# ECONOLAB: INTRODUCCIÓN AL MODELADO Y SIMULACIÓN DE TÓPICOS NODALES DE ECONOMÍA

## Clase 6 - Economía Computacional Basada en Agentes

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Dr. Martín Harracá
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FCEyN - UBA

# Economía Computacional basada en Agentes (ACE)

- Concepto central:

  - **ACE es la modelización computacional de**
    - **procesos económicos,** incluidas economías completas,
    - a modo de **sistemas dinámicos "abiertos" de agentes económicos** que interactúan entre sí.

  - En ACE los agentes económicos no tienen (necesariamente) racionalidad perfecta ni información completa sobre el sistema del cual forman parte.

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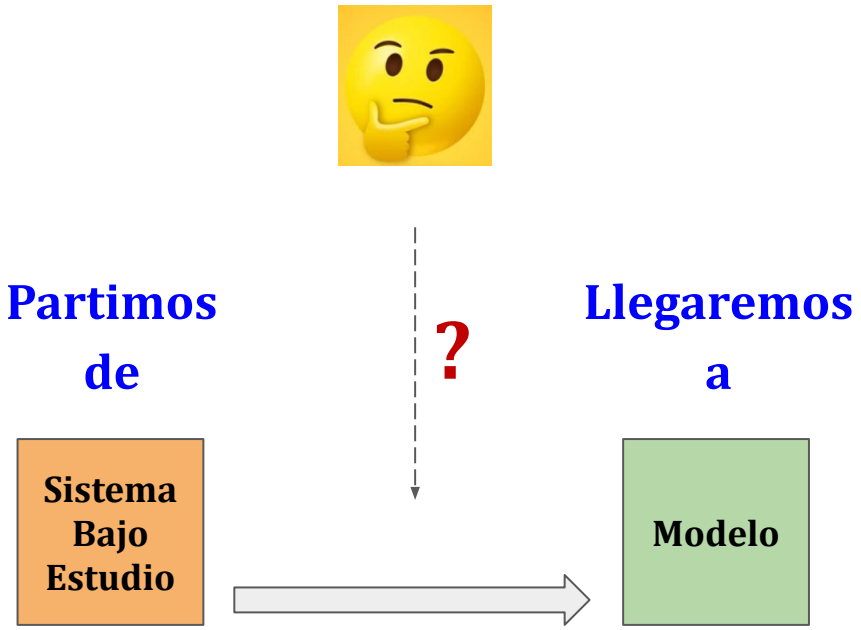
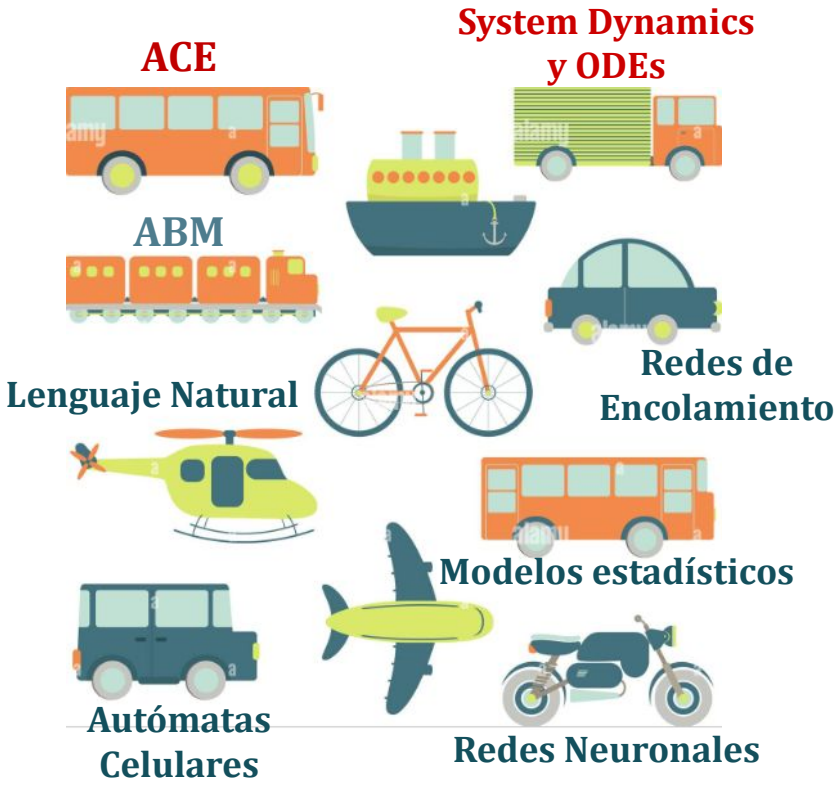
- ACE es una variante particular de **ABM: Agent-Based Modelling**
  - Se adopta un **conjunto de principios de modelado**
    - Metáfora: **Dado un destino, cuál vehículo elegimos para llegar?** Depende de muchas cosas.
    - Una vez que elegimos el vehículo, nos atenemos a **sus reglas de uso, ventajas y desventajas**



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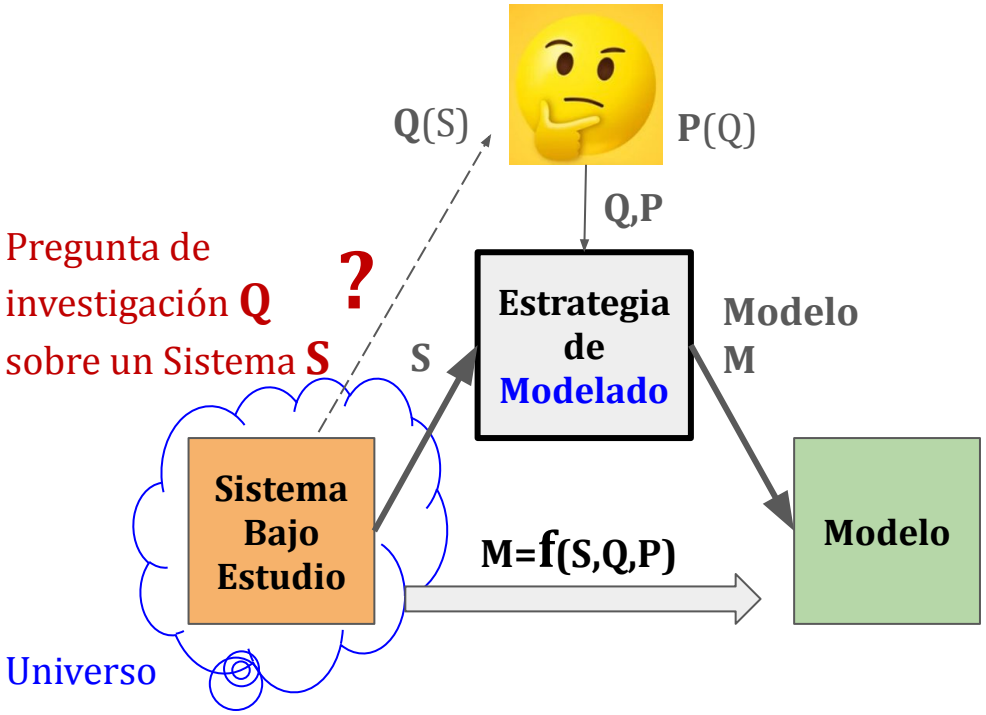


