Collective behavior cellular systems: Concepts and Tools

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collective behavior noun

: the mass behavior of a group whether animal or human (as mob action)

: the unified action of an assembly of persons whether organized or not

Merriam-Webster dictionary

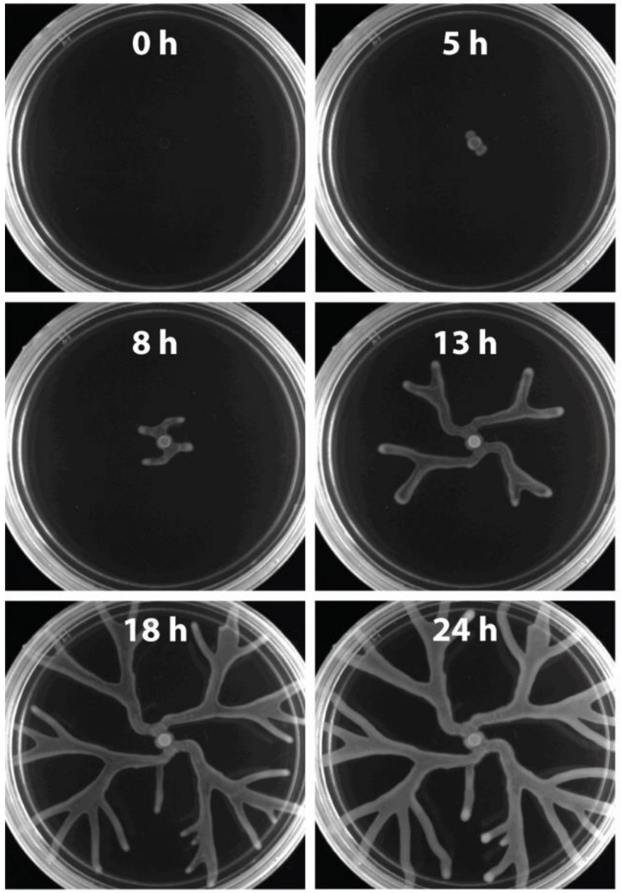
collective behavior psychology

….. the kinds of activities engaged in by sizable but loosely organized groups of people. Episodes of collective behaviour tend to be quite **spontaneous**, resulting from an experience shared by the members of the group that engenders a sense of common interest and identity.

…. participants in crowds, fads, or other forms of collective behaviour share an attitude or behave alike, **not because of an established rule or the force of authority**, and **not because as individuals they have the same attitudes**, but because of a distinctive group process.

Encyclopedia Britannica

Collective Life of Bacteria



P. aeruginosa swarming

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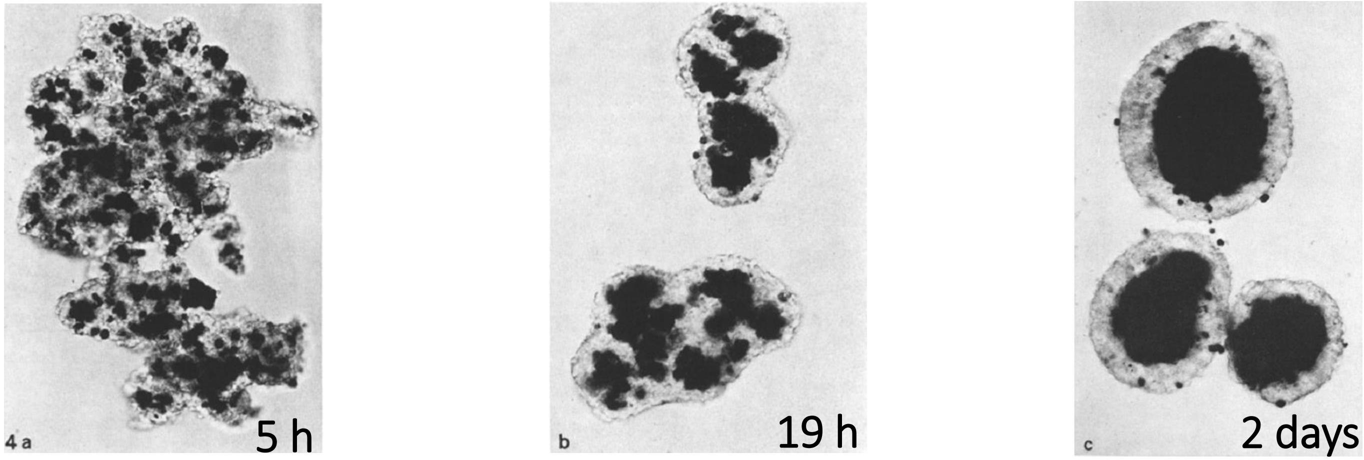
Collective Behavior of Retinal cells



