Network Science: Cooperation in Selfish Environments

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Structure vs dynamics

- *Structure* — shape of the network
  - degree distribution
  - clustering
  - diameter
- *Dynamics* — what is happening in the network
  - navigation
  - gossiping
  - topology building (newscast, cyclone, T-Man)
  - aggregation
  - synchronization
- Structure and dynamics are often interrelated
  - effects of topology on aggregation

Rational dynamics

- So far, the dynamics have been "blind" — nodes have no "free will" or "purpose" but pass around information blindly
- When in fact, nodes are often individuals or other active entities with intent, goals and self-interests
- This results in *rational dynamics*
- *Game theory* is a tool for studying rational dynamics
  - *Strategies* — model intent
  - *Utility* — measure achievement of goals

Rational dynamics
Elements of game theory

- Set of participants called *players*
- Each player has a set of options for behavior called *strategies*
- For each choice of strategies, a player receives a *payoff* that may depend on the strategies selected by other players
- Summarized in the form of a *payoff matrix*

Rational dynamics
Elements of game theory

- Each players knows everything about the structure of the game:
  - who the other players are
  - the set of all possible strategies
  - the payoff matrix
  - but does *not* know the strategies chosen by the other players
- Players are *rational* — each tries to maximize her own payoff, given her beliefs about the strategies used by other players

Rational dynamics
Iterated network games

- Large number of players (nodes in the network)
- A *network* mediates the interactions between players
- Payoffs depend only on local interactions (between nodes that are neighbors in the network)
- Payoff matrix specifies value for each configuration of local neighborhood (without exhaustive enumeration)
- Interested not in "one-shot" outcomes but in the dynamics of *iterated* plays
- The node's overall *utility* is the running average of its payoffs from repeated interactions

Cooperation in selfish environments
Peer-to-peer applications

- Peer-to-peer applications such as file sharing are totally decentralized and "open" — anyone can join them
- They are subject to "free-riding" — selfish users that enjoy the benefits without contributing their share
  - they download but do not allow uploads
  - they store their files but do not contribute disk space for others
- High levels of free-riding can render these systems useless
- How to reduce the level of selfishness (and increase the level of cooperation)?
- "Copy-and-wire" algorithm

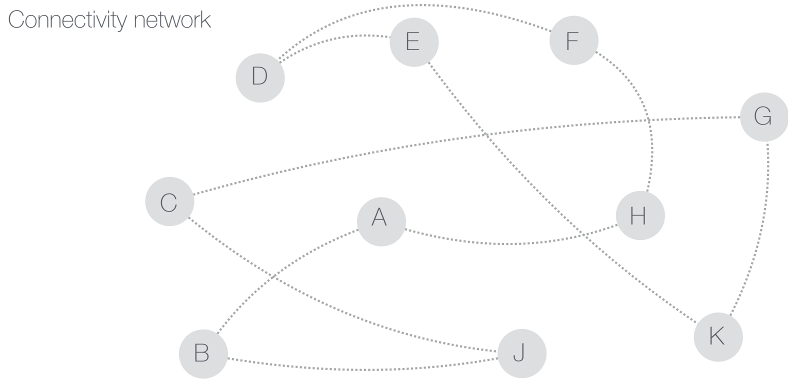
Cooperation in selfish environments
"Copy-and-rewire"

- Two logically distinct networks:
  - Random overlay network to maintain connectivity
  - Application-dependent interaction network
- Periodically, node $\mathcal{P}$ compares its utility with that of a peer $\mathcal{Q}$ selected at random (from the connectivity network)
- If $\mathcal{Q}$ has been achieving higher utility
  - $\mathcal{P}$ copies $\mathcal{Q}$'s strategy
  - $\mathcal{P}$ rewires its links to the neighbors of $\mathcal{Q}$
- With (very) small probability, node $\mathcal{P}$
  - "Mutates" its strategy (picks an alternative strategy at random)
  - Drops all of its current links
  - Links to a random node

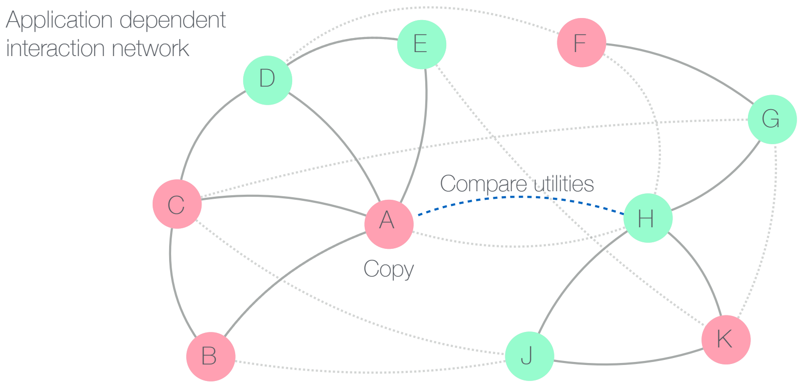
Cooperation in selfish environments
Gossip framework instantiation

