Life,

Or something like it

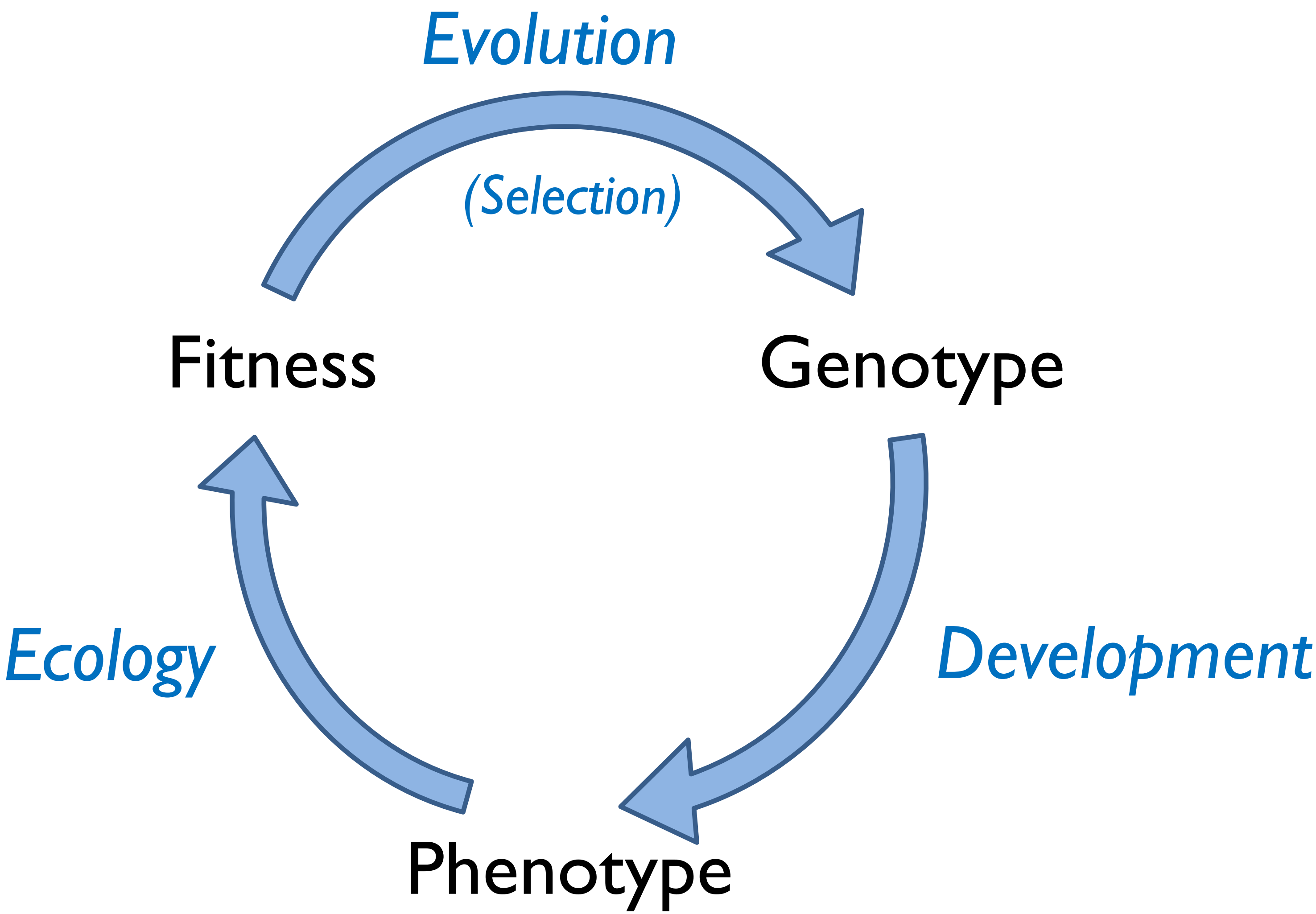
Sitabhra Sinha

Center for Complex Systems and Data Science

The Institute of Mathematical Sciences, Chennai

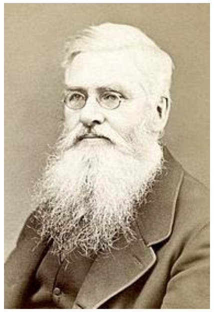
Is there a Grand Unified Theory for Biology ?

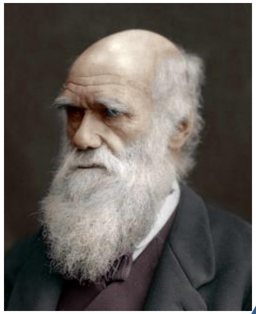
Is there a Grand Unified Theory for Biology ?



Adapted from a talk by Amitabh Joshi (JNCASR)

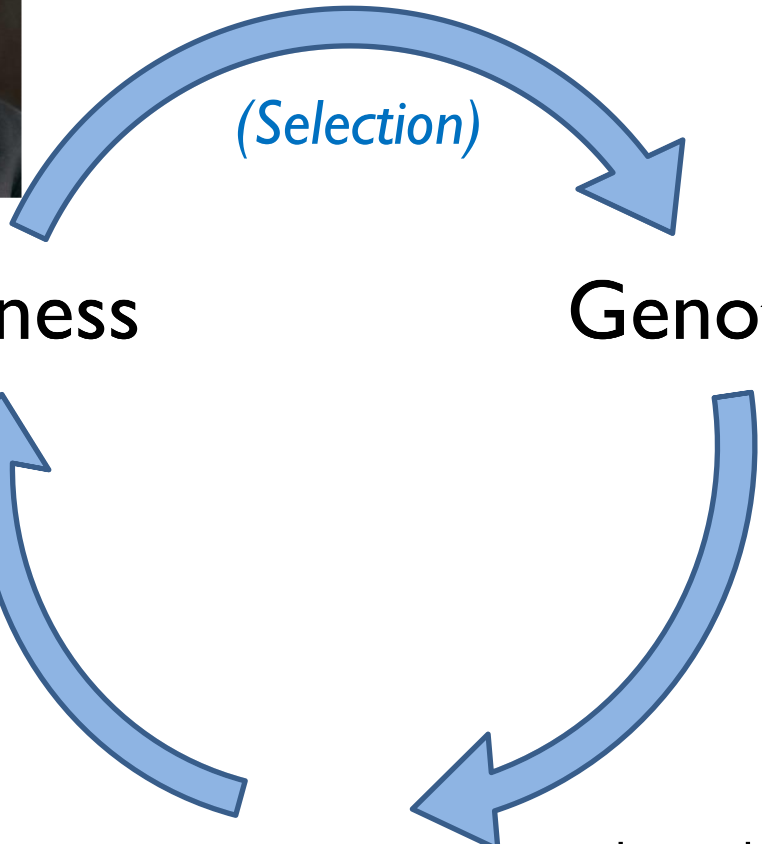
Is there a Grand Unified Theory for Biology ?





individual reproductive success

The complete set of heritable characteristics of an organism

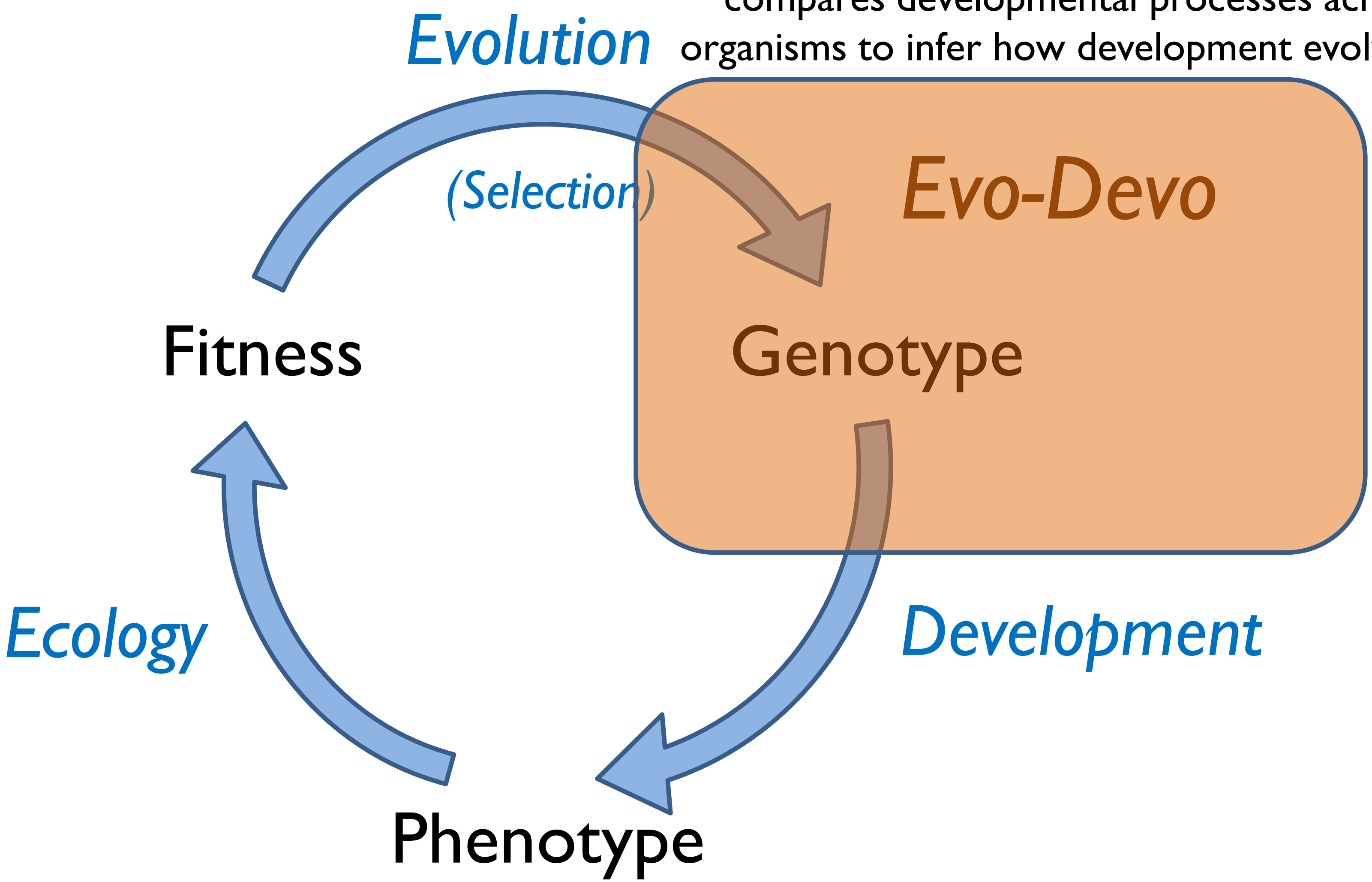


observable characteristics/traits of an organism, including its morphology or physical form and structure

Adapted from a talk by Amitabh Joshi (JNCASR)

Is there a Grand Unified Theory for Biology ?

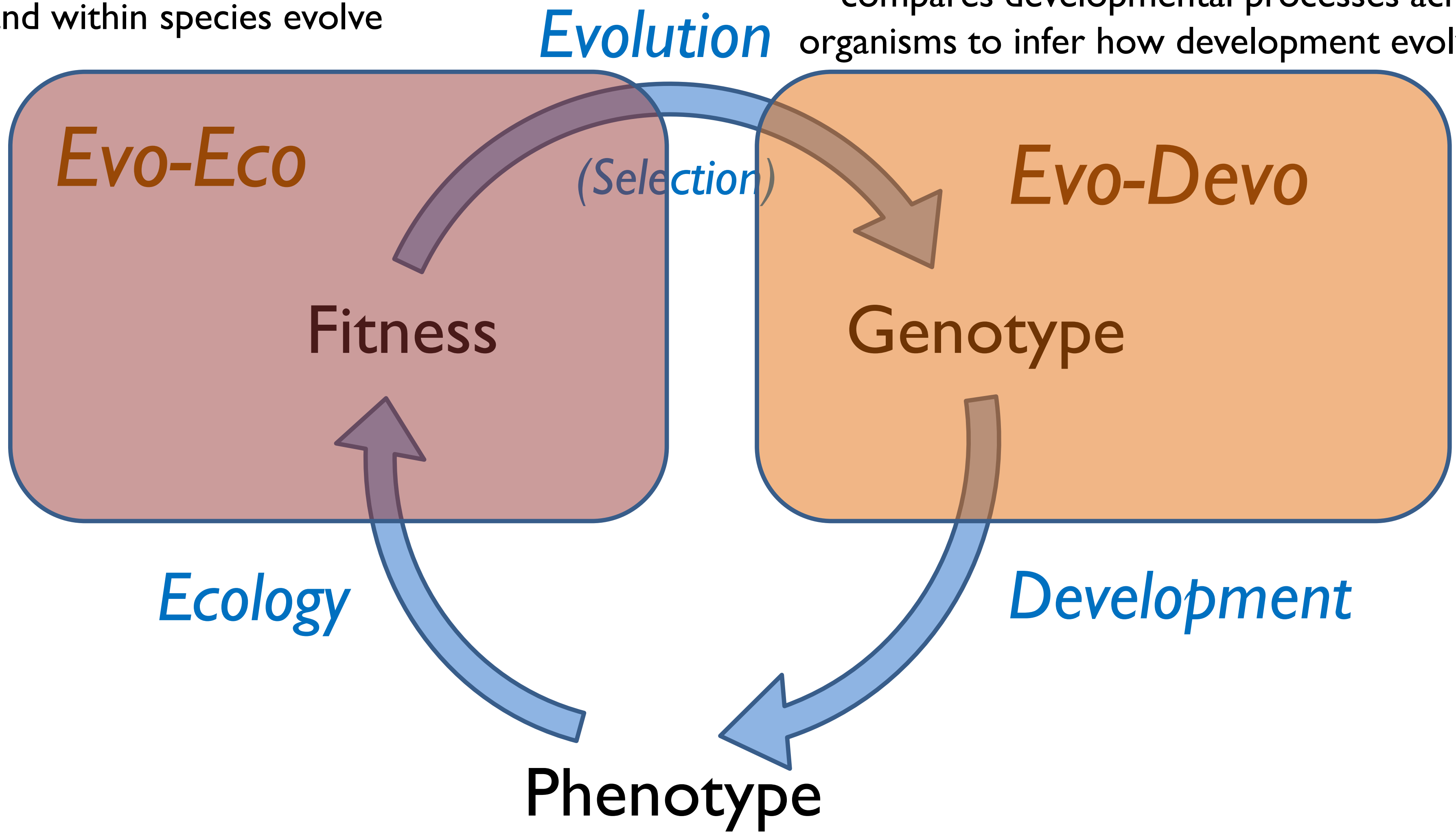
compares developmental processes across organisms to infer how development evolved



Is there a Grand Unified Theory for Biology ?

examines how interactions between and within species evolve

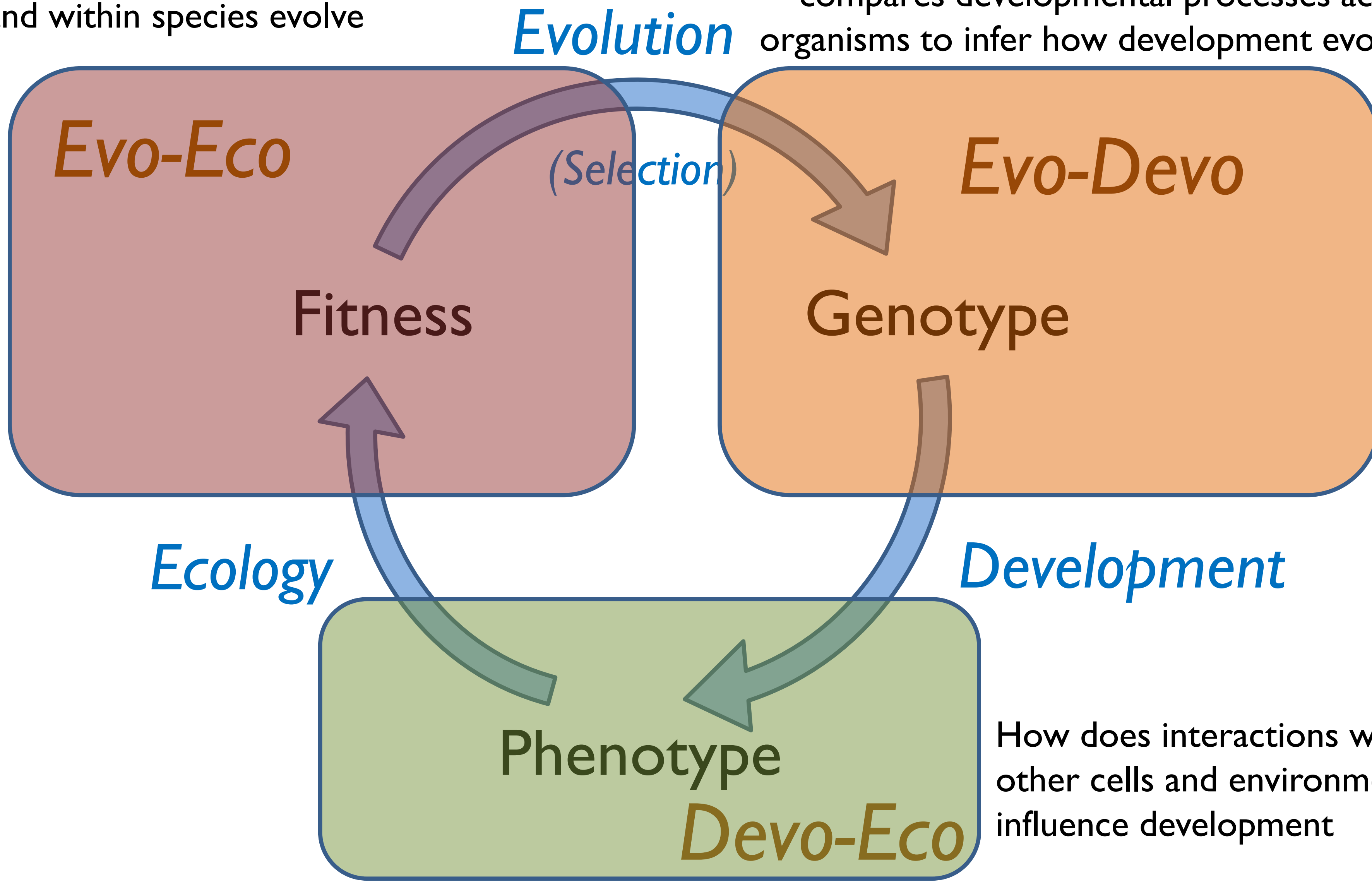
compares developmental processes across organisms to infer how development evolved



Is there a Grand Unified Theory for Biology ?