Neural retinal cell

Pigmented retinal epithelial cell

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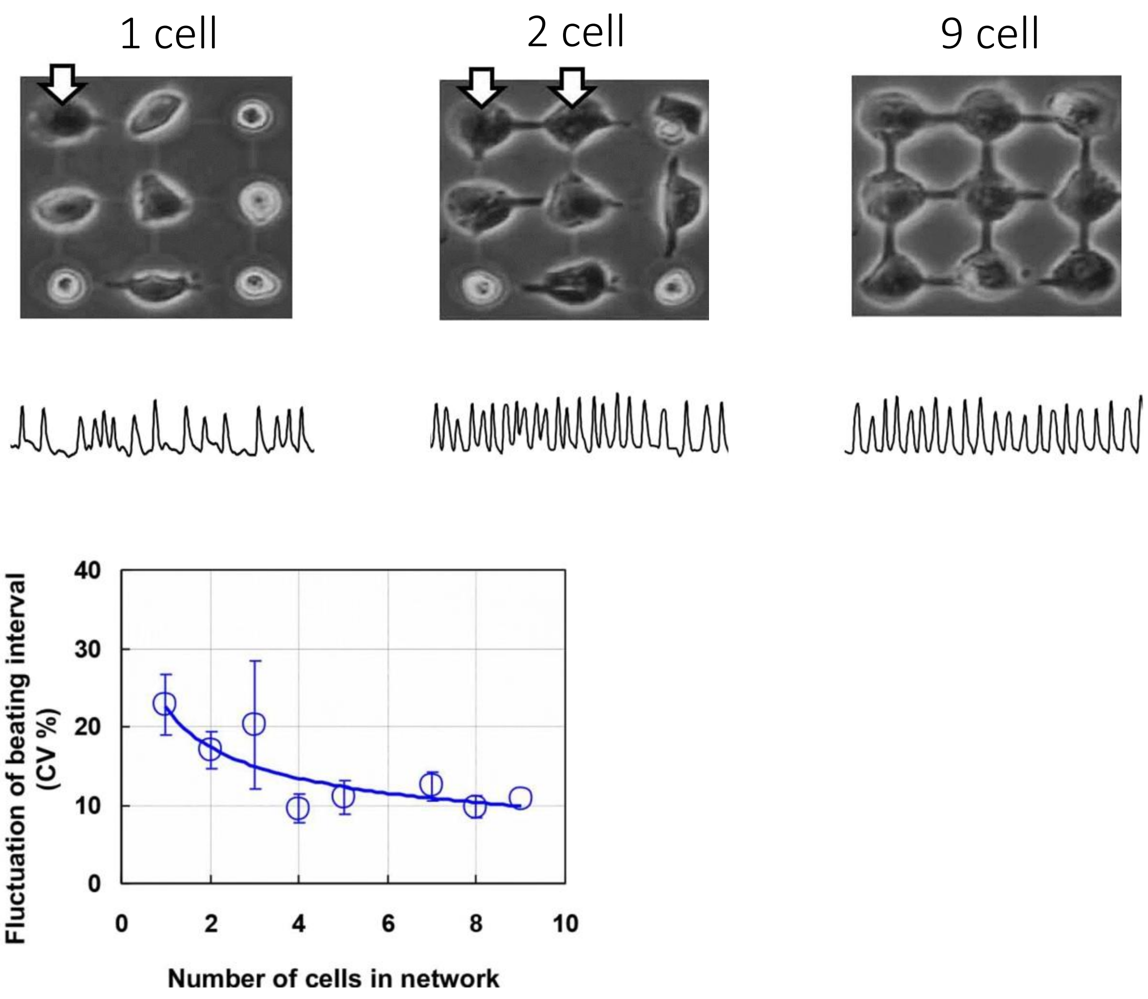
Collective Behavior of Heart Cells



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Working Definition of Collective Behavior

Involves an ensemble of ‘interacting’ entities/agents – homogeneous/heterogenous.

Local interactions (with or without global regulation) generates novel global properties –

Disorder to order transition
Formation of pattern
Collective movement
Synchronized dynamics etc.

Local (and global) interactions affect individual behavior.

