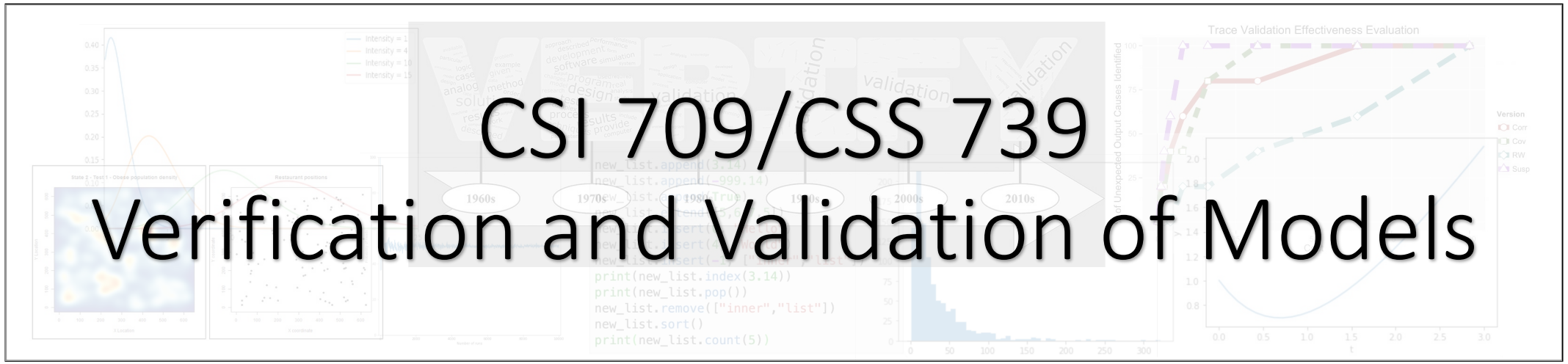

Verification and Validation of Agent-Based Models

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GEORGE MASON UNIVERSITY

Center for Social Complexity

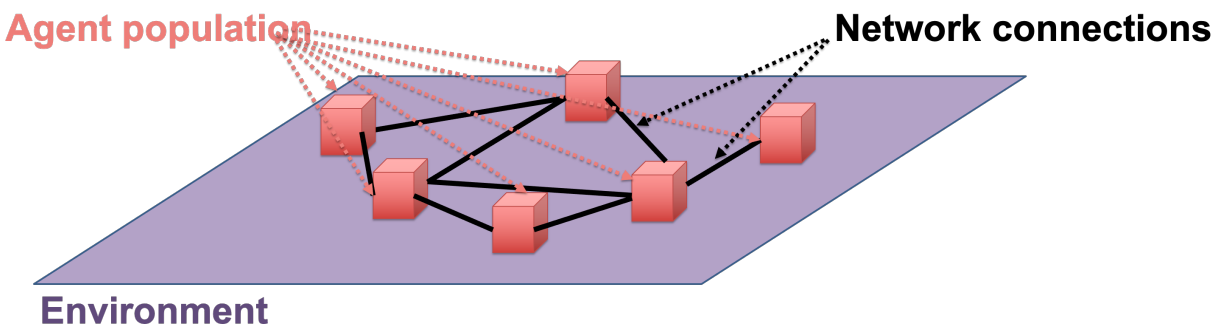
Introductory lecture in a nutshell

- What is an Agent-Based Model (ABM)
- To what extent ABMs require special treatment for verification and validation (V&V)
- A survey of ABM V&V techniques
  - High level findings
  - Selected techniques

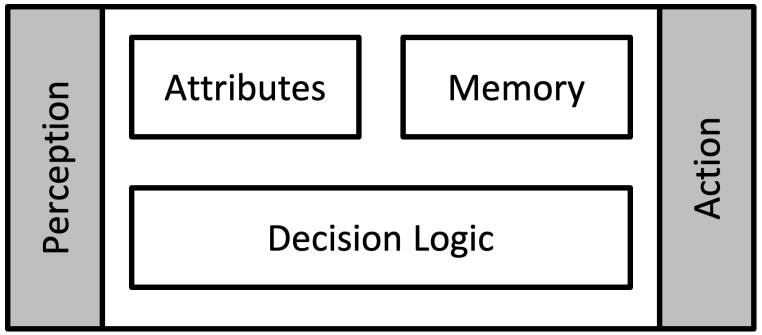
Agent-based model (ABM)

- A computational model that represents a system in terms of its ***interacting*** individual decision-making units called ***agents*** that are situated in an ***environment*** and possibly connected through a ***network***.

