# Introduction to System Dynamics and Agent-Based Modelling

Dr Bernd Wurth (bernd.wurth@Glasgow.ac.uk)

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# Welcome

**Bernd Wurth** *BEng, MSc, PhD*

Lecturer in Entrepreneurship

Adam Smith Business School, University of Glasgow

Researching the complexity and dynamics of innovation and entrepreneurship, from individual decision-making to ecosystems.

Simple models that can answer complex questions.

Sometimes the opposite:

More about this later…

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## About this Workshop

- Introduction to the **foundational concepts** of systems thinking, modelling, and their relevance to studying complex (social) phenomena like entrepreneurship.
- Learn about **system dynamics (SD)** and **agent-based modelling (ABM)** as top-down and bottom-up approaches to complex systems, respectively.
- Engage in **practical exercises** using pre-built models to demonstrate how SD and ABM can be applied to real-world scenarios.
- **Inspiration!** The aim is to introduce new tools for thinking and analysis that can open up fresh avenues for research and provide innovative perspectives on complex issues.

## This Workshop is NOT…

…comprehensive training.

…an advanced methodology course.

…software-specific training.

…providing solutions to specific research problems.

…a critique of other methods and approaches.

# Structure

Welcome and Introduction

1. Systems Thinking
2. System Dynamics
3. Agent-Based Modelling
4. (Venturithm)

# Systems Thinking

# Why Systems Thinking and Simulation?

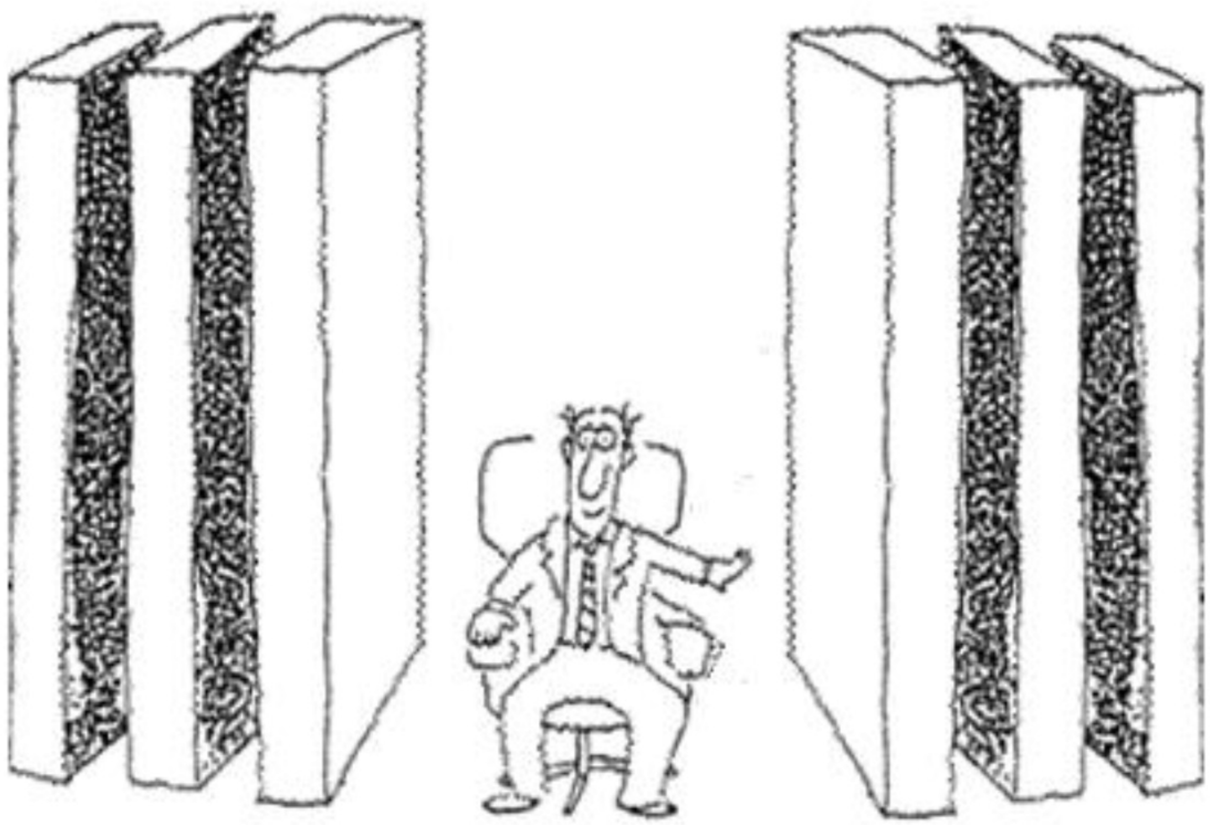
- There have been advances in economics (and innovation/entrepreneurship) with regard to metrics and ‘causal’ inference
  - 2021 Sveriges Riksbank Prize in Economic Sciences in Memory of Alfred Nobel (Angrist/Imbens)

- This is important work, but mostly helps us looking backwards in establishing causality for policies/interventions *a posteriori*

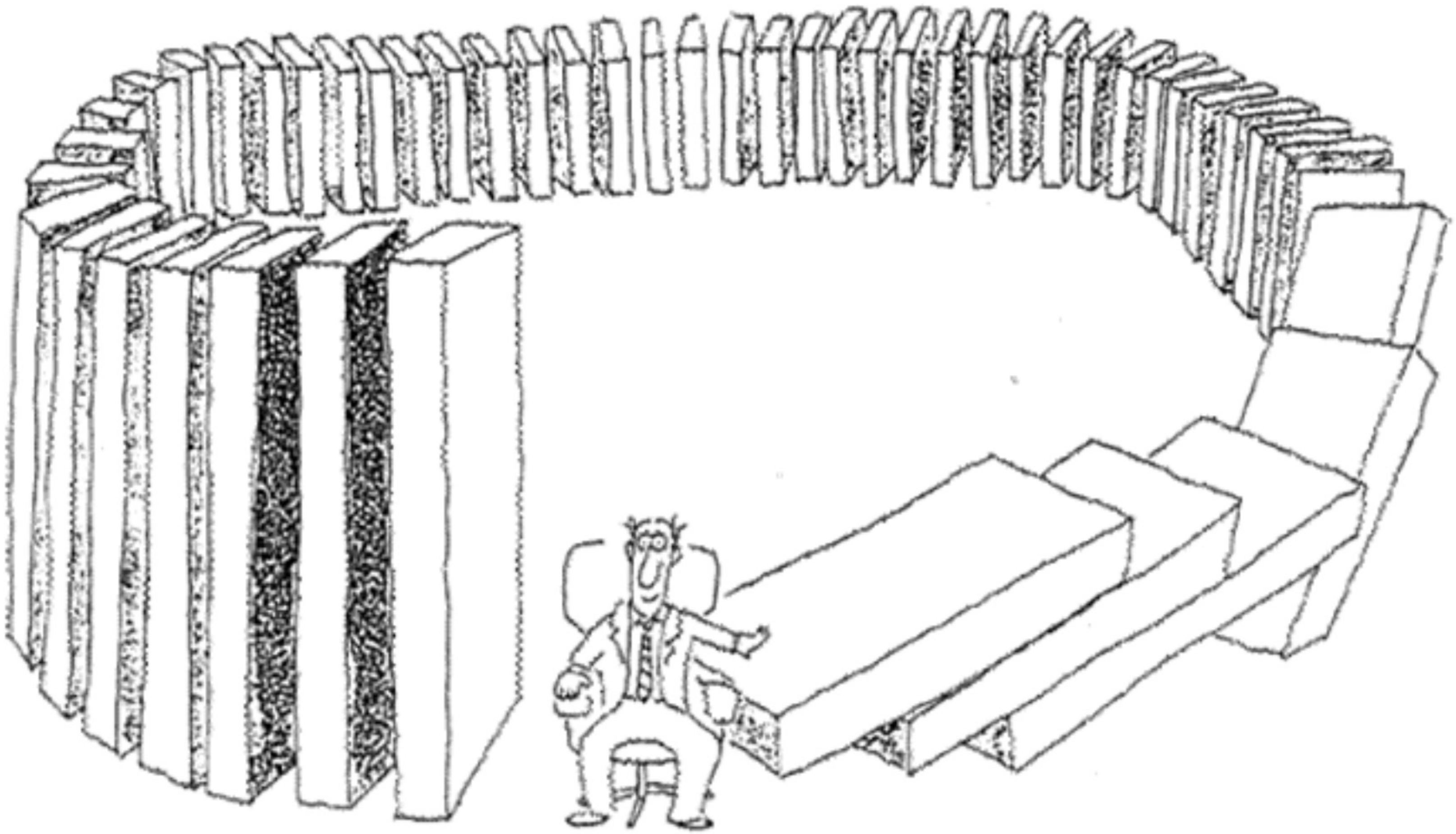
- Systems thinking and simulation can help us understand the potential impact of policies/interventions *a priori*, thinking through interconnected mechanism, processes, feedback, and (un)intended consequences
  - Simulation = tools for thinking ≠ forecasts

