Advancing agent-based complex systems science with data science and artificial intelligence

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Acknowledgements

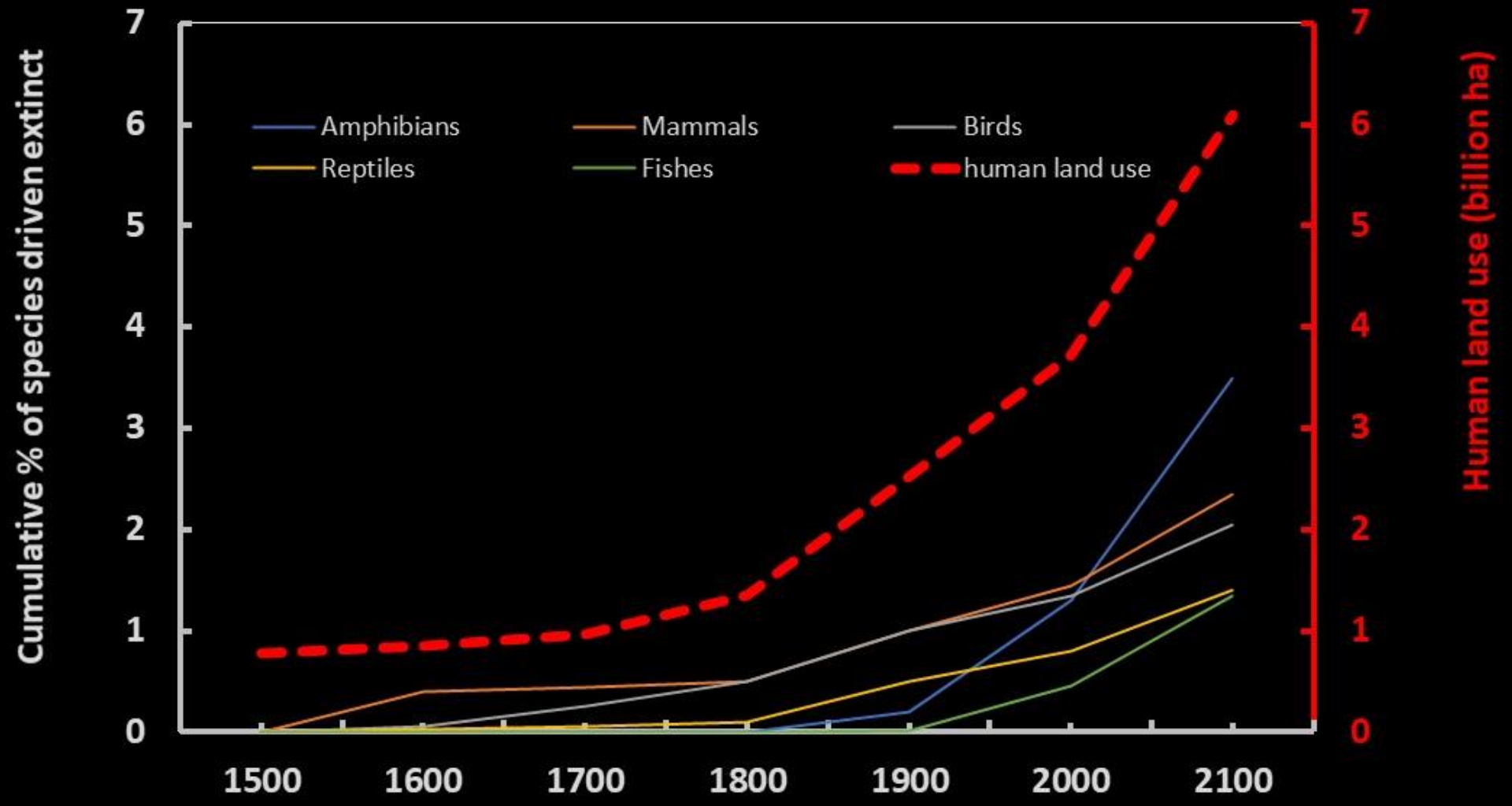
Volker Grimm, Abigail Sullivan, B. L. Turner II, Zhangyang Wang, Nicolas Malleson,

Ruihong Huang, Alison Heppenstall, Christian Vincenot, Derek Robinson, Xinyue Ye,

Jianguo (Jack) Liu, Emilie Lindkvist, Wenwu Tang

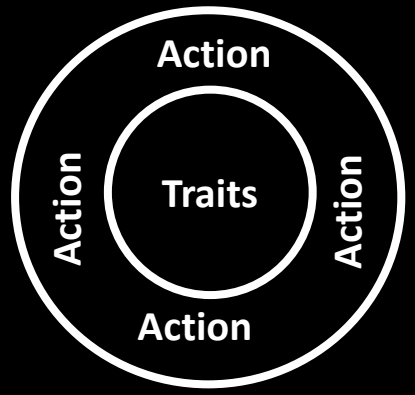
“Agent-based complex systems science in the era of global sustainability crisis”

