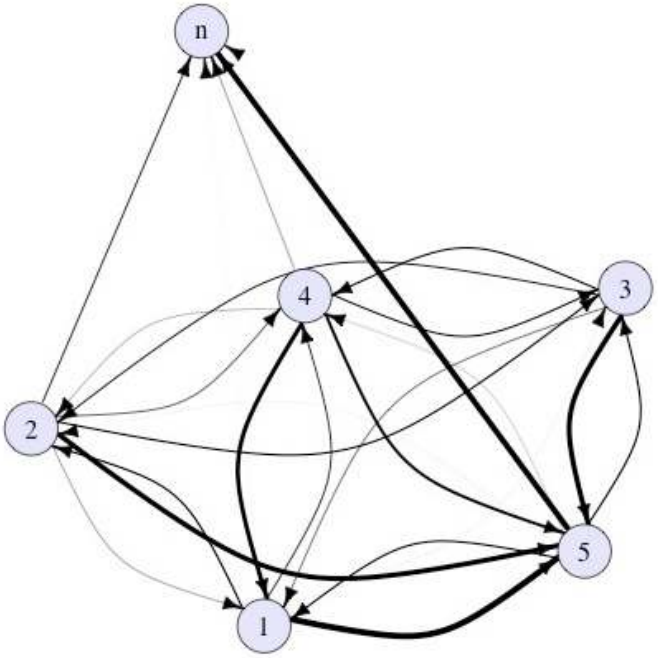


SELF-ASSEMBLING NETWORKS

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Introduction

We provide a proof of concept for how an epistemic network might self-assemble by polymerization as heterogeneous agents investigate nature and each other.

Connections to the Literature

- **Self-assembling games**
  - Barrett, J. & Skyrms, B. (2015)

- **Dynamic network formation & adaptive networks**
  - Bala, V. & Goyal, S. (2000), Goeree, J. et al (2000), Gross, T. & Sayam, H. (2009), Jackson, M. & Watts, A. (2000), Skyrms, B. & Pemantle, R., (2000), Pemantle, R. & Skyrms, B. (2003)

- **Social epistemology**
  - Kitcher, P. (1990, 1993), Rosenstock, S. et al (2016), O'Connor, C. & Bruner, J. (2016), Strevens (2003, 2013), Zollman, K. (2007, 2012), Weisberg M. & Muldoon, R. (2013), Alexander, J. et al (2015)

Motivation

- Implications for social epistemology:
  - Social epistemology needs to study how information is transmitted through a social network.
  - It has been shown by example that this possibility may be sensitive to the network structure in ways that are not obvious without analysis.
  - But social networks are not just given; they evolve.

Motivation

- This project is a step in bringing together two new and developing research programs: the theory of self-assembling games and the theory of network epistemology

- **Upshot:** We will show that even simple, low rationality agents may evolve social networks that allow them to be more successful than they could have been had they investigated nature on their own.

Methodology

- Create an idealized model of a community of inquirers trying to learn about some state of the world in order to take successful action.

- Inquirers learn via *reinforcement learning* (RL), a low rationality dynamic.
  - Success of RL suggests that more sophisticated learning rules may also be successful.
  - Degree of success of RL can provide a baseline against which to measure the effectiveness of other dynamics.
  - RL has a long track record of being applied to interactive decisions.

Methodology

- We consider self-assembly of epistemic networks under two different conditions:
  - Information is transmitted along a link with fidelity
  - Information is transmitted with errors

- We'll see that the different conditions result in qualitatively different kinds of network structures.

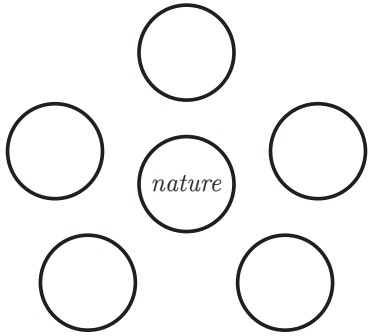
Outline

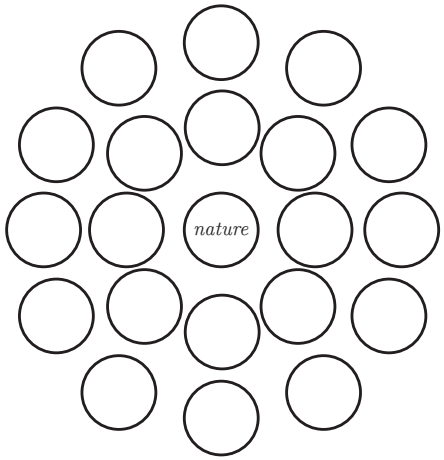
- Introduction
- Motivation
- The Model
- Equilibrium Analysis
- Results: Perfect Communication
- Results: Imperfect Communication
- Discussion
- Next Steps

The Model

- A population of inquirers & Nature

5-agent population





20-agent population

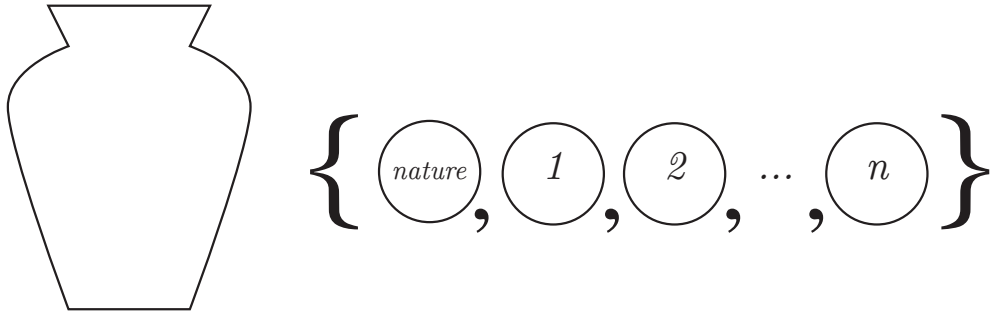
- Inquirers may take one of two actions:
  - observe nature,
  - or consult another agent.

The Model

- Inquirers differ in the reliability of their observations
    - In particular, for each inquirer, her epistemic reliability e_i is fixed at the beginning of each run of simulation in [0,1], uniformly at random.
- Inquirers differ in the reliability of their consultations
    - In particular, for each inquirer, her social reliability s_i is fixed in [0.5,1], uniformly at random.

Reinforcement Learning

- Each inquirer *i* can be thought of as being equipped with an urn with one ball for nature, and one ball for each other agent in the population.



- On her turn, the an inquirer decides whether to observe nature or consult a particular agent by randomly drawing a ball from her urn.

Reinforcement Learning

- If she **investigates nature** (draws the nature ball):
  - Then she succeeds in obtaining the truth with probability equal to her epistemic reliability e_i.
    - If she **succeeds**, then she acts successfully, is prepared to share the truth, and adds another nature ball to her urn.
    - If she **fails**, then she does not act successfully, is unprepared to share the truth, and adds no ball to her urn.

Reinforcement Learning

- If she **consults another agent *j***:
  - If the other agent knows the true state of nature:
    - Then the inquirer **succeeds** in obtaining the truth, is prepared to share it when consulted, acts successfully, and adds another *j*-ball to her urn.
  - If the other agent doesn't know the true state of nature
    - Then the inquirer **fails** to obtain the truth, cannot share it, and adds no ball to her urn.

