(Multi-Agent) Reinforcement Learning: a primer, with applications in economics

Introduction and Basics of Reinforcement Learning

Aldo **Glielmo***

Applied Research Team
General Directorate for IT

A R T
www.bankit.art

*All views and opinions are those of the speaker(s) and do not necessarily reflect the position of Bank of Italy

BANCA D'ITALIA
EUROSISTEMA

Meet the team

Applied Research Team

established 2013, boosted 2017

Permanent staff:
25 people

- 10 [PhDs in Computer Science/Engineering]
- 7 [MSc in Computer Science/Engineering]
- 3 [ongoing (executive) PhDs in Computer Science]
- 2 [PhD in Computational Physics/Mathematics]
- 1 [PhD in Economics]
- 1 [MSc Mathematics]
- 1 [Designer & Scientific Secretary]

SCAN ME

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academic profile
- *research-oriented, post-graduates*
- *oft ambitious/unprecedented projects*

\+

Academic Network

UNIVERSITY OF OXFORD
SAPIENZA UNIVERSITÀ DI ROMA
LUISS
TOR VERGATA UNIVERSITÀ DEGLI STUDI DI ROMA
EURECOM
UNIVERSITÀ DELLA CALABRIA
POLITECNICO MILANO 1863
TU WIEN TECHNISCHE UNIVERSITÄT WIEN Vienna | Austria
ROMA TRE UNIVERSITÀ DEGLI STUDI
UNIVERSITÀ DEGLI STUDI DI MILANO
UNIVERSITÀ degli STUDI di CATANIA

ART R&D **domains**

Computer Science (CS)

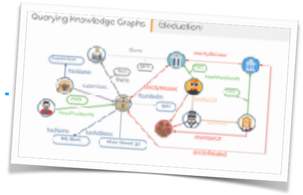
- Digital Comm.
  - Banknote eBook BAN
  - Tier V: An IT documentary IT
  - Interactive exhibit: A Bill of Ideas CMB
- Blockchain, DLTs, cryptography & CBDC
  - Fees, the Bitcoin way
  - Lightning Networks Tracker
  - The evolving path of Privacy
  - itCoin (R&D on CBDCs) MSP

Artificial Intelligence (AI)

- Machine Learning (ML)
  - Activity classification RES
  - Black-box deep ML & NLP UIF
  - Phenomena detection VIG
  - Deep-fake Detection Uni. Catania
- Hybrid ML / AR (Neural-Symbolic) approaches
  - Fact-checking financial claims
  - Smart chatbot

Automated Reasoning (AG) & Knowledge Graphs (KG)

- Role Mining & Optimisation IT
- Declarative close links (P#!)
- Analysis of takeovers ECS
- Fast-changing economic networks PoliMi
- Anti-money laundering on/off blockchain
- KRR on Companies ECS VIG TU Wien
- Dataset anonymisation RDC Oxford
- The Vadalog joint research program



Computational economics

Agent-based modelling (ABM)

- Housing/credit markets ECS Oxford
- Black-it (an OS ABM toolkit) ECS
- AI4ABM calibration Cattolica
- CBDC modelling Cattolica

Black it

Legend

- Internal BoI partner
- External partner

My timeline

KCL Cond. Matter — *SISSA* Data Science / Stat. Bio. — *BoI* Applied Research Team

Sep-2019 — *Oct-2021*

PhD - AI4Science

- Accurate interatomic force fields via machine learning with covariant kernels, ***PRB*** (2017)
- Efficient nonparametric n-body force fields from machine learning, ***PRB*** (2018)
- SPONGE: A generalized eigenproblem for clustering signed networks, ***AISTATS*** (2019)
- Gaussian Process States: A data-driven representation of quantum many-body physics, ***PRX*** (2020)

Postdoc - AI & Data Science

- Hierarchical nucleation in deep neural networks, ***NeurIPS*** (2020)
- Unsupervised learning methods for molecular simulation data, ***Chemical Reviews*** (2021)
- Ranking the information content of distance measures, ***PNAS Nexus*** (2022)
- Redundant representations help generalization in wide neural networks, ***NeuIPS*** (2022)
- DADApy: Distance-based analysis of data-manifolds in Python, ***Patterns*** (2022)

Research Scientist - AI4Econ

- Intrinsic dimension estimation for discrete metrics, ***PRL*** (2023)
- Simulating the economic impact of rationality with reinforcement learning …, ***ICAIF*** (2024)
- Investigating the price determinants of the European Carbon Trading System, ***Quantitative Finance*** (2024)
- Natural-gas storage modelling by deep reinforcement learning, ***ICAIF*** (2025)
- Heterogeneous RBCs via deep multi-agent reinforcement learning, ***AAMAS*** (2026)

Science Home News Journals Topics Careers

Science - PINS Prize for Neuromodulation

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Solving the quantum many-body problem with artificial neural networks

Giuseppe Carleo[1,*], Matthias Troyer[1,2]

nature

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Review Article | Published: 25 July 2018

Machine learning for molecular and materials science

Keith T. Butler, Daniel W. Davies, Hugh Cartwright, Olexandr Isayev & Aron Walsh

Lecture Notes in Physics

Kristof T. Schütt · Stefan Chmiela
O. Anatole von Lilienfeld
Alexandre Tkatchenko · Koji Tsuda
Klaus-Robert Müller *Editors*

