The topological basis for the reliability of power transmission grids

Bowen Fu[1], Leonardo Dueñas-Osorio[2]

[1] Doctoral student, Department of Civil and Environmental Engineering, email: Bowen.Fu@rice.edu

[2] Associate professor, Department of Civil and Environmental Engineering, email: leonardo.duenas-osorio@rice.edu

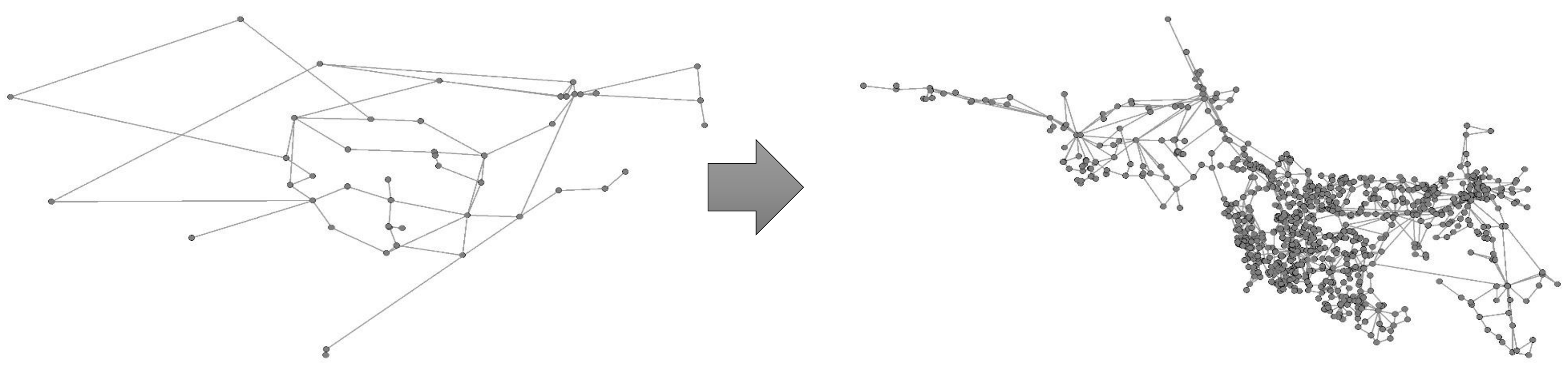
Rice university, 6100 Main Street, Houston, TX 77005

1. Motivation

The reliability of power grids stems from their topological properties. Distributions and spectra carry more information than traditional node-level or system-level average metrics, but are not well understood. In this work, 58 city-level power transmission grids in the U.S. are investigated, as well as synthetic networks that conform to the statistical properties of power grids, emphasizing distributions and spectra properties. Practical topological properties are identified as relevant to reliability, such as handles and onion decomposition spectra, supporting less computational expensive ways to evaluate and improve hard-to-compute reliability.

