SANTA FE INSTITUTE

Beyond collective intelligence: Collective adaptation

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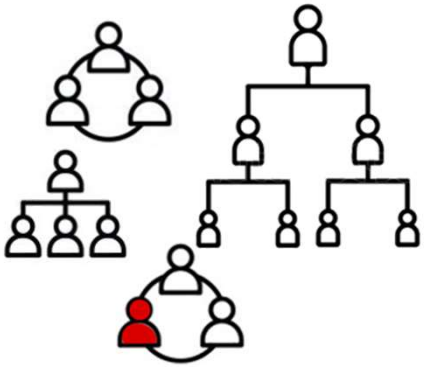
Adaptive collectives: networks and cognitions

Families

Budget allocation?

Next vacation?

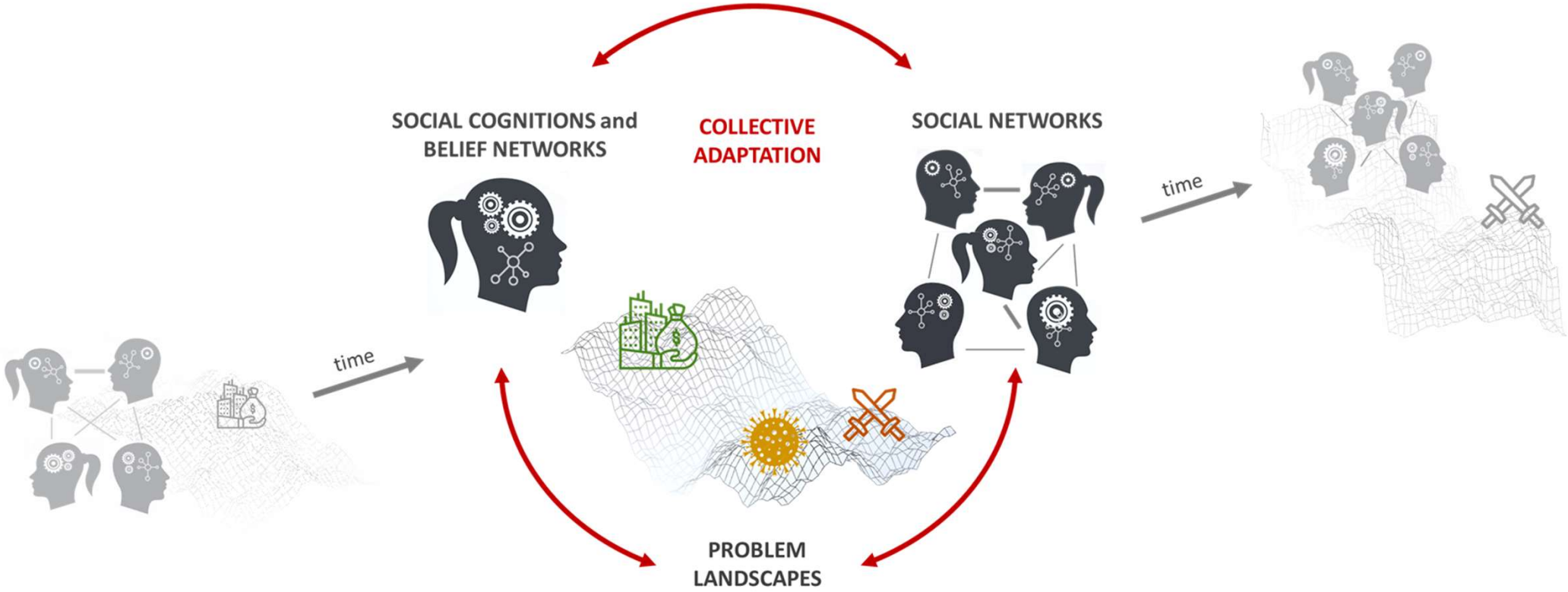
Teams, organizations



Political systems

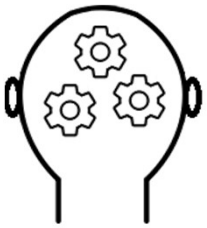
Countries

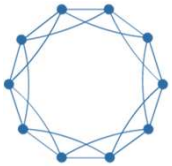
Collective adaptation of complex social systems

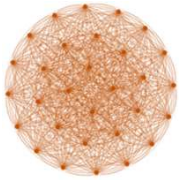


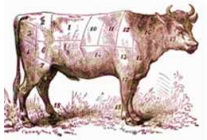
Beyond collective intelligence

- Collective intelligence: What cognitive strategies and social structures are best to solve a specific, well-defined task?







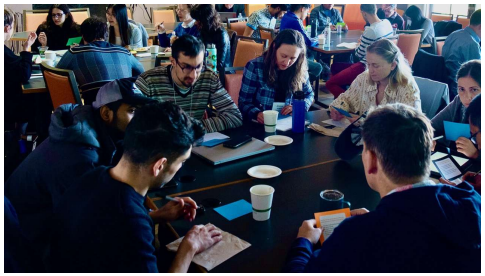


Barkoczi & Galesic, 2018; Galesic et al., 2019
Woolley et al., 2010, 2015; Centola 2023

- Collective adaptation: What trajectories can societies take while navigating multiple and ever-changing problems?
  - Instead of “Who is stupid/intelligent?” we ask

    “How and why did we get here?” “Where are we going”?

Collective adaptation at the summer school



Multiple simultaneous goals

- Learning, collaborating, making friends … impossible to optimize

Dynamic problem landscape

- Importance of different goals is changing over time

Adapting your connections and cognitive strategies

- To accomplish these goals, you team up with different people and use different strategies to make group decisions

Path dependence

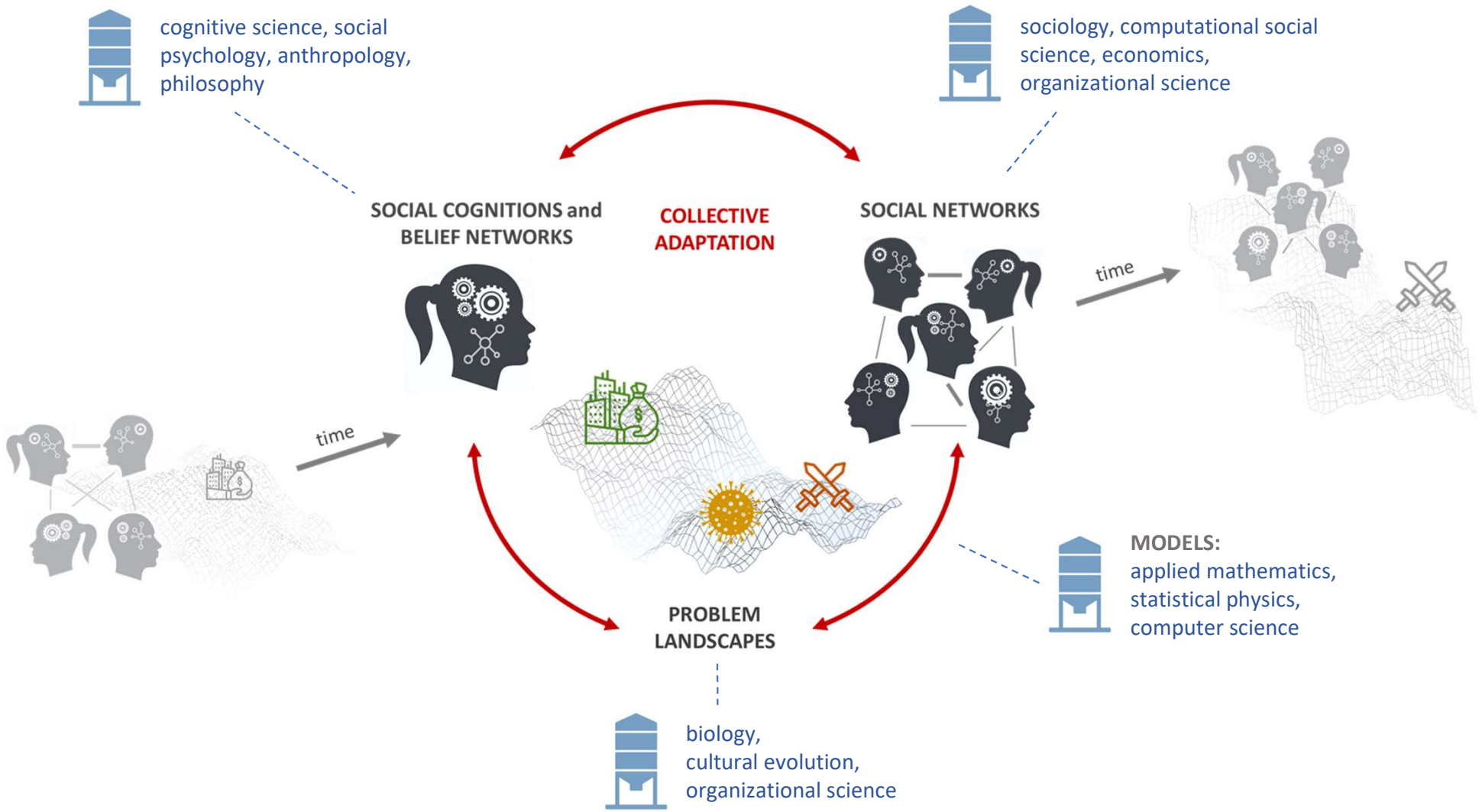
- Groups and strategies chosen to solve early problems will affect the way you solve later problems

Collective myopia

- Not always obvious what is the best way to structure the group or make group decisions

Studying collective adaptation:
State of the art

Collective adaptation: Disciplinary silos

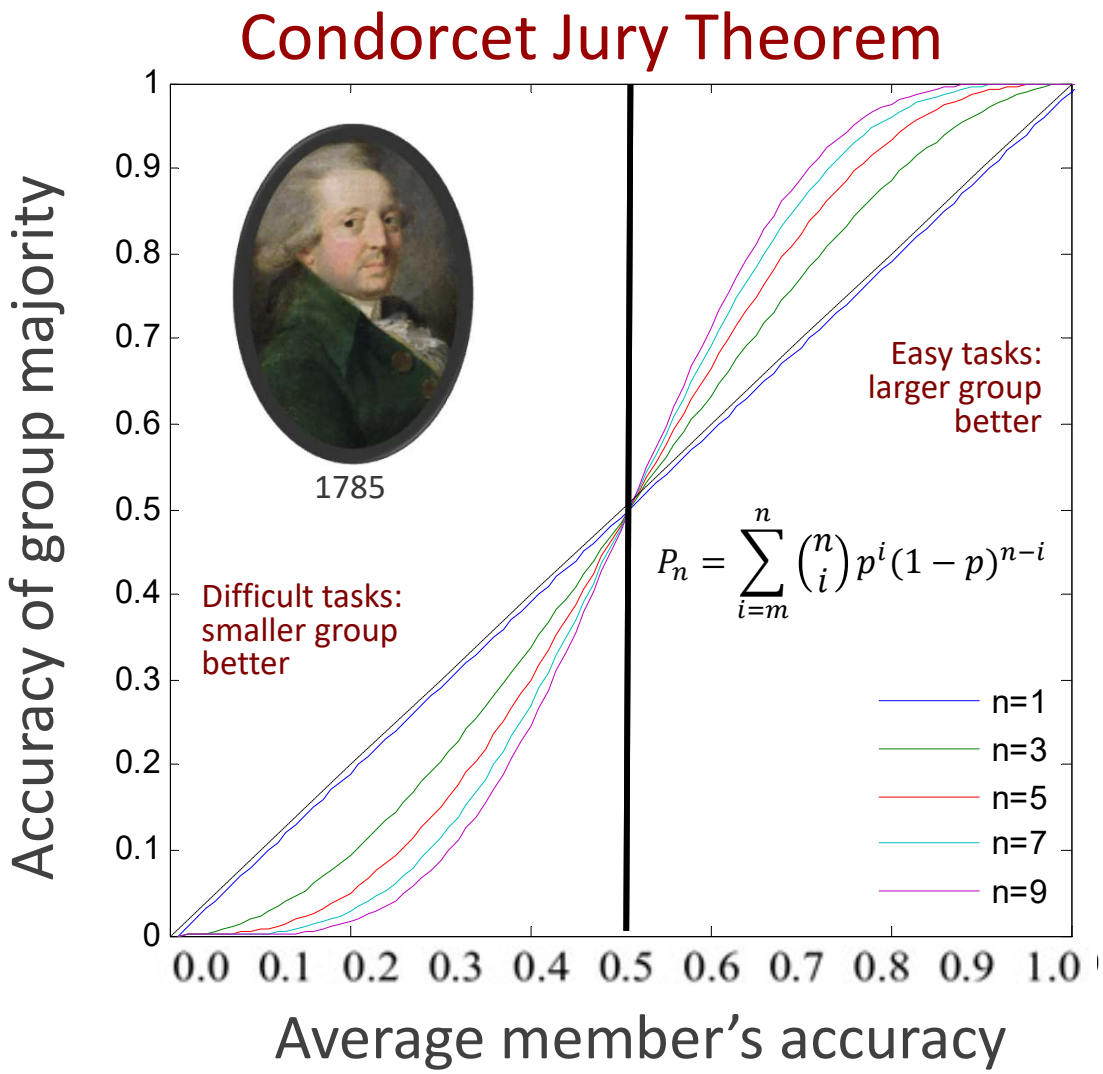


Overlapping views, different labels

- Collective intelligence (Graves, 1842, Woolley et al, 2010, Malone & Bernstein, 2015)
- Social learning (Bandura, 1977; Hoppitt & Laland, 2013; Kendal et al, 2018; Yaniv, 2004)
- Collective problem solving (Conradt & Roper, 2010; Gonzalez et al., 2015; Hills et al., 2015; Mehlhorn et al., 2015)
- Wisdom of crowds (Condorcet, 1783; Galton, 1907; Davis-Stober et al., 2014; Mellers et al., 2014; Budescu & Chen, 2015)
- Group decision making (Page, 2008; Stasser & Titus, 1985)
- Belief dynamics (Centola & Macy, 2007; Epstein, 2014; Galesic et al., 2021; Pentland, 2014; Proskurnikov & Tempo, 2017; Vallacher, Read, & Nowak, 2017)
- Cultural evolution (Boyd & Richerson, 1985; Mesoudi, 2016)
- Game theory (Friedman, 1998; Newton, 2018; Ostrom, 2010)
- Group minds (Goldstone & Theiner, 2017; Hinsz et al., 1997)
- …

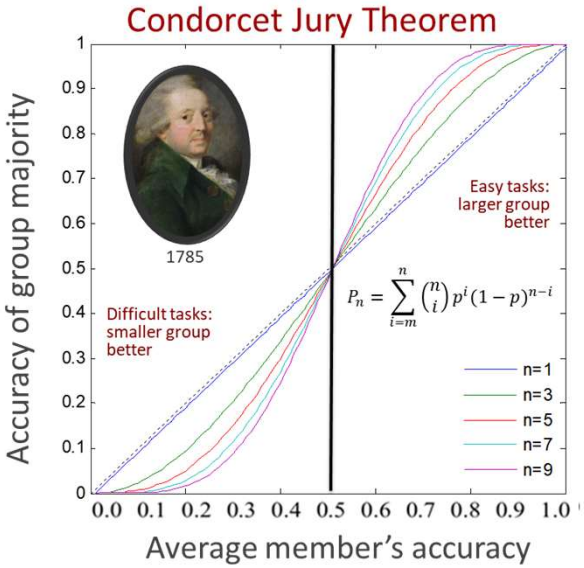
Parallel efforts: an example

Accuracy of majority rule depends on group size:



Parallel efforts: an example

Accuracy of majority rule depends on group size



Rediscoveries:

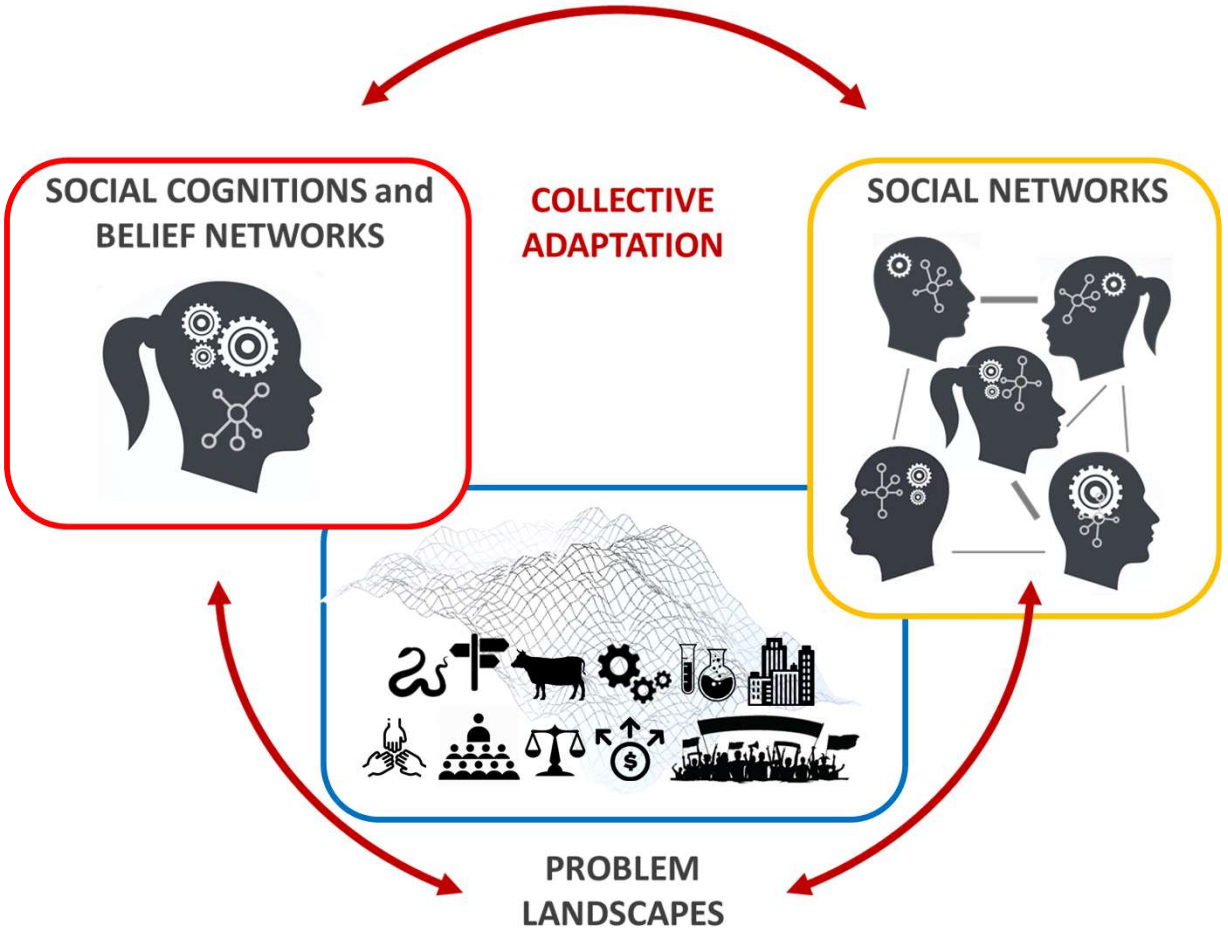
- political science (Grofman et al., 1984)
- cultural evolution (Boyd & Richerson, 1985)
- statistical physics (Krapivsky & Redner, 2003)
- psychology (Hastie & Kameda, 2005)
- sociology (Centola & Macy, 2007)
- biology (King & Cowlishaw, 2007)

Smaller groups can outperform larger groups facing several tasks:

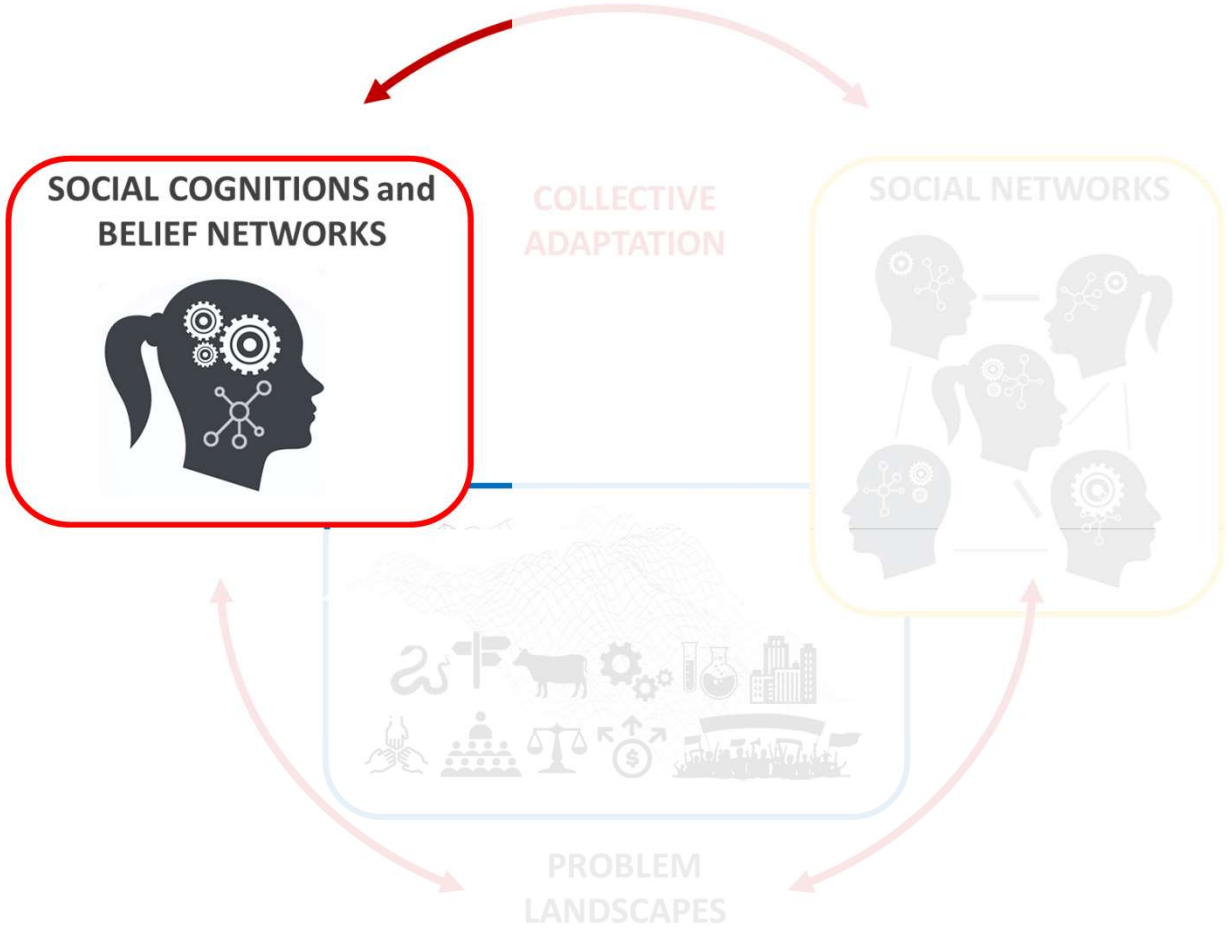
- political science (Grofman et al., 1984)
- biology (Kao & Couzin, 2014)
- cognitive science (Galesic et al., 2018)

Building blocks of collective adaptation

Building blocks



Building blocks



Social cognitions

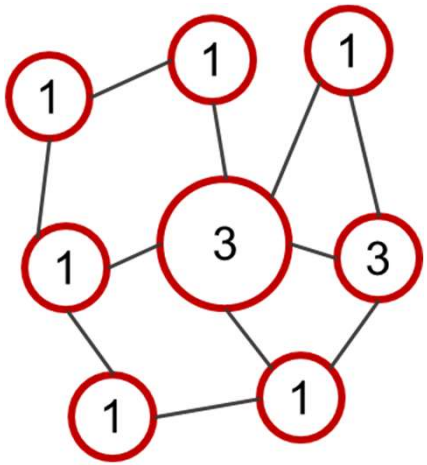
Strategies for social interactions (Hertwig & Hoffrage, 2013):

- integration of social information (Hoppit & Laland, 2013)
- coordination (Grice, 1975; Moussaid et al., 2011)
- cooperation (Axelrod, 1984; Bowles & Gintis, 2013)
- exploration (Hills, et al., 2015; Mehlhorn et al., 2015)
- network building and revision (Jackson, 2010)
- innovation, etc.

Studied under different labels:

- Social learning strategies
- Belief updating strategies
- Group decision-making rules
- Voting procedures
- Aggregation procedures

Strategies for integrating social information



Three basic classes:

- Frequency-dependent strategies: majority, plurality, unanimity, minority rules, complex contagion

  1

  Condorcet 1785; political science (Heinberg, 1932); statistics (Penrose, 1946); psychology (Asch, 1955); economics (Plott, 1967); cultural evolution (Boyd & Richerson, 1985); computer science (Parhami, 1994); statistical physics (Krapivsky & Redner, 2003); biology (King & Cowlishaw, 2007); sociology (complex contagion; Centola & Macy, 2007)

- Averaging strategies: with or without weights, e.g. advice taking, voter model, contagion rules, blending inheritance

  2

  Galton, 1907; economics (DeGroot, 1974; Golub & Jackson, 2010); advice taking (Molleman et al., 2020; Yaniv, 2004); statistical physics (Ising models; Castellano et al., 2009); cultural evolution (blending inheritance: Boyd & Richerson, 1985); network science (contagion; Newman, 2003)

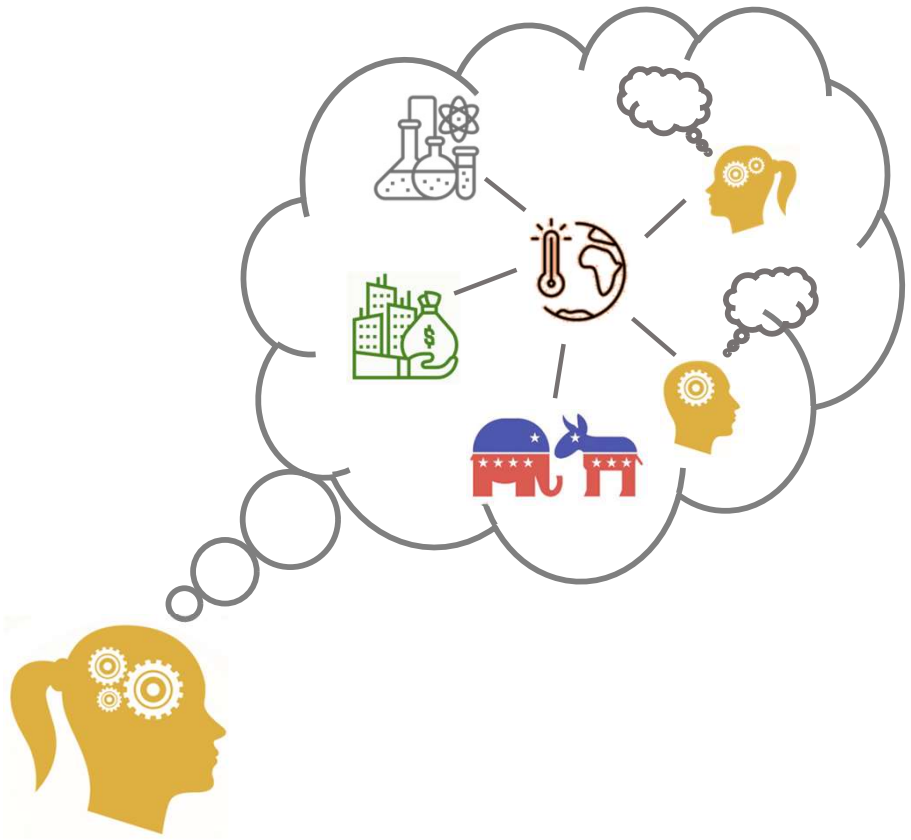
- Model-based strategies: follow leader, expert, similar, confident, liked, best

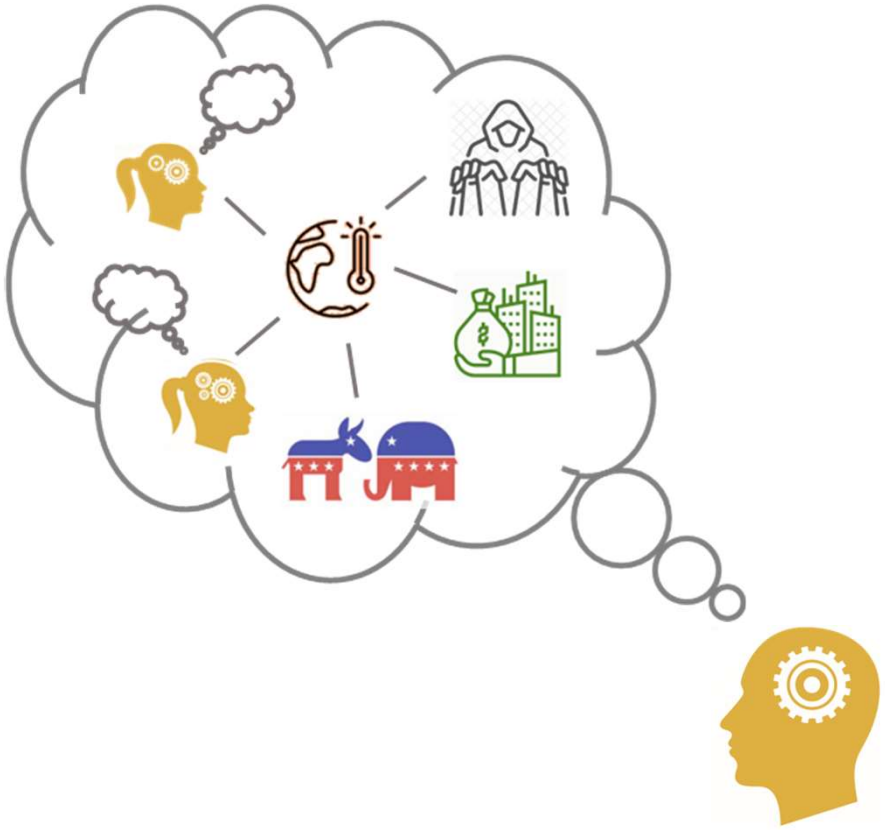
  3

  cultural evolution (high status: Henrich & Gil-White, 2001), social psychology (liking, authority: Cialdini & Trost, 1998), cognitive psychology (similarity, Wisdom et al., 2013), law (confidence; Penrod & Cutler, 1995)

Different beliefs about important problems

Different belief networks



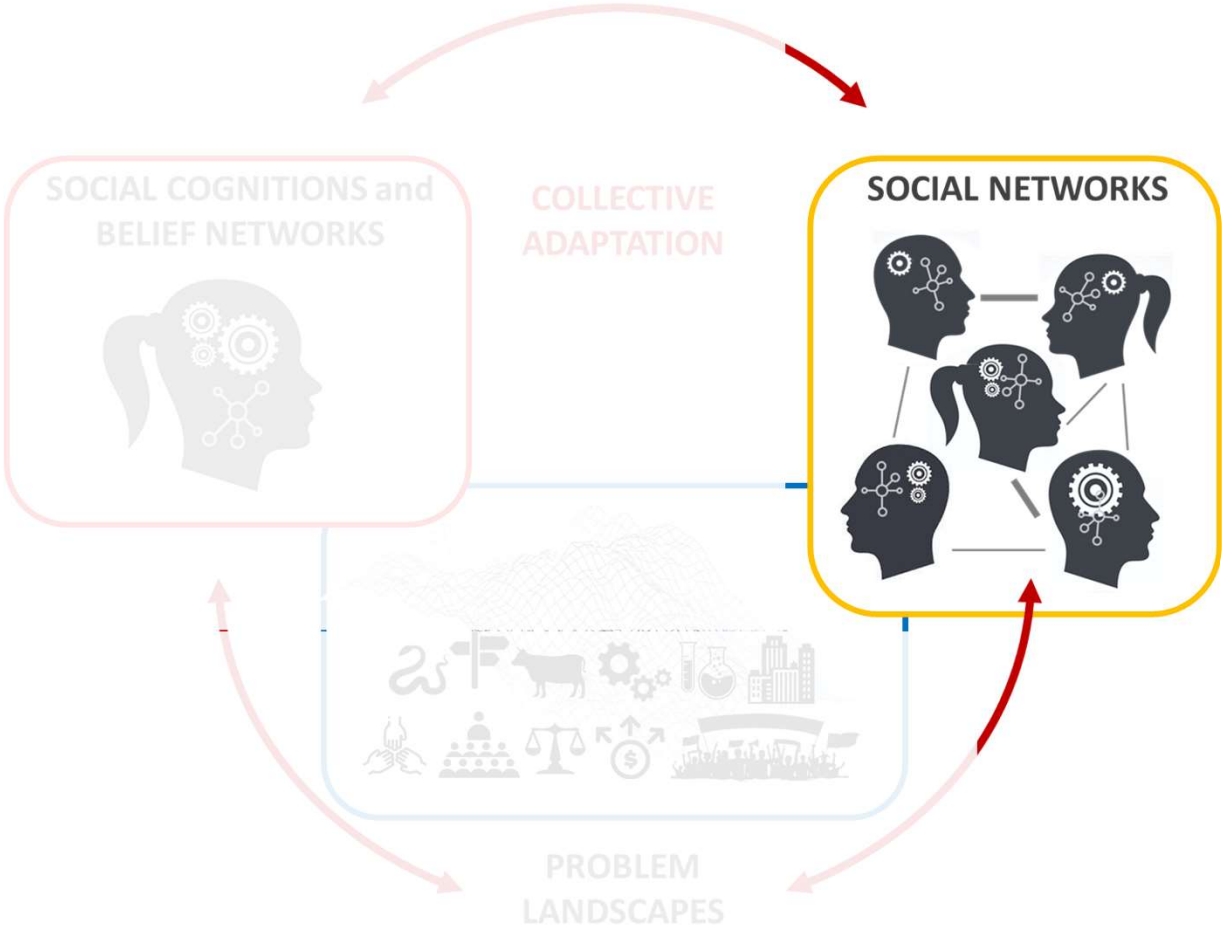


Models of belief dynamics

Many analogies (Olsson & Galesic, in prep, *Trends in Cog Sci*):

