. al. 2016) have produced observations that demand new theories to describe the differences in both the rate and mode of urban development over time. Meanwhile, higher temporal frequency observations have enabled near real-time monitoring of urban change, which has proven particularly useful for disaster responders who are mapping the impacts of hurricanes and storms in urban areas (Roman et. al. 2019) as well as researchers trying to understand the spatiotemporal dynamics of urban thermal environments (Quan et al. 2018) to minimize heat island effects.

All of these methods confront a series of key questions: What is the spatial expression or definition of a city (or metropolitan area)? Specifically, how can we delineate the physical boundaries of a space of social interactions? (Arcaute et al. 2016, Louail et al. 2014; Lobo et al.2019). Where do cities' areas of influence (social, economic, ecological) begin and end? (Luck et al. 2011, Seto et al. 2012) Practitioners of urban science must be aware of the non-trivial choices made when spatially identifying cities.

(iii) The third source of new urban data is urban residents and communities themselves. Technologically and organizationally, urban communities are now able to collect copious and varied data about themselves. Thanks to the democratization of mapping tools (e.g., Google maps, Open Streets Project, UN Global Pulse, ESRI) the documentation of urban phenomena, and its analysis in rich and verifiable ways, is now much easier than even just a few years ago. The ability to collect, curate, analyze and map community data makes it possible to document and tell powerful stories about communities' needs and aspirations, stories that can guide policymaking at local, city, national, and international levels (SDI 2018, Cities Alliance 2019).

Nevertheless, the vast amounts of data now collected by organized community groups and social movements remain just that: data. For example, federations within Slum/Shack Dwellers International (SDI) —a global network of slum dwellers organizations from Africa, Asia and Latin America (http://knowyourcity.info/) —have increasingly expressed that they are data rich, yet analysis poor. In SDI, the goal of these data collection practices has been heavily focused on advocacy and recognition for slum dwellers and their development needs within cities (Patel and Baptiste 2012). An often underappreciated goal of the "Know Your City" data project was to demonstrate the value added and the contribution of the data itself as usable for scientists to advance urban knowledge (Brelsford et al. 2017). There are no more technological and organizational excuses for urban planning not to be informed strongly by the actual needs of and insights from the communities it intends to serve. The data produced within the Know Your City project benefitted from close collaboration and exchange between slum communities and scientists and laid the foundation of how such relationships can develop toward mutual advantage. The value of co-producing knowledge with communities outside the traditional scientific community is an imperative that urban science acknowledges and seeks to systematize (Lobo et al. 2019b).

There is another, and distinct, source of new urban data that shares some of the techniques reviewed above but remains largely unavailable for scientists and citizens to analyze. This is the proprietary commercial data gathered by large tech giants such as Google or Tencent, suppliers of geodata such as ESRI, and lesser known dedicated surveillance data companies. These data are driving the "big urban data" revolution—which is not only about the sheer quantity of data but also about the individual-level behaviors captured by such data—and supporting scientific publications. But the myriad practical and ethical issues of turning urban data into a commodity, the impediments that proprietary data present to reproducibility, the potential selection bias introduced when research is channeled by the availability of data collected for profit and the use of geospatial data for control and even repression should give urban scientists pause and must be seriously considered.

6. Urban Science: What Have We Learned?

Based upon insights accumulated by well-established research traditions in economic geography, urban sociology, urban economics regional science, transportation engineering and anthropology, a set of "first principles" about human social behavior manifested in physical space can be identified (Bettencourt 2013, Lobo et al. 2019a). These are: (i) human interactions are exchanges of material goods and information that take place through social and infrastructural networks embedded in physical space; (ii) the intensity, productivity and quality of individual-level efforts are mediated and enhanced through interaction with others; (iii) any human activity can be thought of as generating benefits and incurring costs (especially the costs of moving people and things over physical space); (iv) human effort is bounded; and, (v) the size (scale) of a human agglomeration is both a consequence and a determinant of the agglomeration's productivity. These principles provide the cornerstones for building a general theory of urbanization.

Urban science has been a scientific enterprise for almost two decades. What insights has urban science generated which cannot be comfortably assigned to any of the extant disciplines that study cities? What conceptual and analytical perspectives has urban science injected into the study of cities and urbanization?

