Modeling Behavior, Learning, and Social Interactions in Dynamic Economic Systems

An Agent-Based Computational Approach

Presenter:

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Presentation Outline

- Why are economic systems so hard to model?
- What is Agent-based Comp Economics (ACE)?
- ACE frameworks as test-beds for economic systems: Two illustrative studies
  1. ACE double-auction market performance study
  2. An ACE trading world (two-sector growth model)
- Pluses & minuses of ACE for social science research in general

Why are Real-World Dynamic Economic Systems So Hard to Model (Well)?

- **Distributed local interactions**
- **Two-way feedbacks** mediated by interactions

  Micro ↔ Agent Interactions ↔ Macro
- **Strategic behavior & uncertainty**
- **Network effects** and **path dependence**
- Critical role of **institutional constraints**

Growing Mainstream Econ Interest in Modeling These Complexities

- **Princeton U Press New 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.

- **Four recent Nobel Prizes:** Akerloff (2001), Kahneman & Smith (2002), Schelling (2005)

Why has it taken so long?

- Until relatively recently, a ***lack of tools*** permitting the quantitative modeling of dynamic economic systems in a compelling, tractable, & testable way.

- The seeming promise of ***rational expectations*** (1973 -1993) that economic outcomes could be studied and understood as the result of purely rational deliberations by individual agents

  → no need for detailed understanding of human cognition and social interactions.

Potential of computational experiments for studying dynamic economic systems

Early recognition by Robert Lucas, Jr., "Methods & Problems in Business Cycle Theory" (1980):

"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

- Fortran programming was/is not well designed for the modeling of real-world ***social*** systems
- Modern **"Agent-Oriented Programming" (AOP)** tools have been specifically designed for this purpose.
- **Agent-based Computational Economics (ACE)** uses AOP tools to study complex interplay among structure, institutions, behavior, learning, and social interactions in dynamic economic systems

What is ACE?

- Computational study of economic processes as **dynamic systems of interacting agents**
- A **culture-dish approach** to the theoretical study of economic processes

ACE Culture-Dish Analogy

- Modeler constructs a virtual economic world populated by various **agent types**
- Modeler sets **initial world conditions**
- Modeler then steps back to observe how the **world develops over time** without intervention **(no imposed equilibrium, rational expectations, etc.)**
- World events are **driven by agent interactions**

ACE Agent Types

Agents = Encapsulated software programs representing **individual, social, biological and/or physical entities**

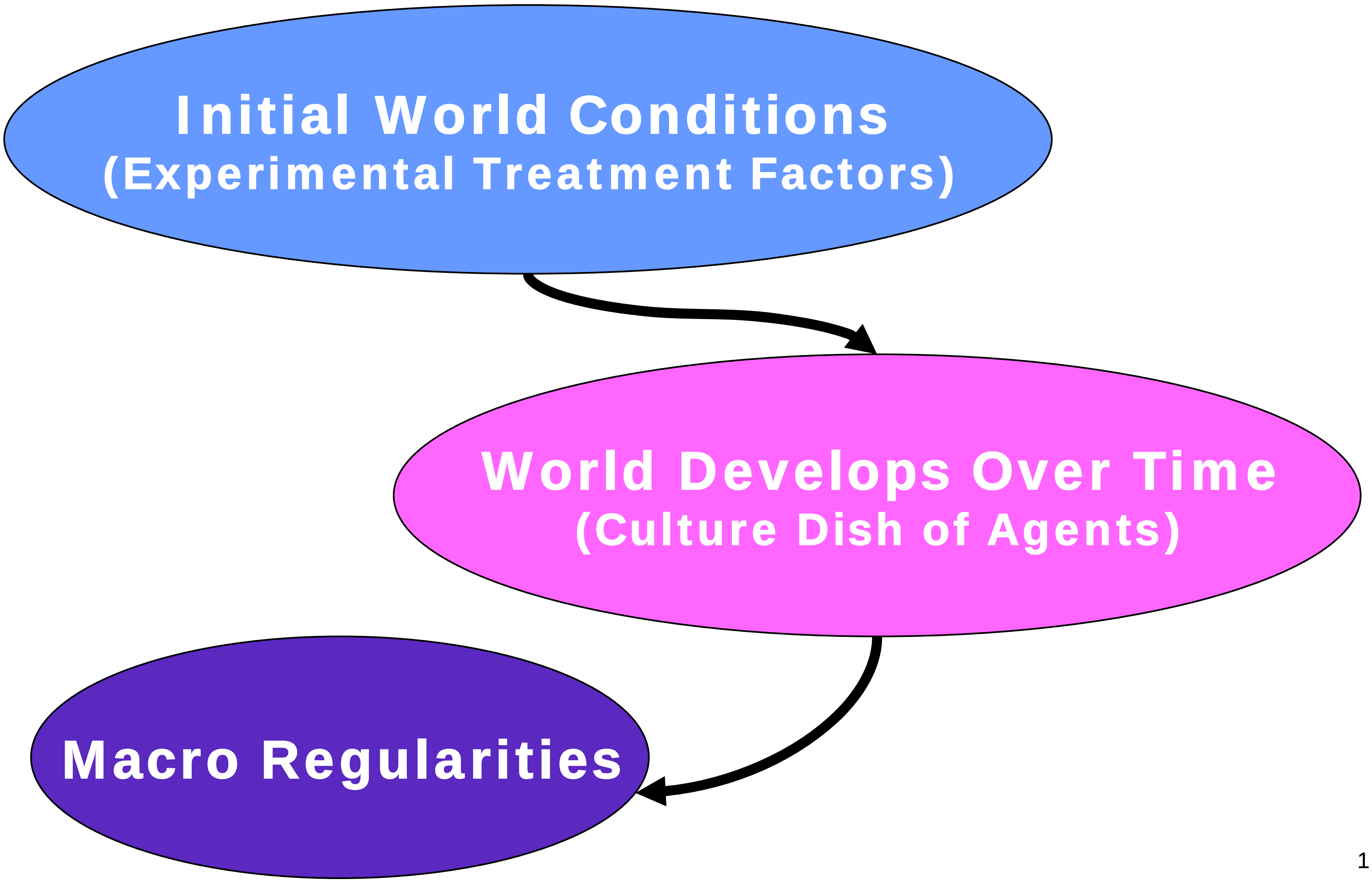
✱ Cognitive agents are capable (in various degrees) of

