Contagion

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Principles of Complex Systems, Vols. 1, 2, & 3D
CSYS/MATH 300, 303, & 394, 2022–2023| @pocsvox

Prof. Peter Sheridan Dodds | @peterdodds

Computational Story Lab | Vermont Complex Systems Center
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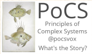

Basic Contagion Models

Global spreading condition

Social Contagion Models
- Network version
- All-to-all networks

Theory
- Spreading possibility
- Spreading probability
- Physical explanation
- Final size

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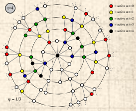

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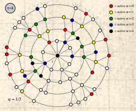

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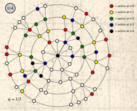

Outline

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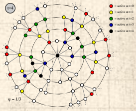


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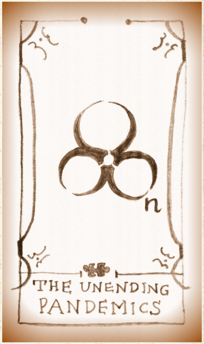
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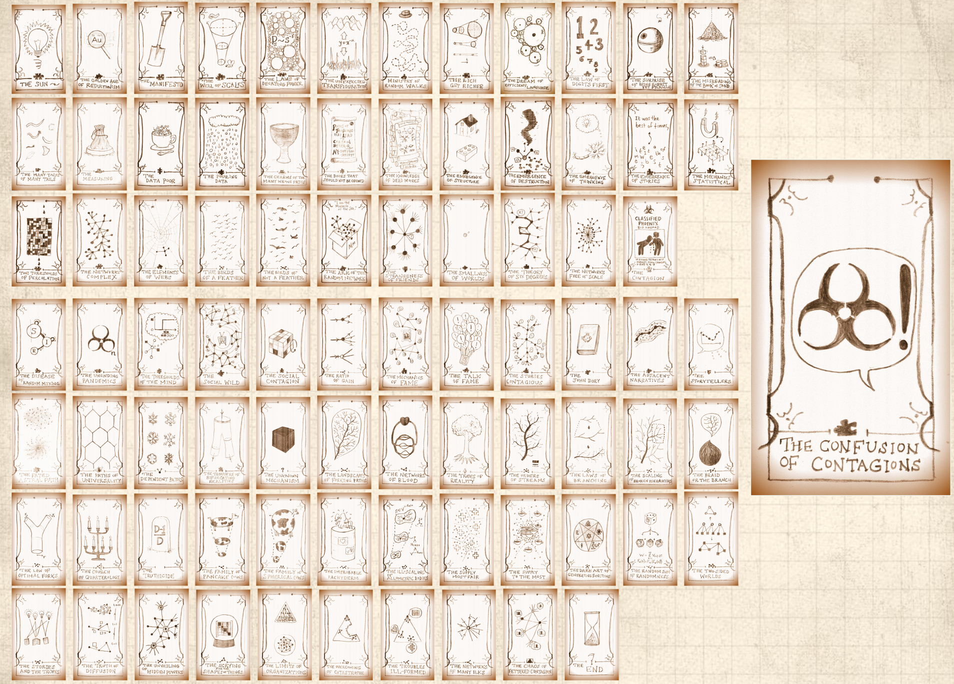
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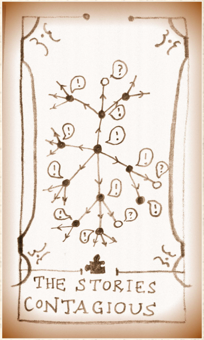
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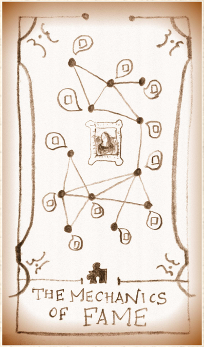
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Contagion models

Some large questions concerning network contagion:

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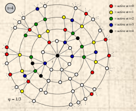

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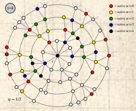

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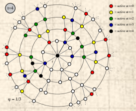

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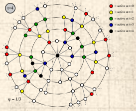

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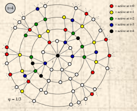

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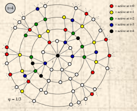

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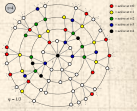
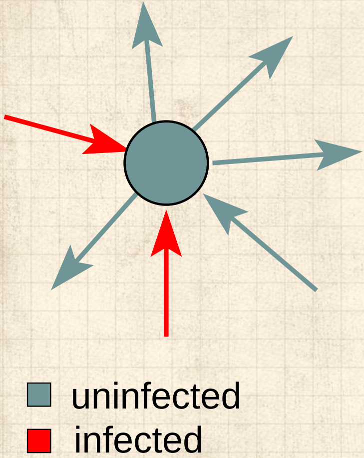
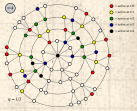
Next up: We'll look at some fundamental kinds of spreading on generalized random networks.



Spreading mechanisms



General spreading mechanism:
State of node i depends on history of i and i's neighbors' states.



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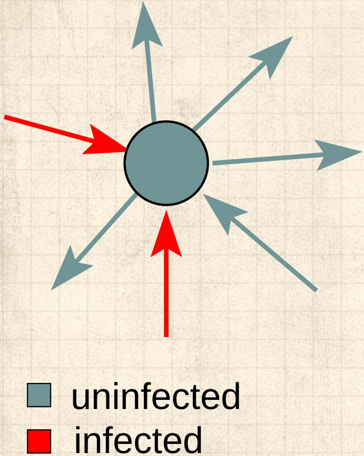

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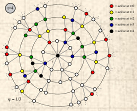

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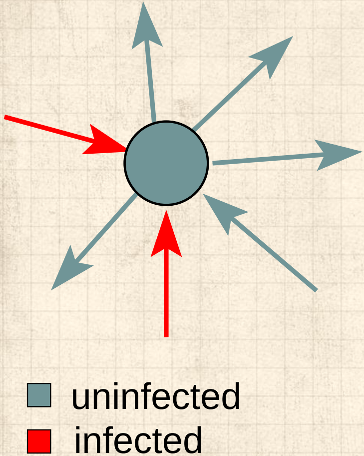
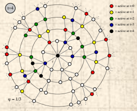


- General spreading mechanism: State of node i depends on history of i and i's neighbors' states.
- Doses of entity may be stochastic and history-dependent.
- May have multiple, interacting entities spreading at once.



Spreading on Random Networks

- For random networks, we know local structure is pure branching.

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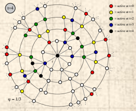

Spreading on Random Networks

- For random networks, we know local structure is pure branching.
- Successful spreading is ∴ contingent on single edges infecting nodes.

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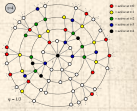

Spreading on Random Networks

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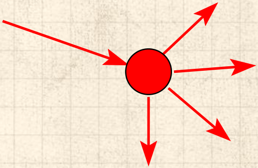
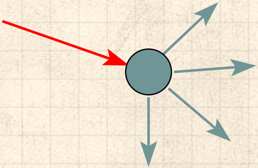
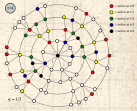
Success



Failure:





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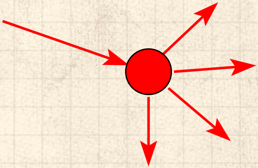

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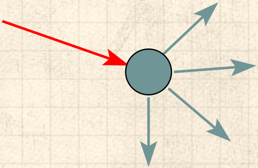
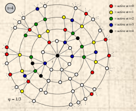


- Focus on binary case with edges and nodes either infected or not.



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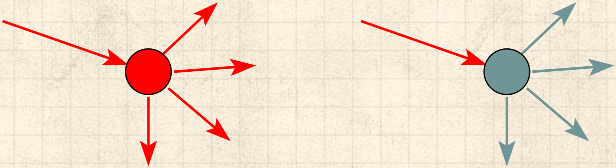

- Focus on binary case with edges and nodes either infected or not.
- First big question: for a given network and contagion process, can global spreading from a single seed occur?

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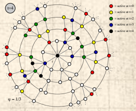
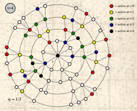


Global spreading condition

- We need to find: [5]
  R = the average # of infected edges that one random infected edge brings about.
- Call **R** the gain ratio.



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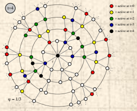

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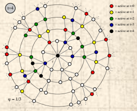
- $$\mathbf{R} = \sum_{k=0}^{\infty} \underbrace{\frac{kP_k}{\langle k \rangle}}_{\text{prob. of connecting to a degree } k \text{ node}}$$



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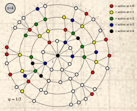

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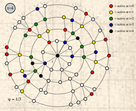

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$$+ \sum_{k=0}^{\infty} \frac{\overbrace{kP_k}}{\langle k \rangle}$$

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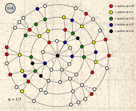

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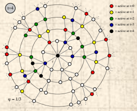

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$$+ \sum_{k=0}^{\infty} \overbrace{\frac{kP_k}{\langle k \rangle}} \bullet \underbrace{0}_{\substack{\text{\# outgoing} \\ \text{infected} \\ \text{edges}}} \bullet \underbrace{(1-B_{k1})}_{\substack{\text{Prob. of} \\ \text{no infection}}}$$

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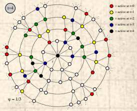

Global spreading condition

- Our global spreading condition is then:

$$\mathbf{R} = \sum_{k=0}^{\infty} \frac{k P_k}{\langle k \rangle} \bullet (k-1) \bullet B_{k1} > 1.$$

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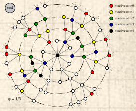

Global spreading condition

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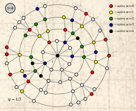

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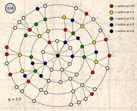
- Case 1: If $B_{k1} = 1$



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- Case 1: If $B_{k1} = 1$ then

$$\mathbf{R} = \sum_{k=0}^{\infty} \frac{kP_k}{\langle k \rangle} \bullet (k-1) = \frac{\langle k(k-1) \rangle}{\langle k \rangle} > 1.$$

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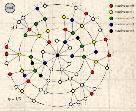

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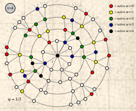
- Good: This is just our giant component condition again.



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- Case 2:

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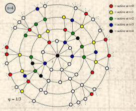

Global spreading condition

- Case 2: If $B_{k1} = \beta < 1$

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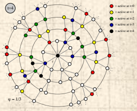

Global spreading condition

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$$\mathbf{R} = \sum_{k=0}^{\infty} \frac{kP_k}{\langle k \rangle} \bullet (k-1) \bullet \beta > 1.$$

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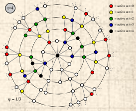

Global spreading condition

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$$\mathbf{R} = \sum_{k=0}^{\infty} \frac{kP_k}{\langle k \rangle} \bullet (k-1) \bullet \beta > 1.$$

- A fraction (1-β) of edges do not transmit infection.

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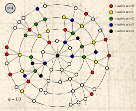

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- A fraction (1-β) of edges do not transmit infection.
- Analogous phase transition to giant component case but critical value of $\langle k \rangle$ is increased.

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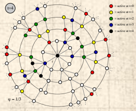

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- A fraction (1-β) of edges do not transmit infection.
- Analogous phase transition to giant component case but critical value of $\langle k \rangle$ is increased.
- Aka bond percolation.

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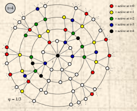

Global spreading condition

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- Aka bond percolation.
- Resulting degree distribution $\tilde{P}_k$:

$$\tilde{P}_k = \beta^k \sum_{i=k}^{\infty} \binom{i}{k} (1-\beta)^{i-k} P_i.$$

Insert question from assignment 9

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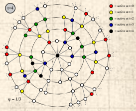

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Insert question from assignment 9

- We can show $F_{\tilde{P}}(x) = F_P(\beta x + 1 - \beta)$.

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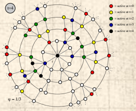

Global spreading condition

- Cases 3, 4, 5, ...:

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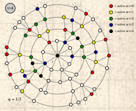
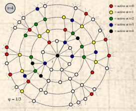


Global spreading condition

- Cases 3, 4, 5, ...: Now allow B_{k1} to depend on k



Global spreading condition

- Cases 3, 4, 5, ...: Now allow B_{k1} to depend on k
- Asymmetry: Transmission along an edge depends on node's degree at other end.

