An introduction to Agent-Based Modeling

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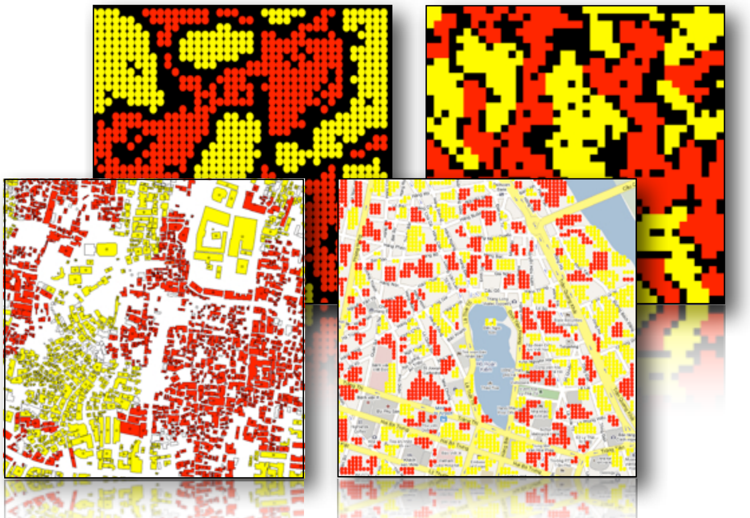
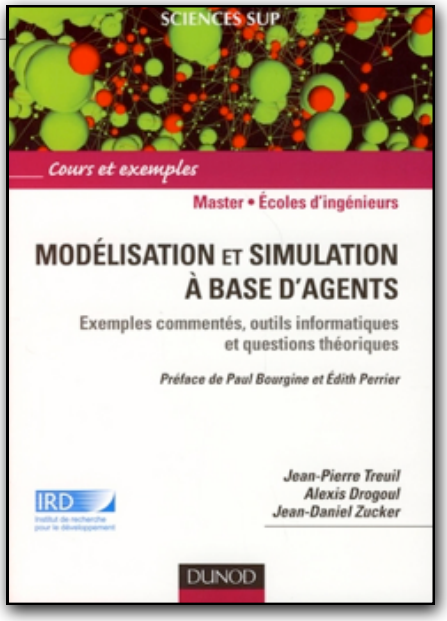


Summary

- This introduction is intended to provide a common vocabulary and some insights into agent-based modeling. Formal definitions, as well as much more developed examples, can be found in the book.
- What we will cover this morning:
  - Models and meta-models
  - Models and simulation
  - Agent-Based meta-model
  - Examples
  - Agent-Based modeling platforms

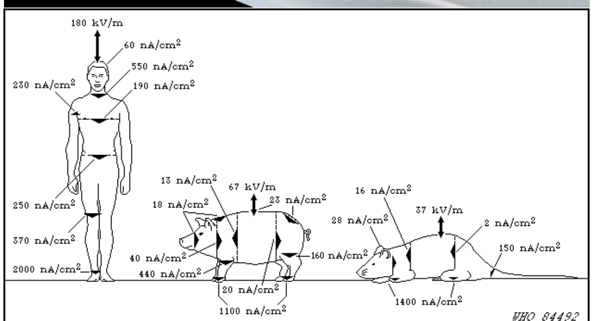


Modeling

- Modeling is the activity by which scientists **build models** (Hartmann 1894).
- It is one of the two main components, with **experimentation,** of the scientific method: researchers spend a lot of their time for building, testing, comparing and revising models, and a number of publications are dedicated to the presentation, application and interpretation of models.
- **But what is exactly a model ?**

Modeling: physical models

- We will not talk about this category of models, which are artefacts built in the real world, since the models we will be covering are designed in order to be simulated on computers.
- However, they will share some properties with the models we will use.



Grounded man, pig, and rat exposed to vertical, 60-Hz, 10-kV/m electric field. Relative body sizes are not to scale. Surface electric field measurements for man and pig and surface field estimates for rats are shown. Estimated axial current densities averaged over selected sections through bodies are shown. Calculated current densities perpendicular to the surface of body are shown for man and pig (From: Kaune & Phillips, 1980).

Models

- **Model (definition)**

It is an abstract construction that allows to understand a **reference system** by answering some **questions** about it.

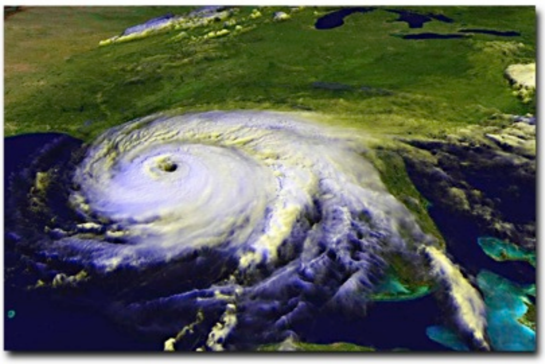
It is a simplified representation of this system, built upon a general **theory** and written in a **modeling language**.

The theory and the language are both specified using a dedicated **meta-model**.

- **The vocabulary underlined is explained after.**

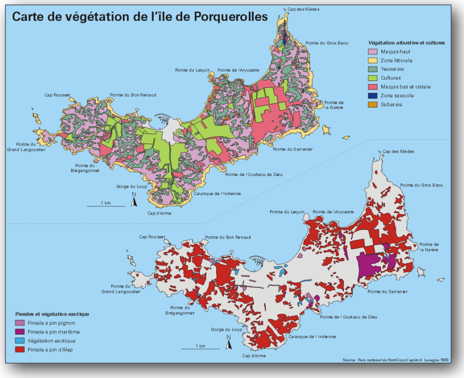
Modeling : Reference system

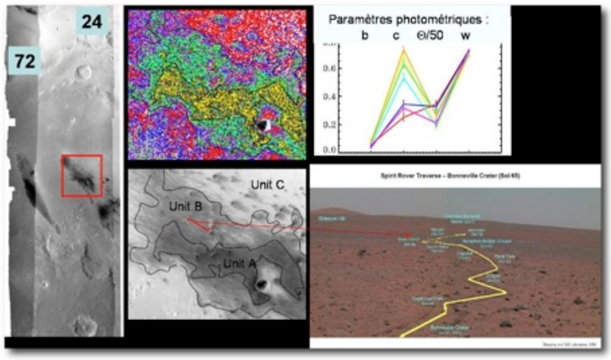
- It is a **part of reality** chosen by scientists, experts, ...
- This part of reality is known thanks to **measures**, **observations** or **experimentations** that produce **data.**
- This data can be of different natures (qualitative, quantitative) and can come from different organisations levels of the reference systems.



Modeling : Question

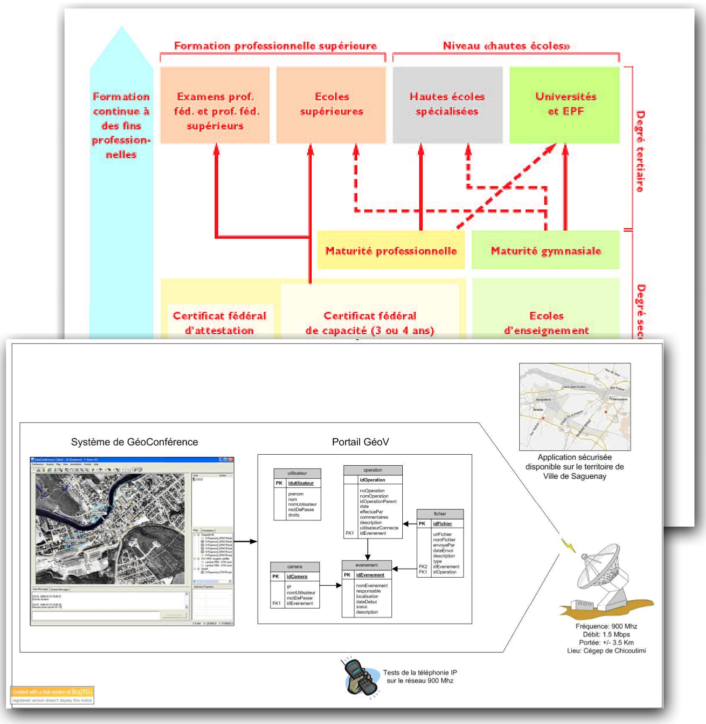
- It is usually the necessity to **find a meaning** (relationships, prediction, understanding, etc.) **in this data** that gives birth to the **modeling question**.
- When the model is used as a support for simulations, the question addressed by the model and that addressed by the simulation are usually the same.





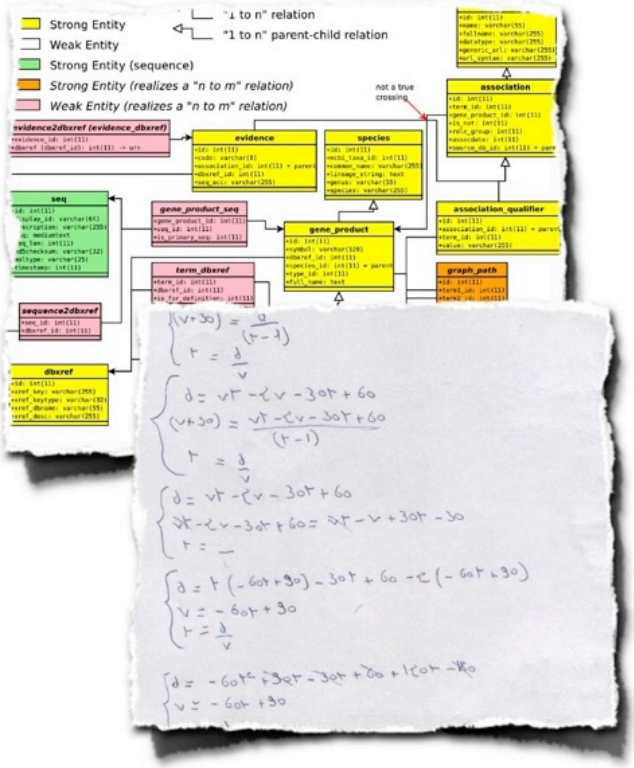
Modeling : simplification

- Models are **abstract and simplified representations** of a reference system.
- A model is therefore **not the system it describes**, but a simplification of it, easier to manipulate and experiment.
- The simplification is based upon hypotheses of the scientific domains involved, or a choice to limit the complexity to take into account.



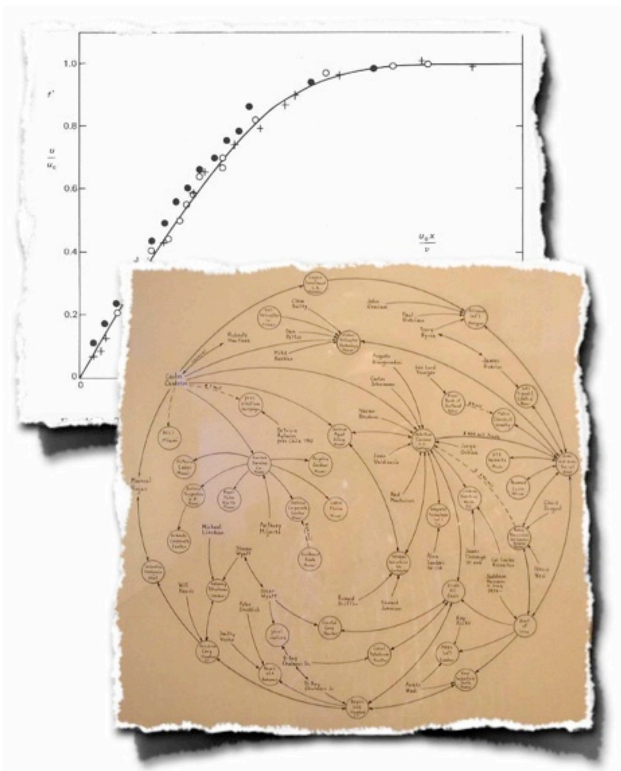
Modeling : language

- Every model is written in a **modeling language**. Its choice depends on many things: traditions, considerations on wanted properties (generalization, analytical demonstration, translation in a computer program, etc.). A modeling language is <u>not</u> <u>necessarily formal.</u>
- A same reference system can be described by different **reference models**, written in **different modeling languages**.
- Its semantic and syntax are built upon abstractions and relations between these abstractions that are described in a **metamodel** (defined later).

