Cities as Complex Systems I

Objectives, Phenomena and Scales

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Work of many people

and more…

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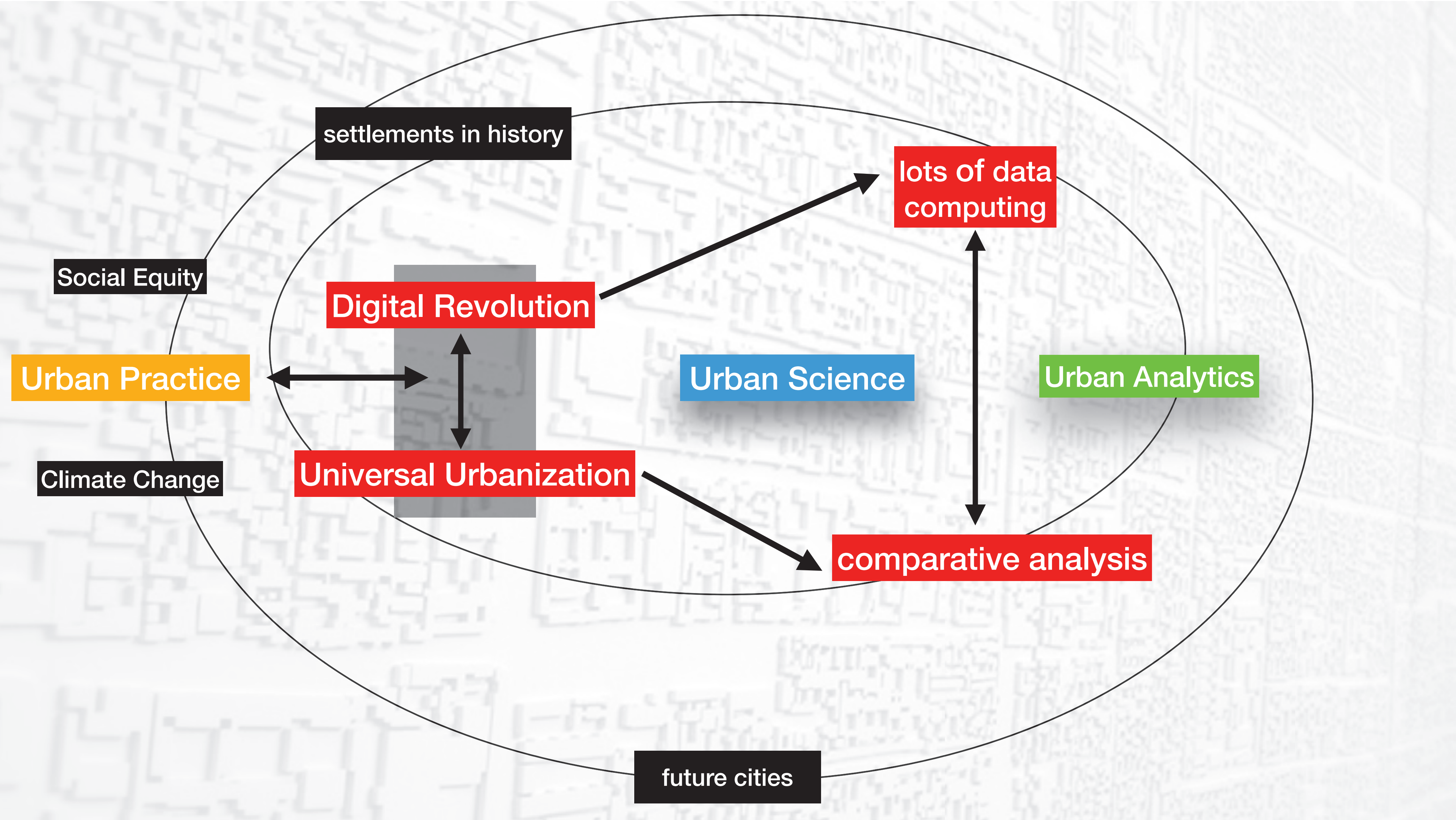
At the Mansueto Institute for Urban Innovation, our researchers come from the social, natural, and computational sciences, along with the humanities. Together, we pursue innovative, interdisciplinary scholarship, develop new educational programs, and provide leadership and evidence to support global, sustainable urban development.

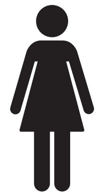
MIurban.chicago.edu

The problem that drives me:

25 years !

credit: telegraph


settlements in history
lots of data
computing
Social Equity
Digital Revolution
Urban Practice
Urban Science
Urban Analytics
Climate Change
Universal Urbanization
comparative analysis
future cities

10^9 

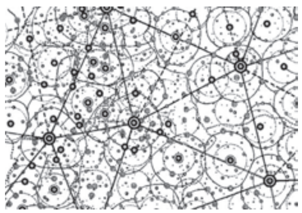
billions

10^6 

millions

10^3 

thousands



10^0

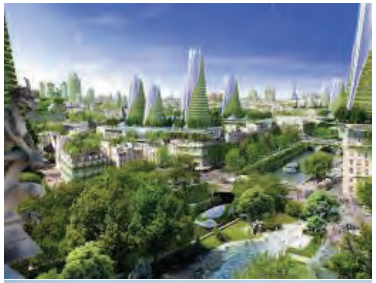
one

Scale	Integration	Mechanism
Individual		**cognition** **life-course** **human development** seeds of economic growth
↕	**livability** **safety** **education** **knowledge**	
Neighborhood		**neighborhood effects** cumulative (dis)advantage sorting, inequality, environmental quality social justice
↕	**selection** **segregation** **mixing** **contagion**	
City		**scaling laws and agglomeration** social + physical networks economy, information, land uses
↕	**migration** **trade** **knowledge diffusion**	
Urban Systems		**laws of geography** gravity law, Zipf's law migration, urban hierarchy

All Scales Matter for Cities
but different problems at different scales

Science: Seek a theoretical framework that can apply throughout history and extrapolate to the future

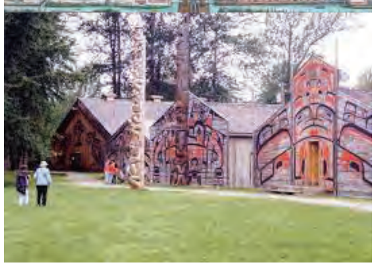
observable, predictive, falsifiable



Future Cities

Present Cities

Cities in History



Settlements

IUS : Ch 1

Technology

Political Systems

Economic Systems

Energy Systems

Transportation Systems

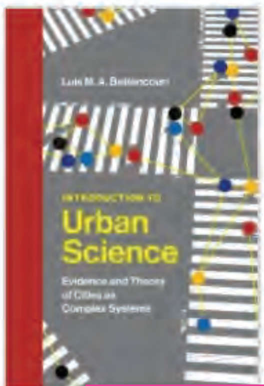
Built Environment Design

Need “micro-foundations” that are deeper and more universal:

1. Networks, 2. Heterogeneous Cost/Benefit, 3. Information

diversity / inequality

origins of growth & change



IUS Chapters

in this talk

Introduction to Urban Science

Evidence and Theory of Cities as Complex Systems

Luís M. A. Bettencourt

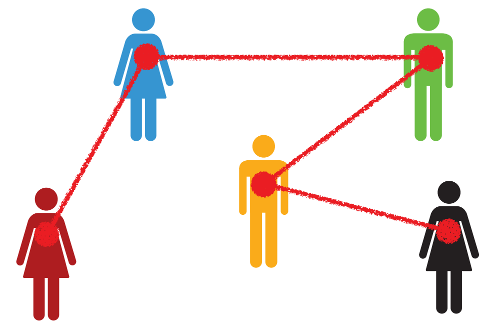
2021

The MIT Press

A novel, integrative approach to cities as complex adaptive systems, applicable to issues ranging from innovation to economic prosperity to settlement patterns.

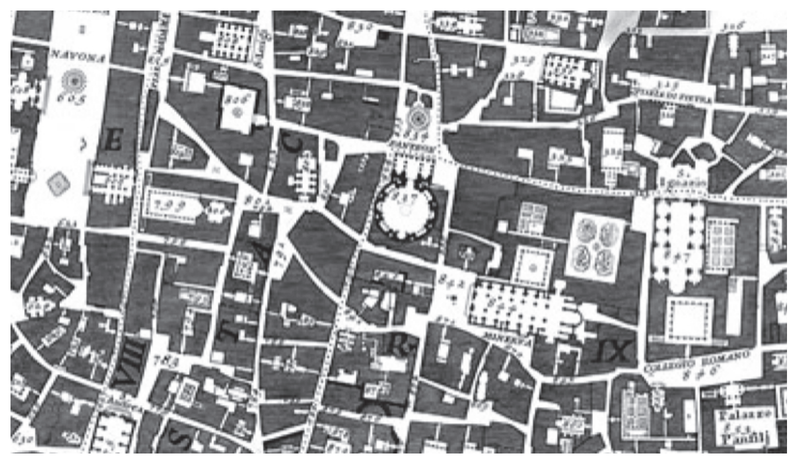
https://mitpress.mit.edu/books/introduction-urban-science

People are connected



What are Cities? Complex Networks

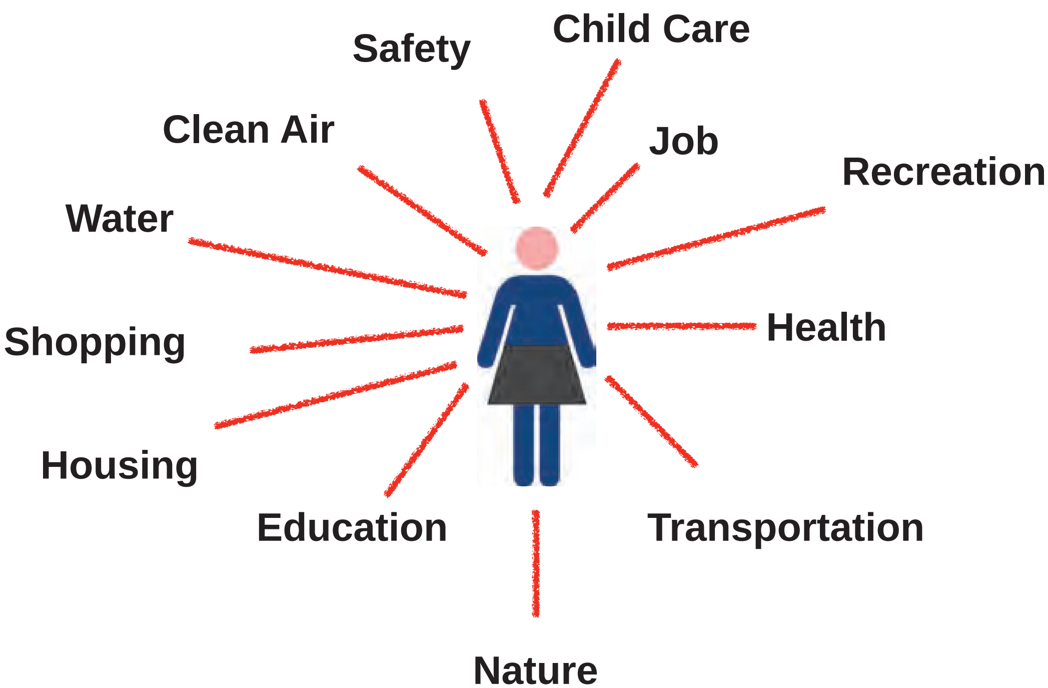
A **“bound-state”** between people, organizations and built spaces

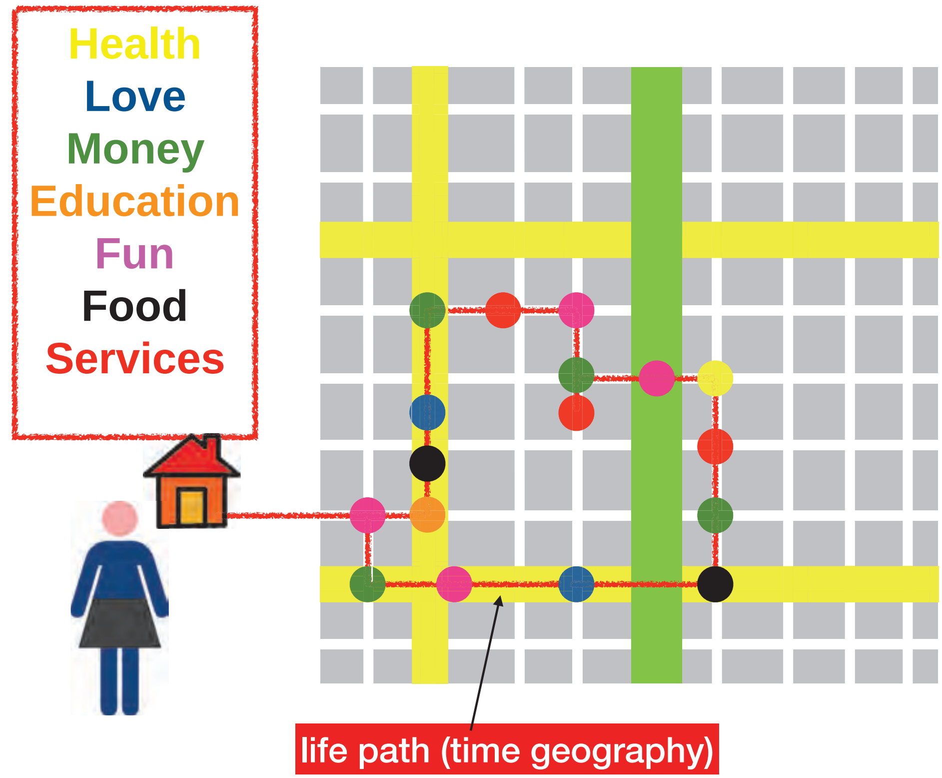


Places are connected

Urban Complexity in a “nutshell”

but this is not how Government Departments think ! Or Research Disciplines !