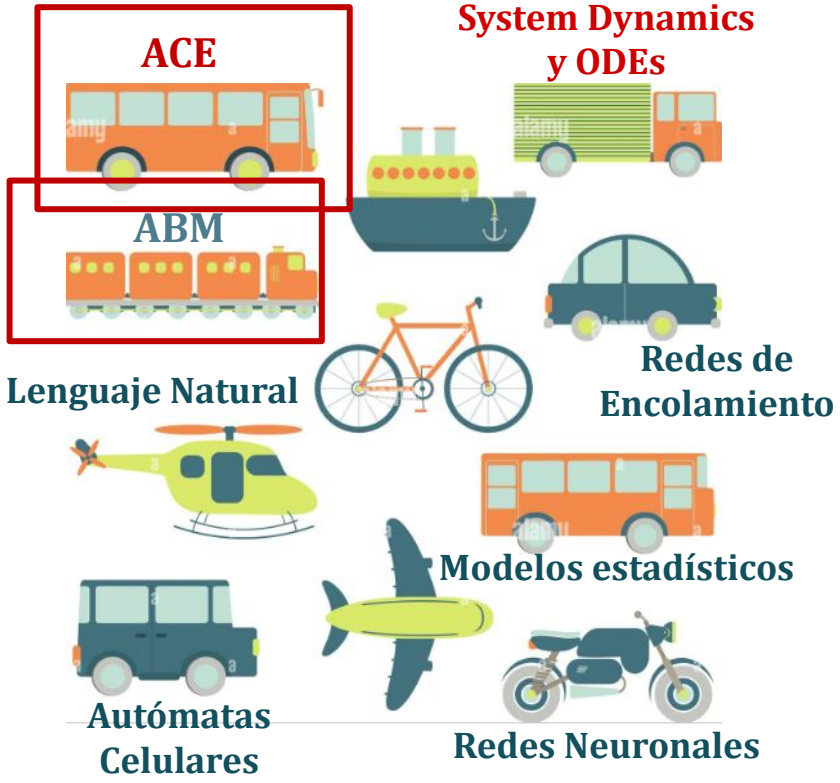

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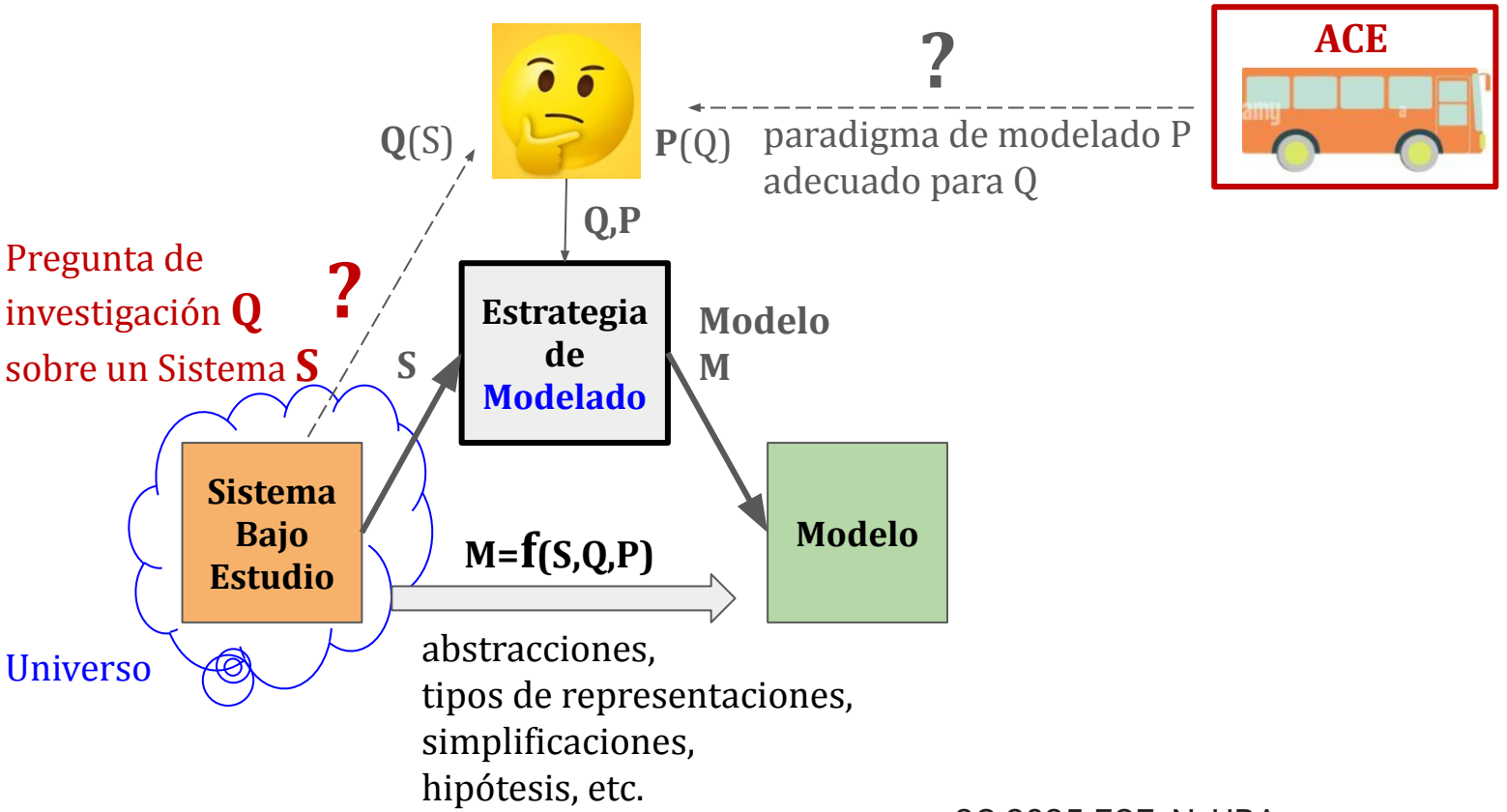

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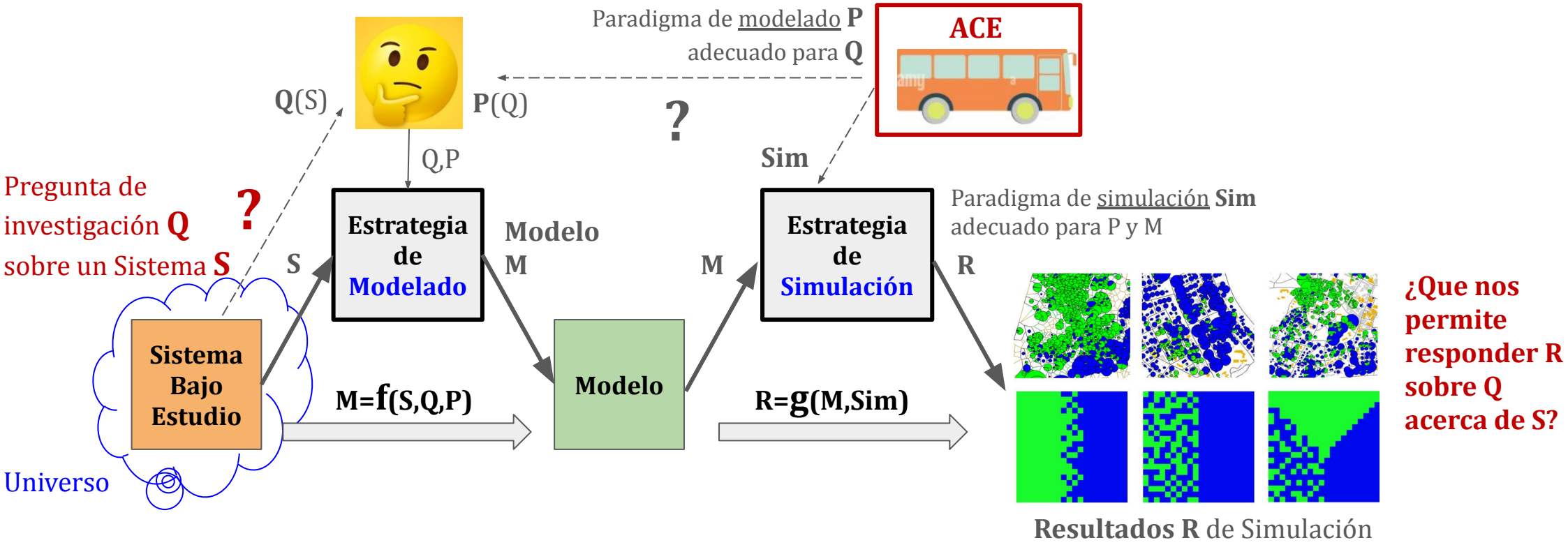

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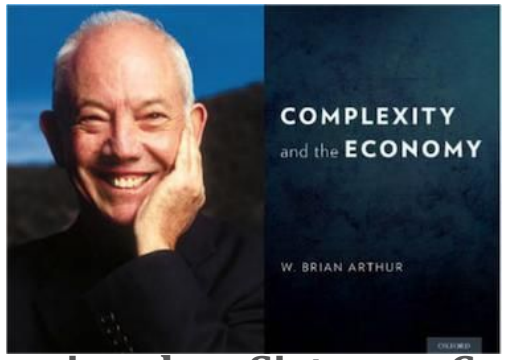
  - En ACE los agentes económicos no tienen (necesariamente) racionalidad perfecta ni información completa sobre el sistema del cual forman parte.

    - A diferencia del "modelado estándar" en economía:
      - **ACE no impone ni asume** la existencia a priori de estados de equilibrio ni de coordinaciones espontáneas entre agentes (estos son solo una posibilidad, que puede darse o no)
    - El **foco de ACE** está puesto en:
      - Los **procesos** económicos (*desenvolvimiento en el tiempo* de las interacciones entre agentes)
      - Las **interacciones locales** entre agentes económicos
      - Las **dinámicas fuera del equilibrio**
      - Las **fases de coordinación y descoordinación**

# Complejidad y Economía Computacional basada en Agentes (ACE)

- Algunos orígenes



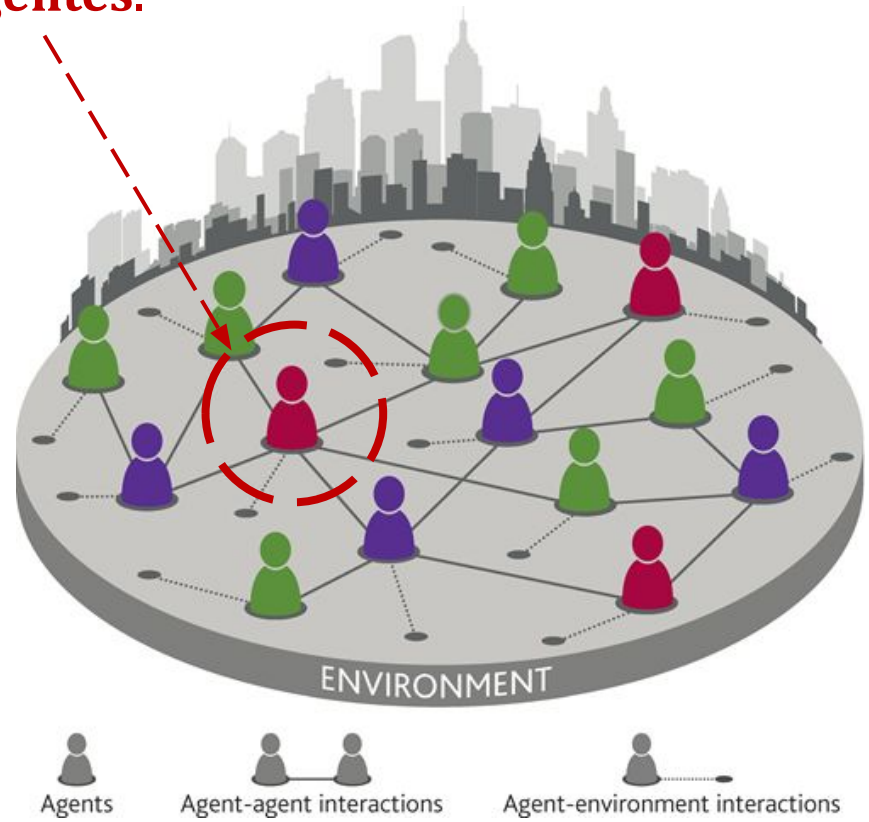

  - **Brian Arthur**: Economic Complexity.
    First director of the Economics Program at the **Santa Fe Institute**.

  - **Santa Fe Institute - Desde mediados de los años 80, referencia internacional en Sistemas Complejos.**
    - *In **George Cowan**'s telling, **the concept of a Santa Fe Institute began to form in the summer of 1956**. He had been invited to the Aspen Institute, where prominent intellectuals from the arts, science, and culture gathered for freeform philosophical exchanges. He had just participated as the lone scientist in a discussion of literature.*
    - *For his part, he had chosen to **talk about entropy – the tendency of systems to move toward disorder –** and what **insights this principle from thermodynamics might offer about the workings of human society**. His talk was not well received by the other participants, who were more accustomed to the ideas of Socrates, Aristotle, and Plato than those of Boltzmann.*

  - **Leigh Tesfatsion** (Agent-Based Computational Economics)
    - **Agent-Based Computational Economics (ACE): "Growing Economies from the Bottom Up"**
    - En esta clase seguiremos de cerca a L.T.