- **Behavioral adaptation**
- **Social communication**
- **Goal-directed learning**
- **Endogenous evolution of interaction networks**
- **"Autonomy"** (self-activation and self-determinism based on private internal processes)

Initial World Conditions
(Experimental Treatment Factors)

- Structural conditions
- Institutional arrangements
- Behavioral dispositions of agents

ACE Culture Dish Analogy…



Four Main Strands of ACE Research

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

ACE and 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 empirical situation.
- Investigate whether the empirical regularities can be ***reliably generated*** as outcomes in this world.

Example: ACE financial market research seeking explanation of several "stylized facts" in combination
www.econ.iastate.edu/tesfatsi/afinance.htm

ACE and Market Design

Key Issue: Does a market design ensure **efficient, fair, & orderly social outcomes over time** even if participants attempt to "game" it for own advantage?

ACE Approach:

- ***Construct an agent-based world*** capturing salient aspects of the market design.
- ***Introduce agents with behavioral dispositions, needs, goals, beliefs, etc.*** Let the world evolve. Observe and evaluate resulting social outcomes.

EXAMPLES: Design of auctions, stock exchanges, electricity markets, automated Internet markets (B2B, job markets, eBay,…)

ACE and Qualitative Analysis

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

ACE Approach:

- ***Construct an agent-based world*** qualitatively capturing key aspects of decentralized market economies (firms, consumers, circular flow, limited information, …)
- ***Introduce traders with behavioral dispositions, needs, goals, beliefs, etc.*** Let the world evolve. Observe the degree of coordination that results.

EXAMPLES: Decentralized exchange economies without a Walrasian Auctioneer, ZI agent double-auction markets,…

Example 1: Study of a Relatively Simple Double-Auction Market Design

- J. Nicolaisen, V. Petrov, L. Tesfatsion, *IEEE Transactions on Evolutionary Computation*,5(5),2001,504-523
  http://www.econ.iastate.edu/tesfatsi/mpeieee.pdf

- **Focus of Study:**

Relative role of structure vs. learning in determining performance of a double-auction design for a day-ahead electricity market.