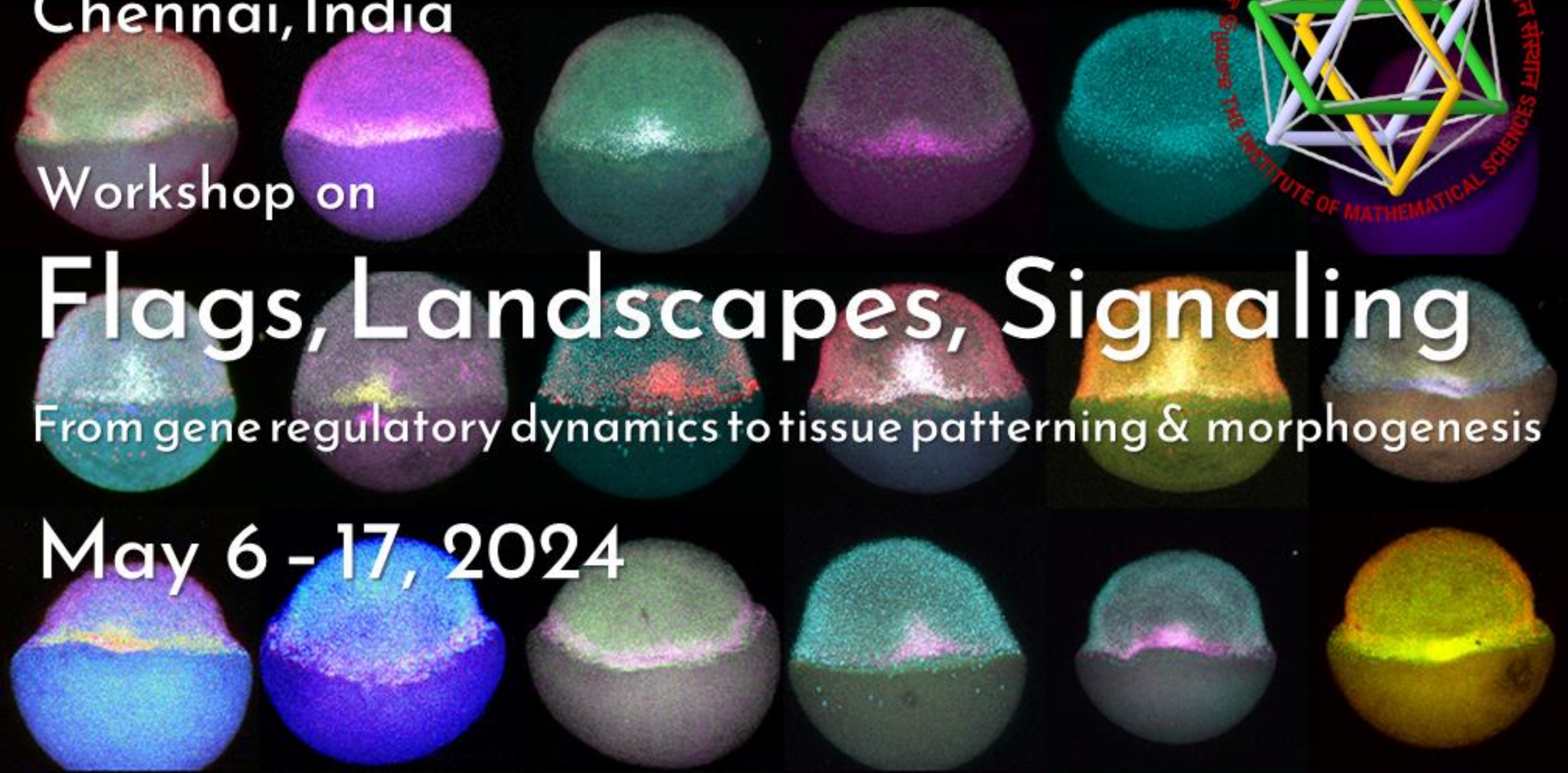
examines how interactions between and within species evolve

compares developmental processes across organisms to infer how development evolved



How does interactions with other cells and environment influence development

The Institute of Mathematical Sciences
Chennai, India



Workshop on

Flags, Landscapes, Signaling

From gene regulatory dynamics to tissue patterning & morphogenesis

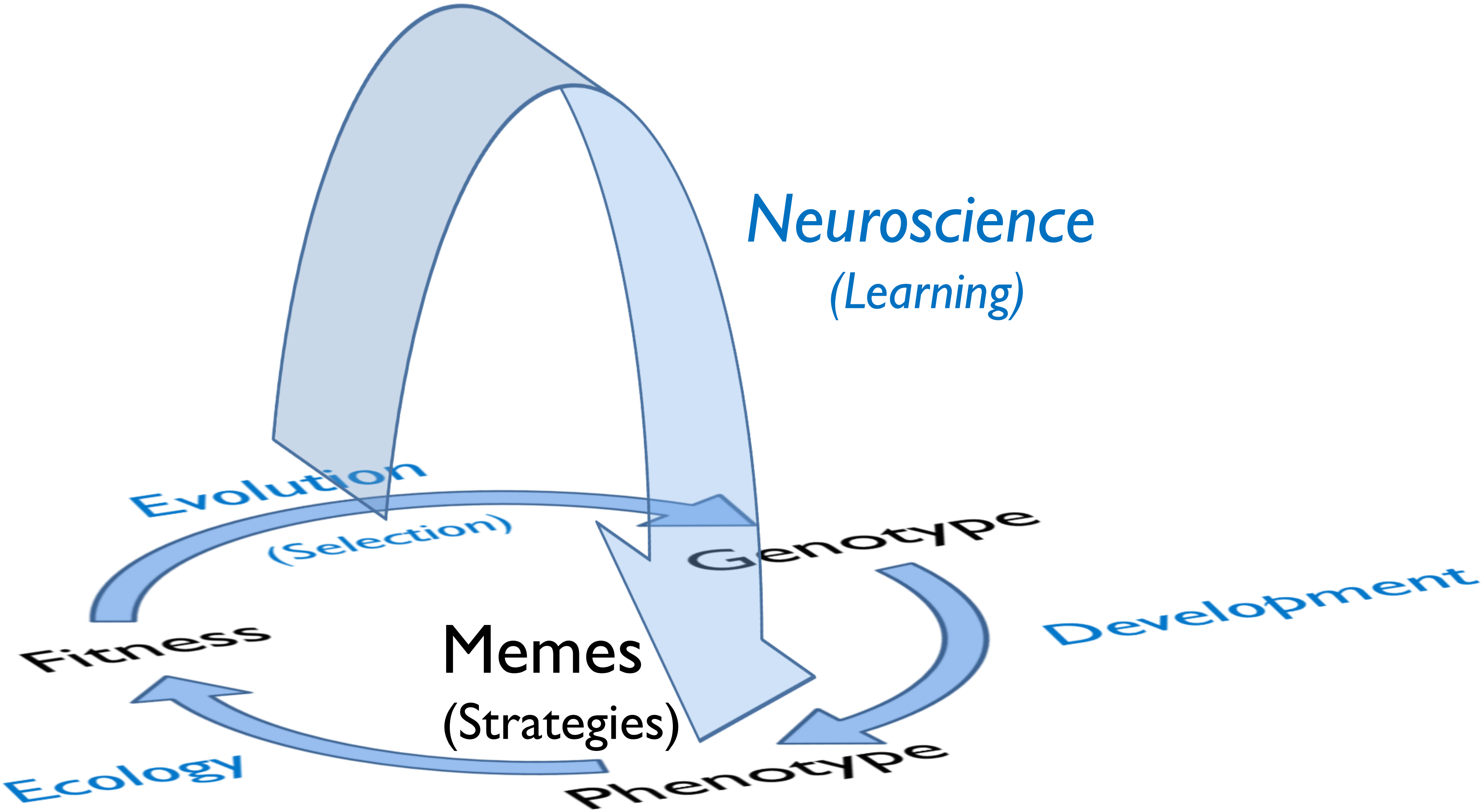
May 6 - 17, 2024

The workshop aims at integrating the principal classes of pattern formation paradigms that have been proposed to explain biological development, e.g., using morphogen gradients to provide cells with positional information or local signaling between cells resulting in lateral inhibition or activation, and how

Speakers include

- Ramray Bhat (IISc)
- Biplab Bose (IIT Guwahati)
- Mohit Kumar Jolly (IISc)
- Sreelaja Nair (IIT Bombay)

Organisms that can learn have one more trick!



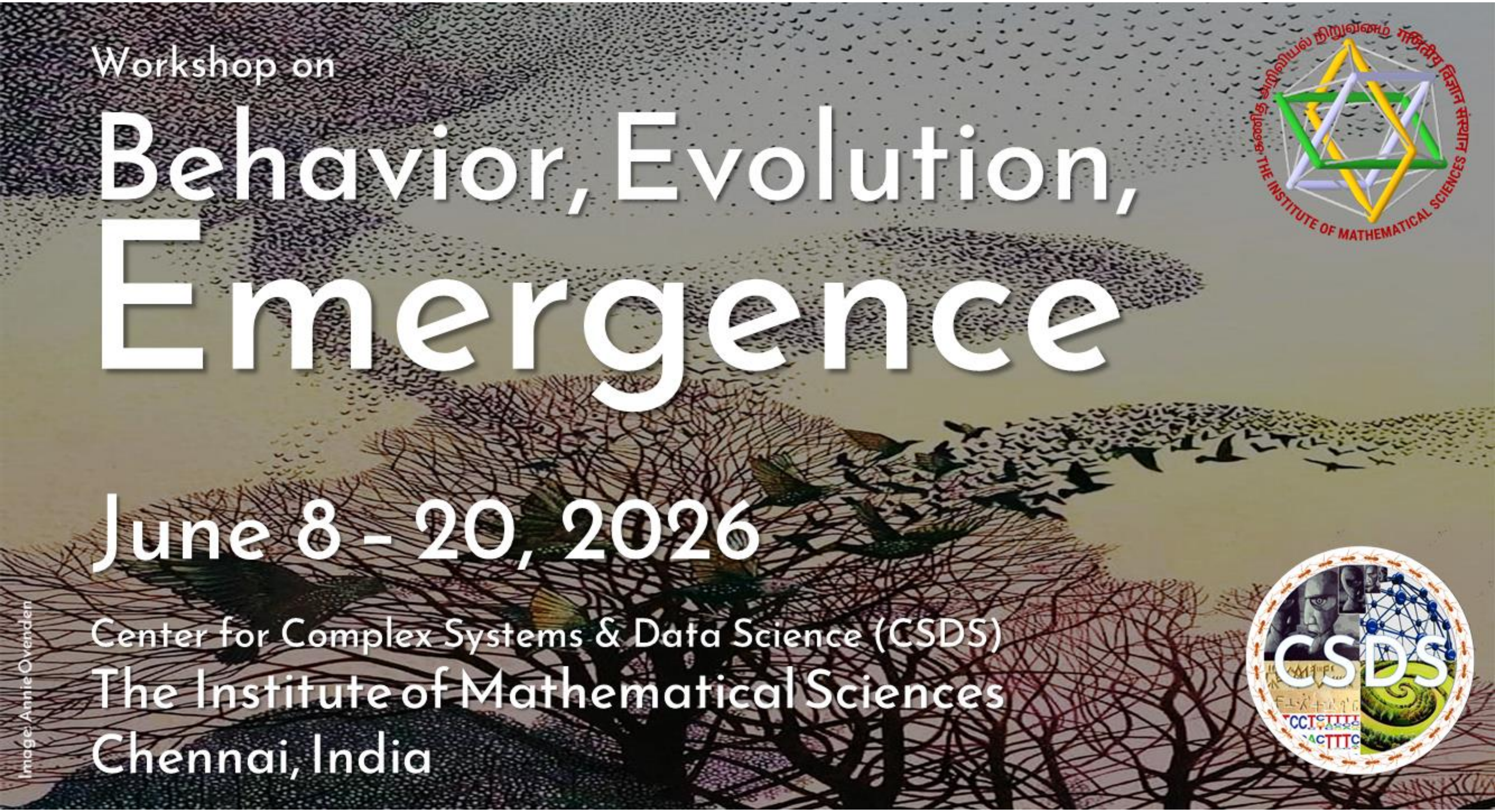
Center for Complex Systems & Data Science (CSDS)
The Institute of Mathematical Sciences
Chennai

Brains, Dynamics & Computation

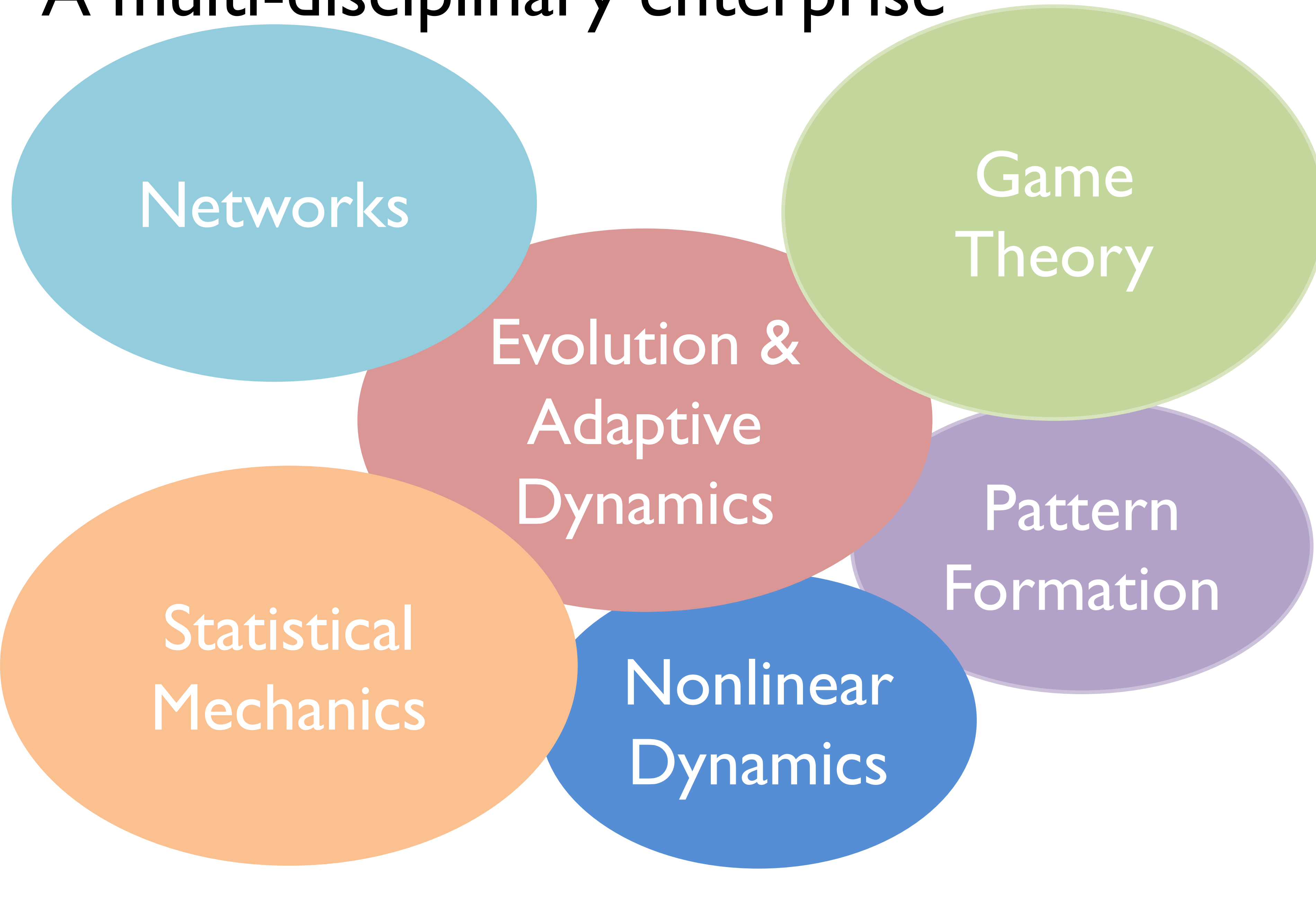
A Workshop on Network Neuroscience

May 22 - June 4, 2025

And so, as a natural consequence…



A multi-disciplinary enterprise



Emergence: More is Different

The elementary entities of science X obey the laws of science Y.

X	Y
solid state or many-body physics	elementary particle physics
chemistry	many-body physics
molecular biology	chemistry
cell biology	molecular biology
•	•
•	•
•	•
psychology	physiology
social sciences	psychology

But this hierarchy does not imply that science X is "just applied Y."

Psychology is not applied biology, nor is biology applied chemistry.

