Agent-Based Macroeconomics:
Constructive Modeling of Decentralized Market Economies

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Presentation Outline

◈ Complexity of economic systems

◈ What is *A*gent-based *C*omp *E*conomics (*ACE*)?

◈ ACE macro modeling: A constructive exercise

◈ ACE macro modeling: Illustration applications:
  1) An ACE Two-Sector Trading World
  2) EURACE: ACE Modeling of the European Union
  3) *DSGL* = *DSGE* + *L*earning Agents

◈ Advantages & disadvantages of ACE modeling

Complexity of Economic Systems

◆ Distributed local interactions

◆ Two-way feedbacks mediated by interactions
   Micro ↔ Agent Interactions ↔ Macro

◆ Strategic behavior ➡ Behavioral uncertainty

◆ Network effects and path dependence

◆ Critical role of institutional constraints

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Increasing mainstream interest in modeling these complexities

❑ **Behavioral Economics**

   From Princeton U Press BE Book Series:

   "Behavioral Economics … uses facts, models, and methods from neighbouring sciences such as psychology, sociology, anthropology and biology to establish descriptively accurate findings about *human cognitive ability and social interaction* and to explore the implications of these findings for economic behavior."

❑ **Nobel Prizes for Eight Behavioral Economists:**

   Herbert Simon (1978), George Akerloff (2001, shared),

   Daniel Kahneman & Vernon L. Smith (2002),

   Thomas C. Schelling (2005, shared), Elinor Ostrom (2009),

   Robert J. Shiller (2013, shared), and Richard Thaler (2017)

Why has it taken so long?

◆ *Lack of tools* permitting quantitative modeling of complex economic systems in a compelling, tractable, & testable way.

◆ *Seeming promise of rational expectations* that economic outcomes can be studied & understood as the result of purely rational deliberations by individual agents

➔ no need for detailed understanding of human cognition and social interactions

➔ but soon ran into major problems (multiple RE solutions, subjective uncertainty in multi-agent game situations,...)

Potential of computational experiments for studying complex economic systems

Early recognition by **Robert Lucas, Jr., "Studies in Business Cycle Theory" (1987): pp. 271 & 288**

"One of the functions of theoretical economics is to provide fully articulated, artificial economic systems that can serve as laboratories in which policies that would be prohibitively expensive to experiment with in actual economies can be tested out at a much lower cost."

"**Our task as I see it…is to write a FORTRAN program** that will accept specific economic policy rules as `input' and will generate as `output' statistics describing the operating characteristics of time series we care about, which are predicted to result from these policies."

A major extension of this vision

◆ Modern *O*bject-*O*riented *P*rogramming *(OOP)* is designed for complex interactive systems.

◆ *A*gent-based *C*omputational *Economics (ACE)* uses OOP to study virtual economic worlds via systematic computational experiments

◆ Commonly used OOP languages: Java, Python, … https://www2.econ.iastate.edu/tesfatsi/acecode.htm

What is ACE ?

*A*gent-based *C*omputational *E*conomics *(ACE)*

◆ Computational modeling of economic processes (including whole economies) as open-ended dynamic systems of interacting agents.

Key ACE Goal for Macroeconomics:

— Facilitate empirically-based macroeconomic modeling for which "market clearing", "correct expectations," & other coordinated states are possible outcomes rather than externally imposed restrictions.

Meaning of "Agent" in ACE

Agent **=** Software entity within a computationally constructed world capable of acting over time on the basis of its own *state*, i.e., its own internal data, attributes, and methods

❑ Agents can represent:

- Individuals   (consumers, traders, entrepreneurs,…)
- Social groupings   (households, communities,…)
- Institutions   (markets, corporations, gov't agencies,…)
- Biological entities   (crops, livestock, forests,…)
- Physical entities   (weather, landscape, electric grids,…)

ACE Agent Types … Cont'd

Decision-Making (DM) agents can exhibit

- Backward-looking adaptation (reactive learning)

- Goal-directed adaptation (anticipatory learning)

- Social communication (talking with each other !!)

- Endogenous formation of interaction networks

- Autonomy, conditional on initially configured states

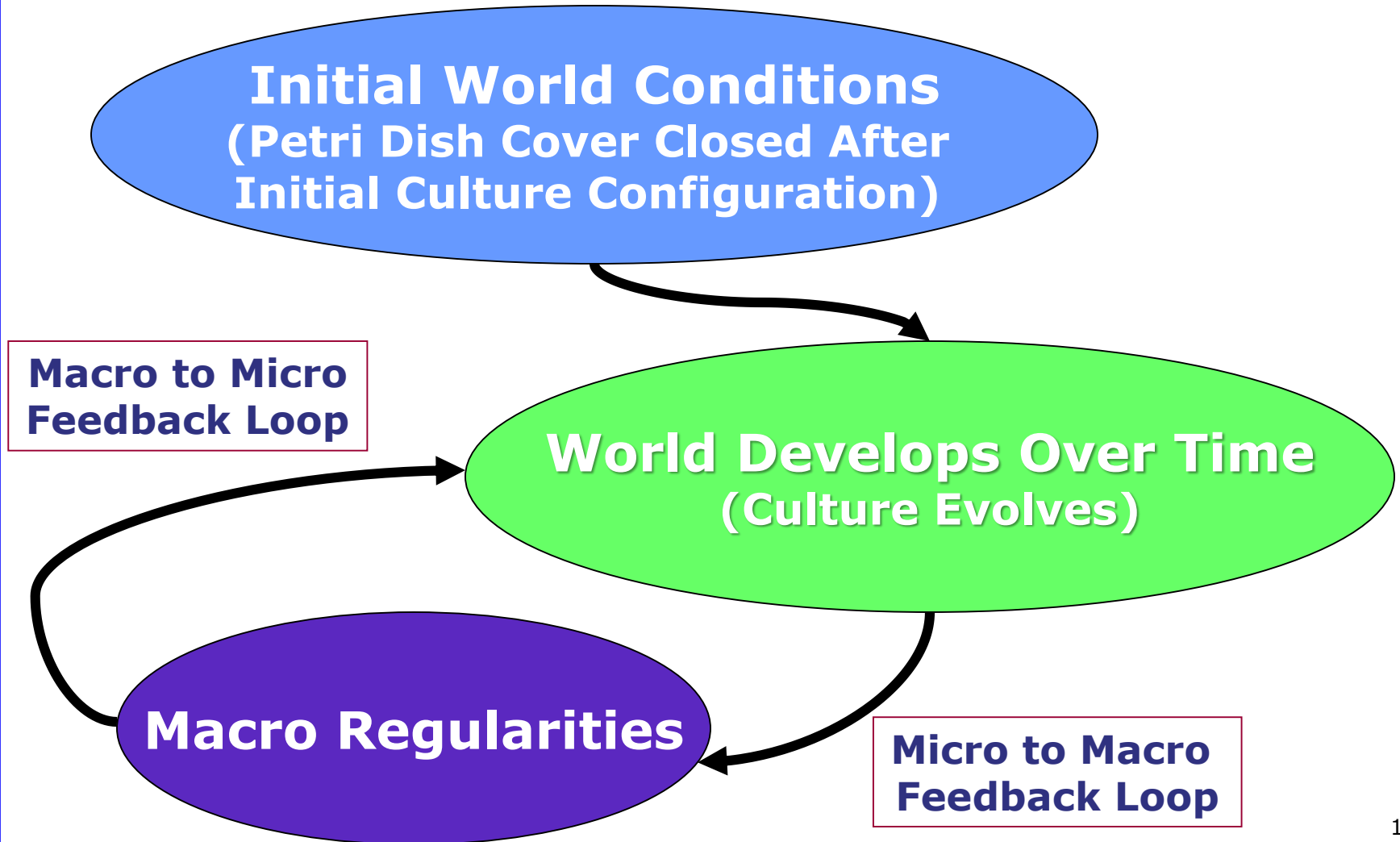# **Example:** Partial Agent Taxonomy for a Macro Model

