Soft-control on Multi-agent Systems

Jing HAN
The Complex Systems Research Center
Academy of Mathematics and Systems Science
Chinese Academy Sciences, Beijing, China.

Network and Complex Systems Talk, Indiana University, Dec. 2012.

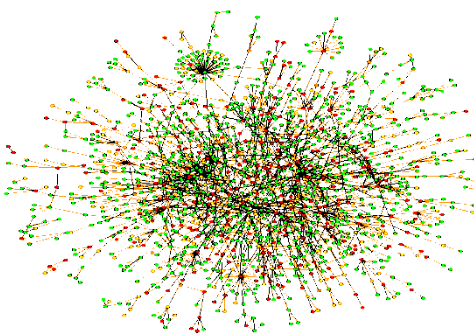
Conclusion

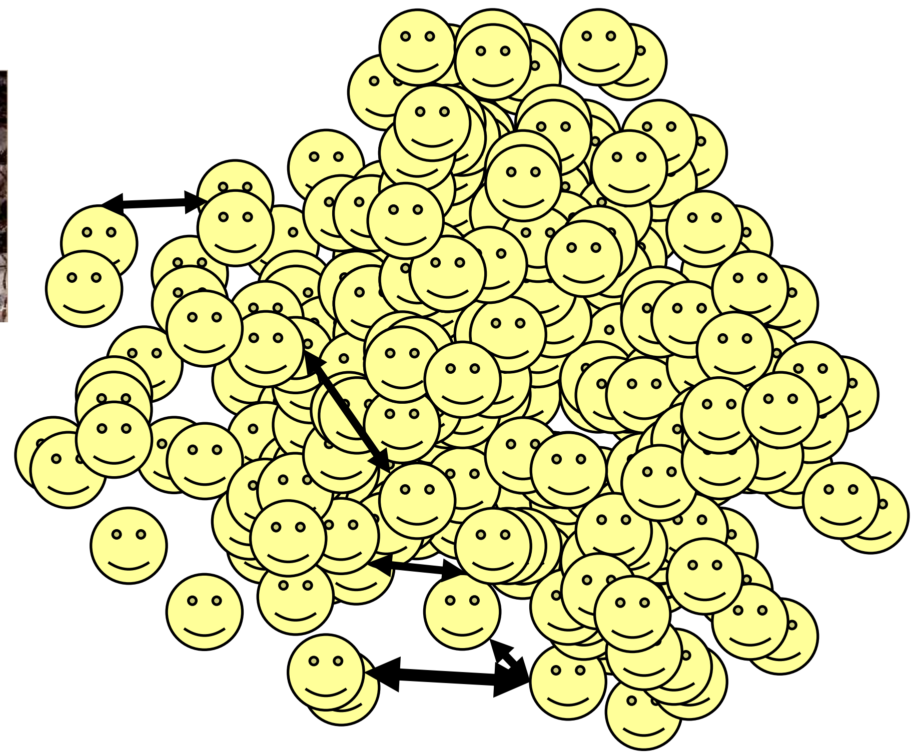
- **Question:**
  - Given a MAS, if it is not allowed
    to change the interacting rule of agents that are already there,
  - is it possible to control the collective behavior of the MAS, and how?
- **Answer:**
  - Yes, it is possible, by adding one or a few “shills”
    two case study: flocking, game
  - This is what we called “Soft-control”

The story

what is Collective Behavior ?

- many agents (individual/part), local interactions (local rule)
  new properties emerge:
  phase transition, pattern formation, group movement , swarm intelligence…



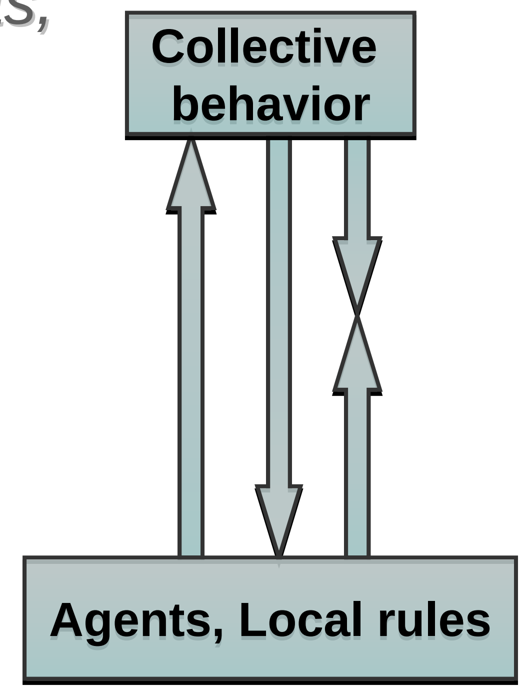


As we know

Collective behavior is one of the most important topics of Complex Systems

Three categories of research on Collective Behavior

1. *Analysis*: *Given the local rules of agents, what is the collective behavior of the system?*
2. *Design*: *Given the desired collective behavior, what are the local rules for agents?*
3. *Intervention*: *Given the local rule of the agents, how we intervene in the collective behavior?*



soft control

This is what this talk about

Soft Control

Case 1: Flocking Model, Consensus

Case 2: Multi-person Game, Cooperation

软控制

Soft Control

Case 1: Flocking Model, Consensus

Case 2: Multi-person Game, Cooperation

软控制

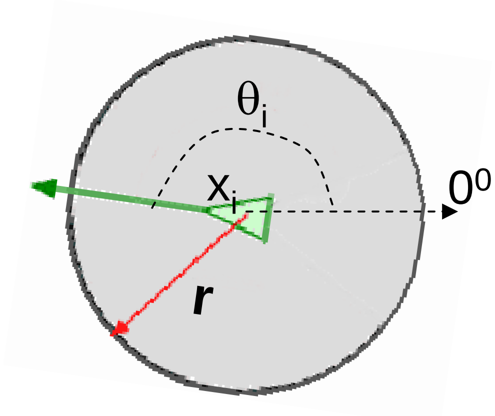
A Group of Birds

Filmed by Jing HAN. 2004. Sept.

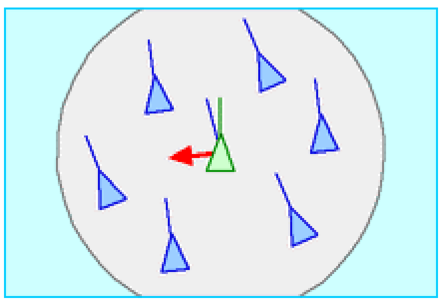
Flocking of birds is a kind of collective behavior

First, the model

The Vicsek Model

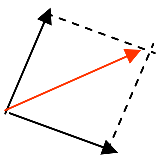


Agent's Neighborhood



Alignment: steer towards the average heading of neighbors

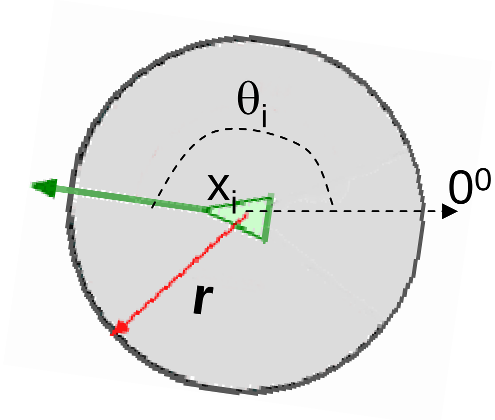
- *n* Agents: (X, θ)
  $x_i(t)$: location
  $\theta_i(t)$: moving direction
- *v* : the constant speed
- *r* : radius of neighborhood, so $N_i(t)=\{j \mid \|x_j-x_i\|\leq r\}$, $n_i(t)=|N_i(t)|$



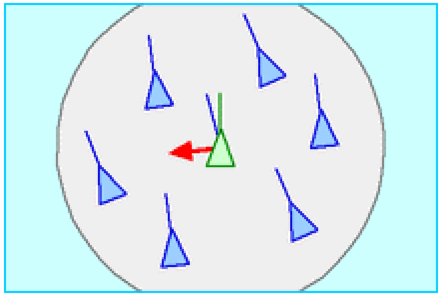
$$\theta_i(t+1) = \arctan\left\{ \frac{\sum_{j\in N_i(t)} \sin\theta_j(t)}{\sum_{j\in N_i(t)} \cos\theta_j(t)} \right\}$$

$$x_i(t+1) = x_i(t) + v(\cos\theta_i(t), \sin\theta_i(t))^\tau$$

The Vicsek Model



Agent's Neighborhood



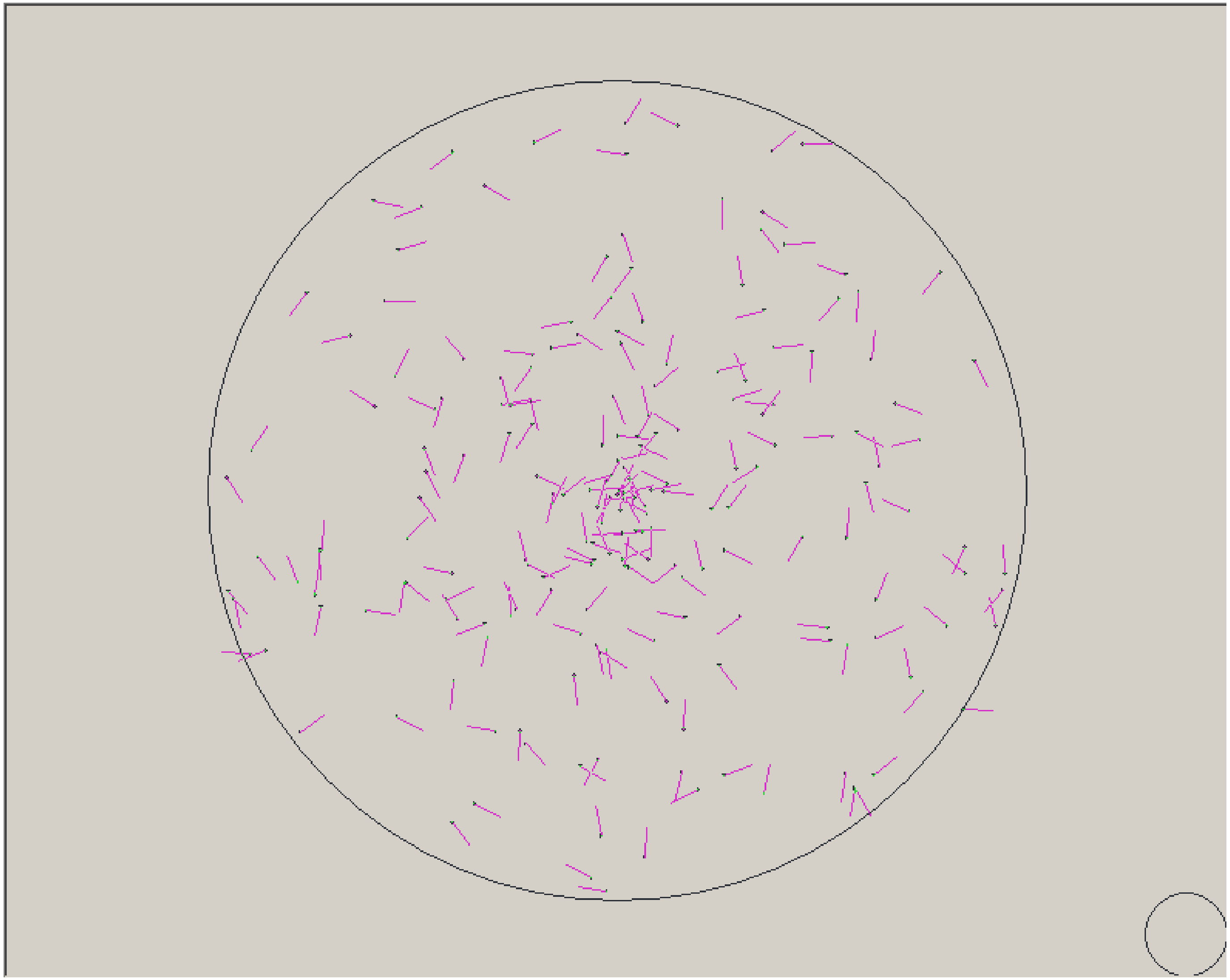
Alignment: steer towards the average heading of neighbors