Machine Learning Meets Quantum Physics

PHYSICAL REVIEW LETTERS

Generalized Neural-Network Representation of High-Dimensional Potential-Energy Surfaces

Jörg Behler and Michele Parrinello
Phys. Rev. Lett. **98**, 146401 – Published 2 April 2007

PHYSICAL REVIEW LETTERS

Gaussian Approximation Potentials: The Accuracy of Quantum Mechanics, without the Electrons

Albert P. Bartók, Mike C. Payne, Risi Kondor, and Gábor Csányi
Phys. Rev. Lett. **104**, 136403 – Published 1 April 2010

PHYSICAL REVIEW LETTERS

Fast and Accurate Modeling of Molecular Atomization Energies with Machine Learning

Matthias Rupp, Alexandre Tkatchenko, Klaus-Robert Müller, and O. Anatole von Lilienfeld
Phys. Rev. Lett. **108**, 058301 – Published 31 January 2012

REVIEWS OF MODERN PHYSICS

Machine learning and the physical sciences*

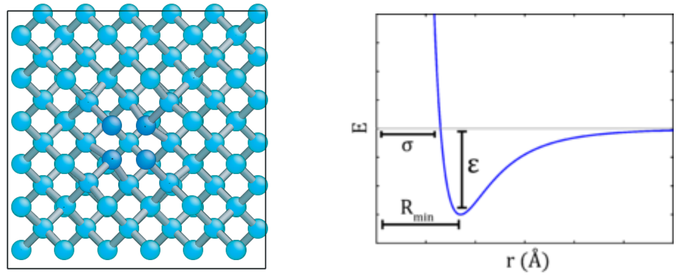
Giuseppe Carleo, Ignacio Cirac, Kyle Cranmer, Laurent Daudet, Maria Schuld, Naftali Tishby, Leslie Vogt-Maranto, and Lenka Zdeborová
Rev. Mod. Phys. **91**, 045002 – Published 6 December 2019

Physical Review X

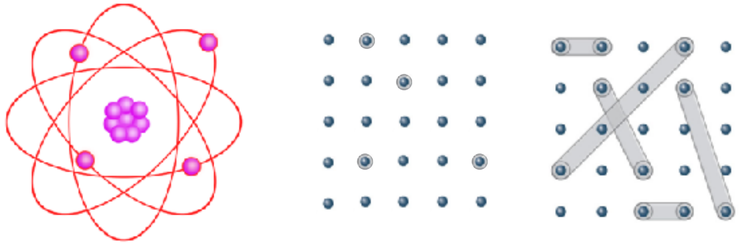
Gaussian Process States: A Data-Driven Representation of Quantum Many-Body Physics

Aldo Glielmo[1,2,*], Yannic Rath[1,*], Gábor Csányi[3], Alessandro De Vita[1], and George H. Booth[1]

