# Predictability in Complex Adaptive Systems

Gary Polhill

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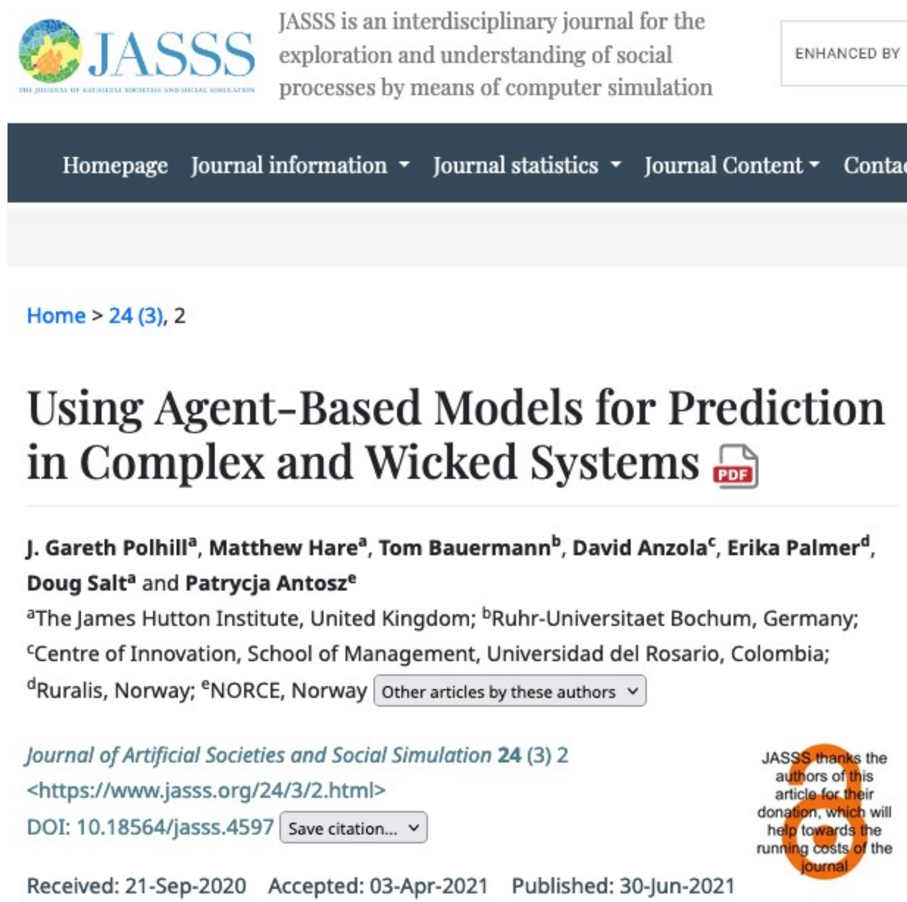
# Outline

- Prediction and Predictability
- Impossibility and Infeasibility
- Complexity and Complicatedness
  - Complexity
  - Asynchrony
  - Wickedness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## Using Agent-Based Models for Prediction in Complex and Wicked Systems

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*Journal of Artificial Societies and Social Simulation* **24** (3) 2
<https://www.jasss.org/24/3/2.html>
DOI: 10.18564/jasss.4597
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JASSS thanks the authors of this article for their donation, which will help towards the running costs of the journal

Received: 21-Sep-2020 Accepted: 03-Apr-2021 Published: 30-Jun-2021

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# Take-home messages

1. **Prediction in complex systems is theoretically possible, but pragmatically infeasible**
   - Typically
   - Under a specific definition of 'complex'
2. **Asynchrony adds exponentially to the infeasibility**
3. **Wickedness renders prediction largely irrelevant where it entails terminological transformation**

# Prediction

- Prediction
  - “the ability to reliably anticipate well-defined aspects of data that is not currently known to a useful degree of accuracy via computations using the model”
    - Edmonds et al. (2019, para. 2.4)
- Useful
  - Subjective criterion
  - Modality of usefulness:
    - Necessarily useful – all stakeholders care about predicted model state
    - Possibly useful – some stakeholders care
    - Necessarily *not* useful – no stakeholders care
  - Assume:
    - Each stakeholder cares about at least one model state

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## Different Modelling Purposes

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*Journal of Artificial Societies and Social Simulation* **22** (3) 6
<https://www.jasss.org/22/3/6.html>
DOI: 10.18564/jasss.3993 Save citation...

