# Emergence in multi-agent systems :

## Cognitive hierarchy, detection, and complexity reduction

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## Emergence in multi-agent systems
## Motivation & Outline

- Motivation : How does the "awareness" of emergent phenomena by agents may introduces "social objects" and downward causation in an agent-based framework (upward - bottom / up) (*cognitive agents*)

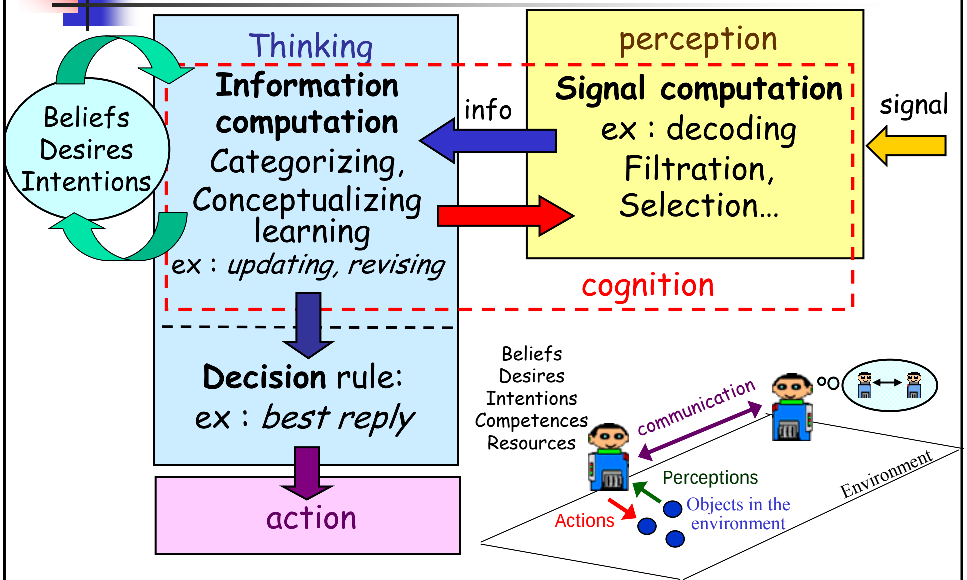
*I What does emerge in complex system models* ?

- Emergence for the philosophers
- Emergence & Multi-Agent System (MAS):
  - (1) The central role of *the observer*
  - (2) *Strong* and *weak emergence*
- Detection & Emergence:
  - *Emergence as a complexity drop*

*II Emergence of classes* in a multi-agents population game: The paradigmatic model of Axtell, Epstein, Young (2001)

  - Weak emergence of classes in a "tag model"
  - An example of multi-level strong emergence with a detection process in multi-agent framework

## The three dimensions of cognitive agent(perception – thinking / decision – action)






## Cognitive Hierarchy

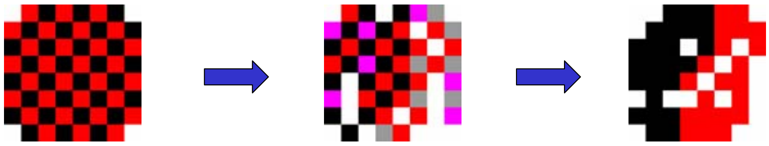
*(Dessalles, Muller, Phan, 2007)*

1. Reactive Agent (RA) has a pre-determined response for a given state of its environment ("*situatedness*",).
   - Such an agent may represent both a material entity (such as a "spin" in a ferromagnetic set) or all living entities (pre-determined patterns of behaviour or "*Darwinian entities*" for Dennett, 1996 ).
2. Behavioural Agent (BA) may modify its behaviour for a given state of its environment according to the observed (historic) payoff from its past actions ("*consciousness*" ).
   - low cognitive rationality, but adaptability + "consciousness" [Bourgine 1993], [Phan 2004]. ("*Skinerian entities*", Dennett, 1996) reinforcement learning - e.g. Q-Learning, classifiers, etc.).
3. Epistemic Agent (EA) uses a model of its environment to pre-select actions ("*awareness*".)
   - medium or high cognitive rationality; In the hierarchy introduced by (Dennett, 1996) both *Popperian and Gregorian entities* are different cognitive levels of epistemic agents.
   - Epistemic Learning : *updating* (parameters) versus *revising (models)*