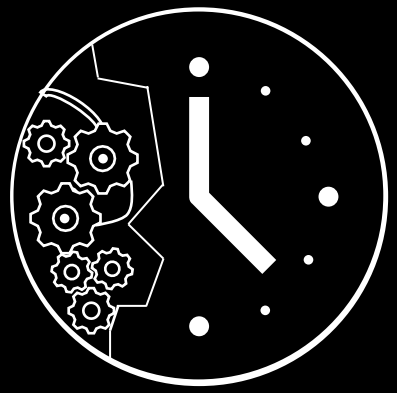
Grand challenges



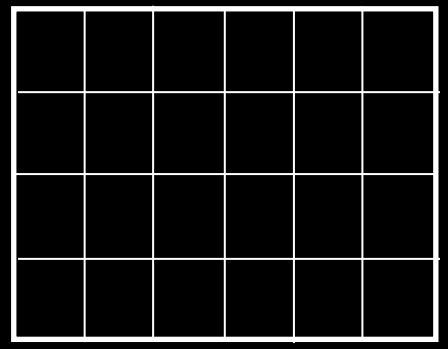
Agents

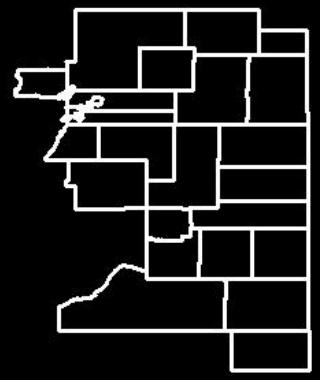
- Actors

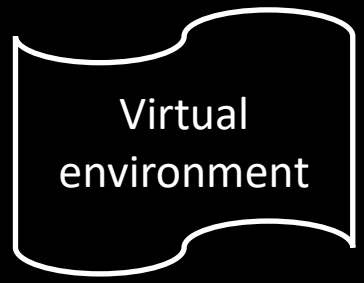




- Environment



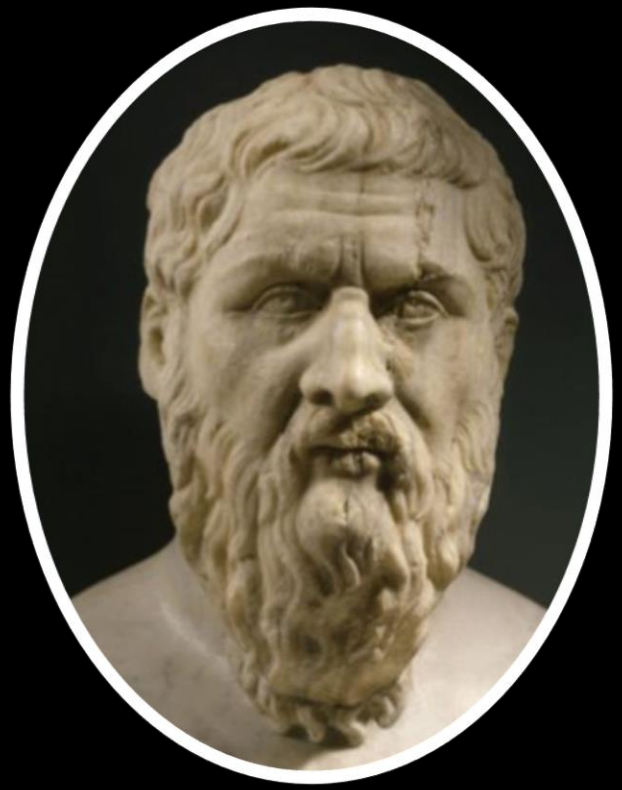




Agent-based Complex Systems (ACS)

- ~ Complex Adaptive Systems or Agent Societies
  - Pivotal role of individual agents and their adaptive behavior
  - Agents' interactions
- Agent-based Complex Systems (ACS) science
  - Understand and track the behavior of agents
  - Explain and predict how system-level patterns emerge
  - How these patterns affect agents' future behavior

Big questions



Hermagoras of Temnos
(1st century BC)

