The Growth Models for Science of Cities

Gezhi Xiu

Complexity Research Group,
Peking University

February 15, 2020

Contents

Overview

- Zipf's law and its formation
  - Zipf's law without fine-tuning: static mesoscopic
  - Stationary distribution of dynamical processes for the sizes of groups of individuals
    - mesoscopic: cities
    - microscopic: individuals
- Gibrat's law and Taylor's law

Fractal Cities

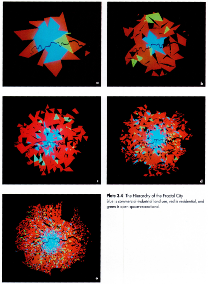


Plate 3.4 The Hierarchy of the Fractal City
Blue is commercial-industrial land use, red is residential, and green is open space-recreational.

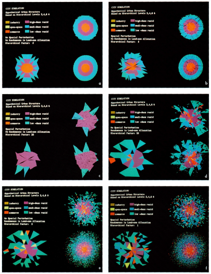


Plate 4.1 A Sampling of the Space of All Cities.

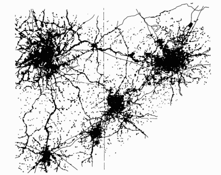


Figure 1.16. Contemporary urban growth patterns (from Chapin and Weiss, 1962).

Figure: Aspects of fractal cities

Fractal Cities

- M. Batty and P. Longley, Fractal Cities: A Geometry of Form and Function (Academic, San Diego/London, 1994).
- Cellular automata have been used to model spatial structure of urban land use over time: Environ. Plan. A 25, 1175 (1993).
- The correlated percolation model

the Zipf's law

The group size distribution.

- the rank distribution of words in large corpora
- the number of employees in firms
- the distribution of family names
- the distribution of city sizes

$$P(n) \sim n^{-1-\gamma} \tag{1}$$

$$\gamma \simeq 1 \tag{2}$$

Models that lead to Zipf's law

Some up-to-date models are really fascinating.

- Models with latent variables can lead to Zipf's law without fine-tuning by mixing together narrow distributions with very different means.(PRL 113, 068102 (2014))
  - static systems (no time dependence)
- The stationary distribution of dynamical processes for the sizes of groups of individuals
  - mesoscopic models at the scale of the groups (e.g., cities) Am. J. Phys. 58, 267 (1990). Variance that is not Gaussian but exponential Gaussian leads to Zipf's law.
  - microscopic models at the scale of the individuals (e.g., dwellers)

Mesoscopic Models

- without the need to fine-tune their parameters to specific values
  - random multiplicative process, Am. J. Phys. 58, 267 (1990).*space independent*
  - Gibrat's law / proportionate random growth, Phys. Rev. E 57, 4811 (1998).
  - the interplay between intermittency and diffusion, Phys. Rev. E 58, 295 (1998).
- however they are coarse-grained descriptions of population dynamics and lack an explicit link to the underlying microscopic processes

Microscopic Models

- Stochastic processes describing the events experienced by an individual, namely births, deaths, and migrations, that ultimately determine the change in the size of a population.
  - Yule's and Simon's models: rich-get-richer, Phil. Trans. R. Soc. Lond. B 213, 21 (1925), Biometrika 42, 425 (1955).
  - Cluster growth and aggregation, Phys. Rev. E 58, 7054 (1998).
  - Reaction diffusion models: explore the role of intermittency in creating spatial inhomogeneities in agreement with Zipf's law, Phys. Rev. Lett. 79, 523
  - Preferential migration to large aggregates, Phys. Rev. Lett. 88, 068301 (2002).
  - Spatial explicit preferential attachment: the probability that a city grows is essentially assumed to be proportional to the size of the city.
  - network growth with redirection, Phys. Rev. X 4, 011008 (2014).
- Only for fine-tuned parameters to get $\gamma = 1$.

Radical Decay

- The correlated percolation model: an urban built environment is shaped by spatial correlations where the occupation probabilities of two sites are more similar the closer they are.

