Generating urban-like networks with DLA

Group 10

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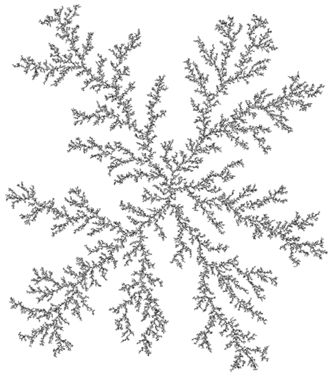
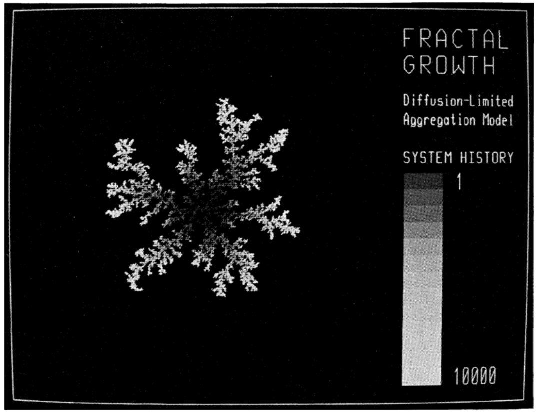
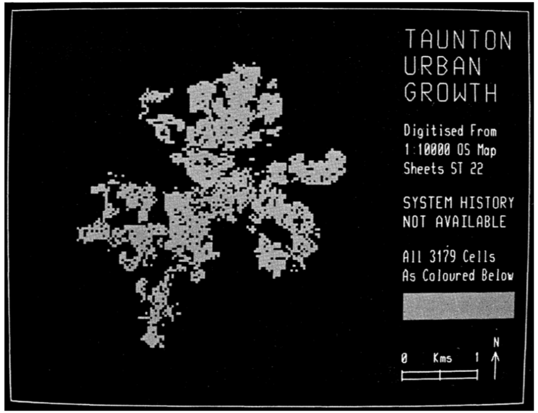
Background

- Diffusion-Limited Aggregation
  - Coral reefs, urban growth…
- The process of DLA largely determines the urban geometry
- Fractal analysis → Network analysis







Batty, et. al, 1989

Research Questions

- Emergent behavior
  - How are parameters related to the patterns?
    - expansion, densification, etc.
  - Can we simulate the formation of real cities?

Detroit, MI, U.S.
Image by Geoff Boeing

Boston, MA, U.S.
Image by Geoff Boeing

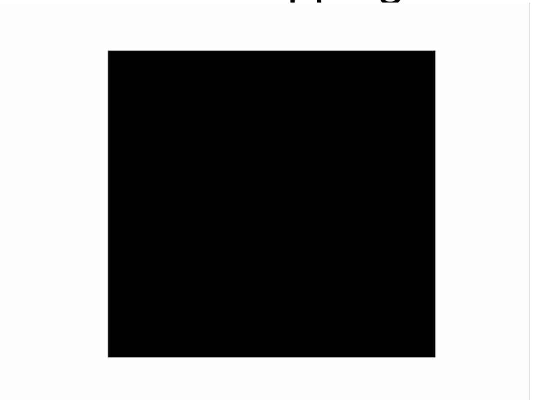
Amsterdam, NL.
Image by Gridlines

Diffusion-Limited Aggregation

- **Diffusion-limited aggregation** (DLA) is the process whereby particles undergoing a random walk due to Brownian motion **cluster** together to form **aggregates** of such particles.
- Diffusion-limited Aggregates are called **brownian trees** or **fractals**.
- Applications in modeling of **crystal formation**, **tumor growth** and **city networks**.

The DLA Algorithm

- Start with a completely empty space (numpy array) and place one particle in it.
- Spawn a random walker which will walk through the space until it hits the structure, once that happens it has a probability of Ps of adhering.
- Third particle is released and the process repeats until a stopping condition is met.