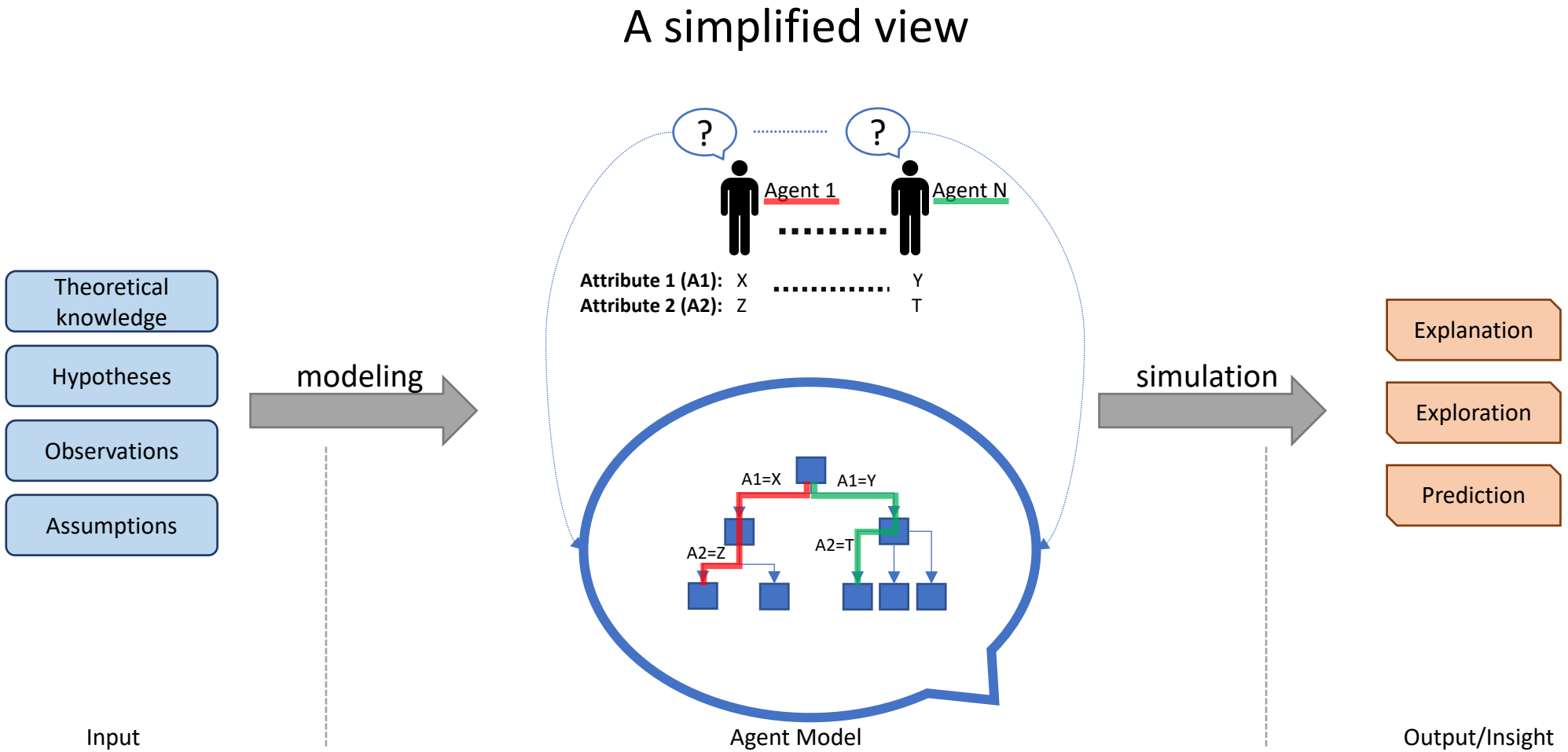
An agent-based model illustration



Structure of a typical agent

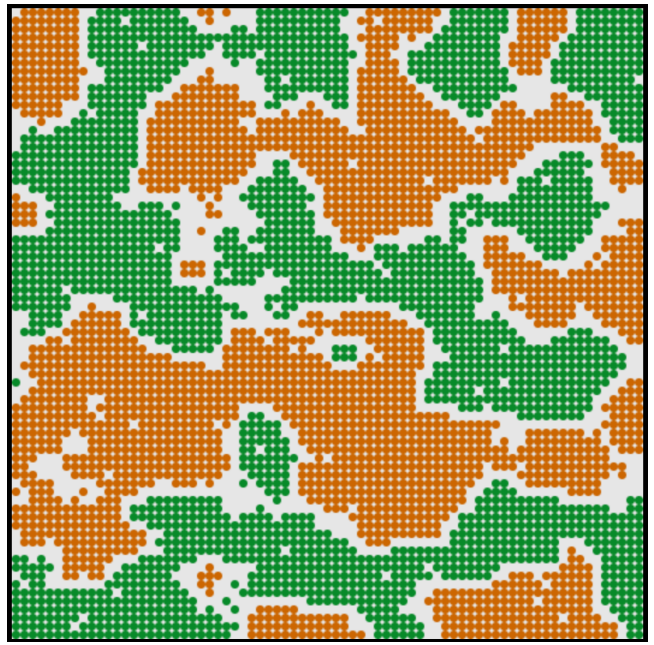


Agent-based modeling



Classical ABMs

Segregation



Sugarscape

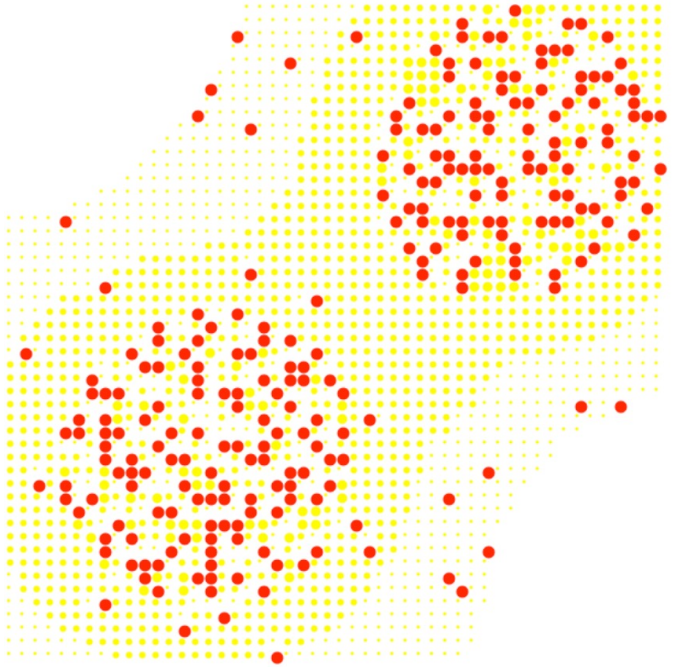
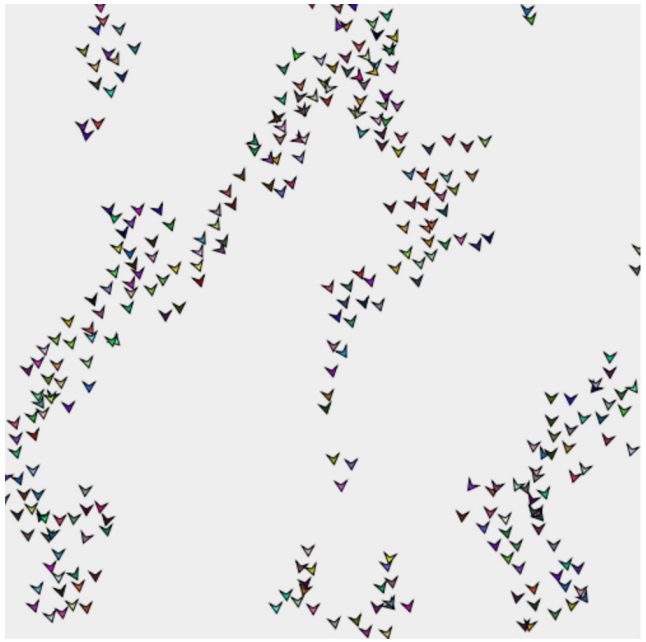


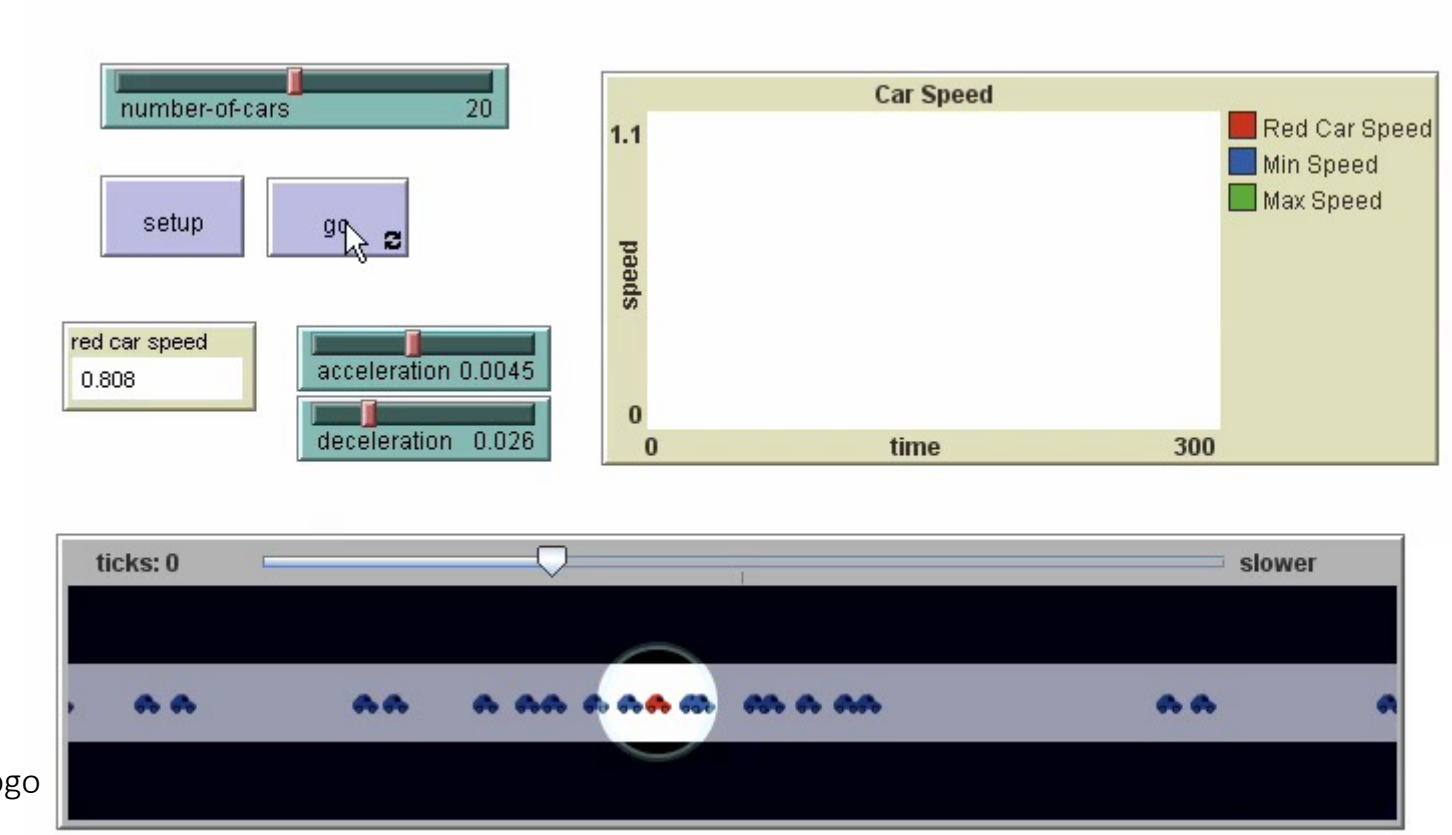
Figure source: Bigbee, A., Cioffi-Revilla, C., & Luke, S. (2007). Replication of Sugarscape using MASON. In Agent-Based Approaches in Economic and Social Complex Systems IV (pp. 183-190). Springer, Tokyo.

Boids



ABM Example: Traffic shockwave jam

- Example:
- Models the movement of cars on a road.
- Each car follows a simple set of rules:
  - If there's a car close ahead, it slows down.
  - If there's no car ahead, it speeds up.
- Demonstrates how traffic jams can form without any obvious incident.
- Simple rules can explain phenomena.



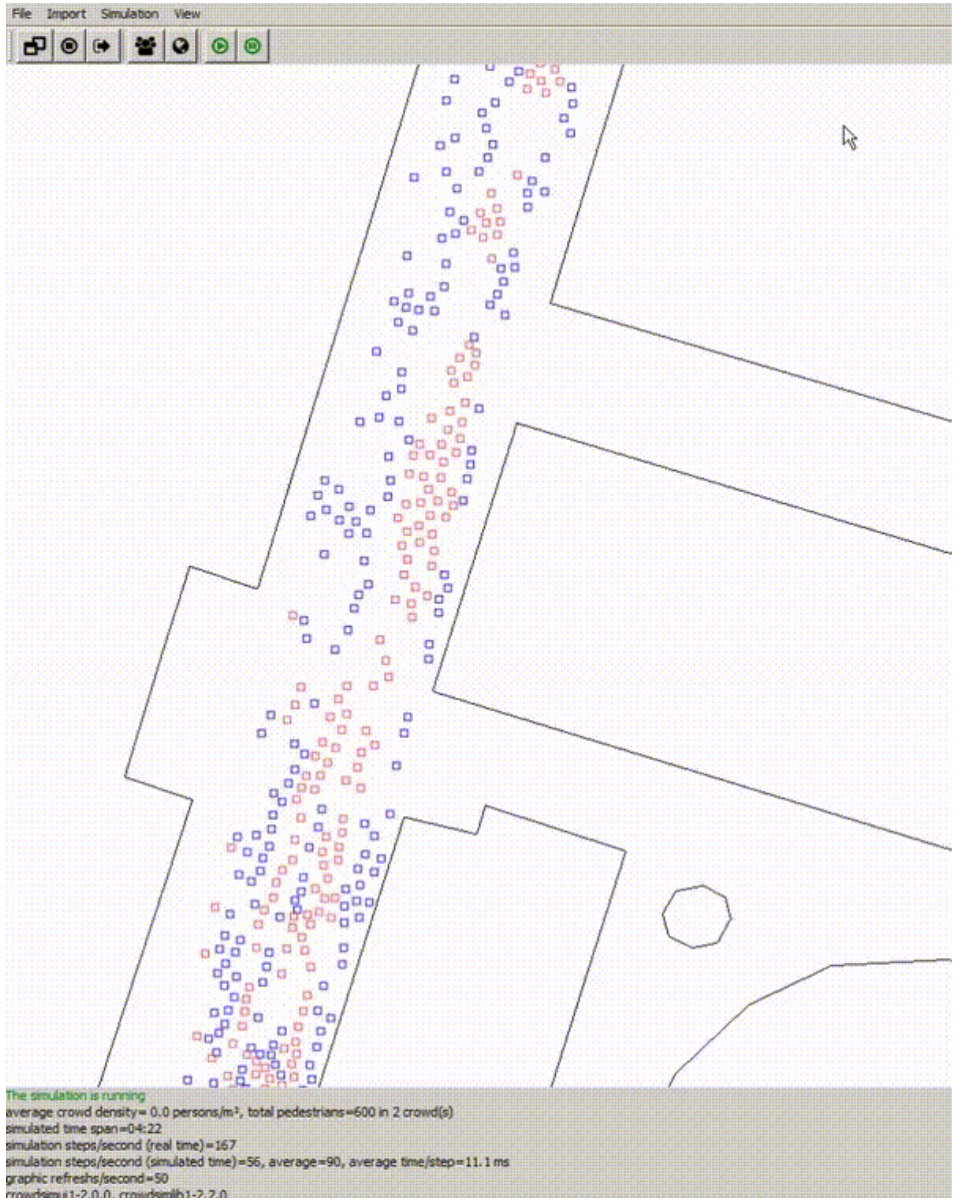
Source: NetLogo

Traffic shockwave jam in real-world

- 22 cars equally spaced on a 230m single lane circle.
- Drivers asked to cruise steadily at 30km/h.
- 1st traffic moved freely.
- Disturbances/clusters soon appear.
- Causing cars to slow/stop.
- Cars at front of cluster can accelerate at 40km/h.
- But these join another jam.