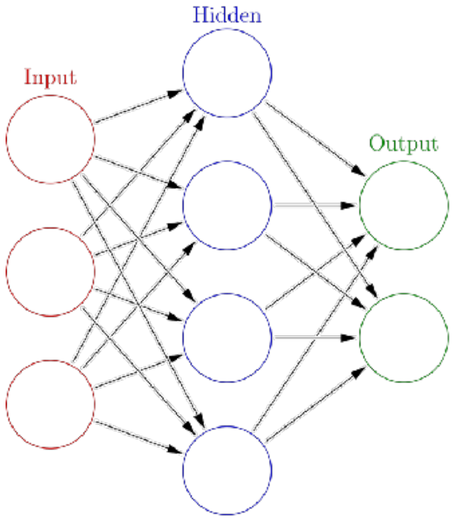
Parametric potential for *atoms*



Parametric wave functions for *electorns*



Neural network (ML) models trained with supervised or reinforcement learning



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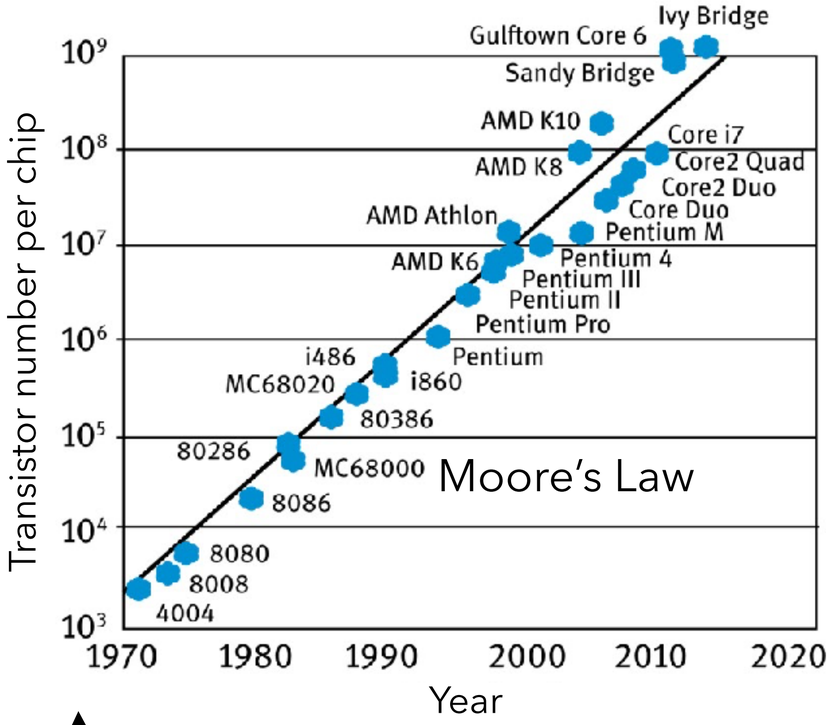
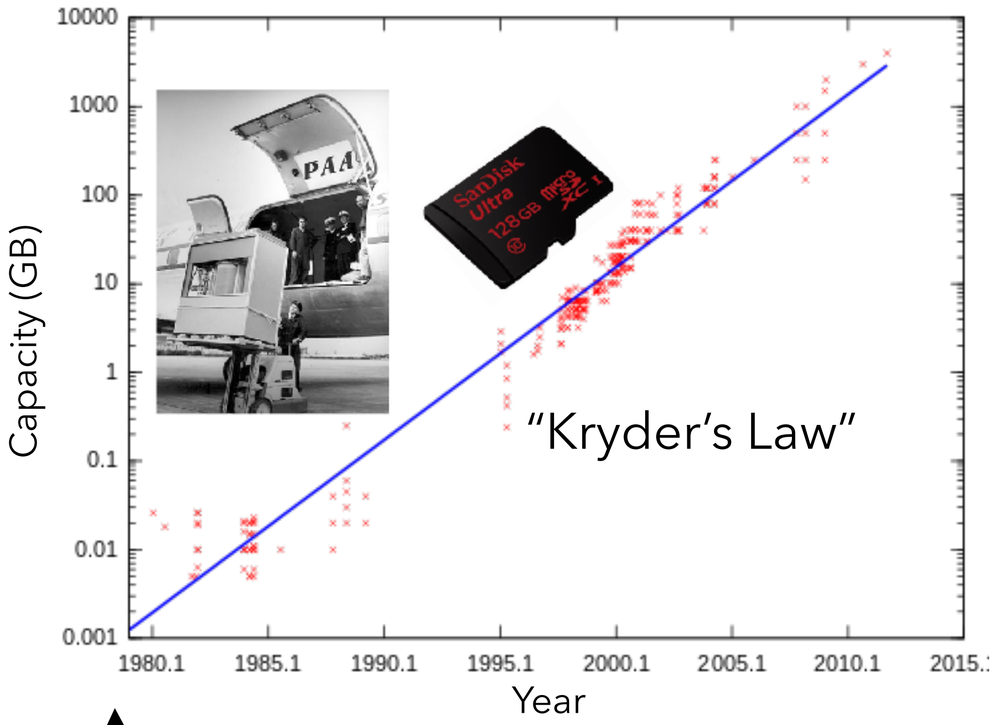
Applied research team