How are these functions integrated over Time? Space? Economic budgets? Needs of different individuals?

When a city doubles in size

its economic productivity per capita increases by 15%

Sveikauskas 1975

https://academic.oup.com/qje/article/89/3/393/1896685?login=true

When a city doubles in size

its per capita violent crime increases by 16%

Glaeser & Sacerdote 1999

https://www.journals.uchicago.edu/doi/abs/10.1086/250109

Growth, innovation, scaling, and the pace of life in cities

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Humanity has just crossed a major landmark in its history with the majority of people now living in cities. Cities have long been known to be society's predominant engine of innovation and wealth creation, yet they are also its main source of crime, pollution, and disease. The inexorable trend toward urbanization worldwide presents an urgent challenge for developing a predictive, quantitative theory of urban organization and sustainable development. Here we present empirical evidence indicating that the processes relating urbanization to economic development and knowledge creation are very general, being shared by all cities belonging to the same urban system and sustained across different nations and times. Many diverse properties of cities from patent production and personal income to electrical cable length are shown to be power law functions of population size with scaling exponents, β, that fall into distinct universality classes. Quantities reflecting wealth creation and innovation have $\beta \approx 1.2 > 1$ (increasing returns), whereas those accounting for infrastructure display $\beta \approx 0.8 < 1$ (economies of scale). We predict that the pace of social life in the city increases with population size, in quantitative agreement with data, and we discuss how cities are similar to, and differ from, biological organisms, for which $\beta < 1$. Finally, we explore possible consequences of these scaling relations by deriving growth equations, which quantify the dramatic difference between growth fueled by innovation versus that driven by economies of scale. This difference suggests that, as population grows,

The increasing concentration of people in cities presents both opportunities and challenges (9) toward future scenarios of sustainable development. On the one hand, cities make possible economies of scale in infrastructure (9) and facilitate the optimized delivery of social services, such as education, health care, and efficient governance. Other impacts, however, arise because of human adaptation to urban living (9, 10–14). They can be direct, resulting from obvious changes in land use (3) [e.g., urban heat island effects (15, 16) and increased green house gas emissions (17)] or indirect, following from changes in consumption (18) and human behavior (10–14), already emphasized in classical work by Simmel and Wirth in urban sociology (11, 12) and by Milgram in psychology (13). An important result of urbanization is also an increased division of labor (10) and the growth of occupations geared toward innovation and wealth creation (19–22). The features common to this set of impacts are that they are open-ended and involve permanent adaptation, whereas their environmental implications are ambivalent, aggravating stresses on natural environments in some cases and creating the conditions for sustainable solutions in others (9).

These unfolding complex demographic and social trends make it clear that the quantitative understanding of human social organization and dynamics in cities (7, 9) is a major piece of the puzzle toward navigating successfully a transition to sustainability. However, despite much historical evidence (19, 20) that cities are the principal engines of innovation and economic growth, a

https://www.pnas.org/content/pnas/104/17/7301.full.pdf

Scaling Relation	Exponent	Error	Observations	Region/Nation	Urban Unit	Year	Reference
Land area							
administrative	$\alpha = 0.75$	NR	412	USA	Cities (political)	1940	*(39)*
administrative	$\alpha = 0.75$	$R^2 = 0.87$	157	England and Wales	Cities (political)	1951	*(39)*
urbanized	$\alpha = 0.66$	[0.65,0.67]	1,800	Sweden	Tätort (urban area)	1960	*(18)*
urbanized	$\alpha = 0.65$	[0.64,0.66]	1,800	Sweden	Tätort (urban area)	1965	*(18)*
urbanized	$\alpha = 0.63$	0.62-0.64	329	USA	MSA	1980-2000	*(42)*
developed	$\alpha = 0.57$	0.56-0.59	329	USA	MSA	1992, 2000	*(42)*
light emissions	$\alpha = 0.65$	$R^2 = 0.62$	4,851	USA	Night-light clusters	1992	*(47)*
Average land area	$\alpha = 0.67$	[0.56,0.75]					
built area	$\alpha = 0.78$	NR	89	USA	Cities (political)	1960	*(44)*
built area, radial	$\alpha = 0.88$	NR	368†	Michigan, USA	Cities (political)	1969	*(40)*
built area	$\alpha = 0.96$	[0.89,1.04]	70	Norfolk, UK	Settlements	1981	*(41)*
built area, radial	$\alpha = 0.87$	[0.75,0.99]	70	Norfolk, UK	Settlements	1981	*(41)*
built area	$\alpha = 0.87$	NR	51	Ontario, Canada	Urban Areas	1966	*(46)*
Average land area*	$\alpha = 0.75$	[0.56,1.04]					
Network area (or volume)							
impervious surfaces	$\nu = 0.85$	0.84-0.86	3,629	World	Cities $> 100,000$	2000	*(16)*
impervious surfaces	$\nu = 0.86$	$R^2 = 0.74$	119	EU	Agglomerations $> 200,000$	1990	*(50)*
built area	$\nu = 0.82$	$R^2 = 0.84$	660	China	Urban Areas	2005	*(51)*
area of roads	$\nu = 0.85$	[0.81,0.89]	451	USA	MSA	2006	Fig. 1A
area of roads	$\nu = 0.83$	[0.74,0.92]	29	Germany	LUZ	2002	*(12)*
Average network volume	$\nu = 0.84$	[0.74,0.92]					
Network length							
length of pipes	$\lambda = 0.67$	[0.55,0.78]	12	Japan	MA	2005	Fig. S1
Socioeconomic rates							
GDP	$\beta = 1.13$	[1.11,1.15]	363	USA	MSA	2006	Fig. 1B, *(12)*
GDP	$\beta = 1.22$	[1.11,1.33]	273	China	Prefectural Cities	2005	Fig. S2A
GDP	$\beta = 1.10$	[1.01,1.18]	35	Germany	LUZ	2004	Fig. S2B
income	$\beta = 1.12$	[1.07,1.17]	12	Japan	MA	2005	Fig. S1A
wages	$\beta = 1.12$	[1.07,1.17]	363	USA	MSA	1969-2009	Fig. S3
violent crime	$\beta = 1.16$	[1.11,1.19]	287	USA	MSA	2003	*(12)*
violent crime	$\beta = 1.20$	[1.07,1.33]	12	Japan	MA	2008	*(62)*
violent crime	$\beta = 1.20$	[1.15,1.25]	27; 5,570	Brazil	MA; Municipios	2003-07	*(25)*, *(62)*
new AIDS cases	$\beta = 1.23$	[1.17,1.29]	93	USA	MSA	2002-3	*(12)*
new patents	$\beta = 1.27$	[1.22,1.32]	331	USA	MSA	1980-2001	*(11, 12)*
supercreative jobs	$\beta = 1.15$	[1.13,1.17]	331	USA	MSA	1999-2001	*(11)*
R&D employment	$\beta = 1.19$	[1.12,1.26]	227-278	USA	MSA	1987-2002	*(11)*
Average socioeconomic rates	$\beta = 1.17$	[1.01,1.33]					
Social interactions							
cell phones	$\beta = 1.12$	[1.00,1.25]	415	Portugal	Cities, LUZ, Municipality	2006-7	*(21)*
land lines	$\beta = 1.12$	[1.05,1.17]	24	UK	Cities	2005	*(21)*
Average social interactions	$\beta = 1.12$	[1.00,1.25]					
Power dissipation							
electrical	$\omega = 1.11$	[1.05, 1.17]	380	Germany	Cities	2002	*(12)*
Average land rents							
median house value	$\delta_L = 0.49$	[0.46,0.52]	363	USA	MSA	2006	*(24)*

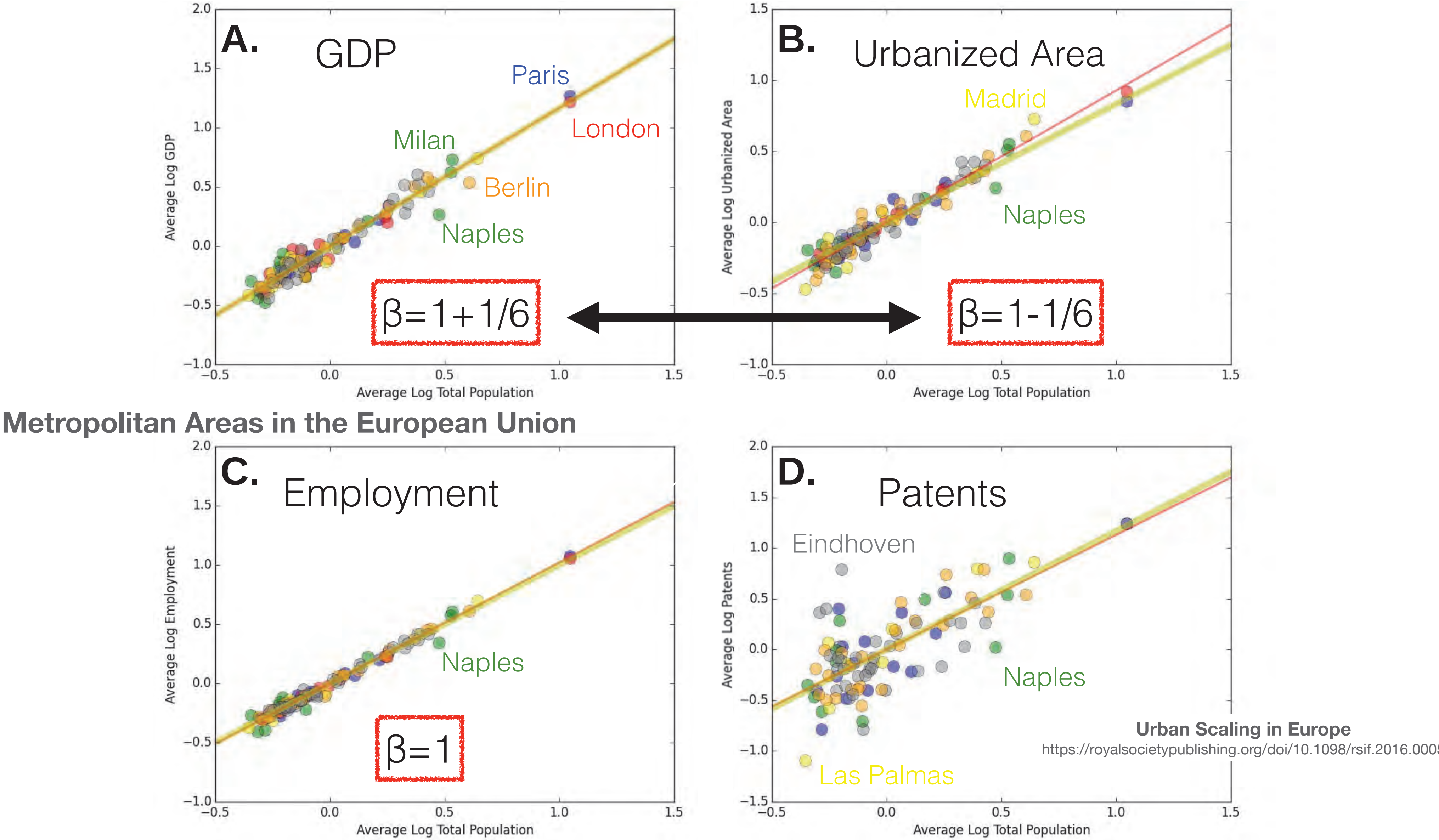
NR=not reported. Error, in order of availability from the source, is given by: 95% confidence intervals (square brackets), ranges, or R^2 values.
Note: Average quantities are the simple (unweighted) averages across rows. Corresponding error intervals are the union of those from individual studies.
* This estimate of *Average land area* includes all 12 rows above, it mixes explicit measurements of built area with others.
† This estimate was obtained by the author through visual inspection of Fig. 1 in Ref. *(39)*.