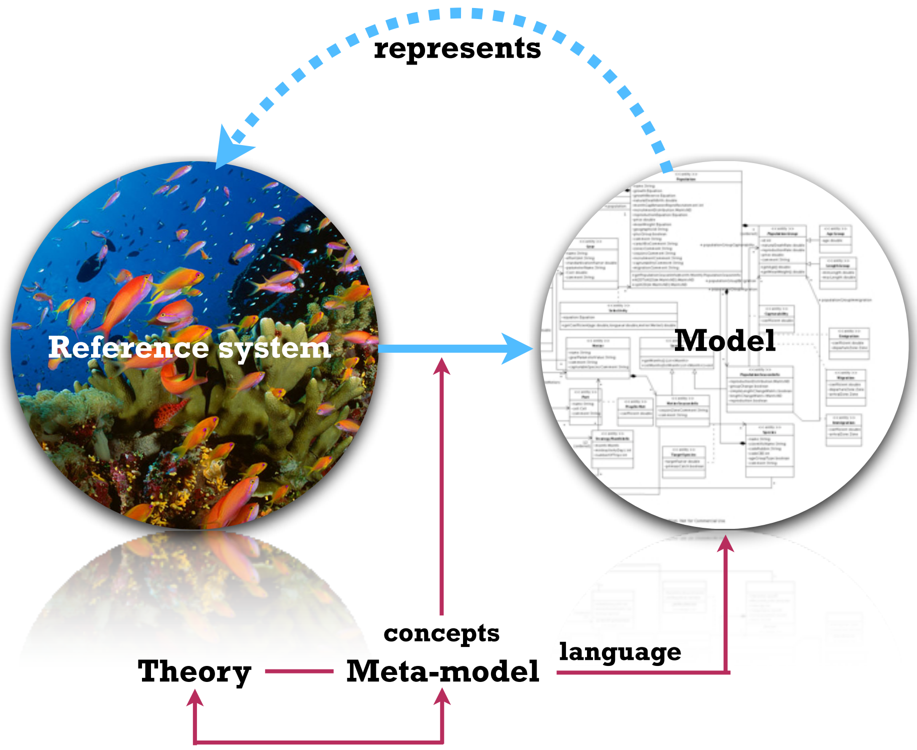


Modeling : theory

- A model illustrates a **theory**, but <u>is not a theory</u> (however, in practice, the two terms are often used with the same meaning).
- The relationship between theories and models is a relationship between the general and the specific (classes and instances, species and individuals, etc.): a theory is meant to describe common properties of a **set** of reference systems, and the model is an **instantiation of a theory** for a specific system.
- The theory is usually defined in the **metamodel** as well.



Summary on models



Modeling : Genericity (lack of)

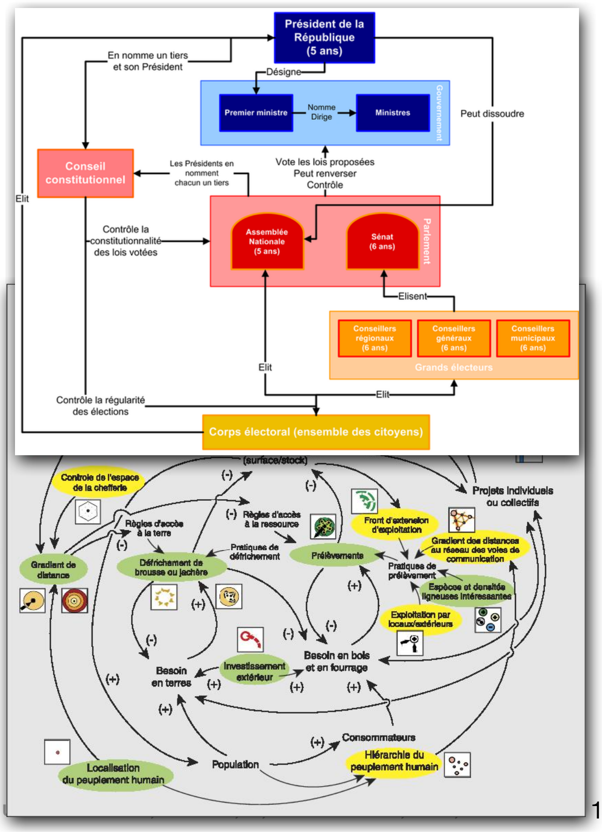
- There is no such thing as **a « generic model »** of a reference system.
- A same system can generate **many different questions** and each of these questions can give birth, depending on the theory chosen, the data available, to **different models expressed in different languages.**
- No generic model of road traffic, ecosystems, ant colonies, but specific models intended to answer one or several questions:
    - What are the conditions for a traffic jam to appear ?
    - What is the influence of agriculture on animals ?
    - How can ants find resources and exploit their environment ?
    - ... Etc...

Modeling : multiplicity

- Conversely, it is possible to design a **multiplicity of models**, each of them based on different meta-models in order to **answer the same question** about the reference system.
- As an example, the formation of traffic jams can be studied using microscopic models (where each vehicle is represented individually) or macroscopic models (where all the vehicles are represented as a flow).
- The choice of models to use will depend, for a large part, on the data available and the facilities offered by the metamodel for translating the original question.
- **Not all models can become supports for simulations.**

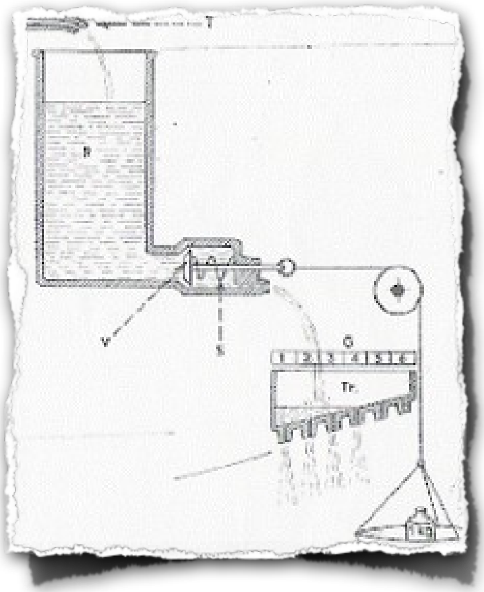
Static/dynamic models

- A model is called **static** when it is the representation of a reference system without any reference to its evolution in time.
- Conversely, a model is called **dynamic** when it includes in its representation some hypotheses or rules that concern the evolution of the reference system.
- ***Simulations are built upon dynamic models.***



Simulation

- The term of « simulation » has been used in Science long before the first computers have appeared (with the meaning of « **imitating a process by another** »).
- It is thanks to the availability of powerful computer systems that this practice has become part of numerous scientific domains: the term of “simulation” now only means **computer simulations**.
- There are **three possible definitions** of *simulation* (but only one interesting for us).



Simulation (1) : Gilbert/Troitzsch

- Popular definition in Social Sciences (cf. Gilbert et Troitzsch, “*Simulation for the social scientist*”).
- Considers that computer simulation is simply a subset of modeling, which consists in designing (and testing) **dynamic models.**
- In this perspective, simulation is not an activity by itself, but a simple consequence of the manipulation of time in some models.
- Says nothing about how to **build** simulations.

Simulation (2) : Trick

- For this author (cf. Michael Trick, “*Introduction to Simulation*”), relationships between modeling and simulation are a little bit more complex.
- Its definition is close to that used in experimental sciences like biology or physics.
- He describes simulation as an activity by itself, which, « *for a [dynamic] model, has the goal of building **experimental mechanisms** that will make the model react in the same way than the reference system on important aspects”*
- However, is simulation only an activity dedicated to building mechanisms ?

Simulation (3) : Shannon

- The third definition considers that **simulation is to a dynamic model what experiments are for the reference system**.
- «[Simulation is] *the process of designing a model of a real system and conducting experiments with this model for the purpose of understanding the behavior of the system and / or evaluating various strategies for the operation of the system* » (Robert E. Shannon, “Introduction to simulation”)
- This definition describes *simulation* as **a specific activity** with its rules, methods, and a **role in scientific exploration.**

Simulation : simple definition

- Based on that of **experimentation** in Science:

Experimentation

Activity by which, with respect to **precise goals**, and with the help of experimental mechanisms, one perturbates a real system to understand its functioning.

Simulation (simple definition)

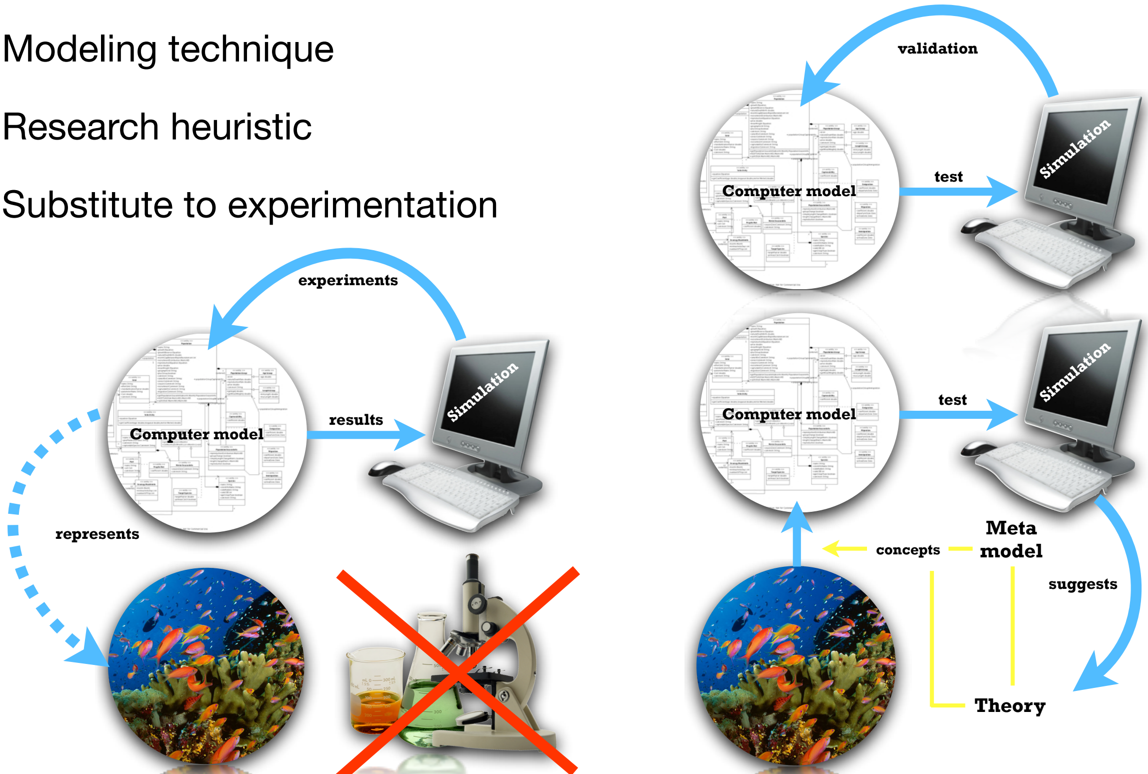
Activity by which, with respect to **precise goals**, and with the help of an experimental mechanism (called **simulator**), one perturbates a **dynamic model** to understand its functioning.