At each stage entirely new laws, concepts, and generalizations are necessary…

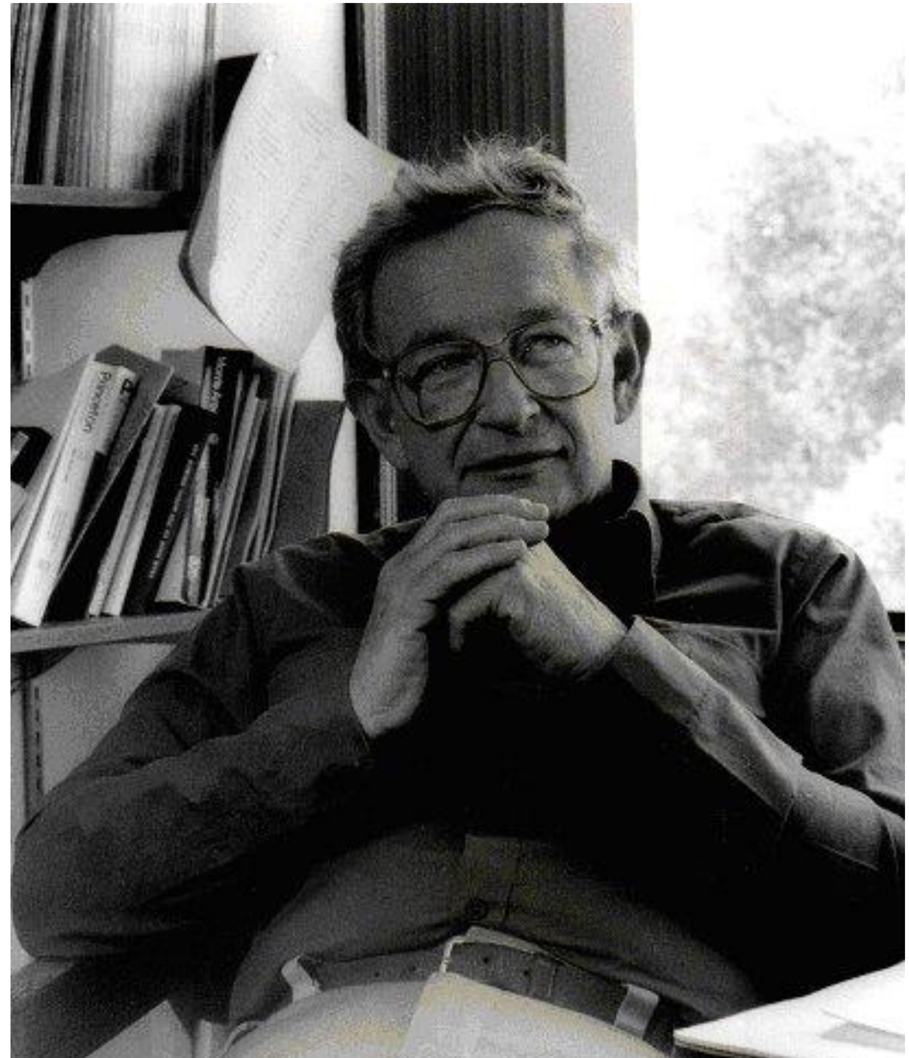


Image: wikipedia

Philip W Anderson

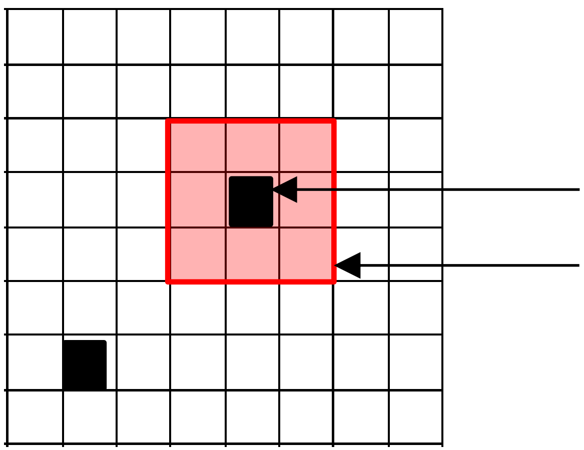
P W Anderson, *Science* 1972

A “toy” example:
The Game of Life (Conway, 1970)

Image: wikipedia

John H Conway

Played on a checkerboard where any cell can be either “dead” or “alive”



“live” cell

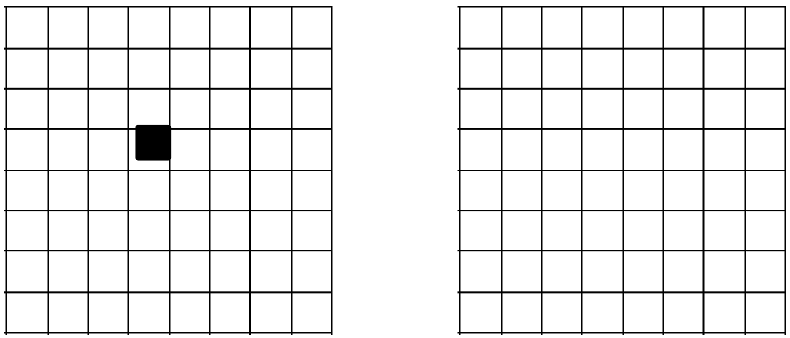
neighborhood of “live” cell

The “Theory of Everything” of Life

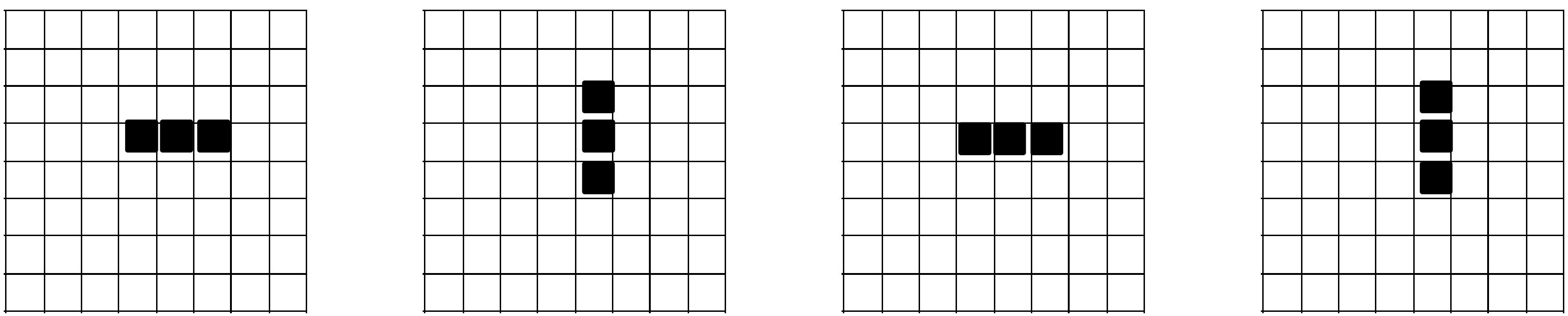
- ❑ Any live cell with < 2 live neighbours dies (“out of loneliness”).
- ❑ Any live cell with 2 or 3 live neighbours lives on to the next generation.
- ❑ Any live cell with > 3 live neighbours dies (“due to overcrowding”).
- ❑ Any dead cell with exactly 3 live neighbours comes alive (“reproduction”).

Let's try it out

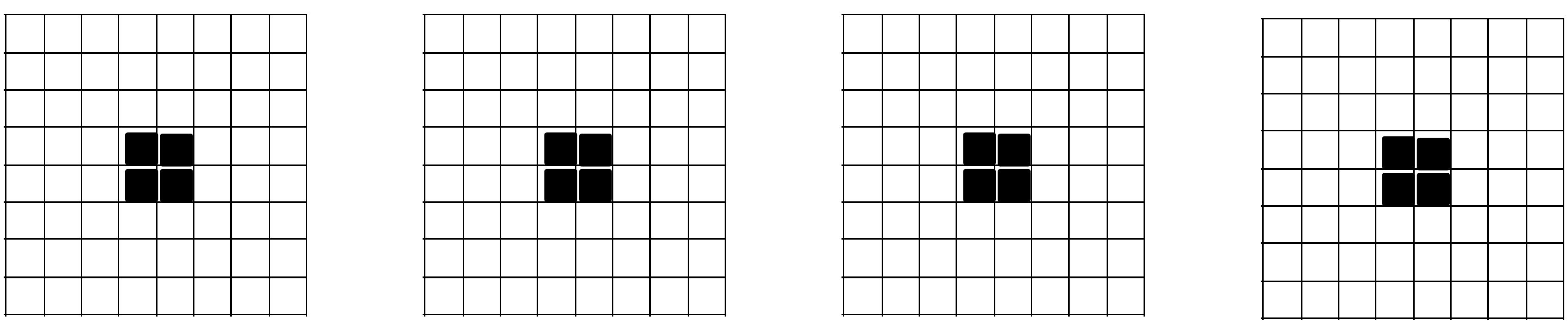
Case 1



Case 2



Case 3



The Game of Life:
A crucible of complexity

Glider

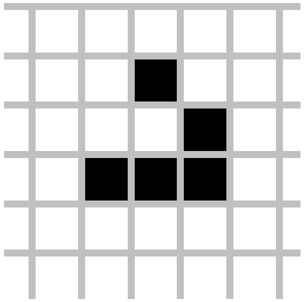


Image:wikipedia

The simple rules of Life give rise to unexpected behavior, e.g.,

- "glider": moves across the board
- "glider gun": creates a "glider" every few iterations.

Image:wikipedia

Conway created AND, OR and NOT logic gates using gliders and glider guns

Game of Life shown to be a universal computer

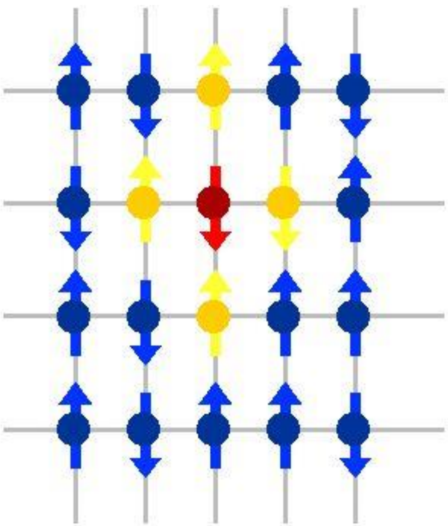
Emergence in Behavior : "The Crowd has no mind"

Explaining the sudden transition of a crowd of individuals to a violent mob for a brief duration

Image: www.ktvu.com

Individuals who are initially in a quiet ("resting") state may be driven by circumstances ("field") & surrounding ("interactions") to an agitated ("excited") state

Spin models as a paradigm for Complex Systems



- Spin orientation: mutually exclusive choices
- Choice dynamics: decision based on information about choice of majority in local neighborhood

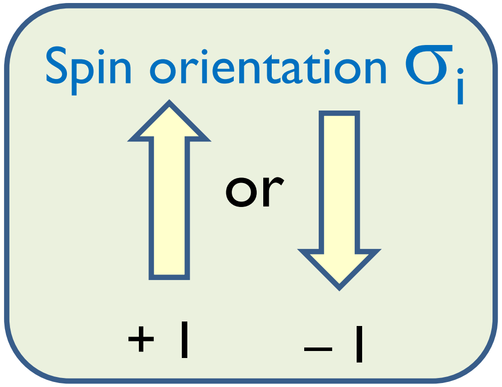
Simplest case: 2 possible choices

Ising model with Ferromagnetic interactions: each agent can be in one of 2 states (Yes/No , +/-)

Collective ordering

Striking analogy in statistical physics

The Ising model described by



spin-orientation coupling

external field

$$H = -\sum_{ij} J_{ij}\, \sigma_i\, \sigma_j - \sum_i h_i\, \sigma_i$$

interaction

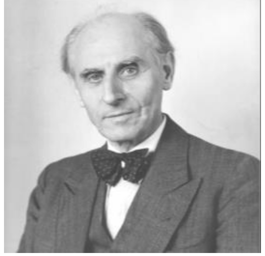
environment

For spontaneous ordering in a ferromagnet, $J_{ij} = J > 0$ and $h_i = h = 0$

Once we introduce thermal fluctuations (at finite temperature $T>0$) system behavior is governed by Free energy $F = U - T\,.\,S$

The Lenz-Ising model (1920-5)

A highly simplified model for explaining spontaneous magnetization


Wilhelm Lenz

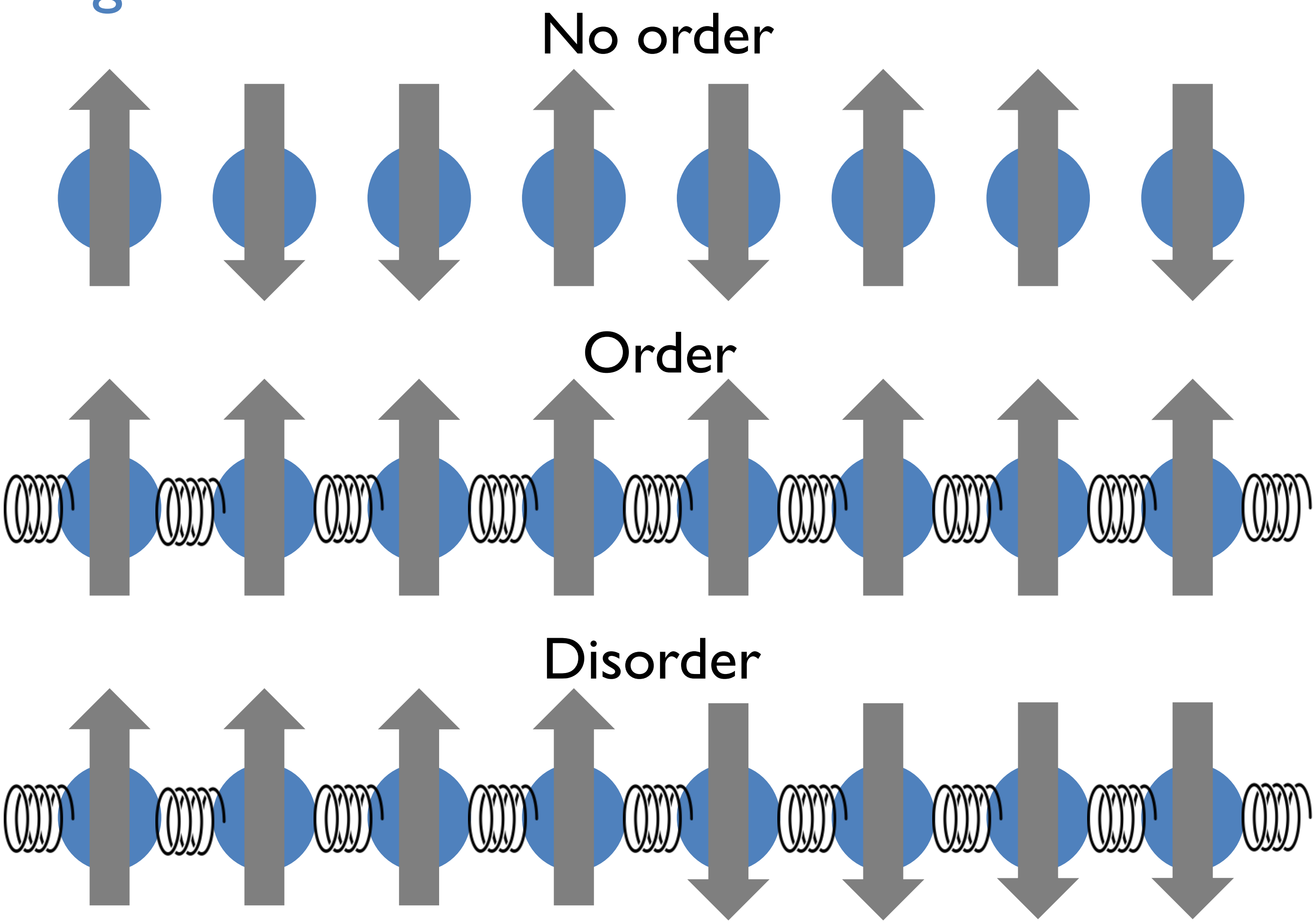

Ernst Ising

Image: wikipedia

In absence of interactions

T=0, with interactions

T>0, with interactions

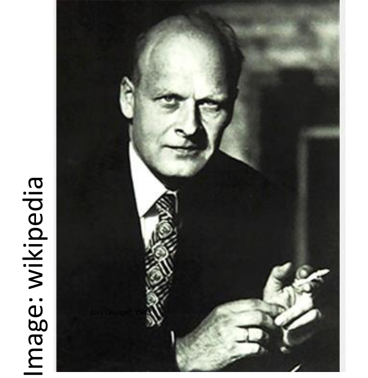


Magnetic moments of atoms reduced to a single (z) component, allowed to be only in 1 of 2 states and interact only with nearest neighbors

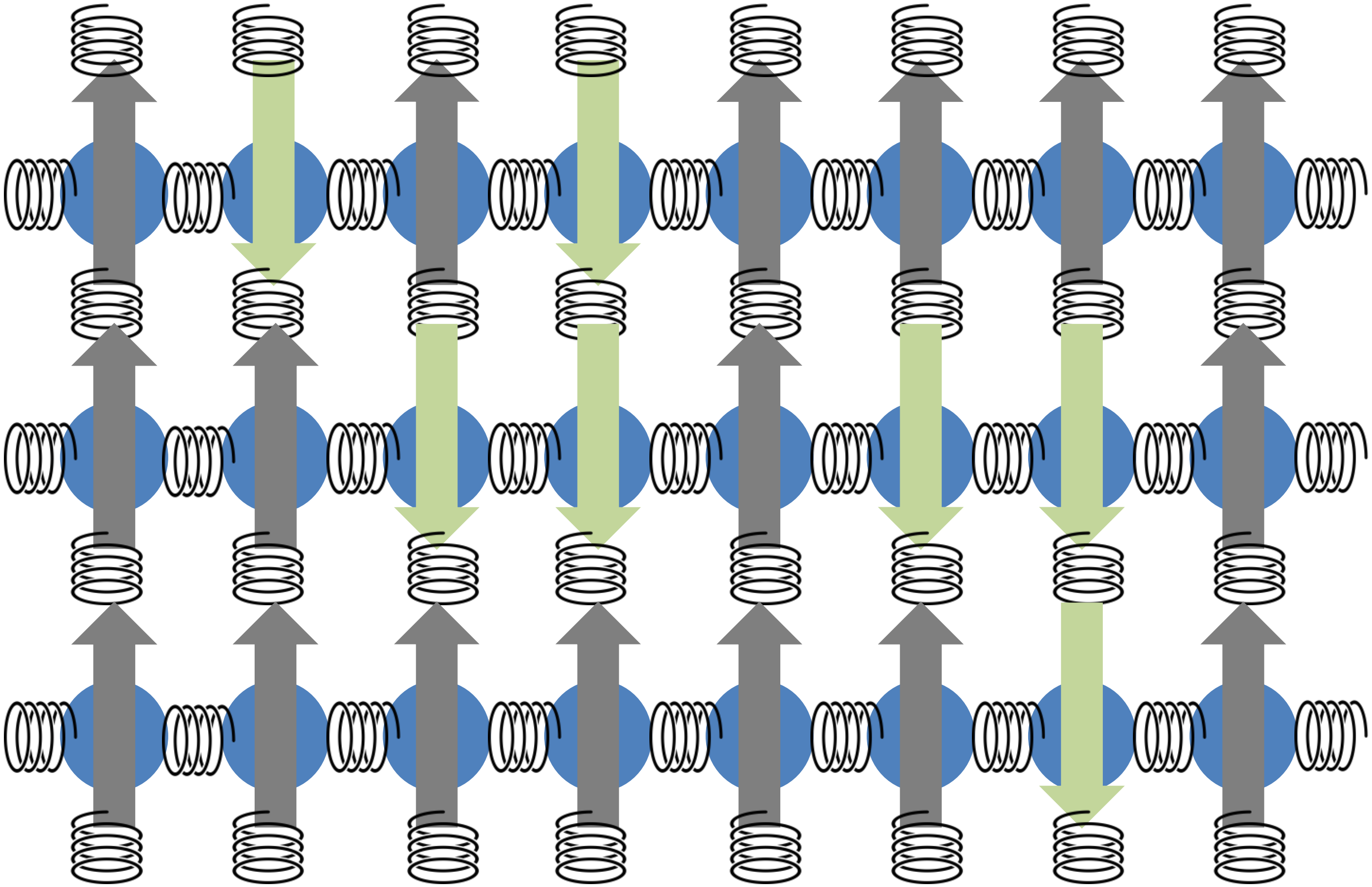
The 2-dimensional Ising model (1944)