National Urban Systems:
USA
European Union
Brazil
South Africa
Japan
China
India
…

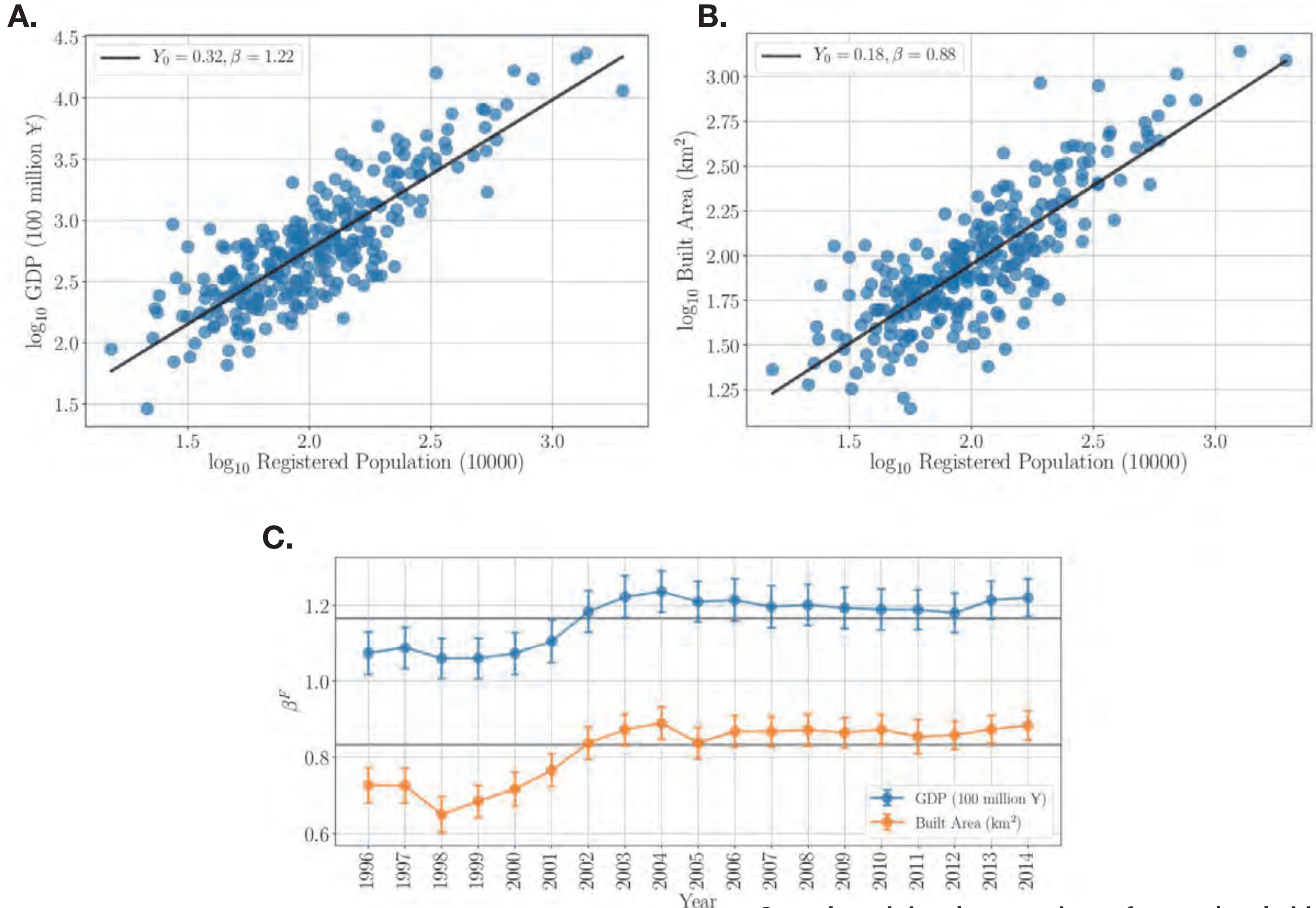
Settlements in History:
Aztecs
Inca
Southwest Pueblo
Maya
Roman Empire
Medieval Europe
19th Century England

Breaks down in:
- Hunter/Gatherer Camps
- Slums (informal settlements)
- Shrinking Cities

https://www.science.org/doi/10.1126/science.1235823


A.
GDP
Paris
London
Milan
Berlin
Naples
β=1+1/6
Average Log GDP
Average Log Total Population
B.
Urbanized Area
Madrid
Naples
β=1-1/6
Average Log Urbanized Area
Average Log Total Population
Metropolitan Areas in the European Union
C.
Employment
Naples
β=1
Average Log Employment
Average Log Total Population
D.
Patents
Eindhoven
Naples
Las Palmas
Average Log Patents
Average Log Total Population
Urban Scaling in Europe
https://royalsocietypublishing.org/doi/10.1098/rsif.2016.0005

Prefectural Cities in China

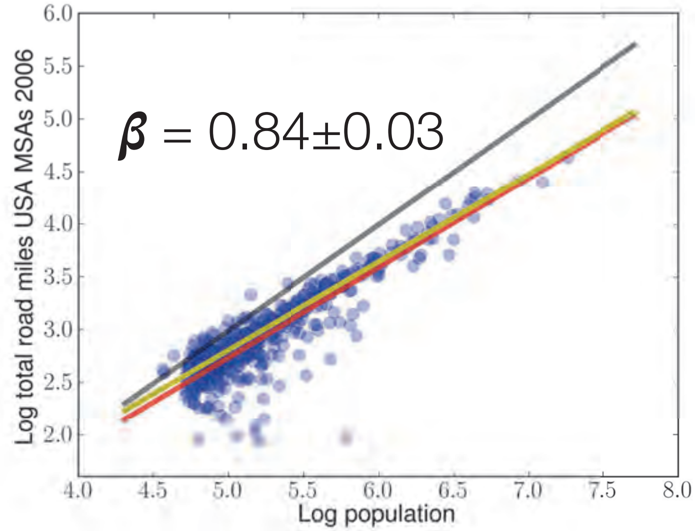


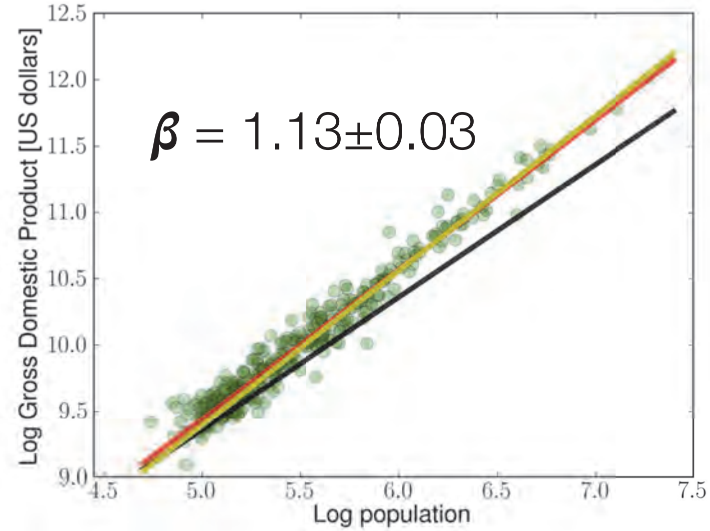
Growth and development in prefecture-level cities in China

https://journals.plos.org/plosone/article?id=10.1371/journal.pone.0221017

Infrastructure & socioeconomic rates

United States: Metropolitan Areas





Volume of Infrastructure

$\sim N^{\beta_i}$

β_i □ $1-\delta$

$\delta \simeq 1/6$

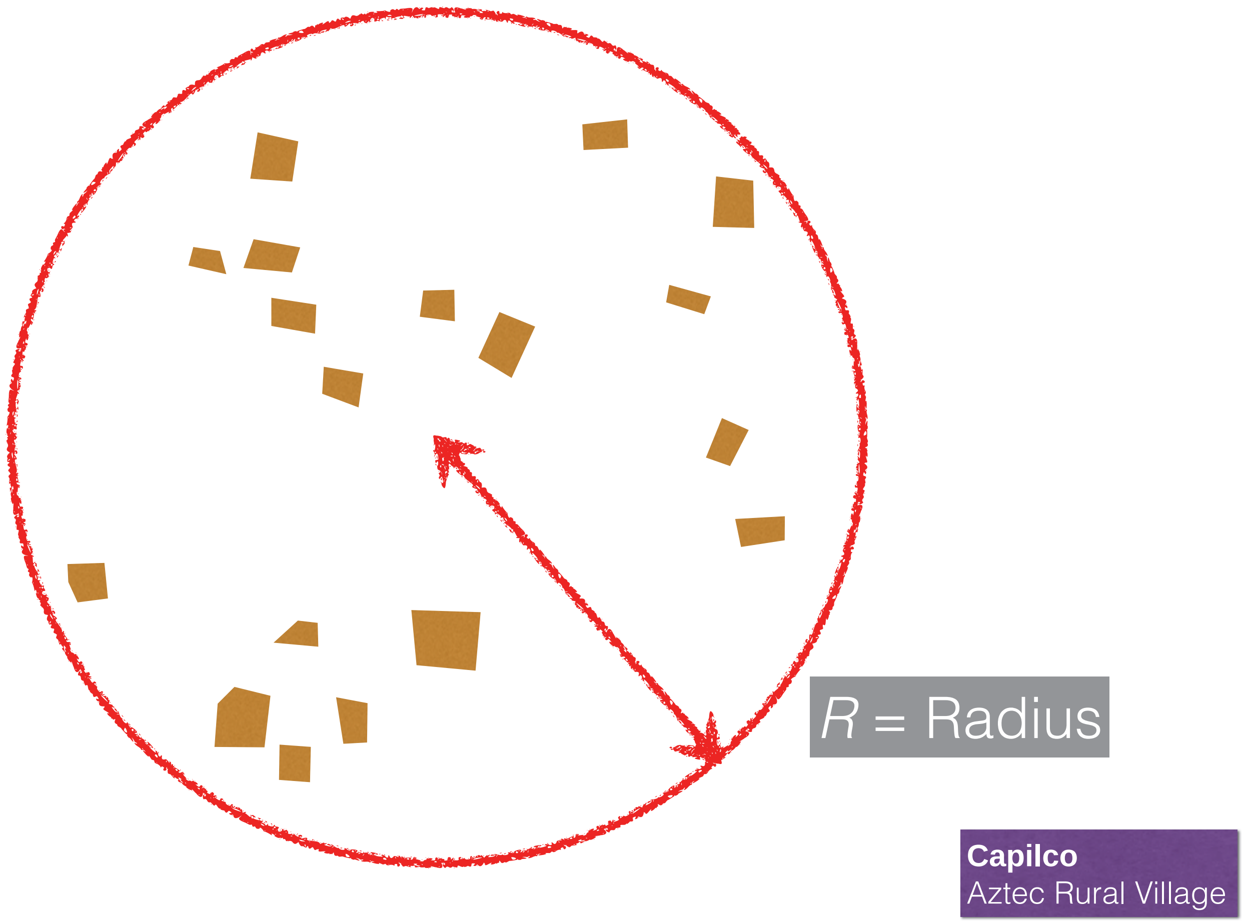
Social Outputs

$\sim N^{\beta_s}$

β_s □ 1 □ δ

The origins of scaling in cities
https://www.science.org/doi/full/10.1126/science.1235823

The Simplest Model of Settlement Scaling: “The Amorphous Settlement”



