Cities as Complex Systems II

Individual and Collective Agents, Dynamics, Information

CSSS, Santa Fe, June 22, 2023

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The next few years are likely to lead to an increasing study of complexity in the context of statistical dynamics, with a view to better understanding physical, economic, social, and especially biological systems.

It will be an exciting time.

As science turns to complexity, one must realize that complexity demands attitudes quite different from those heretofore common in physics.

Goldenfeld & Kadanoff, *Science,* 1999

COMPLEX SYSTEMS

VIEWPOINT

Simple Lessons from Complexity

Nigel Goldenfeld[1] and Leo P. Kadanoff[2]

The complexity of the world is contrasted with the simplicity of the basic laws of physics. In recent years, considerable study has been devoted to systems that exhibit complex outcomes. This experience has not given us any new laws of physics, but has instead given us a set of lessons about appropriate ways of approaching complex systems.

https://www.science.org/doi/10.1126/science.284.5411.87

C. R. Physique 20 (2019) 308–318

Contents lists available at ScienceDirect

Comptes Rendus Physique

www.sciencedirect.com

From statistical physics to social sciences / *De la physique statistique aux sciences sociales*

Towards a statistical mechanics of cities

Vers une mécanique statistique des villes

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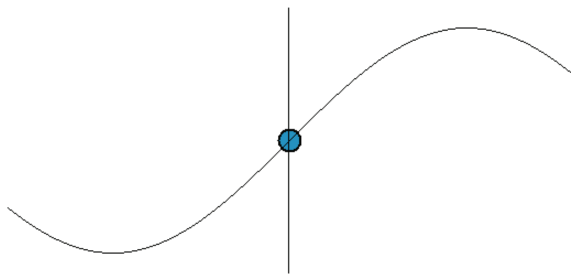
Canonical modeling in physics

$$\dot{x} = \frac{p}{m}, \quad \dot{p} = -\frac{dV(x)}{dx}$$

position momentum

$$\dot{x} \equiv \frac{dx}{dt}$$



Credit : wikipedia

energy

$$E(x,p) = \frac{p^2}{2m} + V(x)$$

Example: $V(x) = gx^2$

Harmonic oscillator

Conservation of Energy (micro-canonical ensemble)

$$\dot{E} = \frac{p}{m}\dot{p} + \frac{dV(x)}{dx}\dot{x} = -\frac{p}{m}\frac{dV(x)}{dx} + \frac{dV(x)}{dx}\frac{p}{m} = 0.$$

Canonical modeling in physics, in contact with heat reservoir

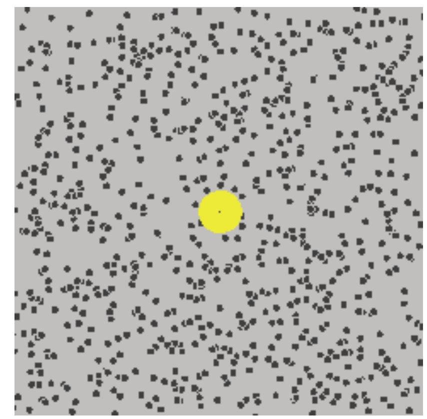
$$\dot{x} = \frac{p}{m}, \qquad \dot{p} = -\gamma p - \frac{dV(x)}{dx} + \chi$$

position

momentum

random force (thermal)

dissipative force



Credit : wikipedia

Internal energy

$$E(x,p) = \frac{p^2}{2m} + V(x)$$

Conservation of Energy (canonical ensemble)

$$\dot{E} = \frac{p}{m}\dot{p} + \frac{dV(x)}{dx}\dot{x} = -\frac{p}{m}\left(\gamma p + \frac{dV(x)}{dx} - \chi\right) + \frac{dV(x)}{dx}\frac{p}{m} = -2\gamma\frac{p^2}{2m} + 2\gamma k_B T$$

$$\rightarrow \quad T_k = \frac{p^2}{2m} = k_B T$$

Thermalization (equipartition in 2D)

$$P(p) = \frac{1}{Z}e^{-\frac{p^2}{2mk_BT}}$$

Maxwell-Boltzmann distribution

Particles in Physics are identical

They are passive: lack ‘behavior’

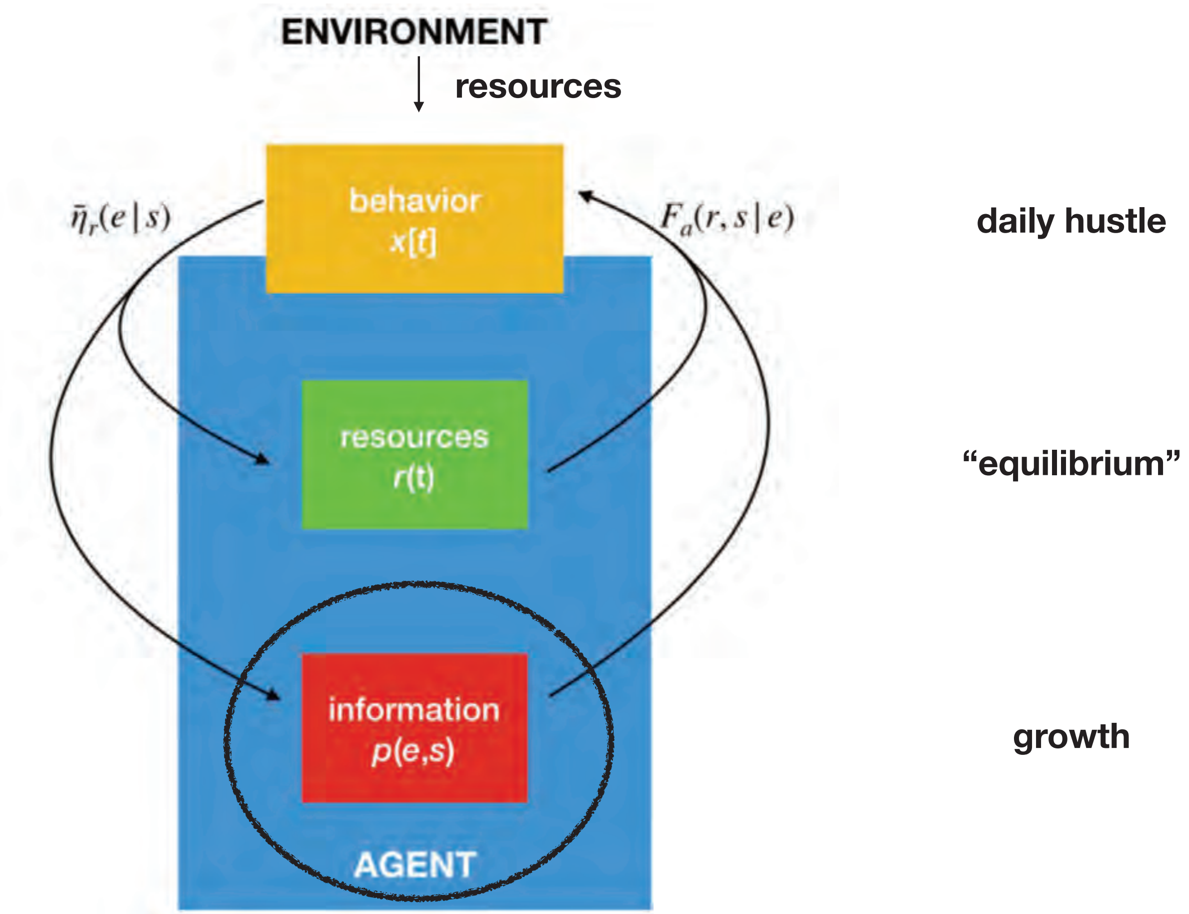
They are purposeless: lack intention

The situation is completely different for agents in complex systems

This requires ability to exert forces that underlie behavior, and make choices between courses of action

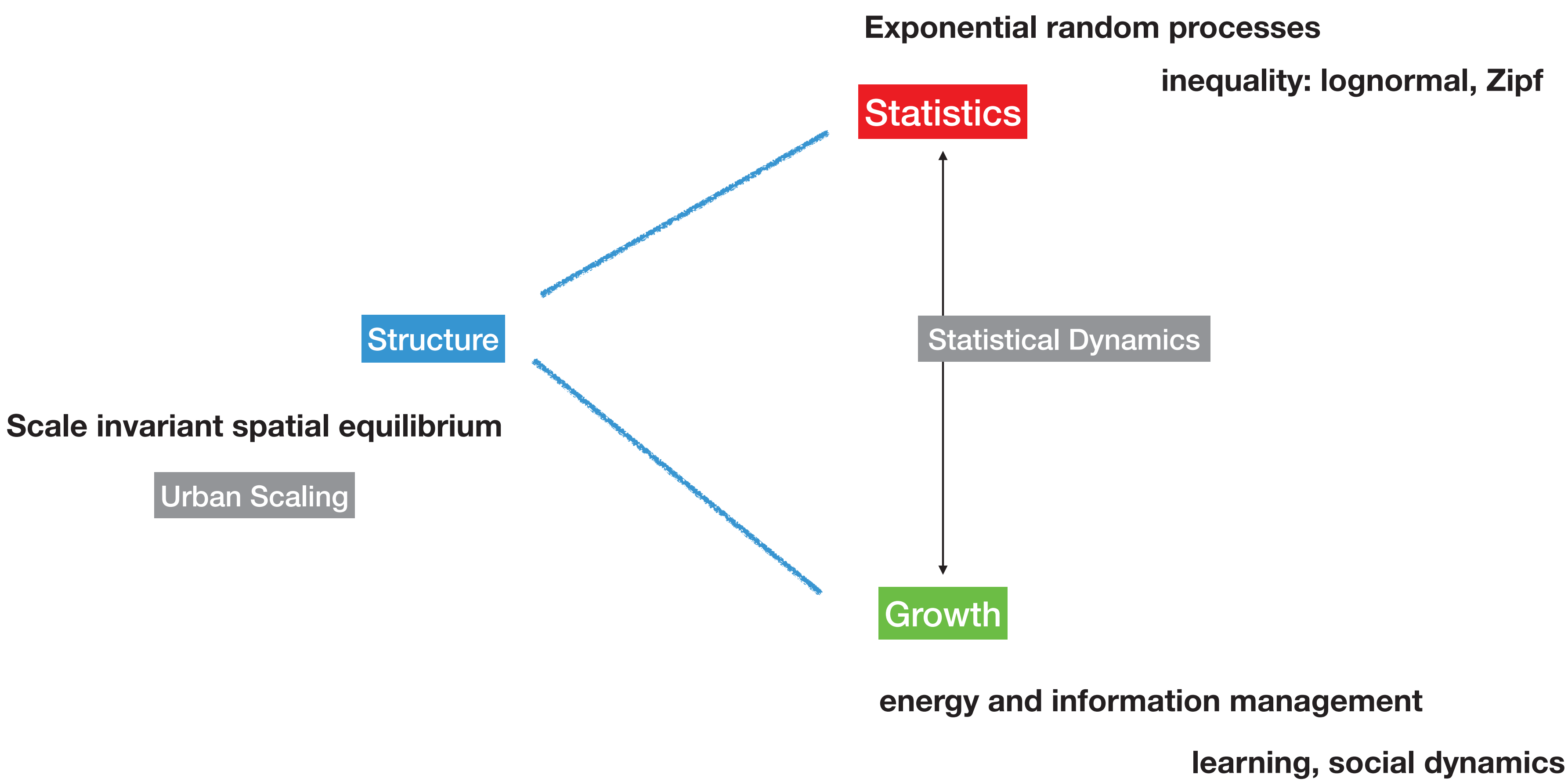
This requires reservoirs of both **energy** and **information**

The general agent in complex systems



Strategic active agents manage resources purposefully in stochastic environments

This has a macroscopic expression for complex systems, such as cities



1. Behavior

$$\dot{x} = p/m, \qquad \dot{p} = -\gamma p - \frac{dV(x)}{dx} + \chi + F_a$$

$$[\gamma] = 1/t$$

self-propelled force, selecting position and velocity

Conservation of energy:

$$\Delta E = -2(\gamma \Delta t)\langle \frac{p^2}{2m} \rangle + 2(\gamma \Delta t) k_B T + \oint F_a \cdot dx$$

Work done by the self-propelling force over a cycle

$$W_a = \oint F_a \cdot dx$$

small

$$\langle \frac{p^2}{2m} \rangle = k_B T + \frac{1}{2(\gamma \Delta t)} W_a$$

$$\bar{E} = \langle \frac{p^2}{2m} \rangle \simeq \frac{1}{2(\gamma \Delta t)} W_a \equiv \bar{w}_a$$

Observed energy is now dominated by behavioral forces

$$P(p_1, p_2) = \frac{1}{Z} e^{-\frac{p_1^2 + p_2^2}{2m\bar{w}_a}}$$

The temperature is the work per unit of dissipation

depends on statistics of $\bar{w}_a$

2. Energy dynamics

A Model of Resource Dynamics

$$\frac{dr(t)}{dt} = y(t) - c(t) = \eta_r(t) r(t)$$

income　　cost

"one-good wealth accumulation model"

e.g. Piketty

change in resources

stock: wealth, energy

"spatial equilibrium"

savings rate = growth rate

growth

$$\eta_r(t) \equiv \frac{y(t)}{r(t)} - \frac{c(t)}{r(t)}.$$

definition

Solution:

$$\ln \frac{r(t)}{r(0)} = \left(\bar{\eta}_r - \frac{\sigma_r^2}{2}\right) t + \Theta(t),$$

noise: $\Theta(t) = \sum_{l=1}^{t} \varepsilon_r(t_l),$ ⟶ **Normal**

Two independent parameters:

Exponential random processes

$$\gamma = \bar{\eta}_r - \sigma_r^2/2$$

Growth rate

at different scales

↓

Inequality → **learning of relevant information**

$\bar{\eta}_r$

average growth rate

maximize

σ_r

"volatility"

minimize

control: households, government

Objectives: change through new knowledge ↔ stability, resilience

The counter intuitive consequences of stochastic geometric growth

Consequences:

zero average, standard deviation: $\sigma_\Theta = \sigma_r\sqrt{t}$

1. $$\ln\frac{r(t)}{r(0)} = \left(\bar{\eta}_r - \frac{\sigma_r^2}{2}\right)t + \Theta(t), \qquad \Theta(t) = \sum_{l=1}^{t} \varepsilon_r(t_l) \quad \sim \sigma_r\sqrt{t}$$

$$= \gamma_r$$

Central Limit Theorem -> Gaussian

lognormal statistics !!

2. $$\frac{1}{t}\ln\frac{r(t)}{r(0)} = \gamma_r + \frac{\Theta(t)}{t} \to \gamma_r,$$

The average growth rate over long times becomes a simple number

ergodicity (population dynamics)

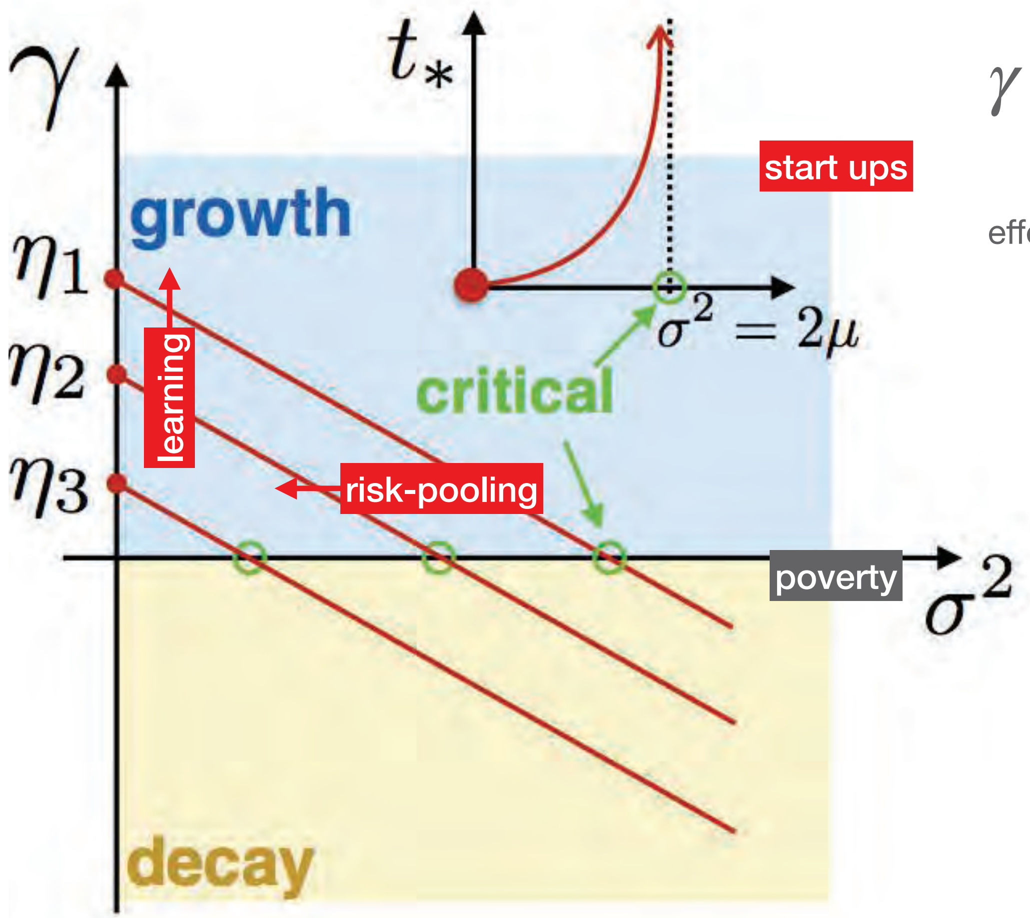
3. $$t_* = \frac{\sigma_r^2}{\left(\bar{\eta}_r - \frac{\sigma_r^2}{2}\right)^2},$$

There is a minimum time to see through the "fog" of sort term fluctuations.