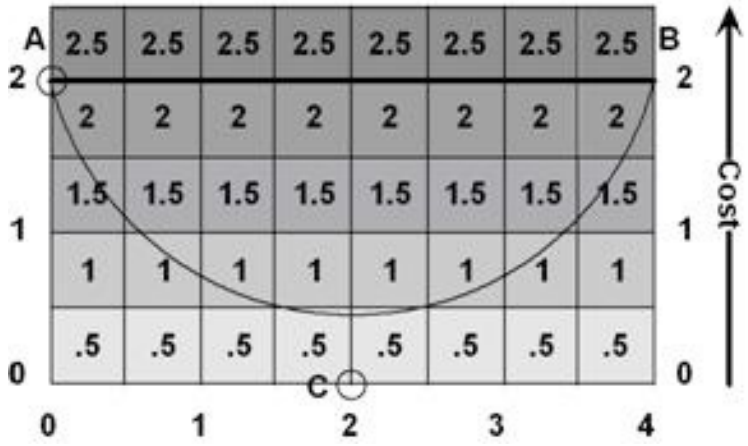
Source: http://www.youtube.com/watch?v=Suugn-p5C1M
New Scientist Article: http://technology.newscientist.com/article/dn13402

ABM Example: Pedestrian movement

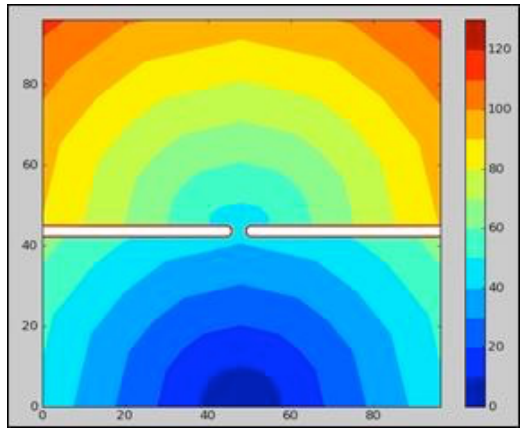


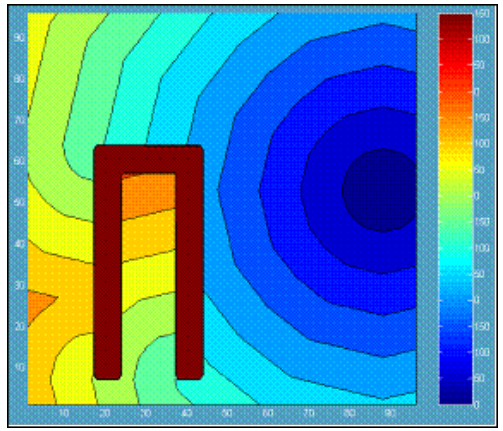
Source: https://twitter.com/stefanhahmann/status/1082213811497635846

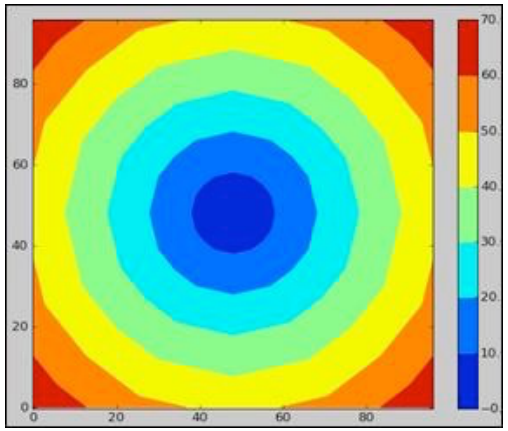
Direction of pedestrian movement: cost surface



- Agents move to lower value cell
- Decision rules are needed if 2 agents want the same cell

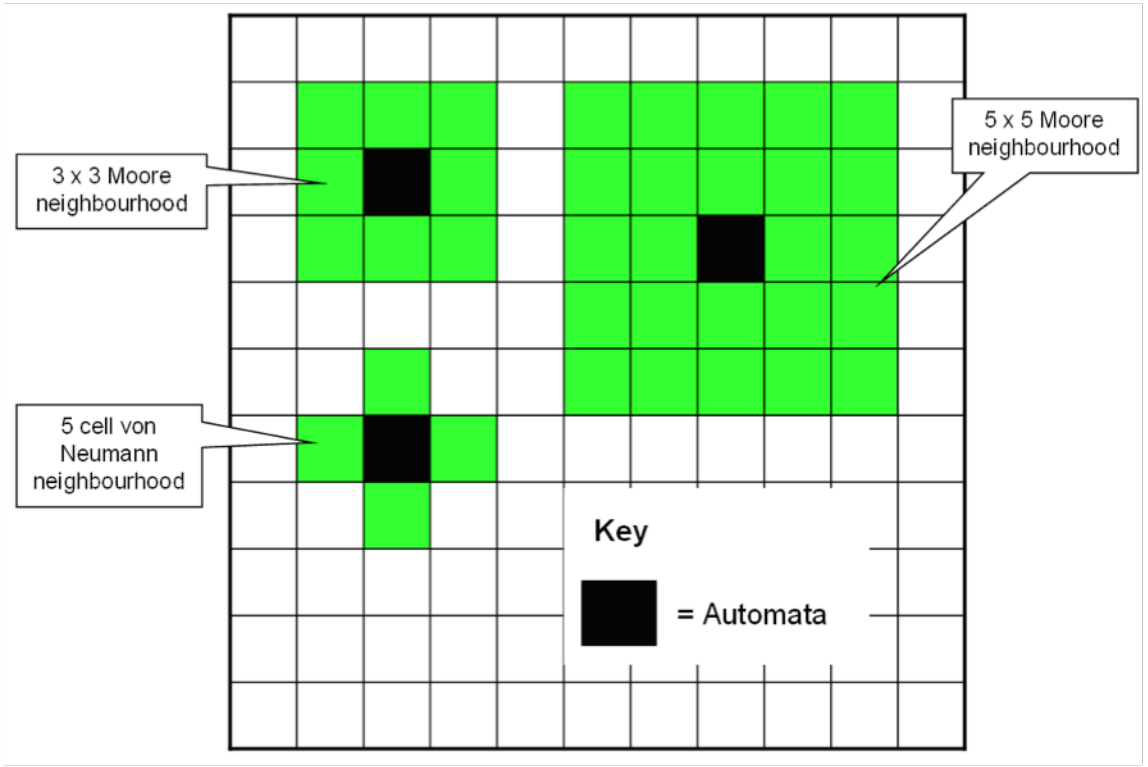






Source: de Smith, M.J., Goodchild, M.F. and Longley, P.A. (2009), ***Geospatial Analysis: A Comprehensive Guide to Principles, Techniques and Software Tools (3rd Edition)***, The Winchelsea Press, Winchelsea, UK.

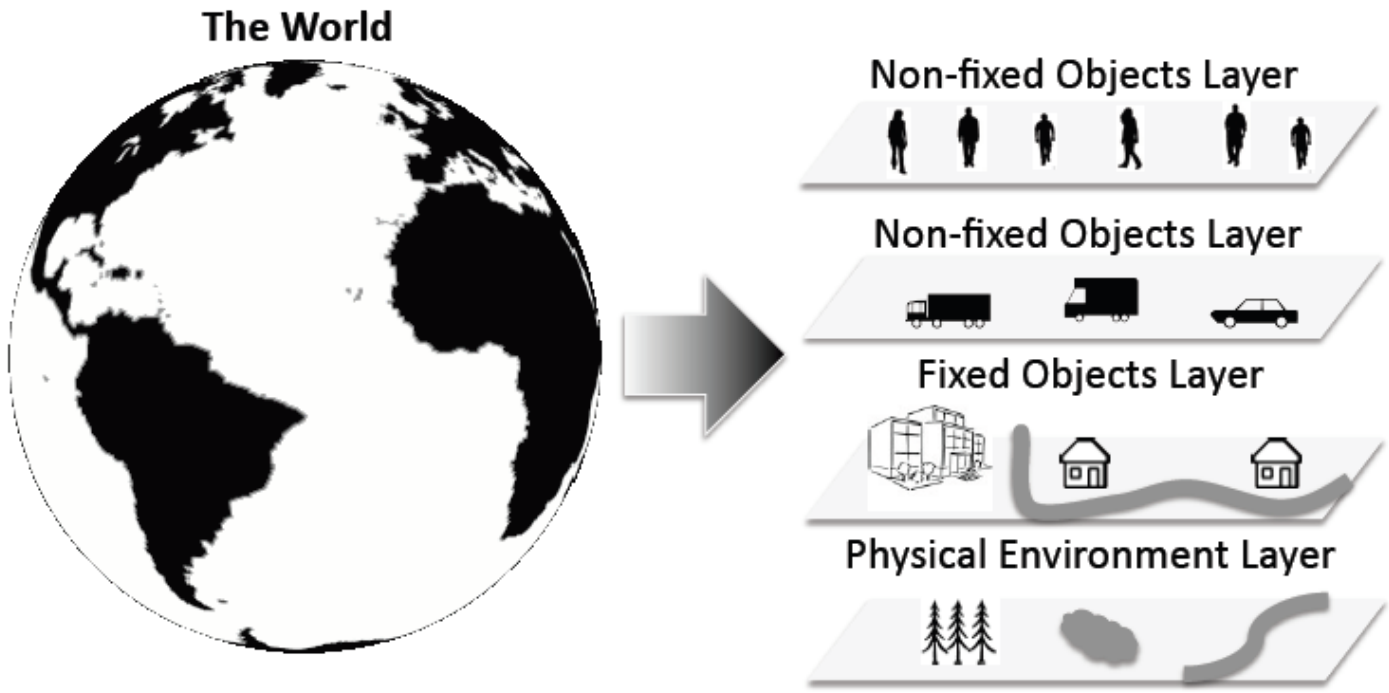
Space representation in ABMs: Grid



- Neighborhood structure
  - Typically Moore (8-way) or von Neumann (4-way) or variations of these.

Crooks, A.T. (2017), Cellular Automata, in Richardson, D., Castree, N., Goodchild, M. F., Kobayashi, A. L., Liu, W. and Marston, R. (eds.), The *International Encyclopedia of Geography: People, the Earth, Environment, and Technology*, Wiley Blackwell. DOI: 10.1002/9781118786352.wbieg0578.

Space representation in ABMs: GIS



- GIS represent the world as a series of **layers** and **objects** of different types.
  - All can be geo-referenced and translated into an ABM.

