Synchronization and Emergence of Intelligence in Networked Agents

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AIM and Research Questions (1)

- Crowds are often ***foolish***,
  but crowds are ***wise*** under certain conditions

- Under what mechanism can we improve the performances of the complex systems that involve human decision-makings?

AIM and Research Questions (2)

Networked Society: All connected with which we interact

Positive and negative network effects

- **Positive networks effects are obvious**

  : More people means more benefits

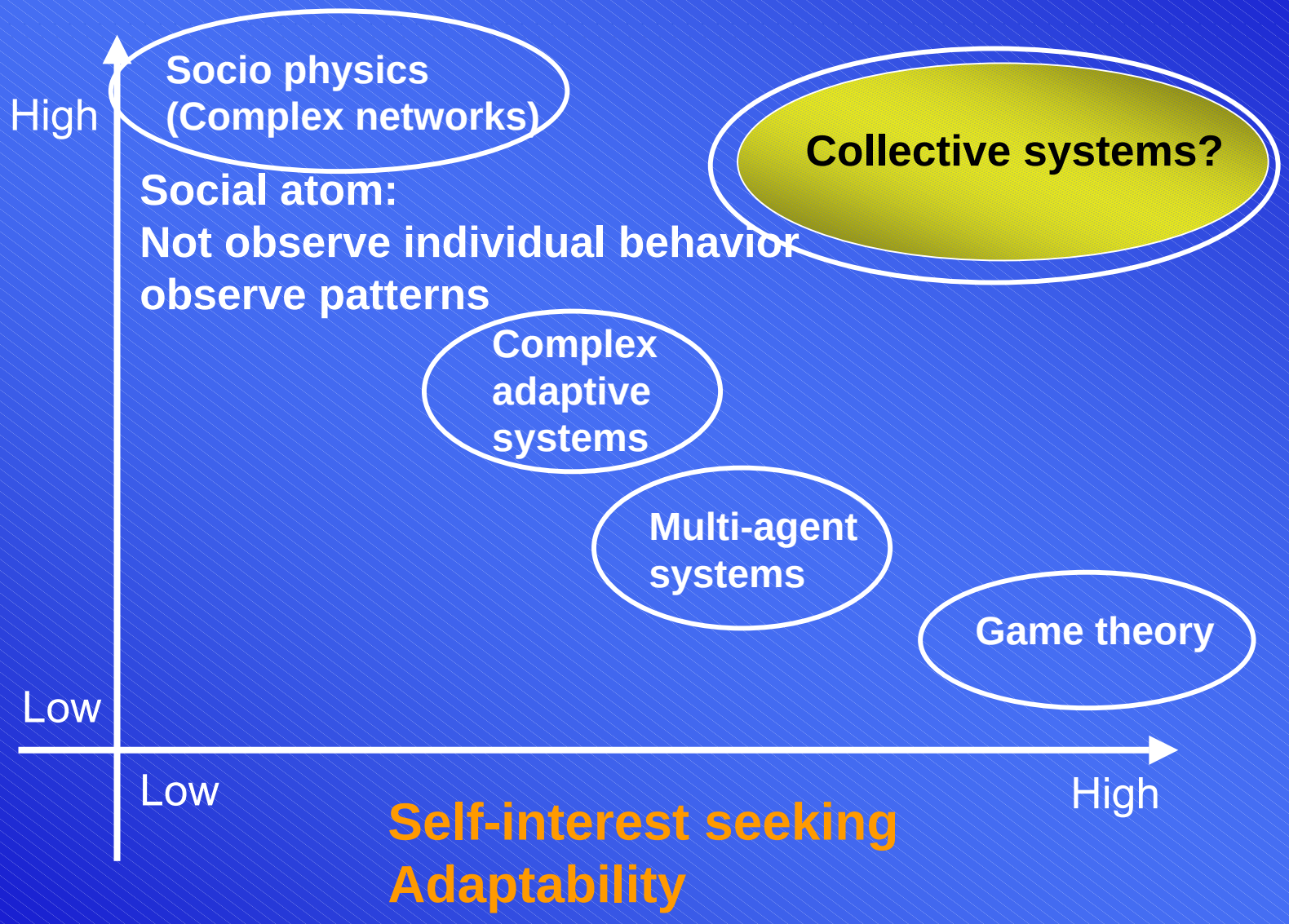
  (Wikipedia depends on positive network effects)

- **Negative network effects result from resource limits**

  : More persons begin to decrease the value of a network

  (daily-life traffic conestions, network overloads)

RESEARCH MAP



Outline

- **Emergence by nature vs. Emergence by design**
- **Madness of crowds vs. Wisdom of crowds**
- **Types of social interactions**

  : Coordination problems

  : Dispersion problems

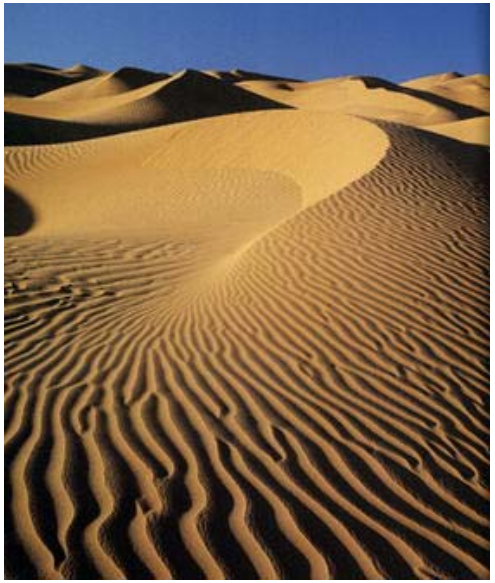
  : Mixed problems
- **Synchronization in complex networks**
- **Emergent intelligence in networked agents**

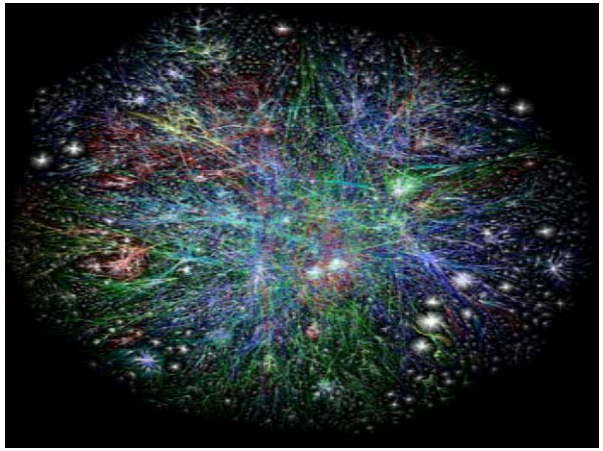
Emergence by Nature

- Emergence by nature (empirical view)
- View emergence as an "innate property" of natural systems

"*Systems self-organize into a complex state, poised between predictable cyclic behavior and unpredictable chaos*"

: Inspires research to discover and explain emergent behaviors





Internet

Emergence by Design

- Emergence by design strategies (operational view)

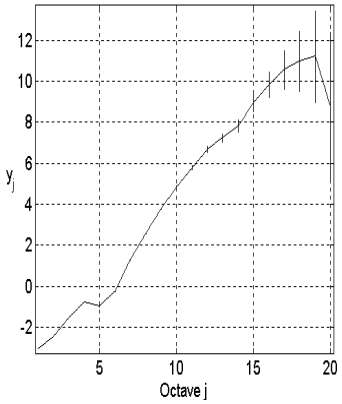
"System-wide behavior emerges from interactions among individual elements"

: Some researchers view emergence as a property that is "designed" into systems

: Inspire research into control techniques to induce desired emergent behaviors

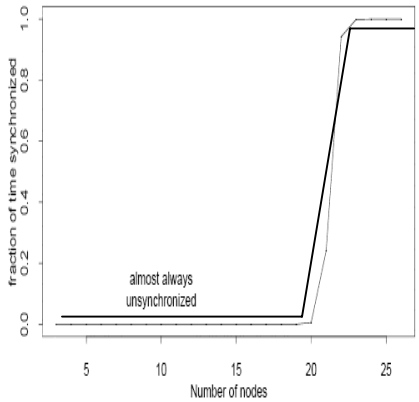
Emergence by Design (2): Illusion of Control?

self-similarities



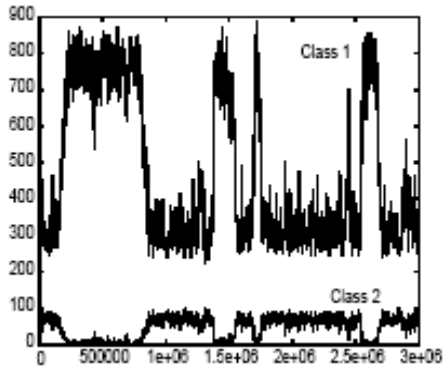
Internet throughput

phase transitions

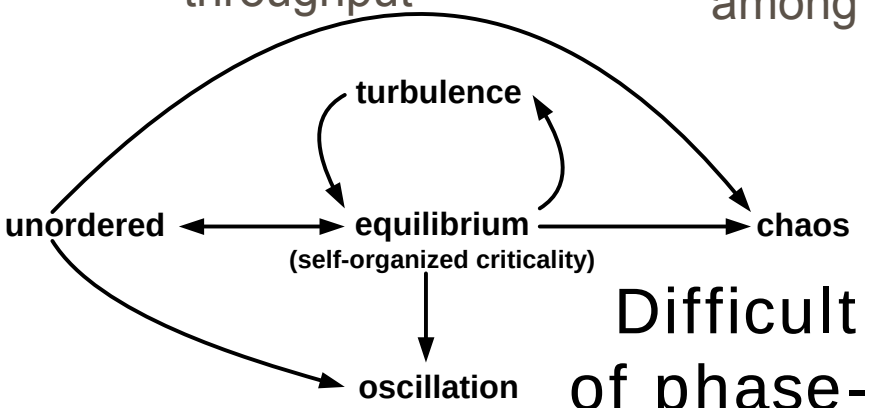


synchronization among routers

Meta-stabilities



distribution of call types in wireless cells



Difficult to predict and control because of phase-transitional behavior

high load ➡ congestion collapse

Madness of Crowds vs. Wisdom of Crowds (1)

- ***Social sciences*** **<crowd psychology: negative sides of human behavior> herding, cascade, group think,…**
- ***Game theory:*** **<the problem of a coordination failure>**
  The existence of externalities lead to coordination failure
- ***Computer science:*** **<the price of anarchy>**
  Selfish behavior may not achieve efficiency at the collective level.

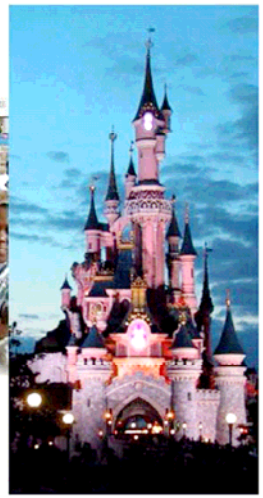
Madness of Crowds vs. Wisdom of Crowds (2)

A large collection of people are smarter than an elite few.

"The Wisdom of Crowds", Surowiecki,(2004)

He suggests new insights regarding how our social activities should be organized.

: The **wisdom of crowds** emerges only under the right conditions (diversity, independence, etc)



Diversity of Social Interactions

- **Type 1: Coordination problems**

Agents are better off if they take the same action.

: Consensus problem (control theory)

: Synchronization (physics/complex networks)

: Herding (economics/psychology)

: Gossip algorithm (computer science)

: Coordination game (game theory)

- **Type 2: Dispersion problems**

Agents are better off if they take the distinct actions.