Received: 06-Sep-2018 Accepted: 08-Jun-2019 Published: 30-Jun-2019



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# Predictability

- Matching models:
  - A population of models that fit the empirical data
- Four kinds of predictability:
  - **Invariably predictable**: All matching models predict the same state
  - **Omissively predictable**: At least one state is not predicted by any matching model
  - **Asymmetrically unpredictable**: All states are possible, but different numbers of match models predict them
  - **Symmetrically unpredictable**: All states are possible; each having the same number of matching models
- Two scales
  - Individual: State spaces of individuals (e.g. agents)
  - System: State spaces of the whole system (population + environment)

Only one predicted outcome

We can rule out some outcomes

Anything can happen but not equally likely

Anything can happen with equal likelihood

# Predictability

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Necessarily useful at whole system level

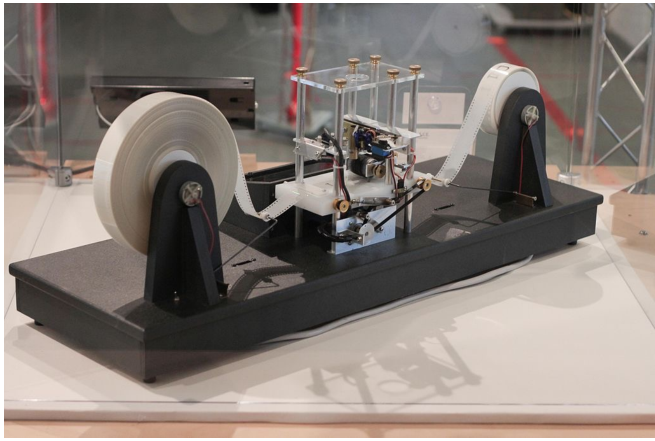
Possibly useful at individual level

Possibly useful at both levels

Necessarily *not* useful at both levels

# Impossibility and Infeasibility

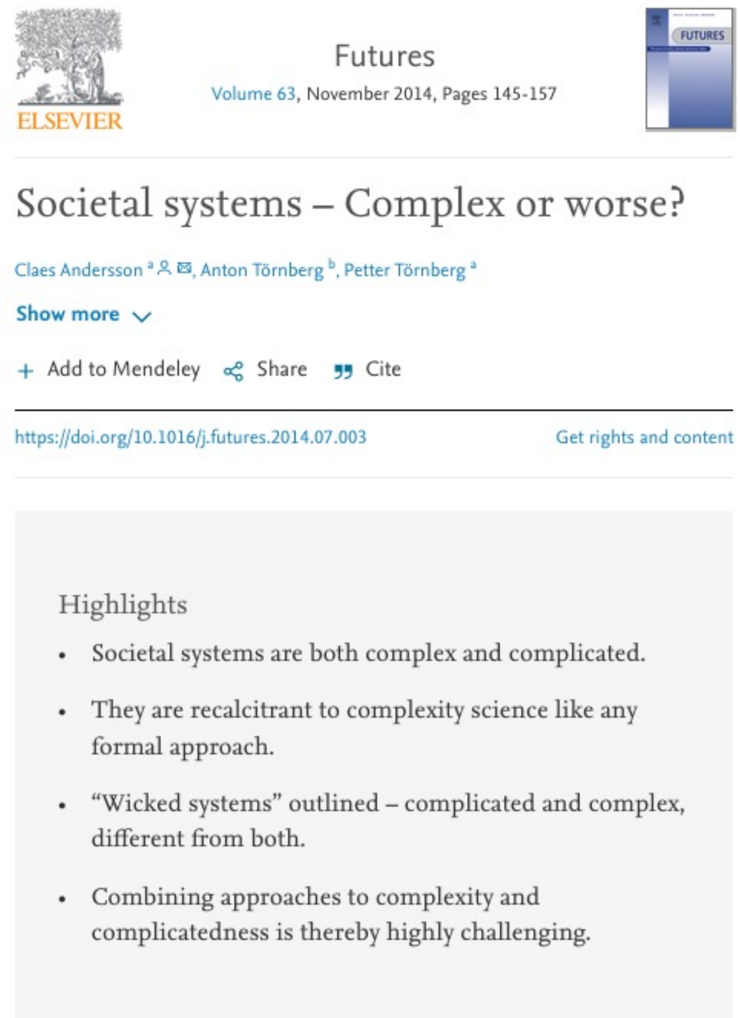
- Turing Machine (TM)
  - Basic theoretical construct in computer science
  - Finite set of internal states
  - Unbounded tape of cells
    - Finite alphabet of symbols, one per cell
  - Transition table
    - Internal state + symbol read from tape → new state + symbol to write + move tape L or R
- A TM can be built to do anything computable
  - Church-Turing thesis
- Impossible
  - Can't design a TM to do it
- Infeasible
  - Can design a TM, but:
    - Might require more atoms to build it than there are in the universe (too much memory)
    - Might require more time to run the program than the life of the universe (too much time)



