From City Modeling to General Complex Networks

Gezhi Xiu

IRSGIS, Peking University

November 2, 2020

1

[1] Presentation for Prof. Yang-Yu Liu's Interview

Outline

About me

- Ph.D. candidate of GIS, Peking University, advised by Prof. Yu Liu
- B.A. of Mathematics and Applied Mathematics, Peking University, advised by Prof. Kai Xu

My current research interests:

- Modeling cities through statistical physics
- General complex network theories

Personalities:

Strongly motivated, curious, optimistic, geeky

Modeling cities with complex systems

Goals

- Aim to solve, interpret, and control urban complex systems
- Study the underlying principles of interdisciplinary networks

Concerns

- Population dynamics
- Economic complexity
- Urban structures
- Mobility and epidemics
- ......

Why important? Why complex systems?

The cross-scale complexity

The study of cities need systems biology theories because of the common pursuits of stability, controllability, identification of universality, and the emergence of motifs, etc..

Figure 1: Natural and human complex phenomena. Source

My research work

Question: How do cities emerge, grow, and *compete* over space?

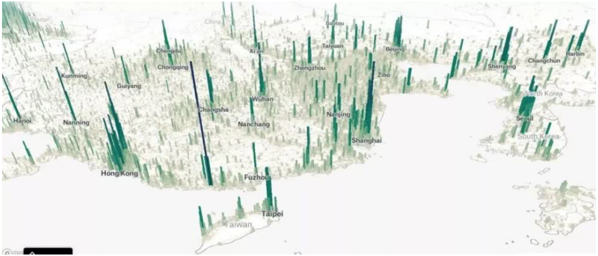


Figure 2: Population distributions of Eastern China and the Korean Peninsula. *Source link*

Why is it important, and what have and haven't been done?

Urbanization is complex and diverse, but scaling laws are similar.

Obvious basic rules behind cities:

- Zipf's law
  - The rank size distributions of cities follow a specific form:$P(n) \sim n^{-(1+\gamma)}$, where $\gamma \approx 1$.
- Clark's Law
  - The spatial distributions of population within a city exponentially decay from urban center: $p(r) \sim P_0 e^{-\alpha r}$.
- Fractality
  - Urban envelopes are fractal.

Why is it important, and what have and haven't been done?

Urbanization is complex and diverse, but scaling laws are similar.

Obvious basic rules behind cities:

- Zipf's law
  - The rank size distributions of cities follow a specific form:$P(n) \sim n^{-(1+\gamma)}$, where $\gamma \approx 1$.
- Clark's Law
  - The spatial distributions of population within a city exponentially decay from urban center: $p(r) \sim P_0 e^{-\alpha r}$.
- Fractality
  - Urban envelopes are fractal.

How to model?

Why is it important, and what have and haven't been done?

Existing models have explained the empirical results of Zipf's, Clark's, and scaling laws.

- migration patterns[?],
- spatial gathering[?],
- reaction-diffusion[?],

......

Leading to asymptotic behavior of Zipf's law.

Emerge? Grow? Compete?

Why is it important, and what have and haven't been done?

Existing models have explained the empirical results of Zipf's, Clark's, and scaling laws.

- migration patterns[?],
- spatial gathering[?],
- reaction-diffusion[?],

  ......

Leading to asymptotic behavior of Zipf's law.

Emerge? Grow? ~~Compete?~~

Observations

Urbanization won't last forever. It is also not driven by pure growth dynamics. It has its own critical dynamics in the percentage of resource. It also has temporal advantages. **Cities are competitive.**

Figure 3: NYC & Detroit. From Michael Batty's thesis, *Diverse cities, successful cities*[**?**].

Economic complexity and cultural evolution

Observations

Urbanization won't last forever. It is also not driven by pure growth dynamics. It has its own critical dynamics in the percentage of resource. It also has temporal advantages. **Cities are competitive.**

Figure 3: NYC & Detroit. From Michael Batty's thesis, *Diverse cities, successful cities*[**?**].

We want it simpler.

Philosophy

Competition for Resource

- Cities grow because they are **competitively** better (than rural area or other cities).
- The **total competitiveness** lies in the **finite active population** $\equiv N^*$.
- Active people either:
  - move in cities and settle somewhere, driven by other actives' attraction, (with rate β_2);
  - or establish a new city, (with rate β_1).

Rank relevant intellectuals?

Competition for Space

- Once a site is occupied by a city, you can settle here only if you belong here.

Model

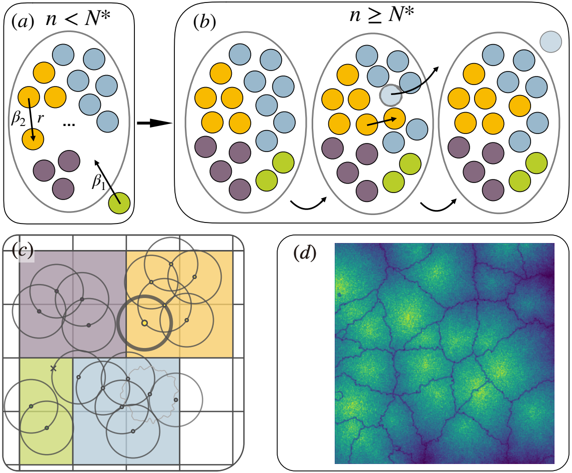


Figure 4: Model sketch: (a) Speeds of additions of # of cities and citizens; (b) The role of the memory kernel; (c) Spatial settings; (d) A realization with $\beta_1 = 0.25$, $\beta_2 = 1$, $r = 0.5$, $N = 10^5$.