# What does that mean?

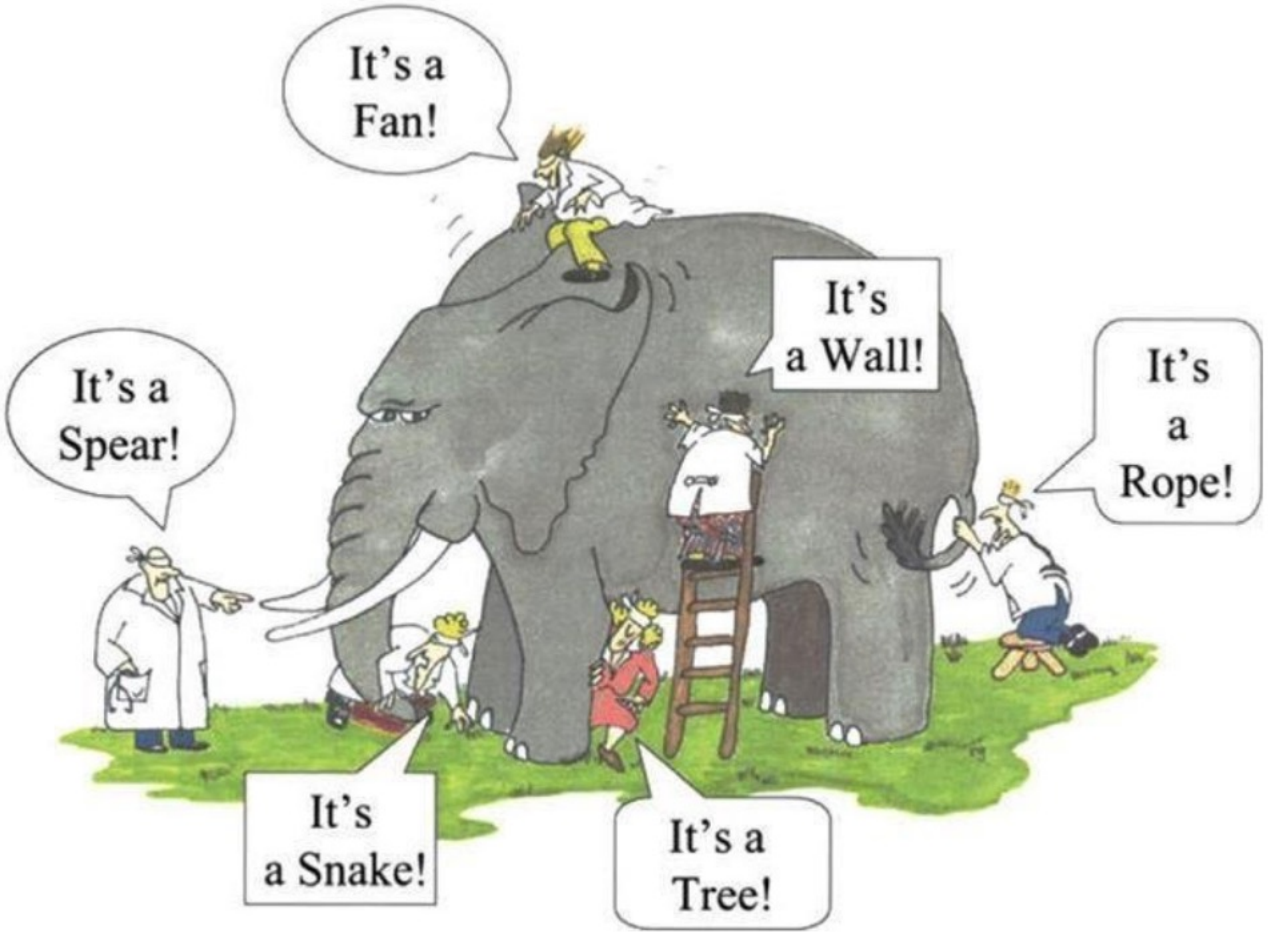
# Unintended Consequences



# Unintended Consequences



# The Blind and the Elephant



# See for yourself…

# From Event-Oriented To Feedback Thinking

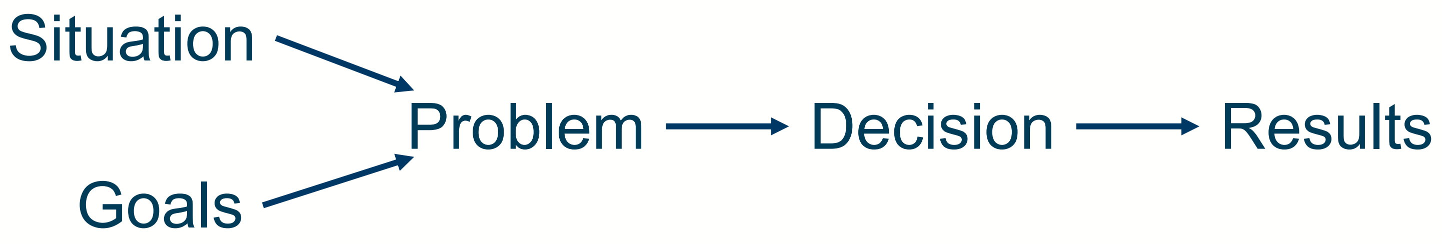
- Event-oriented thinking:

$$
\begin{tikzcd}
\text{Situation} \arrow[dr] & & & \\
& \text{Problem} \arrow[r] & \text{Decision} \arrow[r] & \text{Results} \\
\text{Goals} \arrow[ur] & & &
\end{tikzcd}
$$

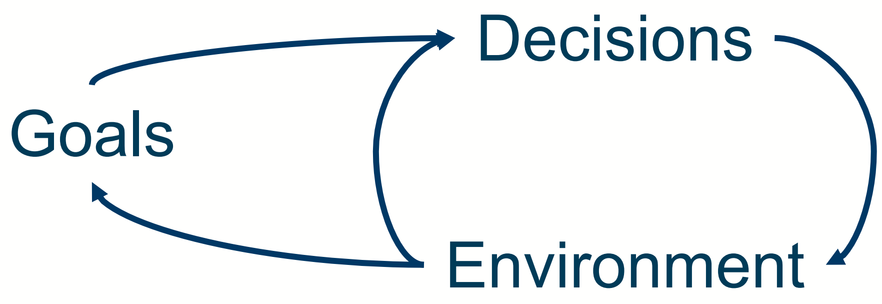
Sterman (2000)

# From Event-Oriented To Feedback Thinking

- Event-oriented thinking:



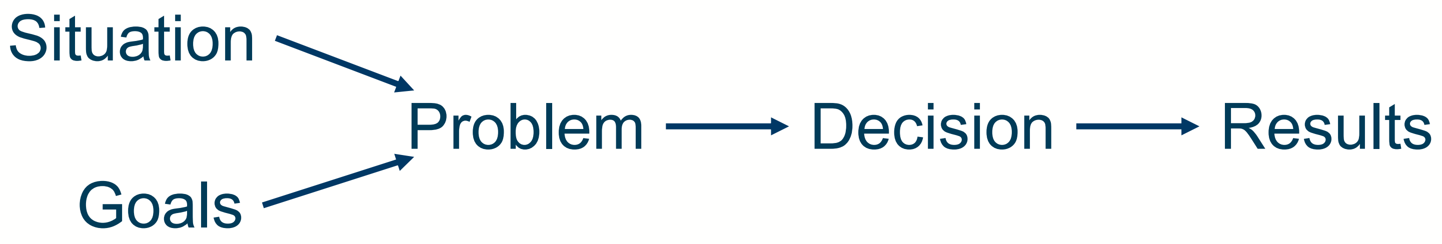

- Feedback thinking:




Sterman (2000)

# From Event-Oriented To Feedback Thinking

- Event-oriented thinking:

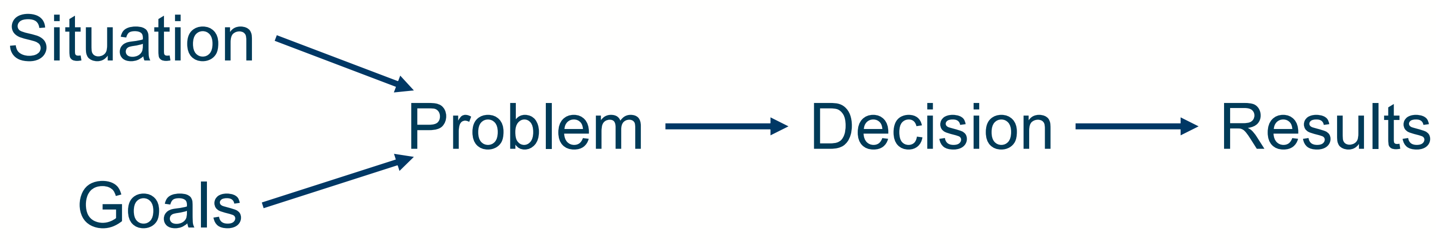



- Feedback thinking:

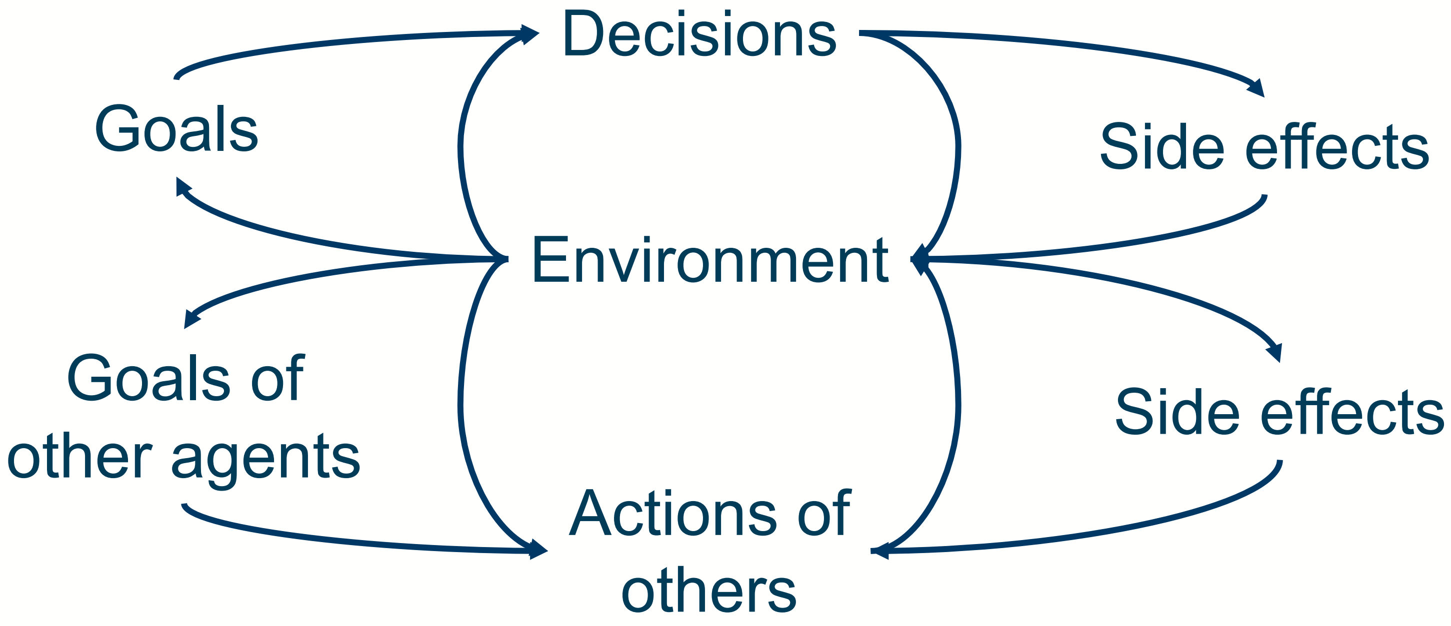

Sterman (2000)

# From Event-Oriented To Feedback Thinking

- Event-oriented thinking:




- Feedback thinking:



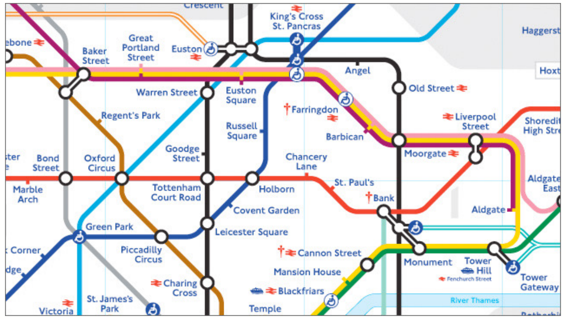

Sterman (2000)

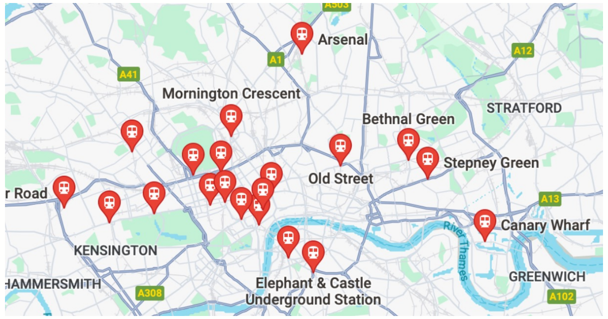
## By thinking in systems, we can:

- …understand complex **interdependencies**.
- …deal with **non-linearity**.
- …better anticipating and reacting to these **emergent behaviors**.
- …understand **feedback** mechanisms and design interventions that enhance rather than hinder progress.
- …understand how **adaptations and evolution** occur, which helps predicting future changes.
- …look at the **‘big picture’** instead of thinking in silos.
- …use a common language to **align different perspectives**.