Model of a Turing Machine

# Complexity and Complicatedness

- Complex
  - Santa Fe Institute conceptualization
    - "Large networks of components with no central control and simple rules of operation"
      - Mitchell (2009, p. 13)
    - Andersson et al. (2014) point out that those components are of the same type
- Complicated
  - Lots of different kinds of component
  - Decomposable functionality
- 'Wicked' (Andersson et al. 2014)
  - Complex and complicated
  - High uncertainty



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Futures

Volume 63, November 2014, Pages 145-157

## Societal systems – Complex or worse?

Claes Andersson [a], Anton Törnberg [b], Petter Törnberg [a]

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Highlights

- Societal systems are both complex and complicated.
- They are recalcitrant to complexity science like any formal approach.
- "Wicked systems" outlined – complicated and complex, different from both.
- Combining approaches to complexity and complicatedness is thereby highly challenging.

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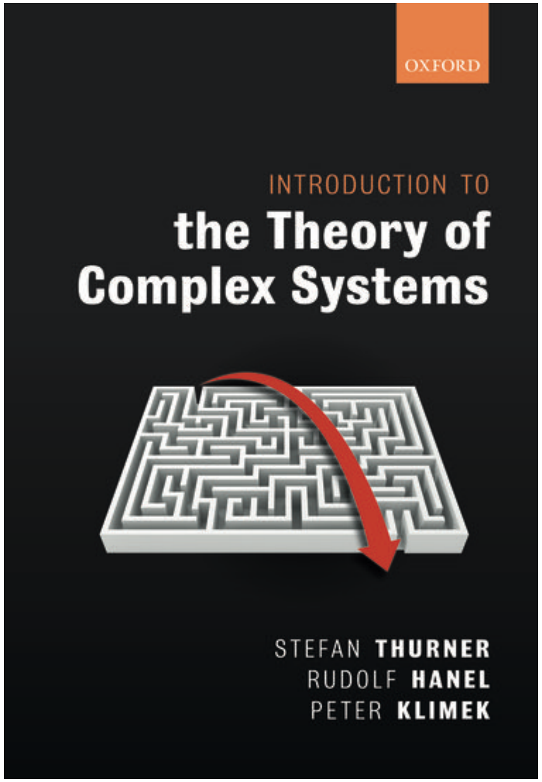
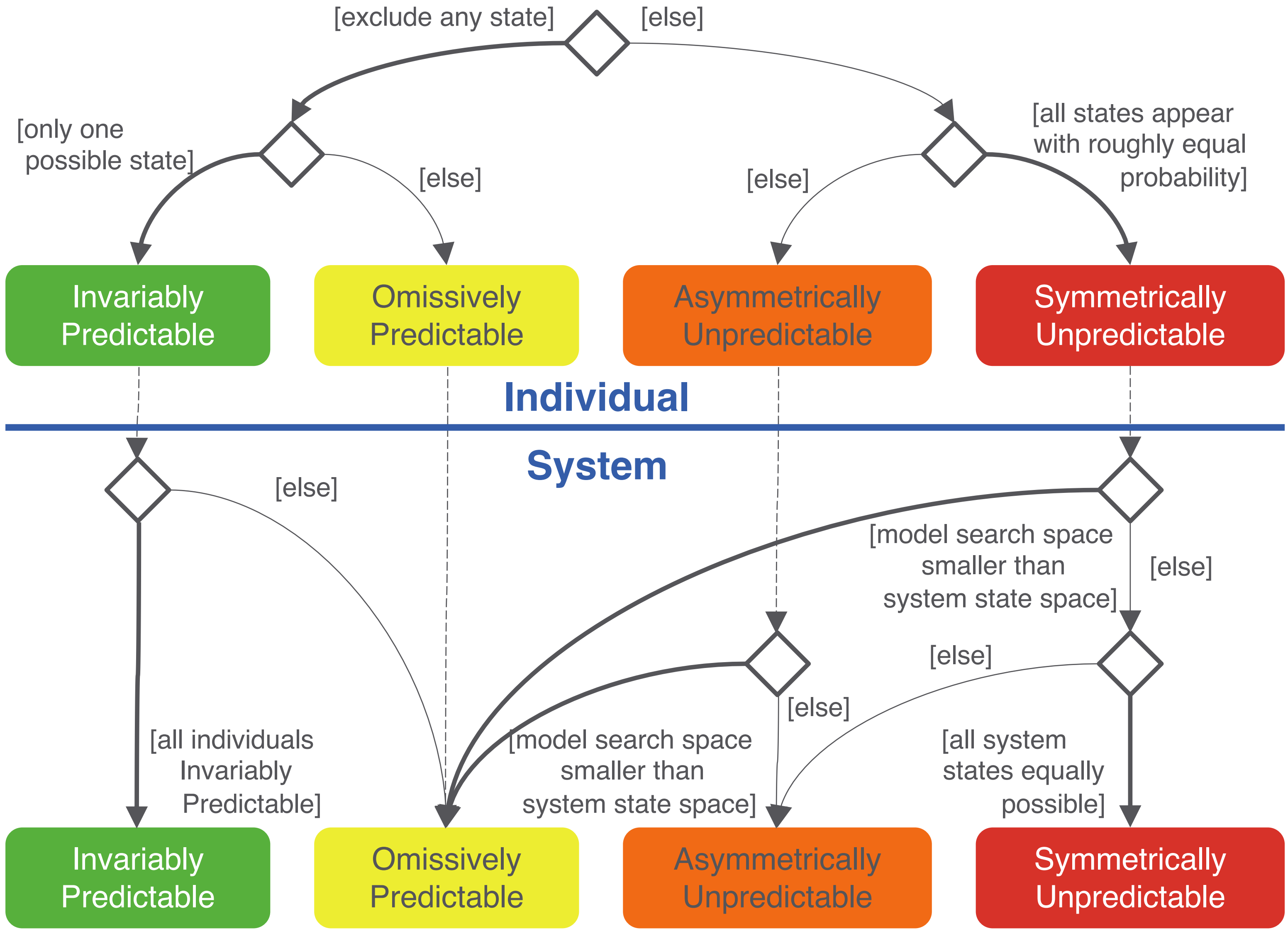
# Mathematical Issues in Complex Systems