Model

Notions:

$N_i(t)$: # of active citizens in i'th city at time t;
$k(t)$: # of cities at time t.

Rules:

- The model is based on continuous space and time context.
- Growth: restricted preferential attachment.
  - $dN_i(t)/dt = \beta_2 N_i(t) - \delta_{\{\sum N_i = N^*\}} \beta_1 k(t) - \delta_{\{\sum N_i = N^*\}} (N^* - N_i(t)) \beta_2,$
  - $dk(t)/dt = \beta_1 k(t).$
- Spatial settings:
  - Grid blocks. Once a block is taken by one city, citizens from other cities cannot survive.
  - New city: uniformly, if empty? confirmed.
  - New active citizen: (r, θ) from an existing active citizen.
- *All parameters:* $r, \beta := \beta_2/\beta_1,$

Results: As an urban system

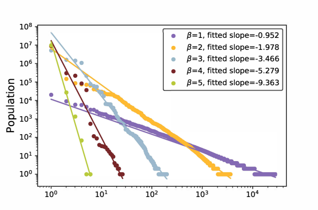


Figure 5: Zipf's law of rank size distribution; $\beta := \beta_2/\beta_1$

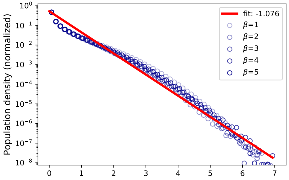


Figure 6: Clark's law for a city's population density.

SYM is a successful model for urban systems that reformulates Zipf's and Clark's law.

Results: Competitions for **resource** and space

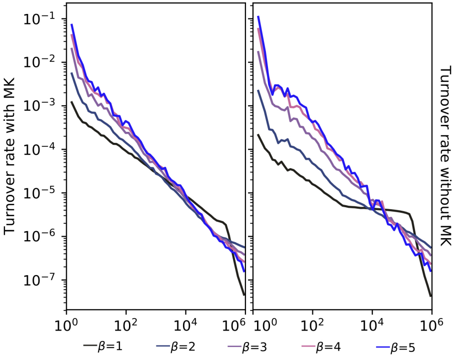
Critical density:

$$\rho_{threshold} = k/\beta.$$

$\uparrow$ with # of cities k. Survival probability of a site $\downarrow$.
When the space is filled, **Critical population:**

$$N_{threshold} = 0.5N^*$$

Turnover rate:



Results: Competitions for resource and **space**

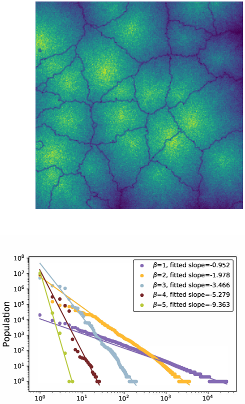


Figure 7: *Above:* Fractal edges drawn from SYM. *Below:* The absolute values of the slopes are expected as β without a spatial context.

- Small cities are advantageous for spatial competitions.
- For large β's, the survival probability of small cities decreases rapidly, bring advantages for big cities.

Our histogram

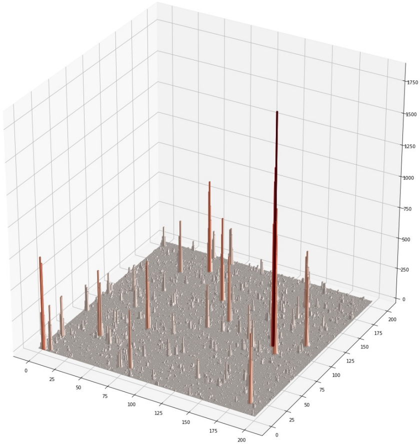


Figure 8: Simulated result.

Insights

- The tendency of vicissitudes is strengthened by the restrictions of resource.
- The bottom-up formations of traditional models are not enough to model cities.
- Zipf's law with $\gamma \approx 1$? **Not quite!**
- Spatial competition has to be taken serious, especially for small areas.
- Critical phenomena from branching process can be broadly adopted.

Research plans: Problems

- How could complex network theory make it better for urban life?
- Dig in complex network, especially structural and temporal heterogeneities of the contact network.
- Feeding back: what does space mean for complex networks?

Physics and society

E.g., how can we interpret and improve *urban traffic networks* through statistical physics?