- Style of interaction: pull
- Local state `S`: Current utility, strategy and neighborhood within an interaction network
- Method `SelectPeer()`: Single random sample
- Method `Update()`: Copy strategy and neighborhood if the peer is achieving better utility

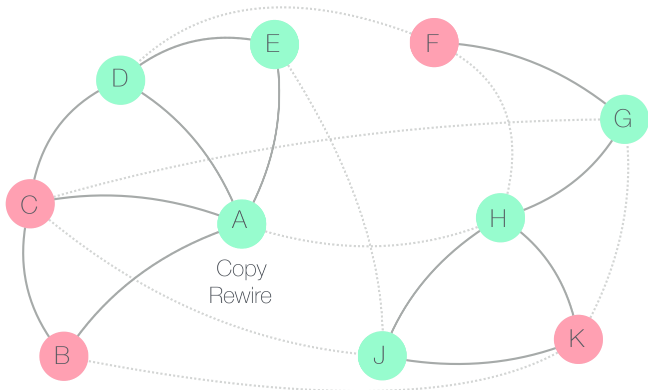
Cooperation in selfish environments
“Copy-and-rewire” algorithm



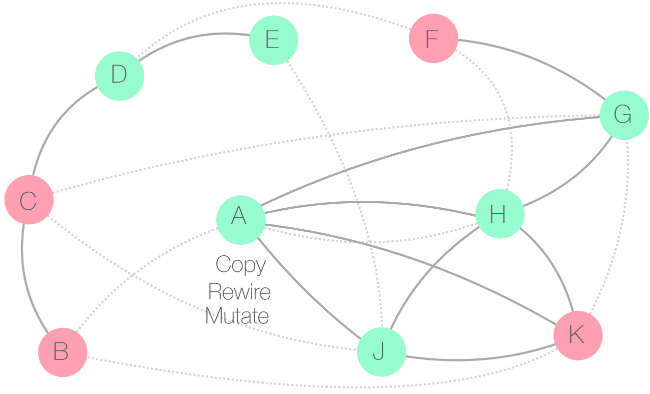
Cooperation in selfish environments
“Copy-and-rewire” algorithm



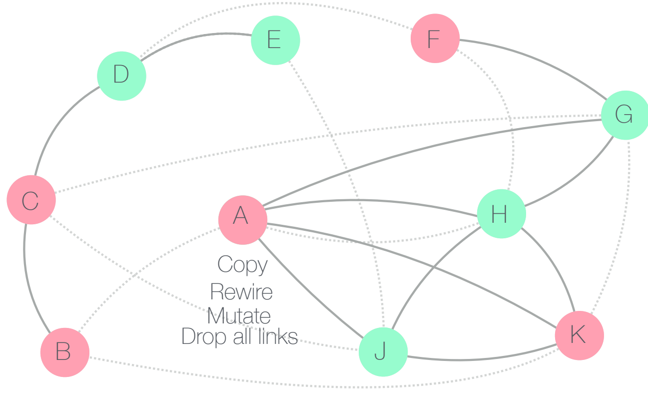
Cooperation in selfish environments
“Copy-and-rewire” algorithm



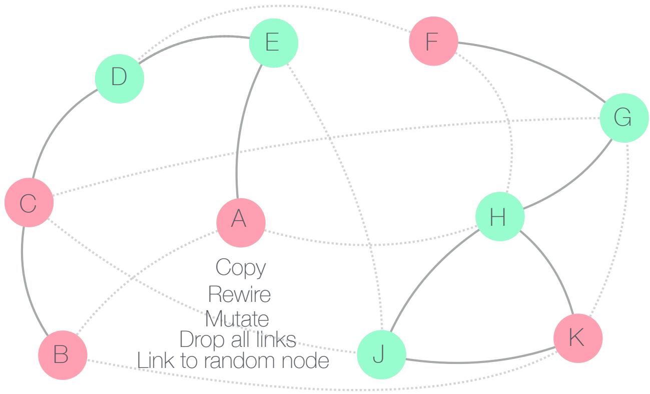
Cooperation in selfish environments
“Copy-and-rewire” algorithm