Emergence in multi-agent systems

## What does emerge in Schelling's model of spatial segregation?

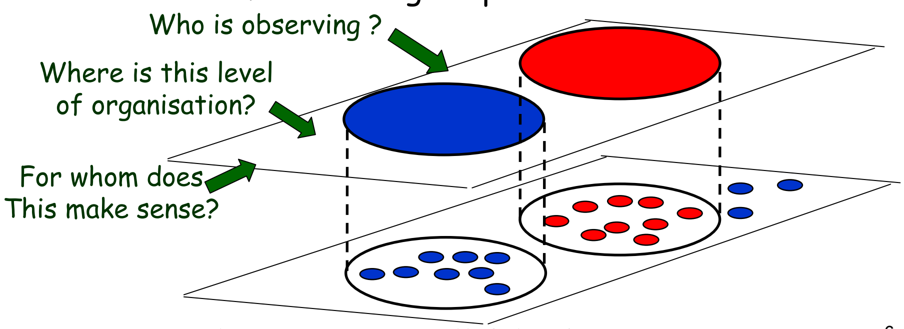
- Schelling's aim was to explain how segregationist residential structures could spontaneously occur, even when people are not so very segregationist themselves.
- Agents interact only locally with their 8 direct neighbours (within a so-called "Moore'' Neighbourhood). *No global representation* about the residential structure *is available for agents*.
- Each agent would stay in a neighbourhood with up to 62% of people with another colour
- A slight perturbation is sufficient to induce local *chain reaction* and the *emergence* of segregationist patterns - «segregation » (clusters) is an *emergent propriety of the model…*



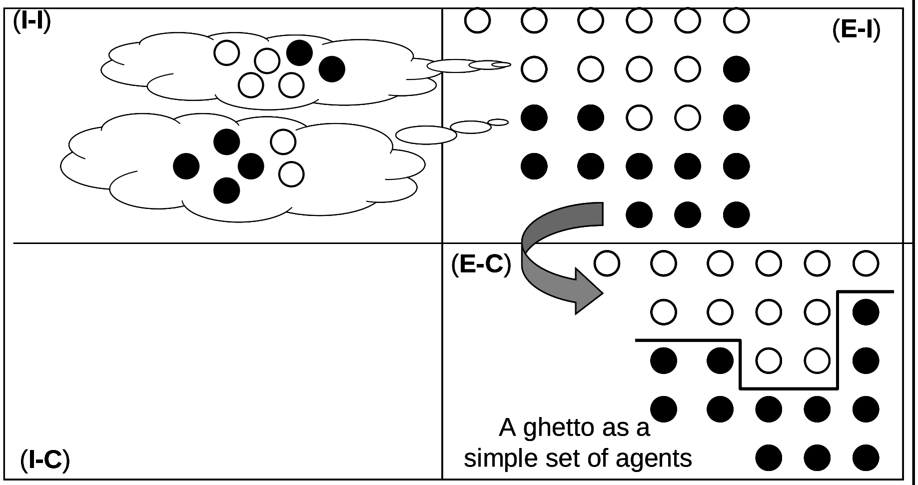


## The Schelling model of Segregation : an ontological emergence ?

- Local interactions are sufficient for the occurrence of spatial homogeneous patterns: spatial segregation is an emerging property of the system's dynamics, not an attribute of the individual agents.
- What is the ontological status of the "levels of organisation" and of the "observer" ? What is the semantics of the emergent phenomenon ?