1. Scaling is a general analytical framework used by many disciplines—from physics to biology and the social sciences—to characterize how population–averaged properties of a collective vary with its size (West 2017). The observation of scale invariance over some range identifies general system types, be they ideal gases, ecosystems, or cities (Brock 1999, Stanley and Perou 2001, Barenblatt 2003, Chave and Levin 2003). The use of scaling in the analysis of cities (*urban scaling*) quantifies many of their arguably fundamental general characteristics, especially their capacity to create interrelated economies of scale in infrastructure and increasing returns to scale in socioeconomic activities (Bettencourt et al. 2007, Bettencourt 2013, Bettencourt et al 2019a).

2. Despite the long-standing metaphor of the "city as an organism," in many important respects cities are very different from biological entities, namely in their capacity to exhibit "increasing returns to scale"—when output increases by more than the proportional change in inputs (Bettencourt et al. 2007).

3. Urban systems are not like engineered systems—a point made by Lynch (1951) and Jacobs (1961)—but are rather "adaptive complex systems" where distributed growth and interaction between cities generate emergent properties affecting the development of individual cities in a feedback loop.

4. Despite the continuous diffusion of innovation waves from one city to others, cities unevenly adapt their structure to innovation waves; some cities lose their leadership in sectors, and others take advantage of the emergence of new innovative activities (Pumain et al. 2009).

5. There are empirical patterns—regarding the relationships among population size, areal extent, productivity and spatial form—that are common to cities and urban systems across time (Angel 2012, Angel et al. 2012, Batty and Longley 1994, Bettencourt et al. 2007a, Fluschnik et al. 2016, Frankhauser 1998).

6. Many urban phenomena are *network* phenomena. For many urban scientists the essential feature of urban areas are interactions—among individuals, households, businesses, economic sectors, and cities. The mathematics of network models has emerged as a ready-made language with which to describe and examine urban interactions across scale (Haggett et al. 1977, Neal 2013, Barthelemy 2017). To understand cities we must view them not simply as places in space but as interactions and flows (of people, goods, and information); to understand flows, we must understand networks—the relations between objects that compose the system of the city (Batty

2013, Bettencourt 2014, West 2017). The topology of these networks both constrains and facilitates urban dynamics. The coupling of different urban systems and their interactions can be represented through multilayer networks (Bianconi 2018, Boccaletti et al. 2014, Kivelä et al. 2014).

7. Delineating cities (or urban areas or metropolitan areas) is not a theory-free exercise: What one chooses to bound within specified physical boundaries needs to correspond to a theorized type of settlements (Arcaute et al. 2015, Strumsky et al. 2019).

8. As the world rapidly urbanizes, human settlements constitute one of the few ecosystems that are significantly increasing in their extent. Urbanist have come to realize that the functioning of cities has many effects on larger regions, global resources, and human well-being. Recent water shortages in Cape Town (South Africa) or in large Indian cities, resulting from lengthening dry seasons and decreasing amounts of rainfall, are attention-grabbing reminders of urban areas' dependence on basic natural resources (Cassim 2018, Nagaraj 2018). Urban ecosystems are fundamentally different from their natural counterparts in the dominant influence of human actions, both intentional and unintentional, on ecosystem functions (Pataki 2015). Urban ecology seeks to understand how urban settings shape the socioecological interactions within ecological systems, and their role as both drivers and responders to environmental change. Cities are not only driving changes in fundamental ecological processes; emerging evidence shows that cities are driving rapid evolutionary change with significant implications for human wellbeing on a contemporary scale (Alberti et al. 2017).

9. *Urban Land Teleconnections*. The impacts of cities on remote areas ("hinterlands') have seldom been considered in urban sustainability assessments, because urban areas are bounded and predefined for the purpose of spatial planning. But urbanization and land change are two global processes with far-reaching spatial consequences—*urban land teleconnections* is a conceptual framework that explicitly links land use and environmental changes to underlying urbanization dynamics. It links places and regions that although far removed geographically are connected through the various environmental consequences of urban expansion (Seto et al. 2012). Urbanization is driven by local processes with global consequences.

7. New Research for Advancing Urban Science

A "science of cities" should not shy away from generating predictions that specify the relative likelihood of a range of outcomes given actions that affect the overall population, built environment, or social fabric. We know that useful predictions can be made in the form of averages across an urban system, but it is not year clear whether prediction is possible at the level of individual cities. The effort should focus on determining what can be predicted, with what degree of precision, and under what conditions, and iterate this process of scientific development and refinement as much as possible.