Cooperation in selfish environments
“Copy-and-rewire” algorithm



Cooperation in selfish environments
“Copy-and-rewire” algorithm



Cooperation in selfish environments
Prisoner’s Dilemma

- Prisoner’s Dilemma (PD) is an abstract game that captures the conflict between “individual rationality” and “common good”
- Two guilty individuals have been captured and while being interrogated in separate rooms, are offered a deal by the police
- Each prisoner can choose between “Confess” (C) and “Deny” (D)
- Each prisoner must act unilaterally — no collusion, conversation

	D	***C***
D	–2, –2	–10, –1
C	–1, –10	–8, –8

- Confession leads to higher *individual* payoff — selfishness
- Denial leads to higher *global* payoff — cooperation

Cooperation in selfish environments
Prisoner's Dilemma

- Note that (*C*, *C*) represents an *equilibrium* state — neither prisoner can improve her payoff by changing her strategy
- No other pair of strategies is an equilibrium — some prisoner is always better off by changing her strategy
- "Dilemma" because both prisoners would have been much better off if both had chosen "Deny"
- But (*D*, *D*) is *not* an equilibrium state
- In general, just because the players are at equilibrium in a game does not mean that they are *happy*

Cooperation in selfish environments
Prisoner's Dilemma

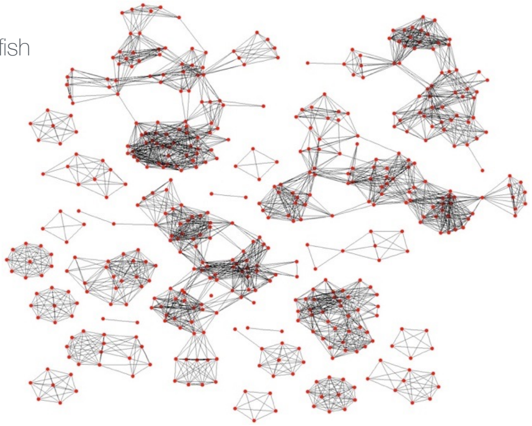
- Test the "copy-and-rewire" algorithm with repeated iterations of Prisoner's Dilemma played on the interaction network
  - Only pure strategies are played (always *C* or always *D*)
  - In each round, a node plays with one random neighbor selected from the interaction network
  - Mutation: flip current strategy
  - Utility: average payoff achieved so far

Cooperation in selfish environments
Simulation results

- 500 nodes
- Connectivity network generated using Newscast
- Initial state:
  - All nodes are selfish
  - Random interaction network

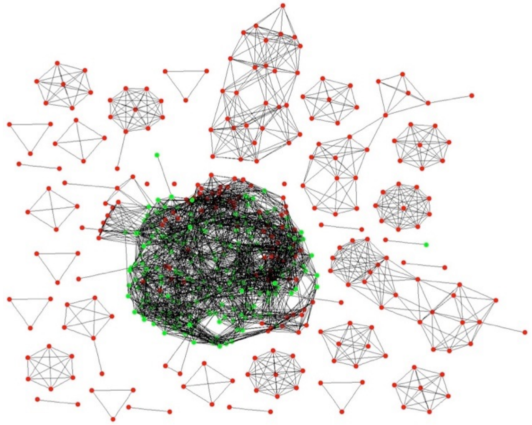
Cooperation in selfish environments
Prisoner's Dilemma @ round 180

Small clusters of selfish nodes start to form



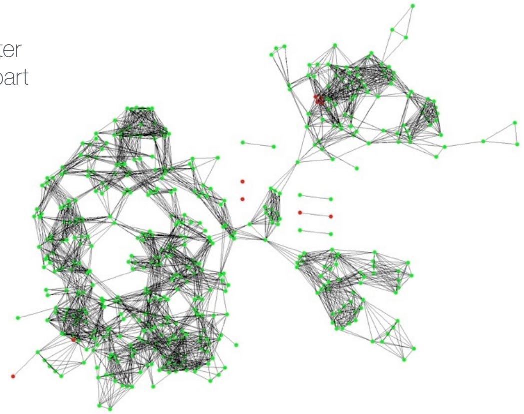
Cooperation in selfish environments
Prisoner's Dilemma @ round 220

Giant cooperative cluster emerges



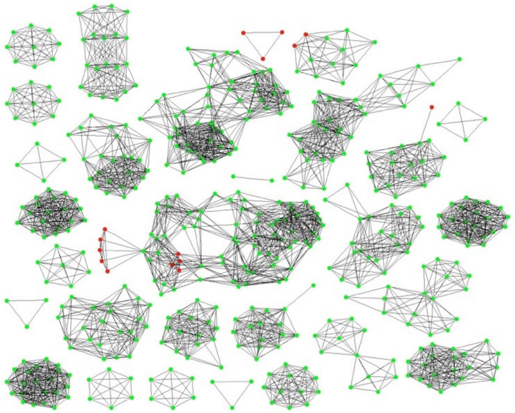
Cooperation in selfish environments
Prisoner's Dilemma @ round 230