# ABM = Agent-Based Modelling

- **ABM**: Una categoría de métodos de modelado. Busca **Flexibilidad** de modelado + **Rigurosidad** lógica
- Foco en aquellos **sistemas cuya dinámica** queda **determinada por:**
  - **secuencias de interacciones entre entidades discretas → Agentes.**



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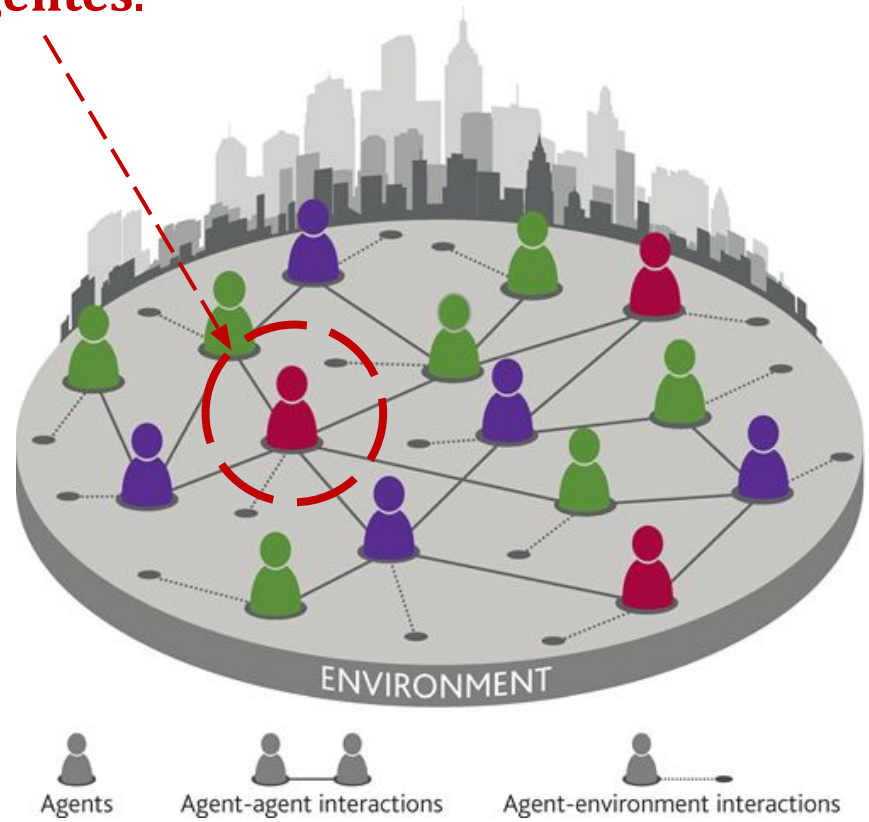
- **Cada Agente de ABM:**
  - Interactúa (observa/reacciona, expone/modifica información) con:
    - **otros agentes (red de interacciones)**
    - **su entorno**
  - Maneja su propia dinámica temporal
  - Tiene memoria (estado interno)
  - Toma decisiones
  - Puede tener objetivos, hacer planes, adaptarse, etc. (algoritmos)



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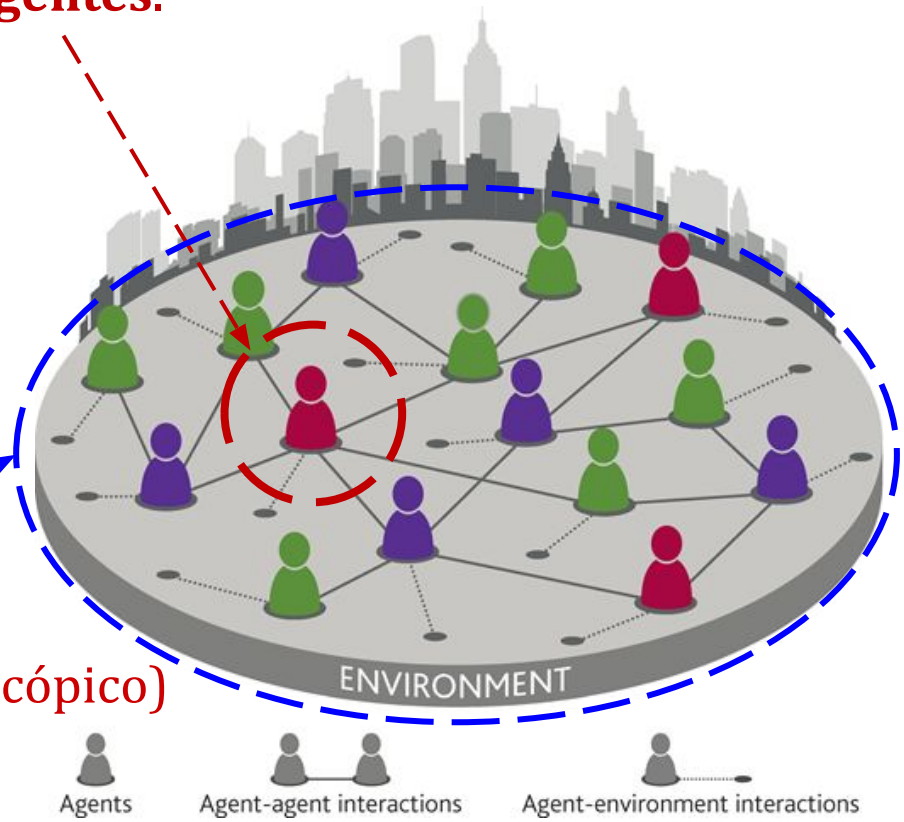


- Las **propiedades a nivel Sistema** (nivel macroscópico) **emergen** a causa de las **interacciones entre Agentes** (nivel microscópico)
  - Modelado "bottom-up", simulación de las interacciones.

- Estos sistemas van desde sistemas de partículas estudiados en física hasta sistemas sociales y naturales acoplados que se estudian en socio-ecología.

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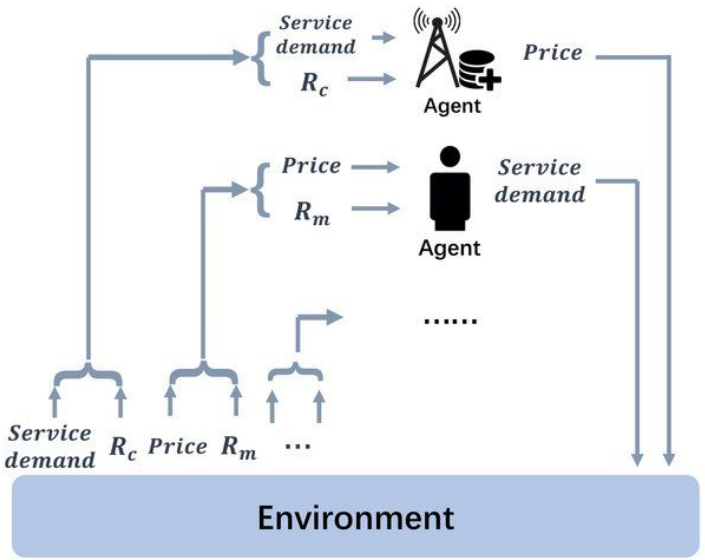
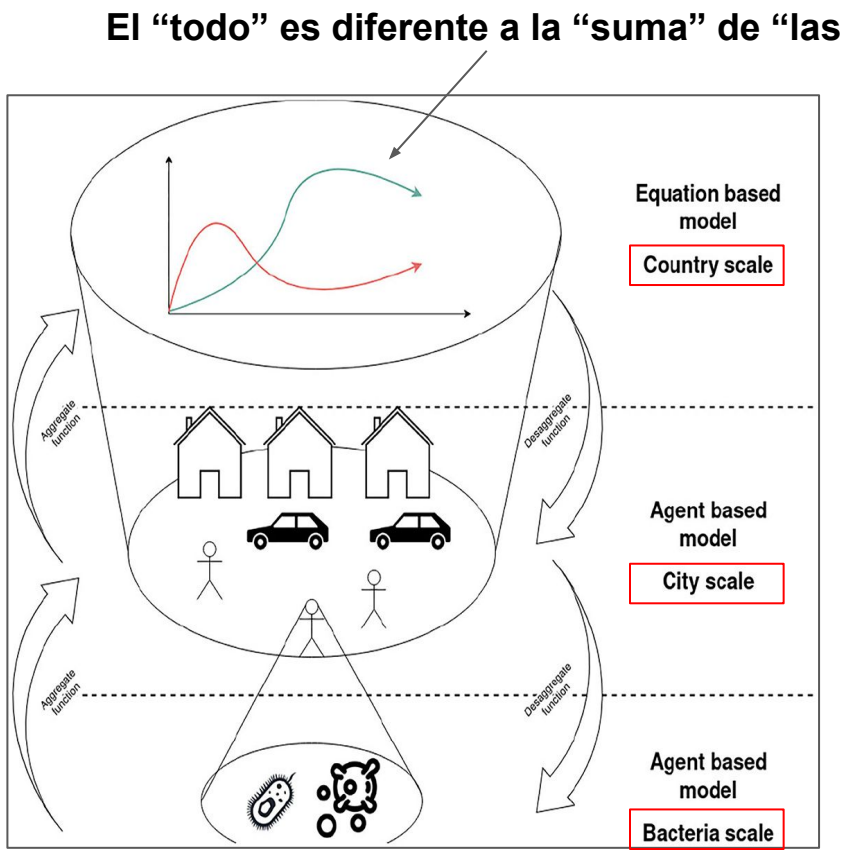
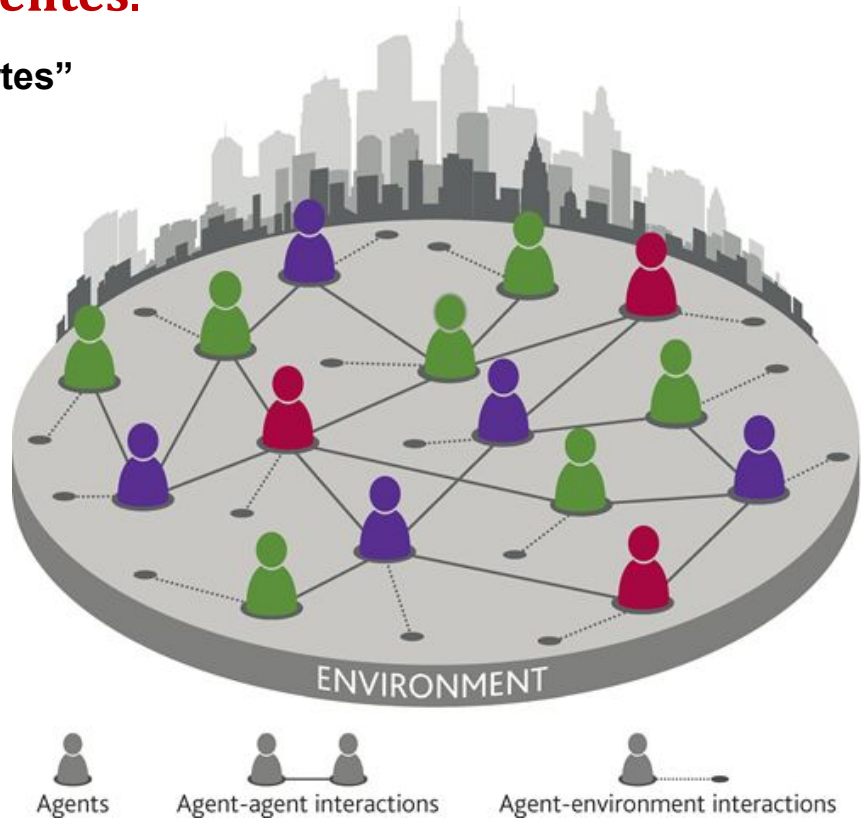