⬇ denotes "has a" relationship; ⬆ denotes "is a" relationship
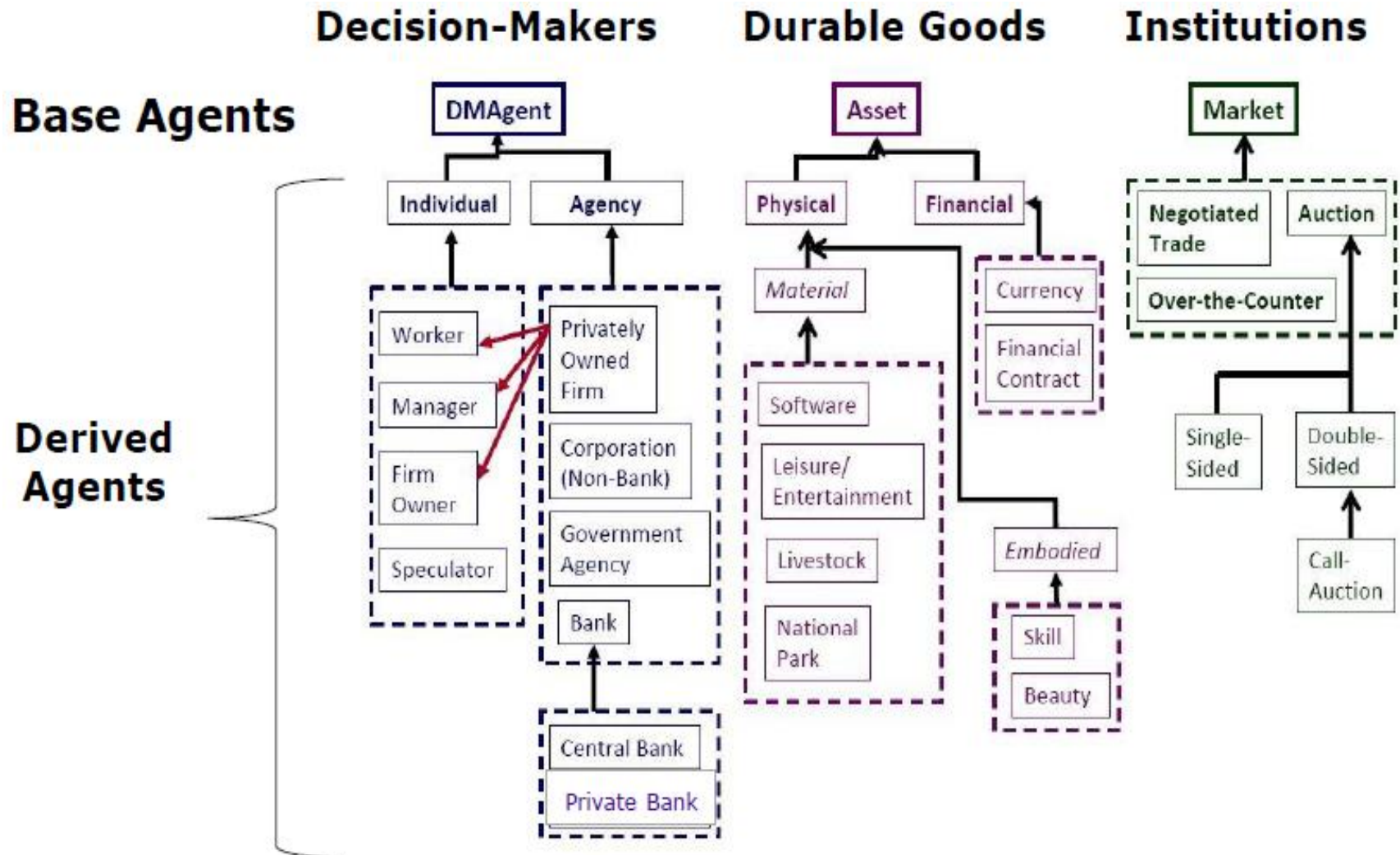
ACE Culture-Dish Analogy

◆ The modeler constructs a virtual economic world populated by various agent types.

◆ The modeler sets (configures) initial agent states.

◆ The modeler then steps back to observe how the world develops in real (CPU) time without further external intervention (no externally imposed market clearing, no externally imposed correct expectations,…) .

◆ **All subsequent world events are driven solely by agent interactions.**

ACE Culture Dish Analogy … Continued

Initial World Conditions
(Petri Dish Cover Closed After Initial Culture Configuration)

Macro to Micro Feedback Loop

World Develops Over Time
(Culture Evolves)

Macro Regularities

Micro to Macro Feedback Loop

ACE Macro Modeling: Constructive Exercise

https://www2.econ.iastate.edu/tesfatsi/amulmark.htm
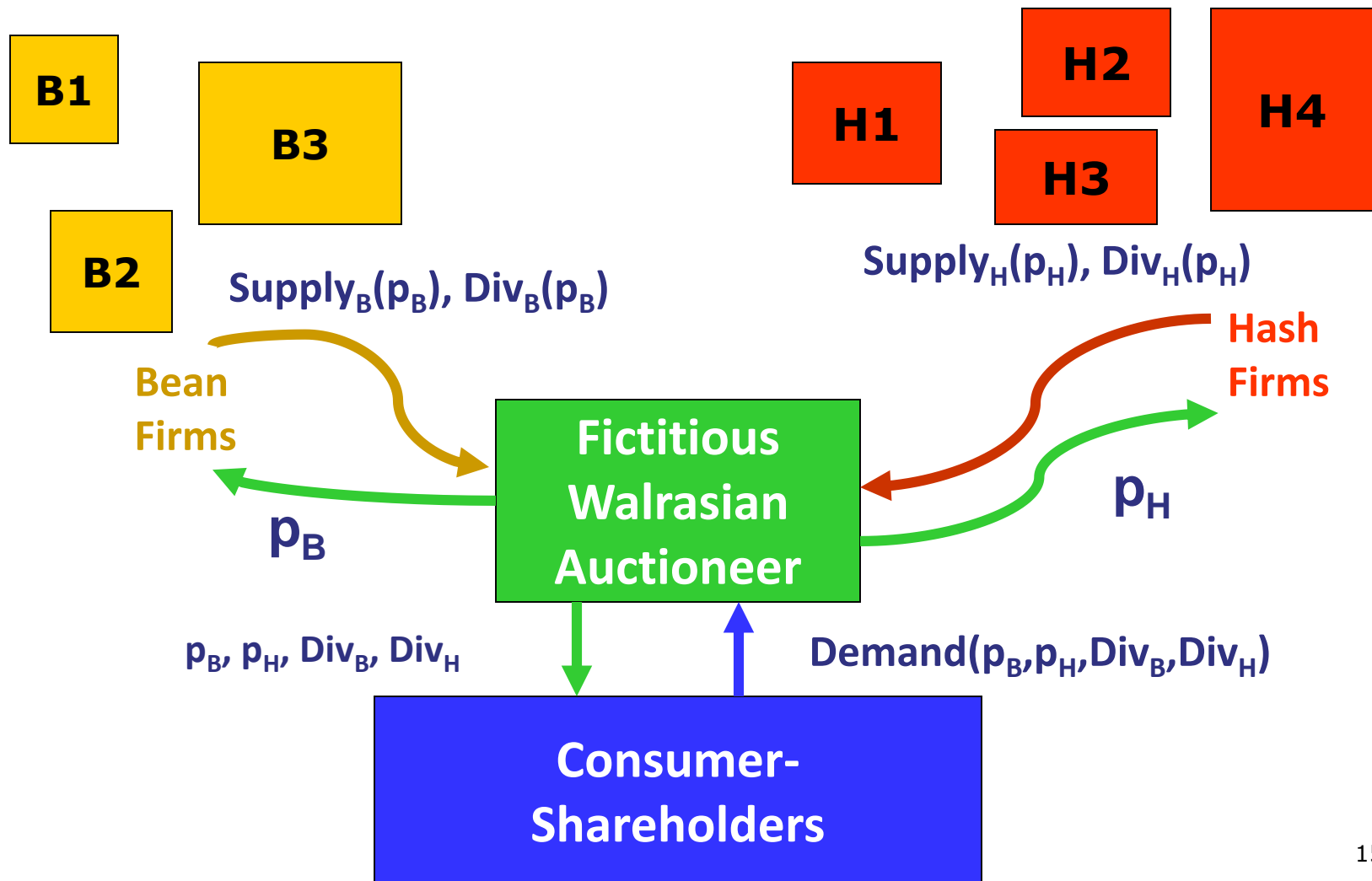

Starting Point:

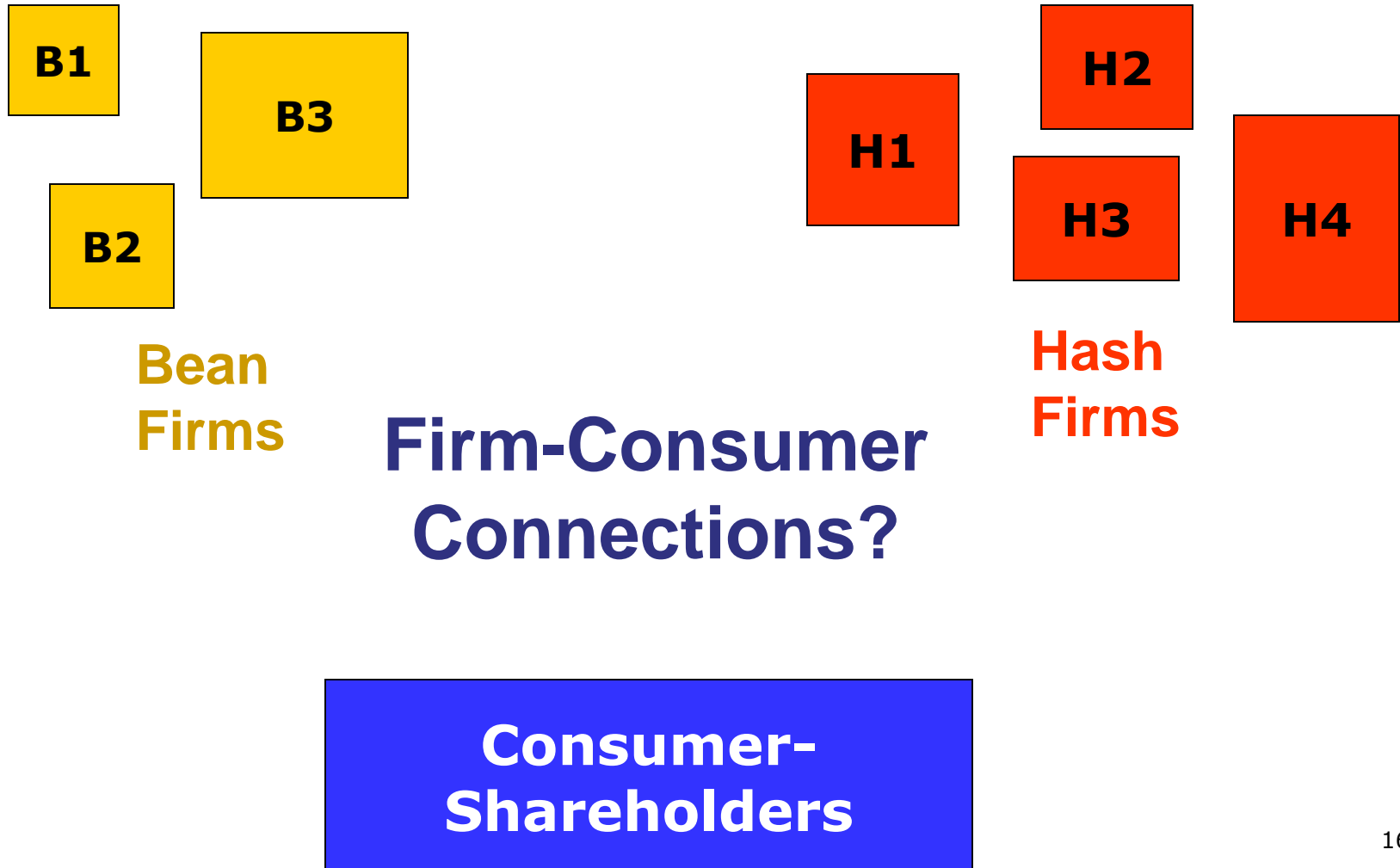Any Walrasian General Equilibrium (WGE) Economy

Exercise:

- **Remove all externally imposed coordination conditions** (e.g., rational expectations, market-clearing prices, …).

- **Replace with agent-driven processes** (production, pricing, trade,…) sufficient to re-establish complete circular flow among firms and consumers.

- **Allow economy to run forward through time** to see if/when economy approaches or attains an "equilibrium" state of some form.

Starting Point for an Illustrative Two-Sector WGE Economy

B1

B3

B2

H2

H1

H3

H4

$Supply_B(p_B)$, $Div_B(p_B)$

$Supply_H(p_H)$, $Div_H(p_H)$

Bean Firms

Hash Firms

Fictitious Walrasian Auctioneer

p_B

p_H

p_B, p_H, Div_B, Div_H

$Demand(p_B, p_H, Div_B, Div_H)$

Consumer-Shareholders

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Pluck Out the Fictitious Auctioneer!

B1

B3

B2

Bean Firms

H1

H2

H3

H4

Hash Firms

Firm-Consumer Connections?

Consumer-Shareholders

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Without the Fictitious Auctioneer …

Careful attention must now be paid to modeling of:

1) **Market Organization**

   - Who trades with whom? [e.g. business-to-business (B2B) transactions, business-to-consumer (B2C) transactions, etc.]

   - In what types of market structures does trading take place? [e.g. double auction, single-sided auction, exchange, bilateral trade, etc.]

2) **Market Behavior**

   - Simple fixed rules of behavior?
   - Behavioral rules adaptively updated based on past experiences?
   - Successive intertemporal re-optimization based on updated expectations regarding future possibilities?
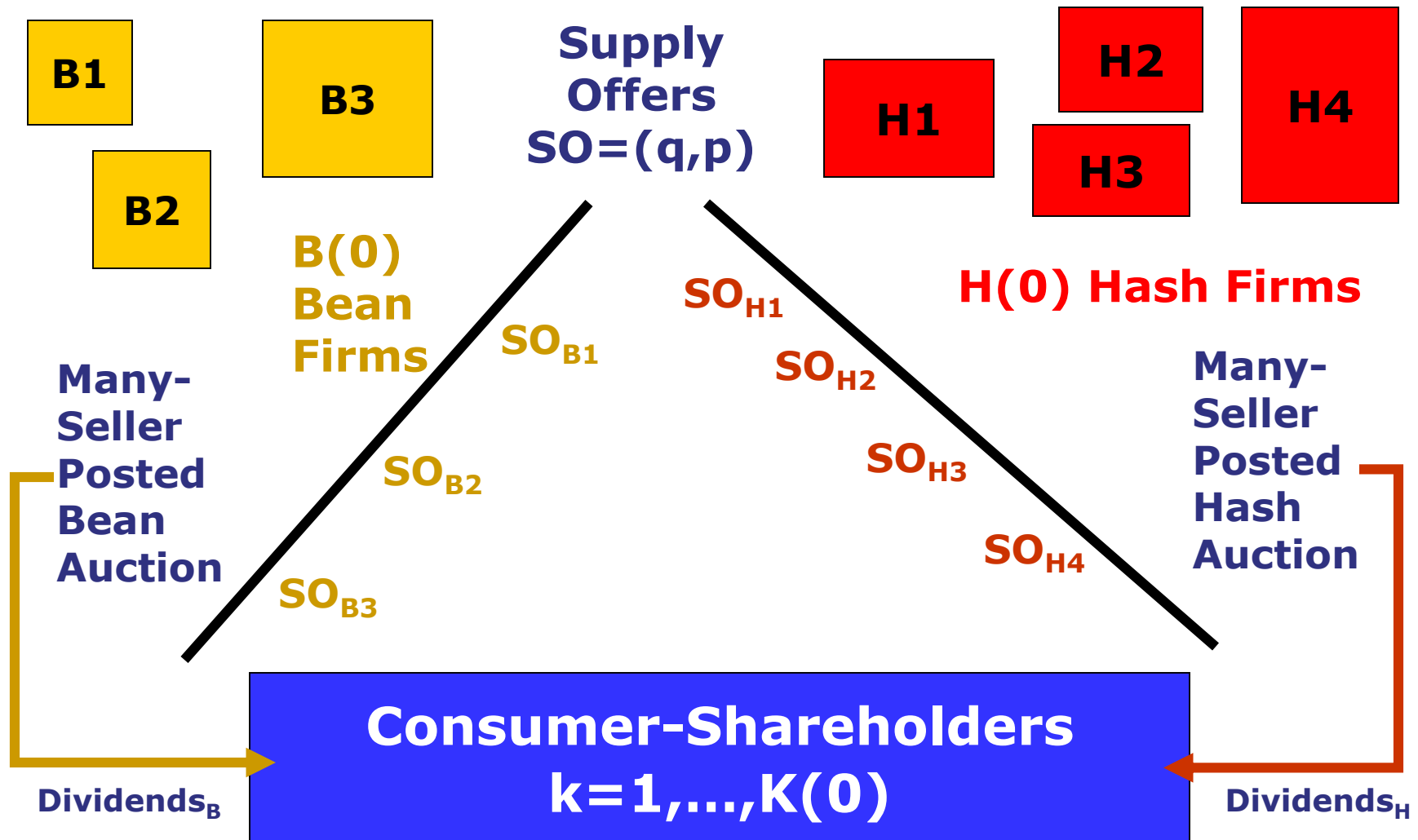
3) Market Procurement Processes

- *Terms-of-Trade:* Set production and price levels

- *Seller-Buyer Matching:*

  - Identify potential sellers/buyers
  - Compare/evaluate opportunities
  - Make demand bids/supply offers
  - Select specific sellers/buyers
  - Negotiate seller/buyer contracts