: Congestion problem (control theory)

: Stock markets (economics)

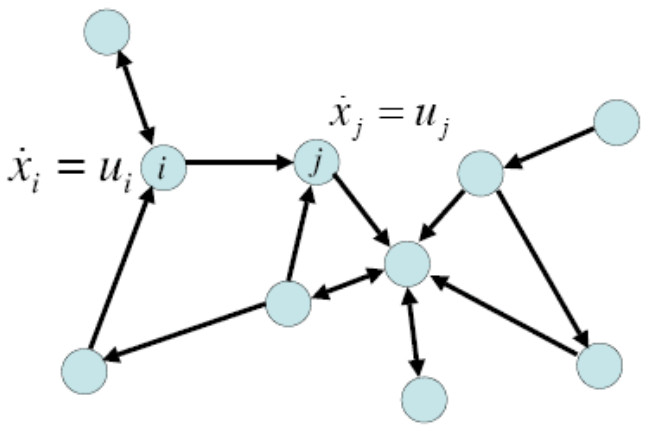
: Minority games (econophysics)

Type 3: Mixture of coordination and dispersion problems

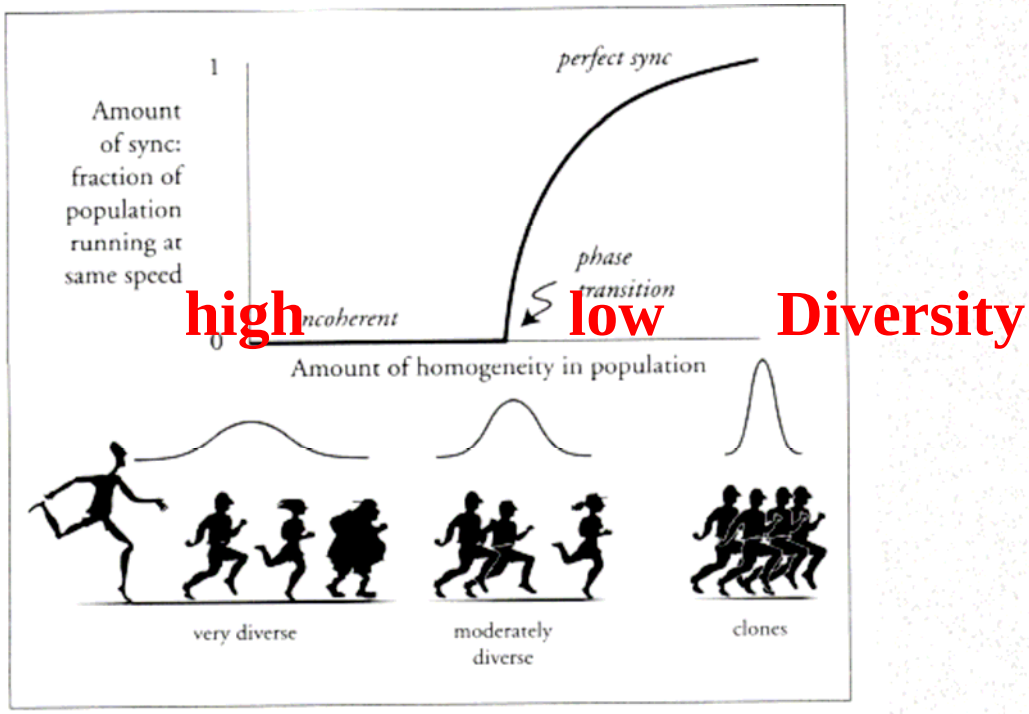
Consensus Problems

- "Consensus" means to reach an agreement regarding a certain quantity of interest that depends on the state of all nodes (subsystems).
- *More specific, a consensus algorithm is a rule that results in the convergence of the states of all network nodes to a common value.*

$$x_i = x_j = \ldots = x_{consensus}$$



Synchronization in Complex Networks



Synchronization: Prevalent appearance in physics and biology

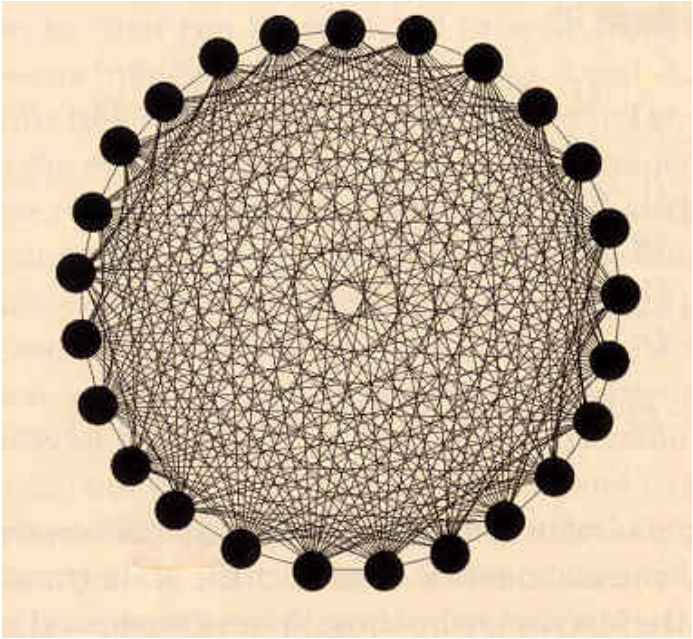
Homogeneity is important for better synchronization

Synchronization in Globally Connected Networks

Observation:

No matter how large the network is, a globally coupled network will synchronize if its coupling strength is sufficiently strong

Good – if synchronization is useful



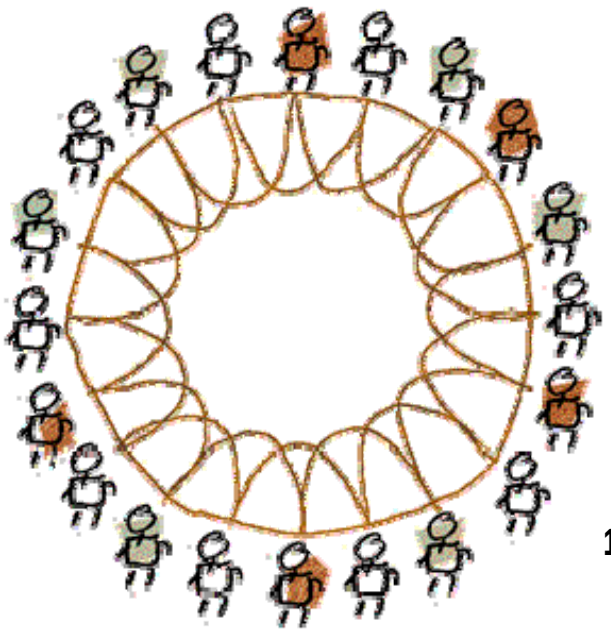
G. Ron Chen (2006)

Synchronization in Locally Connected Networks

Observation:

No matter how strong the coupling strength is,
a locally coupled network will not synchronize if its size is sufficiently large

Good - if synchronization is harmful



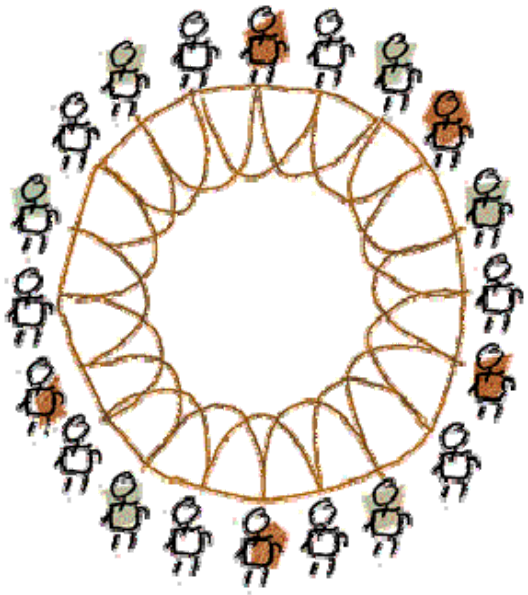
G. Ron Chen (2006)

Synchronization in Small-World Networks

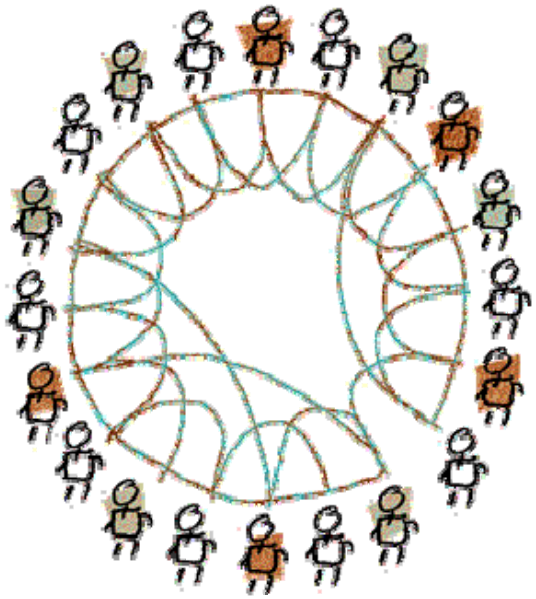
G. Ron Chen (2006)

Start from a nearest neighbor coupled network

small-world network



Add a link, with probability p, between a pair of nodes



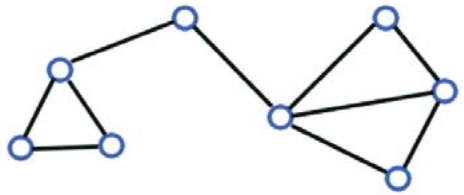
Good news: A small-world network is easy to synchronize!

X.F.Wang and G.R.Chen: Int. J. Bifurcation & Chaos (2001)

Synchronization and Network Topology

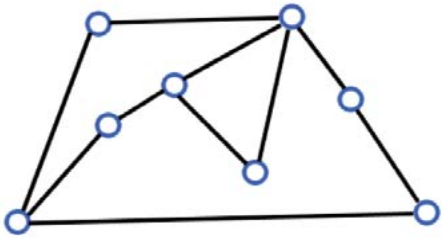
Connectivity of networks does matter for synchronization

Network A



$\lambda_2 = 0.238$

Network B



$\lambda_2 = 0.925$

Laplacian matrix

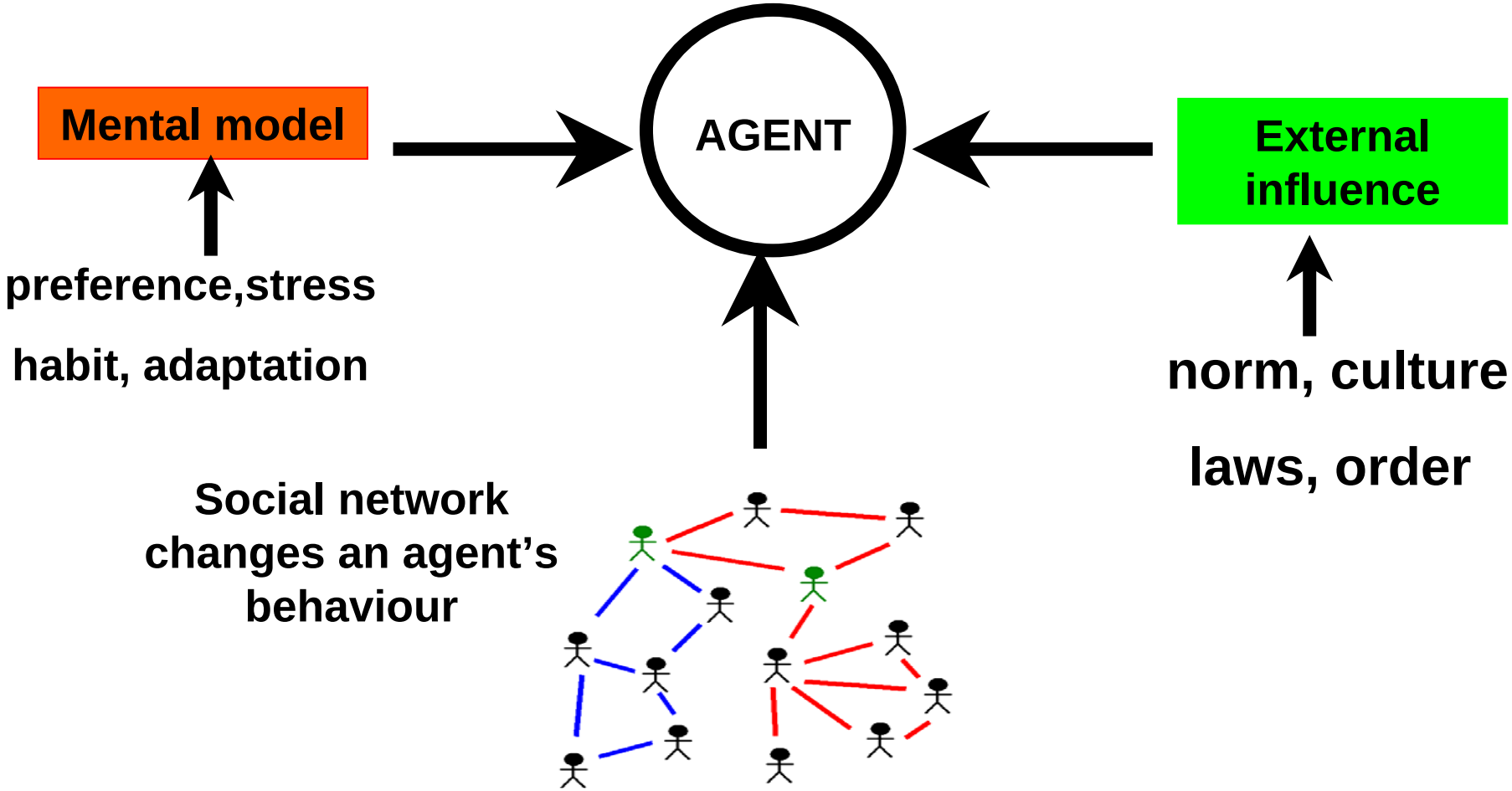
$$\begin{bmatrix} k_1 & & & \{0,-1\} \\ & k_2 & & \\ & & \ddots & \\ \{0,-1\} & & & k_n \end{bmatrix}$$

