

# Agent-Based Computational Modeling and Macroeconomics

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The Economic Crisis and Its Implications  
for the Science of Economics

**Presenter:**

Leigh Tesfatsion

Prof. of Econ, Math, and Electrical & Comp. Eng.

Iowa State University

Ames, Iowa 50011-1070

<http://www.econ.iastate.edu/tesfatsi/>

[tesfatsi@iastate.edu](mailto:tesfatsi@iastate.edu)

# Presentation Outline

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- ❑ Complexity of real-world macroeconomic systems
- ❑ What is *A*gent-based *C*omputational *E*conomics ?
- ❑ *Illustration:* From Walrasian general equilibrium to an ACE Trading World
- ❑ ACE test beds for the systematic experimental study of macroeconomic systems

# Complexity of Real-World Macroeconomic Systems

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- ❑ Macro regularities arise from local interactions among micro entities (producers, consumers, banks, public agencies,...).
- ❑ Interactions are channeled and constrained by current
  - **Structural conditions** (physical/biological limits, resource distribution, infrastructure, technology, weather patterns,...);
  - **Institutional arrangements** (legal system, credit system, business practices, regulations, social norms,...);
  - **Behavioral dispositions** (risk aversion, responsiveness to incentives, learning capabilities, foresight, strategic planning, time-inconsistent preferences, irrational exuberance,...).
- ❑ Structure, institutions, and behavior can in turn evolve.

# Can ACE Help?

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- ◆ **Agent-Based Computational Economics (ACE)** is designed to handle this level of complexity.
- ◆ ACE = Computational study of economic processes as dynamical systems of interacting agents.
- ◆ **Goal:** Development of empirically-grounded dynamical economic theories in which equilibrium is a possible outcome rather than a constraint imposed *a priori*.

# ACE Culture-Dish Analogy

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- ◆ ACE modeler constructs a virtual economic world populated by various **agent types**.
- ◆ Modeler sets **initial agent attributes**.
- ◆ Modeler then steps back to observe how the **world develops in real (CPU) time without further external intervention** (no imposed market clearing, no assumed perfect foresight,...).
- ◆ World events **driven by agent interactions**.

# ACE Agent Types

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**Agent** = Encapsulated bundle of data and methods acting within a computationally constructed world.

□ Agents can represent:

- Individuals (consumers, entrepreneurs,...)
- Social groupings (families, communities,...)
- Biological entities (crops, livestock, forests,...)
- Physical entities (roads, weather, landscapes,...)

# ACE Agent Types...

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**Cognitive agents** are capable (in various degrees) of

- Behavioral adaptation;
- Goal-directed learning;
- Social communication (talking with each other!);
- Endogenous formation of interaction networks;
- Autonomy (self-activation and self-determination based on *private* internal data and methods).

# Importance of Agent Encapsulation

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- ❑ Real-world economies consist of distributed entities with limited info & computational capabilities.
- ❑ **ACE forces adherence to this constraint.**
  - An ACE model is a collection of data and methods encapsulated into separate bundles (“agents”).
  - Procedures encapsulated in the methods of particular agents can only be implemented using the particular resources (data, money, CPU time, reasoning powers, ...) available to these agents.

# Four Main Strands of ACE Research

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- ▣ **Empirical Understanding**  
(possible explanations for empirical regularities)
- ▣ **Normative Understanding**  
(market design, policy selection,...)
- ▣ **Methodological Advancement**  
(representation, visualization, empirical validation,...)
- ▣ **Theory Generation/Qualitative Insight**  
(self-organization of decentralized market economies,...)

# ACE and Theory Generation

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**Illustrative Issue:** What are the performance capabilities of decentralized market economies?  
(*Adam Smith, F. von Hayek, J.M.Keynes, J. Schumpeter, ...*)

## **ACE Approach:**

- ◆ *Construct an agent-based world* qualitatively capturing salient aspects of actual decentralized market economies.
- ◆ *Systematically vary key treatment factors* (learning capabilities, size distribution of firms,...).
- ◆ *For each treatment, let the world evolve* for multiple runs and observe the degree of coordination that results.