What About Self-organization

Self-organization is a process in which pattern (*temporal or spatial*) at the global level of a system emerges solely from numerous interactions among the lower-level components of the system. Moreover, the rules specifying interactions among the system's components are executed using only local information, without reference to the global pattern.

Self-Organization in Biological Systems, by Scott Camazine et al.

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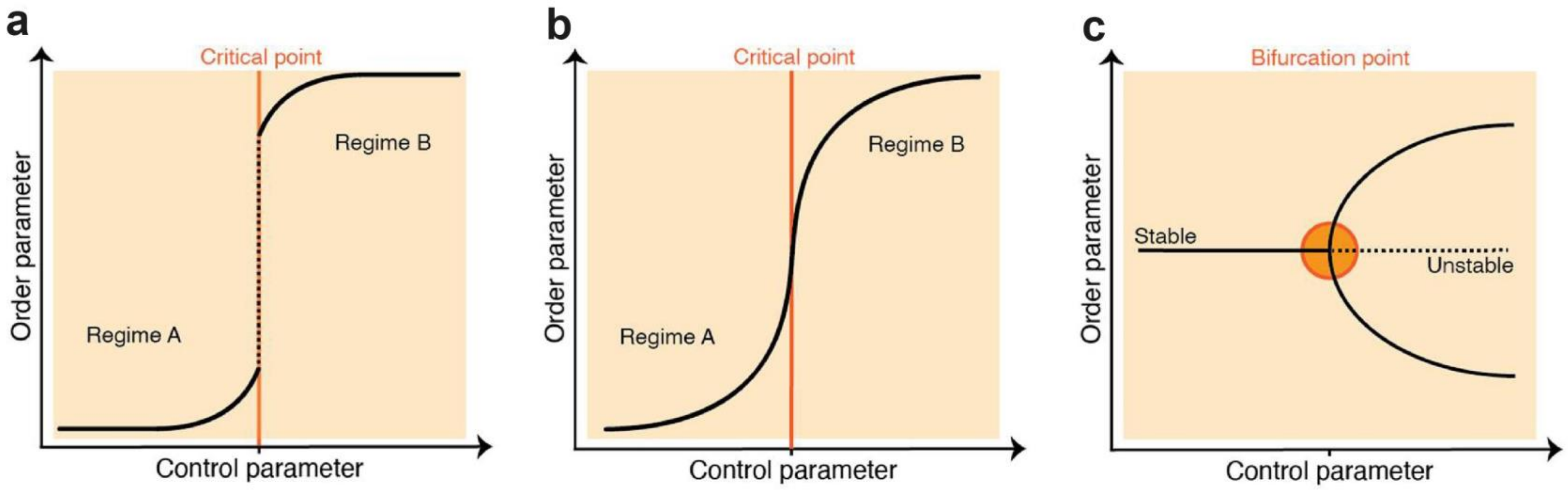
Is not it same as self-assembly?

Criticality In Collective Behavior

Critical phenomena: Qualitative change in the system behavior with a control parameter has a threshold – a critical point. Beyond the critical point the system has different behavior(s) or property(s)

Phase transition is a critical phenomena.



Current Opinion in Systems Biology

A Dollop Of Philosophy

Universality in diversity: Collective phenomena appears in diverse scales and in disparate systems. But they have common underlying governing principles and mathematical structures.

Simplicity hidden in complexity: The rules underlying the behavior of Complex systems are simple

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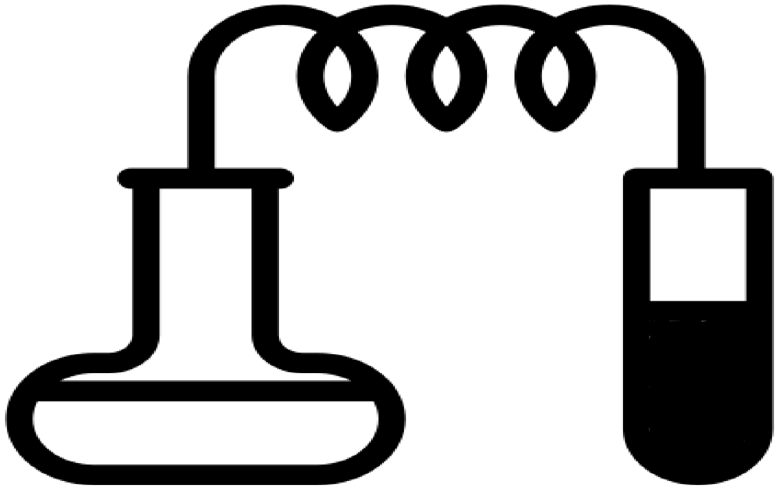
"In the intricate tapestry of complex systems, there exists an intriguing paradox wherein the emergent behaviors and patterns, despite their apparent intricacy, often find their origins rooted in elegantly simple underlying principles." – ChatGPT 3.5