proportional to the uncertainty (volatility, std) between relative income and costs

people with a lot of uncertainty do not see growth as a possibility

Phase diagram



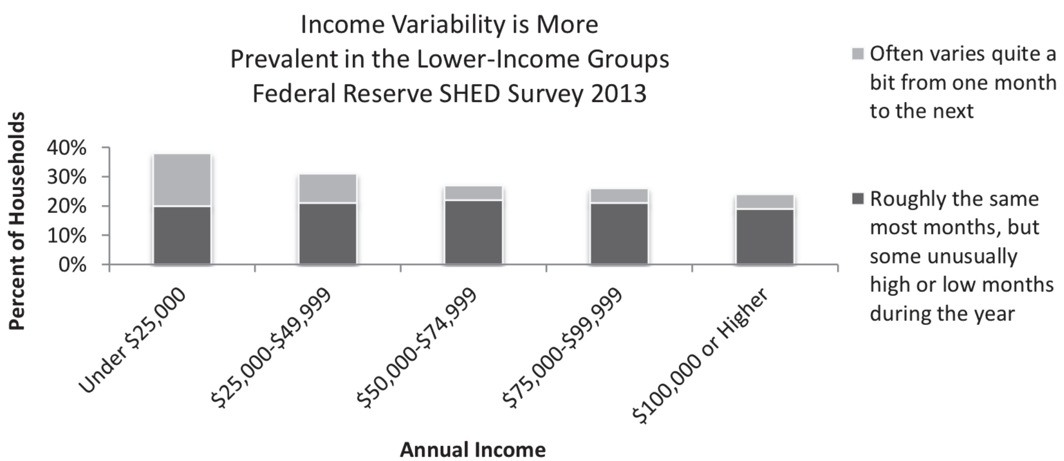
$$\gamma = \eta - \frac{\sigma^2}{2}$$

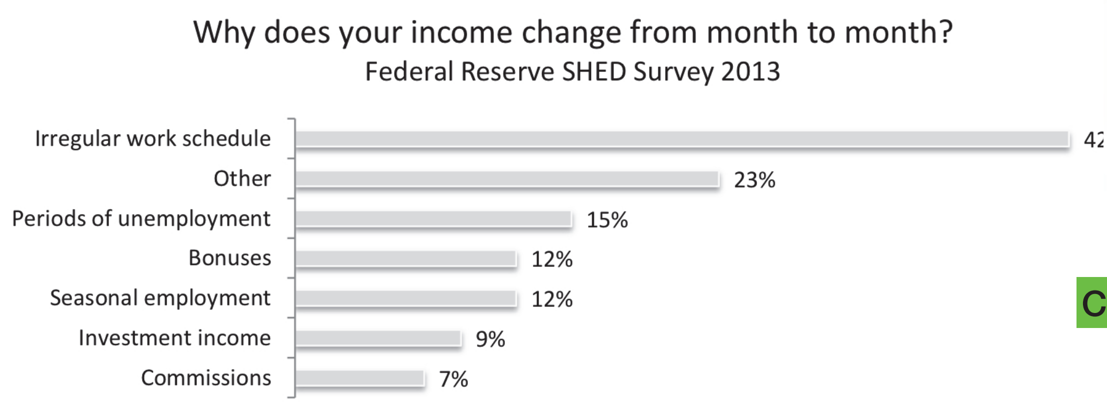
effective growth rate

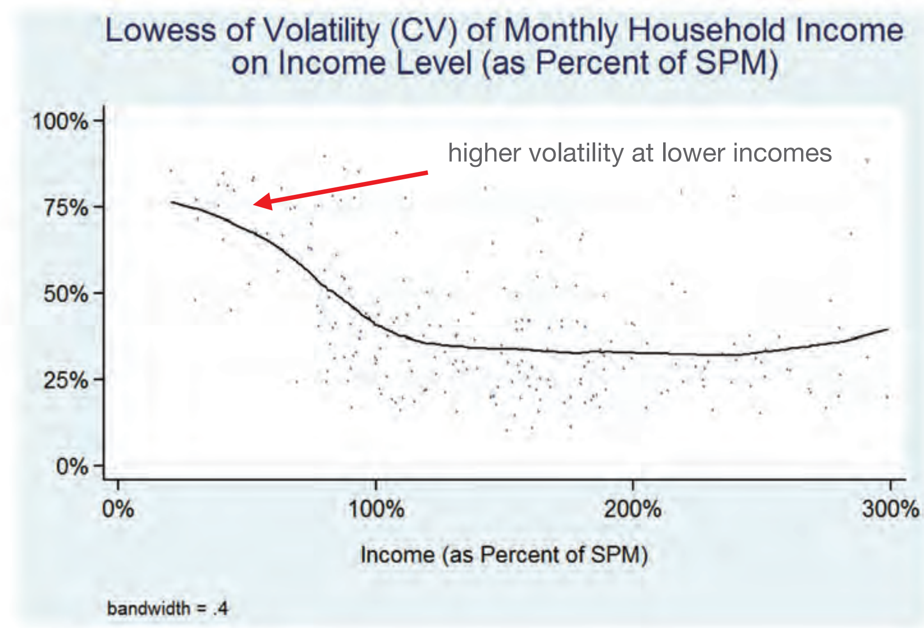
Net Growth Requires Low Fluctuations

Poverty is a low resources, high volatility state

lower effective growth rates, unclear horizons







Can this be studied using registry data in the Netherlands?

from: Income Gains and Month-to-Month Income Volatility: Household evidence from the US Financial Diaries Hannagan + Morduch (2015)

How to lower volatility? How to derive lognormal and power law statistics?

SCIENCE ADVANCES | RESEARCH ARTICLE

SOCIAL SCIENCES

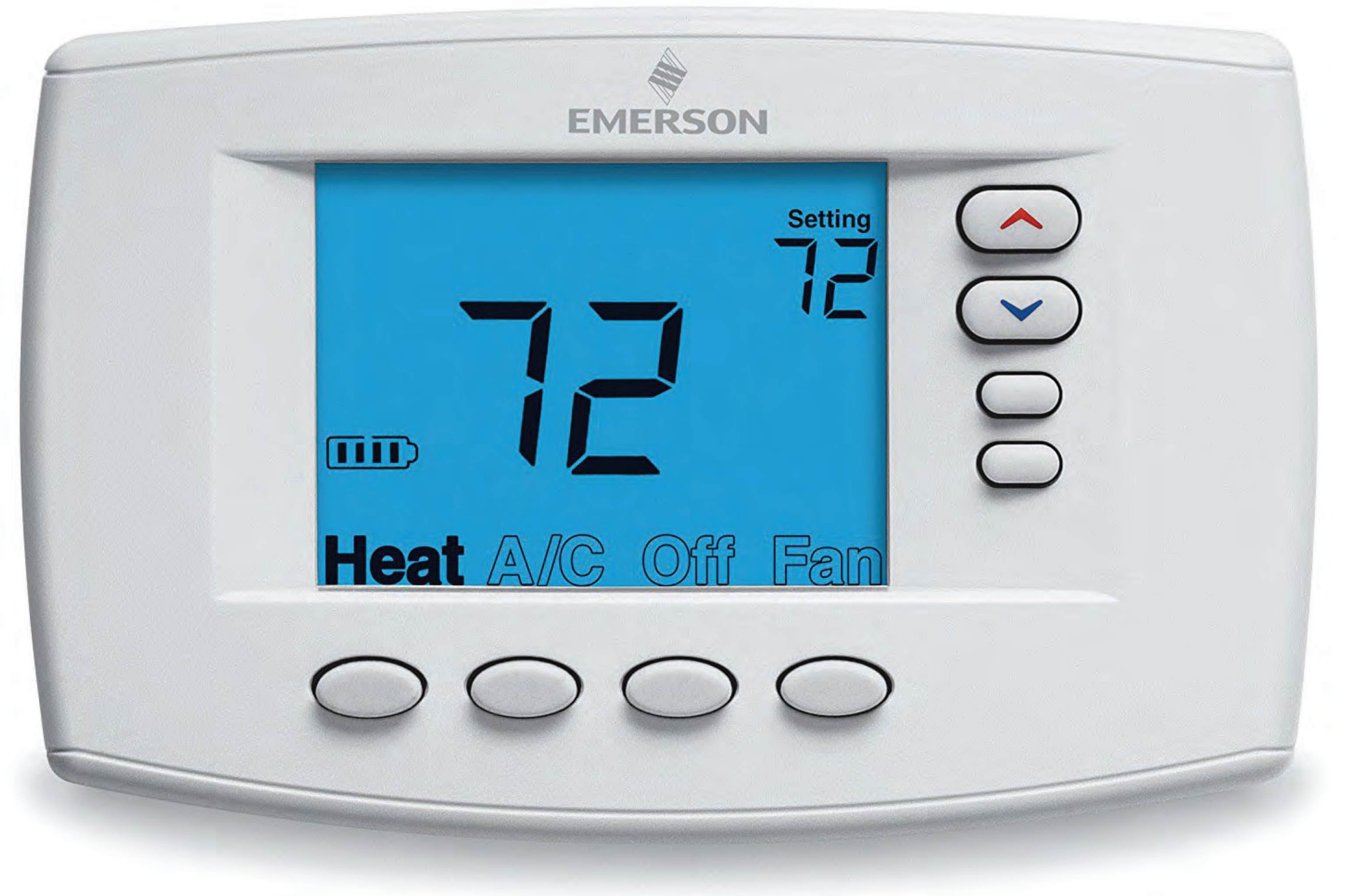
Urban growth and the emergent statistics of cities

Luis M. A. Bettencourt[1,2]

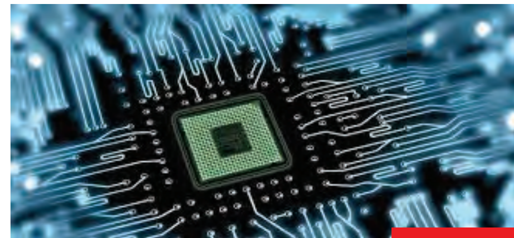
Urban theory models cities as spatial equilibria to derive their aggregate properties as functions of extensive variables, such as population size. However, this assumption seems at odds with cities' most interesting properties as engines of fast and variable processes of growth and change. Here, we build a general statistical dynamics of cities across scales, from single agents to entire urban systems. We include agents' strategic behavior to produce predictable growth rates, which requires balancing relative incomes and costs over time. We implement these dynamics using stochastic differential equations and control theory to demonstrate a number of general emergent properties of cities deriving from limit theorems applied to growth rates. This framework establishes necessary conditions for scaling to be conserved by urban dynamics and shows how exponent corrections can be calculated. These ideas are tested using stochastic simulations and a long timeseries for 382 US Metropolitan Areas over nearly five decades.

https://www.science.org/doi/epdf/10.1126/sciadv.aat8812

Feedback Control is a big part of your life



“stable” airplanes



“error free” computers

Self-driving cars

Balancing humans and robots

Want low fluctuations:

$$\eta_r(t) \equiv \frac{y(t)}{r(t)} - \frac{c(t)}{r(t)} = b(t) - a(t) = \bar{\eta} + u(t) - v(t) = \bar{\eta} + \epsilon(t)$$

definition

income fluctuations

choice expenditures

definition

when I have more money can spend more and vice-versa

Consumption Smoothing

need to average (smoothen) expenditures and incomes over some time
month, season, year

How Control theory works:

PID Controller

$$u(t) = k_P \varepsilon_r(t) + k_I \int_0^t \varepsilon_r(t')dt' + k_D \frac{d\varepsilon_r}{dt},$$

Time costs to track income fluctuations

This gives a simple dynamics for errors

$$\frac{d^2\varepsilon_r}{dt^2} + 2\zeta\omega\frac{d\varepsilon_r}{dt} + \omega^2\varepsilon_r = F/m,$$

$$m = k_D,\ \omega = \sqrt{k_I/k_D} \text{ and } \zeta = \frac{k_P+1}{2\sqrt{k_D k_I}},$$

noisy spring

$$d\varepsilon_r = -\frac{M}{2}\varepsilon dt + \Omega dW(t).$$

$$M = \omega/\zeta = k_I/[2(k_P+1)]$$

error wants to vanish

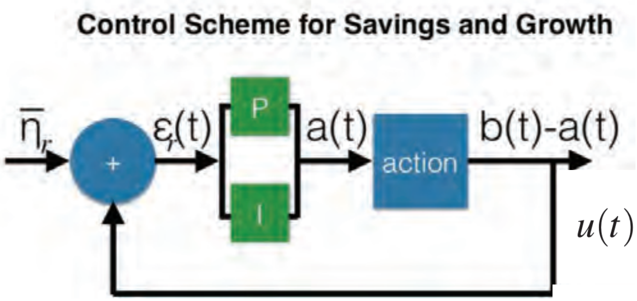
noise

Statistics of error is "under control":

$$P[\varepsilon_r, t|\varepsilon_0] = \sqrt{\frac{M}{2\pi\Omega^2(1-e^{-Mt})}}\, e^{-\frac{M}{2\Omega^2}\left[\frac{(\varepsilon_r-\varepsilon_0 e^{-M/2\ t})^2}{1-e^{-Mt}}\right]} \rightarrow \sqrt{\frac{M}{2\pi\Omega^2}}\, e^{-\frac{M}{2\Omega^2}\varepsilon_r^2},$$

quality of control

Why are relative incomes and costs correlated?

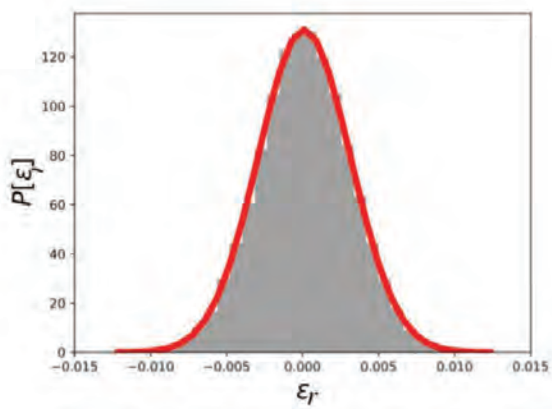


"Consumption Smoothing"

$$u(t) = k_P \varepsilon_r(t) + k_I \int_0^t \varepsilon_r(t')dt' + k_D \frac{d\varepsilon_r}{dt},$$

$$k_D \frac{d^2\varepsilon_r}{dt^2} + (k_P + 1)\frac{d\varepsilon_r}{dt} + k_I \varepsilon_r = \frac{dv}{dt}.$$

damped harmonic oscillator + noise



$$\sigma_\epsilon^2 = 2\Omega^2 \frac{k_P + 1}{k_I}$$

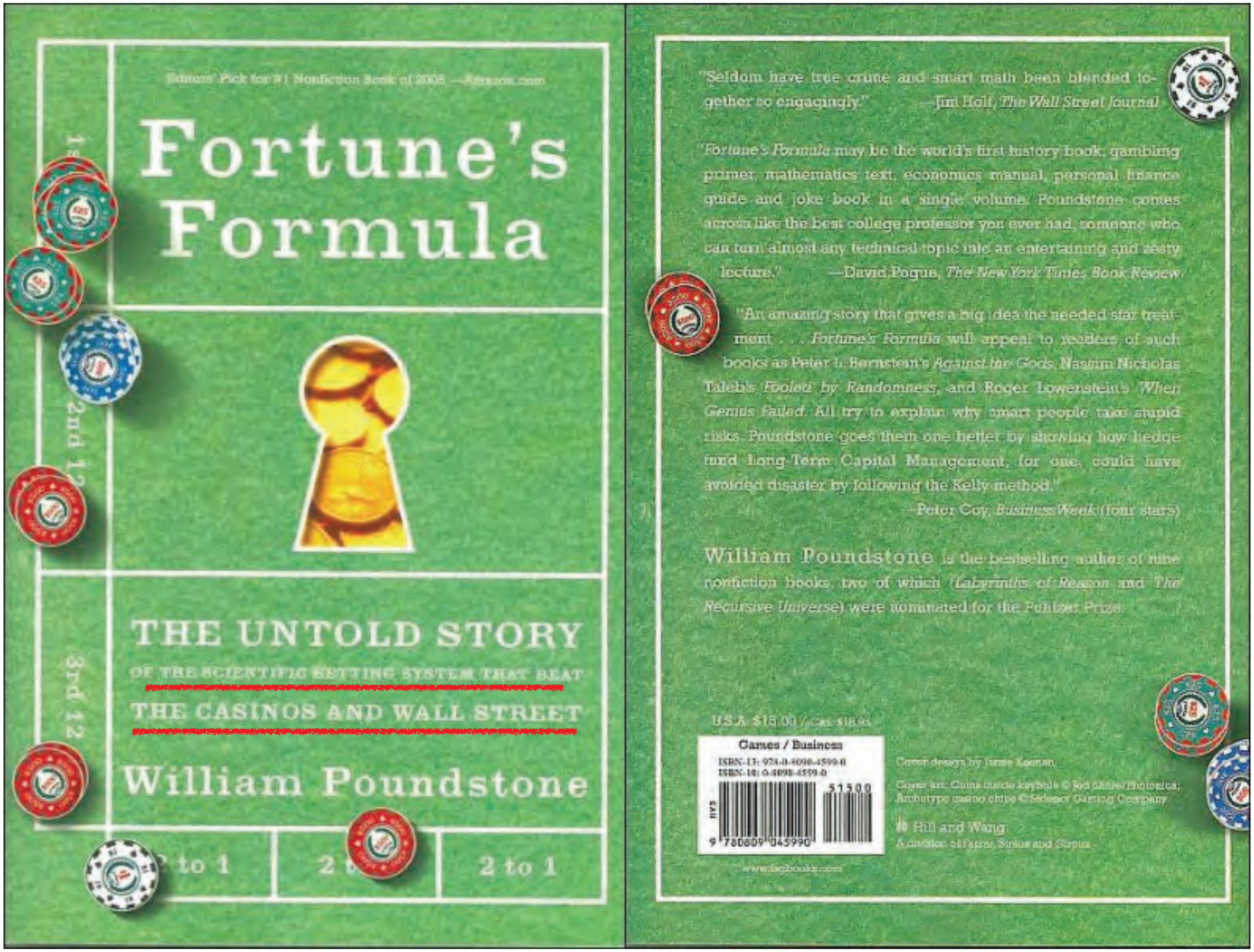
controlled by time-averaging of error

growth rates become Gaussian & growth is geometric and random

At larger (population) scales, there are many more mechanisms:

- insurance
- pension funds
- government social services
- corporate ‘bail-outs’

How to increase growth rates?



http://www.fortunesformula.com/

3. Information

Investment and information

Inter temporal optimization: sequential investment in stochastic environmental outcome

new resources

$$r' \rightarrow o(e_i)f(e_i \mid s)r$$

initial resources

signal

payoff > 1

state of the world

after T steps:

$$r(T) = \Pi_{t=1}^{T} o(e_t)f(e_t \mid s_t)r(0)$$

average growth rate:

$$\bar{\eta}_r = \lim_{T\rightarrow\infty} \frac{1}{T} \ln \frac{r(T)}{r(0)} = v_T \sum_i P(e_i, s_i) \ln f(e_i \mid s) o(e_i)$$

Maximal Growth Rate:

Simple intertemporal optimization without discounting

$$\bar{\eta}_r = \lim_{T\to\infty} \frac{1}{T} \ln \frac{r(T)}{r(0)} = v_T \sum_{e,s} P(e,s) \ln f(e\,|\,s) o(e)$$

best allocation: $f(e\,|\,s) \to P(e\,|\,s)$

fair odds: $o(e) \to 1/P(e)$ (worst case = "efficient markets")

$$\boxed{\bar{\eta}_r^* = v_T \sum_{e,s} P(e,s) \ln \frac{P(e,s)}{P(e)P(s)} = v_T\ I[E;S]}$$

Shannon's Mutual Information

This is also the Optimal Predictor of Environment $|_{\text{Signal}}$ ~ Bayes ~Machine Learning

~maximal fitness

Ultimately, this involves developing a new theory of optimal choice:

better than 'rational choice theory', beyond behavioral economics

- intertemporal (life course)

- deals with uncertainty

- social networks, power, distribution: organizations

- consistent across scales

ELSEVIER

Current Opinion in Psychology

Volume 33, June 2020, Pages 183-188

The effects of low socioeconomic status on decision-making processes

Jennifer Sheehy-Skeffington

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https://doi.org/10.1016/j.copsyc.2019.07.043

Highlights

- Low income groups are criticised for making suboptimal decisions in domains such as health and finance.
- These reflect a psychological shift in response to socioecological cues prevalent in low socioeconomic status (SES) contexts.
- Low SES experiences present the cues of resource scarcity, environmental instability, and low subjective social status.
- These trigger a regulatory shift toward present (over future) goals and the up/down-regulation of specific cognitive skills.

https://www.sciencedirect.com/science/article/pii/S2352250X1930123X?via=ihub

Population dynamics of growth and learning

TOPICS
TOPICS IN COGNITIVE SCIENCE

Free Access

The Rules of Information Aggregation and Emergence of Collective Intelligent Behavior

Luís M. A. Bettencourt

First published: 12 October 2009 | https://doi.org/10.1111/j.1756-8765.2009.01047.x | Citations: 20

should be sent to Luís M. A. Bettencourt, Theoretical Division, MS B284, Los Alamos National Laboratory, Los Alamos NM 87545; or Luís M.A. Bettencourt, Santa Fe Institute, 1399 Hyde Park Road, Santa Fe, NM 87501. E-mail: lmbett@lanl.gov

Abstract

Information is a peculiar quantity. Unlike matter and energy, which are conserved by the laws of physics, the aggregation of knowledge from many sources can in fact produce more information (synergy) or less (redundancy) than the sum of its parts. This feature

IUS Ch 9

https://onlinelibrary.wiley.com/doi/10.1111/j.1756-8765.2009.01047.x

ELSEVIER

Physica A: Statistical Mechanics and its Applications
Volume 607, 1 December 2022, 128180

Statistical dynamics of wealth inequality in stochastic models of growth

Jordan T. Kemp[a], Luis M.A. Bettencourt[b, c, d]

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https://doi.org/10.1016/j.physa.2022.128180

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Highlights

- Agent growth rates and initial resources correlations affect aggregate growth rates.
- Negative correlated growth rate assignments reduce aggregate growth.
- Volatility and growth rate, resource covariance dominate intermediate time dynamics.
- Variances in growth rates across the population dominate long time inequality.
- The effects of heterogeneity on inequality outpace effects on growth.

https://www.sciencedirect.com/science/article/pii/S0378437122007385

PNAS nexus

Volume 2, Issue 4
April 2023

Learning increases growth and reduces inequality in shared noisy environments

Jordan T Kemp, Luís M A Bettencourt Author Notes

PNAS Nexus, Volume 2, Issue 4, April 2023, pgad093,
https://doi.org/10.1093/pnasnexus/pgad093
Published: 22 March 2023 **Article history ▾**

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Article Contents

Abstract

Stochastic multiplicative dynamics characterize many complex natural phenomena such as selection and mutation in evolving populations, and the generation and distribution of wealth within social systems. Population heterogeneity in stochastic growth rates has been shown to be the critical driver of wealth inequality over long time scales. However, we still lack a general statistical theory that systematically explains the origins of these heterogeneities resulting from the dynamical adaptation of agents to their

https://academic.oup.com/pnasnexus/article/2/4/pgad093/7083303

Growth rates for individuals vs collectives

Is the growth rate for a city the average of the growth rates for individuals?