Who

What

When

Where

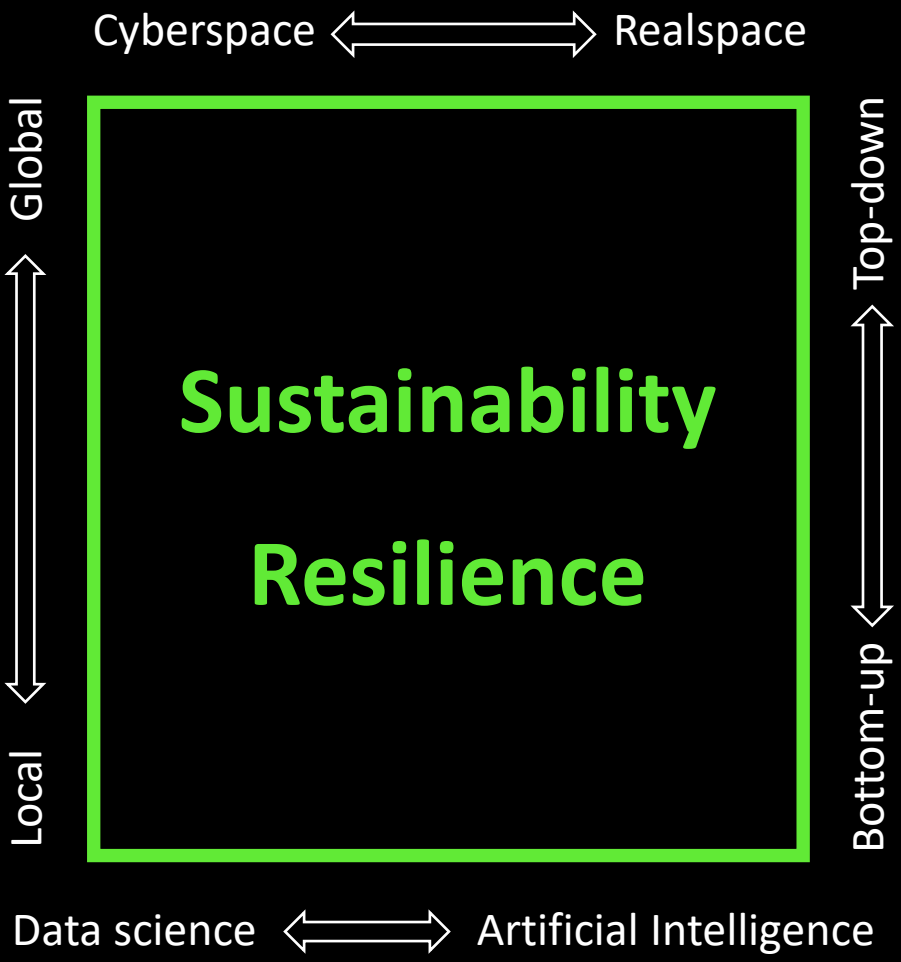
Why

In What Way

By What Means

ACS efforts

Image Credit: slideplayer



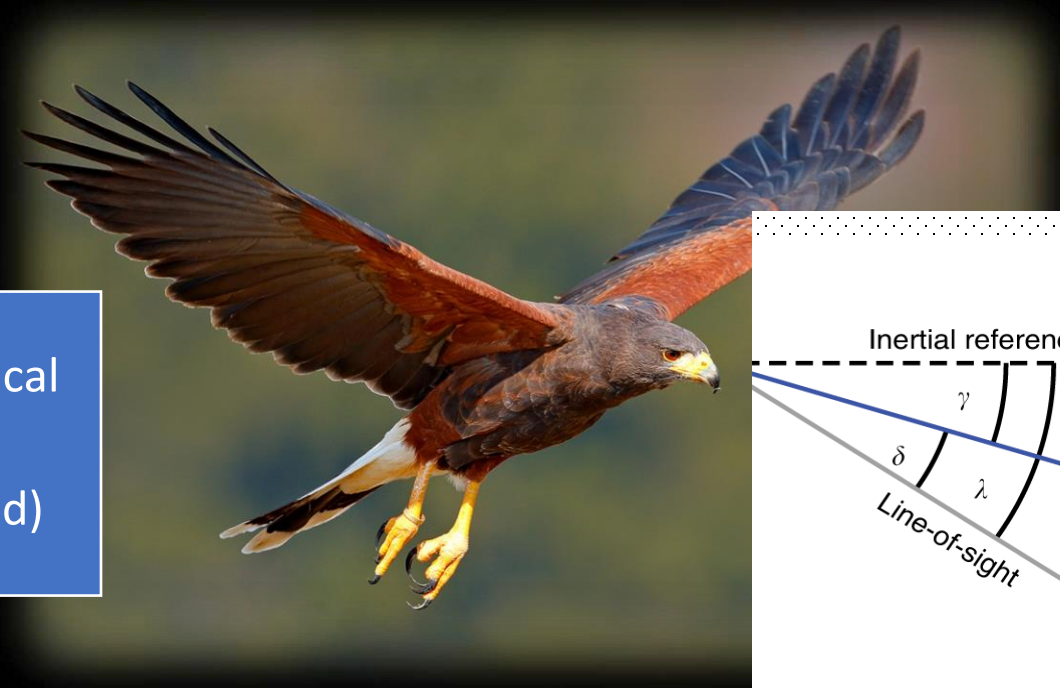
A major challenge in ACS science

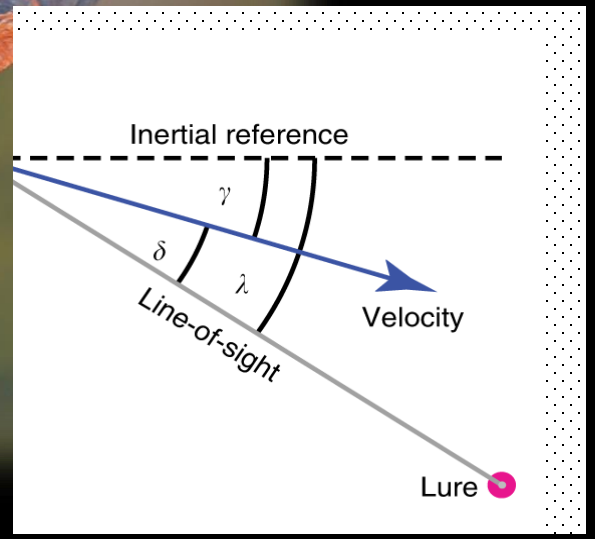
Bottom-up, mechanistic modeling

(theory driven)

Top-down, empirical approach

(pattern-informed)





Brighton, C. H., and G. K. Taylor. 2019. Hawks steer attacks using a guidance system tuned for close pursuit of erratically manoeuvring targets. *Nature Communications* 10 (1):2462.

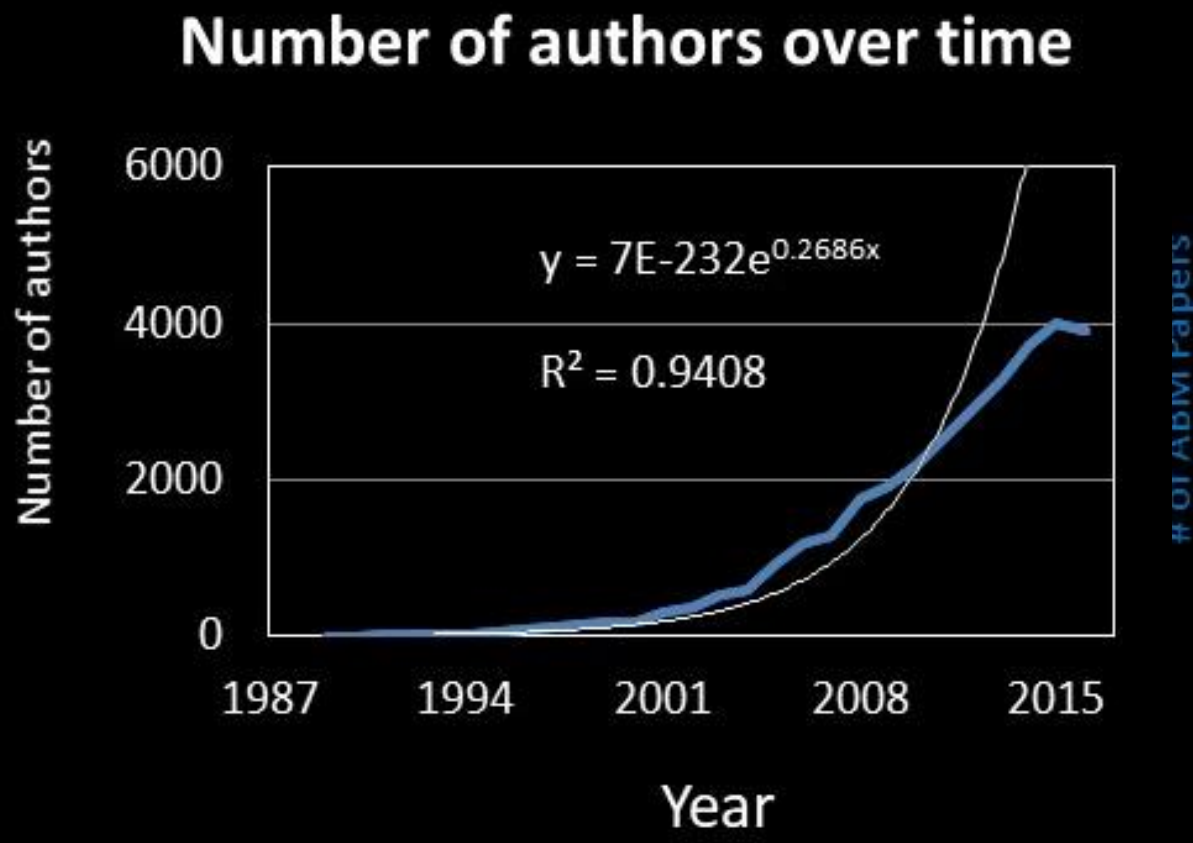
Picture credit: https://www.earth.com/news/hunting-method-hawks-drones/

Curse & blessing?

- Equifinality: a macro-level pattern can be generated through different pathways from micro levels
- Curse: challenge the validity of existing theories
- A blessing: offer more explanative pathways

Modeling ACS using agent-based modeling

- The rise of agent-based modeling since the 1990s
- Milestones:
  - Overview, Design concepts, Details (ODD) protocol
  - Pattern-Oriented Modeling paradigm
  - The Physical, Emotional, Cognitive, and Social factors (PECS) and the Beliefs-Desires-Intentions (BDI) frameworks



Data credit:: Christian Vincenot

Popularity of ABM

- National Academy of Sciences' Sackler Colloquium in 2001
- Special issue in the Proceedings of the National Academy of Sciences
- Criticisms about ABM

Ontology of ABM

- ABM's unique ontology (methodological individualism)
- This ontology allows for modeling
  - adaptive decision-making
  - co-evolutionary nature of ACS elements
  - abrupt changes
  - crises or disasters
  - critical transitions related to interactions

Strengths of ABM:

- Employ more realistic decision-making rules
- Integrate cross-scale and cross-discipline data and methods
- Account for incomplete knowledge and bounded rationality
- Understand the system in an iterative manner
- A holistic, heuristic, and adaptive platform