# Modelling Fundamentals

- *“Essentially, all models are wrong, but some are useful.”*
  - Box and Draper (1987, p. 424)



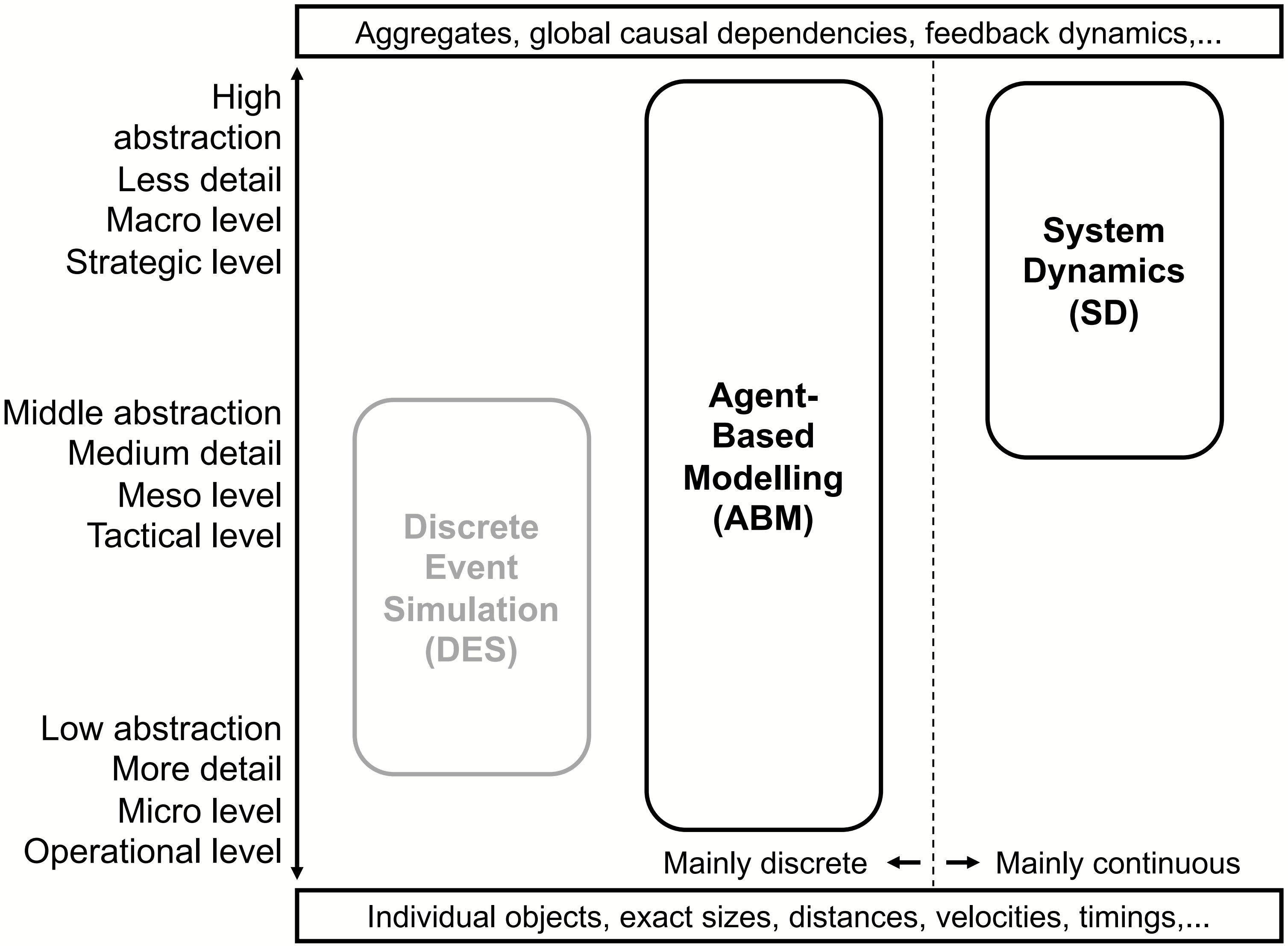




- *“Model a problem, not a system.”*
  - Every modelling/simulation book

# Modelling Approaches

ABM and SD not incompatible but "*regions in a space of modelling assumptions*"

(Rahmandad & Sterman, 2008, p. 1001)




Borshchev and Filippov (2004)

2

# Systems Dynamics

# Origins of System Dynamics

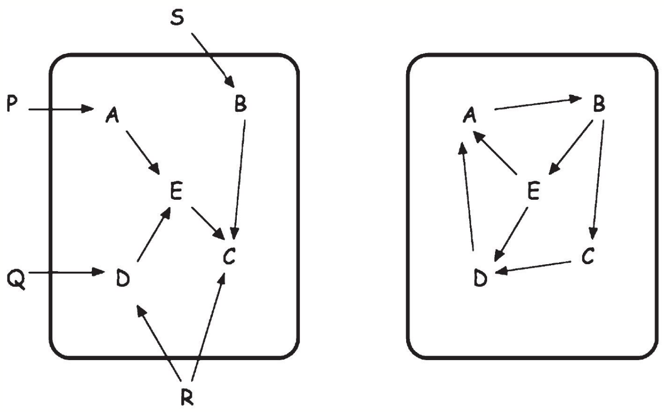
- Developed by Jay W. Forrester at MIT in the 1950s and 60s.
- Grounded in control systems theory and servomechanism.
- First applied to corporate and industrial settings with his seminal book "Industrial Dynamics" (1961).
- Later expanded to include urban and regional planning, public health, and global sustainability, notably illustrated in the 1972 book "Limits to Growth".

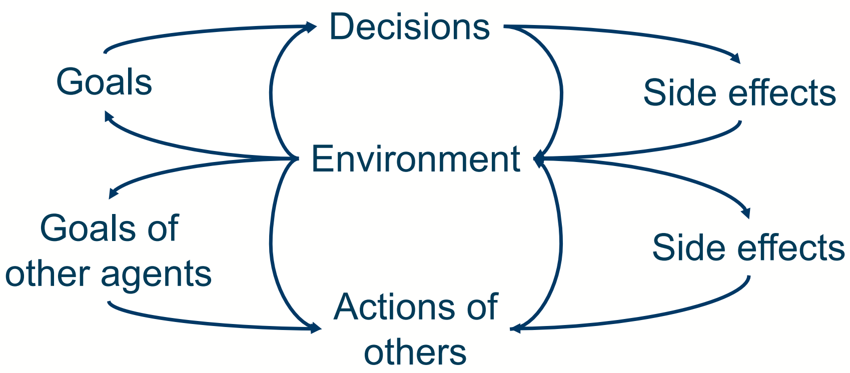
## When to Use System Dynamics

- When the system structure is known or can be elicited (top-down approach).
  - Does not work without this understanding.
  - Learning through the modelling process.
- System structure is static.
- Typically assumes (requires) homogeneity.
- Endogenous explanations without noise (randomness), typically deterministic.

Basic Principles

1. Endogeneity and feedback thinking



# Basic Principles

1. Endogeneity and feedback thinking

2. Structure of a system determines its behaviour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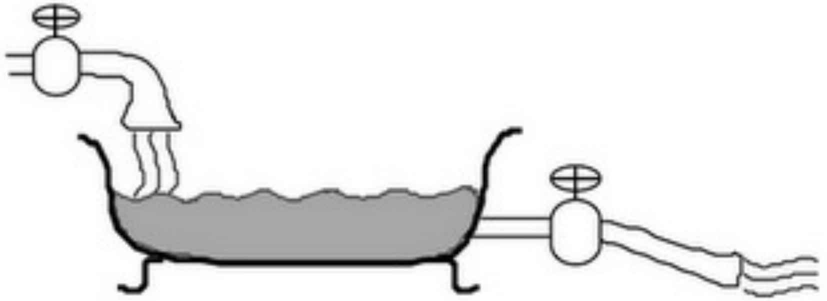
## Basic Principles

1. Endogeneity and feedback thinking
2. Structure of a system determines its behaviour
3. Accumulation
   - Gives systems inertia
   - Provide them with memory



## Causal Loop Diagrams (CLDs)

- Important tool for representing causalities and feedback structures of complex systems.
  - Capturing your hypotheses about the causes of dynamics.
  - Eliciting and capturing the mental models of individual teams.
  - Communicating the important feedbacks you believe are responsible for a problem.

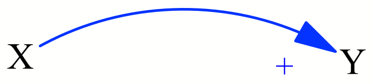
- Build with variables and links.

- For an application, see Wurth et al. (2024).

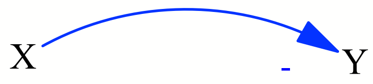
# Link Polarity

- Link polarities describe the structure of the system. The do not describe the behaviour of the variables. That is they describe what would happen if there were a change.

- **Positive Link**: All else equal, if X increases (decreases), then Y increases (decreases) above (below) what is would have been. In the case of accumulations X adds to Y. **(Same Relationship)**



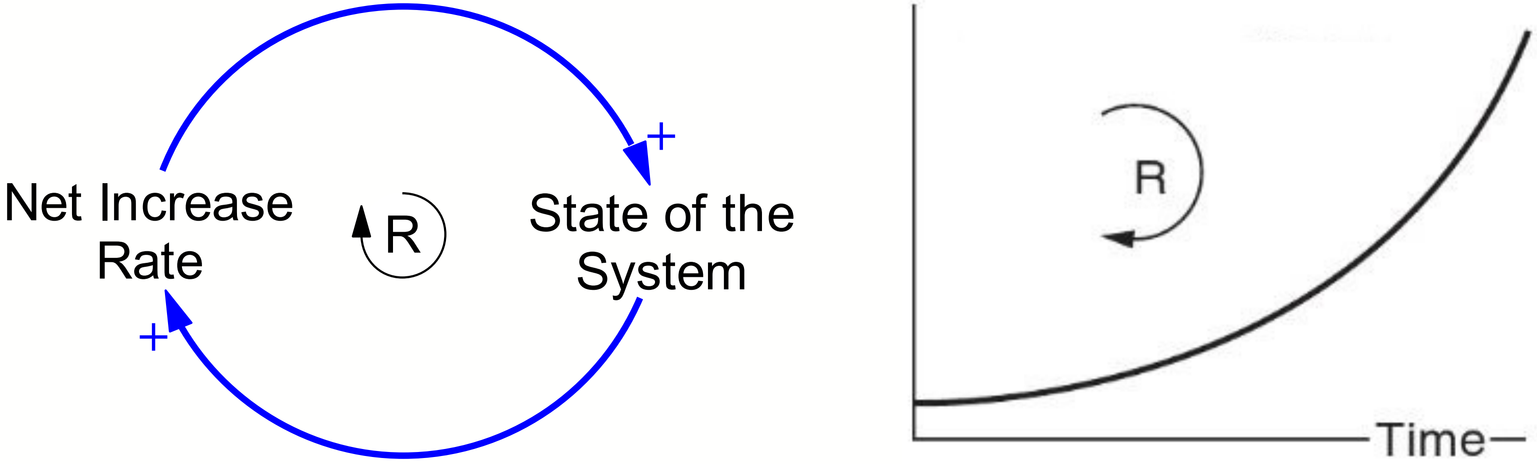

- **Negative Link:** All else equal, if X increases (decreases), then Y decreases (increases) below (above) what is would have been. In the case of accumulations X subtracts from Y. **(Opposite Relationship)**