Source: Andrew Crooks – CSS 645 Slides

Example: two models of disease spread

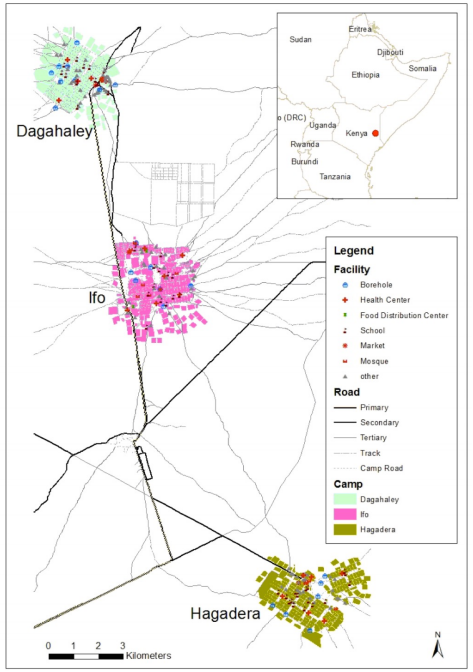
Mathematical model

$$\frac{dS}{dt} = -\frac{\beta I S}{N},$$

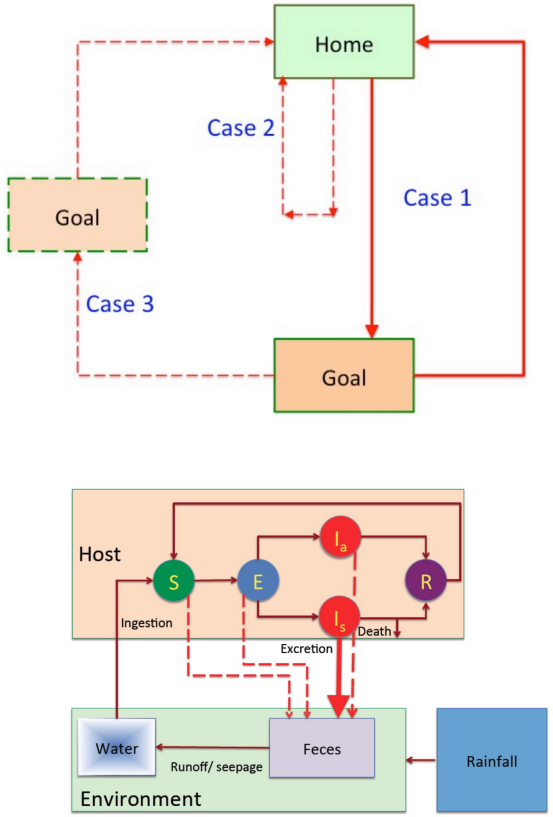
$$\frac{dI}{dt} = \frac{\beta I S}{N} - \gamma I,$$

$$\frac{dR}{dt} = \gamma I,$$

...

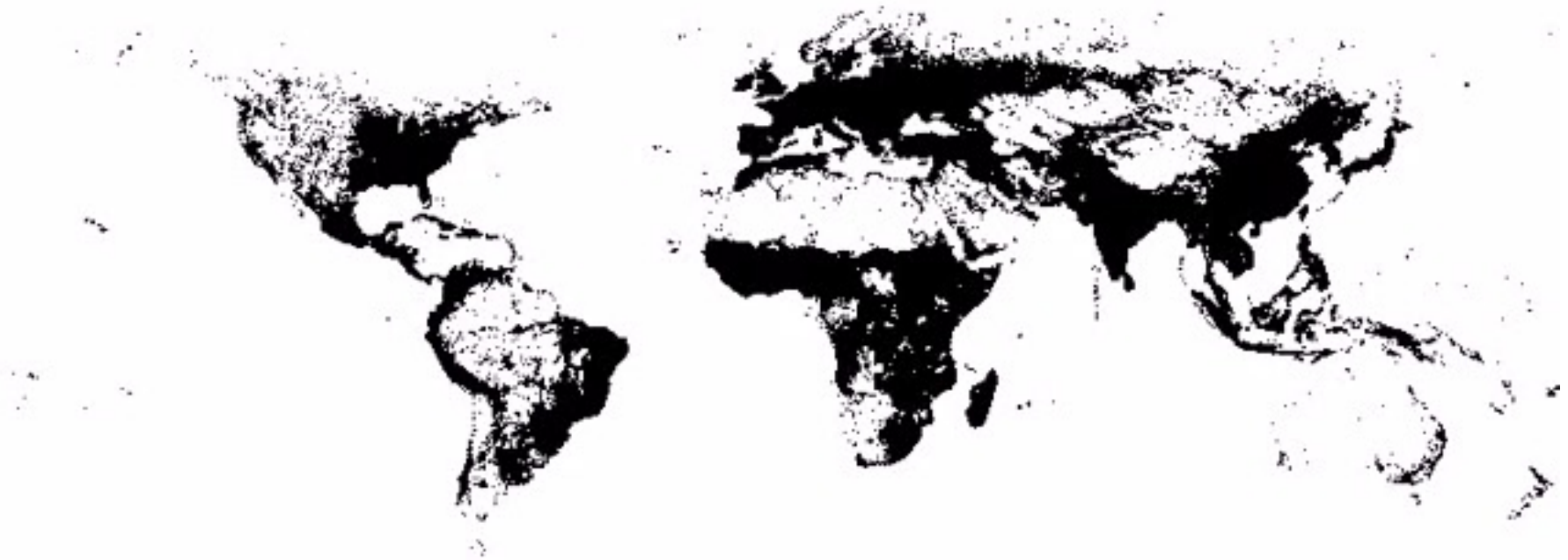


ABM



Crooks, A., & Hailegiorgis, A. (2013, December). Disease modeling within refugee camps: A multi-agent systems approach. In *2013 Winter Simulations Conference (WSC)* (pp. 1697-1706). IEEE.

Global-Scale Agent-Based Models of Disease Transmission



Video source: https://www.youtube.com/watch?v=z4ofZafC69U

Paper: Parker, J., & Epstein, J. M. (2011). A distributed platform for global-scale agent-based models of disease transmission. *ACM Transactions on Modeling and Computer Simulation (TOMACS)*, *22*(1), 1-25.

Agent cognition

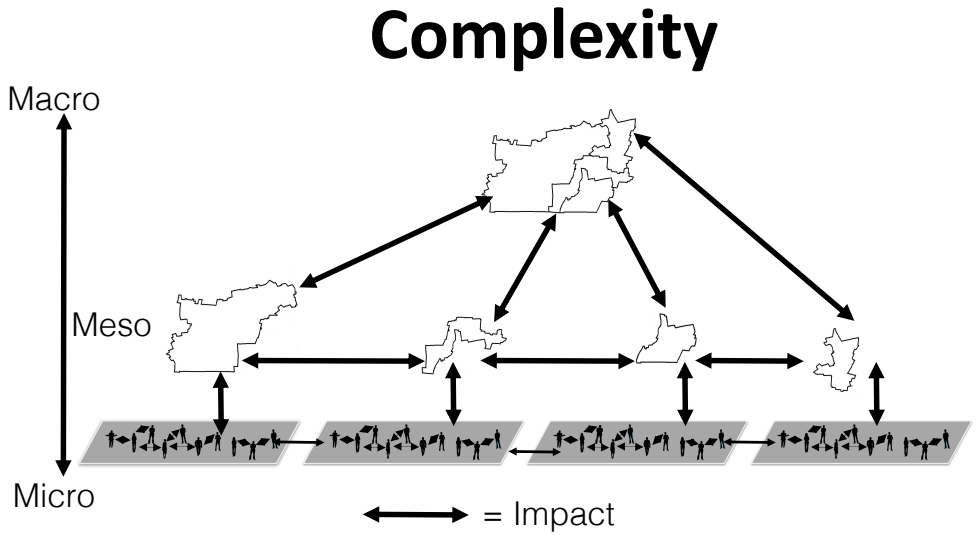
- Agents act according to a model of **cognition**:
  - Range from ***stimulus response*** through to proactive strategy
    - e.g. follow a set of spatial paths to achieve a goal within a certain constraint (e.g. time), when exiting a building during an emergency.

- Many of the more 'traditional' models use **rational choice theory**:
  - Assumes *perfect information* and *perfect rationality* -solving complex equations, *unfettered access to information*, foresight, and infinite analytical ability etc.
  - This may not be appropriate in the presence of spatial interdependencies and feedbacks.

- **Bounded rationality** (in some form) is generally more useful and realistic:
  - Involves discrete and evolving choices that move the agent towards its goal (i.e. limited information)

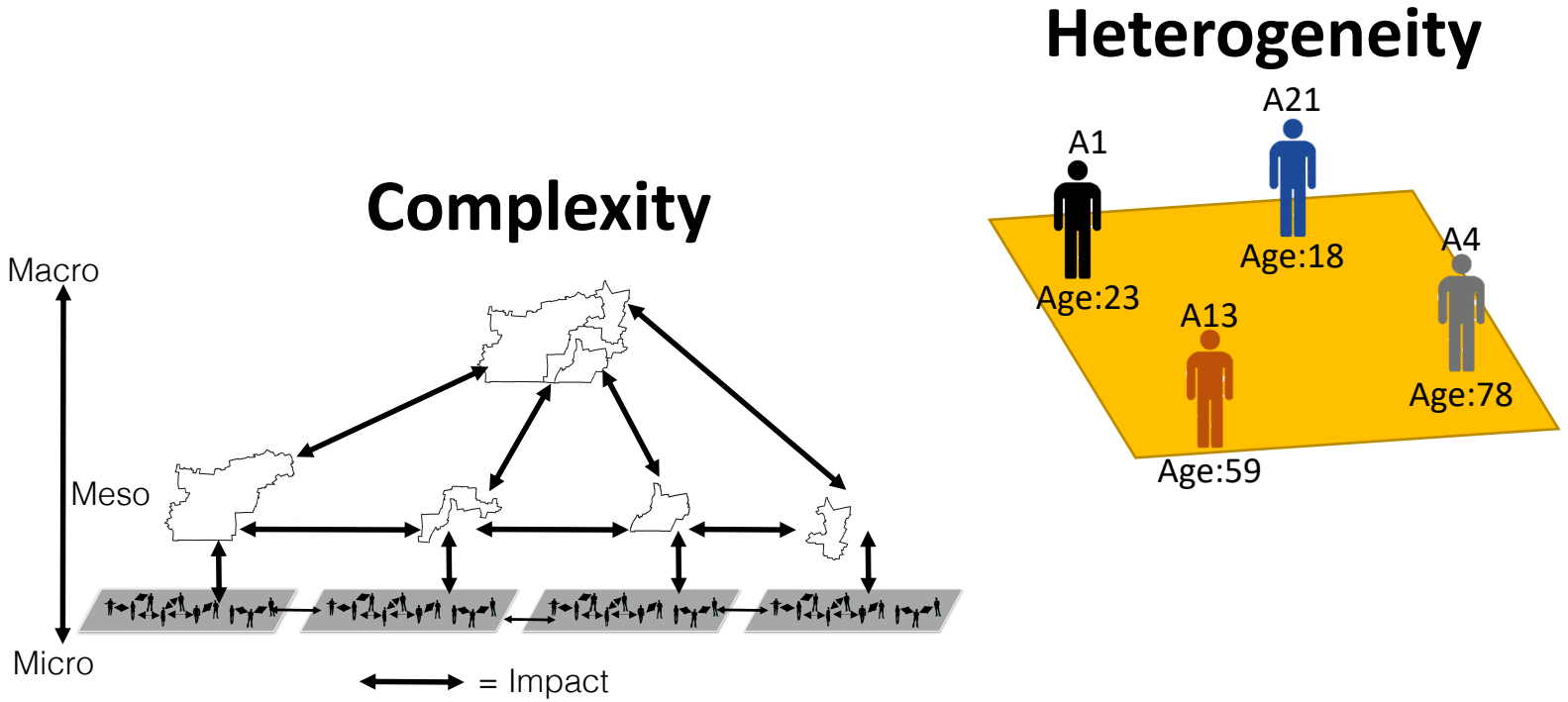
Source: Andrew Crooks – CSS 645 Slides

What is special about ABMs?