Not in general:

$$r_G = \frac{1}{G}\sum_{j=1}^{G} r_j$$

average wealth

$$\frac{dr_G}{dt} = y_G - c_G = (\eta r)_G,$$

growth of wealth per capita in a population

average of product

$$(\eta r)_G = \frac{1}{G}\sum_{j=1}^{G} \eta_j w_j = \eta_G r_G + \text{covar}_G(\eta, r) = [\eta_G + \text{covar}_G(\eta, r/r_G)]\, r_G.$$

average rate

"selection"

Consequences:

$$(\eta r)_G = \frac{1}{G}\sum_{j=1}^{G}\eta_j w_j = \eta_G r_G + \mathrm{covar}_G(\eta, r) = [\eta_G + \mathrm{covar}_G(\eta, r/r_G)]\, r_G.$$

average corrected by co-variance

positive: richer people get higher growth rates

correlation between resources and rates

negative: richer people get lower growth rates

anti-correlation between resources and rates

What situation gives the highest overall growth rates?

What situation gives the lowest inequality?

This is an instance of a very general result

Price Equation of Selection:

$$\bar{\gamma}\Delta\bar{z} = \mathrm{covar}(z,\gamma) + E[\gamma\Delta z]$$

average growth rate ($\bar{\gamma}$)

average trait change ($\Delta\bar{z}$)

Pure selection

$z = \gamma$

$$\Delta\bar{\gamma} = \frac{\sigma_\gamma^2}{\bar{\gamma}} \geq 0.$$

Fisher's Fundamental Theorem

Selection in a heterogeneous population creates growth

Monopoly arrests growth increases to the dominant type

Increasing growth in a population or maintaining it under obsolesce requires maintaining population diversity

This is a large-scale, long term result

For N agents we get:

$$I(e;\{s_i\}) = H[e] - H[e|\{s_i\}]$$

$$= - \sum_{i=1}^{N} \frac{\Delta H[e]}{\Delta s_i} - \sum_{i>j=1}^{N} \frac{\Delta^2 H[e]}{\Delta s_i \, \Delta s_j} - \cdots \frac{\Delta^{\mathrm{N}} H[e]}{\Delta s_1 \ldots \Delta s_N} \, ,$$

$$-\frac{\Delta H[e]}{\Delta s_i} = H[e] - H[e|s_i] = I(e, s_i);$$

For 2 agents we get:

$$I(e;\{s_1, s_2\}) = I(e; s_1) + I(e; s_2) - R_I(e; s_1, s_2); \quad R_I(e; s_1, s_2) = I(s_1; s_2) - I(s_1; s_2|e)$$

Coefficient of redundancy

Coordination given environment

Properties of Information and Institutions

Many problems need organizations: firms, NGOs, governments

Information in a group

$$I(E; \{S_1, S_2, \ldots, S_N\}) \quad \begin{matrix} < \\ = \\ > \end{matrix} \sum_{i=1}^{N} I(E; S_i)$$

redundancy

independence

synergy

more than the sum of the parts

The advantage of collective action requires synergy : diverse collective institutions

Bettencourt, Topics in Cognitive Science, 2009

to evaluate quality of an institution (group)

compare individual action to collective production

$$\Delta r_i = I(E; S_1) r_i(0) - c_i$$

Individual knowledge

$$\Delta r_i = B_i I(E; \{S_1, S_2, \ldots, S_N\}) r_i(0) - C_i$$

distribution of collective gains

collective knowledge

collective costs

Collaborating in the groups is preferred when:

$$B_i I(E; \{S_1, S_2, \ldots, S_N\}) > I(E; S_i) + \frac{C_i - c_i}{r_i(0)}$$

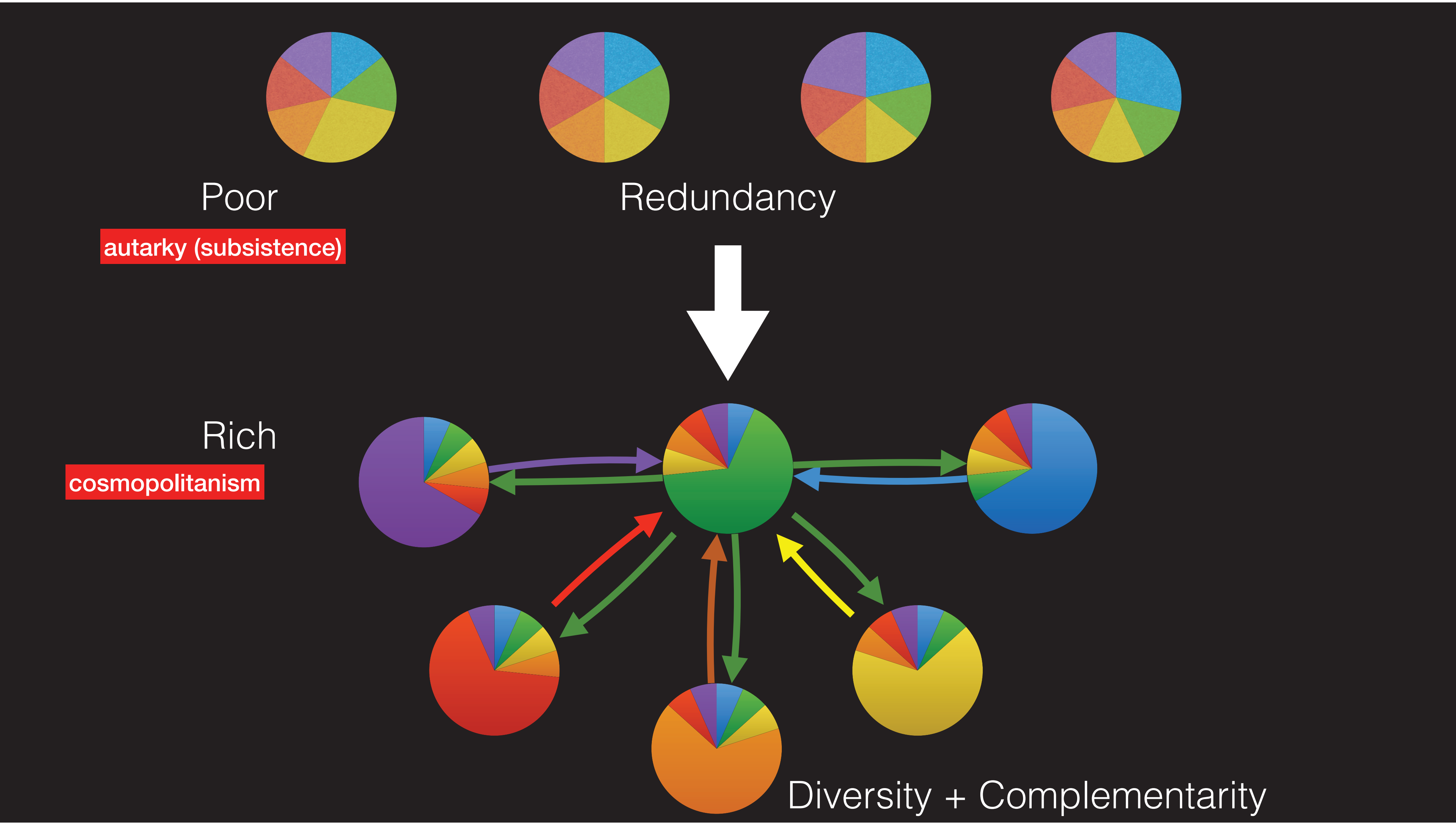
'fair' re-distribution of gains

low costs of collective action vs individual cost

strong synergy

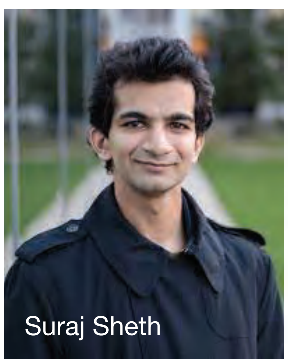
low individual information

cities / firms are good at strong synergies, lower collective costs; but not always fair distribution


Poor
autarky (subsistence)
Redundancy
Rich
cosmopolitanism
Diversity + Complementarity

Human development as a network process (in cities)

1. Measuring Human Development across scales



nature › npj urban sustainability › articles › article

Article | Open Access | Published: 20 February 2023

Measuring health and human development in cities and neighborhoods in the United States

Suraj K. Sheth & Luís M. A. Bettencourt

npj Urban Sustainability **3**, Article number: 7 (2023) | Cite this article

https://www.nature.com/articles/s42949-023-00088-y

Procedural Inequality:

Equality of What?

AMARTYA SEN

THE TANNER LECTURE ON HUMAN VALUES

Delivered at
Stanford University

May 22, 1979

"capabilities approach"

Critique of

1. Marginal Utility
2. Total Utility (welfarism)
3. Rawls Liberalism

https://www.ophi.org.uk/wp-content/uploads/Sen-1979_Equality-of-What.pdf

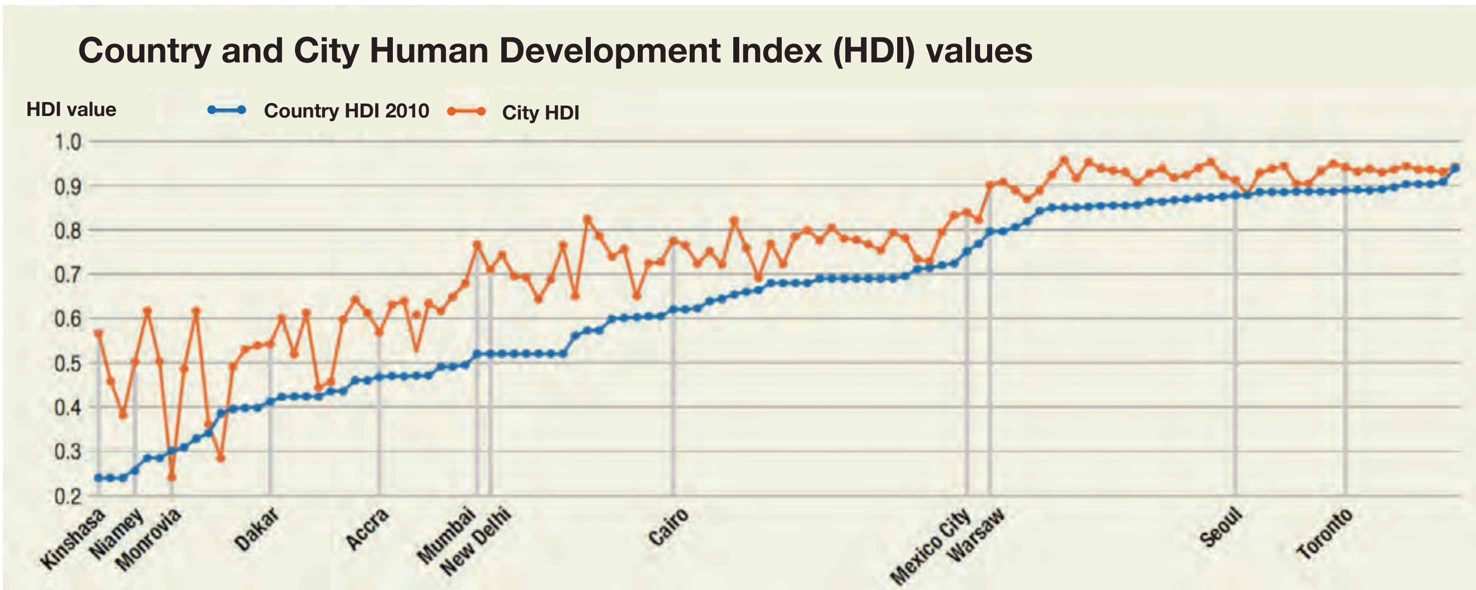
basic capabilities agency empowerment

+ Martha Nussbaum

not money, goods, freedom,…

https://ir.lawnet.fordham.edu/cgi/viewcontent.cgi?article=3391&context=flr

Broad Human Development is a Feature of Larger Cities !



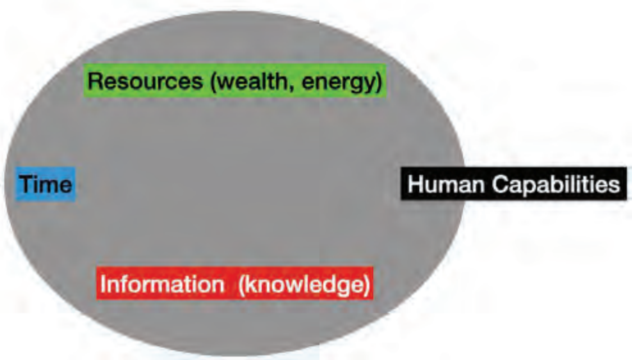
credit: UNDP Human Development Report 2013

Human Development Index

“measures the ability of human populations to lead, long, healthy and fulfilled lives”

Mahbub ul Haq

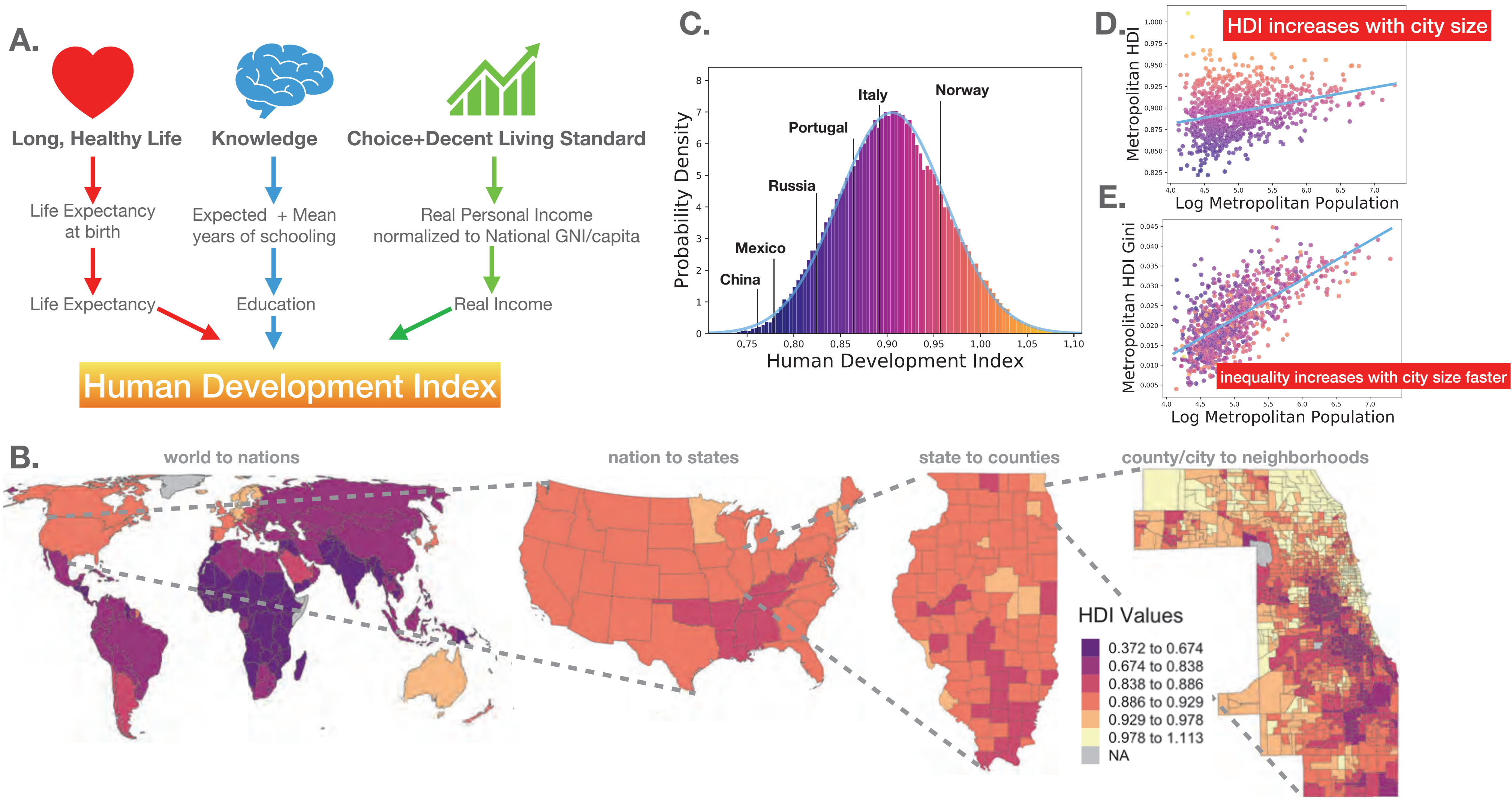
$$\mathrm{HDI}_i = \left(\mathrm{education}_i\,.\,\mathrm{life\ expectancy}_i\,.\,\mathrm{real\ income}_i\right)^{1/3}$$



Rank		Country or Territory	HDI	
2019 data (2020 report)[14]	Change over 5 years (2014)[15]		2019 data (2020 report)[14]	Average annual HDI growth (2010-2019)[15]
1	–	Norway	0.957	▲ 0.20%
2	▲ (7)	Ireland	0.955	▲ 0.65%
2	–	Switzerland	0.955	▲ 0.16%
4	▲ (7)	Hong Kong	0.949	▲ 0.54%
4	▲ (4)	Iceland	0.949	▲ 0.62%
6	▼ (3)	Germany	0.947	▲ 0.24%
7	▼ (3)	Sweden	0.945	▲ 0.41%
8	▼ (2)	Australia	0.944	▲ 0.17%
8	▼ (1)	Netherlands	0.944	▲ 0.32%
10	▼ (6)	Denmark	0.940	▲ 0.28%
11	▼ (2)	Finland	0.938	▲ 0.26%
11	–	Singapore	0.938	▲ 0.35%
13	–	United Kingdom	0.932	▲ 0.24%
14	▲ (1)	Belgium	0.931	▲ 0.25%
14	▲ (3)	New Zealand	0.931	▲ 0.30%
16	▼ (1)	Canada	0.929	▲ 0.34%
17	▼ (3)	United States	0.926	▲ 0.12%