# Illustration: From Walrasian General Equilibrium to an ACE Trading World

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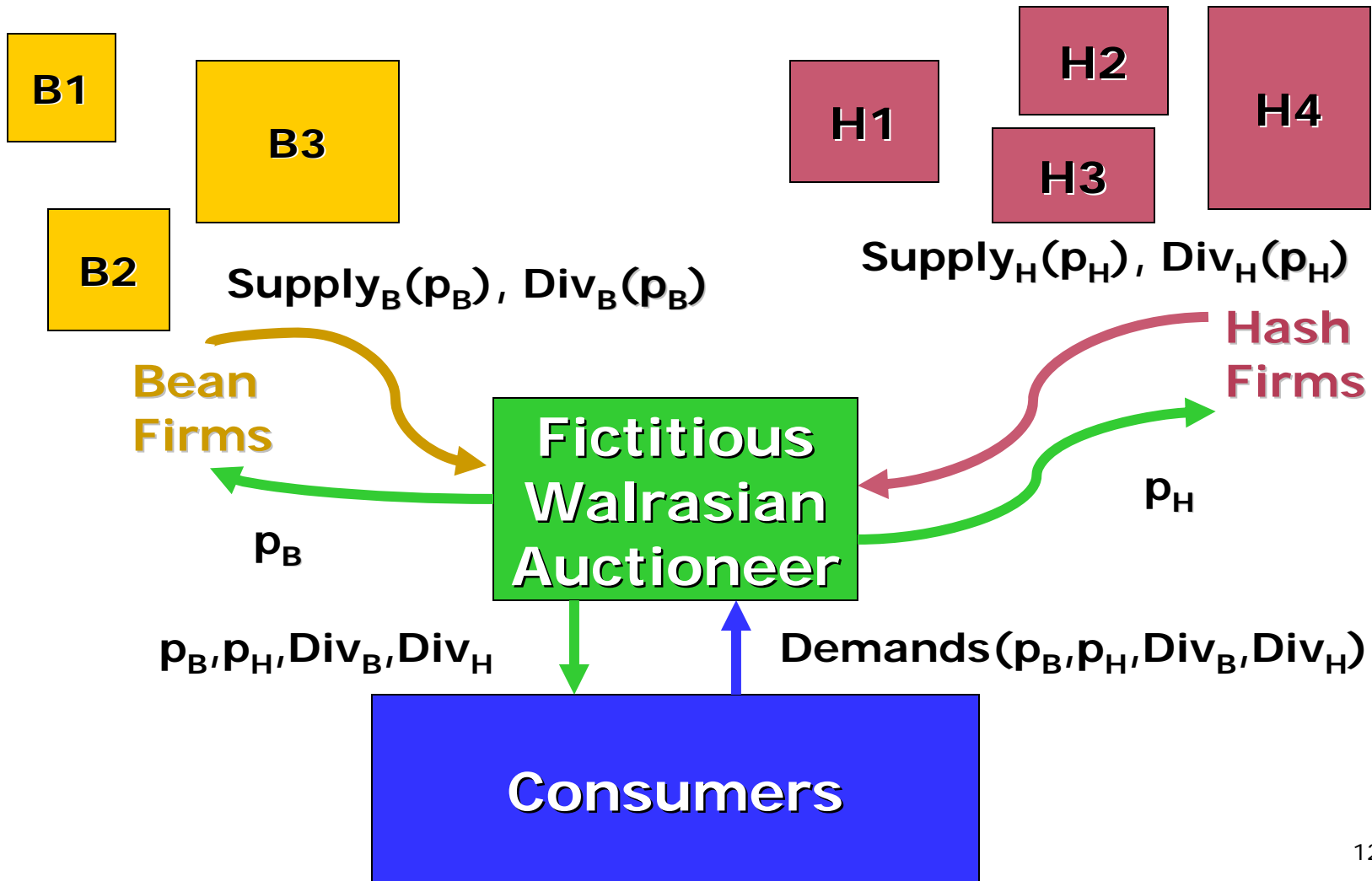
## Starting Point:

Standard Walrasian General Equilibrium Economy

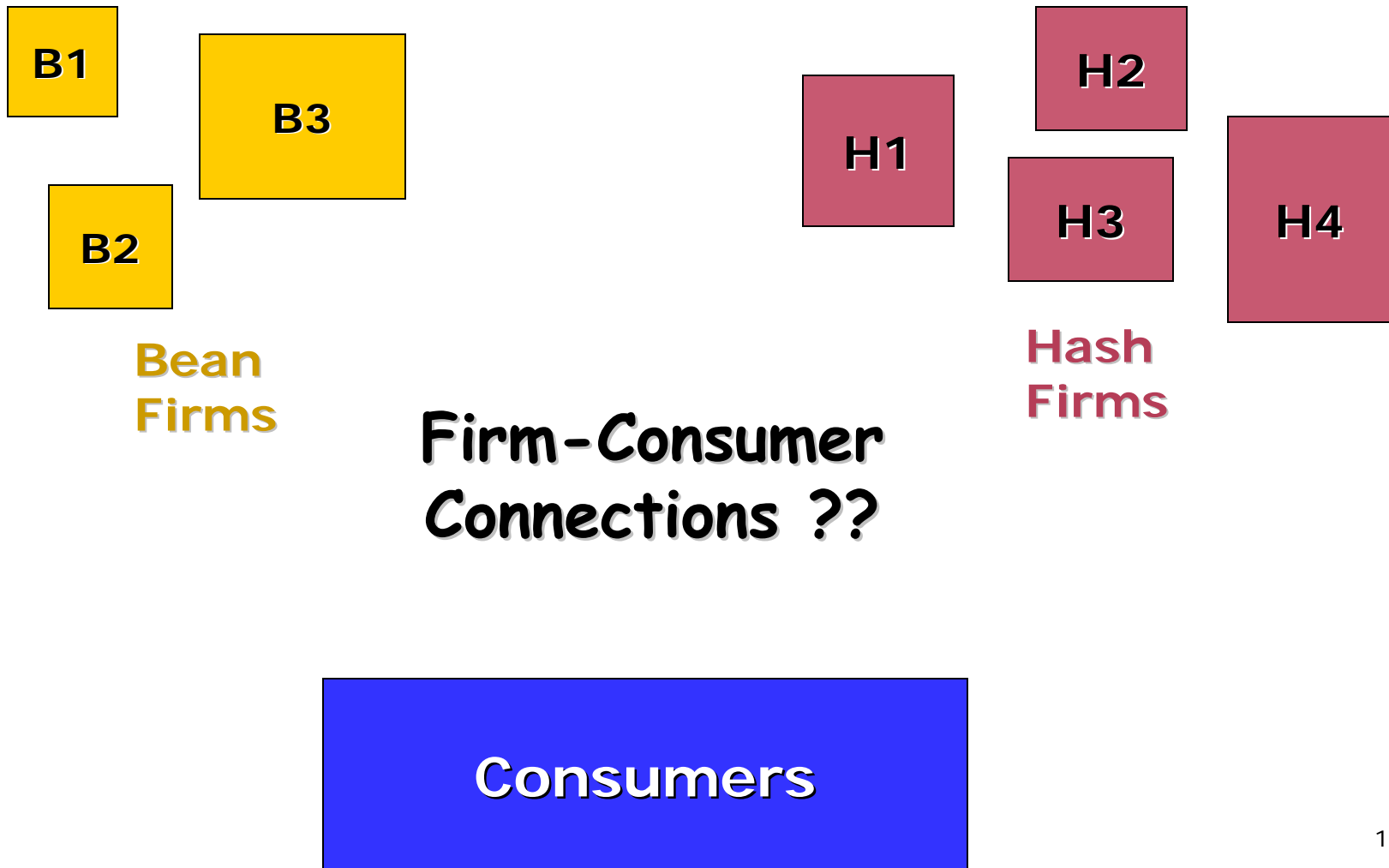
## Exercise:

- **Remove** all imposed *equilibrium* conditions (e.g., market clearing, correct expectations,...).
- **Introduce** minimal *agent-driven* production, pricing, and trade processes needed to re-establish sustained circular flow among firms and consumers.
- **Analyze** the resulting economy to see if/when it is able to attain some form of equilibrium state over time.

# Start from a Standard Walrasian GE Economy (Price-Taking Firms & Consumers, Auctioneer, ...)



# Pluck Out the Fictitious Auctioneer!



# How to Construct a Self-Sustaining Economy without the Fictitious Walrasian Auctioneer ?

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**Attention must now shift FROM** firms & consumers who

- maximize profits and utility in social isolation;
- condition decisions on publicly given -- or correctly expected -- equilibrium (market clearing) prices,

**TO** the trade interaction patterns among profit-seeking firms and utility-seeking consumers who

- recognize that trade is essential for survival as well as for prosperity;
- have individualized endowments and good-for-good "reservation prices"--i.e., marginal rates of (technical) substitution--that constrain their trades.

# Construction of a Self-Sustaining Economy...

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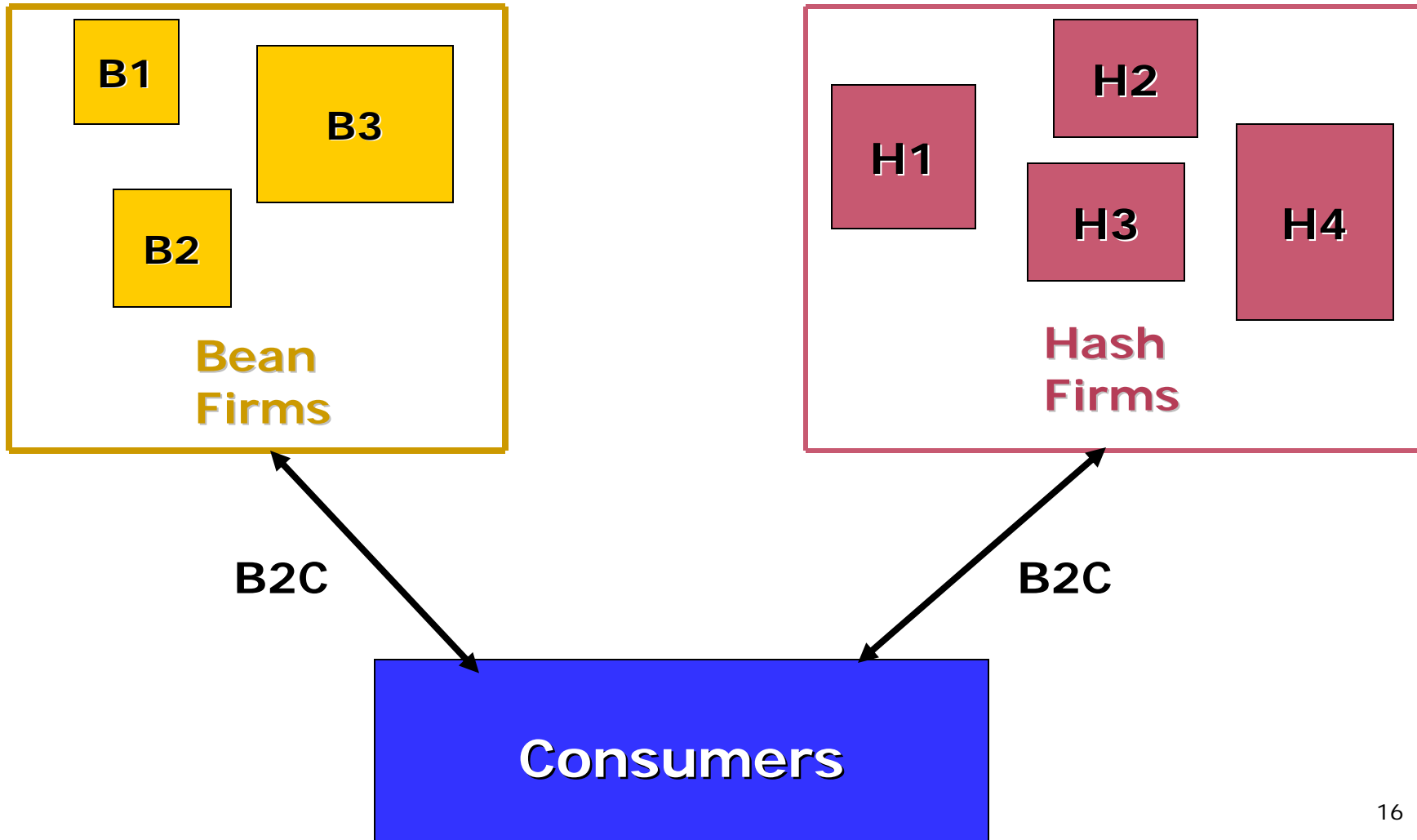
*In particular, careful attention must be paid to:*

## □ Market Organization

- Who is able to trade with whom, and how often?
- Under what types of rules and regulations does trading take place ?
  - Bilateral trade ?
  - Trade mediated by brokers or dealers ?
  - Seller or buyer one-sided posted auctions?
  - Double auctions ?