The origins of scaling in cities
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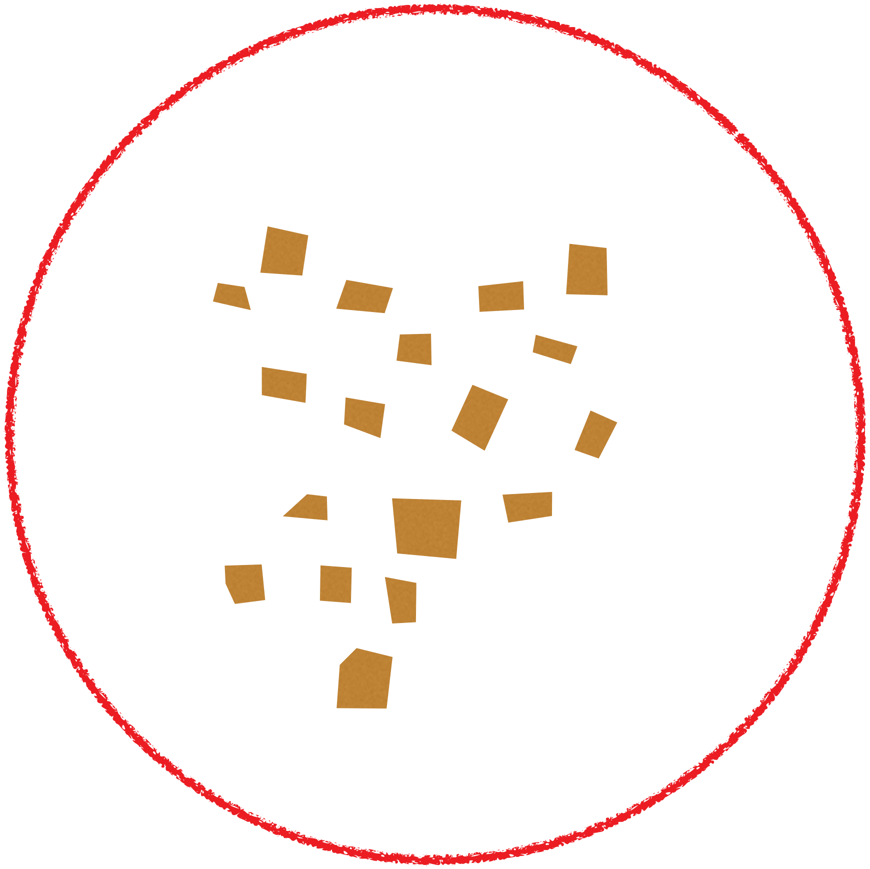

The origins of scaling in cities
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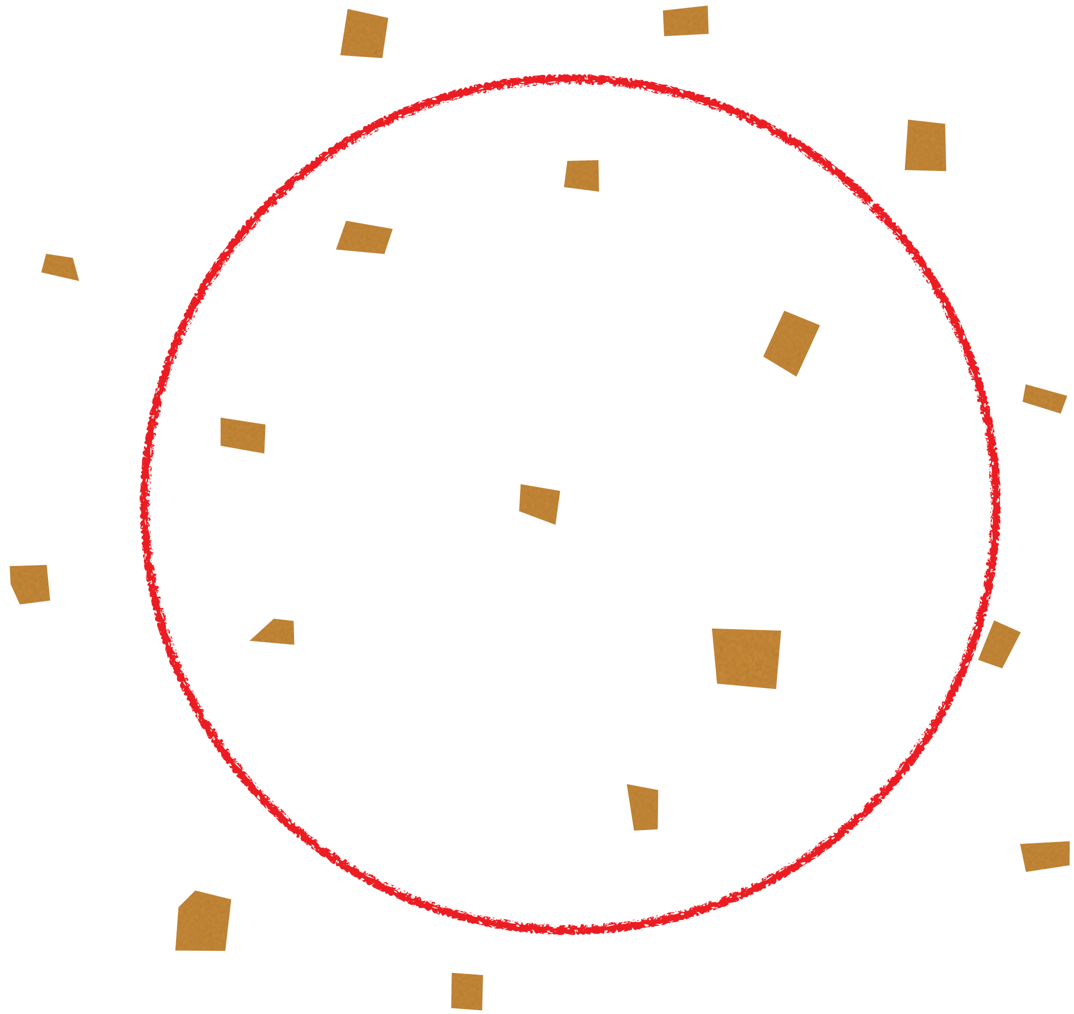
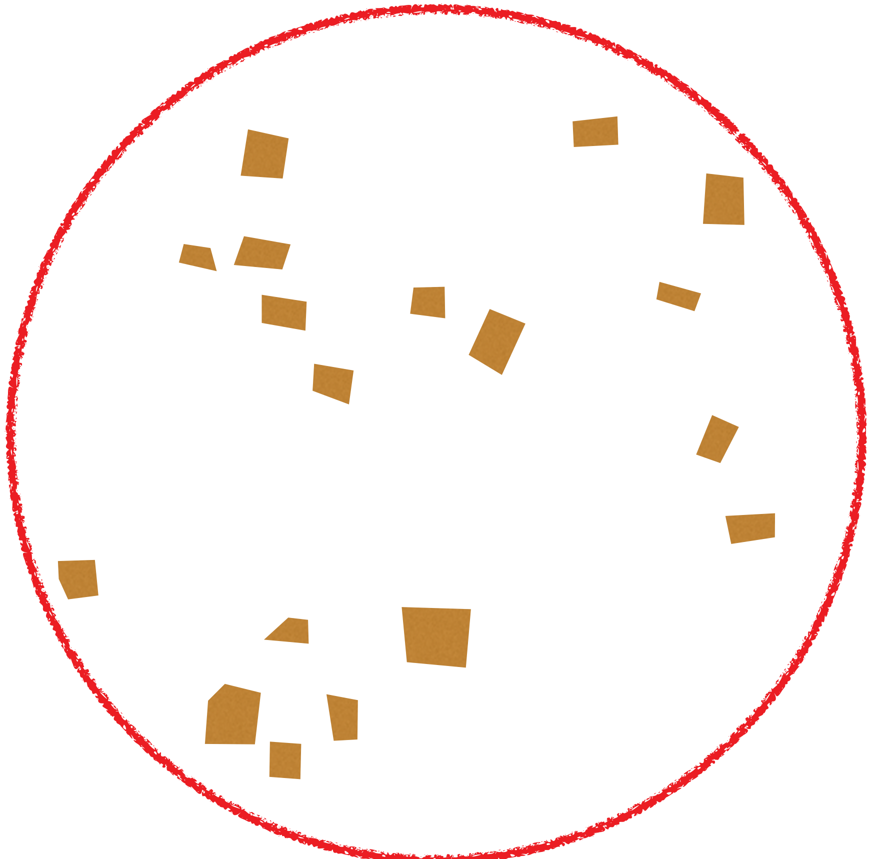


The origins of scaling in cities
https://www.science.org/doi/full/10.1126/science.1235823



For Circle:

$$A = \pi R^2$$

$$G\frac{N}{A} = \textbf{benefit} \sim \textbf{cost} = \epsilon R = \frac{\epsilon}{\sqrt{\pi}} A^{\frac{1}{2}}$$

social interactions — **movement**

This gets us two good things:

“City” Area:

$$A(N) = \left(\frac{\sqrt{\pi}G}{\epsilon}\right)^{\frac{2}{3}} N^{\frac{2}{3}}$$

sublinear

Total Socioeconomic Outputs:

$$Y(N) = G\frac{N^2}{A} = \left(\frac{G^{\frac{1}{2}}\epsilon}{\sqrt{\pi}}\right)^{\frac{2}{3}} N^{\frac{4}{3}}$$

superlinear

Results in: $\delta = \dfrac{1}{3}$ **too big !**

The origins of scaling in cities
https://www.science.org/doi/full/10.1126/science.1235823

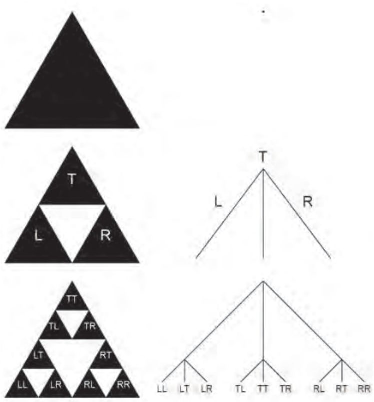
To derive exponents observed in modern cities need to understand hierarchical complex nature of built environments

People interacting over the built environment:
fast (people, ~days) and slow (infrastructure, ~decade) time scales

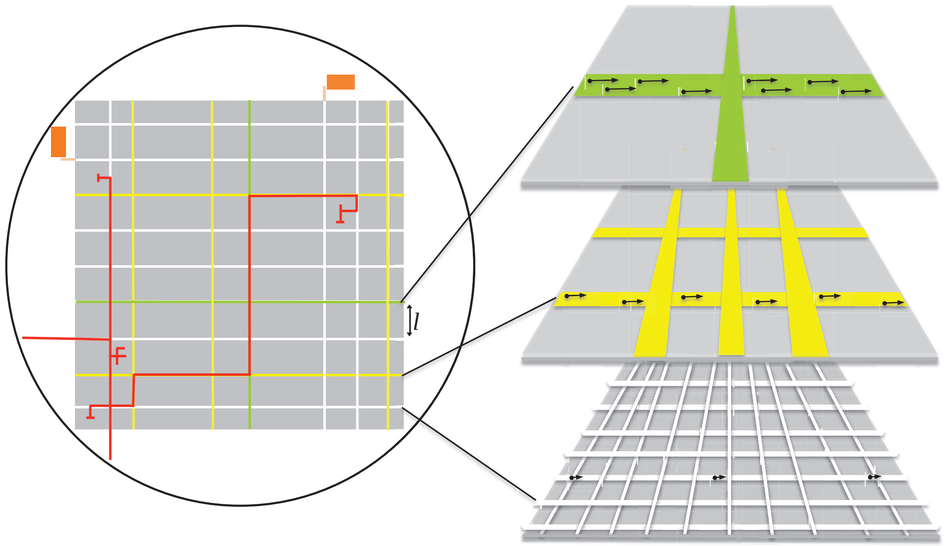
Mumbai Train Station
credit: Randy Olson

note now that spaces are structured, not amorphous: we need to understand the nature of their networks

Infrastructure Networks in the City have a Hierarchy



remember?



