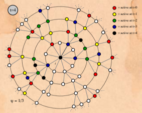
Contagion

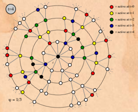
Complex Networks
CSYS/MATH 303, Spring, 2011

Prof. Peter Dodds

Department of Mathematics & Statistics
Center for Complex Systems
Vermont Advanced Computing Center
University of Vermont



Outline

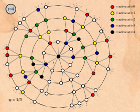


Contagion models

Some large questions concerning network contagion:

1. For a given spreading mechanism on a given network, what's the probability that there will be global spreading?
2. If spreading does take off, how far will it go?
3. How do the details of the network affect the outcome?
4. How do the details of the spreading mechanism affect the outcome?
5. What if the seed is one or many nodes?

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



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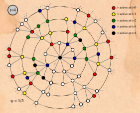

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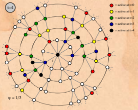

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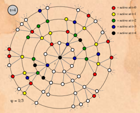

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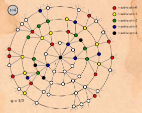

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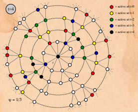

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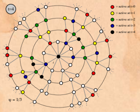
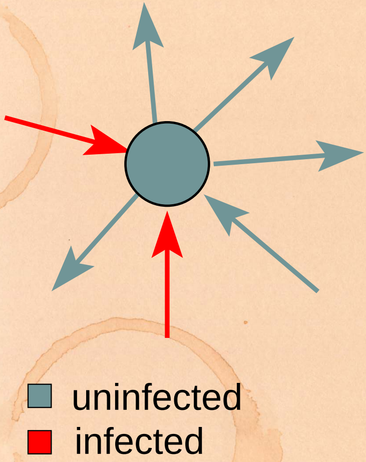
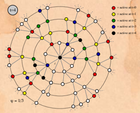


Spreading mechanisms



- **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.



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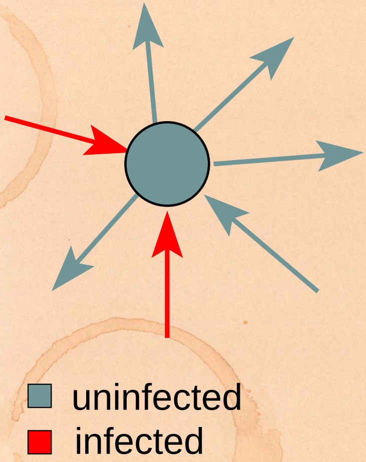

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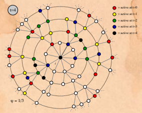

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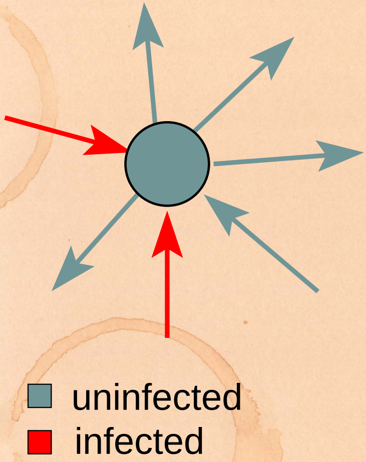

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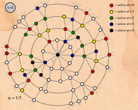
Spreading on Random Networks

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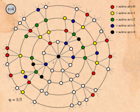

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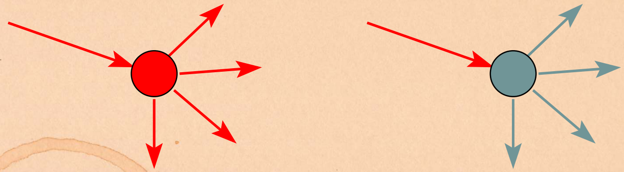

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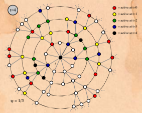

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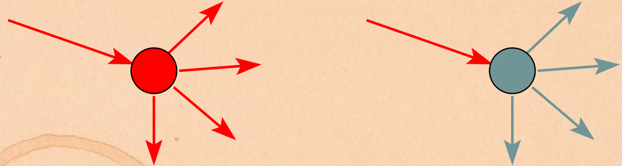

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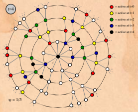

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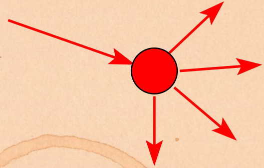

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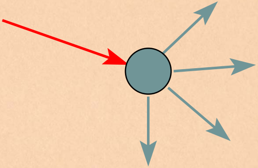

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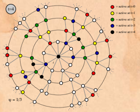
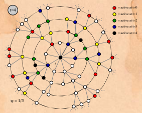


Global spreading condition

- We need to find: [5]
  R = the average # of infected edges that one random infected edge brings about.
- Call **R** the gain ratio.
- Define B_{k1} as the probability that a node of degree k is infected by a single infected edge.
- $$\mathbf{R} = \sum_{k=0}^{\infty} \underbrace{\frac{kP_k}{\langle k \rangle}}_{\text{prob. of connecting to a degree } k \text{ node}} \bullet \underbrace{(k-1)}_{\text{\# outgoing infected edges}} \bullet \underbrace{B_{k1}}_{\text{Prob. of infection}}$$
  $$+ \sum_{k=0}^{\infty} \overbrace{\frac{kP_k}{\langle k \rangle}} \bullet \underbrace{0}_{\text{\# outgoing infected edges}} \bullet \underbrace{(1 - B_{k1})}_{\text{Prob. of no infection}}$$



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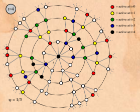

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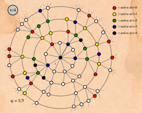

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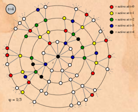

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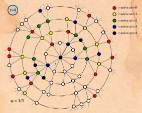

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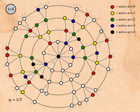

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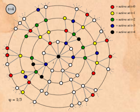

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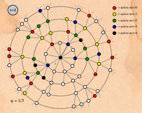


Global spreading condition

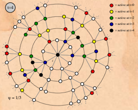
- Our global spreading condition is then:

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

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

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

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



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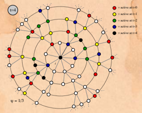

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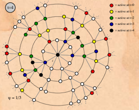

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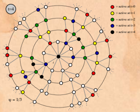

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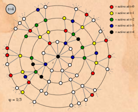

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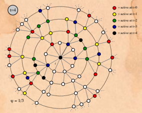
Insert question from assignment 7 (⊞)

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



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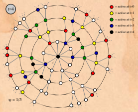

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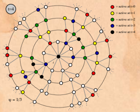

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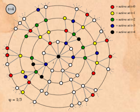

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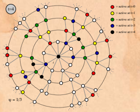

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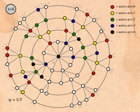

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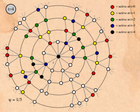

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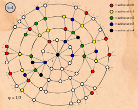

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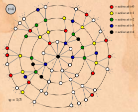

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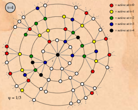

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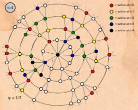

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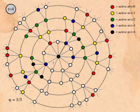

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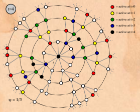

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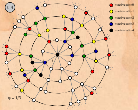

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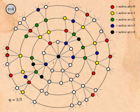

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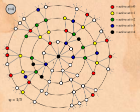

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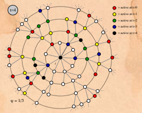

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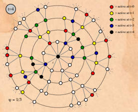

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- Example: $B_{k1} = 1/k$.
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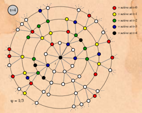

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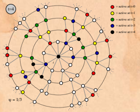

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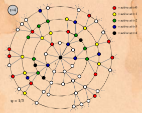

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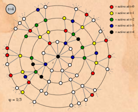

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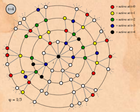

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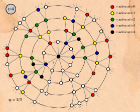

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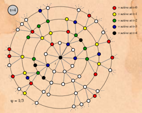

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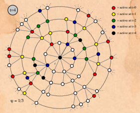

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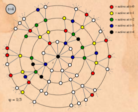