- **Epidemiological models,** where transmission of belief is like a transmission of disease (Newman, 2003; Cooney et al., 2022)
- **Ferromagnetic models,** where beliefs align with each other like spins in a crystal lattice (Castellano, 2009; Dalege et al., 2022)
- **Percolation**, where beliefs seep through a society like liquid through a substance (Duffie et al., 2010; Li & Wang, 2019)
- **Balance**, where beliefs and individuals align in a way that leads to most consistent relationships on the level of pairs and triads (Heider, 1958; Pham et al., 2020)
- **Expected utility**, where beliefs change in line with a weighted average of different cognitions (Ajzen, 1991; Friedkin & Bullo, 2017)
- **Evolution,** where beliefs evolve in the process of cultural learning (Richerson & Boyd, 2008; Anderson & Creanza, 2022)
- **Bayesian networks**, where networks of beliefs change in line with their conditional dependencies (Cook & Lewandowsky, 2016; Pallavicini, 2021)
- **Forces,** where belief change under combined influence of several distinct social forces (Latane, 1981; Harton et all, 2022)
- …

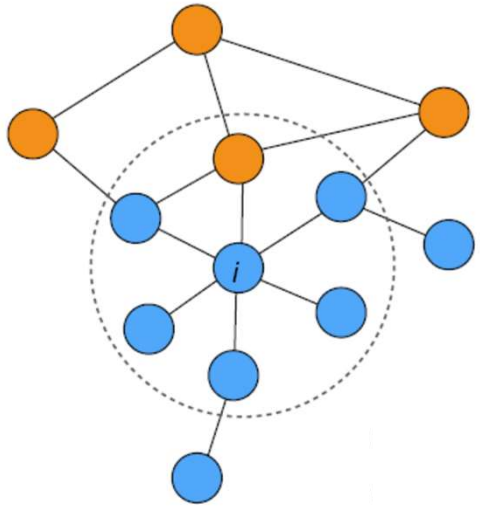
Building blocks



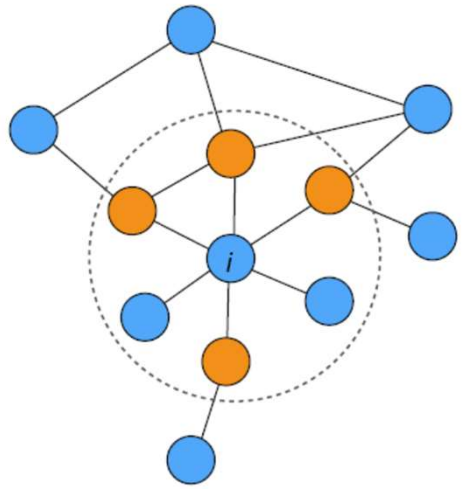
Social environments

- Social networks
  - Perceived vs. objective networks (Thomas theorem, 1928; Denrell, 2005; Gonzalez et al., 2015)
  - Size and connectivity (Derex & Boyd, 2016; Lazer & Friedman, 2007; Mason et al., 2008; Giannoccaro et al. 2018)
  - Homophily (McPherson et al., 2001; Karimi et al., 2018; Lee et al, 2019)
  - Centrality (Barabasi & Albert, 1999; Becker et al., 2017)
  - Directed vs. undirected
- Social artifacts
  - Languages and scripts
  - Communication channels
  - Institutions
  - …

High homophily → False consensus

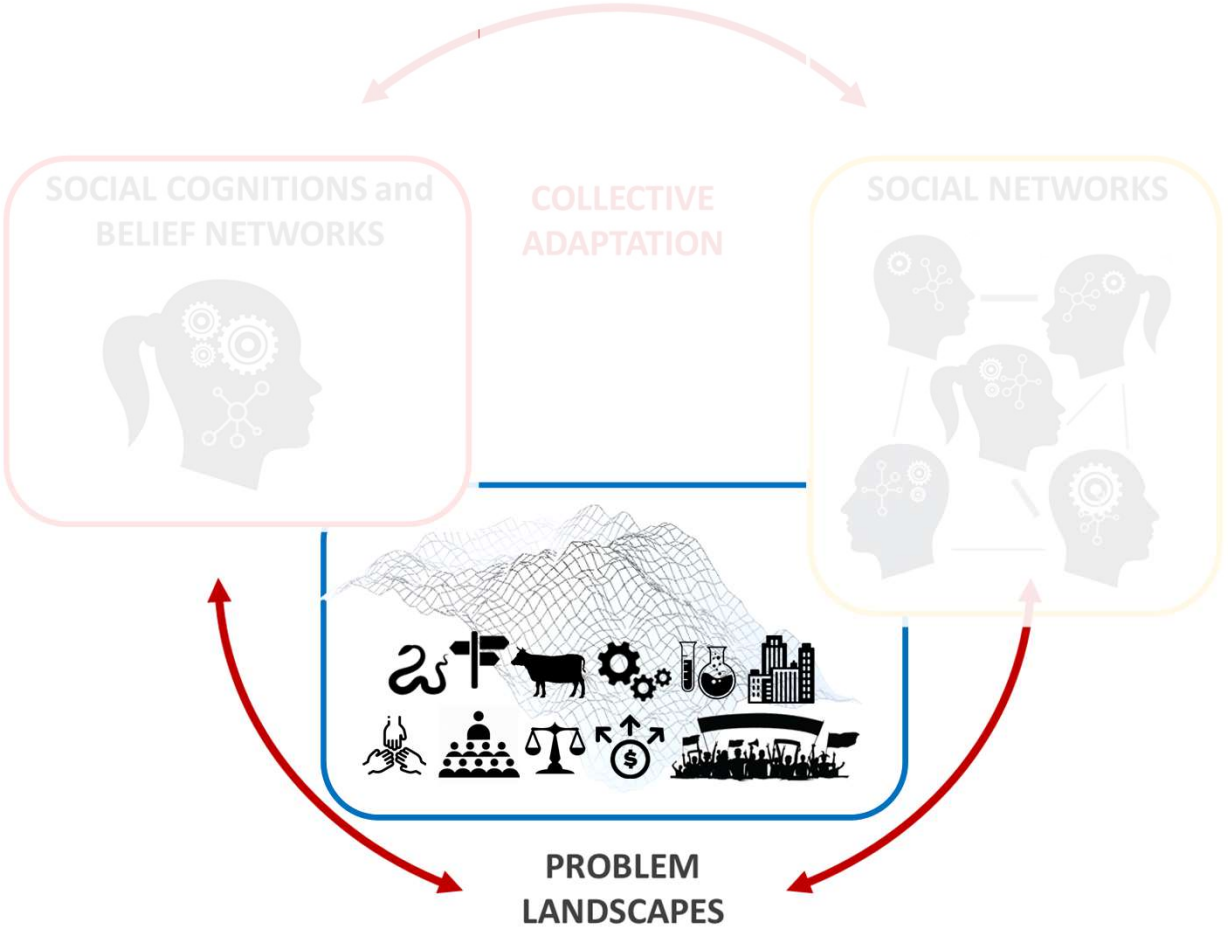


Low homophily → False uniqueness



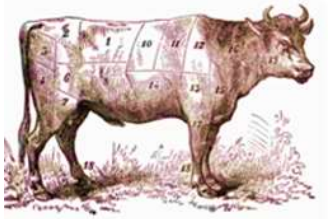
Lee et al., 2019; Galesic, Olsson, Rieskamp, 2018

Building blocks

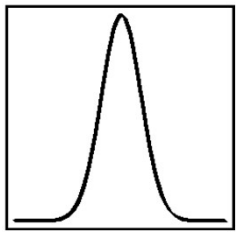


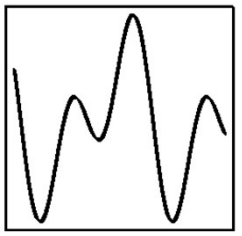
Problem environments

- Structural properties of problems
  - Categorical vs. continuous judgments



  - Simple and complex task landscapes





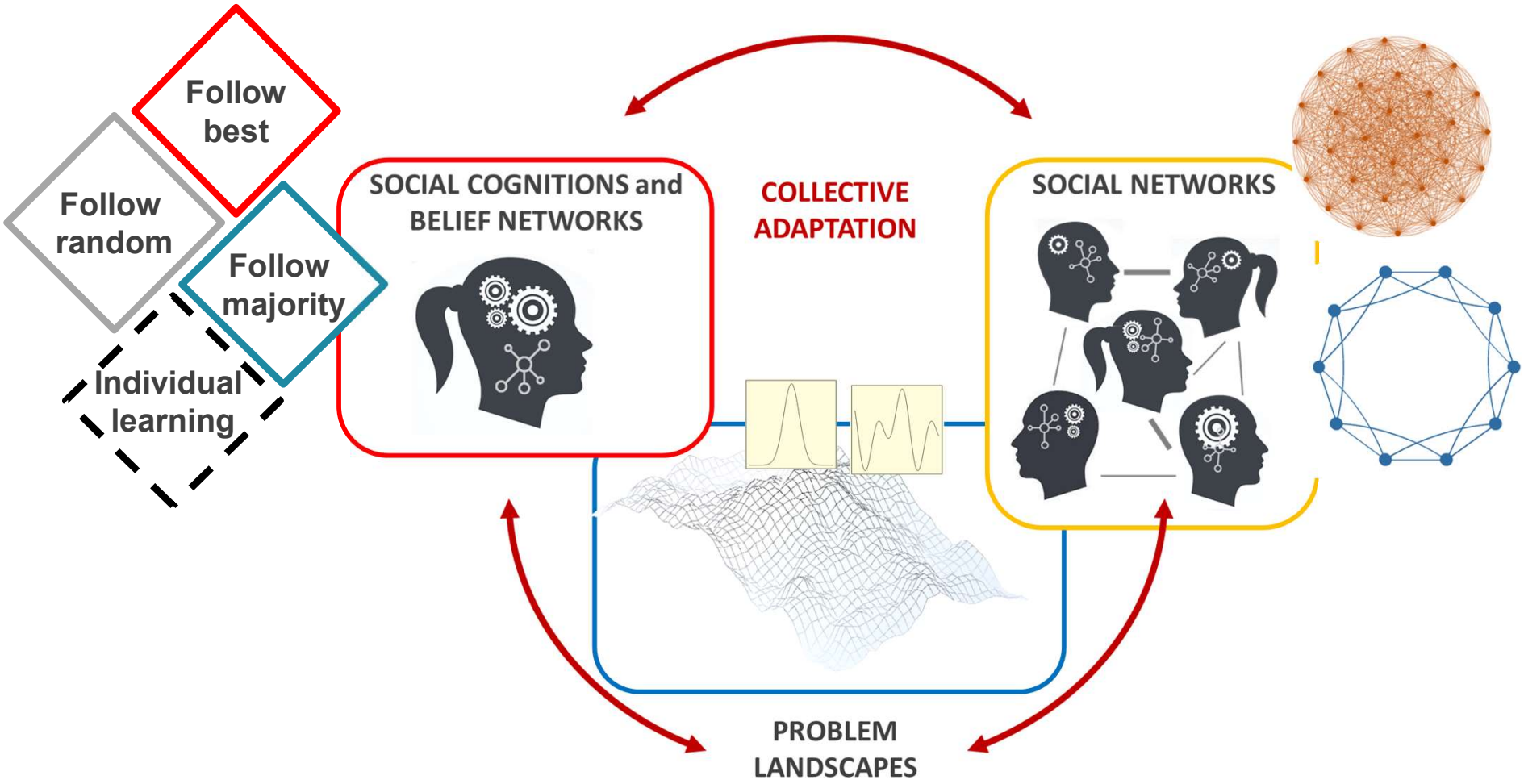
  - One-shot and repeated problems

- Global environment
  - Economic, political, cultural factors that change payoffs of different options, feasibility of different strategies and networks

Interaction of building blocks: an example

Interaction of building blocks: an example

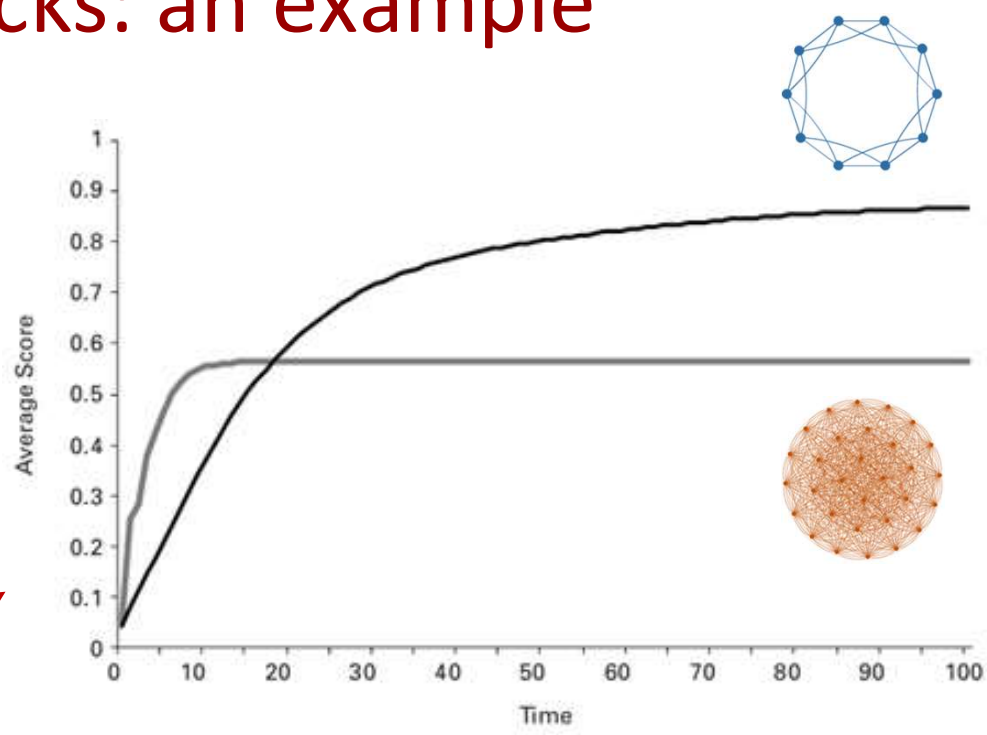
Barkoczi & Galesic (2016), *Nature Communications*



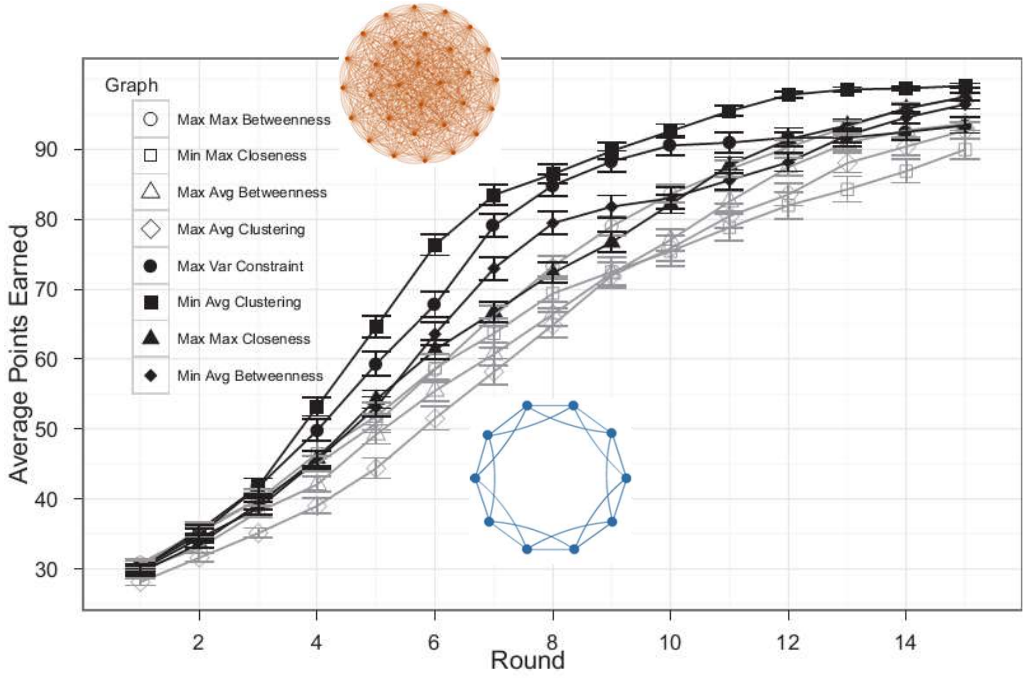
Interaction of building blocks: an example

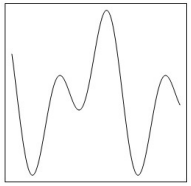
Contradictory findings about network structure and wisdom of crowds