Computer simulation

- Simulation is then to a dynamical model what experimentation is to a target system.
- Consists in running and perturbing a model in a controlled way to answer specific questions.
  - By, at least, varying time.
  - By repeatedly running it with different parameters
  - By modifying its structure

Goals of simulation (in Science)

- Modeling technique
- Research heuristic
- Substitute to experimentation



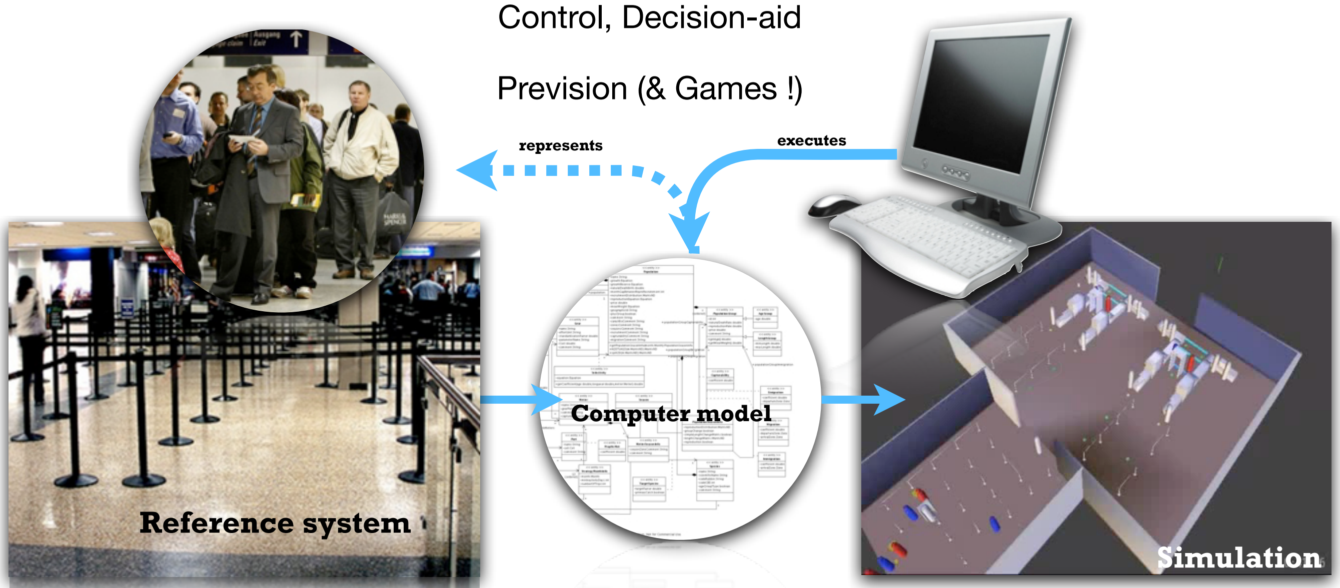
Goals of simulation (applications)

Validation, Understanding

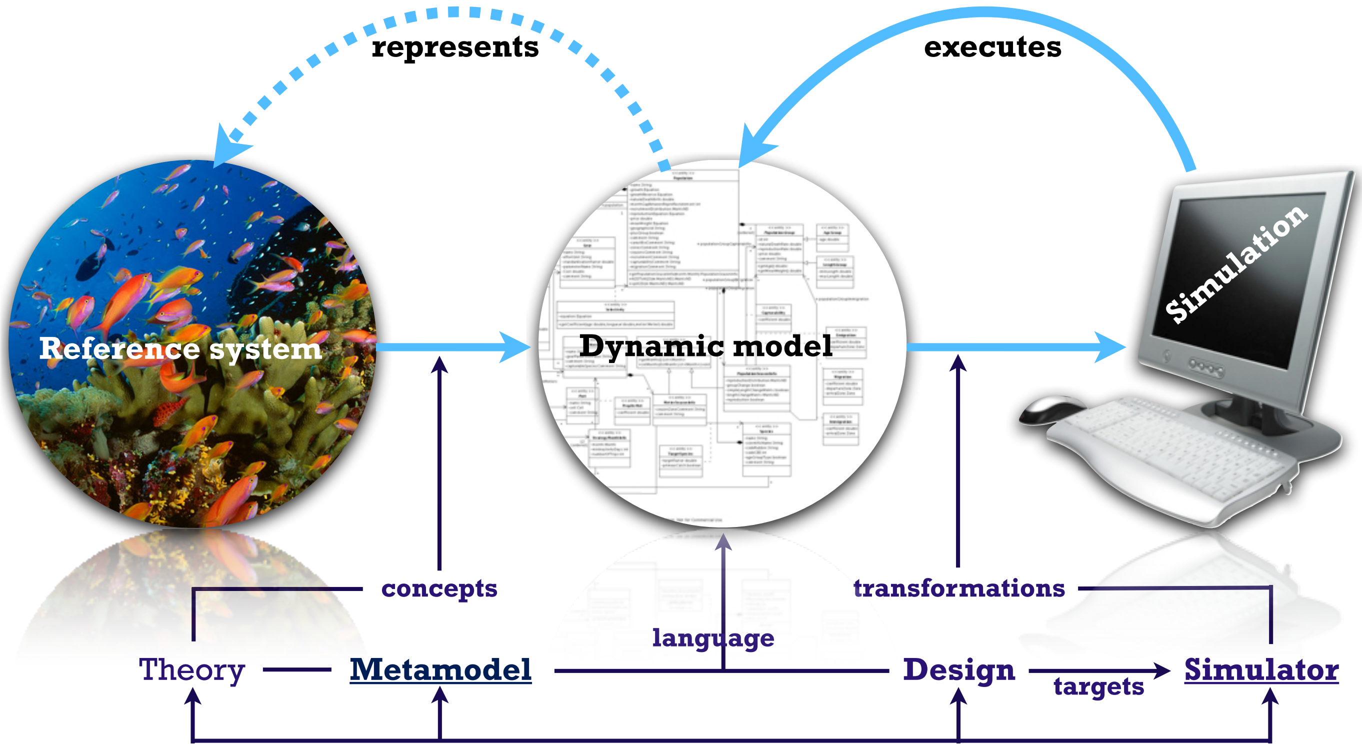
Visualization,Training,

Control, Decision-aid

Prevision (& Games !)

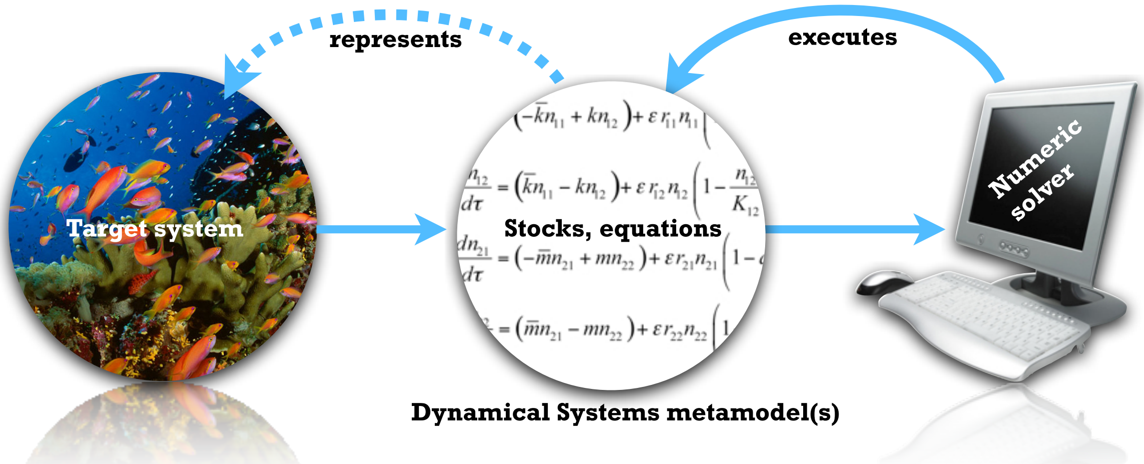


Summary on simulation



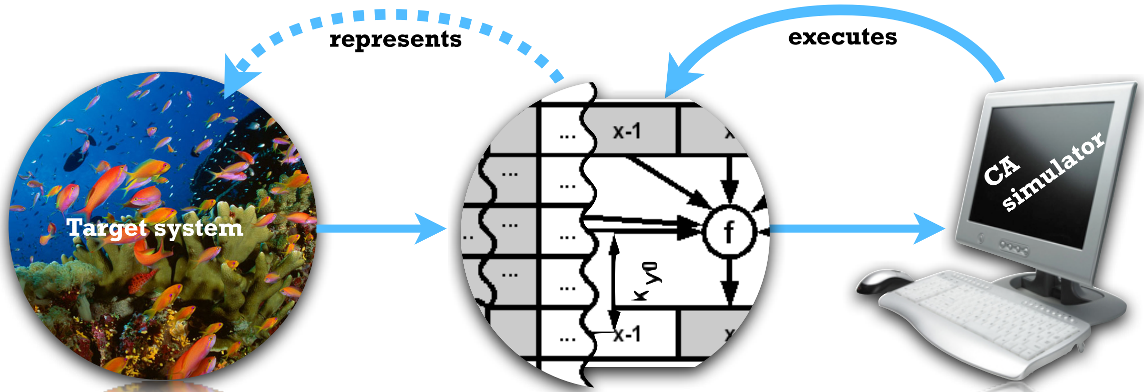
Metamodels

- Metamodel: specifies the language (concepts & syntax) and the entities to use for modeling a system. **Numerous metamodels are used in computer simulations.** They, however, do not all allow to answer the same questions.
- The most used are the different "dynamical systems" metamodels, which usually allow to describe a system at a "global" level, and are also aimed at analytical resolution (rather than simulation)



Metamodels: cellular automata

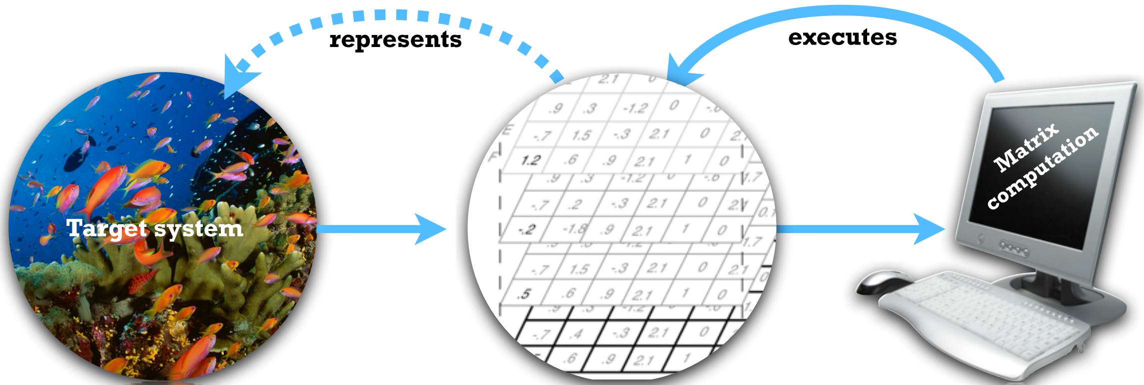
- **Cellular automata metamodels** are based on the description of grids of discrete entities (**cells**), which can be in a finite number of **states**. The transitions from one state to another are controlled by **rules.**
- Allows to take into account an explicit notion of space (neighborhood), and to study dynamics emerging from the interactions between discrete entities.



Cellular automata (neighbouring cells & states)

Metamodels : micro-simulation

- **Micro-simulation metamodels** operate at the level of "individual units". Within a model each unit is represented by a record containing a set of associated attributes. Global rules (transition probabilities) are then applied to these units leading to simulated changes in state.
- Micro-simulation allows to take into account the notion of heterogeneity amont "individuals" and study its effects.