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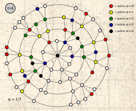

Global spreading condition

- Cases 3, 4, 5, ...: Now allow B_{k1} to depend on k
- Asymmetry: Transmission along an edge depends on node's degree at other end.
- Possibility: B_{k1} increases with k... .

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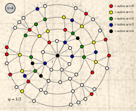

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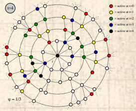

- Cases 3, 4, 5, ...: Now allow B_{k1} to depend on k
- Asymmetry: Transmission along an edge depends on node's degree at other end.
- Possibility: B_{k1} increases with k... unlikely.

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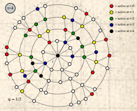

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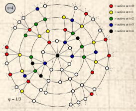

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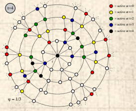

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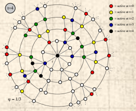

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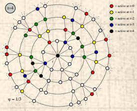
- $B_{k1} \searrow$ is a plausible representation of a simple kind of social contagion.
- The story:
  More well connected people are harder to influence.



Global spreading condition

- **Example:** $B_{k1} = 1/k$.

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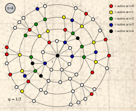

Global spreading condition

- Example: $B_{k1} = 1/k$.
-

$$\mathbf{R} = \sum_{k=1}^{\infty} \frac{kP_k}{\langle k \rangle} \bullet (k-1) \bullet B_{k1}$$

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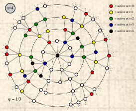

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- Example: $B_{k1} = 1/k$.
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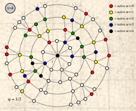

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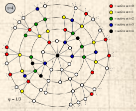

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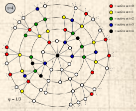

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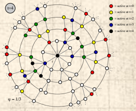

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- Since **R** is always less than 1, no spreading can occur for this mechanism.

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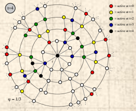

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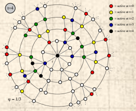

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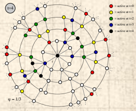
- Decay of B_{k1} is too fast.
- Result is independent of degree distribution.



Global spreading condition

- Example: $B_{k1} = H(\frac{1}{k} - \phi)$
where $0 < \phi \leq 1$ is a threshold and H is the Heaviside function.

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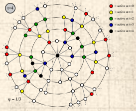

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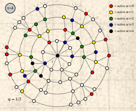

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  they flip when only one of their friends flips.

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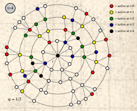

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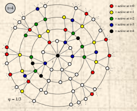

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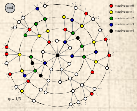

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$$= \sum_{k=1}^{\lfloor \frac{1}{\phi} \rfloor} (k-1) \bullet \frac{kP_k}{\langle k \rangle}$$ where $\lfloor \cdot \rfloor$ means floor.

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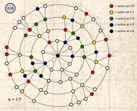

Global spreading condition

- The uniform threshold model global spreading condition:

$$\mathbf{R} = \sum_{k=1}^{\lfloor \frac{1}{\phi} \rfloor} (k-1) \bullet \frac{kP_k}{\langle k \rangle} > 1.$$

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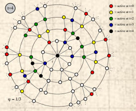

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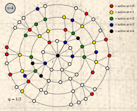

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$$\mathbf{R} = \sum_{k=1}^{\lfloor \frac{1}{\phi} \rfloor} (k-1) \bullet \frac{kP_k}{\langle k \rangle} > 1.$$

- As $\phi \rightarrow 1$, all nodes become resilient and $r \rightarrow 0$.
- As $\phi \rightarrow 0$, all nodes become vulnerable and the contagion condition matches up with the giant component condition.

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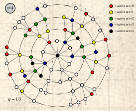

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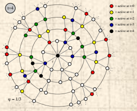
- Key: If we fix ϕ and then vary $\langle k \rangle$, we may see two phase transitions.



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- As $\phi \rightarrow 0$, all nodes become vulnerable and the contagion condition matches up with the giant component condition.
- Key: If we fix ϕ and then vary $\langle k \rangle$, we may see two phase transitions.
- Added to our standard giant component transition, we will see a cut off in spreading as nodes become more connected.

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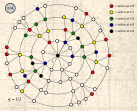

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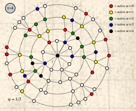
Virtual contagion: Corrupted Blood, a 2005 virtual plague in World of Warcraft:



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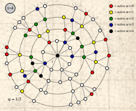

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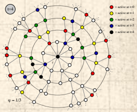
Some important models (recap from CSYS 300)

- Tipping models—Schelling (1971) [11, 12, 13]



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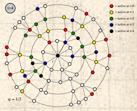
  - Simulation on checker boards.



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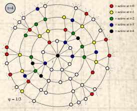

Some important models (recap from CSYS 300)

- Tipping models—Schelling (1971) [11, 12, 13]
  - Simulation on checker boards.
  - Idea of thresholds.

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Some important models (recap from CSYS 300)

- Tipping models—Schelling (1971) [11, 12, 13]
  - Simulation on checker boards.
  - Idea of thresholds.
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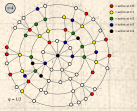
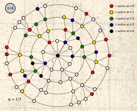


Social Contagion



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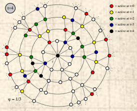
  - Social learning theory, Informational cascades,...



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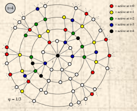

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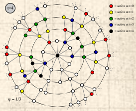
- Mean field Granovetter model $\rightarrow$ network model



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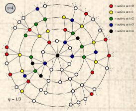
- Mean field Granovetter model $\rightarrow$ network model
- Individuals now have a limited view of the world



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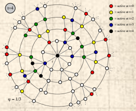
- Interactions between individuals now represented by a network



Threshold model on a network

- Interactions between individuals now represented by a network
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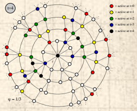

Threshold model on a network

- Interactions between individuals now represented by a network
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- Individual i has k_i contacts

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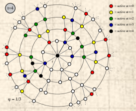

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- Interactions between individuals now represented by a network
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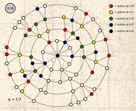
- Individual i has k_i contacts
- Influence on each link is reciprocal and of unit weight



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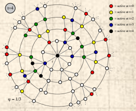

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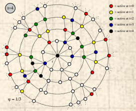

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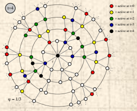

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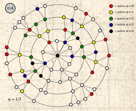

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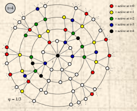
- Individual i becomes active when number of active contacts $a_i \geq \phi_i k_i$
- Activation is permanent (SI)



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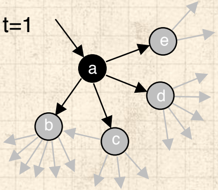
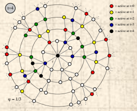


- All nodes have threshold $\phi = 0.2$.



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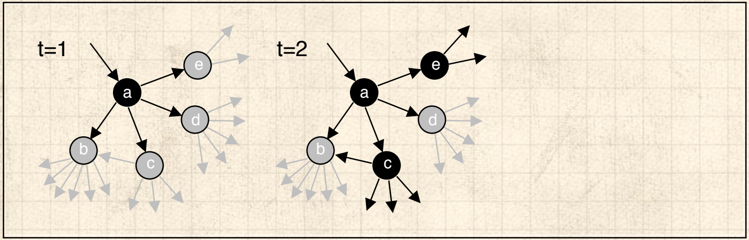

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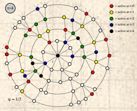

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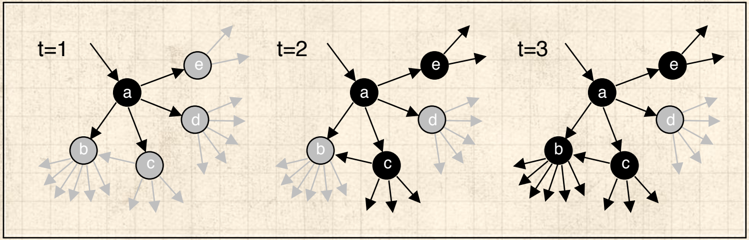

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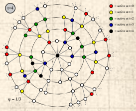
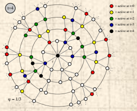


The most gullible

Vulnerables:



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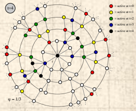

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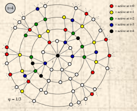

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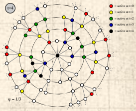

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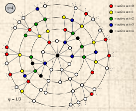

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- Key: For global spreading events (cascades) on random networks, must have a *global component of vulnerables* [15]
- For a uniform threshold ϕ, our global spreading condition tells us when such a component exists:

$$\mathbf{R} = \sum_{k=1}^{\lfloor \frac{1}{\phi} \rfloor} \frac{k P_k}{\langle k \rangle} \bullet (k-1) > 1.$$

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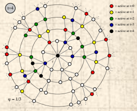
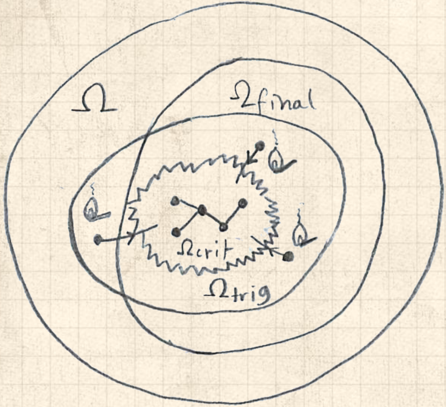


Example random network structure:



- Ω_{crit} = critical mass = global vulnerable component
- Ω_{trig} = triggering component
- Ω_{final} = potential extent of spread
- Ω = entire network

$\Omega_{\text{crit}} \subset \Omega_{\text{trig}};\ \Omega_{\text{crit}} \subset \Omega_{\text{final}};$ and $\Omega_{\text{trig}}, \Omega_{\text{final}} \subset \Omega.$

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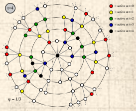
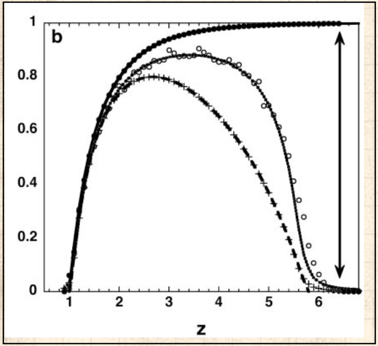


Global spreading events on random networks [15]



$z = \langle k \rangle$

- Top curve: final fraction infected if successful.

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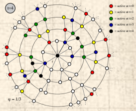

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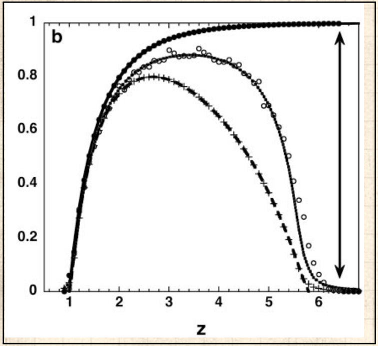

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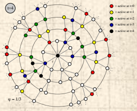
- Top curve: final fraction infected if successful.
- Bottom curve: fractional size of vulnerable subcomponent. [15]



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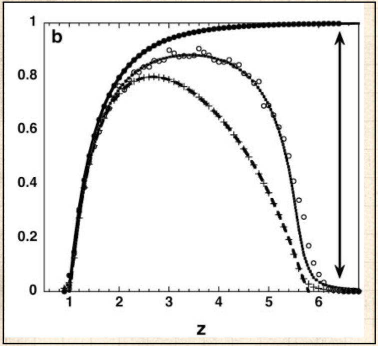

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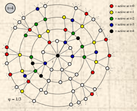

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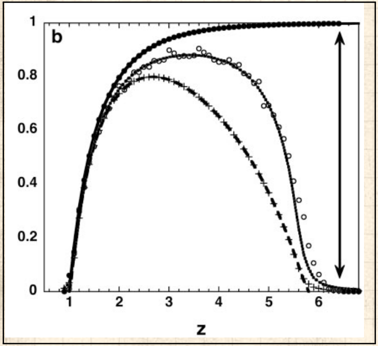

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- Global spreading events occur only if size of vulnerable subcomponent > 0.