- Poorly-connected, slow networks better (Lazer & Friedman, 2007, ASQ; Derex & Boyd, 2016, PNAS)

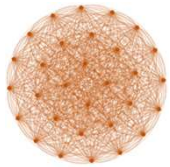


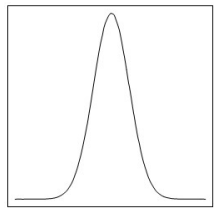
- Well-connected, fast networks better (Mason & Watts, 2012, PNAS)

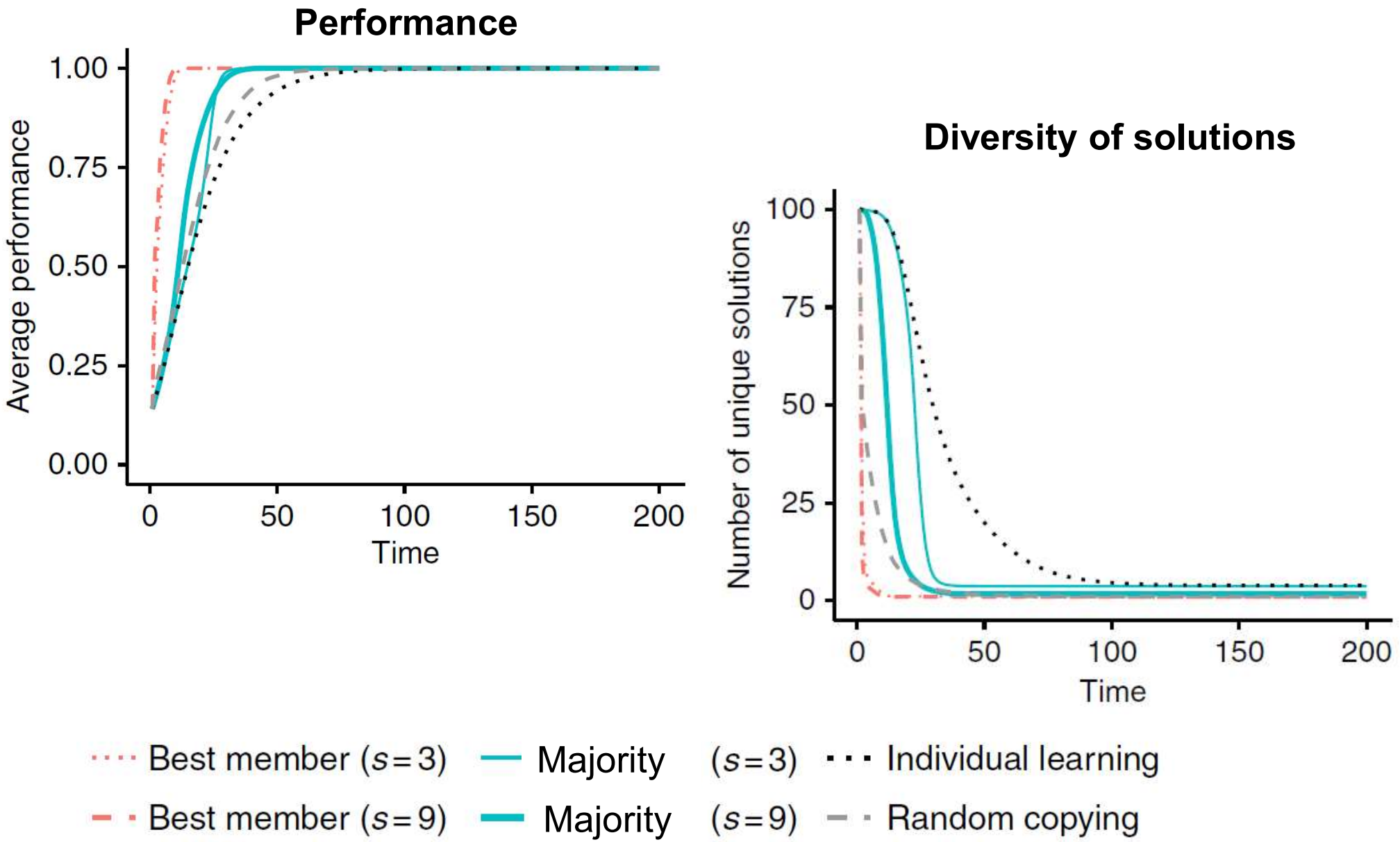




Simple tasks: fast learning strategies better

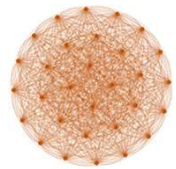


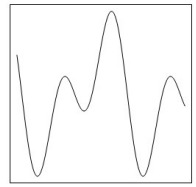


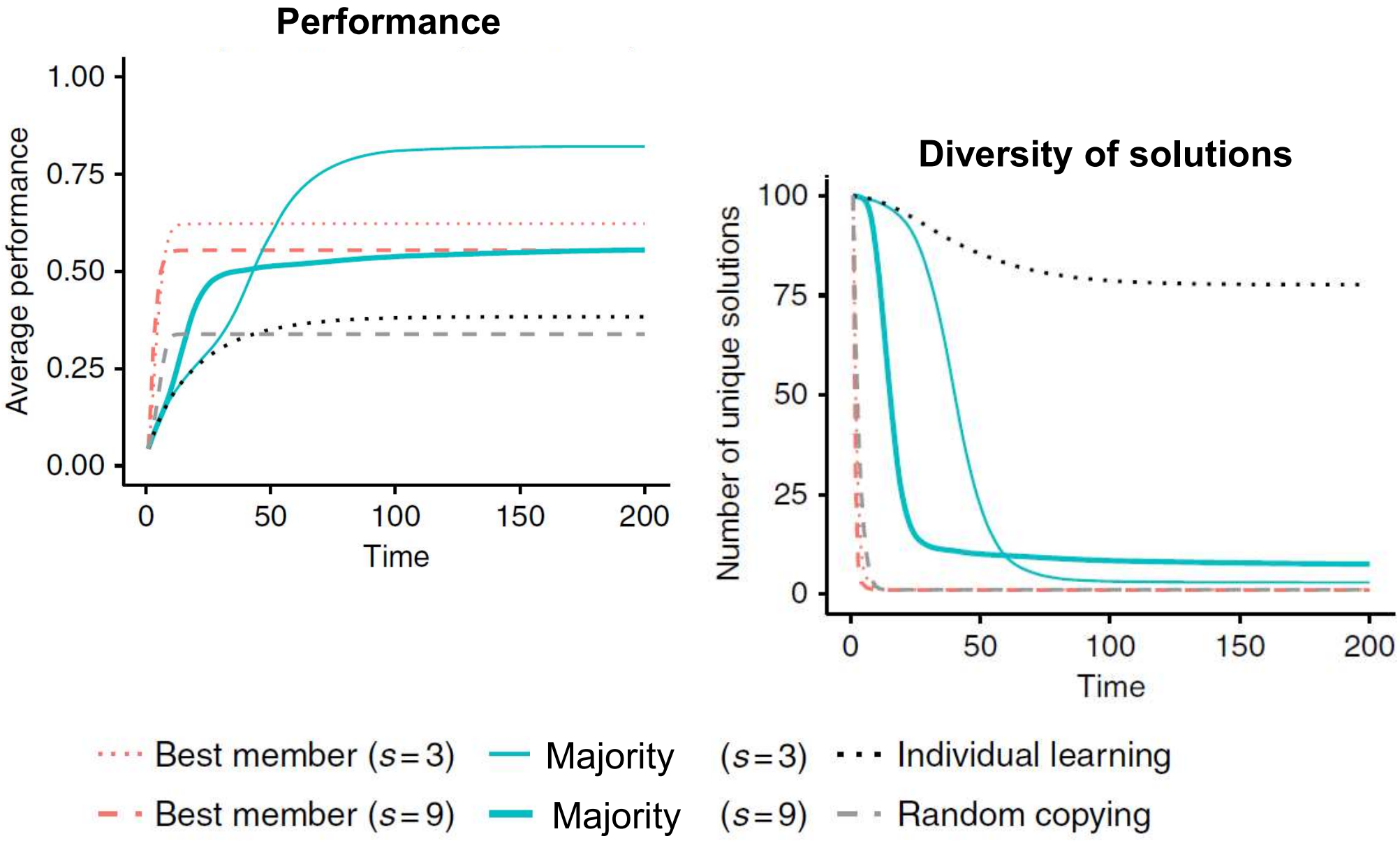


Barkoczi & Galesic (2016), *Nature Communications*

Complex tasks: slow learning strategies better

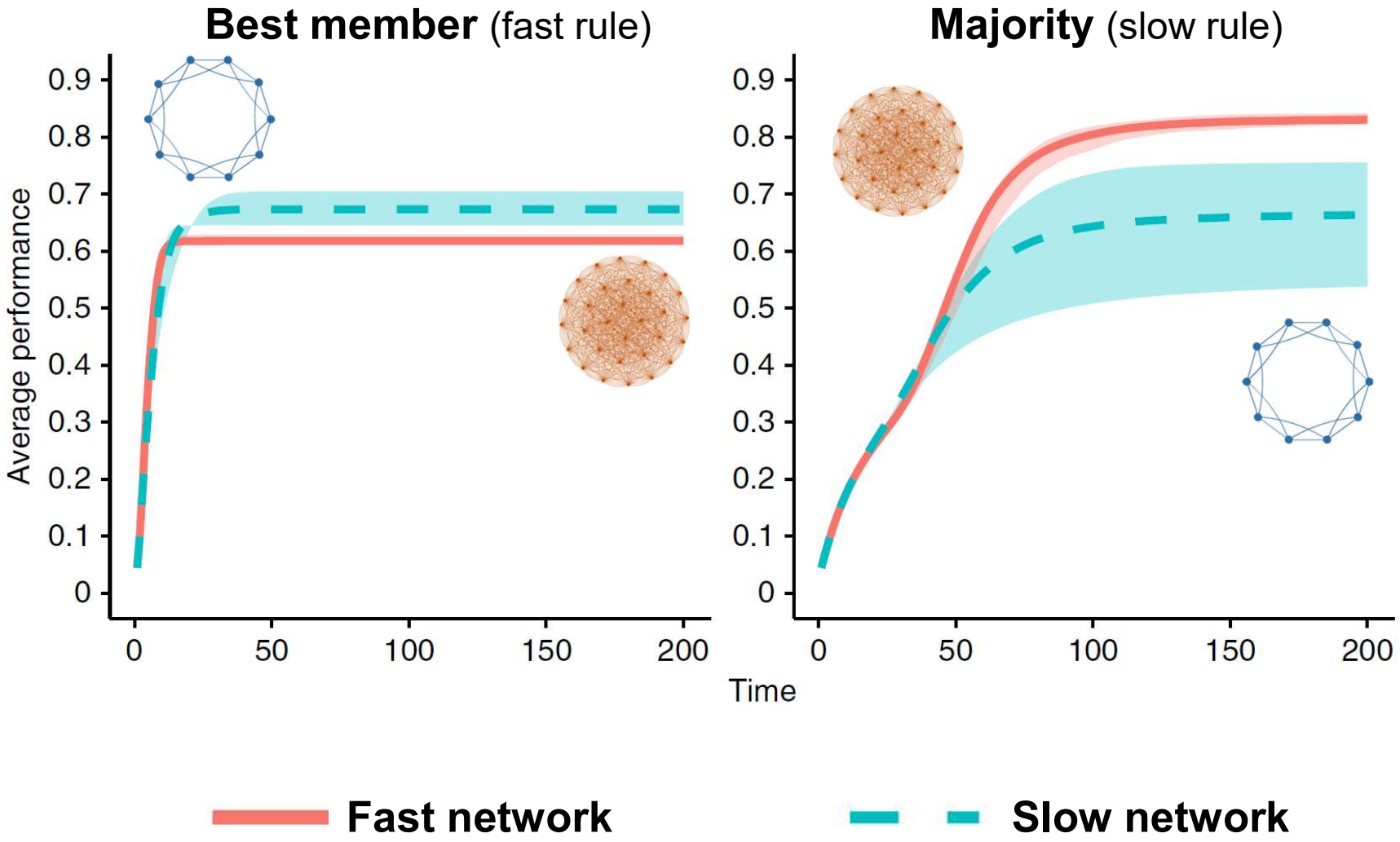






Barkoczi & Galesic (2016), *Nature Communications*

Interplay of networks and learning strategies



Barkoczi & Galesic (2016), *Nature Communications*

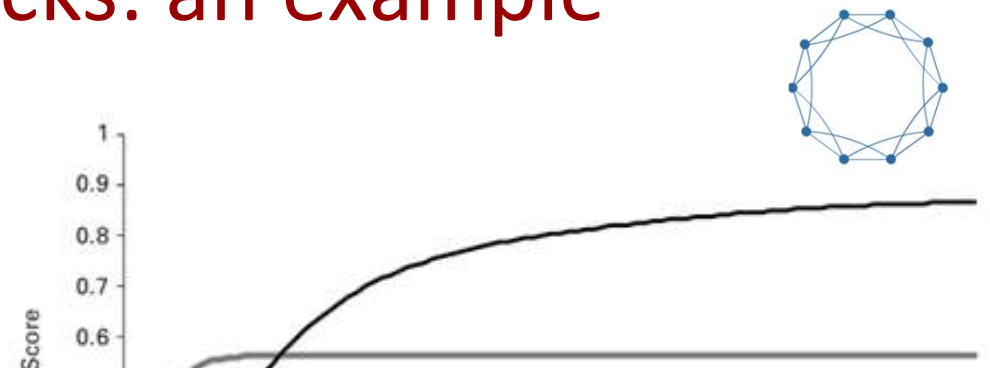
Interaction of building blocks: an example

Contradictory findings about network structure and wisdom of crowds

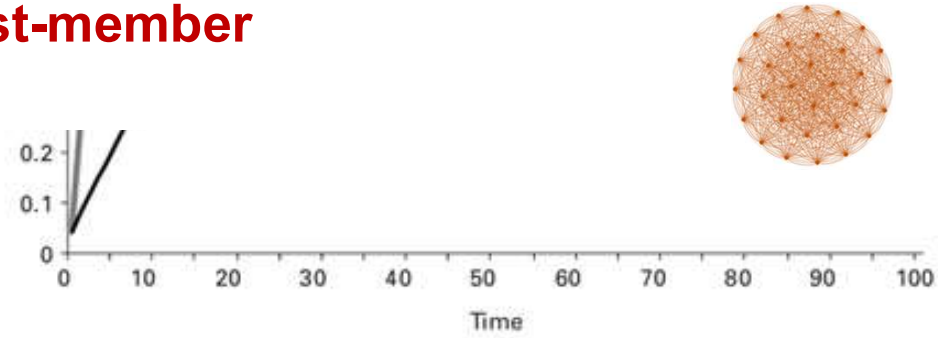
- Poorly-connected, slow networks better (Lazer &

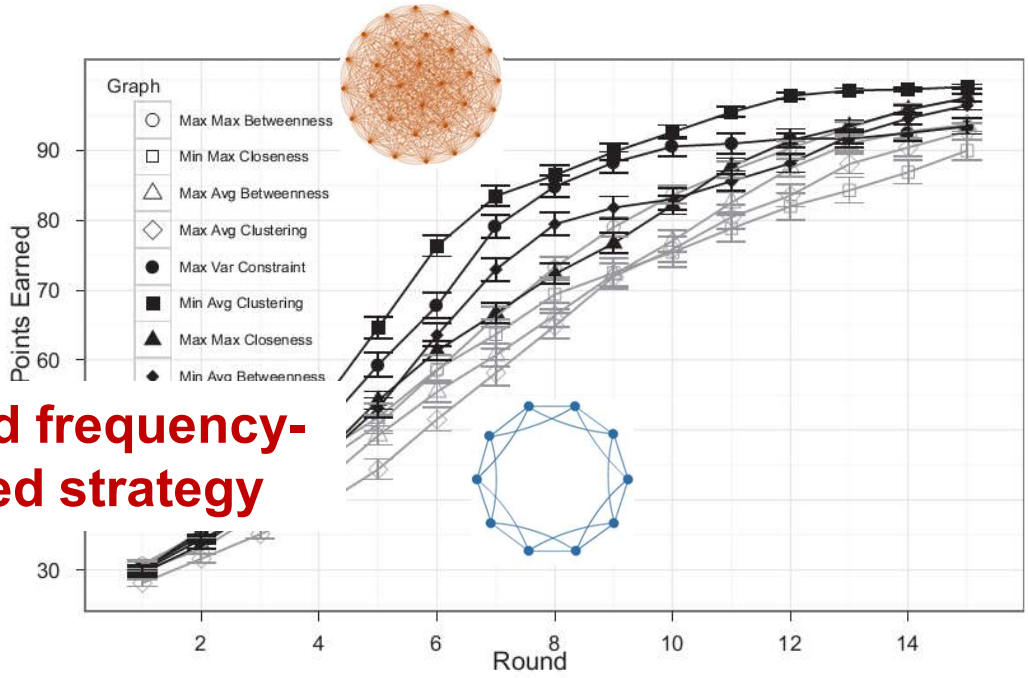
Apparent contradictions can be resolved by taking into account the whole system of cognition and networks

