Urban scaling laws arise from within-city inequalities

Keywords: urban scaling, heavy tails, social networks, urban inequality, science of cities

Extended Abstract

In recent years, researchers from across disciplines have identified striking and seemingly universal relationships between city size and various urban quantities (*1–4*). Cities' total outputs increase more than proportionately with increases in city size, suggesting that inhabitants of larger cities are, on average, better off economically. To explain such a superlinear scaling effect, reference has been made to increasing levels of social interconnectivity (*3,4*) and economic complexity (*5,6*) in dense urban environments. Simple formalizations of cities as interconnected networks have provided predictions that map remarkably very well onto empirical observations derived from city-level data (*3,4,7*).

Painting a picture in which scaling effects are driven by a homogeneous shift of the whole city distribution as the population grows larger, however, the established explanations have overlooked the stark inequalities that exist *within* cities. As we know in the CSS community, human networking and productivity exhibit heavy-tailed distributions, with some individuals contributing disproportionately to aggregate totals. Consequently, we propose that sums and means—rendering past mathematical models tractable and existing empirical analyses straightforward (*1–4,7*)—are poor and misleading indicators of the relevant quantities of cities (*8,9*).

We use granular micro-level data from Sweden, Russia and the United States that provide detailed information of within-city distributions of interconnectivity, productivity and innovation. First, we call attention to urban indicators' heavy tails, particularly in larger cities (see panel *A* in Figure 1). Second, we quantify the implications that differences in city tails have for urban scaling (panel *B*). We show that cities' tails—and, crucially, their growth as cities become larger—disproportionately contribute to superlinear scaling between cities. We find that the tails of within-city distributions and their growth by city size account for 36–80% of previously reported scaling effects. Third, we find that tails explain most of the differences in scaling coefficients between indicators of various levels of complexity (panel *C*). Higher complexity promotes heavier tails, and it is these tails that explain a large part of the scaling differences that have been reported for different complexity levels (*5,6*).

Providing explanatory depth to these findings, we identify a new mechanism—city size-dependent cumulative advantage—that constitutes a key channel through which differences in the size of tails emerge. In a computational model, we formally describe the positive link between heavy tailed distributions within cities and scaling between cities. Building on the assumption that large cities provide novel opportunities of interaction and learning to individuals with varying degrees, the model predicts city size-dependent cumulative advantage at the micro level and tail differences by city size at the macro level, and it marks out the conditions that reproduce our empirical results. An analysis of the earnings trajectories of 1.4 million Swedes confirms the prediction of greater cumulative advantage

effects for tail units in larger cities and the transformation of these effects into superlinear scaling.

Our findings demonstrate that urban scaling is in large part a story about inequality in cities. Our research implies that the causal processes underlying heavier tails in larger cities constitute an indispensable element of urban scaling, and that any theory seeking to explain urban scaling—whether it be through interconnectivity, complexity or other factors—must also explain the emergence of tail differences by city size.

From a policy perspective, these results show that agglomeration effects benefit urban elites the most. Breaking with the "all-boats-will-rise" idea of past scaling research, the processes arising from urban density are particularly operative in the tails of urban distributions, partially excluding a majority of city dwellers from the socio-economic benefits of growing cities.

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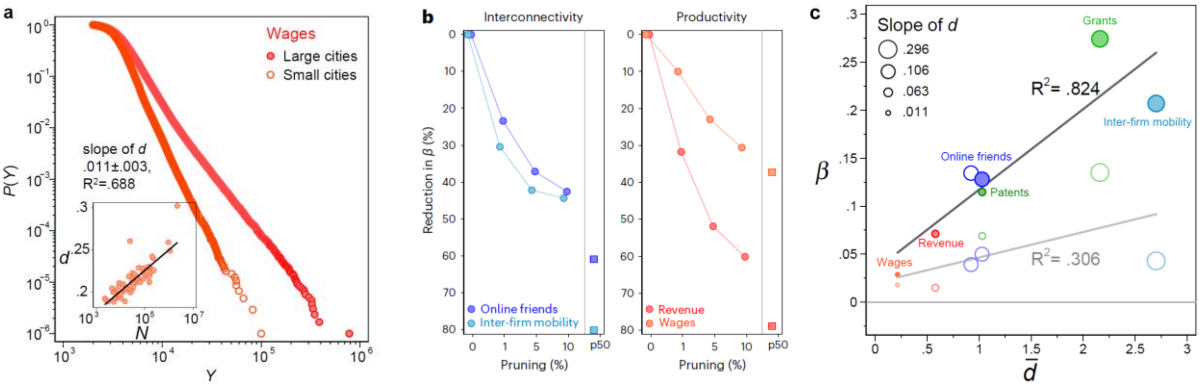

Figure 1. Urban indicators are heavy tailed and within-city tailedness explains a large part of between city scaling. (*A*) The distribution (complementary cumulative density function $P(Y)$) of wage Y is heavy tailed in Swedish cities, and much more so in larger (N >1 million) than in smaller ones (N <100,000). The inset plots d, the proportion of Y that is contributed by the top 10% as compared with the bottom 90% in a city, against city size N. (*B*) The scaling coefficients shrink considerably under differing degrees of tail pruning within cities (1, 5, 10, 50%). (*C*) The scaling effect β hinges on the indicators' average within-city skewness $\bar{d}$. The black line approximates this relationship (slope 0.084±0.040, p=0.009, R^2=0.824). A focus on city medians (empty circles and gray line) renders this association marginal.