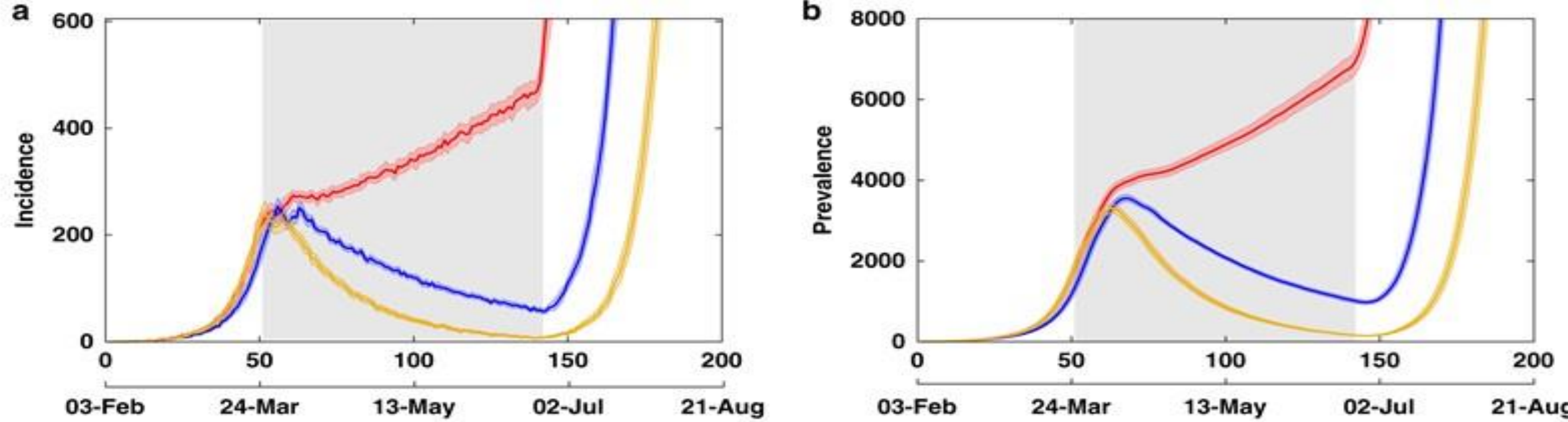
An, L., V. Grimm, A. Sullivan, B.L. Turner II., N. Malleson, A. Heppenstall, C. Vincenot, D. Robinson, X. Ye, J. Liu, E. Lindvist, and W. Tang (2021). Challenges, tasks, and opportunities in modeling agent-based complex systems. Ecological Modeling 457: 109685; doi: 10.1016/j.ecolmodel.2021.109685.

A COVID-19 ABM

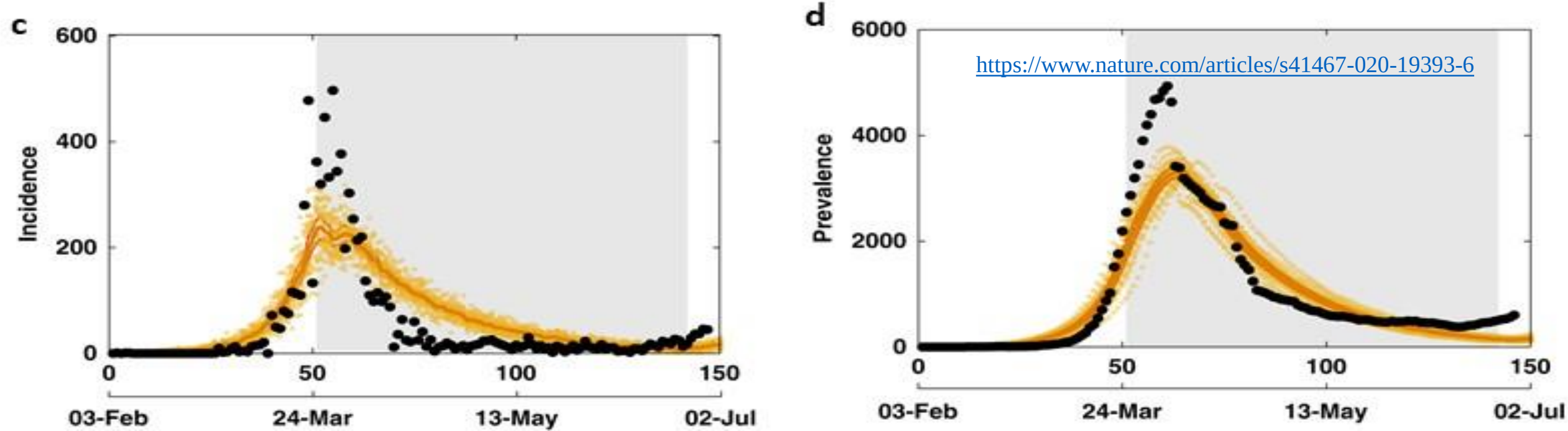
- Goal: To evaluate the effectiveness of intervention strategies in the absence of a COVID-19 vaccine in Australia
- Agents: 24 million people with
  - individual traits
  - Interaction with one another
  - contact rates within different social contexts, and
  - other characteristics of the real population

} potential transmission of the disease

Chang, S. L., Harding, N., Zachreson, C., Cliff, O. M. & Prokopenko, M. Modelling transmission and control of the COVID-19 pandemic in Australia. *Nat. Commun.* **11**, 5710 (2020).



red, blue, and yellow for 70%, 80%, and 90% compliance levels (for social distancing)