- *n* Agents: (X, θ)
  $x_i(t)$: location
  $\theta_i(t)$: moving direction
- *v* : the constant speed
- *r* : radius of neighborhood, so $N_i(t)=\{j \mid \|x_j-x_i\|\le r\}$, $n_i(t)=|N_i(t)|$

Local rule:
only knows the local information, interacting locally;

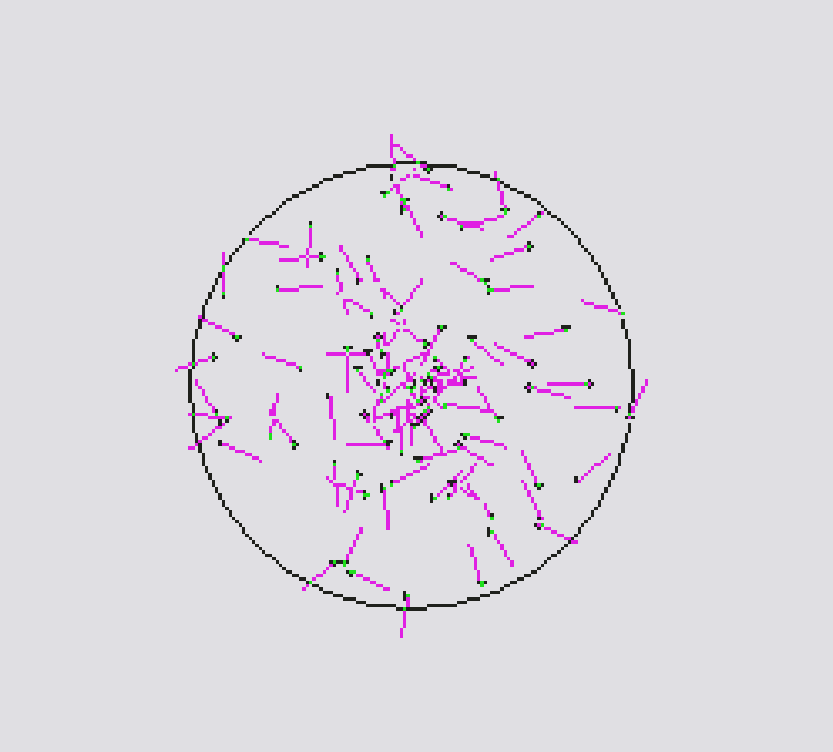
Dynamical interaction network.

Computer Simulation

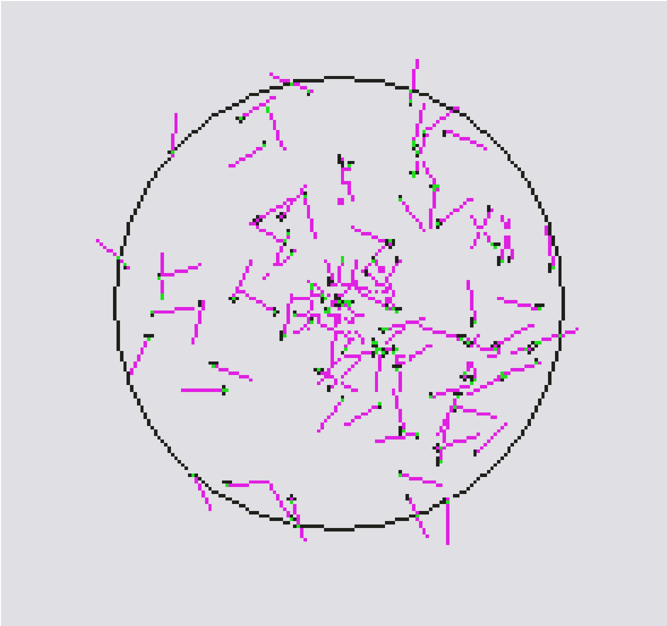


n=100, v=12, r=400. R=3000

Consensus or not?



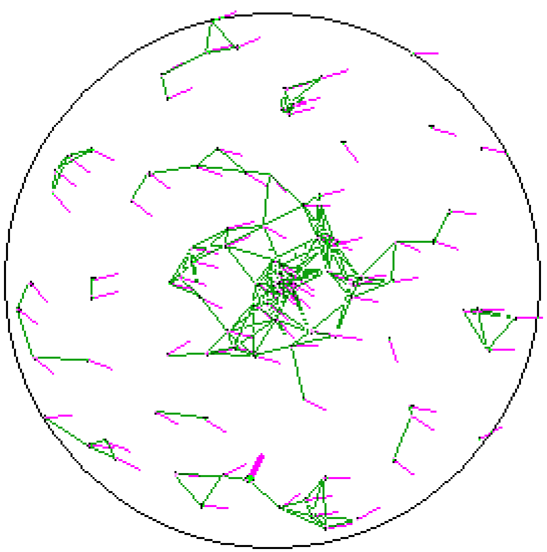
No consensus

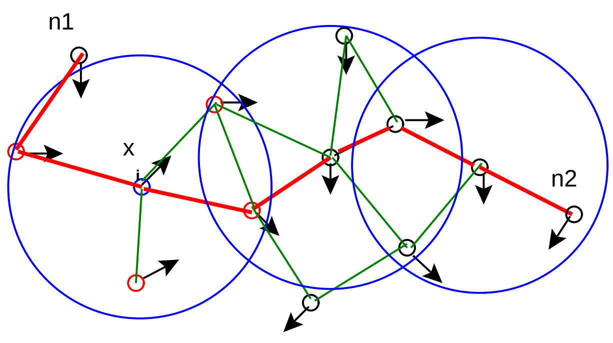


Reach consensus

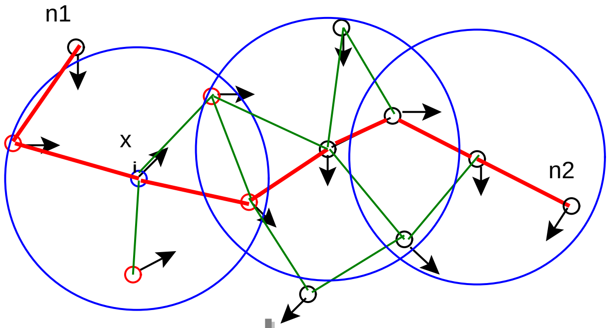
The difficulties of analysis

- Agent's position and heading are strongly coupled.
- The interaction network is dynamical.
- No existing mathematical methods to analyze these nonlinear equations.





Result 1:



Joint connectivity of the neighbor graphs on each time interval [*th, (t+1)h*] with *h >0*

➡

Synchronization of the linearized Vicsek model, i.e., there exists θ_0, such that

$$\lim_{t\to\infty} \theta_i(t) = \theta_0, \qquad \forall i$$

A.Jadbabaie et al., IEEE TAC, 2003

J.N.Tsitsiklis, et al., IEEE TAC, 1984

Results 2 – by my colleagues

Stochastic Framework

The initial positions and headings of all agents are mutually independent, with positions uniformly and independently distributed in the unit square, and headings uniformly and independently distributed in $[-\pi+\varepsilon, \pi-\varepsilon]$ with arbitrary $\varepsilon \in (0, \pi)$.

Theorem 1

Under the random framework, for any model parameters *v*>0 and *r*>0， the Vicsek model will synchronize almost surely if the number of agents is large enough.

This result is consistent with the simulation results given by Vicsek et al.

Z. X. Liu, L. Guo, Automatica, 2009

Results 3 – by my colleagues

Intuitively, the interaction radius *r* can be allowed to decrease with *n*, denoted by r_n to reflect this situation. For such a case, what conditions are needed to guarantee the synchronization of the model?

Theorem 2

Under random framework, if the moving speed and the neighborhood radius satisfy

$$\left(\frac{\log n}{n}\right)^{1/6} << r_n << 1, \quad v_n = O\left(r_n^6 \sqrt{\frac{n}{\log^3 n}}\right).$$

Then the system can reach synchronization almost surely for large *n*.

Z. X. Liu, L. Guo, Automatica, 2009

Results 4 – by my colleagues

Furthermore, an interesting and natural question is: what is the smallest possible interaction radius for synchronization?

Theorem 3

Suppose that *n* agents are independently and uniformly distributed in $[0, 1]^2$ at the initial time instant, and that $nr_n^2/\log n \to \alpha \in (1/\pi, \infty]$ *and* $r_n \to 0$ as $n \to \infty$. If $v_n = o\left(r_n(\log n)^{-1}n^{-2}\right)$, then the system will synchronize with high probability for all initial headings and sufficiently large n.

G. Chen, Z. X. Liu, L. Guo, SIAM J. on Control and Optimization, 2011.

But what if the group does not reach consensus?

Can we intervene in and help?

without destroying the local rule of the already-existing agents

Soft Control (2005-)

- Outline
  - The Key Points of 'Soft Control'
  - Computer Simulations
  - A Case Study

Collaborate with Lei GUO, Ming Li and Lin Wang.

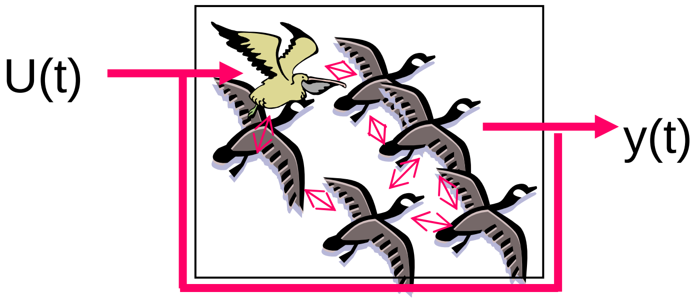
•Jing Han, L. Guo, and M. Li, *Guiding a group of locally interacting autonomous mobile agents*, in Proceedings of the 24th Chinese Control Conference., 184-187, July, 2005.

•Jing Han, Ming Li and Lei Guo. *Soft Control on Collective Behavior of a Group of Autonomous Agents by a Shill Agent*. Journal of Systems Science and Complexity (2006) 19: 54–62

•Jing Han, Lin Wang. *New Strategy of the Shill: 'Consistent Moving'*. Proceedings of the 29th Chinese Control Conference July 29-31, 2010, Beijing, China

•Jing Han, Lin Wang. *Nondestructive Intervention to Multi-agent Systems Through an Intelligent Agent.* (Submitted to PLoS ONE, under reviewed). 2012

Key Points of 'Soft Control'



- **The system:**
  - Many agents
    more is different
  - Each agent follows a local rule
    Autonomous, distributed
  - Agents locally interact with each other, not isolated (all the time)
    The local effect may spread and affect the whole

- **The "Control":**
  - To change the local rules of existing agents is NOT allowed
    Can not implement by changing adjustable global parameters
  - Add one (or a few) special agent – shill, control interface
    Shill: is controlled by us, not following the local rule
    is treated as an ordinary agent by the existing agents.

Key Points ... Co...