## The methodological individualist approach: emergence of ghettos in Schelling's model of segregation






## Philosophical emergentism (1)

- Philosophical emergentism deals with the questions of novelty, unpredictability, reductionism and holism.
- Lewes [LEW 75] places emergence at the interface between levels of organisation.
- For *descriptive emergentism*, the properties of the "whole" "cannot even in theory, be deduced from the most complete knowledge of the properties of [the parts] in isolation" [Broad 1925, Chapter 2].
- Emergent properties result from the *relations* between parts, and in some cases from some irreducible macro causal power from the system itself (i.e. downward causation).
- The relational properties that structure the system are neither at the level of the whole nor at the level of the parts, but are constitutive of both

## Philosophical emergentism (2)

| | Synchronic determination | Diachronic determination |
|---|---|---|
| Weak (reducible) | weak emergentism | weak diachronic emergentism |
| Strong (irreducible ) | (strong) synchronic emergentism | strong diachronic emergentism |
| | — Novelety → | |

| Irreducibility ↓



## Emergence & MAS : (1) The central role of *the observer*

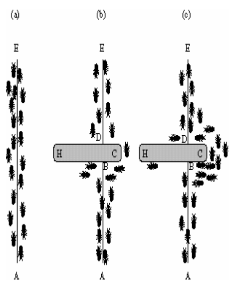
- Muller (2002) distinguishes two levels when defining emergence in MAS: the *process* and the *observation of this process*. A phenomenon is emergent if:
  - I. There is a system composed of agents interacting among themselves and with their environment. *The description of this system as a process is formalized in a language D.* (ie. binary choice with interactions {-1,+1})
  - II. The dynamics of this system produces a *structural phenomenon observable in the "traces of execution"*. (ie. convergence of agent's choice towards -1 OR + 1)
  - III. The *global phenomenon* is observed by an *external observer* (*weak emergence*) or by the agents themselves (*strong emergence*) and *described in a language distinct from D* (ie: "order parameter" M)

(IV) Irreducibility from D' to D

- Emergence is *a category relative to an observer*: a *subjective* category in case of "human-like" agents (perception, categorisation…)
- In Social Science, Emergence can deal both with *upward causation* (weak emergence) and *downward* causation (strong emergence).

## Emergence & MAS :
## (2) Strong and weak emergence

- In *weak emergence*, the observer is *external to the system*.
  (only upward causation: from agents -> system)

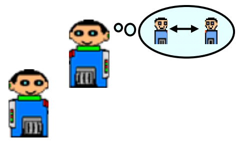



In *strong emergence* the system becomes reflexive, through the mediation of the agents:

(I) Agents can observe and identify phenomena in the process which represents the evolution of the whole system within which they interact.

(II) The agents can describe these phenomena in a specific "language" (e.g. an "order parameter")

(III) The identification of an "emergent" phenomenon by the agents involves a *change of behaviour*, therefore a *feedback from the level of observation to the process level* (i.e; a downward causation)



Emergence is *immanent* in the system

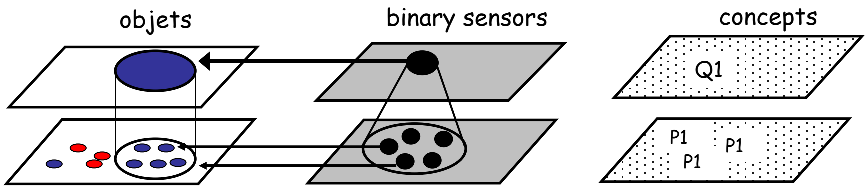


## Detection & Emergence:
## *Emergence as a complexity drop* (1)

- Emergence, as defined in (Dessalles 1992) and (Bonabeau & Dessalles 1997), *does not require the system to be layered in predefined levels*, but it may be interpreted both in terms of levels and in terms of hierarchies of theories.
- The existence of connected binary sensors explicitly or *implicitly* creates a level hierarchy through partial redundancy.

The hierarchy of description levels and the hierarchy of observation levels (sensors) are parallel
Source : Dessalles (1992)

Concepts are hierarchically organized binary sensors
Source : Dessalles (1992)




* Dessalles, Phan 2005

## Detection & Emergence:
## *Emergence as a complexity drop* (2)

- Emergence is measured by the difference between the expected structural complexity and the actually observed structural complexity.

$$E = C_{exp} - C_{obs}$$

- *Structural complexity is the minimal description of the system's state available to the observer.* It depends on the set of observations tools (binary sensors).
- Complexity drop occurs when some sensors become suddenly active, making the activity of redundant sensors dispensable in the description of the system's state.
- Emergence corresponds to a negative discontinuity of structural complexity through time.