- **Laplacian matrix = Degree – Adjacency matrix**

- **$\lambda_1 = 0$ is always an eigenvalue of a Laplacian matrix**
- **λ_2 is called the algebraic connectivity, and is a good measure of synchronization.**

Agent vs. Social Atom

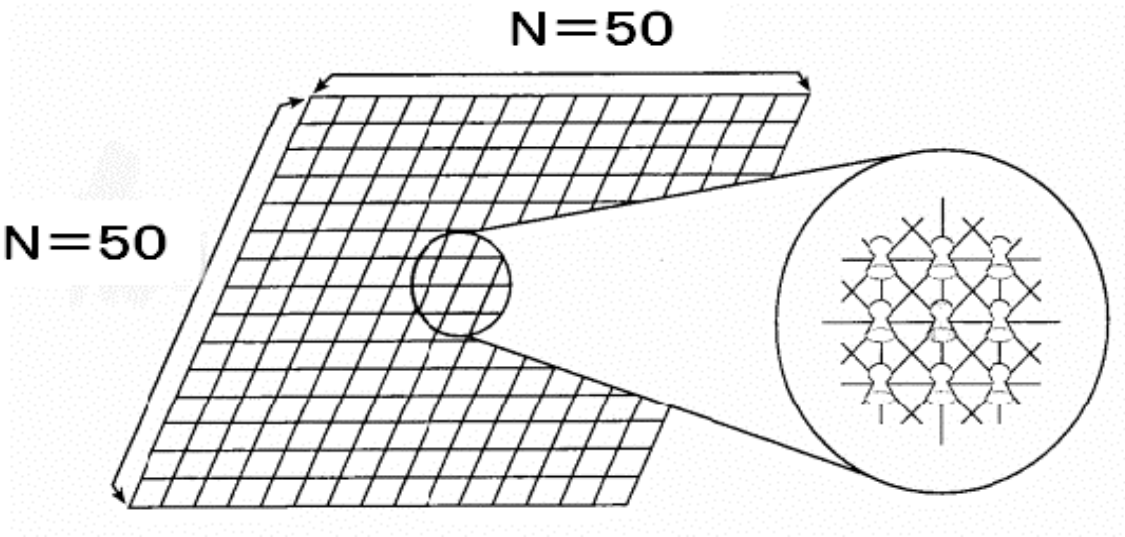
D. Green (2006)

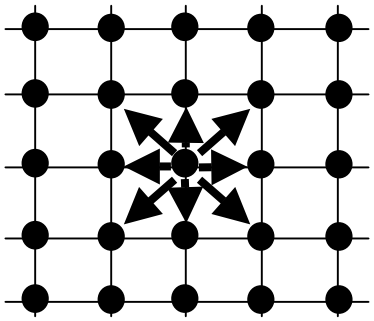


Repeated Games on Networked Agents

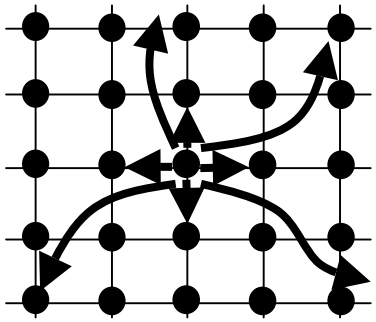
✓ Types of pair-wise interactions

- ❑ Prisoner's dilemma game
- ❑ Coordination game
- ❑ Hawk-dove game
- ❑ Chicken game (battle-of-sexes game)

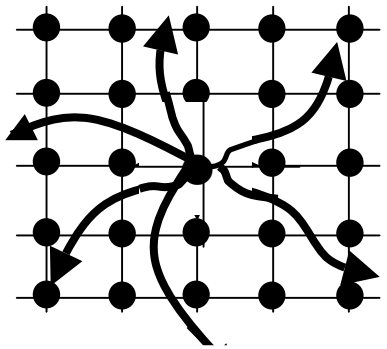




Local model



Small-world model



Random model

Measurement: The Price of Anarchy

- Equilibria of selfish agents are not efficient outcomes

(Social optimal is usually not achieved by Nash equilibrium strategy)

Price of anarchy (POA):

- Quantify inefficiency in terms of a global objective

$$\text{Price of Anarchy} = \frac{\text{optimal objective function value}}{\text{objective function value at Nash equilibrium}}$$

Collective intelligence do matter to decrease POA

Fixed Rule vs. Rule Evolution

- ***Learning***: Memory-based strategy choice : Memory $\rightarrow A_t$ (strategy at time t)
- ***Is a short memory enough or a longer memory may be necessary in more complex games?***

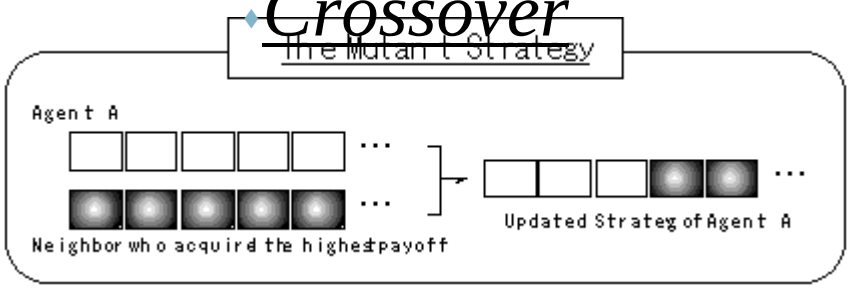
  : Reactionary strategy with history one: $(h_{t-1}) \rightarrow A_t$

  : Finite history of k: $\{ (h_{t-k}, \ldots, h_{t-2}, h_{t-1}) \} \rightarrow A_t$

- ***Agents play the game repeatedly by evolving a rule rather than by a fixed rule such as TFT.***

bit	past strategy		strategy at t
	Own	Opp	
4	0	0	#
5	0	1	#
6	1	0	#
7	1	1	#

- *Crossover*



Simulation Results (1)

(1) Dilemma game

	C	D
C	3, 3	0, 5
D	5, 0	1, 1

POA=3

(2) Coordination game

	C	D
C	1, 1	-9, 0
D	0, -9	0, 0

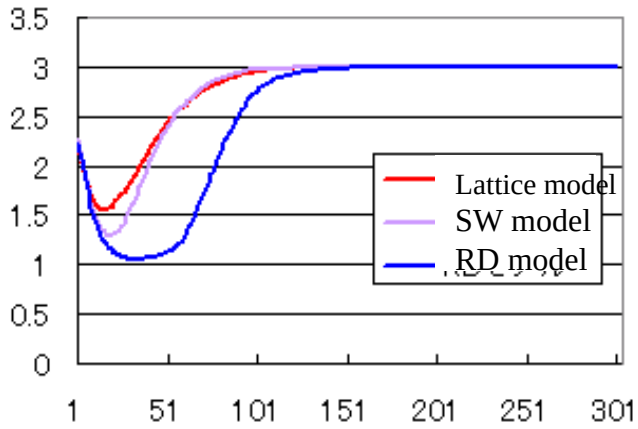
POA=Infinity

(3) Hawk-Dove game

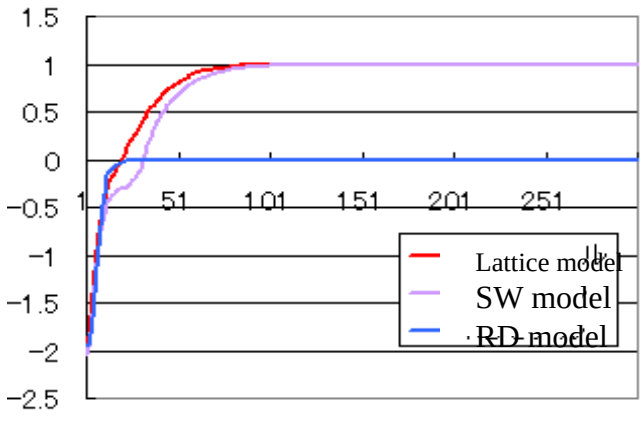
	C	D
C	5, 5	0, 10
D	10, 0	-1, -1

POA=5

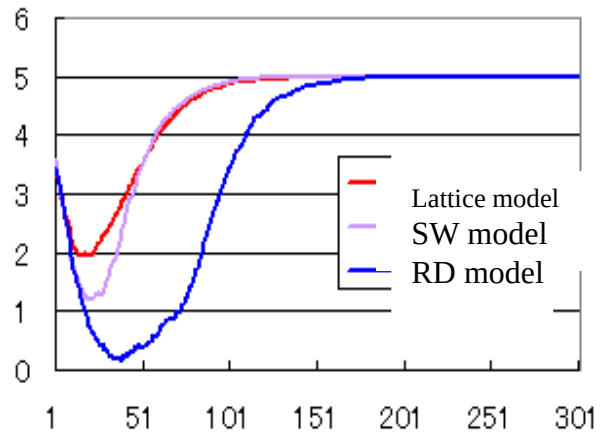
The average payoff per generation



POA=1



POA=1

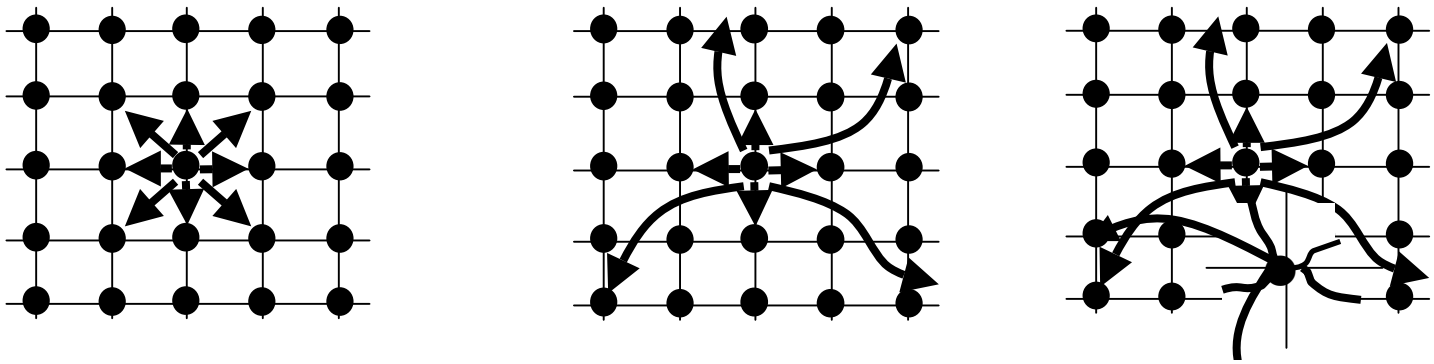


POA=1

Synchronization in Games on Networks

- **What is the impact of the interaction structure on synchronization in games on networks?**