Influence of the sticking probability on the aggregate

Sticking probability = 0.01

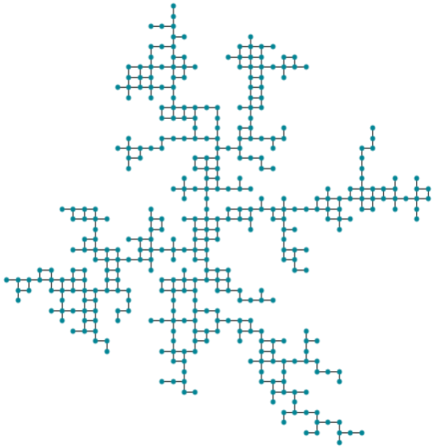
Sticking Probability = 1

Notable Implementation Details

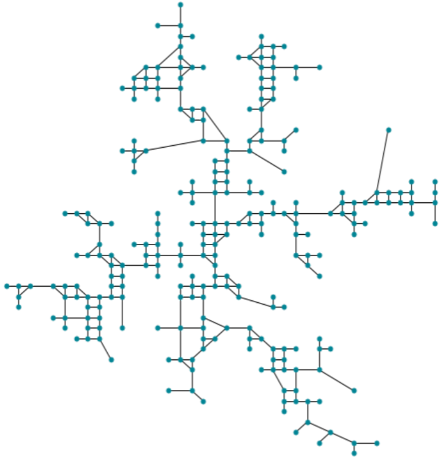
- Square Lattice DLA is used.
    - Discretises the space domain
- Walkers are bounded in a radius around the aggregate, so walkers can not walk off into the distance.
    - Yields significant speedup

From DLA to networks

1. Generate a binary grid with DLA.



2. Convert each occupied cell into a node and make links between neighbours to the east, west, south and north.



3. Simplify the network by removing nodes of degree = 2.

Network parameters in relation to cities

- Average degree ($\hat{k}$) - measures how many streets on average combine into a junction.
- Average clustering ($\hat{c}$) - measures how fragmented the city is. Lower clustering - less fractured city.
- Diameter (d) - measures how many junction need to be travelled through in the longest shortest path in the city.
- Entropy (H) - measures the disorder in the city. Higher entropy - higher variation in the street orientation angles.
- Percent 1st degree nodes (P_{de}) - dead-end streets.
- Percent 4th degree nodes (P_{4w}) - 4-way junctions.

Comparison with real cities

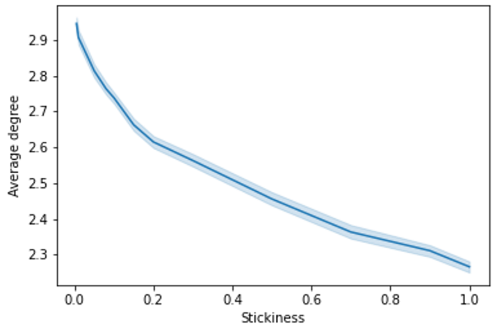
City	$\hat{k}$	$\hat{c}$	H	P_{de}	P_{4w}
Bangkok, Thailand	2.296	0.021	3.482	0.385	0.079
Oslo, Norway	2.741	0.094	3.578	0.170	0.116
Riyadh, Saudi Arabia	3.042	0.017	3.181	0.028	0.107
Las Vegas, NV, USA	2.667	0.047	2.797	0.238	0.168
Manila, the Philippines	3.073	0.039	3.522	0.108	0.299

stickiness	$\hat{k}$	$\hat{c}$	H	P_{de}	P_{4w}
0.005	2.936	0.089	1.210	0.153	0.259
0.010	2.921	0.090	1.217	0.156	0.252
0.100	2.737	0.099	1.301	0.217	0.194
0.300	2.551	0.104	1.425	0.271	0.130
0.500	2.458	0.104	1.494	0.301	0.101
0.700	2.367	0.093	1.551	0.332	0.078
1.000	2.278	0.082	1.633	0.366	0.055

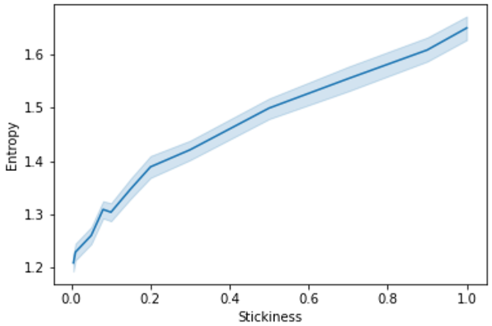
City network data obtained via OSMnx package on python

How does stickiness affect network properties?