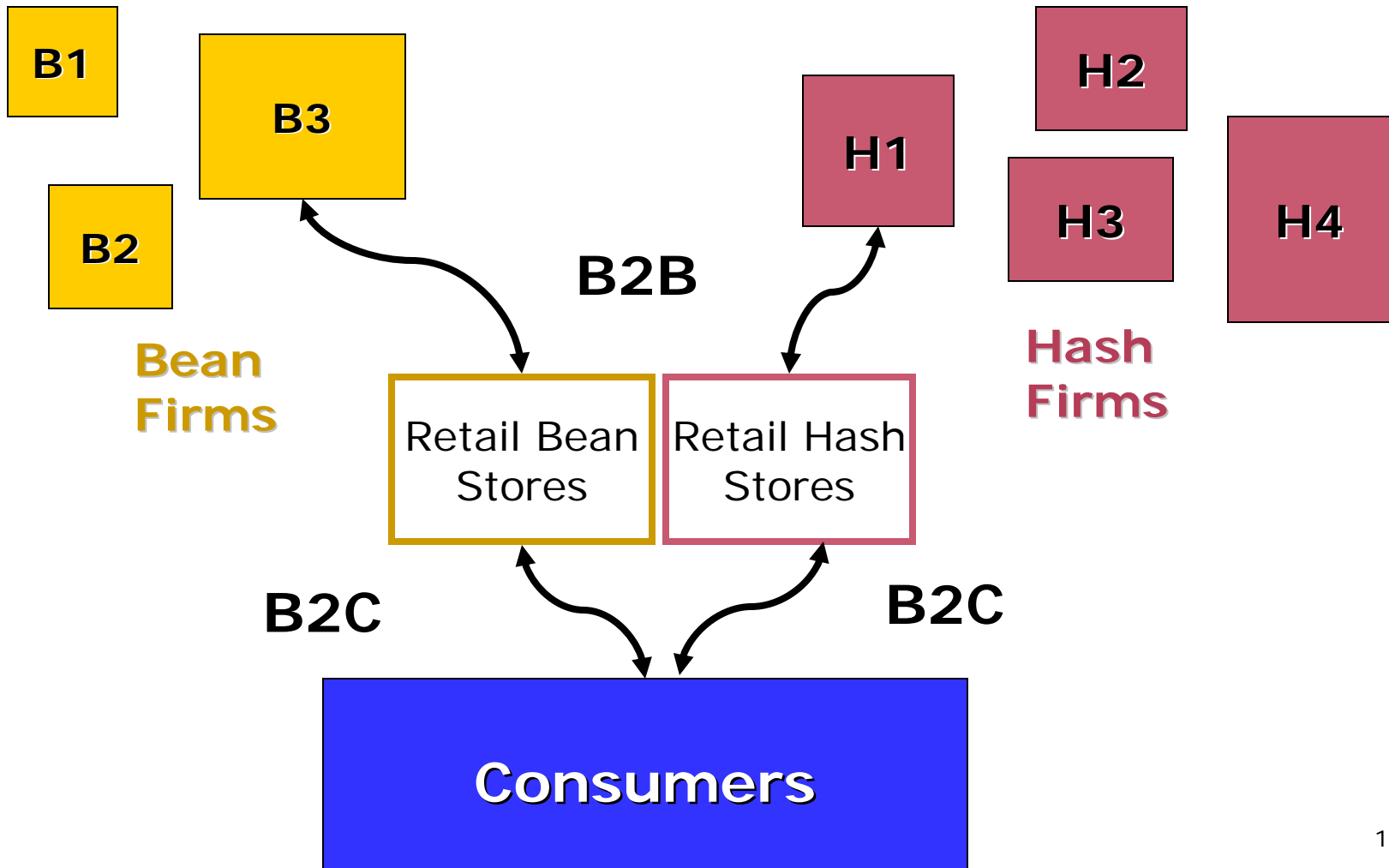
# Ex.1: Bilateral Trade

(Business-To-Consumer = B2C)