Key Issues Addressed

- Sensitivity of market performance to changes in **market structure:**

  RCON = Relative seller/buyer **concentration**

  RCAP = Relative demand/supply **capacity**

- Sensitivity of market performance to changes in **trader learning:**

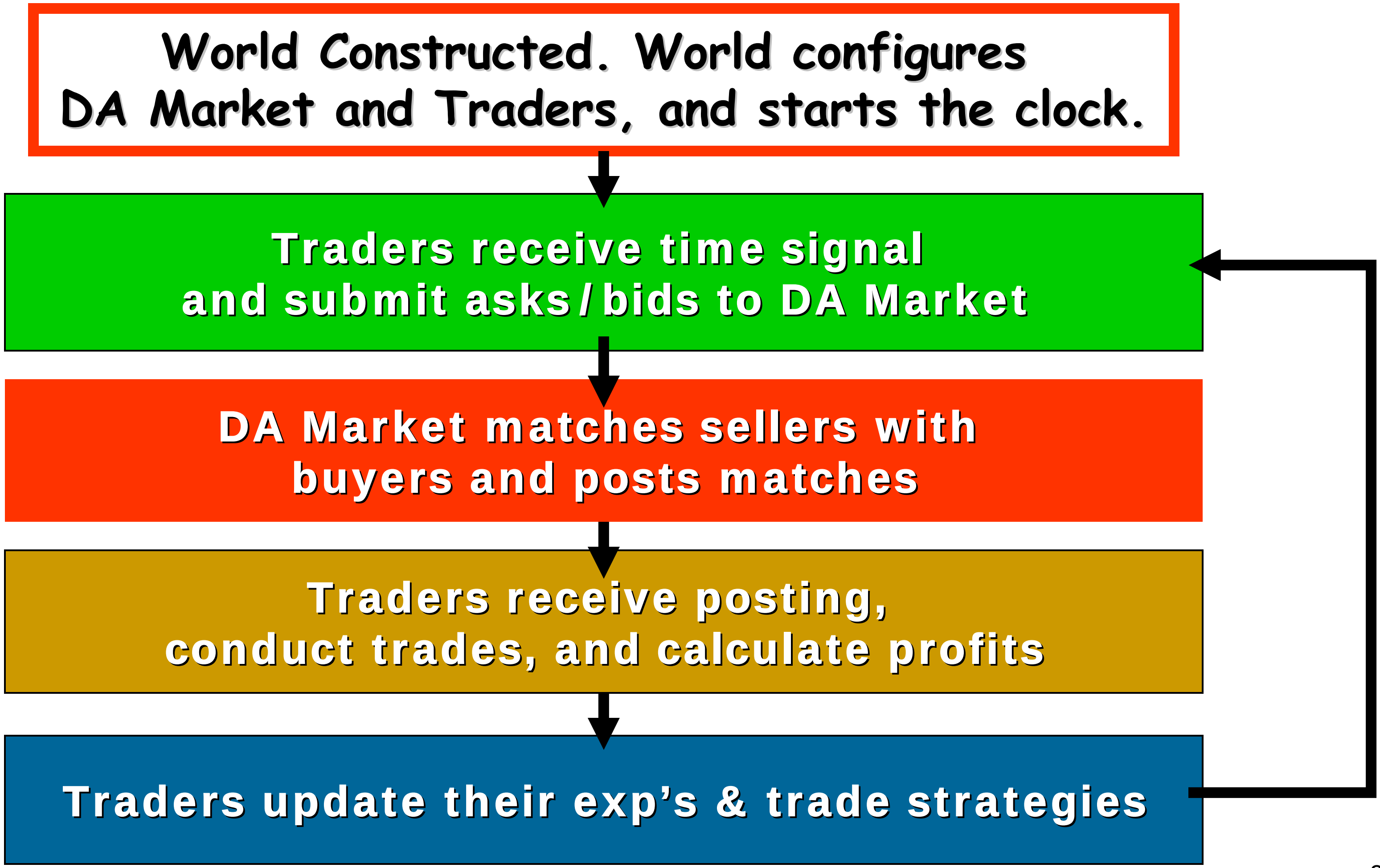
  Individual learning via **Reinforcement Learning (RL)**

