

1-11-2019

# Latent Space Models for Temporal Networks

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## Recommended Citation

Alt, Jasper, "Latent Space Models for Temporal Networks" (2019). *Systems Science Friday Noon Seminar Series*. 73.

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# Latent Space Models for Temporal Networks

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## References

- **This talk based on work (with Rajesh Venkatachalapathy) submitted to NetSci 2019.**
- **A fuller manuscript (with Rajesh) is in progress.**
- **Peres et. al. “Mobile Geometric Graphs” (2010)**
- **Holme, P. “Modern Temporal Network Theory: A Colloquium”**

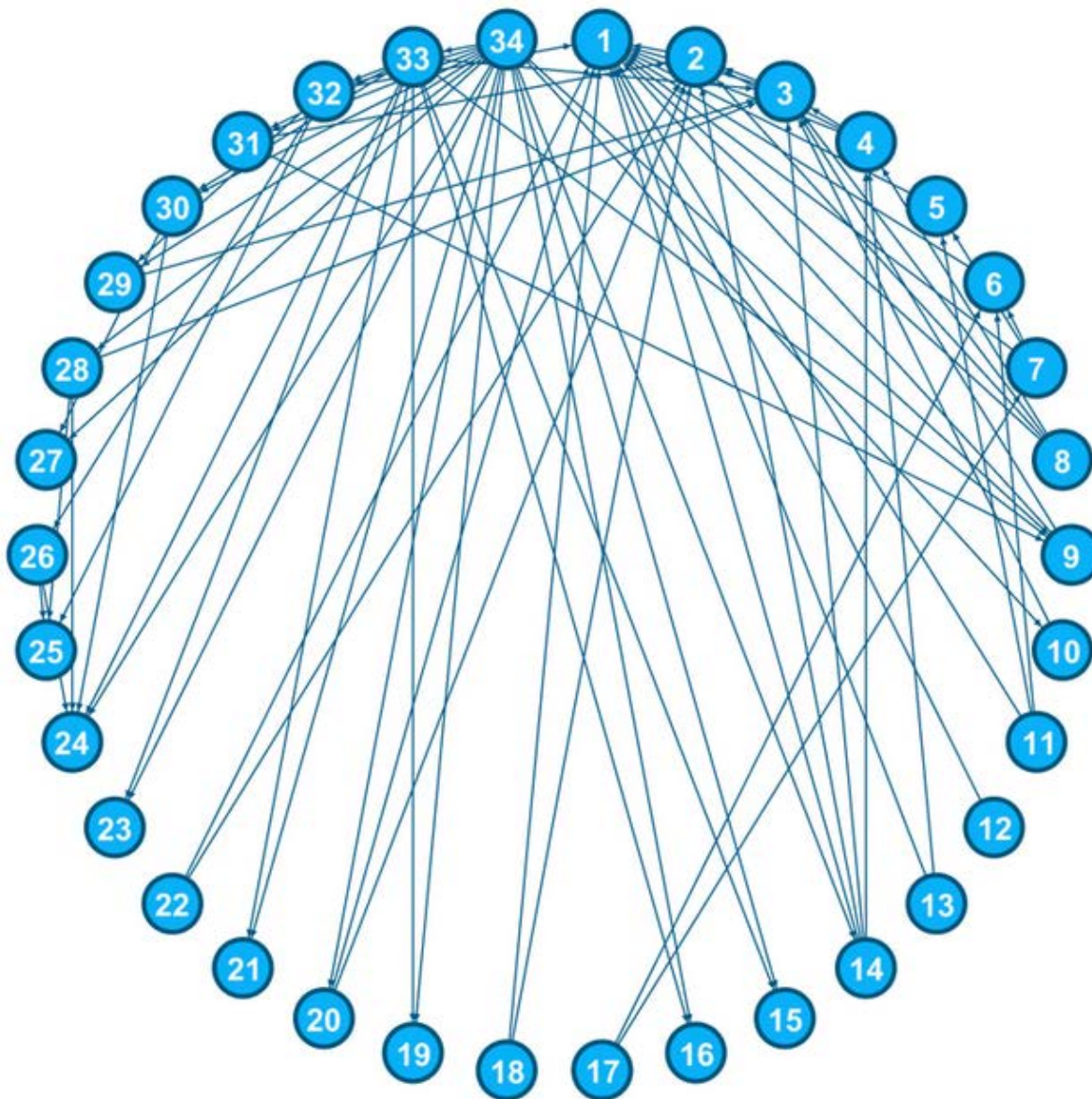
**(2015)**

## **Outline**

- **Homophily and latent space**
- **Random geometric graphs and Brownian motion**
- **Mobile geometric graphs**
- **Implementation**
- **Observations**
- **Current and future work**