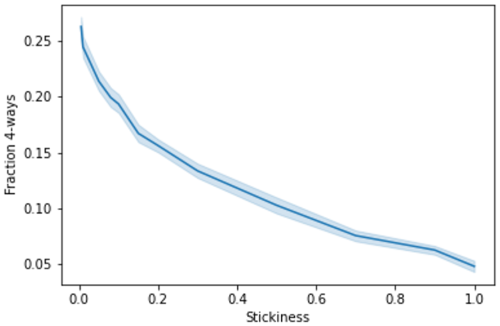
Average degree



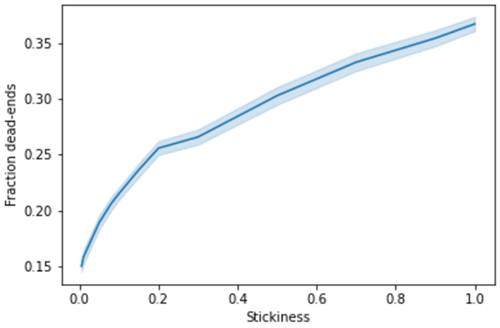
Entropy



Percentage 4-way



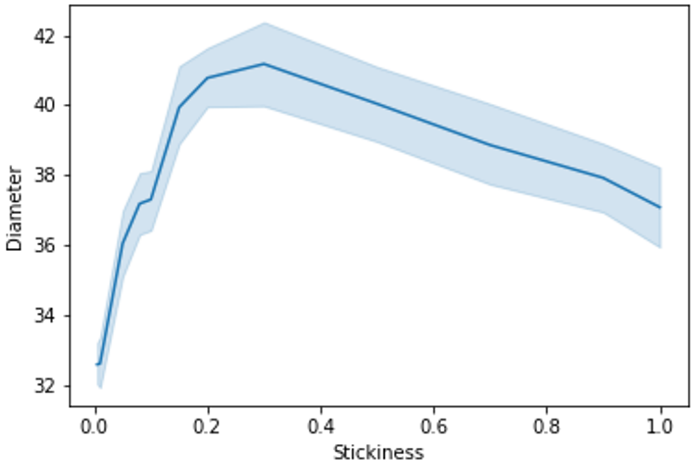
Percentage dead-ends



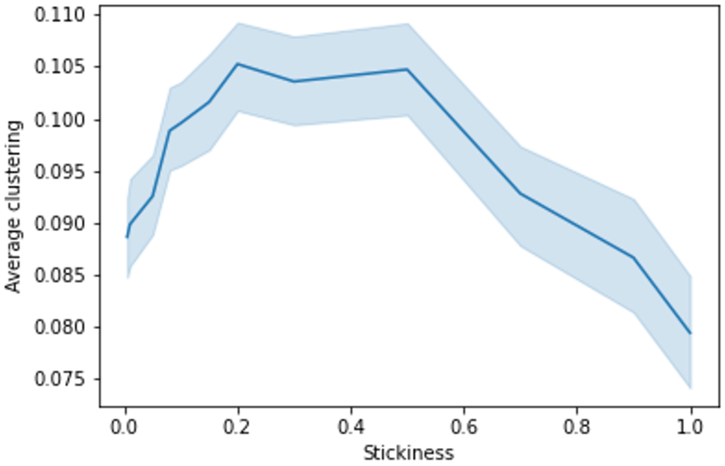
Results: 50 runs with 400 walkers at stickiness = 1, 0.9, 0.7, 0.5, 0.3, 0.2, 0.15, 0.1, 0.08, 0.05, 0.01, 0.005

How does stickiness affect network properties?

Diameter



Average clustering

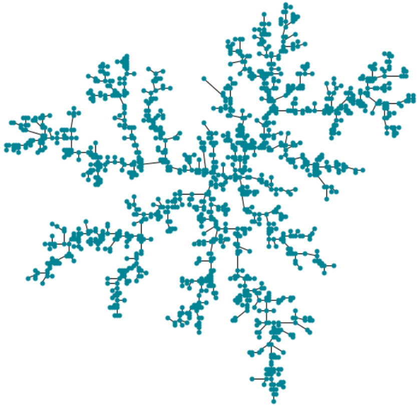


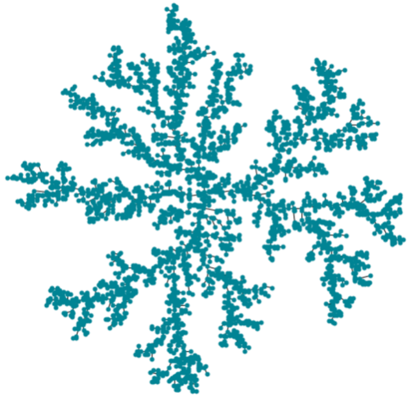
Results: 50 runs with 400 walkers at stickiness = 1, 0.9, 0.7, 0.5, 0.3, 0.2, 0.15, 0.1, 0.08, 0.05, 0.01, 0.005