Cut The Clutter



Mechanistic details of a phenomena

Generalized rules & design principles

$$f(x)$$

A Toy Model

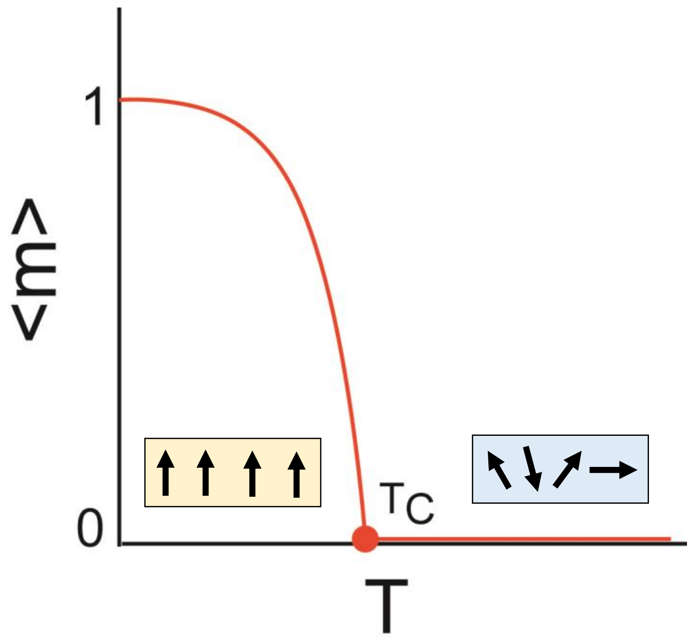
What is possible.

What is not possible.

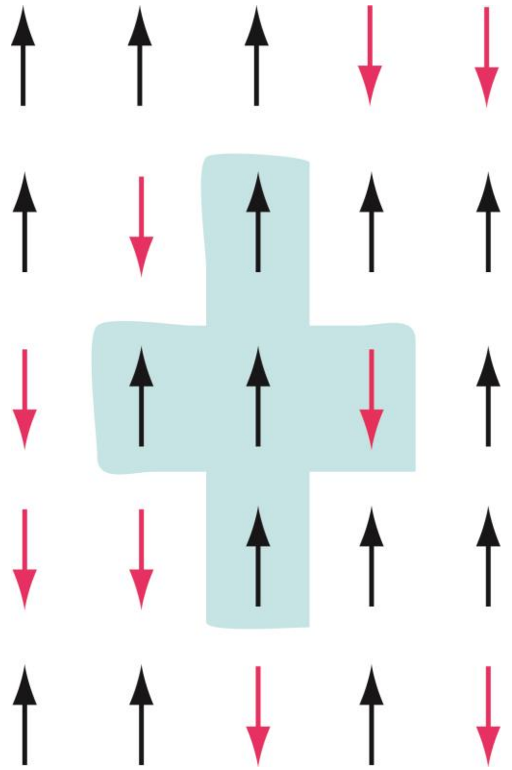
Similarity among apparently different complex phenomenon

Poster Boy Of Phase Transition

Spontaneous magnetization ferromagnets



The Ising Model - A Centenarian



Energy of the system:

$$H = -J \sum_{<ij>} s_i s_j \qquad J > 0$$

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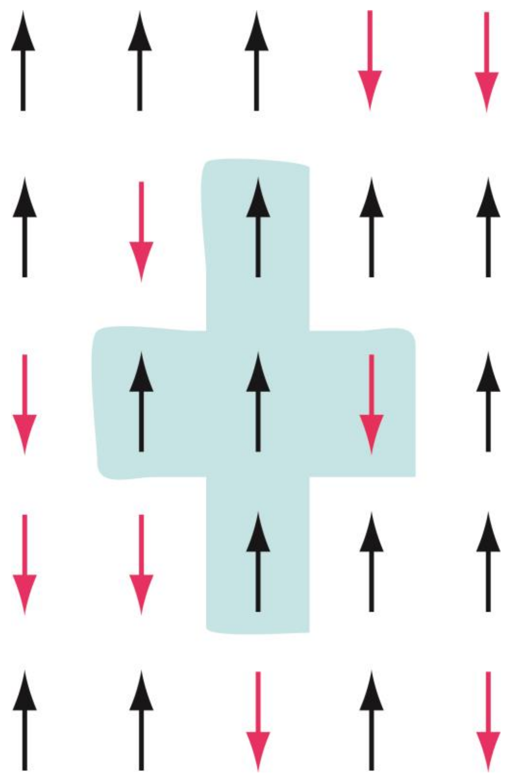
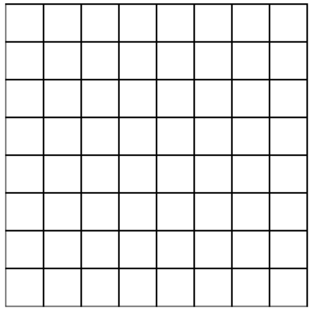