- *Trade:* Transactions carried out

- *Settlement:* Payment processing and shake-out

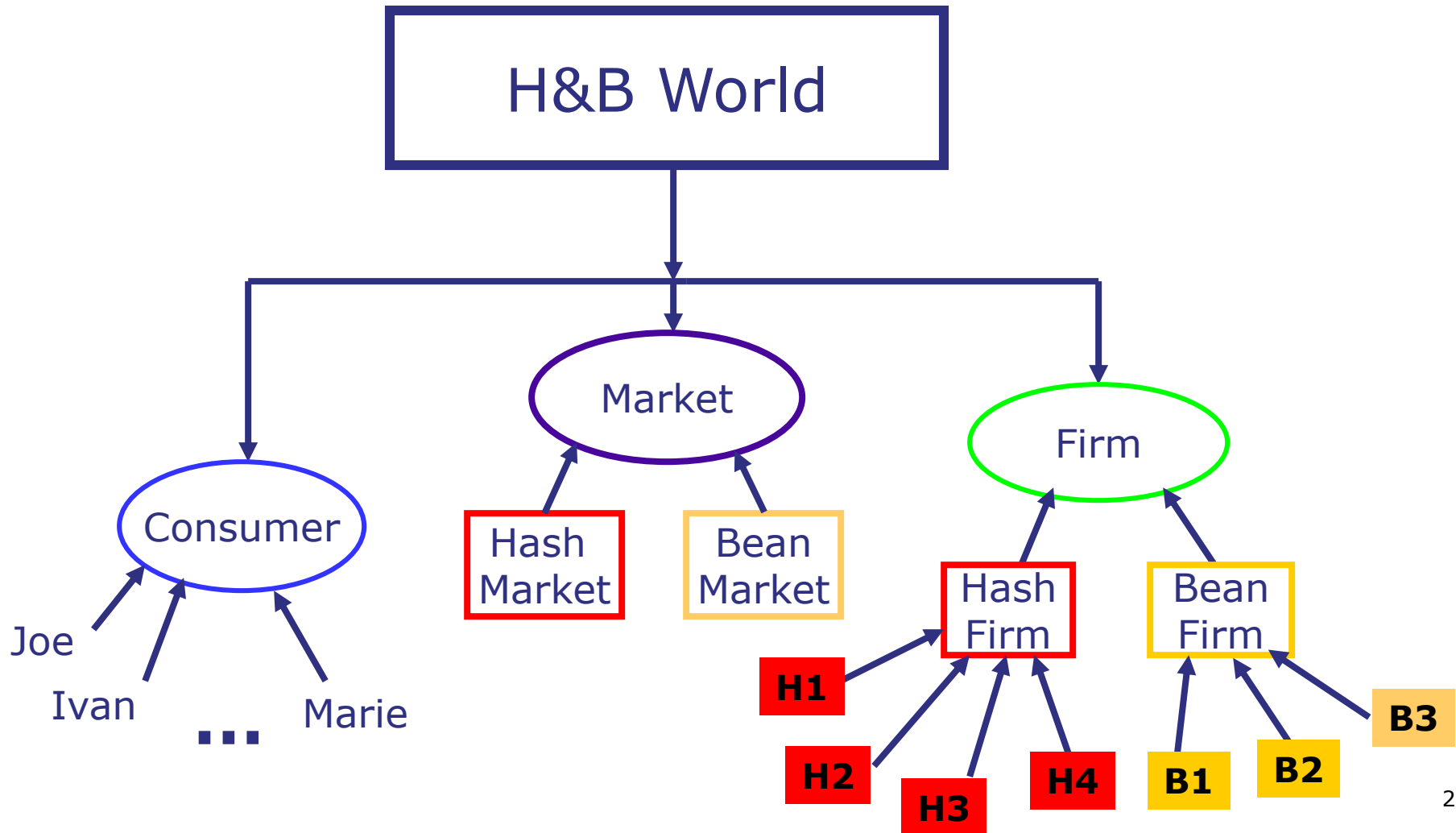- *Manage:* Long-term seller/buyer relations

Can ACE help?

➢ How might ACE be used to model market organization, behavioral dispositions, and procurement processes?

A Simple Illustrative ACE Hash-and-Beans (H&B) Economy

B1

B2

B3

Supply Offers SO=(q,p)

H1

H2

H3

H4

B(0) Bean Firms

H(0) Hash Firms

SO_{B1}

SO_{B2}

SO_{B3}

SO_{H1}

SO_{H2}

SO_{H3}

SO_{H4}

Many-Seller Posted Bean Auction

Many-Seller Posted Hash Auction

Consumer-Shareholders k=1,…,K(0)

Dividends$_B$

Dividends$_H$

Agent Taxonomy for ACE H&B Economy

↓ denotes "has a" relationship;   ↑ denotes "is a" relationship

Overview of Activity Flow in the ACE H&B Economy

World agent constructed. World agent then constructs & configures consumer, market, and firm agents and starts a world "clock".

loop

Firm agents receive clock time signal and post quantities/prices in H & B markets

Consumer agents receive clock time signal and begin price discovery process

Firm/consumer agents match, trade, calculate profits/utilities, & update wealth levels

Firm/consumer agents update their expectations & behavioral strategies

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Activity Flow for Firms

◆ Each firm f starts out (T=0) with **money $M_f(0)$** and a **production capacity $Cap_f(0)$**

◆ Firm f's **pro-rated sunk cost $SC_f(T)$** for $T \geq 0$ is proportional to its current capacity $Cap_f(T)$

◆ At beginning of each $T \geq 0$, firm f selects a **supply offer = (production level, unit price)**

◆ At end of $T \geq 0$, firm f is *solvent* if it has $NetWorth(T) = [Profit(T) + M_f(T) + ValCap_f(T)] > 0$

◆ If solvent, firm f **allocates its profits** (+ or -) between M_f, CAP_f, & dividend payments.

Activity Flow for Consumer-Shareholders

◆ Each consumer k **starts out** (T=0) with a **lifetime money endowment profile**

$$(Mk_{youth} , Mk_{middle} , Mk_{old})$$

◆ In each T $\geq$ 0, consumer k's **utility** is measured by

$U_k(T) = (hash(T) - h_k{}^*)^{\alpha_k} \bullet (beans(T) - b_k{}^*)^{[1-\alpha_k]}$

◆ In each T $\geq$ 0, consumer k seeks to secure maximum utility by **searching** for beans and hash to buy at the **lowest possible prices**.

◆ At end of each T $\geq$ 0, whether consumer k **lives or dies** depends on whether or not he secures at least his **subsistence needs** $(b_k{}^*, h_k{}^*)$.

Possible Experimental Treatment Factors

- **Initial number of consumers** [K(0)]

- **Initial number/size of firms** [H(0), B(0), $Cap_f(0)$]

- **Firm learning** (supply offers & profit allocations)

- **Firm cost functions**

- **Firm initial money holdings** [$M_f(0)$]

- **Firm rationing protocols** (for excess demand)

- **Consumer learning** (price discovery & demand bids)

- **Consumer money endowment profiles** (rich, poor, ↗ , ↘ , life cycle u-shape)

- **Consumer preferences** (θ values)

- **Consumer subsistence needs** (b*,h*)

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World Agent

Public Access:

// **Public Methods**
The ***World Event Scheduler,*** i.e., a system clock that
permits inhabitants to time and synchronize activities
(e.g., opening/closing of H & B markets);
Protocols governing firm collusion;
Protocols governing firm insolvency;
Methods for receiving data;
Methods for retrieving World data.

Private Access:

// **Private Methods**
Methods for gathering, storing, and sending data;
// **Private Data and Attributes**
World physical attributes (spatial configuration, …);
World inhabitants (H & B markets, firms, consumers);
World inhabitant states (data, attributes, methods).

Market Agent

Public Access:

// **Public Methods**
getWorldEventSchedule(clock time);
Protocols governing the public posting of supply offers;
Protocols governing matching, trades, and settlements;
Methods for receiving data;
Methods for retrieving Market data.

Private Access:

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

// **Private Data and Attributes**

Market design (many-seller posted auction, …)

Data recorded about firms (e.g., supplies, sales);
Data recorded about consumers (e.g., demands, purchases);
Address book (communication links).

Consumer Agent

Public Access:

 // **Public Methods**
   getWorldEventSchedule(clock time);
   getWorldProtocols (stock share ownership);
   getMarketProtocols (price discovery process, trade process);
   Methods for receiving data;
   Methods for retrieving stored Consumer data.

Private Access:

 // **Private Methods**
   Methods for gathering, storing, and sending data;
   Method for determining own budget constraint;
   Method for searching for lowest prices (**LEARNING**);
   Methods for changing my methods (**LEARNING TO LEARN**).
 // **Private Data and Attributes**
   Own attributes (history, utility function, current wealth,…);
   Data about external world (posted supply offers, …);
   Address book (communication links).