The model

- In this way, the inquirers investigate the world in rounds of play, repeated over multiple generations.
- Each generation is characterized by a particular empirical problem that must be solved for successful action. An agent who knows how to solve the problem knows the truth.
- Each round, the inquirers take turns attempting to solve the current problem by observation or consultation with an agent.
- We will consider simulations consisting of 200 generations where each generation has 100 full rounds of play.

The model

- In each round, the inquirers are randomly ordered, and they play once each in turn.
- A play begins with the inquirer whose turn it is drawing a ball from her urn.
- After each inquirer has played once in random order, the round ends and the inquirers begin a new round with the same empirical problem and what they have learned regarding its solution.
- At the end of a generation, the inquirers start a new investigation with a fresh a empirical problem and begin again in a state of complete ignorance.

Reinforcement Learning

A Simulation (=200 generations)

A Generation (=100 turns)
At the end of each generation, there is a new empirical problem to be investigated, and all agents are reset to a state of ignorance.

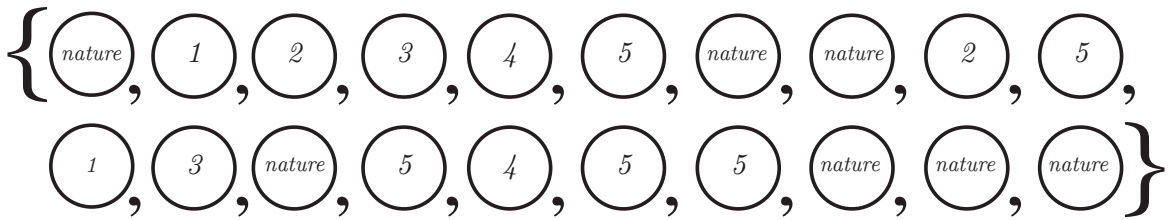
A Round (=N turns)
All enquirers in the population take their turn.

A Turn
An inquirer draws a ball from her urn, consults either another agent or nature, and adds an appropriate ball to her urn if successful.

Reinforcement Learning

- So, after *r* rounds, an inquirer will have at most *r+n+1* balls in her urn.

- For example, in a 5-agent population, after 20 rounds, a single inquirer may have the following urn composition.



  - This urn contains five 'nature' and five 'agent 5' balls.

- The idea: Over many rounds of play, we examine the proportions of the balls in player urns to see what actions have been most reinforced—i.e., who has each inquirer learned to consult.

Equilibrium analysis

- On a single play of the game, each agent either consults nature or precisely one other agent. The combination of the pure strategies corresponding to these actions defines a network.

- **Definition (Nash Network):** A *Nash network* is one such that no agent could gain in payoff by unilaterally changing her strategy. It is a *strict Nash network* if any agent unilaterally changing her strategy would decrease her payoff.

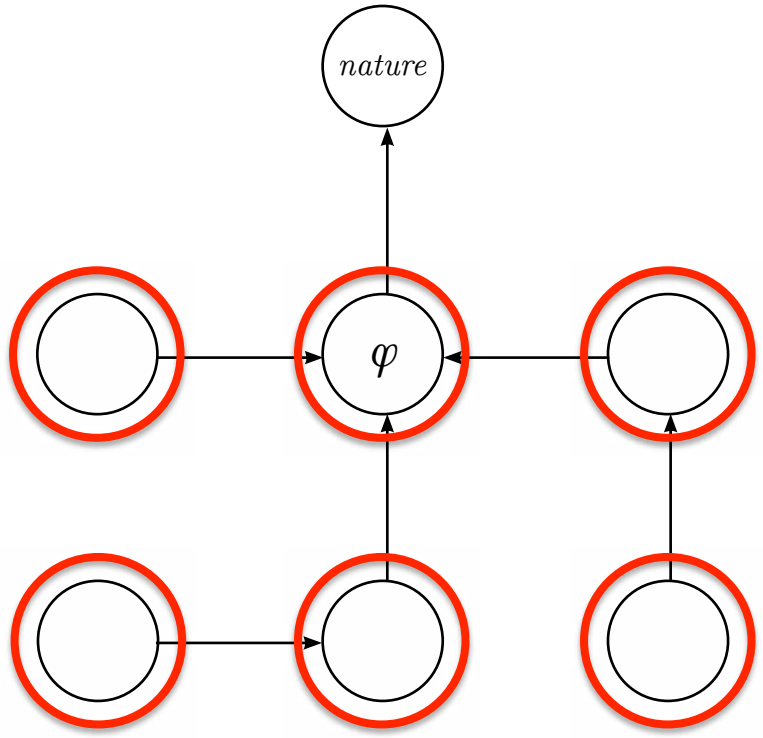
Equilibrium analysis

- We will take an agent's payoff to be her expected return on the single play where the value of getting the truth is 1 and not getting it is 0.

- For perfect communication we will set aside the measure-zero cases where agent epistemic reliabilities are exactly 0 or 1 and for imperfect communication the cases where social reliabilities are exactly 0.5 or 1.

- Finally, we will suppose that there is always a single most epistemically reliable agent in the population.

Equilibrium Analysis

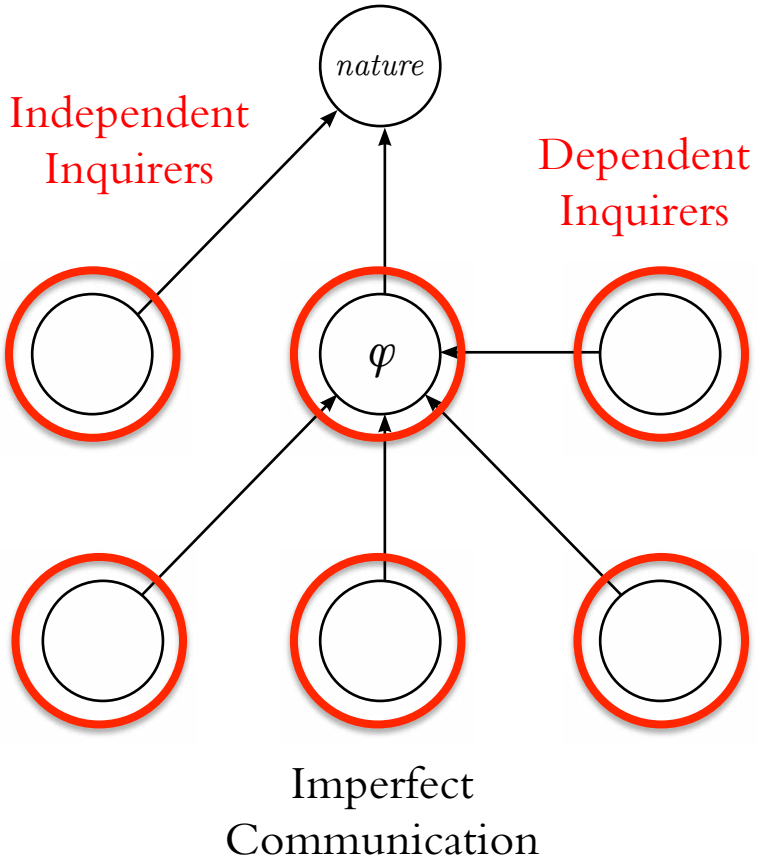


Perfect Communication

Claim 1. The Nash networks for perfect communication are exactly those where the most reliable agent consults nature and every other agent has a path to the most reliable agent.