Source: Crooks, A.T., Malleson, N., Manley, E. and Heppenstall, A.J. (2019), ***Agent-based Modelling and Geographical Information Systems: A Practical Primer***, Sage, London, UK.

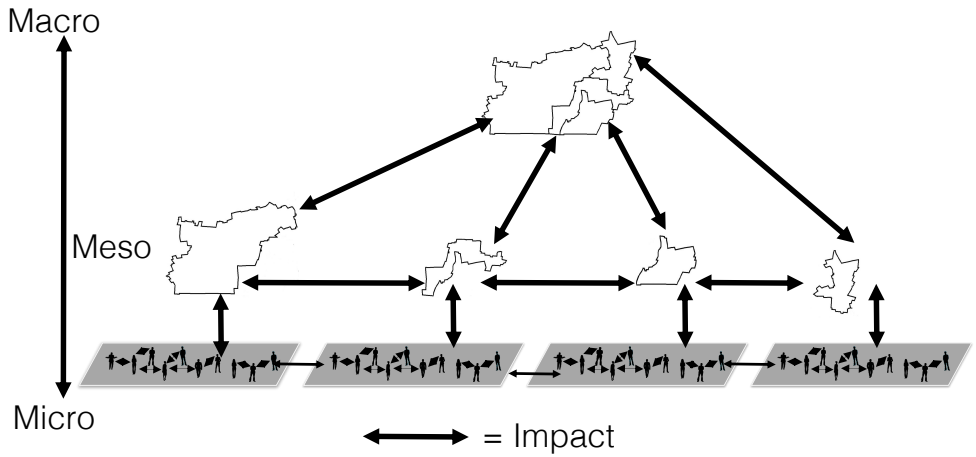
What is special about ABMs?



Source: Crooks, A.T., Malleson, N., Manley, E. and Heppenstall, A.J. (2019), ***Agent-based Modelling and Geographical Information Systems: A Practical Primer***, Sage, London, UK.

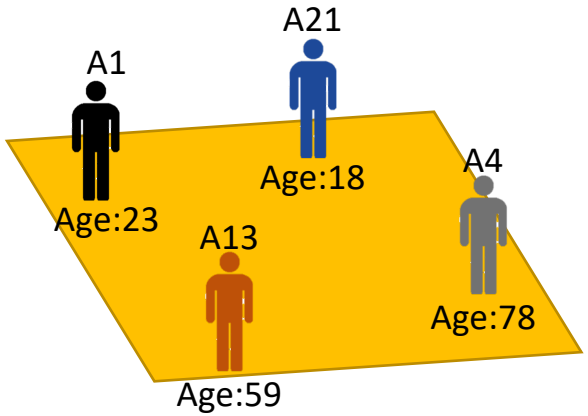
What is special about ABMs?

Complexity

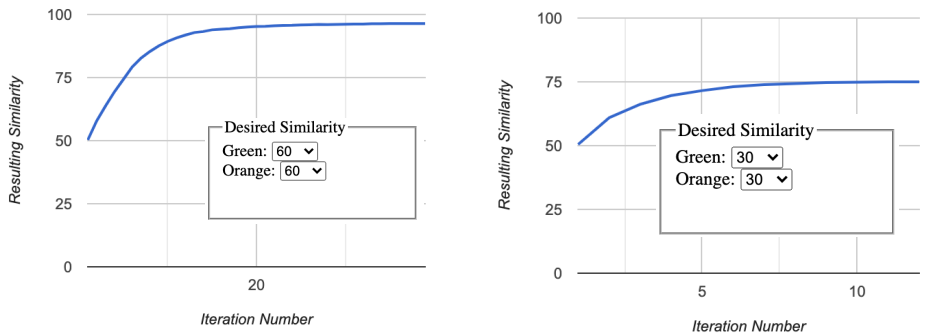


Source: Crooks, A.T., Malleson, N., Manley, E. and Heppenstall, A.J. (2019), ***Agent-based Modelling and Geographical Information Systems: A Practical Primer***, Sage, London, UK.

Heterogeneity

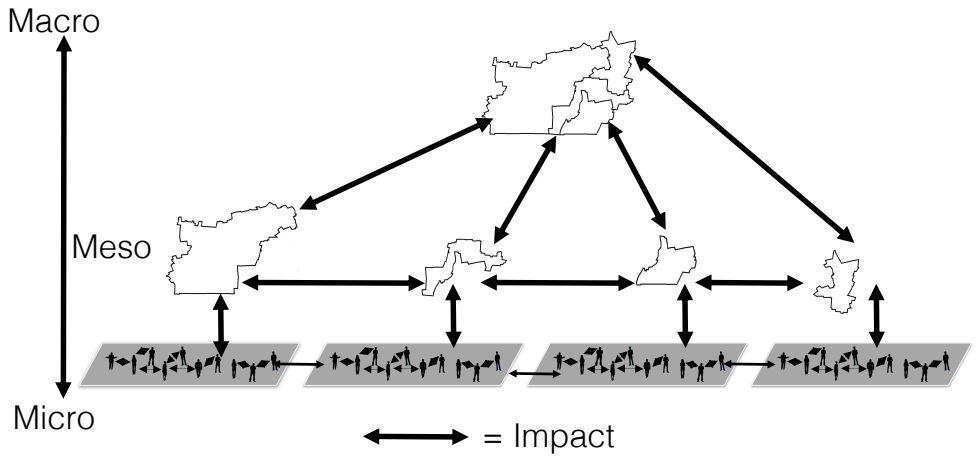


Non-linearity

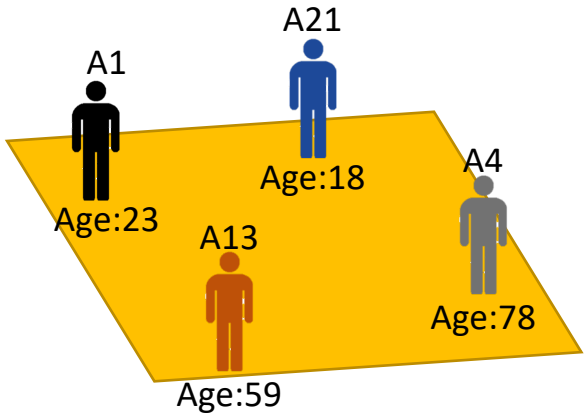


What is special about ABMs?

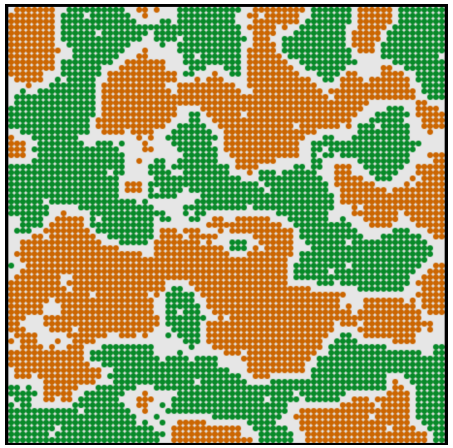
Complexity



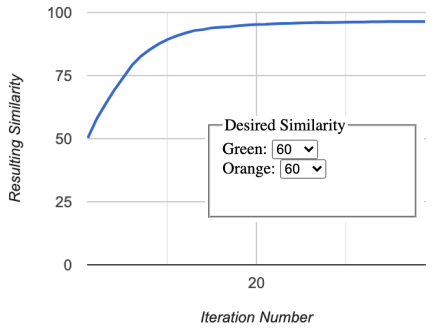
Heterogeneity

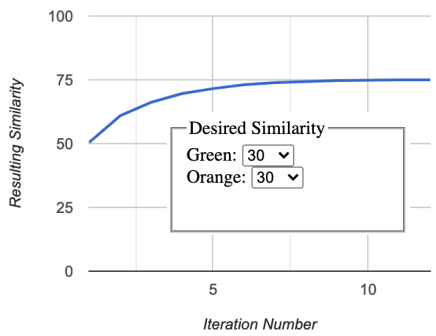


Emergence



Non-linearity





Source: Crooks, A.T., Malleson, N., Manley, E. and Heppenstall, A.J. (2019), *Agent-based Modelling and Geographical Information Systems: A Practical Primer*, Sage, London, UK.

Agent-based model reporting protocols

Designed for two purposes

1. How does one share and disseminate the model
   - i.e., share models to those we seek to influence or think such models will inform
   - Methods include visualization of models, decision support systems, online laboratories etc.

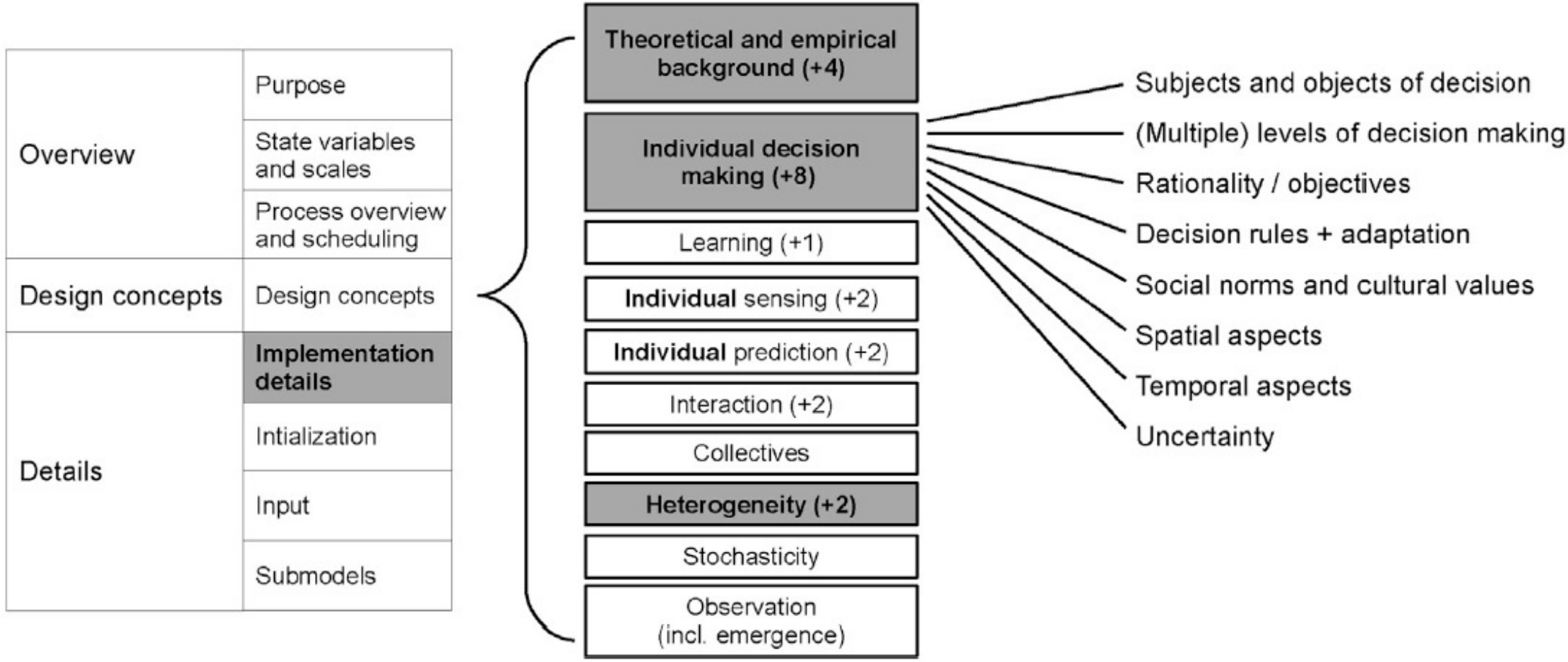
2. How do we communicate models to other scientists
   - i.e., for replication and experiment

The ODD protocol

Overview	Purpose
	Entities, state variables and scales
	Process overview and scheduling
Design concepts	Design concepts
Details	Initialization
	External input
	Submodels

Grimm, V., Berger, U., Bastiansen, F., Eliassen, S., Ginot, V., Giske, J., ... & DeAngelis, D. L. (2006). A standard protocol for describing individual-based and agent-based models. *Ecological modelling*, *198*(1-2), 115-126.