Taylor's law

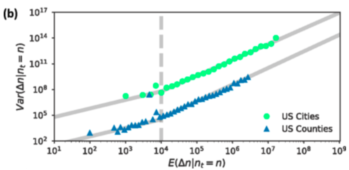
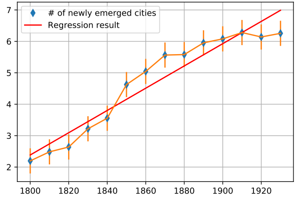


Figure: The variance of population in year $t + 1$ conditioned to the population in year t (y axis) vs the average population in year $t + 1$ conditioned to the population in year t (x axis) for cities (circles) and counties (triangles) in the United States during the period 1970–2010.

My Current Work: Spatial Yule Model

How can we address more aspects of urban studies within a simpler model?

Observations



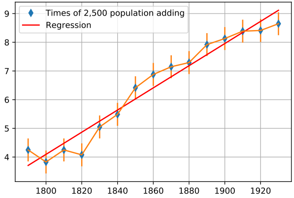
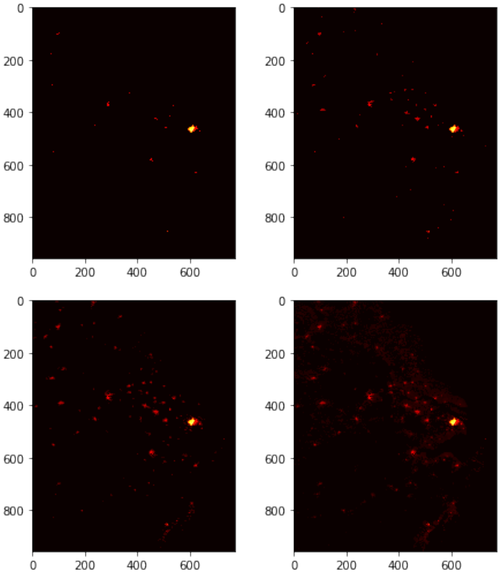
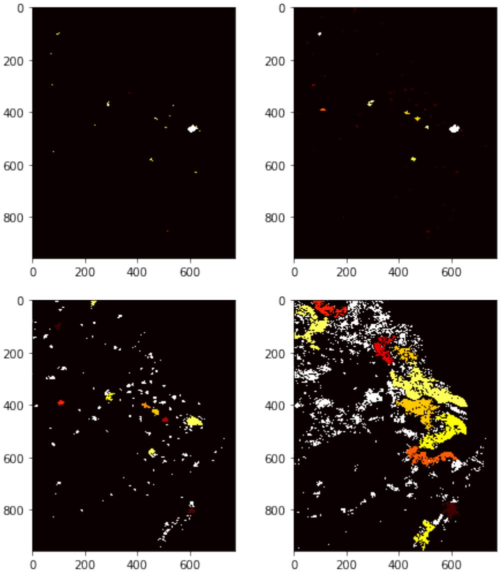


Figure: We take 2,500 as the study unit and get a) The emerging speed of cities in the United States, and b) the counts that 2,500 population are added to an existing city. Both slopes are around 0.04, $p < 0.0001$.

Population based spreading



Population based spreading



Formation Philosophy

- Scaling of inner- intra-city (area, population, infrastructure)
  - Gradient descent to the sum of two-dimensional normal distributions for a optimal locating problem lead to some scaling behavior.
- Interacting cities lead to Zipf's law and fractality of urban boundary.
- Asymptotic behaviors (standard cause of scaling) is far from reality.

Rules

The background is on a $L \times L$ grid space. The growing mechanism states as follows:

1. Growth rate per capita β_2, and the growth rate for # of cities β_1.
   - ignoring the correspondence to real-life time scale, the actual effective parameter the relative $\beta := \beta_2/\beta_1$.
2. The distance a ball lands a meta-population nearby as a constant, r, towards a random direction θ.
3. The *productive* balls are limited, with no more than N^*.

In all, this model relies on three parameters, the relative speed for city generation β, the diffusion rate r, and the size of the memory kernel N^*.