Computation and data availability

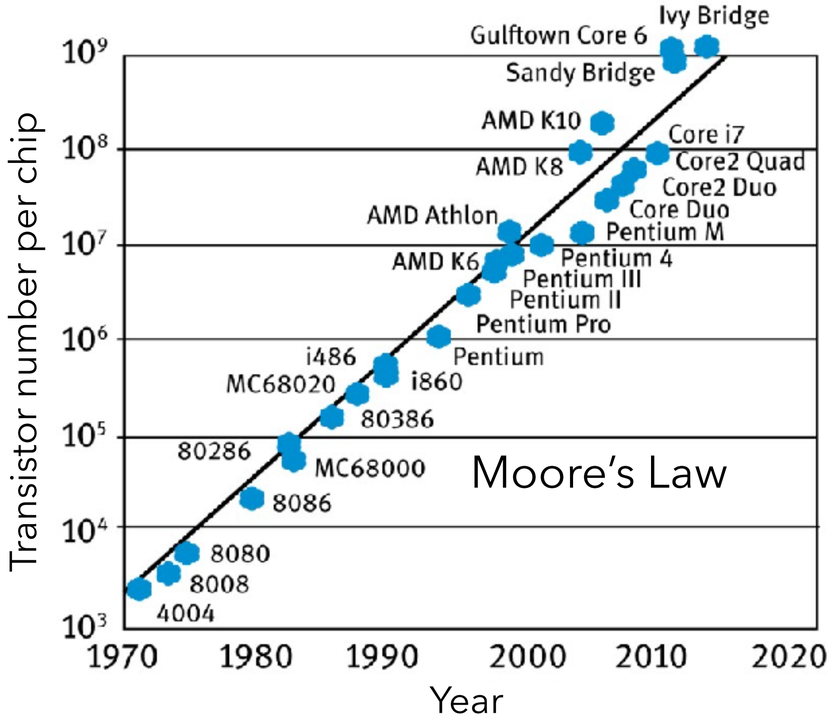


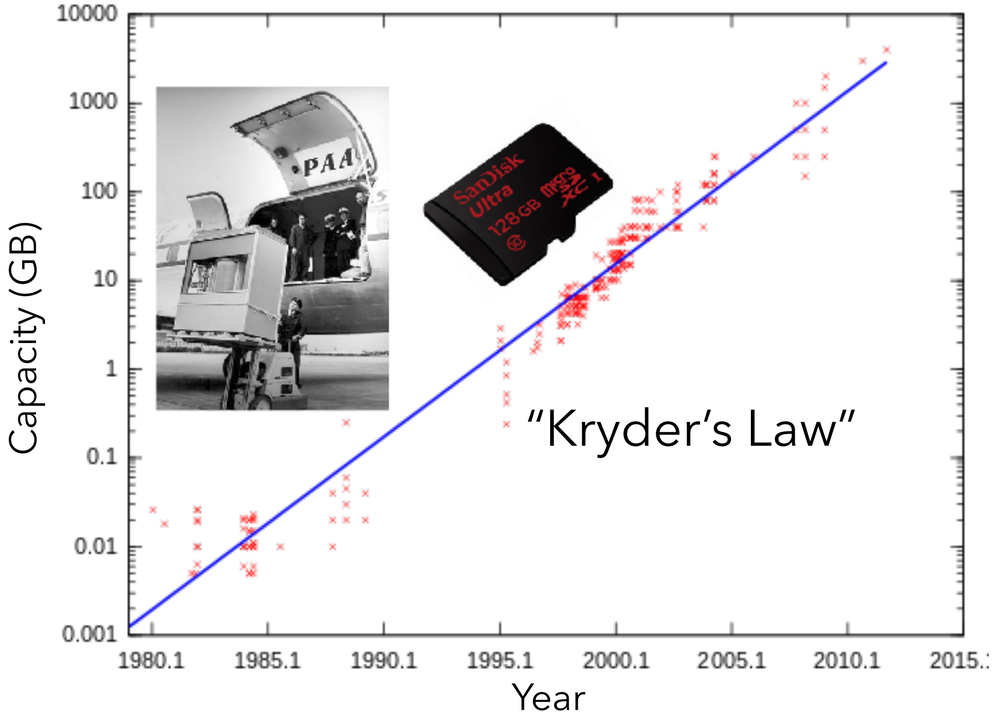
exponential increase in
computational power

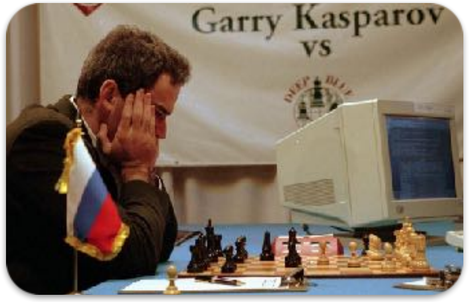


exponential increase in
data availability

ABMs and computation: more ML



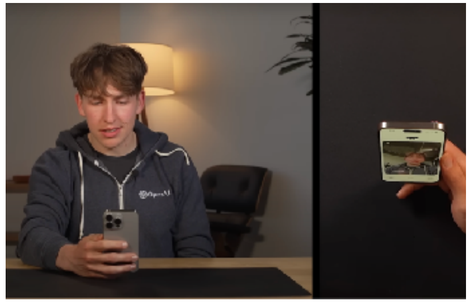




IBM Deep Blue - 1990's

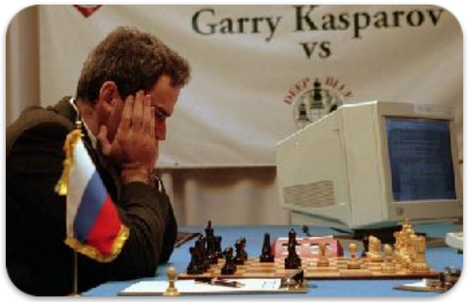
IBM Watson - 2000's

Deep Mind AlphaGo - 2010's



OpenAI ChatGPT - 2020's

Econ and computation: more ML

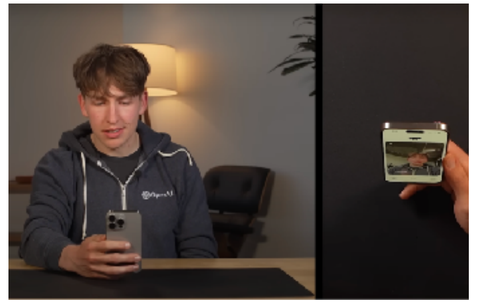


🧠 Traditional Economics

Based on sophisticated human-designed carefully crafted rules and databases

🤖 ML-driven Economics

Based on algorithms that can *self-improve* using *more data* and/or *more computation*



How can we enable this transition?