Metropolis Algorithm:

Calculate the energy of the system H_b
Randomly pick a spin
Flip the spins
Calculate energy of the system H_n
Calculate $\Delta H = H_n - H_b$
Accept the Flip with $P = min(e^{-\Delta H/T}, 1)$

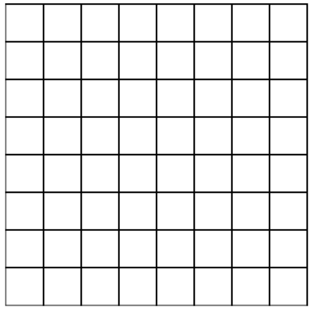
Percolation – A Phase Transition

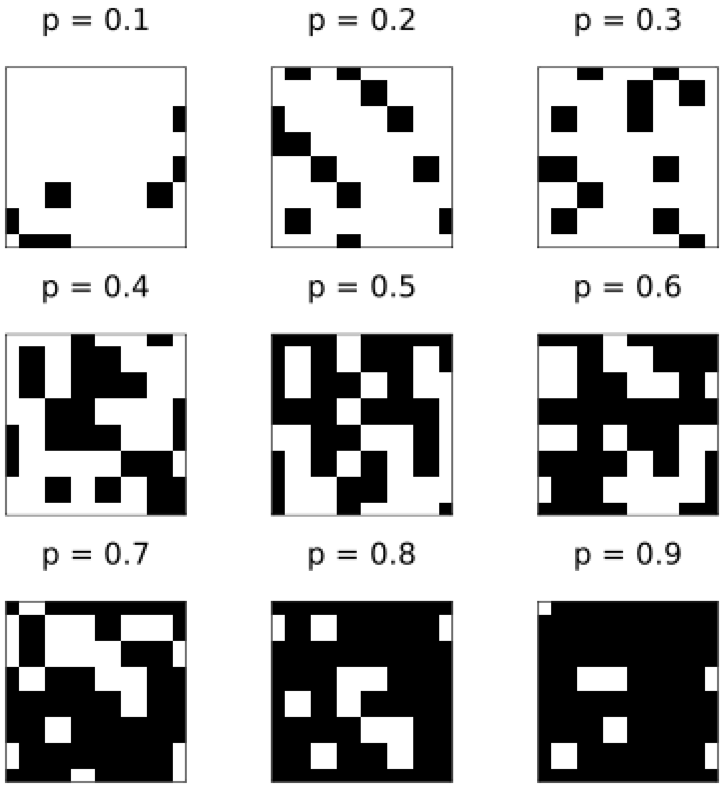


Get a square grid of cells

Color each cell black with probability p

Percolation – A Phase Transition





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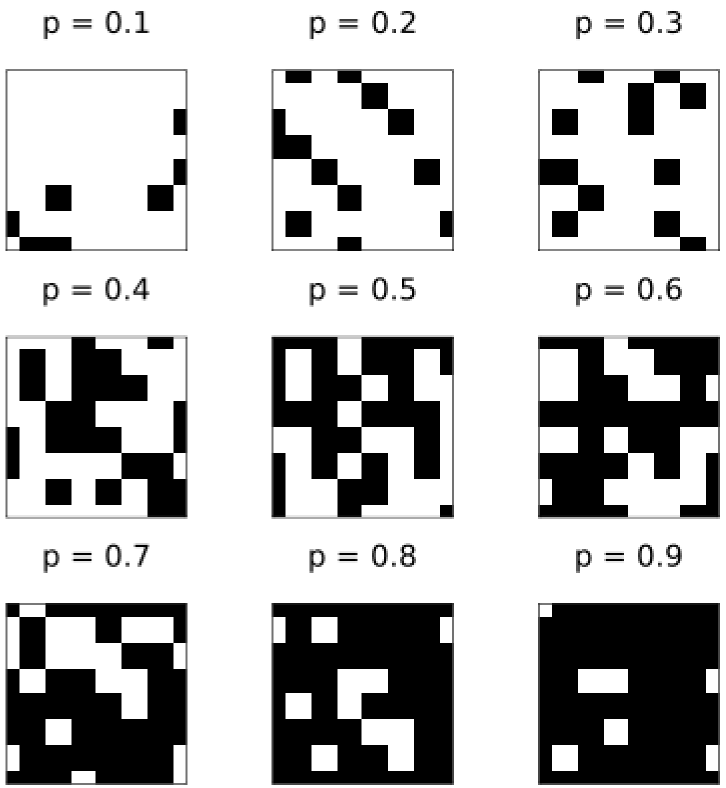