- **The lattice networks, where the connectivity among agents is mostly reserved, foster to promote to better synchronization**



Local model

Small-world model

Random model

Social Interaction: Type 2

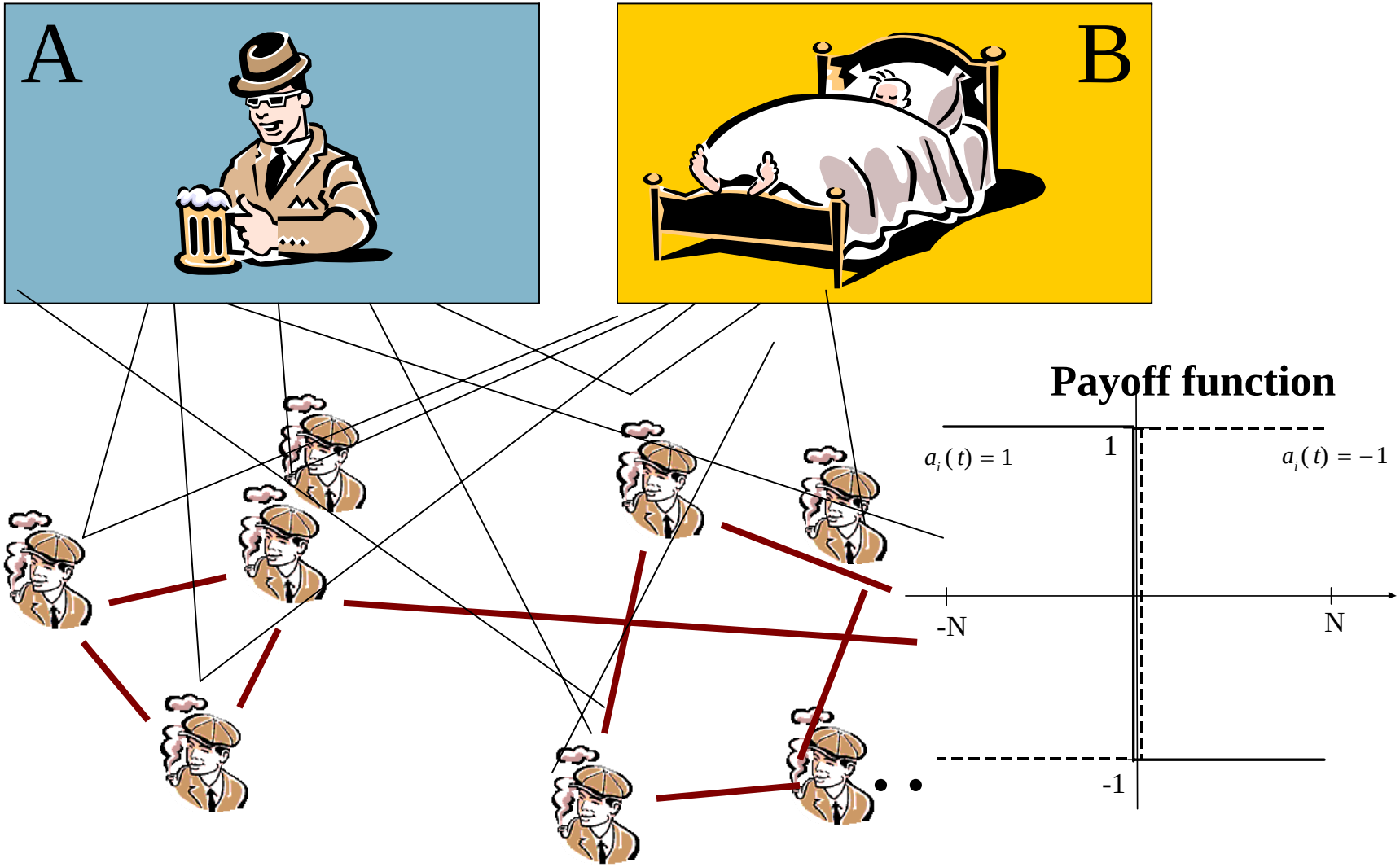
- **Type 2: Dispersion problems:**

Agents are better off if they take the distinct actions.

: Stock markets

: Minority games (game theory)

The El Farol Bar Problem/ The Minority Games



Agents gain if they are in the minority side.

Global Minority Games

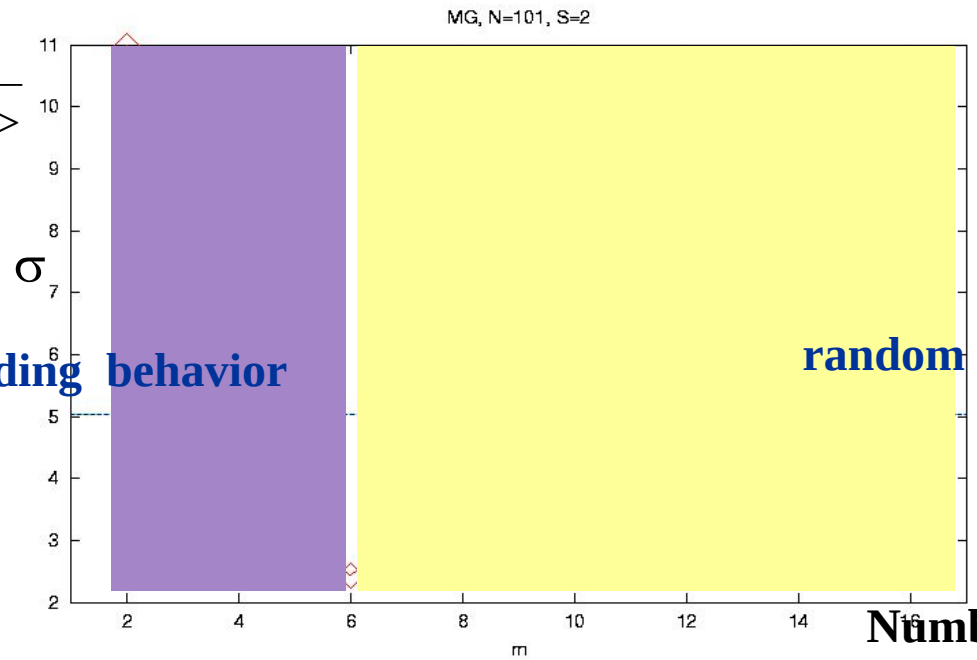
Minority game: important for the study of fluctuation.

Moderate diversity: important for emergence of coordination

(inefficiency)

$$\sigma = \sqrt{<(A - N/2)^2>}$$

A=# of agents who attended



Challet, Zang (2005)

Nash equilibrium

(S1: 0.5, S2: 0.5)

Number of behavioral rules

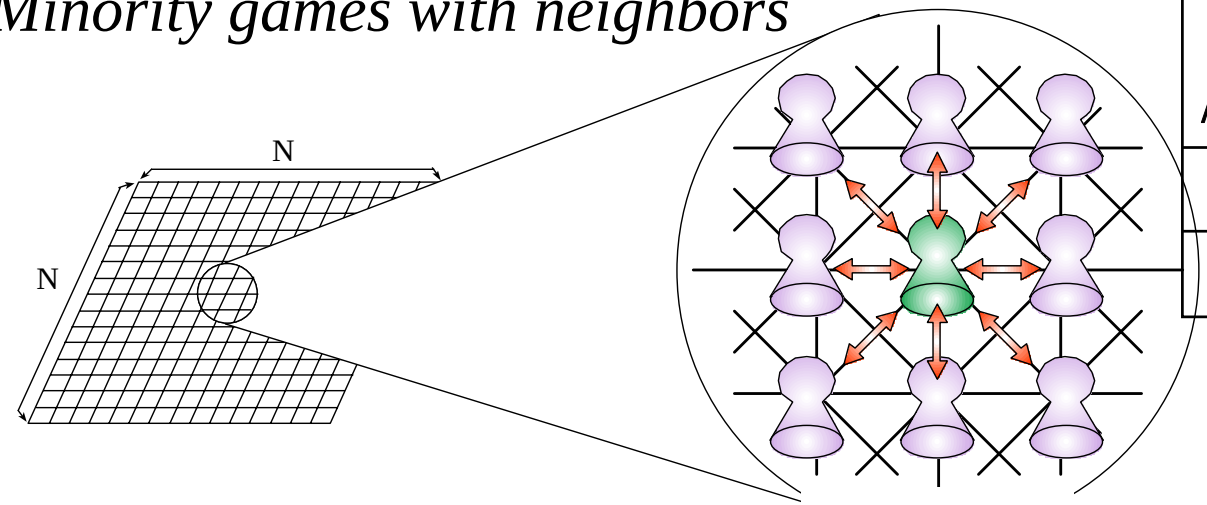
homogeneous

diversity

Efficient coordination is emergent

Local Minority Games with Coupled Strategy

Minority games with neighbors



Agent \ Other agent	S_1	S_2
S_1	0, 0	1, 1
S_2	1, 1	0, 0

Payoff matrix of two agents

Give-and-Take Rule

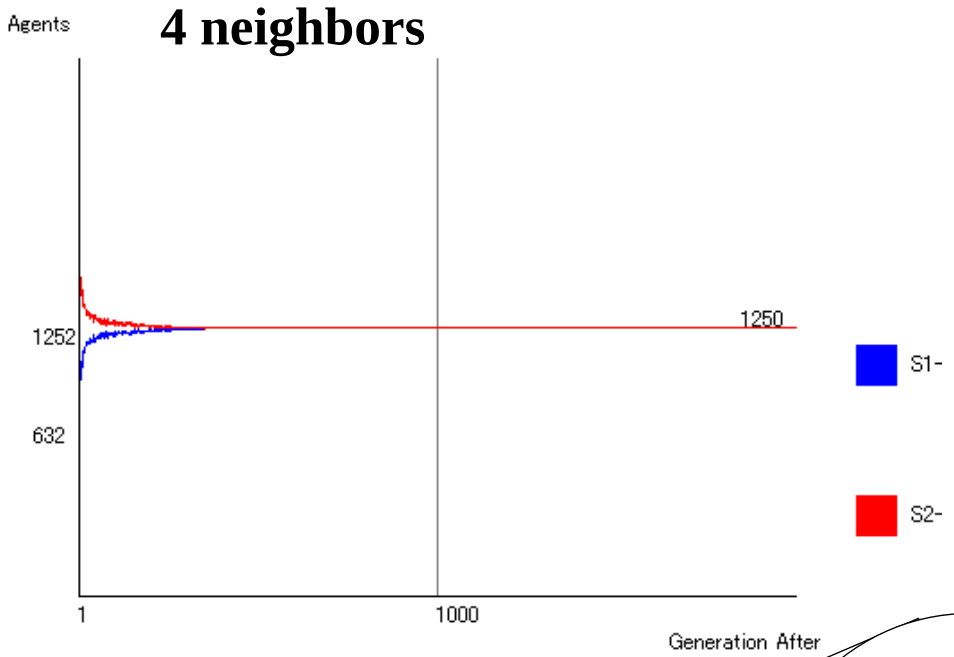
(in contrast with win-stay, loose-shift)