Micro-simulation (matrices of individuals, transition rules)

Metamodels : agent-based

- A more complete definition will be given later. However, agent-based metamodels can be described as a further aim to take into account, in a model, the heterogeneity of individuals and the locality in space.
- Basically, an agent-based model is composed of individual units, situated in an explicit space, and provided with their own attributes and rules.

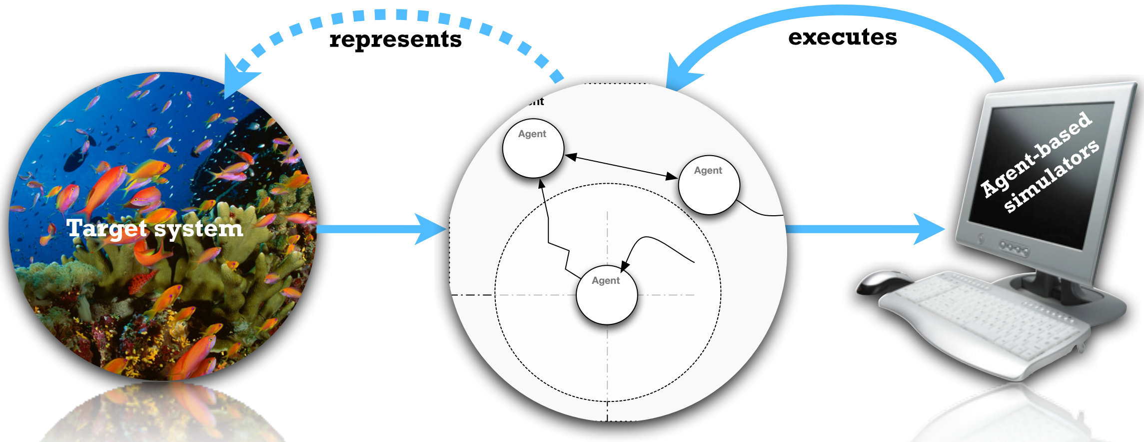
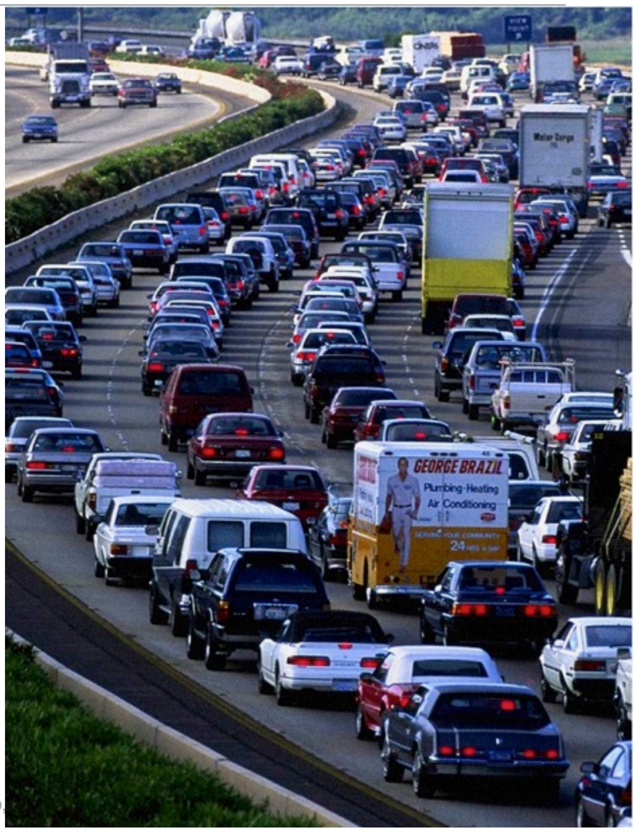


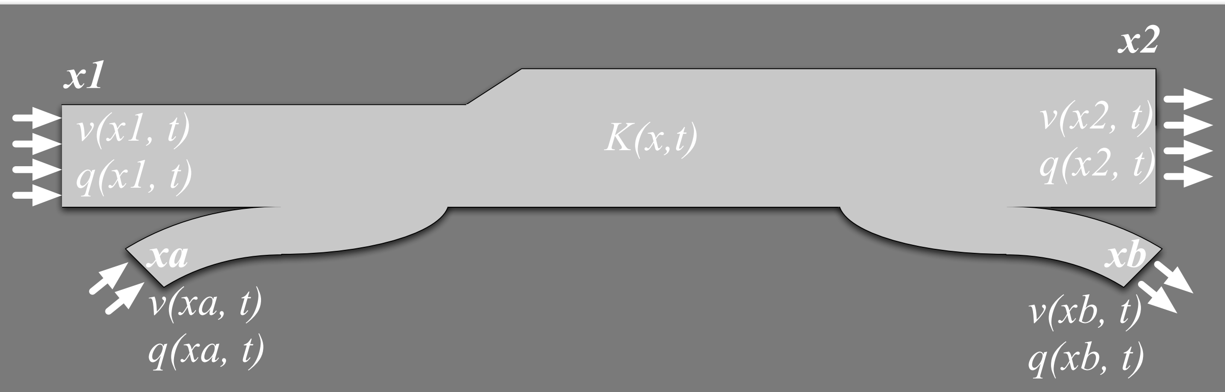
Illustration : road traffic

- Traffic jams, delays,...
  - How to understand them ?
  - How to anticipate them ?
  - How to control them ?
- Difficulties
  - “Experiments” are difficult
  - Reproduction is impossible
  - A classical scientific approach is difficult to use
- Simulation is the only solution.



Macroanalytic metamodels

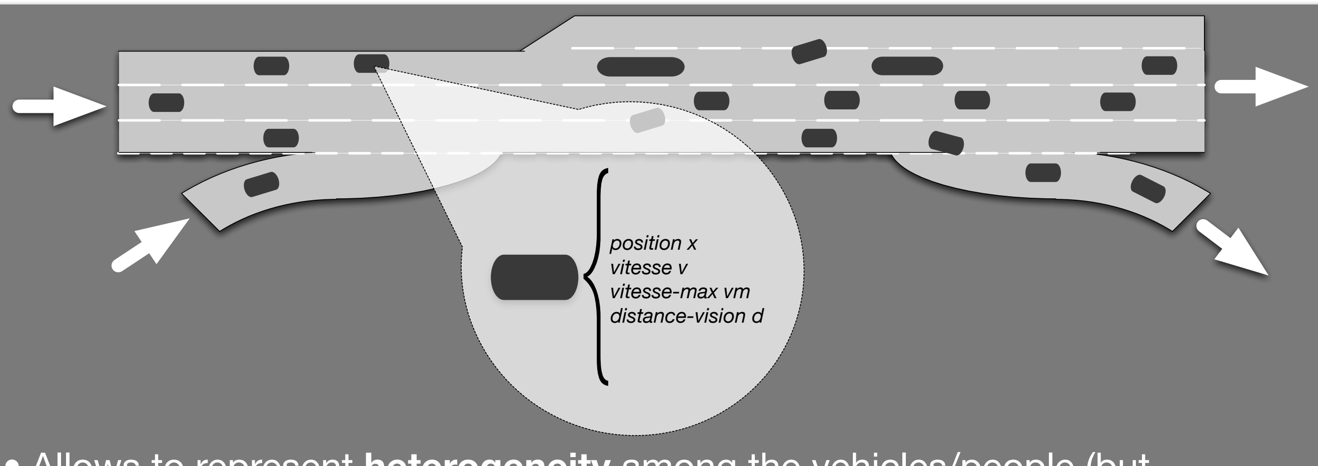
- Usually based on a (physical) analogy between the flow of traffic and the flow of a fluid in a pipe.



- Flow of vehicles characterized by macroscopic attributes, individual behaviors averaged in global equations.

Microanalytic meta-models

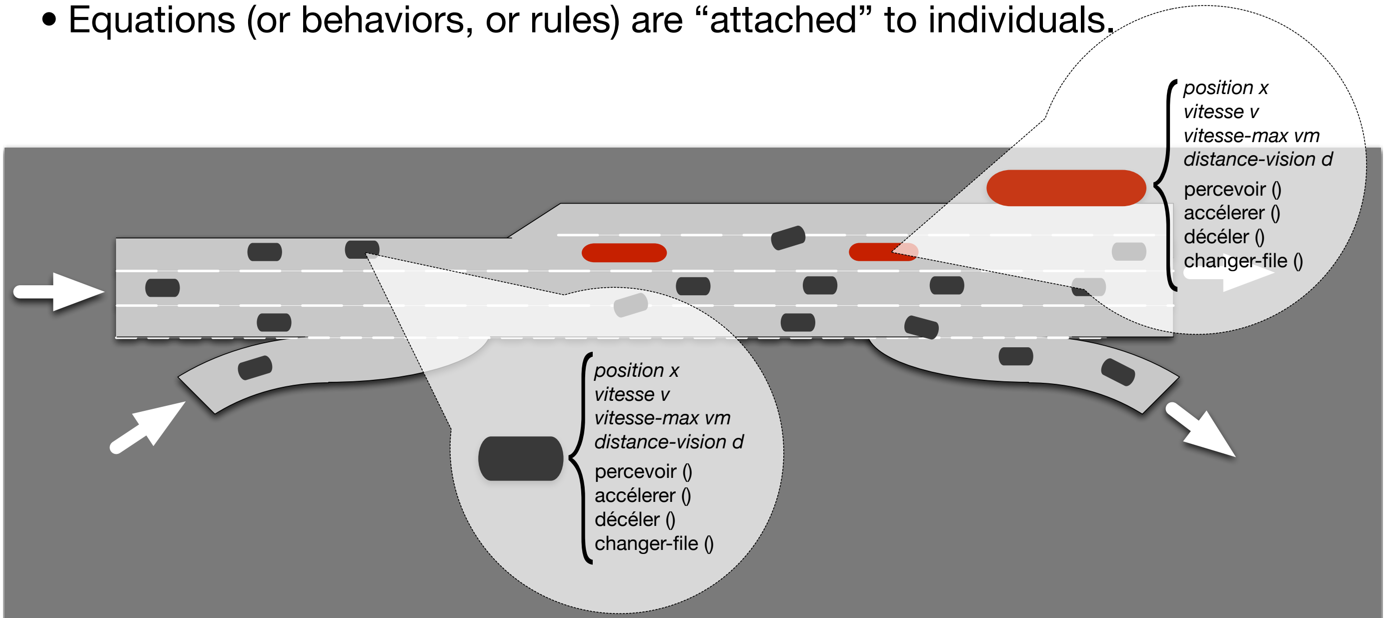
- Each vehicle is represented by a vector of attributes, which is modified by global equations.