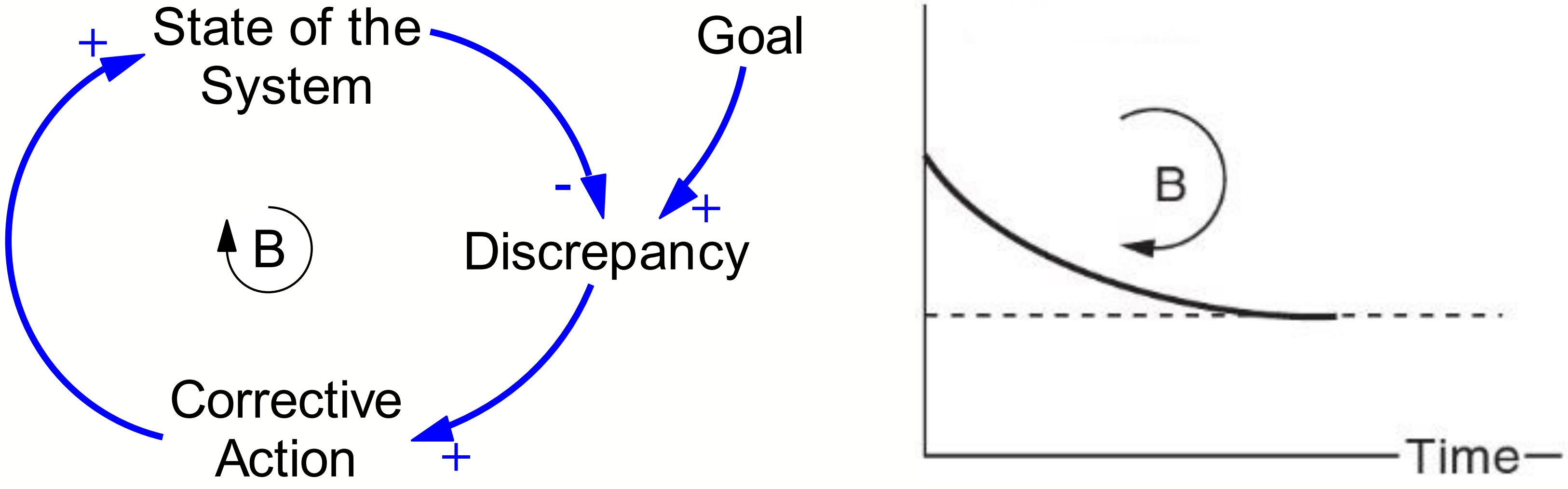


## Feedback Loops

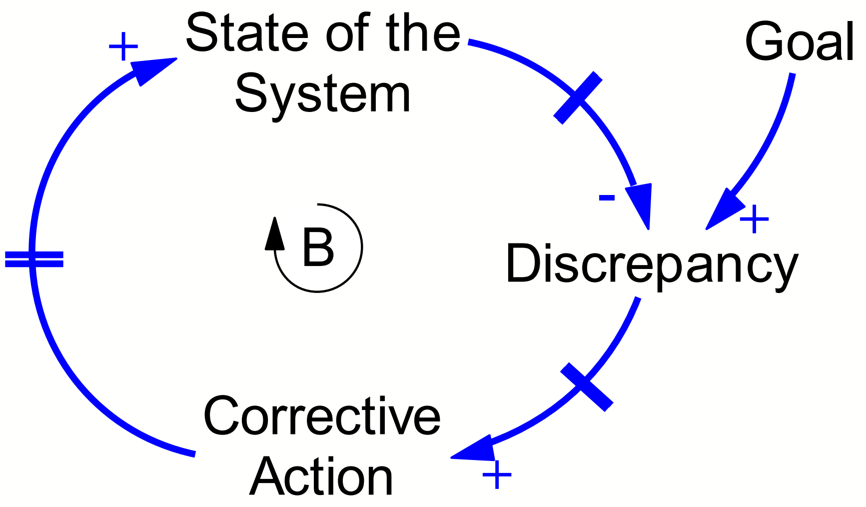
- **Positive (reinforcing) feedback loops**
  - Positive loops are self-reinforcing, therefore they seek to grow exponentially forever.
- However, since no quantity can grow for ever, there must be limits to growth. These limits are created by negative feedback.
- **Negative (balancing) feedback loops**
  - Negative loops are self-correcting. They counteract change.

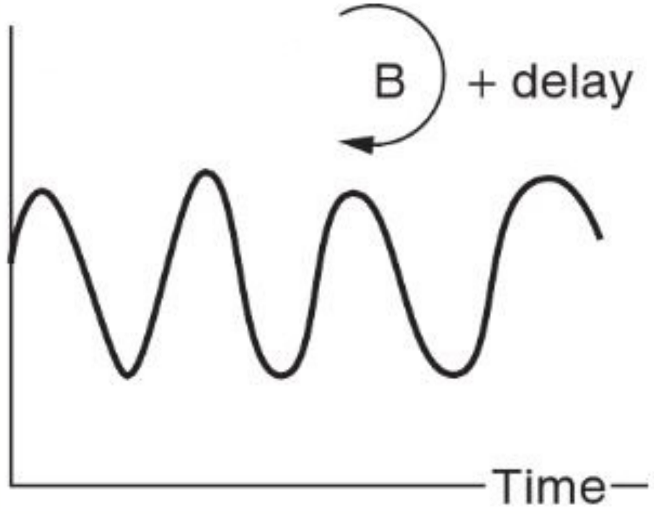
# Patterns of Behaviour (I)

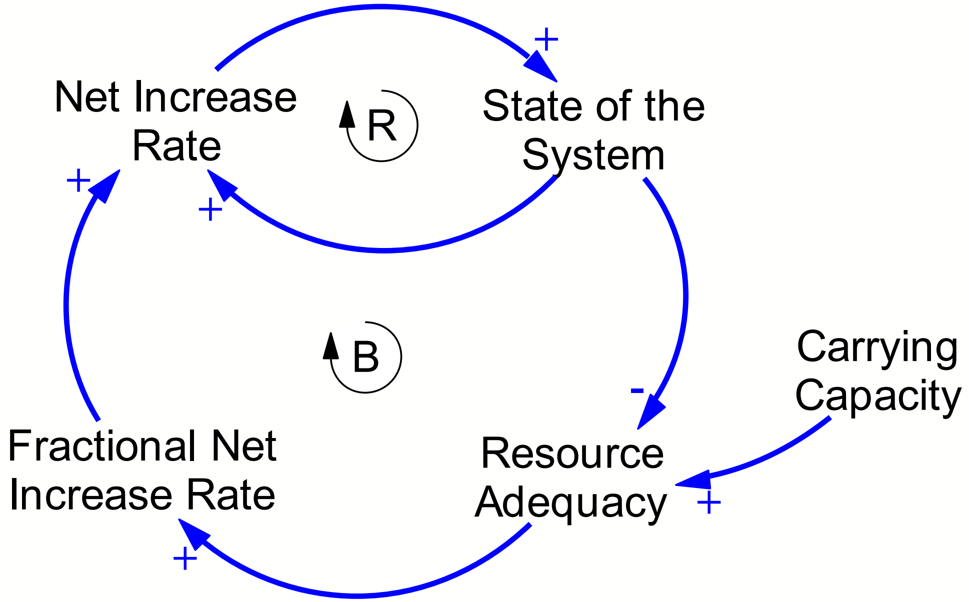


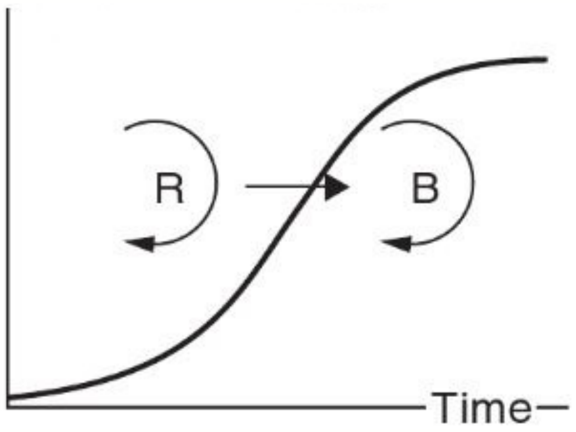



# Patterns of Behaviour (II)

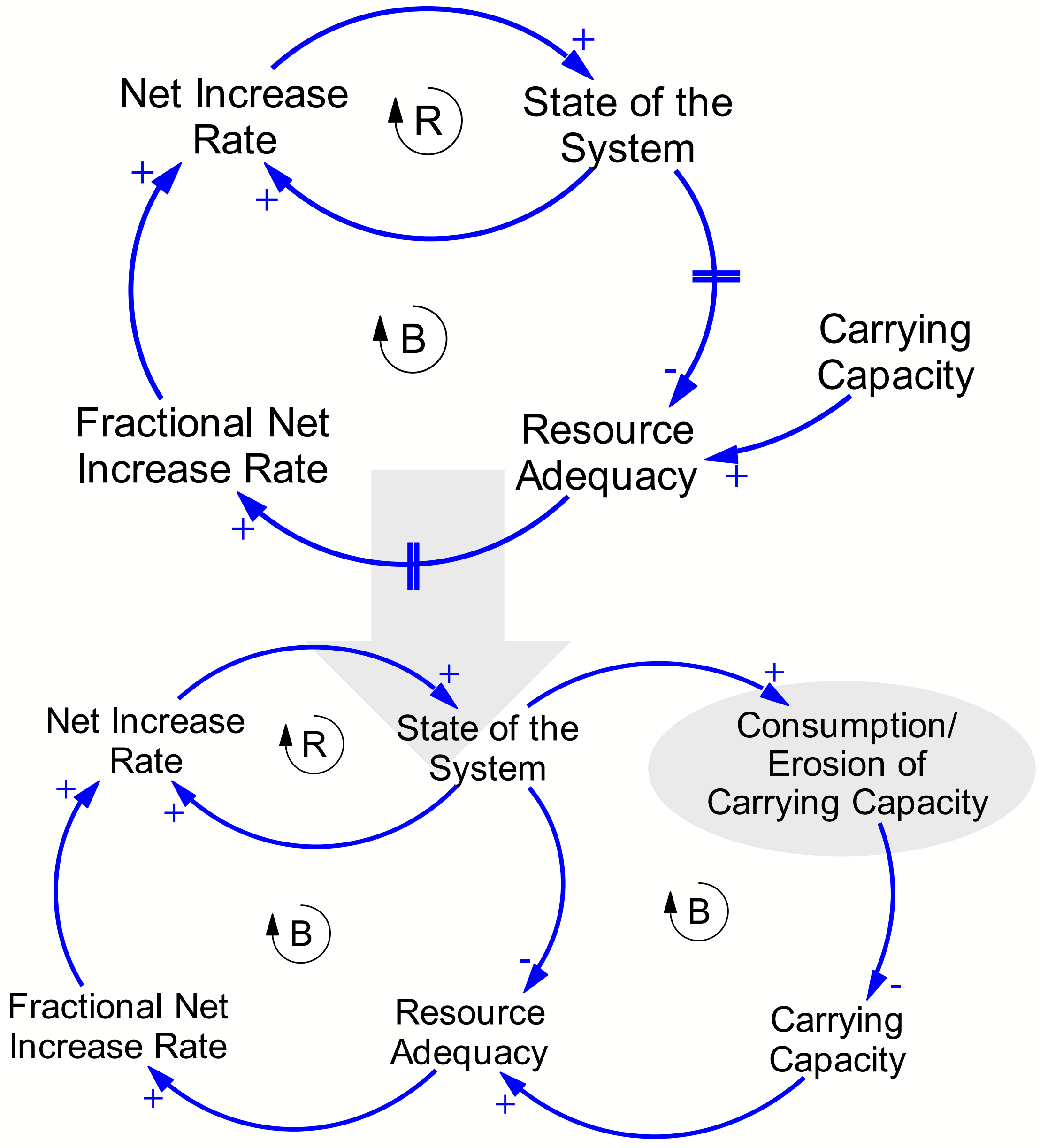


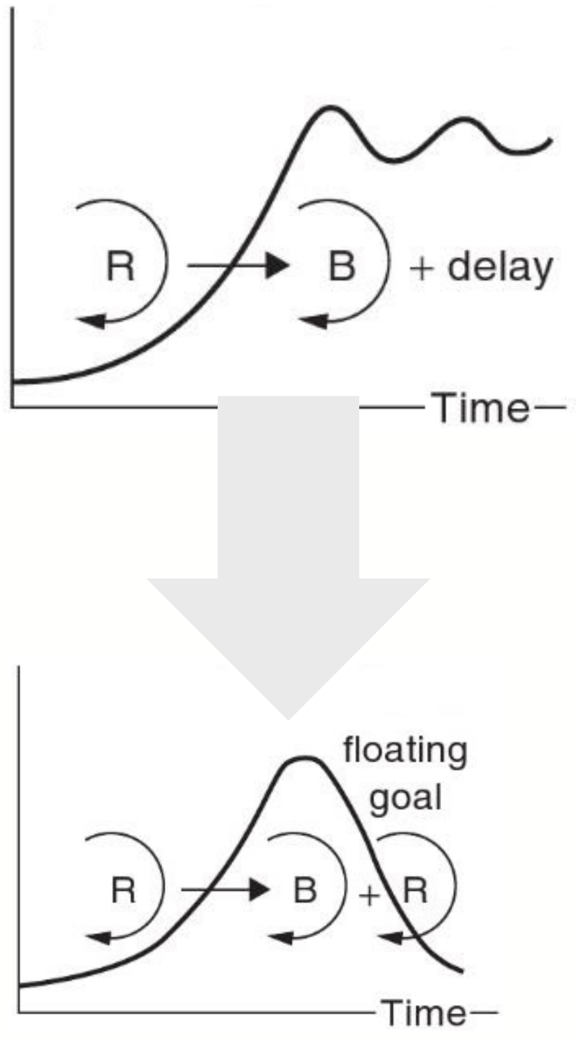



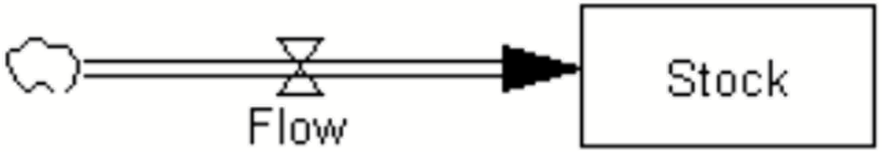
# Patterns of Behaviour (III)



## Stock and Flow Diagrams (SFDs)

- Stocks
  - Collection of stuff, an aggregate. E.g., water in a lake, population of sheep, a capital stock, ...
- Flows
  - Brings things out of or into a stock. (Modelled as a pipe with a faucet which controls how much runs through it). E.g., water outflow, sheep births/deaths, investments, ...