Points

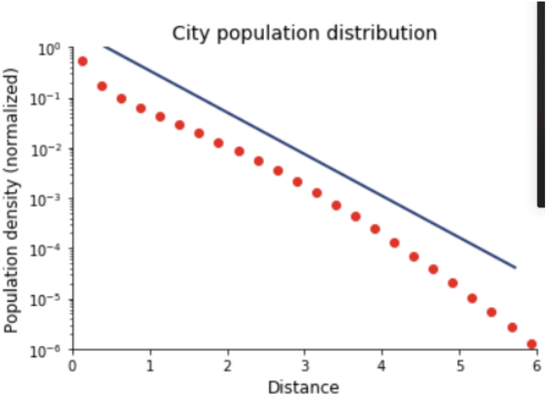
1. possessiveness
2. homogeneity
3. cut-off
   - comparing to logistic?

- The settings provide a border line between free growth (Scaling laws) and constrained growth (vicissitude phenomena).

Results

- Clark's law of urban population density
- Zipf's law of city population sizes
- vicissitude
- fractality

Clark's law


City population distribution
Population density (normalized)
Distance
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
0
1
2
3
4
5
6


City population distribution
n density (normalized)
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}

Zipf's law

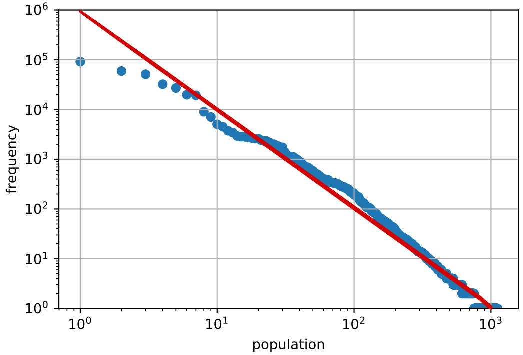


Figure: Simulated result for $\beta = 1$. When $\beta \approx 1$, the population distribution across cities is close to the case in reality, $P(n) \sim n^{-2}$.

Scalings for area sizes

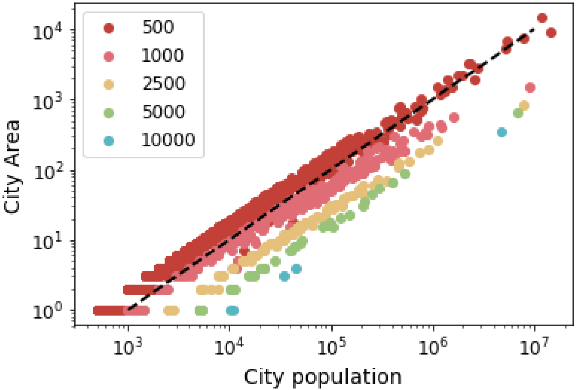


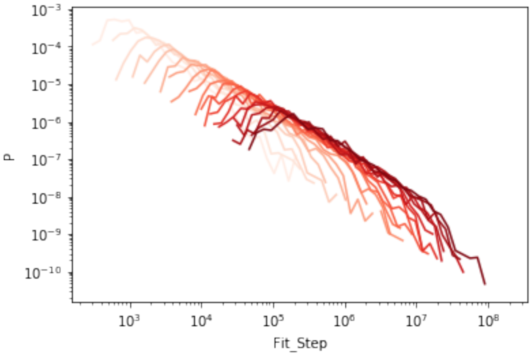
Figure: Population versus area

Vicissitude

- Blockwise

$$\rho_{threshold} = k\beta_1/(2\beta_2) + N^*/2 \tag{3}$$

- Citywise



Fractality

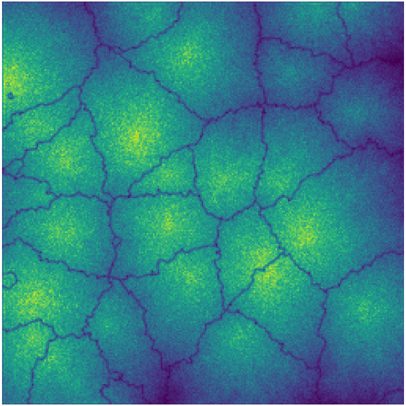


Figure: Fractality is driven by the probabilistic competition for edging space.

Topics about *what is a city*?

Owuor Otieno, Mark . (2017, October 23). What is the Difference Between a City and a Town? Retrieved from https://www.worldatlas.com/articles/what-is-the-difference-between-a-city-and-a-town.html