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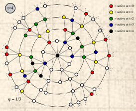

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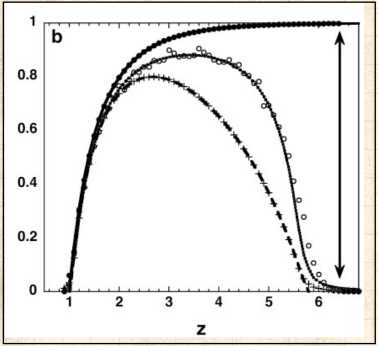

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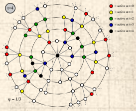

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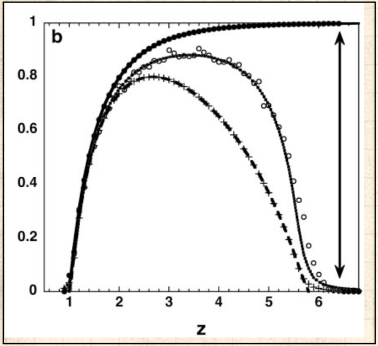

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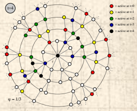
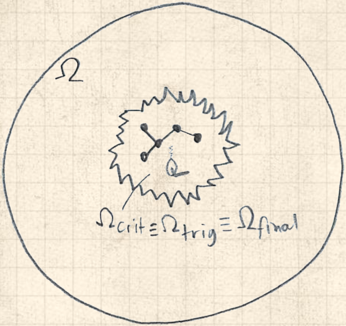
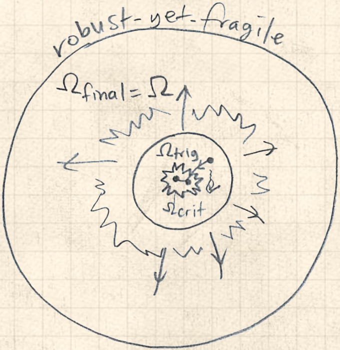
- 'Ignorance' facilitates spreading.

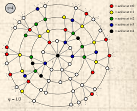


Cascades on random networks





- Above lower phase transition
- Just below upper phase transition



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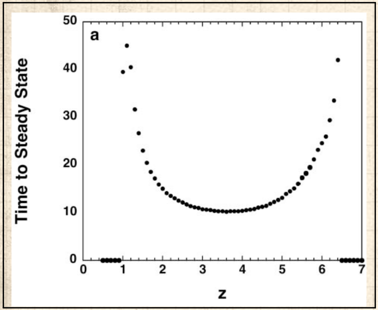
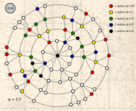


(n.b., $z = \langle k \rangle$)

- Time taken for cascade to spread through network. [15]



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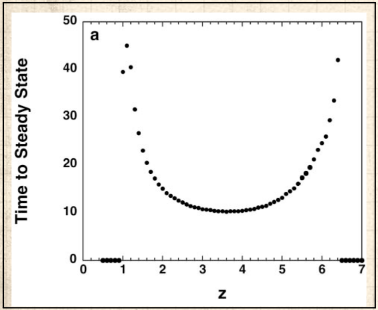
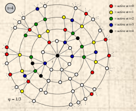


(n.b., $z = \langle k \rangle$)

- Time taken for cascade to spread through network. [15]
- Two phase transitions.



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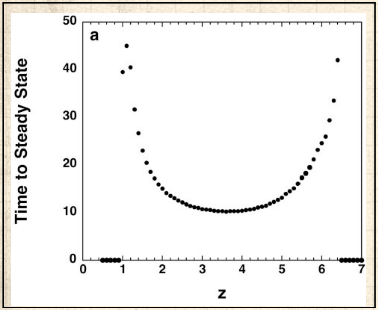
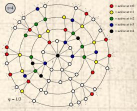


(n.b., $z = \langle k \rangle$)

- Time taken for cascade to spread through network. [15]
- Two phase transitions.

- Largest vulnerable component = critical mass.



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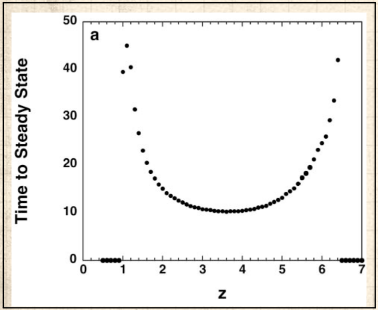
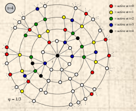


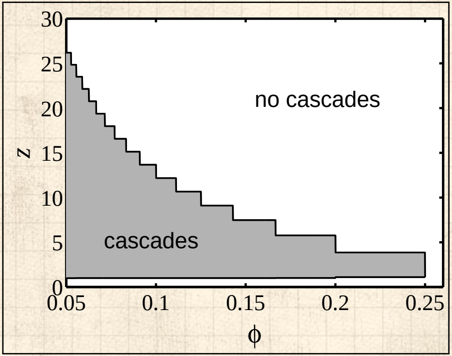
(n.b., $z = \langle k \rangle$)

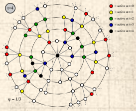
- Time taken for cascade to spread through network. [15]
- Two phase transitions.

- Largest vulnerable component = critical mass.
- Now have endogenous mechanism for spreading from an individual to the critical mass and then beyond.



Cascade window for random networks

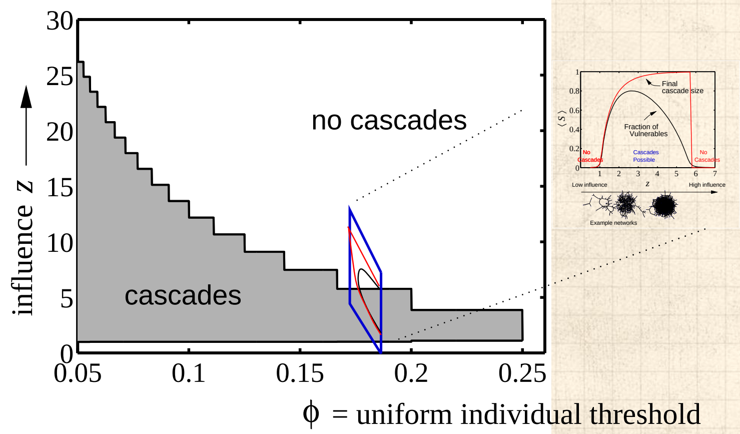


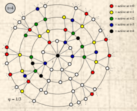


(n.b., $z = \langle k \rangle$)

- Outline of cascade window for random networks.

Cascade window for random networks





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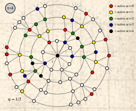
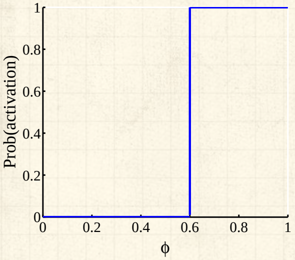


Granovetter's Threshold model—recap

- Assumes deterministic response functions



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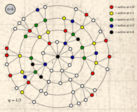

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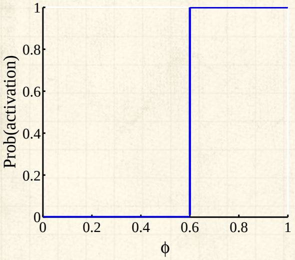
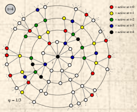


- Assumes deterministic response functions
- ϕ_* = threshold of an individual.



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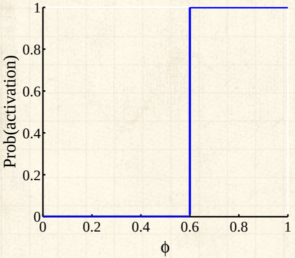
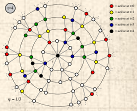


- Assumes deterministic response functions
- ϕ_* = threshold of an individual.
- $f(\phi_*)$ = distribution of thresholds in a population.



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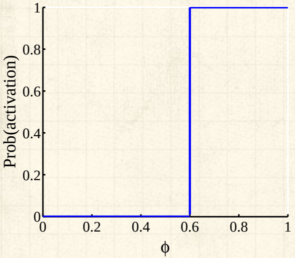
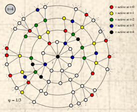


- Assumes deterministic response functions
- ϕ_* = threshold of an individual.
- $f(\phi_*)$ = distribution of thresholds in a population.
- $F(\phi_*)$ = cumulative distribution = $\int_{\phi'_*=0}^{\phi_*} f(\phi'_*)\mathrm{d}\phi'_*$



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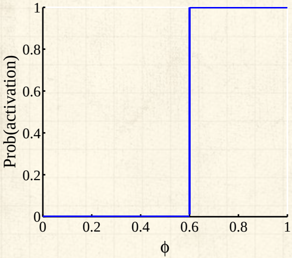
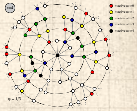


- Assumes deterministic response functions
- ϕ_* = threshold of an individual.
- $f(\phi_*)$ = distribution of thresholds in a population.
- $F(\phi_*)$ = cumulative distribution = $\int_{\phi'_*=0}^{\phi_*} f(\phi'_*)\mathrm{d}\phi'_*$
- ϕ_t = fraction of people 'rioting' at time step t.



Social Sciences—Threshold models

- At time $t + 1$, fraction rioting = fraction with $\phi_* \le \phi_t$.

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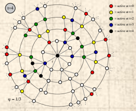

Social Sciences—Threshold models

- At time $t+1$, fraction rioting = fraction with $\phi_* \le \phi_t$.
- $$\phi_{t+1} = \int_0^{\phi_t} f(\phi_*)\mathrm{d}\phi_* = F(\phi_*)\big|_0^{\phi_t} = F(\phi_t)$$

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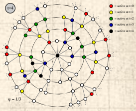
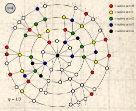


Social Sciences—Threshold models

- At time $t+1$, fraction rioting = fraction with $\phi_* \le \phi_t$.
- $$\phi_{t+1} = \int_0^{\phi_t} f(\phi_*)\mathrm{d}\phi_* = F(\phi_*)\big|_0^{\phi_t} = F(\phi_t)$$
- $\Rightarrow$ Iterative maps of the unit interval $[0, 1]$.



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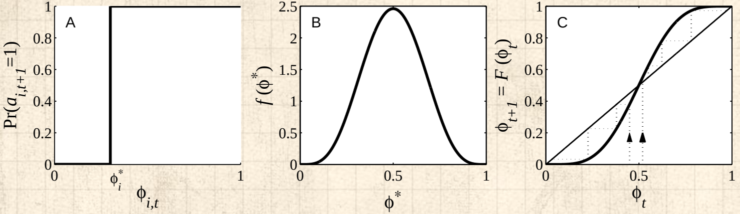
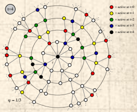
Action based on perceived behavior of others.



- Two states: S and I
- Recover now possible (SIS)
- ϕ = fraction of contacts ‘on’ (e.g., rioting)



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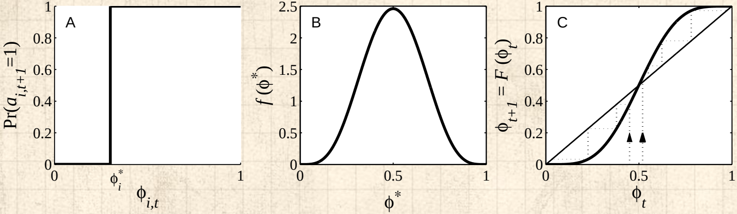

- Two states: S and I
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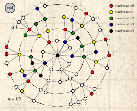
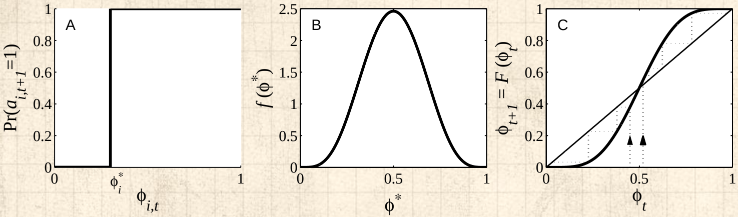
- Discrete time, synchronous update (strong assumption!)



Social Sciences—Threshold models

Action based on perceived behavior of others.