## **0. Social Networks**

- **Maps of relationships between actors**
- **What do the actors tell us about the networks?**
- **What do the networks tell us about the actors?**



*A social network (Wikipedia)*

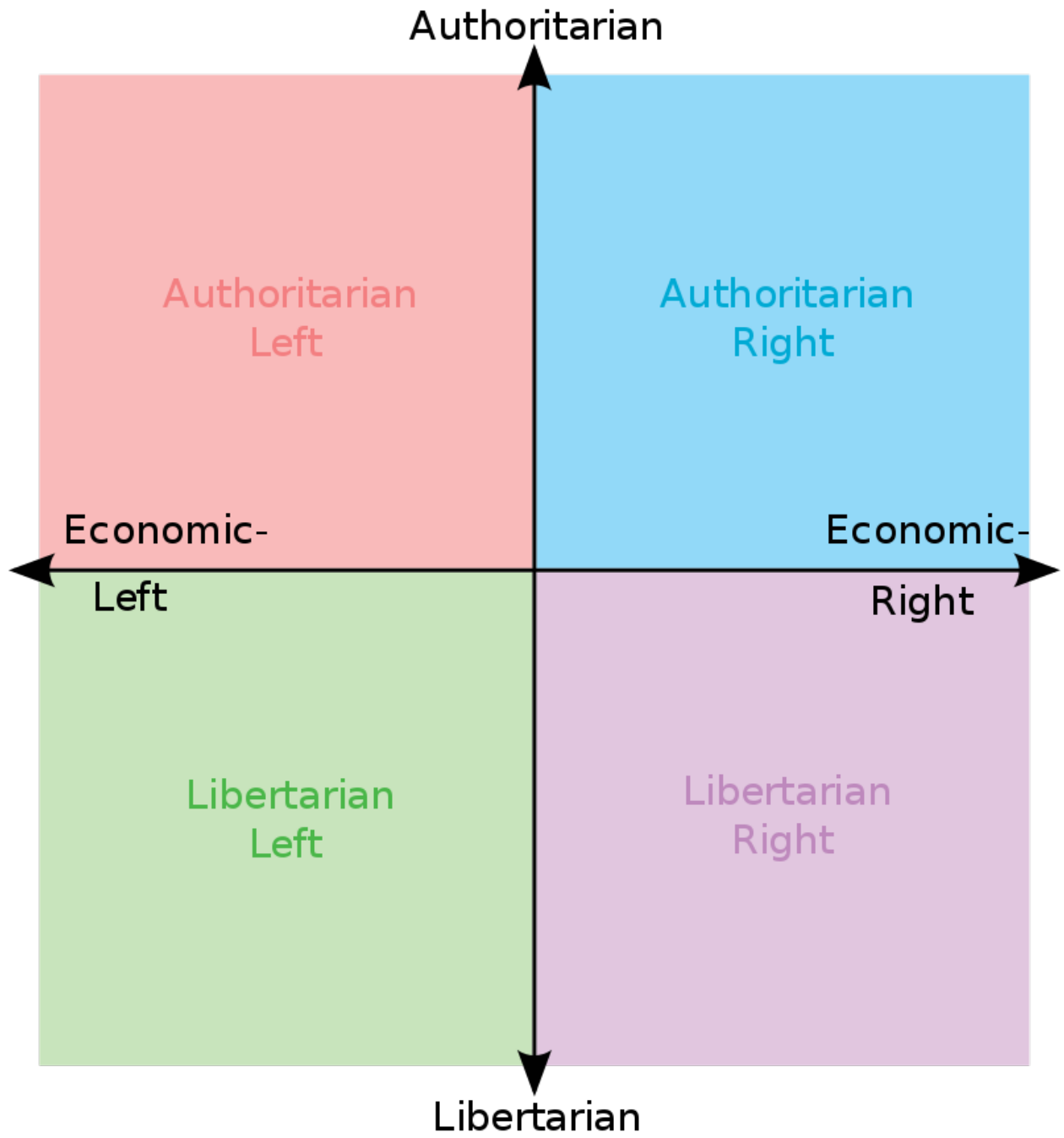
# 1. Homophily

## **“Birds of a feather flock together”**

- **Actors with common attributes are more likely to form ties**
- **Ties between actors may indicate common attributes**
- **Typically expressed in an informal way**
  