Firm Agent

Public Access:

 // **Public Methods**

 getWorldEventSchedule(clock time);

 getWorldProtocols (collusion, insolvency);

 getMarketProtocols (posting, matching, trade, settlement);

 Methods for receiving data;

 Methods for retrieving Firm data.

Private Access:

 // **Private Methods**

 Methods for gathering, storing, and sending data;
 Methods for calculating own expected/actual profit outcomes;
 Method for allocating own profits to shareholders;
 Method for updating own supply offers (**LEARNING**);
 Methods for changing my methods (**LEARNING TO LEARN**).

 // **Private Data and Attributes**

 Own attributes (history, profit function, current wealth,…);
 Data about external world (rivals' supply offers, demands,…);
 Address book (communication links).

Interesting Issues for Exploration

◆ Initial conditions → **carrying capacity?**
(How many firms/consumers survive over the long run?)

◆ Initial conditions → **market clearing?**
(Supplies adequate to meet demands?)

◆ Initial conditions → **market efficiency?**
(No wastage of physical resources or utility?)

◆ Standard firm concentration measures at T=0 →
good predictors of long-run firm market power?

◆ Importance for market performance of **learning vs. market structure?** *(Gode/Sunder, Journal of Political Economy, 1993)*

ACE Hash-and-Beans Economy Implementation (C. Cook, 2005, C#/.Net)

ACE Macro Illustrations

1) Agent Island: An Extended ACE Hash & Beans Economy
(Marc Oeffner, Thesis, 2008, Julius-Maximilians-Universitat Wurzburg)
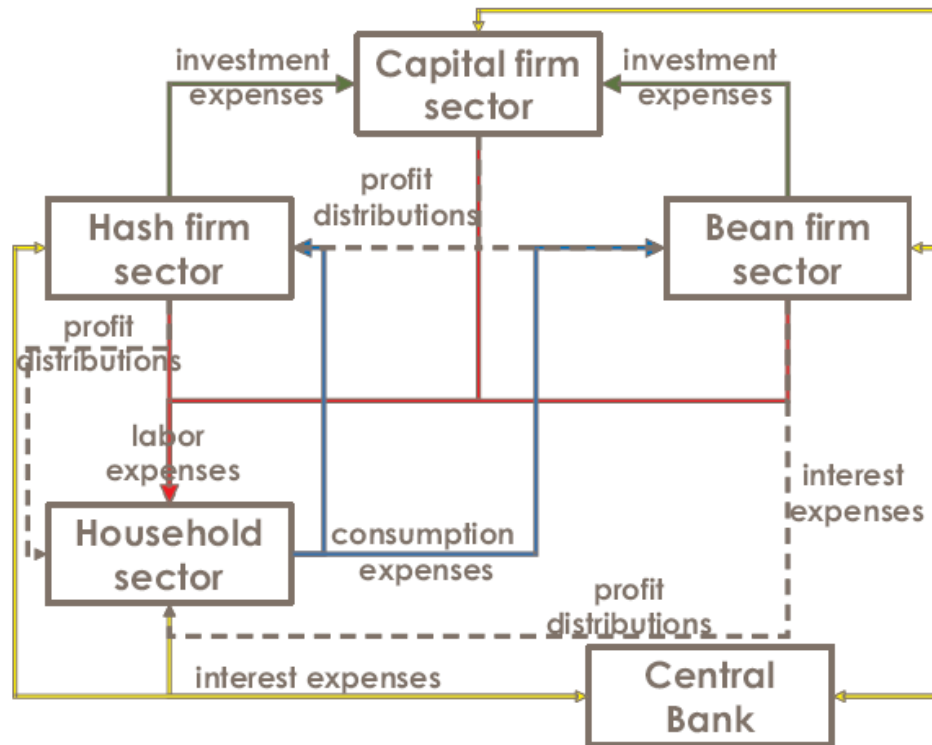
Figure 2.1: Markets and transactions on Agent Island

Thesis/Code (SeSAm) Available At:
  https://www2.econ.iastate.edu/tesfatsi/amulmark.htm

Equity and Loan Financing in Agent Island
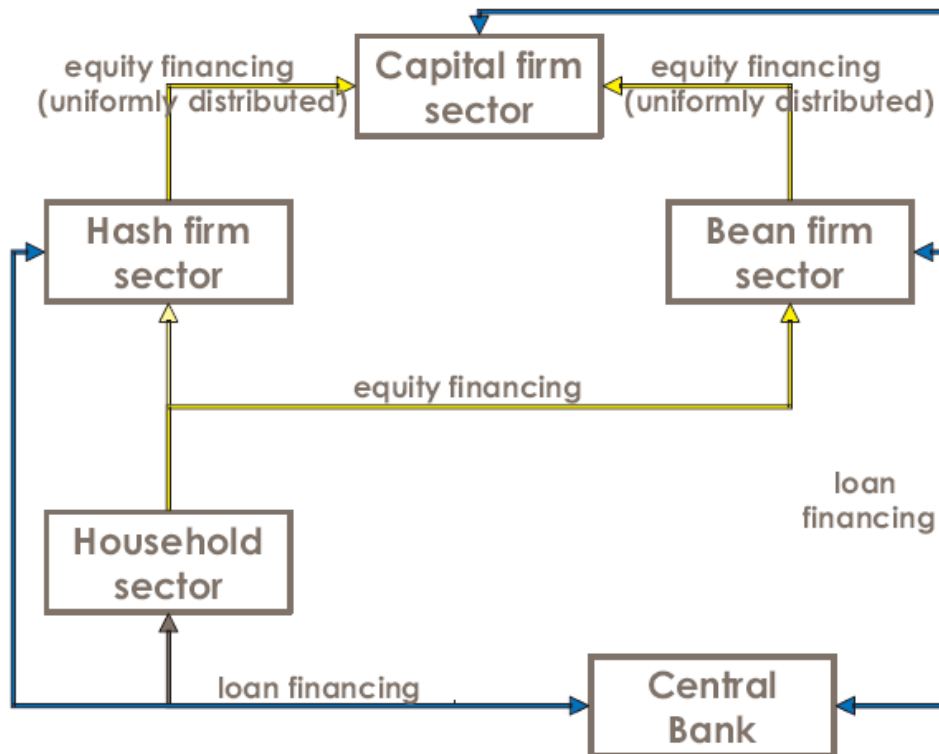
Figure 2.2: Financing contracts on Agent Island

Direct Finance:
   Purchase of initial public offerings of securities, e.g., stocks (equities), bonds,…

Indirect Finance:
    Loans obtained through a financial intermediary, such as a bank
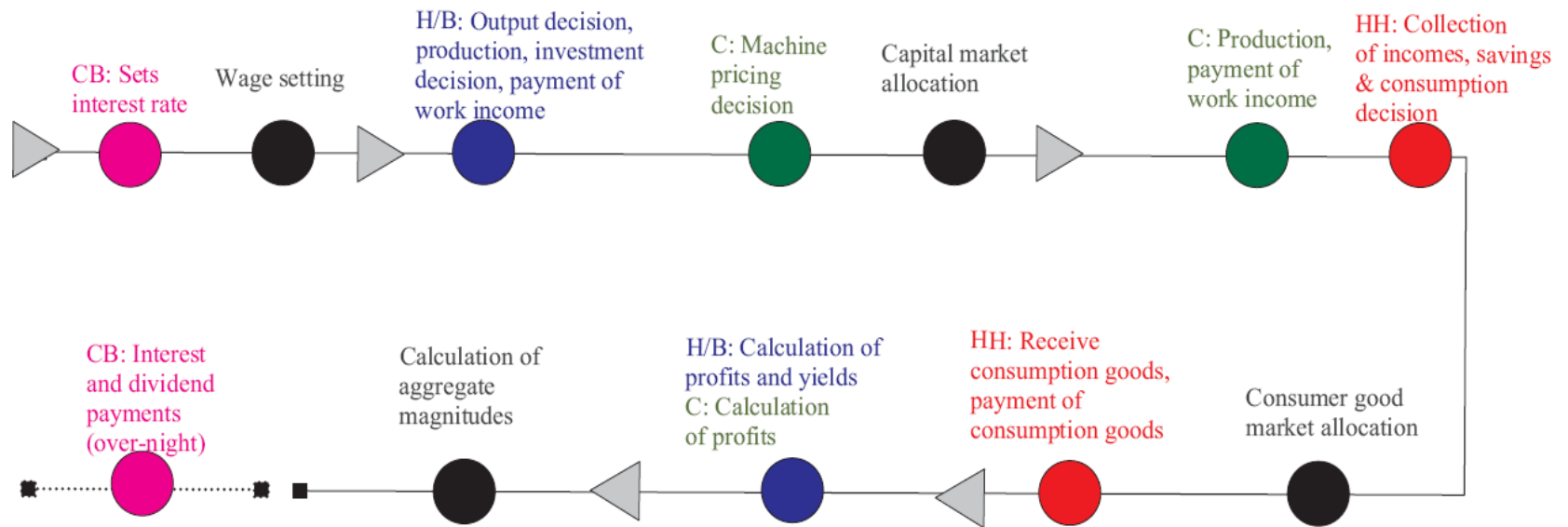
Daily Activity Flow in Agent Island