Operaciones de agregación y desagregación



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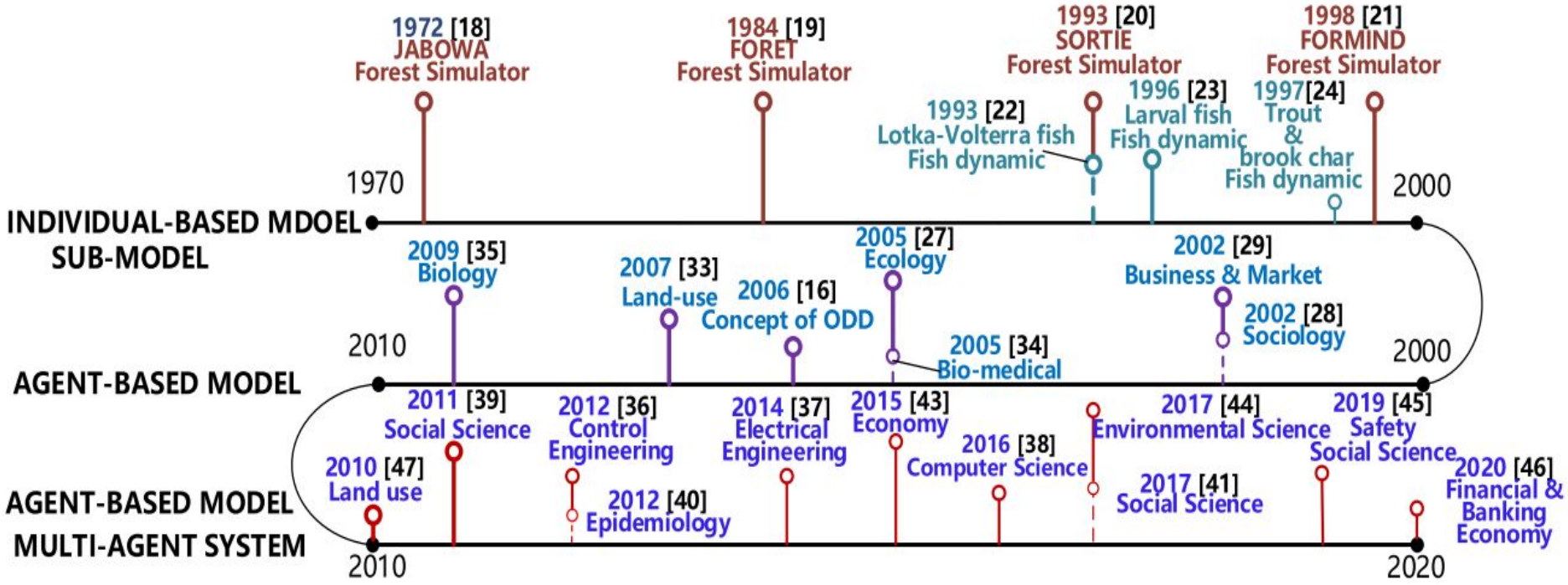



Zhang et al. 2023

- **Orígenes y significados** de **ABM** analizado desde el punto de vista de autores en **sistemas socioeconómicos**:
  - Arthur [1], Axtell and Farmer [3], Chen [5, 6, 7], Epstein [12], Epstein and Axtell [13], Gallegati [14], Kirman [18], Railsback and Grimm [22], Wilensky and Rand [47]

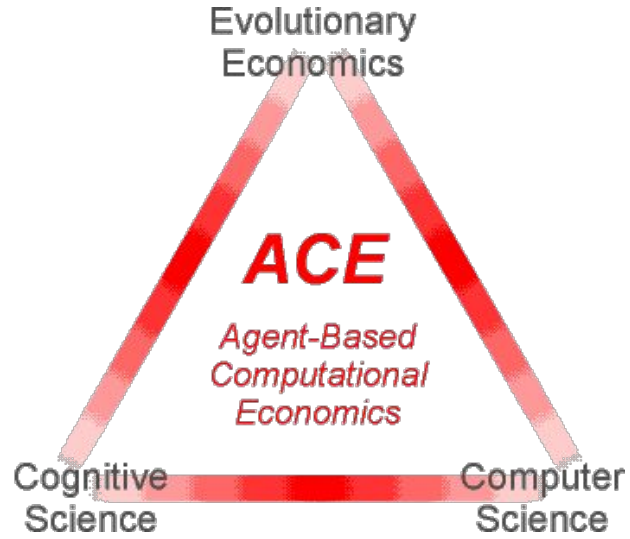
- Agent-Based Computing: Overview of **Software Agent Platforms** Available in 2023 (Wrona et al. 2023)

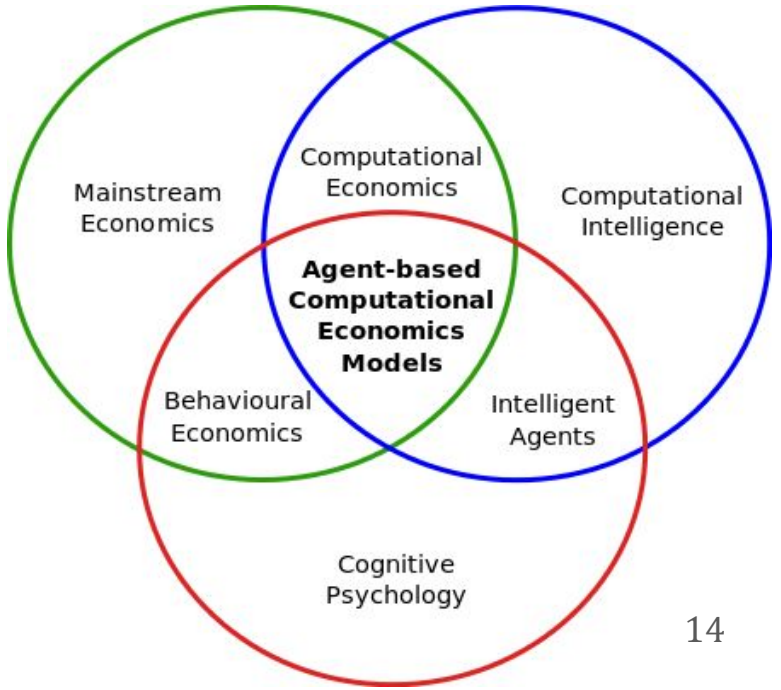

[1] https://doi.org/10.1038/s42254-020-00273-3
[3] https://oms-inet.files.svdcdn.com/production/files/JEL-v2.0.pdf?dm=1655807626
[5] https://doi.org/10.1007/978-3-642-01799-5_8
[6] https://doi.org/10.1016/j.jedc.2011.09.003
[7] https://doi.org/10.4324/9781315734422
[12] https://books.google.com.ar/books/about/Generative_Social_Science_Studies_in_Age.html
[13] https://doi.org/10.7551/mitpress/3374.001.0001
[14] https://doi.org/10.1007/978-3-319-93858-5
[18] https://doi.org/10.23941/ejpe.v4i2.81
[22] https://doi.org/10.4000/oeconomia.5533
[47] https://doi.org/10.1186/s40294-016-0027-6

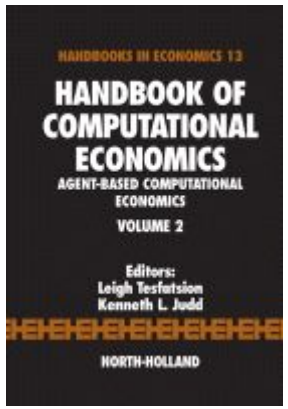
# ACE: Una variante particular de ABM ⟶ **Foco en sistemas económicos.**

Propuesto por **Leigh Tesfatsion,** luego de Computing in Economics and Finance (CEF1996), Geneva, Switzerland, June 26-28, 1996.

- **ACE agent:**
  - *a **software entity** within a computationally-constructed world, characterized at each instant by its current **state** (**data, attributes, and/or methods**)*
  - *capable of affecting the trajectory of outcomes for its **world***
  - *broad range of **entities**: e.g., individual lifeforms, social groupings, institutions, and/or physical phenomena*
  - *embody wide ranges of rationality and different forms of stochasticity*




Handbook of Computational Economics Vol. 2: Agent-Based Computational Economics

# ACE: Economic Systems as “Locally-Constructive Sequential Games”

- Los agentes interactuantes pueden ser heterogéneos
- Open-ended dynamics
- Los agentes interactuantes representan tomadores de decisiones **con estrategias** (simples/sofisticadas)
- Todos los **agentes** son “localmente constructivos”
  - Sus decisiones y acciones en cualquier momento dado son determinados por su propio **estado interno** (datos, atributos, y/o métodos) disponibles en ese instante
  - Los datos pueden ser **aprendidos** e incluso **recordados**
  - Las acciones son tomadas individualmente por cada agente en cada momento
  - Cada acción individual puede influir los estados de otros agentes (“cercanos”) en instantes futuros

▸ In **Sequential Games** economic interactions involve **sequences of decisions made by multiple agents over time.**

▸ In **Locally-Constructive Sequential Games,** each agent makes decisions sequentially, **taking into account their local information and incentives at each step**, without necessarily coordinating or considering the global consequences of their actions.

# ACE Modeling Principles

- **(MP1) Agent Definition:** An agent is a software entity within a computationally constructed world that can affect world outcomes through expressed actions.

- **(MP2) Agent Scope:** Agents can represent a broad range of entities, e.g., individual life-forms, social groupings, institutions, and/or physical phenomena.

- **(MP3) Agent Local Constructivity:** An intended action of an agent at a given instant is determined by the agent's state (data, attributes, and/or methods) at this instant.

# ACE Modeling Principles

**(MP4) Agent Autonomy:** All agent interactions (expressed agent actions) at a given instant are determined by the ensemble of agent states at this instant.

**(MP5) System Constructivity:** The state of the world at a given instant is determined by the ensemble of agent states at this instant.

**(MP6) System Historicity:** Given an initial ensemble of agent states, any subsequent world event (change in agent states) is induced by prior or concurrent agent interactions.

**(MP7) Modeler as Culture-Dish Experimenter:** Role of the modeler is limited to configuration and setting of initial agent states, & to non-perturbational observation, analysis, and reporting of world outcomes.