A model for self-organized coordination

The system spontaneously orders at $T < T_c$



Lars Onsager

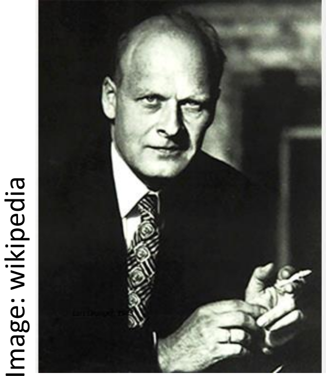


The 2-dimensional Ising model (1944)

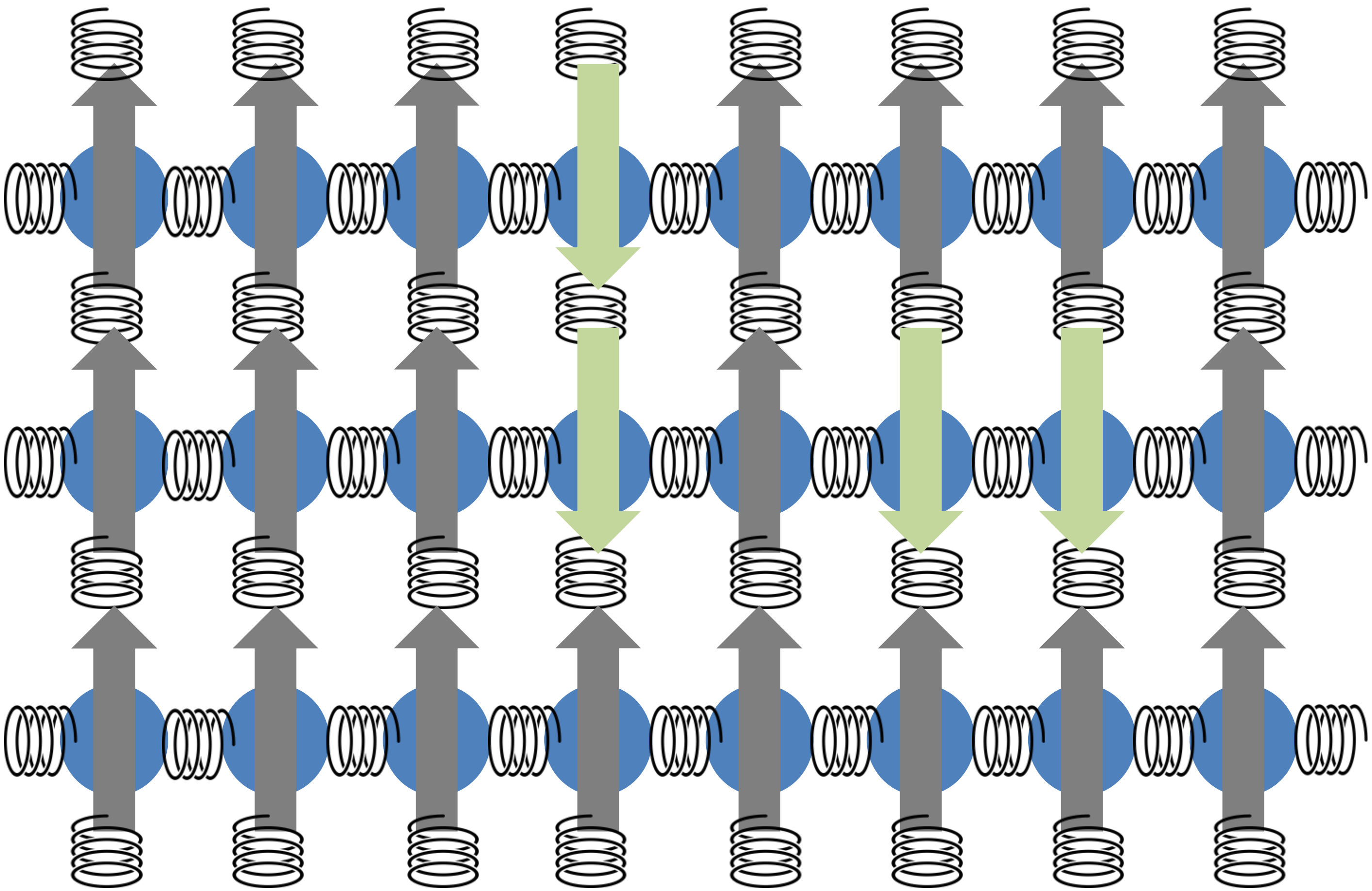
A model for self-organized coordination

The system spontaneously orders at $T < T_c$

Image: wikipedia



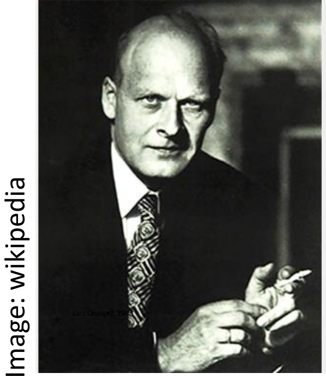
Lars Onsager



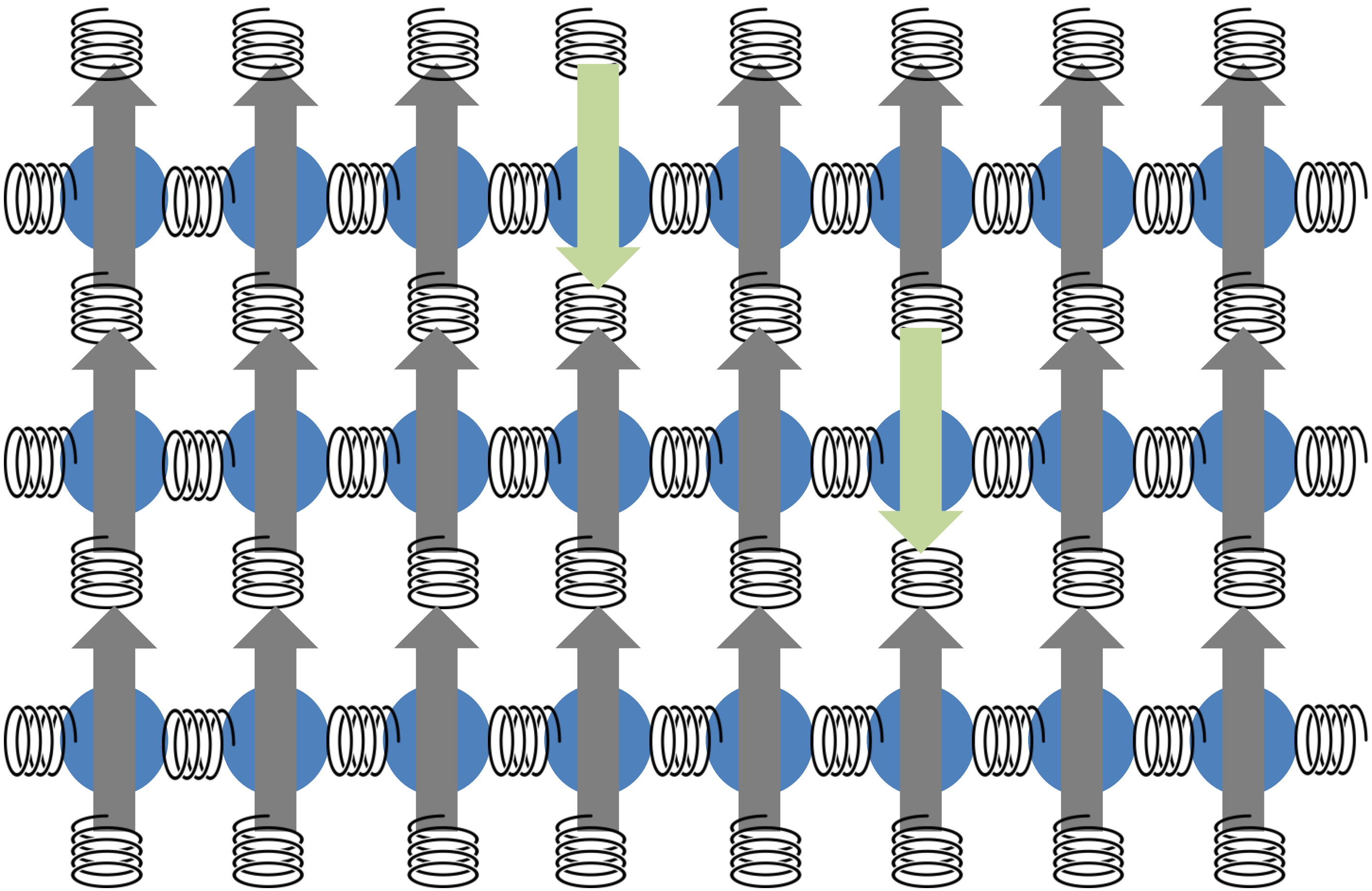
The 2-dimensional Ising model (1944)

A model for self-organized coordination

The system spontaneously orders at $T < T_c$



Lars Onsager

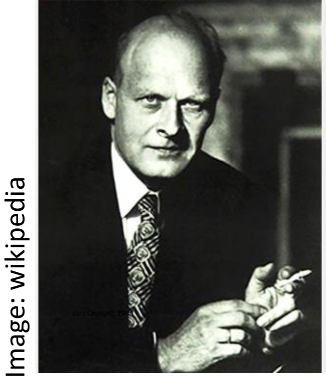


The 2-dimensional Ising model (1944)

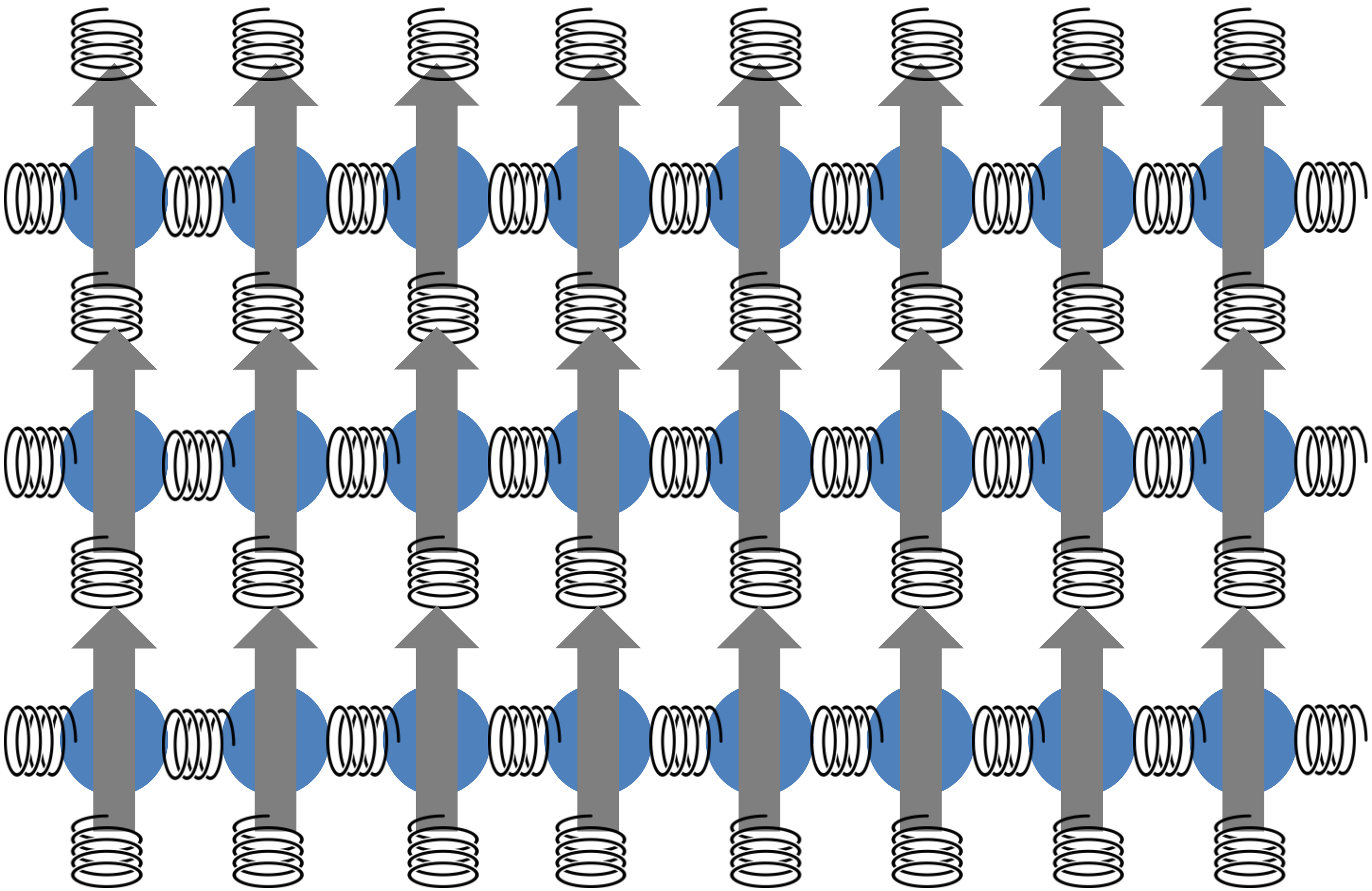
A model for self-organized coordination

The system spontaneously orders at $T < T_c$

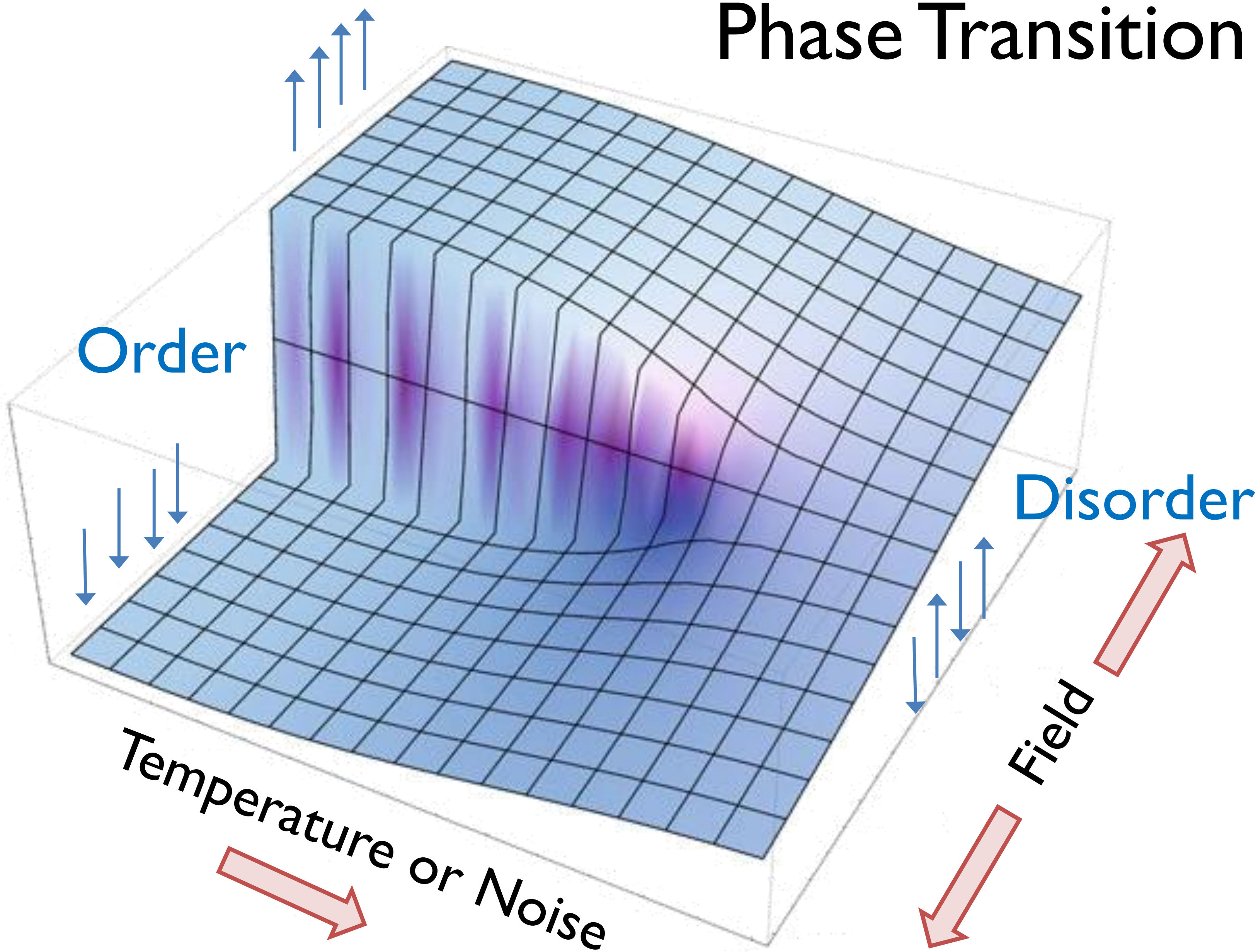
Image: wikipedia



Lars Onsager

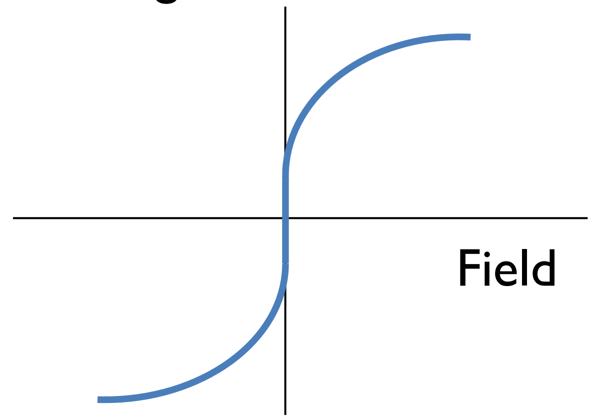


Phase Transition



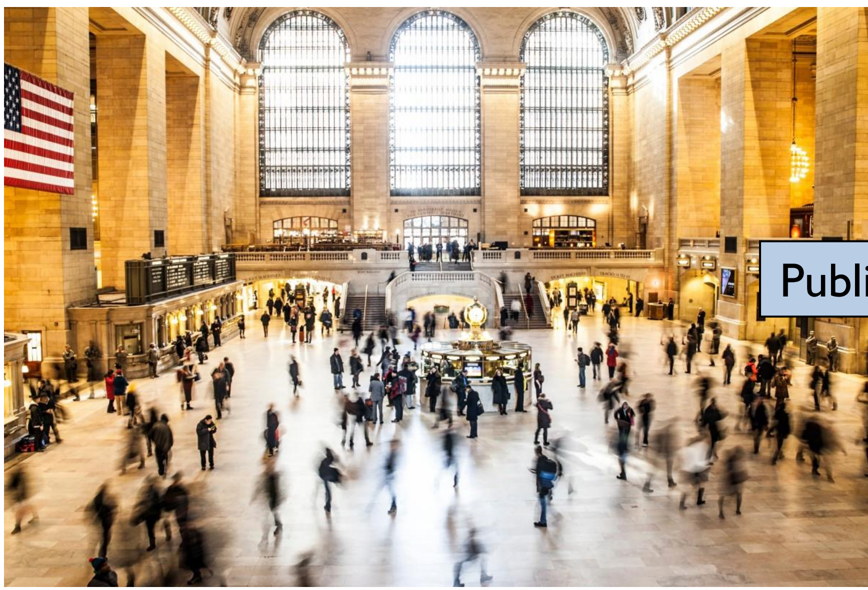
Selinger, Introduction to the Theory of Soft Matter, Springer