Urban science is not merely an exercise in rephrasing what is known in the language of the social sciences, nor is it an attempt at making crude analogies, or vaporous metaphors, between social and natural systems. Existing answers may be revisited considering new theoretical constructs and empirical observations but most crucially a science of cities needs to show its scientific mettle by generating, and answering, new questions. New research paths, lines of inquiry and questions that the next generation of urban science can and should take on include the following (and note that many of these questions cross disciplinary boundaries).

1. Why has urbanization been such a seemingly inexorable process in history? Is urbanization reversible?

2. What are the mechanisms connecting urbanization and socioeconomic development throughout history? Why are some episodes of rapid urbanization (such as those taking place in Africa and Latin America) not associated with significant economic development?

3. How do neighborhood-level properties interact and aggregate to generate city-wide dynamics? What are the roles of neighborhoods and communities inside cities in urban development?

4. The inability to improve living conditions in cities for so many urban dwellers makes it imperative for us to reexamine the basic assumptions underlying urban development policy and practice. In particular, the role of informal settlements and poor neighborhoods ("slums") in urban development needs to be revisited and with the participation of slum dwellers. What determines whether slums provide a path to prosperity or become poverty traps?

5. Will the "megacities" now emerging be fundamentally different than cities heretofore? Can Phil Anderson's (1972) famous phrase, "more is different", be rephrased as "larger becomes different"?

6. What would sustainable urbanization look like? How does sustainable urbanization manifest itself at the level of individual cities and at the level of urban systems? In what ways will it be significantly different—with regards to how energy, resources and information flow into and out of cities—from previous urbanization episodes?

7. How will climate change affect urban environments? How can cities "decarbonize," thereby contributing to climate change mitigation, while still acting as engines of socioeconomic development?

8. Why has urban poverty and racial/ethnic segregation proven so difficult to overcome?

9. How can the experiences of individuals revealed through ethnography and that of communities and neighborhoods illuminated by sociology be linked to quantitative "big-data" research?

10. How do the properties of urban networks affect the functioning of cities? And how do urban networks and their constituent cities co-evolve?

11. What has been the nature of the boundary between "urban" and "rural"? How permeable will this boundary become?

12. Is wealth inequality an inevitable consequence of the concentration of people, resources, and ideas in urban settings? How variable has wealth inequality been throughout episodes of

urbanization? How anomalous or inevitable is the current experience of rising inequality in cities worldwide? Is increasing urban wealth inequality a phenomenon resulting from fundamental feature of agglomeration, and thus unlikely to be affected by policy interventions, or is it the result of specific policies, choices and incentives which together make urbanization a driver of socioeconomic disparities? (This issue is now sufficiently pressing, politically and policy-wise, that it was the theme of the Federal reserve Bank of Boston's 63rd Economic Policy Conference (www.bostonfed.org/housedivided2019/)).

13. How do the processes underlying urbanization relate to educational attainment, occupational choice, and other factors (at the level of the individual, the household and society at large) that have been linked to income inequality?

14. Will the benefits of aggregation be increased or reduced by processes such as "digitalization," the continued decrease in transport costs, "virtual reality," and AI? Can the benefits of scale be realizable in medium-sized and small settlements? Can these new technologies change the fundamental nature of cities?

15. How will digitalization and AI affect urban mobility (and consequently, urban form)?

16. What is the nature of the boundary between the social sphere and ecology in cities? How can an understanding of the way cities interact with, and draw from, the natural environment, affect the practice of urban management and planning?

17. Climate and environment were important determinants of urban development prior to the Industrial Revolution (see, e.g., Redman (1999) and Harper (2017)). Climate is likely to again play an important role in the development of cities as climate change and urban development are expected to warm some cities (Cao 2018, Hondula et al. 2019, Krayenhoff et al. 2018). How will cities affect localized climate? Can infrastructure-based adaptation offset projected night-time warming in urban environments? How do urban climates affect socioeconomic performance?

18. What are the processes through which material outcomes in cities are achieved? There is at present little understanding of how aspects of urban politics, planning/decision making processes, policy, and other factors interact to allow some options being prioritized and others downplayed or ignored. Increased data availability and more sophisticated analytical tools could make it possible to become increasingly scientific and predictive about the social, political, and policy dynamics that lead to certain urban outcomes.