## Detection & Emergence:
## *Emergence as a complexity drop* (3)

- Emergence is measured by the difference between the expected structural complexity and the actually observed structural complexity.

$$E = C_{exp} - C_{obs}$$

- For instance:
  - → If the system has only level 1 sensors (i.e. input sensors) active, then the situation is *maximally complex*, as the state of each sensor must be specified.
  - → When a level 2 sensor Di becomes activated by a configuration {Dik} of level 1 sensors, the activity of each Dik may be omitted in the minimal description, as the activity of *Di subsumes the activity of the Dik*.
  - → The delayed activation of Di brings to complexity drop, and thus emergence.
- Emergence corresponds to a negative discontinuity of structural complexity through time.

* Dessalles, Phan 2005

# Emergence in multi-agent systems II :

## Axtell Epstein & Young (2001) revisited





## I – Evolutionary Bargaining: « sharing game »

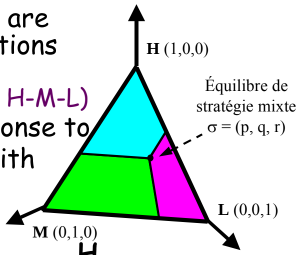
- The *one-shot bargaining game between random pairs of agents* is drawn from the Nash bargaining model.
  - ➔ Each pair of agent try to share a "cake" of size 100.
  - ➔ Only the couples of proposals which sum up to S ≤ 100 are accepted
  - ➔ Other couples of strategies lead to zero payoffs
- The are three Nash equilibriums in pure strategy, with one equitable balance - (M, M) - and two inequitable ones (H,L), (L,H)
- Problem: Are local interactions among agents sufficient to « select » a global equilibrium (in pure strategies) without « *common knowledge* » (Young, 1993)

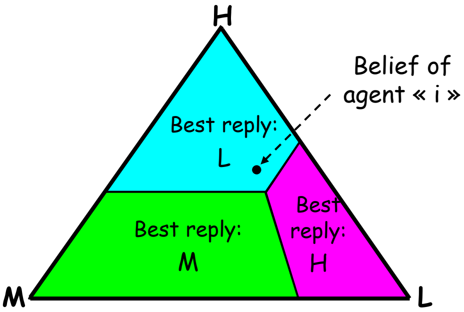
| | H = 70 | M = 50 | L = 30 |
|---|---|---|---|
| H = 70 | 0,0 | 0,0 | 70,30 |
| M = 50 | 0,0 | 50,50 | 50,30 |
| L = 30 | 30,70 | 30,50 | 30,30 |

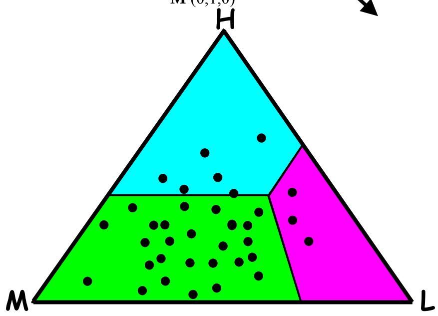
Emergence of classes in a multi-agents population game:
the paradigmatic model of Axtell, Epstein, Young (2001)

# II – Agent's beliefs and behavior

- Agent beliefs about the behavior of the others are inferred from a finite sample of last confrontations (size m) $\sigma^i = (p^i, q^i, 1\text{-}p^i\text{-}q^i)$.
  (agent belief are projected as a point of the simplex H-M-L)
- At each period, each agent play their best response to these beliefs with probability $\varepsilon$ and randomly with probability 1- $\varepsilon$ (trembling hand)