Figure 2.3: Intra-period sequence of decisions and actions
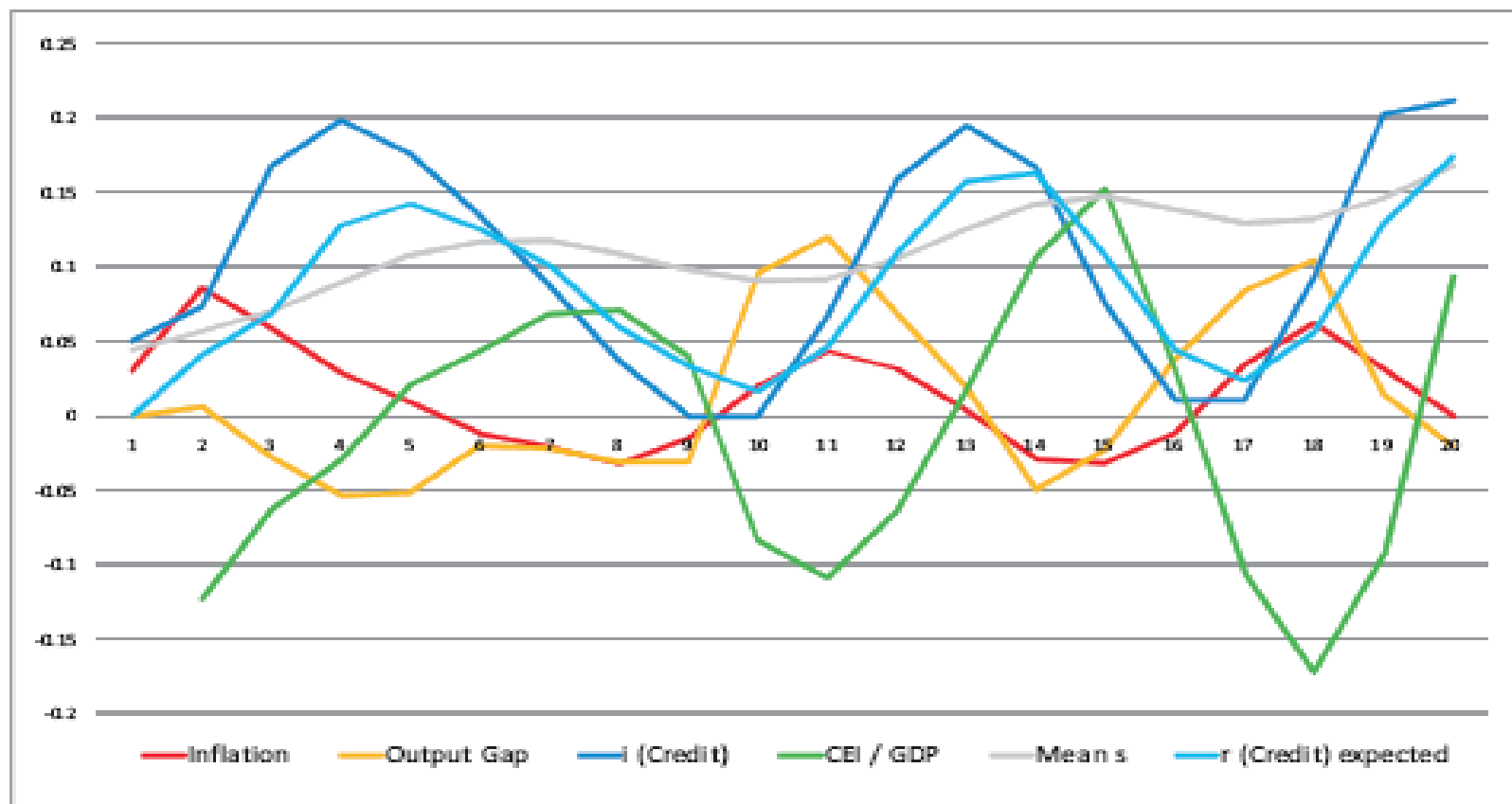
Sample outcomes for Agent Island

Figure 3.33: Stylized facts of the second rerun in the baseline case
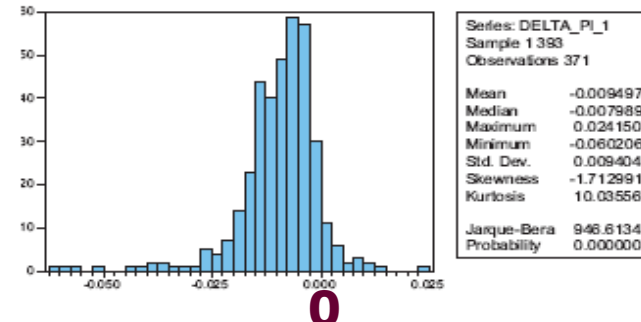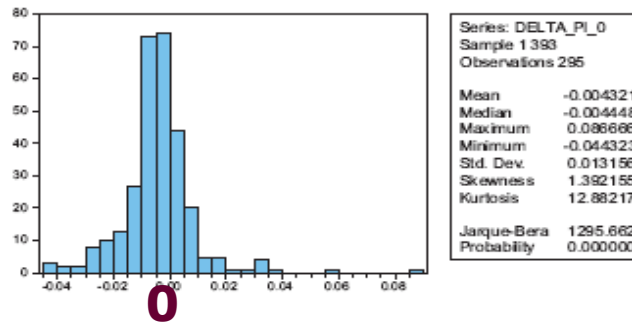
Notes: CEI = Circuit Equilibrium Indicator measuring excess planned expenditures (>0) or excess planned receipts (<0)
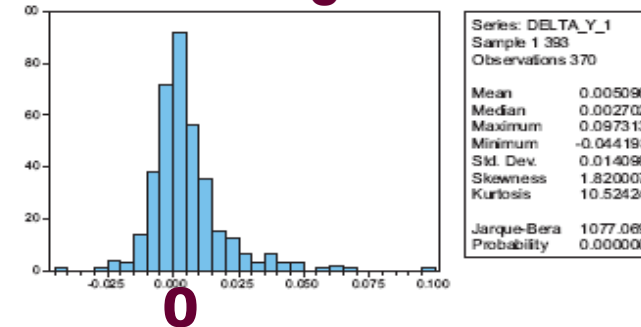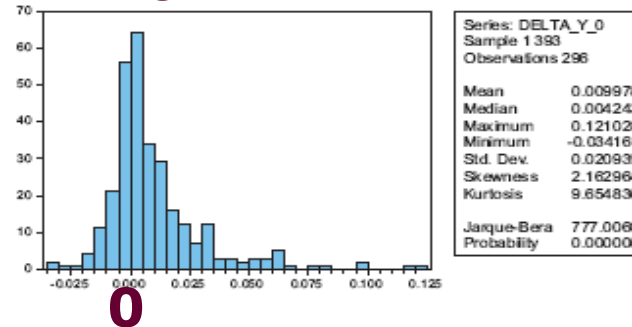
s = household financial savings

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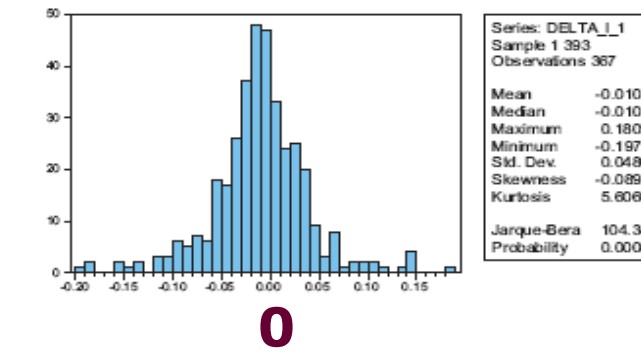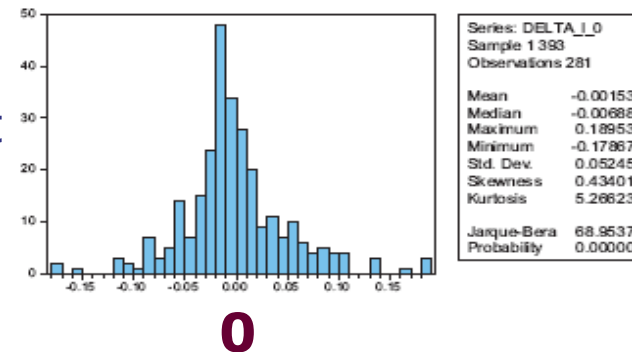**Period 1 (Shock Time)** **Period 2 (After Shock Time)**

Inflation

Real GDP

Investment demand

Note: Left panels illustrate the effect in the period of the shock, right panels illustrate the effect one period after the interest rate shock.