- **Latin prefix, Greek Suffix**
- **Idiophily?**

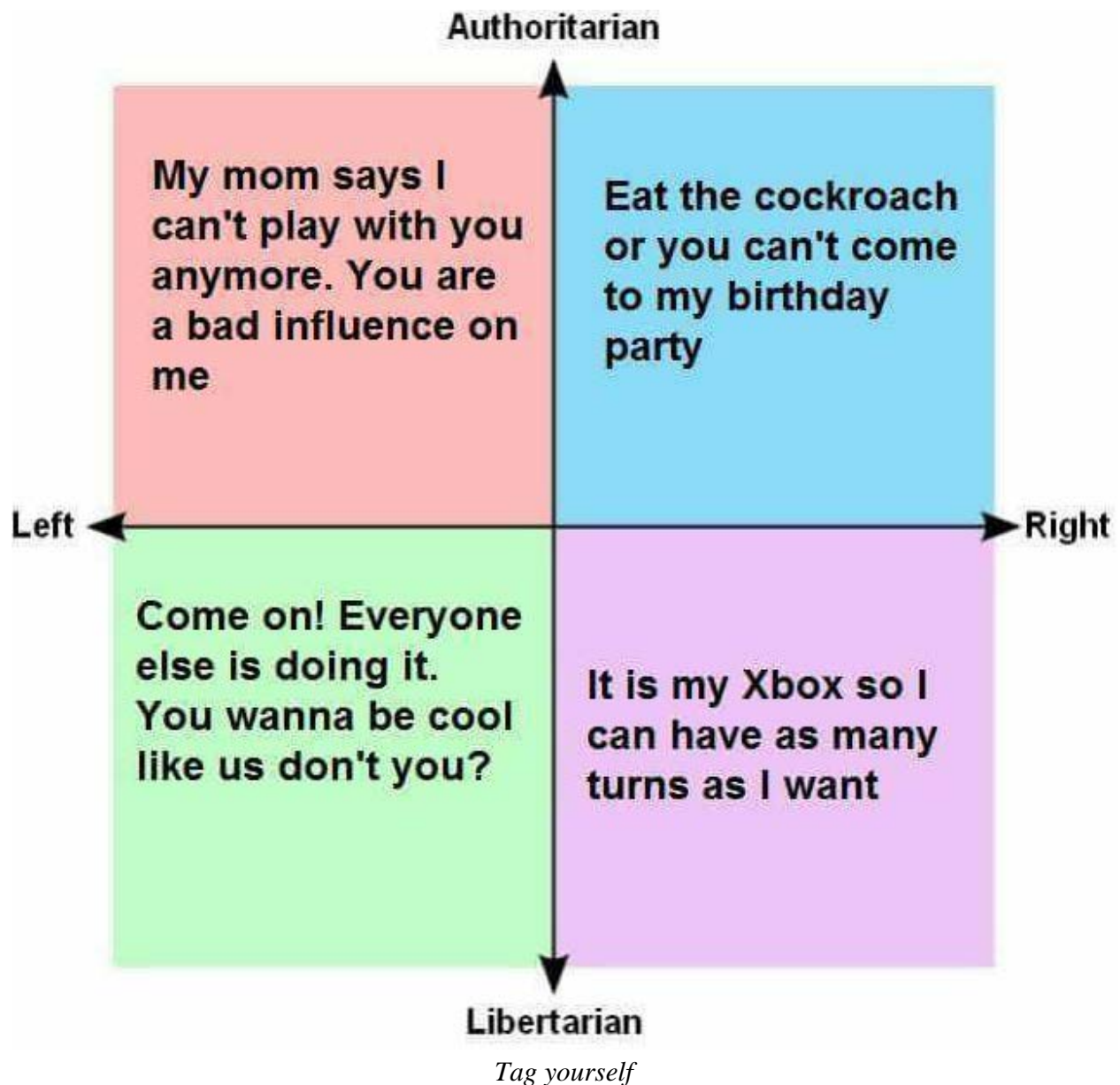
## **2. Latent Space**

- **Can we state something more formal?**
- **Combinations & intensities of attributes assign the actors to coordinates in a *latent space***
- **More attributes in common, or attributes with similar intensities, mean the actors are closer together in this space.**
- **Tobler's Law: Everything is related to everything else, but near things are more related than distant things.**
- **(Q. Are there *any* networks that do *not* correspond to a latent space?)**