- Allows to represent **heterogeneity** among the vehicles/people (but only in terms of attributes: transition rules are still global)

Individual-based meta-models

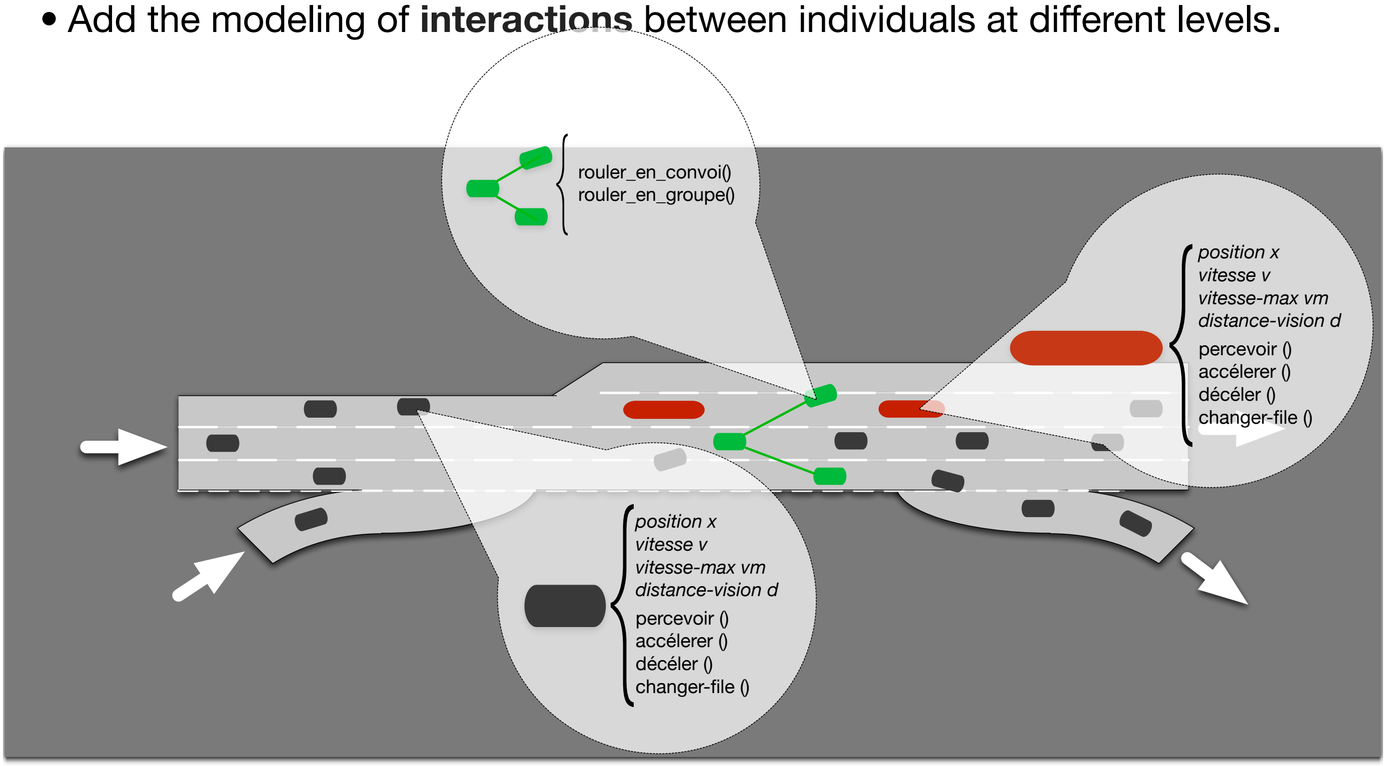
- Equations (or behaviors, or rules) are “attached” to individuals.



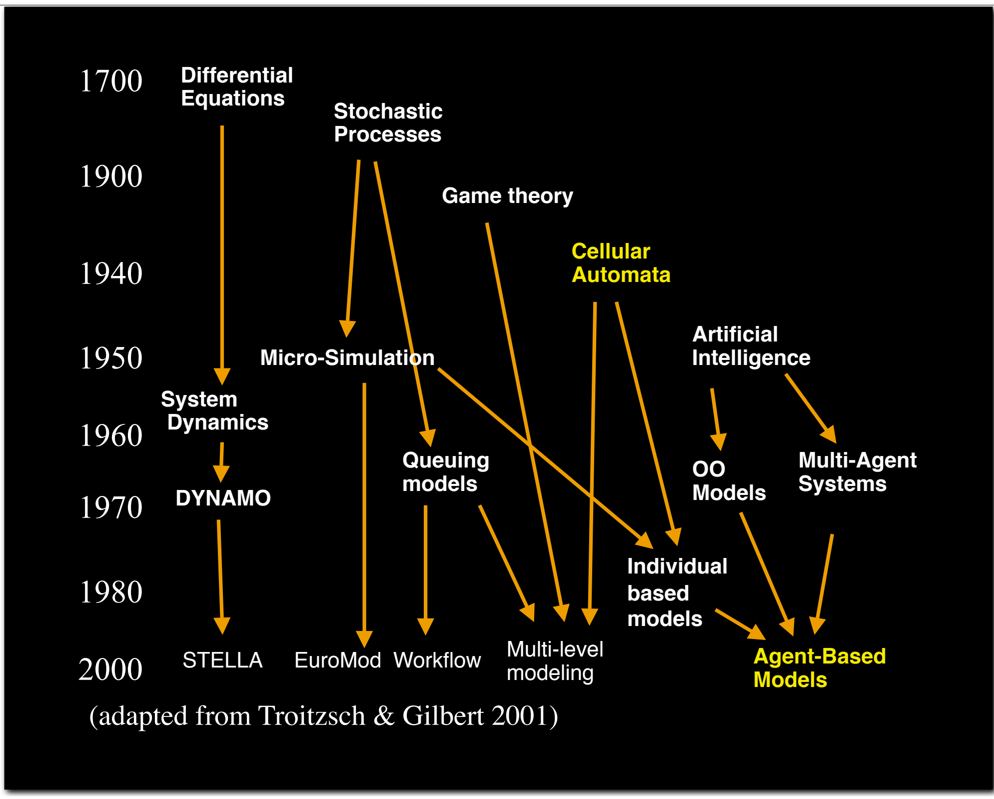
- Allow for **heterogeneous behaviors** and stochasticty.
- Analytical results impossible to obtain: **simulation is the only possibility.**

Agent-based meta-models

- Add the modeling of **interactions** between individuals at different levels.