Order-disorder transition



"Field" induced transition from

"Disorder"



Creative Commons

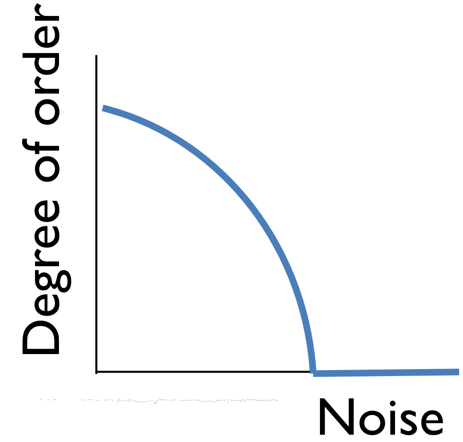
Public announcement

"Order"

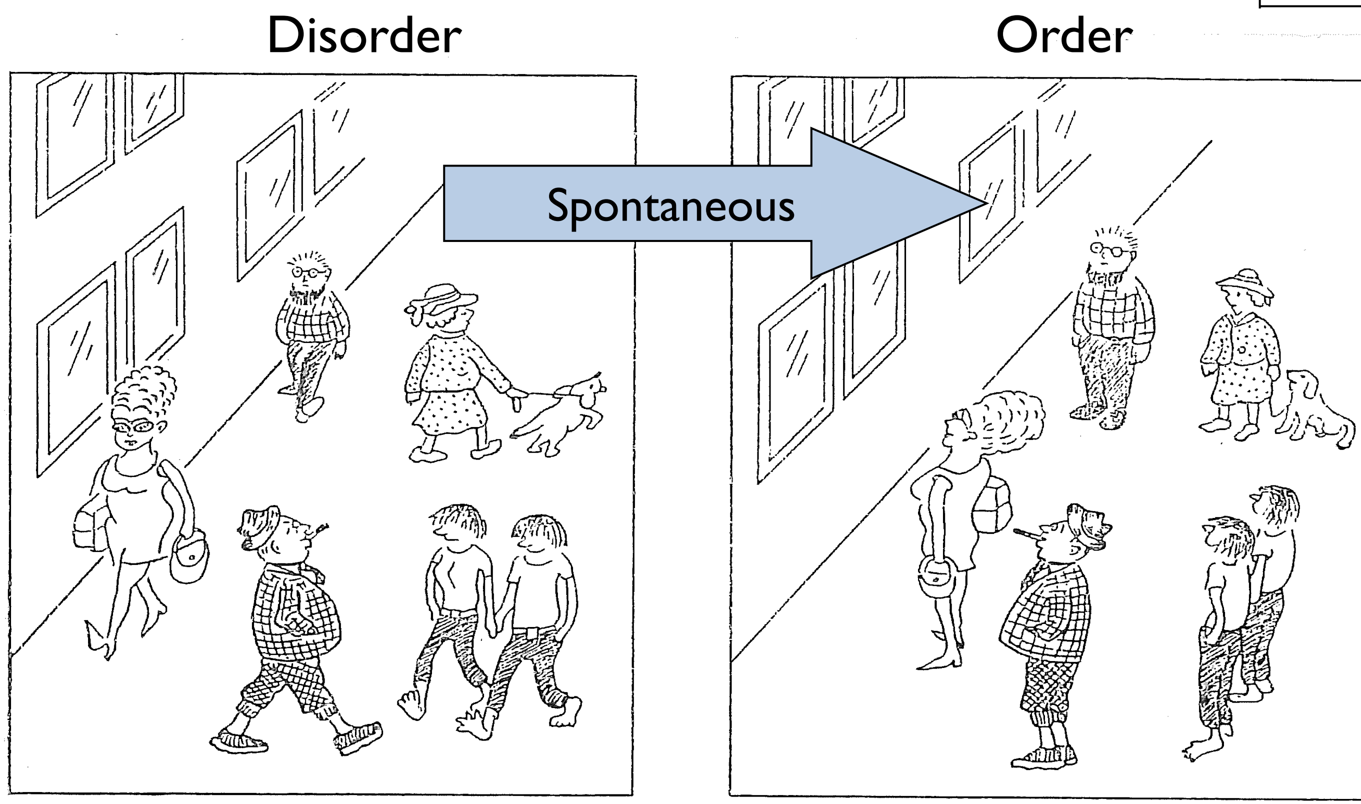
Jake Wyman/Corbis

Discontinuous or First-order phase transition

Cooperative phenomenon



Self-organized transition from

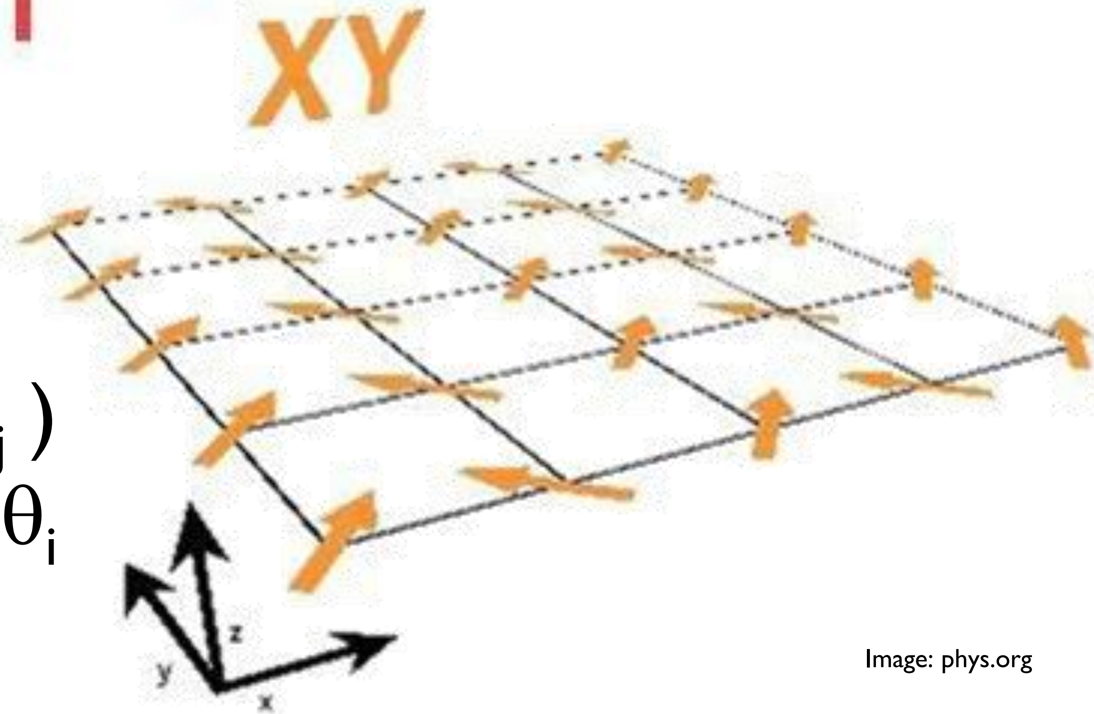


Kikoin & Kikoin, Molecular Physics, Mir

Continuous phase transition

From Discrete states to Continuous states

$$H = -\sum_{ij} J_{ij}\,\sigma_i\,\sigma_j - \sum_i h_i\,\sigma_i$$



$$H = -\sum_{ij} J_{ij} \cos(\theta_i - \theta_j) - \sum_i h_i \cos\theta_i$$

Image: phys.org

Mermin-Wagner Theorem

(1966)

In 1 and 2 dimensions, continuous symmetries cannot be spontaneously broken at finite temperature in systems with sufficiently short-range interactions

Image:academictree.org

David Mermin

Image: uni-due

Herbert Wagner

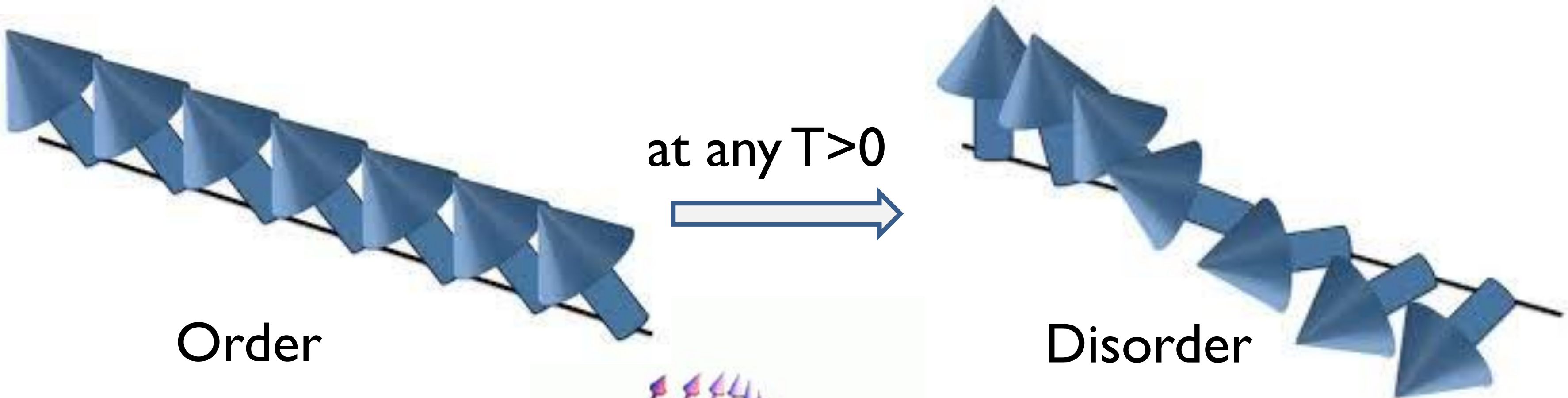
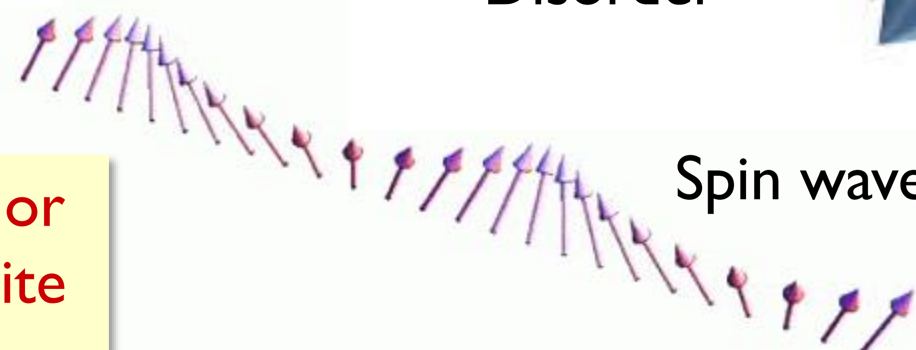


Image:www.damtp.cam.ac.uk



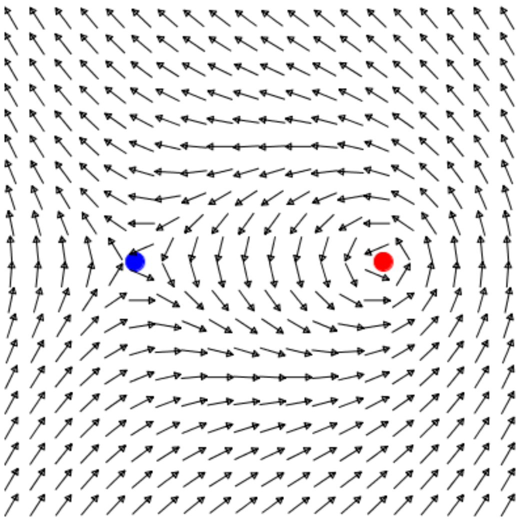
Spin waves

Image:marconivan.org

No long-range order in 1D or 2D lattice of XY spins at finite temperature


Image:shutterstock

Topological phase transitions



Transition in a 2-D system from bound vortex-antivortex pairs at low temperatures to unpaired vortices and anti-vortices above a critical temperature

Image: Brown Univ

Michael Kosterlitz

Image: New York Times

David Thouless

2016

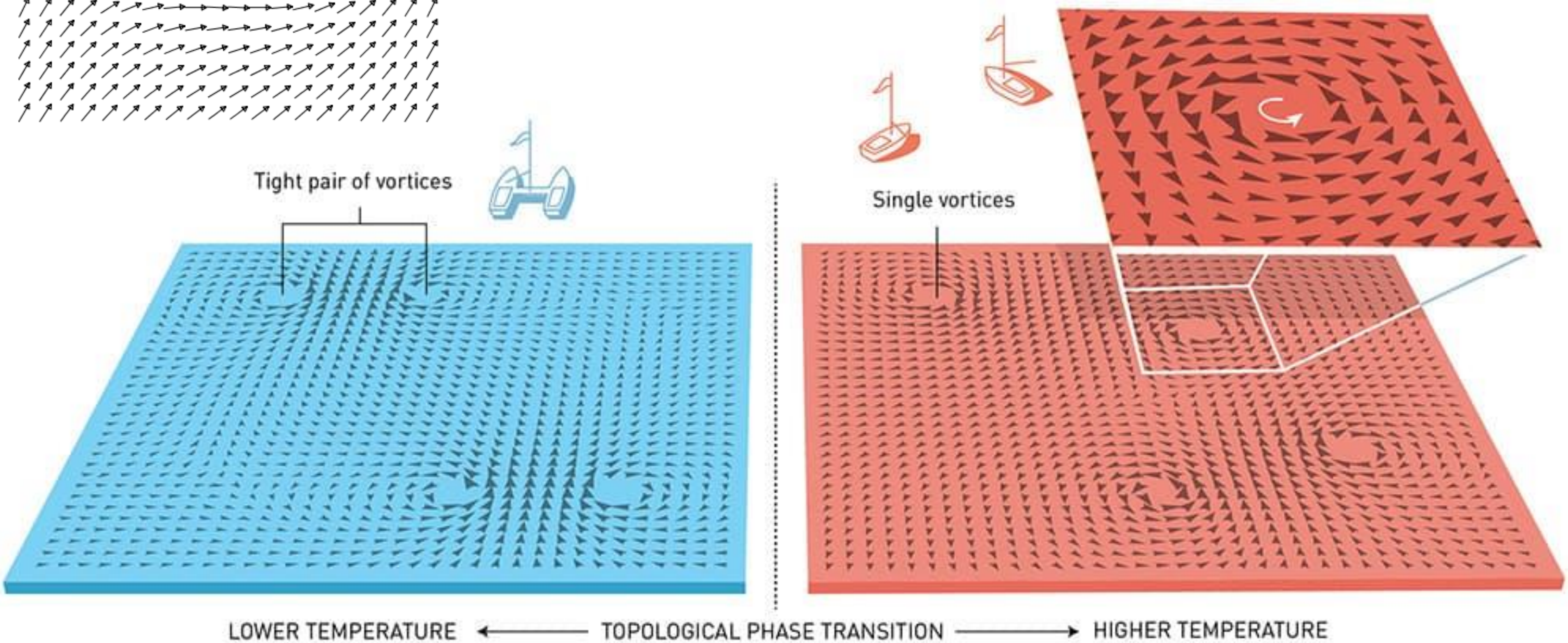
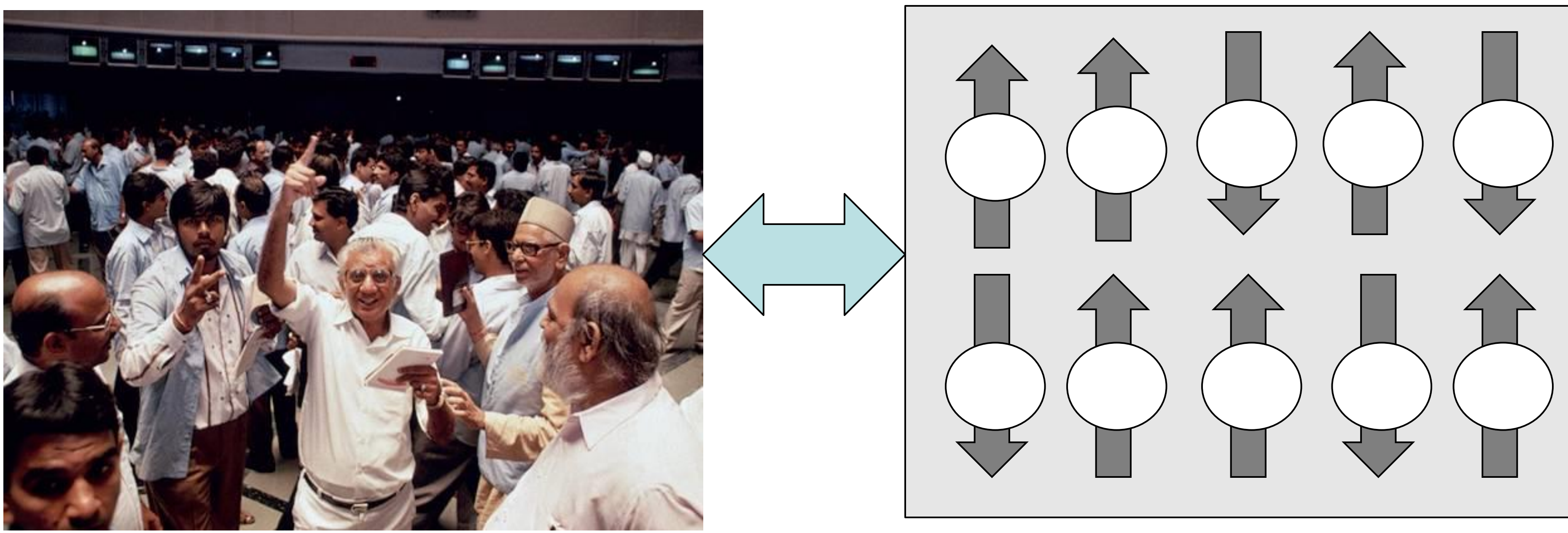


Illustration: ©Johan Jarnestad/The Royal Swedish Academy of Sciences

Collective behavior for physicists…



But… Agents are not spins! Not simply responding inertly to forces!