  Social mimicry via **Genetic Algorithms (GAs)**

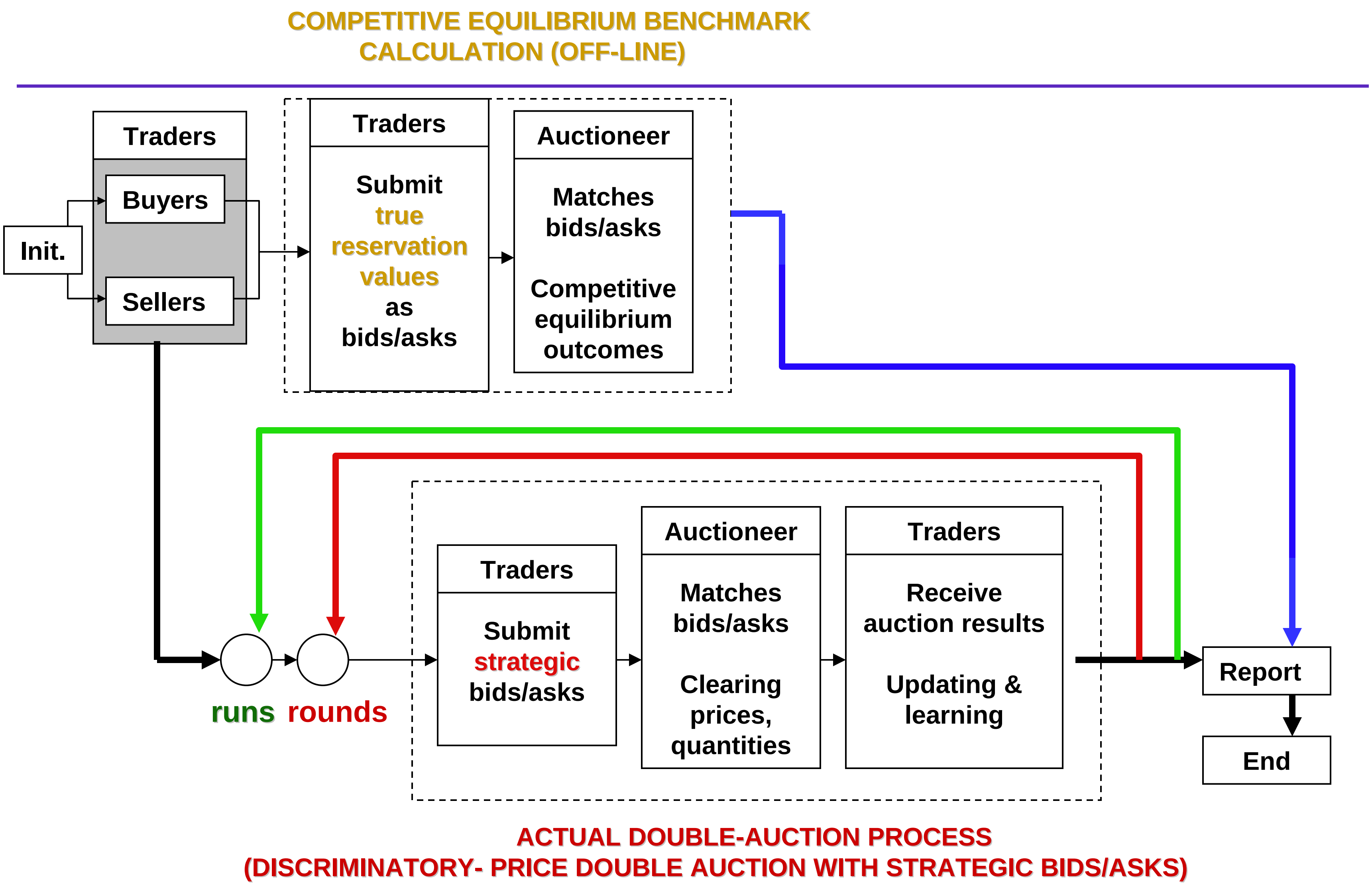
Market Performance Measures

- **Market Efficiency:** Actual total net benefits extracted from the market relative to maximum possible total net benefits (competitive benchmark ideal).
- **Market power:** The manner in which actual extracted total net benefits are distributed among the market participants.

Dynamic Flow of DA Market: Simple View



Dynamic Flow of DA Market: Detailed View

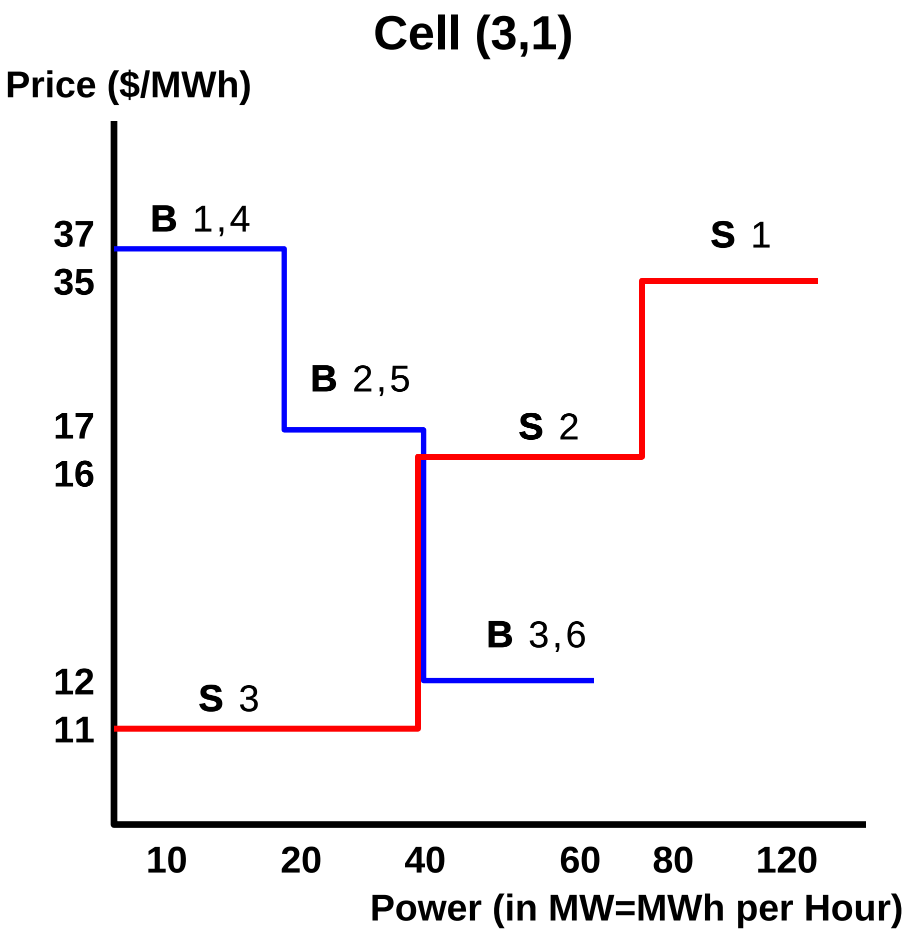


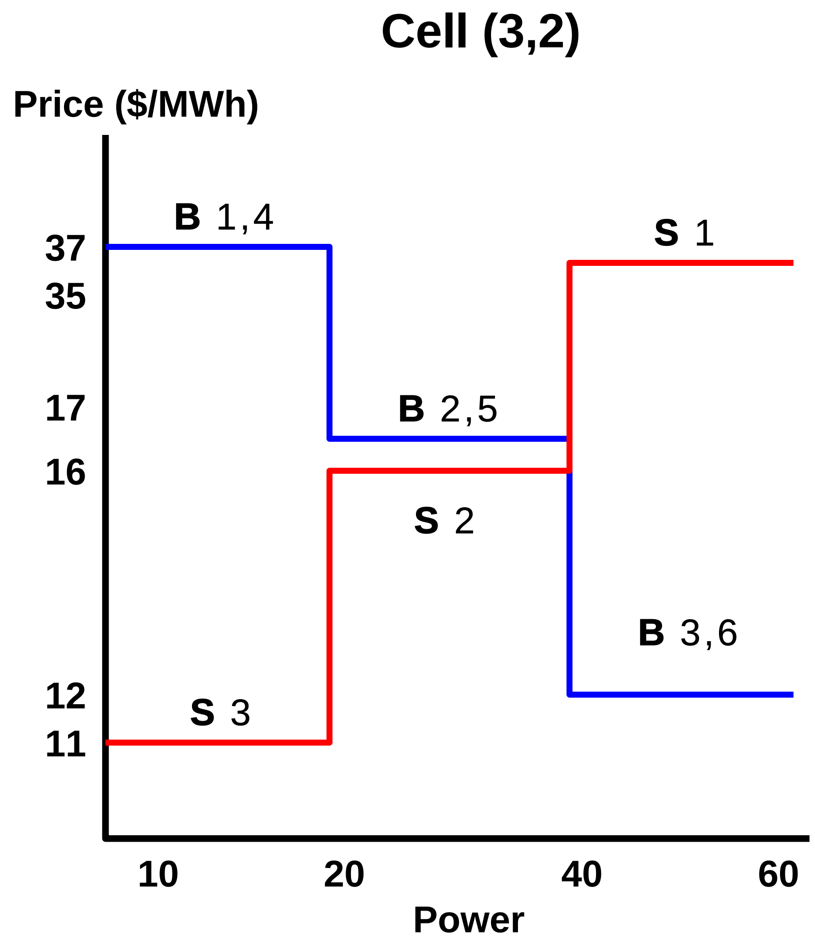
Structural Treatment Factor Values
(tested for each learning treatment)