Figure 3.30: Baseline case – effects of an increase of credit interest rates by 1 percentage point in the simulation data depicted by histograms for inflation rates (upper panels), real output (central panels), and investment demand (lower panels)

Sample PDFs for *outcome changes* due to a 1% increase in the credit interest rate occurring in period 1 and maintained in future periods

EURACE Objectives

- **From a scientific point of view**
  - The study and the development of multi-agent models that reproduce, at the aggregate economic level, the emergence of global features as a self-organized process from the complex pattern of interactions among heterogeneous individuals

- **From a technological point of view**
  - The development, with advanced software engineering techniques, of a software platform in order to realize a powerful environment for large-scale agent-based economic simulations

- **From a societal point of view**
  - Outstanding impact on the economic policy design capabilities of the European Union, allowing "what-if" analysis in order to optimize the impact of regulatory decisions that will be quantitatively based on European economy scenarios

EURACE Consortium 2/3

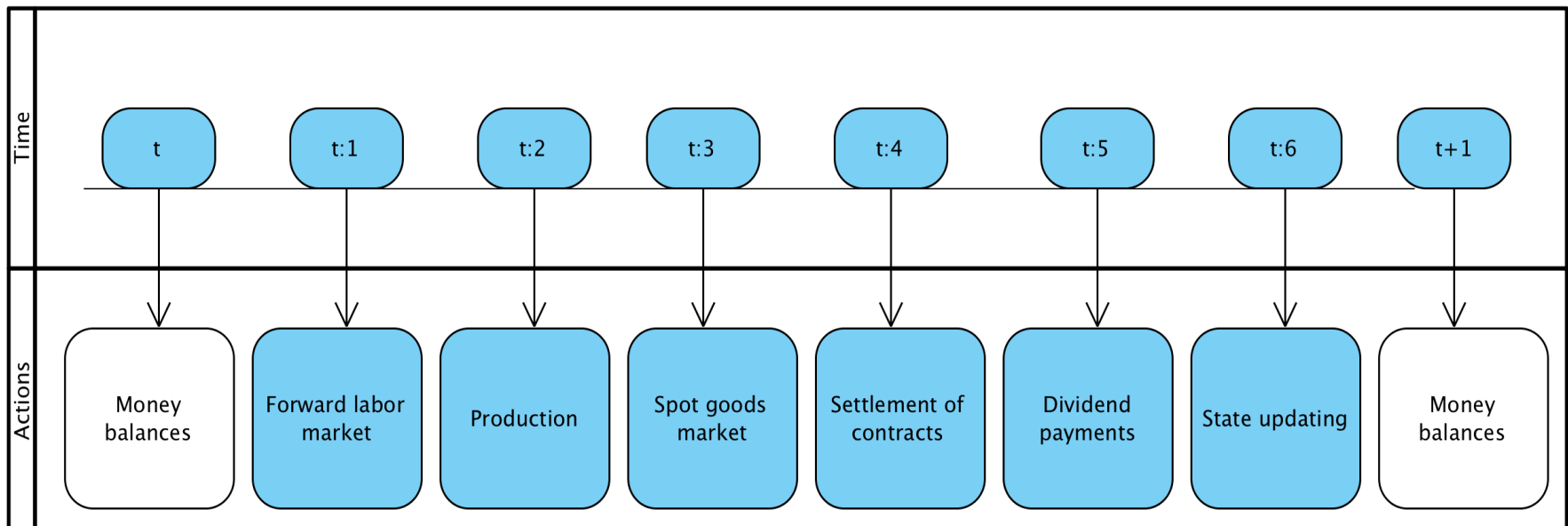| Participant	Country	Role	Research Unit Head	Competences
University of Genoa	Italy	Coordinator	Silvano Cincotti	Agent-based computational economics and software engineering. Economic policy design
University of Bielefeld	Germany	Partner	Herbert Dawid	Agent-based computational economics. Economic policy design
Université de la Méditerranée	France	Partner	Christophe Deissenberg	Agent-based computational economics. Economic policy design
National Research Institute of Electronics and Cryptology	Turkey	Partner	Kaan Erkan	Software engineering
University of Ancona	Italy	Partner	Mauro Gallegati	Agent-based computational economics. Economic policy design
University of Sheffield	UK	Partner	Mike Holcombe	Software engineering and computer science
University of Cagliari	Italy	Partner	Michele Marchesi	Software engineering
Rutherford Appleton Laboratory (STFC), was CCLRC until April 2007	UK	Partner	Christopher Greenough	Computer science

Interactions in EURACE

3) *DSGL = DSGE + Learning* Agents

https://www2.econ.iastate.edu/tesfatsi/amulmark.htm
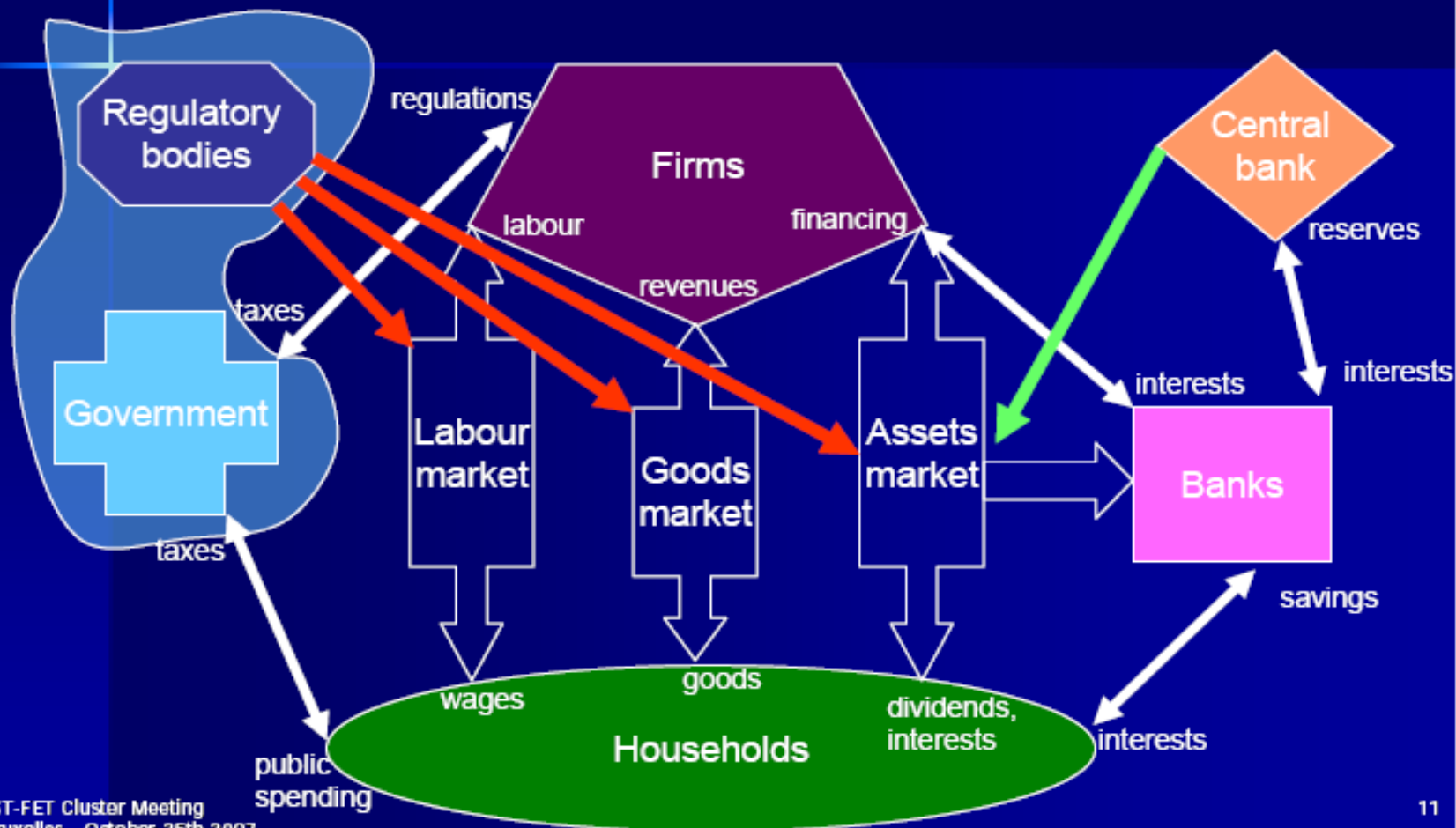
Example: E. Sinitskaya & L. Tesfatsion, "Macroeconomies as Constructively Rational Games," *J. of Economic Dynamics and Control*, Vol. 61, 2015, 152-182. Working Paper version online: http://www2.econ.iastate.edu/tesfatsi/MacroConstructiveRationalityWP.SinitskayaTesfatsion.pdf

Time	t	t:1	t:2	t:3	t:4	t:5	t:6	t+1

| **Actions** | Money balances | Forward labor market | Production | Spot goods market | Settlement of contracts | Dividend payments | State updating | Money balances |

Sequence of Market Activities During a Typical Period t

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❑ **Consumers/firms have intertemporal utility/profit maximization goals**

❑ **Four types of locally-constructive decision methods are tested for consumers & firms**

▪ ***Reactive Learner:*** If this has happened, what should I do?