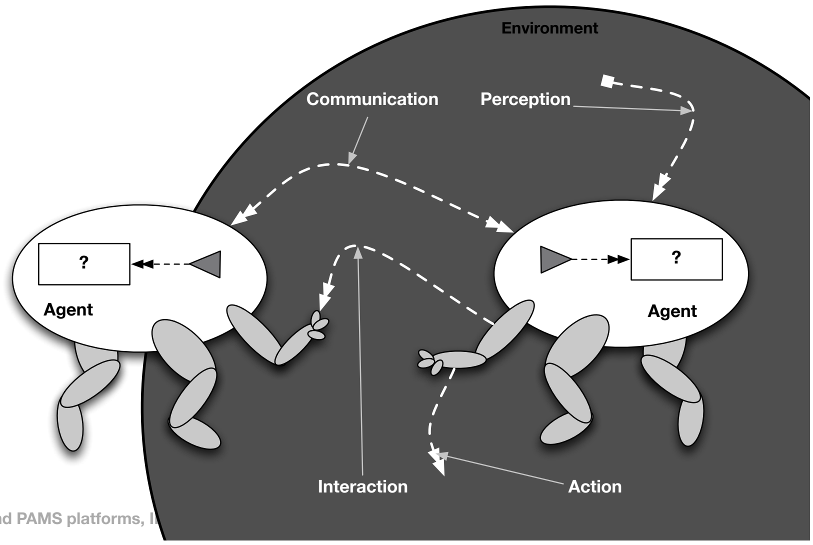


Brief history

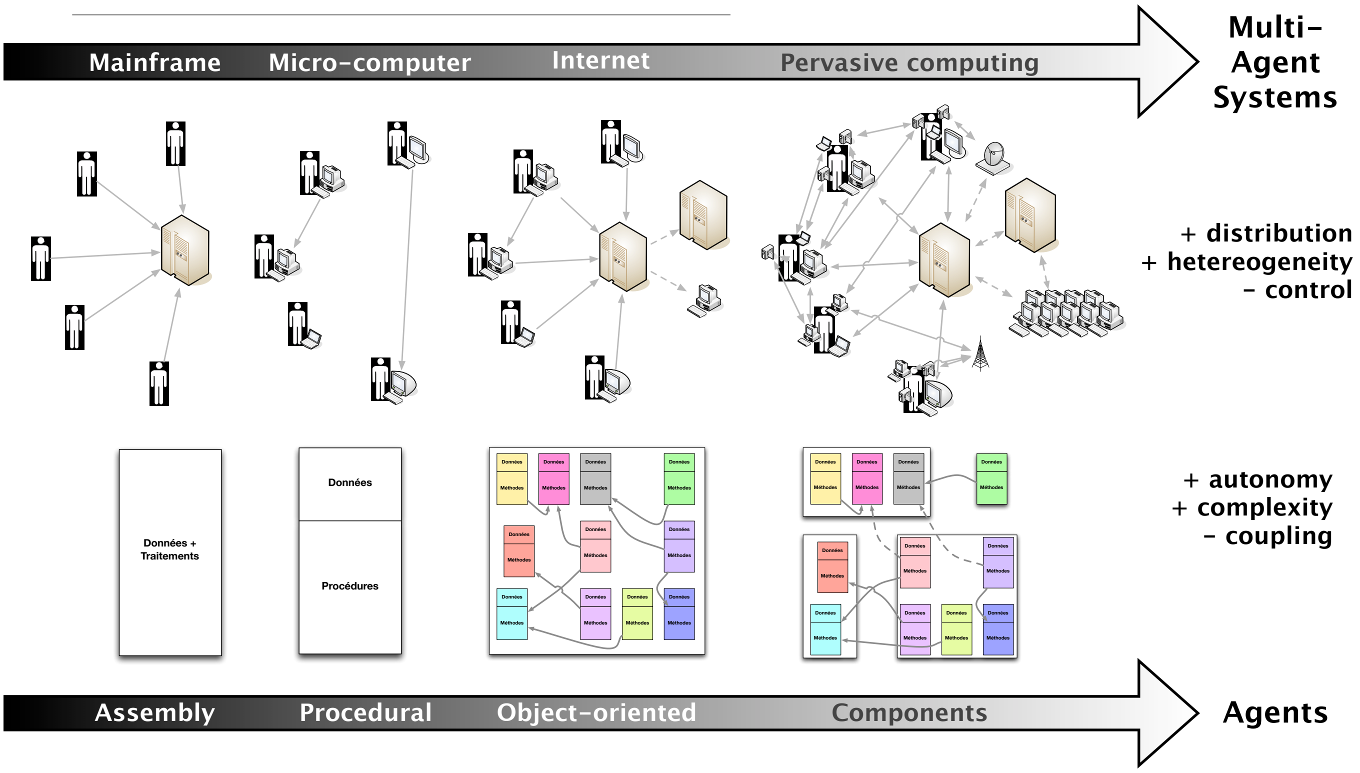


Agent-based models

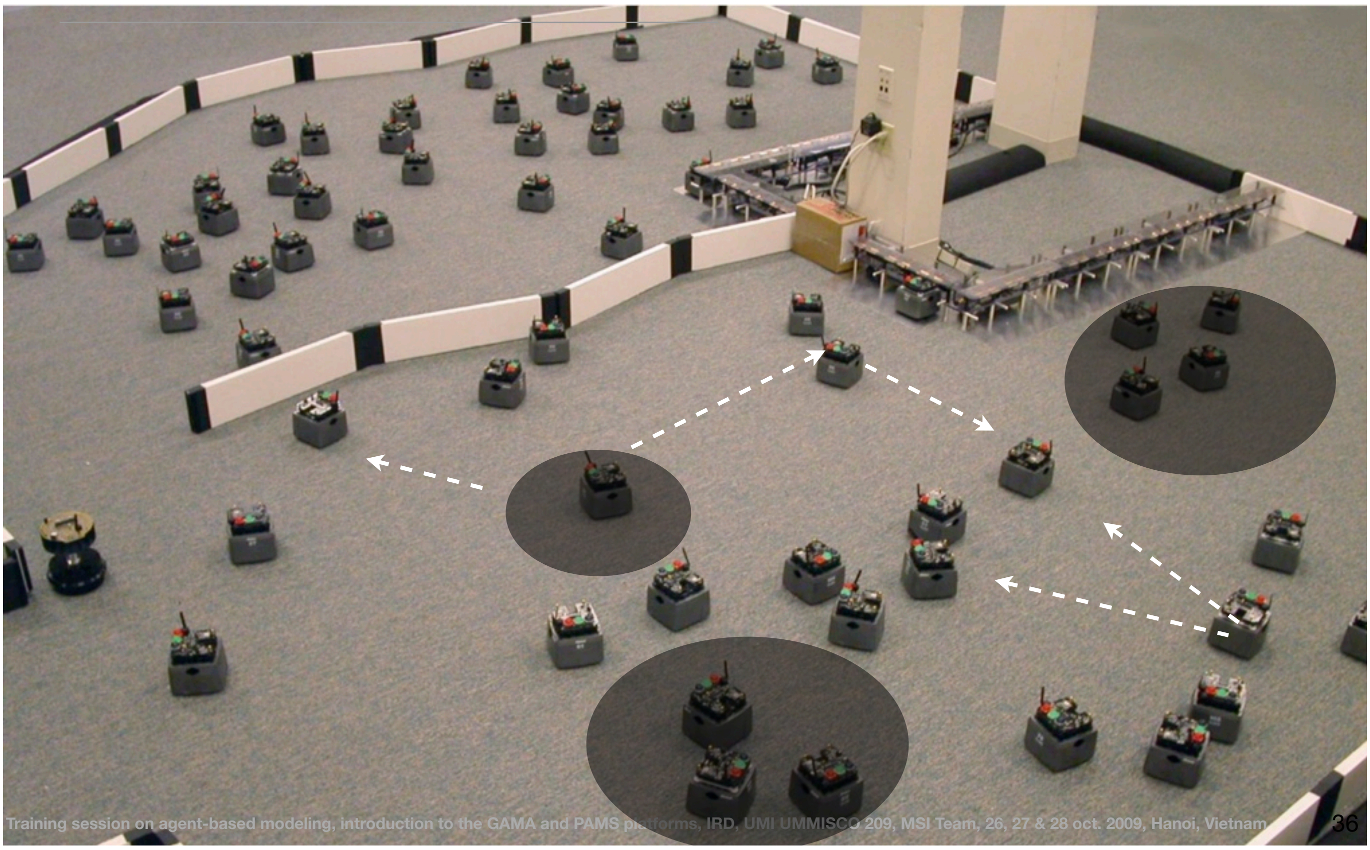
- They are based, mostly, on researches made in a domain of Computer Science and Artificial Intelligence called "**multi-agent systems**" (MAS).
- This domain deals with building systems made up of a number of autonomous, heterogeneous, interacting software components called "**agents**".



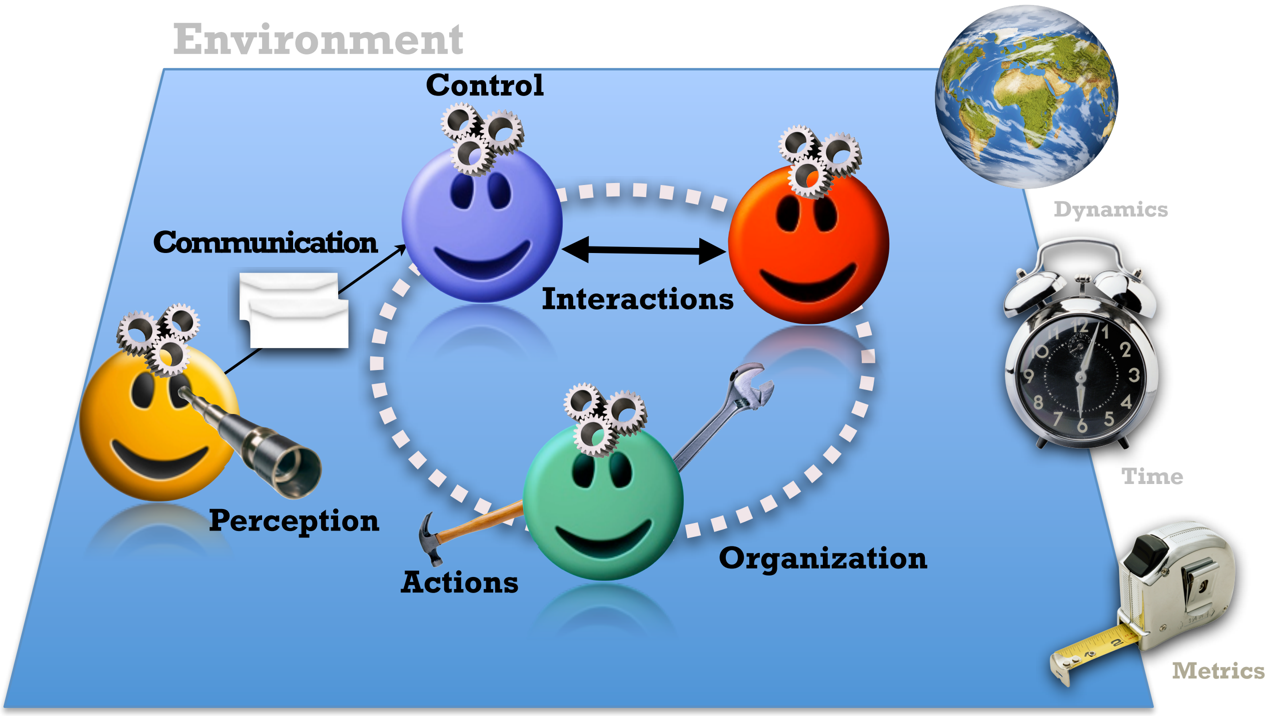
(Quick) History of computing



Analogy with robots



Agent-based Metamodel

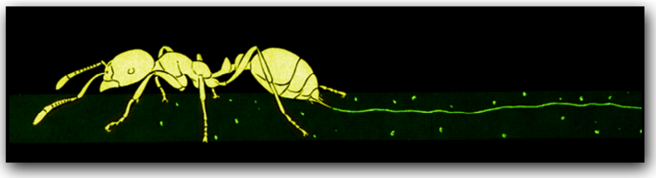


Simple example: ant foraging

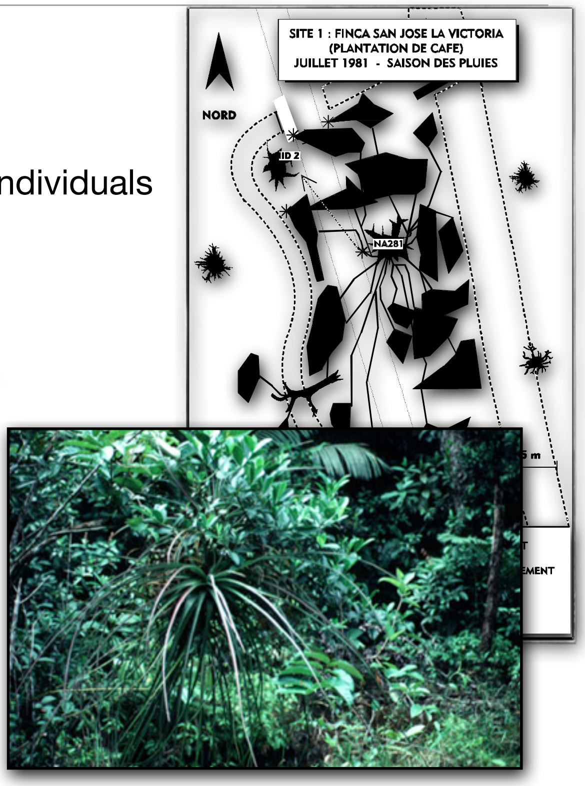
- Foraging : collective behaviors of search and transport of food to the colony
- Local mechanism of **recruitement**
  - Either by contact

  - Or by using chemical substances to attract others

Foraging : a complex system

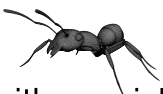


- A colony of ants can forage a very large environment in a quasi-optimal way
  - Example : *Pachycondila apicalis* (~200 individuals of 5mm each, foraging zone ~1000m2)
- **No map** !
- **No planified strategy** !

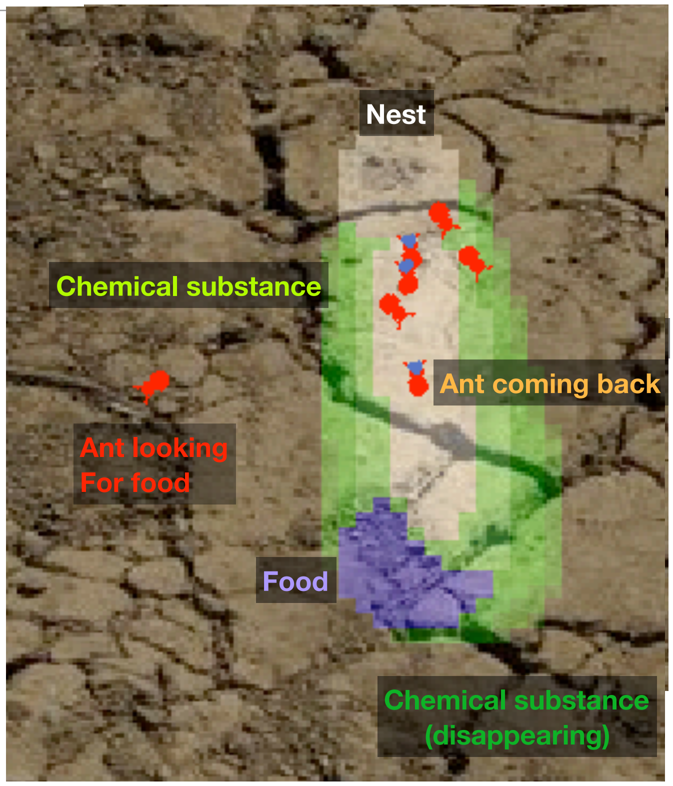
- **No leader** !
- Dynamical and **constantly changing** environment (tropical forest).

Foraging: model

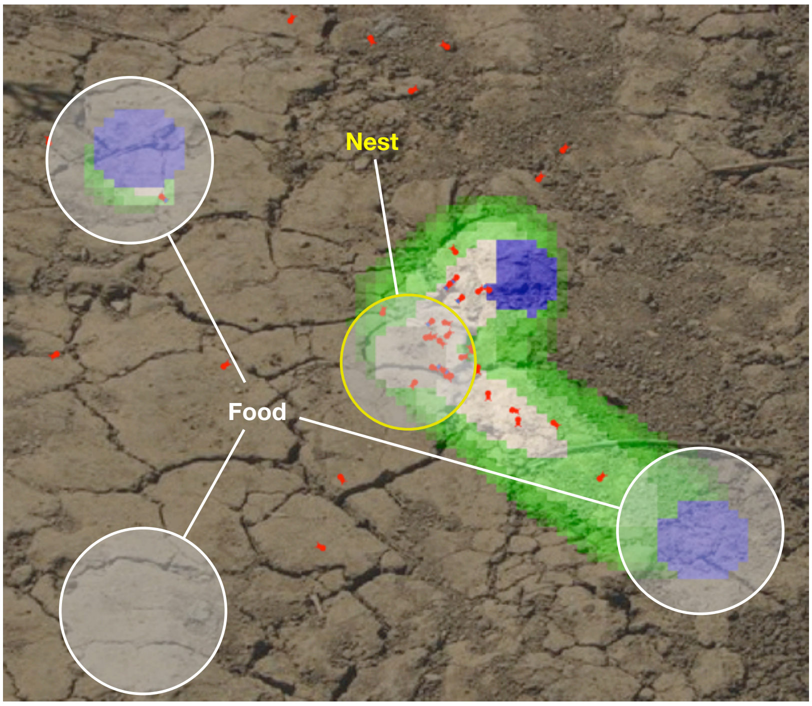
- Components (agents) of the system :
  - Software ants