$\theta_0(t+1)$= controlled
$x_0(t+1)= x_0(t)+v\cdot\alpha(t+1)$
or controlled
v would be variable

$\theta(t+1)=(\theta(t)+\alpha(t)+\theta'(t))/3$
$x(t+1)=x(t)+v\cdot\theta(t+1)$

U(t)

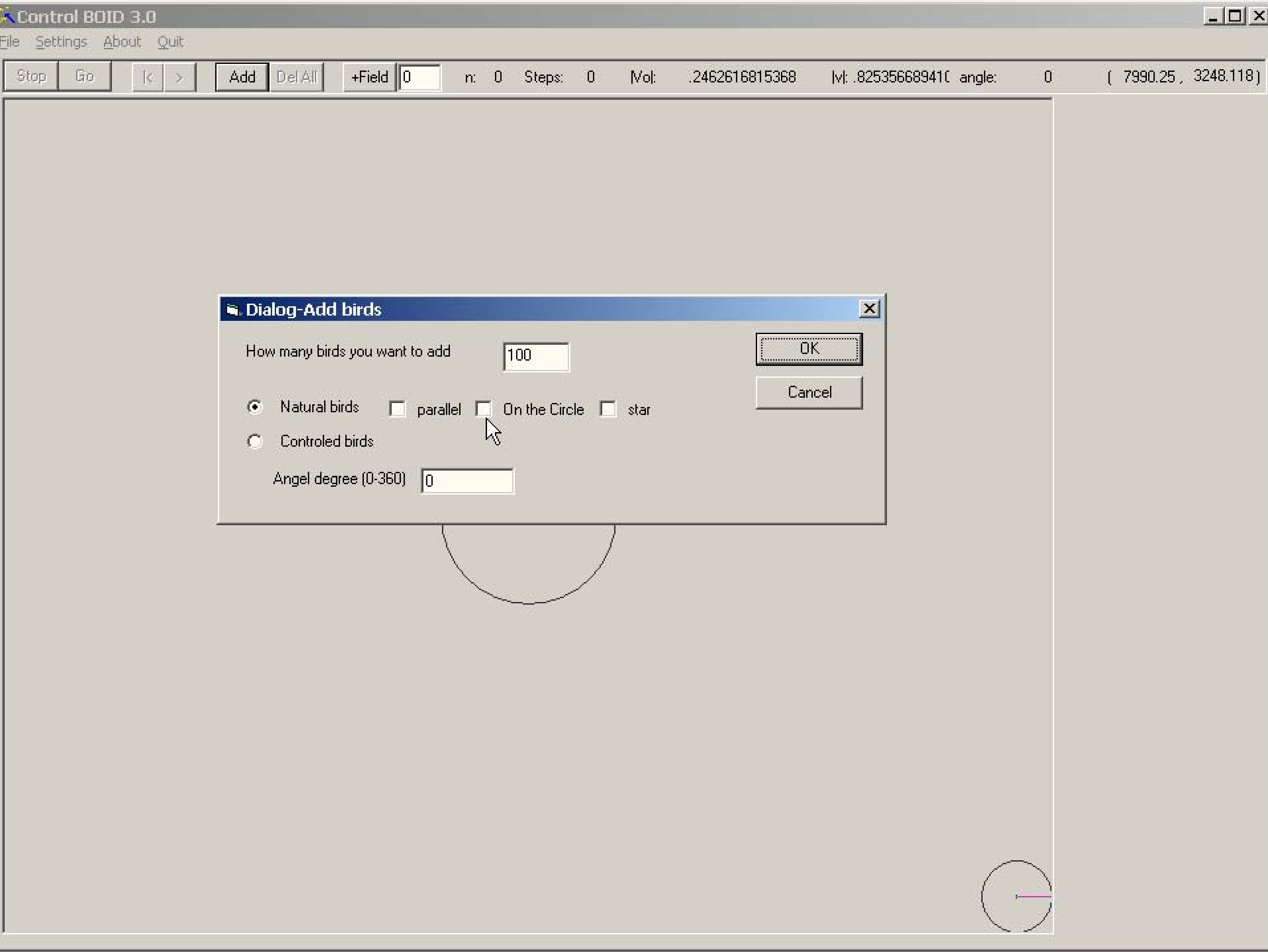
- The system:

•**Shill is not treated as a special leader**
Nondestructive intervention

•**Shill's influence on others = normal agents**
Normal agents not aware of the 'control' -- soft

- **The "Control":**
  - To change the local rules of existing agents is NOT allowed
    Can not implement by changing adjustable global parameters
  - Add one (or a few) special agent – shill, control interface
    Shill: is controlled by us, not following the local rule
    is treated as an ordinary agent by the existing agents.

Computer Simulation for the Idea


Control BOID 3.0
File Settings About Quit
Stop Go |< > Add Del All +Field 0 n: 0 Steps: 0 |Vo|: .2462616815368 |v|: .82535668941(angle: 0 (7990.25 , 3248.118)
Dialog-Add birds
How many birds you want to add
100
OK
Cancel
Natural birds
parallel
On the Circle
star
Controled birds
Angel degree (0-360)
0

A Case Study

- **The system**:
  A group of *n* agents with initial headings $\theta_i(0) \in [0, \pi)$
  One shill is added
- **Goal**: all agents move to the direction of 0 eventually.
- **Control**: What is the moving strategy of the shill?

- **Assumptions:**
  - The local rule about the ordinary agents is known
  - The position $x_0(t)$ and heading $\theta_0(t)$ of the *shill* can be controlled at any time step t
  - The state information (headings and positions) of all ordinary agents are observable at any time step

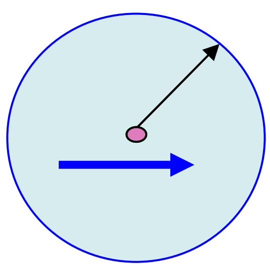
Attributes of the Shill

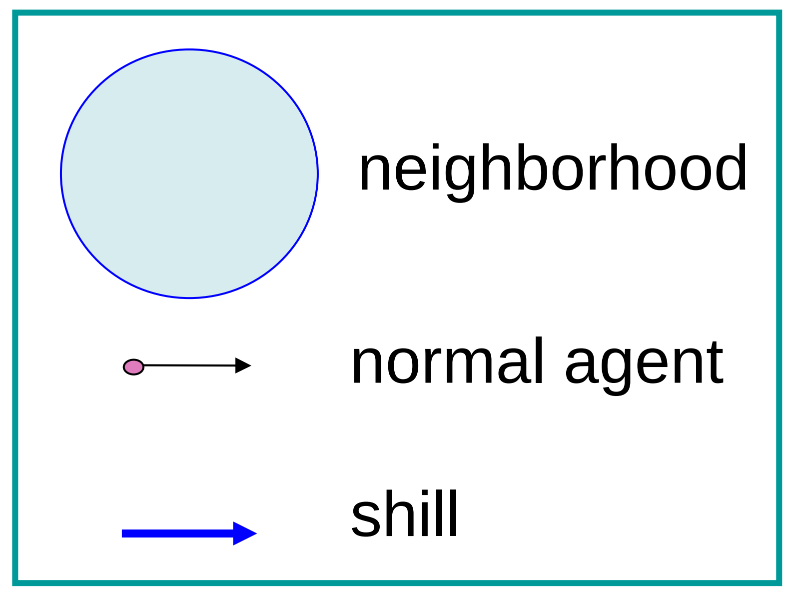
- **Smart: intelligent, feedback**
  may know more information
  - Not follow the Alignment rule
    Instead, it can be re-designed
  - Has its own strategy, to affect the 'bad guys'
    (whose heading is not close to zero)
- **More energy: should be able to move faster than normal agents, $v_s > v$**

How a shill affects a ‘bad guy’?

- **How?**

Be the neighbor of a bad guy with heading 0

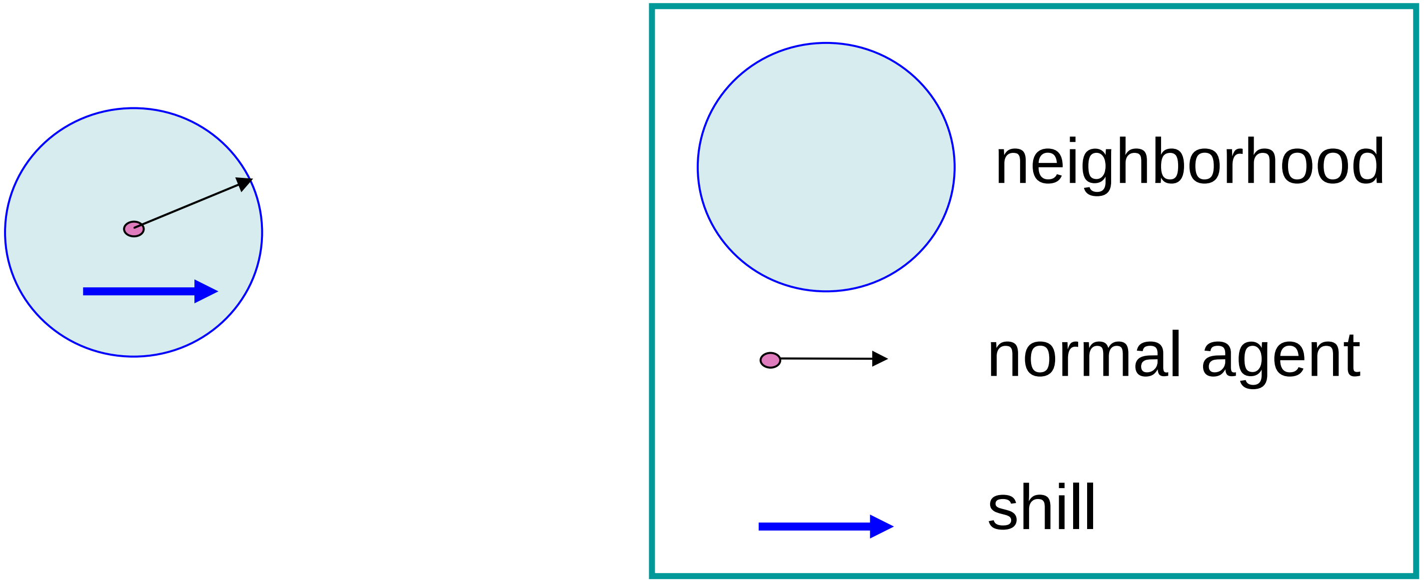




How a shill affects a 'bad guy'?

- **How?**

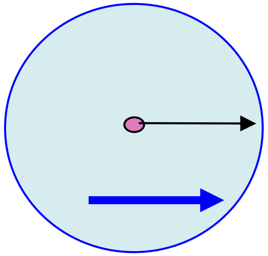
Be the neighbor of a bad guy with heading 0

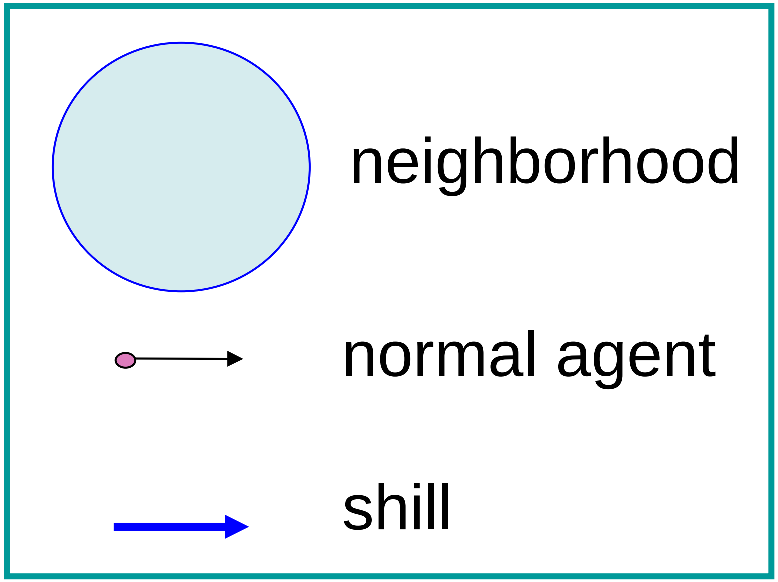


How a shill affects a 'bad guy'?