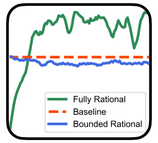
GitHub bancaditalia

Line **1.** High-quality **open-source** software

Line **2.** Faster ML-based **calibration**

our focus

Line **3.** **AI-driven** economic agents



ART
Applied research team

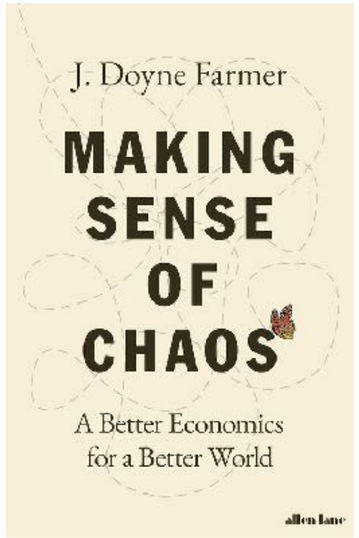
Economics in a nutshell

Economics = Accounting + Behaviour

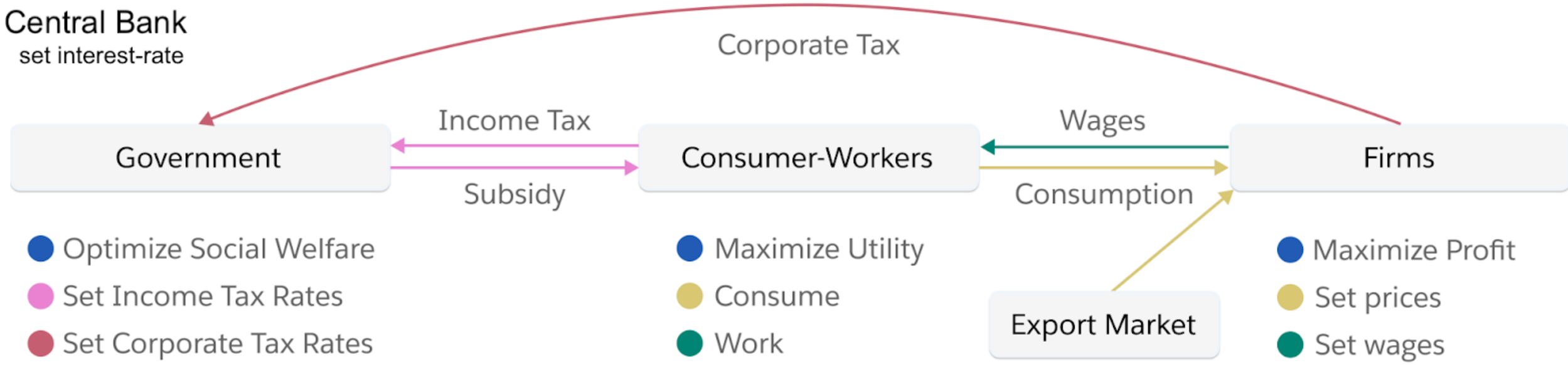
We can think about the **economy** schematically as an **interaction of accounting and human decision-making**.

Accounting is represented by the network of *balance sheets*, which continually changes as people make economic decisions. These *decisions take many forms*: What product to consume? What product to offer? Whom to hire? When to borrow? How much and from whom? All these decisions constitute economic activity. To understand the economy, we have to understand human behavior as it relates to *economic decision-making*, and we need to understand how this interacts with the underlying network of balance sheets.

Accounting and decision-making **both pose difficult problems but in very different ways**. Accounting is complicated but well-understood, whereas decision-making requires an understanding of human nature that is still incomplete.



Economics in a nutshell



[Curry et al., Analyzing Micro-Founded General Equilibrium Models …, 2022]

- Economics = Accounting + Behaviour
- The economy is a system of heterogeneou decision-making agents interacting through markets and making economic decisions

Traditional econ in a nutshell: the RBC

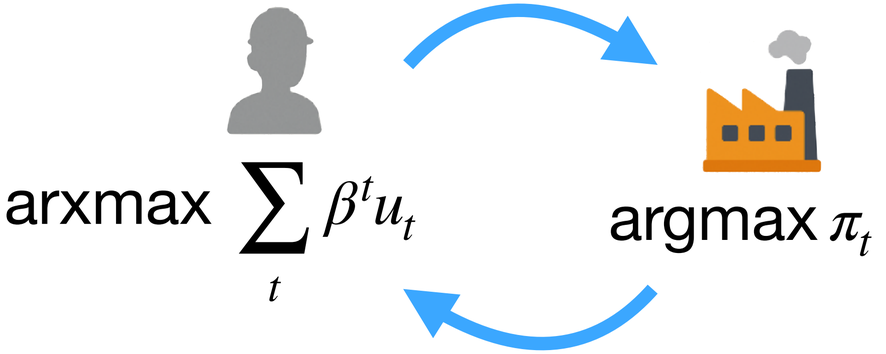
❌ Very limited or completely absent **heterogeneity**

❌ **Unrealistic behaviour** coming from assumptions of perfect "rationality"

✔ Behavioural **rules are easy to specify** in advance

✔ Behaviour optimally adapts to **changes in policy**

✔ Models are **simple to design** and analyse



$$\mathscr{L} = \mathbb{E}_0 \sum_{t=0}^{\infty} \beta^t \Big[u(c_t, 1 - \ell_t) + \lambda_t \big(Y(k_t, \ell_t) - c_t - i_t \big) + \mu_t \big((1 - \delta) k_t + i_t - k_{t+1} \big) \Big]$$

- Traditional economics has focussed on decision making and has invented the "homo economicus"
- And **frameworks** that represents the economy as a **general equilibrium** outcome of intertemporally **optimising representative agents** facing stochastic shocks