Cooperative cluster starts to break apart

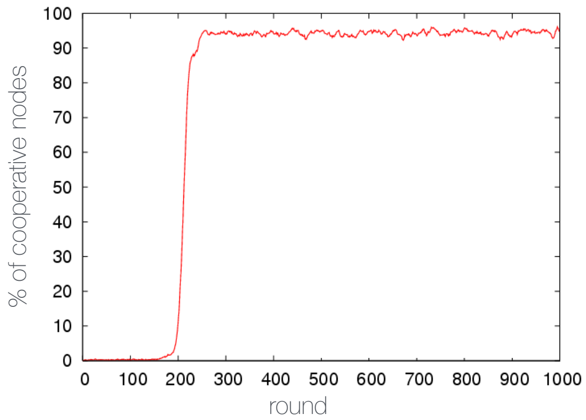


Cooperation in selfish environments
Prisoner's Dilemma @ round 300

Small cooperative clusters formed, selfish nodes become isolated



Cooperation in selfish environments
Phase transition



Cooperation in selfish environments
Resulting dynamics

- "Copy-and-rewire" causes the interaction network to evolve, resulting in the nodes to "move" in search of better neighborhoods
- Equilibrium states achieve very high levels of cooperation
- Group-like selection between clusters
  - Clusters of cooperative nodes grow and persist
  - Selfish nodes tend to become isolated
- Can be seen as a "strategic" (as opposed to "stochastic") network formation process

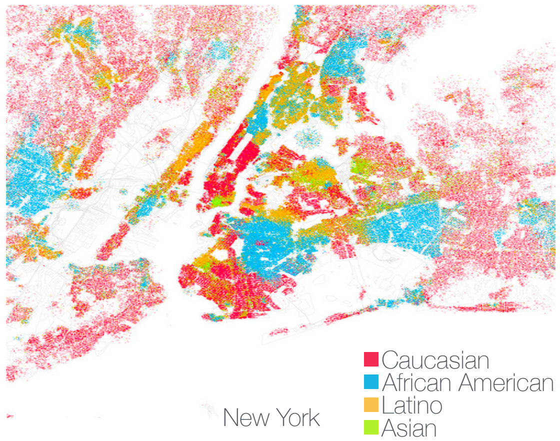
Homophily

- Homophily — "Birds of a feather flock together"
- Individuals seek similar individuals
- Homophily is observed across race, gender, age, religion, income in a wide variety of networks — neighborhood, friendship, marriage, loans, etc.
- Some reasons for homophily:
  - Opportunity
  - Social pressure
  - Cost/benefit
  - Social competition
- Peer effects — related but different property where individuals *adopt* the behavior of their peers

Homophily
Segregation

- Population of individuals
- Each individual has a "type"
- Individuals achieve a "utility" based on the types of other individuals in their neighborhood in comparison to their own type
- Individuals care about where they live
- Individuals can move if they are not happy about their current neighborhood

Segregation in the wild (race)



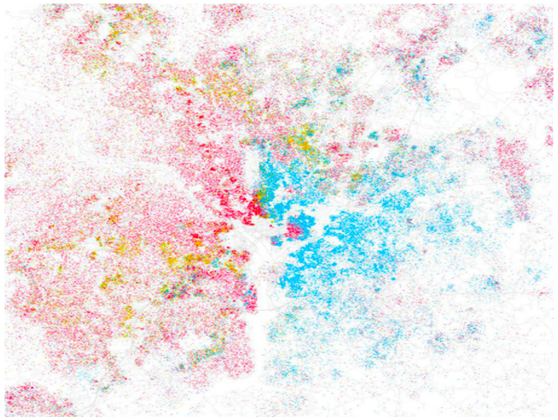
Segregation in the wild (race)

Los Angeles

Segregation in the wild (race)

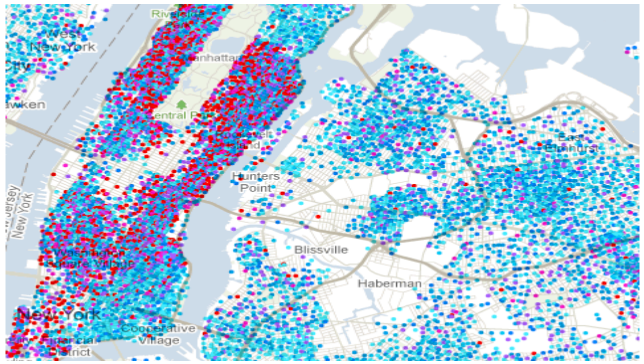
Houston

Segregation in the wild (race)