Equilibrium Analysis

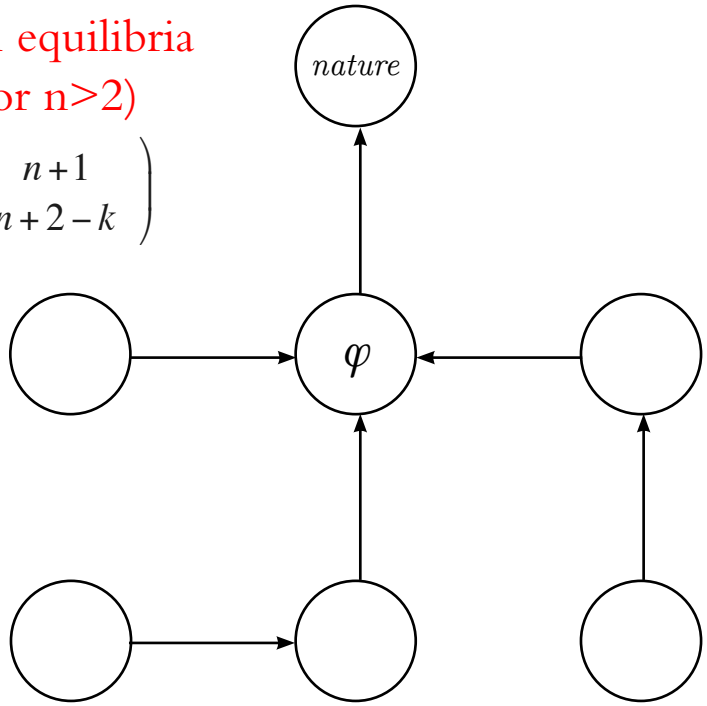
Claim 2. The Nash networks for imperfect communication are exactly those where the most reliable agent ϕ consults nature, and agents i for whom $e_i < e_{\phi s_i}$ consult agent ϕ, while agents for whom $e_i > e_{\phi s_i}$ consult nature.



Equilibrium Analysis

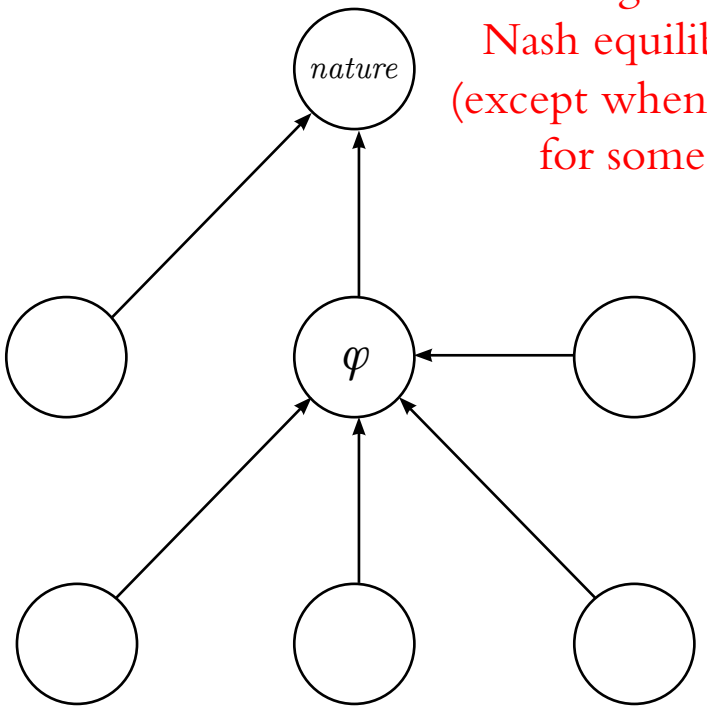
Many non-strict Nash equilibria (for n>2)

$$\sum_{k=1}^{n} \binom{n+1}{n+2-k}$$



Perfect Communication

A single strict Nash equilibrium (except when $e_i = e_\phi s_i$ for some i).