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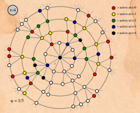
Global spreading condition

- Example: $B_{k1} = H(\frac{1}{k} - \phi)$
  where $0 < \phi \leq 1$ is a threshold and H is the Heaviside function (⊞).
- Infection only occurs for nodes with low degree.
- Call these nodes vulnerables:
  they flip when only one of their friends flips.
-

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

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



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- Example: $B_{k1} = H(\frac{1}{k} - \phi)$ where $0 < \phi \leq 1$ is a threshold and H is the Heaviside function (⊞).
- Infection only occurs for nodes with low degree.
- Call these nodes vulnerables: they flip when only one of their friends flips.
- $$\mathbf{R} = \sum_{k=1}^{\infty} \frac{kP_k}{\langle k \rangle} \bullet (k-1) \bullet B_{k1} = \sum_{k=1}^{\infty} \frac{kP_k}{\langle k \rangle} \bullet (k-1) \bullet H\left(\frac{1}{k} - \phi\right)$$

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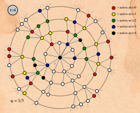

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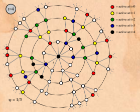

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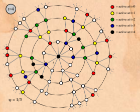

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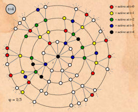

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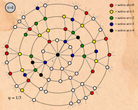
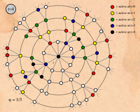


Global spreading condition

- The uniform threshold model global spreading condition:

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

- As $\phi \to 1$, all nodes become resilient and $r \to 0$.
- As $\phi \to 0$, 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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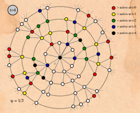

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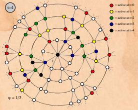

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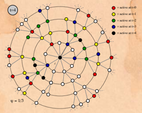

The University of Vermont

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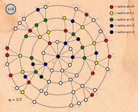

Outline

Basic Contagion Models

Global spreading condition

Social Contagion Models

- Network version
- All-to-all networks
- Theory

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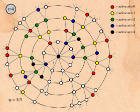

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  - Simulation on checker boards.
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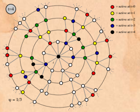

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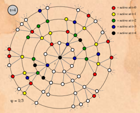

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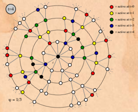

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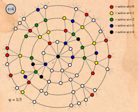

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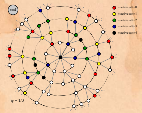

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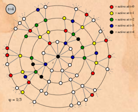

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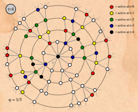
- Mean field Granovetter model → network model
- Individuals now have a limited view of the world



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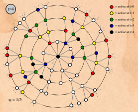

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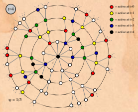

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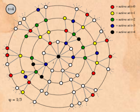
- Individual i has k_i contacts
- Influence on each link is reciprocal and of unit weight
- Each individual i has a fixed threshold ϕ_i
- Individuals repeatedly poll contacts on network
- Synchronous, discrete time updating
- Individual i becomes active when number of active contacts $a_i \geq \phi_i k_i$
- Activation is permanent (SI)



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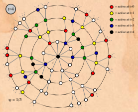

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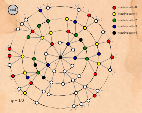

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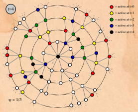

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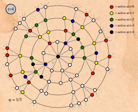

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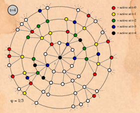

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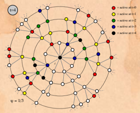

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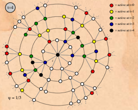

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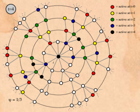

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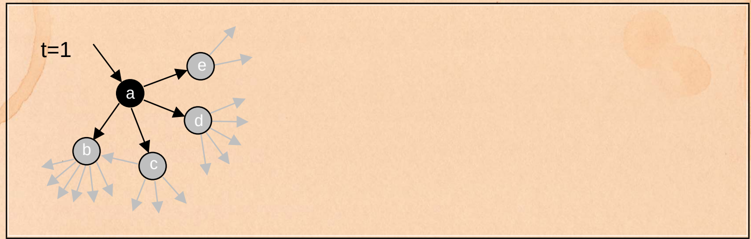

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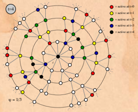

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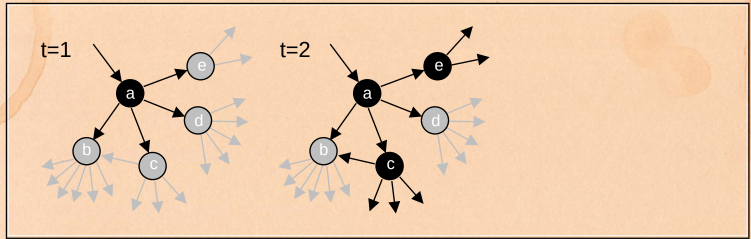

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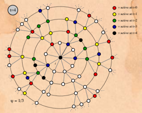

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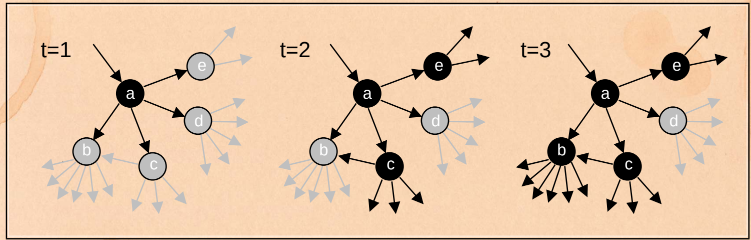

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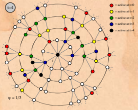
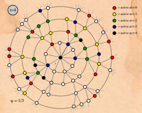


The most gullible

Vulnerables:

- Recall definition: individuals who can be activated by just one contact being active are vulnerables.
- The vulnerability condition for node i: $1/k_i \geq \phi_i$.
- Means # contacts $k_i \leq \lfloor 1/\phi_i \rfloor$.
- Key: For global spreading events (cascades) on random networks, must have a *global component of vulnerables* [13]
- For a uniform threshold ϕ, our global spreading condition tells us when such a component exists:

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



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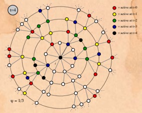

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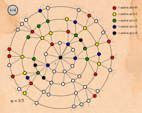

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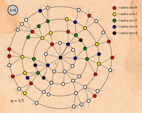

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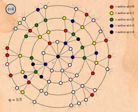

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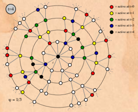
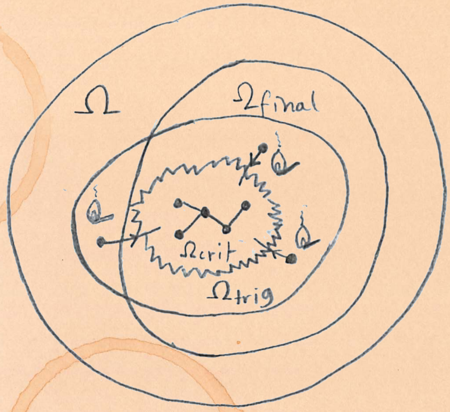
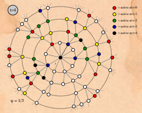


Example random network structure:

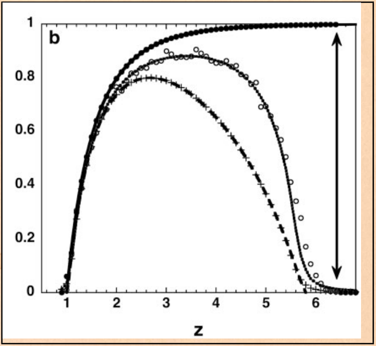


- Ω_{crit} = critical mass = global vulnerable component
- Ω_{trig} = triggering component
- Ω_{final} = potential extent of spread
- Ω = entire network

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



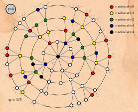
Global spreading events on random networks



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

- Top curve: final fraction infected if successful.
- Middle curve: chance of starting a global spreading event (cascade).
- Bottom curve: fractional size of vulnerable subcomponent. [13]

- Global spreading events occur only if size of vulnerable subcomponent > 0.
- System is robust-yet-fragile just below upper boundary [3, 4, 12]
- 'Ignorance' facilitates spreading.