ABMs in a nutshell

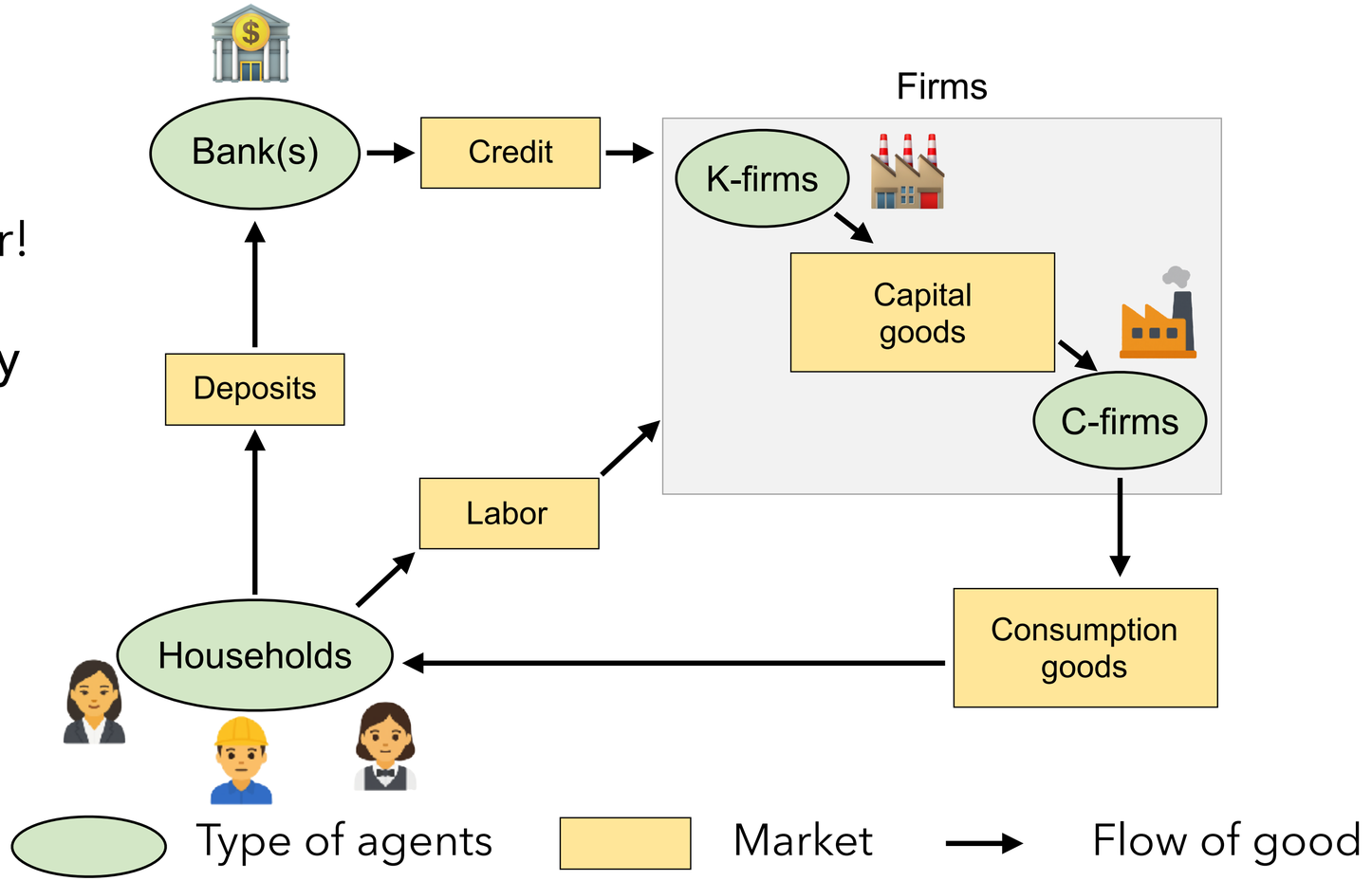
✔ Unconstrained **heterogeneity**!

✔ **Realistic**, boundedly rational behaviour!

✖ Behavioural **rules are difficult to specify** in advance…

✖ Behaviour does not necessarily adjust as a result of a **changing policy**

✖ Models are **hard to design and analyse**…

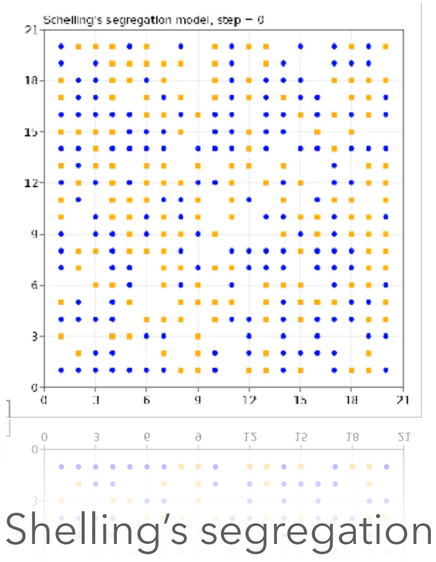


- Agent-based economics has focussed on multiple agents, heterogeneity, and accounting
- And has built **computational frameworks** that represents an economy as the **outcome of interactions among heterogeneous, boundedly rational agents** whose behavior and expectations emerge from adaptive rules rather than imposed equilibrium conditions

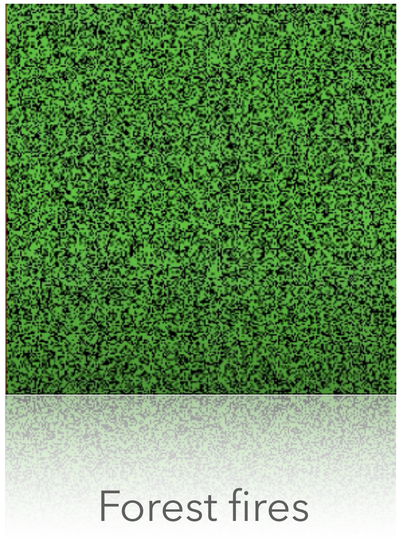
ABMs in a nutshell

Agent-based models (ABMs) grew from toy models to realistic simulations with **thousands of heterogeneous interacting** agents