Imperfect Communication

Results: Perfect Communication

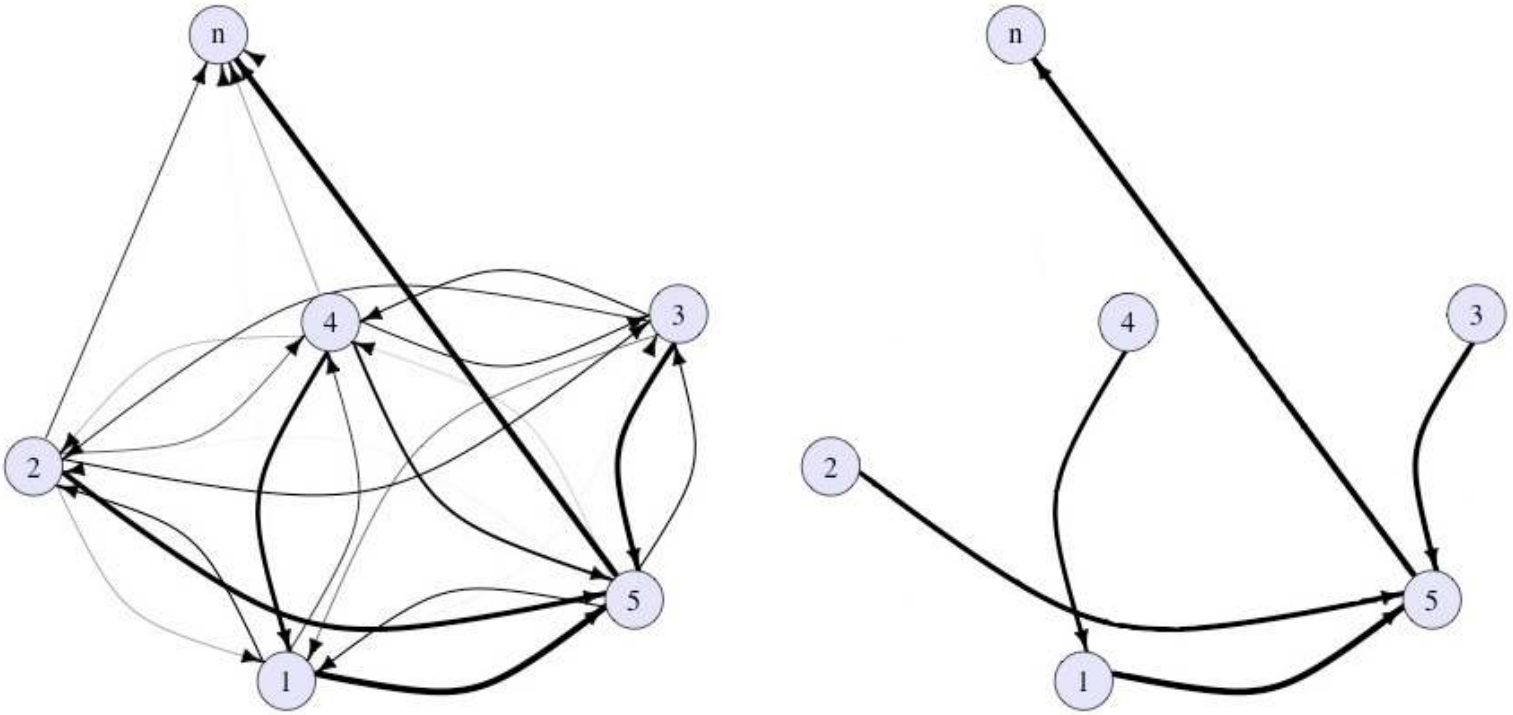
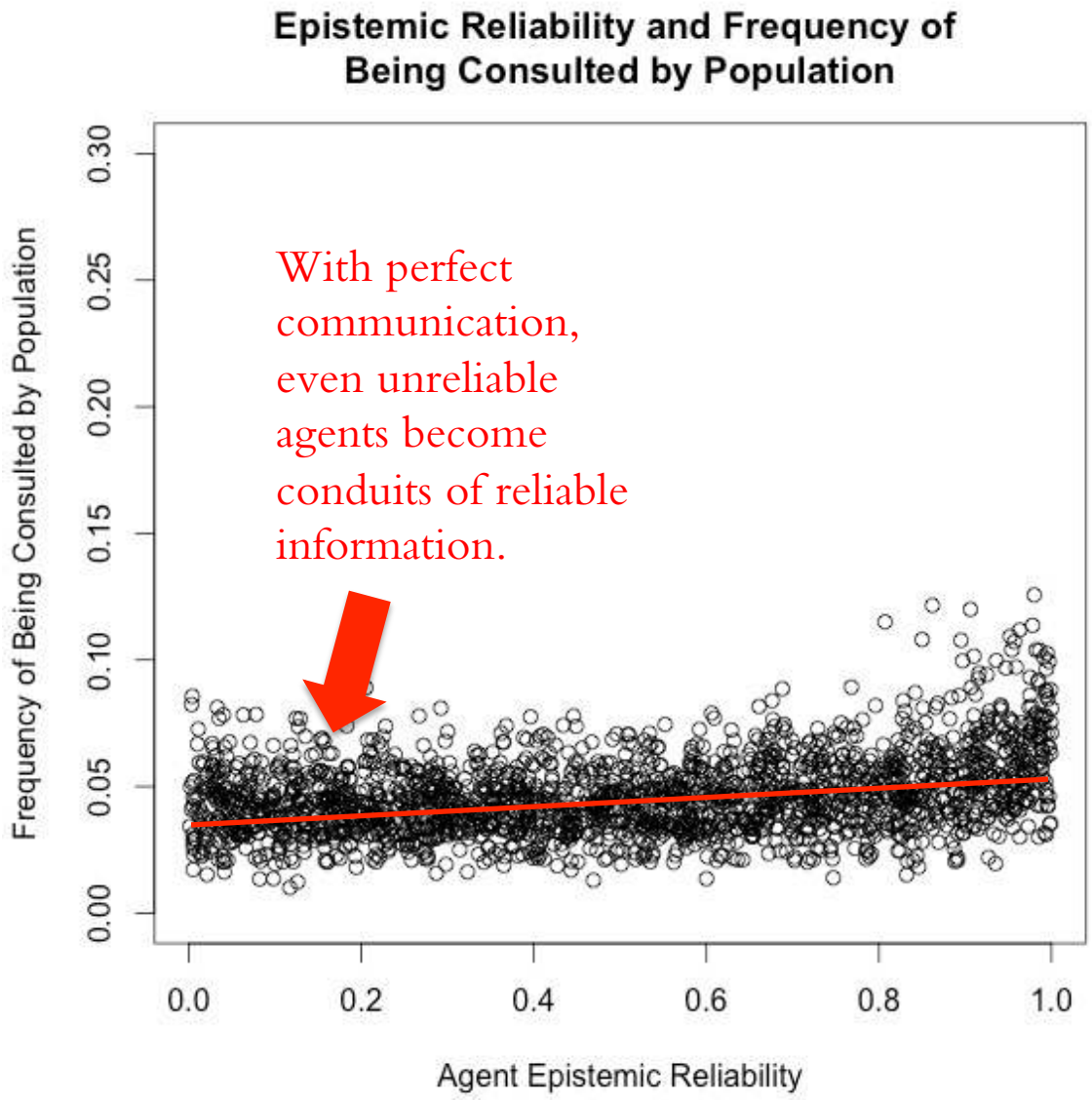