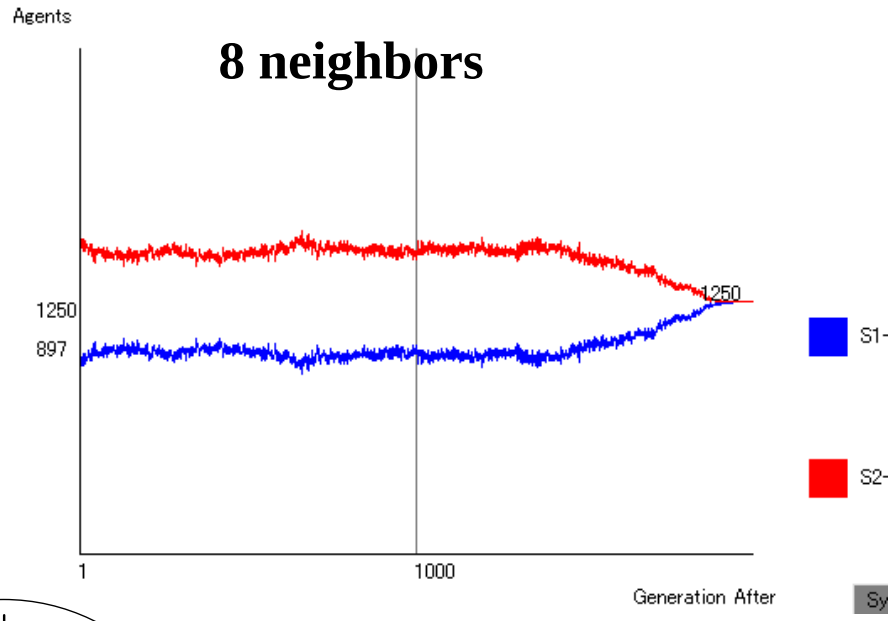
$$p_i(t) < 0.5, a_i(t) = S_1(Gain) \Rightarrow a_i(t+1) = S_2$$

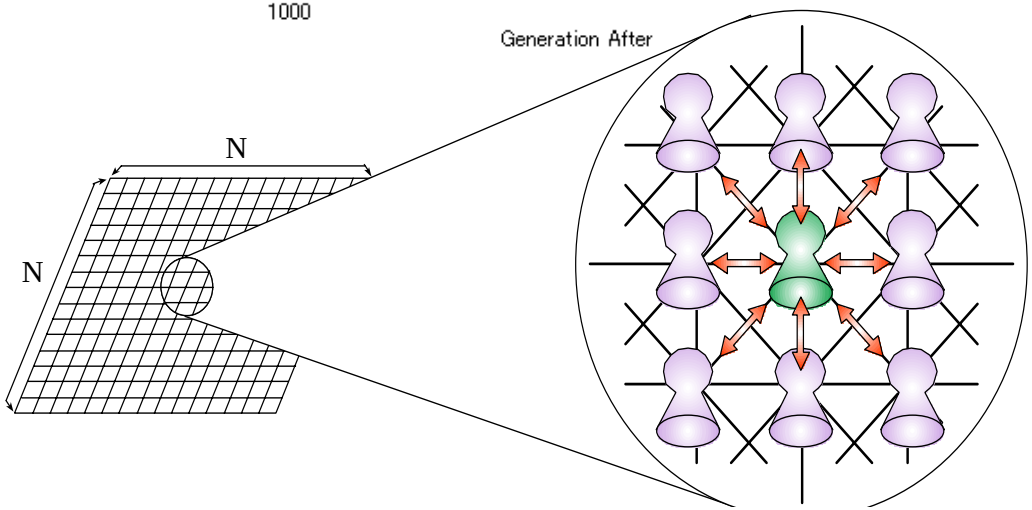
$$p_i(t) > 0.5, a_i(t) = S_2(Gain) \Rightarrow a_i(t+1) = S_1$$

$p_i(t)$ *: The proportion of agents choosing* S_1

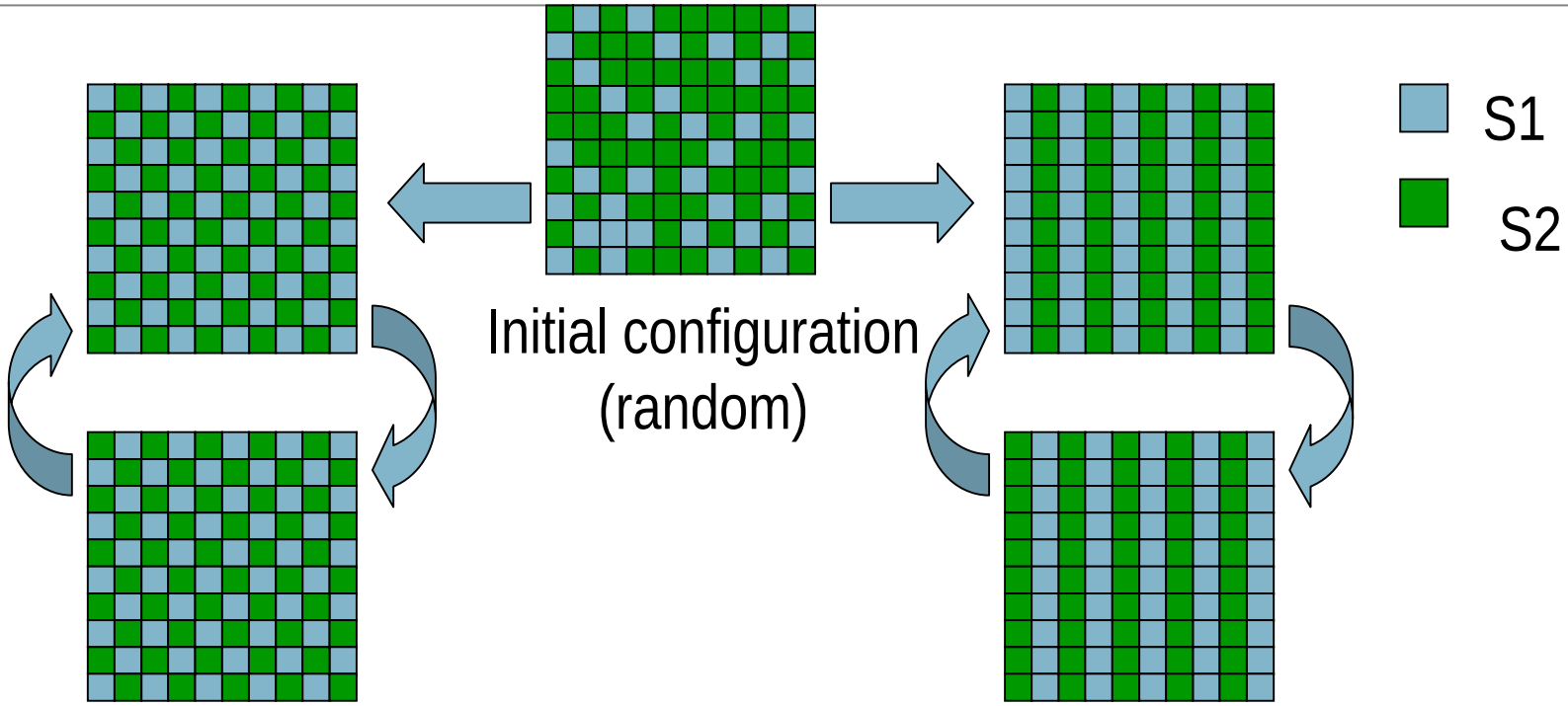
Emergent Coordination in Local Minority Games







Synchronized Behavior and Emergence of Collective Intelligence



Neighborhood size = 4

POA=1

Other agent / Agent	S_1	S_2
S_1	0 0	1 1
S_2	1 1	0 0

Neighborhood size = 8

POA=1

Generalized Rock-Scissors-Paper Games

- λ =2: Conventional R-S-P game
- λ >2: Dispersion games

Agent A / Agent B	S1 (Rock)	S2 (Scissor)	S3 (Paper)
S1 (Rock)	1 / 1	0 / λ	λ / 0
S2 (Scissor)	λ / 0	1 / 1	0 / λ
S3 (Paper)	0 / λ	λ / 0	1 / 1

POA=1.5

- A Nash equilibrium strategy: (S_1: 1/3, S_2: 1/3, S_3: 1/3)
- The expected payoff at Nash equilibrium : (λ +1)/3
- Pareto-efficiency (average payoff): λ /2

But a winner gets, and loser gets nothing.

Rock-Scissors-Paper Games on the Lattice(1)

Co-existence of competing species:
:Kerr *et al.* (2002) demonstrated spatial structure allows biodiversity using RSP game

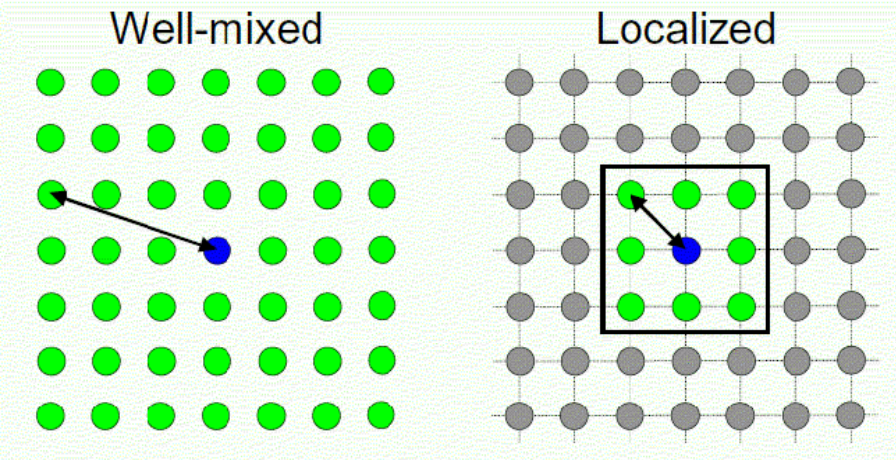
A \ B	S_1 (Rock)	S_2 (Scissor)	S_3 (Paper)
S_1 (Rock)	0, 0	1, −1	−1, 1
S_2 (Scissor)	−1, 1	0, 0	1, −1
S_3 (Paper)	1, −1	−1, 1	0, 0

<Evolutionary Process>
: A pair plays Rock-Paper-Scissors, and winner replaces loser

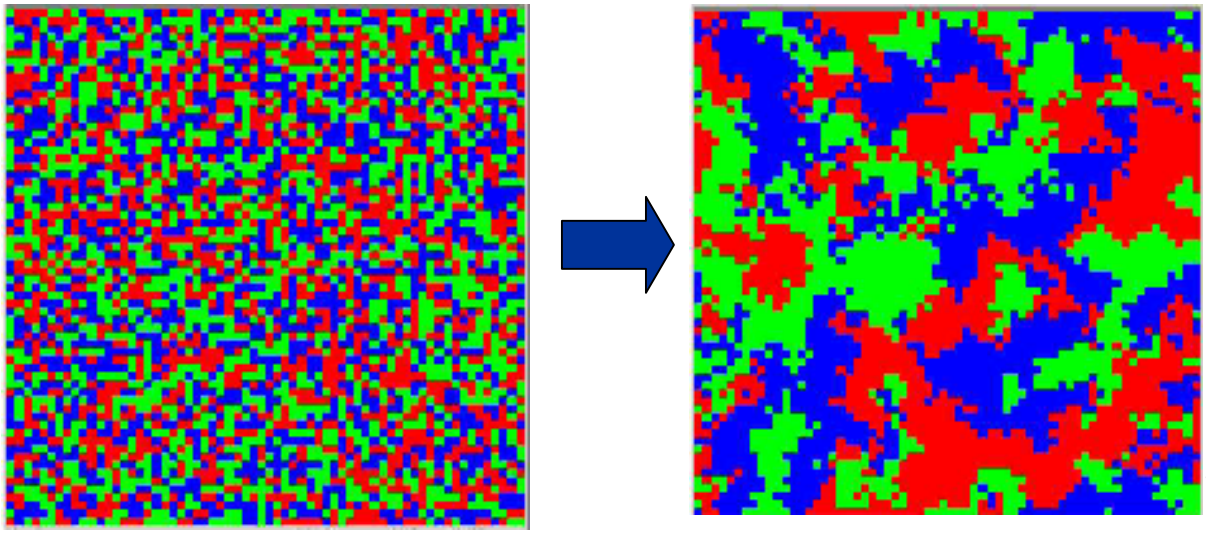
- **R + P→2P (Paper wins and increases one more paper)**
- **P + S→2S (Scissors wins and increases one more scissors)**
- **S + R→2R (Rock wins and increases one more rock)**