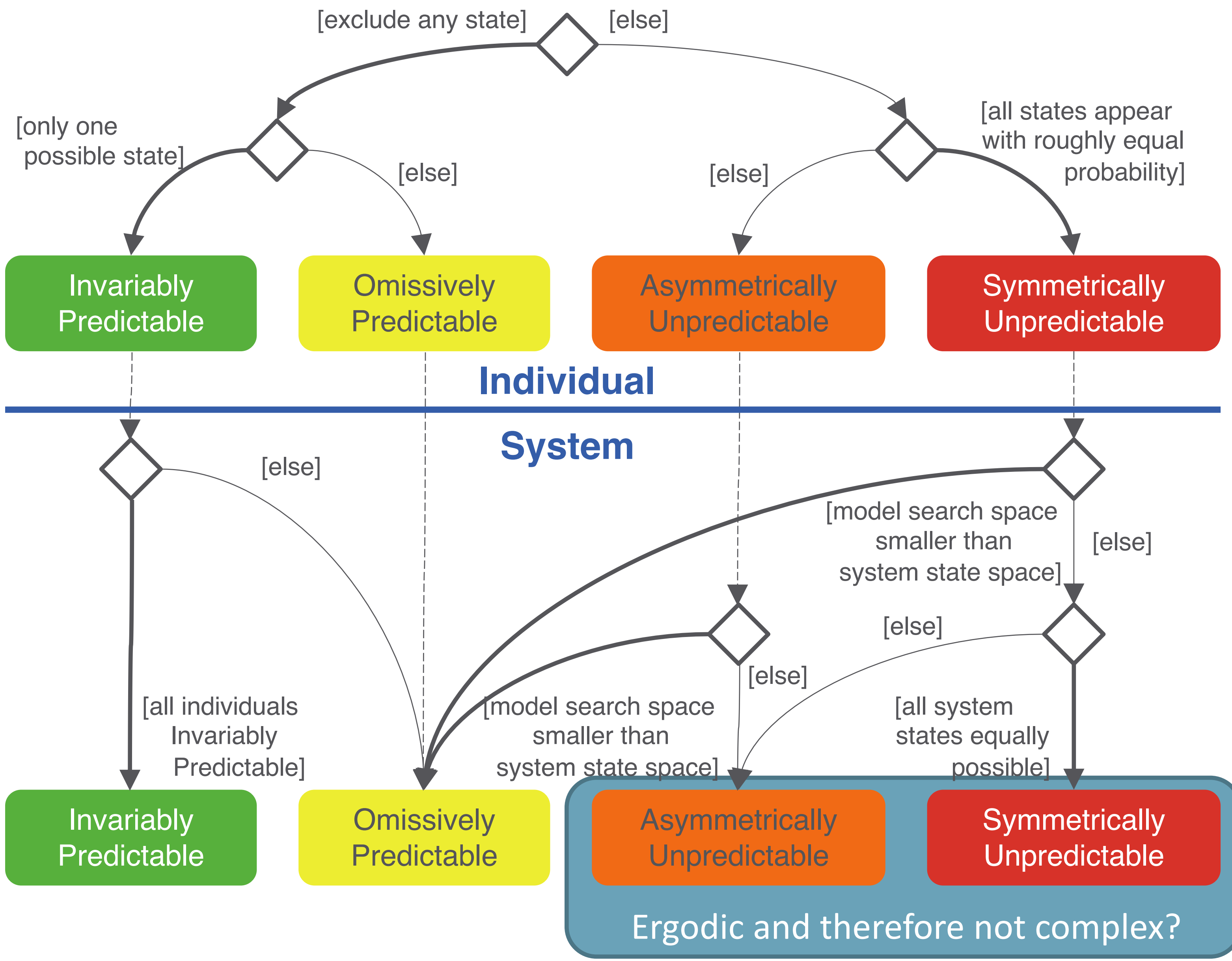
- Nonlinearity (p. 8)
- Non-ergodicity (p. 350)
  - Path dependence means law of large numbers does not hold (p. 85)
- Non-Markovian (p. 350)
- Out-of-equilibrium (p. 317)