The US is now # 17

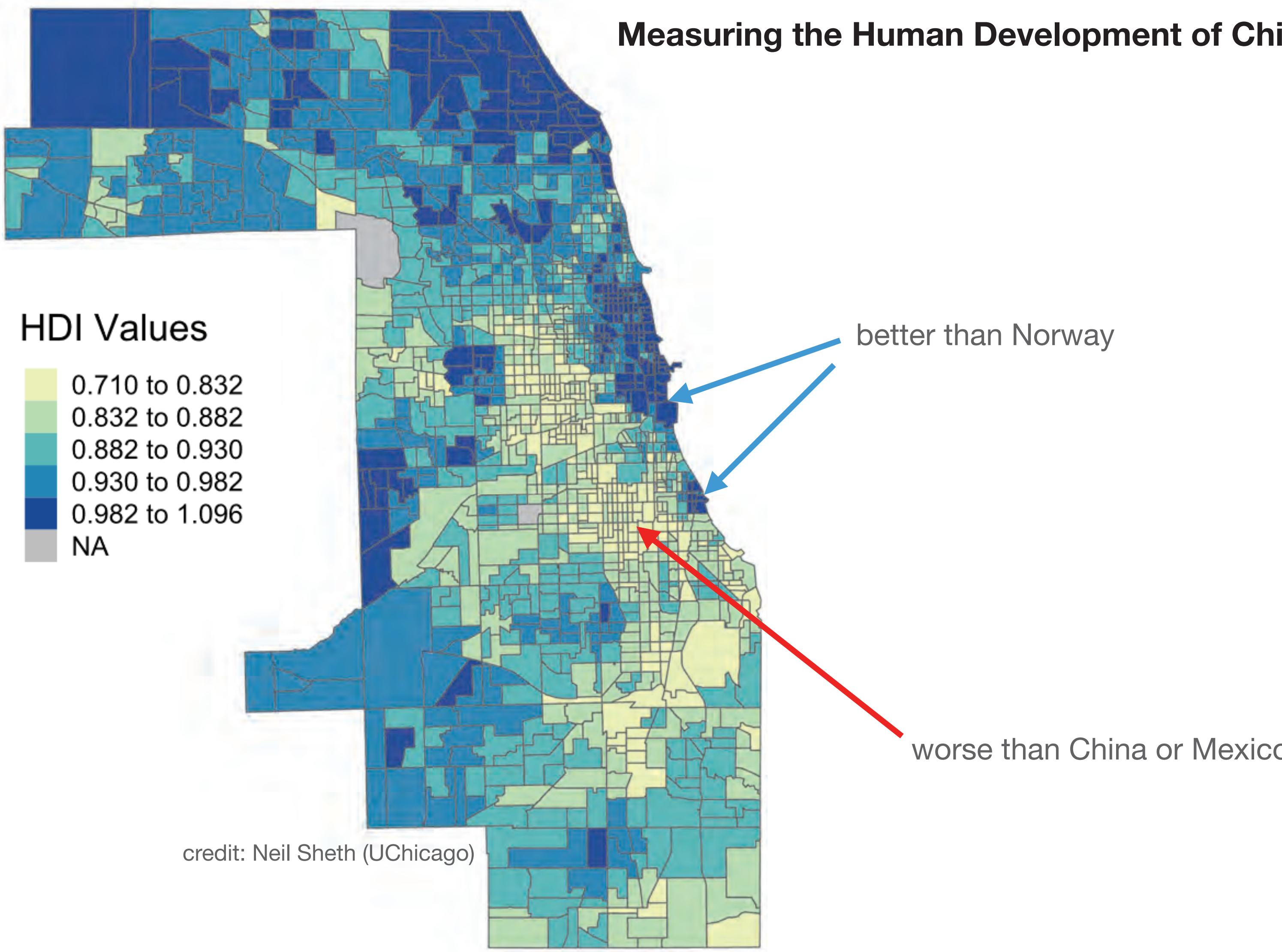
because of health and educational inequality



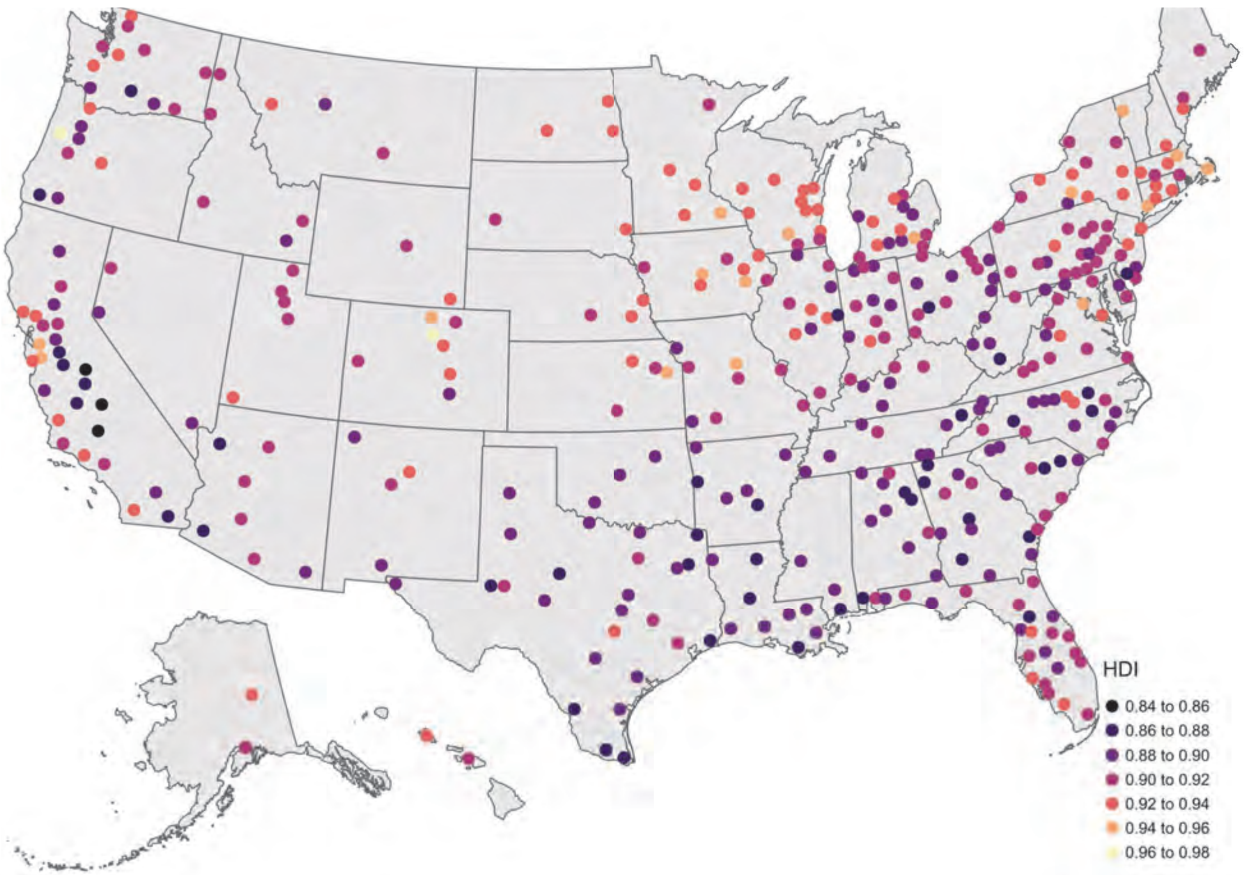
https://papers.ssrn.com/sol3/papers.cfm?abstract_id=3961750

Check out the interactive map at: https://communityhdi.org/

Measuring the Human Development of Chicago neighborhoods

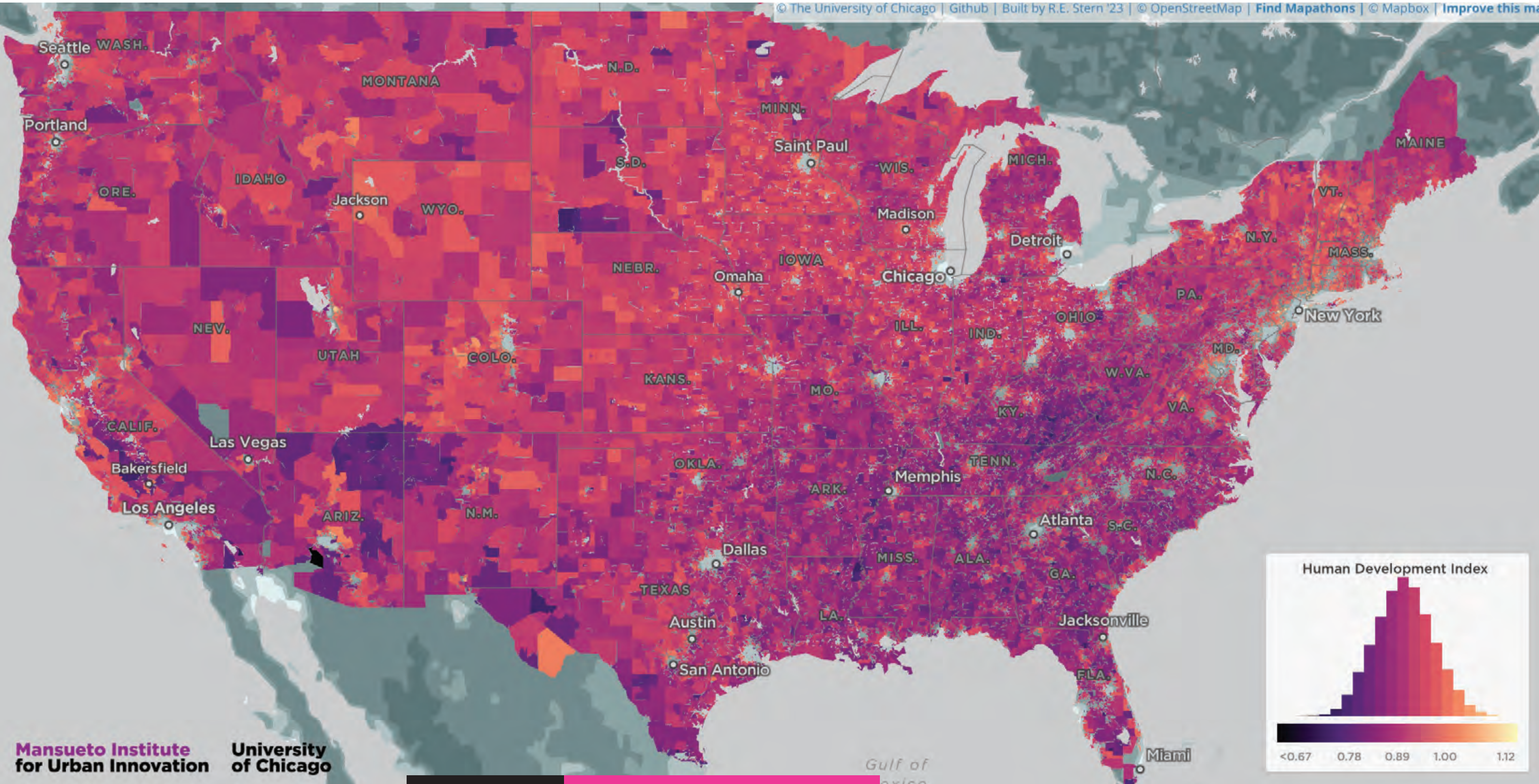


https://papers.ssrn.com/sol3/papers.cfm?abstract_id=3961750

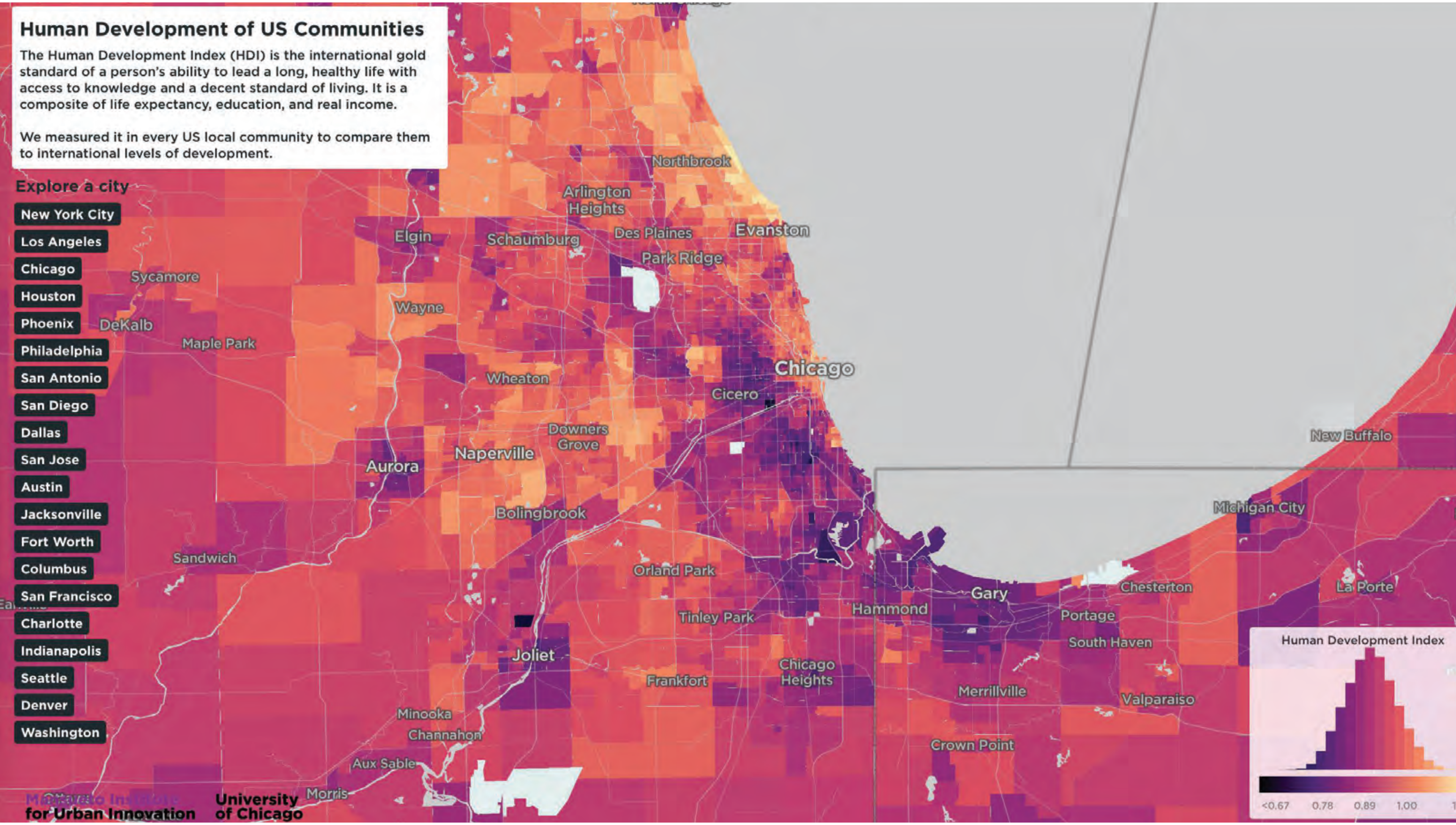


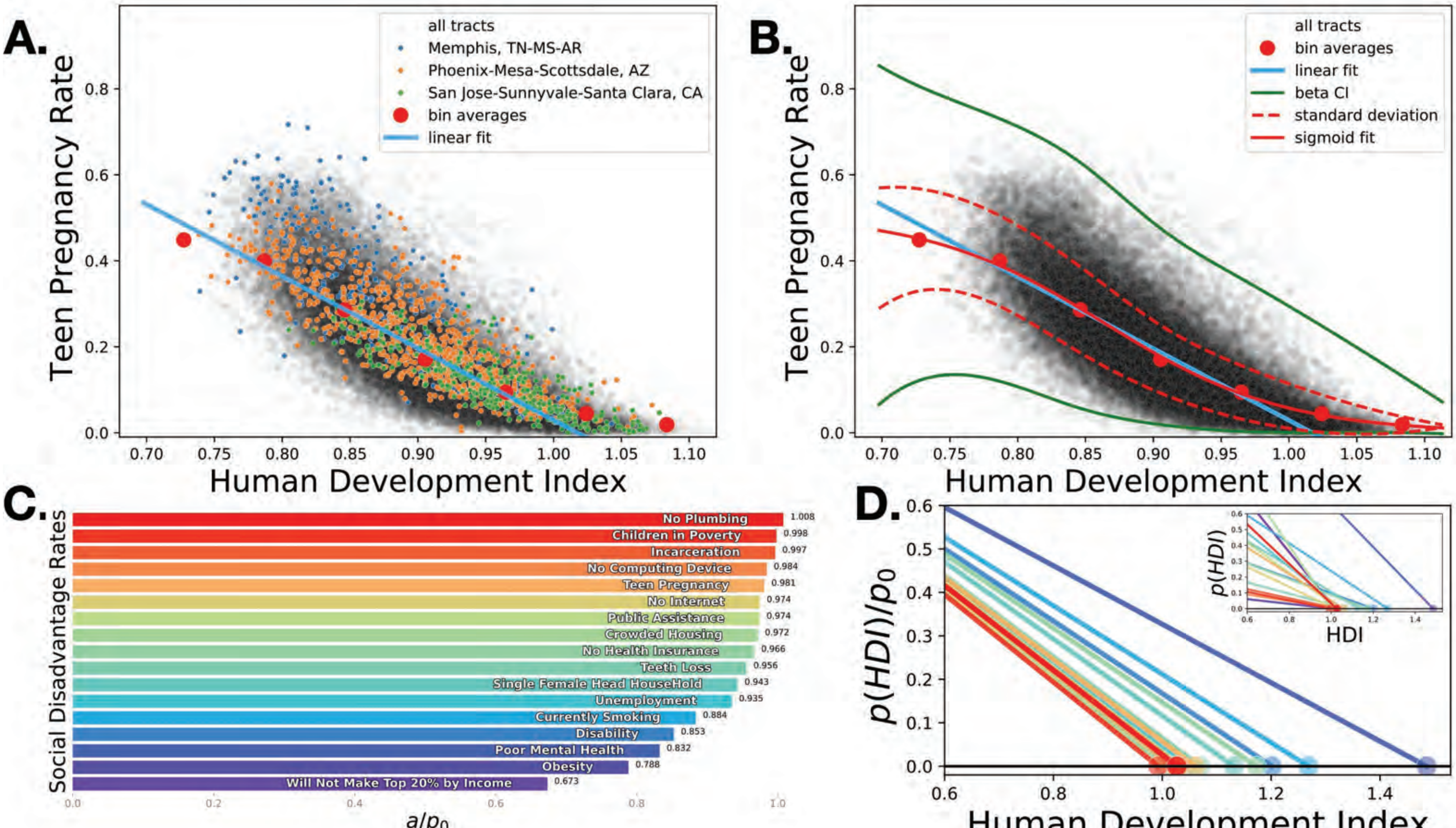
State/Federal District	HDI	Metropolitan Area	HDI
Massachusetts	0.9407	Boulder, CO	0.9624
Connecticut	0.9378	Corvallis, OR	0.9622
Vermont	0.9348	Ann Arbor, MI	0.9570
New Hampshire	0.9345	Iowa City, IA	0.9567
Minnesota	0.9330	San Jose-Sunnyvale-Santa Clara, CA	0.9557
New Jersey	0.9281	Bridgeport-Stamford-Norwalk, CT	0.9553
District of Columbia	0.9273	Ames, IA	0.9532
Maryland	0.9271	Lawrence, KS	0.9496
North Dakota	0.9244	Boston-Cambridge-Newton, MA-NH	0.9491
Colorado	0.9240	San Francisco-Oakland-Hayward, CA	0.9486
Texas	0.8964	Gadsden, AL	0.8647
South Carolina	0.8935	McAllen-Edinburg-Mission, TX	0.8641
Nevada	0.8919	Lake Havasu City-Kingman, AZ	0.8637
Oklahoma	0.8879	Laredo, TX	0.8614
Tennessee	0.8874	Dalton, GA	0.8614
Kentucky	0.8843	Brownsville-Harlingen, TX	0.8605
Alabama	0.8839	Yakima, WA	0.8604
Louisiana	0.8838	Pine Bluff, AR	0.8601
West Virginia	0.8832	Bakersfield, CA	0.8595
Arkansas	0.8798	Visalia-Porterville, CA	0.8579
Mississippi	0.8762	Madera, CA	0.8572

https://papers.ssrn.com/sol3/papers.cfm?abstract_id=3961750



Check it out: https://communityhdi.org/


Human Development of US Communities
The Human Development Index (HDI) is the international gold standard of a person's ability to lead a long, healthy life with access to knowledge and a decent standard of living. It is a composite of life expectancy, education, and real income.
We measured it in every US local community to compare them to international levels of development.
Explore a city
New York City
Los Angeles
Chicago
Houston
Phoenix
Philadelphia
San Antonio
San Diego
Dallas
San Jose
Austin
Jacksonville
Fort Worth
Columbus
San Francisco
Charlotte
Indianapolis
Seattle
Denver
Washington
Northbrook
Arlington Heights
Evanston
Elgin
Schaumburg
Des Plaines
Park Ridge
Sycamore
Wayne
DeKalb
Maple Park
Chicago
Wheaton
Cicero
Downers Grove
New Buffalo
Naperville
Aurora
Bolingbrook
Michigan City
Sandwich
Orland Park
Gary
Chesterton
La Porte
Hammond
Tinley Park
Portage
South Haven
Joliet
Chicago Heights
Frankfort
Merrillville
Valparaiso
Minooka
Channahon
Crown Point
Aux Sable
Morris
for Urban Innovation
University of Chicago
Human Development Index
<0.67
0.78
0.89
1.00