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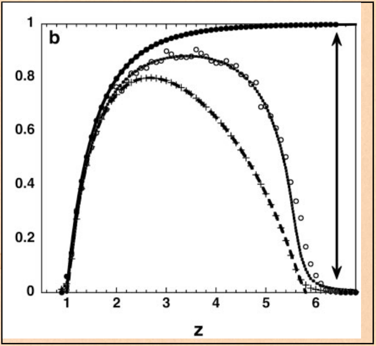

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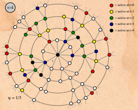

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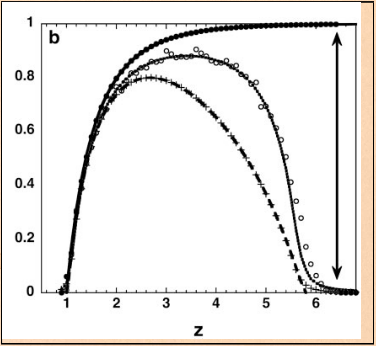

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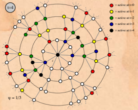

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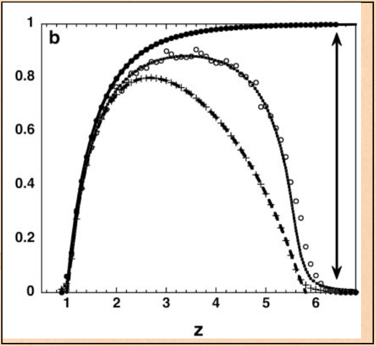

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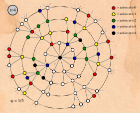

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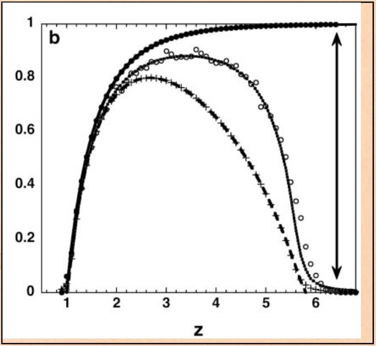

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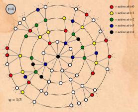

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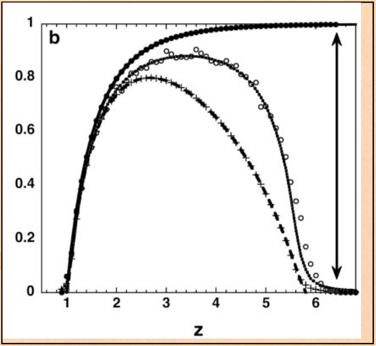

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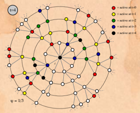
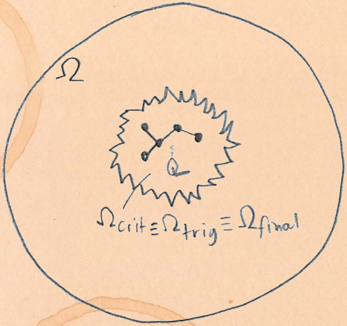
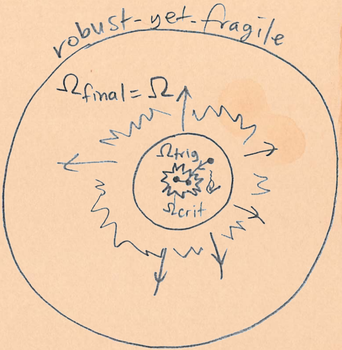
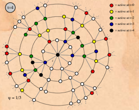


Cascades on random networks





- Above lower phase transition
- Just below upper phase transition



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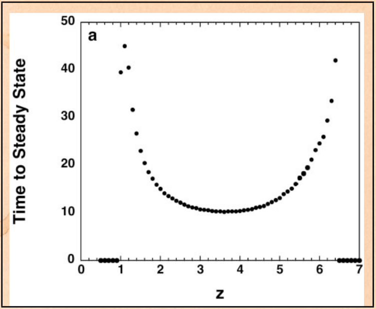
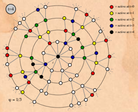


(n.b., $z = \langle k \rangle$)

- Time taken for cascade to spread through network. [13]
- Two phase transitions.
- Largest vulnerable component = critical mass.
- Now have endogenous mechanism for spreading from an individual to the critical mass and then beyond.



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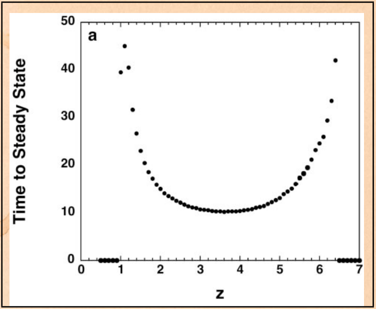

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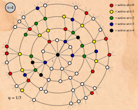

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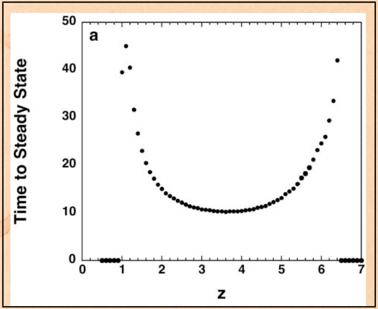

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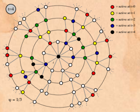

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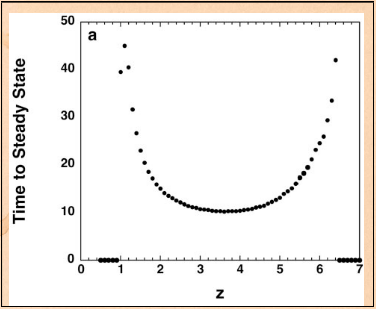

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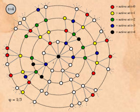
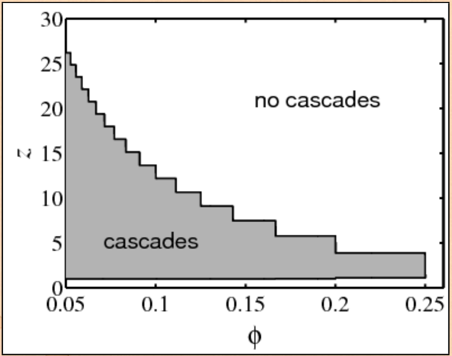
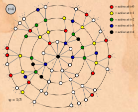


Cascade window for random networks



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

- Outline of cascade window for random networks.



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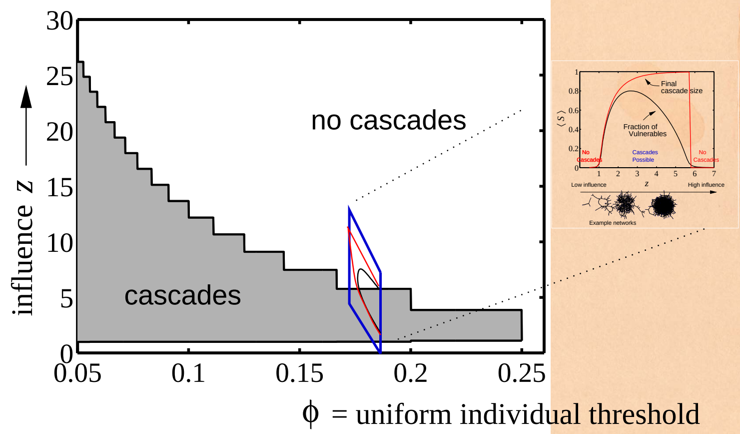
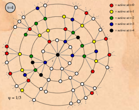




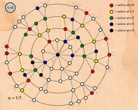
Outline

Basic Contagion Models

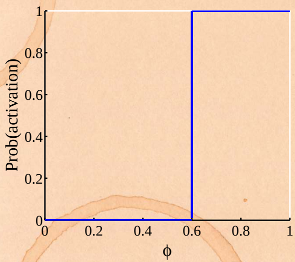
Global spreading condition

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

References



Granovetter's Threshold model—recap



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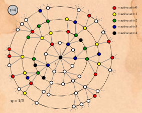
- ϕ_* = threshold of an individual.
- $f(\phi_*)$ = distribution of thresholds in a population.
- $F(\phi_*)$ = cumulative distribution = $\int_{\phi'_*=0}^{\phi_*} f(\phi'_*)\mathrm{d}\phi'_*$
- ϕ_t = fraction of people 'rioting' at time step t.