- **How?**

  Be the neighbor of a bad guy with heading 0





- How to make headings of all agents converge to 0?

- Details of the Strategy

Point 1: "Everyone in a Period"

- According the 'jointly-connected' theorem,

  if the shill can

  periodically affect every agent with heading zero

  In a period of M (or ≤M) steps, all agents are affected by the shill at least once.

  the group will converge to heading zero.

Difficulty: How does the shill move?

- After affects a target agent,

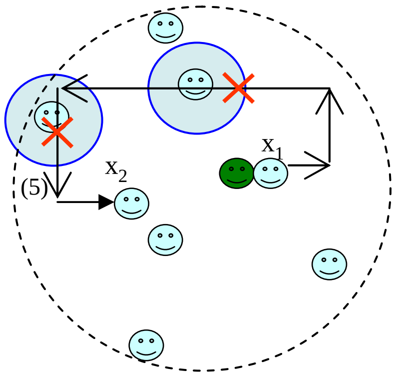
  how does the shill move to the next target

  without

  putting negative effect on the group ?

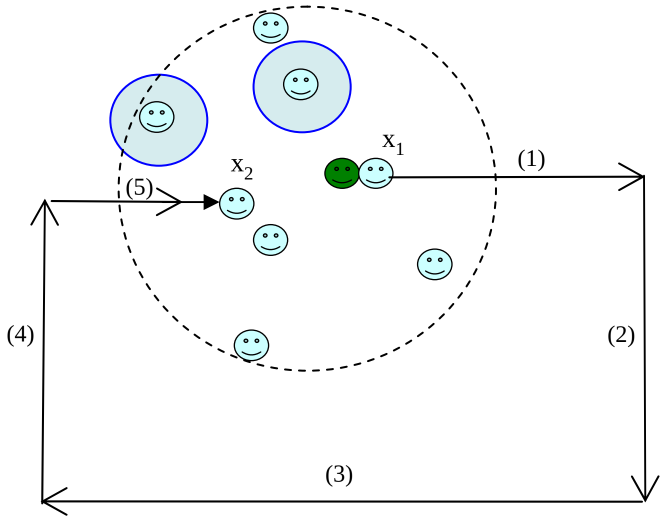
Point 2:

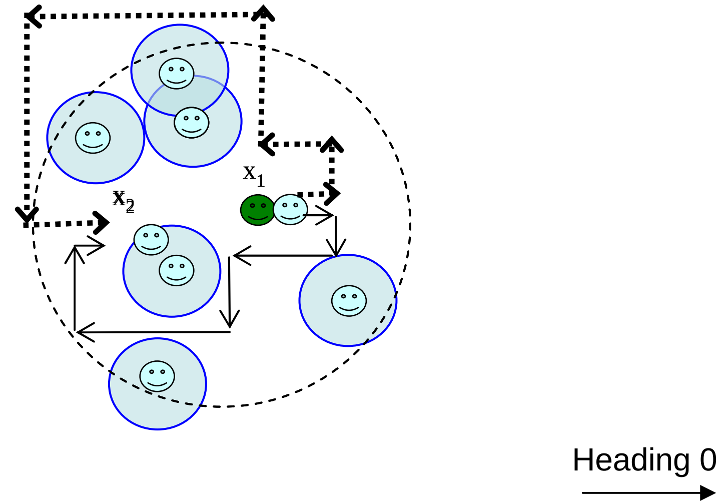
- How does it move from one location to another location without putting negative effects?



Point 2: "Zero when have neighbors"

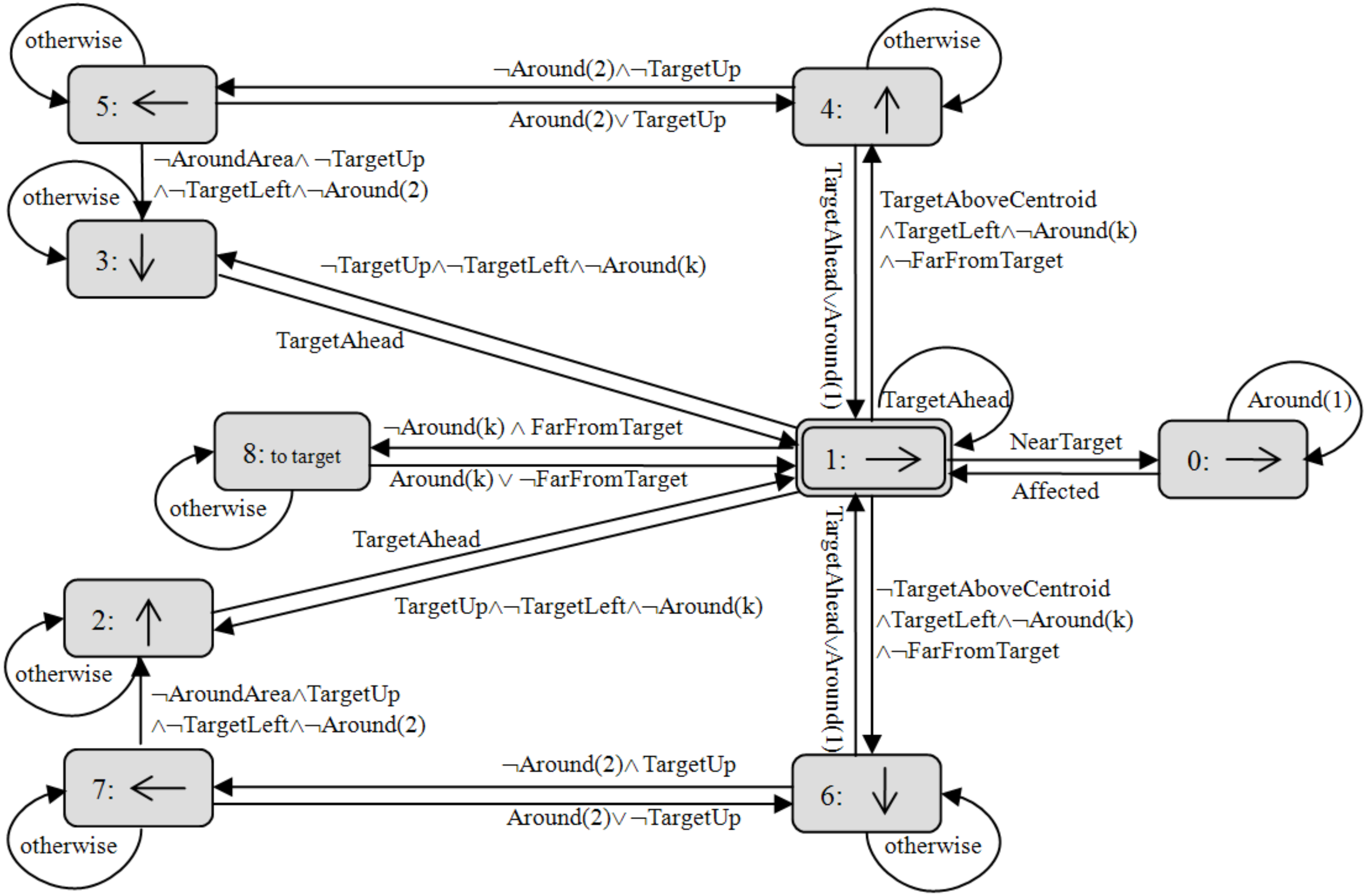
- How does it move from one location to another location without putting negative effects?





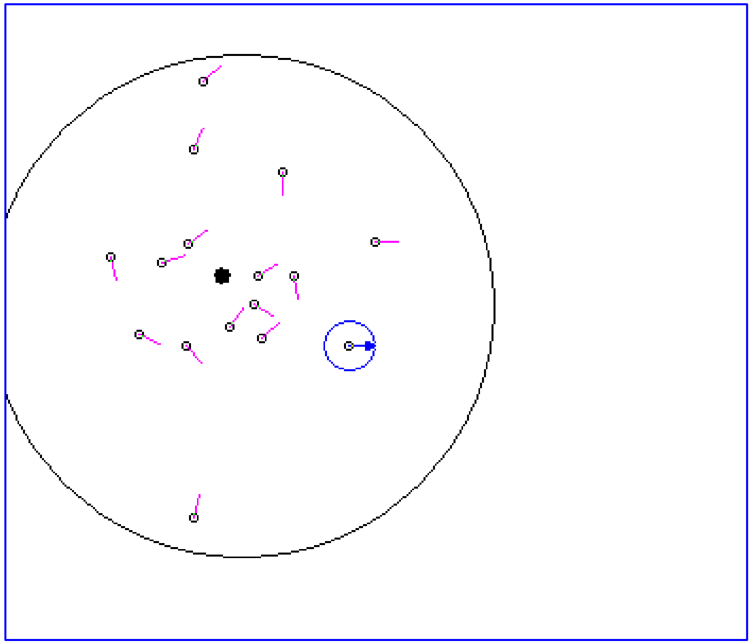
If there are neighbors, the shill should move with heading zero;
If no neighbors, the shill can move to any direction.