- The benefits of public transport[?], $T/P = 1 - p$
- Topology and the spatial evolution of neighborhoods v.s. slums in cities[?]
- Urbanization correlated to hantavirus epidemics

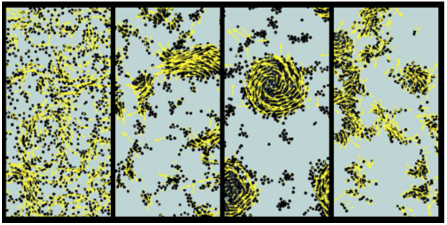


Figure 9: Collective Dynamics of microbial. H. Karani et al., Phys. Rev. Lett. (2019)

Physics and society

A design for road network generation towards cities without slums:

- Based on the generation method in [?] with different optimization purpose: from *connecting to the network the still unconnected centers using as little as possible road length*, to a *linear combination of connectivity and tendency to get a block surrounded by roads*.

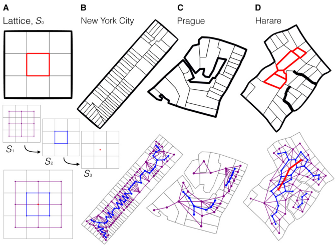


Figure 10: Towards cities without slums, [?]

Structures in complex systems

- Predictability[?, ?] through *compression of graphical structures* or *permutation entropy*.
- Controllability[?, ?, ?]
- Minimum of complex network[?]
- Geometric renormalization for the growth of modular networks[?]
- ......

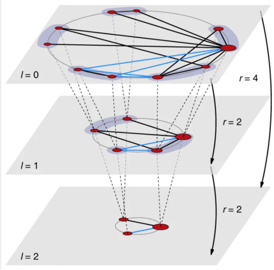
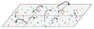


Figure 11: Structural transitions of network by renormalizaiton group. From Ref.[?]

Feeding back: What can those beyond links tell network?

- Density-based analysis: carbon emission, spatial structures, anomalous structures(tumors)...
- The variations of controllability of network is non-linear...
- Spatial networks, represented by epidemic models, are now highly related to human mobility models, as a preface of Physical Review E:



PRE SPOTLIGHT

Human Mobility and Epidemic Dynamics

Impact of travel patterns on epidemic dynamics in heterogeneous spatial metapopulation networks
Shunjiang Ni and Wenguo Weng
Phys. Rev. E **79**, 016111 (2009)

Dengue epidemics and human mobility
D. H. Barmak, C. O. Dorso, M. Otero, and H. G. Solari
Phys. Rev. E **84**, 011901 (2011)

Epidemic spreading induced by diversity of agents' mobility
Jie Zhou, Ning Ning Chung, Lock Yue Chew, and Choy Heng Lai
Phys. Rev. E **86**, 026115 (2012)

Epidemic spreading in localized environments with recurrent mobility patterns
Clara Granell and Peter J. Mucha
Phys. Rev. E **97**, 052302 (2018)

Persistent spatial patterns of interacting contagions
Li Chen
Phys. Rev. E **99**, 022308 (2019)

Q1: Density-based versus link-based

Various attempts beyond link structures:

- Simplicial models of social contagion
  - speed of contagion helps to identify the most vulnerable or dangerous individuals in an outbreak
- Contact-Based Model for Epidemic Spreading on Temporal Networks[?]
- My model of SYM

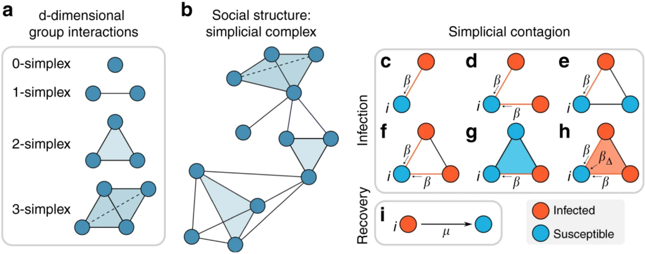
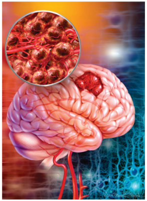


Figure 12: Simplicial contagion model. Source

Q2: Function versus threats



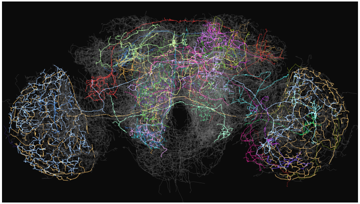


Figure 13: Brain tumor (*source*), and Neural network(*source*). It is interesting how functional organs, e.g., the brain, interconnects more topologically through links, such as synapsis or pipes; while the threat parts, such as tumors in brains and slums in cities, are usually spatial clusters.

Q3: What's more?

Let's find out together.

Research plans: Timelines

Timelines: My visit will start from June or July.

- to 2020-08	Settle down, material reading, pick two/three projects
2020-09 to 2020-10	Basic experiments, discussions on values, feasibility, research proposals
2020-11 to 2021-06	Finish a work, revalue the aims below
2021-07 to -	Collaborate on challenging topics

Aims:

- (Hopefully) Find universal laws that exist both in human societies and microbial;
- Improve the theoretical basis of complex network theory;
- Give optimizations and solutions to cities with statistical physics.

Thank you for listening!

email: xiugz@pku.edu.cn
personal page: gxiu.github.io