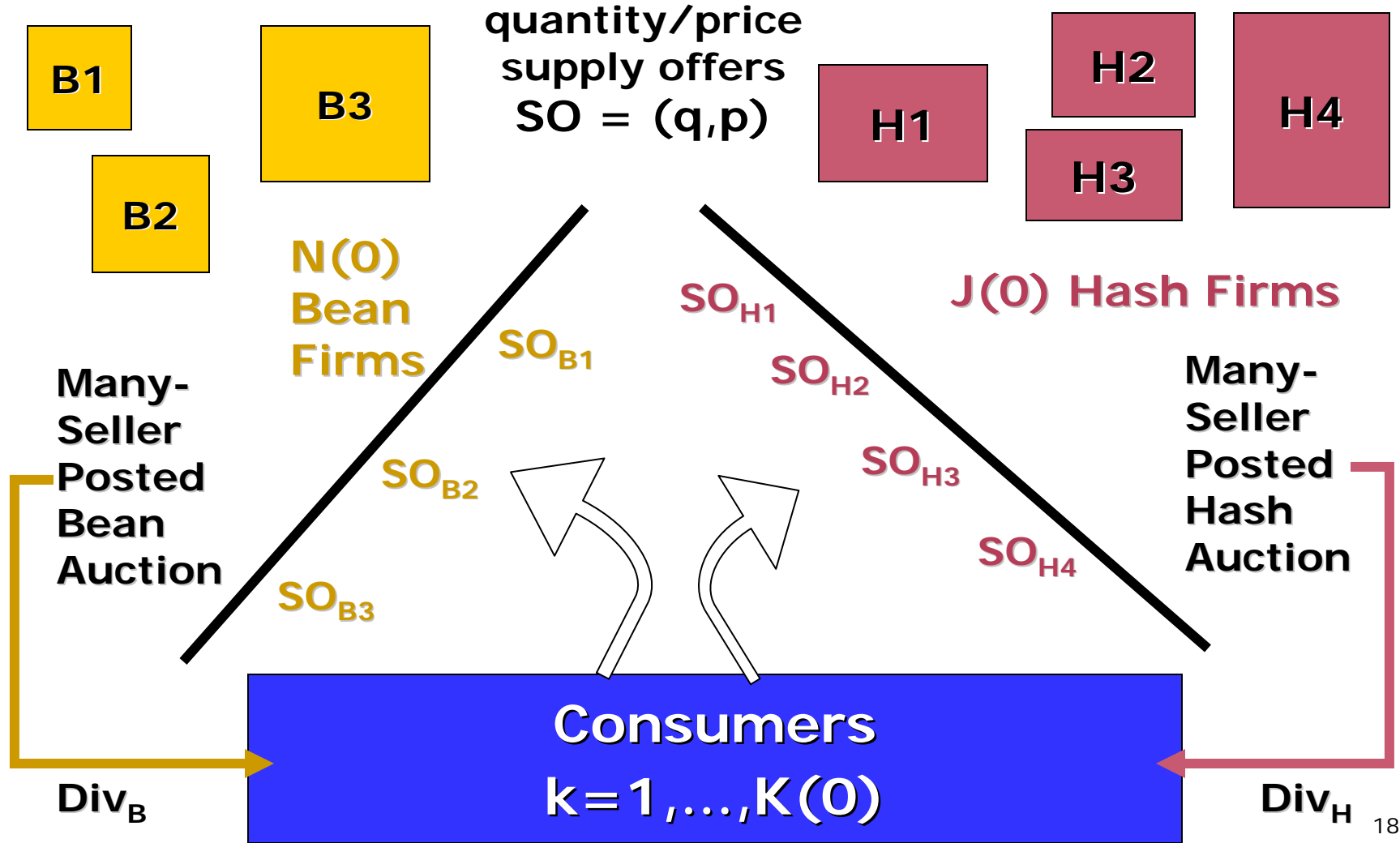


# Ex.2: Store-Mediated Trade

(Producers → Retail Stores → Consumers)



# Example 3: Trade Through Many-Seller Posted Auctions



# Construction of a Self-Sustaining Economy...

Careful attention must also be paid to:

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## □ Market-making activities

- Seller price/quantity offers ?
- Buyer price/quantity bids ?
- Seller-buyer matching ?
- Price determination from seller/buyer interactions ?

## □ What happens when things go wrong

- Excess demand (inventory run down or stock-outs)
- Excess supply (inventory pile-up or waste)
- Insolvency (firm negative net worth)
- Starvation (consumer subsistence needs not met)