Finite-State Machine of moving algorithm

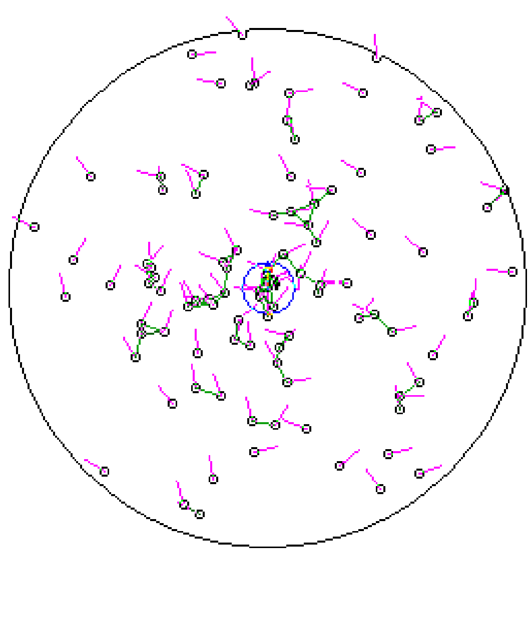


Demos

Case 1: loose group

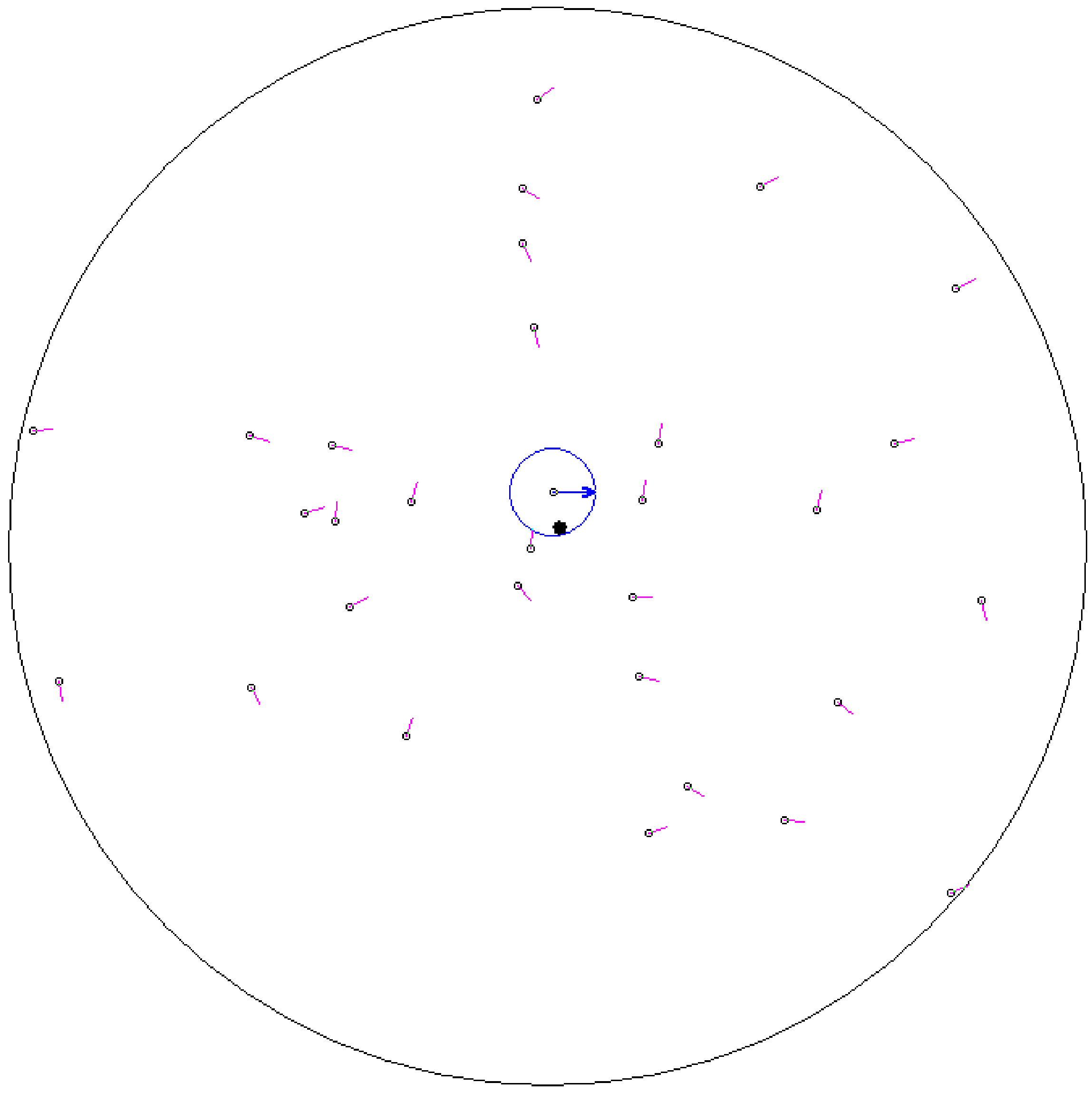


Case 2:crowded group



Case 3: shill moves faster

- Shill moves inside the group



Main Theorem

Theorem 3. *If the shill strategy satisfies condition Λ, it can lead headings of all normal agents converge to the desired value θ^*. Furthermore, locations of all normal agents can be covered by a circle with a fixed radius R^* at every time step, where*

$$R^* = D + vb\Delta_0 \frac{2-\lambda}{1-\lambda},$$

$D \leq R$ *is the radius of the minimal circle enclosing all the normal agents at time* 0,

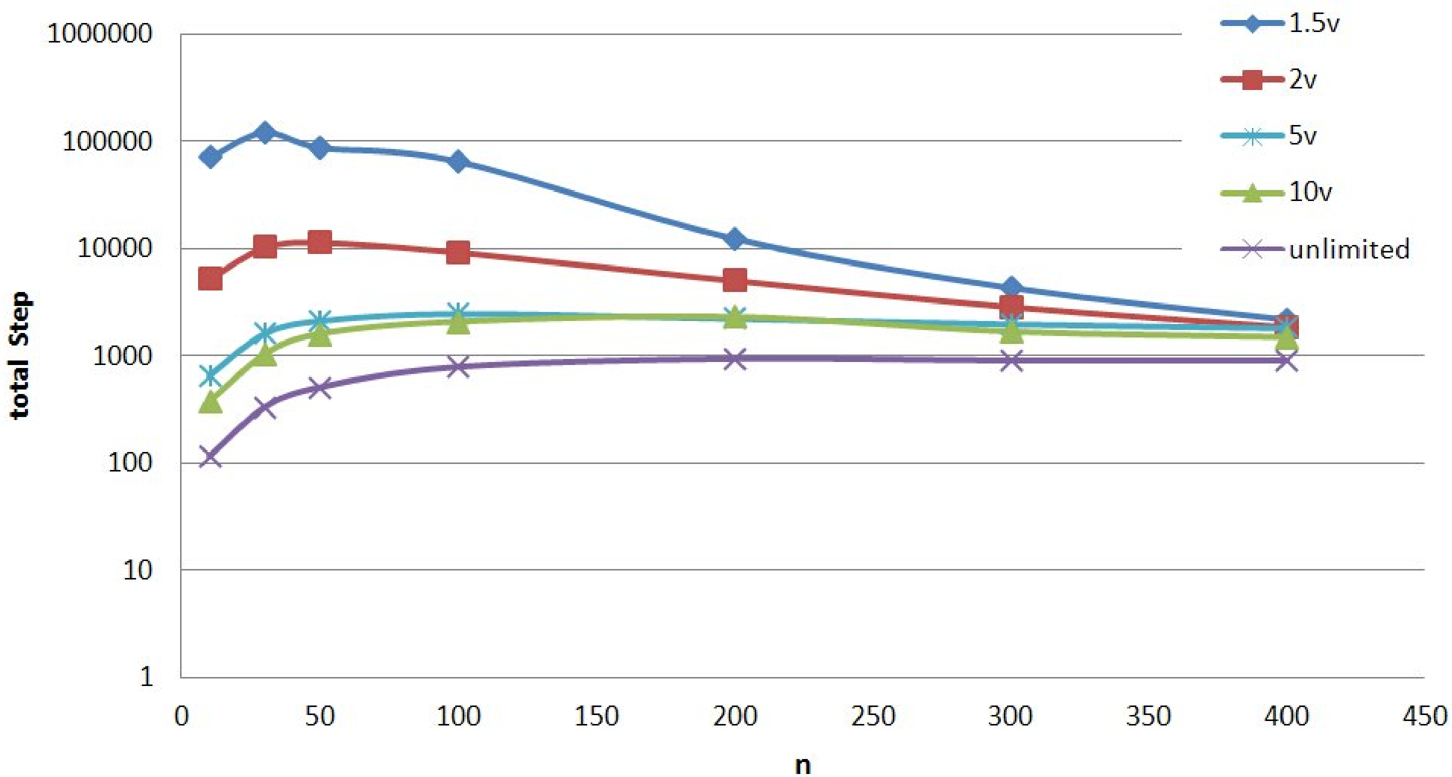
$$b = \sigma^{-1}, \quad \lambda = \sigma^{\frac{1}{L}}, \quad \sigma = 1 - \left(\frac{\cos\bar{\theta}}{n+1}\right)^L, \quad L = nH,$$

$$\bar{\theta} = \max_{i \in \{0,1,2,\cdots,n\}} |\theta_i(0)|, \quad \triangle_0 = \max_{i,j \in \{0,1,2,\cdots,n\}} \{\tan\theta_i(0) - \tan\theta_j(0)\},$$

- With this strategy, the group can reach consensus
- The shill speed has a bound: 2R*(H)+3v, H is the period

New Strategy of the Shill:' Consistent Moving'. ***Jing Han, Lin Wang. Proceedings of the 29th Chinese Control Conference, p4459-4464, 2010, China.**

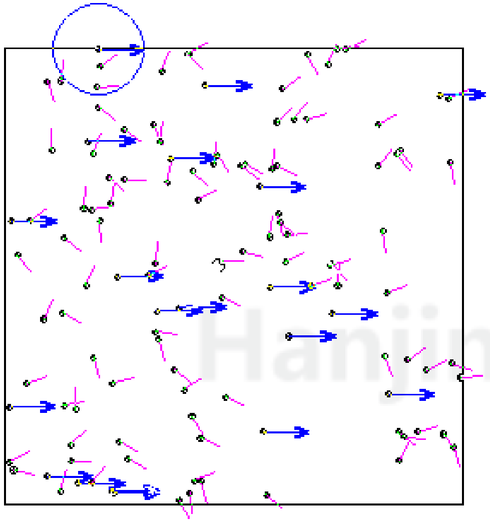
- One shill can lead the group to consensus.
- Higher speed of the shill usually leads to faster convergence.
- When v_0 is low, low density system needs longer time
- When v_0 is high, larger group needs longer time



Mean totalStep under different settings of *group size* $n = \{10, 30, 50, 100, 200, 300, 400\}$ *and shill speed* $v_0 = \{1.5v, 2v, 5v, 10v, \infty\}$.
Stop when $max_i|\theta_i| \leqslant \arccos 0.9999$.

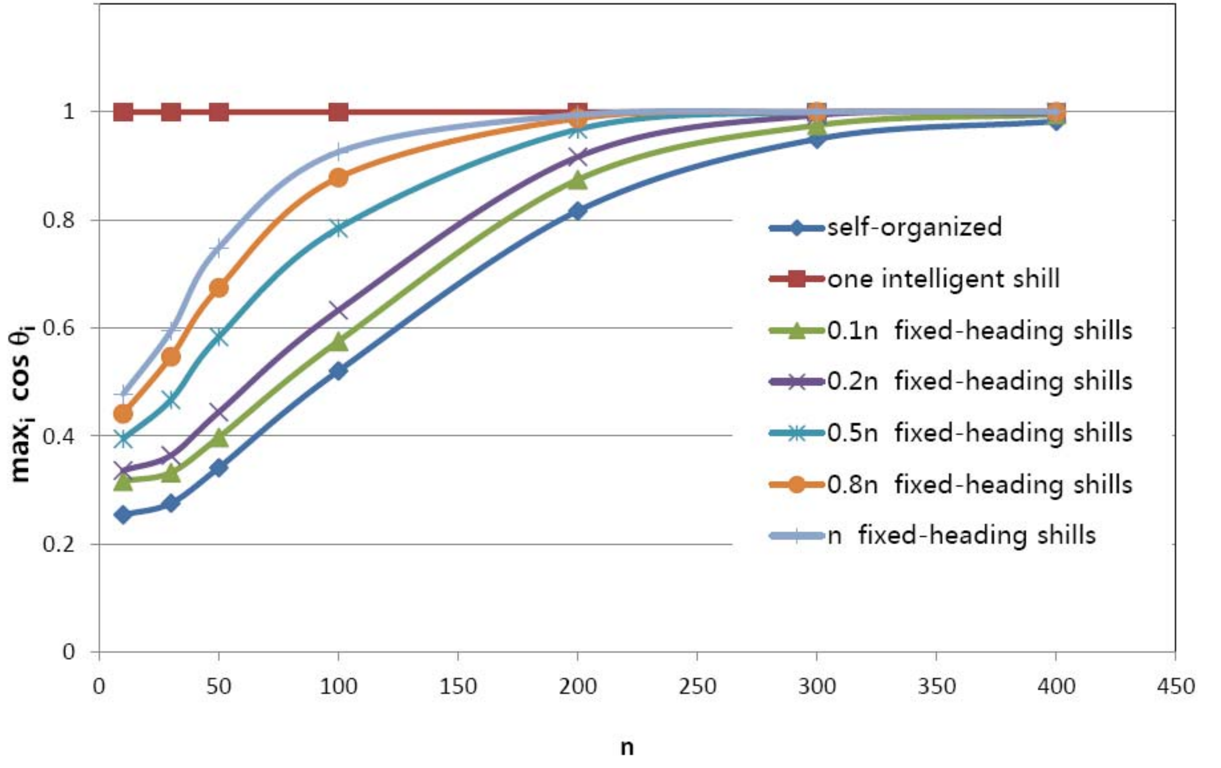
Comparing with Adding a Number of ‘leaders’

- Add some fixed-heading shills
  (‘informed agents’ in Couzin’s paper, ‘leaders’ in Liu’s paper)
- Simple shills, do not use feedback information
- Need a number of them to guarantee consensus



20 fixed-heading shills are added into a group with 100 normal agents.