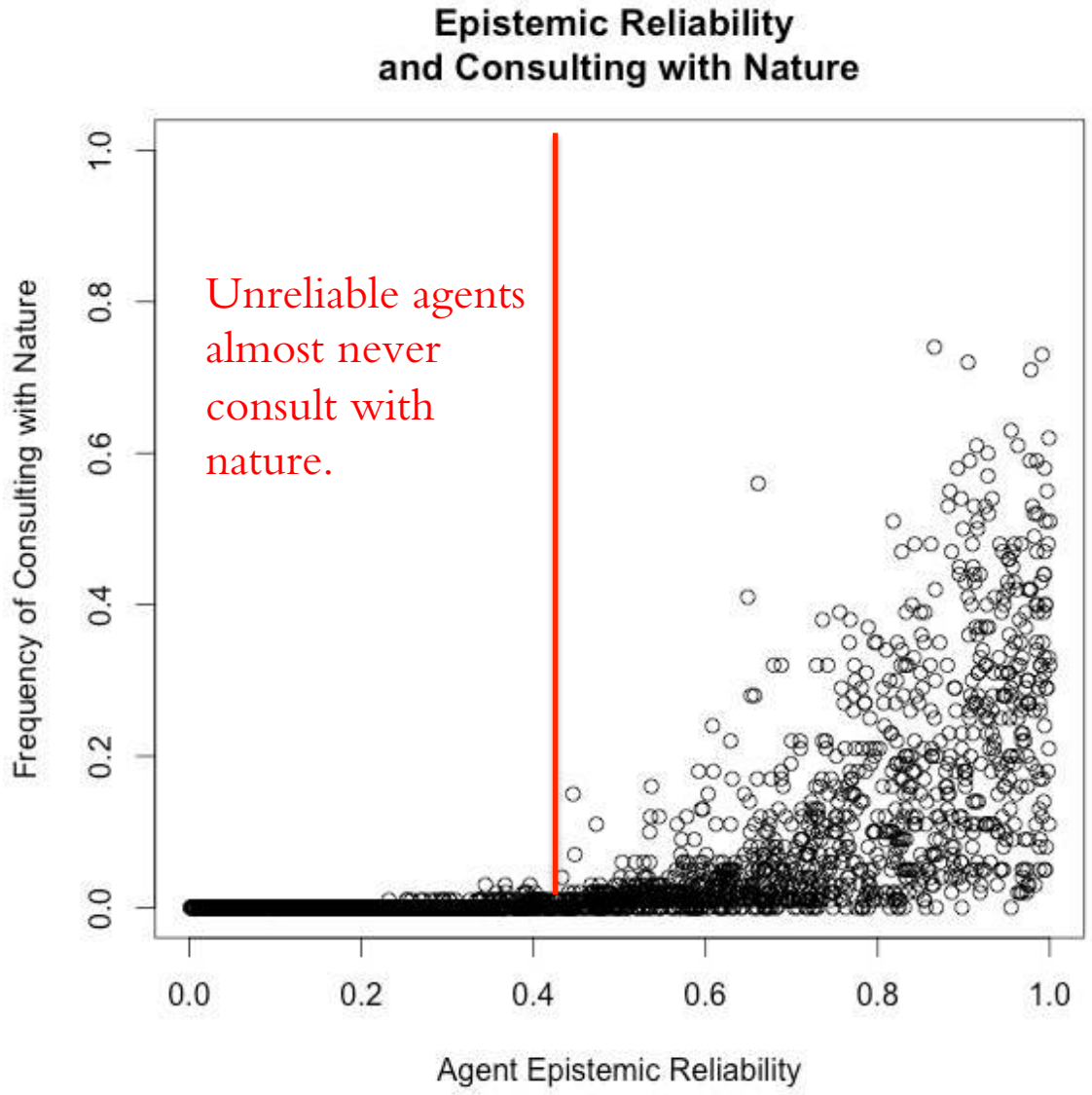
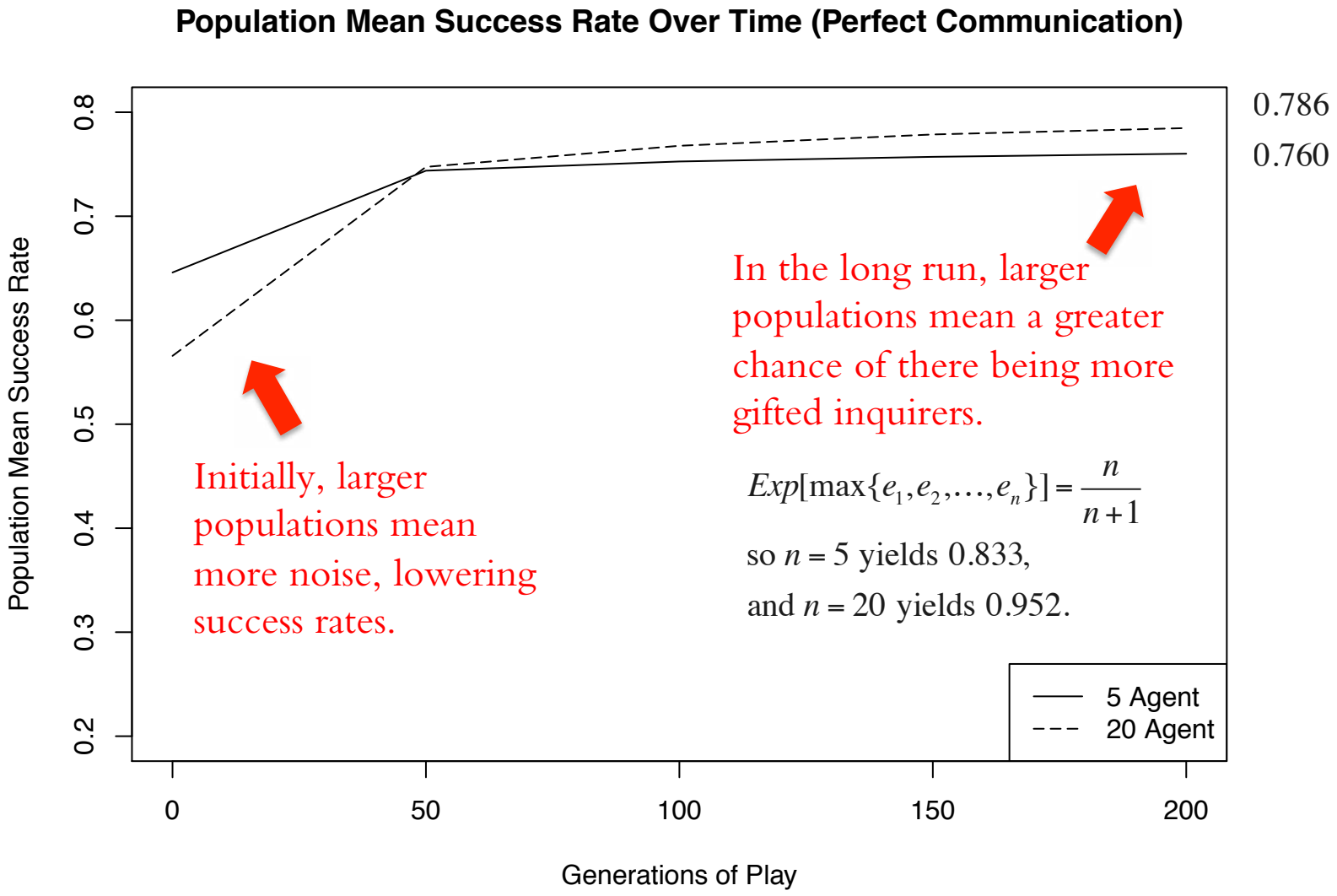
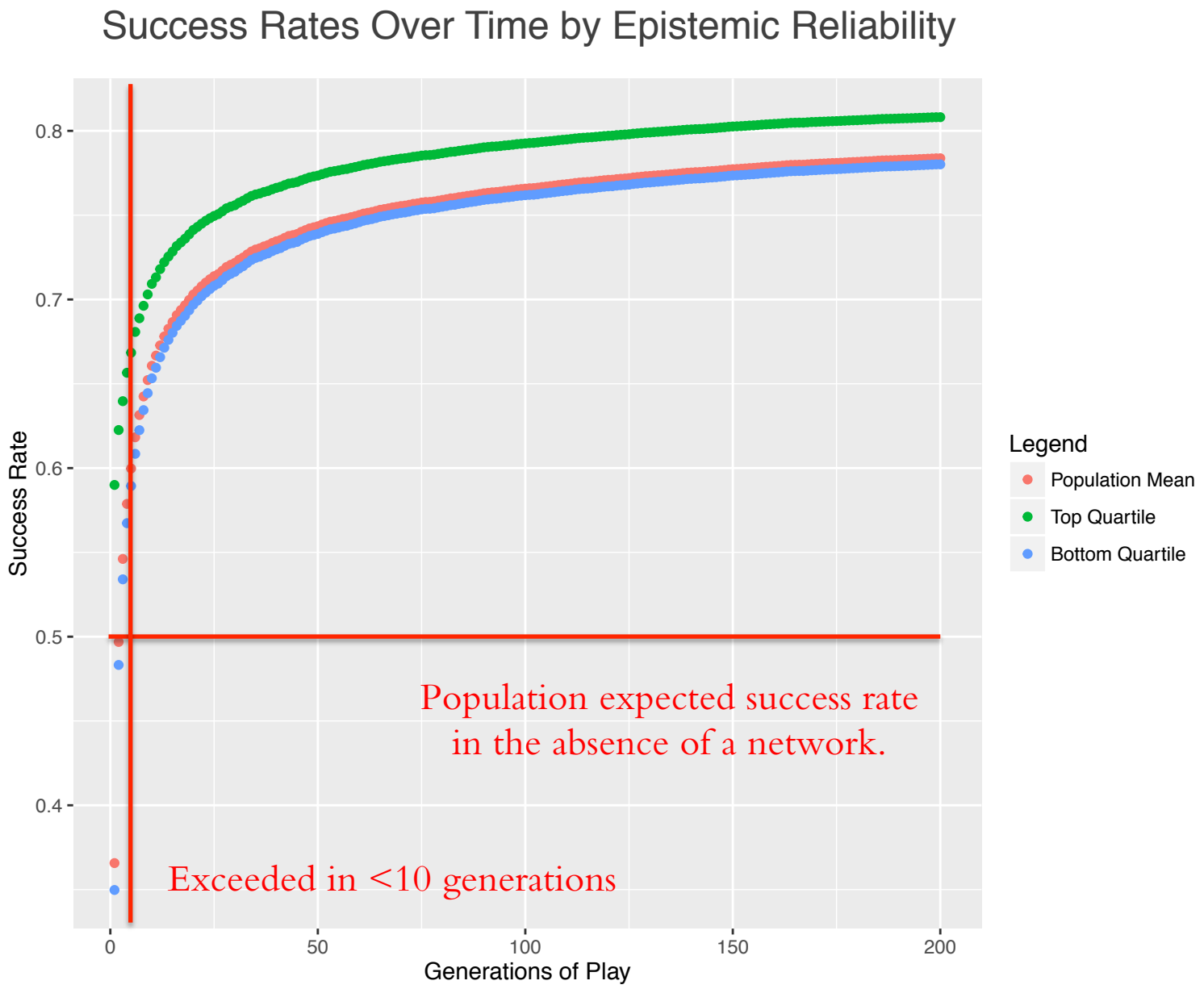