# Main Strands of ACE Research

**1) Empirical Understanding**
(possible explanations for empirical regularities)
**Key Issue:** Is there a causal explanation for persistently observed empirical regularities?

**ACE Approach:** Construct an agent-based world **capturing salient aspects of the <u>empirical situation</u>**. Investigate whether the empirical regularities can be **reliably generated as outcomes** in this world.

**2) Normative Design**
(institutions, policies, regulations ...)
**Key Issue:** Will a proposed design ensure efficient, fair, and orderly outcomes over time, even if participants attempt to "game" the design for their own advantage?

**ACE Approach:** Construct an agent-based world **capturing salient aspects of the <u>proposed design</u>**. Introduce agents with initially configured states appropriate for the purpose at hand. Let the world evolve. Observe and evaluate resulting outcomes.

# Main Strands of ACE Research

**3) Qualitative Insight/Theory Generation** (e.g., self-organization of decentralized markets, ...)

**Illustrative Issue:** Performance capabilities of economies with decentralized markets?

(Adam Smith, L. von Mises, F. von Hayek, J.M. Keynes, J. Schumpeter, ... )

**ACE Approach:** Construct an agent-based world **qualitatively capturing key aspects of the economy** (firms, consumers, banks, government, circular flow, limited information, ... )

**Configure decision-making agents with behavioral dispositions, needs, goals, beliefs**, ...

Let the world evolve & observe results.

"Qualitatively captured aspects": Relevance of "toy models"

# ACE admite cambios en la estructura de los modelos

- The interactions of these *agents induce all dynamics* (**state** changes) for the modeled system, starting *from initial agent **states*** (configured and set by the modeler)
- As a **result of these interactions**:
  - each agent experiences “time” locally, as an unfolding sequence of events;
  - the dimension and content of agent states can change;
    - changes in sensed surroundings; changes in recorded observations; changes in physical attributes; changes in beliefs; and belief-induced changes in **action rules**
  - agents can **subsume other agents as components**
  - agents can **break apart into smaller component agents**
  - new **agents can be created (added)**
  - existing **agents can be destroyed (removed)**

# Modelos dinámicos tradicionales. Espacio de Estados.

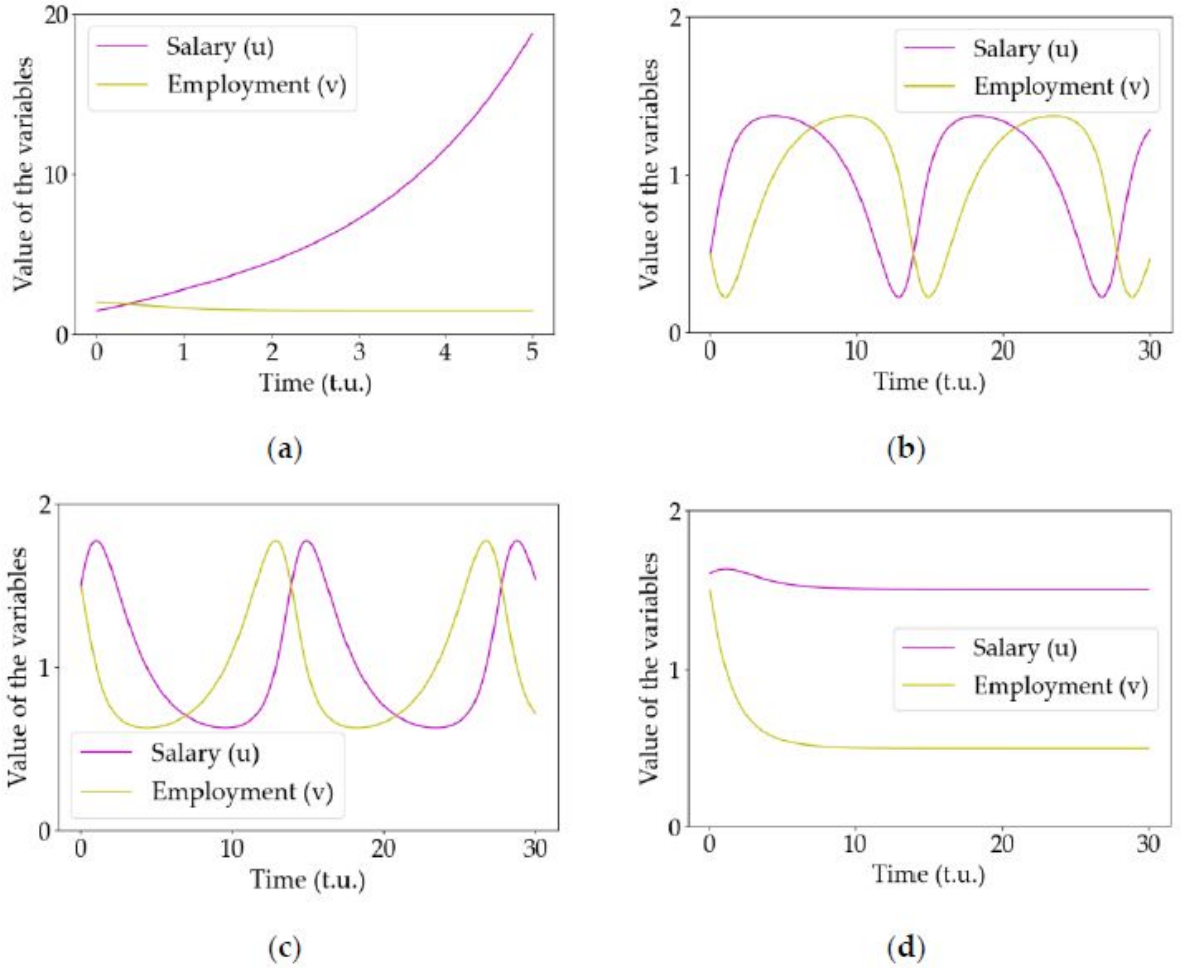
- Modern economic theory also relies heavily on **state-space models.**
- Ejemplo clásico: Modelo de Crecimiento de Goodwin
  - Foco en: **Salario (*u*) y Empleo (*v*)**

$$\frac{dv}{dt} = [s - (\alpha + \beta) - us]v,$$

$$\frac{du}{dt} = [-(\gamma + \alpha) + \rho v]u,$$

*dx/dt =* ***velocidad de cambio*** *de x(t) respecto de t*

*Modelo de Goodwin: posibles* ***modos de operación***




Yañez Rodriguez & Muñuzuri, 2023

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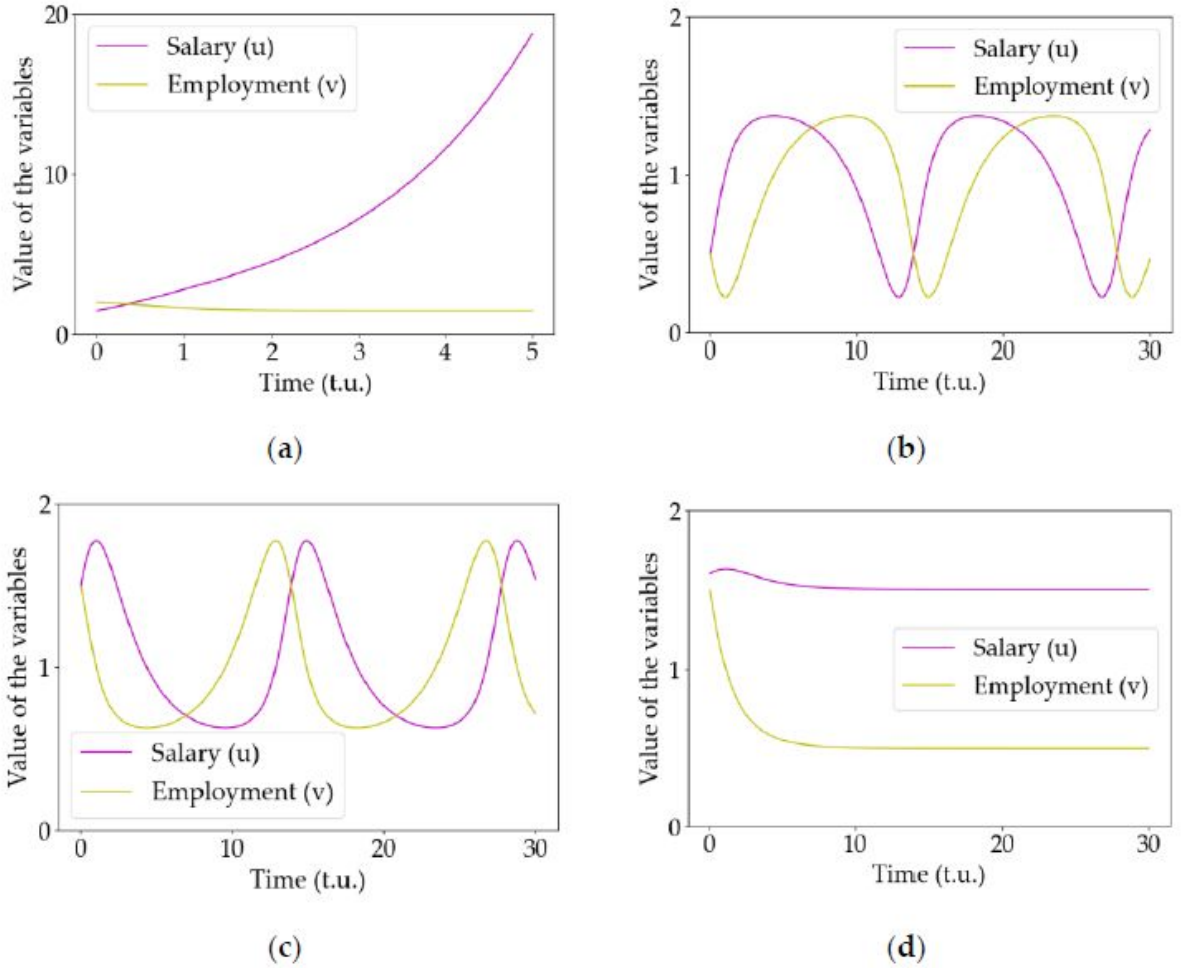
$q$ output,
$k$ capital,
$w$ wage,
$a = a_0 e^{\alpha t}$ labour productivity, where $\alpha$ is the growth parameter,
$s = q/k = 1/\sigma$ capital productivity,
$k/q = \sigma$ capital-output ratio,
$u = w/a$ workers' share of product,
$(1 - w/a)$ capitalists' share of product,
$(1 - w/a)q = \dot{k}$ surplus = profit = savings = investments,
$\dot{k}/k = \dot{q}/q = (1 - w/a)/\sigma$ profit rate,
$n = n_0 e^{\beta t}$ labour supply, where $\beta$ is the growth parameter,
$l = q/a$ employment,
$v = l/n$ employment rate.

$$\frac{\dot{w}}{w} = -\gamma + \rho v$$

Orlando & Sportelli 2021

*Modelo de Goodwin: posibles **modos de operación***




Yañez Rodriguez & Muñuzuri, 2023

# Modelos dinámicos tradicionales. Espacio de Estados.

- Estos modelos usualmente incorporan una o más de estas características:
  - modeler-imposed
    - rationality
    - optimality
    - equilibrium conditions

*"... modelers should not be forced to rely on a priori model specifications whose only justification is analytical tractability"*
Tesfatsion, 2017

  - ***… that could not (or would not) be met by locally-constructive and autonomous agents interacting within economic systems that satisfy the ACE modeling principles***

- Ejemplo: Modelo de Goodwin, suposiciones "a nivel sistema"

(a) steady technical progress (disembodied),
(b) steady growth in the labour force,
(c) only two factors of production, labour and "capital" (plant and equipment), both homogeneous and non-specific,
(d) all quantities real and net,
(e) all wages consumed, all profits saved and invested,
(f) a constant capital-output ratio,
(g) a real wage rate that rises in the neighbourhood of full employment.