https://www.nature.com/articles/s41467-020-19393-6

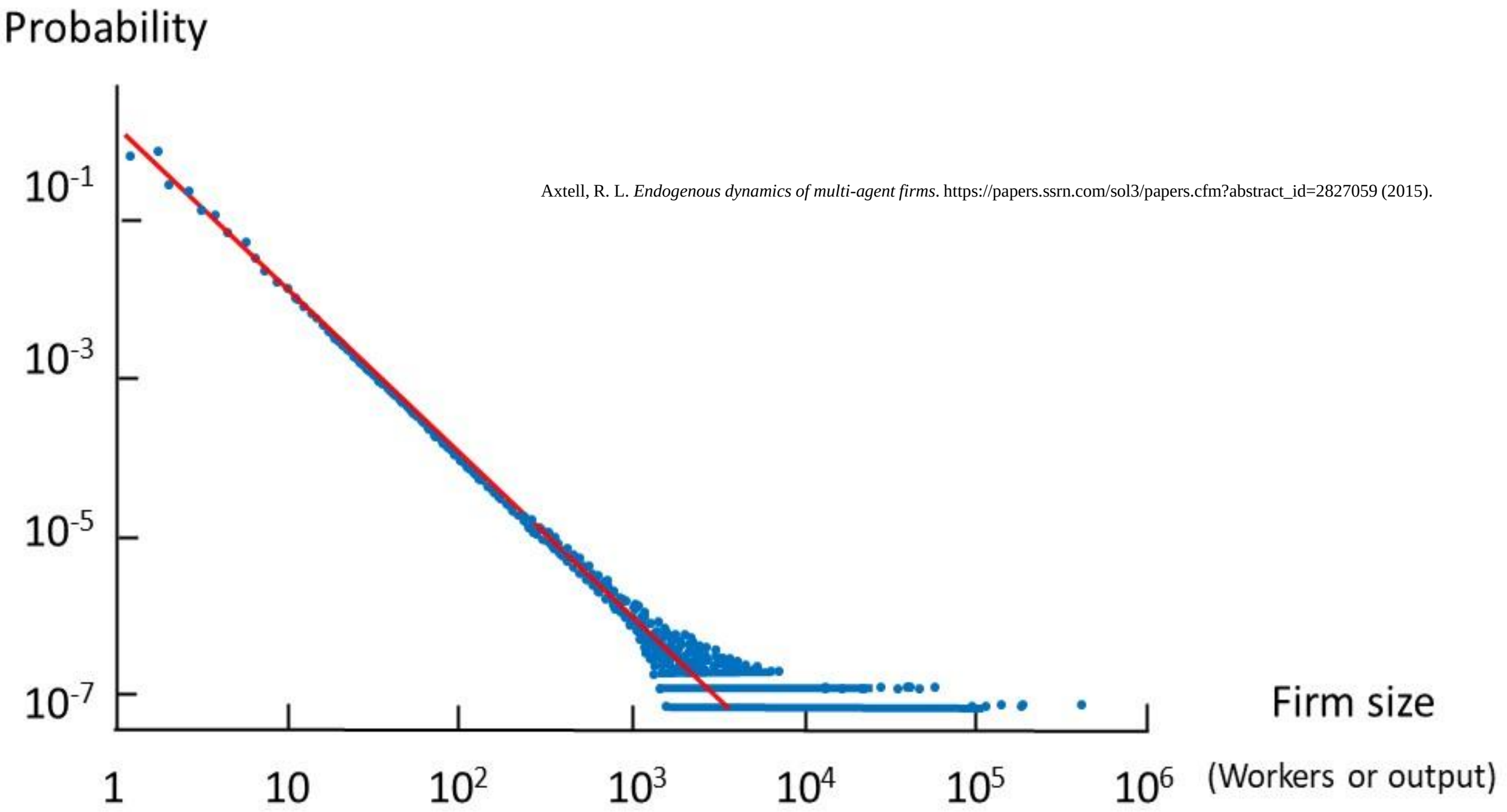
“Curse” of equifinality

A few parameters are calibrated out of observed data as shown in the paper, the above patterns might be generated by different parameter values or pathways

ABM for workers in the U.S.

- Goal: To formulate new theory that explains (Axtell 2001, 2015):
  - high levels of turnover (e.g., individual workers' job changes)
  - firm termination or start-up
- Agents: 120 million workers in private sector with
  - pursue their own self-interest
  - seeking alternative jobs within a limited social network (2~6 friends)

Axtell, R. L. *Endogenous dynamics of multi-agent firms*. https://papers.ssrn.com/sol3/papers.cfm?abstract_id=2827059 (2015).
Axtell, R. L. Zipf distribution of U.S. firm sizes. *Science* **293**, 1818–1820 (2001).



Axtell, R. L. *Endogenous dynamics of multi-agent firms*. https://papers.ssrn.com/sol3/papers.cfm?abstract_id=2827059 (2015).

The contribution of ABM

- No need to rely on
  - exogenous shocks
  - firm-specific (e.g., technological or productivity-related) variables,
  - product markets, prices, and consumption patterns

ABM challenges

- Developing integrated human-environment ABMs
- Modeling human behavior
- Module reusability and transparency
- Model verification and validation
- High-performance computing
- Building spatially explicit ABMs

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Advance ACS modeling

- Guidelines
  - Modelers
  - Reviewers
  - Novices
- Common ABM toolkits and software package (85+ platforms)
- ABM education and communication

An, L., V. Grimm, A. Sullivan, B.L. Turner II., N. Malleson, A. Heppenstall, C. Vincenot, D. Robinson, X. Ye, J. Liu, E. Lindvist, and W. Tang (2021). Challenges, tasks, and opportunities in modeling agent-based complex systems. Ecological Modeling 457: 109685; doi: 10.1016/j.ecolmodel.2021.109685.

Think “out of the box”?

Artificial intelligence

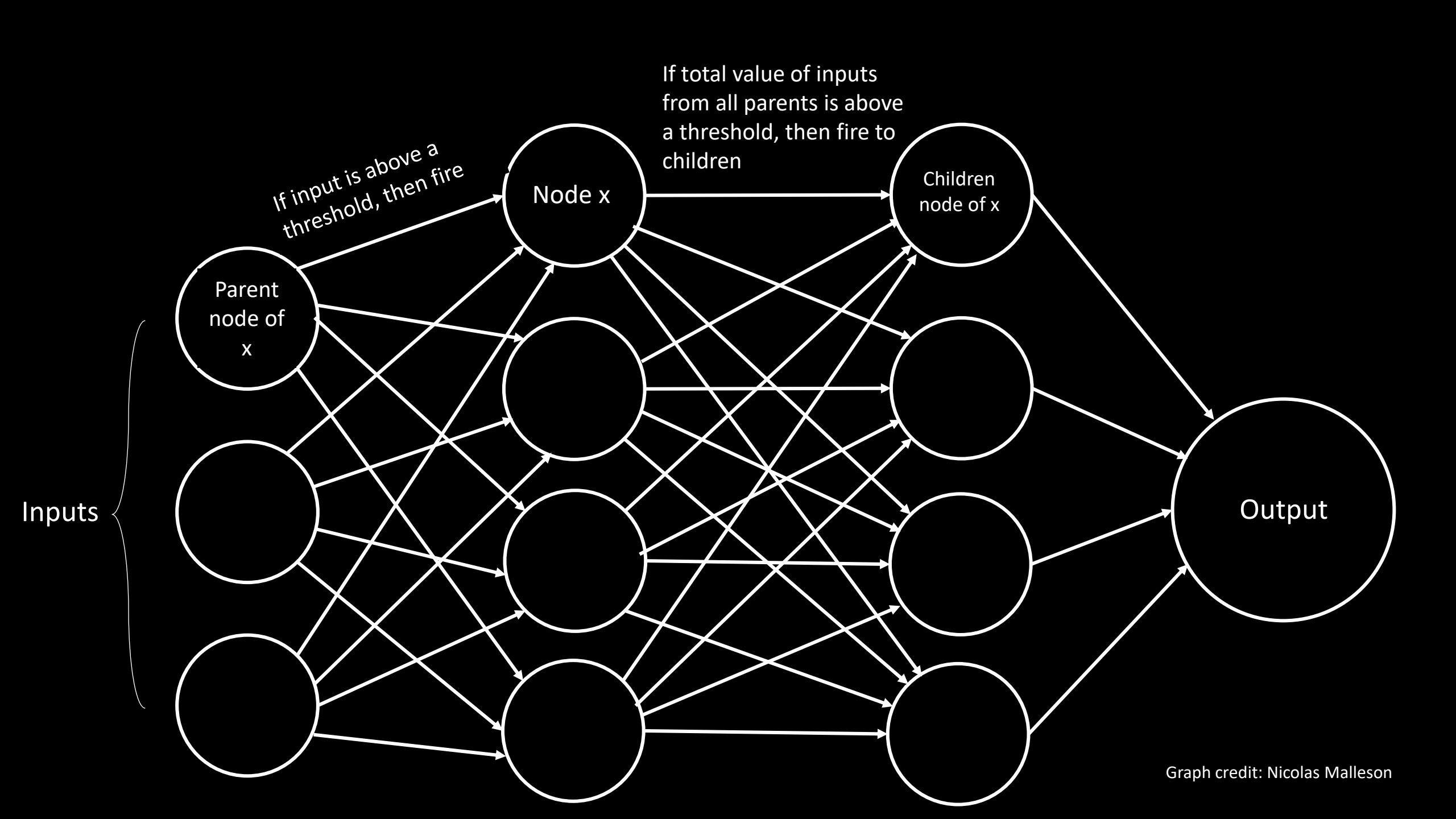
- Machines: able to simulate human intelligence
- Many new forms of data
  - Big data
  - Qualitative data (e.g., text, images, videos, audio documents)
- Capability to handle such data