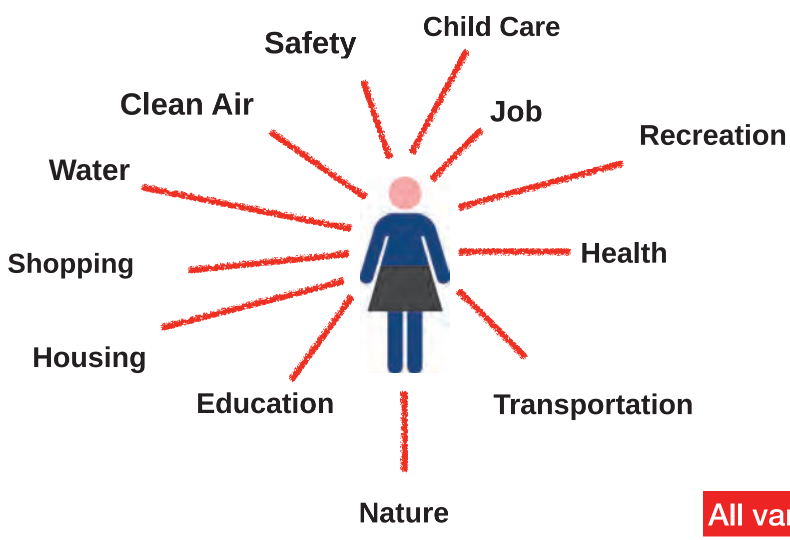
https://papers.ssrn.com/sol3/papers.cfm?abstract_id=3961750

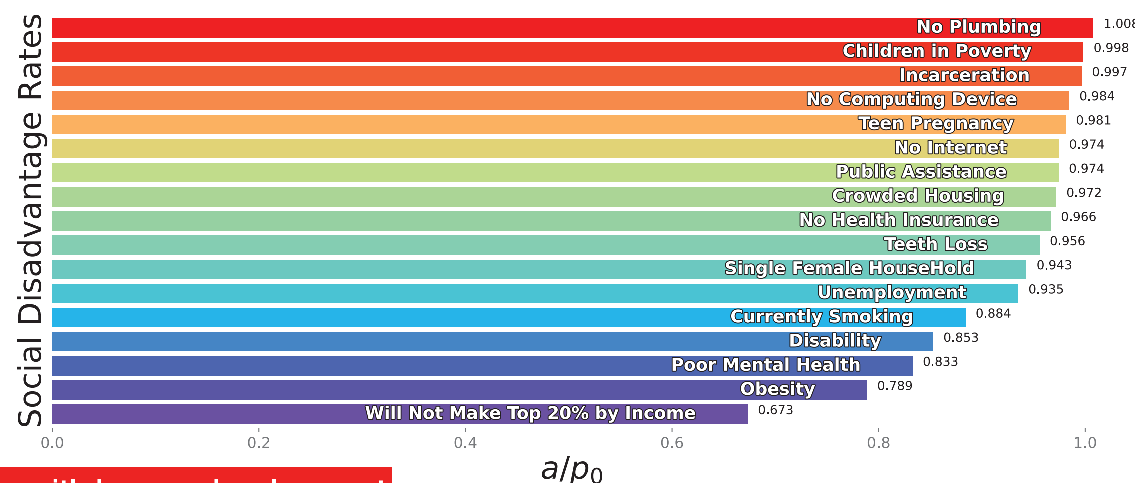
“Anna Karenina Principle” of Human Development

A deficiency in any one of a number of factors dooms an endeavor to failure.
Consequently, a successful endeavor (subject to this principle) is one for which every possible deficiency has been avoided.

https://en.wikipedia.org/wiki/Anna_Karenina_principle

All *high* human development communities are alike (“no problems”); but each *low* human development community is challenged in its own way





All vary together with human development

Solution: ensure systemic human capabilities = education *and* health *and* decent real income

Human development as a network process (in cities)

2. Incipient city networks and spatial network development

can we accelerate it, and make it better?

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HOME › SCIENCE ADVANCES › VOL. 4, NO. 8 › TOWARD CITIES WITHOUT SLUMS: TOPOL...

RESEARCH ARTICLE SOCIAL SCIENCES

Toward cities without slums: Topology and the spatial evolution of neighborhoods

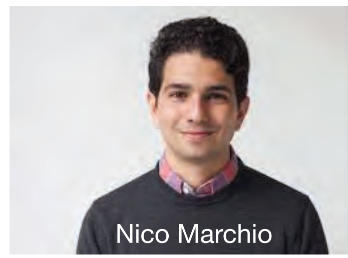
CHRISTA BRELSFORD, TAYLOR MARTIN, JOE HAND, AND LUÍS M. A. BETTENCOURT Authors Info & Affiliations

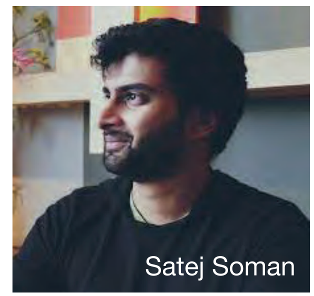
SCIENCE ADVANCES · 29 Aug 2018 · Vol 4, Issue 8 · DOI: 10.1126/sciadv.aar4644

Abstract

The world is urbanizing quickly with nearly 4 billion people presently living in urban areas, about 1 billion of them in slums. Achieving sustainable development from rapid urbanization relies critically on creating cities without slums. We show that it is possible to diagnose systematically the central physical problem of slums—the lack of spatial accesses and related services—using a topological analysis of neighborhood maps and resolved by finding solutions to a sequence of constrained optimization problems. We set up the problem by showing that the built environment of any city can be decomposed into two types of networked spaces—accesses and places—and prove that these spaces display universal topological characteristics. We then show that while the neighborhoods of developed cities express the same common topology, urban slums fall into a different topological class. We demonstrate that it is always possible to find solutions that grow a street network in existing slums, providing universal accesses at minimal disruption and cost. We then show how elaborations of this procedure that include local preferences and reduce travel distances between places result from additional access construction. These methods are presently taking effect in neighborhoods in Cape Town (South Africa) and Mumbai (India), demonstrating their practical feasibility and emphasizing their role as a platform to enable communities and local governments to combine technical knowledge with local aspirations into contextually appropriate urban sustainable development solutions.

https://www.science.org/doi/10.1126/sciadv.aar4644





Open Access Editor's Choice Article

Worldwide Detection of Informal Settlements via Topological Analysis of Crowdsourced Digital Maps

by Satej Soman [1,*], Anni Beukes [1], Cooper Nederhood [1], Nicholas Marchio [1] and Luís M. A. Bettencourt [1,2,3]

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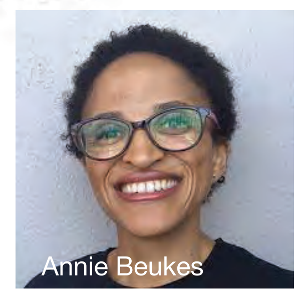
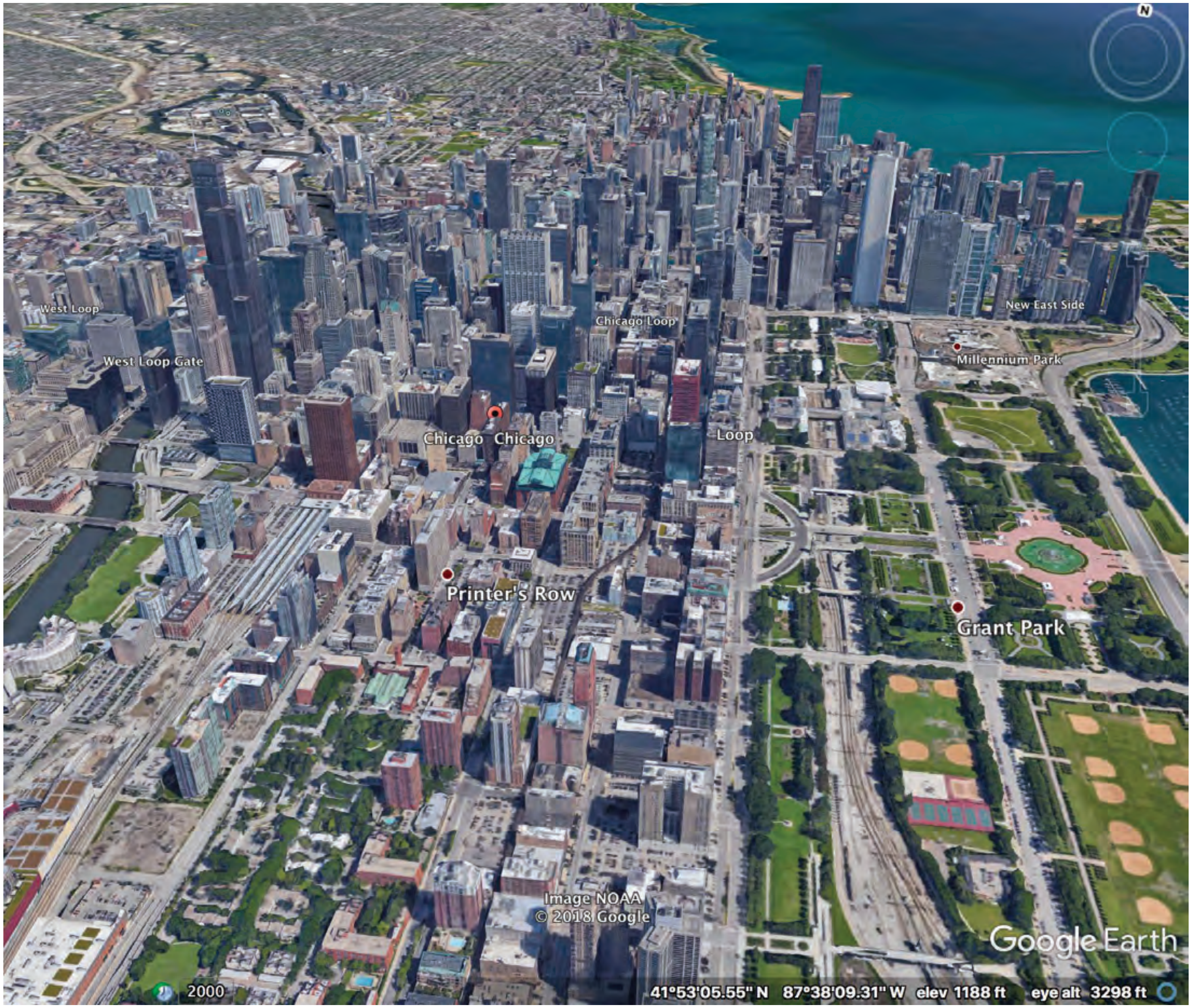
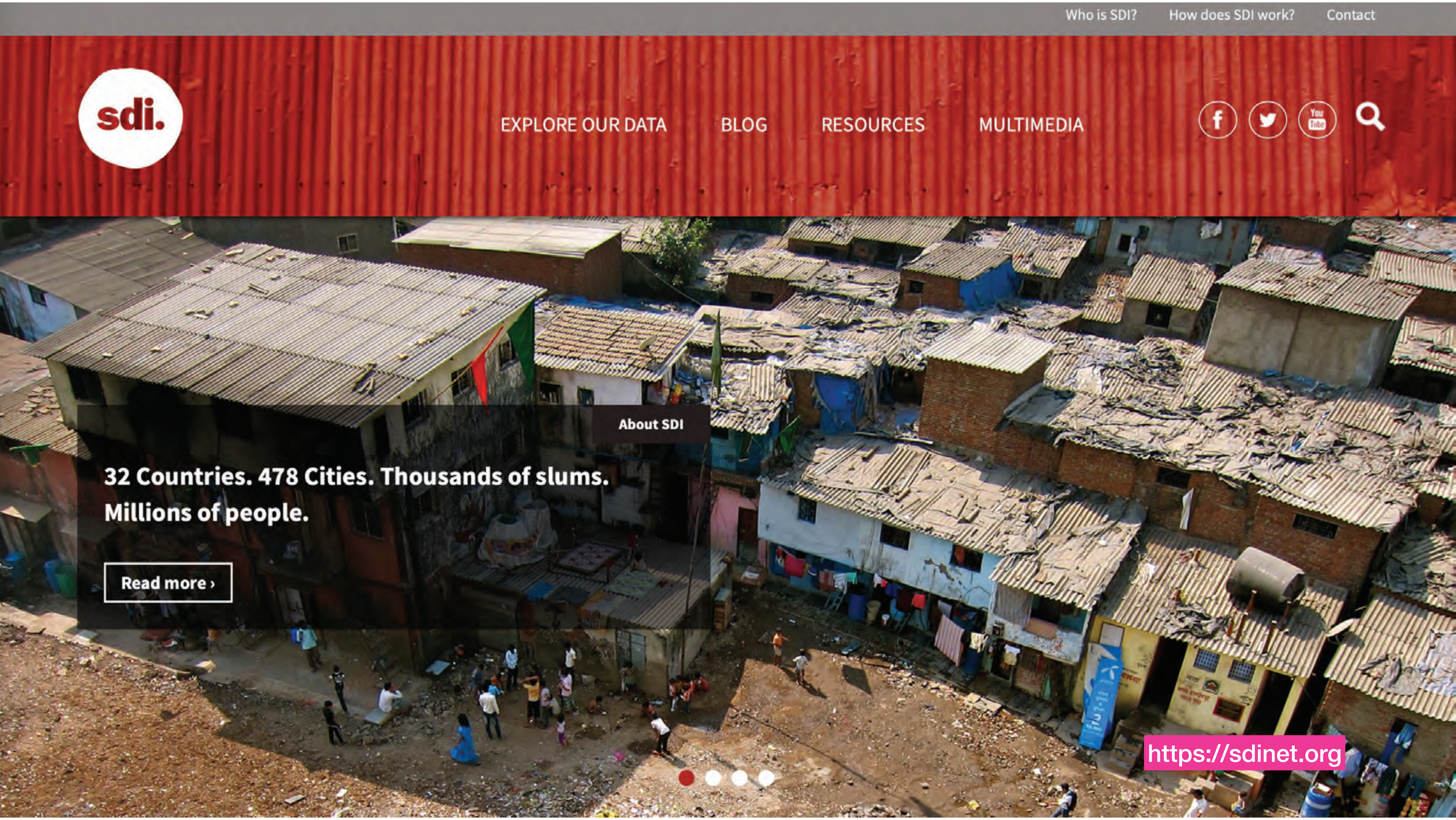
3 Department of Sociology, University of Chicago, Chicago, IL 60637, USA
* Author to whom correspondence should be addressed.

ISPRS Int. J. Geo-Inf. **2020**, *9*(11), 685; https://doi.org/10.3390/ijgi9110685




West Loop
West Loop Gate
Chicago Loop
New East Side
Millennium Park
Chicago
Chicago
Loop
Printer's Row
Grant Park
Image NOAA
© 2018 Google
Google Earth
2000
41°53'05.55" N 87°38'09.31" W elev 1188 ft eye alt 3298 ft


© 2018 AfriGIS (Pty) Ltd.
Google Earth
2005
34°03'43.43" S 18°40'19.20" E elev 142 ft eye alt 317 ft


Who is SDI?
How does SDI work?
Contact
sdi.
EXPLORE OUR DATA
BLOG
RESOURCES
MULTIMEDIA
About SDI
32 Countries. 478 Cities. Thousands of slums.
Millions of people.
Read more ›
https://sdinet.org

Sanitation

Working toilet seats to people:
1:18,326

Total number of toilets seats:
2

Number of working toilets seats:

Types of toilets in use:

- Flush
- ✓ **Pour flush**
- Chemical
- ✓ **Pit latrine**
- Hanging toilet
- Flush

Water

Number of taps:
9

Working taps to people:
1:4,072

Average cost of access per month:
50,000 SLL

Number of working taps:

Mapping households is very slow and labor intensive

Infrastructure

Electricity available:
Yes

Garbage collections per week:
N/A

Garbage location:
Common area inside settlement

Road types:
Gravel roads

Main means of transportation:

- ✓ **Bus**
- ✓ **Motorbike**
- Car
- Bicycle
- Train
- Walking
- Taxi
- Other

Organised Community

Number of savings groups:
18

Community leadership?
Yes

How often does the community meet?
Other

Does the community leadership talk to the city?
N/A

Relationship with authorities:
Good

How often does the community meet with the city?
Monthly

Health Access

Most common diseases:

- **Malaria**
- **Typhoid**
- **Diarrhea**
- **Other**

Access to health clinics:
Yes

Average walking time to nearest health clinic (minutes):
Unknown

Access to AIDS clinics:
Yes

Average walking time to nearest Aids clinic (minutes):
30 minutes to 1 hour

Access to hospitals:
Yes

Average walking time to nearest hospital (minutes):
more than 1 hour

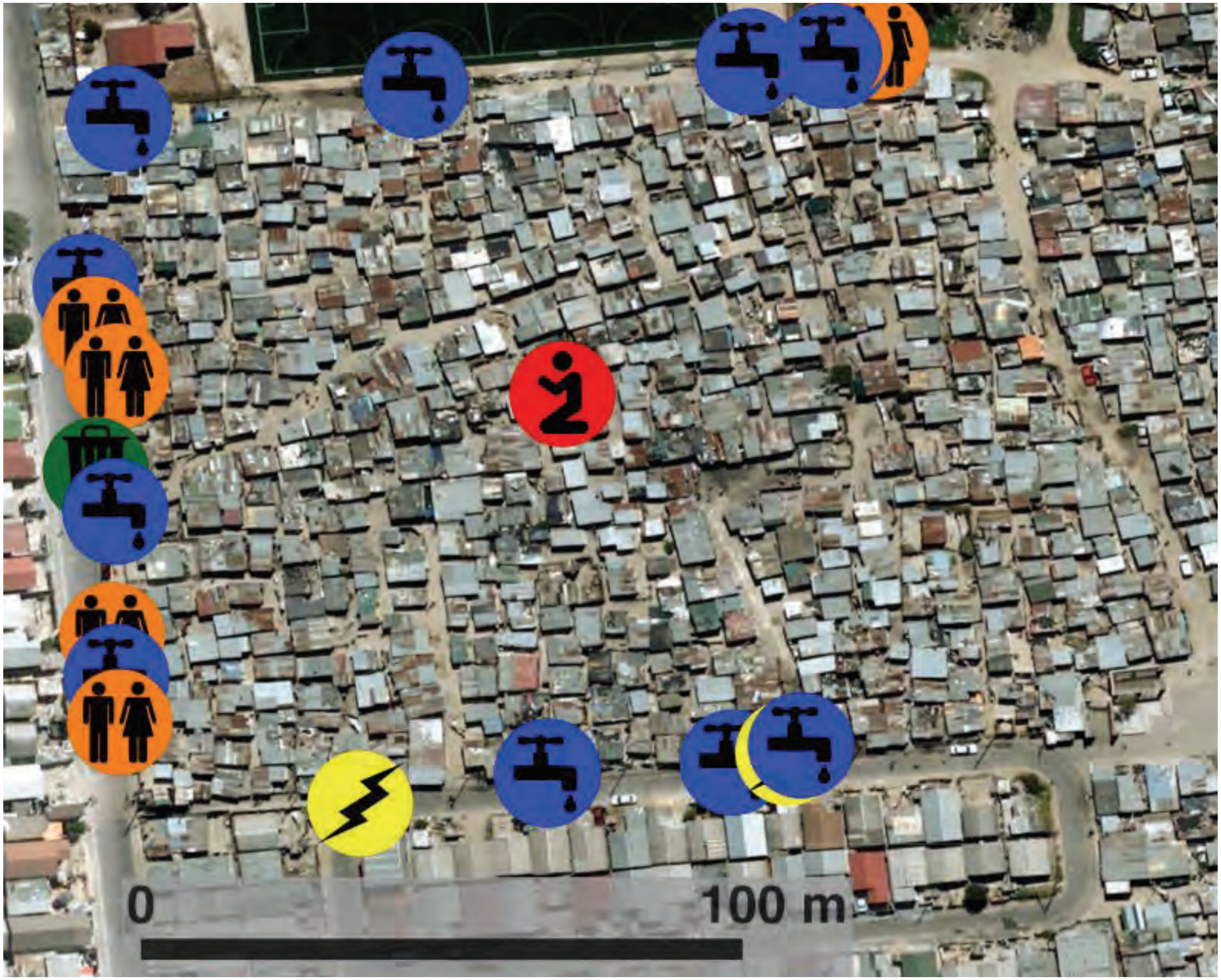
Commercial Establishments & Facilities

- ✓ **Playground**
- Banks
- Firestations
- ✓ **Police stations**
- ✓ **General shops**
- ✓ **Informal markets**
- ✓ **Food shops**
- Clothing shops
- ✓ **Furniture shops**
- ✓ **Temples**
- Mosques
- ✓ **Churches**
- ✓ **Communications**
- ✓ **Car repair**

https://knowyourcity.info

Street → Reblocking !