Orlando & Sportelli 2021

# ACE Agent Rationality

- For ACE researchers, as for economists in general, **the modeling of decision-makers** is a primary concern
- **(MP1)–(MP7)** are constraints inherent in every real-world dynamic system

- **ACE decision-making agents**
  - can be **modeled as rational (or irrational)** just like real-world decision-makers
  - can range from **simple behavioral rules to sophisticated anticipatory learning algorithms** for the approximate achievement of intertemporal objectives:
    - **Reactive Reinforcement Learning (RL)**. Roth-Erev reactive reinforcement learning, ... ;
    - Belief-based learning. Fictitious play, Camerer/Ho EWA algorithm, ... ;
    - Anticipatory learning. Q-learning, adaptive dynamic programming, ... ;
    - Evolutionary learning. Genetic algorithms, genetic programming, ... ;
    - Connectionist learning. Associative memory learning, artificial neural network
    - Deep Learning. Using ANNs with multiple hidden layers, ... .

# Taxonomías de Agentes (orientación a objetos)

Ejemplo ilustrativo

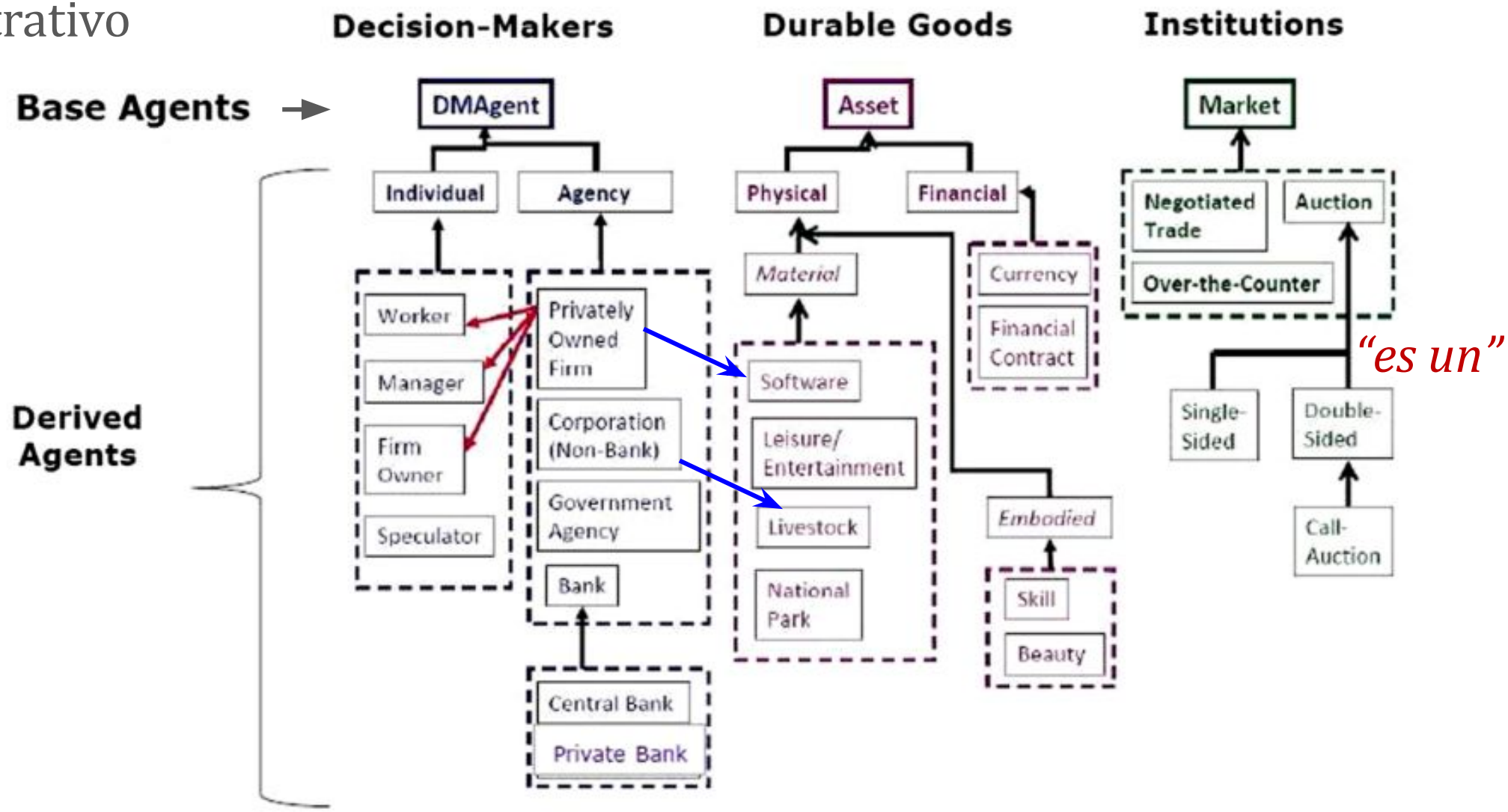



Figure 1. Partial agent taxonomy for an ACE macroeconomic model. Up-pointing arrows denote 'is a' relationships and down-pointing arrows denote 'has a' relationships.

# Agentes como objetos de software

**agent World**
{
**Public Access:**

**// Public Methods**
The *World Event Schedule*, a system clock permitting World inhabitants to time and order their activities (method activations), including synchronized activities such as offer posting and trade;
Protocols governing the ownership of stock shares;
Protocols governing collusion among firms;
Protocols governing the insolvency of firms;
Methods for retrieving stored World data;
Methods for receiving data.

**Private Access:**

**// Private Methods**
Methods for gathering, storing, and sending data.

**// Private Data**
World attributes (e.g., spatial configuration);
World inhabitants (e.g., markets, firms, consumers);
Attributes of the World's inhabitants;
Methods of the World's inhabitants;
History of World events;
Address book (communication links);
Recorded communications.
}

**agent Firm**
{
**Public Access:**

**// Public Methods**
getWorldEventSchedule(clock time);
getWorldProtocol(ownership of stock shares);
getWorldProtocol(collusion among firms);
getWorldProtocol(insolvency of firms);
getMarketProtocol(posting of supply offers);
getMarketProtocol(trading process);
Methods for retrieving stored Firm data;
Methods for receiving data.

**Private Access:**

**// Private Methods**
Methods for gathering, storing, and sending data;
Method for selecting my supply offers;
Method for rationing my customers;
Method for recording my sales;
Method for calculating my profits;
Method for allocating my profits to my shareholders;
Method for calculating my net worth;
Methods for changing my methods.

**// Private Data**
My money holdings, capacity, total cost function, and net worth;
Information about the structure of the World;
Information about World events;
Address book (communication links);
Recorded communications.
}

**agent Consumer**
{
**Public Access:**

**// Public Methods**
getWorldEventSchedule(clock time);
getWorldProtocol(ownership of stock shares);
getMarketProtocol(price discovery process);
getMarketProtocol(trading process);
Methods for retrieving stored Consumer data;
Methods for receiving data.

**Private Access:**

**// Private Methods**
Methods for gathering, storing, and sending data;
Method for determining my budget constraint;
Method for determining my demands;
Method for seeking feasible and desirable supply offers;
Method for recording my purchases;
Method for calculating my utility;
Methods for changing my methods.

**// Private Data**
My money holdings, subsistence needs, and utility function;
Information about the structure of the World;
Information about World events;
Address book (communication links);
Recorded communications.
}

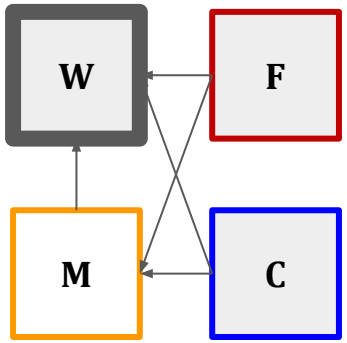
**agent Market**
{
**Public Access:**

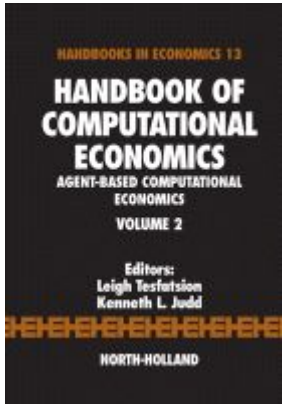
**// Public Methods**
getWorldEventSchedule(clock time);
Protocols governing the public posting of supply offers;
Protocols governing the price discovery process;
Protocols governing the trading process;
Methods for retrieving stored Market data;
Methods for receiving data.

**Private Access:**

**// Private Methods**
Methods for gathering, storing, and sending data.

**// Private Data**
Information about firms (e.g., posted supply offers);
Information about consumers (e.g., bids);
Address book (communication links);
Recorded communications.
}




[Handbook of Computational Economics Vol. 2: Agent-Based Computational Economics]

# PERSPECTIVES

Arthur, W.B. Foundations of complexity economics. *Nat Rev Phys* 3, 136–145 (2021). https://doi.org/10.1038/s42254-020-00273-3

## Foundations of complexity economics

*W. Brian Arthur*

Abstract Conventional, neoclassical economics assumes perfectly rational agents (firms, consumers, investors) who face well-defined problems and arrive at optimal behaviour consistent with — in equilibrium with — the overall outcome caused by this behaviour. This rational, equilibrium system produces an elegant economics, but is restrictive and often unrealistic. Complexity economics relaxes these assumptions. It assumes that agents differ, that they have imperfect information about other agents and must, therefore, try to make sense of the situation they face. Agents explore, react and constantly change their actions and strategies in response to the outcome they mutually create. The resulting outcome may not be in equilibrium and may display patterns and emergent phenomena not visible to equilibrium analysis. The economy becomes something not given and existing but constantly forming from a developing set of actions, strategies and beliefs — something not mechanistic, static, timeless and perfect but organic, always creating itself, alive and full of messy vitality.

