A mathematical framework for understanding cities: Part social reactor, part network

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Members of the Santa Fe Institute Cities and Urbanization Team include (from left) Hyejin Youn, Luis Bettencourt, and Marcus Hamilton. Credit: Santa Fe Institute photo by InSightFoto

Cities have long been likened to organisms, ant colonies, and river networks. But these and other analogies fail to capture the essence of how cities really function.

New research by Santa Fe Institute Professor Luis Bettencourt suggests a city is something new in nature – a sort of social reactor that is part star and part network, he says.

"It's an entirely new kind of complex system that we humans have created," he says. "We have intuitively invented the best way to create vast social networks embedded in space and time, and keep them growing and evolving without having to stop. When that is possible, a social species can sustain ways of being incredibly inventive and productive."

In a paper published this week in *Science*, Bettencourt derives a series of mathematical formulas that describe how cities' properties vary in relation to their population size, and then posits a novel unified, quantitative framework for understanding how cities function and grow.

His resulting theoretical framework predicts very closely dozens of statistical relationships observed in thousands of real cities around the world for which reliable data are available.

"As more people lead urban lives and the number and size of cities expand everywhere, understanding more quantitatively how cities function is increasingly important," Bettencourt says. "Only with a much better understanding of what cities are will we be able to seize the opportunities that cities create and try to avoid some of the immense problems they present. This framework is a step toward a better grasp of the functioning of cities everywhere."

What has made this new view of cities possible is the growing opportunities in recent years to collect and share data on many aspects of urban life. With so much new data, says Bettencourt, it's easier than ever to study the basic properties of cities in terms of general statistical patterns of such variables as land use, urban infrastructure, and rates of socioeconomic activity.

For more than a decade, Bettencourt and members of SFI's Cities & Urbanization research team have used this data to painstakingly lay the foundation for a quantitative theory of cities. Its bricks and mortar are the statistical "scaling" relationships that seem to predict, based on a city's size, the average numerical characteristics of a city, from the number of patents it produces to the total length of its roads or the number of social interactions its inhabitants enjoy.

Those relationships and the related equations, models, network analyses, and methods provide the basis for Bettencourt's theoretical framework.

So what is a city? Bettencourt thinks the only metaphor that comes close to capturing a city's function is from stellar physics: "A city is first and foremost a social reactor," Bettencourt explains. "It works like a star, attracting people and accelerating social interaction and social outputs in a way that is analogous to how stars compress matter and burn brighter and faster the bigger they are."

This, too, is an analogy though, because the math of cities is very different from that of stars, he says.

Cities are also massive social networks, made not so much of people but more precisely of their contacts and interactions. These social interactions happen, in turn, inside other networks – social, spatial, and infrastructural – which together allow people, things, and information to meet across urban space.

Ultimately, cities achieve something very special as they grow. They balance the creation of larger and denser social webs that encourage people to learn, specialize, and depend on each other in new and deeper ways, with an increase in the extent and quality of infrastructure.

Remarkably they do this in such a way that the level of effort each person must make to interact within these growing networks does not need to grow.

How these networks fit together, and the tensions and tradeoffs among them, often determines how productive or prosperous a city is, or whether it fissions into smaller 'burbs, or if people want to live in them or don't, Bettencourt says.

His framework has practical implications for planners and policy makers, he says. To keep these social reactors working optimally, planners need to think in terms of urban policies that create positive social interactions at low costs in terms of mobility and energy use, for example. The paper shows how obstacles to socialization, such as crime or segregation, and enablers that promote the ability of people to connect, such as transportation and electricity, all become part of the same equation.

It even names a couple of U.S. cities that appear to suboptimal in terms of their social interactivity. Brownsville, Texas, and Riverside, Calif., for example, might benefit from policies to improve citywide connectivity. Bridgeport, Conn., which includes Connecticut's "Gold Coast," could be a victim of its own socioeconomic success, as high mobility costs suggest more compact urban living or more efficient transportation might be in order.

The framework is a first theoretical step, Bettencourt says, and much more needs to be done. In the coming years, more and better data from cities in developing nations will become available, which will provide new opportunities to test the theory in places where understanding urbanization is most critical.

"Rapid urbanization is the fastest, most intense social phenomenon that ever happened to humankind, perhaps to biology on Earth," says Bettencourt. "I think we can now start to understand in new and better ways why this is happening everywhere and ultimately what it means for our species and for our planet."

More information: "The Origins of Scaling in Cities," by L.M.A. Bettencourt at Santa Fe Institute in Santa Fe, NM. *Science*, 2013.

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