# Exercise: CLD and SFDs

- Task 1: Find the causal links and feedback loops (and implement in Vensim).

Potential Adopters

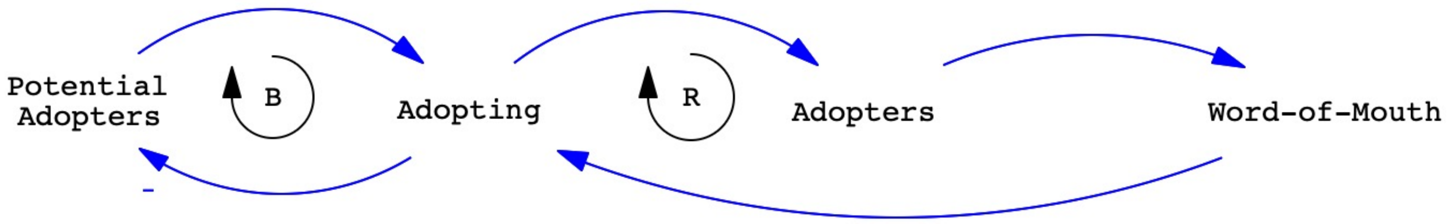
Adopting

Adopters

Word-of-Mouth

# Exercise: CLD and SFDs

- Task 1: Find the causal links and feedback loops (and implement in Vensim).




- Task 2: Identify the stocks and flows (and change the model structure in Vensim).

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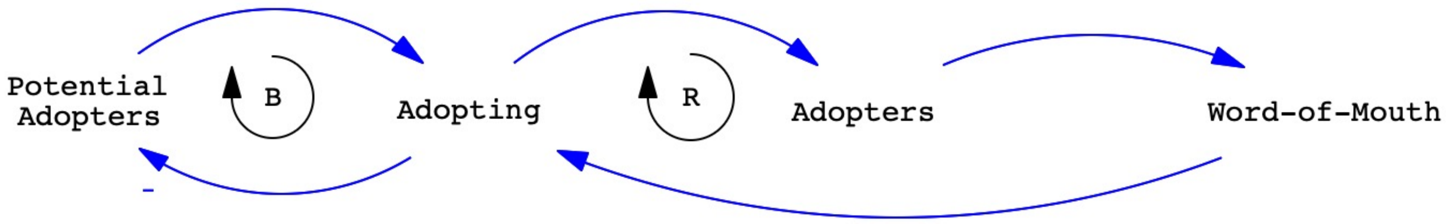


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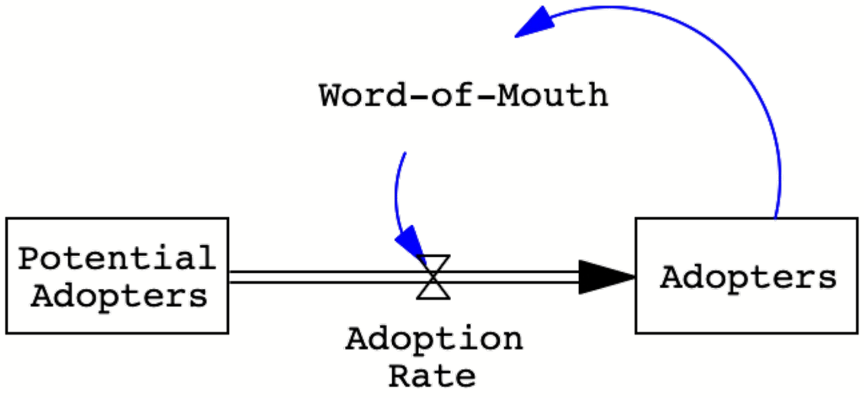
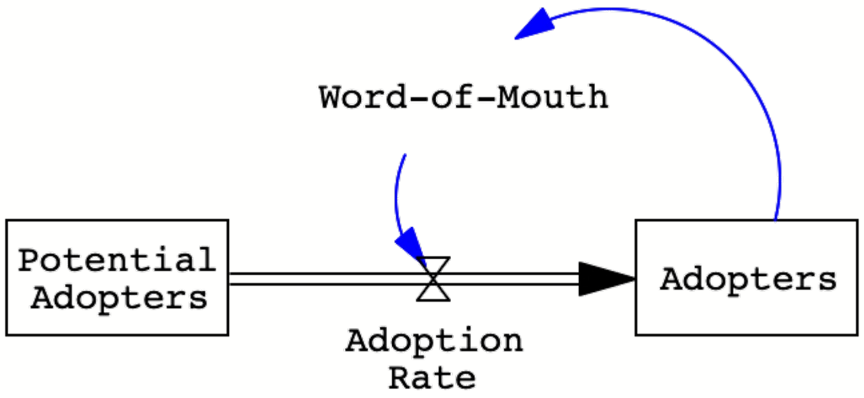


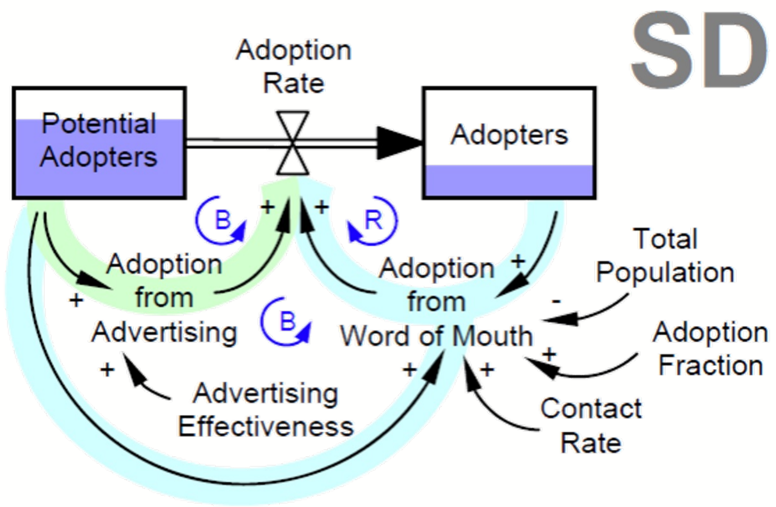
# Need for Simulation

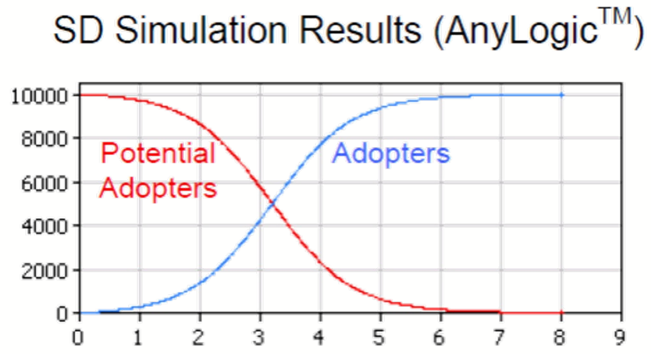
- Is this sufficient to help us plan production?




- No! We need to consider the quantitative features of the process
  - Initial number of potential and actual customers
  - Specific way in which sales flow depends on potential customers

# Simulating the Diffusion of Innovation




Borshchev and Filippov (2004), based on Sterman (2000)

# System Dynamics Practice (I)

Recreate the SFD shown on the right (same as on the previous slide) and parametrise the model as follows:

Potential Adopters = INTEG (-Adoption Rate, Total Population – Adopters)

Purchasers = INTEG (Purchase Rate,0)

Adoption Rate = Adoption from Marketing + Adoption from WoM

Adoption from Marketing = Potential Adopters * Effectiveness of Advertising

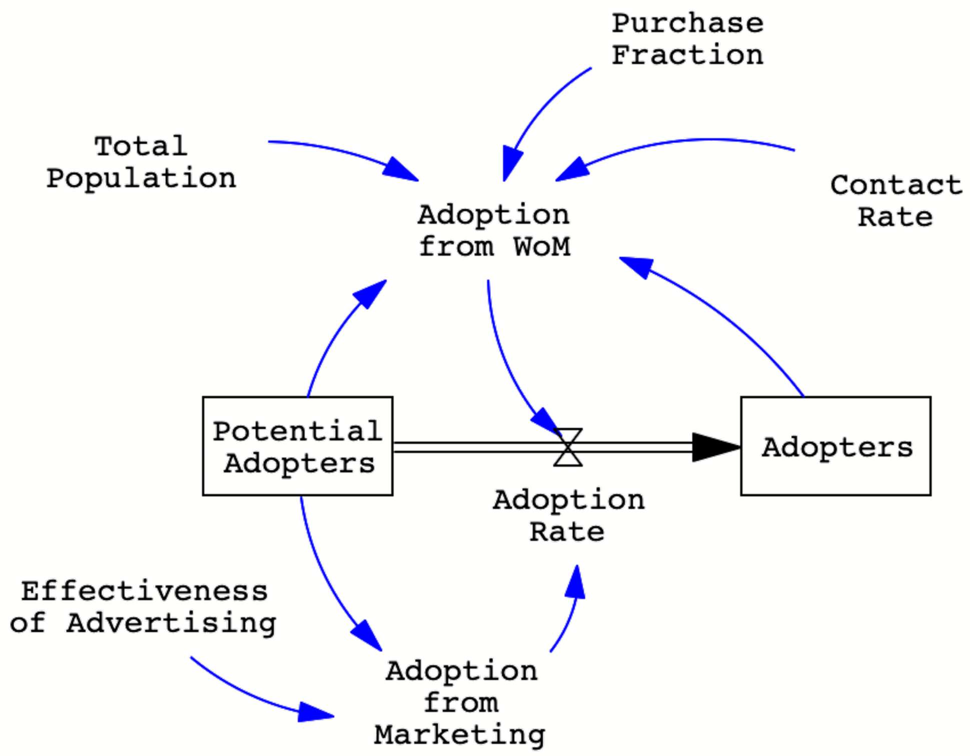
Adoption from WoM = Contact Rate * Purchase Fraction * Potential Adopters * (Adopters / Total Population)