Real city network vs DLA networks

Riga, Latvia

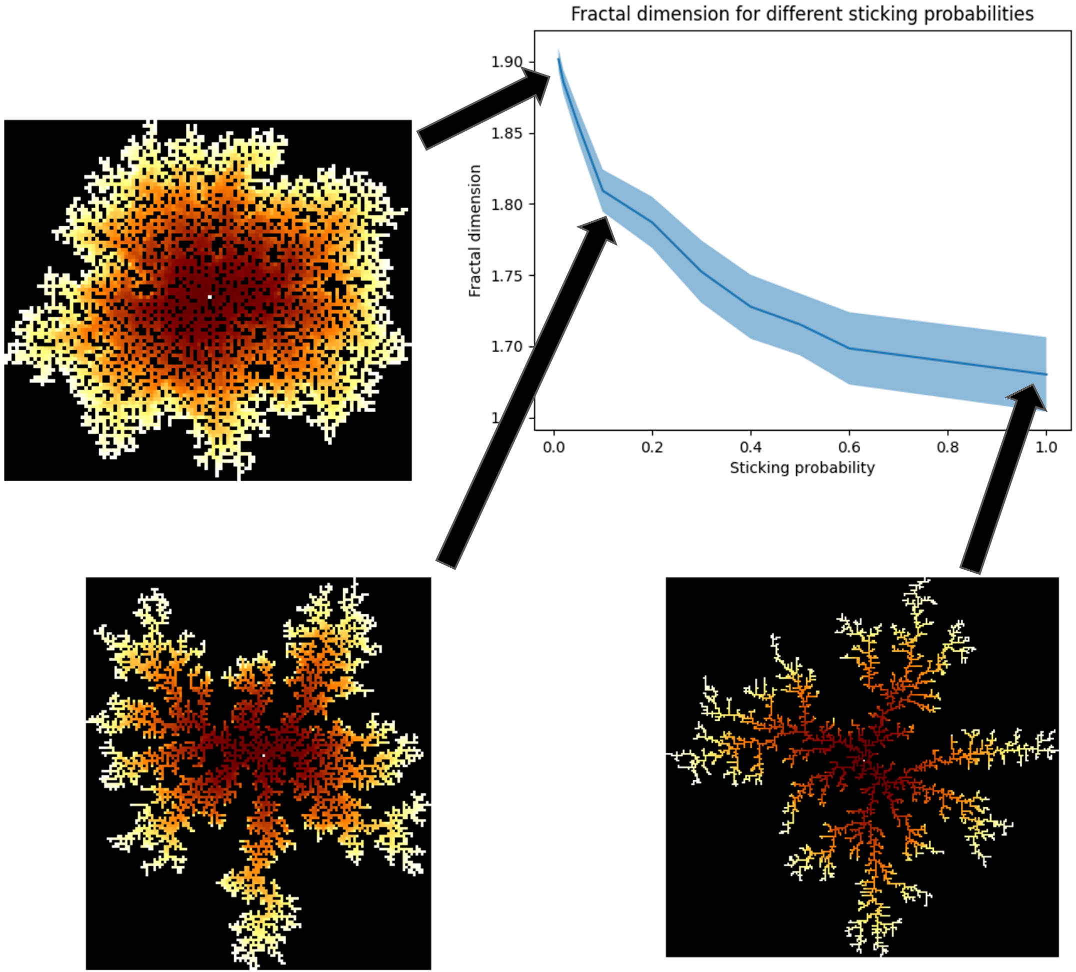
Vilnius, Lithuania





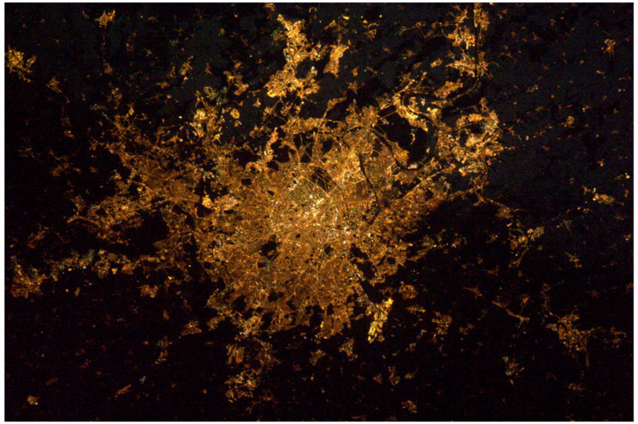
Dynamic stickiness

- No DLA structure seems to really resemble a city, even if network results aren't too far off.
- Seems that a city could resemble a mix of lower and higher stickiness in some way.