$i = 0$ **Highways: wider + faster**

infrastructure hierarchy levels

$N_i = b^i$ **Main Roads**

units of infrastructure at level i

$i = h$ $h = \frac{\ln N}{\ln b}$ **Local Roads**

$N = b^h$

$s_i = s_* b^{(1-\delta)(h-i)}$ **width segments**

$s_0 = s_* b^{(1-\delta)h} \gg s_h = s_*$

width highways — keeps increasing with city size (and individual flows)

width doorways — same everywhere

$a_i = ab^{(\alpha-1)i}$ **land area segments**

$a_h = ab^{(\alpha-1)h} = aN^{\alpha-1}$

land area per person

$l_i = \frac{a_i}{l}$ **infrastructure length segments**

$l_h = \frac{a}{l} N^{\alpha-1}$ **minimal distance between people**

IUS Ch 3

The Cost of Socializing in the City

Conservation of Current across infrastructural levels

$$J_i = s_i \rho_i v_i N_i = s_{i-1} \rho_{i-1} v_{i-1} N_{i-1} = J_{i-1}$$

$$\rho_0 v_0 \gg \rho_h v_h$$

highways faster and more densely packed

doorways the same everywhere

$$\rho_i v_i = b^{\delta(h-i)} \rho_* v_*$$

flow per unit area

$$J_i = J = J_0 N, \text{ with } J_0 = s_* \rho_* v_*$$

Resistance accounts for Cost of Movement:

$$r_i = r \frac{l_i}{s_i} \qquad R_i = \frac{r_i}{N_i} = \frac{ar}{ls_*} b^{-(1-\alpha+\delta)i-(1-\delta)h}$$

Parallel resistance because flow can take alternate routes (decentralized networks)

$$W = J^2 \sum_{i=1}^{h} R_i = J^2 \frac{ar}{ls_*} b^{-(1-\delta)h} \frac{1-b^{-(1-\alpha+\delta)(h+1)}}{1-b^{-1+\alpha-\delta}} \simeq W_0 N^{1+\delta}, \quad W_0 = \frac{arJ_0^2}{ls_*(1-b^{-1+\alpha-\delta})},$$

Cost of Transportation scales super linearly
like Social Benefits !! -> Spatial Equilibrium independent of City population size

Implications: **Many quantitative predictions + general consequences**

Urban scaling relation	Exponent prediction $D = 2, H_m = 1$	Exponent prediction General D, H_m
Land area $A = aN^{\alpha}$	$\alpha = 2/3$	$\alpha = \frac{D}{D + H_m}$
Network volume $A_n = A_0 N^{\nu}$	$\nu = 5/6$	$\nu = 1 - \delta$
Network Length $L_n = L_0 N^{\lambda}$	$\lambda = 2/3$	$\lambda = \alpha$
Interactions/capita $k = k_0 N^{\delta}$	$\delta = 1/6$	$\delta = \frac{H}{D(D + H_m)}$
Social outputs $Y = Y_0 N^{\beta}$	$\beta = 7/6$	$\beta = 1 + \delta$
Power dissipation $W = W_0 N^{\omega}$	$\omega = 7/6$	$\omega = 1 + \delta$
Land rents ($\$/m^2$) $P_L = P_0 N^{\beta_L}$	$\beta_L = 4/3$	$\beta_L = 1 + 2\,\delta$

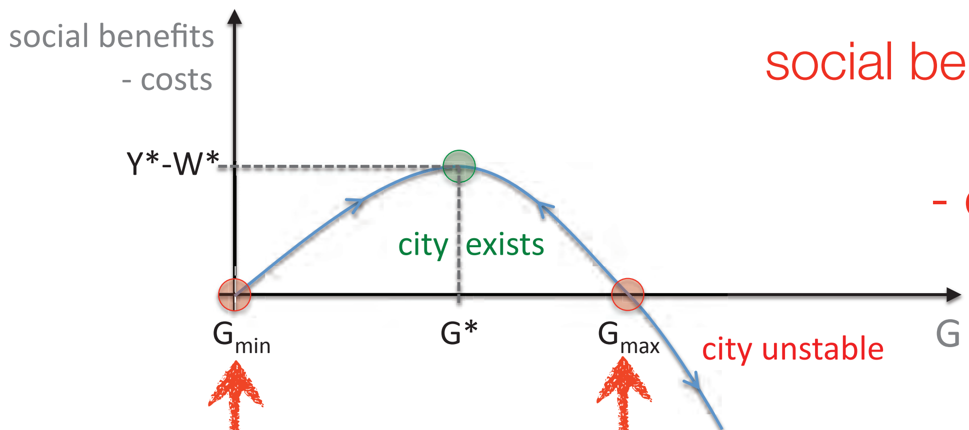
Number of Professions
COVID-19 Transmissibility
Cost of Housing
Congestion Costs
Building Height and Shape
Information Infrastructure
Water Consumption
Fractal Dimension of Land Use
...

Summary of Urban Scaling relations and exponent predictions for various important quantities. Note that agglomeration effects vanish when $H_m \to 0$ because then people remain spatially separated social networks fail to emerge (we will look at internet quantities later).

Spatial equilibrium between social benefits and costs

cities can exist at “any” population size: scale-invariance

Real “Income”: $Y(N) - W(N)$



social benefits: $Y(N) \sim G \dfrac{N^2}{A_n(N)} \sim N^{7/6}$

- costs: $W(N) \sim W_0 \dfrac{I^2}{A_n(N)} \sim N^{7/6}$

$Y_0 \sim G^{1-\alpha}$ and $W_0 \sim G^{\alpha}$

calculation in IUS pp 88-89

Congestion/Danger

High Costs/Dispersion

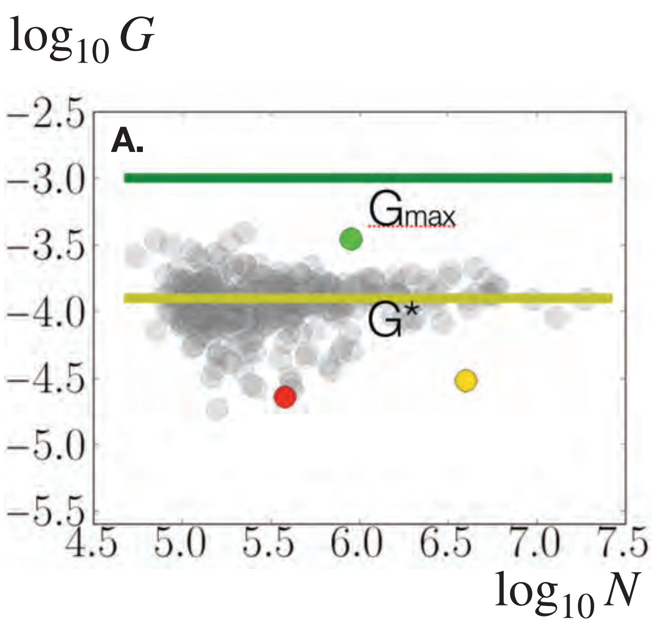
~Lagos

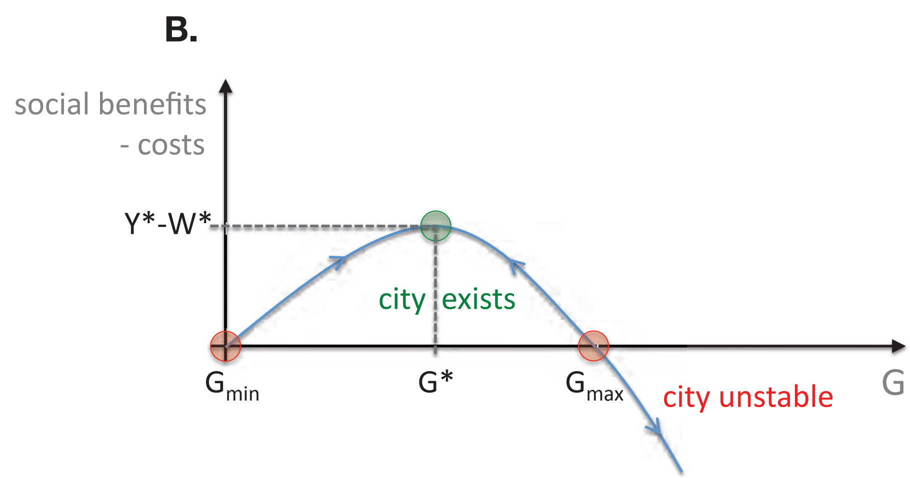
~”Florida”

Poor, congested, intense, dangerous

Diffuse, sprawling, uneventful

Scale invariance of degrees of freedom per capita





$$\log G = \log \frac{Y}{N} + \log \frac{A_n}{N}$$

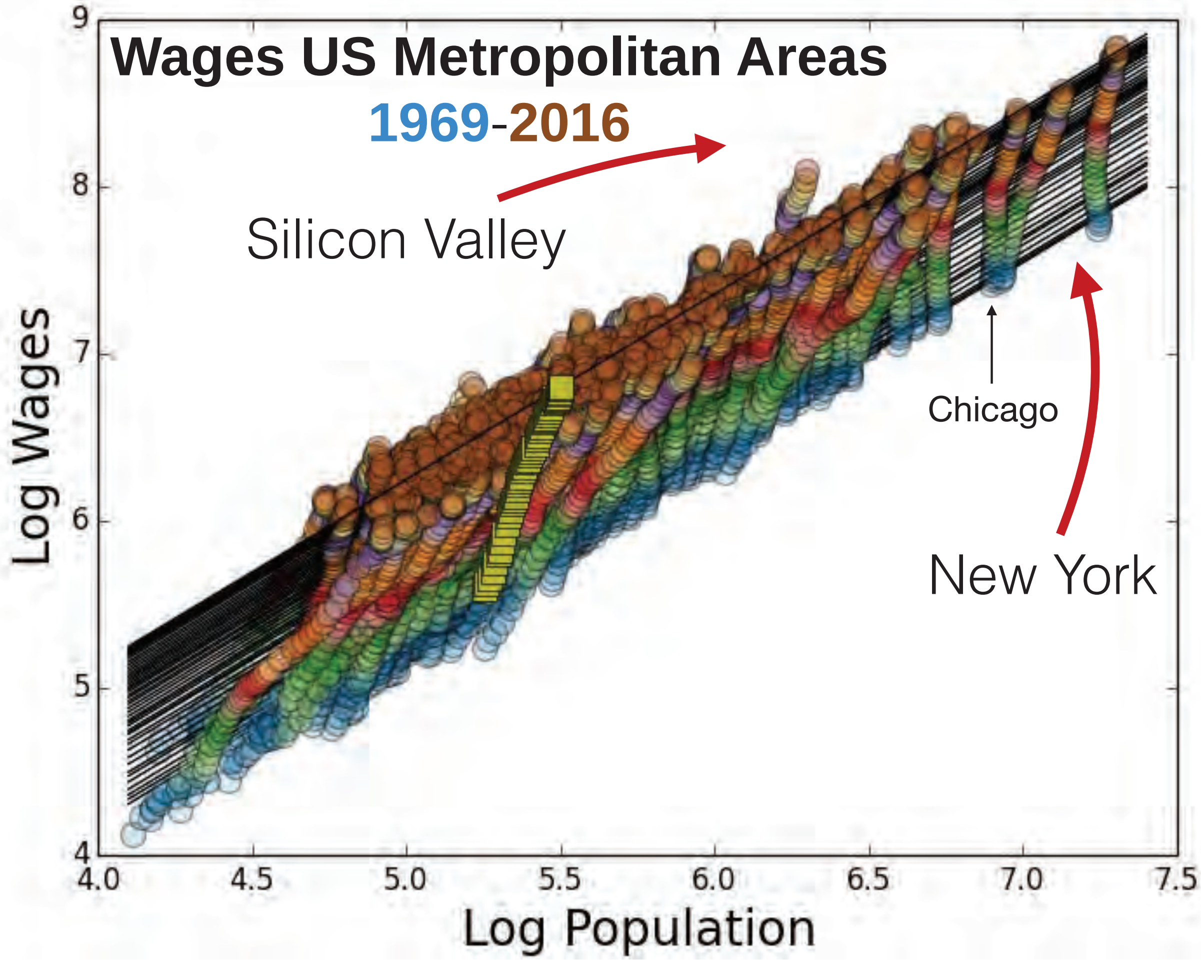
Total degrees of freedom per capita

social "volume"