*Wikipedia: The political compass*





### 3. Homophily in Latent Space

The graph at right is described by an  $n \times n$  adjacency matrix  $\mathbf{A}$ , where  $n = 10$ ; whose entries

$$A_{ij} = \begin{cases} f(d_{ij}) & \text{if } f(d_{ij}) > m \\ 0 & \text{otherwise} \end{cases} \quad \text{where } f(d_{ij}) = \frac{1}{1 + e^{0.5(5 - d_{ij})}}, \quad \frac{1}{1 + e^{0.5(5 - d_{ij})}}, \quad 1 - \frac{d_{ij}^2}{2}, \quad X_i$$

```

var X = get("X"); inc("Xi"); set("x", X[get("Xi")]); update("blurb_dij"); distanceFunction = distances[get("Xi")];
figure[1].load([0, matriculate(figure[2].data, get("m"))]); var X = get("X"); dec("Xi"); var Xi = get("Xi"); set("x",
X[get("Xi")]); update("blurb_dij"); distanceFunction = distances[get("Xi")]; figure[1].load([0, matriculate(figure[2].data,
get("m"))]); ,

```

\$blurb\$ [ " $d_{ij}$  \text{ is the } \href{http://en.wikipedia.org/wiki/Euclidean\_distance}{Euclidean} \text{ distance between } i \text{ and } j", " $d_{ij}$  \text{ is the } \href{http://en.wikipedia.org/wiki/Manhattan\_distance}{Manhattan} \text{ distance between } i \text{ and } j", " $d_{ij}$  \text{ is the } \href{http://en.wikipedia.org/wiki/Hamming\_distance}{Hamming} \text{ distance between } i \text{ and } j", " $x_i y_i$  \text{ and } x\_j y\_j", ] get("blurbs")[get("Xi")] set("blurb", get("blurbs")[get("Xi")]); , and  $m = 0.35$  inc("m"); figure[1].load([0, matriculate(figure[2].data, get("m"))]); dec("m"); figure[1].load([0, matriculate(figure[2].data, get("m"))]); is an arbitrary cutoff distance. If the edge weights are interpreted as probabilities of connections, then the matrix describes a distribution of possible graphs reflecting the same underlying social space.

*Click and drag the points to change the graph.*

## 4. Latent Space Dynamics

- **We know attributes can change.**
- **This means the actors' positions in latent space change.**
- **There are *many* possible ways this could happen.**
- **In social contexts, we expect nontrivial dynamics.**