Rock-Scissors-Paper Games on the Lattice(2)

Well-mixed model: two randomly chosen agents can be paired
Localized model: agents can only be paired with neighbors



Forming niches is not enough
For the study of emergence



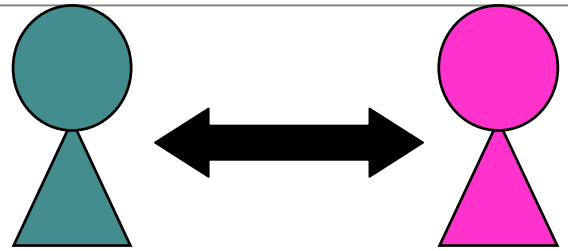
: Rock

: Scissor

: Paper

RSP Games with Coupled Strategy

•Previous Strategy		•Next Strategy
•Own	•Opponent	
•0	•0	•#
•0	•1	•#
•0	•2	•#
•1	•0	•#
•1	•1	•#
•1	•2	•#
•2	•0	•#
•2	•1	•#
•2	•2	•#



- ***Coupled strategy choice***

Strategy choice is driven by the outcomes of the joint actions

Evolution of coupling rule

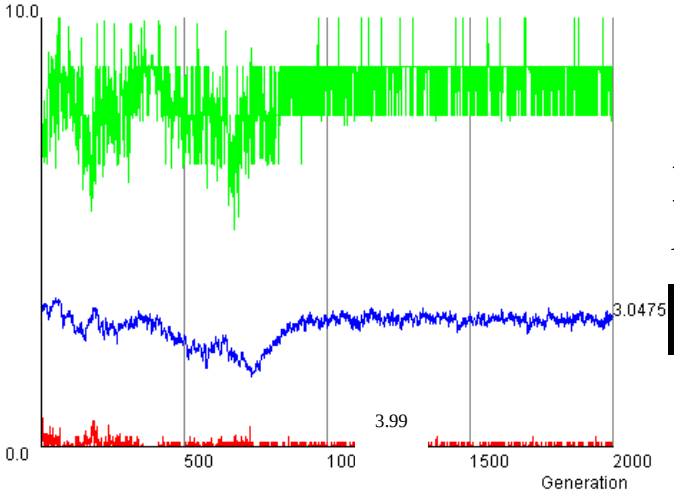
Agents update the coupling rule by changing value of # .

0 : Rock,
1: Scissor,
2: Paper
#: 0, 1 or 2

Simulation Results: λ =10

Nash equilibrium: 3.3
Pareto-efficiency: 5
POA=1.5

: Highest payoff



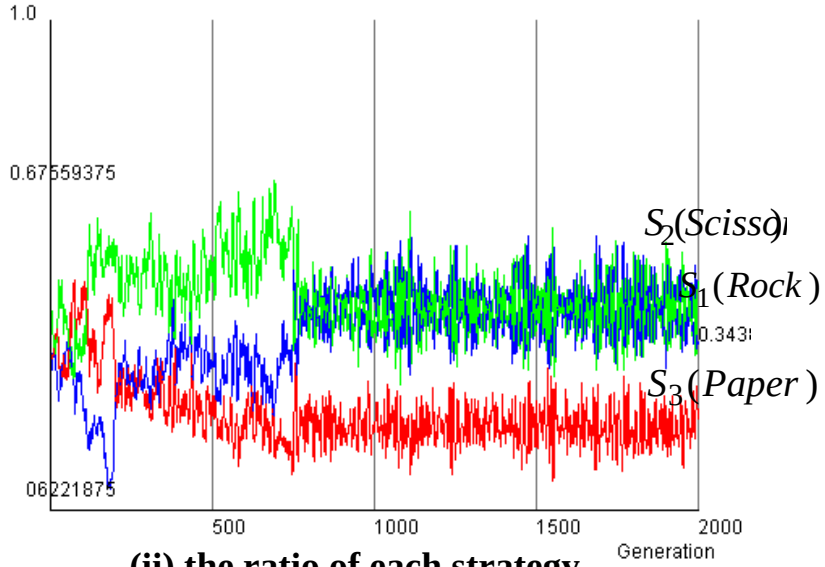
Error rate: 0%

Average Payoff

2.8

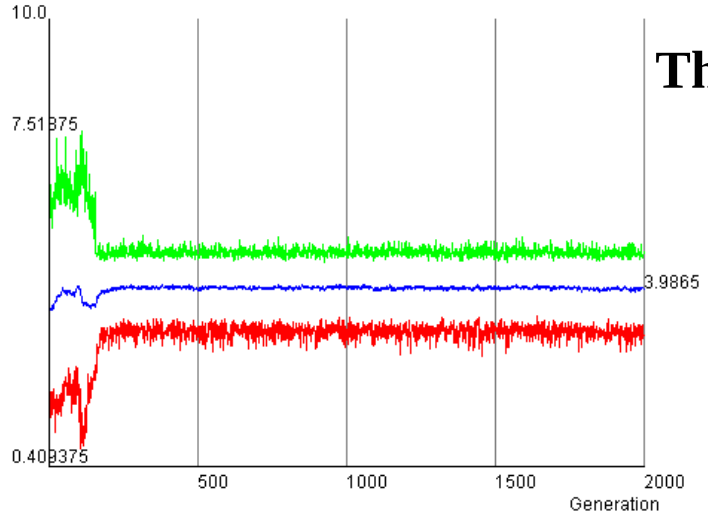
Lowest Payoff

(i) The average payoff per agent



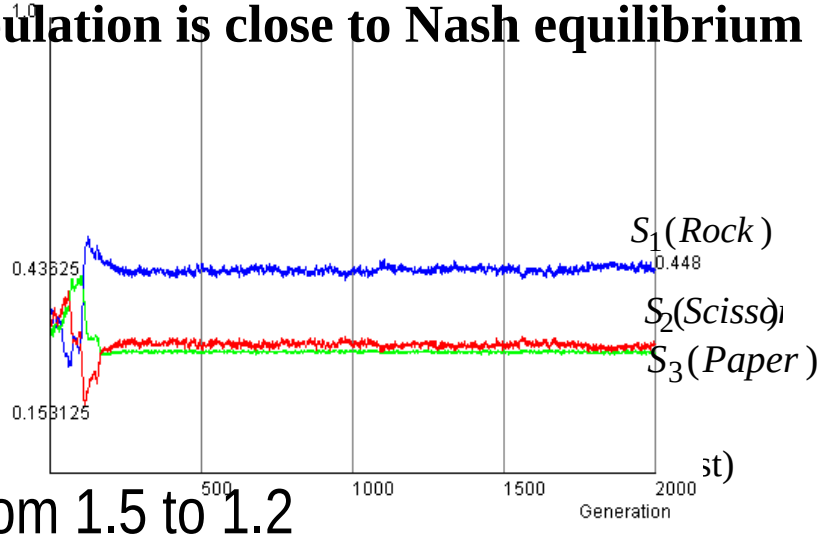
(ii) the ratio of each strategy

The strategy population is close to Nash equilibrium



Error rate: 10%

4.0



POA: decreased from 1.5 to 1.2

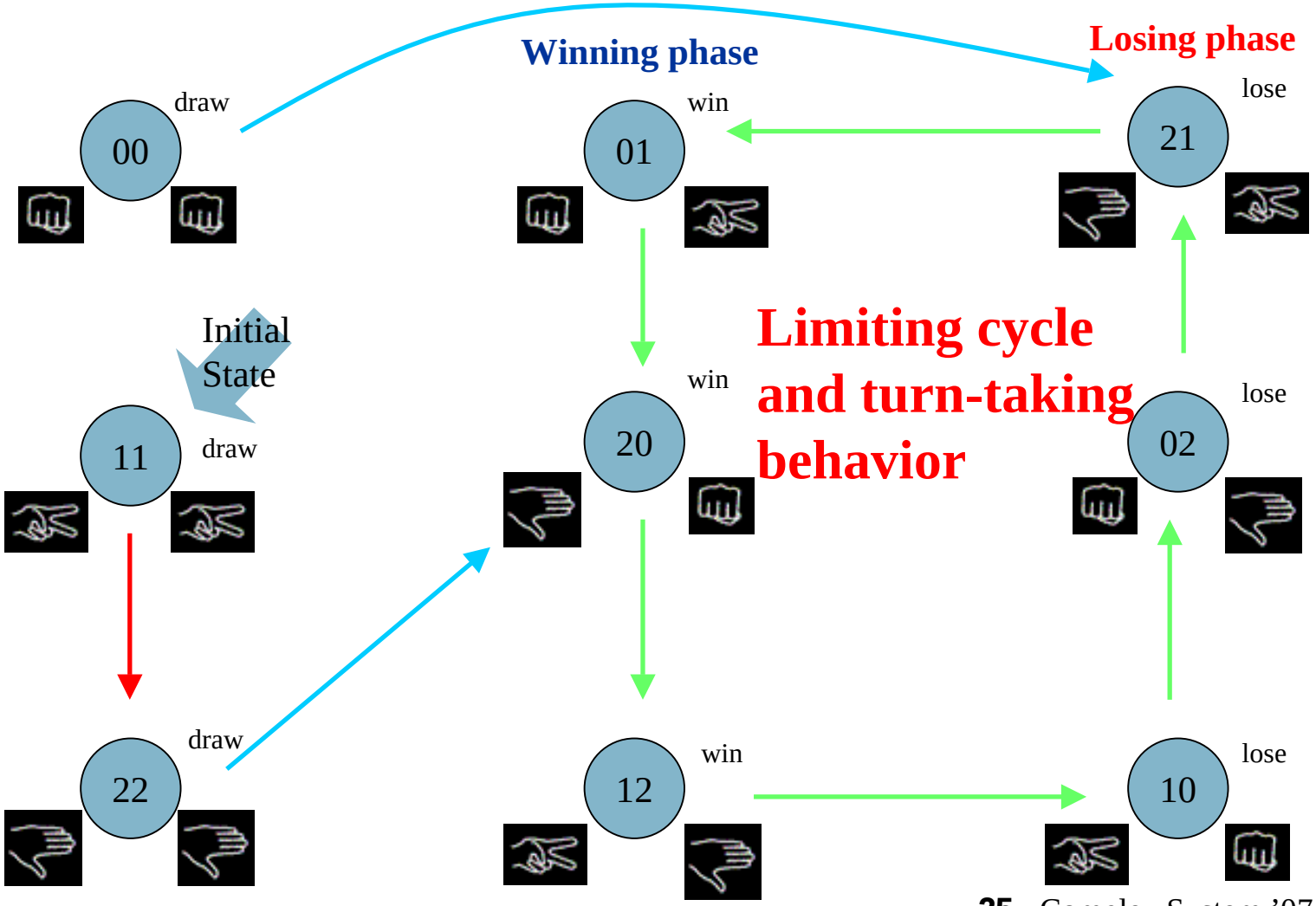
What Did Agents Learn?

The rules of 2,500 agents were aggregated into 8 rules with some common values.