- New idea: dynamic stickiness!
- Fixed stickiness -> changing stickiness within same simulation.

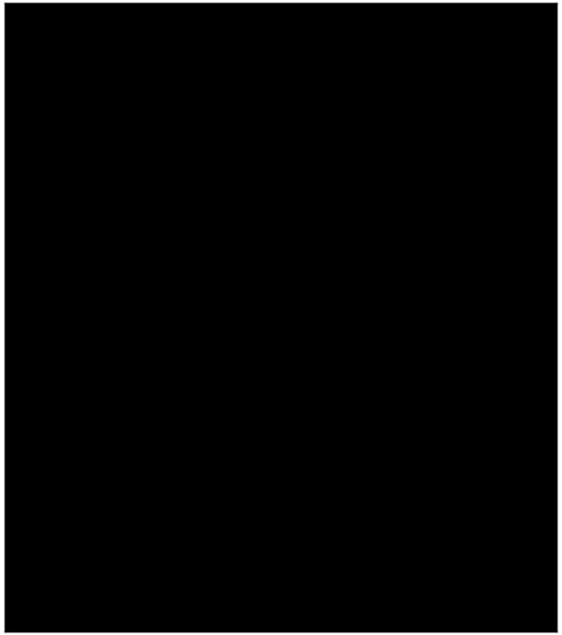


Dynamic stickiness

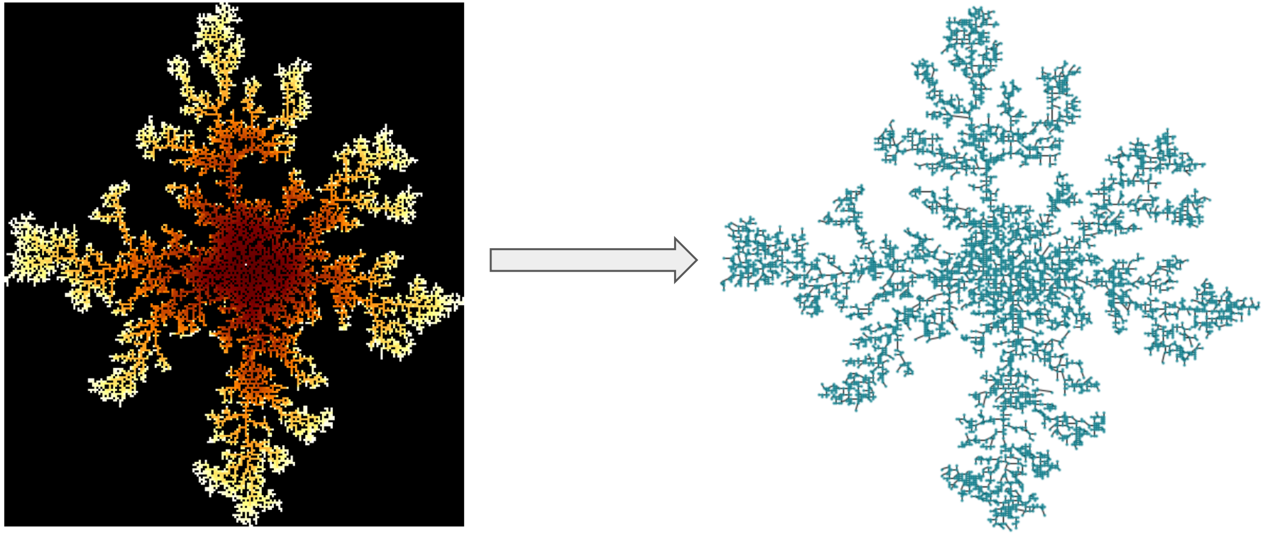
- Form a center -> spread out -> form adjoining neighbourhoods.
- Sine wave -> step function.
- Recognizable periods of exploration/exploitation or expansion/densification.