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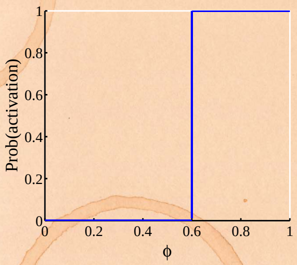

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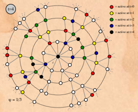

Social Contagion

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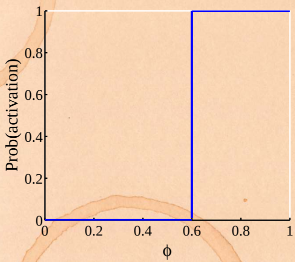

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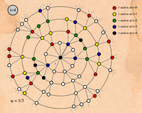

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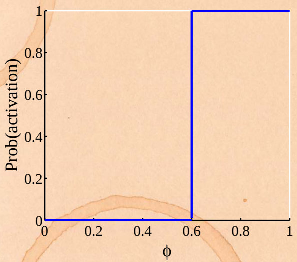

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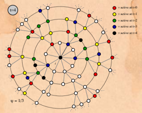

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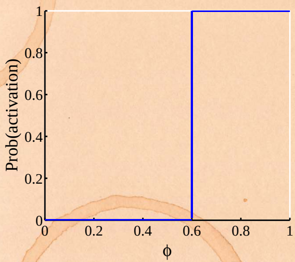

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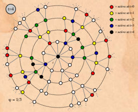
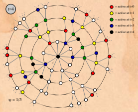


Social Sciences—Threshold models

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



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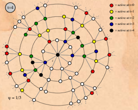

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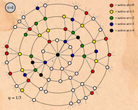
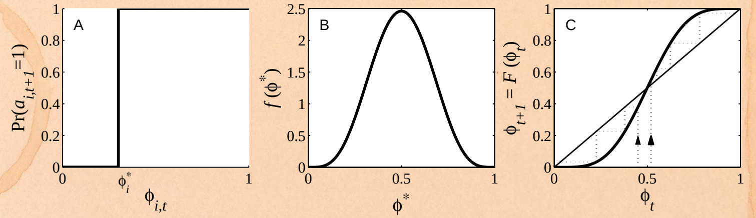
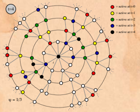


Social Sciences—Threshold models

Action based on perceived behavior of others.

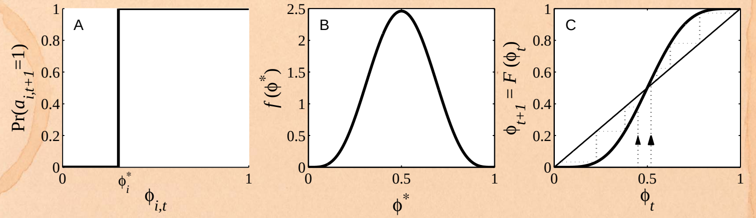


- Two states: S and I
- Recover now possible (SIS)
- ϕ = fraction of contacts 'on' (e.g., rioting)
- Discrete time, synchronous update (strong assumption!)
- This is a Critical mass model



Social Sciences—Threshold models

Action based on perceived behavior of others.



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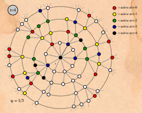

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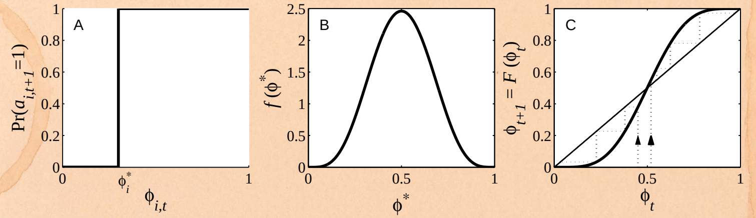

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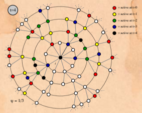

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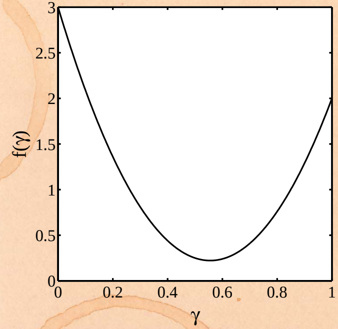
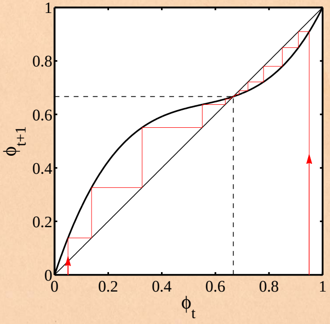
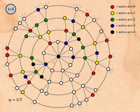




- Example of single stable state model



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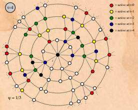

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1. Collective uniformity $\not\Rightarrow$ individual uniformity
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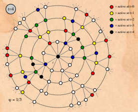

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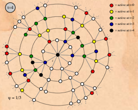

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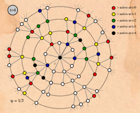

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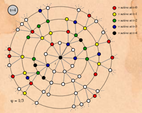

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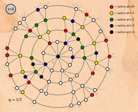
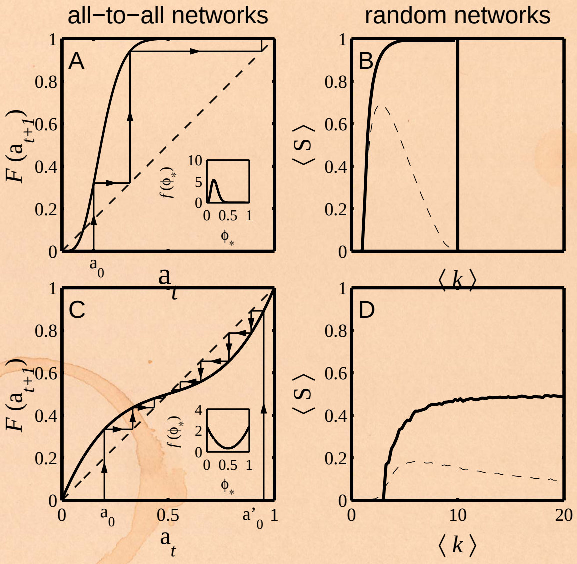
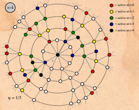


All-to-all versus random networks





Outline

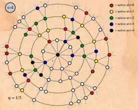
Basic Contagion Models

Global spreading condition

Social Contagion Models

- Network version
- All-to-all networks
- Theory

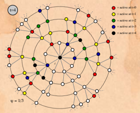
References



Threshold contagion on random networks

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, $P_{\mathrm{trig}} = S_{\mathrm{trig}}$.
3. The expected final size of any successful spread, S.
   - n.b., the distribution of S is almost always bimodal.