	00	01	02	10	11	12	20	21	22	Number of Agents with the Same Rule
Rule Type 1	2	2	2	0	2	1	1	0	2	126
Rule Type 2	2	2	2	0	2	1	1	0	0	76
Rule Type 3	1	2	2	0	2	1	1	0	2	58
Rule Type 4	1	2	2	0	2	1	1	0	0	54
Rule Type 5	2	2	2	0	0	1	1	0	2	40
Rule Type 6	1	2	2	0	0	1	1	0	2	19
Rule Type 7	2	2	2	0	0	1	1	0	0	17
Rule Type 8	1	2	2	0	0	1	1	0	0	10

Phase Diagram of the Strategy Choices

They converge into the limiting cycle where desirable synchronization is emerged



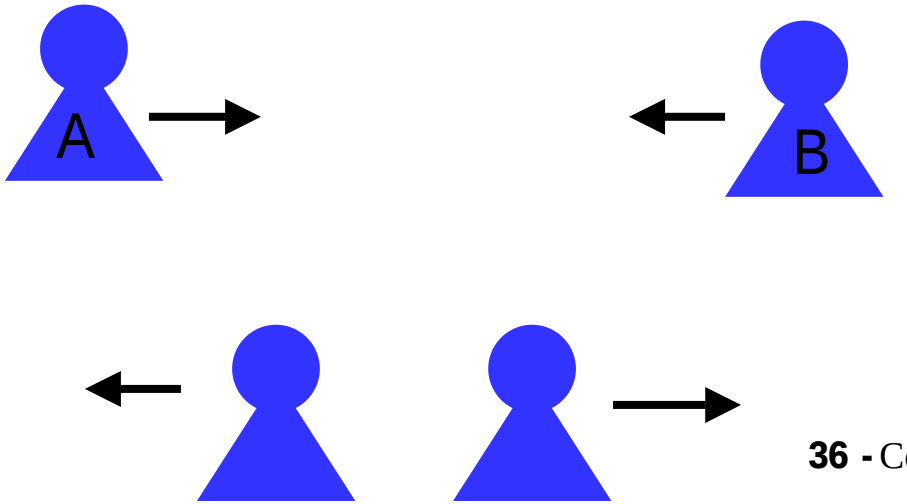
Social Interaction: Type 3

Type 3: Mixture of coordination and dispersion

Economics:Tug-of-war between increasing returns and decreasing returns

Human behavior: Reconcile the tension between centripetal and centrifugal

Close, but not too close

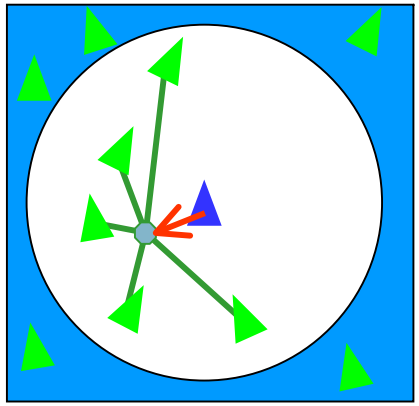


BOID Model: Flocking Formation

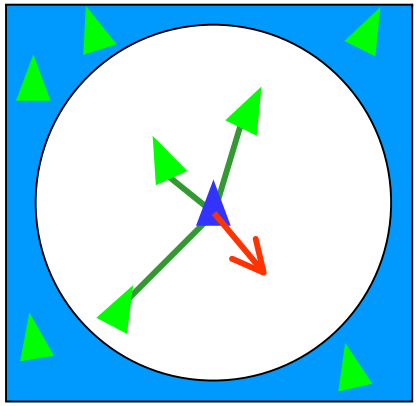
Craig W. Reynolds (1994)

Frocking Behavior emerges with three coupling rules

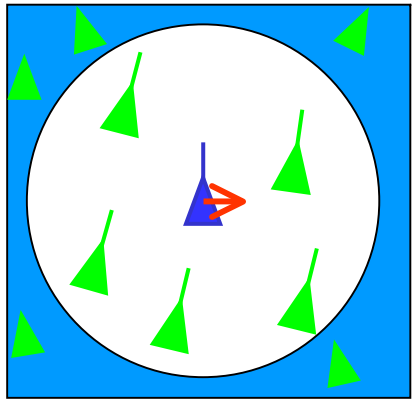
- **Cohesion**: Head for the perceived center of mass of the neighbors.
- **Separation**: Don't get too close to any neighbor or object.
- **Alignment**: Try to match the speed and direction of nearby neighbors.



Cohesion



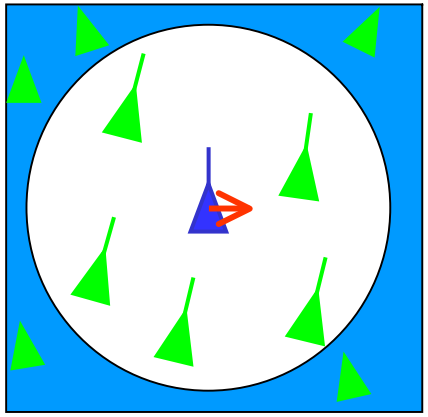
Separation



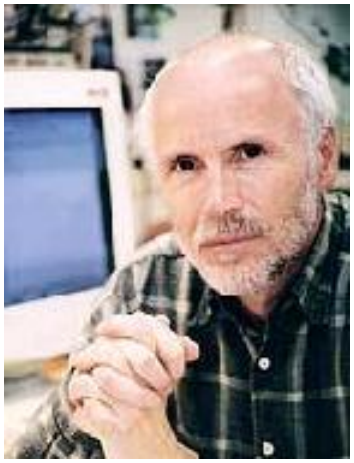
Alignment

Flocking: Social Atomic View

Alignment



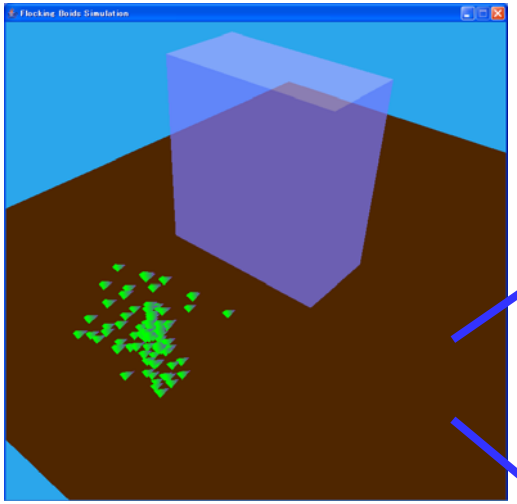
Vicsek considered consensus problem,
and found the phase transition in flocking

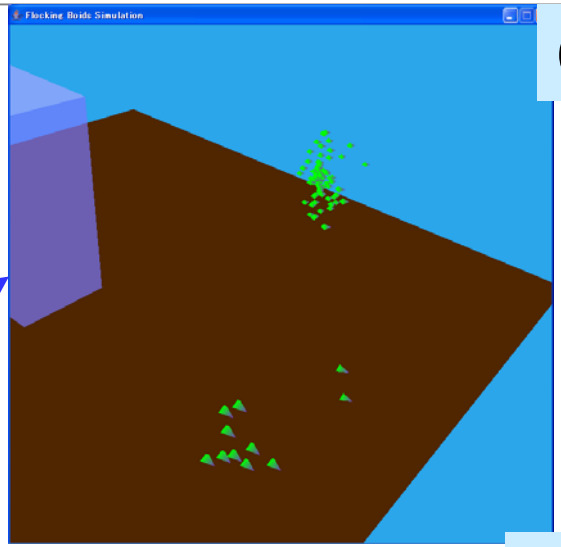


T. Vicsek

Vicsek T,etc: Novel type of phase transition in a system of self-driven particles. Phys Review Letter (1995); 75.

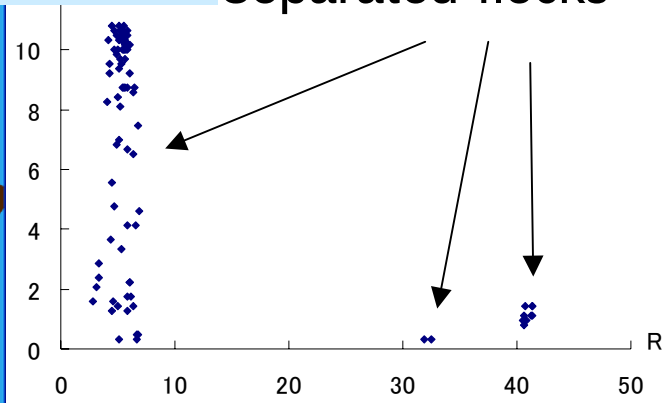
Flocking with Adaptive Coupling Rules





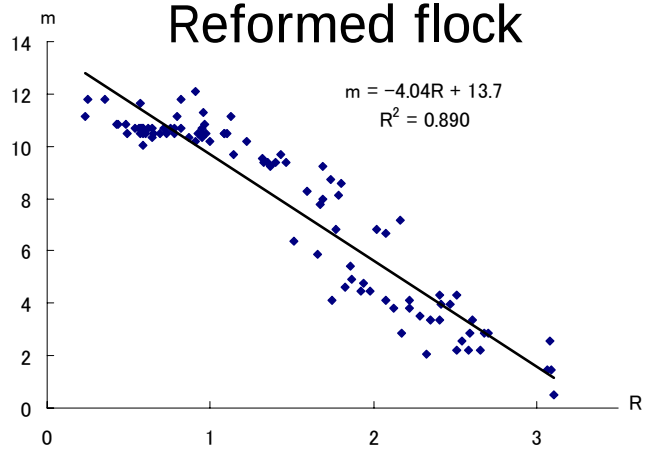
Case 1

Separated flocks



Case 2

Reformed flock



Task: obstacle avoidance while sustaining flock

Aoyagi, M. and A. Namatame, "Self-Guidance of Massively Flocking Behavior", Proceedings of the International Joint Workshop on Massively Multi-Agent Systems and Challenges in Large-Scale Coordination in Multi-Agent Systems, May 9 2006.

Flocking Behavior: Agent's View

Force of an agent

$$\vec{F}_{fi} = \vec{F}_{ci} + \vec{F}_{si} + \vec{F}_{ai} = \underbrace{\left(w_c - \frac{w_s}{D} \right) \vec{e}_D}_{\text{Adaptive cohesion \& separation}} + \underbrace{w_a \vec{e}_V}_{\text{Adaptive alignment}}$$

$$\begin{cases} D = \left| \sum_j^{n_i} \vec{d}_{ij} \right| \\ \vec{e}_D = \dfrac{\sum_j^{n_i} \vec{d}_{ij}}{\left| \sum_j^{n_i} \vec{d}_{ij} \right|} \end{cases}, \quad \begin{cases} V = \left| \sum_j^{n_i} \vec{v}_{ij} \right| \\ \vec{e}_V = \dfrac{\sum_j^{n_i} \vec{v}_{ij}}{\left| \sum_j^{n_i} \vec{v}_{ij} \right|} \end{cases}$$

Adaptive cohesion & separation

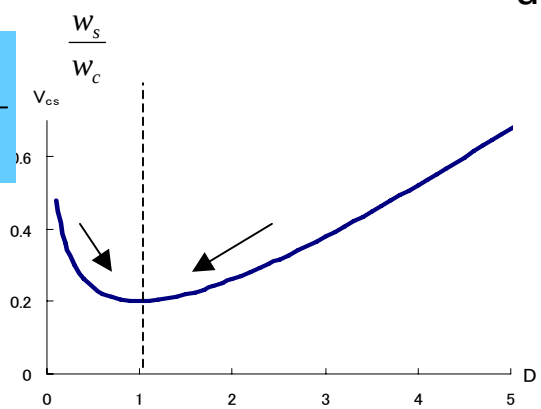
(combine attractive force and repulsive force)

Force $\vec{F}_{csi} = \left(w_c - \frac{w_s}{D} \right) \vec{e}_D$

the sum of the position vector

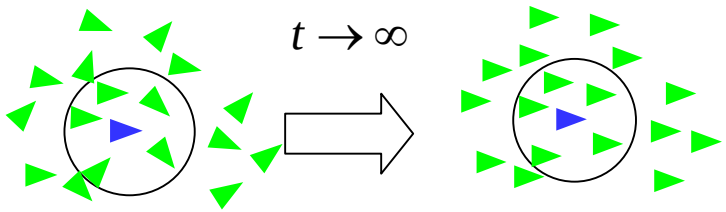
$$t \to \infty \Rightarrow D = \left| \sum_j^{n_i} \vec{d}_{ij} \right| \to \frac{w_s}{w_c}$$

$$\phi_{fi} = w_c D - w_s \log D$$



Adaptive alignment

consistent velocity: consensus



different velocities

same velocity

Consensus: the sum of the relative velocity vector

$$t \to \infty \Rightarrow V = \left| \sum_j^{n_i} \vec{v}_{ij} \right| \to 0$$

Secret of Emergent flocking:
Self-control with implicit potential function

Summary (1)
Self-interest vs. Mutual Benefit

- **Self-interested agents are faced with the dilemma of acting in their own interest or pursuing a more cooperative action in social contexts**