Paris at night from ISS. Image from ESA/NASA.

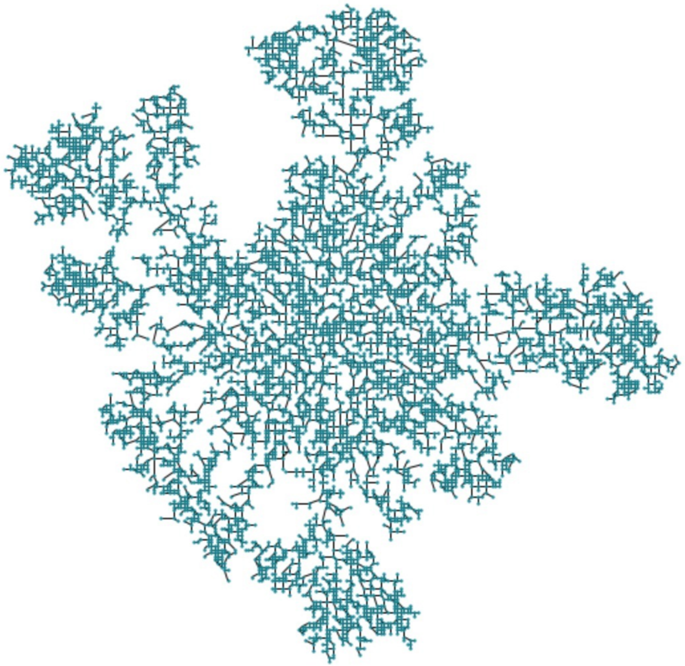


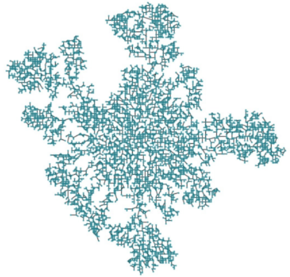
Dynamic stickiness



$\hat{k}$	$\hat{c}$	H	P_{de}	P_{4w}
2.746761	0.100093	1.801226	0.208205	0.18831

Real city comparison: Berlin





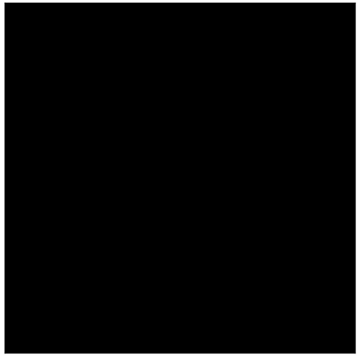
	Berlin	DLA model
Average degree	2.998	2.910
Clustering	0.052	0.094
Entropy	3.572	1.701
Dead ends	0.120	0.153
4-ways	0.257	0.235
Fractal dimension	1.845 ± 0.01	1.848 ± 0.009

Conclusions

- Tried new type of DLA method/analysis and compared results to real cities.
- Did we show whether DLA could be used to show city formation? Unclear.
- Patterns of networks with dynamic stickiness do resemble city structure visually, but network details are still quite different.
- However, we consider using dynamic stickiness a success.
- Literature on this subject is extremely scarce, we hope to have contributed at least to some extent.

Future work

- To possibly come to better results and more interesting structures, we have some recommendations.
- Change grid to hexagonal cells to introduce more freedom of movement, or take even further to continuous space.
- Geological structures often get in the way of growth; how would the model react to having no-go zones such as water/mountains?
- More experimentation with dynamic stickiness. There are tons of different scalings to try here and could also be combined with different grid spaces.



References

- Batty, M., Longley, P., & Fotheringham, S. (1989). Urban growth and form: scaling, fractal geometry, and diffusion-limited aggregation. *Environment and planning A*, *21*(11), 1447-1472.
- Boeing, G. (2019). Urban spatial order: Street network orientation, configuration, and entropy. *Applied Network Science*, *4*(1), 1-19.
- Halsey, T. C. (2000). Diffusion-limited aggregation: a model for pattern formation. *Physics Today*, *53*(11), 36-41.
- Meakin, P. (1983). Formation of fractal clusters and networks by irreversible diffusion-limited aggregation. *Physical Review Letters*, *51*(13), 1119.

Appendix: From network to fractal