ODD with human decision-making



Müller, B., Bohn, F., Dreßler, G., Groeneveld, J., Klassert, C., Martin, R., Schlüter, M., Schulze, J., Weise, H. and Schwarz, N. (2013), 'Describing Human Decisions in Agent-based Models – ODD + D, An Extension of the ODD Protocol', *Environmental Modelling and Software*, 48: 37-48.

ODD and V&V of ABMs

- ODD is not built for V&V
- It's repetitive and time-consuming to create
- Some journals require ODD of your model during submission
- Still, it helps for independent assessment of ABMs
  - Model purpose
  - Key decision mechanisms and processes
  - With an available source code, one can conduct verification

Two mindsets for V&V of ABMs

It is just a model

- Use existing V&V techniques designed for other modeling paradigms.

ABMs have unique characteristics

- Thus, design and use V&V techniques tailored for ABMs.

Unique characteristics of ABMs

- Attribute the source of error
  - E.g.: was it agent decision code or agent interactions?
  - E.g.: does the model produce good results using buggy code?
- Scalability
  - E.g.: If you manage to run 100 million agents, how can you keep track of individual agents and their behavior?
  - E.g.: Results will not scale linearly if you increased number of agents.
- Computational cost
  - E.g.: running calibration and sensitivity analysis

A meta-analysis on ABM-specific V&V*

Gowri Prathap & Hamdi Kavak

*Work in progress

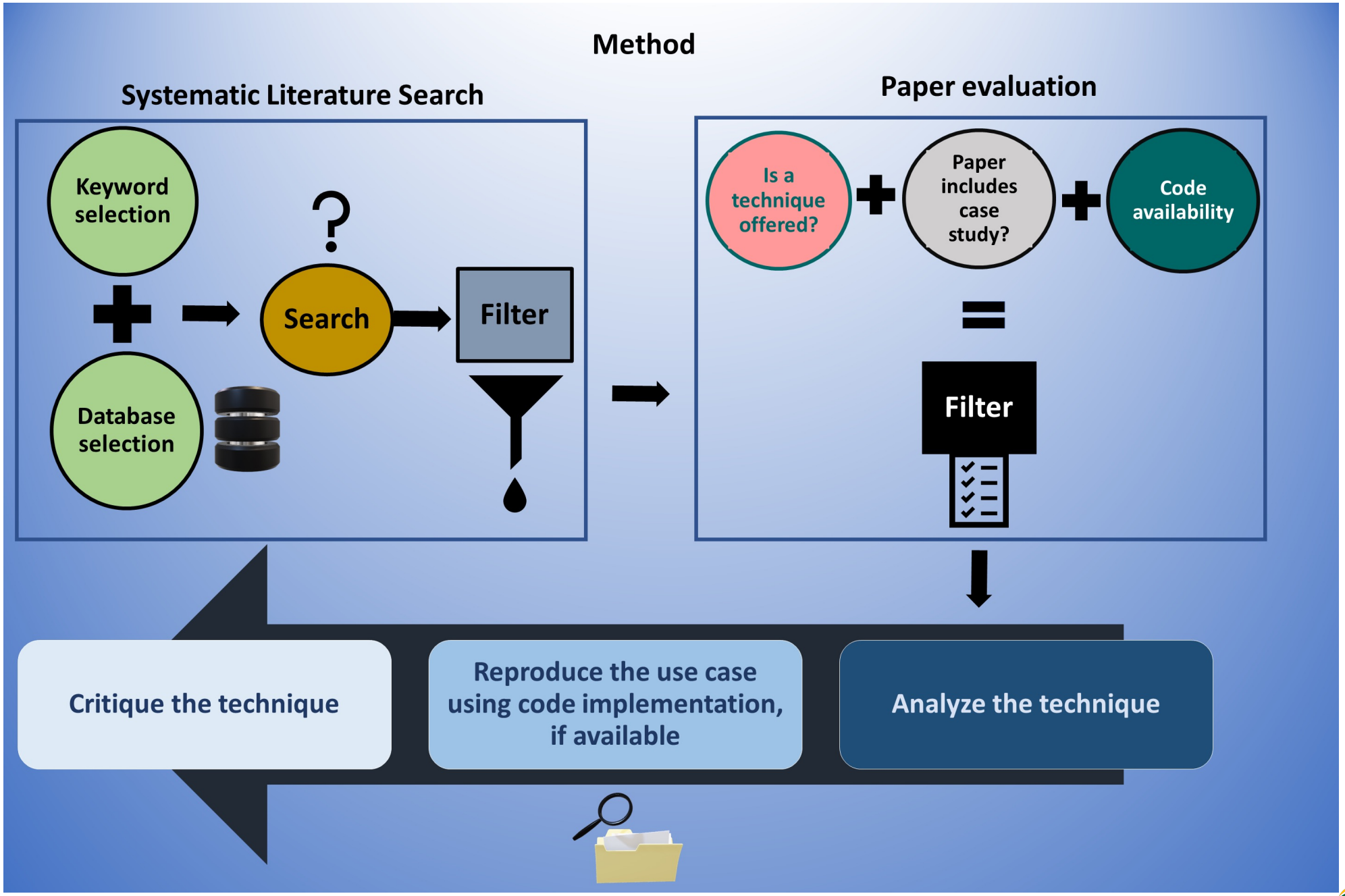
A meta-analysis on ABM-specific V&V

- Goal
  - Evaluate ABM-specific V&V techniques published in peer-reviewed papers.
- Approach
  - A systematic literature search (Wee & Banister, 2016)
  - Filtered articles based on a set of criteria
- Critically evaluated papers based on
  - Reproducibility
  - Applied V&V technique type
  - Ease of use
  - Adoption
  - Targeted model type
  - Computational approach

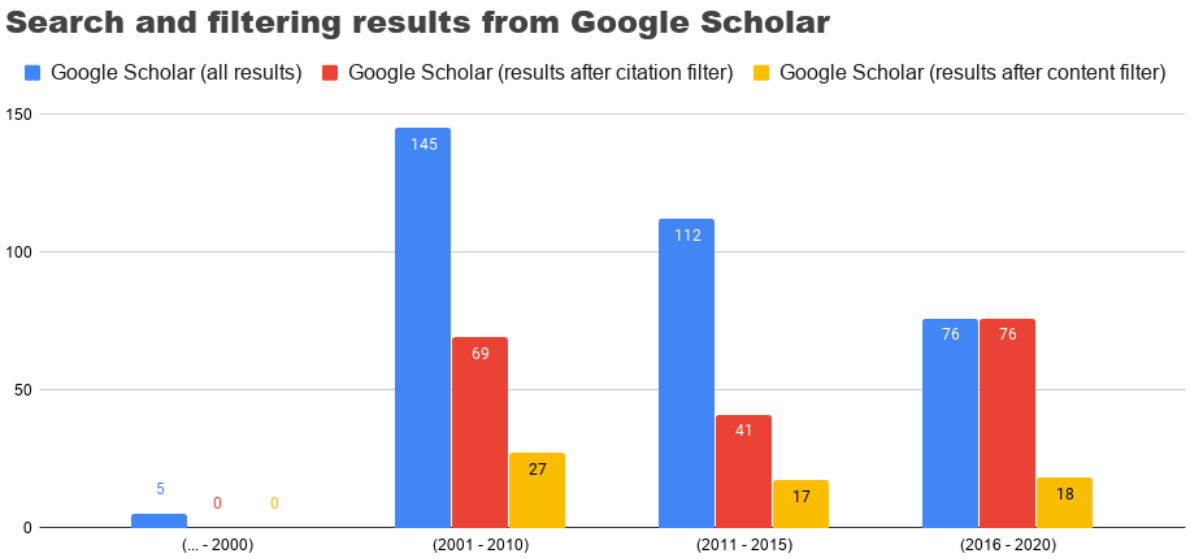
Wee, B. V., & Banister, D. (2016). How to write a literature review paper?. *Transport Reviews*, *36*(2), 278-288.

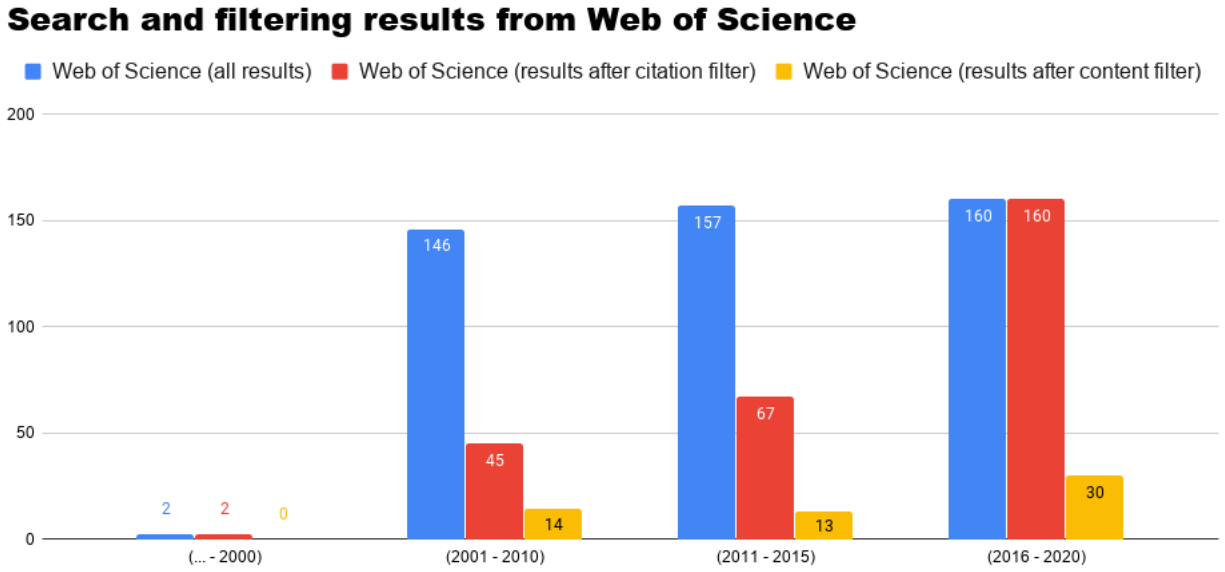
Purpose of this study

- Understand the state of the art when it comes to V&V of ABMs
- Identify gaps in the literature
- Improve scientific practice
  - Improve reproducibility and reusability of existing V&V techniques
  - Host code of techniques in a public repository
  - Offer special badges to encourage better practices
  - Provide use cases to benchmark techniques