# Complex systems and predictability



# Complex systems and predictability



# Are complex systems really predictable?

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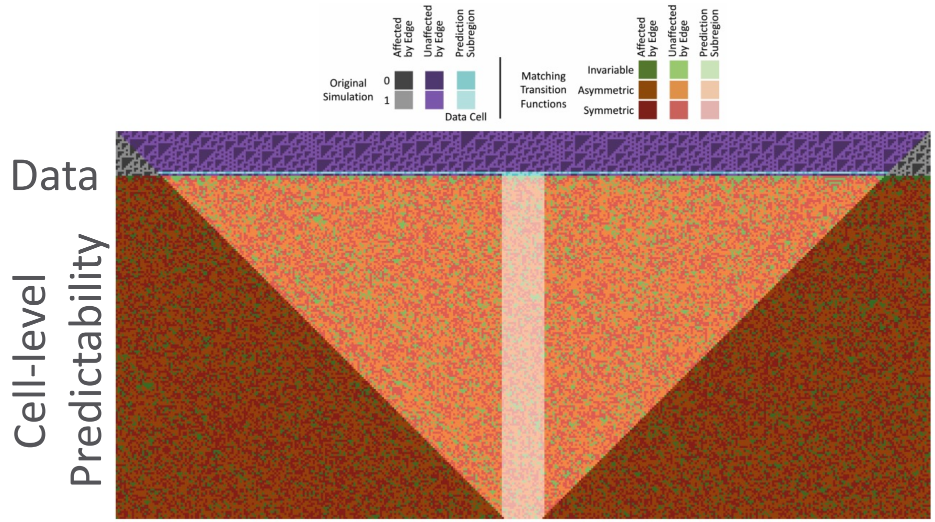
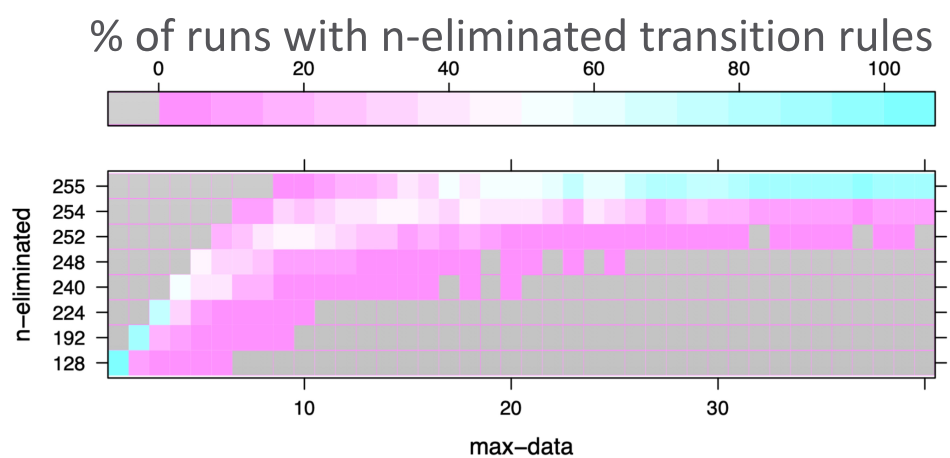
- Example of cellular automata (CA)
  - Defined by
    - Cell state alphabet
    - Neighbourhood
    - Cell transition rule
- Certain transition rules classed as ‘complex’
  - Wolfram (1984): Class 4 (complex) CAs unpredictable except by simulation
  - Cook (2004): Rule 110 elementary CA capable of universal computation
- CA data generator
- Search transition rule space
- Run rules that match the data




‘Elementary’ Cellular Automaton
(Four matching transition rules)



# But…

- Predictability based on transition rule space search
  - Polhill et al. (2021) paper shows that this space is finite for CAs, and even asynchronous TMs
    - Assumes knowledge of alphabet and for TMs, the number of internal states
  - **So, not impossible…**
- Transition rule space can be *very* big
  - *Exhaustive* search infeasible
    - E.g. ~$10^{154}$ possibilities for family of 2D CAs to which Conway's Game of Life belongs
  - **…but infeasible**