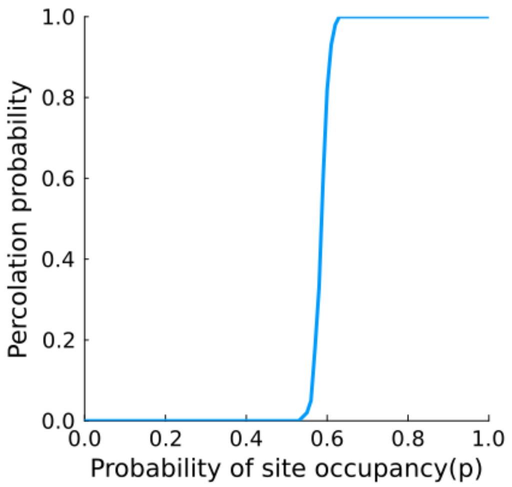

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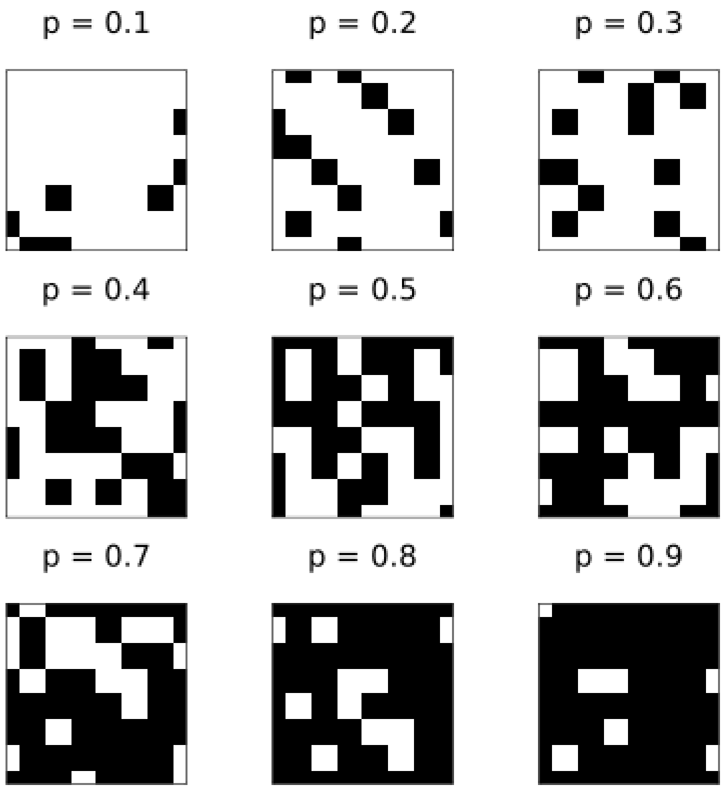
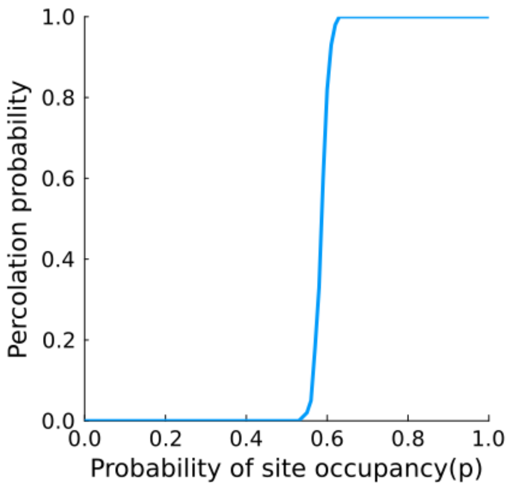
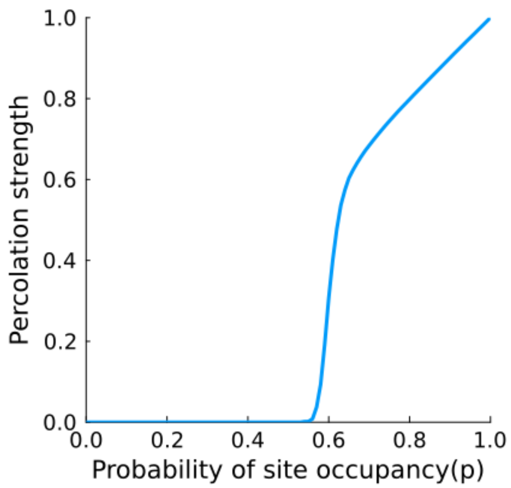