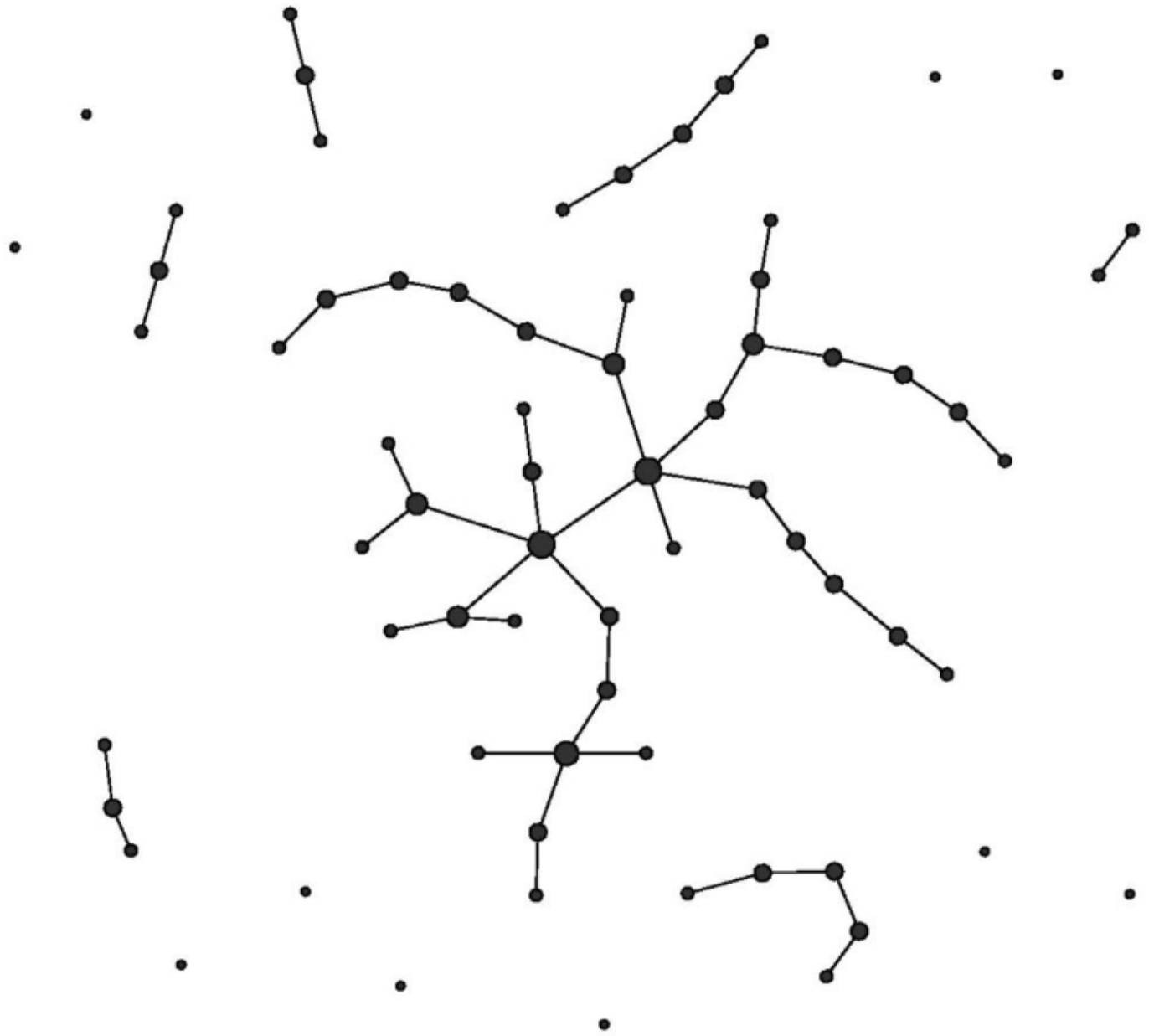
- **People influence each other and are influenced by social forces.**

<b>Paranormal Beliefs (2016-2018)</b>	<b>2016</b>	<b>2017</b>	<b>2018</b>	<b>Change 2016-2018</b>
Ancient, advanced civilizations, such as Atlantis, once existed	39.6	55.0	56.9%	17.3%
Aliens have visited Earth in our ancient past	27.0	35.0	41.4%	14.4%
Places can be haunted by spirits	46.6	52.3	57.7%	11.1%
Aliens have come to Earth in modern times	24.7	26.2	35.1%	10.4%
Bigfoot is a real creature	13.5	16.2	20.7%	7.2%
Some people can move objects with their minds	19.1	25.0	26.2%	7.1%
Fortune tellers and psychics can foresee the future	14.1	19.4	17.2%	3.1%

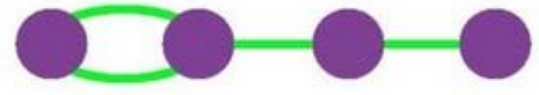
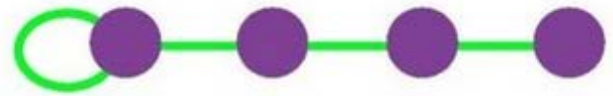
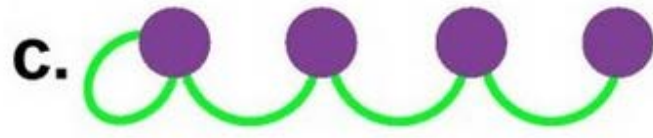
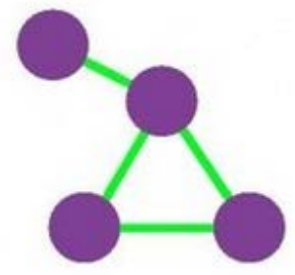
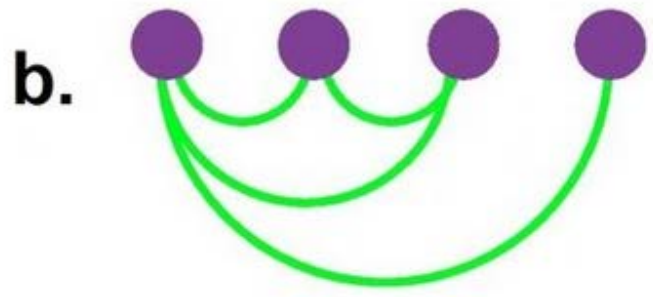
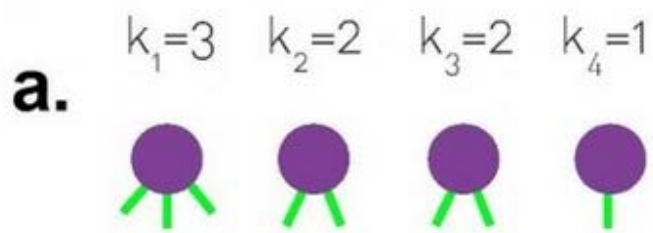
*Chapman University Survey of American Fears*