  - An environment with special zones (nest and food)
- Rules/Behaviors :
  - Each ant leaves the nest and searches randomly (**no map, no strategy**)
  - When it finds food, it comes back to the nest and deposits a chemical substance on its way
  - When it finds some substance, it follows the path to the food.
  - **Environment** : diffuses the chemical substance and wipes it after some time



Foraging: simulation



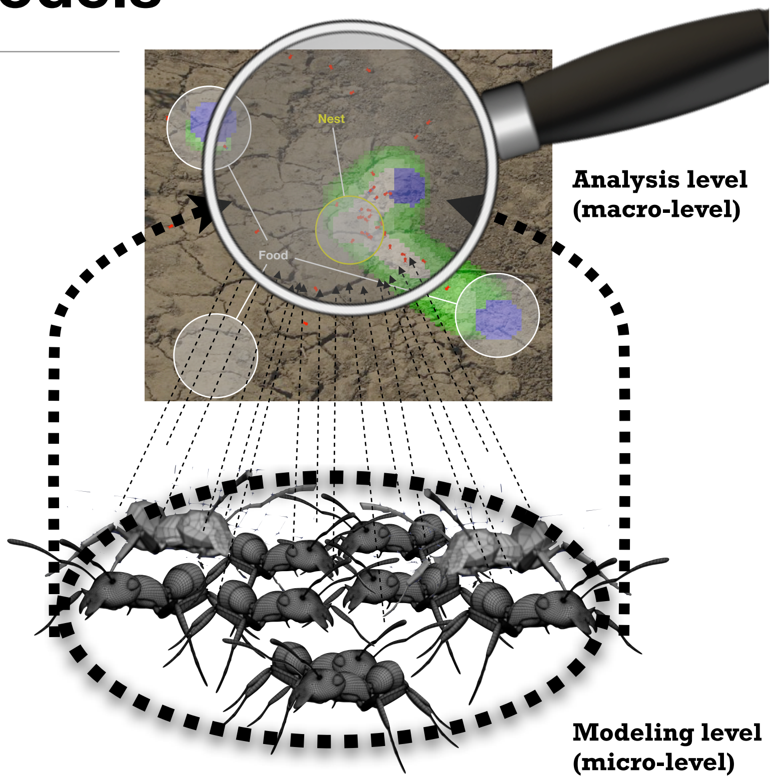
ABM: Versatile Models

- An "agent" can represent any aggregation of objects of the target system, at any spatial scale and across different time horizons.

- The versatility of ABMs constitutes a large part of their success.

Multiple scales models

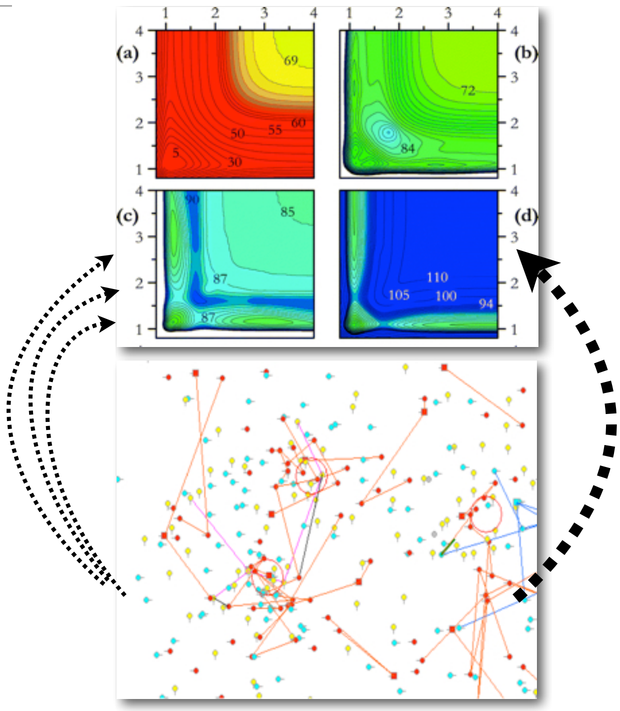
- The ability to simulate individual actions (micro-level) and measure the resulting system outcomes is useful for studying the effects on processes that operate at **multiple scales and organisational levels** (macro-levels).



Generative models

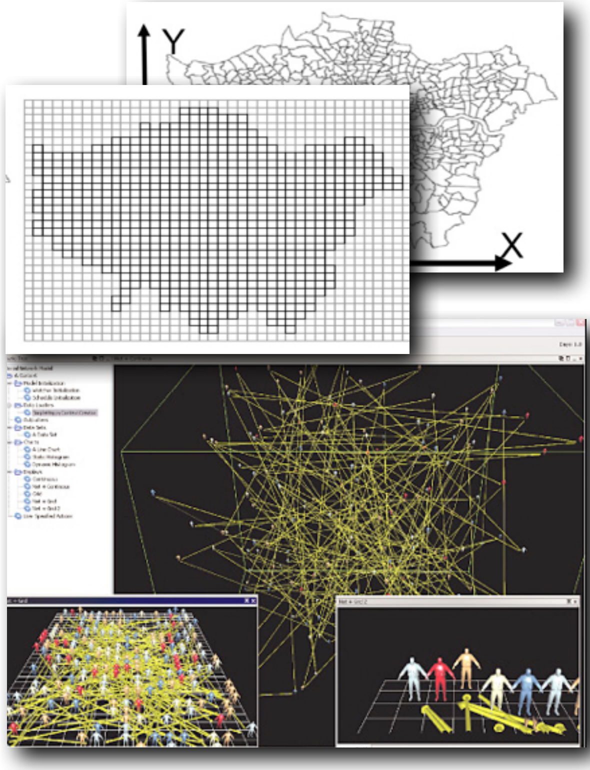
- ABMs complement traditional analytic mathematical methods by using a **bottom-up, generative approach** to model emergent outcomes.

- Where analytic methods are intended to characterize the equilibria of a system, ABMs give the possibility of **generating those equilibria** (and understanding their conditions of emergence).



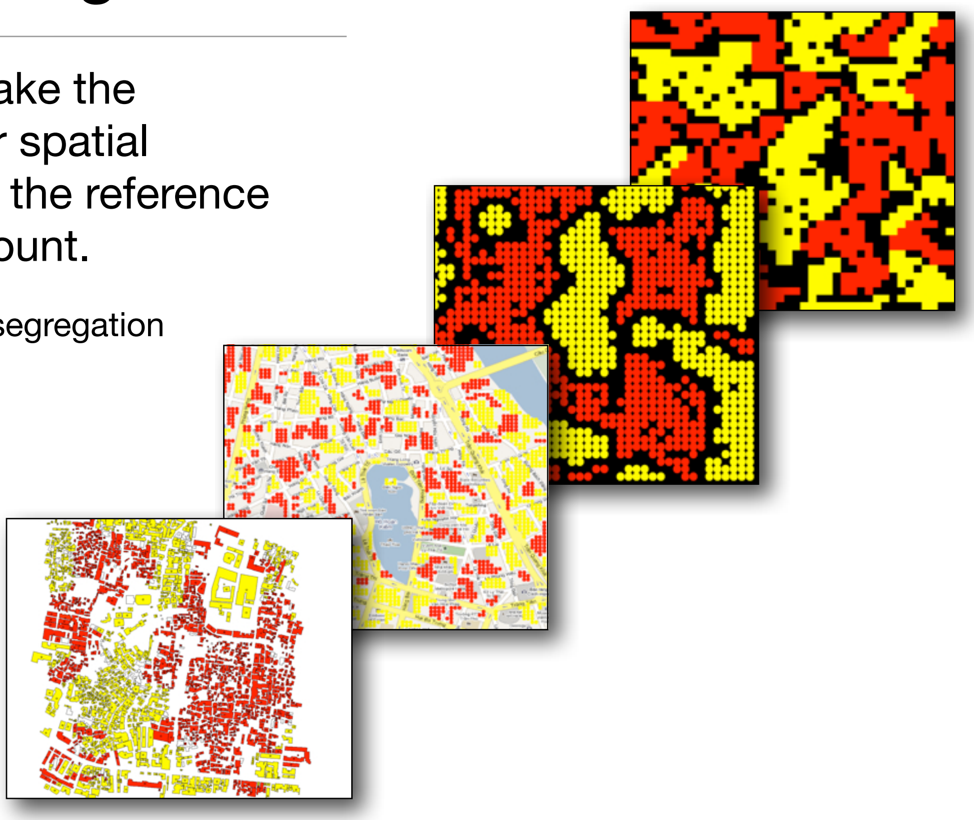
Spatially explicit models

- Environments in ABMs provide services (perception, movements, localization, etc.) and topological structures.
- As ABM metamodels allow for a great deal of flexibility when defining the environment of agents, **any formalism, from 2D grids, to GIS data, to arbitrary graphs, can be used.**
- We will see more on that later on in GAMA.

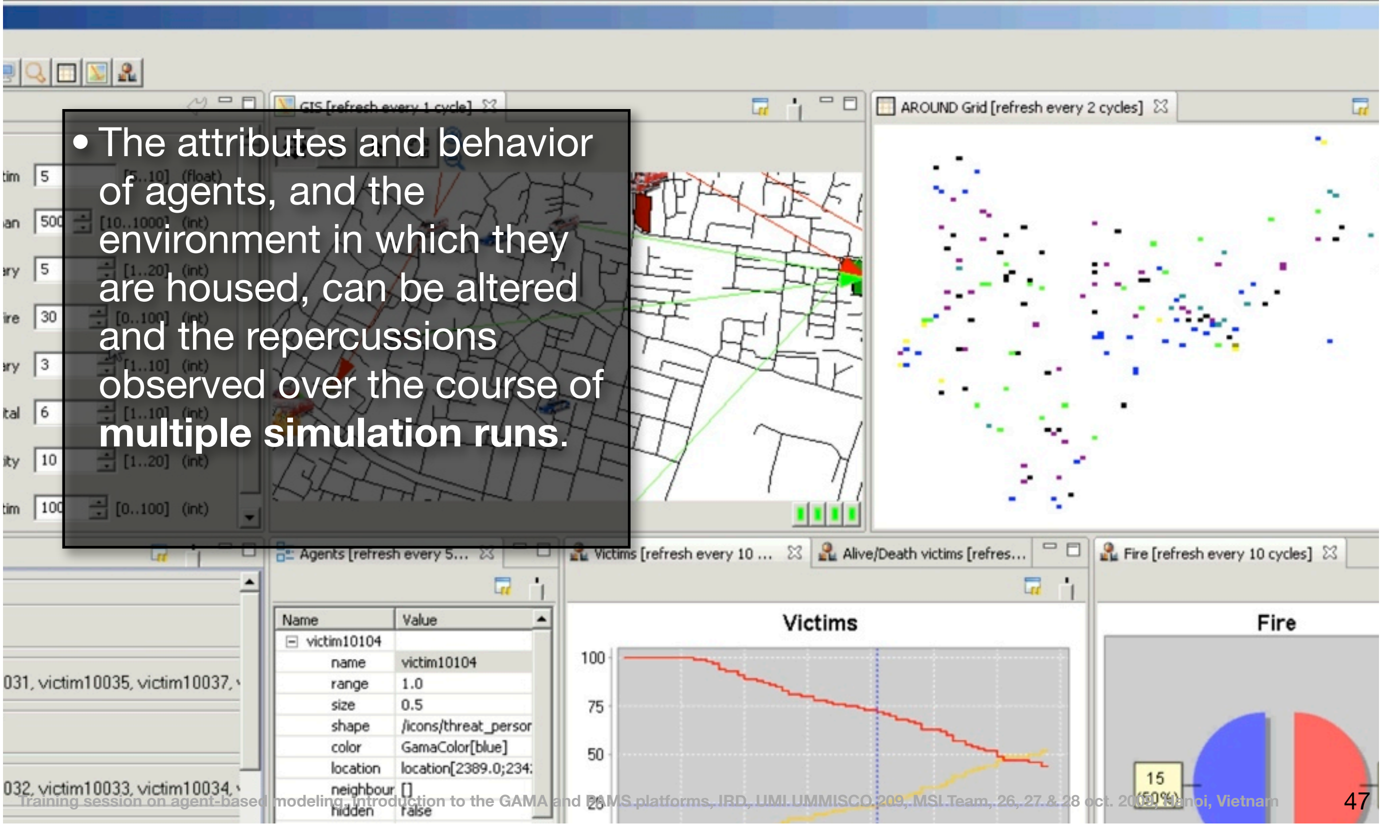


ABM: Heterogeneous models

- ABMs allow to take the individual and/or spatial heterogeneity of the reference system into account.
- Example: residential segregation