Ns = Number of Sellers
Nb = Number of Buyers
Cs = Seller Supply Capacity
Cb = Buyer Demand Capacity
RCON=Ns/Nb
RCAP=NbCb/NsCs

		RCAP		
		1 / 2	1	2
RCON	2	Ns = 6 Nb = 3 Cs = 10 Cb = 10	Ns = 6 Nb = 3 Cs = 10 Cb = 20	Ns = 6 Nb = 3 Cs = 10 Cb = 40
	1	Ns = 3 Nb = 3 Cs = 20 Cb = 10	Ns = 3 Nb = 3 Cs = 10 Cb = 10	Ns = 3 Nb = 3 Cs = 10 Cb = 20
	1 / 2	Ns = 3 Nb = 6 Cs = 40 Cb = 10	Ns = 3 Nb = 6 Cs = 20 Cb = 10	Ns = 3 Nb = 6 Cs = 10 Cb = 10

Aggregate True Demand and Supply per Hour





The Computational World

Public Access:

// **Public Methods**

The ***World Event Schedule,*** i.e., a system clock that permits inhabitants to time and synchronize activities (e.g., submission of asks/bids into the DA market);

Protocols governing trader collusion;

Protocols governing trader insolvency;

Methods for receiving data;

Methods for retrieving World data.

Private Access:

// **Private Methods**

Methods for gathering, storing, and sending data;

// **Private Data**

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

World inhabitants (DA market, buyers, sellers);

World inhabitants' methods and data.

The Computational DA Market

Public Access:

// **Public Methods**

getWorldEventSchedule(clock time);
Protocols governing the public posting of asks/bids;
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**

Data recorded about sellers (e.g., seller asks);
Data recorded about buyers (e.g., buyer bids);
Address book (communication links).

A Computational DA Trader

Public Access:

// **Public Methods**

getWorldEventSchedule(clock time);
getWorldProtocols (collusion, insolvency);
getMarketProtocols (posting, matching, trade, settlement);
Methods for receiving data;
Methods for retrieving Trader data.

Private Access:

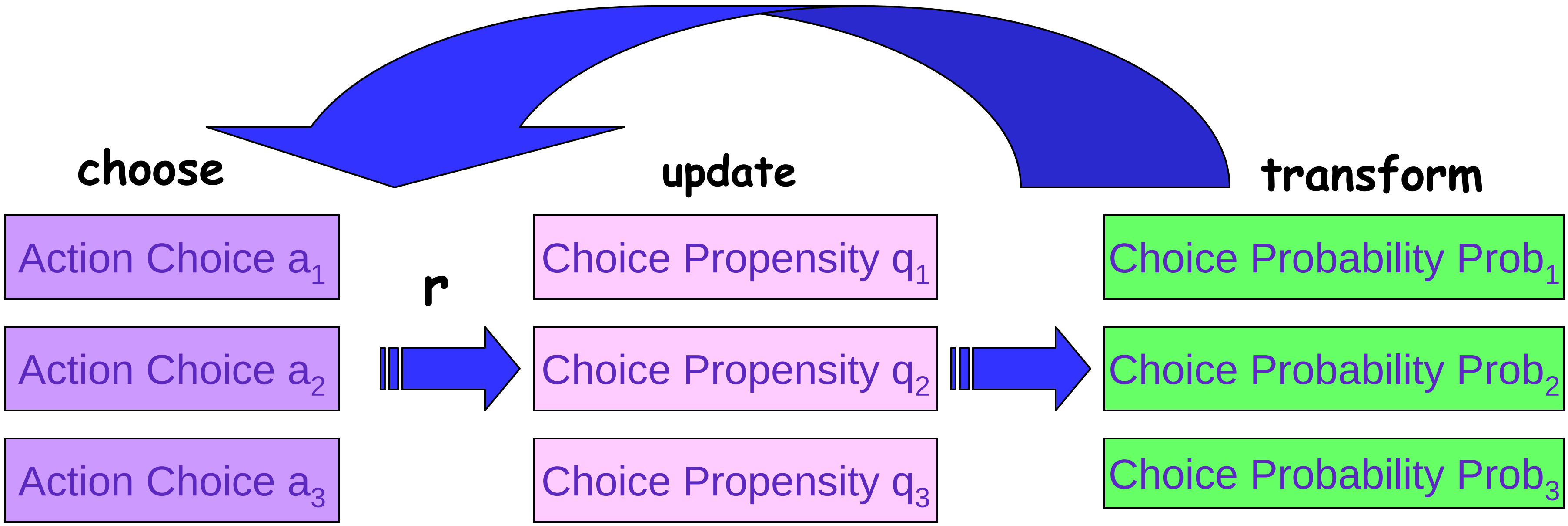
// **Private Methods**

Methods for gathering, storing, and sending data;
Methods for calculating expected & actual profit outcomes;
Method for updating my ask/bid strategy (**LEARNING**).

// **Private Data**

Data about me (history, profit function, current wealth,…);
Data about external world (rivals' asks/bids, …);
Address book (communication links).

DA Traders Choose Bids/Asks ("Actions") via *Modified* Roth-Erev Reinforcement Learning (RL)



- Each DA trader maintains action choice propensities q, normalized to action choice probabilities Prob, to choose actions. A good (bad) reward r' for action a' results in a strengthening (weakening) of the propensity q' for a'.

Modified Roth-Erev RL

1. **Initialize** action propensities to an initial propensity value.
2. **Generate** choice probabilities for all actions using current propensities.
3. **Choose** an action according to the current choice probability distribution.
4. **Update** propensities for all actions using the reward for the last chosen action.
5. **Repeat** from step 2.

Original Roth-Erev RL Propensity Updating

Parameters:

- $q_j(0)$ Initial propensity
- ϵ Experimentation
- ϕ Recency (forgetting)

Variables:

- a_j Current action choice
- q_j Propensity for action a_j
- a_k Last action chosen
- r_k Reward for action a_k
- t Current time step
- N Number of actions

$$q_j(t+1) = [1-\phi]q_j(t) + E_j(\epsilon, N, k, t)$$

$$E_j(\epsilon, N, k, t) = \begin{cases} r_k(t)[1-\epsilon] & \text{if } j = k \\ r_k(t)\frac{\epsilon}{N-1} & \text{if } j \neq k \end{cases}$$

Modified Roth-Erev RL Propensity Updating

- Update function E_j *modified* so that updating of propensities occurs even with 0-valued rewards r.
- Letting a_j = any feasible action choice and a_k = currently chosen action, this *modified* E_j is:

$$E_j(\epsilon, N, k, t) = \begin{cases} r_k(t)[1-\epsilon] & \text{if } j = k \\ q_j(t)\frac{\epsilon}{N-1} & \text{if } j \neq k \end{cases}$$

*** Market efficiency with unmodified Roth-Erev updating tended to be low (e.g. 20%) due to lack of matching during initial learning phase.**

Sample Table of Experimental Results

TABLE VI

EXPERIMENTAL MARKET POWER AND EFFICIENCY OUTCOMES FOR THE BEST FIT MRE ALGORITHM WITH 1000 AUCTION ROUNDS AND PARAMETER VALUES $s(1) = 9.00$, $r = 0.10$, AND $\epsilon = 0.20$

Relative Concentration		Relative Capacity 1/2: MP	StdDev	Relative Capacity 1: MP	StdDev	Relative Capacity 2: MP	StdDev
2	All Buyers:	-0.13*	(0.09)	-0.15*	(0.09)	0.10	(0.30)
	All Sellers:	0.55*	(0.38)	0.38*	(0.33)	-0.10	(0.25)
	Buyer[1]:	-0.12*	(0.08)	-0.13*	(0.10)	0.10	(0.30)
	Buyer[2]:	-0.20	(0.40)	-0.75*	(0.33)	ZP	(0.00)
	Buyer[3]:	ZP	(0.00)	ZP	(0.00)	ZP	(0.00)
	Seller[1]:	ZP	(0.00)	ZP	(0.00)	ZP	(0.00)
	Seller[2]:	ZP	(0.00)	-0.50	(1.34)	-0.12	(0.34)
	Seller[3]:	0.54	(0.63)	0.45*	(0.40)	-0.10	(0.22)
	Seller[4]:	ZP	(0.00)	ZP	(0.00)	ZP	(0.00)
	Seller[5]:	ZP	(0.00)	-0.42	(1.67)	-0.08	(0.36)
	Seller[6]:	0.55	(0.60)	0.46*	(0.41)	-0.09	(0.24)
	Efficiency:	99.81	(0.02)	96.30	(0.05)	99.88	(0.06)
1	All Buyers:	-0.22*	(0.12)	-0.13*	(0.10)	0.13	(0.33)
	All Sellers:	0.80*	(0.53)	0.28	(0.35)	-0.10	(0.26)
	Buyer[1]:	-0.21*	(0.11)	-0.11*	(0.10)	0.13	(0.33)
	Buyer[2]:	-0. 31	(0.44)	-0.80*	(0.40)	ZP	(0.00)
	Buyer[3]:	ZP	(0.00)	ZP	(0.00)	ZP	(0.00)
	Seller[1]:	ZP	(0.00)	ZP	(0.00)	ZP	(0.00)
	Seller[2]:	ZP	(0.00)	-0.37	(1.89)	-0.10	(0.34)
	Seller[3]:	0.76*	(0.63)	0.34	(0.45)	-0.11	(0.24)
	Efficiency:	92.13	(0.09)	94.59	(0.07)	100.00	(0.00)
1/2	All Buyers:	-0.21*	(0.12)	-0.14*	(0.08)	0.09	(0.24)
	All Sellers:	0.67*	(0.46)	0.30	(0.31)	-0.07	(0.19)
	Buyer[1]:	-0.18*	(0.12)	-0.14*	(0.10)	0.09	(0.27)
	Buyer[2]:	-0.37	(0.47)	-0.77*	(0.44)	ZP	(0.00)
	Buyer[3]:	ZP	(0.00)	ZP	(0.00)	ZP	(0.00)
	Buyer[4]:	-0.20*	(0.11)	-0.11	(0.11)	0.10	(0.25)
	Buyer[5]:	-0.38	(0.47)	-0.73*	(0.46)	ZP	(0.00)
	Buyer[6]:	ZP	(0.00)	ZP	(0.00)	ZP	(0.00)
	Seller[1]:	ZP	(0.00)	ZP	(0.00)	ZP	(0.00)
	Seller[2]:	ZP	(0.00)	0.14	(2.69)	-0.08	(0.27)
	Seller[3]:	0.63*	(0.55)	0.32	(0.48)	-0.07	(0.17)
	Efficiency:	91.84	(0.09)	94.24	(0.07)	100.00	(0.00)