Future goals are the driving force for behavior

Teleodynamics

Telos “end”	+	Dunamis “power”

Agents are necessarily “forward-looking”,
⇒ current actions are influenced by perception of future events.

perception may of course be influenced by what has happened in the past …
but also by biases and prejudices of the individual actors

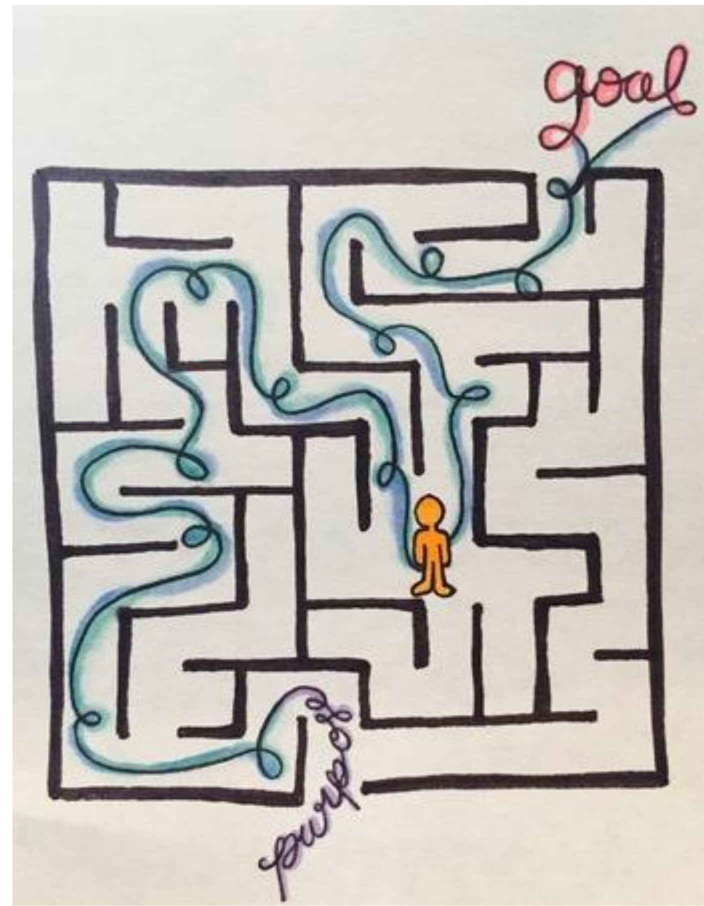


Image: www.adlerpedia.org

The Goalie's anxiety at the penalty kick

Image: shutterstock.com

From spins to games

"I think that I will pick A"

But "she thinks that I think that I will pick A"

But "she thinks that I think that she thinks that I think that I will pick A"

And so on…

An infinite regress of *theories of mind* two opponents use to guess the action that the other will choose

How to choose course of action ?

The Theory of “Games”

- *Games*: Strategic interactions between agents
- *Agents*: Variety of entities, ranging from individuals to organizations and nations, or even, computer programs.
- Each agent receives a *payoff* depending upon the strategy choice made by all agents including herself
- Agents aim to maximize their payoff by choosing optimal strategies, taking into account that other agents will also be doing the same

Early attempts at using the concept of games for analyzing strategic thinking: **Kriegsspiel**, a war-game used for training Prussian officers

2-person symmetric single-stage games

Each agent (*A* and *B*) has two possible strategies (Actions 1 and 2)

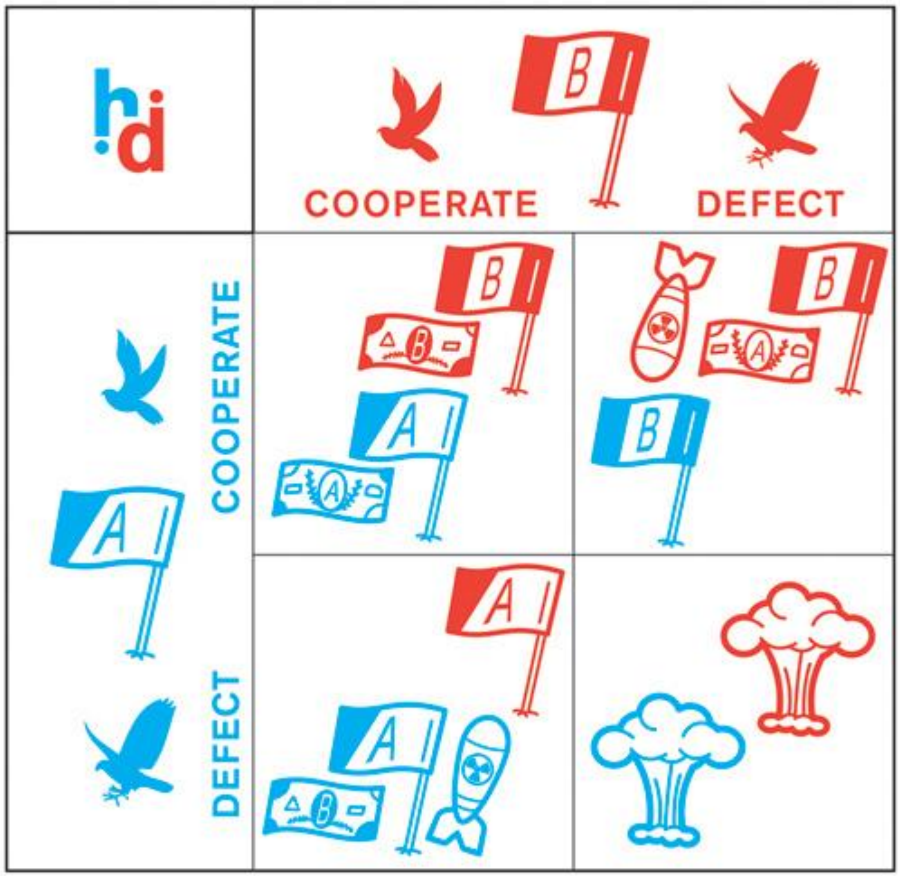
Each agent receives a payoff corresponding to the pair of choices made by them:

Agent A		Agent B: Action 1	Agent B: Action 2
	Action 1	(R,R)	(S,T)
	Action 2	(T,S)	(P,P)

An agent may employ a mixed strategy, in which she randomly selects her options, choosing Action 1 with some probability p and Action 2 with probability $(1 - p)$. A pure strategy corresponds to p=0 or p=1

Example: Hawk-Dove or Chicken

T > R > S > P (=0)



Evolutionary Games Infographics Project

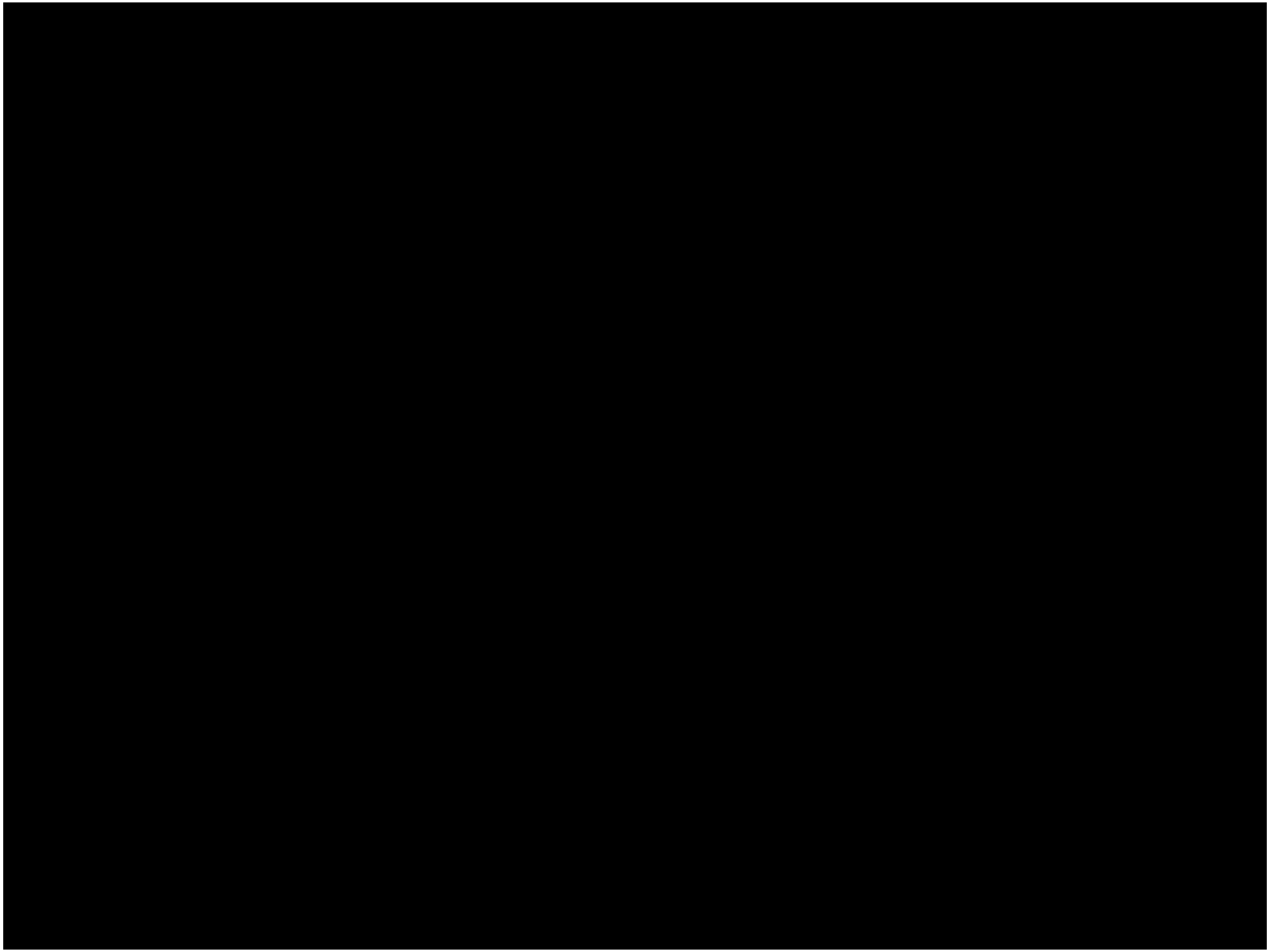
Strategy defined by probability p of Action 1
[probability of Action 2 is(1-p)]

Strategic interaction between 2 agents choosing either

- ❑ Action 1: being docile
- ❑ Action 2: being aggressive

An agent benefits by being aggressive only if the other is docile but is better off being docile otherwise, as cost of mutual aggression is high.

The Chicken Run: Rebel Without A Cause (1955)



https://www.youtube.com/watch?v=BGtEp7zFdrc&t=12s

Video: Film Studies Fundamentals

Nash Equilibrium

J. F. Nash, "Equilibrium Points in n-Person Games"
Proc. Natl. Acad. Sci. USA, 1950

An important solution concept for
Non-cooperative games in which players make decisions independently

While the actions of players may result in cooperation, it must be self-organized

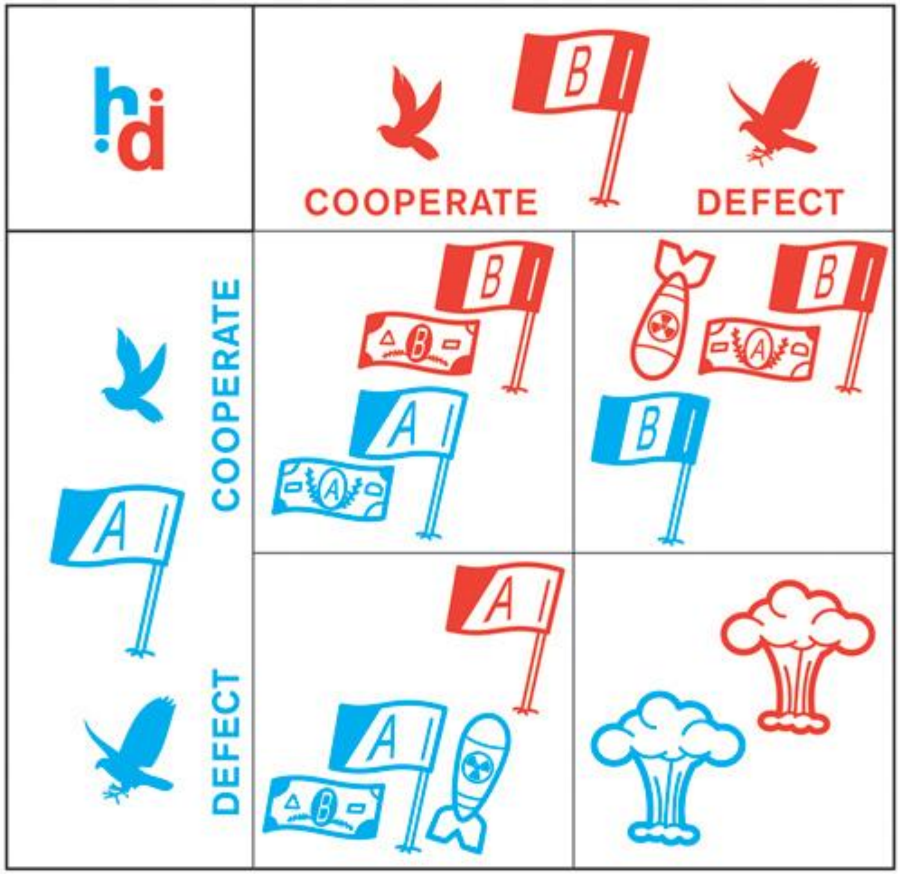
Informally
Nash equilibrium is a state where after every agent has selected their optimal 'Nash' strategies, none of the agents can improve their payoff by **unilaterally** deviating from it.

A game can have multiple Nash equilibria – in which case one needs to employ additional refinement (selection) criteria to decide which equilibrium agents will choose

John F Nash
(1928-2015)

Example: Hawk-Dove or Chicken

$T > R > S > P\ (=0)$



Evolutionary Games Infographics Project

Strategy defined by probability p of Action 1
[probability of Action 2 is(1-p)]

Strategic interaction between 2 agents choosing either

- ❑ Action 1: being docile
- ❑ Action 2: being aggressive

An agent benefits by being aggressive only if the other is docile but is better off being docile otherwise, as cost of mutual aggression is high.

Extensively investigated in the context of arms race & mutually assured destruction

Three Nash equilibria:

- $p^* = S/(T + S - R)$ a mixed strategy
- $p^*=1$ a pure strategy
- $p^*=0$ a pure strategy

The Nash equilibrium of a game may sometimes be inferior to an alternate choice of actions by the agents in which all the parties get higher payoff … gives rise to "social dilemmas" such as

Prisoners Dilemma

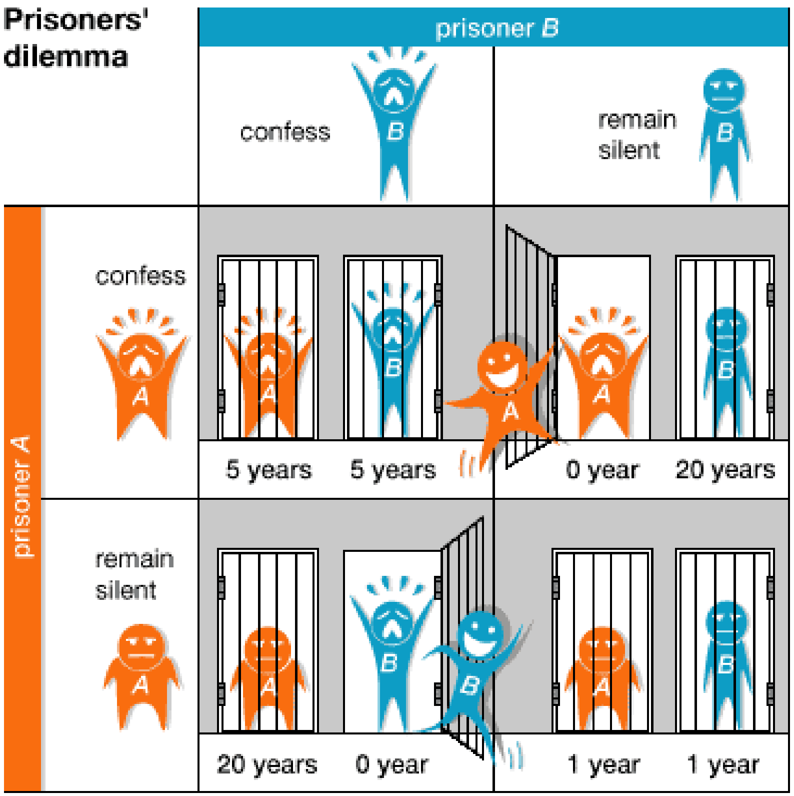
originally framed by Merrill Flood and Melvin Dresher at RAND (1950)

T > R > P > S

Payoff Matrix

B / A	Cooperate	Defect
Cooperate	R, R	S, T
Defect	T, S	P, P

T: Temptation to defect
R: Reward for cooperation
P: Punishment for mutual defection
S: Sucker's payoff



Evolutionary Games Infographics Project

Pride and Prejudice: Eliabeth-D'Arcy "Meet-not-so-cute"

https://www.youtube.com/watch?v=6fOtWQwp7ak

BBC 1995

Pride & Prejudice

Using game theory

D’Arcy’s strategy

Elizabeth’s strategy

	Cooperate (Receptive)	Defect (Aloof/Hostile)
Cooperate (Receptive)	(2,2) Mutual happiness	(–1, 3) Elizabeth insulted D’Arcy triumphs
Defect (Aloof/Hostile)	(3, –1) Elizabeth triumphs D’Arcy insulted	(0,0) Mutual distrust (Novel’s reality)