FIGURE. 5-agent model with perfect communication


Epistemic Reliability and Frequency of Being Consulted by Population
With perfect communication, even unreliable agents become conduits of reliable information.
Frequency of Being Consulted by Population
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.0
0.2
0.4
0.6
0.8
1.0
Agent Epistemic Reliability


Epistemic Reliability
and Consulting with Nature
Unreliable agents
almost never
consult with
nature.
Frequency of Consulting with Nature
0.0
0.2
0.4
0.6
0.8
1.0
Agent Epistemic Reliability


Population Mean Success Rate Over Time (Perfect Communication)
Population Mean Success Rate
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0
50
100
150
200
Generations of Play
0.786
0.760
In the long run, larger populations mean a greater chance of there being more gifted inquirers.
Initially, larger populations mean more noise, lowering success rates.
$Exp[\max\{e_1, e_2, \ldots, e_n\}] = \frac{n}{n+1}$
so $n = 5$ yields 0.833,
and $n = 20$ yields 0.952.
5 Agent
20 Agent


Success Rates Over Time by Epistemic Reliability
Success Rate
0.8
0.7
0.6
0.5
0.4
0
50
100
150
200
Generations of Play
Population expected success rate
in the absence of a network.
Exceeded in <10 generations
Legend
Population Mean
Top Quartile
Bottom Quartile

Upshot

- Even on simple reinforcement learning, the epistemic community typically learns who the most reliable inquirers are.

- The most reliable inquirers observe nature more often and are consulted more often by their colleagues. Their observations are disseminated throughout the evolved network.

- The network that self assembles promotes overall reliability; most inquirers are much more successful in the evolved network than had they made their own observations.

Results: Imperfect Communication

- Recall: Now, each agent is also randomly assigned a social reliability in the interval [0.5, 1] with uniform probability at the beginning of each run of the model.

- Imperfect communication might represent poor eavesdropping abilities, a tendency toward misunderstanding, or just recurrent failures to convince agents to report their results truthfully.

- This leads to three important changes in the evolved network:
  - Long signaling chains are no longer viable.
  - The most reliable inquirers are more frequently identified.

Results: Imperfect Communication

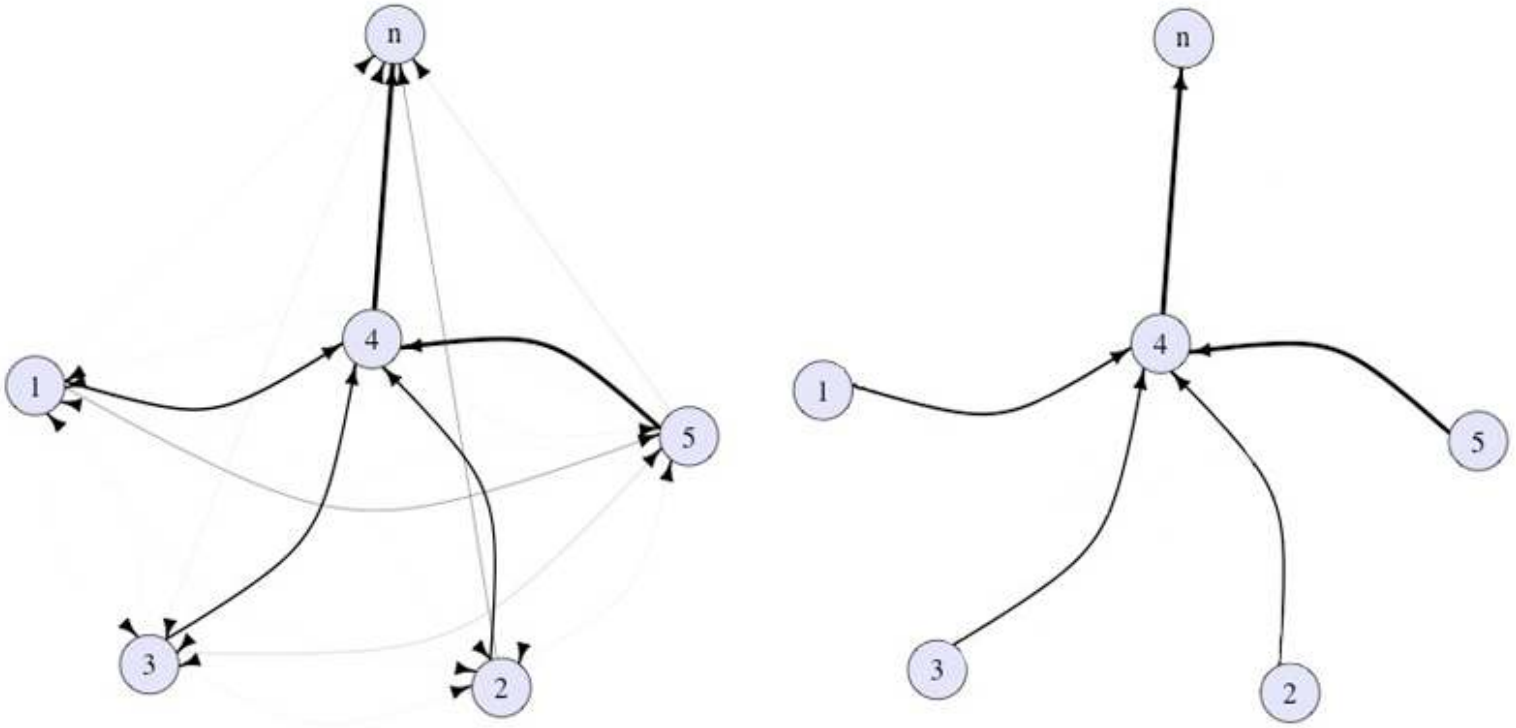
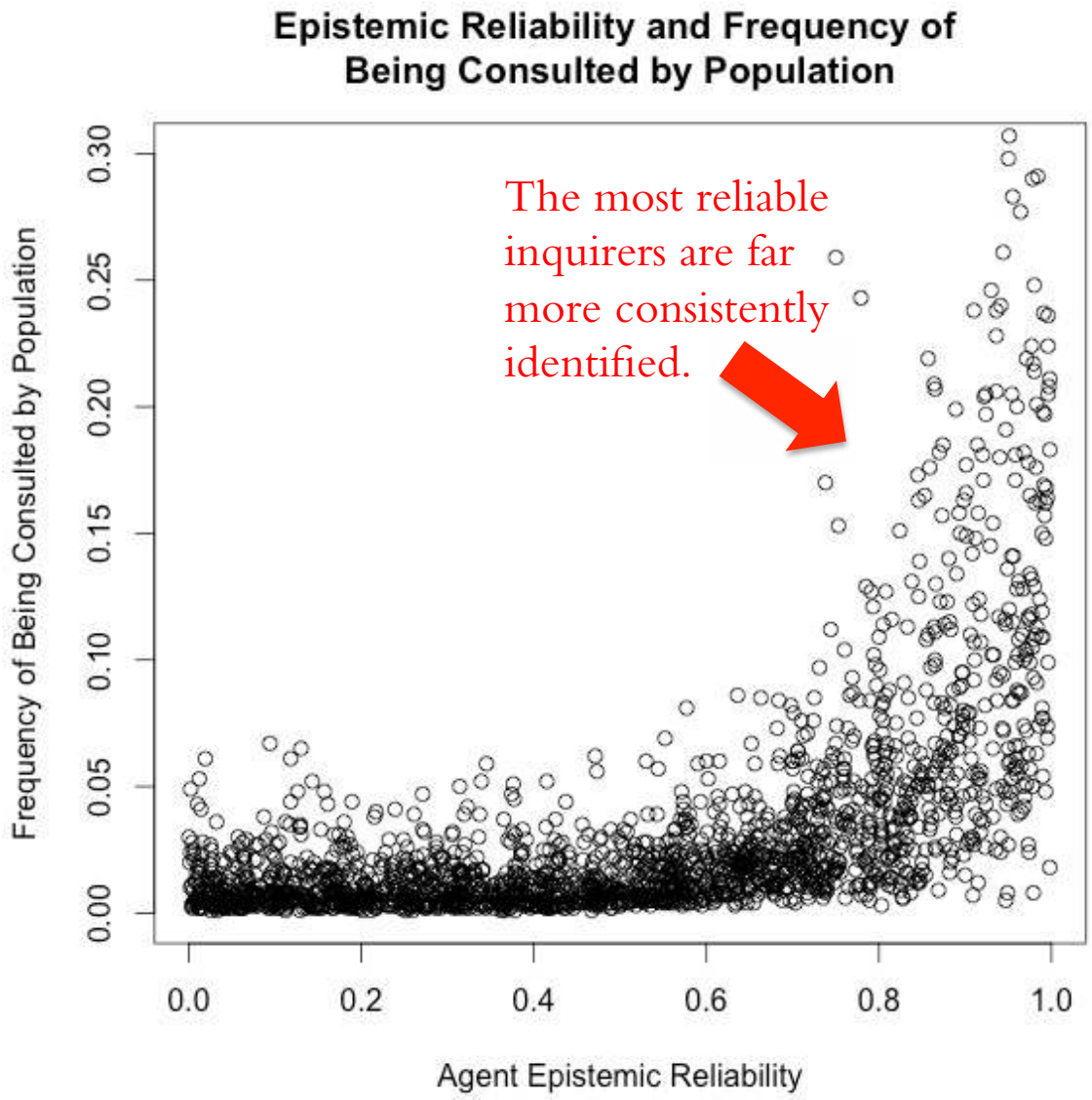