- Well-connected, fast networks better (Mason & Watts, 2012, PNAS)

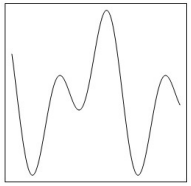


Used best-member strategy



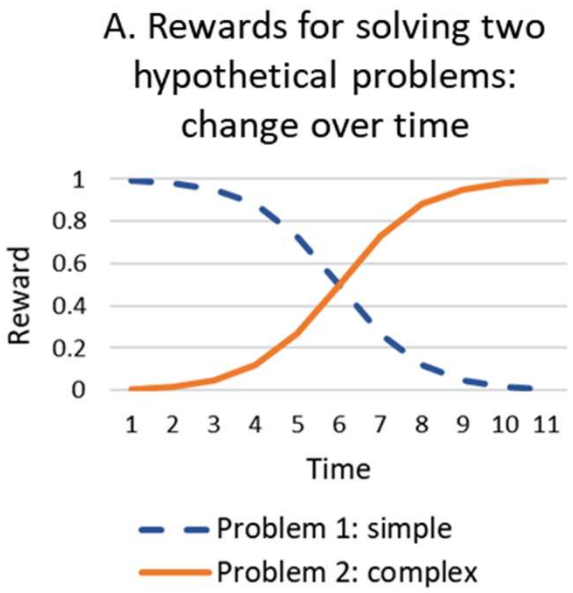


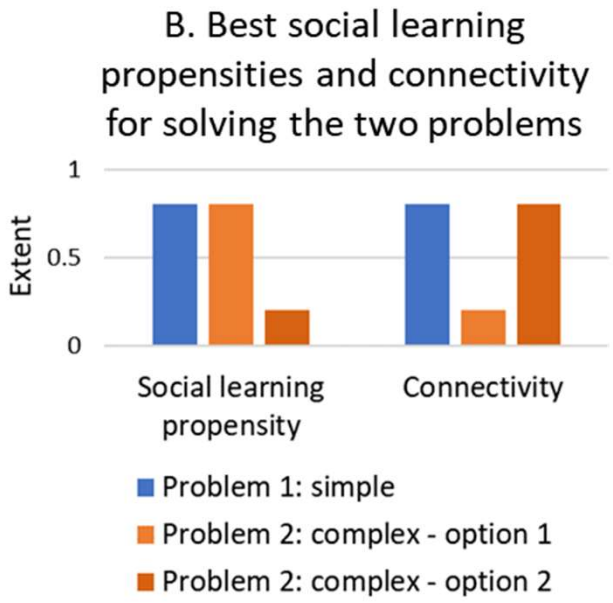
Used frequency-based strategy



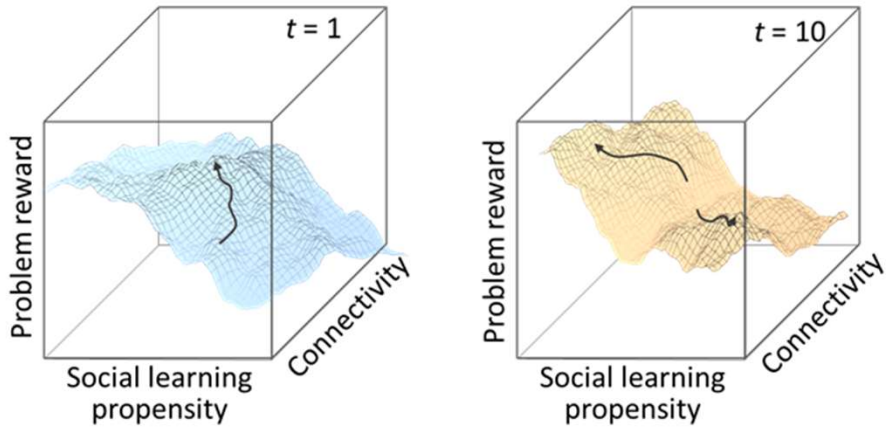
Emergence of collective adaptation

A simple example

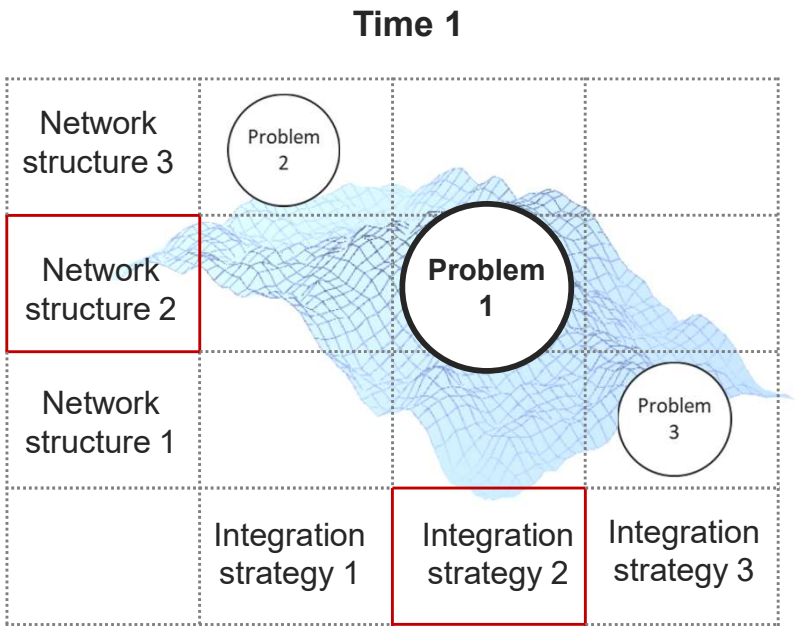


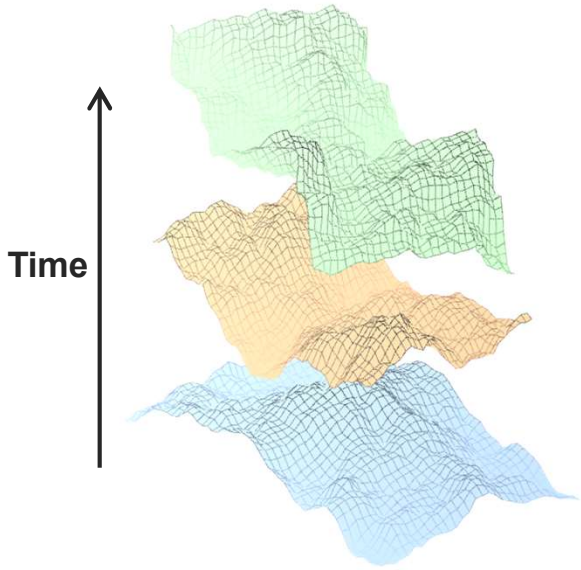


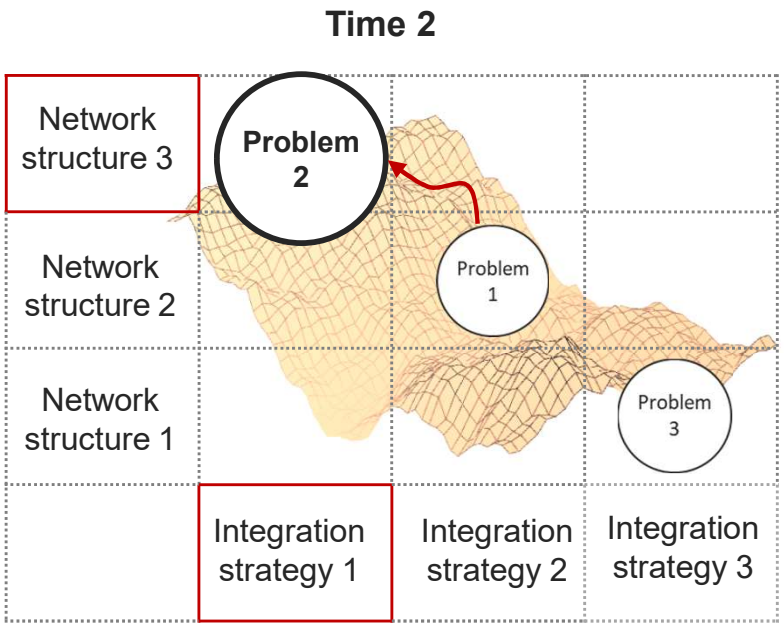
C. The resulting problem landscapes

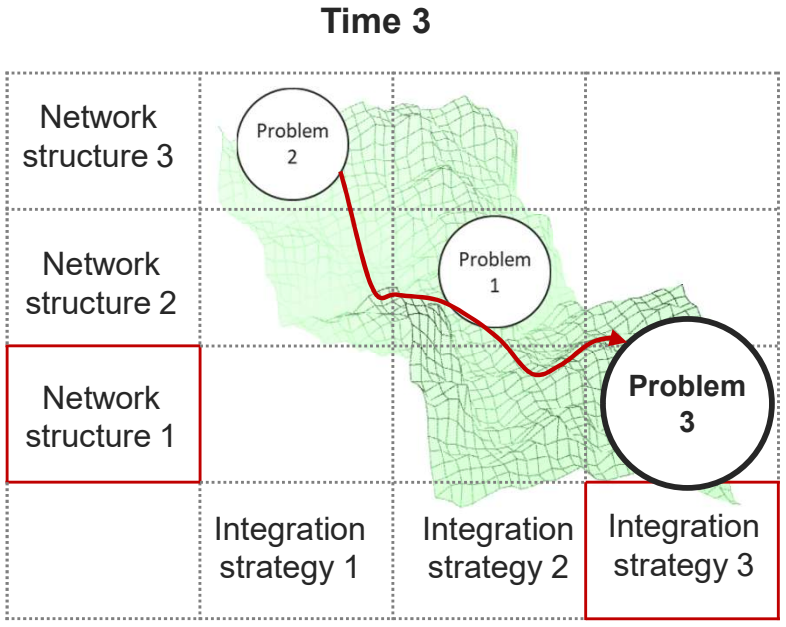


Emergence of collective adaptation

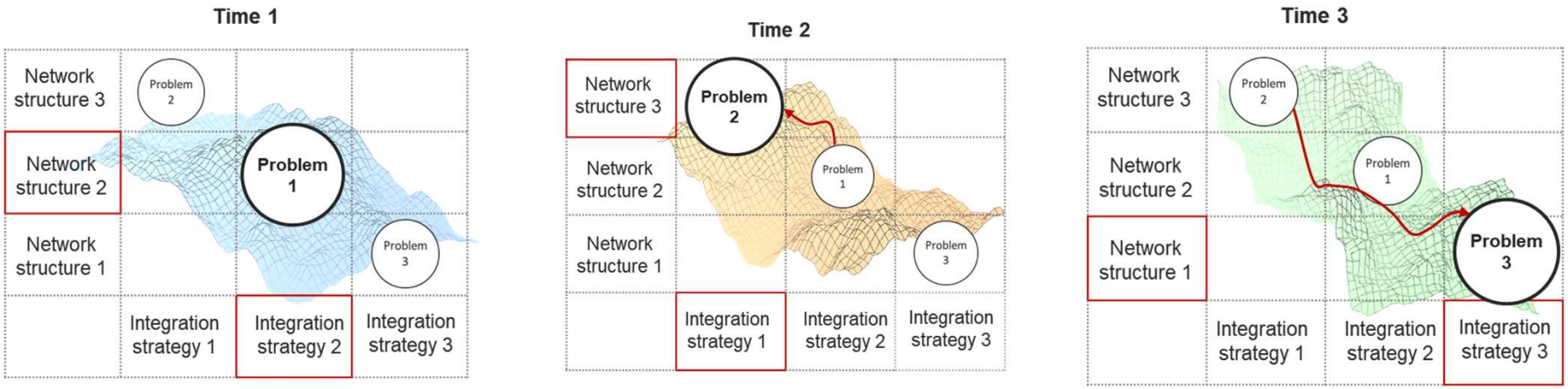








Five implications



1) Path dependence
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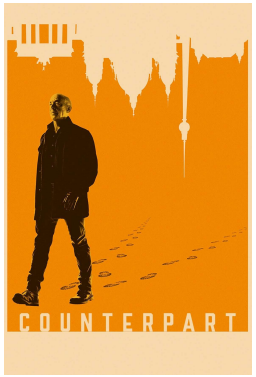
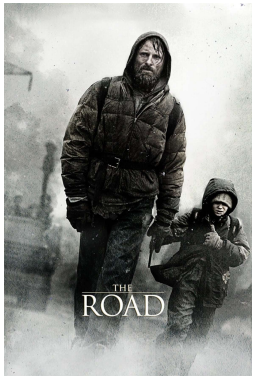




Quantitative models of collective adaptation

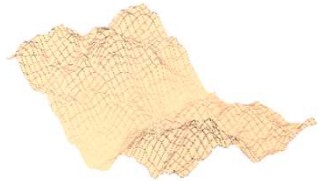
Modeling challenges

Models of collective adaptation …

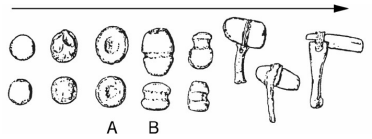
- Should be simple, but grounded in theories of human cognition and sociality
- Should represent the dynamic interplay of cognition, network, and problem structures
- Should produce quantitative predictions that can be tested by empirical data

Analogies for modeling collective adaptation

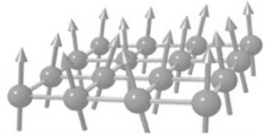
- No analogy is completely correct but some are useful
- Adaptive landscapes
  - Easy to understand and flexible, but can lead to wrong intuitions for high-dimensional, constantly changing spaces (Gavrilets, 2004; Agarwala & Fisher, 2019, Fragata et al., 2019)



- Cultural evolution
  - From tools to institutions, typically no network structure (but see Smolla & Akçay, 2019)

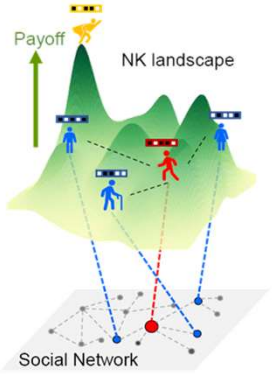


- Statistical physics
  - Reducing dissonance on individual and collective level, no meta-level rules for switching strategies and structures when problems change

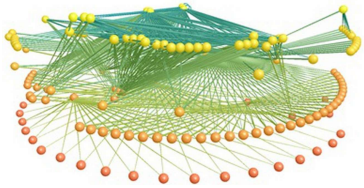


$$\mathcal{H}_i = -h_i^{\mathrm{soc}}\sigma_i - h_i\sigma_i$$

- Reinforcement learning
  - Of social learning strategies (Ha & Jeong, 2022), of networks
  - Of individual welfare functions (Wolpert & Tumer, 2001)



- Ecosystem modeling
  - Dynamic interaction networks



- Combinations of analogies

  Different analogies for different building blocks, for example:
  - Drift diffusion model of learning + an evolutionary process of adaptation to different groups structures and costs of errors (Tump et al., 2022)
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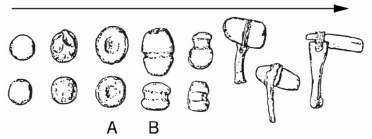

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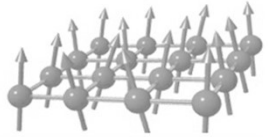

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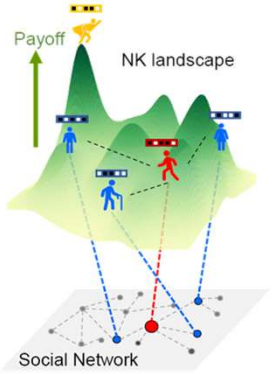

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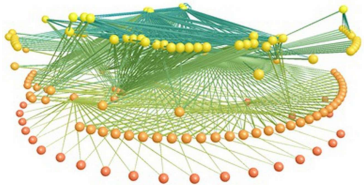