Critical Exponents Of Phase Transition

Near the critical point, thermodynamics quantities show scaling with the control parameter

Landau model of 2nd-order phase transition

$$F(\phi) = F(0) + at\phi^2 + a_4 t\phi^4$$

$$t = \frac{T - T_c}{T}$$

For t < 0, the equilibrium order parameter,

$$\phi^* = t^{1/2}$$

Critical Exponents Of Phase Transition

Near the critical point, thermodynamics quantities show scaling with the control parameter

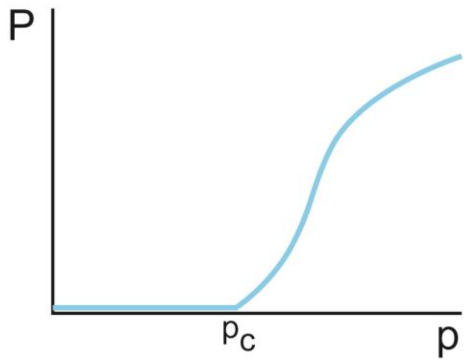
In some phase transitions, thermodynamic quantities show

power law scaling with control parameter,

$$X = A|t|^{\omega}$$

A is a constant; ω is a critical exponent.

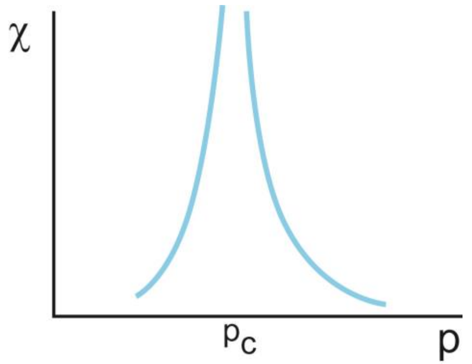
Critical Exponents In Percolation



Percolation strength $P = \frac{C_L}{L^2}$ $\qquad P \sim (p - p_c)^{\beta}$

Average cluster size $\chi = \frac{\sum_s s^2 n_s}{\sum_s s n_s}$ $\qquad \chi \sim |p - p_c|^{-\gamma}$

s: cluster size excluding the largest one



Correlation length ξ $\qquad \xi \sim |p - p_c|^{-\nu}$

Cluster number density $n_s = \frac{N_s}{L^2}$ $\qquad$ At p_c $\quad n_s \sim s^{-\tau}$

N_s: Number of cluster of size s

Universality Classes

The critical exponents do not depend upon microscopic details of the system.

Depends upon system dimension

We can categorize different phase transitions into different **Universality classes**.

Critical exponents are same for all systems in an universality class.

For 2D random percolation

$\beta = 5/36$ $\gamma = 43/18$ $\nu = 4/3$ $\tau = 187/91$

But percolation threshold varies with system

2d square lattice: $p_c = 0.593$ 2d triangular lattice: $p_c = 0.5$

Scaling In A Finite System

$X \sim (p - p_c)^{\omega}$ $\qquad$ $X \sim \xi^{-\frac{\omega}{\nu}}$ $\qquad$ as, $\xi \sim (p - p_c)^{-\nu}$

Size of our lattices are finite. Near p_c the lattice length scale is smaller than the correlation length of percolation.