Advances in data science

- Scientific methods, programming tools, and appropriate data infrastructures
- Machine learning
  - help derive model structures
  - verify or rebut the underlying mechanisms, forces, and/or processes behind macro-patterns

Neural networks

- One type of versatile algorithms in machine learning
- A neural network consists of layers of nodes that are connected by links
  - nodes are analogous to agents in the context of ACS
  - links are agent-agent or agent-environment relationships (rules)


If total value of inputs from all parents is above a threshold, then fire to children
If input is above a threshold, then fire
Node x
Children node of x
Parent node of x
Inputs
Output
Graph credit: Nicolas Malleson

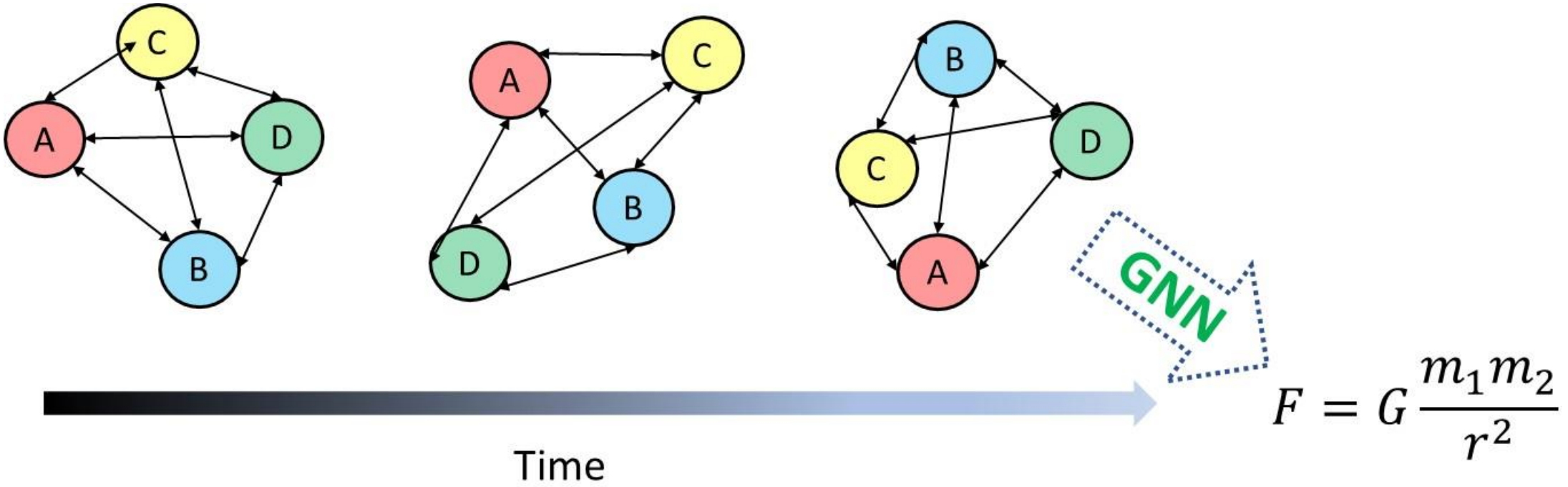
Opportunities for ABM

- Assign and implement each agent with its own unique regression equation or neural networks
  - agent behavior ← optimizing the regression equations or neural networks
  - not common so far
- Downside: difficulty of interpretation

Graph neural networks (GNNs)

- A graph: a structure (frequently mathematical) that models pairwise relations between nodes, in which all nodes (agents) are connected by edges or links.
  - graphs are similar to patterns in the pattern-oriented modeling
- GNNs link nodes horizontally and good for predictive tasks

Machine learning's success



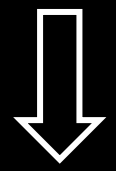
Cranmer, M. *et al.* Discovering symbolic models from deep learning with inductive biases. *ArXiv200611287 CsLG* (2020).

Recovering ACS rules via machine learning

- A balance between the internal mechanism and its predictive power
- A three-step strategy
  - Step 1: build an edge model to represent links or edges amongst all agents
  - Step 2: develop a node model, in which each node receives messages from other nodes, and the magnitude of each message is calculated from Step 1
  - Step 3: establish a global model to aggregate and update the status of all above messages and nodes