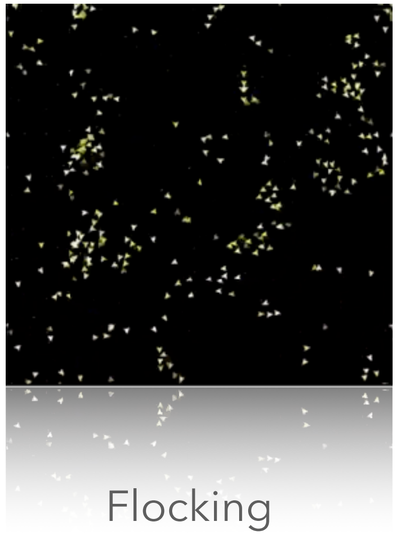
1980's — 2000's — 2020's



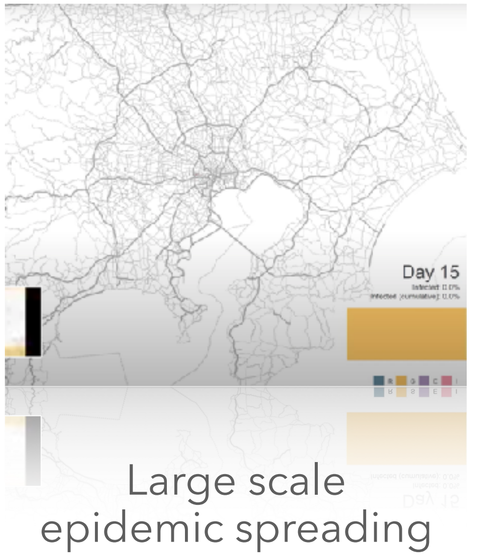
Shelling's segregation



Forest fires



Flocking

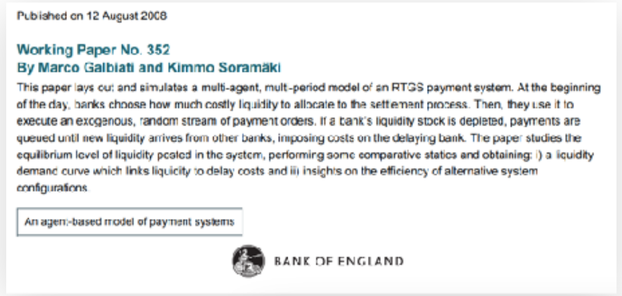


Large scale epidemic spreading

ABMs in a nutshell: central banks

High modelling **flexibility**
Intrinsically **non-equilibrium**
Complementary to traditional models

- heterogeneity
- bounded rationality


Published on 12 August 2008

Working Paper No. 352
By Marco Galbiati and Kimmo Soramäki

This paper lays out and simulates a multi-agent, multi-period model of an RTGS payment system. At the beginning of the day, banks choose how much costly liquidity to allocate to the settlement process. Then, they use it to execute an exogenous, random stream of payment orders. If a bank's liquidity stock is depleted, payments are queued until new liquidity arrives from other banks, imposing costs on the delaying bank. The paper studies the equilibrium level of liquidity posted in the system, performing some comparative statics and obtaining: i) a liquidity demand curve which links liquidity to delay costs and ii) insights on the efficiency of alternative system configurations.

An agent-based model of payment systems

BANK OF ENGLAND

2008


No. 686 - Exploring agent-based methods for the analysis of payment systems: A crisis model for StarLogo TNG

Temi di Discussione

(Working Papers)

by Luca Arciero, Claudia Biancotti, Leandro D'Aurizio, Claudio Impenna
August 2008

2008


BANK OF ENGLAND

Staff Working Paper No. 619
Macroprudential policy in an agent-based model of the UK housing market
Rafa Baptista, J Doyne Farmer, Marc Hinterschweiger, Katie Low, Daniel Tang and Arzu Uluc

October 2016

2016


No. 1338 - Macroprudential policy analysis via an agent-based model of the real estate sector

Temi di Discussione

(Working Papers)

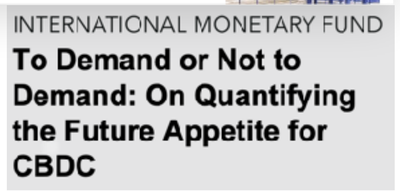
by Gennaro Catapano, Francesco Franceschi, Michele Loberto and Valentina Michelangeli
June 2021

2021

Housing market


CANVAS: A Canadian Behavioral Agent-Based Model

by Cars Hommes,[1] Mario He,[2] Sebastian Poledna,[3] Melissa Siqueira[4] and Yang Zhang[2]


INTERNATIONAL MONETARY FUND

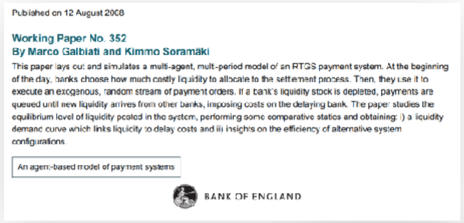
To Demand or Not to Demand: On Quantifying the Future Appetite for CBDC