19. In recent years, it has become popular in fields such as economics to undertake field experiments that break up major grand challenges into smaller problems that can be tested empirically through controlled experimentation (indeed the 2019 economics Nobel prize was awarded to scholars at the forefront of applying experimental models to development economics). Urban sustainability and the science of cities are fields where rigorous experimentation could be significant in testing key theories and hypotheses.

20. How can urban science become truly global in scope? For too long studies of cites and urbanization have drawn mainly on the experiences of Western Europe and North America. The historical experiences of urbanization in Africa, Asia and the Western hemisphere before the arrival of the Europeans need to inform the identification of the *fundamentals* of urbanization.

21. How is urban science informed by, and how does it inform, our understanding of complex adaptive systems more generally? Cities are arguably not organisms, nor machines, nor ecosystems, nor brains. So, echoing Jane Jacob's question of what type of a problem do cities represent, urban scientists must ask what type of complex system are cities?

22. Can advances in AI help the transition to more sustainable cities? Advances in AI allow us to identify patterns before we can explain their origins. The expectation is that AI and "big data" will make it possible to detect generic behavior prior to the construction of theory. Will AI help us to advance knowledge faster by identifying the drivers of urban systems to better understand how cities (urban systems, specific urban forms) can help ameliorate the effects of climate change and improve the resilience of cities?

23. The importance of urban environments in producing consistent novel cognitive challenges and behavioral adaptations is an important part of research in social psychology (Milgram 1970); there is evidence suggesting that specific ways of living in cities and specific urban forms affect human psychological and physical well-being (Montgomery 2013). How can insights from social psychology and social anthropology be integrated into urban science so as to inform the design of livable and productive cities?

8. Understanding the Urban in Urban Sustainability

In a 2018 report, the National Science Foundation (NSF) calls for the development of a new "sustainable urban systems science" to address "fundamental research questions that need to be answered so that the transformative social and technological changes forecasted in urban areas may be harnessed to benefit society at all scales—local, national, and global." (NSF 2018) Equally compelling, appeals for the development of urban sustainability science had been made previously (Grimm et al. 2008, Pataki 2015, McDonnell and MacGregor-Fors 2016, National Academies 2016).

If urban science aims at a fundamental understanding of the processes that shape and sustain cities, the ultimate applied objective of this body of knowledge must be to help create global urban sustainable systems. "Urban sustainability" at the moment remains more a collection of methods (for example, "urban metabolism"—an accounting exercise of inflows and outflows) and aspirations than a science (Waldrop 2019). The ecological, energetic, physical, biological and social aspects of cities need to be integrated into a consistent theory, but one that grounds the treatment of cities as social systems embedded in physical and biological networks (Grimm et al. 2008). The perspectives that cities are "social-ecological-infrastructural systems" (Ramaswami et al. 2012), or "social-ecological-technological systems" (Grimm et al. 2017) conceive cities as social systems embedded in engineered and natural infrastructures. These perspectives have provided a rich conceptual vocabulary with which to describe how ecological and physical factors constrain and facilitate cities, but the essential nature of cities as physical spaces of social interactions is often lost in these narratives.

Considerations of urban ecology can nevertheless inform the construction of general theories about cities and urbanization and in so doing point out how the dependence of cities on natural environments can be quantified and compared (McPhearson et al. 2016). The general viewpoint of urban ecology does not yet generate formal (i.e., mathematical) models which truly integrate, at the level of equations describing dynamics, the social with the ecological. A more developed and theoretically grounded urban science could help elucidate the factors that sustainable urban systems share with current ones. This, in turn, can suggest how the ongoing processes of urbanization need to be managed differently if cities and urbanization are to contribute to improving global sustainability.

Sustainable cities must be livable cities, and livability needs to be understood broadly (McDonnell and MacGregor-Fors 2016). The "Sustainable Development Goals" of the United Nations are suffused with considerations of equity, well-being, peace and justice (United Nations 2019). As the NSF's 2018 report recognizes, urban sustainability is not only about making cities less taxing on the natural environment but also about making them places where citizens can fulfill their aspirations. Insights gained from urban science can be linked with the practice of planning and urban decision-making, in order to wrestle with the empirical fact of growing inequalities within urban environments (Florida 2017). The benefits of urbanization seem to be accruing mostly to a few cities within urban systems with the "rich getting richer" and small- and medium-sized urban areas getting left behind (Atkinson et al 2019). Our understanding of how cities function as engines of development, of the drivers of urbanization, and of the social, economic and physical factors that shape urban areas all need to improve (analytically and empirically) for effective policymaking to occur. In short, more and better science is needed for urbanization to become a vehicle for achieving *shared* prosperity (Glaeser and Joshi-Ghani 2013).