2. Power Grids

1. Real city-level power grids in the U.S.:



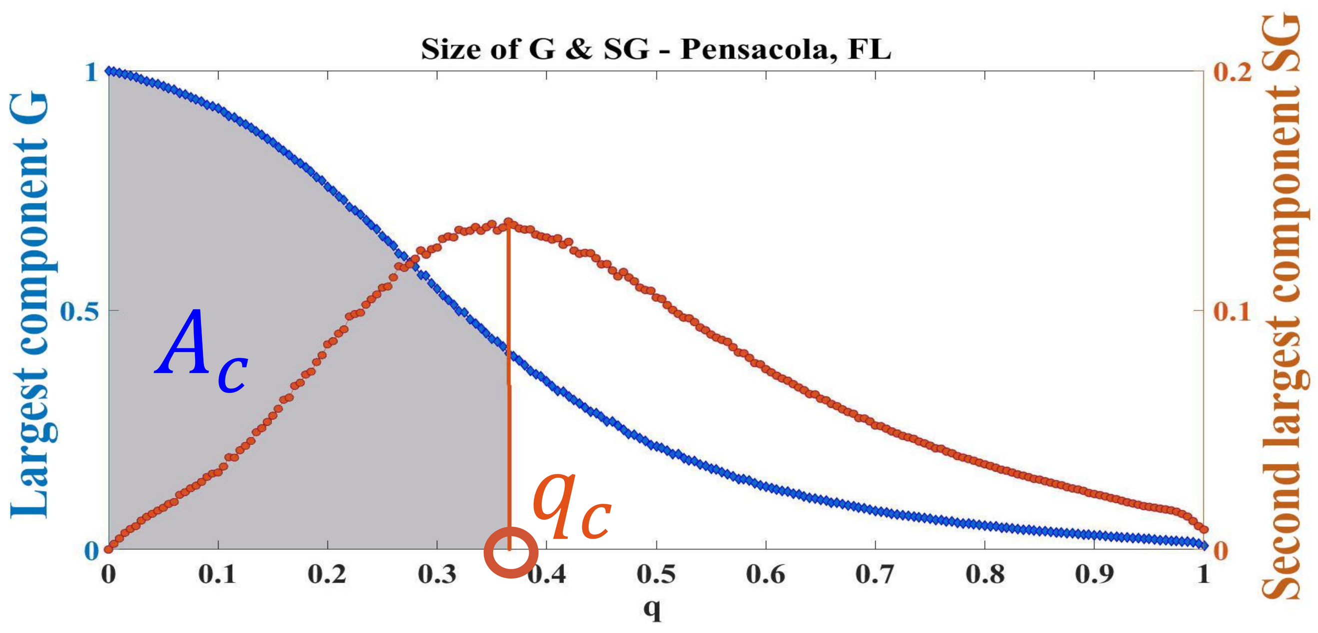
Amarillo, TX (47 nodes, 62 links) Los Angeles, CA (1036 nodes, 1511 links)

2. Synthetic power grids: Generated by random growth model [1]

3. Reliability

Reliability is a #P-hard problem, which is very computationally expensive.

Random percolation:



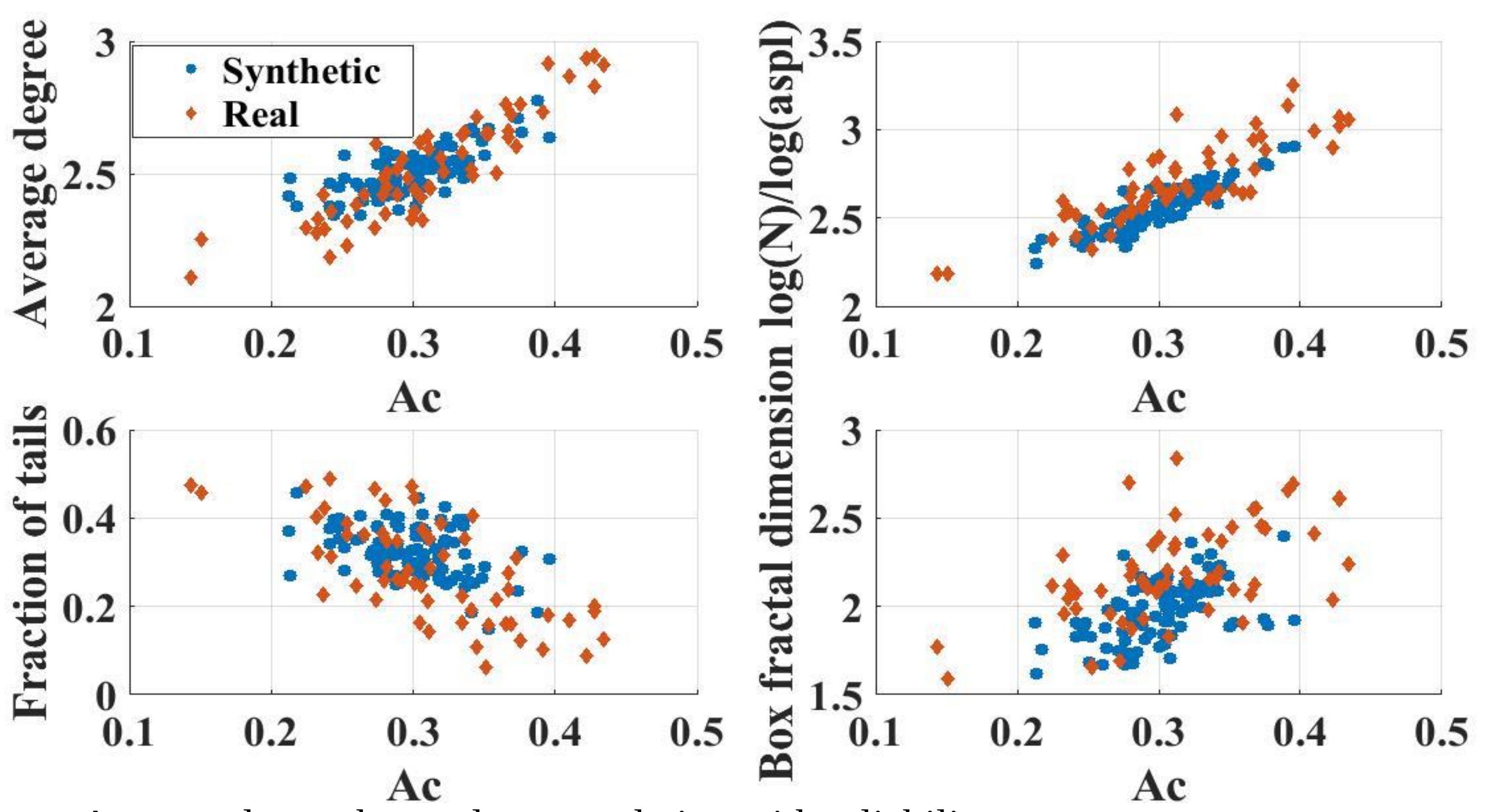
A_c:

- Connectivity criticality (q_c) and supercritical performance (curve)
- Uncertainties: component aging, operational failures, failures from interdependencies, etc.

4. Results

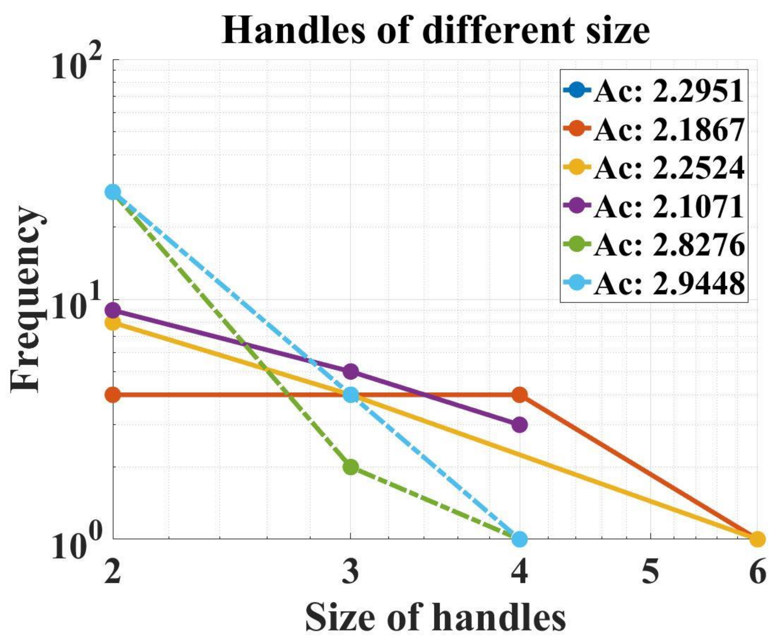
1. Reliability vs. Topological metrics:

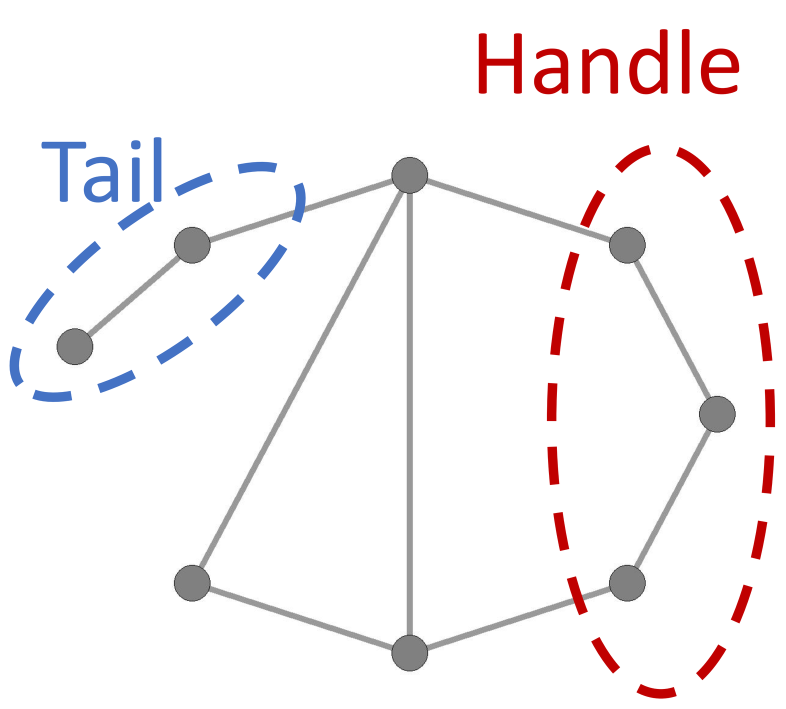
Real city-level power grids in the U.S. and synthetic power grids:



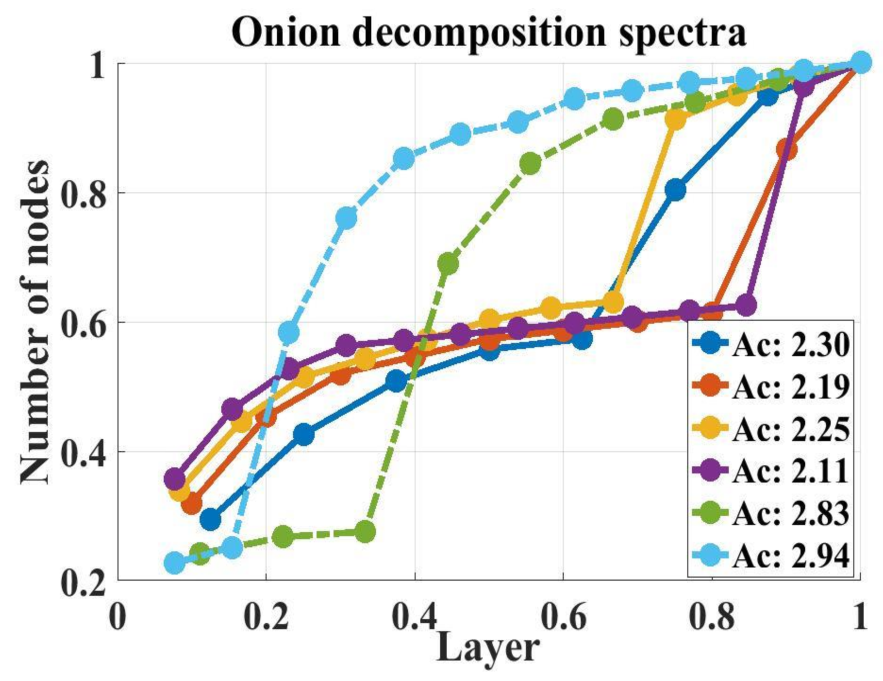
- Average degree has a clear correlation with reliability.
- The fraction of tails, ratio between network scale (N) and average shortest path length (ASPL), and fractal dimension [2] also correlate with reliability.