Total Population = 100,000

Purchase Fraction = 0,0013

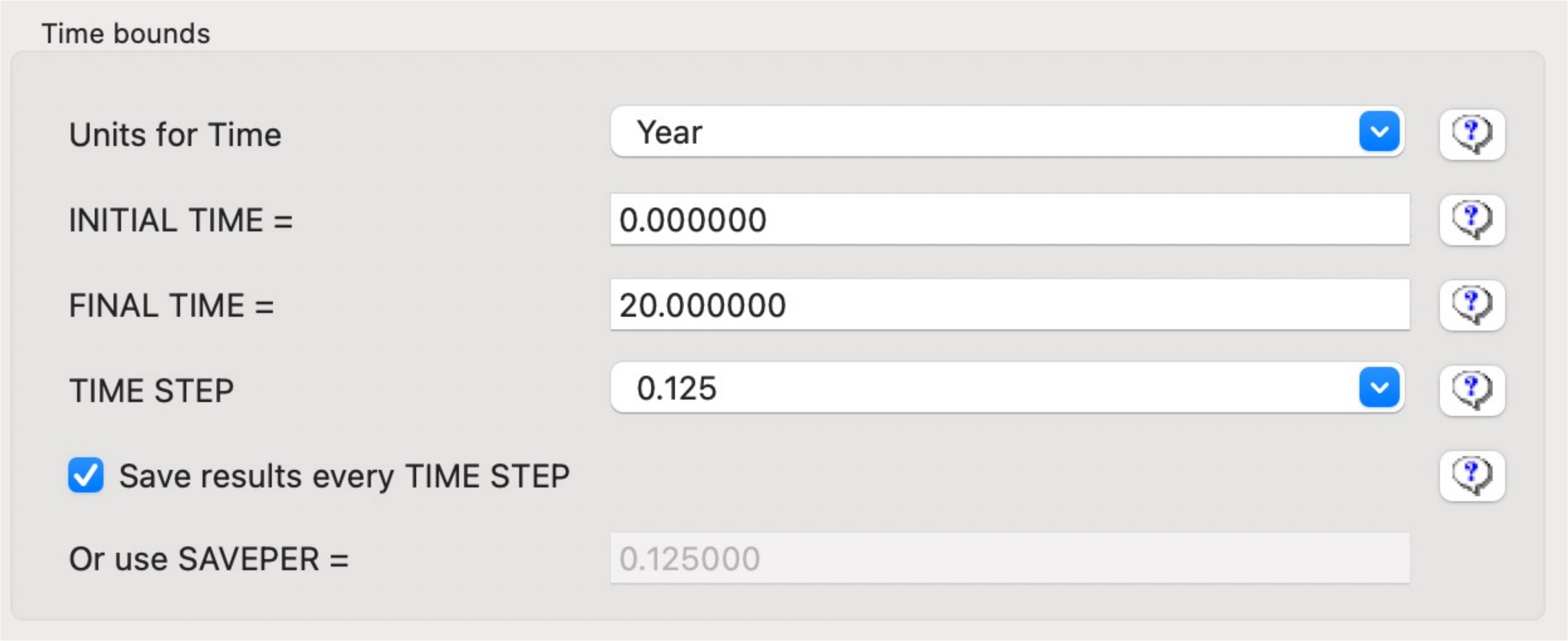
Contact Rate = 500

Advertising Effectiveness = 0,017 and if we set simulation step 0,125



# System Dynamics Practice (I)

Use the following model settings (Model > Settings):

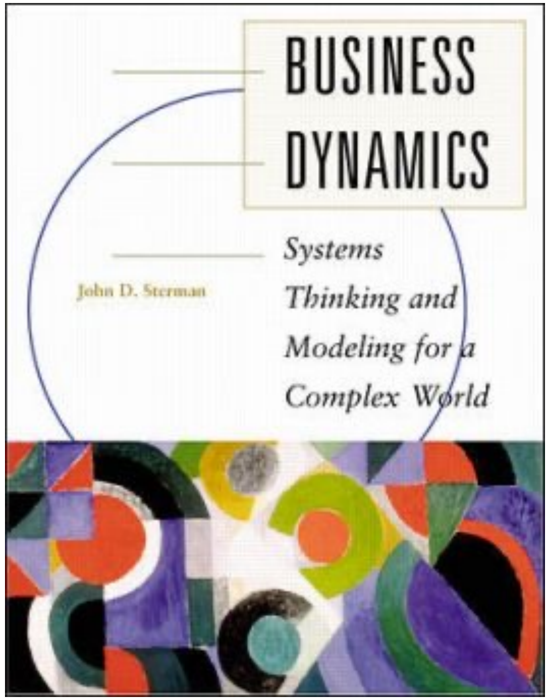


# System Dynamics Practice (II)

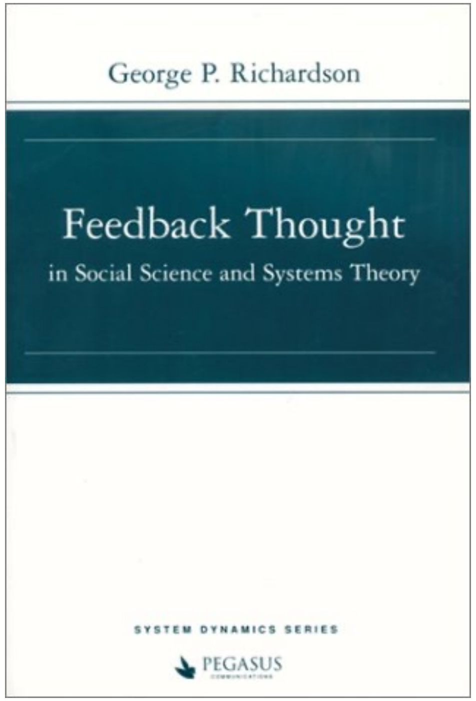
- Either use your own version or go to https://github.com/BWurth/workshop-eerss24 and download the “**Practice SD Part 1 Solution.mdl**” from the “**practice_sd**” folder as a starting point.

- Rather than a generic ‘adoption’ process, we are offering a digital services that based on a freemium model.
  - Modify the SFD to reflect these changes.
  - Which additional stocks, flows, and variables are required?

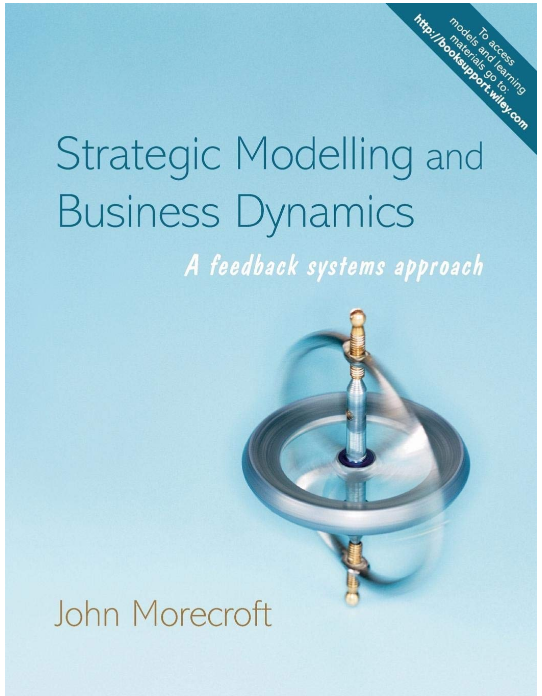
# SD Resources




Sterman (2000)




Richardson (1999)




Morecroft (2007)

# Agent-Based Modelling

## Origins of Agent-Based Modelling

- Roots in computer science and AI in the mid-20th century.
- Influenced by early cybernetics and systems theory.
- Significant precursor to ABM was cellular automata (von Neumann and Ulam) in the 1940s.
- Early application of ABM was Thomas Schelling's segregation model (1971).
- Adoption in economics and social sciences n the late 1990s and early 2000s, with growing cross-disciplinary applications.

## Three Schools of Agent Thinking

- Artificial Intelligence – AI
  - Agents as autonomous identities solving problems
- Multi-Agent Systems – MAS
  - Distributed control of systems, software
- Agent-Based Modelling (and Simulation) – ABM(S)
  - Simulating (real world) phenomena

*No hard boundaries, see Horton (2023).*

## Thesis of the Approach (Fundamental for Social Science)

*“Fundamental social structures and group behaviors emerge from the interaction of individual agents operating on artificial environments under rules that place only bounded demands on each agent’s information and computational capacity.”*

Epstein and Axtell (1996)

# When to Use Agent-Based Modelling

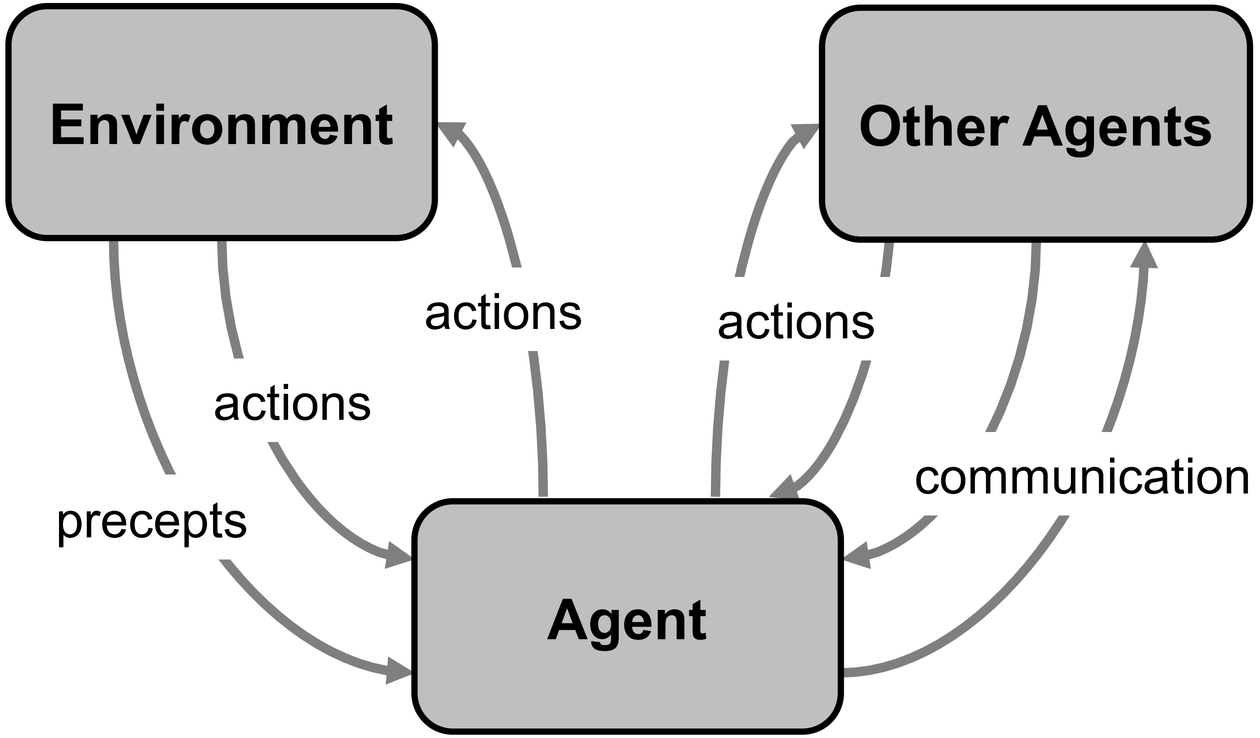
- When there is a natural representation as agents.
  - Decisions and behaviours can be defined **discretely** (with boundaries).
  - When it is important that agents **adapt and change** their behaviour.
  - When it is important that agents learn and engage in **dynamic strategic behaviour**.
  - When it is important that agents have a dynamic relationships with other agents, and agent **relationships form and dissolve**.
  - When it is important that agents **form organizations** and adaptation and learning are important at the organization level.
  - When it is important that agents have a **spatial component** to their behaviours and interactions.
- When process/structural change needs to be a result of the model, rather than an input to the model.

# Components of ABMs

- Agents
  - Characteristics
  - States
  - Rules

Behaviour

- Environment
- Time




North and Macal (2007); Railsback and Grimm (2012); Salamon (2011)

# Agent Characteristics (Essential)

- Self-contained, modular and uniquely identifiable.
  - Modularity requirement implies that an agent has a boundary.
  - Attributes that allow the agent to be distinguished from / recognized by other agents.
- Autonomous and self-directed.
  - Function independently in its environment and in its interactions with other agents.
  - Behaviour that relates sensed information to decisions / actions.
- Has a state that varies over time.
  - State represents the essential variables associated with its current situation.
- Social having dynamic interactions with other agents.
  - Protocols for interaction and ability to recognize and distinguish the traits of other agents.

# Agent Characteristics (Optional)

- May be adaptive.
  - Ability to learn and adapt its behaviours based on its accumulated experiences.
  - Populations of agents may be adaptive through the process of selection.
- May be goal-directed.
  - Compare the outcome of its behaviours relative to its goals and adjust its responses and behaviours in future interactions.
- May be heterogeneous.
  - Agent characteristics and behaviours may vary in their extent and sophistication.
  - Endowed with different amounts of resources or accumulate different levels of resources as a result of agent interactions, further differentiating agents.

## Agent States

- *Difference between agent state and behaviour and model state and behaviour.*

- State that represents the essential variables associated with its current situation.
  - Resources or knowledge that agents know or have (including memory).
  - Can be private or public.
  - Can be static or dynamic and can depend on the rules.
- State of an agent is a composite.
  - Internal and local and global.