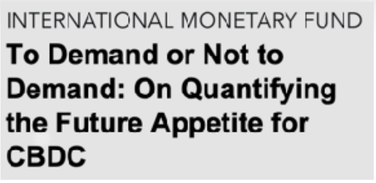
2022-2023

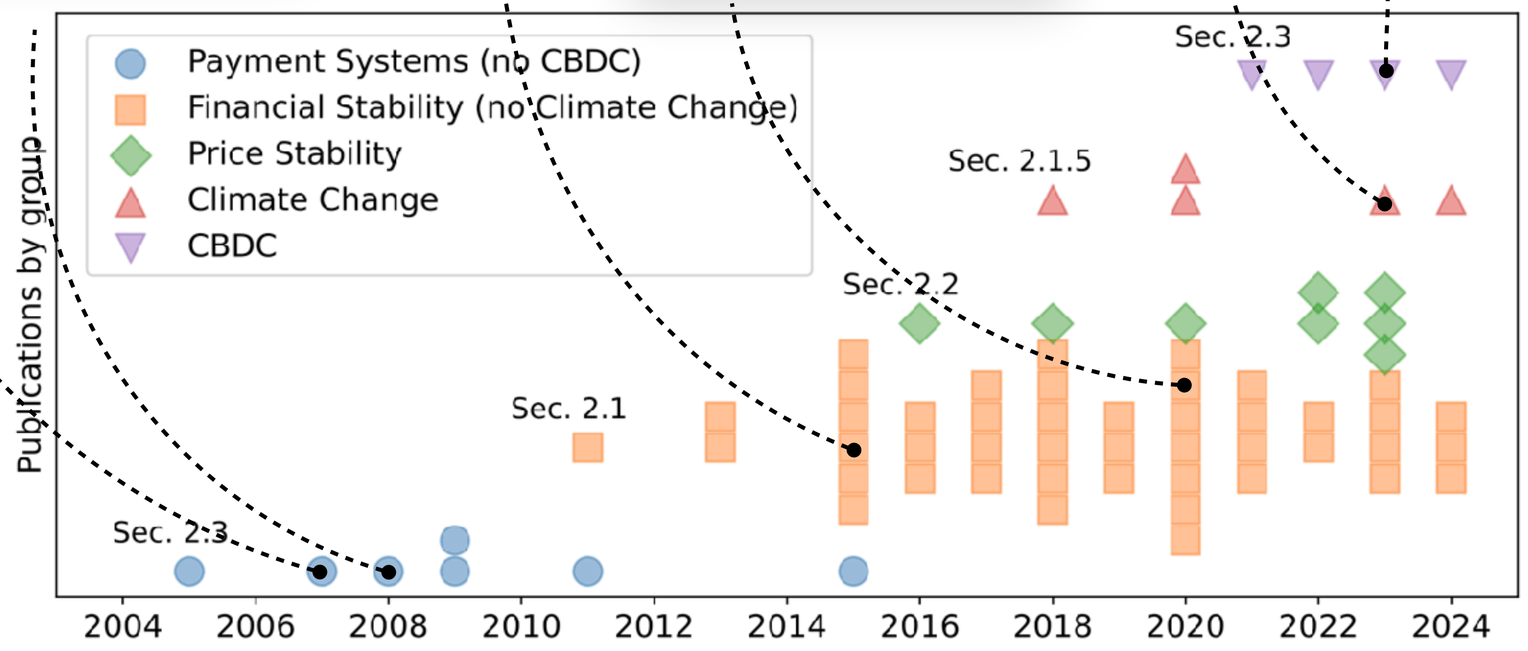
Macro and CBDC

Payment systems

ABMs in a nutshell: central banks







***Agent-based modeling at central banks: Recent developments and new challenges**, w. Borsos (BoH), Carro (BoS), Hinterschweiger (BoE), Kaszowska (BoP), Uluc (BoE)*

Book available!

What's next ?

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Applied research team

ABMs and Traditional Econ

✔ Unconstrained **heterogeneity**

✔ **Realistic**, boundedly rational behaviour

✘ Behavioural **rules are difficult to specify** in advance…

✘ Behaviour does not necessarily adjust as a result of a **changing policy**…

✘ Models are **hard to design** and analyse…

✘ Very limited or completely absent **heterogeneity**…

✘ **Unrealistic behaviour** coming from assumptions of perfect "rationality"…

✔ Behavioural **rules are easy to specify** in advance

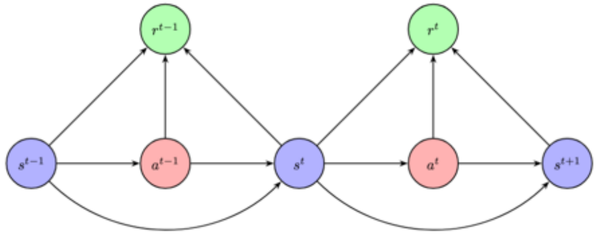
✔ Behaviour optimally adapts to **changes in policy**

✔ Models are **simple to design** and analyse

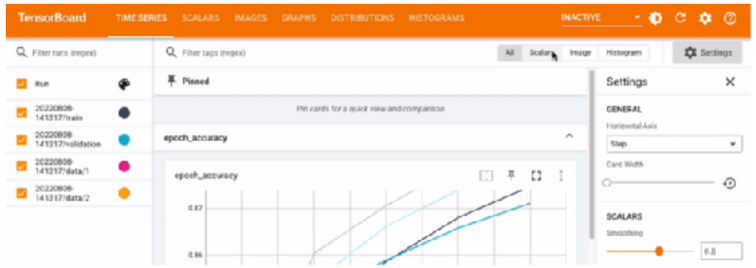
Can we do better by leveraging modern computation?

Course objectives

1. Learn the ***basic theoretical concepts*** behind Reinforcement Learnin and Multi-Agent Reinforcement Learning



2. Experiment with the ***practical application*** of RL and MARL to different porblems



3. Understand how these techniques are used for research at the intersection of ***economics and computer science***