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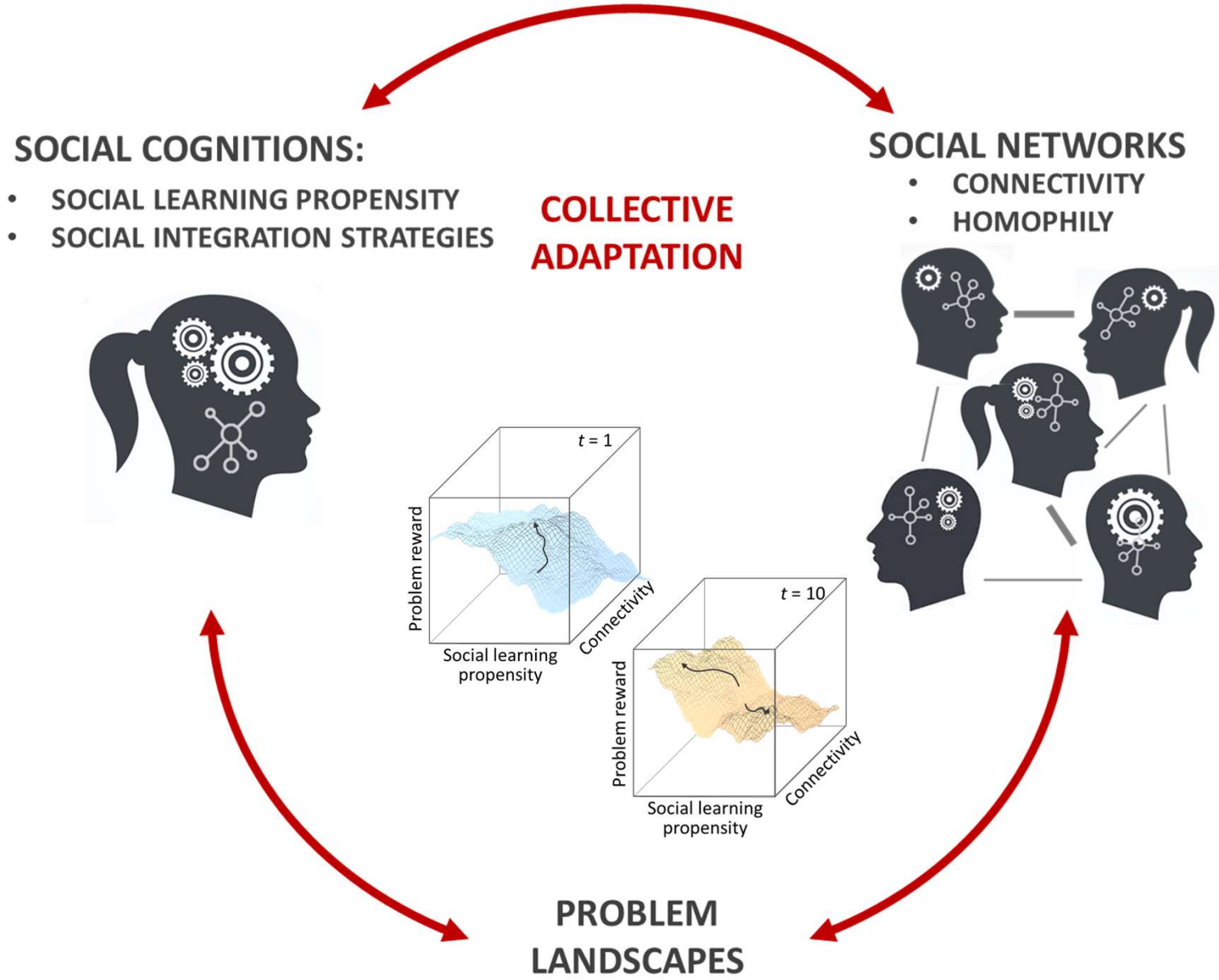
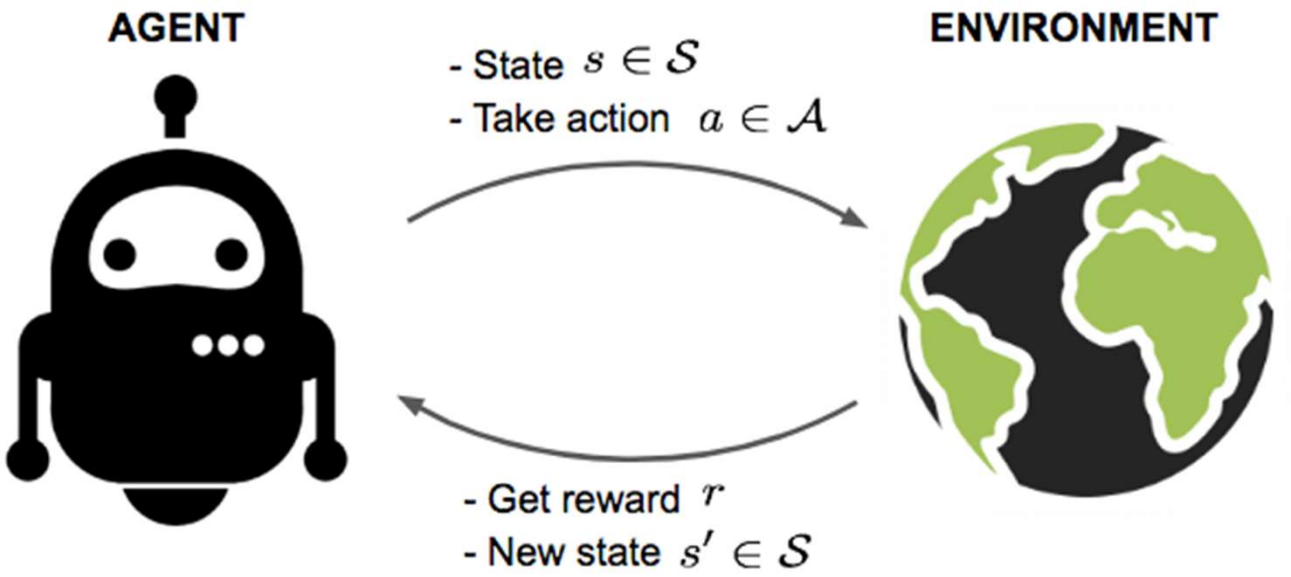
Modeling examples

1. Co-adaptation of social cognitions and social networks



1. Co-adaptation of social cognitions and social networks

Modeling: **Reinforcement learning** of suitable social cognitions and social networks



https://lilianweng.github.io/posts/2018-02-19-rl-overview/

1. Co-adaptation of social cognitions and social networks

Modeling: **Reinforcement learning** of suitable social cognitions and social networks

State of the world: learned value of different cognitions and networks

$W_{f,t} = W_{f,t-1} + \alpha\left(R_{x,t} - V_{x,t-1}\right)$ …weight of a feature, e.g. connectivity

$V_{x,t} = \sum_{f \in x} W(f)$ …overall value of a particular point in the problem environment

Action: choosing the combination of cognitions and networks that currently seems best

$$p(x)_t = \frac{V_{x,t}}{\sum_{x \in X} V_{x,t}}$$ …choosing the point with the highest value

Reward: success in solving the important current problems

$R_{x,t,i} = R^{ind}_{x,t,i} + R^{col}_{x,t,i} + \eta \sum_{j \neq i} R_{x,t,j}$ …reward includes individual and collective parts

1. Co-adaptation of social cognitions and social networks

Modeling: **Reinforcement learning** of suitable social cognitions and social networks

+ **Cultural evolution** on longer time scales

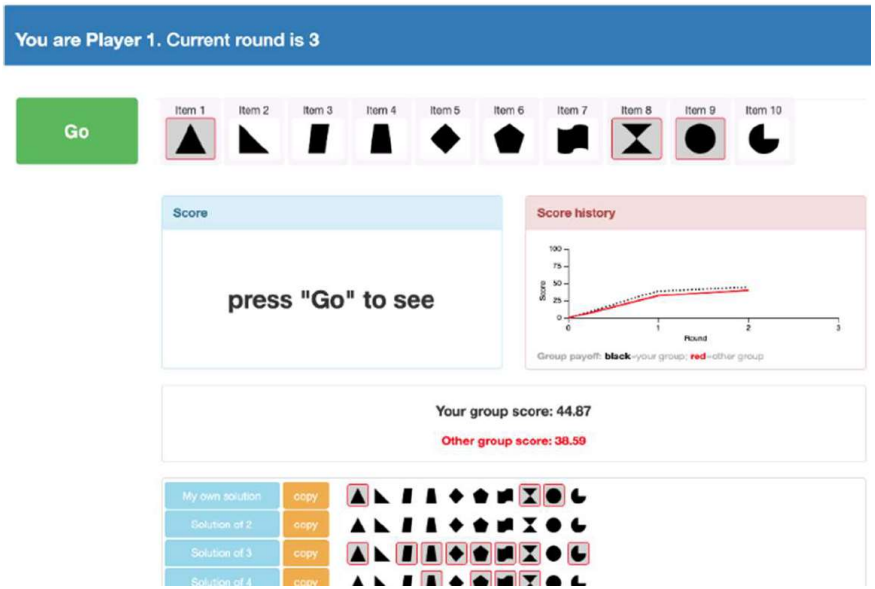
- to learn about possible cognitions and networks
- to learn the best value of parameter α (speed of adaptation)

$$W_{f,t} = W_{f,t-1} + \alpha\left(R_{x,t} - V_{x,t-1}\right)$$

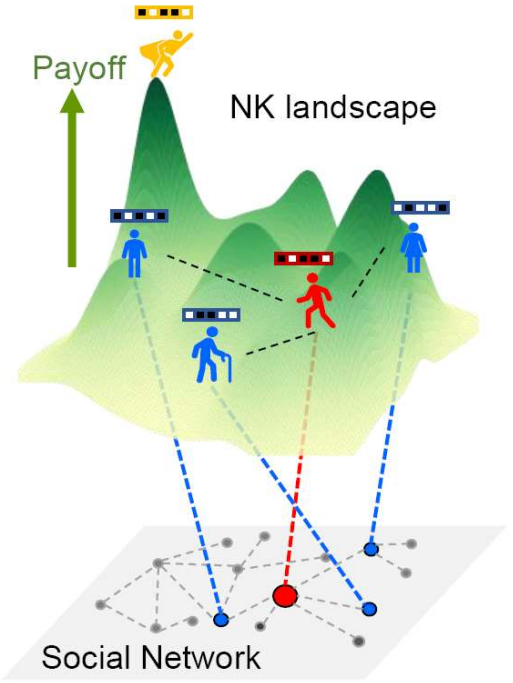
1. Co-adaptation of social cognitions and social networks

Data: Group experiments

- Participants solve problems in groups
- Problems change over time
- Can learn from each other
- Can rewire their networks



Galesic et al., 2022



Ha & Jeong, 2022

2. Different beliefs about important problems

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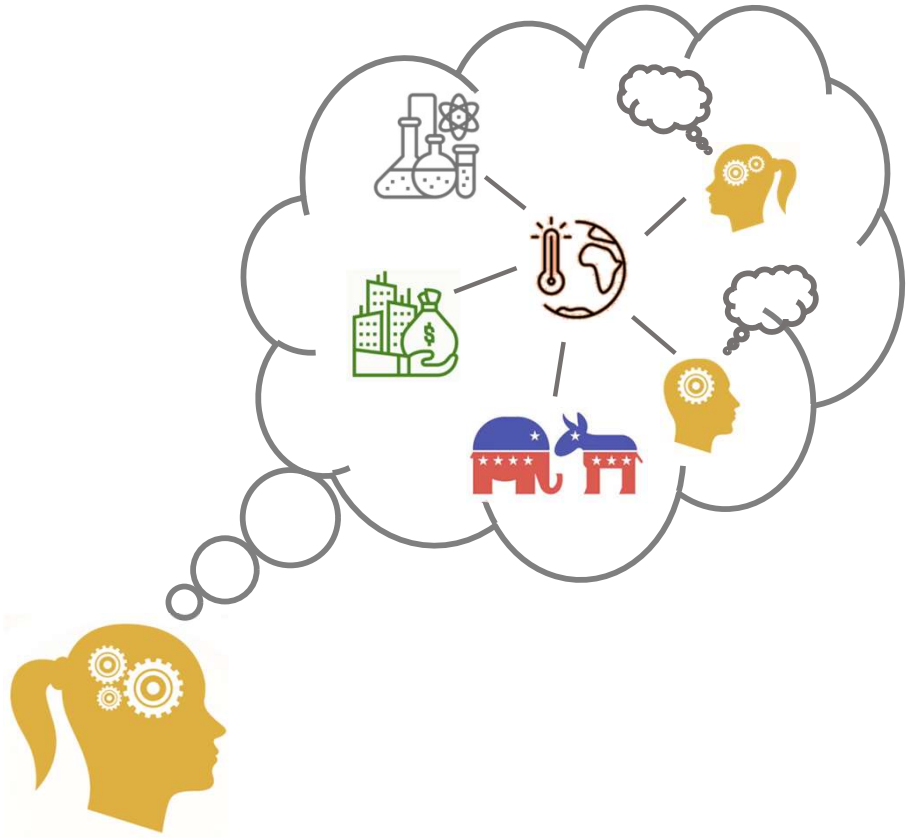
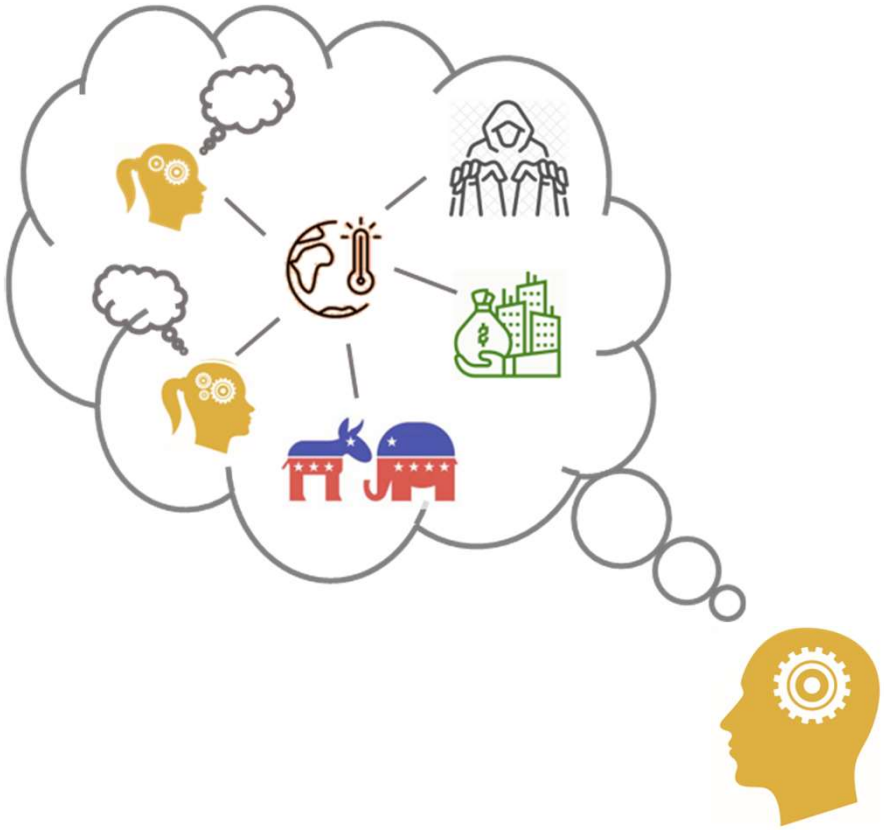
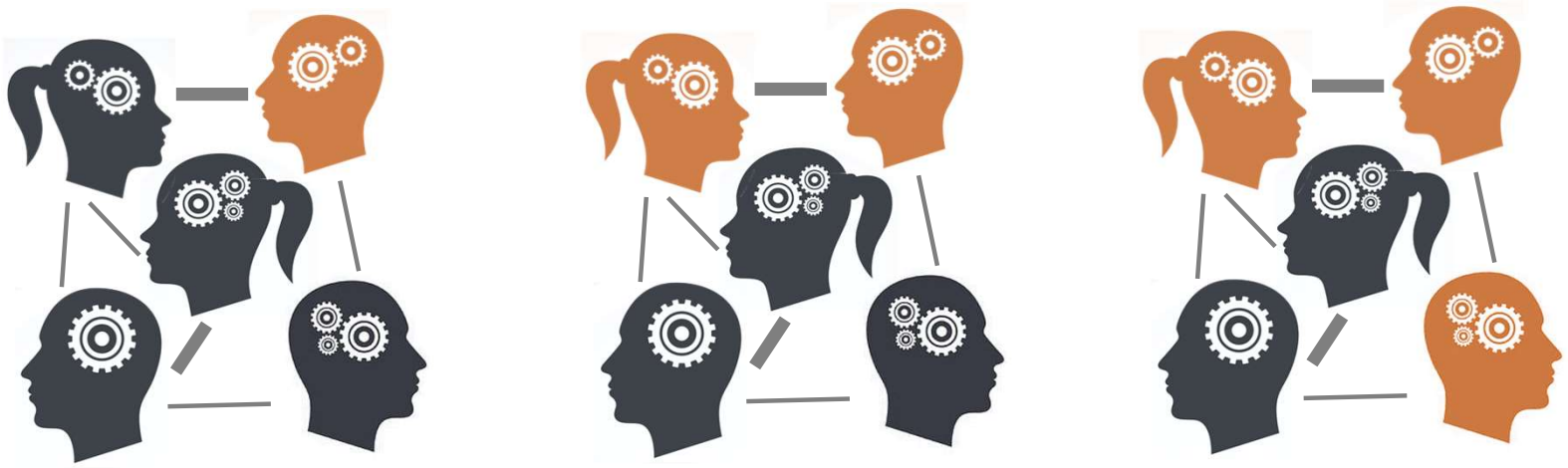
→ Different belief networks