One intelligent shill performs better than adding a number of fixed-heading shills when measured by the synchronization level.



Synchronization level (mean $\max_i \cos\theta_i$) *for group size n = 10, 30, 50, 100, 200, 300, 400 for 3* cases: self-organized without any intervention; one intelligent shill with $v_0 = 5v$ *is added into the* group; 0*.1n, 0.2n, 0.5n, 0.8n and n fixed-heading shills are added into the group respectively.*

More Questions …

- Optimal strategy?
- What if the shill can only see locally?
- How much information we need to know about the system?
- If the shill doesn't know the interaction rule of agents, how does the shill learn and lead the group? (Learning and Adaptation)
- What if two shills with different objective direction? How they compete?
- …

Soft-control is not just for …

the Vicsek's model

- Would be applied to other systems:
  many autonomous agents with local interactions

Soft Control

Case 1: Flocking Model, Synchronization

Case 2: Multi-person Game, Cooperation

软控制

Soft Control

Case 1: Flocking Model, Synchronization

Case 2: Multi-person Game, Cooperation

软控制

Soft-control Promotes Cooperation

- Multi-Agent Model
  Evolutionary Multi-player Repeated Prisoner Dilemma
- Cooperation might not emerges
- Soft Control:
  Add shills to promote cooperation

Collaborate with my former PhD Student Xin Wang

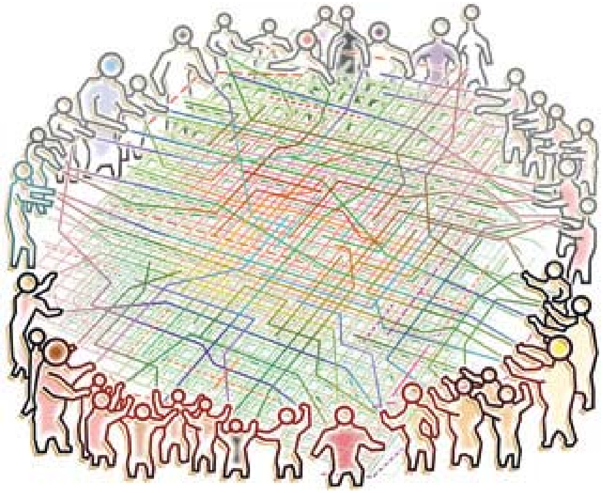
•X.Wang, J,Han, H.Han. Special Agents can Promote Cooperation in Populations. PLoS ONE 6(12), 2011.

COOPERATION exists anytime and anywhere, from the animal population to the human society.

Ants cooperate to build a bridge

Amish benefit from cooperation in roof-raising

DEFECTION is found in a group of self-interest agents.



Each herder is willing to put more cows onto the land, even though the carrying capacity of the commons is exceeded and it is run out rapidly.

Tragedy of the commons (Garrett Hardin, 1968)

- Does cooperation exist in a group of self-interest agents?
- If not, can soft-control introduce cooperation?

Question

The model

Evolutionary Multi-player Repeated Prisoner Dilemma

- **Prisoner Dilemma (PD)**
- **Repeated:** **end-unknown β-round of PD**
- **Multi-player:** **population, pairs of players**
- **Evolutionary:** **survival of the fittest**

- **This is a popular model to study cooperation in population**

Prisoner Dilemma (PD)

A classical game, Blue Player vs. Red Player

Both win

lost more
win more

	Cooperate	Defect
Cooperate	3 3	0 5
Defect	5 0	1 1

Nash Equilibrium

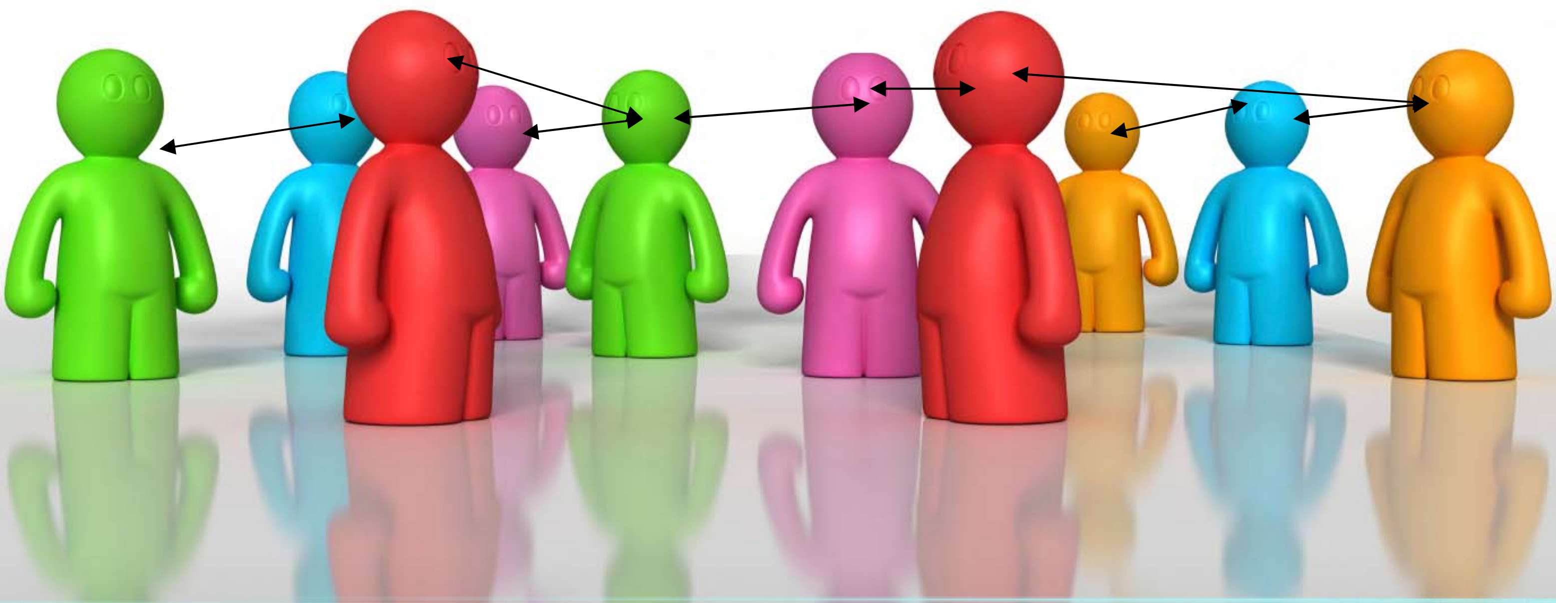
win more
lost more

Payoff matrix

Both lost

shows why two individuals might not cooperate, even if it appears that it is best to do so

Evolutionary Multi-player Repeated Prisoner Dilemma



Cooperation level is very low under some circumstances

Old Question

“In which conditions, can cooperation occur from self-interested individuals without centralized control?”

---- Robert Axelrod, *The Evolution of Cooperation*,1984.

Most work focuses on…

The study for direct reciprocity:

- Find 'good' strategies of agents
  - Tit for tat (TFT)
  - Win Stay Lost Shift (WSLS)
- Assign agents with extra abilities or characteristics
  - Tag Mechanism
  - Mobility of agents
- Locate agents on the spatial structure
  - Regular graphs, scale-free networks, …

They are about how to design the system.

What if the system is given and shows no cooperation, what can we do?

OUR WORK

promote cooperation in a non-cooperative group while

keeping already-existing agents unchanged

They still do what they usually do,
they do not aware the “control”.

Basic Model (I)

- **N_A normal agents**
- **Strategy for normal agents**
  - Reactive strategy ---- (y, p, q)
    - y --- the probability of cooperation on the first move
    - p --- the conditional probability of taking cooperation corresponding to the opponent's last move of defection
    - q --- the conditional probability of taking cooperation corresponding to the opponent's last move of cooperation

Basic Model (II)

- **Play rules**
  - Pair of agents *i* and *j* play an end-unknown β-round Prisoner's Dilemma Game (complete interaction, incomplete interaction)
  - update fitness (total payoff) f_i and f_j

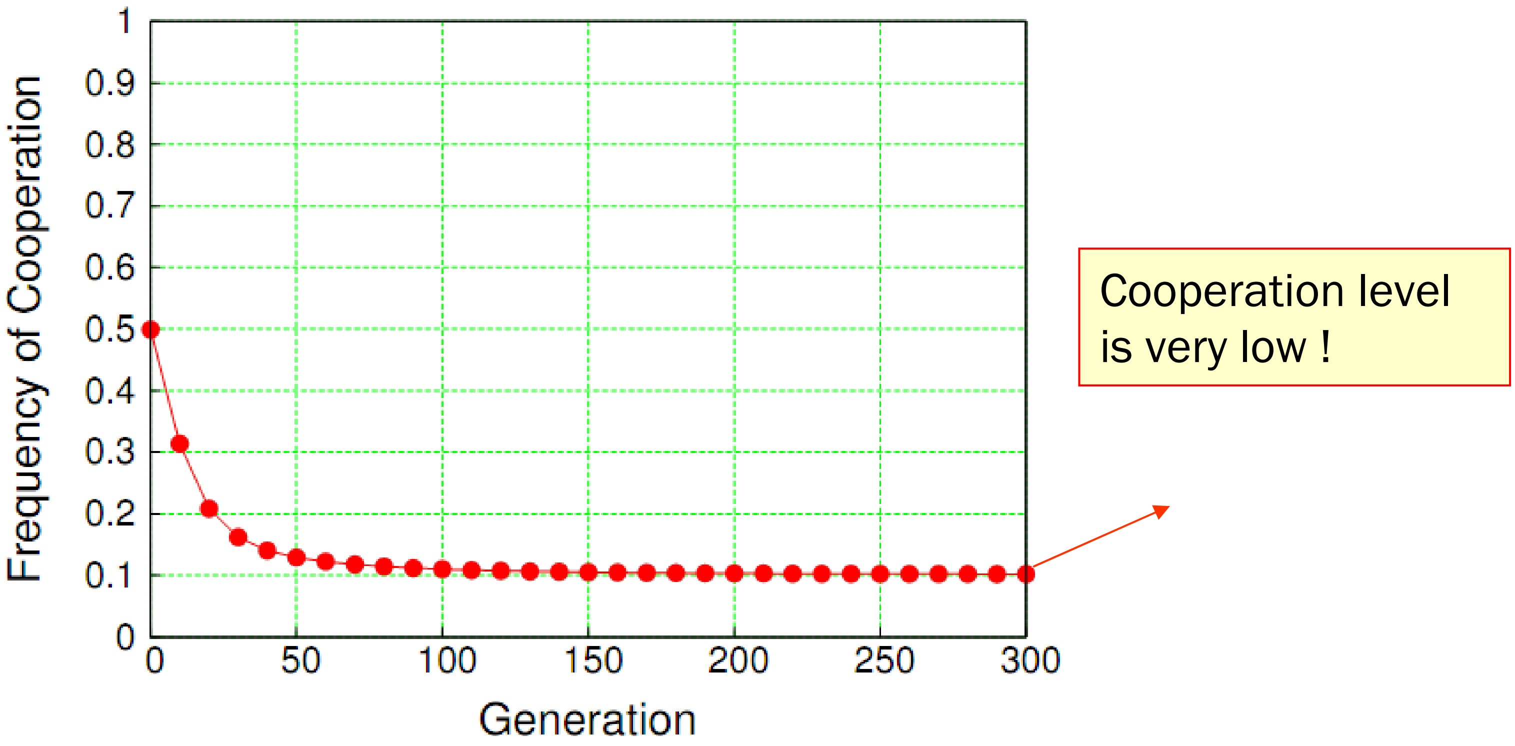
Basic Model (III)

- **Reproduction**
  - Survival of the fittest

$$E\{\#_i(t)\} = \frac{f_i(t)}{\sum_{k \in \mathcal{A}} f_k(t)} N_A \qquad \forall i \in \mathcal{A}$$

where $f_i(t) = \sum_{j \in \mathcal{A} \setminus \{i\}} f_{ij}(t)$

Basic Model – simulation



The frequency of cooperation in the well mixed population.