- Two states: S and I
- Recover now possible (SIS)
- ϕ = fraction of contacts 'on' (e.g., rioting)
- Discrete time, synchronous update (strong assumption!)
- This is a Critical mass model

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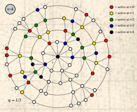

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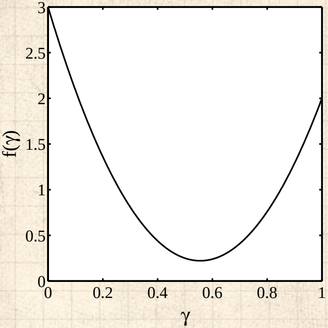
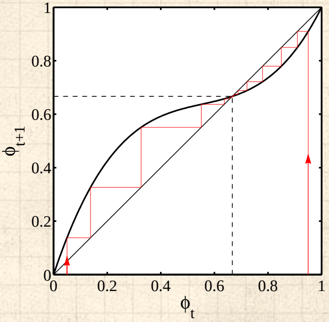
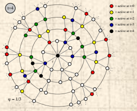




- Example of single stable state model



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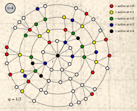
Implications for collective action theory:



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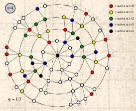

Implications for collective action theory:

1. Collective uniformity $\nRightarrow$ individual uniformity

Social Sciences—Threshold models

Implications for collective action theory:

1. Collective uniformity $\not\Rightarrow$ individual uniformity
2. Small individual changes $\Rightarrow$ large global changes

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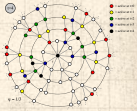

Social Sciences—Threshold models

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Next:

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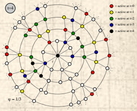

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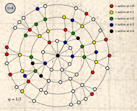
Next:

- Connect mean-field model to network model.



Social Sciences—Threshold models

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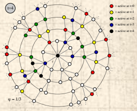
- Connect mean-field model to network model.
- Single seed for network model: $1/N \to 0$.



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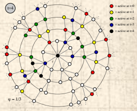
Next:

- Connect mean-field model to network model.
- Single seed for network model: $1/N \to 0$.
- Comparison between network and mean-field model sensible for vanishing seed size for the latter.



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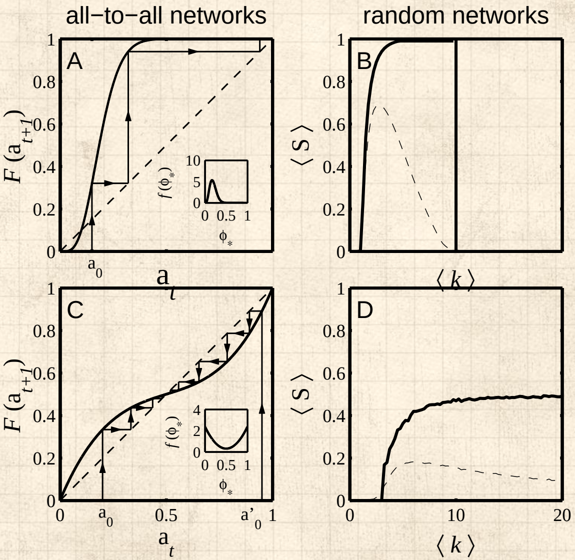

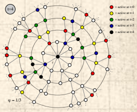

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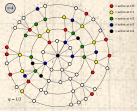

Spreadworthiness: Cat videos

Bowling with Ragdolls:

https://www.youtube.com/watch?v=XX-g2nmqL9Q?rel=0

- Organic extreme outlier?
- Success did not spread to other videos.

Threshold contagion on random networks

Three key pieces to describe analytically:

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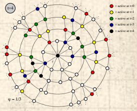

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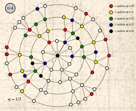

Three key pieces to describe analytically:

1. The fractional size of the largest subcomponent of vulnerable nodes, S_{vuln}.

Threshold contagion on random networks

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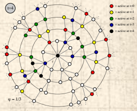
Three key pieces to describe analytically:

1. The fractional size of the largest subcomponent of vulnerable nodes, S_{vuln}.
2. The chance of starting a global spreading event, $P_{\text{trig}} = S_{\text{trig}}$.



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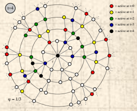

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2. The chance of starting a global spreading event, $P_{\text{trig}} = S_{\text{trig}}$.
3. The expected final size of any successful spread, S.

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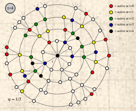

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1. The fractional size of the largest subcomponent of vulnerable nodes, S_{vuln}.
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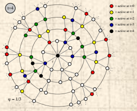
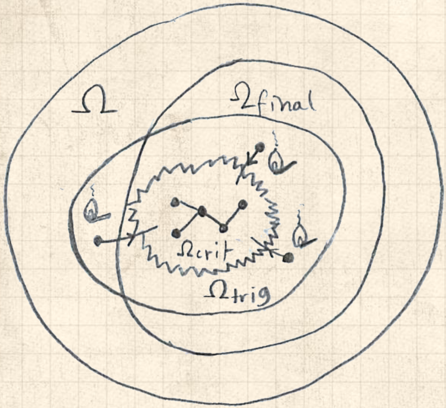
3. The expected final size of any successful spread, S.
    - n.b., the distribution of S is almost always bimodal.



Example random network structure:



- $\Omega_{\text{crit}} = \Omega_{\text{vuln}} =$ critical mass = global vulnerable component
- $\Omega_{\text{trig}} =$ triggering component
- $\Omega_{\text{final}} =$ potential extent of spread
- $\Omega =$ entire network

$\Omega_{\text{crit}} \subset \Omega_{\text{trig}}$; $\Omega_{\text{crit}} \subset \Omega_{\text{final}}$; and $\Omega_{\text{trig}}, \Omega_{\text{final}} \subset \Omega$.

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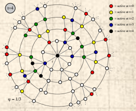

Threshold contagion on random networks

- First goal: Find the largest component of vulnerable nodes.

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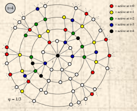

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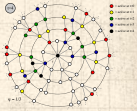

- First goal: Find the largest component of vulnerable nodes.
- Recall that for finding the giant component's size, we had to solve:

$$F_\pi(x) = xF_P\left(F_\rho(x)\right) \text{ and } F_\rho(x) = xF_R\left(F_\rho(x)\right)$$

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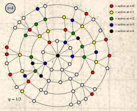
- We'll find a similar result for the subset of nodes that are vulnerable.



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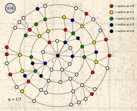
- This is a node-based percolation problem.



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- We'll find a similar result for the subset of nodes that are vulnerable.
- This is a node-based percolation problem.
- For a general monotonic threshold distribution $f(\phi)$, a degree k node is vulnerable with probability

$$B_{k1} = \int_0^{1/k} f(\phi)\,\mathrm{d}\phi\,.$$

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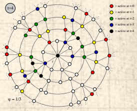

Threshold contagion on random networks

- We now have a generating function for the probability that a randomly chosen node is vulnerable and has degree k:

$$F_P^{(\text{vuln})}(x) = \sum_{k=0}^{\infty} P_k B_{k1} x^k.$$

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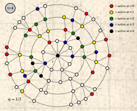

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$$F_R^{(\text{vuln})}(x) = \sum_{k=0}^{\infty} \frac{k P_k}{\langle k \rangle} B_{k1} x^{k-1}$$

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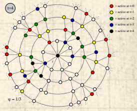

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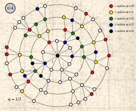

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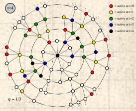

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- Detail: We still have the underlying degree distribution involved in the denominator.

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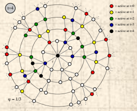

Threshold contagion on random networks

- Functional relations for component size g.f.'s are almost the same ...

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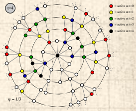

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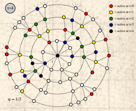

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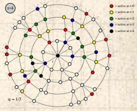
$$F_\pi^{(\text{vuln})}(x) = \underbrace{1 - F_P^{(\text{vuln})}(1)}_{\substack{\text{central node} \\ \text{is not} \\ \text{vulnerable}}} + x F_P^{(\text{vuln})}\left(F_\rho^{(\text{vuln})}(x)\right)$$



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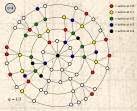

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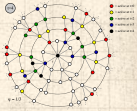

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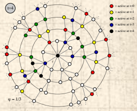
- Can now solve as before to find

$$S_{\text{vuln}} = 1 - F_\pi^{(\text{vuln})}(1).$$



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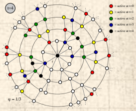

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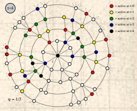
- **Second goal:** Find probability of triggering largest vulnerable component.



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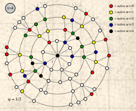
- Second goal: Find probability of triggering largest vulnerable component.
- Assumption is first node is randomly chosen.



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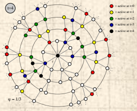
- Same set up as for vulnerable component except now we don't care if the initial node is vulnerable or not:

$$F_{\pi}^{(\text{trig})}(x) = x F_{P}\left(F_{\rho}^{(\text{vuln})}(x)\right)$$

$$F_{\rho}^{(\text{vuln})}(x) = 1 - F_{R}^{(\text{vuln})}(1) + x F_{R}^{(\text{vuln})}\left(F_{\rho}^{(\text{vuln})}(x)\right)$$



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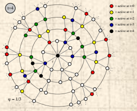
- Solve as before to find $P_{\text{trig}} = S_{\text{trig}} = 1 - F_{\pi}^{(\text{trig})}(1)$.



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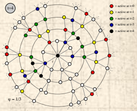

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Physical derivation of possibility and probability of global spreading:

- Possibility: binary indicator of phase. Global spreading events are either possible or can never happen.

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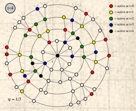

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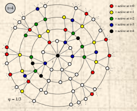

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- For random networks, global spreading possibility is understood as meaning a giant component of vulnerable nodes exists.

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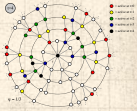
- Next: what's the probability that a randomly infected node will cause a global spreading event?



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- Call this P_{trig}.

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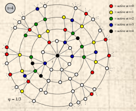

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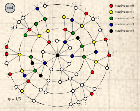
- Call this P_{trig}.
- As usual, it's all about edges and we need to first determine the probability that an infected edge leads to a global spreading event.



Physical derivation of possibility and probability of global spreading:

- Possibility: binary indicator of phase. Global spreading events are either possible or can never happen.
- For random networks, global spreading possibility is understood as meaning a giant component of vulnerable nodes exists.
- Next: what's the probability that a randomly infected node will cause a global spreading event?
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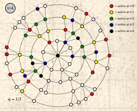

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- Call this Q_{trig}.
- Later: Generalize to more complex networks involving assortativity of all kinds.

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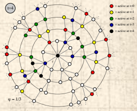

Probability an infected edge leads to a global spreading event:

- Q_{trig} must satisfying a one-step recursion relation.

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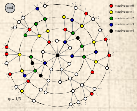

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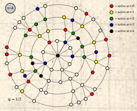

Probability an infected edge leads to a global spreading event:

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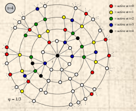

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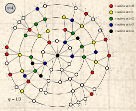

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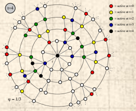
  3. At least one of the node's outgoing edges leads to a global spreading event = 1 - probability no edges do so = $1 - (1 - Q_{\text{trig}})^{k-1}$.



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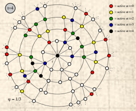
  3. At least one of the node's outgoing edges leads to a global spreading event = 1 - probability no edges do so = $1 - (1 - Q_{\text{trig}})^{k-1}$.
- Put everything together and solve for Q_{trig}:

$$Q_{\text{trig}} = \sum_k \frac{kP_k}{\langle k \rangle} \bullet B_{k1} \bullet \left[1 - (1 - Q_{\text{trig}})^{k-1}\right].$$



Good things about our equation for Q_{trig}:

$$Q_{\text{trig}} = \sum_k \frac{kP_k}{\langle k \rangle} \bullet B_{k1} \bullet \left[1 - (1 - Q_{\text{trig}})^{k-1}\right] = f(Q_{\text{trig}}; P_k, B_{k1})$$

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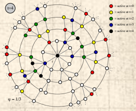

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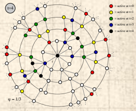

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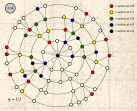

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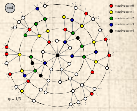

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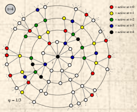

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- Start with a suitably small seed $Q_{\mathrm{trig}}^{(1)} > 0$ and iterate while rubbing hands together.