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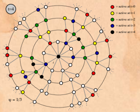

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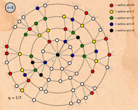

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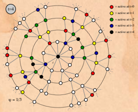

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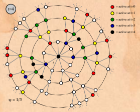
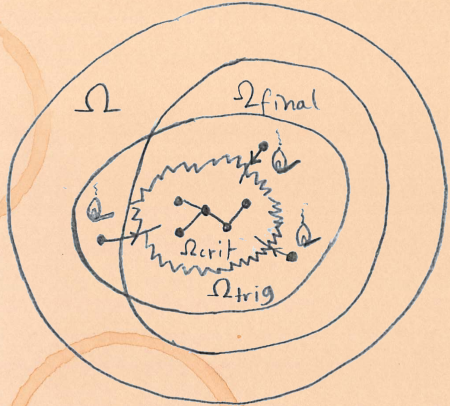
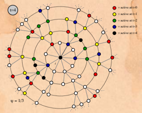


Example random network structure:



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

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



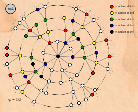
Threshold contagion on random networks

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

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

- 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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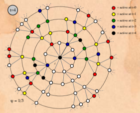

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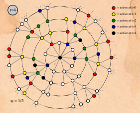

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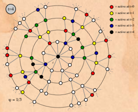

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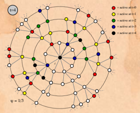


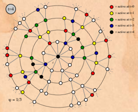
Threshold contagion on random networks

- Everything now revolves around the modified generating function:

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

- Generating function for friends-of-friends distribution is related in same way as before:

$$F_R^{(\mathrm{vuln})}(x) = \frac{\frac{\mathrm{d}}{\mathrm{d}x} F_P^{(\mathrm{vuln})}(x)}{\frac{\mathrm{d}}{\mathrm{d}x} F_P^{(\mathrm{vuln})}(x)\big|_{x=1}} .$$



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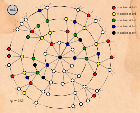

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$$F_\pi^{(\mathrm{vuln})}(x) = \underbrace{1 - F_P^{(\mathrm{vuln})}(1)}_{\substack{\text{central node}\\ \text{is not}\\ \text{vulnerable}}} + x F_P^{(\mathrm{vuln})}\left(F_\rho^{(\mathrm{vuln})}(x)\right)$$

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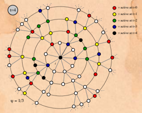

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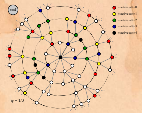

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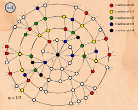

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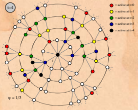

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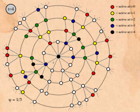

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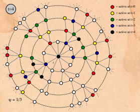

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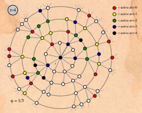
- Second goal: Find probability of triggering largest vulnerable component.
- Assumption is first node is randomly chosen.
- Same set up as for vulnerable component except now we don't care if the initial node is vulnerable or not:

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

$$F_{\rho}^{(\mathrm{vuln})}(x) = 1 - F_R^{(\mathrm{v})}(1) + x F_R^{(\mathrm{vuln})}\left(F_{\rho}^{(\mathrm{vuln})}(x)\right)$$

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



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

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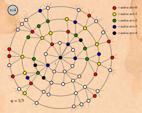

Threshold contagion on random networks

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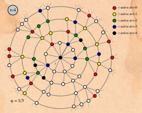

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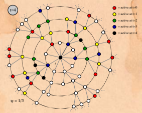

Threshold contagion on random networks

- Third goal: Find expected fractional size of spread.
- Not obvious even for uniform threshold problem.
- Difficulty is in figuring out if and when nodes that need ≥ 2 hits switch on.
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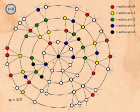

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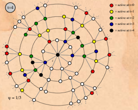

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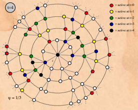

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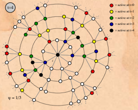

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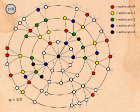

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Idea:

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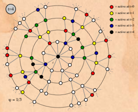

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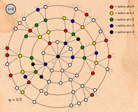

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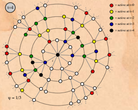

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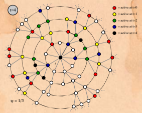

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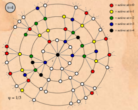

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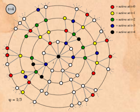

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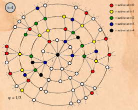

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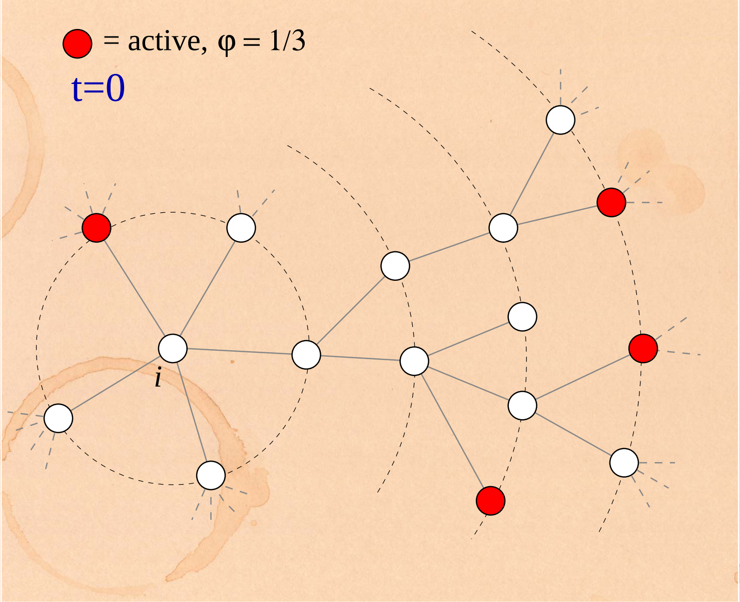

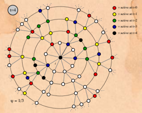

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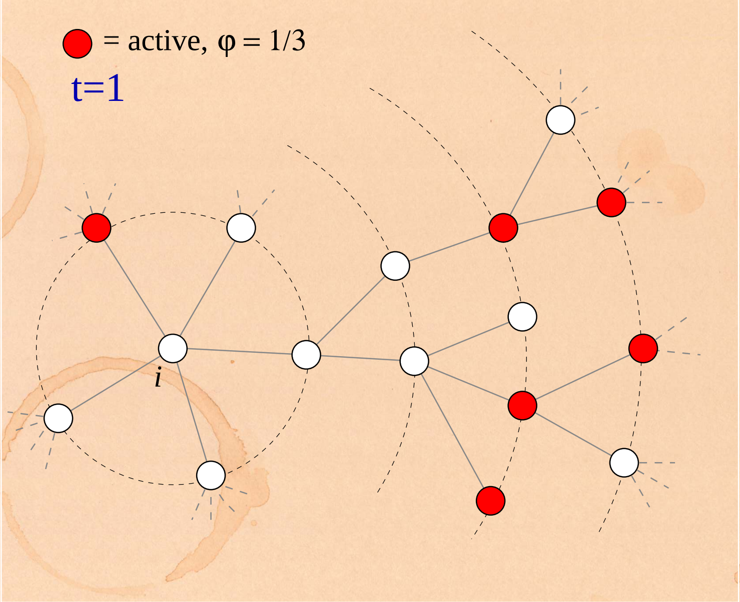

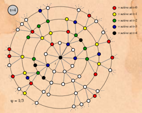

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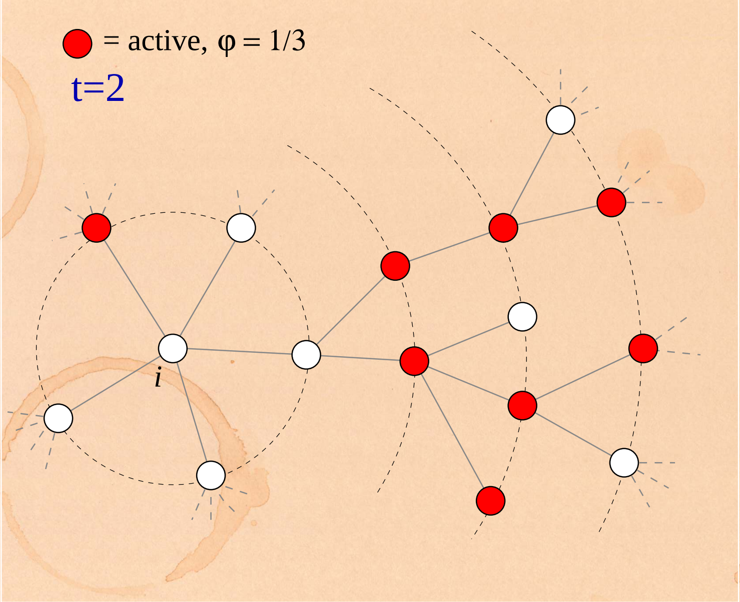