Averaged on 50 runs over 100 samples.

(y,p,q) is uniformly distributed in $[0,1]^3$, N_A=500, β=10

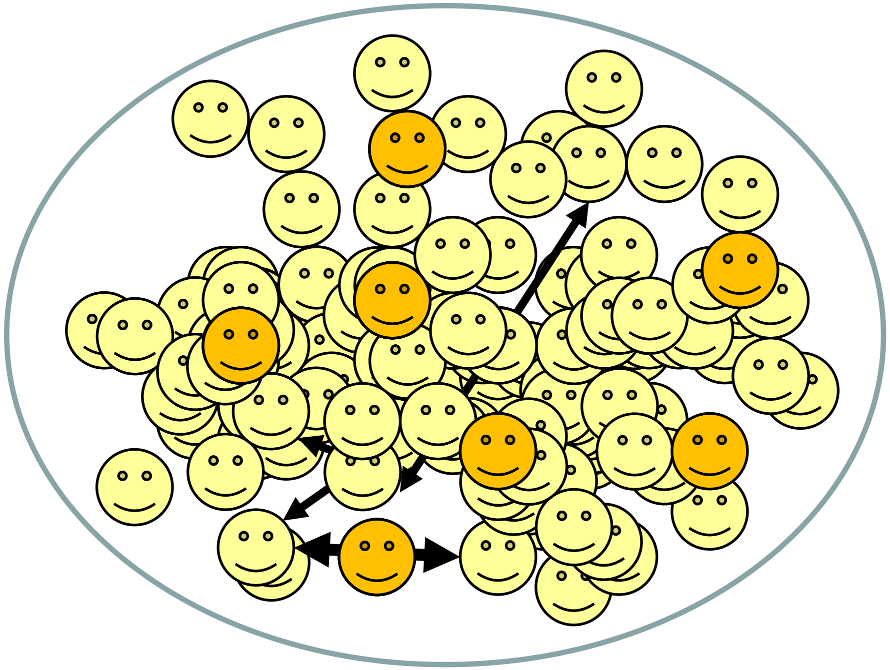
Analytical study

- Self-organized, without shills complete interaction

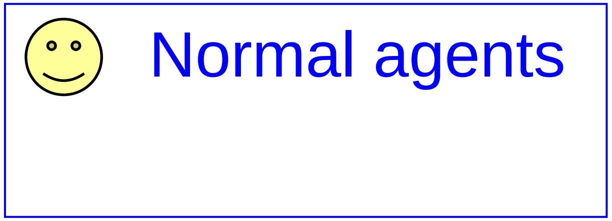
Proposition 1. Assume that the population plays the 2-stage RPD for any given R, S, T, P which satisfy T > R > P > S and R > (T + S) / 2. The types of mixed reactive strategies n is sufficiently large to contain any possible strategy, then the frequency of cooperation f_c converges to 0.

OUR WORK:

- <u>**Evolutionary Repeated Multi-player PD**</u>



Cooperation level is very low



(frequency of cooperative action in the group)

- **Add shills: Increase the cooperation level**

Model with Shills (I)

- **N_s: number of shills**
- **Attributes of shills**
  - Comply with play rules in the original group
    Shills are treated as normal agents by normal ones
  - No preliminary knowledge of normal agents' strategies
  - Recognize other shills and share information
  - different strategy
    not the (y, p, q) form

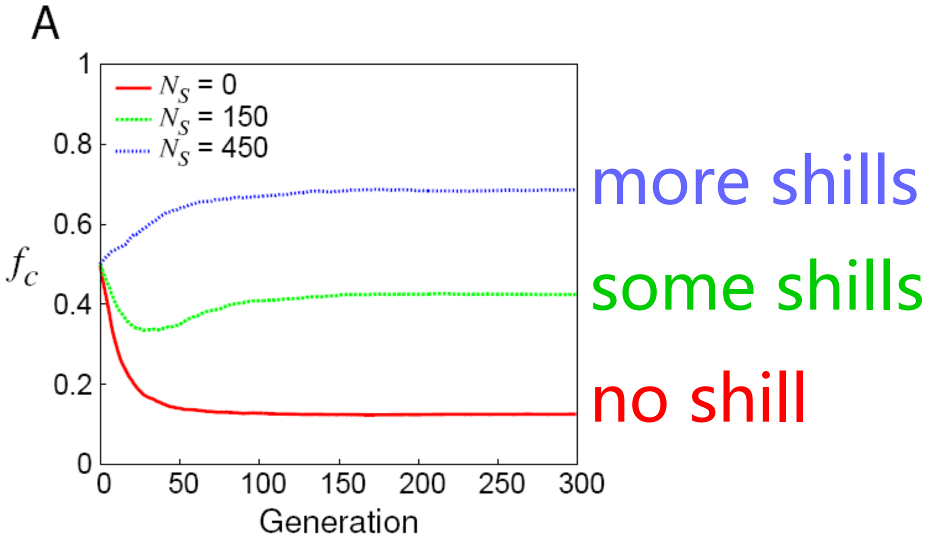
Model with Shills (II)

- **Shill strategy**
  - Information sharing:
    shill *s* plays with normal agent *i*, *s* will share the action sequence of agent *i* with other shills
  - Frequency-based Tit for Tat (F-TFT)
    Cooperate with the probability proportional to the frequency of cooperation of the opponent
    reward cooperator, punish defector

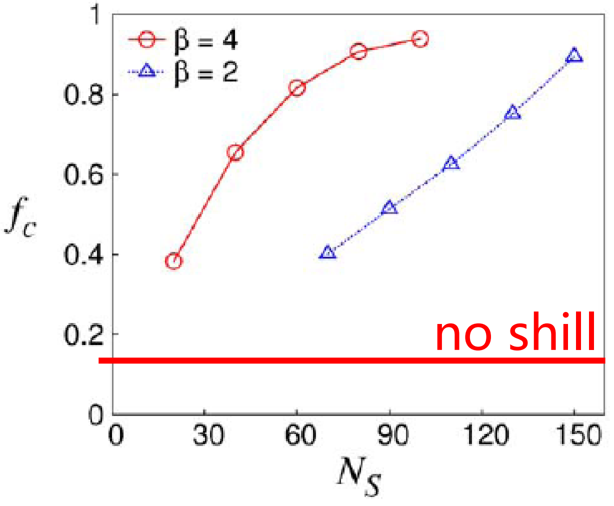
$$(D) \rightarrow f(C) = 0$$
$$(DCDD) \rightarrow f(C) = \frac{1}{4}$$

Soft control is possible to promote cooperation

- **The evolution of cooperation frequency (f_c). N_A =500**



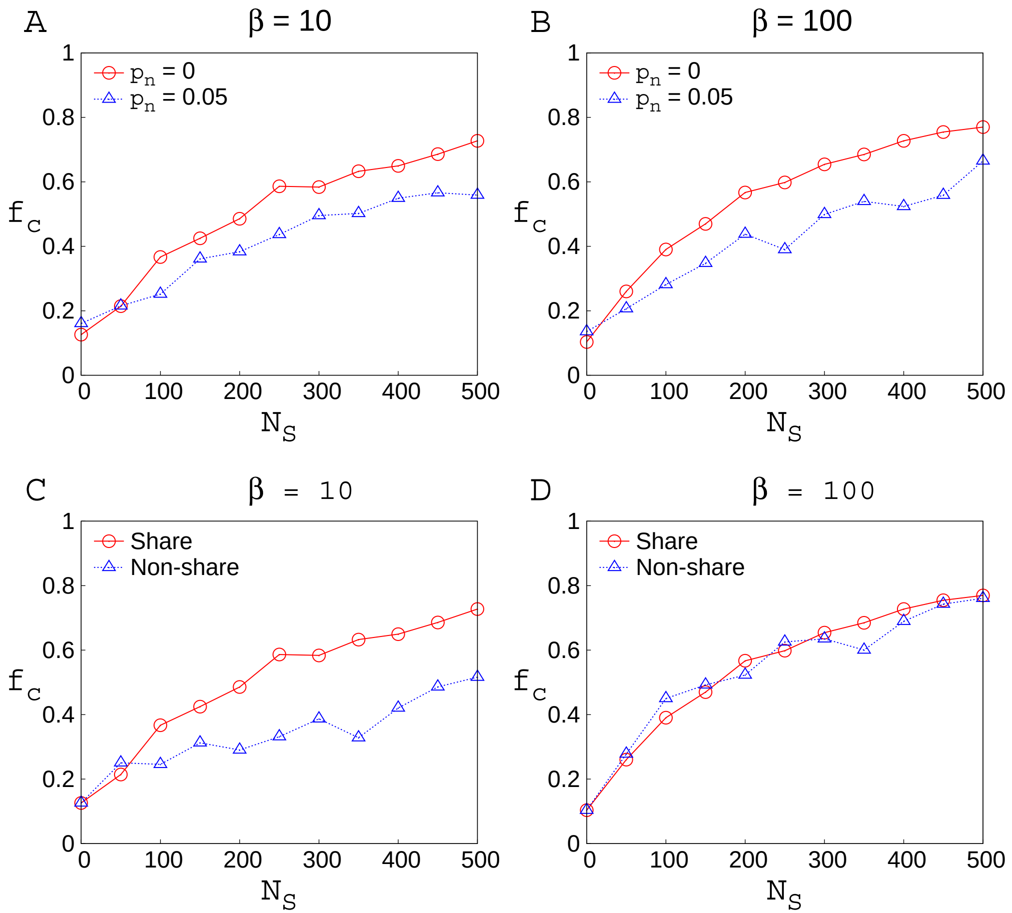
Complete interaction (interaction network is fully-connected graph)



Incomplete interaction (interaction network is not fully-connected graph)

•Robust to noise

•Sharing information is more important in short-term game, comparing to the case of long-term game