FIGURE. 5-agent model with imperfect communication

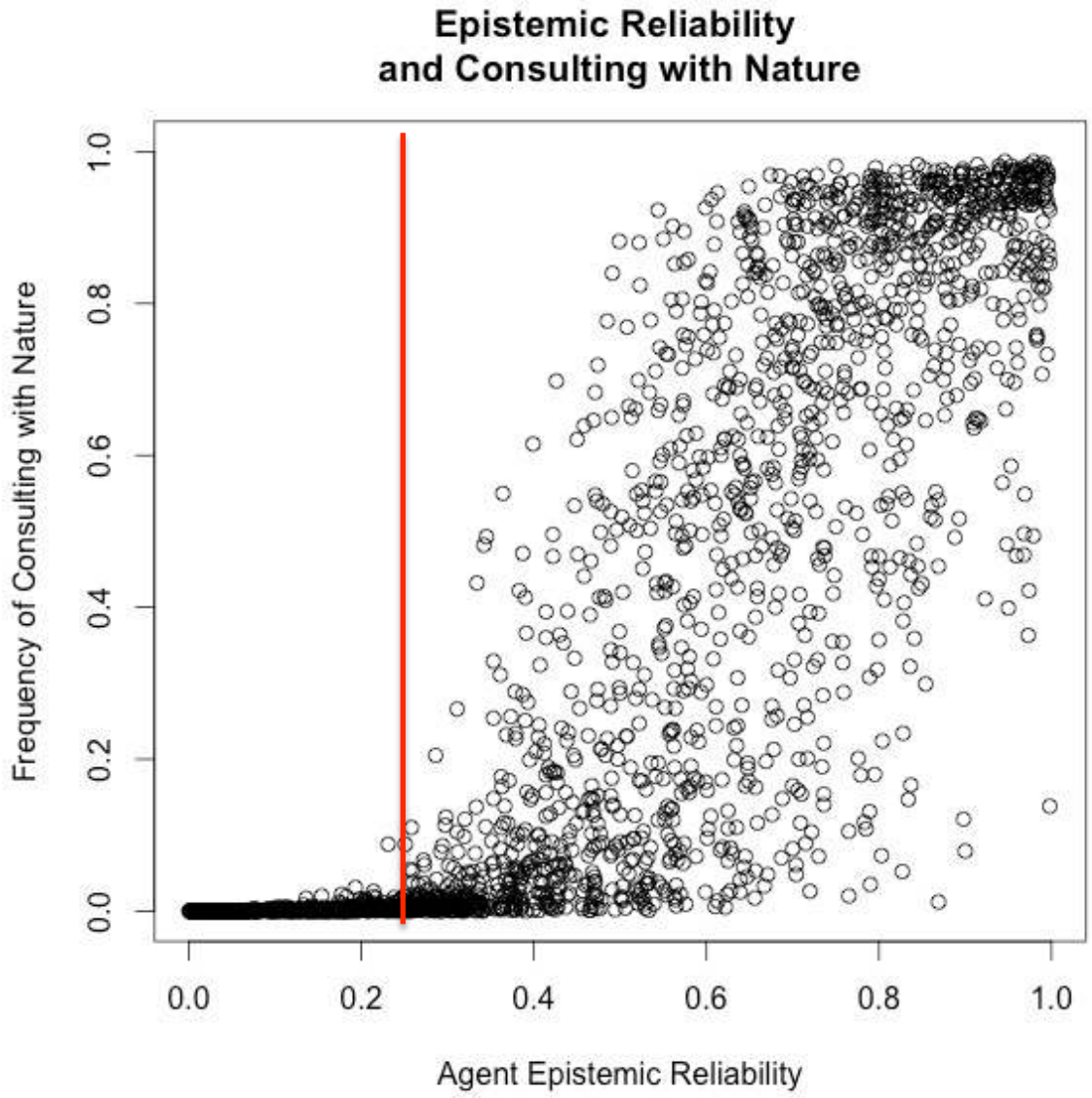

Epistemic Reliability and Frequency of Being Consulted by Population
The most reliable inquirers are far more consistently identified.
Frequency of Being Consulted by Population
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.0
0.2
0.4
0.6
0.8
1.0
Agent Epistemic Reliability

Comparison of Frequency of Being Consulted by Population

Epistemic Reliability	Perfect Communication	Imperfect Communication
Top Quartile	0.058	0.093
Mean	0.047	0.033
Bottom Quartile	0.042	0.011

Contrast: expected frequency if consultation were at random is 0.048.