Urban life can be expected to change considerably as various streams of technological change converge to affect urban mobility. In the "information age," which will soon become the "age of AI," and for the first time since the first affordable automobile of 1908, the mobility landscape may fundamentally alter with significant implications for energy use by urban dwellers. Digitalization and AI have the potential to foster three revolutions in urban transport: ride sharing, electrification, and automatization. Together these three developments can transform mobility via shared electric and automated vehicles that facilitate accessibility and reduce congestion (Sperling 2018). But the environmental implications of the possible mobility revolution are not obvious. Autonomous mobility might lead to an increase in private transportation, to the detriment of public transportation. And if autonomous and electric vehicles simply replace oil-fueled private automobiles, urban sprawl and peri-urban expansion might even accelerate. Can urban science, and its insights on how agglomerated humans solve problems, inform the design of public policies to steer digitalization towards fostering sustainability in urban transport? (Creutzig et al. 2019)

A recent IPCC report highlights the significant and alarming consequences that climate change is expected to have on urban areas (IPCC 2018). The manner in which cities will adapt to climate change and respond to "extreme weather effects" is rife with equity concerns. (Cities Alliance 2019, Solecki et al. 2019). A range of critical issues have been identified specific to how cities will need to respond to climate change in cities (Bai et al. 2018). Of particular concern are the effects of climate change on urban areas in the developing world; they have experienced, and are continuing to experience, rapid growth in population and built environments. Much of this population growth contributes to the expansion of informal settlements ("slums"). Managing the consequences of climate change, and supporting the far-reaching transformations necessary to significantly improve cities' resilience, will require changes in urban governance and institutions (Dodman 2019, Williams 2019); these changes need to be informed by community involvement and a scientific understanding of how cities interact with the natural environment.

9. Urban Science 2.0: What is Needed to Advance

Most humans now live in cities and literally billions of more people will, in the next few decades, become urban dwellers. We are building huge new cities and expand existing ones, with urbanization thus becoming one of the main drivers components of the "Anthropocene" (Rockström et al. 2009, Waters 2016). Creating better cities (more sustainable, more equitable, more democratic, more productive) would immensely help to address many of the grand challenges we face from poverty to climate change. But this will only happen if we get city-building and city-management right. We now have the opportunity to construct—building upon prior work—a scientific enterprise up to the challenge of reliably informing urban clinical practice and policy-making.

Just as the science of biological evolution includes a variety of kinds of data and approaches—observational, experimental, and historical data, at scales from DNA to ecosystems—a science of cities should also encompass varied kinds of data and methodological approaches. It should integrate diverse data types, social contexts, and scales of analysis under a limited number of theories or models. It should be historical, recognizing path dependencies and temporal continuities, while also identifying generalizable facts about cities. What is needed to further the advance of "urban science"?

1. A deeper dialogue among researchers who study urban systems across different eras, scales and disciplines, aimed at synthesis of commonalities and recognition of contextual factors.

2. New collaborations among urban scientists, ecosystem scientists, climate scientists and evolutionary biologists to better understand how cities (as social and ecological settings) can adapt to climate change.

3. More and better comparative data collection, referring to the same type of spatial units, same observables and same proxy indicators. The consistent and comparable measurement of urbanization and urban activity should be a top priority for statistical offices and census bureaus throughout the world.

4. Deeper commitment to open science, especially regarding the sharing of urban data (a counterweight to the increasing commoditization of urban data).

5. Conceptual frameworks that connect properties of individual cities to properties of the urban and national systems they are a part of. Theories must specifically describe city-level processes, focusing on their mutual impacts and synchronizations.

6. More attention paid to statistical characterization of urban data and explicit efforts to agree on what the empirical patterns are. For example, the recent literature has been marked by debate over the extent to which urban data are power law distributed, and the relationship between urban metrics and the spatial units over which they are measured.

7. Identify the most relevant ingredients and processes for constructing a theory of cities: what are the necessary (or minimal set) of processes required to build models (or simulations) of a city?