Table 1 | **Differences between neoclassical and complexity economics**

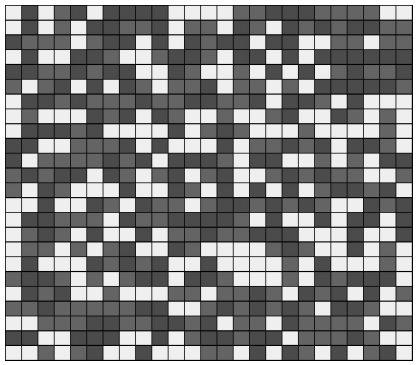
| Feature[a] | Neoclassical economics | Complexity economics |
|---|---|---|
| Agents | Representative, with 1, 2, *N* or a distribution of types | Diverse |
| Organizing principle | Equilibrium. Agent behaviour consistent with aggregate outcome | Nonequilibrium. Agent behaviour reacts to aggregate outcome |
| Metaphor | Well-functioning machine | Ecology: of forecasts, actions, strategies |
| What is faced by agents | Well-defined problem | Ill-defined situation |
| Behaviour | Agents optimize | Agents face fundamental uncertainty, they try to make sense, explore |
| Structural change | The equilibrium shifts | Novelty causes endogenous restructuring |
| Rationality | Perfect and boundless | Rationality usually not defined |
| Feedbacks | Diminishing returns | Increasing, as well as diminishing, returns |
| Time | Equilibrium is timeless | History and path taken matter |
| Dominant theme | Allocation of resources | Formation of structures |
| System | Closed to new behaviour | Open. System can be exploited |
| Methods used | Mathematics (quantities, incentives in balance) | Mathematics and computation (algorithmic and event-driven) |
| Temporary phenomena | Excluded by equilibrium | Possibly emerge |
| Interaction | Homogeneous | Channelled by networks |
| Evolution of economy | Outcomes usually seen as in stasis. Not evolving | Economy self-creating, in perpetual novelty |

# **Ejemplo:** AgroDEVS - Modelo de Agentes para Cambios en Usos de la Tierra

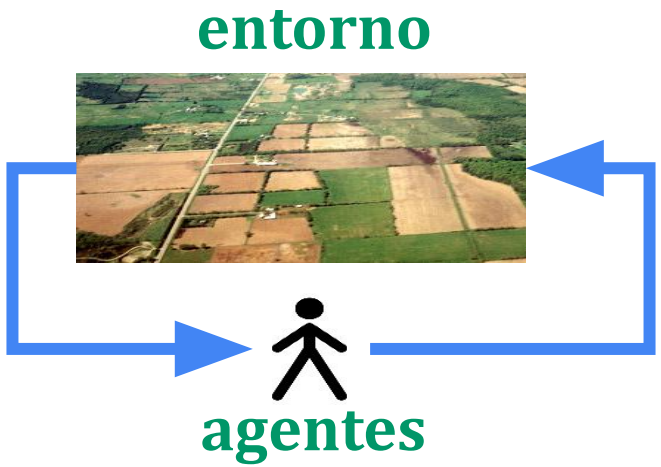
## Dinámicas Productor-Economía-Ambiente

- Paisaje virtual de **agentes** (productores):
  - interactuando entre sí
  - interactuando con su **entorno** (clima y precios)
- Simula la toma de decisiones (Nivel Tecnológico y Uso de la Tierra) y sus consecuencias:
  - económicas (margen económico)
  - ambientales (renovabilidad de la producción)
- A escalas:
  - individual (establecimiento)
  - paisaje (región)


**grilla de 25x25 lotes**

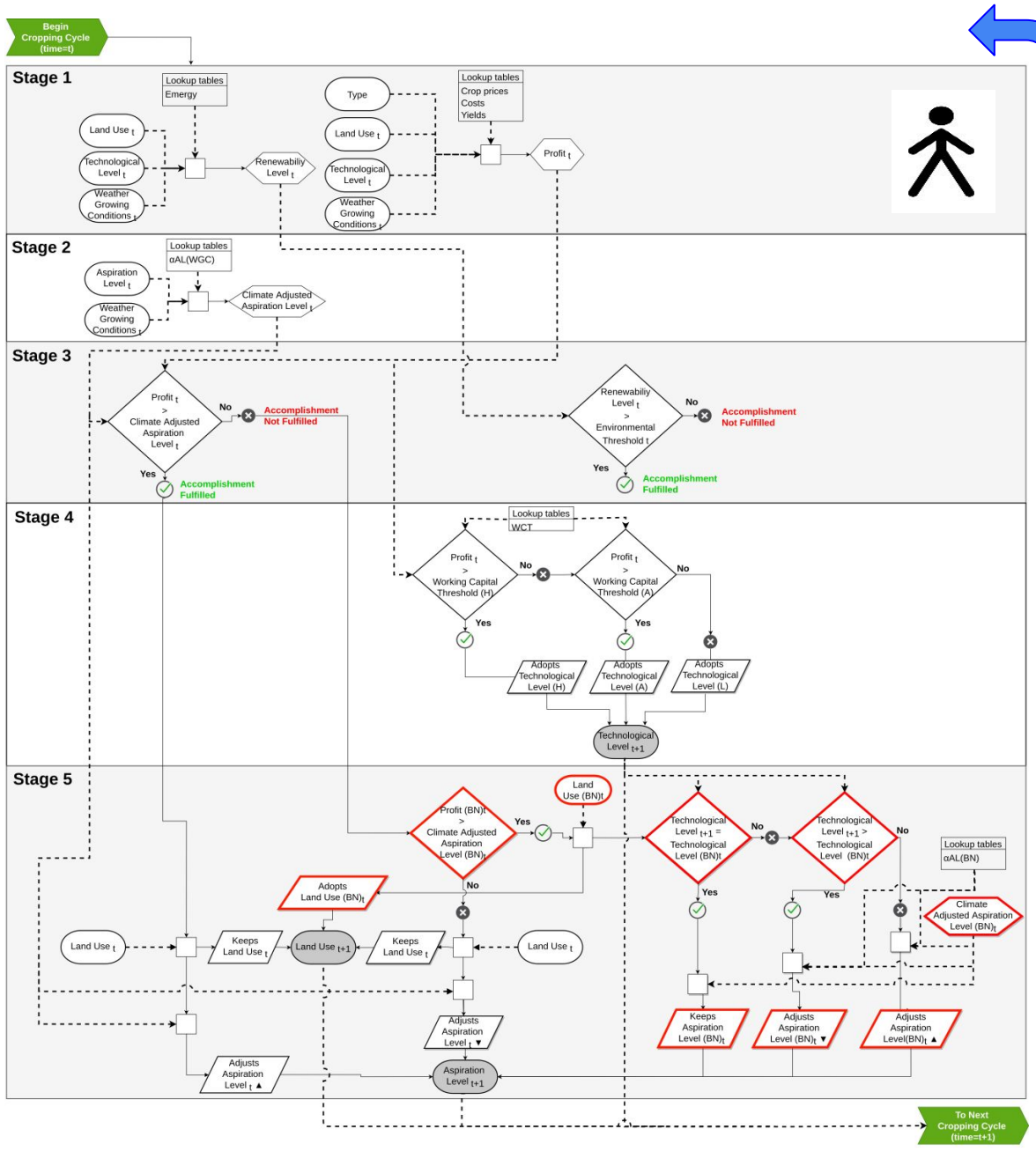


1 agente/lote
625 lotes



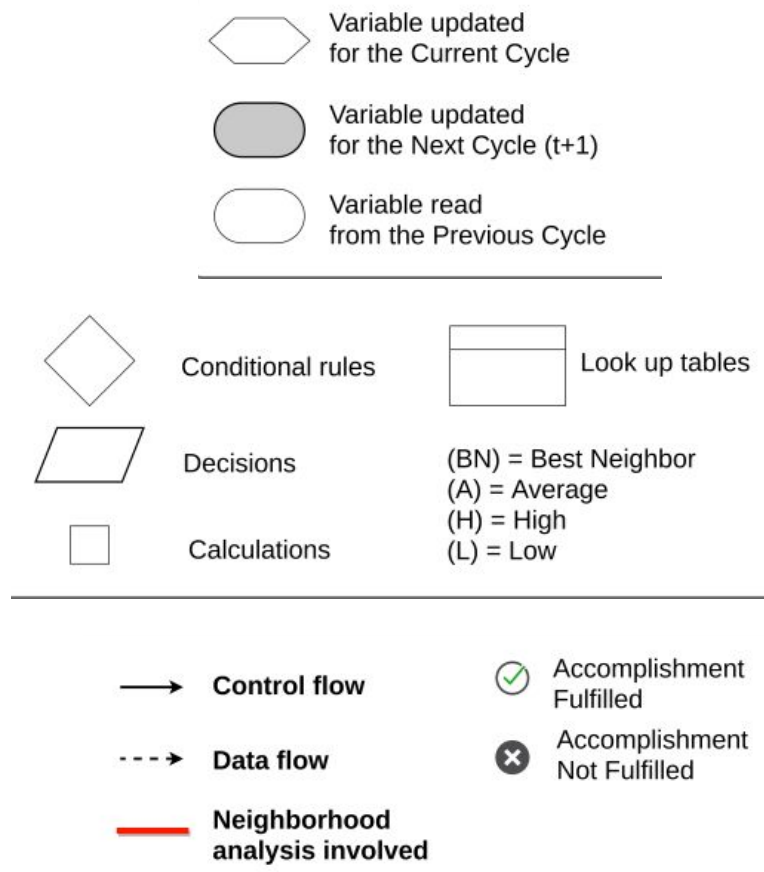

*"An Integrated **Ecological-Social** Simulation Model of **Farmer Decisions** and Cropping System Performance in the **Rolling Pampas (Argentina)**"* Pessah et al., 2019