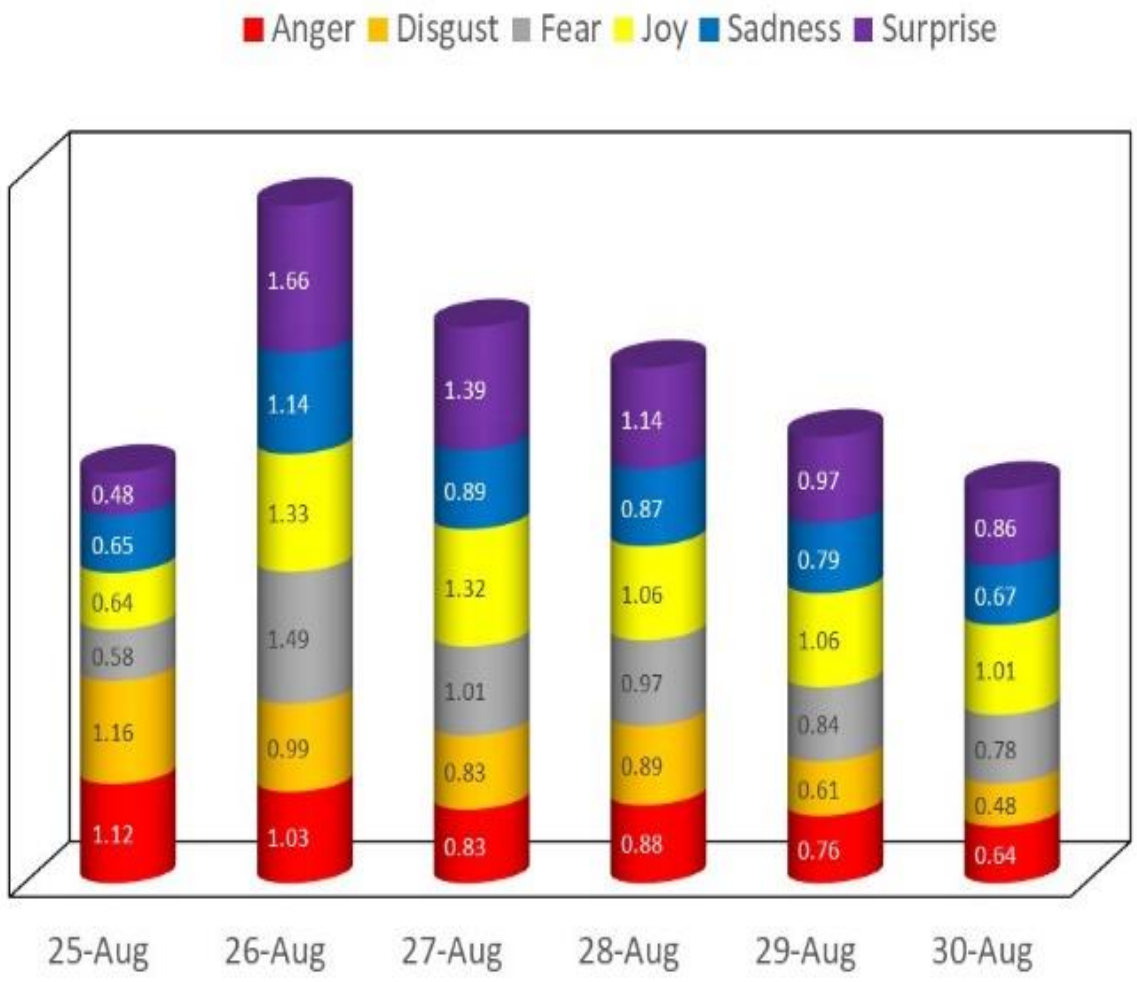
Mining qualitative data

Deep neural networks in natural language processing

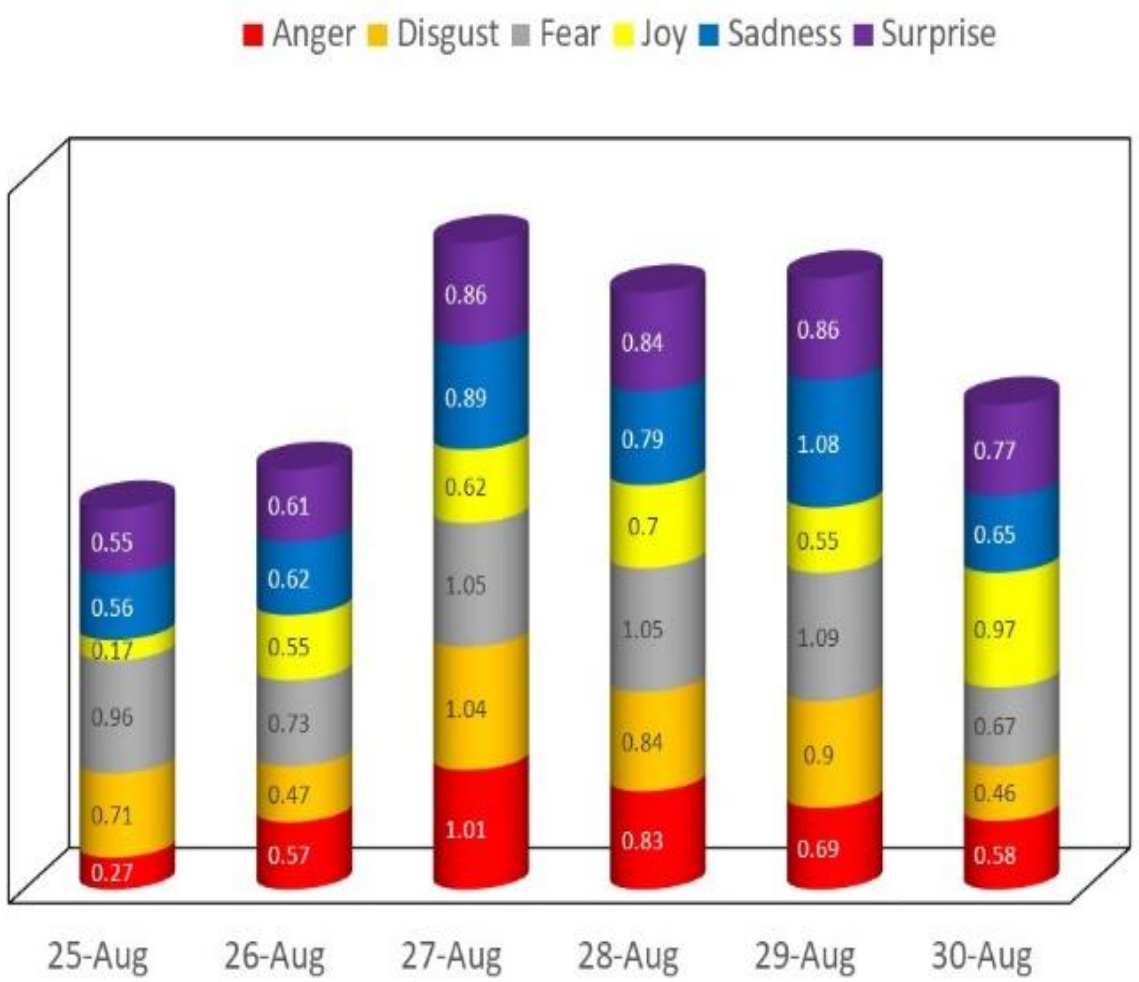


Effectively translates English text (e.g., in social media) into ABM rules or data patterns

Emotion analysis



help and rescue



flood-control infrastructures

Applications in ACS modeling

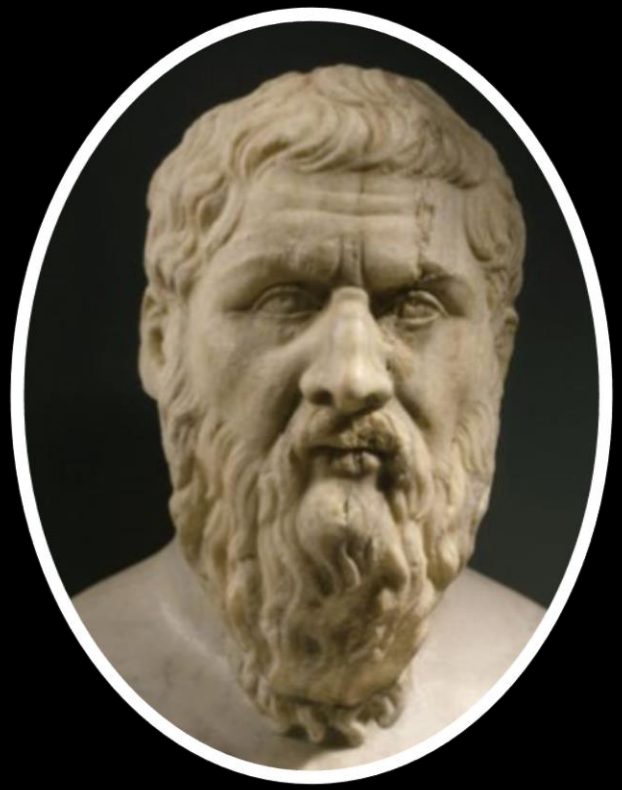
“Sadness” data → ABM’s rules or predictions