8. Identify common underlying parameters and processes, defined formally to by-pass discipline-specific jargon. By doing so, a multidisciplinary science can produce comprehensive knowledge to support governments' policies that aim to make future cities more livable for all (not only the well-to-do); decrease their environmental footprint, their social inequalities and segregation; and improve their economic resilience and the well-being for all citizens and inhabitants of cities and their surrounding areas.

The research paths outlined above can only be advanced if a multidisciplinary effort is put in place. A science for cities, and more generally of urban systems, aims at bridging the different disciplines towards creation of a coherent understanding of urbanization. The multidisciplinary and transdisciplinary nature of urban science is the source of its intellectual strength and novelty but also the source of difficulties finding institutional and funding support for teaching and research activities. Urban science is being done by researchers typically housed in academic units organized around the standard disciplines. Although there are a few high-visibility and explicitly multidisciplinary academic initiatives around urban science (the Mansueto Institute for Urban Innovation at the University of Chicago, the Center for Urban Science and Progress at New York University, the Urban Dynamics Institute at Oak Ridge National laboratory, the School of Cities at the University of Toronto and the Bartlett Centre for Advanced Spatial Analysis at University College London prominent among them) urban science is a distributed enterprise which makes it challenging (and frustrating) to obtain funding support from Foundations and institutions geared to support disciplinary-based research on cities and urbanization.

With regards to teaching in urban science and training of future "urban scientists," there are similar and additional challenges. It is difficult to obtain sources of funding for graduate students interested in pursuing careers in "urban science." With the exception of a few Masters' programs (e.g., Master of Urban Innovation at the University of Toronto, Master in Applied Urban Science and Informatics at New York University, the urban tech program at the Jacobs Technion-Cornell Institute at Cornell Tech, Master in Governing the Large Metropolis at the Urban School of the Paris Institute of Political Studies, Masters of Science in Smart Cities and Urban Analytics from the Bartlett Centre for Advanced Spatial Analysis at UCL) doctoral-level training in urban science must be cobbled together from course offerings at discipline-specific academic units. As urban science continues to develop, the need to train future generations of urban scientists in a transdisciplinary field will become more pressing (Lobo et al. 2019b).

We understand the argument that urban science research must not be constrained by practical considerations; however, it will also be of no use if not guided by (big) problems in the field. Even more challenging (or problematic?) for urban scientists is the injection of advocacy in the urban science narrative: questions as to the distributive effects of urban development strategies, and the role of democracy and community control in local public institutions. The right to education, to leisure, and to affordable housing should be essential performance indicators of cities (Chakrabarti 2014). Decisions on how to plan and manage cities are key to making cities drivers of shared prosperity (Bertaud 2002). The long-standing refrain from scientists is that their work must not be clouded by normative statements, but in the case of cities and urbanization, urban science should animate our moral imaginations as to how productive, wealth-creating, poverty-reducing, decarbonized, resilient, and sustainable cities can also be *just* social settings (Fainstein 2010). The scientific goals animating urban science should not completely overshadow the possibilities for "translational research" (borrowing from the medical sciences, an effort to build on basic scientific research to design new policies, create new diagnostics, and identify feasible interventions helping to make cities work for everyone). Understanding and intelligently managing cities requires the interfacing of the social, biological (ecology and evolution), physical, computational (data) and engineering sciences. How can we establish a two-way dialogue between praxis and urban science without compromising the autonomy of either?

Cities, and the problems and opportunities they represent, are emblematic of a complex system. Just as no one should own cities or the data generated by urban dwellers, no one discipline should have prior claim on understanding cities. Breaking down academic silos, overcoming organizational inertia, coordinating systematic and comparative data collection efforts, facilitating research efforts across institutions, disciplines and national boundaries, supporting research which is avowedly novel (and thus risky), building and maintaining research support infrastructures, periodically and frequently bringing different stakeholders to exchange perspectives, findings, and insights, openly confront disagreements and forge common paths—the magnitude and the urgency of the efforts (and funding) required to do all of this, and more, should not be underestimated. We deliberately avoid making specific funding or programmatic recommendations (City Shoot? International Urbanization Observatory? Urban Genome Project?). But the daringness of urban science and the urgency of the moment need be matched with leadership on the part of science and R&D agencies, academia, international financial institutions and NGOs to *promote* and *support* engagements which facilitate the transdisciplinary and translational promise of urban science.

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