Washington DC

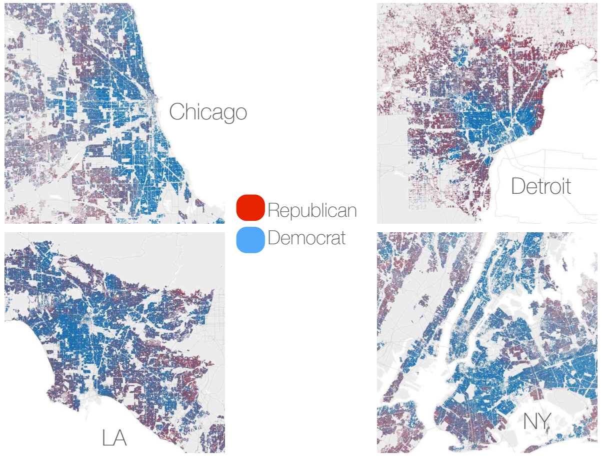
Segregation in the wild (income)



> $200K

< $30K

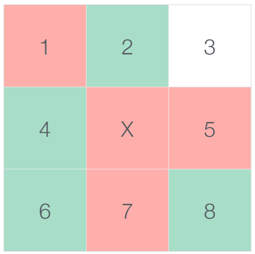
Segregation in the wild (political affiliation)



Schelling's threshold model

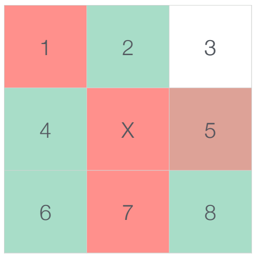
- Thomas Schelling — University of Maryland economist
- Schelling's Segregation Model to study homophily in a fixed grid network based on a threshold t
- The eight compass neighbors (N, S, E, W, NE, NW, SE, SW) of an individual define its "neighborhood"
- If the percentage of same-type individuals in its neighborhood is at least t, the given individual is *happy* and *stays* where it is
- Otherwise, it is *unhappy* and it *moves* to another (empty) grid position
- Collective game

Schelling's threshold model
Neighborhood



Neighborhood of location X

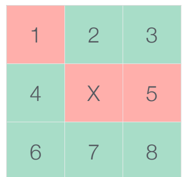
$t = 3/7 = 42.8\%$



"stay"

Schelling's threshold model
As an iterated network game

- Played on a $k \times k$ grid, with large number of players
- Strategy of a player is where it decides to live — there are k^2 possible strategies
- Fixed grid network mediates interactions by limiting a player's payoffs to depend only on the occupants of neighboring cells



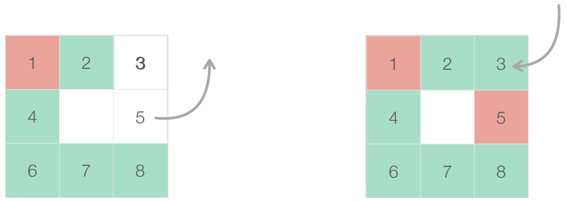
- For the occupant of location X, the payoff matrix would still need to have 3^8 entries

Schelling's threshold model
As an iterated network game

- Let h denote the percentage of neighboring cells that have the same type as the occupant of location X
- For Schelling's Model with threshold t, the payoff matrix for occupant of location X can be condensed to just 2 entries:
  - if $h \geq t$ then payoff is 1
  - if $h < t$ then payoff is 0
- Not interested in "one-shot" but iterated plays
- Players can change their strategy by moving
  - move to a random empty cell if payoff is 0
- Equilibrium dynamics (when it exists) where all players are happy with payoff 1

Schelling's threshold model
Cascading moves

$t = 2/7 = 28.5\%$



Exodus Genesis

- NetLogo "Library/Social Science/Segregation"

Schelling's threshold model
Remarks

- Difficult to infer *collective behavior* from *individual preferences*
  - Tolerance of 51% (almost perfect *desegregation*) led to 94% of the individuals having similar type neighbors (almost total segregation)
- True also in other *decentralized* systems
- Possible counter examples in *centralized* systems (people not allowed to move unilaterally but are told where to live by a central authority)
- Similar to solving a system of equations (individual preferences or PageRanks) in a constrained system