## Complex Set of Market Processes Routinely Engaged in By Real-World Traders

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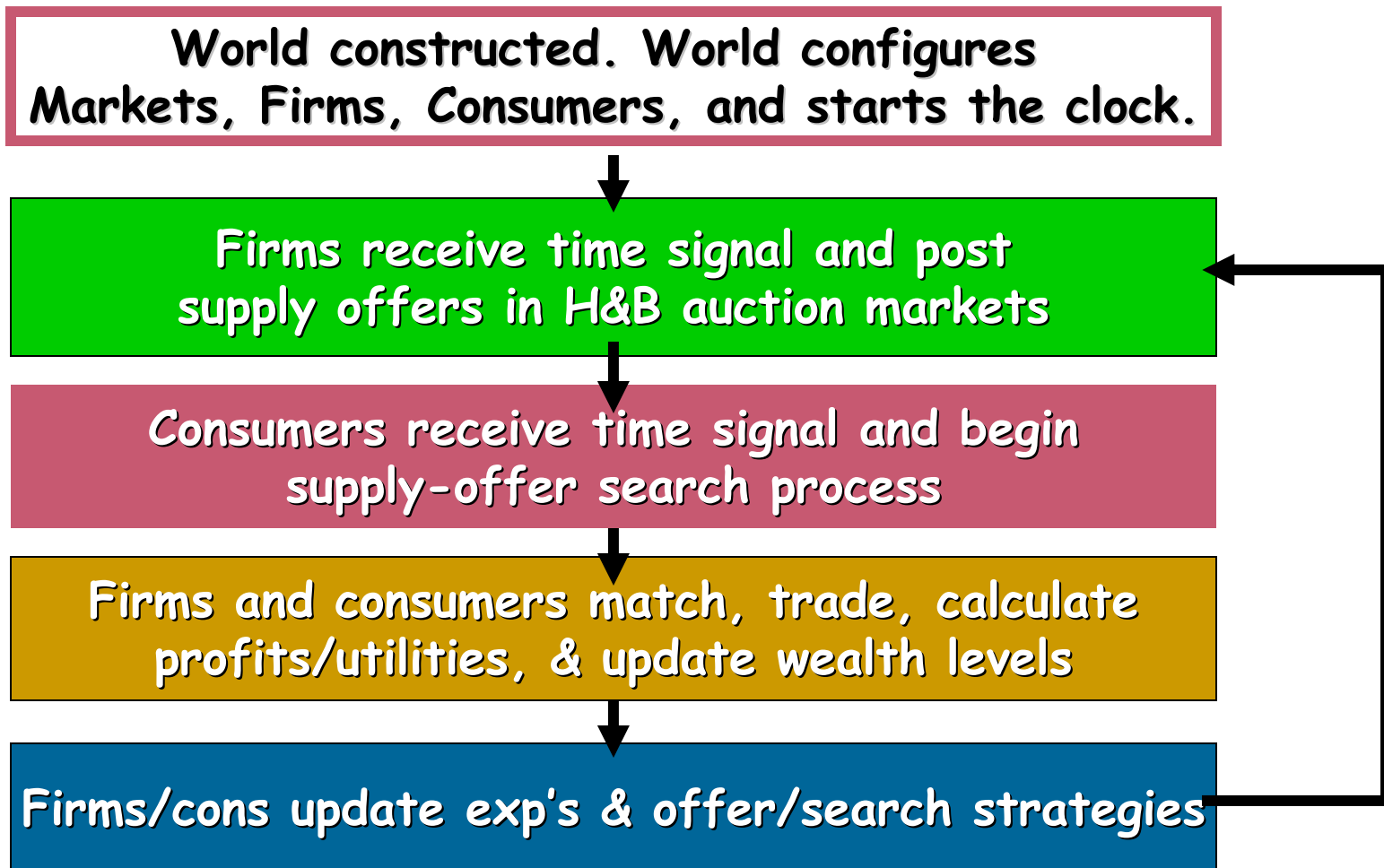
- ◆ *Terms of Trade*: Set production and price levels
- ◆ *Seller-Buyer Matching*:
  - Identify potential suppliers/customers
  - Compare/evaluate opportunities
  - Make demand bids/supply offers
  - Select specific suppliers/customers
  - Negotiate supplier/customer contracts
- ◆ *Trade*: Transactions carried out (or contracts broken)
- ◆ *Settlement*: Payments carried out (or default occurs)
- ◆ *Learning*: Strategy revisions, exit/entry decisions
- ◆ *Management*: Long-term supplier/customer relations

## Can ACE Modeling Help?

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- ❑ No need to make the strong assumptions of Walrasian general equilibrium.
- ❑ ACE facilitates a more empirically grounded modeling of decentralized market economies.
- ❑ ACE permits modeling of complex market organizations and processes routinely engaged in by real-world traders.

# Illustration: Dynamic Activity Flow in an ACE Hash & Beans Trading World



# Dynamic Activity Flow for Firms Over Time Periods $T \geq 1$

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- ◆ Each firm  $f$  starts out with positive *net worth*  $NW_f(0)$  and *plant production capacity*  $Cap_f(0)$ .
- ◆ Firm  $f$ 's *sunk cost*  $SC_f(T)$  for  $T \geq 1$  is proportional to its plant production capacity,  $Cap_f(T-1)$ .
- ◆ At beginning of each  $T \geq 1$ , firm  $f$  selects a *supply offer* = (production level, unit price).
- ◆ At end of  $T \geq 1$ , firm  $f$  is *solvent* if it has positive net worth:  $NW_f(T) = [Profits_f(T) + ValueCap_f(T)] > 0$
- ◆ If solvent, firm  $f$  *allocates its profits* (+ or -) between retained earnings, dividends, and/or capacity purchase/sale; otherwise it exits world.

# Dynamic Activity Flow for Consumers over Time Periods $T \geq 1$

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- ◆ Each consumer  $k$  starts out with a lifetime *money endowment profile* and *stock shares* for H & B firms.
- ◆ In each  $T \geq 1$ , consumer  $k$ 's **utility** is measured by
$$U_k(T) = (\text{hash}(T) - h_k^*)^{\alpha_k} \cdot (\text{beans}(T) - b_k^*)^{[1-\alpha_k]} .$$
- ◆ In each  $T \geq 1$ , consumer  $k$  seeks to secure highest possible utility by *searching* for hash and beans to buy at *lowest possible prices*, subject to stock-out risk.
- ◆ At end of each  $T \geq 1$ , consumer  $k$  *dies* unless he secures at least his *subsistence needs*  $(h_k^*, b_k^*)$ .