North and Macal (2007); Railsback and Grimm (2012)

## Agent Rules and Behaviours

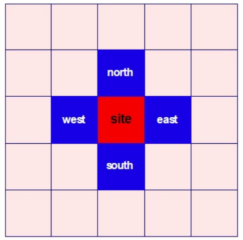
- Agents' “internal models”
- Decision and transformation rules → from inputs and states to action and behaviour
- Can be static or dynamic
  - Adaption

Epstein & Axtell (1996); North and Macal (2007)

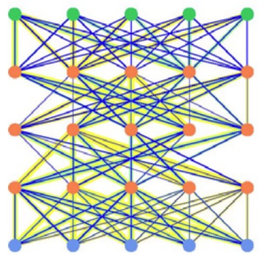
## Environment

- Surrounds the agent population.
- Provides the agent with information and structure.
- Everything that is not an agent but is relevant.
- It affects the agents and the agents can affect it.
- Exemplary structures:

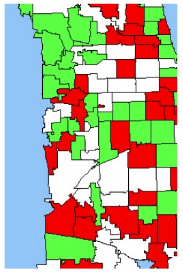
**Euclidean Space: *2D, 3D***




**Grid: *von Neumann neighborhood***



**Network**



**GIS: Geographic Information System**

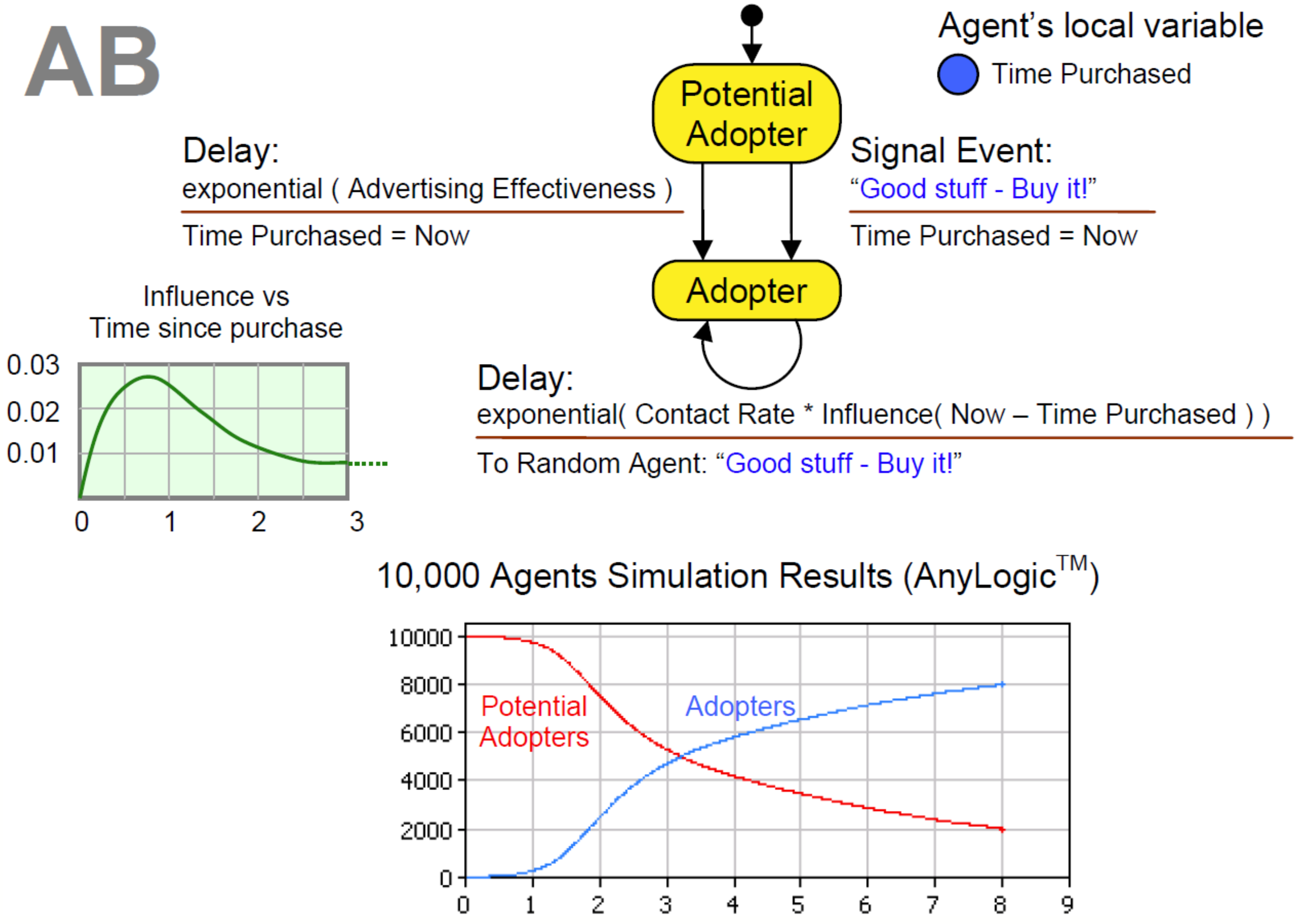
North and Macal (2007); Railsback and Grimm (2012)

# Time

- Time handling can be discrete or continuous.
  - Time progresses in ticks.
  - Ticks are similar to dt in SD.
- Between two ticks, everything is assumed to happen at the same time, attempting to simulate the parallelism in the real world.
- As computers are serial processing machines, the order of agent iteration is very important.

North and Macal (2007); Railsback and Grimm (2012)

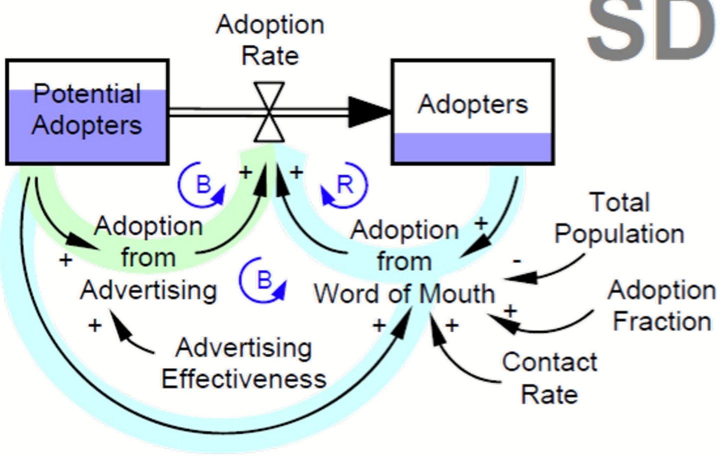
# Example: Diffusion of Innovation



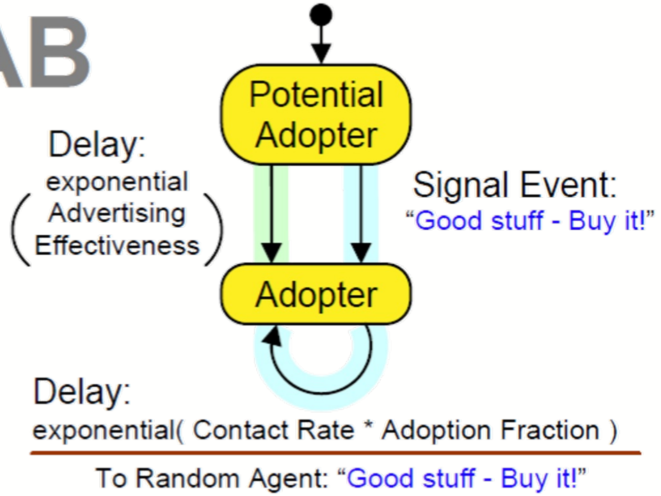

Borshchev and Filippov (2004)

# Example: Diffusion of Innovation

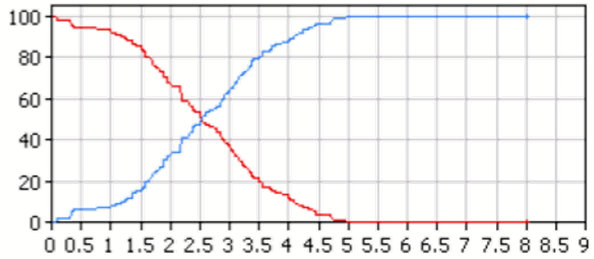
SD



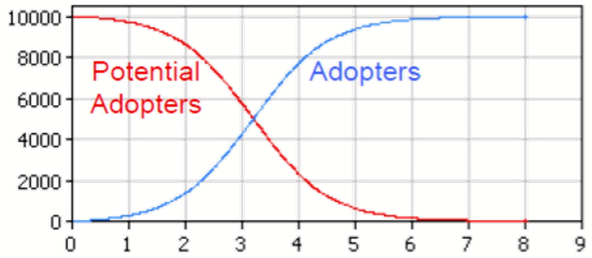

AB



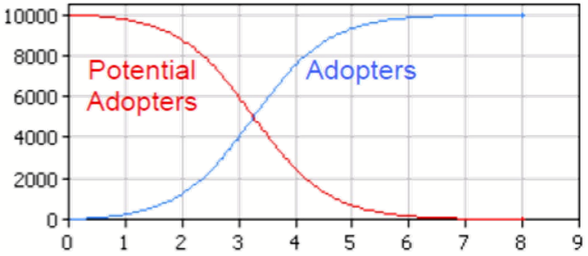

100 Agents Simulation Results (AnyLogic™)




SD Simulation Results (AnyLogic™)




10,000 Agents Simulation Results (AnyLogic™)



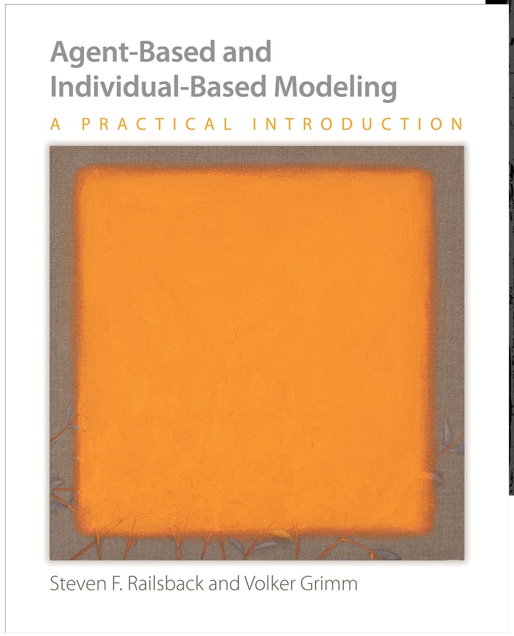

Borshchev and Filippov (2004)

# Agent-Based Modelling Practice

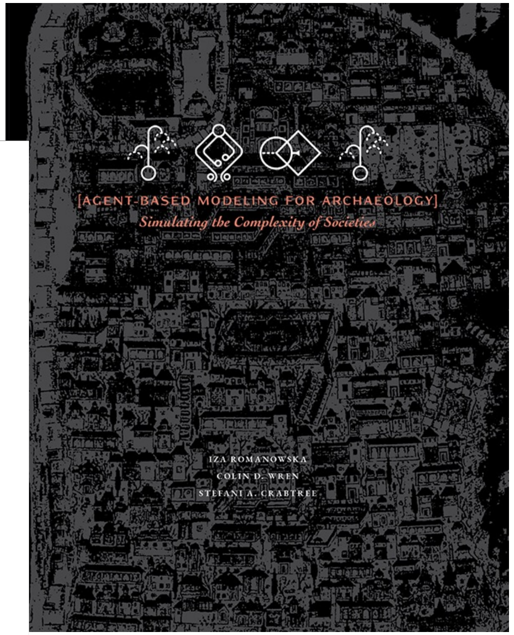
- Go to https://github.com/BWurth/workshop-eerss24 and navigate to the '**practice_abm**' folder and have a look at either or both of the following:
  - NetLogo: Diffusion.nlogo
  - Python: main.py (needs to be copied into a new project)