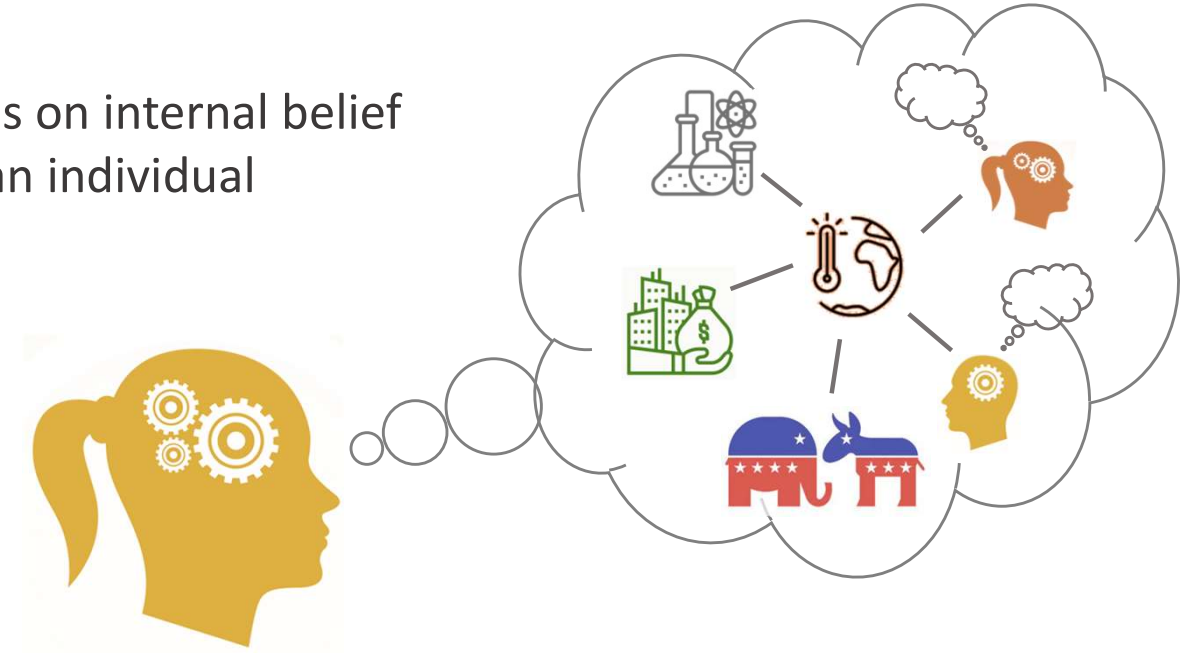


Models of belief dynamics

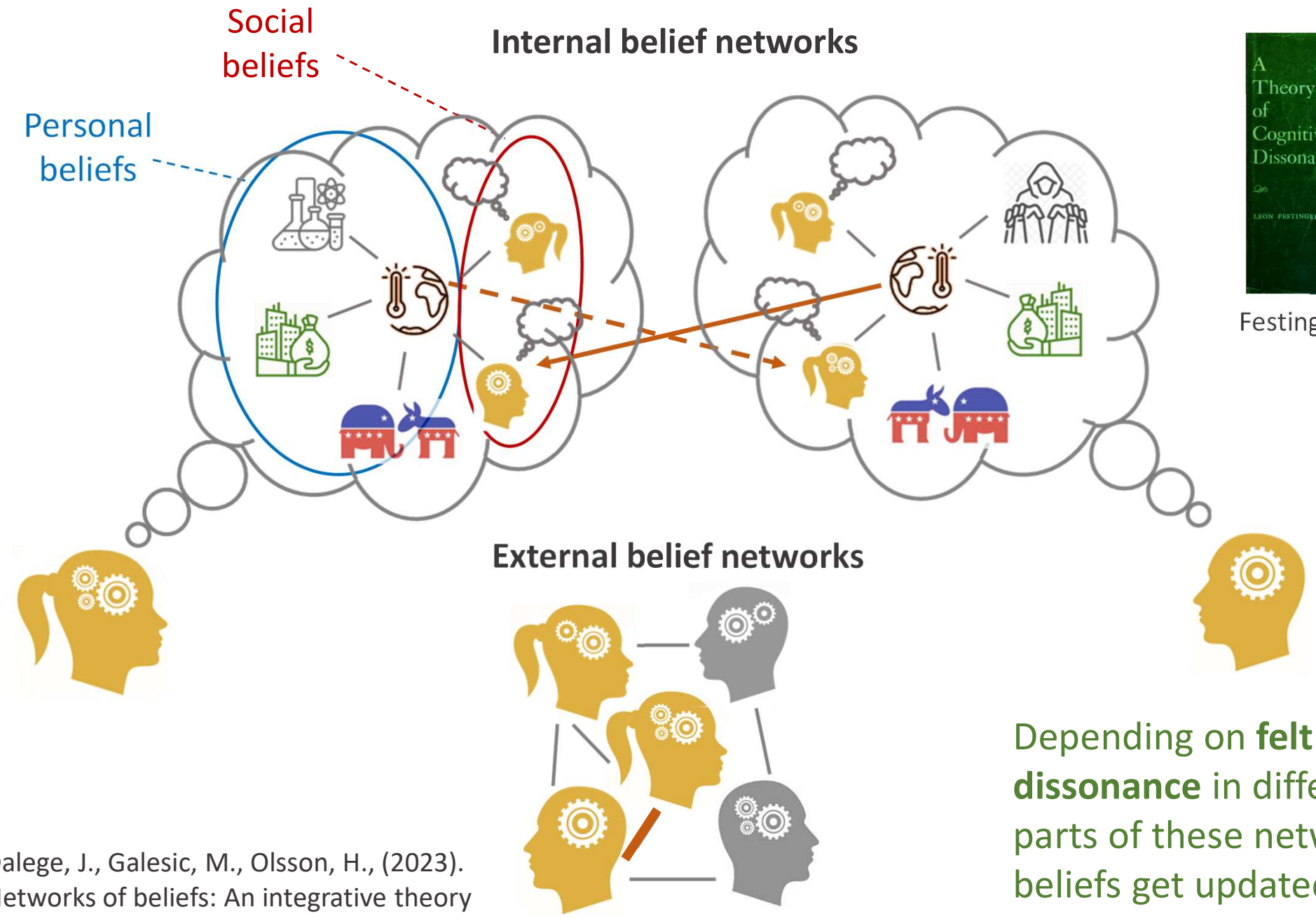
Type 1: Focus on single beliefs in social networks

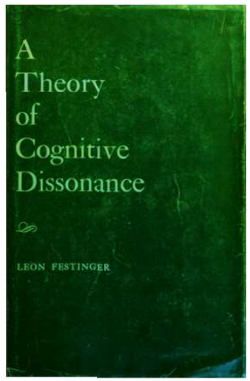


Type 2: Focus on internal belief network of an individual



Integrating social and belief networks: Networks of beliefs



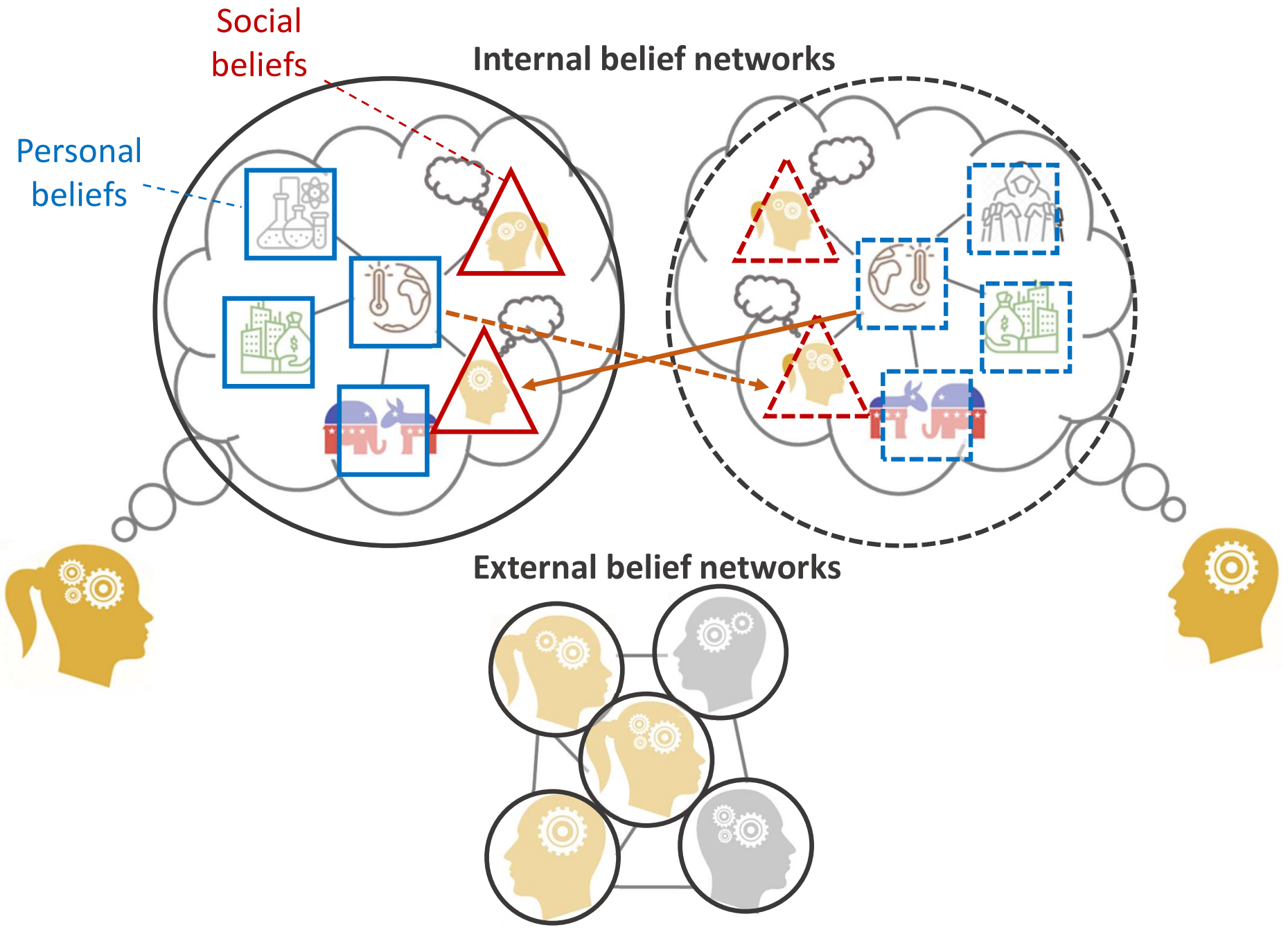


Festinger, 1957

Depending on **felt dissonance** in different parts of these networks, beliefs get updated

Dalege, J., Galesic, M., Olsson, H., (2023). Networks of beliefs: An integrative theory of individual- and social-level belief dynamics. https://osf.io/368jz/

Networks of beliefs: Visual notation



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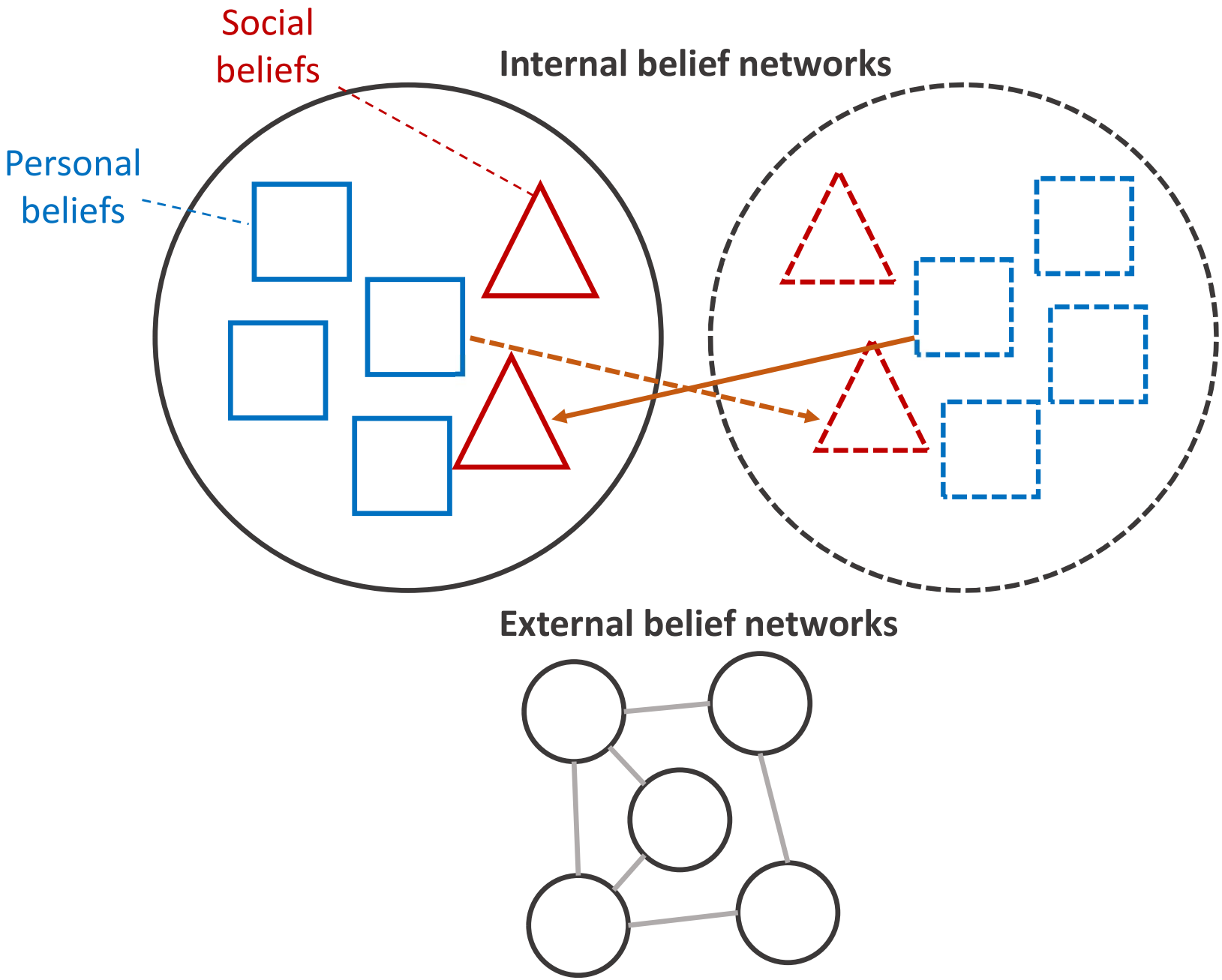

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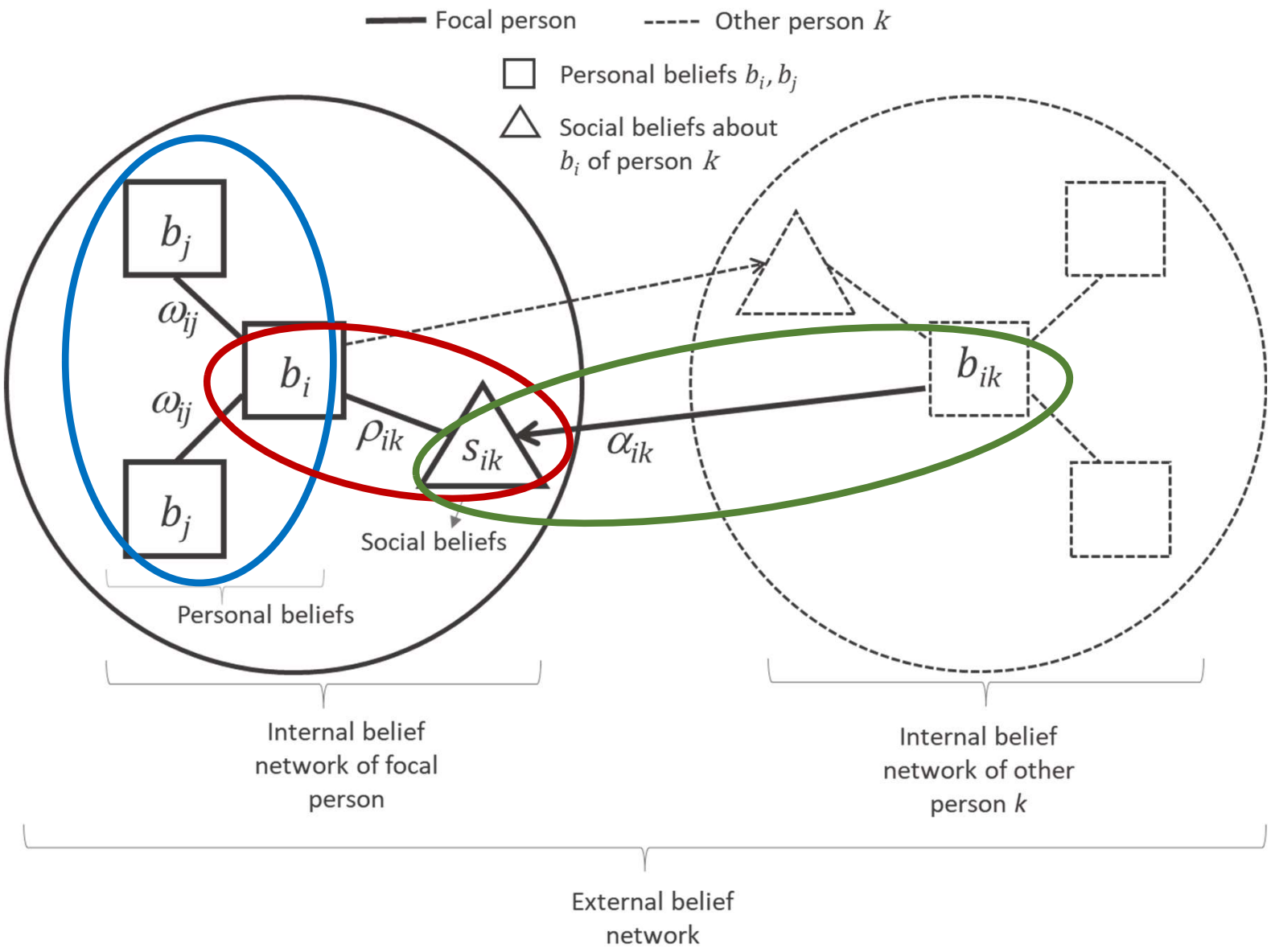