# Experimental Design Treatment Factors for Firms and Consumers

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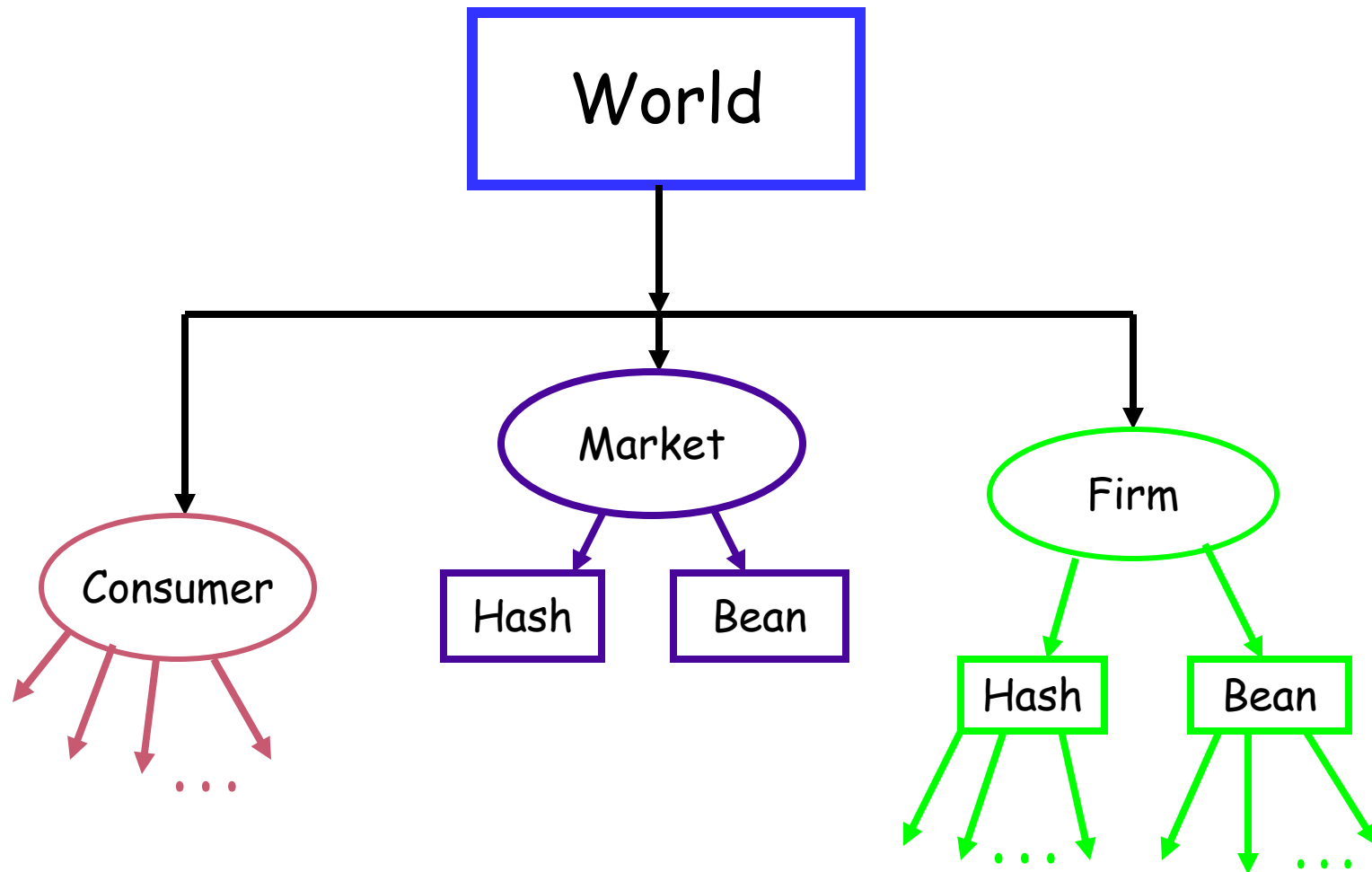
## □ Initial firm data and methods

- Number of hash/bean firms, net worth levels, production capacities, cost functions, ...
- Learning methods (supply offer determination), rationing methods, profit allocation methods,...

## □ Initial consumer data and methods

- Number of consumers, money endowment profiles, stock share holdings, preferences, subsistence needs, beliefs, risk aversion, ...
- Learning methods (price discovery, precautionary savings, stock-out avoidance,...)

# ACE H&B Trading World: Agent Hierarchy



# World Agent (Structural)

## Public Access:

### // **Public Methods**

The *World Event Schedule*, 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 getting, storing, processing, & sending data;

### // **Private Data**

World attributes (e.g., spatial configuration);

World inhabitants (H & B markets, firms, consumers);

World inhabitants' methods and data;

# Market Agent (Institutional)

## 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 getting, storing, processing, & sending data;

### // **Private Data**

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

# Firm Agent (Cognitive)

## 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 getting, storing, processing, & sending data;  
Methods for calculating expected & actual profit outcomes;  
Methods for supply offer selection, profit allocation...;  
Methods for updating my methods (**PLASTICITY**);

### // **Private Data**

Data about me (history, capacity, cost function, net worth,...);  
Data about external world (rivals' supply offers, ...);  
Address book (communication links);