Every building gets street access, an address, services.


0
100 m

“This question is so banal, but seemed to me worthy of attention in that [neither] geometry, nor algebra, nor even the art of counting was sufficient to solve it.”

Kart Gottlieb Ehler

The Königsberg Bridge problem asked whether it was possible for a person to walk through the city, crossing each bridge once and only once. Image credit: ScienceSource/SPL.

Leonard Euler

“*geometria situs*” —> topology

https://www.pnas.org/doi/10.1073/pnas.1904847116

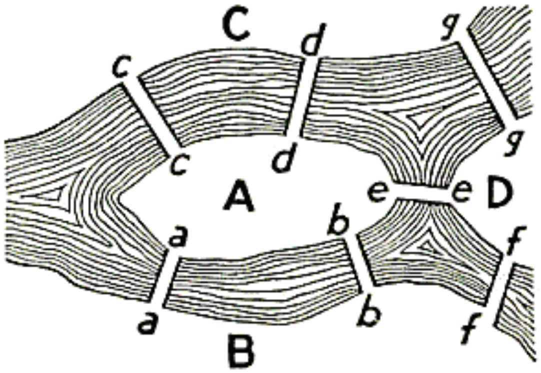
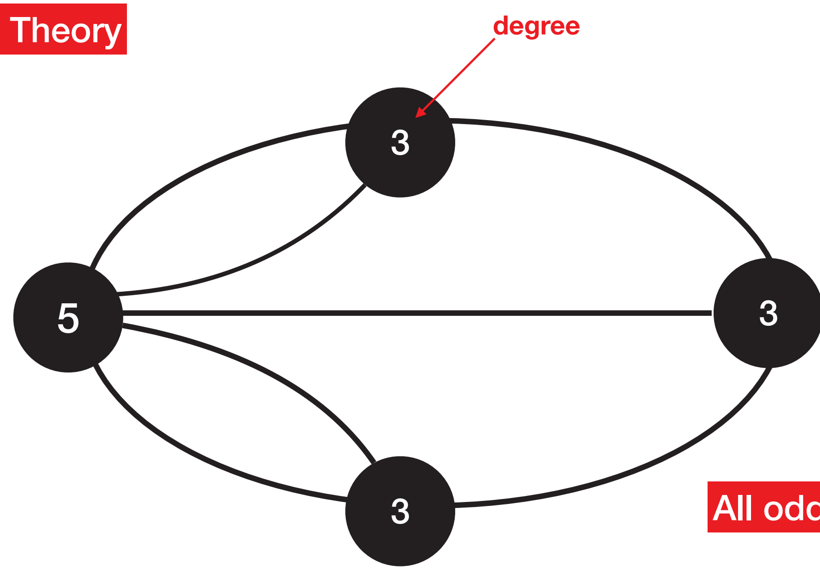


FIGURE 98. *Geographic Map: The Königsberg Bridges.*

https://mathworld.wolfram.com/KoenigsbergBridgeProblem.html

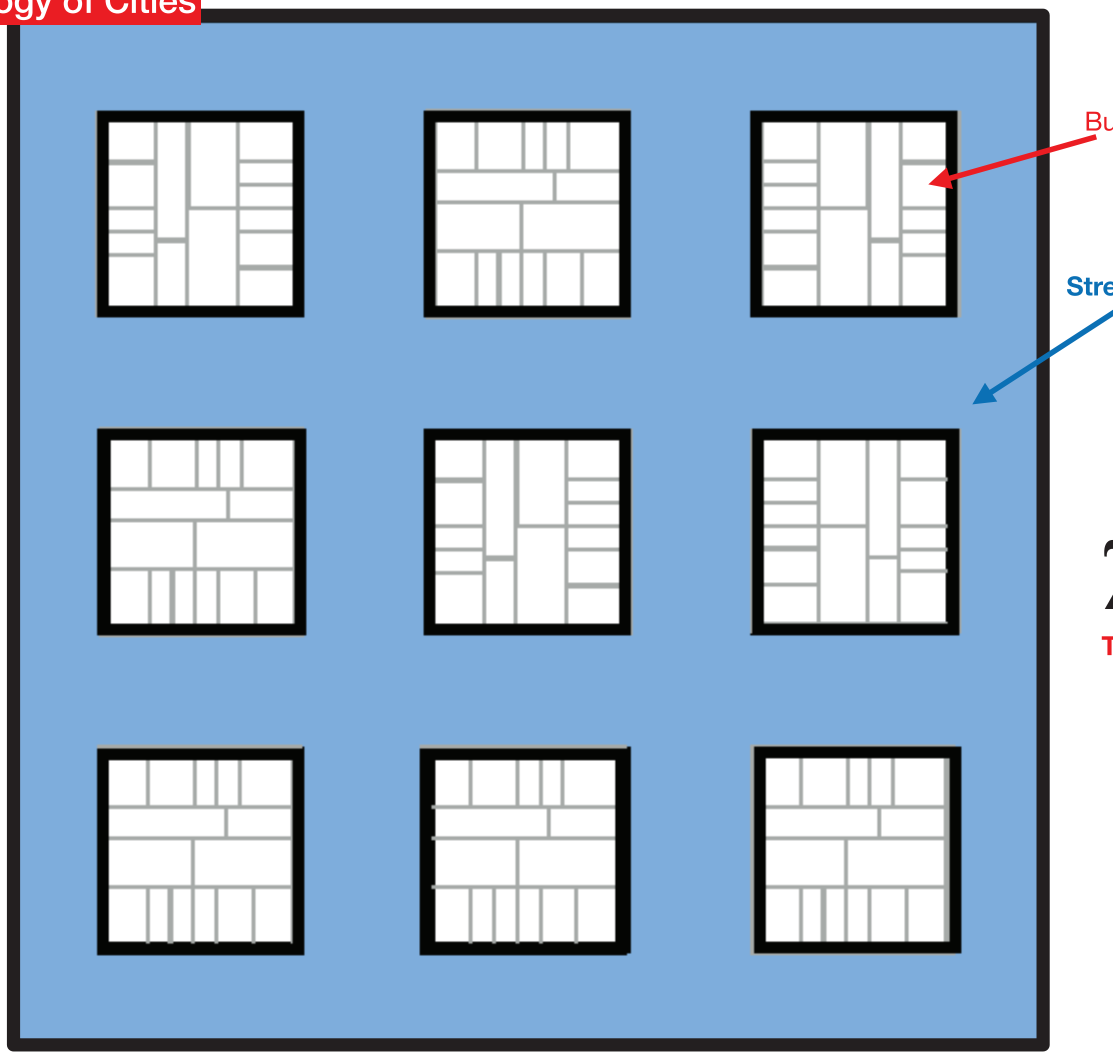
number of bridges must be even, expect at starting and finishing points

Geometry —> Topology —> Graph Theory



All odd degre: Eulerian circuit is not possible !