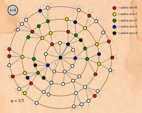

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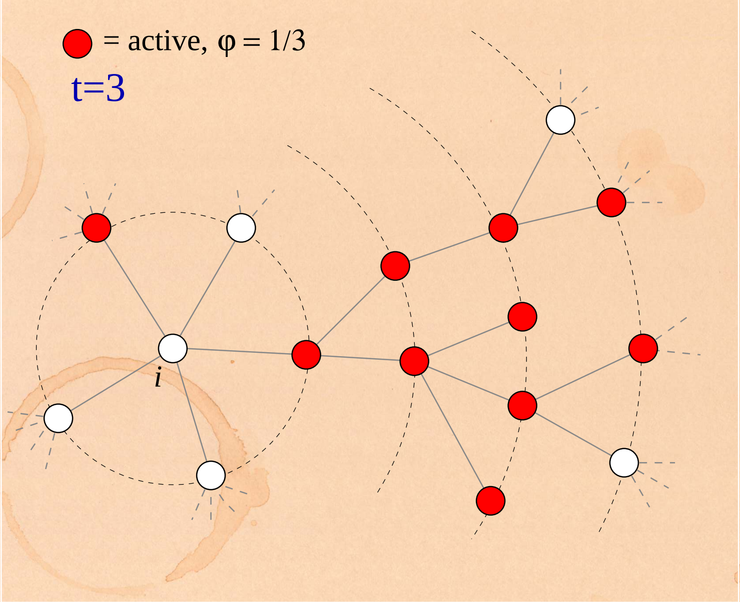

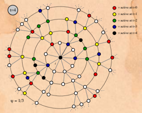

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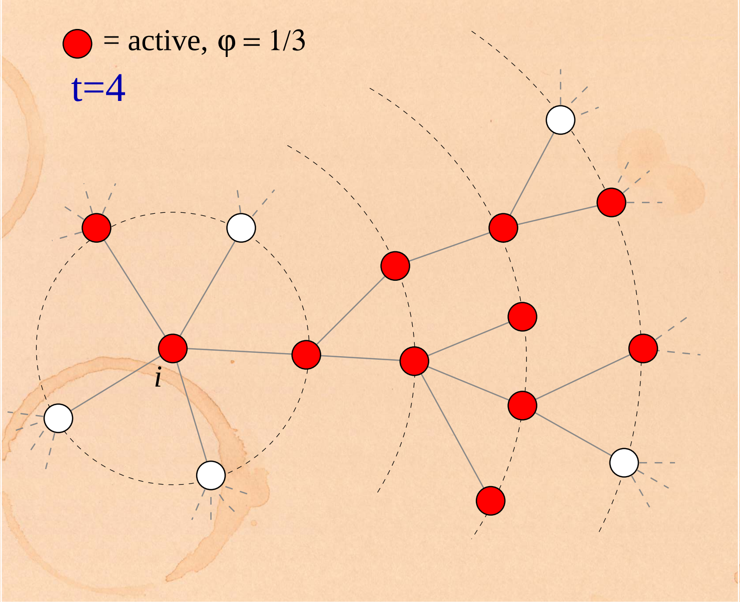

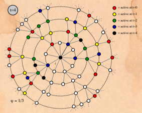

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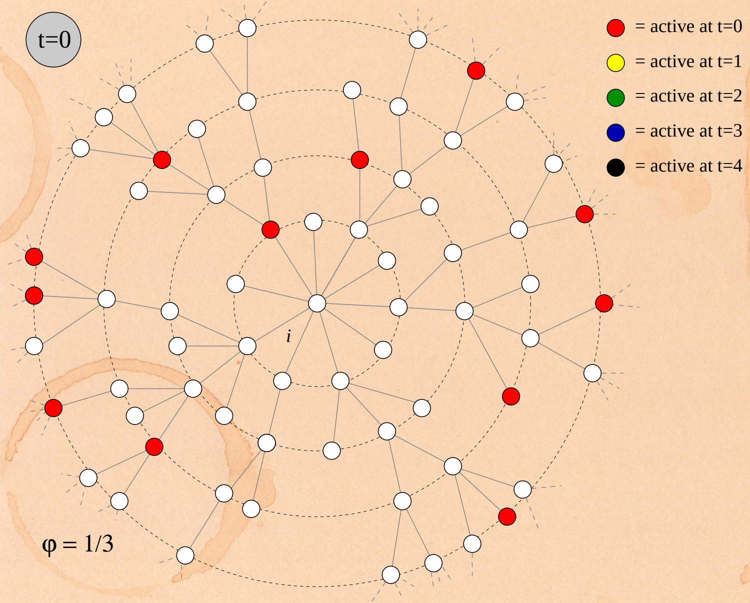

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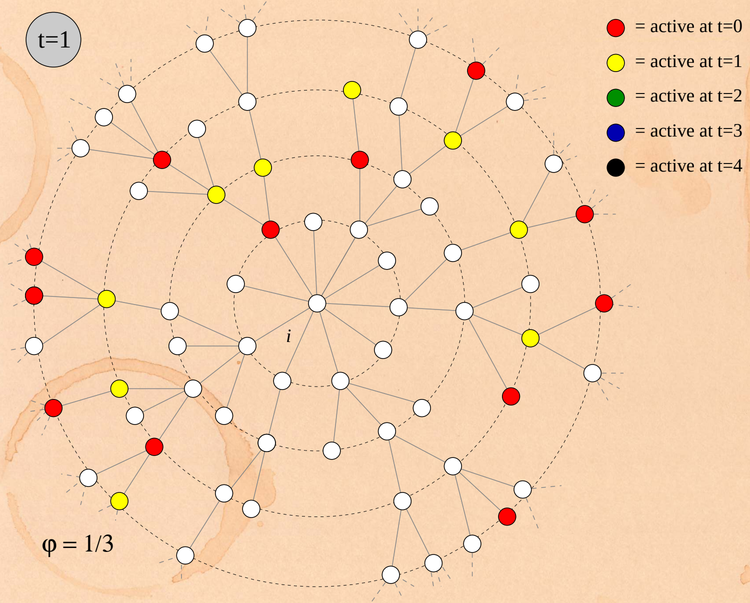

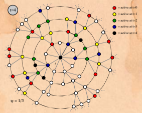

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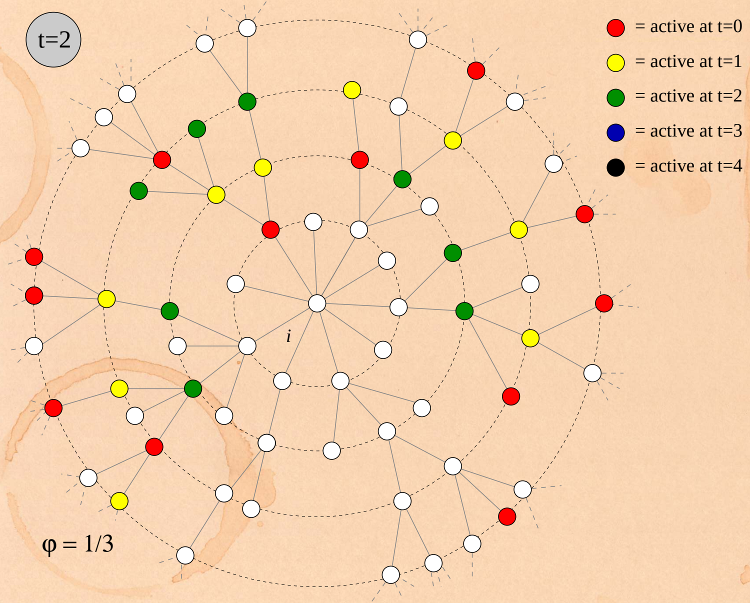