Method
Systematic Literature Search
Keyword selection
Database selection
?
Search
Filter
Paper evaluation
Is a technique offered?
Paper includes case study?
Code availability
Filter
Critique the technique
Reproduce the use case using code implementation, if available
Analyze the technique

Literature search and filtering results





Final number of papers after paper evaluation

(... - 2000)	0
(2001 - 2010)	15
(2011 - 2015)	14
(2016 - 2020)	27

56 papers

Most influential papers

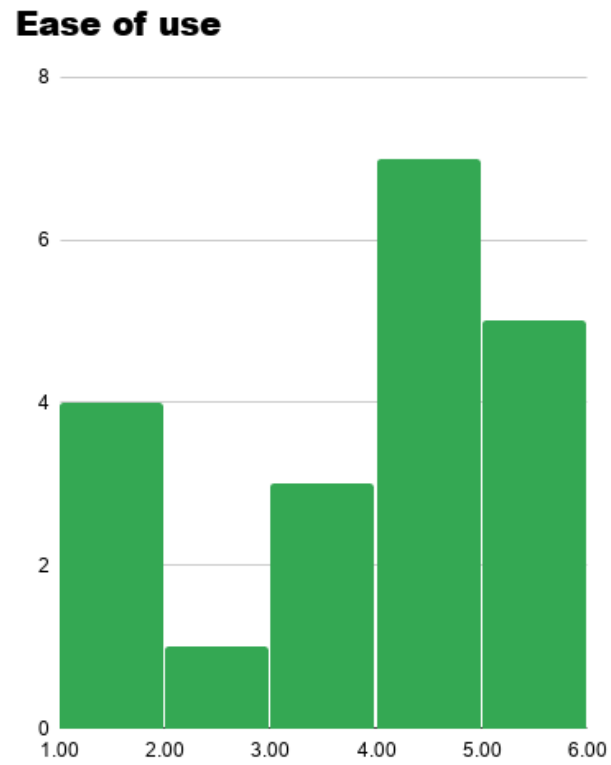
- Highest citation/year scores in its year category

Year category	Paper name	Authors (year)	Citations/year
2001 - 2010	Path dependence and the validation of agent-based spatial models of land use.	Brown, D. G., Page, S., Riolo, R., Zellner, M., & Rand, W. (2005)	27.19 (GS) 14.56 (WoS)
2011 - 2015	Calibration and validation of agent-based models of land cover change.	See, L. (2012).	5.56 (GS) N/A (WoS)
2011 - 2015	A generic testing framework for agent-based simulation models.	Gürcan, Ö., Dikenelli, O., & Bernon, C. (2013)	3.00 (GS) 1.38 (WoS)
2016 – 2020	Agent-based model calibration using machine learning surrogates.	Lamperti, F., Roventini, A., & Sani, A. (2018)	23.67 (GS) 7.33 (WoS)

As of Fall 2020

Reproducibility and ease of use

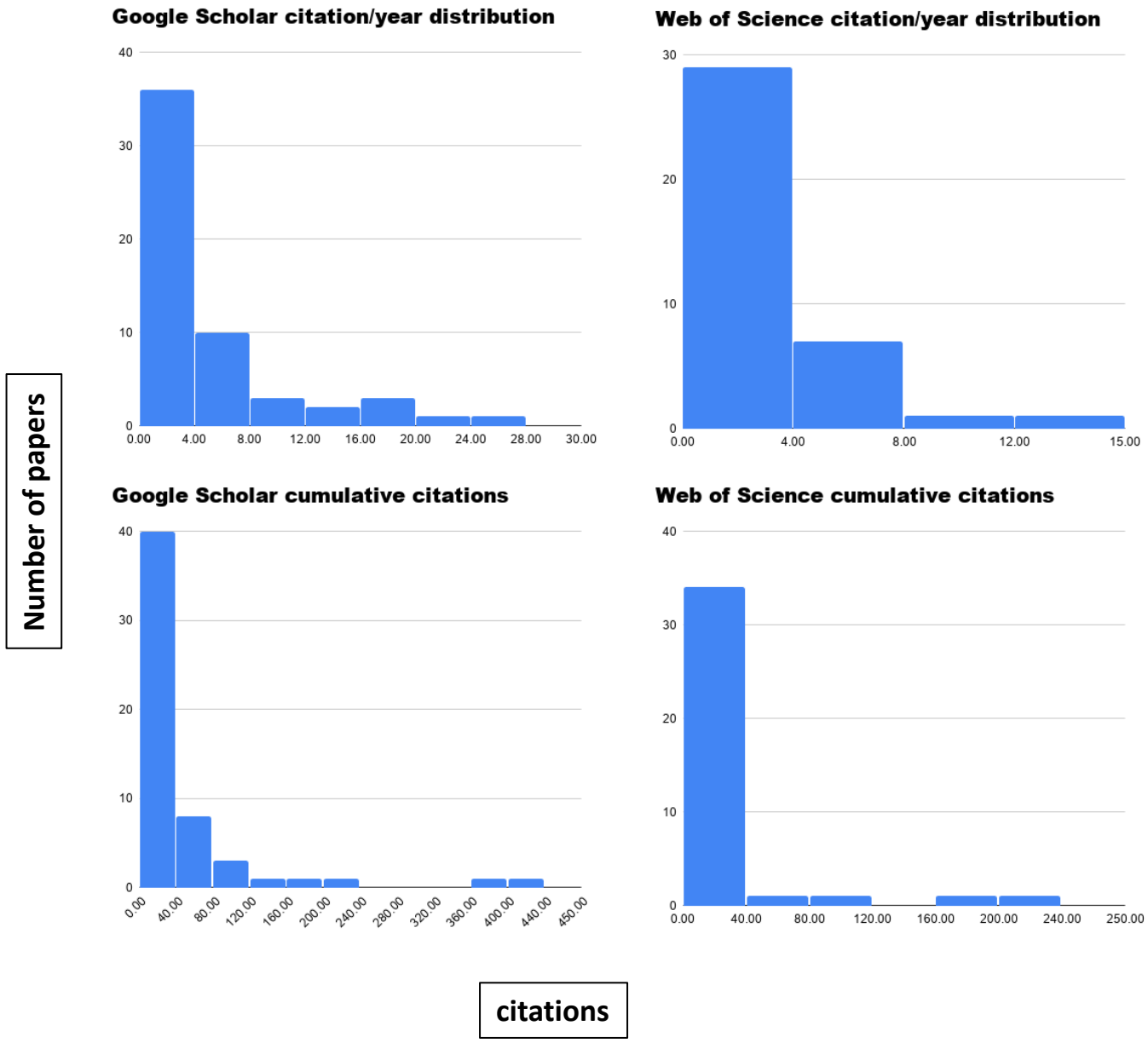
- Code reproducibility
  - Source code available: 25%
    - Runs without error: 71%
  - Source code **not** available: 75%
    - Pseudo-code/algorithm available: 19%
    - Mathematical formalism available: 76%
- Ease of use (those with at least source code or pseudo-code / algorithm available)
  - 1: very difficult …. 5: very easy



Verification or validation or both?

- Verification only: 7%
- Validation only: 66%
- Both verification and validation: 27%