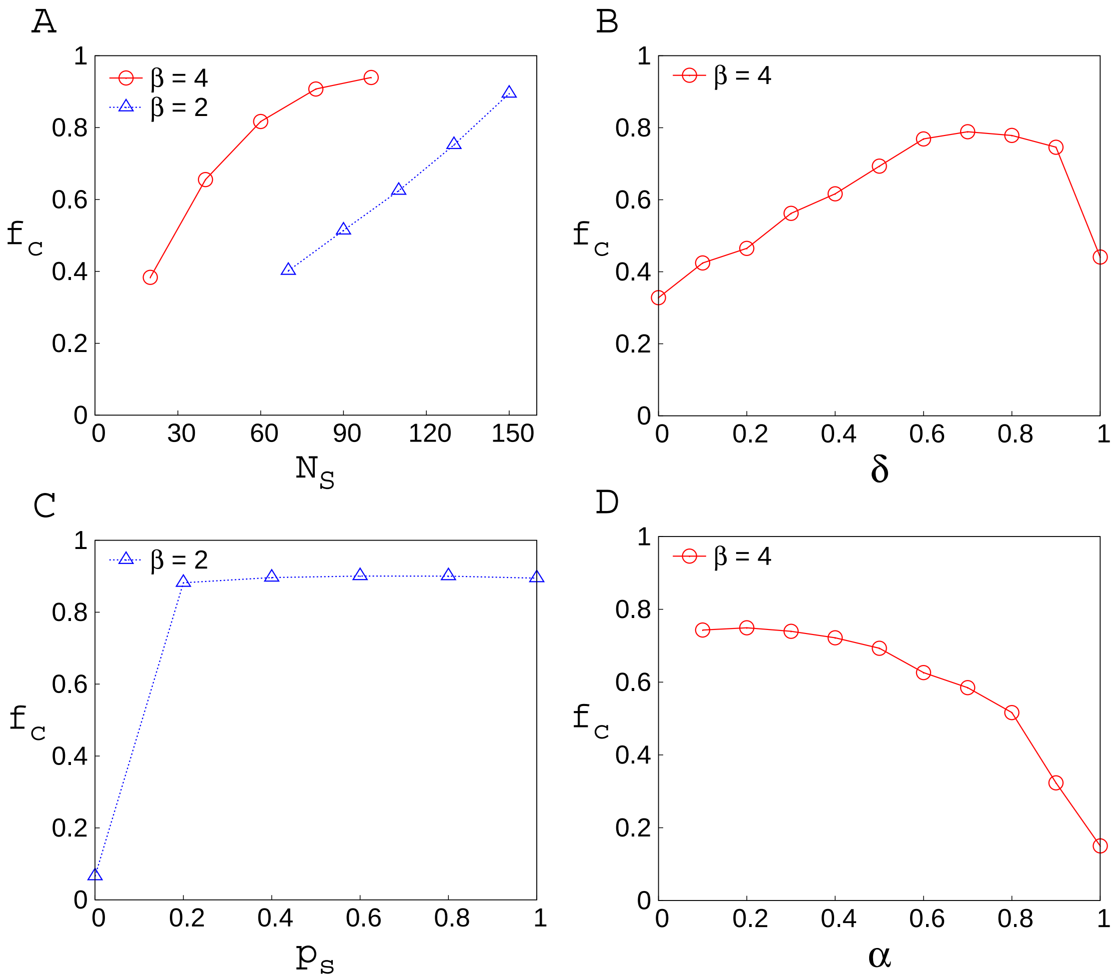
•Short-term (β = 10) vs. long-term (β = 100) games

•Noise-free (p_n = 0) vs. noisy (p_n = 0.05) interaction

•Sharing vs. non-sharing information

In incomplete interaction case:

- selection based on sharing information enhances performance significantly
- partial share(20%) is as effective as complete share



Parameters:

δ — the selection level

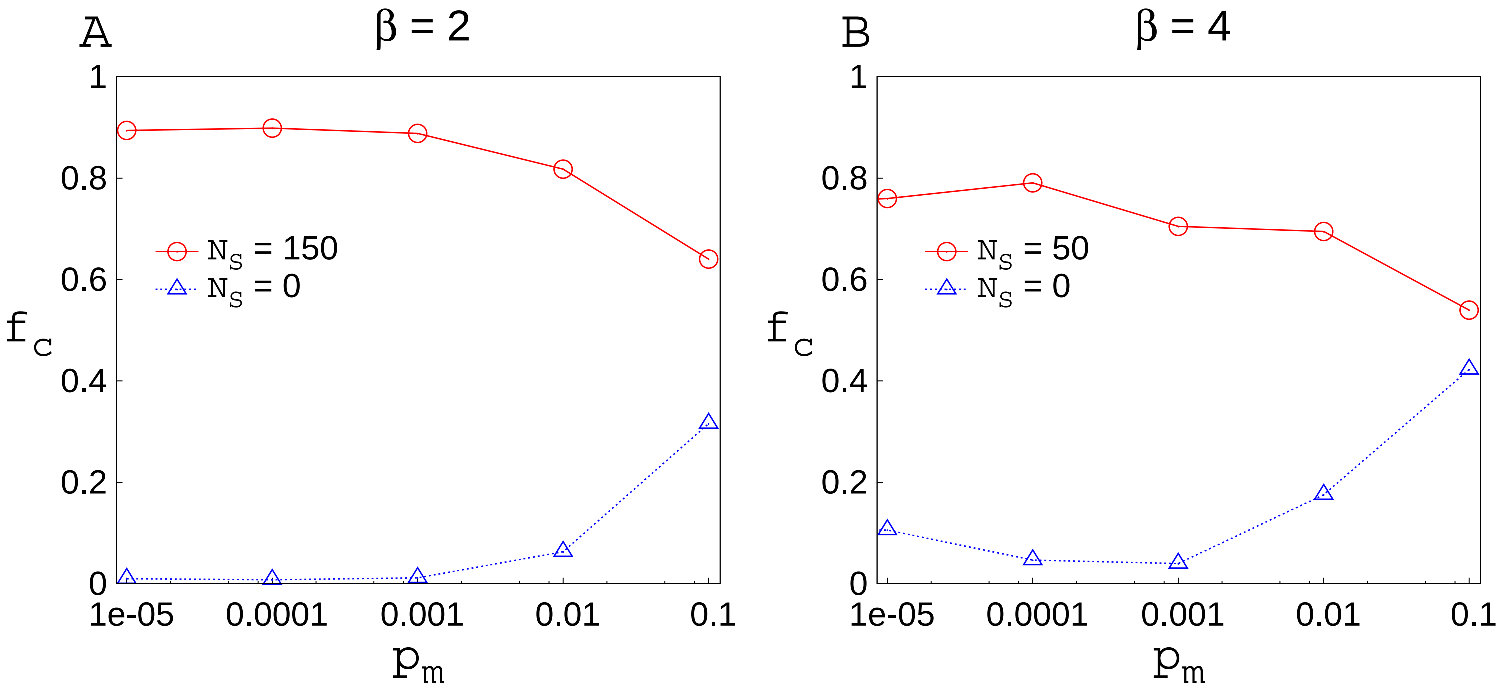
p_s — the sharing proportion

α — the interaction locality

Use much fewer shills comparing to complete interaction

Soft-control is robust in the case with mutation in reproduction

- **Mutation in reproduction**



From Simulations

- **shills can promote cooperation level significantly in different scenarios!**
  - Sharing information
  - Opponent selection
  - Reward cooperators
    Punish defectors
    Both

Analytical study

- **Soft-control, with shills complete interaction**

Proposition 2. Assume that the population plays the β-stage RPD for any given R, S, T, P which satisfy $T > R > P > S$ and $R > (T + S) / 2$. The types of mixed reactive strategies n is sufficiently large to contain any possible strategy. Also assume that shills use the strategy F-TFT. Then exists $x^* \geqslant 0$, when the proportion of shills is larger than x^*, the frequency of cooperation f_c converges to one.

Summary

- **Conclusions in this case study**
  - Soft control is possible to promote cooperation while keeping local rules in the original population
  - Robust to noise, mutation
  - Sharing knowledge is more important in short-term IPD, comparing to the case of long-term RPD
  - Works well in complete and incomplete interaction case
  - In incomplete interaction case
    - selection based on sharing information enhances performance significantly
    - partial share is as effective as complete share

More to study …

- Influence of different spatial structures
- Other forms of strategy: deterministic finite automata, look-up table, neural networks, etc.
- Consider the opposite problem, i.e. introducing shills to destroy cooperation
- Real person game experiment
- Consider other games, e.g. Public Goods Game or Fashion Game
- …

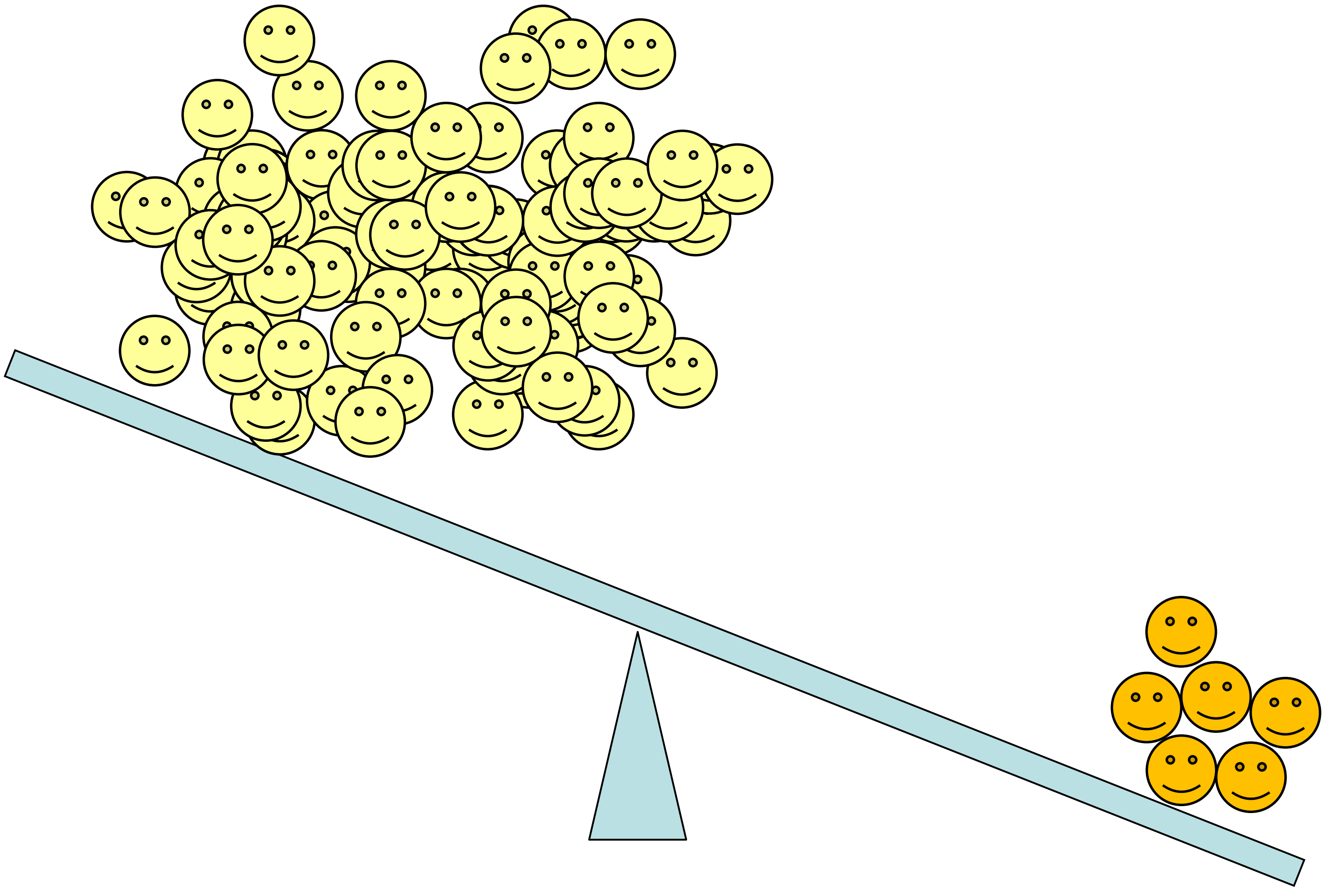
Review of this talk

Soft-control is

- FOR **multi-agent systems**
- TO **change the collective behavior**
- CAN'T
  - adjust global parameters
  - change local rule of the existing agents
- CAN:
  - add one or a few shills
  - (other methods) …

One or a few smart shills, can change the collective behavior of a group without changing the already-existing agents!

One/a few can change a group!



Need further study

- Use soft-control to intervene in other multi-agent systems (panic/rumor control, public opinion, market,…)
- Use soft-control while designing man-made MAS
- Controllability of soft control in a general framework
- Anti-soft-control problem: how to recognized and prohibit shills (especially in C2C ecommerce)
- …

Thank you !

Demos, talks and papers can be downloaded from
http://Complex.amss.ac.cn/hanjing/

hanjing@amss.ac.cn

Welcome to visit
the Complex Systems Research Cent of AMSS, CAS, Beijing.

Email me!

数系天地 勤笃求真

Complex Systems Research Center @AMSS

Http://complex.amss.ac.cn