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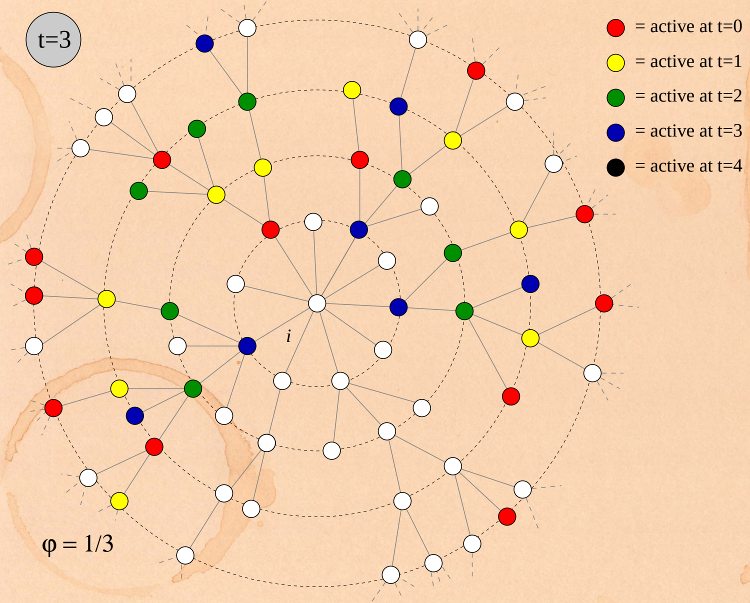

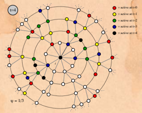

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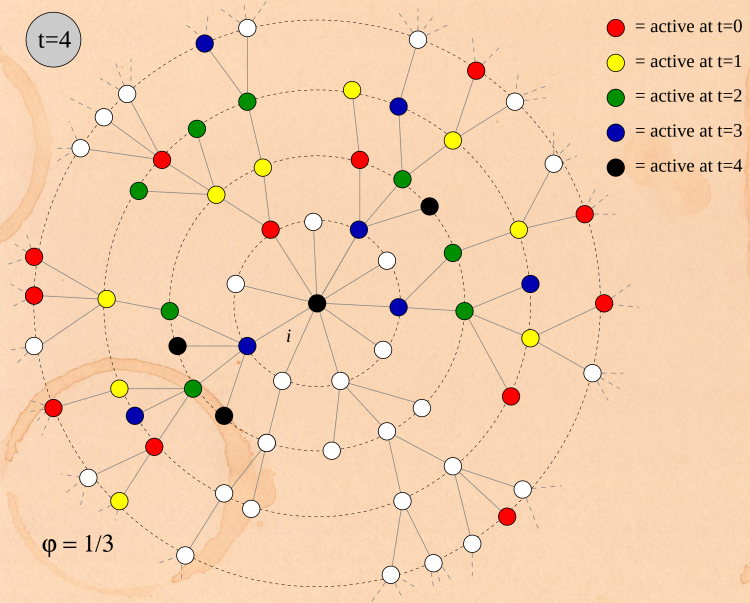

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Notes:

- Calculations are possible nodes do not become inactive (strong restriction).
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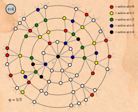
- We can in fact determine $\mathbf{Pr}$(node of degree k switching on at time t).
- Asynchronous updating can be handled too.



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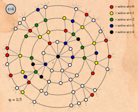

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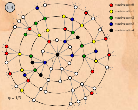

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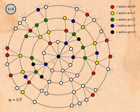

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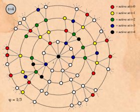

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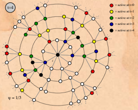
Pleasantness:

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



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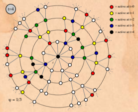

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- Notation:
  $\phi_{k,t} = \mathbf{Pr}$(a degree k node is active at time t).
- Notation: $B_{kj} = \mathbf{Pr}$ (a degree k node becomes active if j neighbors are active).
- Our starting point: $\phi_{k,0} = \phi_0$.
- $\binom{k}{j}\phi_0^j(1-\phi_0)^{k-j} = \mathbf{Pr}$ (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:

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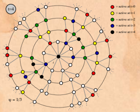

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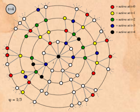

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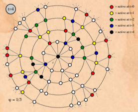

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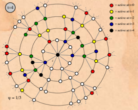

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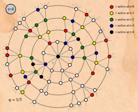

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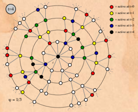

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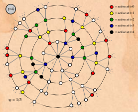

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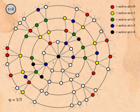

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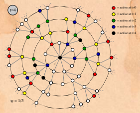

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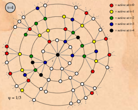

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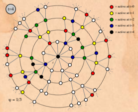

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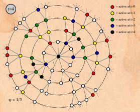

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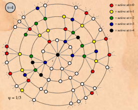

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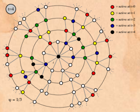

Expected size of spread

First connect θ_0 to θ_1:

- $\theta_1 = \phi_0 +$

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

- $\frac{kP_k}{\langle k \rangle} = R_k$ = **Pr** (edge connects to a degree k node).
- $\sum_{j=0}^{k-1}$ piece gives **Pr**(degree node k activates) of its neighbors $k-1$ incoming neighbors are active.
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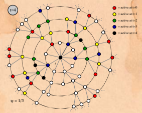
- See this all generalizes to give θ_{t+1} in terms of θ_t...



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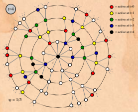


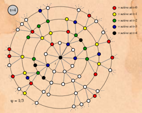
Expected size of spread

Two pieces: edges first, and then nodes

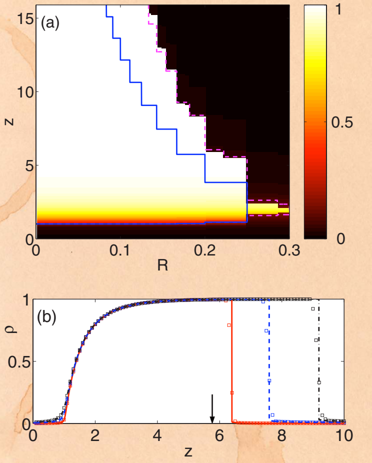
1. $$\theta_{t+1} = \underbrace{\phi_0}_{\text{exogenous}} + \underbrace{(1-\phi_0)\sum_{k=1}^{\infty}\frac{kP_k}{\langle k\rangle}\sum_{j=0}^{k-1}\binom{k-1}{j}\theta_t^{\,j}(1-\theta_t)^{k-1-j}B_{kj}}_{\text{social effects}}$$

   with $\theta_0 = \phi_0$.

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

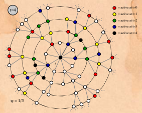


Comparison between theory and simulations



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.



Notes:

- Retrieve cascade condition for spreading from a single seed in limit $\phi_0 \rightarrow 0$.
- Depends on map $\theta_{t+1} = G(\theta_t; \phi_0)$.
- First: if self-starters are present, some activation is assured:

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

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 if

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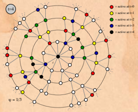
Insert question from assignment 8 (⊞)



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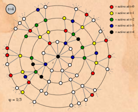

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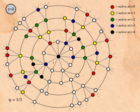

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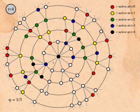

Notes:

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.

Non-vanishing seed case:

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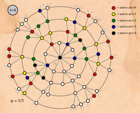

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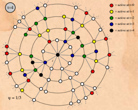

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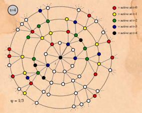

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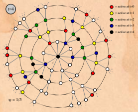

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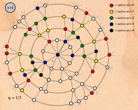
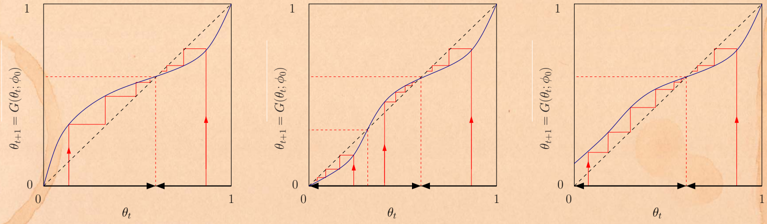
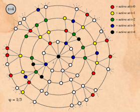


General fixed point story:



- 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.
- So choice of ϕ_0 dictates both G and starting point—can't start anywhere for a given G.