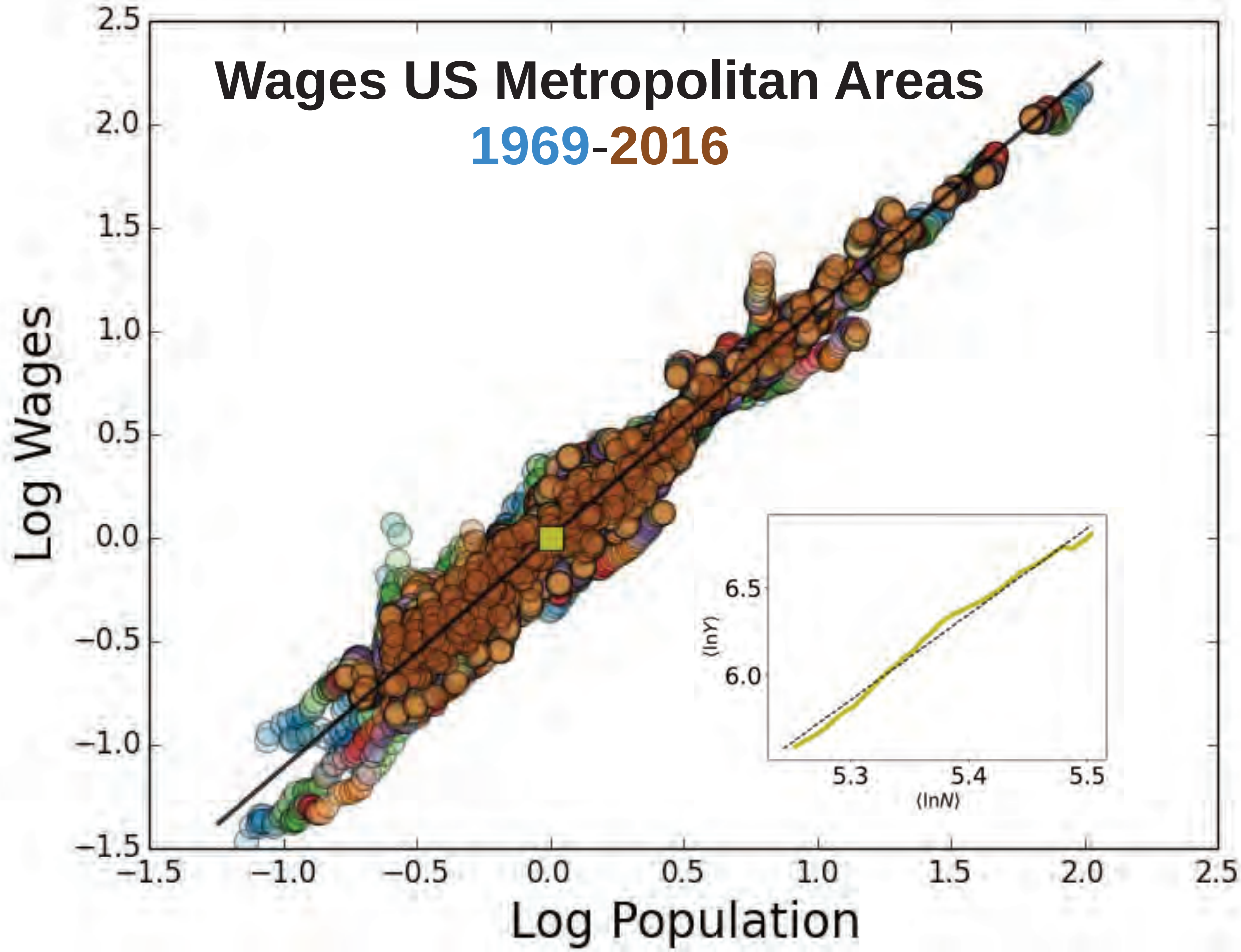
spatial "volume"

In larger cities, there is more social space and less physical space and vice-versa in smaller cities

Scale invariance of growth rates



Economic growth is an Collective Property of the System of Cities



Renormalization of Mean-Field Scaling Exponents from Weak Scale Dependence

$$R_i(t) \to R_i(0)e^{\gamma_i t} \simeq Y_0(0)N_i(0)^{\beta+\bar{B}_i t} e^{\gamma^{(0)} t}$$

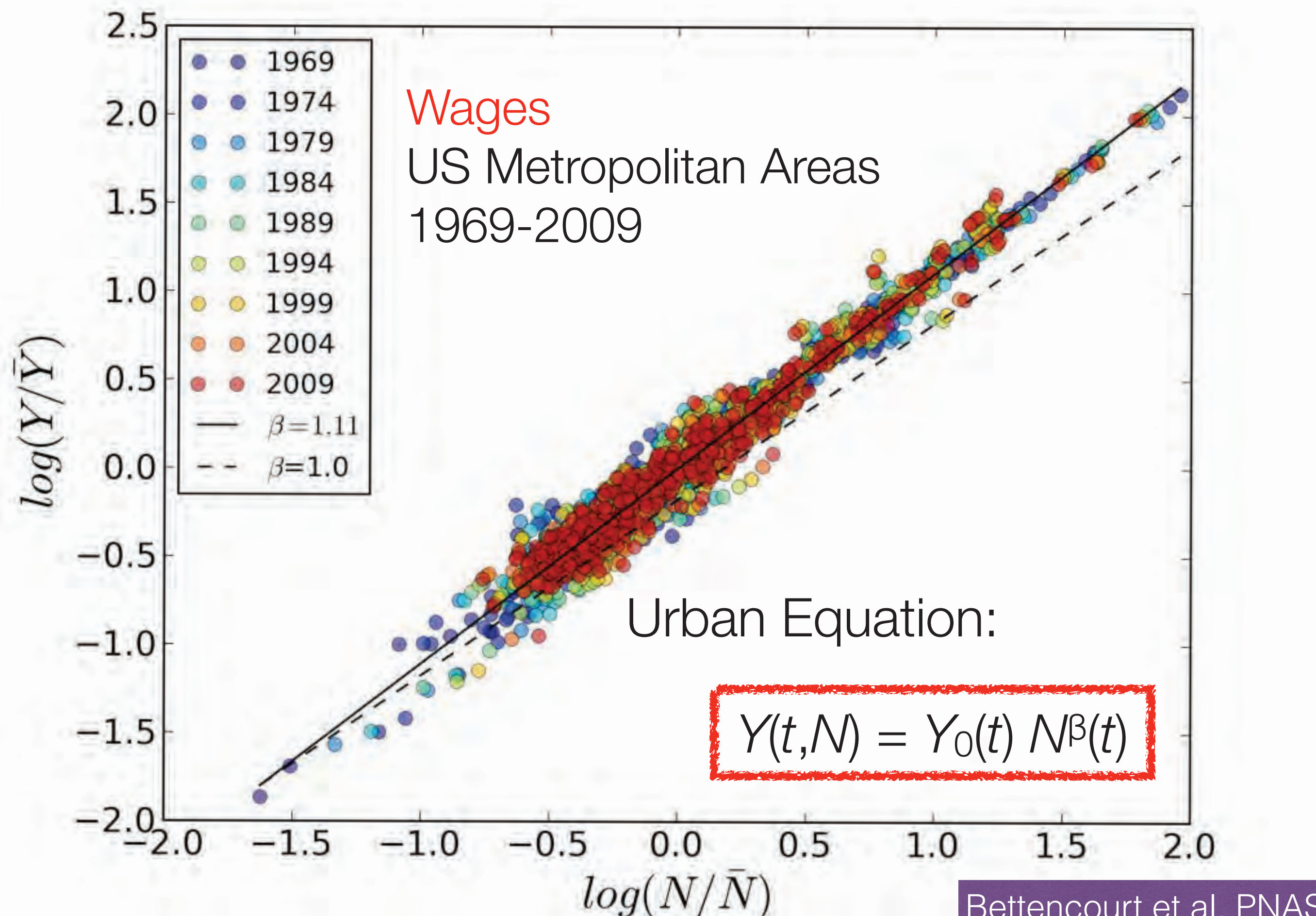
$$B_i(\ln N_i) = \frac{d\gamma_i}{d\ln N_i} \to \gamma_i(t) = \int B_i d\ln N_i \simeq \gamma^{(0)} + \bar{B}_i \ln N_i + \ldots$$

running of scaling exponents

$$B_i(\ln N_i) = -\frac{1}{2}\frac{d\sigma_i^2}{d\ln N_i}$$

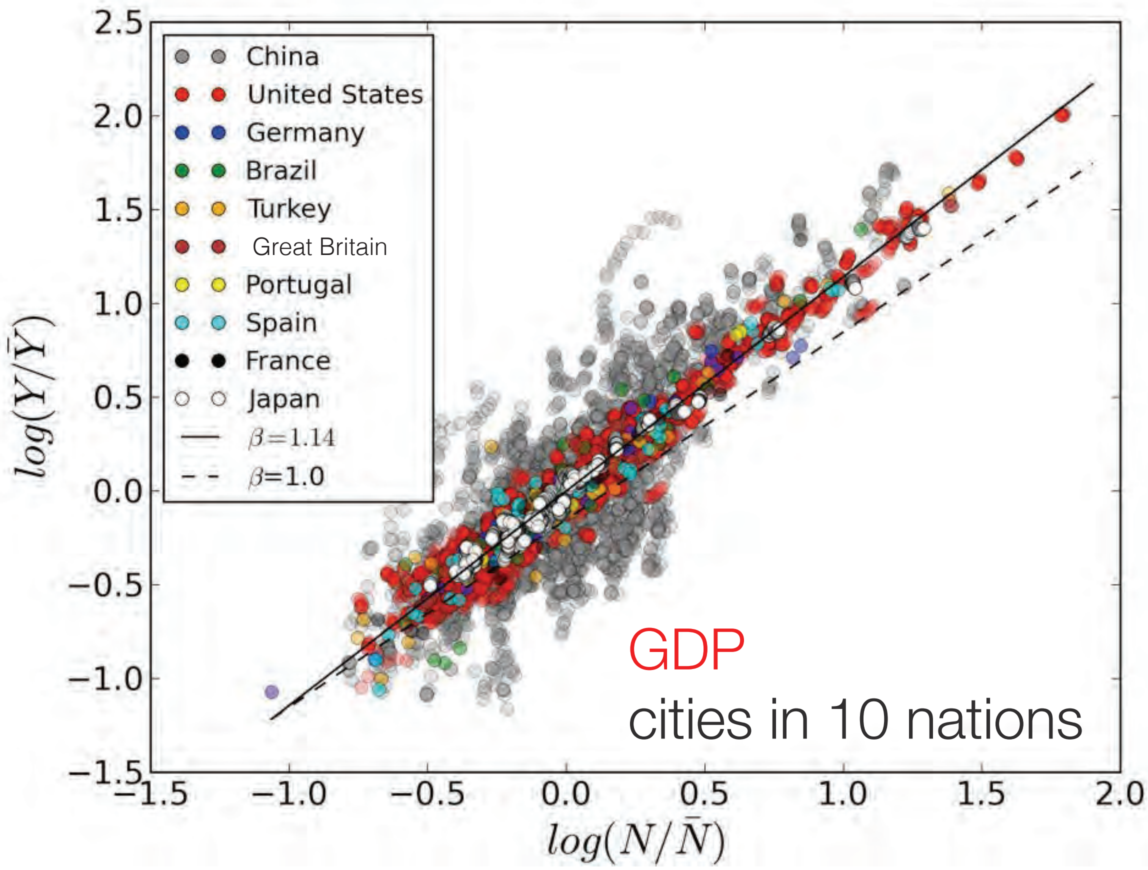
corrections from scale dependent of volatilities, exponents “run”

A law in **time** ...