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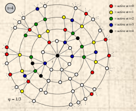

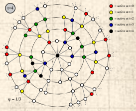

- Global spreading is possible if the fractional size S_{vuln} of the largest component of vulnerables is "giant".

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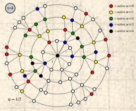

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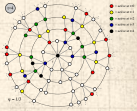

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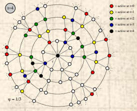

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- As for S_{vuln}, P_{trig} is non-zero when $Q_{\text{trig}} > 0$.

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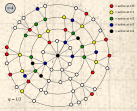

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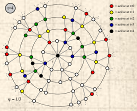

Connection to generating function results:

- We found that $F_\rho^{(\text{vuln})}(1)$—the probability that a random edge leads to a finite vulnerable component—satisfies

$$F_\rho^{(\text{vuln})}(1) = 1 - F_R^{(\text{vuln})}(1) + 1 \cdot F_R^{(\text{vuln})}\left(F_\rho^{(\text{vuln})}(1)\right).$$

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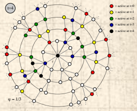

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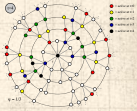

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- Some breathless algebra it all matches:

$$Q_{\text{trig}} = \sum_{k=0}^{\infty} \frac{kP_k}{\langle k \rangle} \bullet B_{k1} \bullet \left[1 - \left(1 - Q_{\text{trig}}\right)^{k-1}\right].$$

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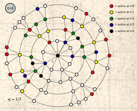

Fractional size of the largest vulnerable component:

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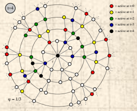

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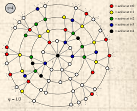

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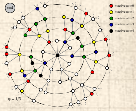
- Excited scrabbling about gives us, as before:

$$S_{\text{vuln}} = \sum_{k=0}^{\infty} P_k B_{k1} \left[1 - \left(1 - Q_{\text{trig}}\right)^k\right].$$



Triggering probability for single-seed global spreading events:

- Slight adjustment to the vulnerable component calculation.

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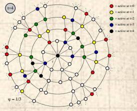

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- Slight adjustment to the vulnerable component calculation.
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$$F_{\pi}^{(\text{trig})}(1) = 1 \cdot F_P\left(F_{\rho}^{(\text{vuln})}(1)\right).$$

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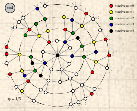

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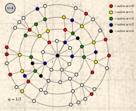

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- More scruffing around brings happiness:

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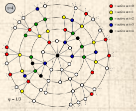

Connection to simple gain ratio argument:

- Earlier, we showed the global spreading condition follows from the gain ratio $\mathbf{R} > 1$:

$$\mathbf{R} = \sum_{k=0}^{\infty} \frac{k P_k}{\langle k \rangle} \bullet (k-1) \bullet B_{k1} > 1.$$

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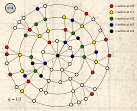

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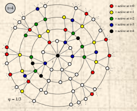

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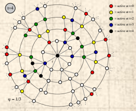

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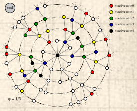

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- When does this equation have a solution $0 < Q_{\text{trig}} \leq 1$?

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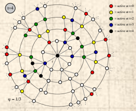

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- When does this equation have a solution $0 < Q_{\text{trig}} \leq 1$?
- We need to find out what happens as $Q_{\text{trig}} \to 0$. [9]

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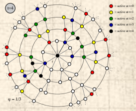

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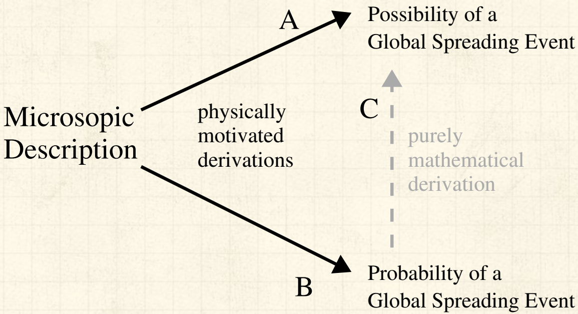
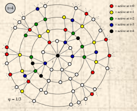
What we're doing:





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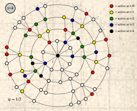

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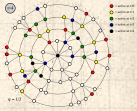

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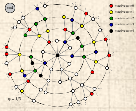

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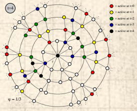

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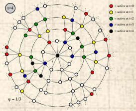

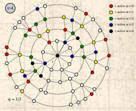

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- Inequality?

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- Repeat: Above is a mathematical connection between two physically derived equations.

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- Repeat: Above is a mathematical connection between two physically derived equations.
- From this connection, we don't know anything about a gain ratio **R** or how to arrange the pieces.

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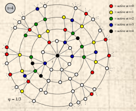

Threshold contagion on random networks

- Third goal: Find expected fractional size of spread.

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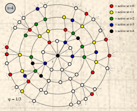

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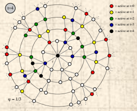

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- Difficulty is in figuring out if and when nodes that need ≥ 2 hits switch on.

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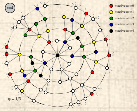

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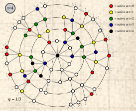

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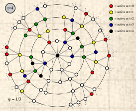
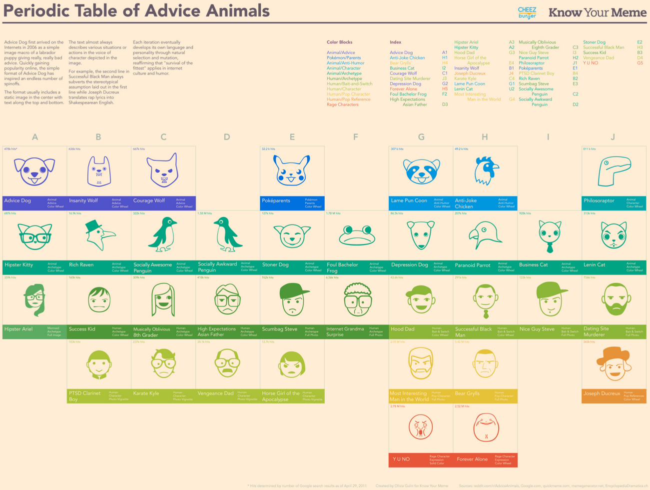
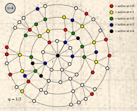
  "Seed size strongly affects cascades on random networks," Phys. Rev. E, 2007. [7]
- Developed further by Gleeson in "Cascades on correlated and modular random networks," Phys. Rev. E, 2008. [6]



Meme species:





More here at http://knowyourmeme.com

Expected size of spread

Idea:

- Randomly turn on a fraction ϕ_0 of nodes at time $t = 0$

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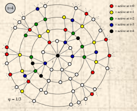

Expected size of spread

Idea:

- Randomly turn on a fraction ϕ_0 of nodes at time $t = 0$
- Capitalize on local branching network structure of random networks (again)

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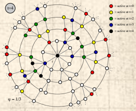

Expected size of spread

Idea:

- Randomly turn on a fraction ϕ_0 of nodes at time $t = 0$
- Capitalize on local branching network structure of random networks (again)
- Now think about what must happen for a specific node i to become active at time t:

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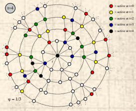

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- Randomly turn on a fraction ϕ_0 of nodes at time $t = 0$
- Capitalize on local branching network structure of random networks (again)
- Now think about what must happen for a specific node i to become active at time t:
  - $t = 0$: i is one of the seeds (prob = ϕ_0)

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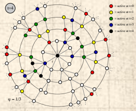

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Idea:

- Randomly turn on a fraction ϕ_0 of nodes at time $t = 0$
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- Now think about what must happen for a specific node i to become active at time t:
  - $t = 0$: i is one of the seeds (prob = ϕ_0)
  - $t = 1$: i was not a seed but enough of i's friends switched on at time $t = 0$ so that i's threshold is now exceeded.

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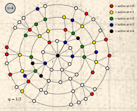

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- Now think about what must happen for a specific node i to become active at time t:
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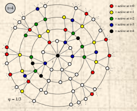
  - $t = 1$: i was not a seed but enough of i's friends switched on at time $t = 0$ so that i's threshold is now exceeded.
  - $t = 2$: enough of i's friends and friends-of-friends switched on at time $t = 0$ so that i's threshold is now exceeded.



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  - $t = 2$: enough of i's friends and friends-of-friends switched on at time $t = 0$ so that i's threshold is now exceeded.
  - $t = n$: enough nodes within n hops of i switched on at $t = 0$ and their effects have propagated to reach i.

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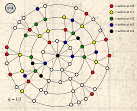

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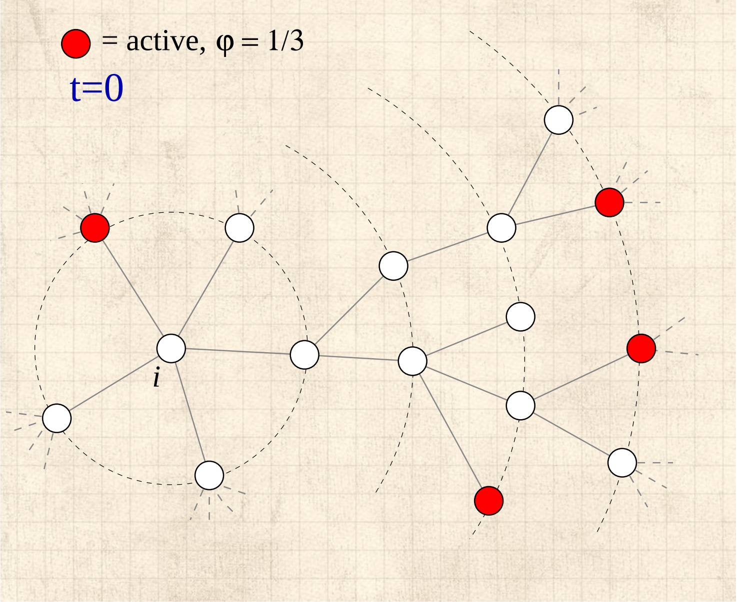

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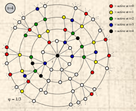

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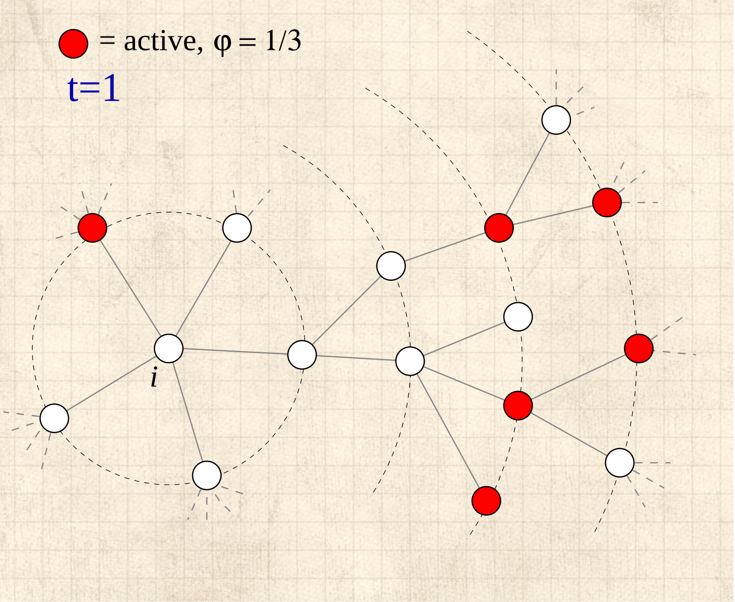