# Consumer Agent (Cognitive)

## 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**

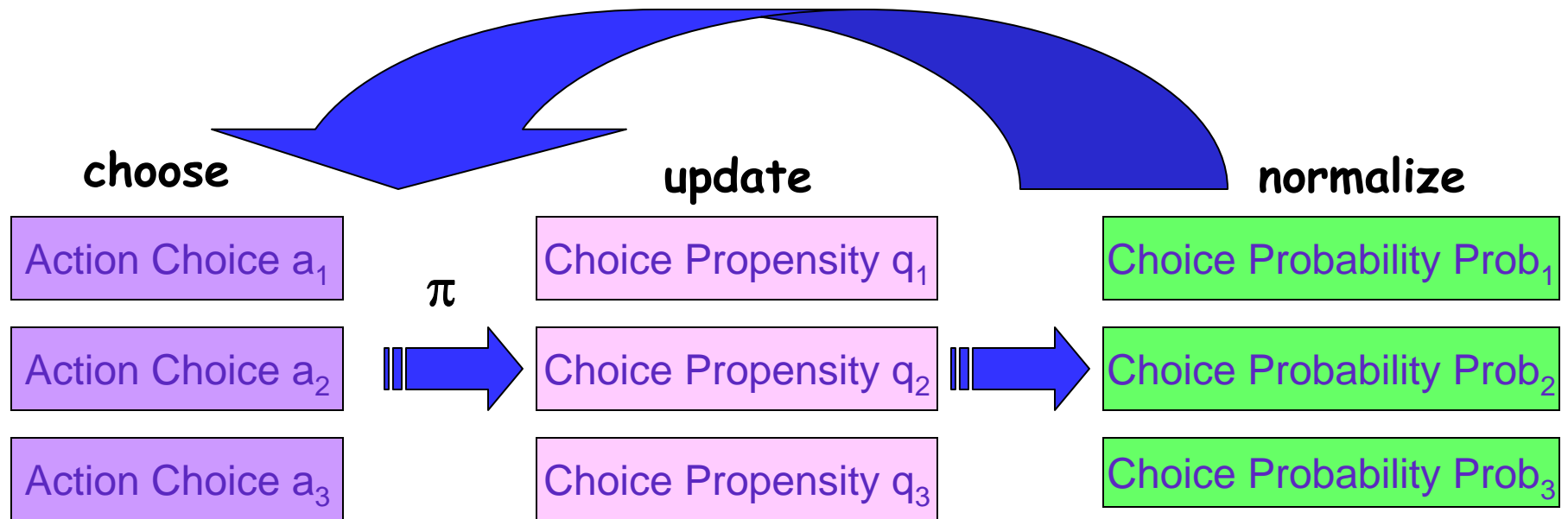
Methods for getting, storing, processing, & sending data;  
Method for searching for lowest prices;  
Methods for updating my methods (**PLASTICITY**);

### // **Private Data**

Data about me (history, preferences, current income,...);  
Data about external world (posted supply offers, ...);  
Address book (communication links);

# Firm & Consumer Learning?

## Illustration: Stochastic Reinforcement Learning



- Action choice  $a'$  leads to earnings/utility  $\pi'$ , followed by updating of action choice propensities  $q$  based on this reward, followed by normalization of these propensities into action choice probabilities Prob.

# Interesting Issues for Exploration

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- ◆ Initial conditions → **carrying capacity?**  
(Survival of firms/consumers in long run)
- ◆ Initial conditions → **market clearing?**  
(Walrasian general equilibrium benchmark)
- ◆ Initial conditions → **market efficiency?**  
(Walrasian general equilibrium benchmark)
- ◆ Standard concentration measures at  $T=1$  →  
**good predictors of long-run market power?**
- ◆ Importance of **learning vs. market structure**  
for market performance? (*Gode/Sunder, JPE, 1993*)

# ACE H&B Trading World as a Test Bed ? (Cook & Tesfatsion, 2009)

Form1  
File Tools Window Help

Untitled 1 (Empty Lab)

## Hash & Bean Multi-Market Economy Model

CONSUMERS	Group	Count	Consumer Details		
	Cons Type 1	100	Group Name:	Consumption Needs:	Endowment Schedule:
	Cons Type 2	100	Cons Type 2	Hash: 3	Lifecycle [edit]
			Count: 100	Beans: 3	Initial: 25
			Add	Preference: [edit]	$\alpha = 0.505$ Slightly Prefers Hash
<b>Total:</b>		<b>200</b>			

FIRMS	Group	Count	Firm Details		
	Large	1	Group Name:	Initial Assets:	Cost Function:
	Small	20	Small	Money: 50	Default [edit]
			Hash Firms: 20	Capacity: 10	^ Capacity: 1.0
			Bean Firms: 20	Profit Distribution:	Learning Strategy:
			Add	Money: 0.5	Random P & Q (Del) [edit]
				Dividends: 0.5	
<b>Total:</b>	<b>21</b>	<b>21</b>			

Experiment Number: 1 Trial Count: 5 Trial Length ( TMax): 100

**START**

# Recommended Tasks

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- Develop ACE test beds that permit systematic study of macroeconomic systems.
  - Test beds can be tailored to specific issues (agent scale, agent taxonomy, agent plasticity, ...).
  - Test beds should be open source to permit replication.
  - Findings should be replicated using multiple software & hardware platforms (*model verification*).
  
- Evaluate test-bed generated theories against actual data to the fullest extent possible. (*empirical validation*).

# Wrap-Up: Key Points

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- ★ **In real-world macroeconomies...**
  - macro regularities arise from interactions among heterogeneous entities with limited info/capabilities;
  - interactions are conditioned by structure, institutions, and behavioral dispositions that can in turn evolve.
- ★ **ACE encapsulation of processes into agents...**
  - forces modelers to respect agent heterogeneity and limits on info & computational capabilities;
  - facilitates the modeling of complicated dynamic feedbacks among structure, institutions, behavioral dispositions, and agent interactions.

# ACE On-Line Resources

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- ◆ **ACE Website Homepage:**  
[www.econ.iastate.edu/tesfatsi/ace.htm](http://www.econ.iastate.edu/tesfatsi/ace.htm)
- ◆ **ACE Macroeconomic Research Site:**  
*Learning/Coordination in Decentralized Market Economies*  
[www.econ.iastate.edu/tesfatsi/amulmark.htm](http://www.econ.iastate.edu/tesfatsi/amulmark.htm)
  - Pointers to surveys and research studies
  - Pointers to preliminary attempts to build ACE test beds for simple macroeconomic systems