# Asynchrony

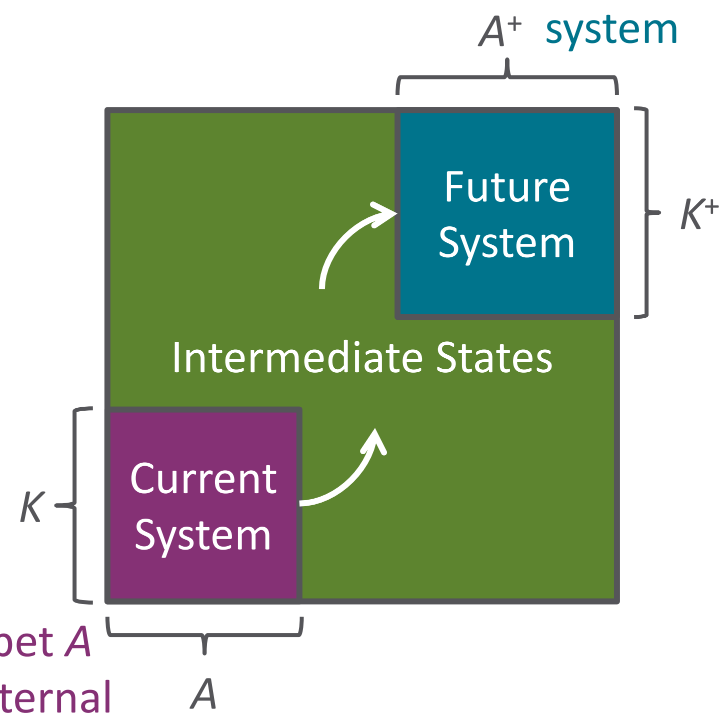
```
ask turtles [
  forward [pcolor] of patch-here
  ask patch-here [
    set pcolor [color] of myself
  ]
]
```

- System state is vector of states of components
  - Complex (and complicated) systems have lots of components
- Scheduling determines how system state at time *T* is computed from state at *T* – 1
  - Which component calculates its behaviour when, and using which data?
- What if scheduling is non-computable?
  - Even if all matching models agree about state at time *T*, to calculate state at time *T* + *n*:
    - Have to explore all possible orderings of components behaving
    - Exponential in *n* and number of components
    - Partial computability (if unknown) means we might explore options for ordering that would not happen
- **Asynchrony adds exponentially to the problem of prediction**

# Wickedness

- Andersson & Törnberg (2018) refer to ontological uncertainty in wicked systems
  - “emergence of qualitative novelty”
- New vocabulary in transformed systems
  - No existing data uses that vocabulary
  - For each model that fits the data *K* and *A*:
    - Can include (tentative) new vocabulary $K^+$ and $A^+$
    - But every possible transition rule involving $K^+$ and $A^+$ will fit!
    - All future states then equally likely
      - Symmetric unpredictability
      - Necessarily *NOT* useful
- **In wicked systems, prediction is useless as the system evolves away from the data’s vocabulary**
  - N.B. Some definitions of complexity would include this kind of evolution as a feature

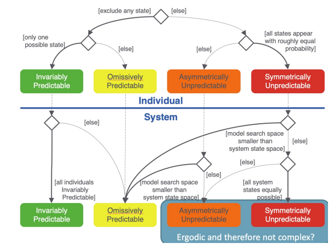
Alphabet $A^+$ and internal states $K^+$ of transformed system

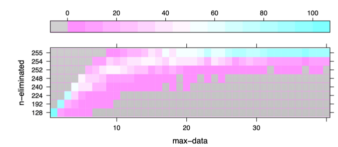



Alphabet *A* and internal states *K* of empirical data

# Conclusion

- When we think about different kinds of predictability, complex systems should be at least omissively predictable because they are non-ergodic
- **However, exhaustively searching the space of possible transition functions is infeasible for all but the simplest cellular automaton**
- **Asynchrony makes computing the prediction itself infeasible due to combinatorial explosion in options needing to be explored**
- **Evolution of systems away from vocabulary used for observed data makes prediction useless because all future states are equally likely from matching models**

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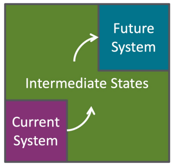

**Thanks** to my colleagues:
Matt Hare, Tom Bauermann, David Anzola, Erika Palmer, Doug Salt and Patrycja Antosz

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Agent-based modelling work at The James Hutton Institute has been funded by the Scottish Government, the European Union, the Macaulay Development Trust, the Economic and Social Research Council, and the Research Council of Norway