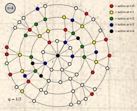

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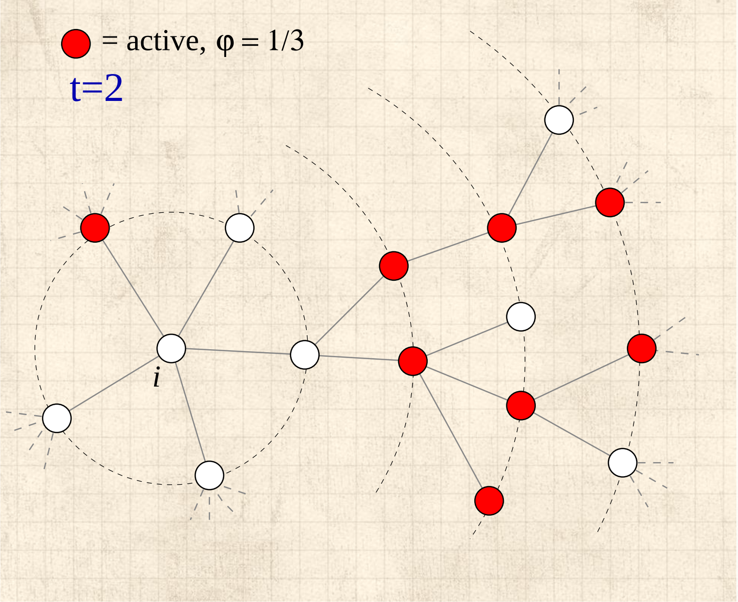

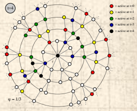

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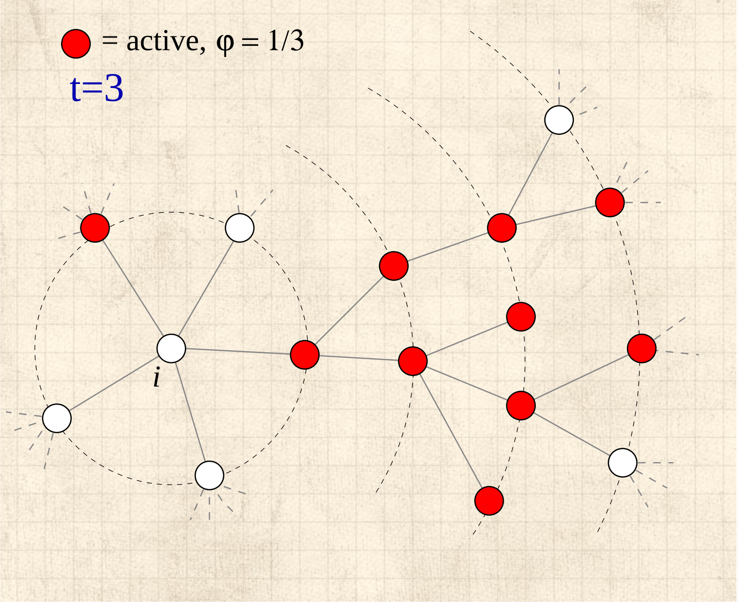

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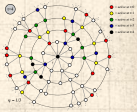

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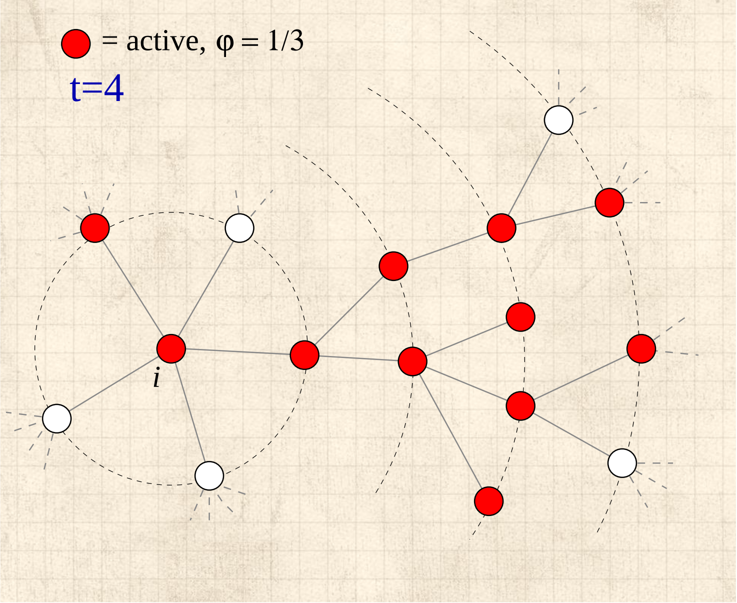

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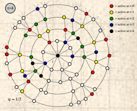

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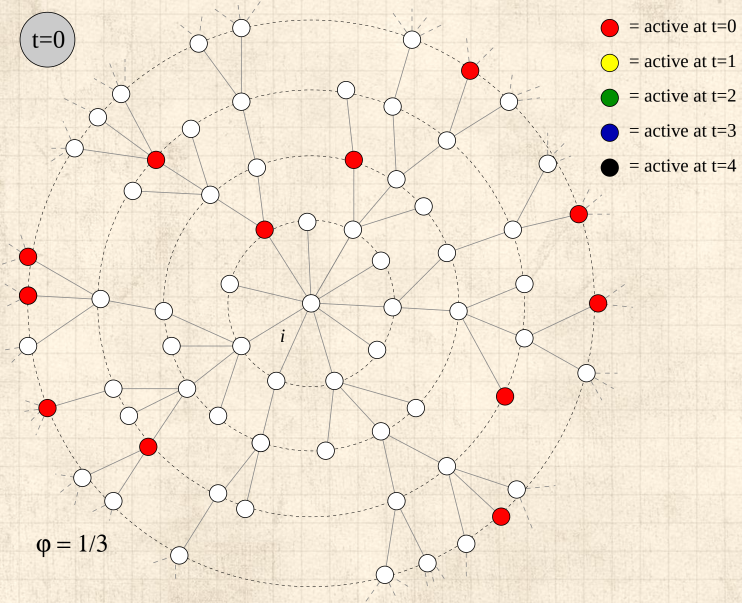

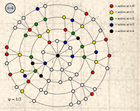

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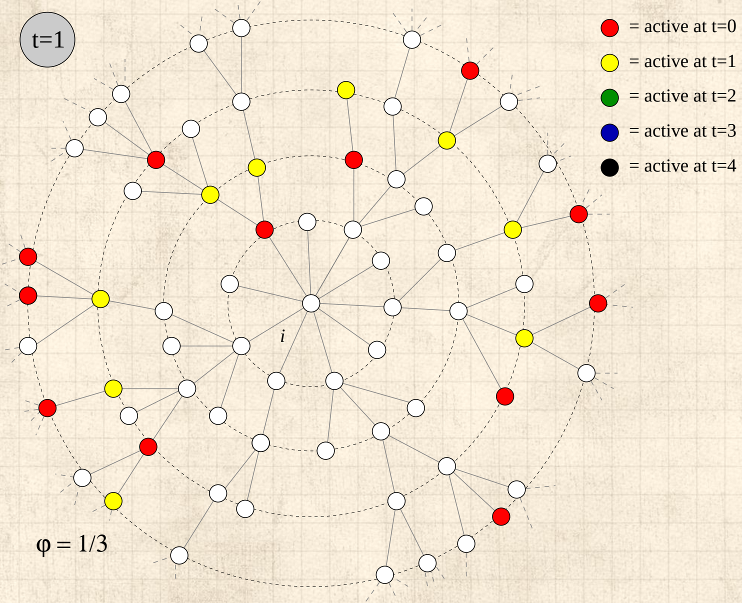

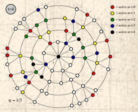

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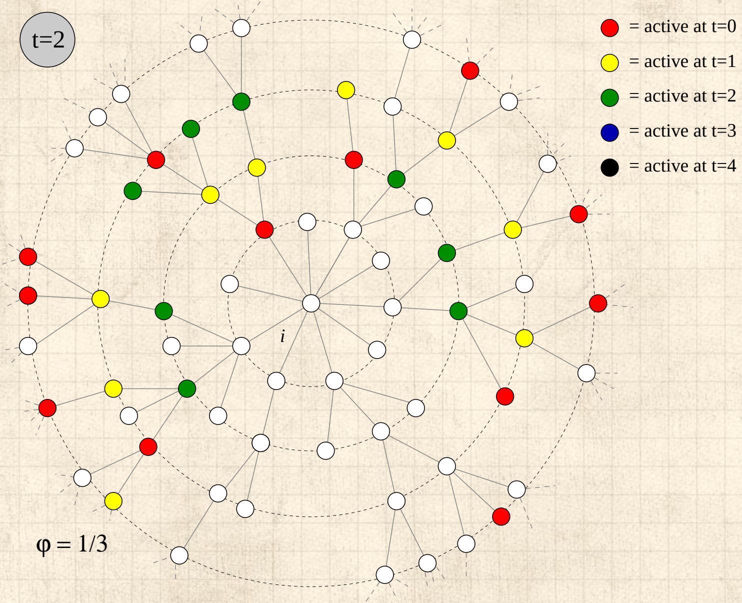

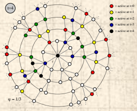

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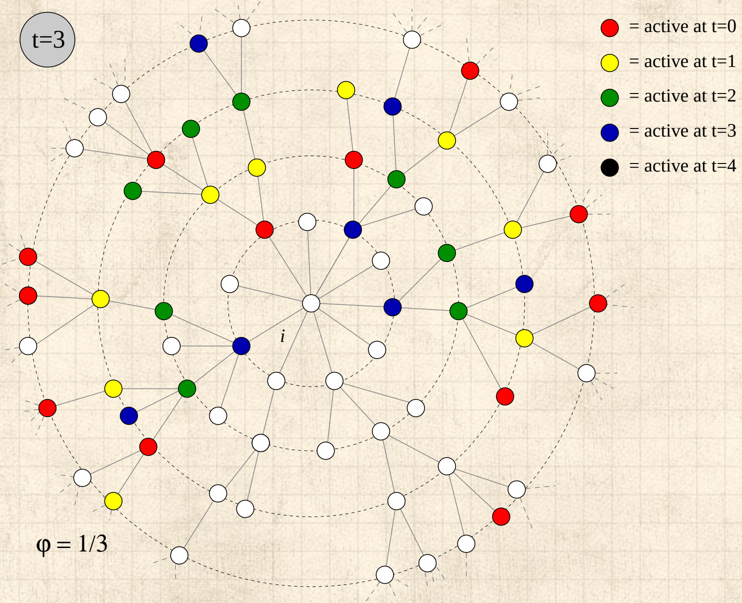

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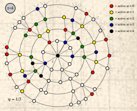

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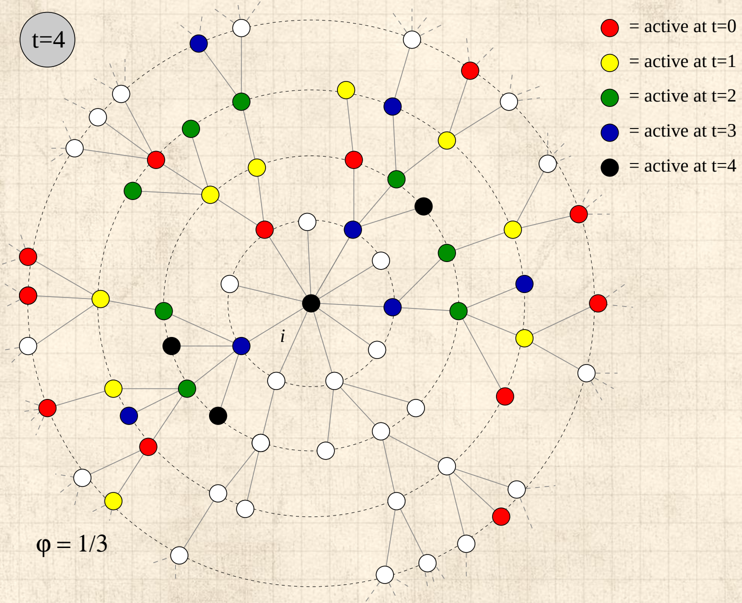

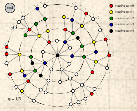

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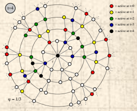

Notes:

- Calculations presume nodes do not become inactive (strong restriction, liftable)

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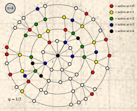

Notes:

- Calculations presume nodes do not become inactive (strong restriction, liftable)
- Not just for threshold model—works for a wide range of contagion processes.

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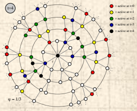

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- We can analytically determine the entire time evolution, not just the final size.

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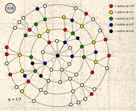

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- We can analytically determine the entire time evolution, not just the final size.
- We can in fact determine **Pr**(node of degree k switches on at time t).

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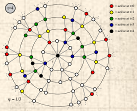

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- We can analytically determine the entire time evolution, not just the final size.
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- Even more, we can compute: **Pr**(specific node i switches on at time t).