ACS science

- We call for transboundary efforts that blur disciplinary, economy, and political boundaries
- A new systems science
  - inductive reasoning
  - deductive reasoning
  - abductive reasoning (for social scientists)
  - their integration—all nourished by data science and AI

ACS science, along with ABM, may advance and become a new generic systems theory. This makes the whole humanity to have an effective means to tackle the grand challenges

Big questions



Hermagoras of Temnos
(1st century BC)

Who

What

When

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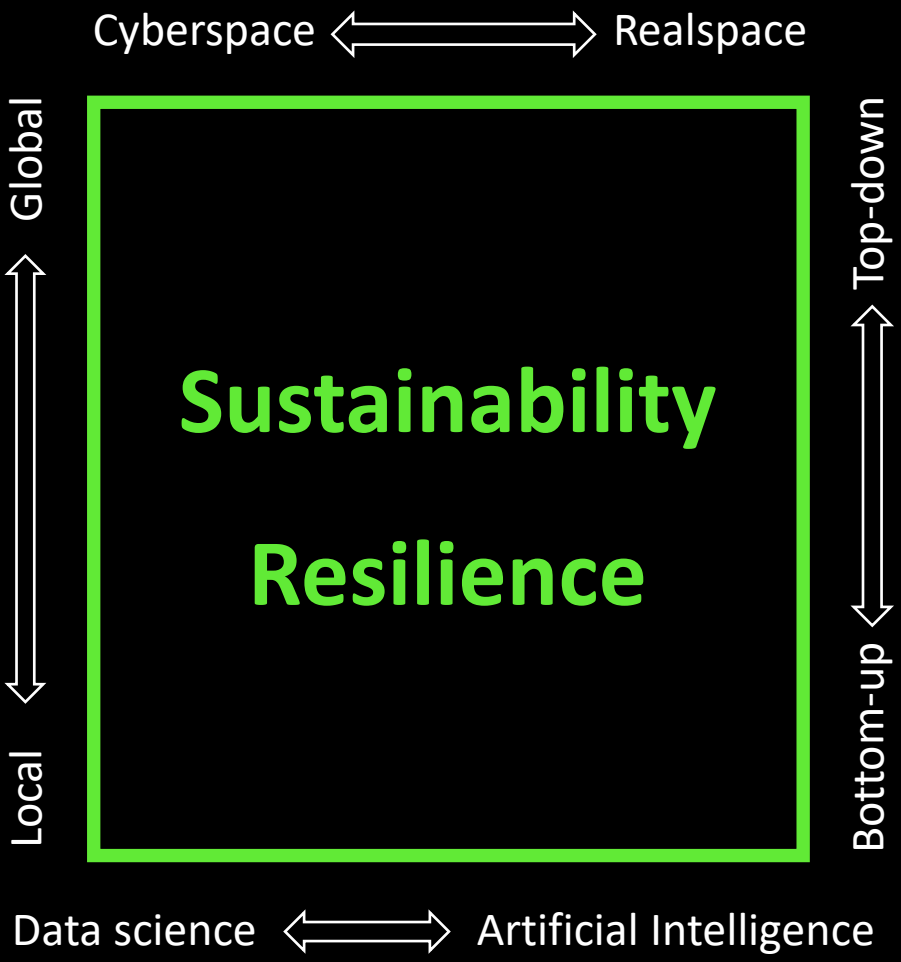
ACS efforts

Image Credit: slideplayer



ACS dreams

Li An of San Diego, USA
(21st century)

Who

What

When

Where

Why

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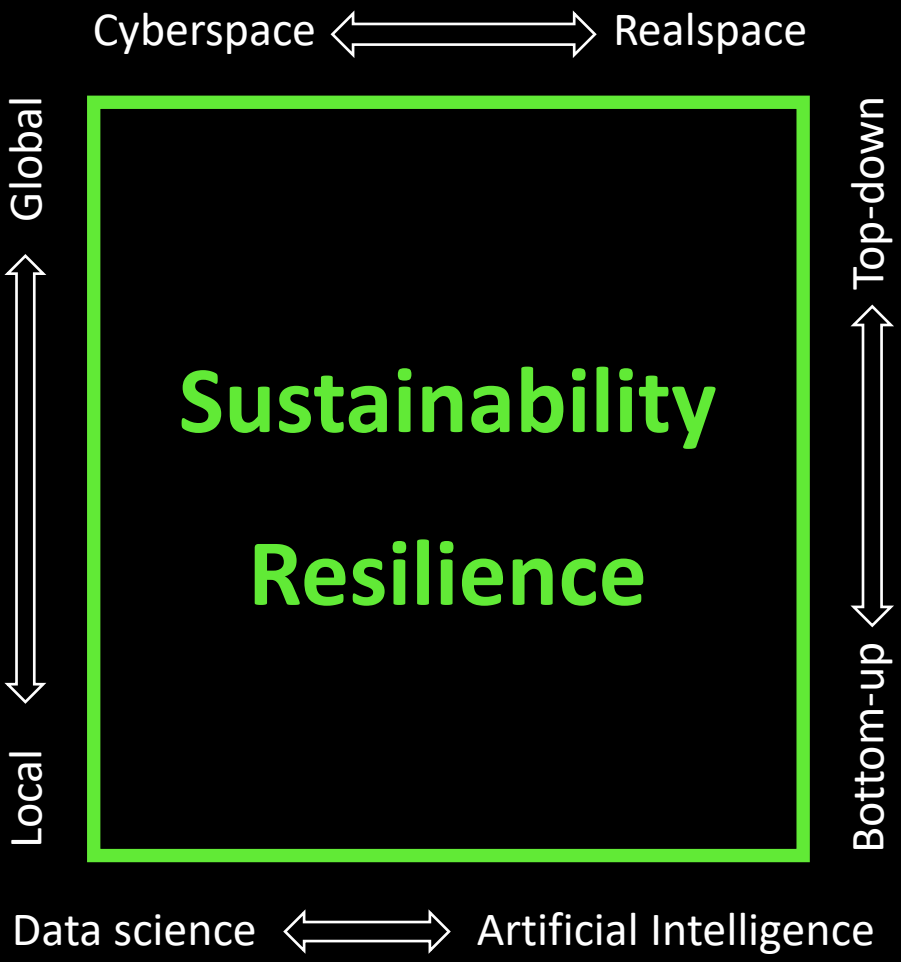
ACS efforts



Hold fast to dreams

Hold fast to dreams
For if dreams die
Life is a broken-winged bird
That cannot fly

Hold fast to dreams
For when dreams go
Life is a barren field
Frozen with snow

Author: Langston Hughes (1902-1967)

Thank you

- Research website http://complexities.org/
- Contact info anli@complexities.org