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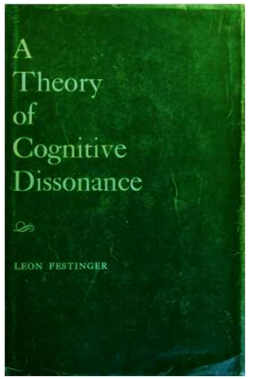
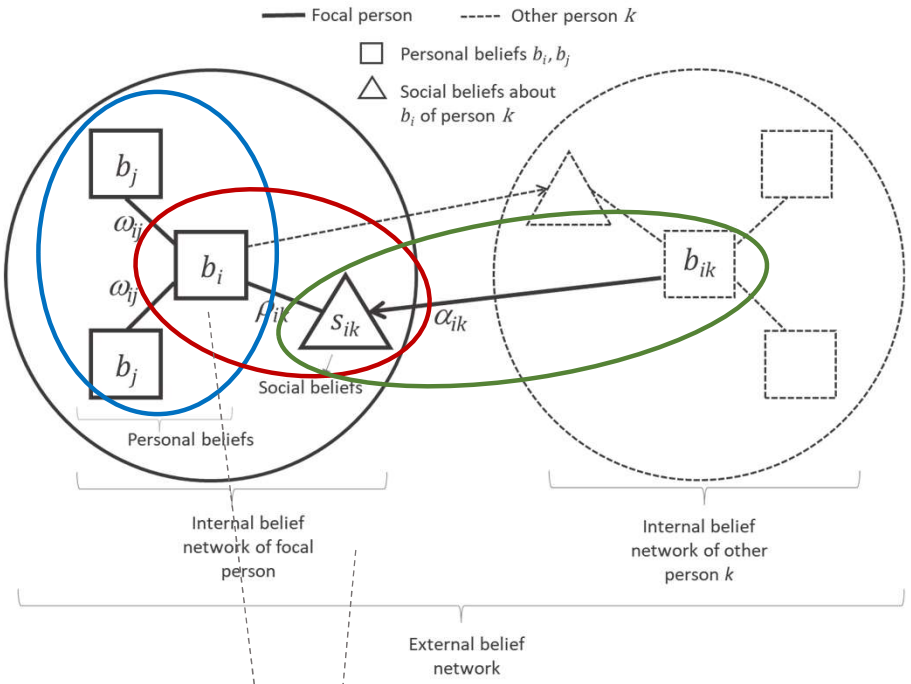




Potential dissonances

Personal dissonance

$$H_{pers} = -\sum_{ij} \omega_{ij} b_i b_j$$

Social dissonance

$$H_{soc} = -\sum \rho_{ik}\, b_i s_{ik}$$

External dissonance

$$H_{ext} = -\sum_i \sum_k \alpha_k s_{ik} b_{ik}\,,$$

Updating personal beliefs

$$P(b_i \rightarrow b_i') \approx 1/1 + e^{\Delta(\beta_{pers} H_{pers} + \beta_{soc} H_{soc})}$$

Updating social beliefs

$$P(s_i \rightarrow s_i') \approx 1/1 + e^{\Delta(\beta_{soc} H_{soc} + \beta_{ext} H_{ext})}$$

Felt dissonances

Depend on **attention** to personal, social, and external dissonances

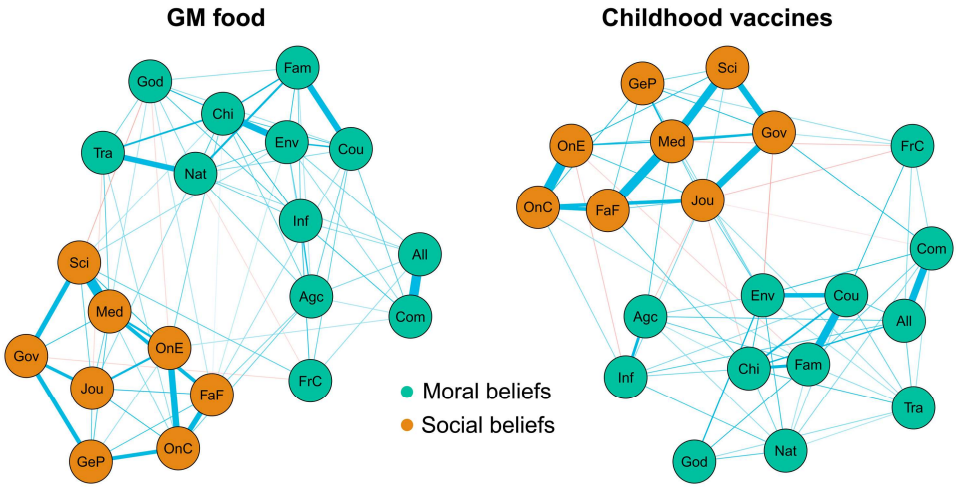
$$\beta_{pers}, \beta_{soc}, \beta_{ext}$$

Dalege, Galesic, & Olsson, (2023)

Networks of beliefs: Empirical tests

Data

- Networks of beliefs measured in longitudinal surveys



Dalege & van der Does, 2022, *Science Advances*

Dalege, Galesic, & Olsson, 2023, https://osf.io/368jz/

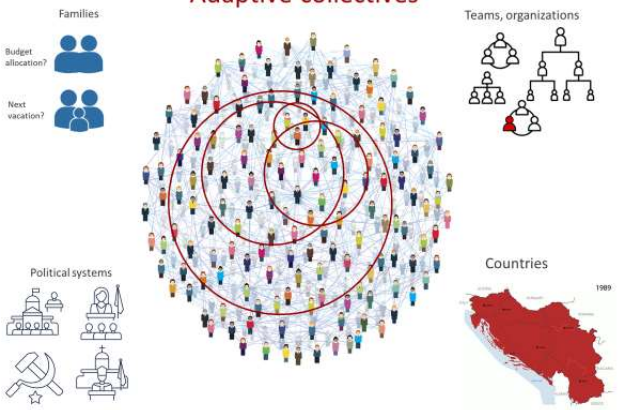
- Networks of topics discussed in comment sections of news sites across the US political spectrum, each month, over 5 to 8 years

BERTopic networks on Gateway Pundit, Jaksic et al., 2023

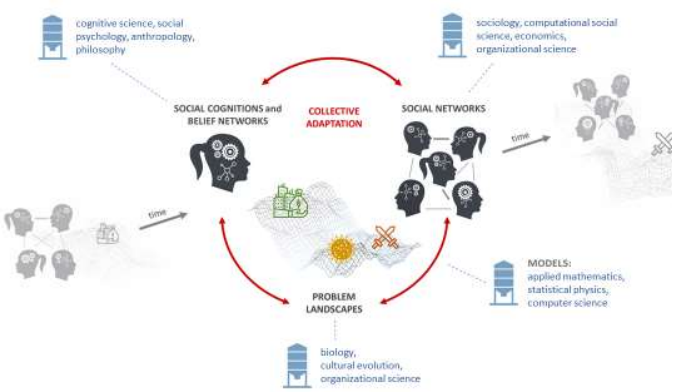
Outlook

What we know

Adaptive collectives

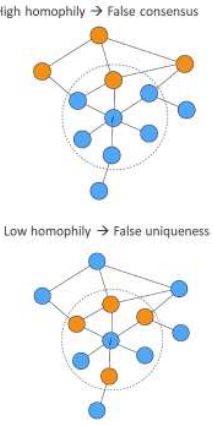


Collective adaptation: Disciplinary silos



Social environments

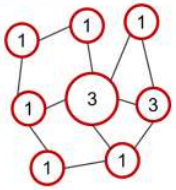
- Social networks
  - Perceived vs. objective networks (Thomas theorem, 1928; Denrell, 2005; Gonzalez et al., 2015)
  - Size and connectivity (Derex & Boyd, 2016; Lazer & Friedman, 2007; Mason et al., 2008; Giannoccaro et al. 2018)
  - Homophily (McPherson et al., 2001; Karimi et al., 2018; Lee et al, 2019)
  - Centrality (Barabasi & Albert, 1999; Becker et al., 2017)
  - Directed vs. undirected
- Social artifacts
  - Languages and scripts
  - Communication channels
  - Institutions
  - …



Lee et al., 2019; Galesic, Olsson, Rieskamp, 2018

Strategies for integrating social information

Three basic classes:



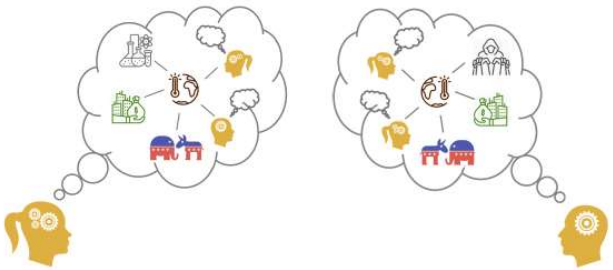
- Frequency-dependent strategies: majority, plurality, unanimity, minority, complex contagion… rules (1)

  Condorcet 1785; political science (Heinberg, 1932); statistics (Penrose, 1946); psychology (Asch, 1955); economics (Plott, 1967); cultural evolution (Boyd & Richerson, 1985); computer science (Parhami, 1994); statistical physics (Krapivsky & Redner, 2003); biology (King & Cowlishaw, 2007); sociology (complex contagion; Centola & Macy, 2007)
- Averaging strategies: with or without weights, e.g. advice taking, voter model, contagion rules, blending inheritance (2)

  Galton, 1907; economics (DeGroot, 1974; Golub & Jackson, 2010); advice taking (Molleman et al., 2020; Yaniv, 2004); statistical physics (Ising models; Castellano et al., 2009); cultural evolution (blending inheritance: Boyd & Richerson, 1985); network science (contagion; Newman, 2003)
- Model-based strategies: follow leader, expert, similar, confident, liked, best (3)

  cultural evolution (high status: Henrich & Gil-White, 2001), social psychology (liking, authority: Cialdini & Trost, 1998), cognitive psychology (similarity, Wisdom et al., 2013), law (confidence; Penrod & Cutler, 1995)

Different belief networks



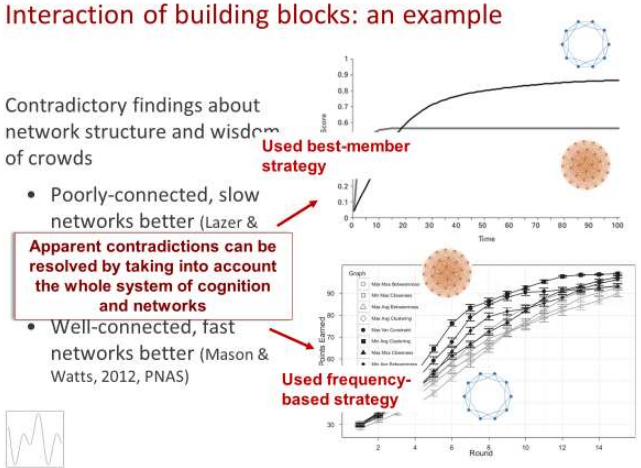
Interaction of building blocks: an example

Contradictory findings about network structure and wisdom of crowds

- Poorly-connected, slow networks better (Lazer &

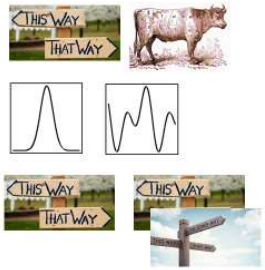
Apparent contradictions can be resolved by taking into account the whole system of cognition and networks

- Well-connected, fast networks better (Mason & Watts, 2012, PNAS)



Problem environments

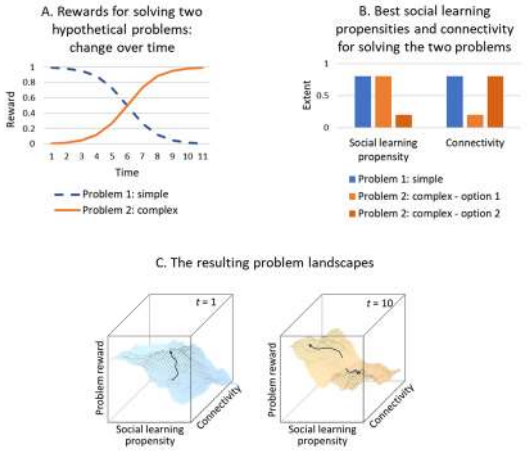
- Structural properties of problems
  - Categorical vs. continuous judgments
  - Simple and complex task landscapes
  - One-shot and repeated problems



- Global environment
  - Economic, political, cultural factors that change payoffs of different options, feasibility of different strategies and networks

What we are working on

A simple example



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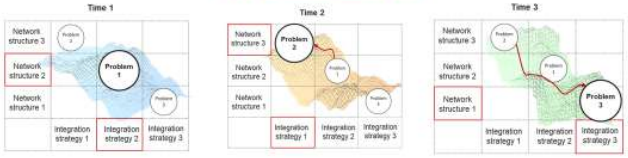

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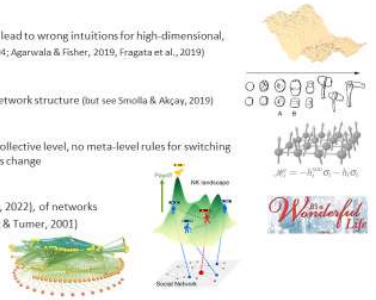

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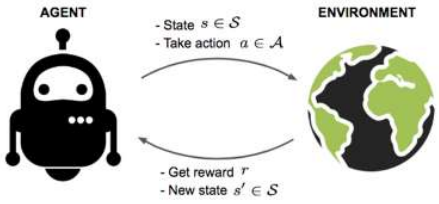
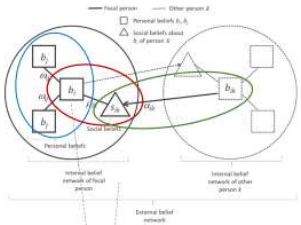


https://lilianweng.github.io/posts/2018-02-19-rl-overview/

Networks of beliefs: Mathematical notation



Potential dissonances

Personal dissonance

$$H_{pers} = -\sum_{ij} \omega_{ij} b_i b_j$$

Social dissonance

$$H_{soc} = -\sum \rho_{ik}\, b_i s_{ik}$$

External dissonance

$$H_{ext} = -\sum_i \sum_k \alpha_k s_{ik} b_{ik},$$

Updating personal beliefs

$$P(b_i \to b_i') \approx 1/1 + e^{\Delta(\beta_{pers} H_{pers} + \beta_{soc} H_{soc})}$$

Updating social beliefs

$$P(s_i \to s_i') \approx 1/1 + e^{\Delta(\beta_{soc} H_{soc} + \beta_{ext} H_{ext})}$$

Felt dissonances

Depend on **attention** to personal, social, and external dissonances

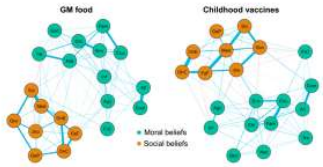
$\beta_{pers}, \beta_{soc}, \beta_{ext}$

Dalege, Galesic, & Olsson, (2023)

Networks of beliefs: Empirical tests

Data

- Networks of beliefs measured in longitudinal surveys



Dalege & van der Does, 2022, *Science Advances*
Dalege, Galesic, & Olsson, 2023, https://osf.io/368jz/

- Networks of topics discussed in comment sections of news sites across the US political spectrum, each month, over 5 to 8 years

BERTopic networks on Gateway Pundit, Jaksic et al., 2023

What we hope to understand

1. How do collectives change their integration strategies and network structures to adapt to different problems?
2. How do radically different beliefs about what problems are important affect collective adaptation?
3. Why is it sometimes hard for collectives to reach seemingly obvious solutions to a particular problem?
4. Can we anticipate new problems that might emerge because of the way societies adapted to past problems?
5. Can we reduce less desirable consequences of collective adaptation to emerging problems?