Laura and Petrarch : Love and Nonlinear Dynamics

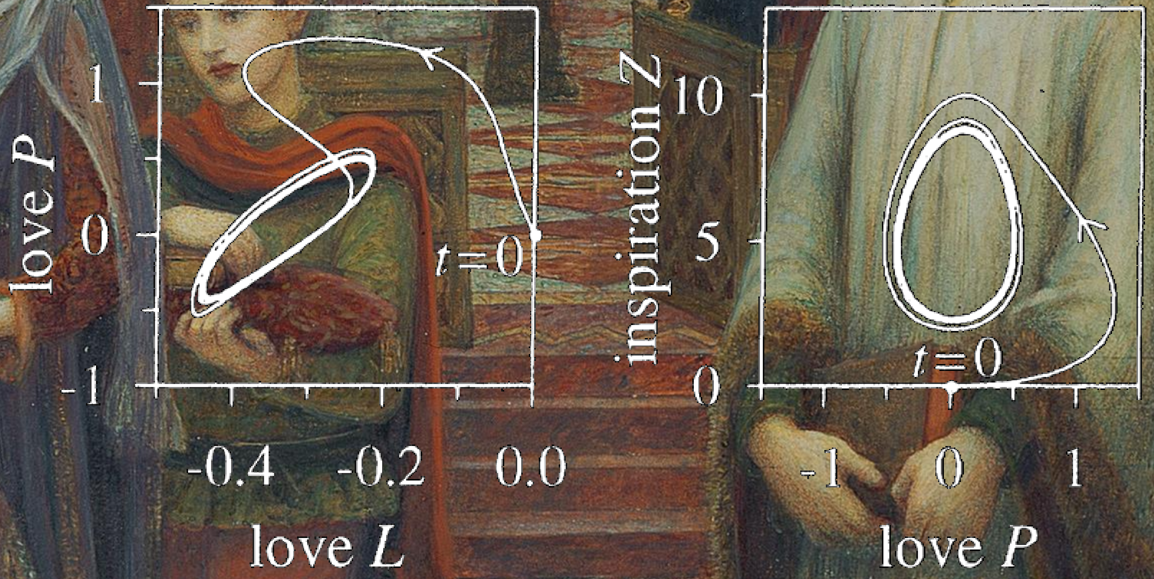
Marie Spartali Stillman, The First Meeting of Petrarch and Laura, 1889

Laura and Petrarch : Love and Nonlinear Dynamics

$$\frac{dL(t)}{dt} = -\alpha_1 L(t) + R_L(P(t)) + \beta_1 A_P,$$

$$\frac{dP(t)}{dt} = -\alpha_2 P(t) + R_P(L(t)) + \beta_2 \frac{A_L}{1+\delta Z(t)},$$

$$\frac{dZ(t)}{dt} = -\alpha_3 Z(t) + \beta_3 P(t),$$

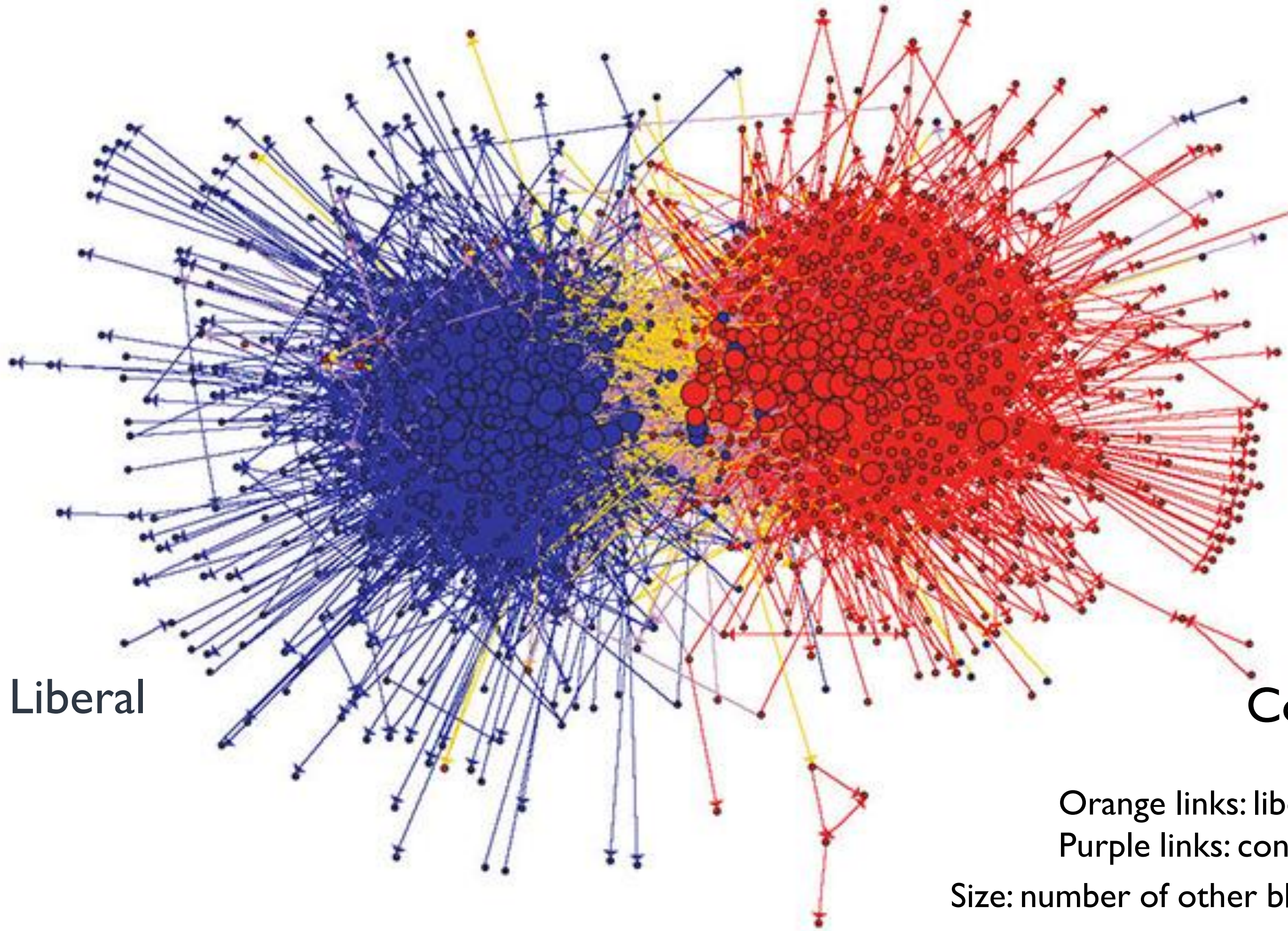


Marie Spartali Stillman, The First Meeting of Petrarch and Laura, 1889

How do you describe a complex system?

Interaction between social groups

Blogosphere: Network structure of political blogs during the 2004 US elections



Orange links: liberal → conservative
Purple links: conservative → liberal
Size: number of other blogs linking to a blog

Image: L. A. Adamic & N. Glance, LinkKDD '05 (2005)

Romeo and Juliet Dramatis Personae

Escalus, Prince of Verona
Mercutio, Kinsman of the Prince and friend of Romeo
Paris, a young Count, kinsman of the Prince
Page to Count Paris

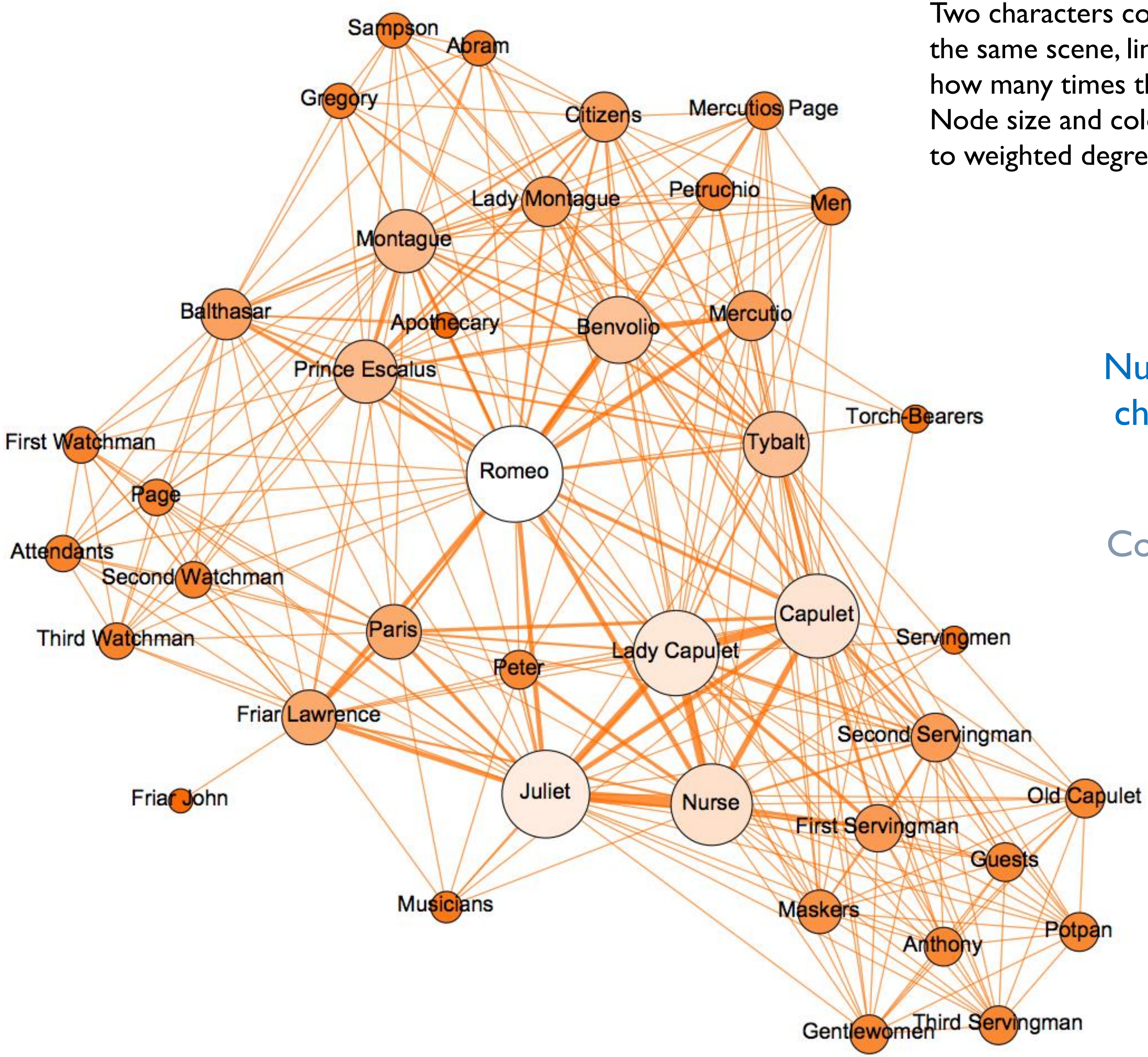
Montague, head of a Veronese family
Lady Montague, wife to Montague
Romeo, son of Montague
Benvolio, nephew of Montague and friend of Romeo
Abram, servant of Montague
Balthasar, servant of Romeo

Capulet, head of another Veronese family
Lady Capulet, wife to Capulet
Juliet, daughter to Capulet
Tybalt, nephew of Lady Capulet
Petruchio, friend of Tybalt
Second Capulet, cousin of Capulet
Nurse of Juliet
Peter, servant of Juliet's nurse
Sampson, Gregory — Servants of the Capulets
Servingmen of the Capulets (Anthony, Potpan etv.)

Friar Laurence, Friar John — Franciscans
An Apothecary of Mantua
Musicians (Simon Catling, Hugh Rebeck, James Soundpost)
Three Watchmen
Citizens of Verona, maskers torchbearers, pages, servants

Chorus

Two characters connected if they appear in the same scene, link width proportional to how many times they appear together
Node size and color intensity proportional to weighted degree



Number of characters **41**

Connection density **37%**

Image: Martin Grandjean, 2016
www.martingrandjean.ch

How do you build a complex system?

It's not enough to know the components

We also need to know how each component relate or interact with the others

How do we describe all these interactions ?

We use the language of Networks

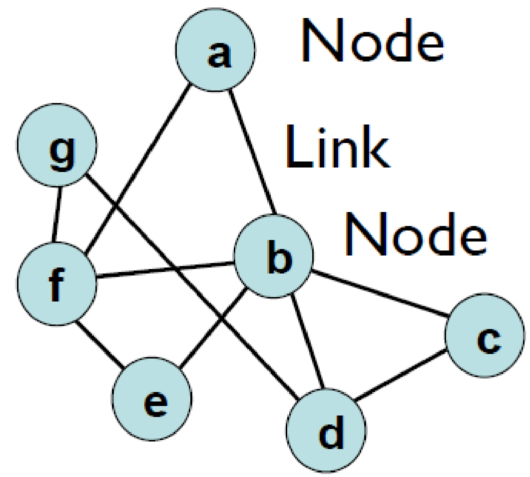
What is a network ?

Components = Nodes or Vertices

Interactions = Links or Edges

System = Network or Graph

Network…



…and its adjacency matrix

Network structure is specified by

adjacency matrix A

A_{ij} = 1, if a link exists between i and j ($\neq$ i)
= 0, otherwise

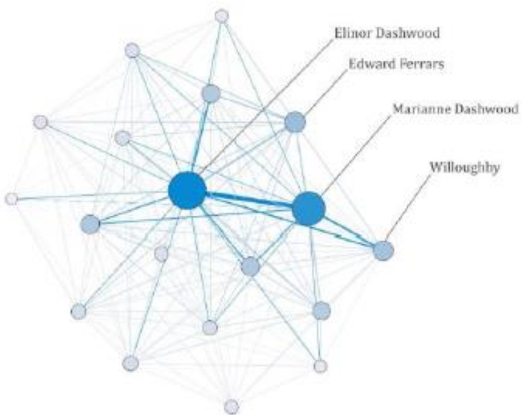
a	b	c	d	e	f	g	
0	1	0	0	0	1	0	a
1	0	1	1	1	1	0	b
0	1	0	1	0	0	0	c
0	1	1	0	0	0	1	d
0	1	0	0	0	1	0	e
1	1	0	0	1	0	1	f
0	0	0	1	0	1	0	g

Social Networks in Fictional World

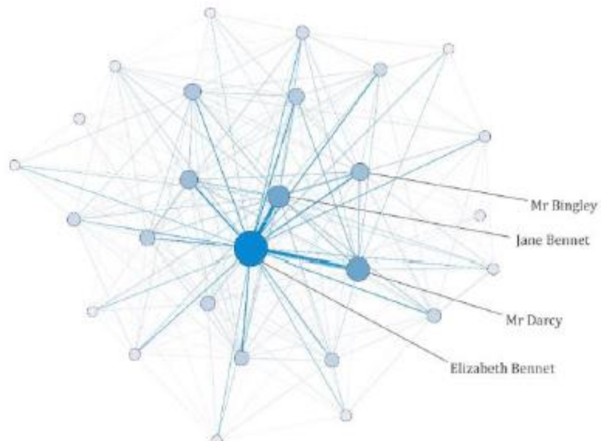
Generally tend to be much simpler than those in reality, …

Example: Jane Austen's novels

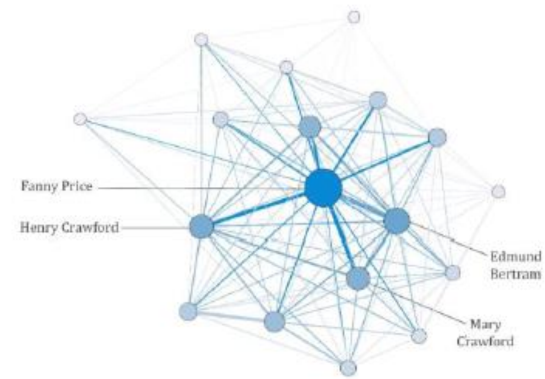
SENSE AND SENSIBILITY (1811)



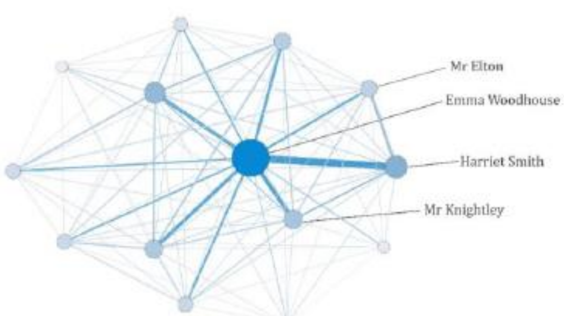
PRIDE AND PREJUDICE (1813)



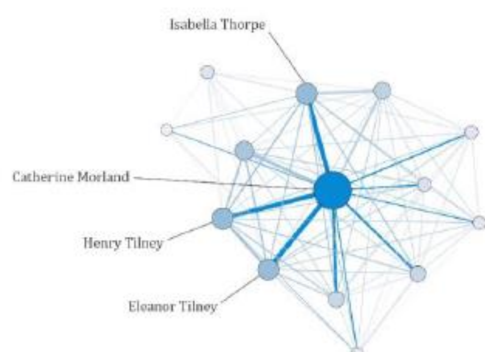
MANSFIELD PARK (1814)



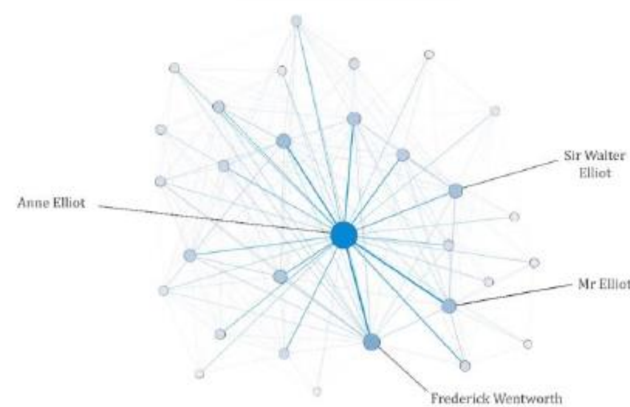
EMMA (1815)



NORTHANGER ABBEY (1817)