## 5. Null Models

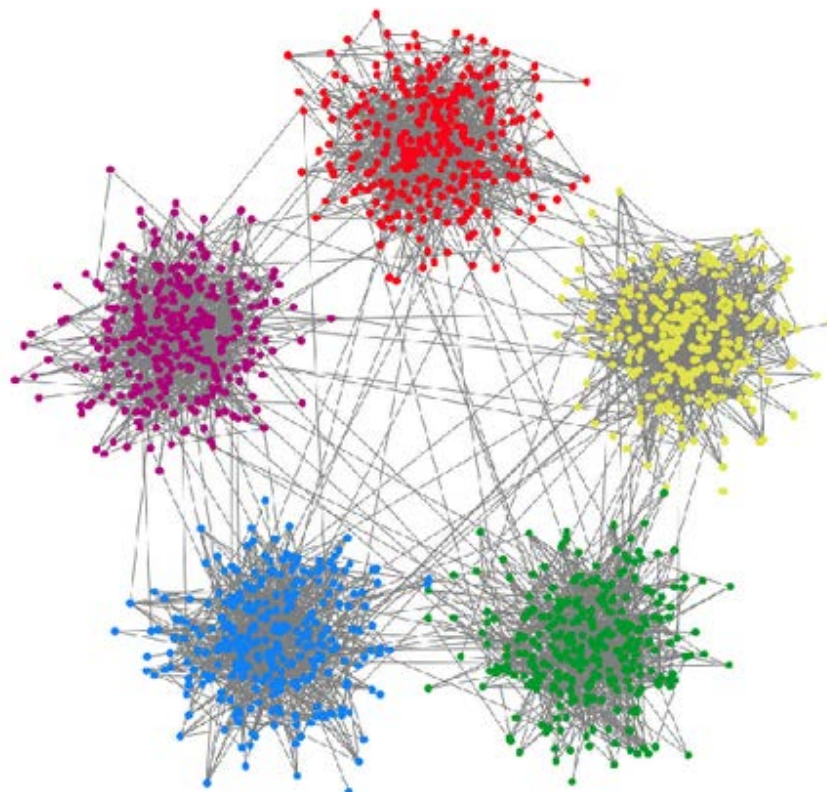
- **Network science has some big null models.**
- **Erdos-Renyi — random graphs**
- **Configuration models — random with fixed degree sequence**
- **Stochastic block models — random with some community structure**



*Wikipedia: Erdos-Renyi model*



*Wikipedia: Configuration model*



*Emmanuel Abbe: Stochastic block model*

- **Good null models show what can be explained by chance.**
- **Random dynamics are useful for testing non-random alternatives.**
- **A good null model for latent space network dynamics will have random dynamics.**