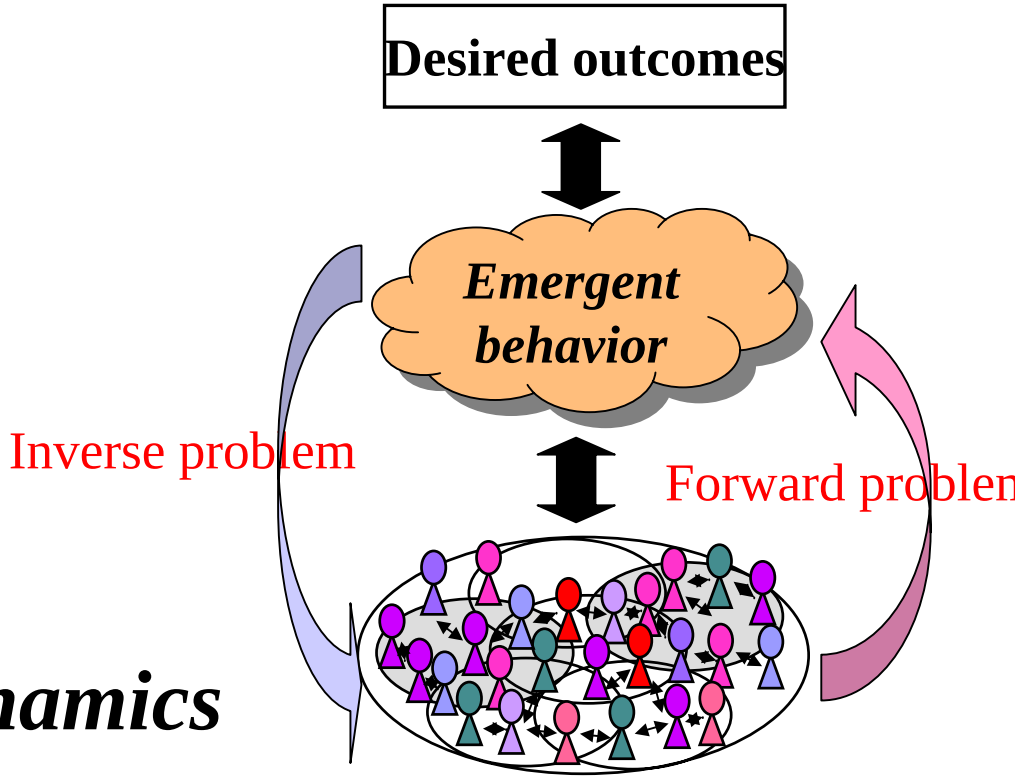
- **A challenging task is to identify conditions under which agents are more coordinated than they are acting in their own interest.**

Summary (2)

Secret of Emergent intelligence:
Better ways of couplings

: Coupling with aggregates (micro-macro loop)

: Coupling with neighbors



Coupled evolutionary dynamics would work for better coordination with mutual benefits

Social interaction of agents with micro-motives

Concluding Remarks (1): Five Stages of Research

1) Observe: Gather data to demonstrate power law behavior in a system.
2) Interpret: Explain the import of this observation in the system context.
3) Model: Propose an underlying model for the observed behavior of the system.
4) Validate: Find data to validate (and if necessary specialize or modify) the model.
5) Control: Design ways to control and modify the underlying behavior of the system based on the model.

Focus on control issues (guidance) : Lots of open research problems in the study of complex systems

Concluding Remarks (2): Challenging Issues

How to control smarter agents using ICT

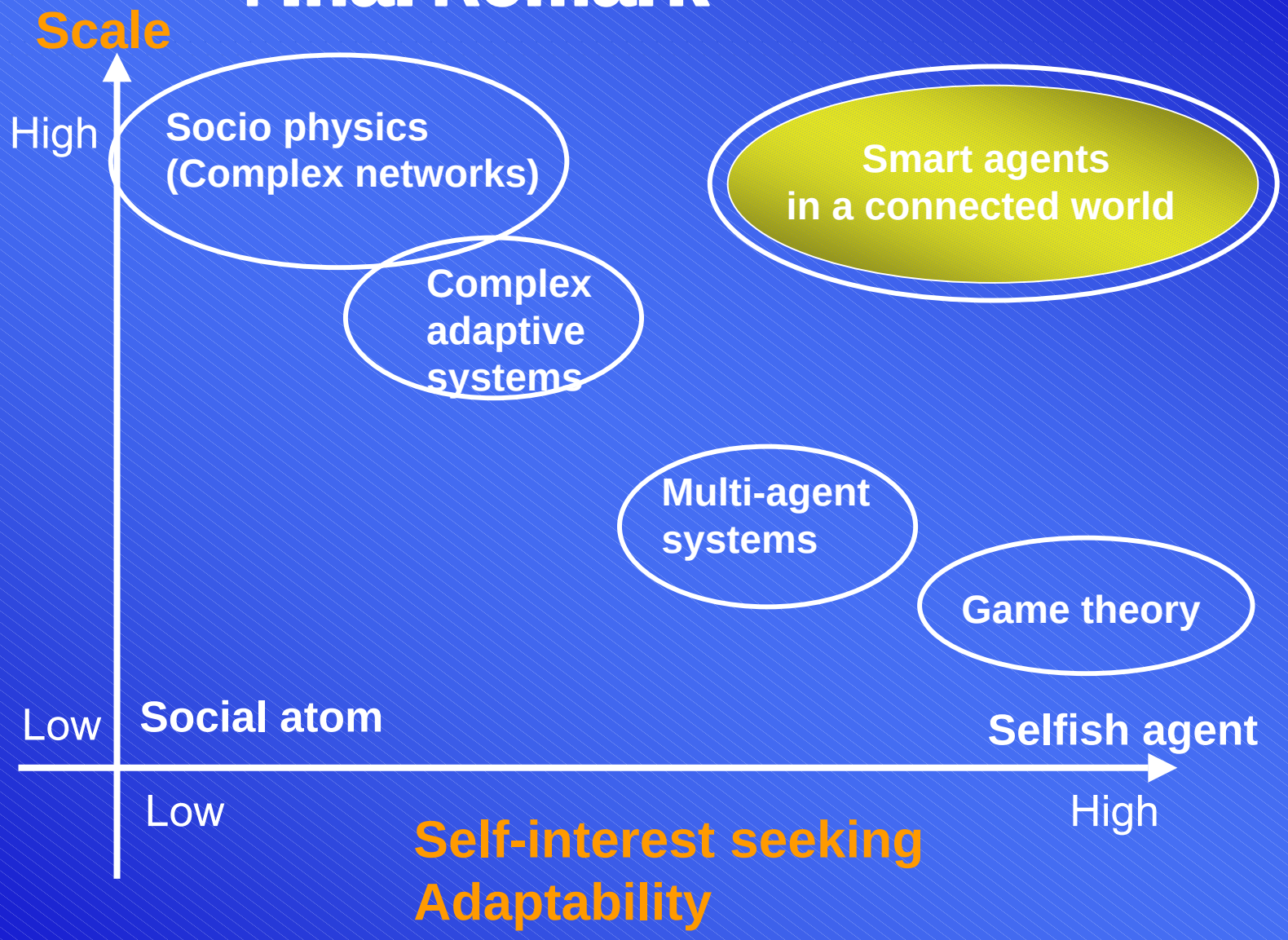
(ICT:Information/Communication Technology)

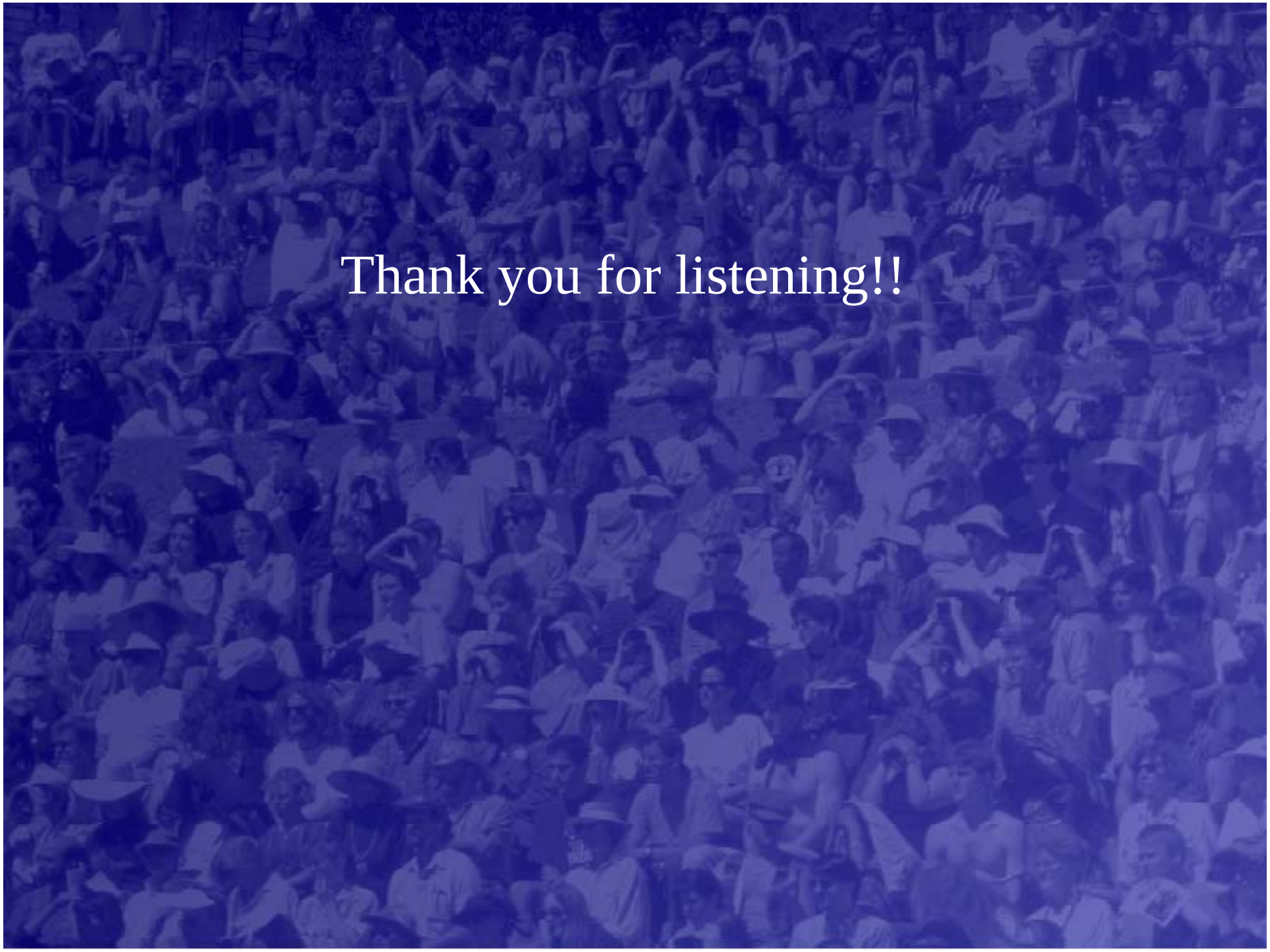
In-Car Navigation Systems

- Smart intersections
- Smart highways
- Smart 'skyways'
- Smart dispatch of urban emergency vehicles
- Smart routing of people and vehicles

- **Smart agents often change their behaviors by getting information on the aggregate using ICT**
- **Congestion controls in a networked world should receive much attention**

Final Remark





Thank you for listening!!