- Help with AgentPy: https://agentpy.readthedocs.io/en/latest/
- NetLogo Tutorials: https://ccl.northwestern.edu/netlogo/docs/sample.html

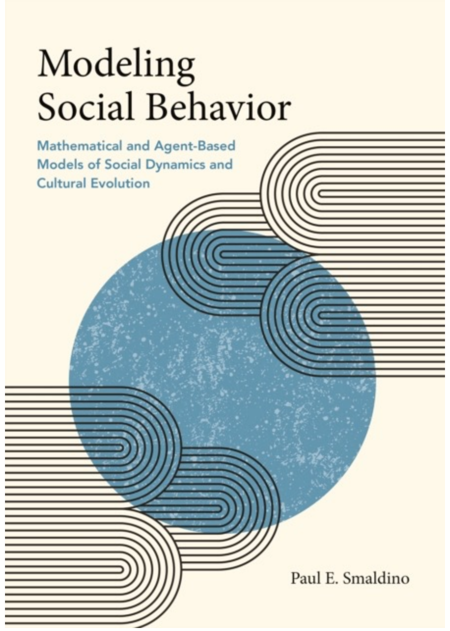
# ABM Resources



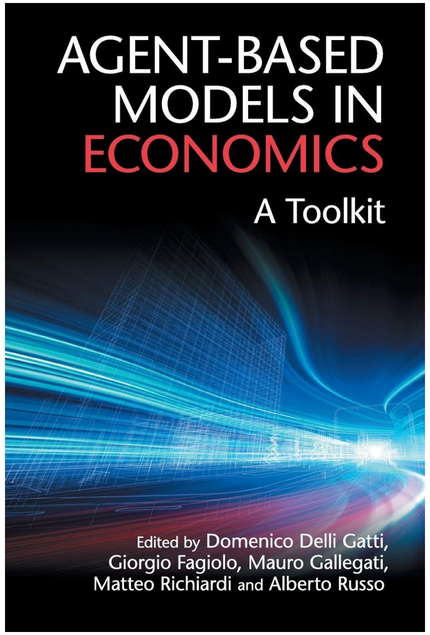

Railsback and Grimm (2012)
→ NetLogo



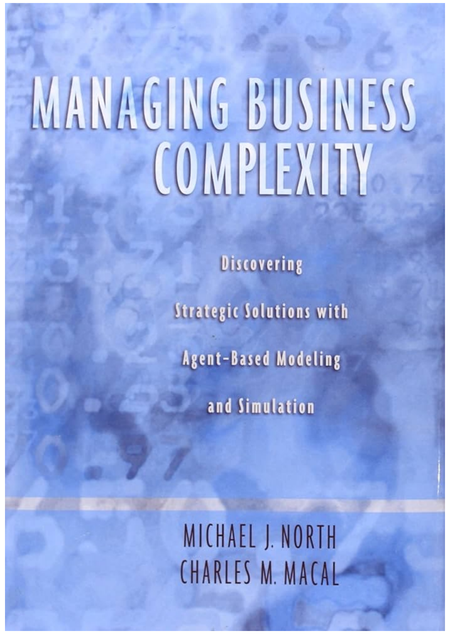

Romanowska et al. (2021)
→ NetLogo
→ Free ebook




Smaldino (2023)
→ NetLogo




Gatti et al. (2018)
→ Economics




North and Macal (2007)
→ Business

# Feeling inspired?

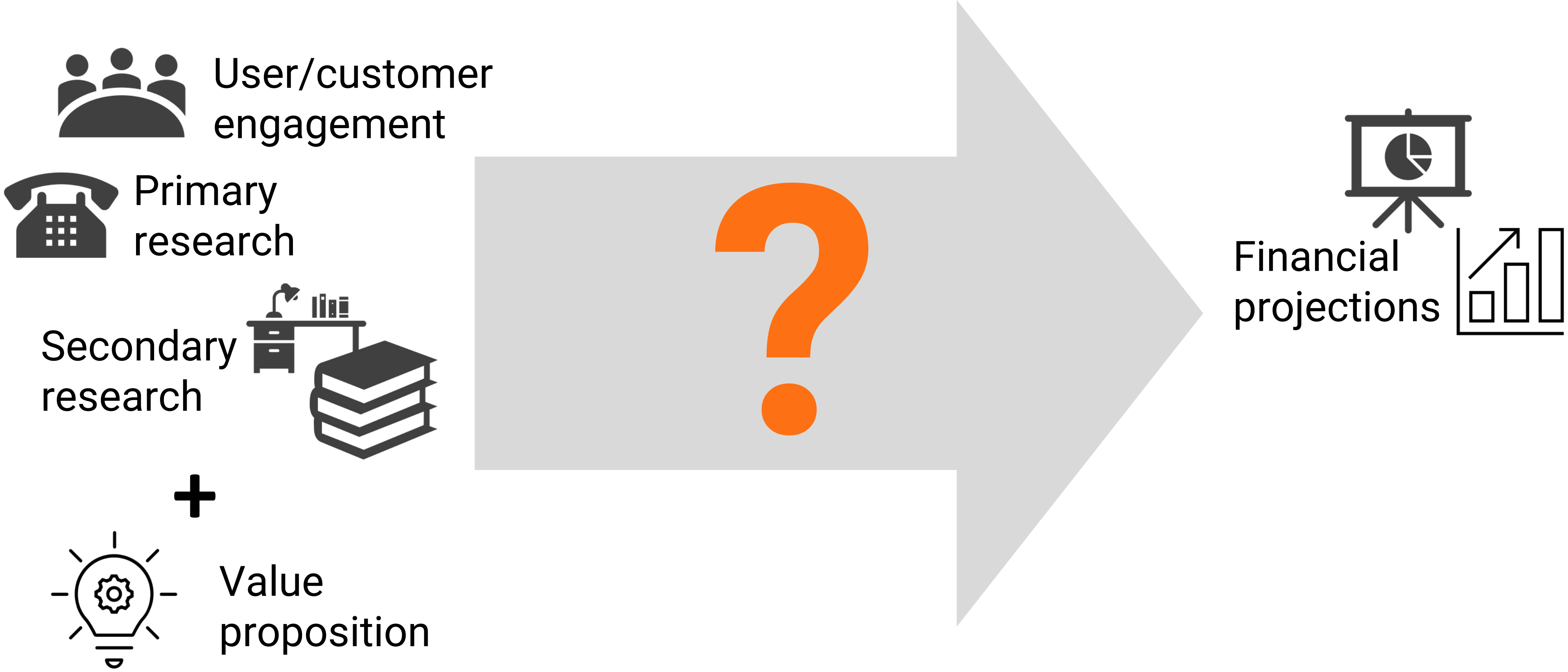
- What is/are your key takeaway(s)?
- How could this be used in or combined with your research?
- New research ideas/avenues?
- Anything that we didn’t cover that you would like to know more about?

# Venturithm

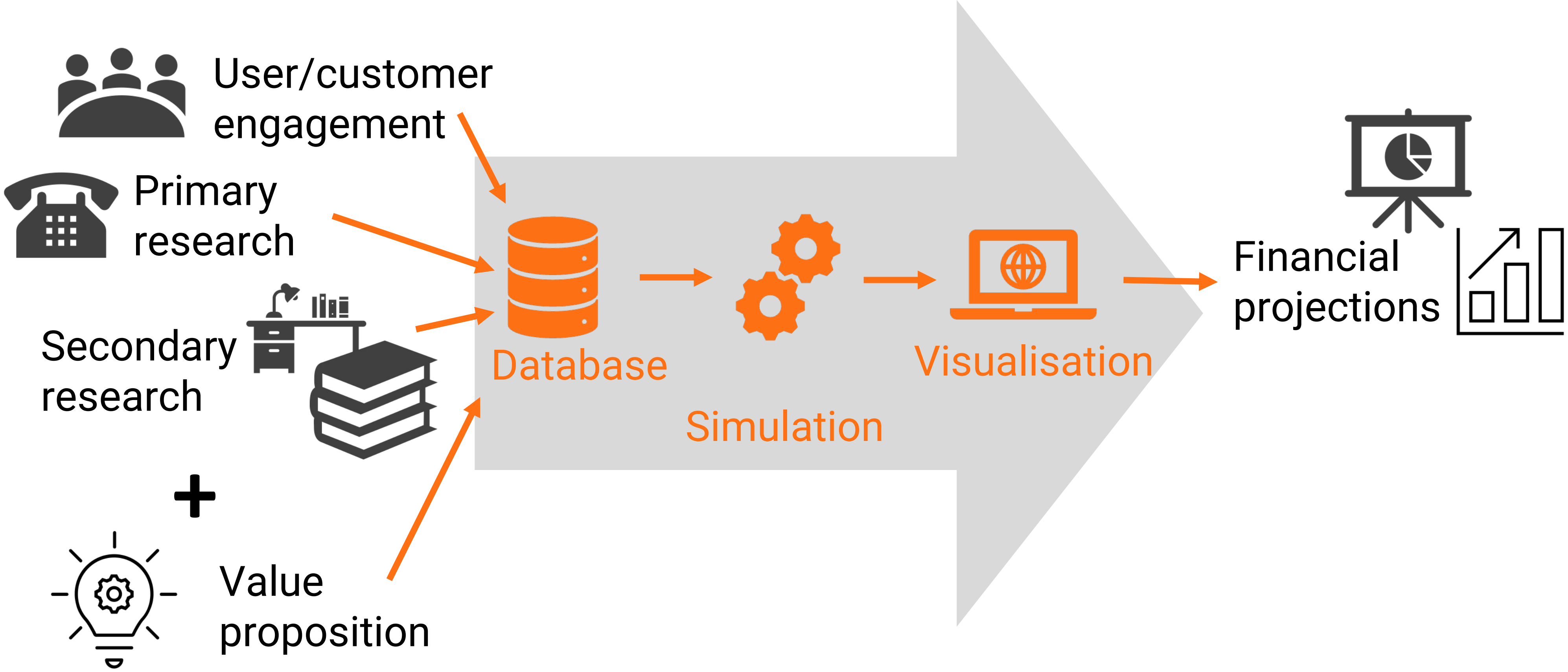
4

**Venturithm** is the only platform on the market that allows you to more fully understand your venture and its potential.

# The Problem


User/customer engagement
Primary research
Secondary research
+
Value proposition
?
Financial projections

# The Solution: Venturithm



# How we help…

**…entrepreneurs:**
use one platform to build, experiment, and scale your new venture!

**…universities and educators:**
teach entrepreneurship in an interactive and engaging way based on students' own ideas.

**…incubators and accelerators:**
provide tailored support and mentoring for your cohorts and identify issues quickly.

**…investors and funders:**
scrutinise inputs instead of assumed outputs and get confidence in start-ups and founders.

Dashboard Compare versions Cohorts

B Welcome Bernd!

Venturithm - Version: UK Universities

Cancel

Save draft version

1 2 3 4 5 6

## General

Help with this Section

What is the name of your venture? *

Venturithm

What is the name of this version? *

Version: UK Universities

Who is part of the team?

Enter value here

What is the aim of this version?

Enter value here

What are your mission and vision for this venture? *

Mock mission

What is your slogan or tagline? *

Mock slogan

Dashboard Compare versions Cohorts

B Welcome Bernd!

Venturithm - Version: UK Universities

Cancel | Save draft version

1 2 3 4 5 6

## Customer & Value Proposition

Help with this Section

Who is the end user of your product or service?

Students in the UK

What percentage of your customers is aware of the problem? *

0% 25% 100%

Do potential customers who are aware of the problem actively search for solutions and options?

Yes No

How novel is your product or service? *

0 0.6 1

Which problem do you solve or what do you do for your end user?

Mock problem solved

What does your target user currently do? How do they address or cope with this problem?

Enter value here

How complex is the decision-making process of your customer or user? *

Medium

# Help us turn this...

# ...into this!

**Let's create a better way to build and grow new ventures.**

**Thank you for your support!**

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University of Glasgow

# Thank you!

If you have any questions, please get in touch:
bernd.wurth@glasgow.ac.uk