- **This will make it easier to spot networks that don't.**

## **6. Temporal Networks**

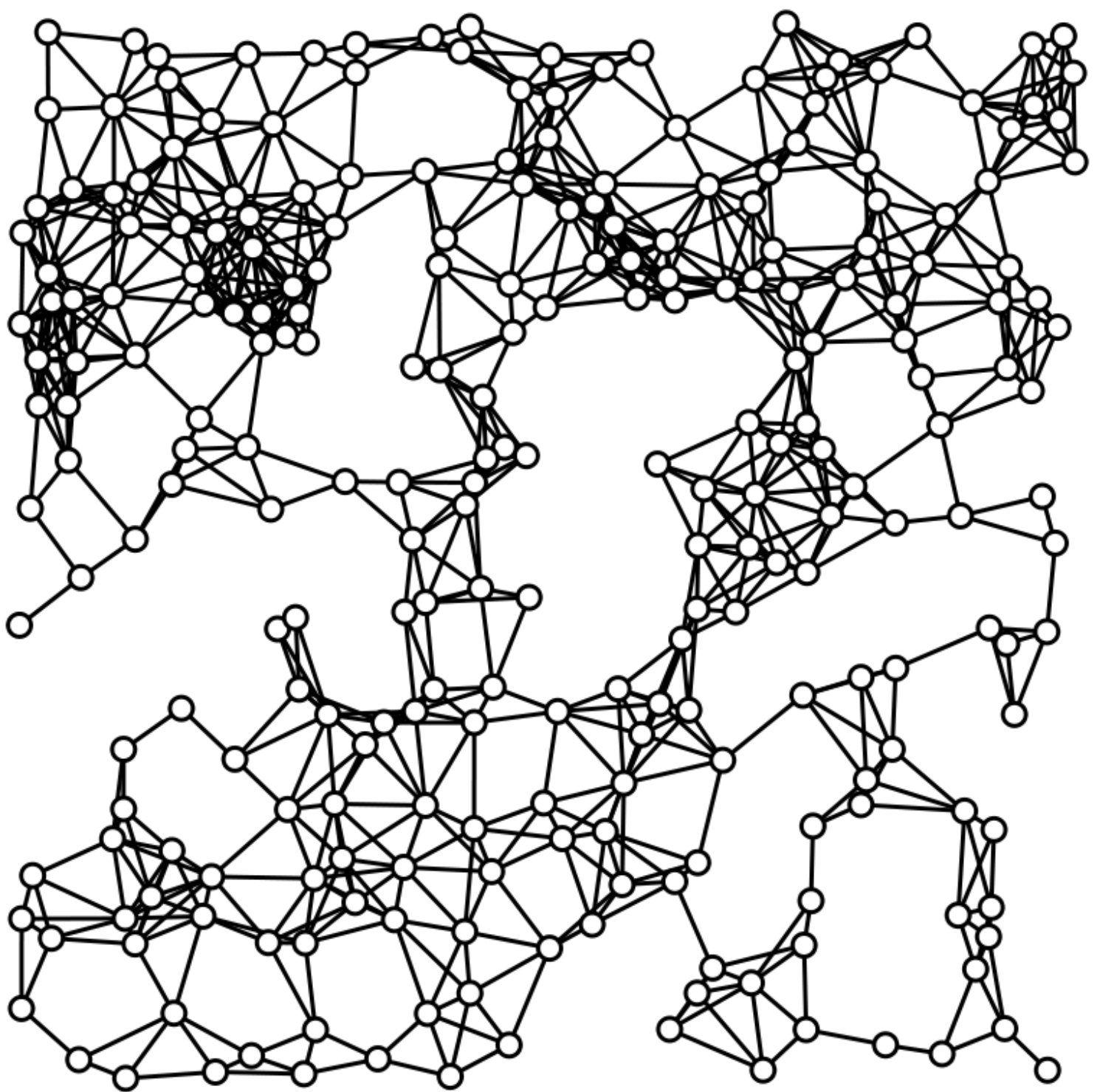
- **We typically understand static networks to be ‘snapshots’ of dynamic networks.**
- **Real networks are *temporal*.**
- **Static networks can be instantaneous snapshots or aggregate over a window of time.**
- **What is a null model for temporal networks?**
- **Random, but time dependent**



# **Building Blocks**

## **6. Random Geometric Graphs**

- **Graphs**
- **Geometric**
- **Random**



*Wikipedia: Random geometric graph*

- **Nodes are placed using some *point process***
- **(say, uniformly at random)**
- **Nodes within some radius of one another are connected.**
- **Studied in the context of wireless networks.**

## **7. Brownian Motion**

- **Move a normally distributed distance in either direction.**
- **Like a particle in a fluid.**
- **Shows up in physics, statistics, quantitative finance, etc.**
- **Preserves the intensity of point processes.**

## 8. Mobile Geometric Graphs

- **Random geometric graphs with Brownian motion**
- **Brownian motion adds time dependence while preserving randomness**
- **Very little studied**
- **Existing work focuses on the mathematical statistics of their communication properties.**

**Contd**