- In imperfect communication, the overall frequency of consulting with other agents goes down.
- However, since "second-hand" information has becomes less reliable, the most reliable agents are more consistently identified by the population.



A dramatic overall increase in direct investigation of nature, even for moderately unreliable inquirers.

Comparison of Frequency of Investigating Nature

Epistemic Reliability	Perfect Communication	Imperfect Communication
Top Quartile	0.229	0.818
Mean	0.069	0.346
Bottom Quartile	0.000	0.002

Any inquirer whose epistemic reliably is higher then her social reliability does better observing nature directly.

- While imperfect communication leads to a modest increase in the relative consultation rate of the most reliable agents, there is an order-of-magnitude, absolute increase in direct investigation.
- The most epistemically reliable inquirers almost always observe nature directly.

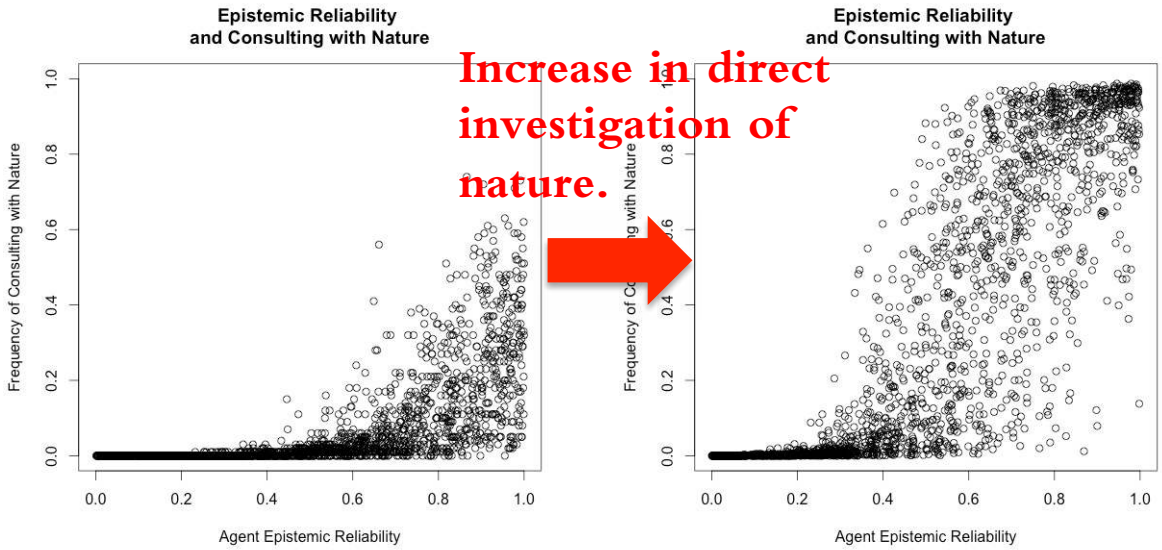
Effects of Social Reliability

Social Reliability	Frequency of Investigation of Nature	Frequency of Consultation by Population
Top Quartile	0.247	0.047
Mean	0.346	0.033
Bottom Quartile	0.476	0.023

The effect of social reliability is much smaller than that of epistemic reliability.

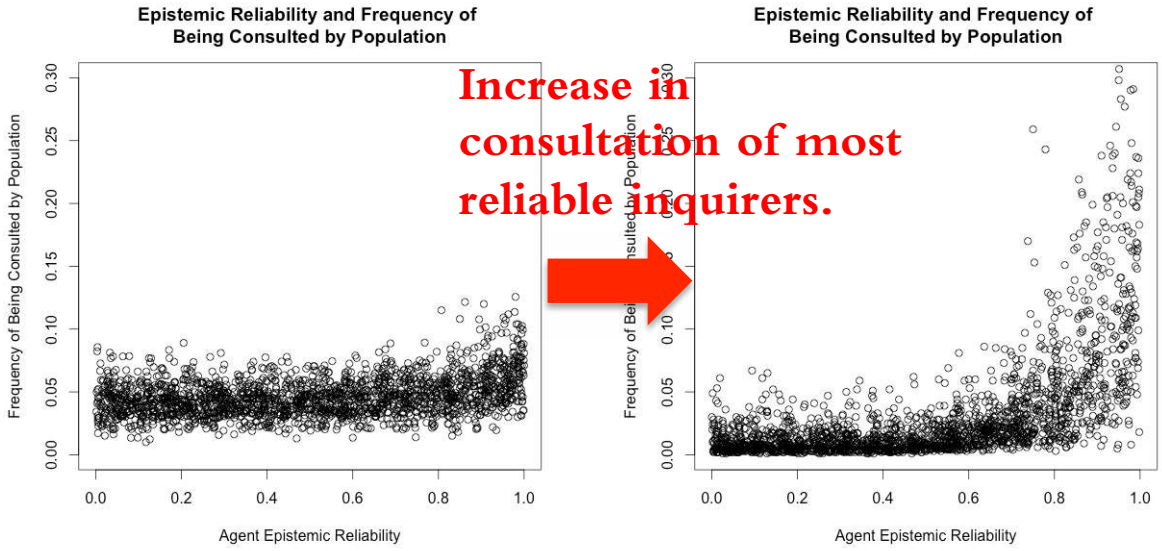
- Socially reliable inquirers are on average less likely to than other agents to investigate nature and more likely than other agents to consult their peers. The inverse is true of socially unreliable agents.
- Socially reliable inquirers are on average consulted more frequently than socially unreliable inquirers.

Frequency of Investigating Nature



Increase in direct investigation of nature.

Frequency of Being Consulted by Population



Increase in consultation of most reliable inquirers.

Perfect Communication

Imperfect Communication

Success Rates Comparison

Epistemic Reliability	Perfect Communication	Imperfect Communication	No Network
Top Quartile	0.859	0.846	0.875
Mean	0.786	0.647	0.5
Bottom Quartile	0.732	0.584	0.125

- Top quartile of reliable agents barely effected by imperfect communication.
- Bottom quartile is hit hardest by imperfect communication.
- In both models, most of the population does better than they would in the absence of the evolved network.

Conclusion

- We've shown how an epistemic network may spontaneously self-assemble from the evolving dispositions of even very simple, low-rationality agents.

- The modeled inquirers start by consulting each possible source of information indiscriminately. As they learn from their experience, however, they self-assemble a network by polymerization.

- The resulting epistemic network is well customized to the strengths and weaknesses of the heterogeneous agents. And typical inquirers in the self-assembled network do much better together than they could possibly do apart.

Next Steps

- Introduce costs for inquiry and allow agents to charge for sharing information.
- Consider the effect of different types of empirical problems with heterogeneous agents who exhibit different degrees of competence for each type of problem.
- Consider the inflow of new agents to the population.

Thank you.

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