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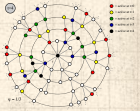
- We can analytically determine the entire time evolution, not just the final size.
- We can in fact determine **Pr**(node of degree k switches on at time t).
- Even more, we can compute: **Pr**(specific node i switches on at time t).
- Asynchronous updating can be handled too.



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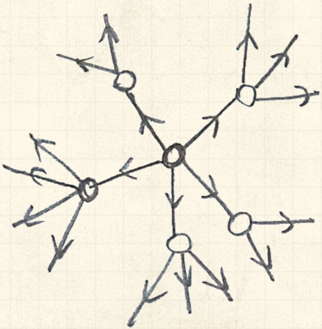
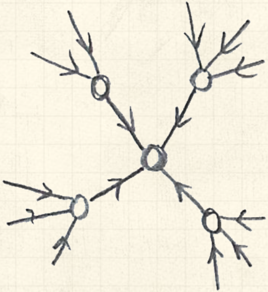
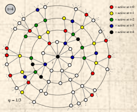
Pleasantness:

- Taking off from a single seed story is about expansion away from a node.







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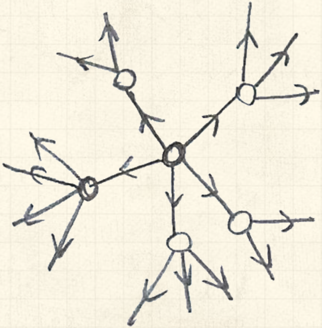
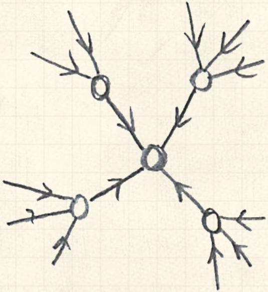
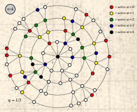
Pleasantness:

- Taking off from a single seed story is about expansion away from a node.
- Extent of spreading story is about contraction at a node.







Expected size of spread

- **Notation:**
  $\phi_{k,t} = \mathbf{Pr}(\text{a degree } k \text{ node is active at time } t)$.

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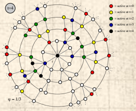

Expected size of spread

- Notation:
  $\phi_{k,t} = \mathbf{Pr}(\text{a degree } k \text{ node is active at time } t)$.
- Notation: $B_{kj} = \mathbf{Pr}$ (a degree k node becomes active if j neighbors are active).

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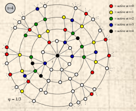

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- Our starting point: $\phi_{k,0} = \phi_0$.

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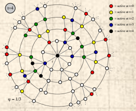

Expected size of spread

- Notation:
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- Notation: B_{kj} = **Pr** (a degree k node becomes active if j neighbors are active).
- Our starting point: $\phi_{k,0} = \phi_0$.
- $\binom{k}{j}\phi_0^j(1-\phi_0)^{k-j}$ = **Pr** (j of a degree k node's neighbors were seeded at time $t = 0$).

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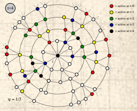

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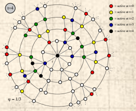
- Our starting point: $\phi_{k,0} = \phi_0$.
- $\binom{k}{j}\phi_0^j(1-\phi_0)^{k-j}$ = **Pr** (j of a degree k node's neighbors were seeded at time $t=0$).
- Probability a degree k node was a seed at $t=0$ is ϕ_0 (as above).



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- Notation: B_{kj} = **Pr** (a degree k node becomes active if j neighbors are active).
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- $\binom{k}{j}\phi_0^j(1-\phi_0)^{k-j}$ = **Pr** (j of a degree k node's neighbors were seeded at time $t=0$).
- Probability a degree k node was a seed at $t=0$ is ϕ_0 (as above).
- Probability a degree k node was not a seed at $t=0$ is $(1-\phi_0)$.

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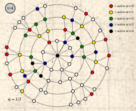
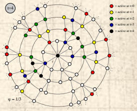


Expected size of spread

- Notation:
  $\phi_{k,t}$ = **Pr**(a degree k node is active at time t).
- Notation: B_{kj} = **Pr** (a degree k node becomes active if j neighbors are active).
- Our starting point: $\phi_{k,0} = \phi_0$.
- $\binom{k}{j}\phi_0^j(1-\phi_0)^{k-j}$ = **Pr** (j of a degree k node's neighbors were seeded at time $t = 0$).
- Probability a degree k node was a seed at $t = 0$ is ϕ_0 (as above).
- Probability a degree k node was not a seed at $t = 0$ is $(1 - \phi_0)$.
- Combining everything, we have:

$$\phi_{k,1} = \phi_0 + (1-\phi_0)\sum_{j=0}^{k}\binom{k}{j}\phi_0^j(1-\phi_0)^{k-j}B_{kj}.$$



Expected size of spread

- For general t, we need to know the probability an edge coming into a degree k node at time t is active.

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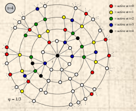

Expected size of spread

- For general t, we need to know the probability an edge coming into a degree k node at time t is active.
- Notation: call this probability θ_t.

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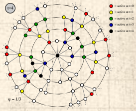

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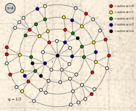

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- For general t, we need to know the probability an edge coming into a degree k node at time t is active.
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- Story analogous to $t = 1$ case. For specific node i:

$$\phi_{i,t+1} = \phi_0 + (1-\phi_0) \sum_{j=0}^{k_i} \binom{k_i}{j} \theta_t^{\,j} (1-\theta_t)^{k_i - j} B_{k_i j}.$$

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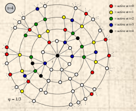

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- Average over all nodes with degree k to obtain expression for ϕ_{t+1}:

$$\phi_{t+1} = \phi_0 + (1 - \phi_0) \sum_{k=0}^{\infty} P_k \sum_{j=0}^{k} \binom{k}{j} \theta_t^j (1 - \theta_t)^{k-j} B_{kj}.$$

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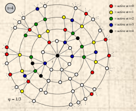

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- So we need to compute θ_t...

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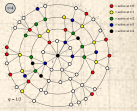

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- Average over all nodes with degree k to obtain expression for ϕ_{t+1}:

$$\phi_{t+1} = \phi_0 + (1 - \phi_0) \sum_{k=0}^{\infty} P_k \sum_{j=0}^{k} \binom{k}{j} \theta_t^j (1 - \theta_t)^{k-j} B_{kj}.$$

- So we need to compute θ_t... massive excitement...

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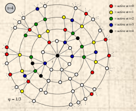

Expected size of spread

First connect θ_0 to θ_1:

- $\theta_1 = \phi_0 +$

$$(1-\phi_0)\sum_{k=1}^{\infty}\frac{kP_k}{\langle k\rangle}\sum_{j=0}^{k-1}\binom{k-1}{j}\theta_0^{\,j}(1-\theta_0)^{k-1-j}B_{kj}$$

- $\frac{kP_k}{\langle k\rangle} = Q_k$ = **Pr** (edge connects to a degree k node).
- $\sum_{j=0}^{k-1}$ piece gives **Pr** (degree node k activates if j of its $k-1$ incoming neighbors are active).
- ϕ_0 and $(1-\phi_0)$ terms account for state of node at time $t=0$.

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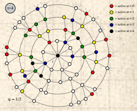

Expected size of spread

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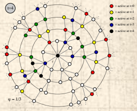
- $\frac{k P_k}{\langle k\rangle} = Q_k$ = **Pr** (edge connects to a degree k node).
- $\sum_{j=0}^{k-1}$ piece gives **Pr** (degree node k activates if j of its $k-1$ incoming neighbors are active).
- ϕ_0 and $(1-\phi_0)$ terms account for state of node at time $t=0$.
- See this all generalizes to give θ_{t+1} in terms of θ_t...



Expected size of spread

Two pieces: edges first, and then nodes

1. $$\theta_{t+1} = \underbrace{\phi_0}_{\text{exogenous}} + \underbrace{(1-\phi_0)\sum_{k=1}^{\infty}\frac{kP_k}{\langle k \rangle}\sum_{j=0}^{k-1}\binom{k-1}{j}\theta_t^{\,j}(1-\theta_t)^{k-1-j}B_{kj}}_{\text{social effects}}$$

   with $\theta_0 = \phi_0$.

2. $$\phi_{t+1} = \underbrace{\phi_0}_{\text{exogenous}} + \underbrace{(1-\phi_0)\sum_{k=0}^{\infty}P_k\sum_{j=0}^{k}\binom{k}{j}\theta_t^{\,j}(1-\theta_t)^{k-j}B_{kj}}_{\text{social effects}}.$$

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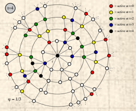
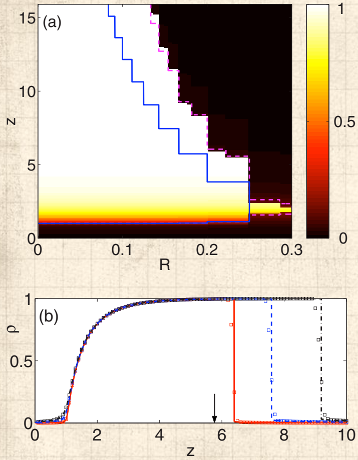


Comparison between theory and simulations



From Gleeson and Cahalane [7]

- Pure random networks with simple threshold responses
- R = uniform threshold (our ϕ_*); z = average degree; $\rho = \phi$; $q = \theta$; $N = 10^5$.
- $\phi_0 = 10^{-3}$, 0.5×10^{-2}, and 10^{-2}.
- Cascade window is for $\phi_0 = 10^{-2}$ case.
- Sensible expansion of cascade window as ϕ_0 increases.

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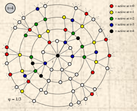

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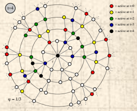
Notes:

- Retrieve cascade condition for spreading from a single seed in limit $\phi_0 \rightarrow 0$.



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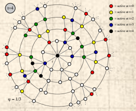
- Depends on map $\theta_{t+1} = G(\theta_t; \phi_0)$.



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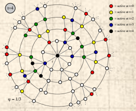
$$G(0; \phi_0) = \sum_{k=1}^{\infty} \frac{k P_k}{\langle k \rangle} \bullet B_{k0} > 0.$$

meaning $B_{k0} > 0$ for at least one value of $k \geq 1$.



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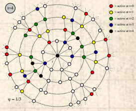
meaning $B_{k0} > 0$ for at least one value of $k \geq 1$.

- If $\theta = 0$ is a fixed point of G (i.e., $G(0;\phi_0) = 0$) then spreading occurs for a small seed if

$$G'(0;\phi_0) = \sum_{k=0}^{\infty} \frac{kP_k}{\langle k \rangle} \bullet (k-1) \bullet B_{k1} > 1.$$

Insert question from assignment 10



Notes:

In words:

- If $G(0;\phi_0) > 0$, spreading must occur because some nodes turn on for free.

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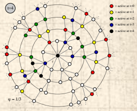
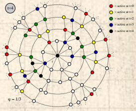


Notes:

In words:

- If $G(0;\phi_0) > 0$, spreading must occur because some nodes turn on for free.
- If G has an unstable fixed point at $\theta = 0$, then cascades are also always possible.



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- If $G(0;\phi_0) > 0$, spreading must occur because some nodes turn on for free.
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Non-vanishing seed case:

- Cascade condition is more complicated for $\phi_0 > 0$.

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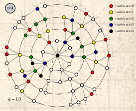

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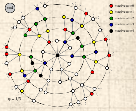

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Non-vanishing seed case:

- Cascade condition is more complicated for $\phi_0 > 0$.
- If G has a stable fixed point at $\theta = 0$, and an unstable fixed point for some $0 < \theta_* < 1$, then for $\theta_0 > \theta_*$, spreading takes off.

Notes:

In words:

- If $G(0;\phi_0) > 0$, spreading must occur because some nodes turn on for free.
- If G has an unstable fixed point at $\theta = 0$, then cascades are also always possible.

Non-vanishing seed case:

- Cascade condition is more complicated for $\phi_0 > 0$.
- If G has a stable fixed point at $\theta = 0$, and an unstable fixed point for some $0 < \theta_* < 1$, then for $\theta_0 > \theta_*$, spreading takes off.
- Tricky point: G depends on ϕ_0, so as we change ϕ_0, we also change G.