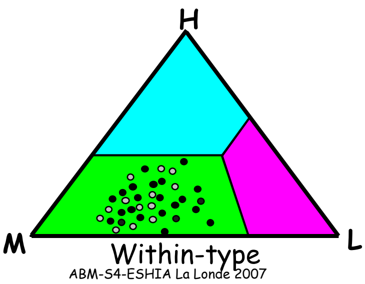



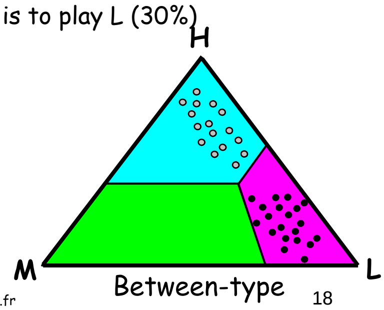


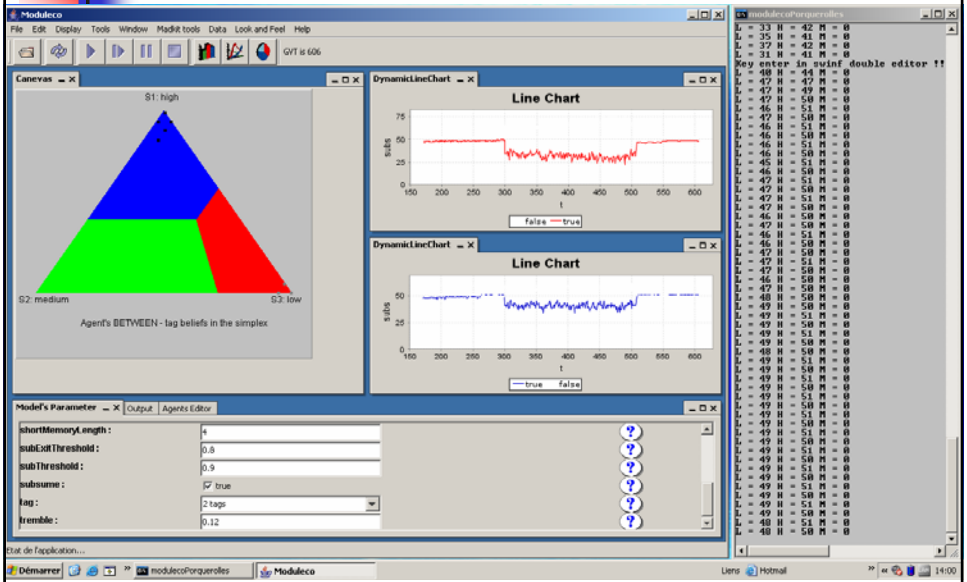

Emergence of classes in a multi-agents population game:
the paradigmatic model of Axtell, Epstein, Young (2001)

# III - Emergence of self-reinforcing classes

- Agents have « meaningless » tag (AEY, 2001), and maintain a different sample for each group of agents (same tag)
- « classes » formation (by definition) corresponds to a specific structure of belief with a *fair behavior within group* but unfair , behavior between groups
  - ➔ Both black and grey are fair within their group (Play M – 50%)
  - ➔ Blacks have self-reinforced beliefs in the « submissive » behavior of grey. Their best response is to play H (70%)
  - ➔ Conversely, Grey have self-reinforced beliefs in the « dominant » behavior of Blacks. Their best response is to play L (30%)







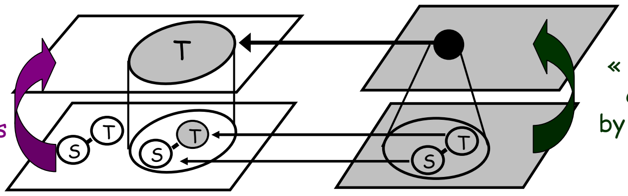

Emergence of classes in a multi-agents population game:

# AEY revisited: towards strong emergence

## Agents, groups and beliefs within a two-level architecture

- New assumption:
  - ➔ agents minimize the procedural cost of informational computation, and can shift in their inference process for "sample" towards "tag".

« external » Behavior of the agents




« Internal » cognition by the agents

- The key feature is the procedural control threshold function (not necessary the same for all agents).
- *Symbolic inferential object* (tag) is a "social object". The resulting dynamics may differs from the simple upward one (possibility of lock in)
- Consequences : *changes in the dynamic proprieties of the model* (ie. bimodal invariant distribution, stochastic stability..)
- The degree of autonomy of the "social objects" depends on trigger properties of the procedural control threshold function