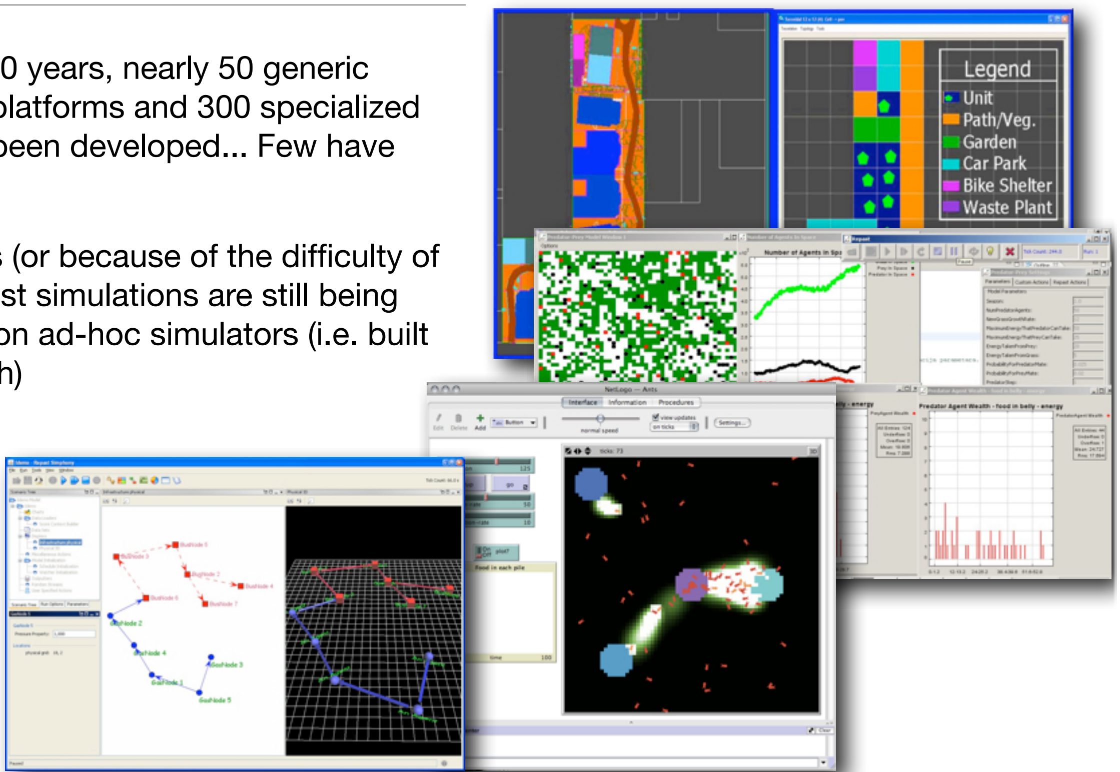
ABM: Miniature laboratories



- The attributes and behavior of agents, and the environment in which they are housed, can be altered and the repercussions observed over the course of **multiple simulation runs**.

Platforms

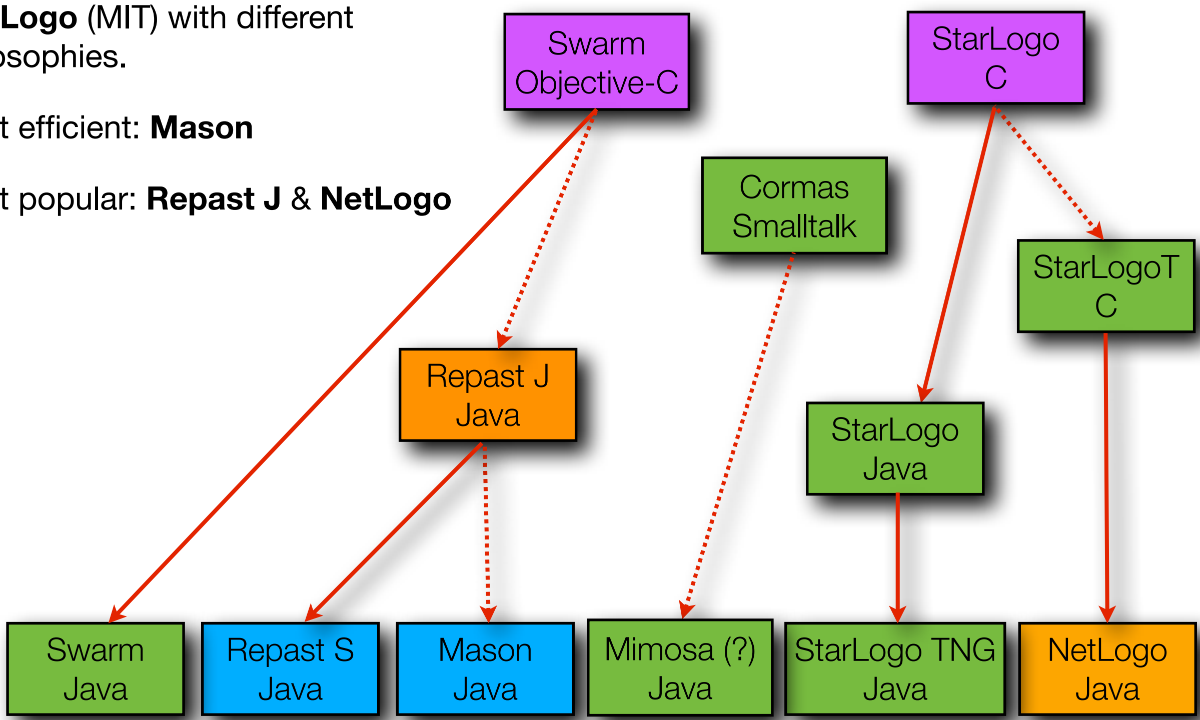
- In the last 20 years, nearly 50 generic simulation platforms and 300 specialized ones have been developed... Few have survived.
- Despite this (or because of the difficulty of choice), most simulations are still being developed on ad-hoc simulators (i.e. built from scratch)



Background

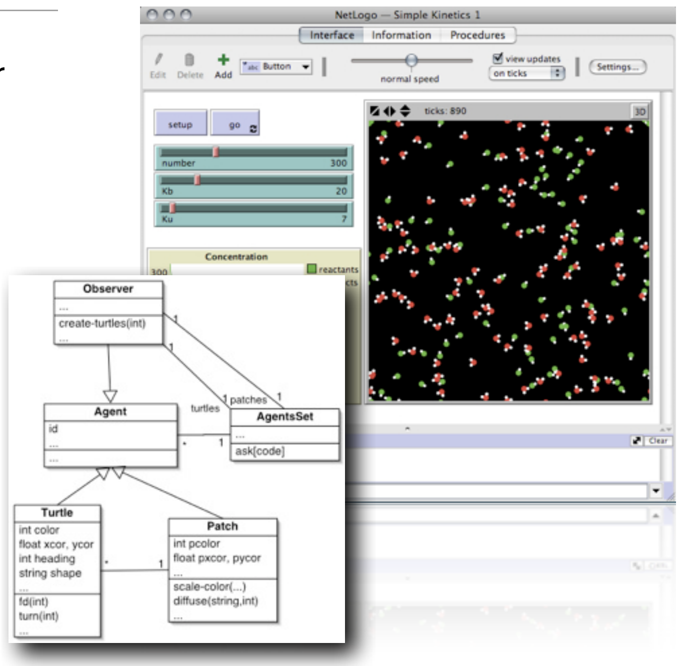
Castle, Christian J. E., and Andrew T. Crooks. 2006. Principles and Concepts of Agent-Based Modelling for Developing Geospatial Simulations. Working paper 110, Centre for Advanced Spatial Analysis, University College London

- Grand ancestors: **Swarm** (SFI) & **StarLogo** (MIT) with different philosophies.
- Most efficient: **Mason**
- Most popular: **Repast J** & **NetLogo**



Netlogo

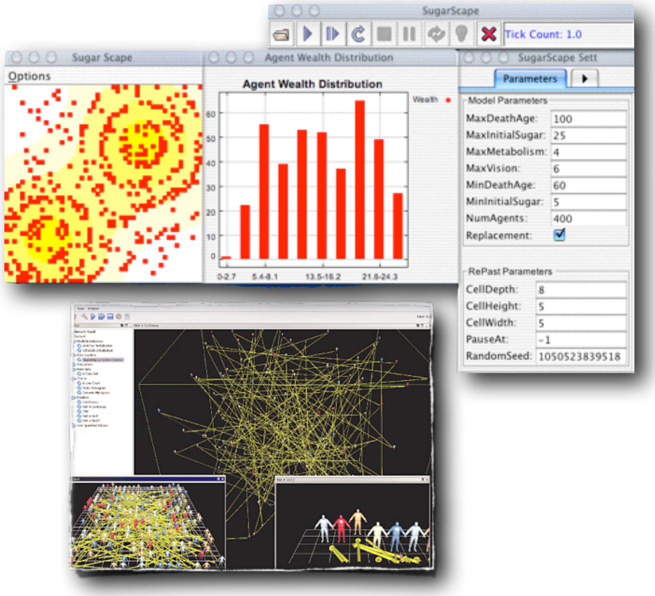
- Intended to be a pedagogical tool rather than a platform.
- **Pros**:
  - Very easy to learn.
  - Immediate visual feedback with a clever UI.
  - Lots of models.
  - Very good documentation.
- **Cons**:
  - Metamodel is not extensible
  - No agent architectures
  - Specific language violates object-oriented principles
  - Limited to “small” models.



Wilensky, U. 1999. NetLogo. http://ccl.northwestern.edu/netlogo/. Center for Connected Learning and Computer-Based Modeling, Northwestern University. Evanston, IL.

Repast J (& S)

- A robust object-oriented toolkit for agent-based simulation rather than a platform.
- **Pros**:
  - Well designed libraries, esp. for environments.
  - Links with GIS, statistical softwares.
  - Good simulation framework (MVC-based)
  - Open-source (Java)
- **Cons**:
  - No ABM metamodel,
  - No agent architectures,
  - No communication framework.
  - Very complex to learn (esp. The latest version)



North, M.J., N.T. Collier, and J.R. Vos, "Experiences Creating Three Implementations of the Repast Agent Modeling Toolkit," ACM Transactions on Modeling and Computer Simulation, Vol. 16, Issue 1, pp. 1-25, ACM, New York, New York, USA (January 2006).

Conclusion

- Now that this part is over, we can head to the core of the training session : putting into practice all these great ideas in GAMA.
- We will first have a quick presentation of GAMA, its environment and modeling language.
- Practice will take the form of "tutorials" (mixed with step-by-step explanations) on two agent-based models:
  - Forest fires
  - Schelling's segregation