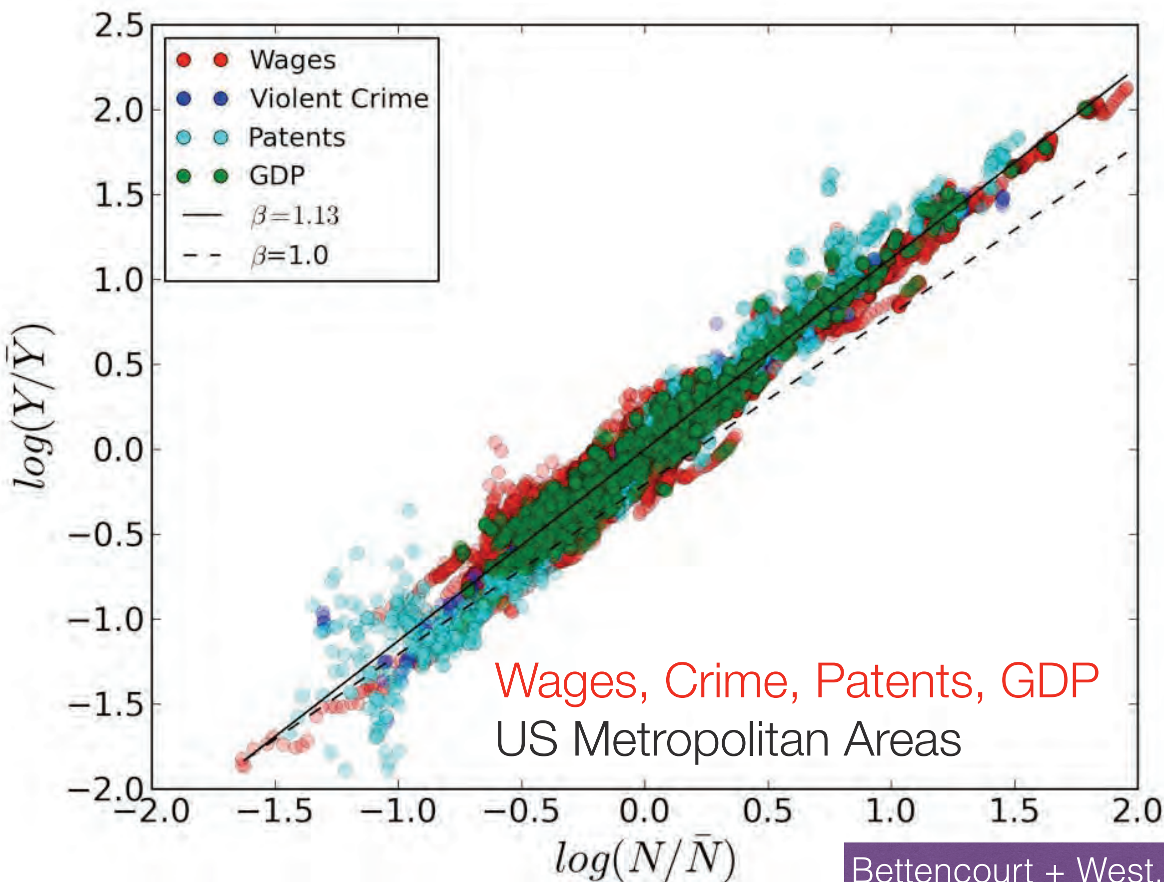


Bettencourt et al, PNAS 2007

A law in **across nations** ...



A law in **across quantities** ...



Bettencourt + West, *Nature* 2010

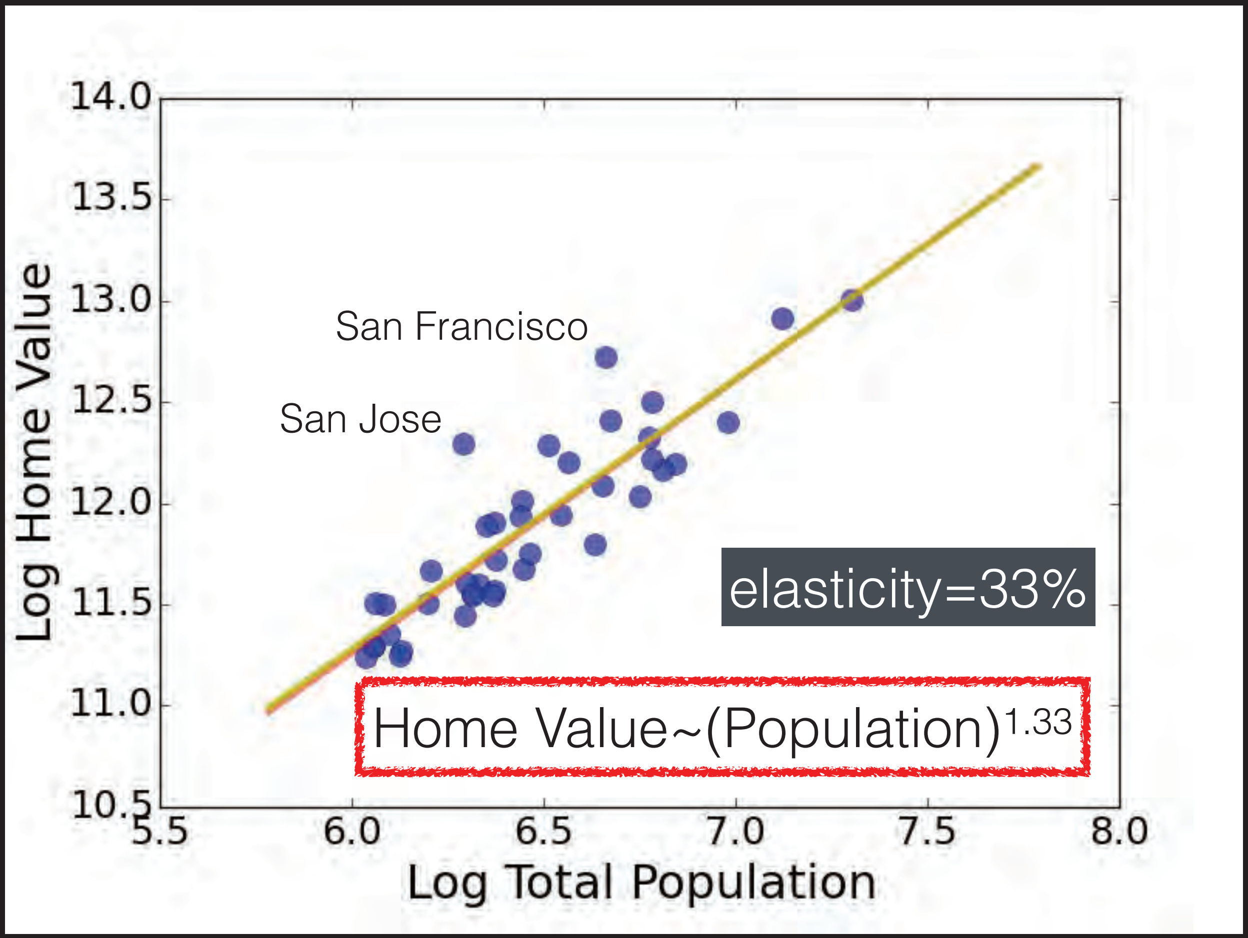
https://www.nature.com/articles/467912a

(Some) Consequences


credit: MacLean

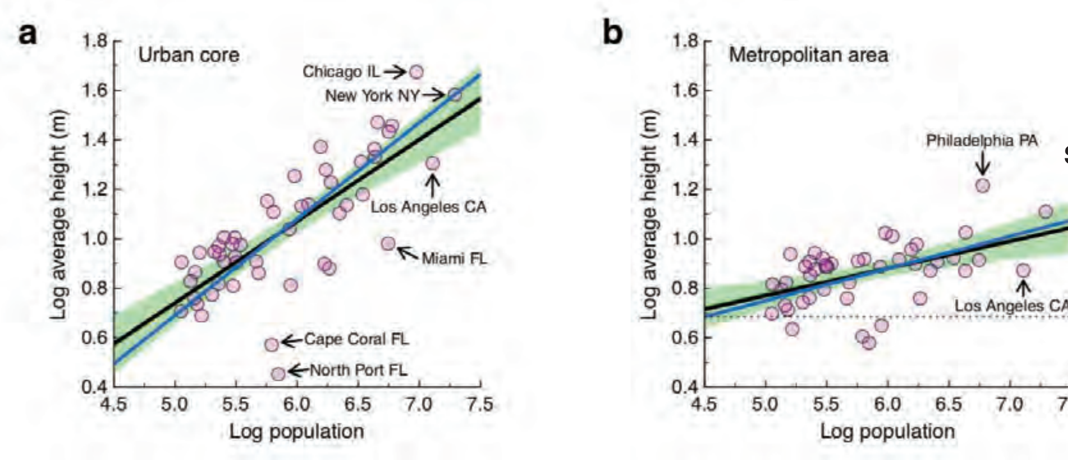
credit: Robert Stone

Home Value US Metros

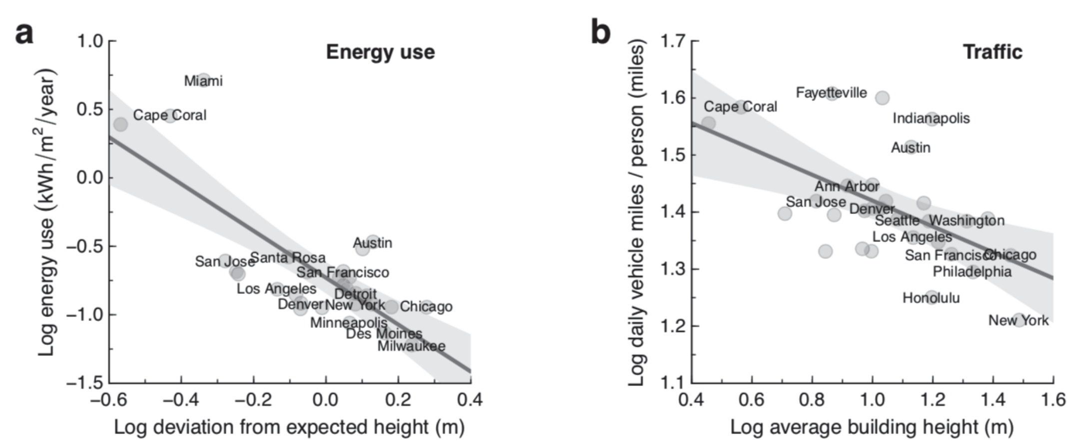


Housing is never affordable in large cities

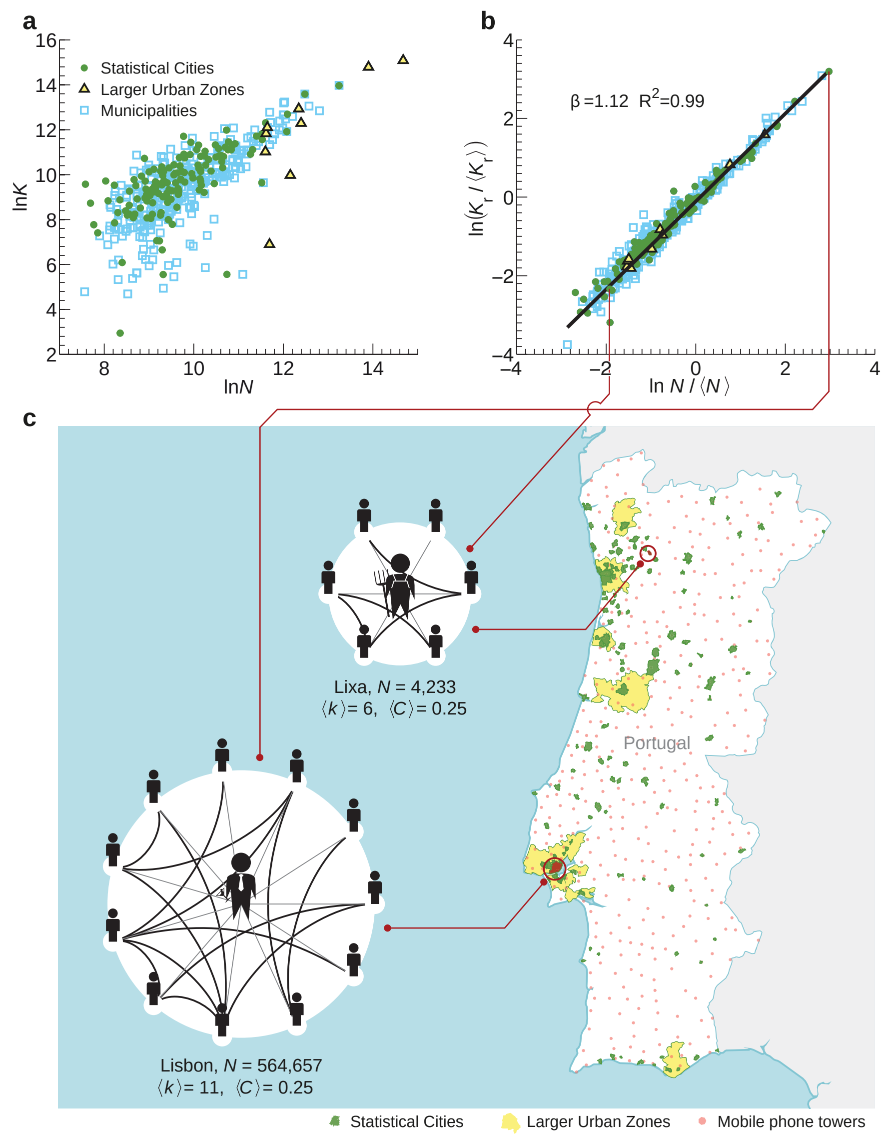
The city in 3D
shape, energy use and mobility