## Emergence in Multi-Agent Systems (MAS)
## Some references – Any questions ?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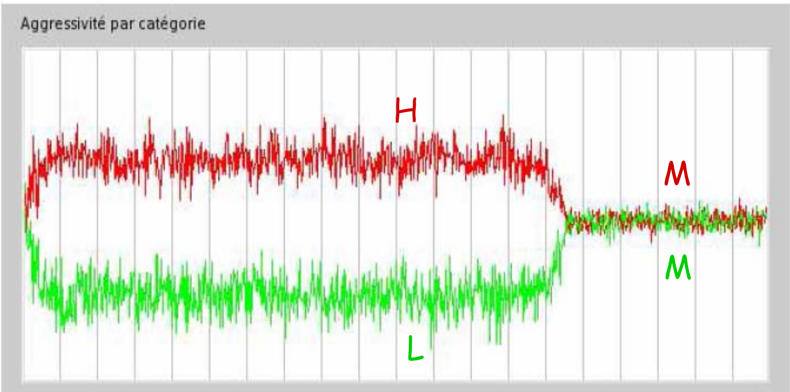
Emergence of classes with costly signalling:

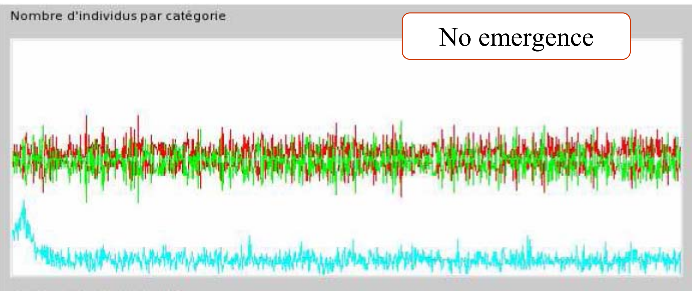
## Instability of the class behaviour in the model with exogenous tag



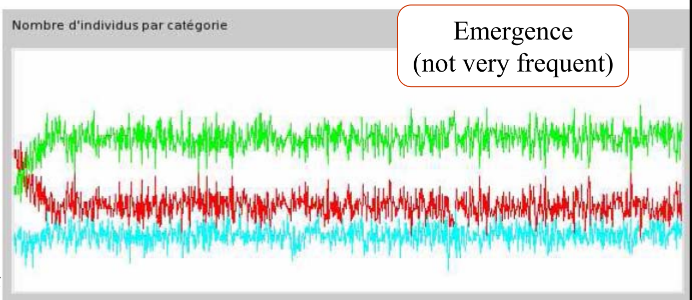

(weak) emergence and collapse of a non equitable state with random initialisation.

## Extension: endogenous tag (*costly signalling - 1* )

1000 steps, 100 agents, noise 10%, Cost 10, memory of size 7, initialized at random



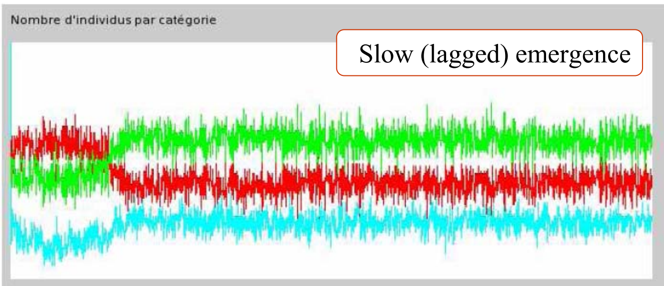

In blue: number of tag change

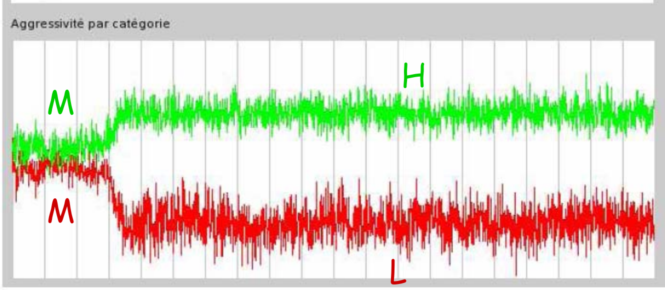





## Extension: endogenous tag (*costly signalling - 2* )

2000 steps, 100 agents, noise 10%, Cost 10 memory of size 7, initialized at random




In blue: number of tag change
Green : winners,
red « *suckers* »