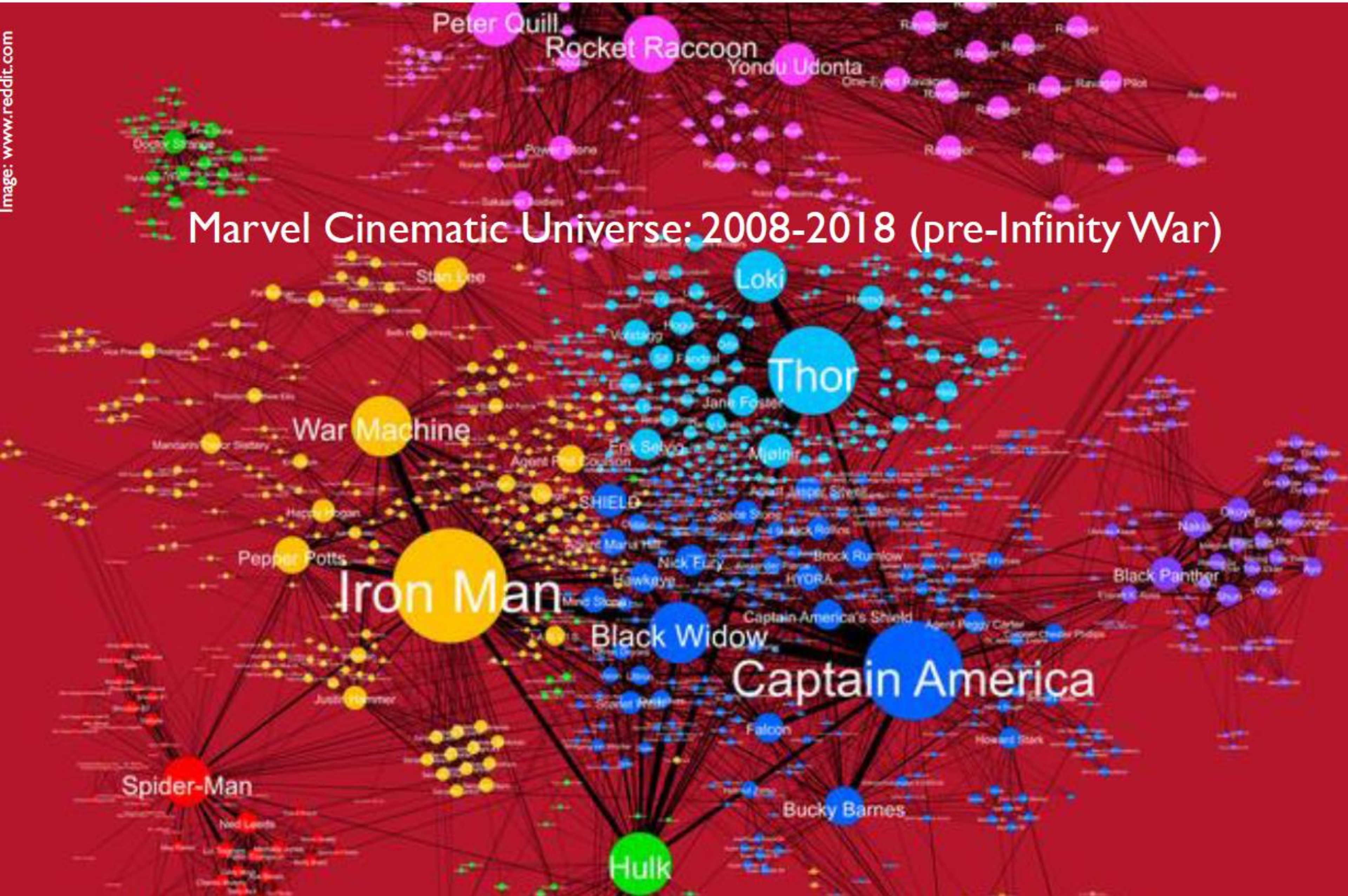
PERSUASION (1818)



Source: https://theseaofbooks.com/ (Centre for Cultural Analytics,Univ College Dublin)

Social Networks in Fictional World

Generally tend to be much simpler than those in reality, but there are exceptions!



Explaining the rise of the Medici

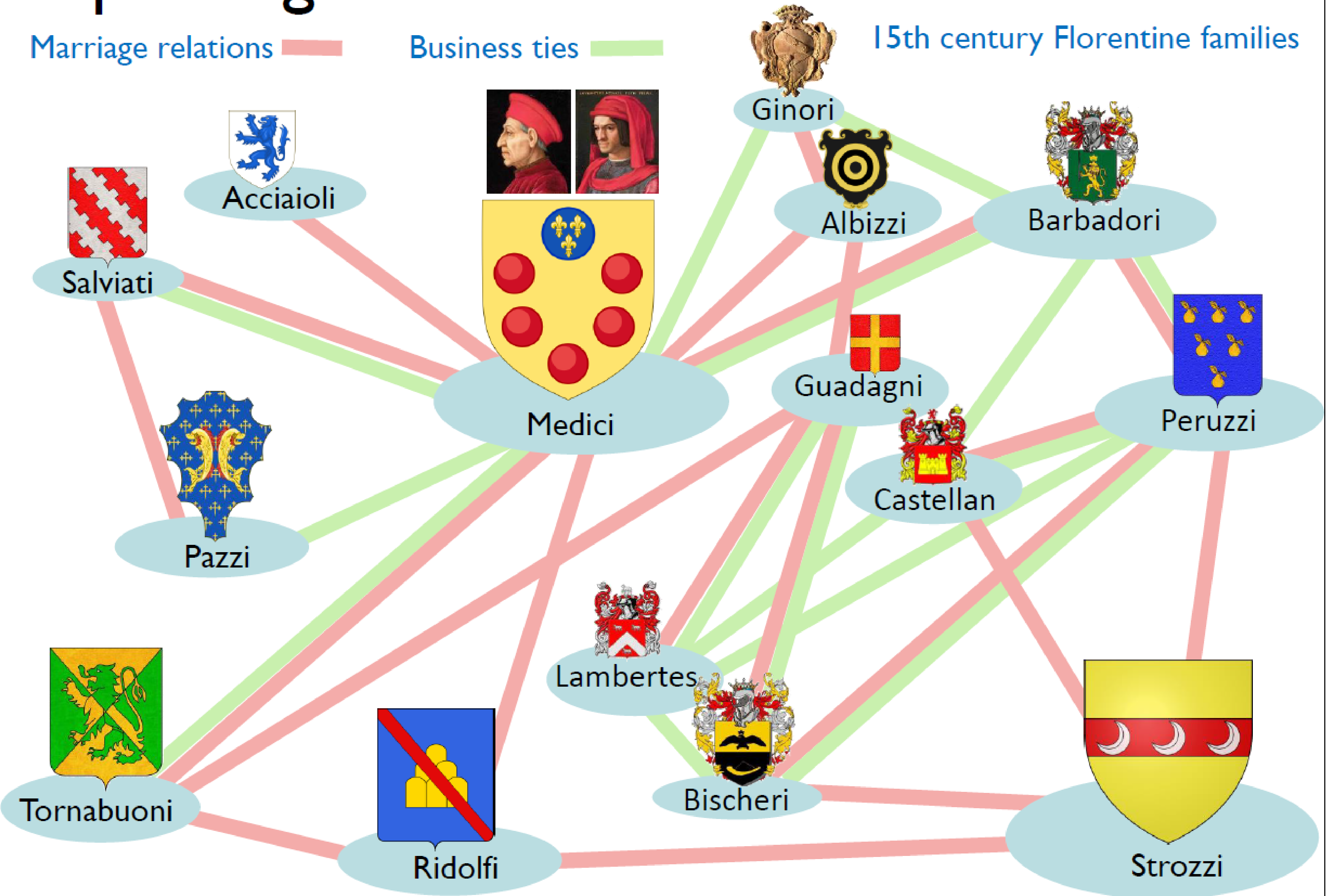
Image: www.theflorentine.net

Medici: Masters of Florence trailer

https://www.youtube.com/watch?v=SFUWvceed5s

Data: John F Padgett (1993)

Explaining the rise of the Medici



Re-constructing networks

Example: Macaque troupe social network

UAS-GKVK Campus, Bangalore
Data: Anindya Sinha (NIAS, B'lore)
Analysis: Raj K Pan & Sumithra Surendralal (IMSc)

The Bonnet Macaque (*Macaca radiata*) seen widely in southern India

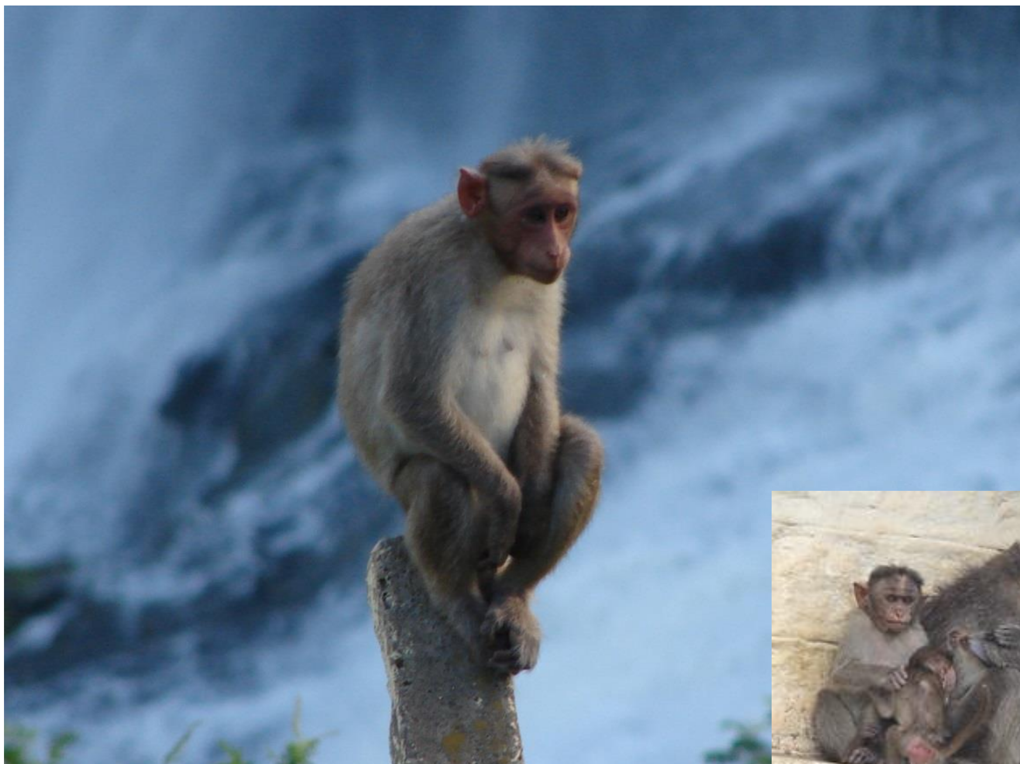


Image: Arunkumar

Usually live in large (~ 40) multi-male, multi-female troops where the adult individuals (~ 10) develop strong affiliative relationships

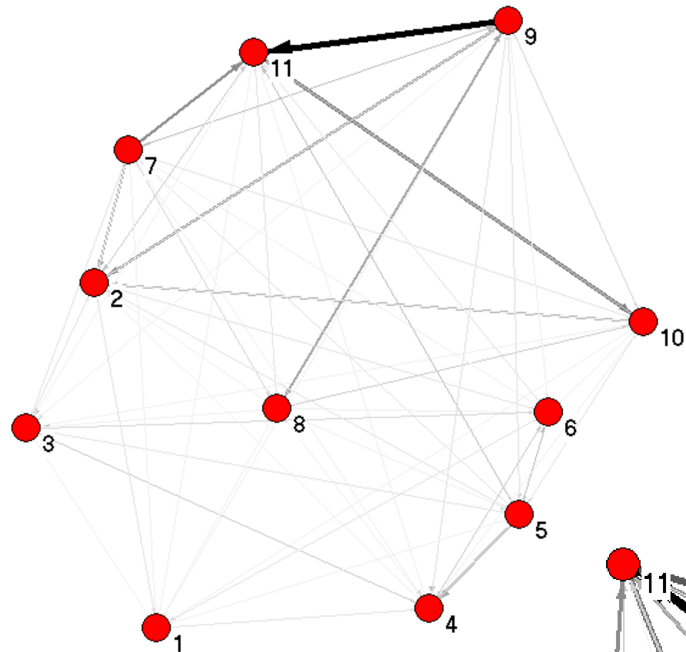
Image: Ramki (www.wildventures.com)

Macaque Social Networks can be defined in terms of

- grooming frequency
- total grooming time
- approach frequency

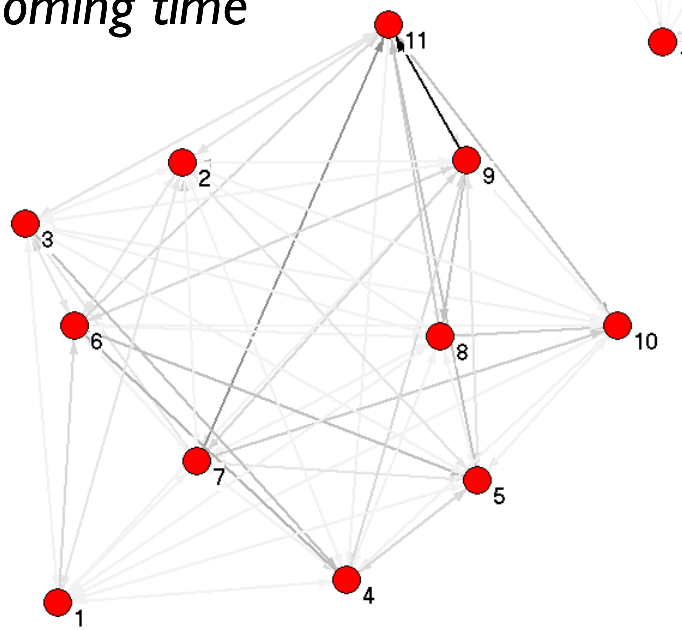
Numbers refer to rank among the adult females from 11 (most dominant) to 1 (least dominant)

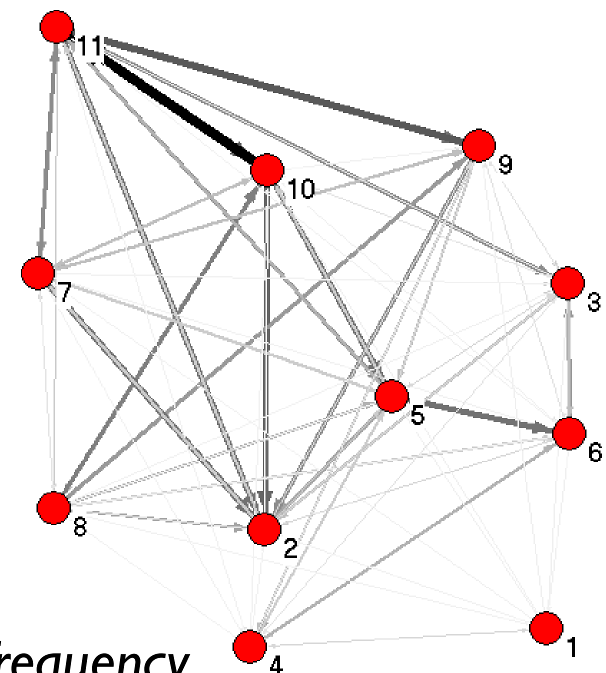
Data: 1993-1997



grooming frequency

grooming time





approach frequency

Network analysis can predict group dynamics !

Female bonnet macaques
•usually remain in the group throughout their life
•as adults, form strong linear matrilineal dominance hierarchies that are **stable** over time

Male bonnet macaques
•as adults, form **unstable** dominance hierarchies
•occupy low ranks when young, high when mature and at peak of health

Community detection generates consistent partitions for females, not for males

Gender	Type	Q	N.comm	Q_{random}±std	Modules
Female	AG.Freq	0.1205	2	0.0812±0.0173	[1 3 4 5 6] [2 7 8 9 10 11]
	AG.Time	0.1397	2	0.0983±0.0209	[1 3 4 5 6] [2 7 8 9 10 11]
	AF	0.1095	2	0.0729±0.0197	[1 3 4 5 6] [2 7 8 9 10 11]
Male	AG.Freq	0.0852	2	0.1301±0.0247	[1 4 9 10 11 12] [2 3 5 6 7 8]
	AG.Time	0.1646	4	0.1369±0.0244	[1 2 4 6] [3 5 7] [8 9] [10 11 12]
	AF	0.2398	4	0.1426±0.0253	[1 3] [2 4] [5 8 9][6 7 10 11 12]

Predictive power: Observation in 1998 showed the group had split into two (11,10,9,8,7,2) and (6,5,4,3) [1 had died]

And so that's how we planned the program

Schedule

Behaviour, Evolution & Emergence 2026

	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday
Time\Date	**Jun-8**	**Jun-9**	**Jun-10**	**Jun-11**	**Jun-12**	**Jun-13**	**Jun-14**	**Jun-15**	**Jun-16**	**Jun-17**	**Jun-18**	**Jun-19**	**Jun-20**
10:00-11:00	Somdatta	Sitabhra	V Sasidevan	Sitabhra	S Menon			K Isvaran	S Saini	J Jhawar	V Torsekar	A Sinha	Student Talks
11:00-11:30	TEA/COFFEE							TEA/COFFEE					
11:30-12:30	Sitabhra	Hareesh J	Sitabhra	S Menon	S Menon			V Guttal	S Saini	J Jhawar	A Bhat	M Jain	Student Talks
12:30-1:30	S Zimik	S Zimik	Sitabhra	Hareesh J	Hareesh J			V Guttal	J Jhawar	A Bhat	M Jain	MK Pal	Student Talks
1:30-2:30	LUNCH							LUNCH					
2:30-3:30	V Sasidevan	S Zimik	S Menon	S Sane	Hareesh J			S Saini	A Sumana	A Sumana	A Joshi	P Varuni	Student Talks
3:30-4:00	TEA/COFFEE							TEA/COFFEE					
4:00-5:00	V Sasidevan	V Sasidevan	R Klages	P Varuni	A Amador			A Sharma	R Bhat	R Bhat	L Eigentler	A Joshi	Closing
5:00-6:00	Mixer	Group projects	Group projects	Group projects	Group projects			Group projects	Group projects	Group projects	Group projects		

Legend:

Statistical Physics of Collective Phenomena	Evolutionary Games and Adaptive Dynamics
Crowds in Motion: Herding, Flocking, Swarming	Nonlinearity and Pattern Formation
Group Behaviour in Living Systems (Quorum-sensing)	Research talks
Complex Networks: Theory & Algorithms	Online talks
The Mathematics of Conflict & Cooperation	Other activities