The General Topology of Cities

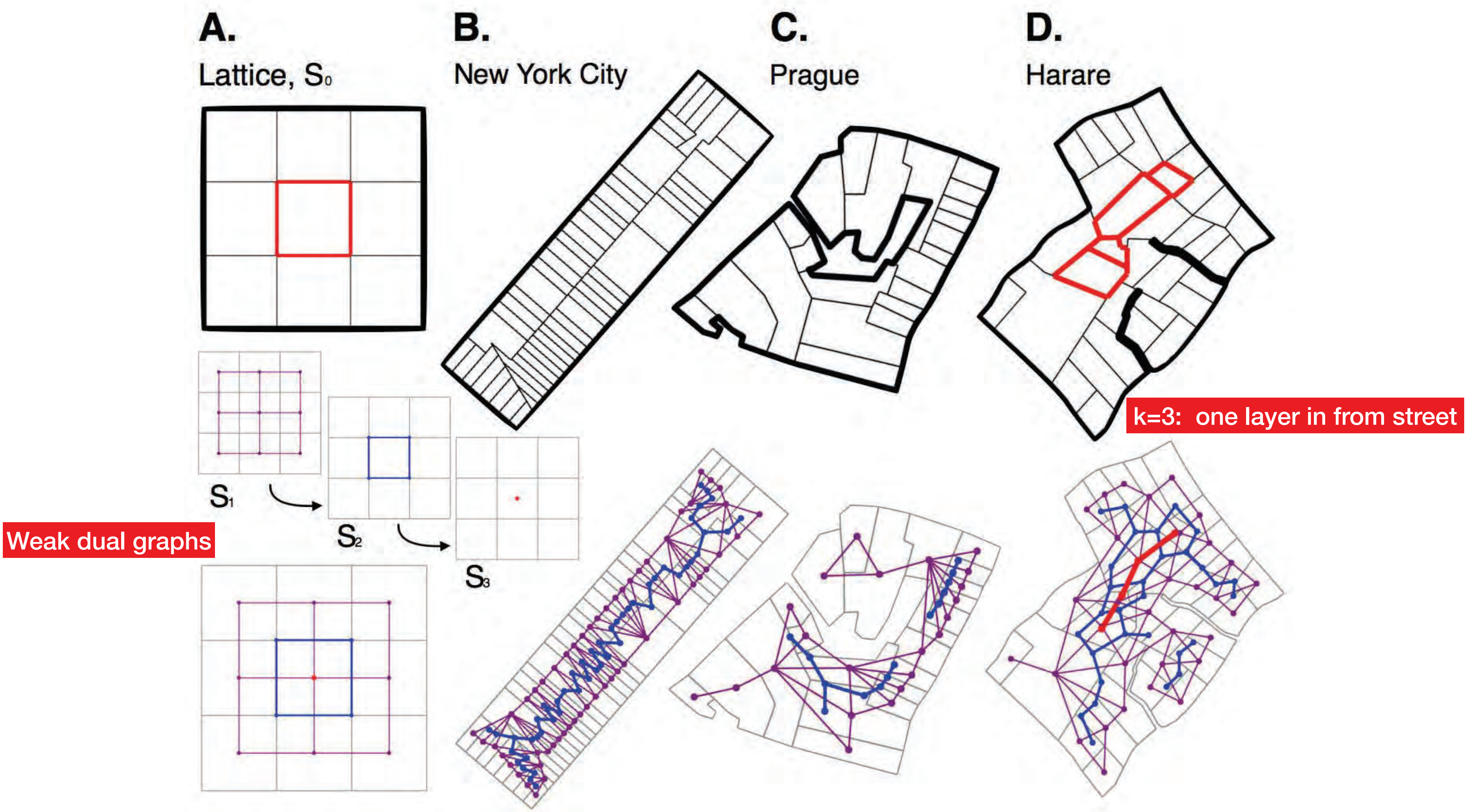


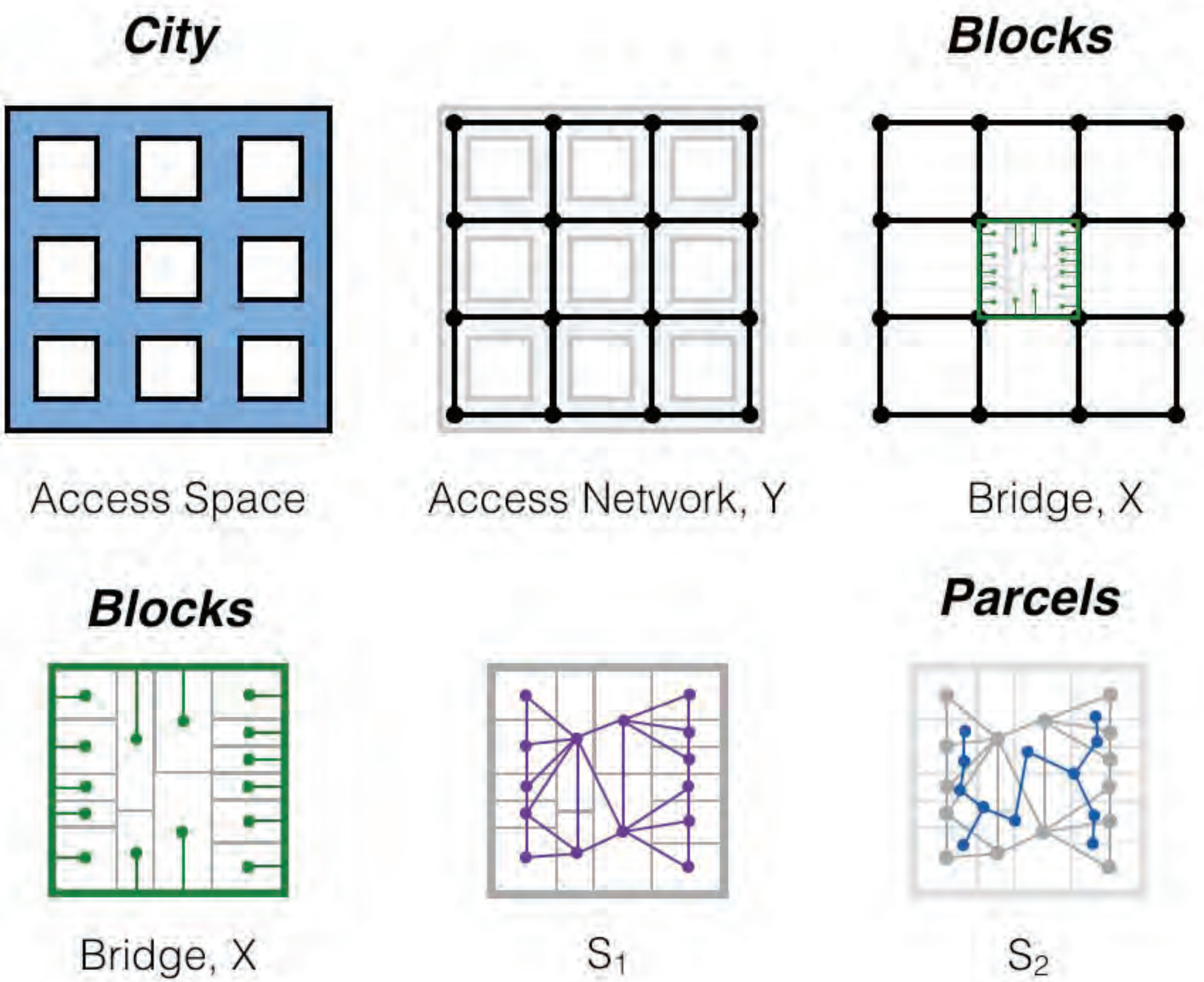
$$\chi \,\square\, 1 - b$$

The Euler characteristic of a city with *b* blocks

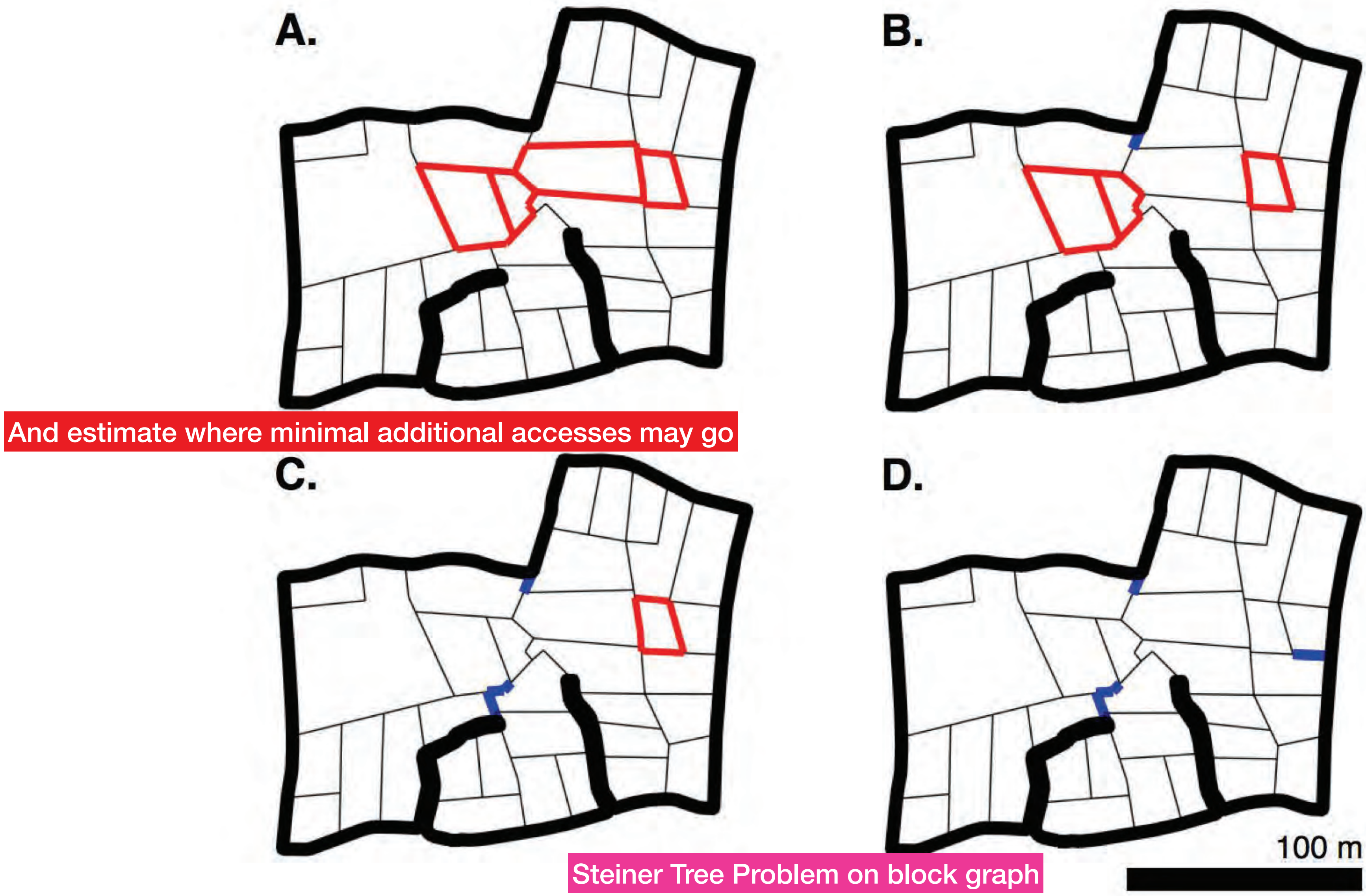
Equivalent to a disk with *b* holes

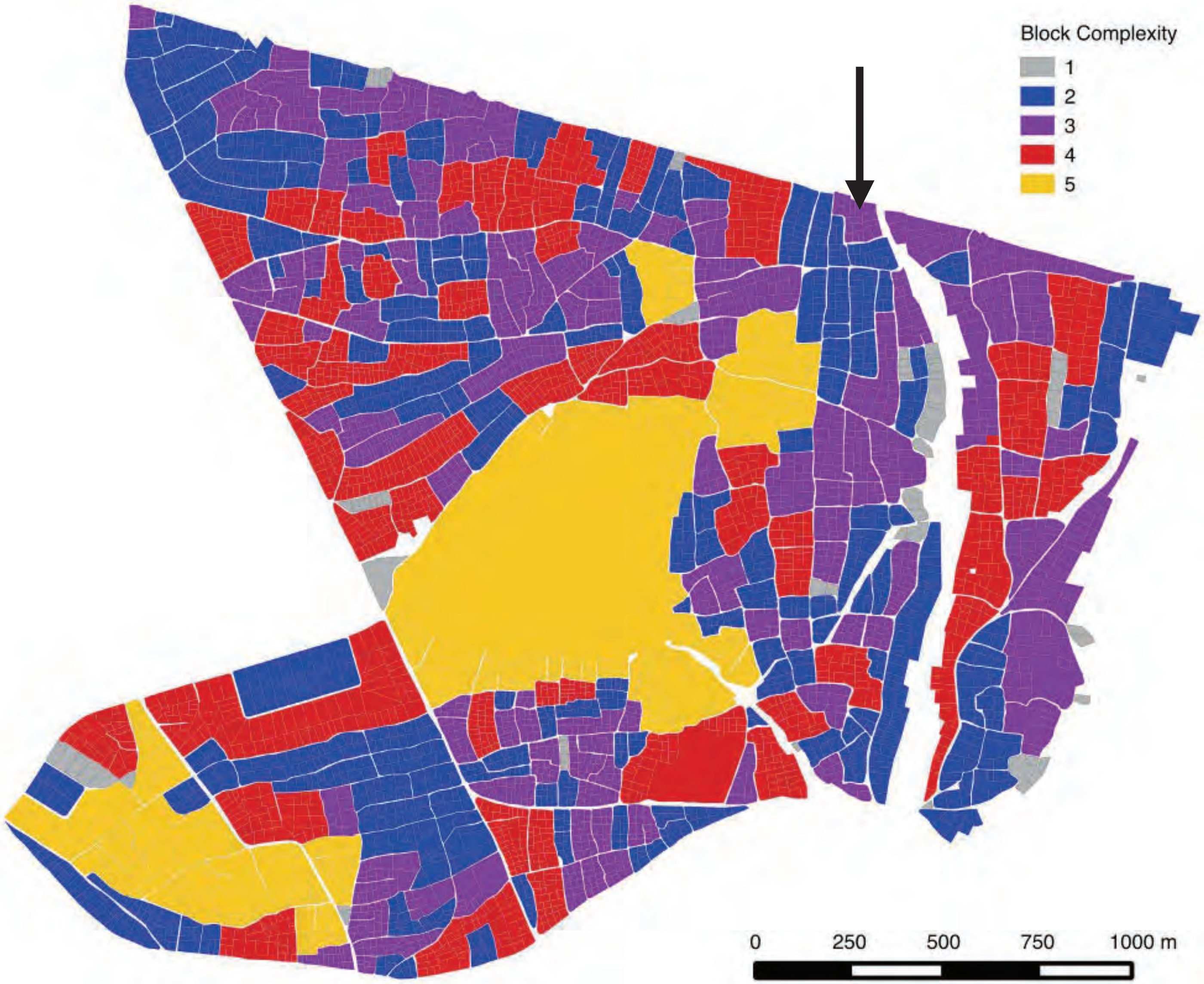
Every city is topologically like this, but geometry varies


A.
Lattice, S0
B.
New York City
C.
Prague
D.
Harare
k=3: one layer in from street
S1
S2
S3
Weak dual graphs



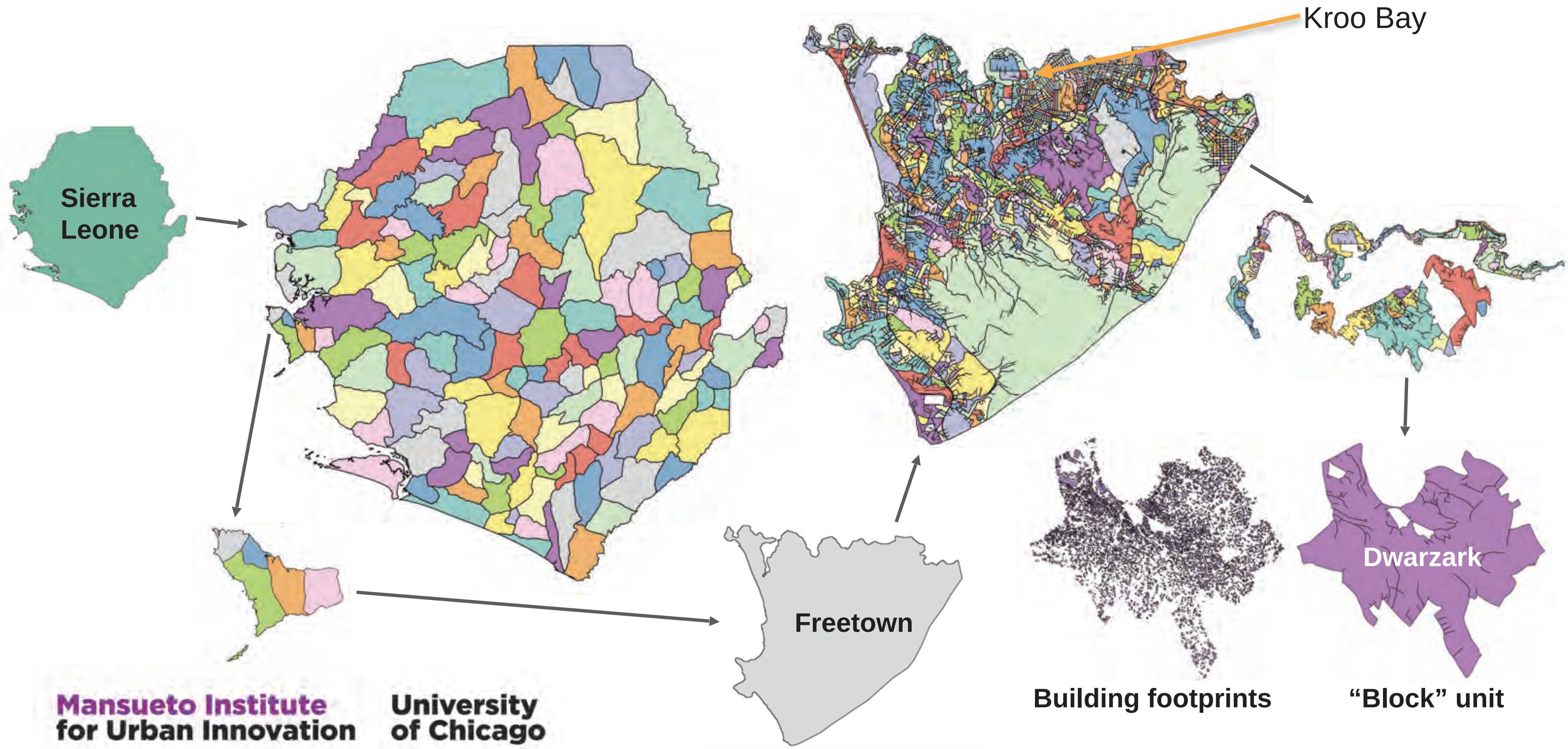
Algorithm for analyzing the topology of any city : And identify buildings without accesses


A.
B.
And estimate where minimal additional accesses may go
C.
D.
100 m
Steiner Tree Problem on block graph


Block Complexity
1
2
3
4
5
0
250
500
750
1000 m

Understanding settlements from global to local scales

a global map (of cities) neighborhood by neighborhood



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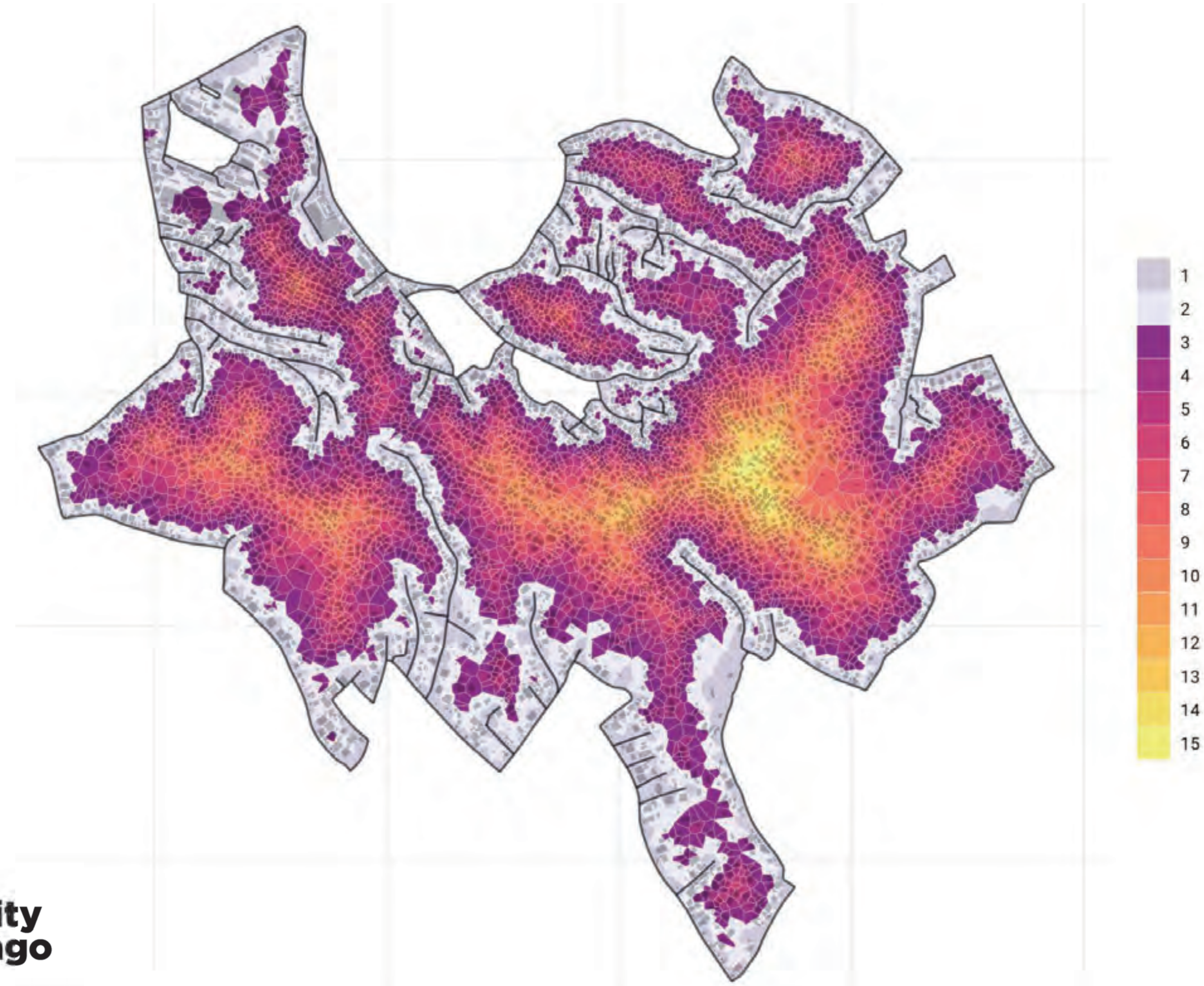
Detecting informality down to the street block

Building footprints

“Block” unit



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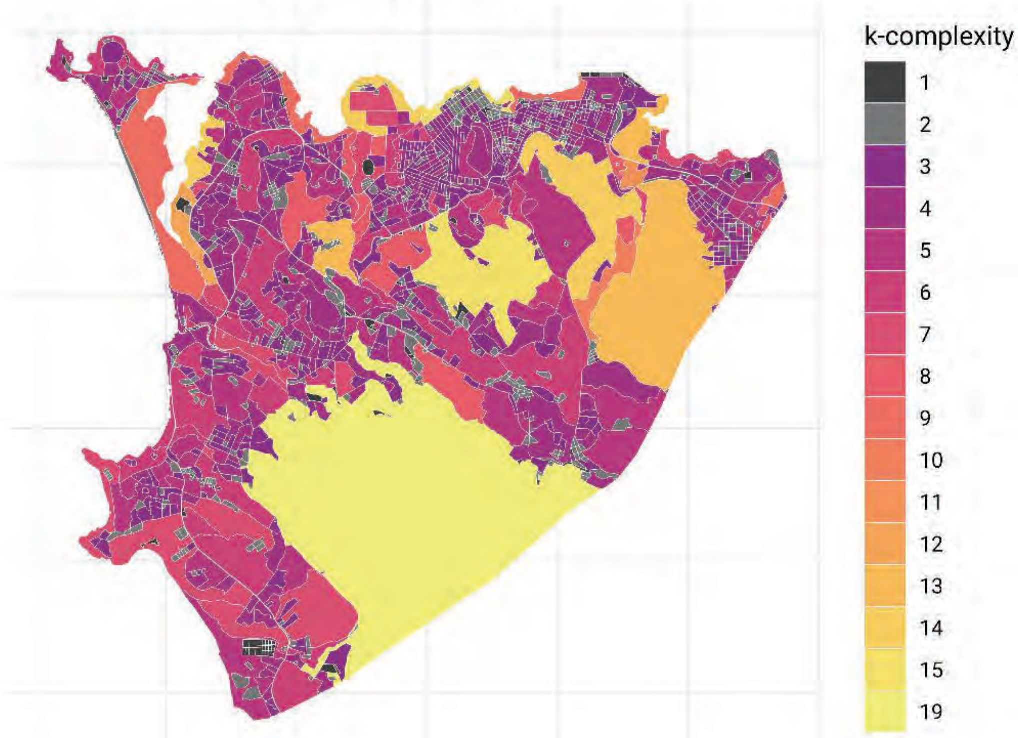
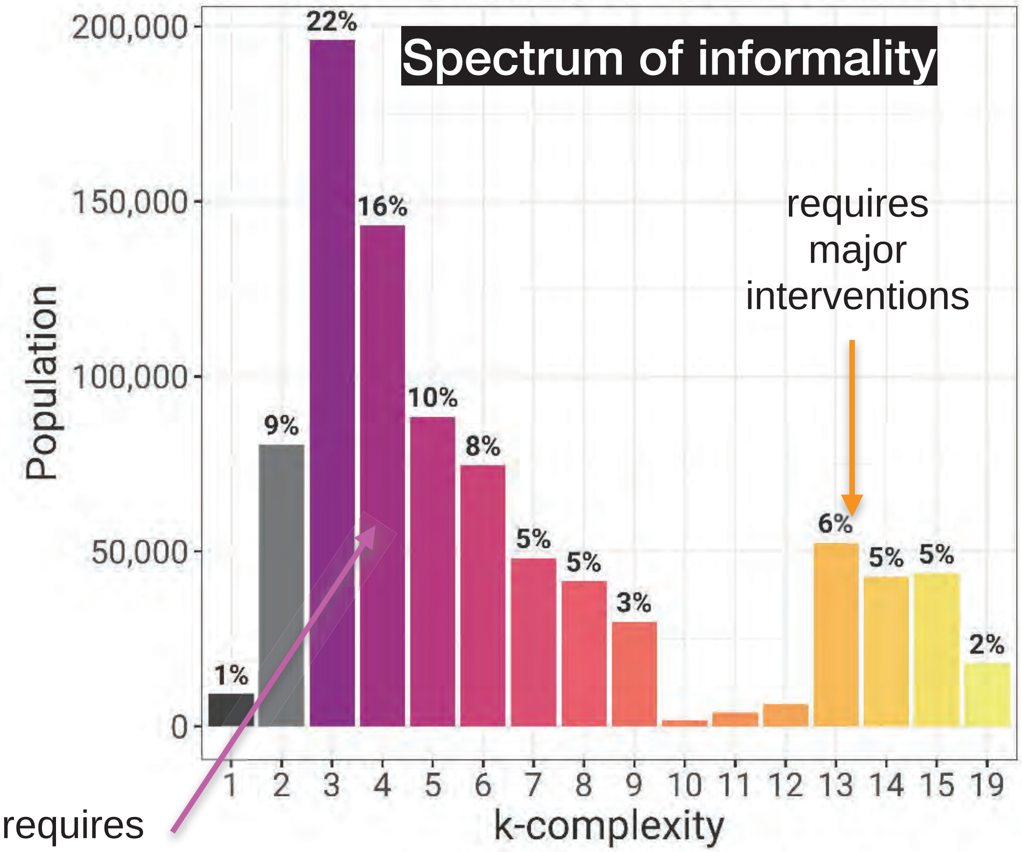
Mapping informality and population in Freetown