Citation


Google Scholar citation/year distribution
Web of Science citation/year distribution
Google Scholar cumulative citations
Web of Science cumulative citations
Number of papers
citations
0.00
4.00
8.00
12.00
16.00
20.00
24.00
28.00
30.00
15.00
40.00
80.00
120.00
160.00
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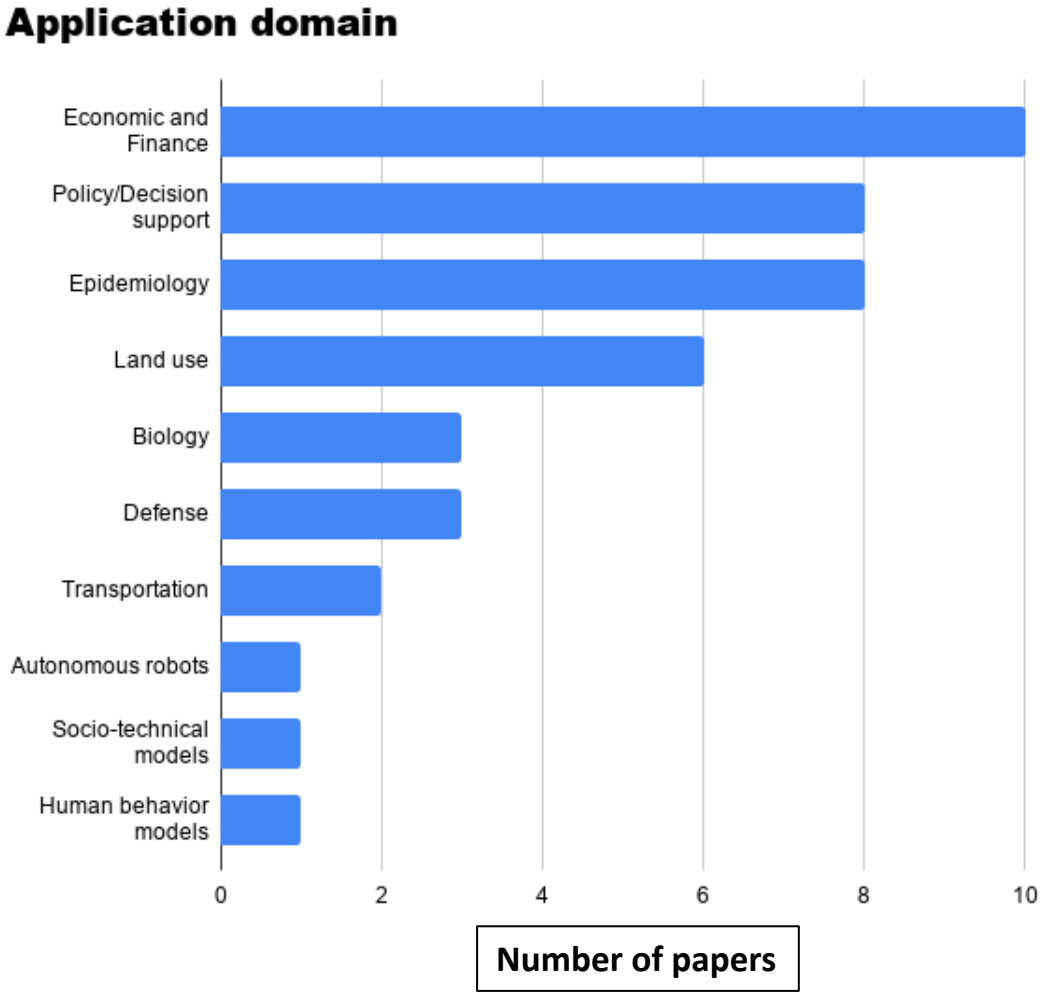
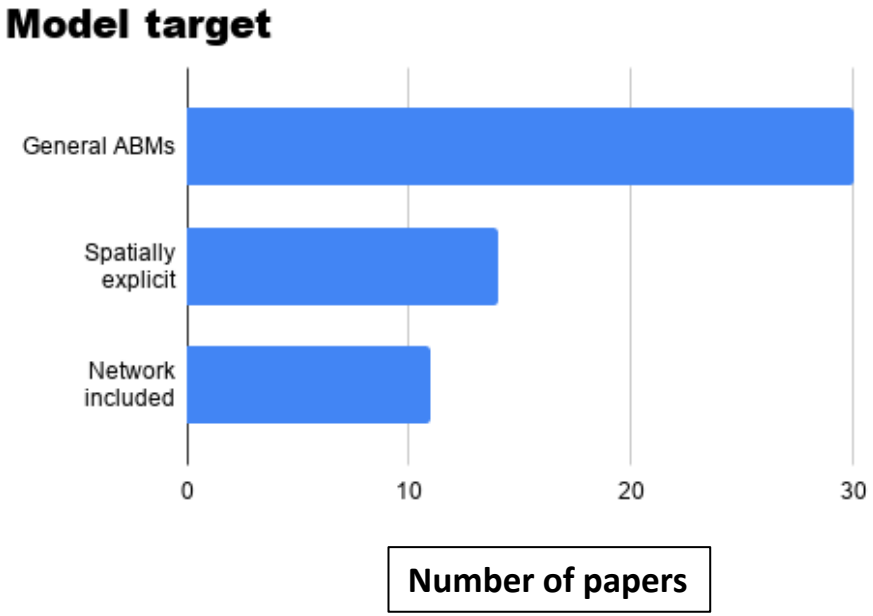
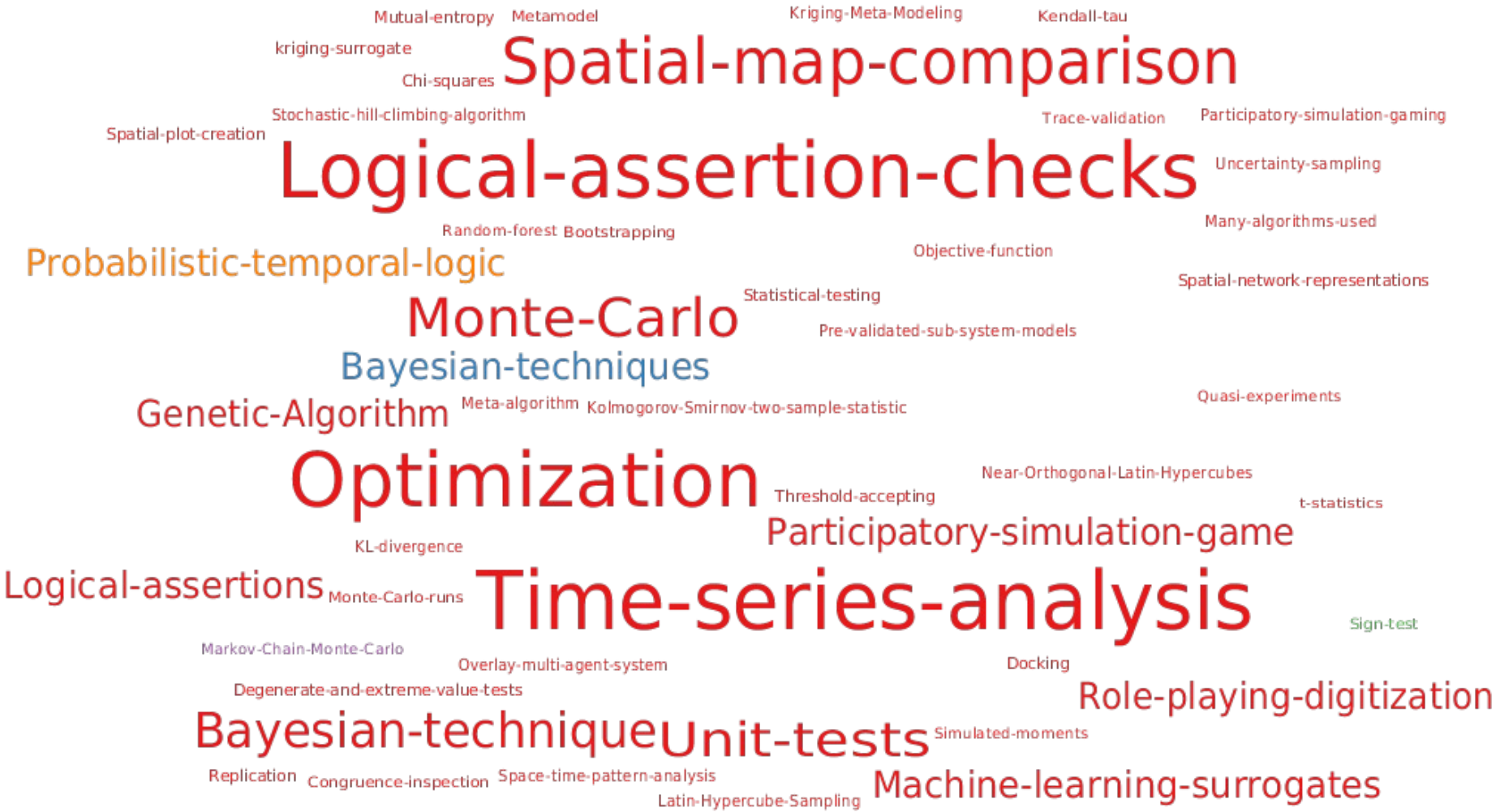
240.00
280.00
320.00
360.00
400.00
440.00
450.00
250.00

Targeted model type





Computational approaches



Findings

- Many techniques don't have associated code.
  - This is a recipe for re-inventing the wheel.
- Adoption (i.e., citations) are getting better
  - Meaning researchers are willing to use existing V&V techniques.
- Certain domains (e.g., economic and finance) offer more techniques than others.
  - Thus, cross-domain and multi-disciplinary initiatives are needed.
- We need a better characterization for ABMs and V&V techniques to facilitate a common language
  - This study will provide one

Selected techniques from the survey

Multi-level verification and validation

Papers

- A generic testing framework for agent-based simulation models (Gurcan et al., 2013) => Repast and MASON
- RatKit: Repeatable Automated Testing Toolkit for Agent-Based Modeling and Simulation (Cakirlar et al., 2014) => Repast

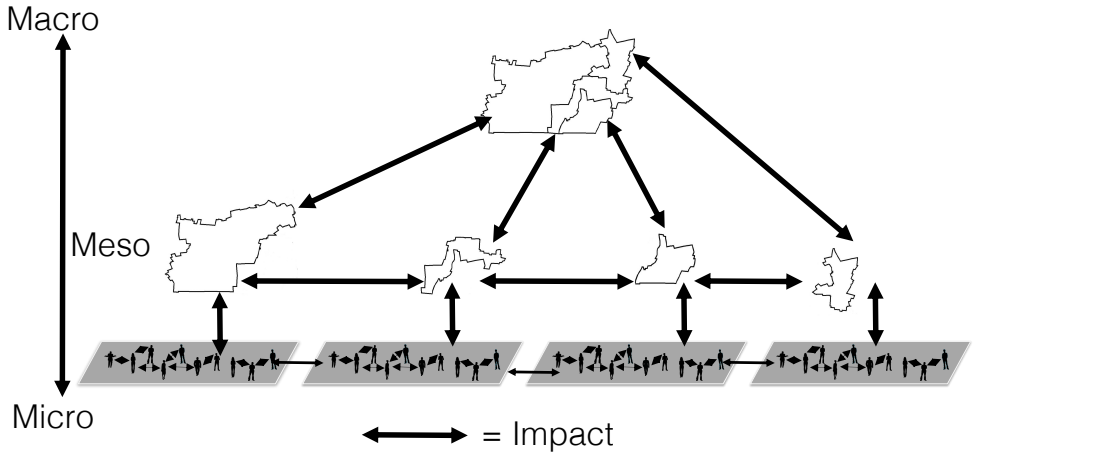


Figure source: Crooks, A.T., Malleson, N., Manley, E. and Heppenstall, A.J. (2019), ***Agent-based Modelling and Geographical Information Systems: A Practical Primer***, Sage, London, UK.

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  - *Meso-level:* tests on groups or sub-societies. Applied after micro-level tests are completed.
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- Open source and implemented in Java; applied to Repast and MASON.
  - Extends JUnit

Multi-level verification and validation: summary

Both papers (Gurcan et al., 2013 and Cakirlar et al., 2014) are from the same group of authors.

While the idea is great, the solutions are not.

Application makes the code base cluttered with additional parameters, XML files, .jar files.

It is **not integrated;** it is **coupled** with the code base.

The software is buggy. We had difficulty replicating their own examples, let alone testing other models.

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  - Participatory simulation game is developed to enable real people's integration to the simulation.
  - People play (make choices) as if they are an agent and their choices are recorded.
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- Two examples
  - Role-playing games as a mean to validate agent-based models: an application to stakeholder-driven urban freight transport policy-making (Le Pira et al., 2017)
  - Framework for modelling multi-stakeholder city logistics domain using the agent based modelling approach (Anand et al., 2016)

Surrogate/meta modeling

- Imagine you need to run thousands of simulations to explore the parameter space.
- If the model is large-scale, which is costly to run, it is a smart decision to reduce cost of a model run.
- Surrogate modeling or meta modeling is a computational technique that treats a model as an **input-output machine** and tries to learn the patterns between input and output. Two techniques used in these papers:
  - Machine learning
  - Kriging

Papers

- Agent-based model calibration using machine learning surrogates (Lamperti et al., 2018).
- An empirical validation protocol for large-scale agent-based models (Barde & Hoog, 2017)
- Validation and Calibration of an Agent-Based Model: A Surrogate Approach (Zhang et al., 2020)

Other ideas to dig in

- Deep learning et al. for surrogate modeling.
- Static code analysis to uncover model structure to examine against conceptual model.
- Visualize a sample of agents' trajectories (e.g., decision making logs) to verify model code.
- Data mining and machine learning to find patterns in simulation output data.