SFI TRANSMISSION

COMPLEXITY SCIENCE FOR COVID-19

STRATEGIC INSIGHT: Policies for responding to pandemics should be rooted in a scientific understanding of cities.

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It is hardly surprising that the vast majority of COVID-19 cases have occurred in cities; after all, more than 80 percent of the world's population lives in urban environments, and these are significantly denser than either suburban or rural communities. Consequently, understanding the detailed transmission, spread, and mitigation of the disease — and developing realistic pathways to long-term sustainable biological, social, and economic recovery — is intimately tied to developing a deeper understanding of the principles underlying the structure and dynamics of cities. This is critical at both a coarse-grained global scale as well as at a more fine-grained local level. Indeed, a much-needed conceptual perspective is one in which we view this as a quintessential complex adaptive system, where all components are inevitably interrelated, resulting in a plethora of "unintended consequences."

We should not be totally surprised that an accidental mutation of a virus in a city in China, when left unchecked, would potentially lead to huge unemployment in the U.S., the fall of global markets, no football games in Spain, less pollution in India, and a shortage of yeast in the U.K.: the ultimate "butterfly effect," where the subsequent time development is exponentially sensitive to the initial conditions, making detailed predictions extremely challenging. We are seeing that many dimensions of society are severely less robust than we might have thought. The spread of COVID-19 is a complex chaotic phenomenon in more ways than one!

The big question is, of course: to what extent, if any, can any of this be quantitatively predictable? It certainly involves considerably more than "just" traditional epidemiology, vaccinology, and health care. In the near term, these obviously play a dominant role, but as we move forward into the recovery phase, and more importantly, into developing a long-term sustainable phase, this needs to be holistically integrated with socioeconomic dynamics — such as finance, inequality, neighborhood structure, and so on — coupled to the physical infrastructural organization of buildings, transport, etc. In a word, we need to develop and integrate our thinking about epidemics and similar "predictable" threats — such as earthquakes, tsunamis and conflicts — across multiple time and spatial scales, with a quantitative "Science of Cities." It is a daunting challenge.

Despite this, some baby steps have been made. Urban scaling, the theoretical framework quantifying how urban metrics change with size, reveals that cities are highly nonlinear yet share surprisingly "universal" commonalities.[1] For example, socioeconomic quantities (Y) like wages, patents, and wealth scale superlinearly with population size (N) following a classic simple power law whose exponent is ~ 1.15: i.e., as $N^{1.15}$. In English, this means that their percentage increase is 15 percent larger than that of the population: i.e., $dY/Y = 1.15\ dN/N$. Consequently, the bigger the city, the more wealth, innovation, and social connectivity there is *per capita* — a major reason why cities are so attractive. This has its origins in the mathematics and dynamics of social networks. Cities are machines we evolved to facilitate, accelerate, amplify, and densify social interactions. The larger the city, the more the average individual interacts with other people in a multiplicative positive feedback process; by engaging in social discourse, exchanging ideas and information, making financial transactions, and, unfortunately, transmitting viruses![2]

Consequently, all of the benefits and attractions of larger cities that result from increased social connectivity have a dark side: more crime, greater inequality, more pollution, and more disease, all following superlinear scaling laws.[3] Not only are there systematically more cases but, equally importantly, their growth rate, like all socioeconomic urban phenomena, increases systematically faster. If the number of cases increases exponentially with time (t) as e^{rt}, then the rate parameter (r) is predicted to systematically increase with city size as ~ $N^{0.15}$. Consequently, a city of a million people will double the number of cases in approximately half the time a city of 10,000 (one hundredth of its size) will, since r changes by a factor $(100)^{0.15} \sim 1.99$.

Such superlinear scaling predictions have been confirmed with data from past AIDS epidemics,[1,4] so it is not surprising that the growth rate of COVID-19 has likewise followed similar laws, at least in its initial phase before intervention, as recently shown.[5] The underlying theory potentially provides a quantitative framework for mitigating the spread of the disease by appropriately pruning the social network (i.e., by decreasing connectivity, or "social distancing"). But, importantly, the city's social network is coupled with the physical constraints of infrastructural networks like transport and commerce. This necessary component is typically missing from epidemiological models, which are therefore blind to the strong dependence of social distancing on a city's size. Consequently, they are unable to incorporate or predict the inherently greater risk in larger cities, a fact which needs to be taken into account when formulating policy decisions.

There are a plethora of other problems and risks associated with the pandemic that are being hotly debated, many related to the economy, poverty, and quality of life, and therefore, by implication, to the role of cities. How does an individual's risk of infection change based on the city, or the particular neighborhood, they live in? Can urban scaling theory help formulate optimal strategies for aiding cities of different sizes? What can we learn from urban scaling theory that might inform us about trajectories of recovery and what cities and urban life might look like post-pandemic? To what extent can humans live by the internet alone? Or is physical three-dimensional social connectivity, the very essence of urban life, like sleep: without it you die, regardless of how much nutrition, entertainment, or money you have? The short, but incomplete, answer to these questions is that cities are not monochromatic, and comprehensive policies for preparing responses to, and recovery from, a variety of crises should begin by at least taking into account the overall size and underlying network structures of cities.

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