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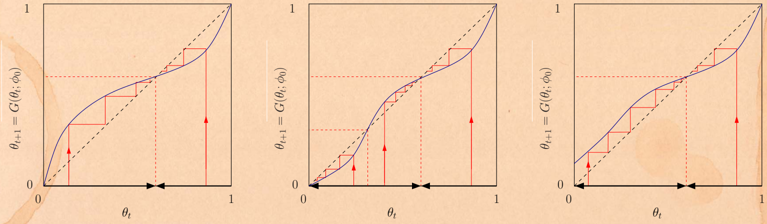

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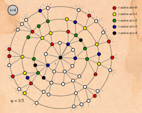

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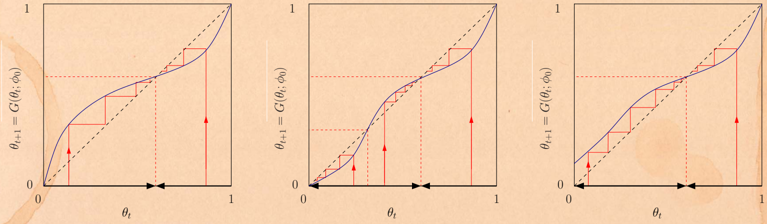

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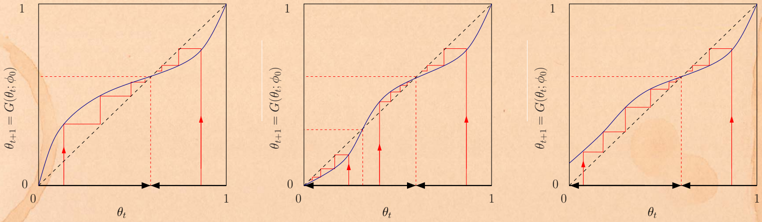

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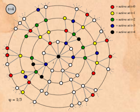
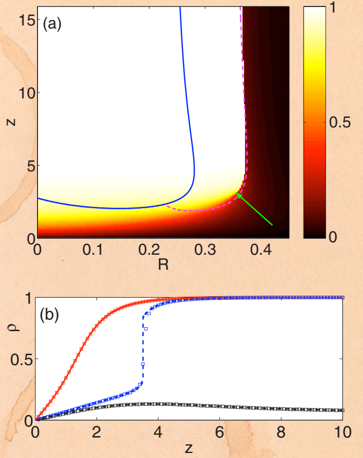
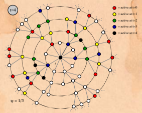


Comparison between theory and simulations



From Gleeson and Cahalane [7]

- 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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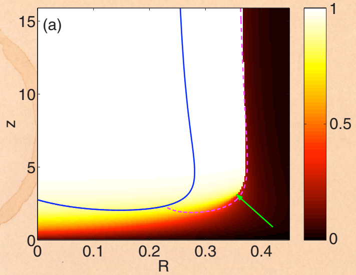

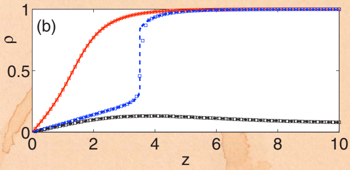

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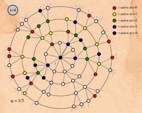

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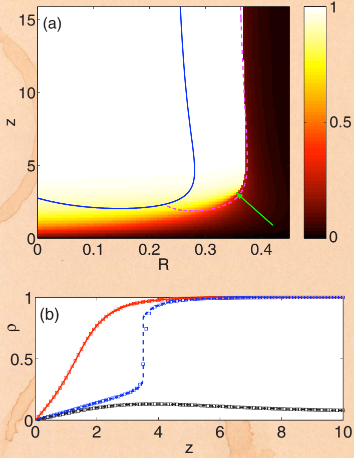

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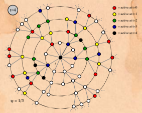

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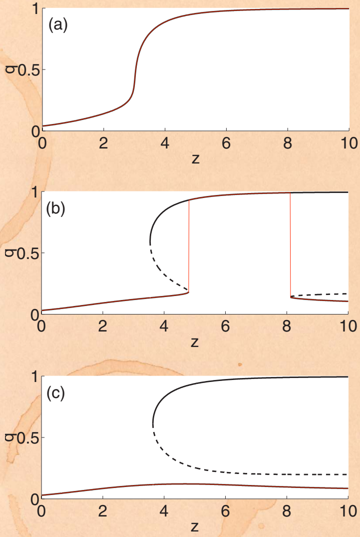

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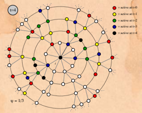
- Plots of stability points for $\theta_{t+1} = G(\theta_t; \phi_0)$.
- n.b.: 0 is not a fixed point here: $\theta_0 = 0$ always takes off.
- Top to bottom: R = 0.35, 0.371, and 0.375.
- n.b.: higher values of θ_0 for (b) and (c) lead to higher fixed points of G.
- Saddle node bifurcations appear and merge (b and c).



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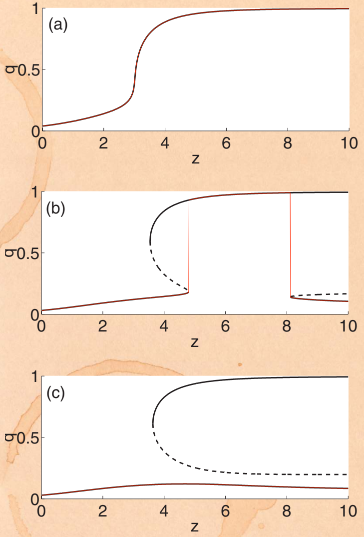

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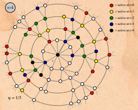

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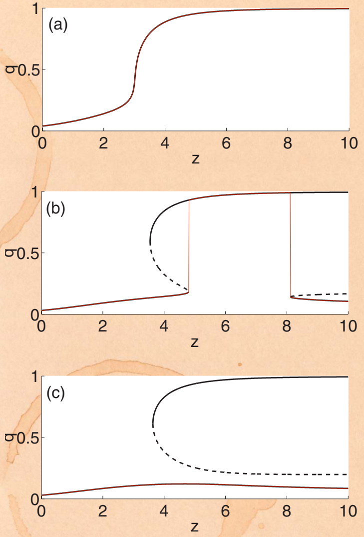

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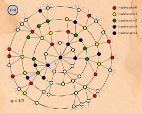
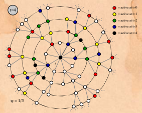


Spreadarama

Bridging to single seed case:

- Consider largest vulnerable component as initial set of seeds.
- Not quite right as spreading must move through vulnerables.
- But we can usefully think of the vulnerable component as activating at time $t = 0$ because order doesn't matter.
- Rebuild ϕ_t and θ_t expressions...



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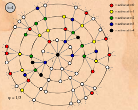

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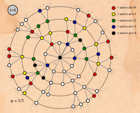

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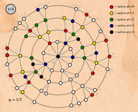


Spreadarama

Two pieces modified for single seed:

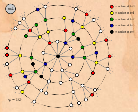
1. $\theta_{t+1} = \theta_{\text{vuln}} +$

$$(1-\theta_{\text{vuln}}) \sum_{k=1}^{\infty} \frac{kP_k}{\langle k \rangle} \sum_{j=0}^{k-1} \binom{k-1}{j} \theta_t^{\,j} (1-\theta_t)^{k-1-j} B_{kj}$$

   with $\theta_0 = \theta_{\text{vuln}}$ = **Pr** an edge leads to the giant vulnerable component (if it exists).

2. $\phi_{t+1} = S_{\text{vuln}} +$

$$(1-S_{\text{vuln}}) \sum_{k=0}^{\infty} P_k \sum_{j=0}^{k} \binom{k}{j} \theta_t^{\,j} (1-\theta_t)^{k-j} B_{kj}.$$



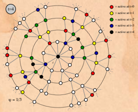
Time-dependent solutions

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 $\alpha \rightarrow 0$, updates become effectively independent.
- Now can talk about $\phi(t)$ and $\theta(t)$.



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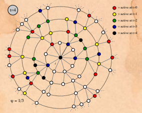

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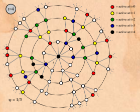

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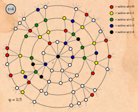

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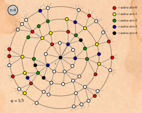

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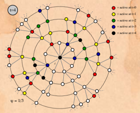

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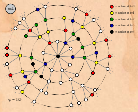

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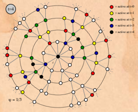

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