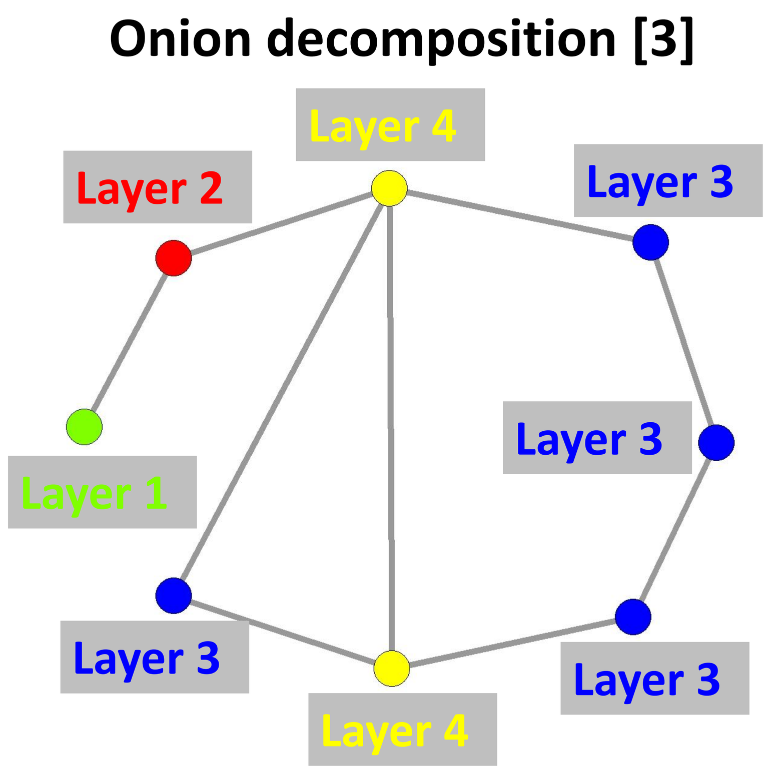
2.Reliability vs. Distribution:



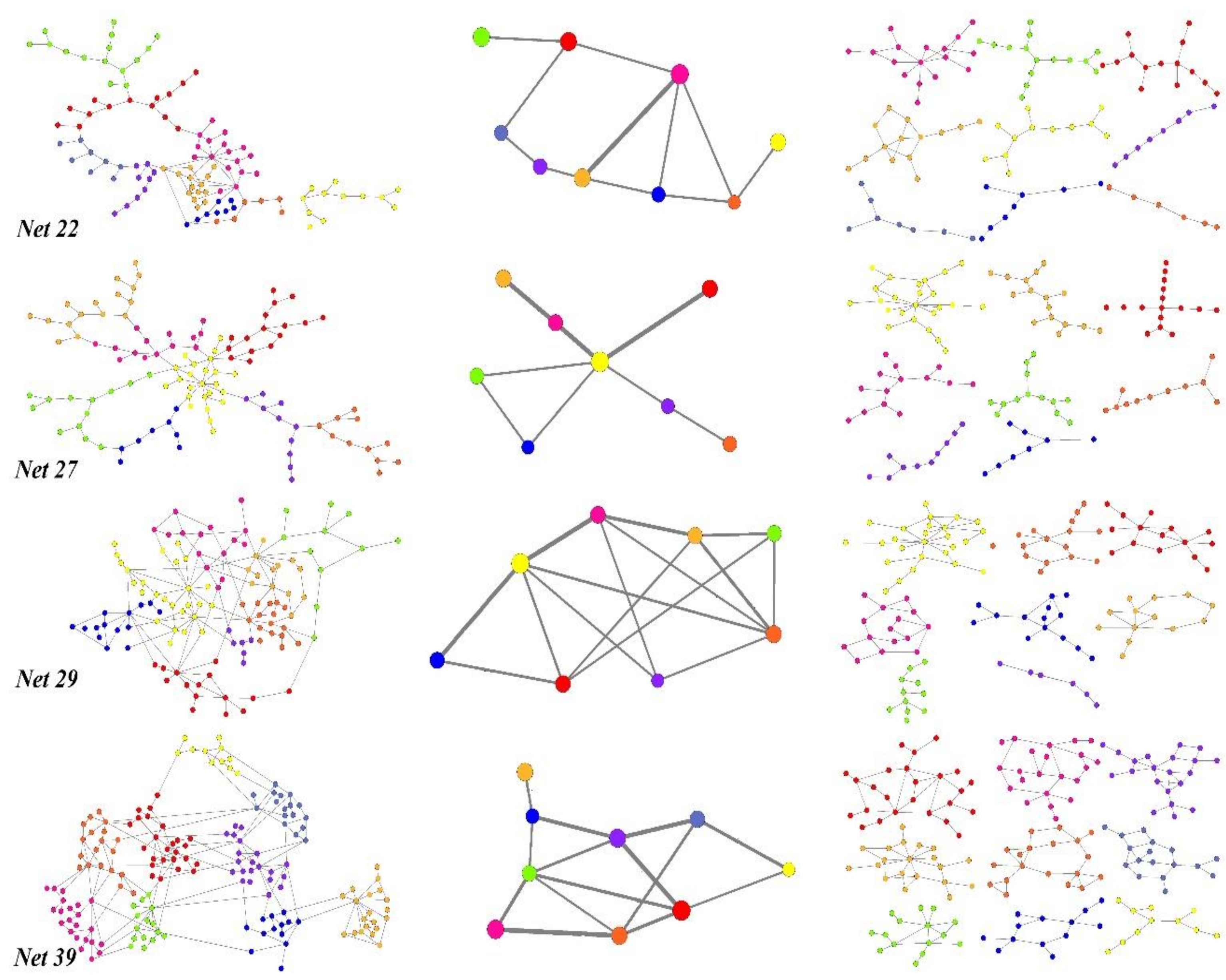


3. Reliability vs. Spectra:





4. Reliability & Community structure [4]:



5. Conclusions and future work

Conclusion:

- System-level metrics, such as high average degree, low fraction of tails, high log(N)/log(aspl) and high fractal dimension yield higher reliability.
- Distributions of sizes of handles, and onion decomposition spectra, are relevant to the reliability of power grids.
- Density of community structures reflects the reliability of power grids.

Future work:

- Bound network reliability analytically with MST and triangulation.
- Approximate reliability more efficiently informed by topological properties.
- Enhance network reliability and resilience (by incorporating power flow) by tuning relevant topological properties.

Acknowledgements

The work reported here has been funded in part by the National Science Foundation through Grant CMMI-1436844 and by the U.S. Department of Defense through the MURI grant W911NF-13-1-0340.

References

[1] Schultz, Paul, Jobst Heitzig, and Jürgen Kurths. "A random growth model for power grids and other spatially embedded infrastructure networks." *EPJ ST* 223.12 (2014): 2593-2610.

[2] Song, Chaoming, Shlomo Havlin, and Hernan A. Makse. "Self-similarity of complex networks." *Nature* 433.7024 (2005): 392.

[3] Hébert-Dufresne, Laurent, Joshua A. Grochow, and Antoine Allard. "Multi-scale structure and topological anomaly detection via a new network statistic: The onion decomposition." Scientific reports 6 (2016): 31708.

[4] Newman, Mark EJ. "Modularity and community structure in networks." *PNAS* 103.23 (2006): 8577-8582.