We want to represent the scaling in terms of L not ξ

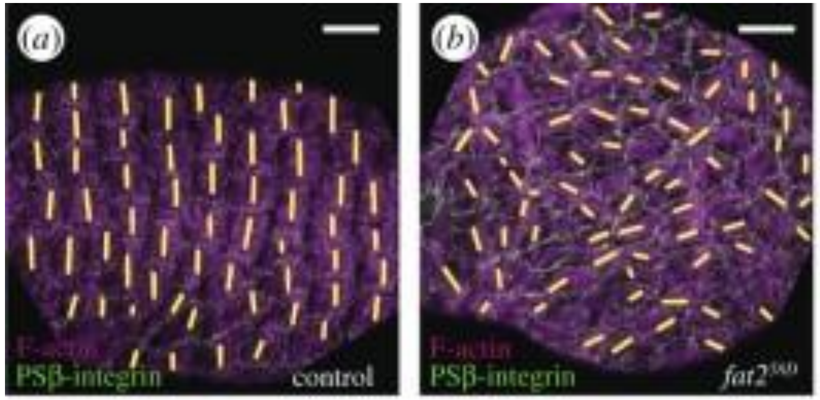
$$X \sim (p - p_c)^{\omega} G\left(\frac{L}{\xi}\right) \sim \xi^{-\frac{\omega}{\nu}} G\left(\frac{L}{\xi}\right) = \xi^{-\frac{\omega}{\nu}} \left(\frac{L}{\xi}\right)^{-\frac{\omega}{\nu}} Y\left(\frac{L}{\xi}\right) = L^{-\frac{\omega}{\nu}} Y\left(\frac{L}{\xi}\right)$$

Finite-size scaling ansatz:

$P = L^{-\beta/\nu} F[(p - p_c)L^{1/\nu}]$ $\qquad$ $\chi = L^{\gamma/\nu} G[(p - p_c)L^{1/\nu}]$

Percolation In Egg Chamber

Drosophila follicle epithelium

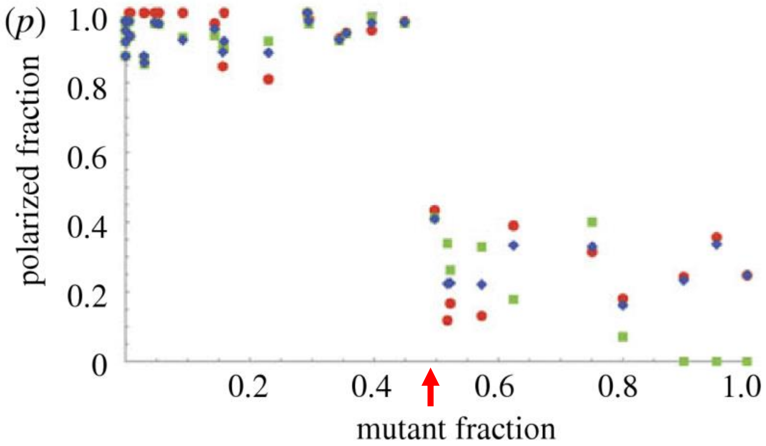


Wt

Fat2^{58D}

Actin filament

Mosaic experiment



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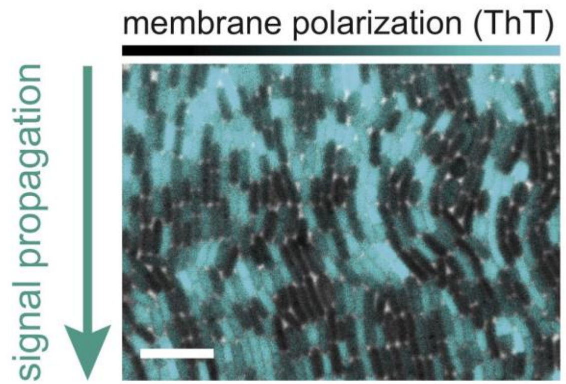
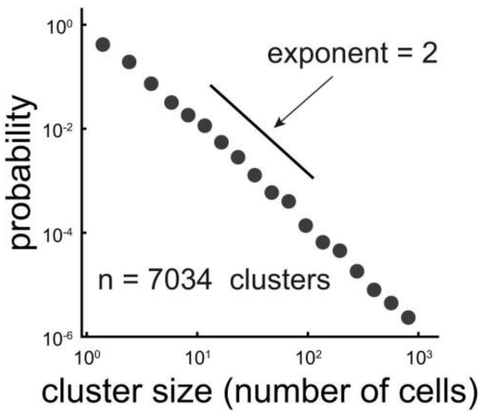
Signal Propagation In A Community





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Key topics

- Collective behavior as phase transition
- Ising model and 2D Percolation
- Scaling rules and Universality