# Ciclo de **Toma de Decisiones** por cada Agente en AgroDEVS



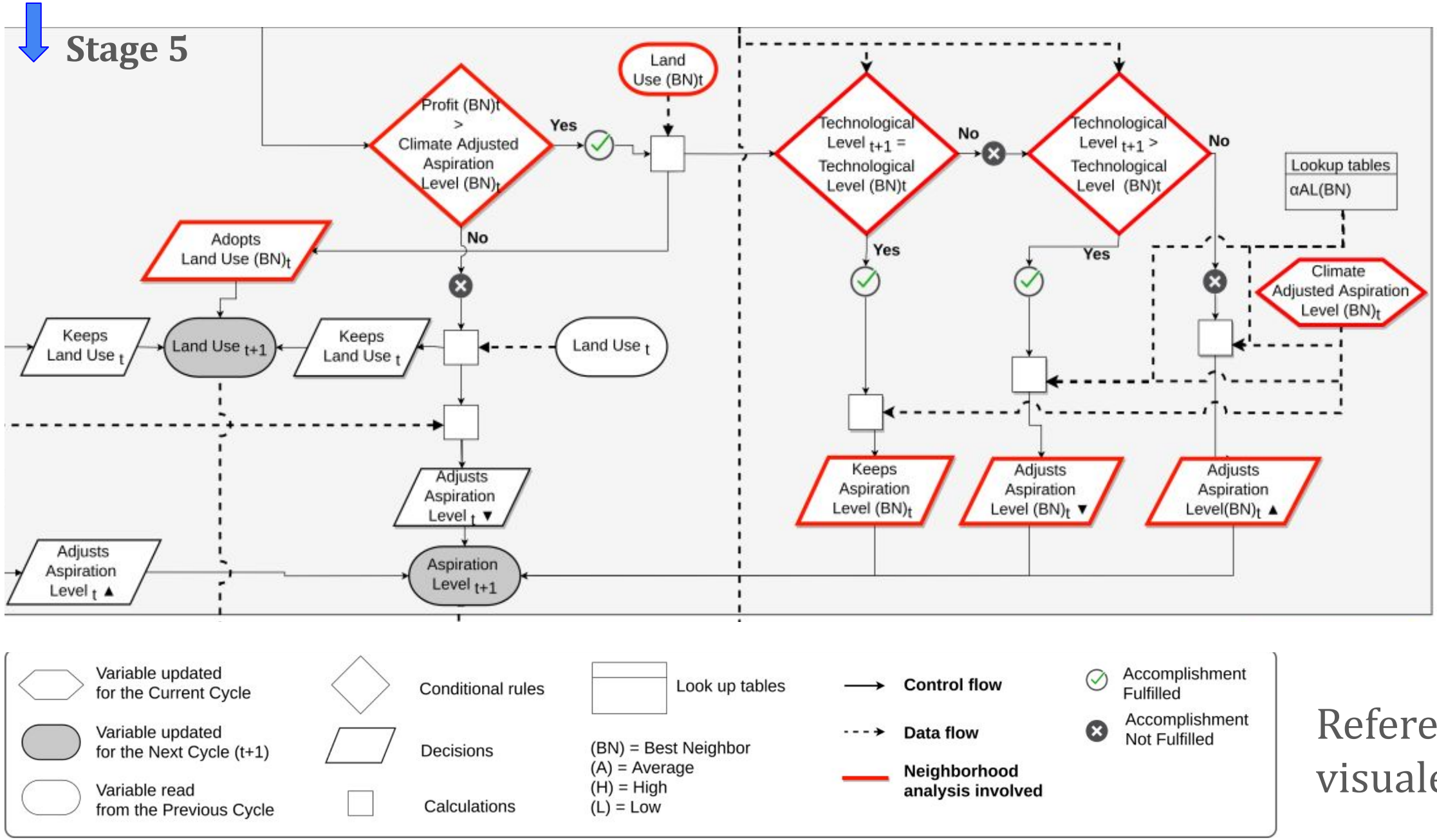

**t+1** **(siguiente campaña de siembra)**

*Tipificación del proceso de toma de decisiones productivas en sistemas agrícolas argentinos. Pessah, S.; Ferraro, D.O. (2017)*




## Referencias visuales

# Ciclo de **Actividades** por cada Agente en AgroDEVS



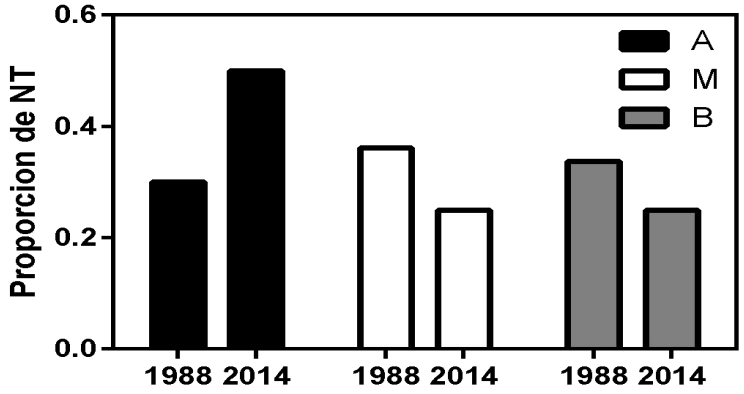

Detalle de la **Etapa 5**

Referencias visuales

# AgroDEVS: Modelo de Agentes para Cambios en Usos de la Tierra

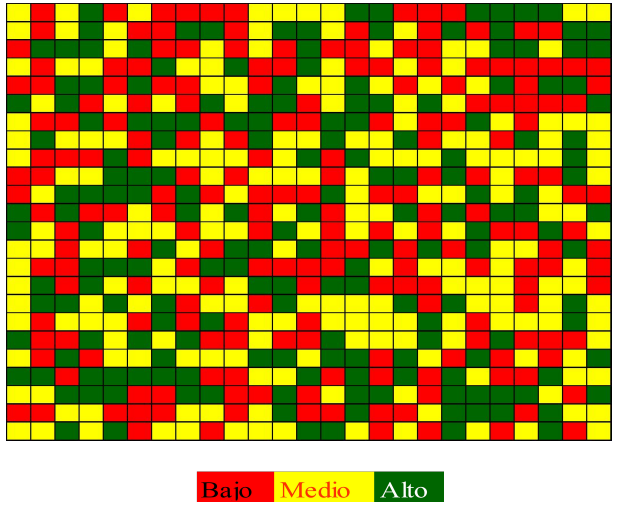
## Resultados

### Nivel Tecnológico (NT) del cultivo

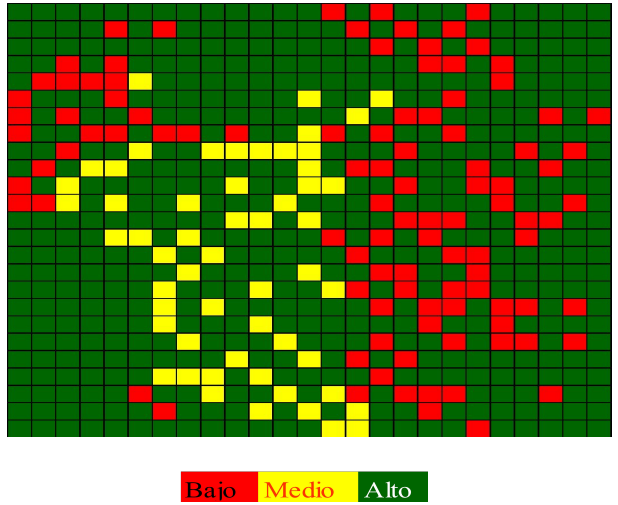



- Aumenta la proporción de agentes en NT alto
- La adaptación al NT depende de la naturaleza del evento anterior
- Persiste la variabilidad entre agentes

Distribución NT (1988)

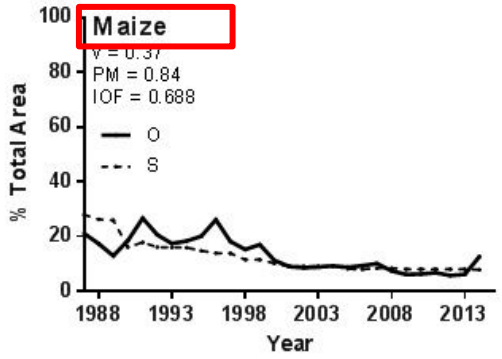



Distribución NT (2014)

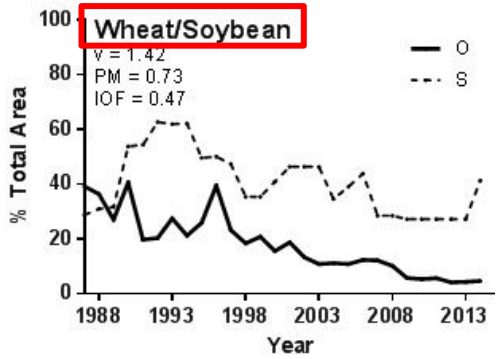


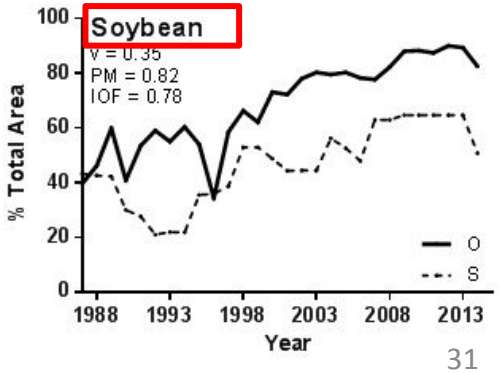

### Uso de la Tierra (LU)

- Ajuste de M y S > T/S
- AgroDEVS captura el sentido de cambios en LU
- Variables exógenas a AgroDEVS que pueden afectar la decisión de cambio de LU
- Capacidad de Comercialización
- Cambio en precios relativos




*O: Observado*
*S: Simulado*



# Otros ejemplos:

- **The impact of prudential regulations on the UK housing market and economy: insights from an agent-based model (2024)**

  https://www.bankofengland.co.uk/working-paper/2024/the-impact-of-prudential-regulations-on-the-uk-housing-market-and-economy

  Marco Bardoscia, Adrian Carro, Marc Hinterschweiger, Mauro Napoletano, Lilit Popoyan, **Andrea Roventini** and Arzu Uluc


## Abstract

We develop a macroeconomic agent-based model to study the joint impact of borrower and lender-based prudential policies on the housing and credit markets and the economy more widely. We perform three experiments: (i) an increase of total capital requirements; (ii) an introduction of a loan-to-income (LTI) cap on mortgages to owner-occupiers; and (iii) a joint introduction of both experiments at the same time. Our results suggest that tightening capital requirements leads to a sharp decrease in commercial and mortgage lending, and housing transactions. When the LTI cap is in place, house prices fall sharply relative to income, and the homeownership rate decreases. When both policy instruments are combined, we find that housing transactions and prices drop. Both policies have a positive impact on real GDP and unemployment, while there is no material impact on inflation and the real interest rate.