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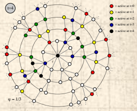
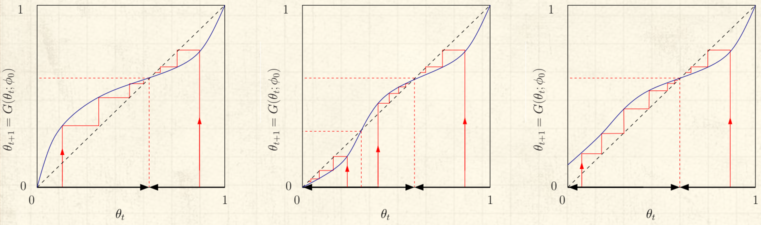


General fixed point story:



- Given $\theta_0 (= \phi_0)$, θ_∞ will be the nearest stable fixed point, either above or below.

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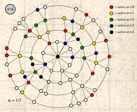

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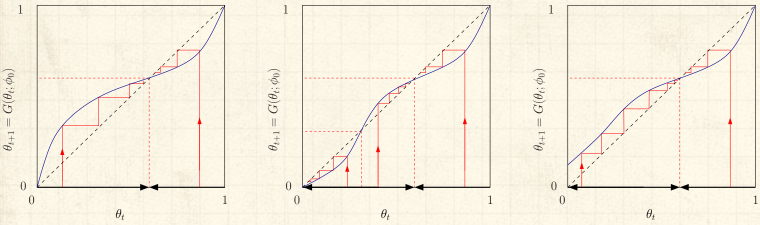

- Given $\theta_0 (= \phi_0)$, θ_∞ will be the nearest stable fixed point, either above or below.
- n.b., adjacent fixed points must have opposite stability types.

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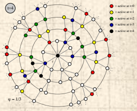

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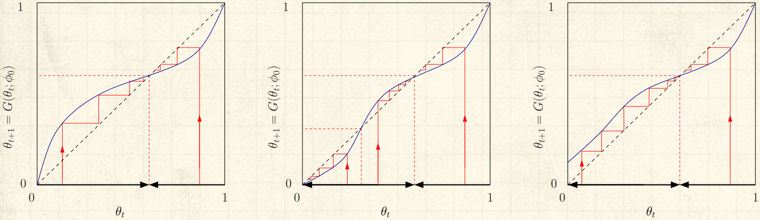

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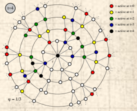
- n.b., adjacent fixed points must have opposite stability types.
- Important: Actual form of G depends on ϕ_0.



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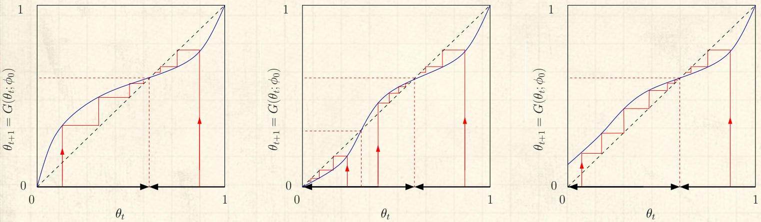

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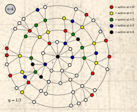

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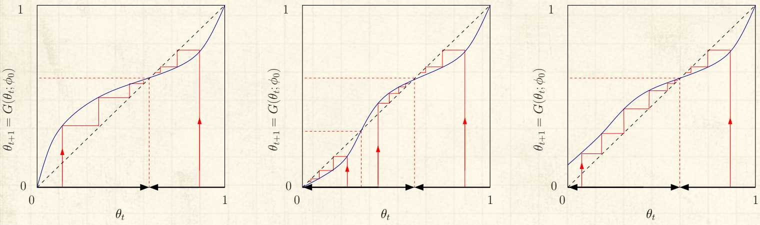

- Given $\theta_0 (= \phi_0)$, θ_∞ will be the nearest stable fixed point, either above or below.
- n.b., adjacent fixed points must have opposite stability types.
- Important: Actual form of G depends on ϕ_0.
- Important: ϕ_t can only increase monotonically so ϕ_0 must shape G so that ϕ_0 is at or above an unstable fixed point.
- First reason: $\phi_1 \geq \phi_0$.

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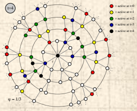
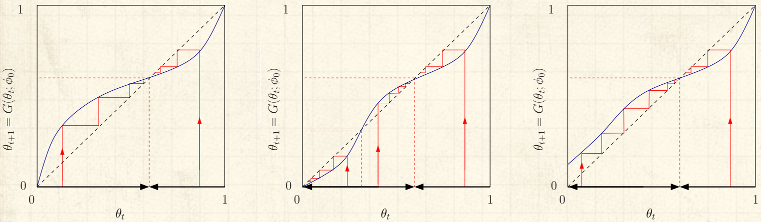


General fixed point story:



- Given $\theta_0 (= \phi_0)$, θ_∞ will be the nearest stable fixed point, either above or below.
- n.b., adjacent fixed points must have opposite stability types.
- Important: Actual form of G depends on ϕ_0.
- Important: ϕ_t can only increase monotonically so ϕ_0 must shape G so that ϕ_0 is at or above an unstable fixed point.
- First reason: $\phi_1 \geq \phi_0$.
- Second: $G'(\theta; \phi_0) \geq 0$, $0 \leq \theta \leq 1$.

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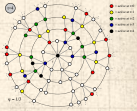

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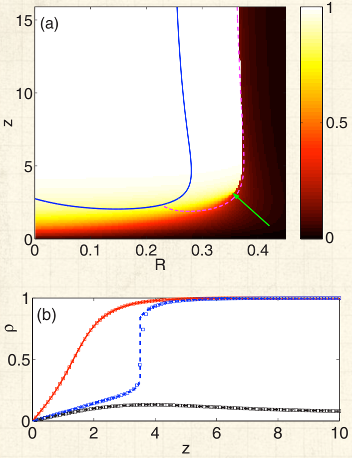
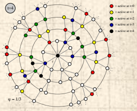
Interesting behavior:



- Now allow thresholds to be distributed according to a Gaussian with mean R.
- R = 0.2, 0.362, and 0.38; $\sigma = 0.2$.

From Gleeson and Cahalane [7]



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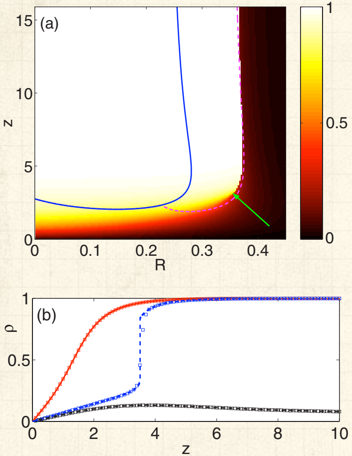
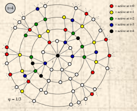


- Now allow thresholds to be distributed according to a Gaussian with mean R.
- R = 0.2, 0.362, and 0.38; $\sigma = 0.2$.
- $\phi_0 = 0$ but some nodes have thresholds ≤ 0 so effectively $\phi_0 > 0$.

From Gleeson and Cahalane [7]



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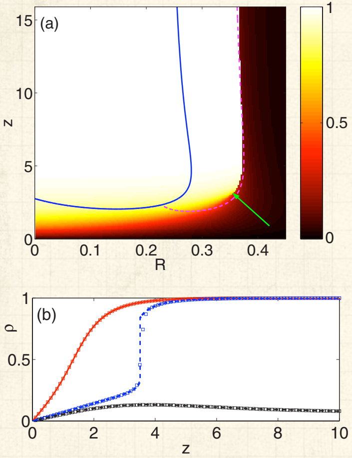

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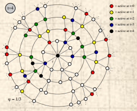
- Now allow thresholds to be distributed according to a Gaussian with mean R.
- R = 0.2, 0.362, and 0.38; $\sigma = 0.2$.
- $\phi_0 = 0$ but some nodes have thresholds ≤ 0 so effectively $\phi_0 > 0$.
- Now see a (nasty) discontinuous phase transition for low $\langle k \rangle$.



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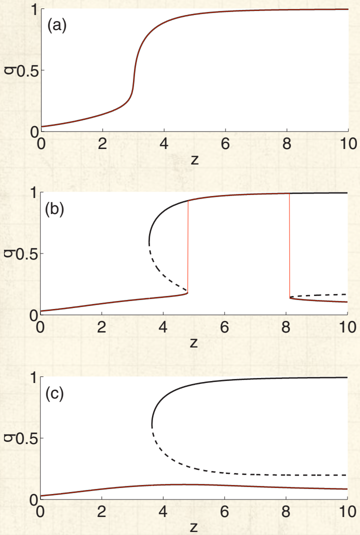
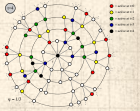


- Plots of stability points for $\theta_{t+1} = G(\theta_t; \phi_0)$.
- n.b.: 0 is not a fixed point here: $\theta_0 = 0$ always takes off.
- Top to bottom: R = 0.35, 0.371, and 0.375.
- Saddle node bifurcations appear and merge (b and c).

From Gleeson and Cahalane [7]



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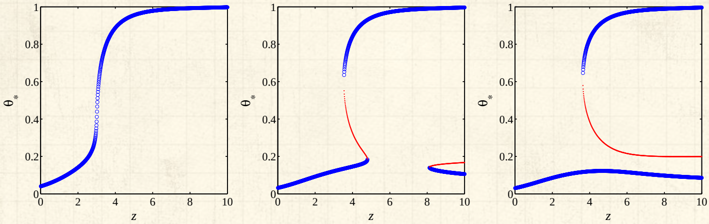
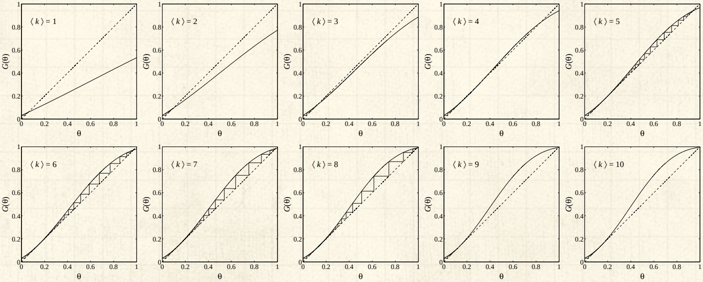
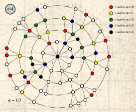
What's happening:



Fixed points slip above and below the $\theta_{t+1} = \theta_t$ line:





Time-dependent solutions

Synchronous update

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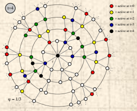

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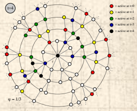

Synchronous update

- Done: Evolution of ϕ_t and θ_t given exactly by the maps we have derived.

Time-dependent solutions

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Asynchronous updates

- Update nodes with probability α.

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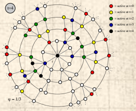

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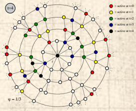

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- As $\alpha \to 0$, updates become effectively independent.

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Synchronous update

- Done: Evolution of ϕ_t and θ_t given exactly by the maps we have derived.

Asynchronous updates

- Update nodes with probability α.
- As $\alpha \to 0$, updates become effectively independent.
- Now can talk about $\phi(t)$ and $\theta(t)$.

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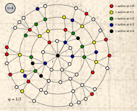

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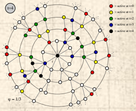

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- Threshold model leads to idea of vulnerables and a critical mass. [16, 8]

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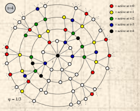

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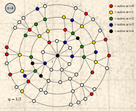

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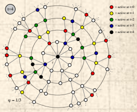

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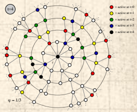

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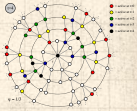

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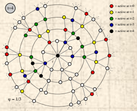
- The single seed contagion condition and triggering probability can be fully developed using a physical story. [5, 9]
- Many connections to other kinds of models: Voter models, Ising models, ...



Neural reboot (NR):

Pangolin happiness:

https://www.youtube.com/watch?v=LMiYjkG4onM?rel=0

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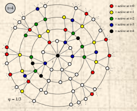

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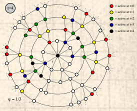

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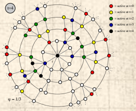

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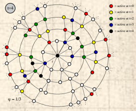

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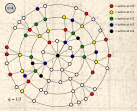

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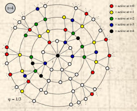

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