scaling prediction



with Markus Schläpfer and Joseph Lee

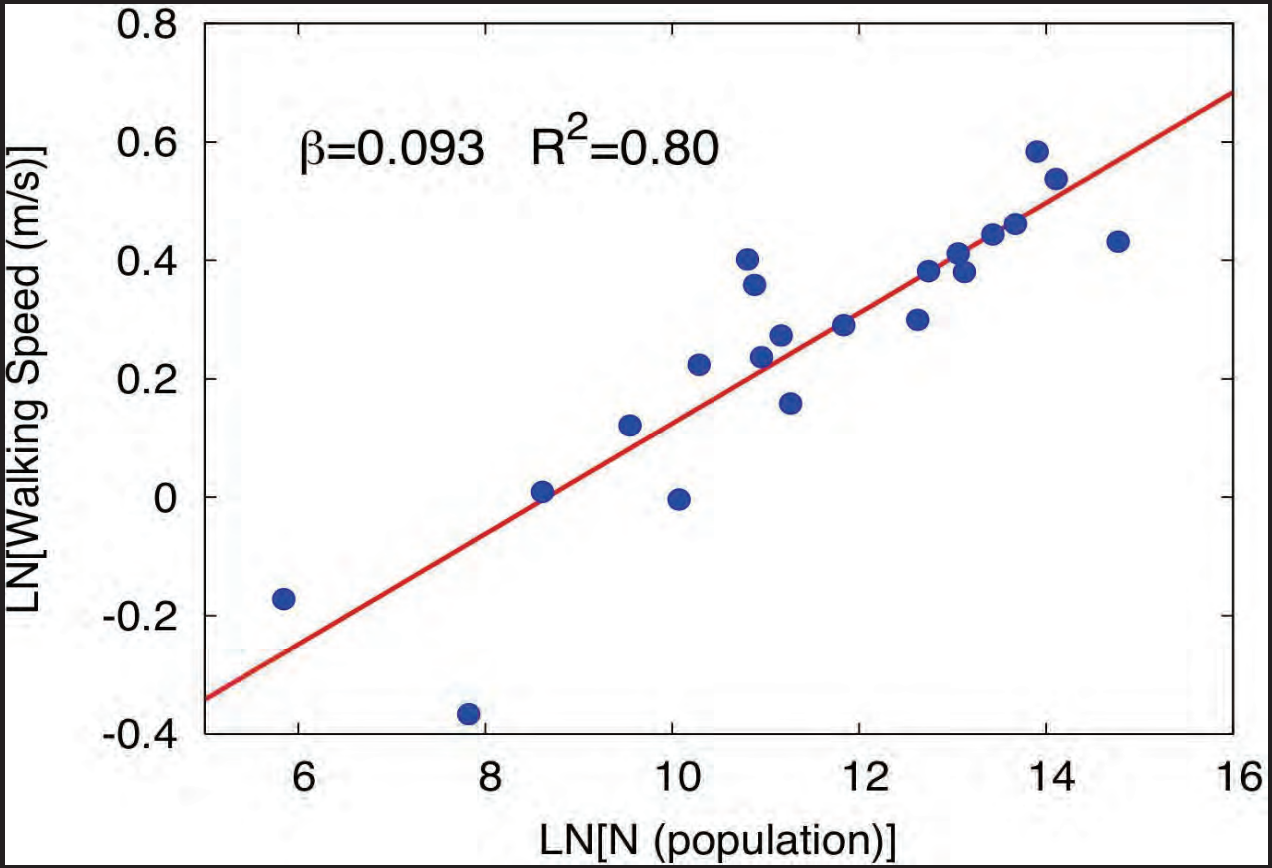


Urban cellphone networks

$\beta = 1.12\text{-}1.19$

Schläpfer, Bettencourt et al, J R Soc I. 2014

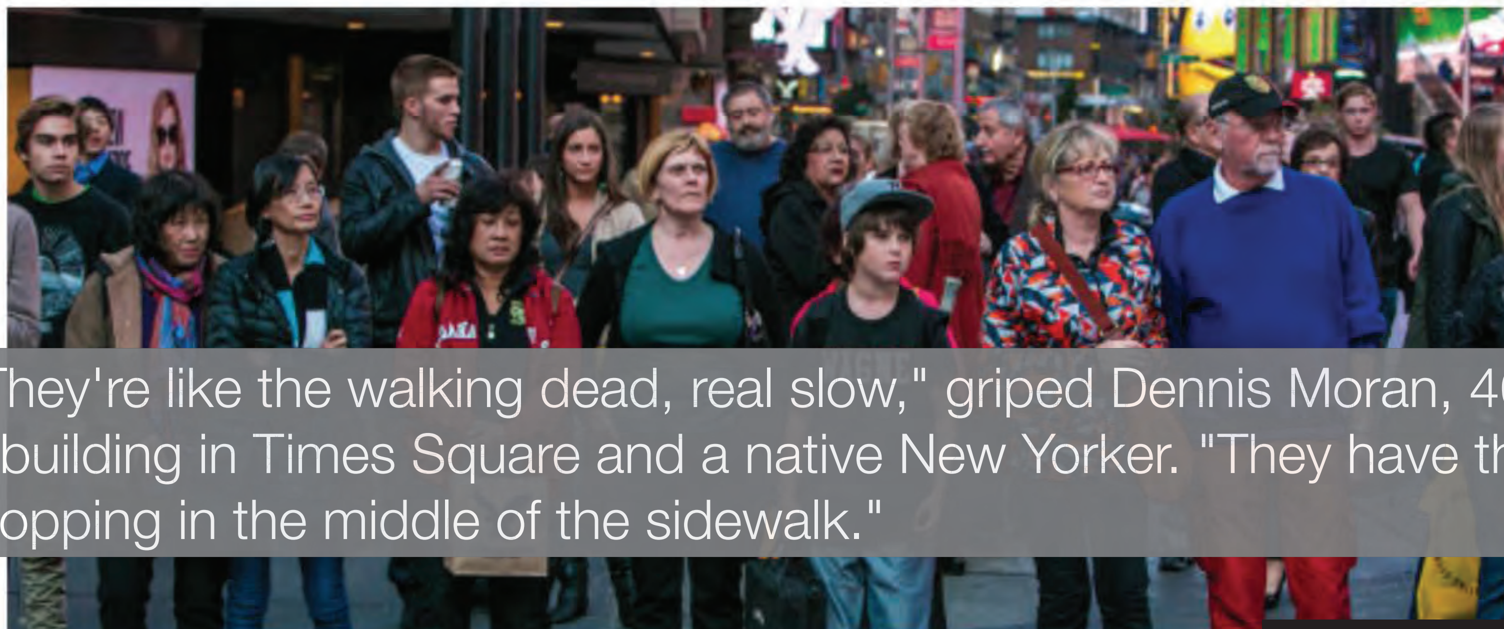
Walking Speed vs Population Size



Bettencourt et al, PNAS 2007

NYC Tourists Are 'Like Walking Dead,' Anger Fast-Paced New Yorkers During Holiday Season

By JAKE PEARSON 12/12/13 01:07 PM ET EST **AP**



"They're like the walking dead, real slow," griped Dennis Moran, 46, a fire safe
a building in Times Square and a native New Yorker. "They have this unnatural
stopping in the middle of the sidewalk."

credit: Huffington Post

Evidence and theory for lower rates of depression in larger US urban areas

Mental Health

…and a number of cognitive and behavioral traits

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Edited by William A. V. Clark, University of California, Los Angeles, CA, and approved June 18, 2021 (received for review October 27, 2020)

It is commonly assumed that cities are detrimental to mental health. However, the evidence remains inconsistent and at most, makes the case for differences between rural and urban environments as a whole. Here, we propose a model of depression driven by an individual's accumulated experience mediated by social networks. The connection between observed systematic variations in socioeconomic networks and built environments with city size provides a link between urbanization and mental health. Surprisingly, this model predicts lower depression rates in larger cities. We confirm this prediction for US cities using four independent datasets. These results are consistent with other behaviors associated with denser socioeconomic networks and suggest that larger cities provide a buffer against depression. This approach introduces a systematic framework for conceptualizing and modeling mental health in complex physical and social networks, producing testable predictions for environmental and social determinants of mental health also applicable to other psychopathologies.

cities | depression | social networks | built environment | complex systems

Living in cities changes the way we behave and think (1–3). mental health in cities vs. rural areas (7, 8). However, this evidence and that linking SWB and cities (15–18) have remained mixed and often explicitly inconsistent (19, 20) due to differences in 1) reporting (e.g., surveys vs. medical records); 2) types of measurement (e.g., surveys vs. interviews); 3) definitions of what constitutes urban; and 4) the mental disorders studied (e.g., schizophrenia vs. depression).

For these reasons, it is desirable to create a systematic framework that organizes this diverse body of research and interrogates how varying levels of urbanization influence mental health across different sets of indicators. Here, we begin to build this framework for depression in US cities. We show that, surprisingly, the per capita prevalence of depression decreases systematically with city size.

Like earlier classic approaches, our strategy frames the effects of city size on mental health through the lens of the individual experience of urban physical and socioeconomic environments. Crucial to our purposes, many characteristics of cities have been recently found to vary predictably with city population size. These systematic variations in urban indicators are explained by denser built environments and their associated increases in the intensity of human interactions and resulting adaptive

ECOLOGY

PSYCHOLOGICAL AND COGNITIVE SCIENCES

https://www.pnas.org/doi/10.1073/pnas.2022472118

City Population, Majority Group Size, and Residential Segregation Drive Implicit Racial Biases in U.S. Cities

Mansueto Institute for Urban Innovation Research Paper 36

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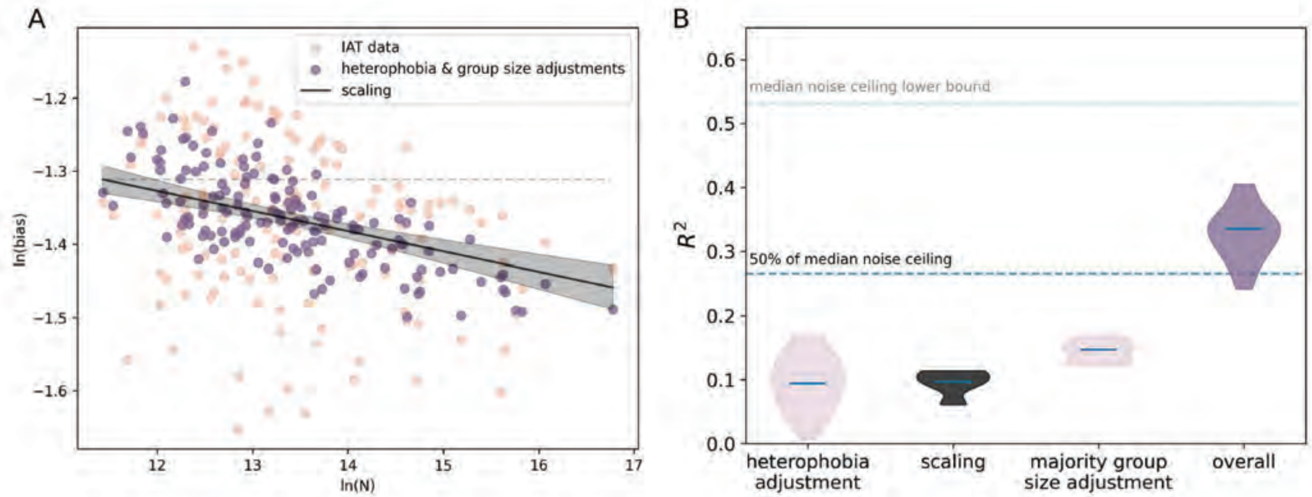

Abstract

Implicit biases, expressed as differential treatment towards out-group members, are pervasive in human societies. These biases are often racial or ethnic in nature and create disparities and inequities across many aspects of life. Recent research has revealed that implicit biases are, for the most part, driven by social contexts and local histories. However, it has remained unclear how and if the regular ways in which human societies self-organize in cities produce systematic variation in implicit bias strength. Here we leverage extensions of the mathematical models of urban scaling theory to predict and test between-city differences in implicit racial biases. Our model comprehensively links scales of organization from city-wide infrastructure to individual psychology to quanti-tatively predict that cities that are (1) more populous, (2) more diverse, and (3) less segregated have lower levels of implicit biases. We find broad empirical support for each of these predictions in U.S. cities for data spanning a decade of racial implicit association tests from millions of individuals. We conclude that the organization of cities strongly drives the strength of implicit racial biases and provides potential systematic intervention targets for the development and planning of more equitable societies.