Informal settlements



Total Population: 880,537

Population distribution across levels of informality



requires
minor extensions
of streets+services

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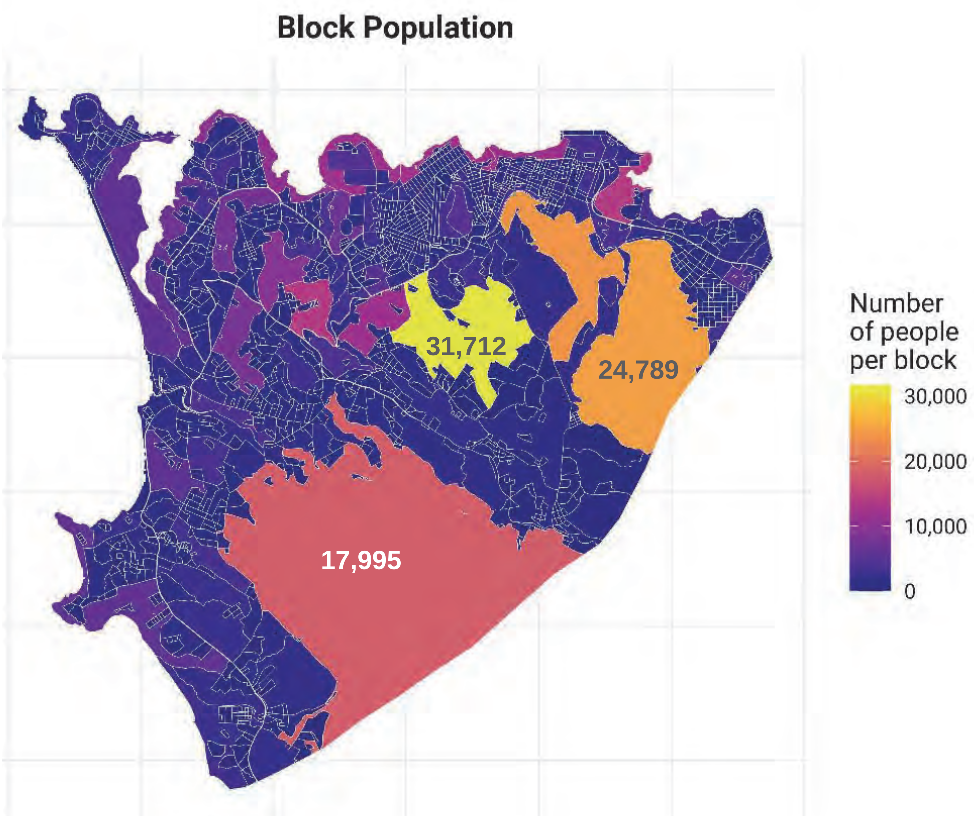
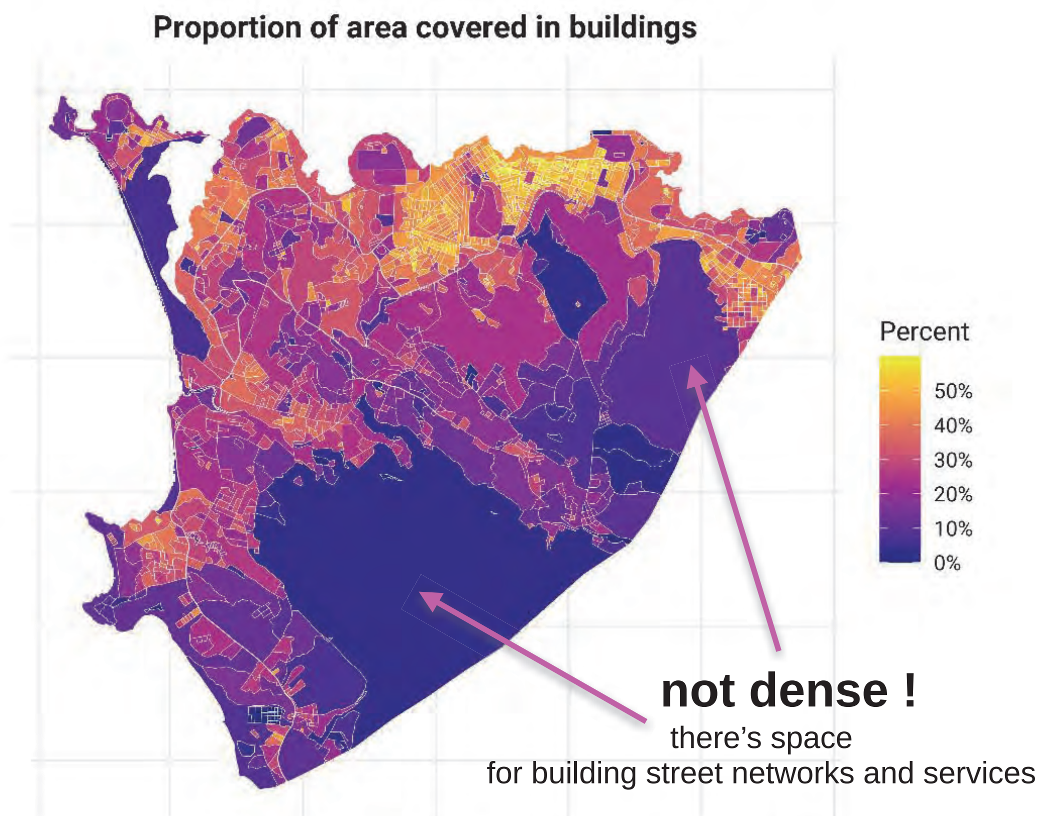
New indicators for measuring development in cities



Total Population: 880,537



Legend color scale is top-coded with max value of 100%

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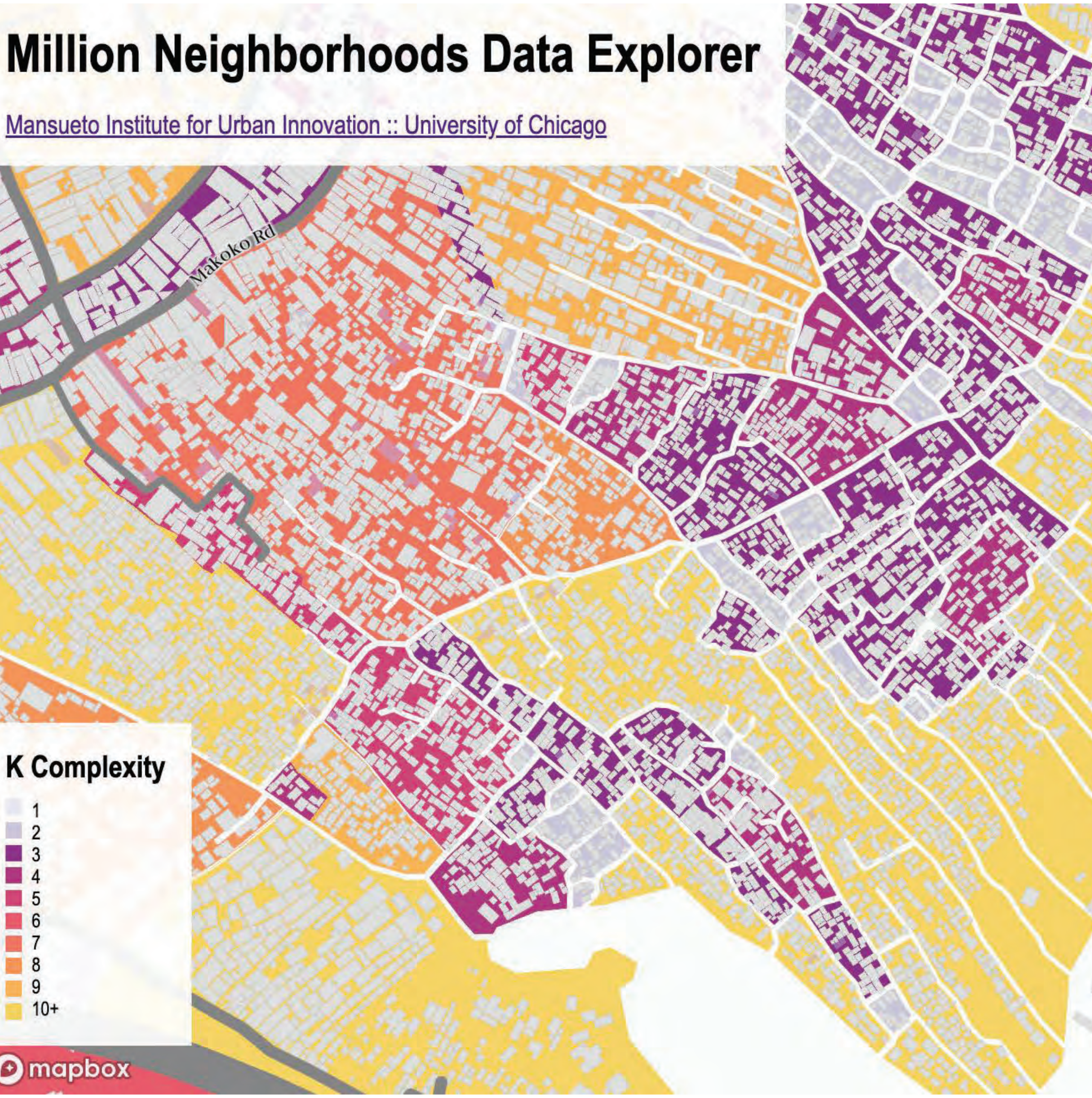


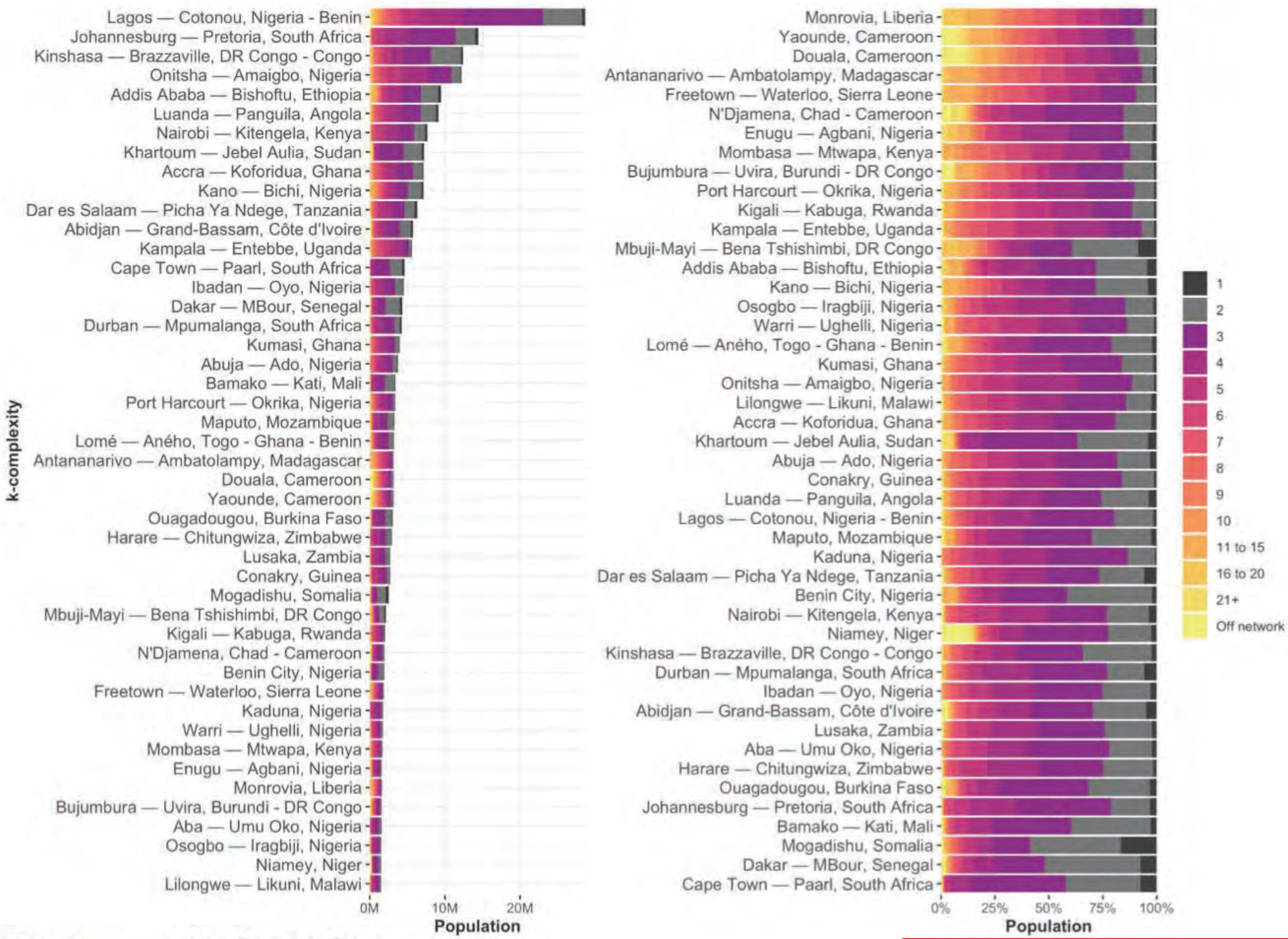
To take up this project, young residents of Makoko were taught to pilot drones and populate the map with images from the community. Hounkpe is one of the residents on the project that is also teaching residents how to fly drones.

YASUYOSHI CHIBA/AFP/Getty Images

A classroom session at a private school in the Makoko on March 1, 2019.

"For years, Makoko has been ignored by governments of the state. This project is the first part of a conversation around inclusion. We are helping map out Makoko so that governments and other organizations can provide interventions and access to social services like electricity, healthcare, and education." Ottaviani told CNN.

https://www.cnn.com/2020/02/26/africa/nigeria-makoko-mapping-intl/index.html



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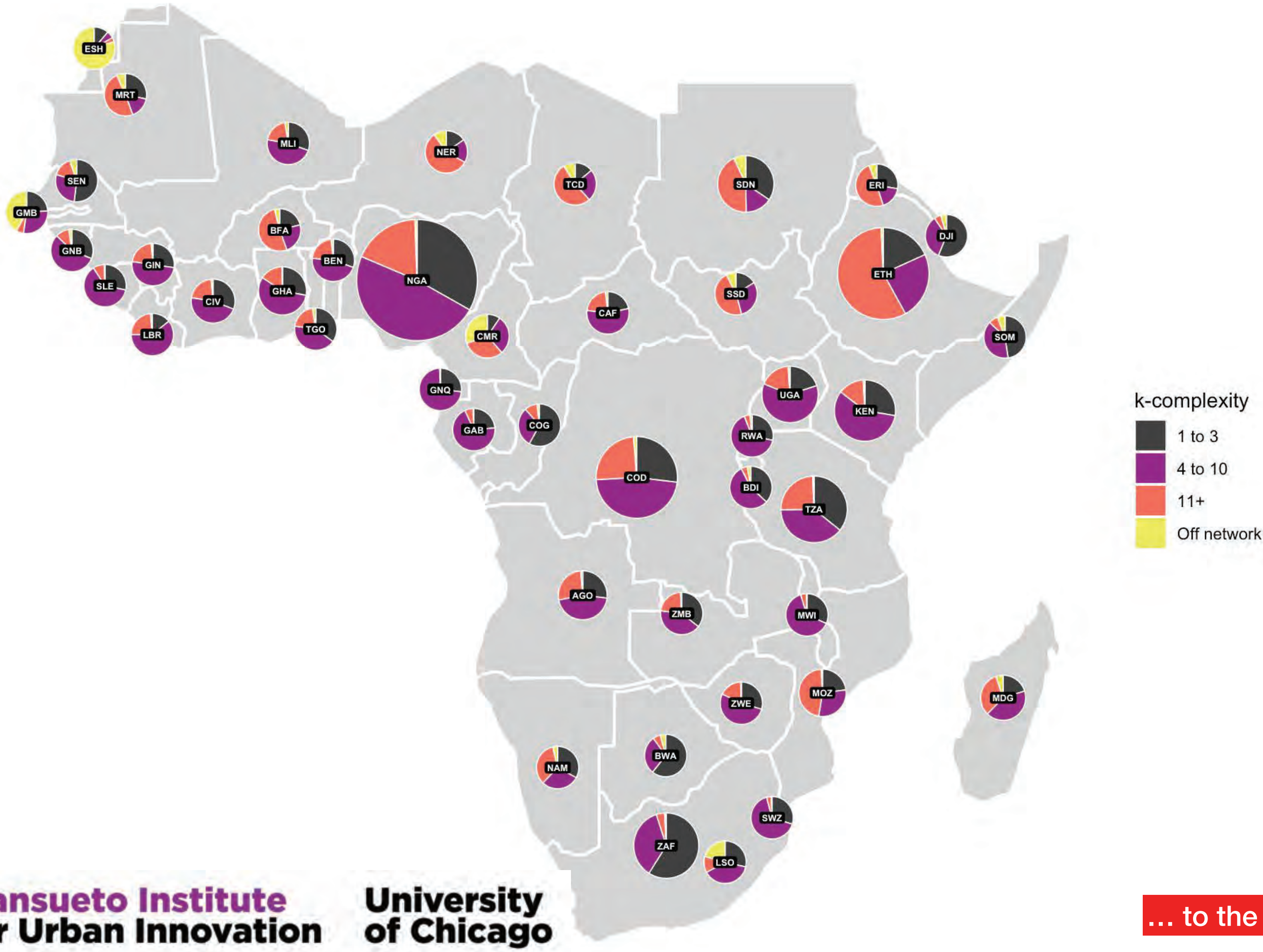
Every city, town and hamlet: every block

New block level data worldwide



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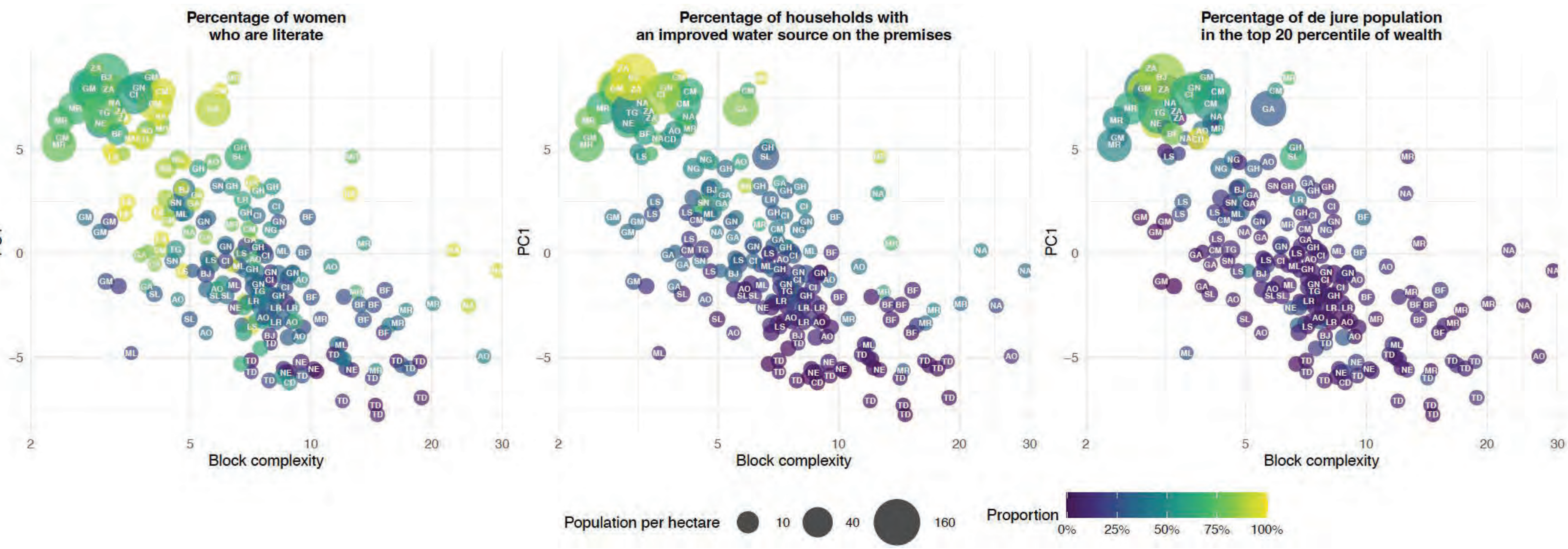
… to the continent.

Human development and connectivity



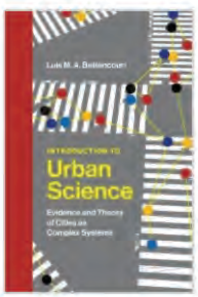
ISO	Country
AO	Angola
BF	Burkina Faso
BJ	Benin
CD	DR Congo
CI	Cote d'Ivoire
CM	Cameroon
GA	Gabon
GH	Ghana
GM	The Gambia
GN	Guinea
LR	Liberia
LS	Lesotho
ML	Mali
MR	Mauritania
NA	Namibia
NE	Niger
NG	Nigeria
SL	Sierra Leone
SN	Senegal
TD	Chad
TG	Togo
ZA	South Africa

From international human and health surveys

Thank you !

Luís M. A. Bettencourt
@BettencourtLuis   Bettencourt@uchicago.edu   https://luisbettencourt.org

More on the complex systems, science of cities and lots of data:



Introduction to Urban Science

Evidence and Theory of Cities as Complex Systems

Luís M. A. Bettencourt

2021

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

The MIT Press

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