  – **RL**: Reactive learner that uses a modified version of a Roth-Erev reinforcement learning algorithm (Roth/Erev GEB 1995, AER 1998)

▪ ***Anticipatory Learner:*** If I do this, what will happen?

  – **FL**: Forward-learner that uses Q-learning (Watkins, 1989)

  – **EO-FH**: Explicit optimizer that uses a rolling-horizon learning method

  – **EO-ADP**: Explicit optimizer that uses an adaptive dynamic programming learning method (value function approximation)

Key Findings: E. Sinitskaya & L. Tesfatsion, JEDC, 2015

❑ <u>Good</u> performance requires decision-makers to engage in the exploitation of their current information <u>and</u> in searches for new information.

❑ <u>Simpler</u> decision rules with some degree of anticipatory learning <u>can outperform</u> more sophisticated decision rules.

❑ ***Best* performance is attained when consumers & firms *all* use rolling fixed-horizon (EO-FH) decision rules.** This decision-rule configuration for firms and consumers is

- ▪ *Pareto efficient*

- ▪ *A Nash equilibrium*

Rolling-Horizon Decision Rule EO-FH Does Best

- (F:E0-FH, C:E0-FH) = Pareto-Efficient Nash Equilibrium
- **Consumer Payoff Matrix**: A **darker color** indicates a **higher attained average utility for consumers**

	C:RL	C:FL	C:EO-FH	C:EO-ADP
F:RL	N10	N21	N31	N39
F:FL	N22	N16	N32	N40
F:EO-FH	N33	N34	N26	N41
F:EO-ADP	N42	N43	N44	N36

Note: The "Nxy" terms, above, are test case designations, not payoffs.

Rolling-Horizon Decision Rule EO-FH Does Best…Cont'd

- (F:E0-FH, C:E0-FH) = Pareto-Efficient Nash Equilibrium
- **Firm Payoff Matrix:** A **darker color** indicates **higher attained average profit for firms**

	C:RL	C:FL	C:EO-FH	C:EO-ADP
F:RL	N10	N21	N31	N39
F:FL	N22	N16	N32	N40
F:EO-FH	N33	N34	N26	N41
F:EO-ADP	N42	N43	N44	N36

Note: The "Nxy" terms, above, are test case designations, not payoffs.

Potential **Disadvantages** of ACE
for Macroeconomic Modeling

❑ Intensive experimentation often needed to generate useful (sufficiently complete) outcome distributions.

❑ Empirical validation issues: How to test outcome distributions against actual empirical realizations?
https://www2.econ.iastate.edu/tesfatsi/EmpValid.htm

❑ Robustness of simulated outcomes to use of alternative hardware and software platforms needs to be assured.

❑ Acquiring needed computer modeling skills can take significant effort. (The increasing availability of agent-based modeling toolkits helps -- see the following site.)
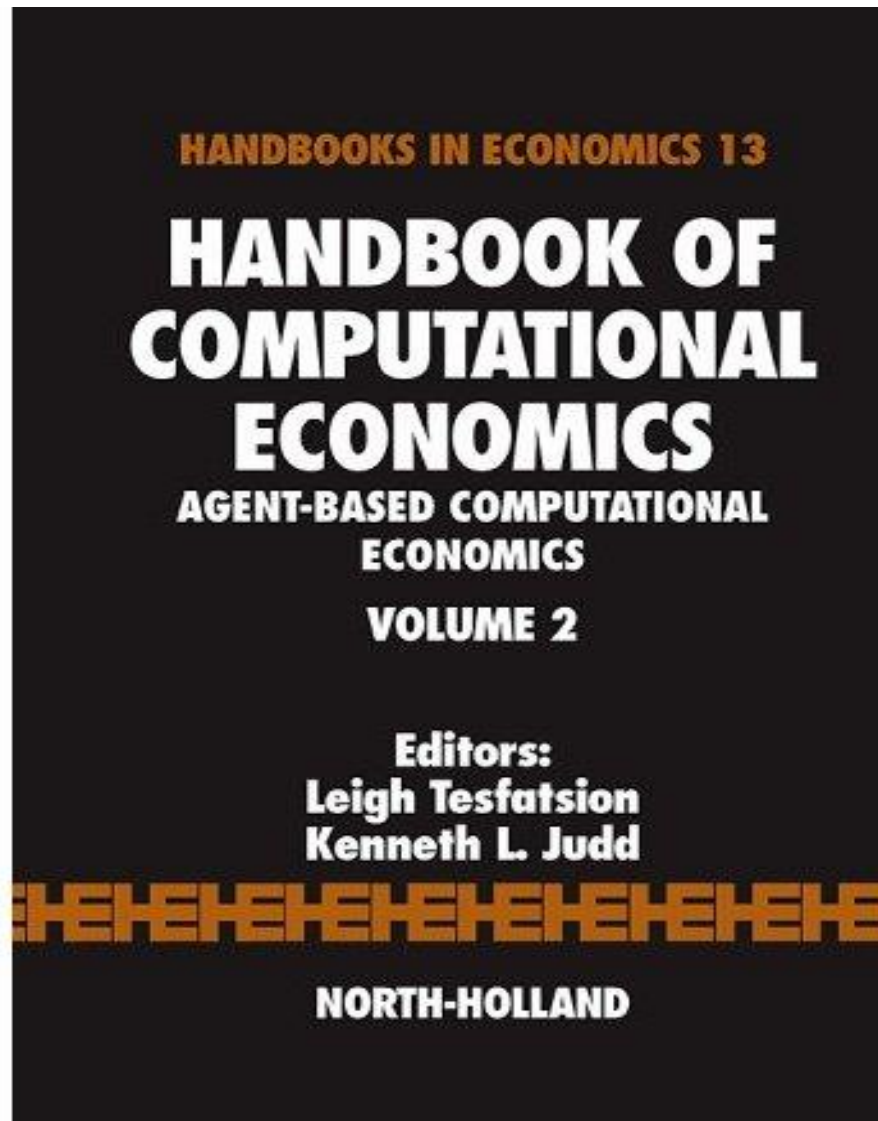
https://www2.econ.iastate.edu/tesfatsi/abmread.htm

Potential **Advantages** of ACE for Macroeconomic Modeling

❑ **Permits systematic experimental study** of economic systems with detailed empirical grounding of initial conditions in terms of structures, institutions, and behavioral dispositions.

❑ **No need to impose fictitious coordination devices** (equilibrium assumptions, rational expectations, single representative consumers, single composite goods,…)

❑ **Facilitates creative experimentation** (sensitivity of outcomes to alternative structural constraints, new types of institutions, alternative modes of behavior…)

On-Line Resources

❑ **Key Background Paper:** L. Tesfatsion (2017), "Modeling Economic Systems as Locally-Constructive Sequential Games," *Journal of Economic Methodology*, Vol. 24, Issue 4, 384-409.

https://lib.dr.iastate.edu/econ_workingpapers/23

❑ **ACE Macroeconomic Research:**

https://www2.econ.iastate.edu/tesfatsi/amulmark.htm

❑ **ACE Website Homepage**

https://www2.econ.iastate.edu/tesfatsi/ace.htm

❑ **Online Guide for Newcomers to Agent-Based Modeling in the Social Sciences**

https://www2.econ.iastate.edu/tesfatsi/abmread.htm

☐ **ACE Handbook:** L. Tesfatsion & Kenneth L. Judd, Editors, Handbooks in Economics Series, Elsevier/North-Holland, 2006
https://www2.econ.iastate.edu/tesfatsi/hbace.htm