ZP indicates that zero profits were earned both in the auction and in competitive equilibrium.

Summary of Policy-Relevant DA Findings

- **Market Efficiency:** Generally high (above 90%) when traders individually use Modified Roth-Erev RL **but not** when traders use Original Roth-Erev RL or GA social mimicry (***type of learning can matter***).
- **Structural Market Power:** Microstructure of the DA market is strongly predictive for the relative market power of traders (***rule details matter***).
- **Strategic Market Power:** Traders are **not** able to change their relative market power through learning (***importance of countervailing power***).

Example 2: From Standard Walrasian Equilibrium to an ACE Trading World
(www.econ.iastate.edu/tesfatsi/hbintlt.pdf)

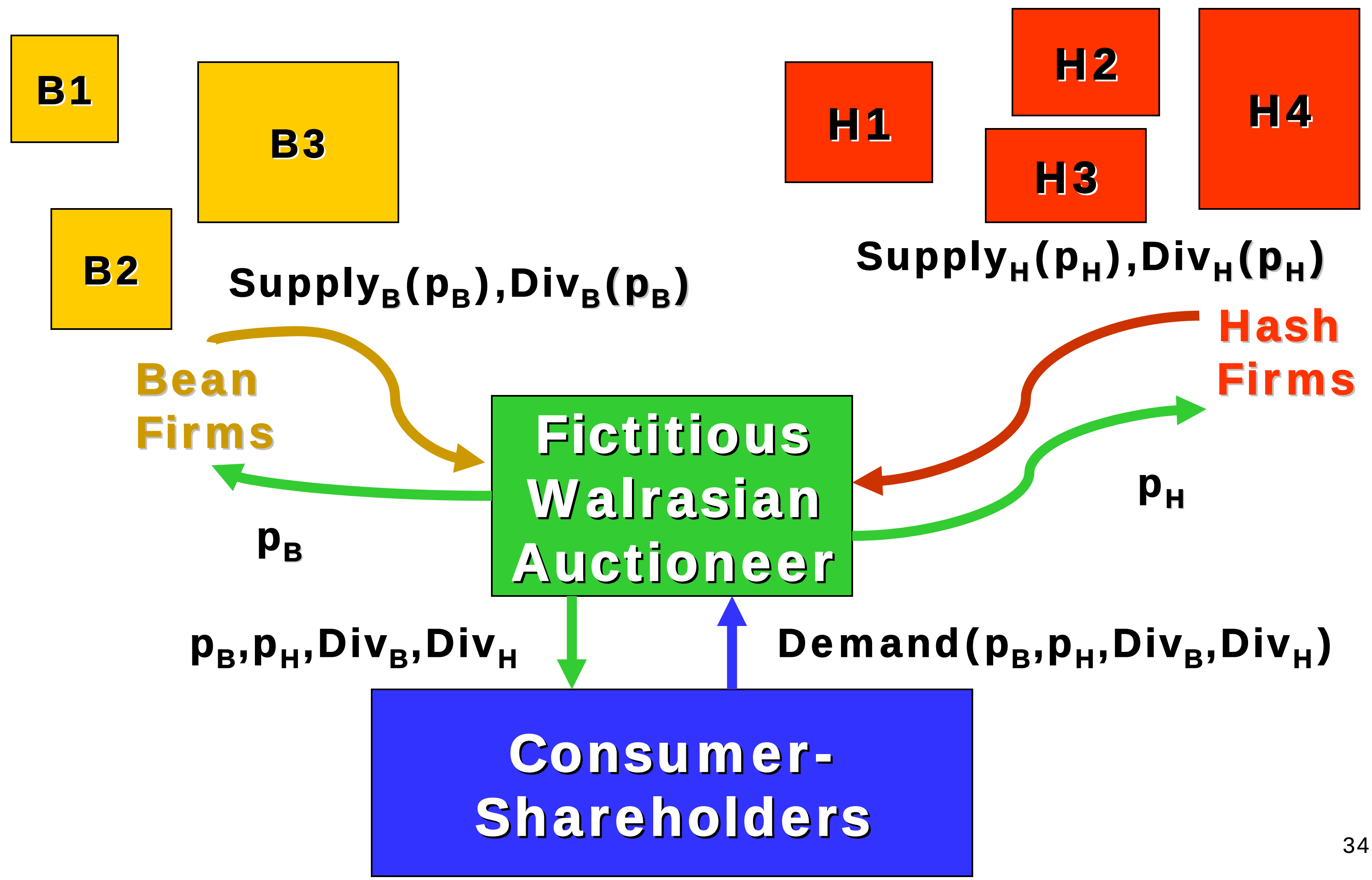
Starting Point:

Two-Sector Walrasian Equilibrium Economy

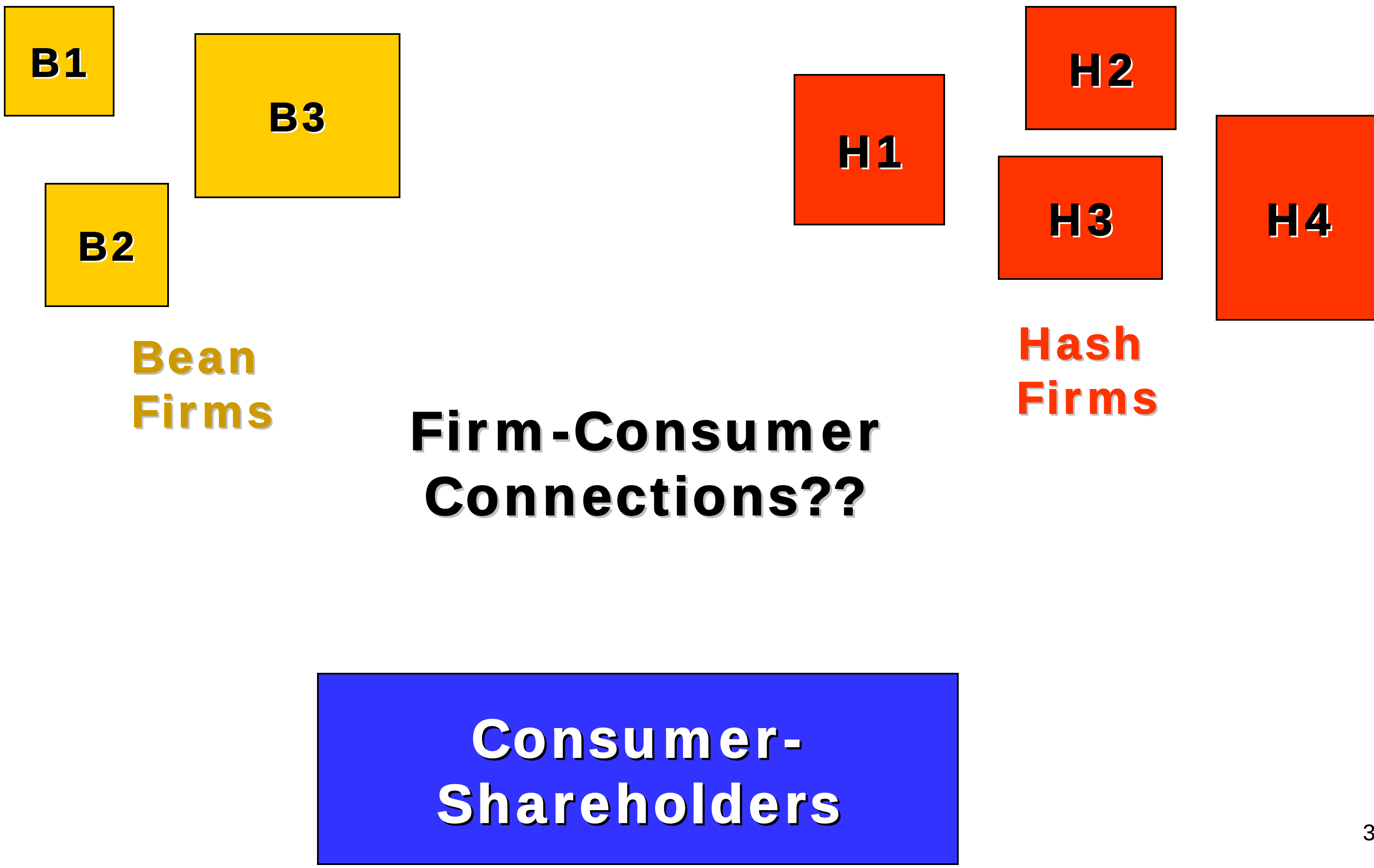
Exercise:

- **Remove** all imposed ***equilibrium*** conditions (e.g., market clearing, correct expectations,…)
- **Introduce** minimal ***agent-driven*** production, pricing, and trade processes needed to re-establish complete circular flow among firms and consumers
- **Experiment** to see if/when resulting economy is able to attain an "equilibrium" state over time

Starting Point: Simple Example of a Walrasian Equilibrium Economy



Plucking Out the Fictitious Auctioneer

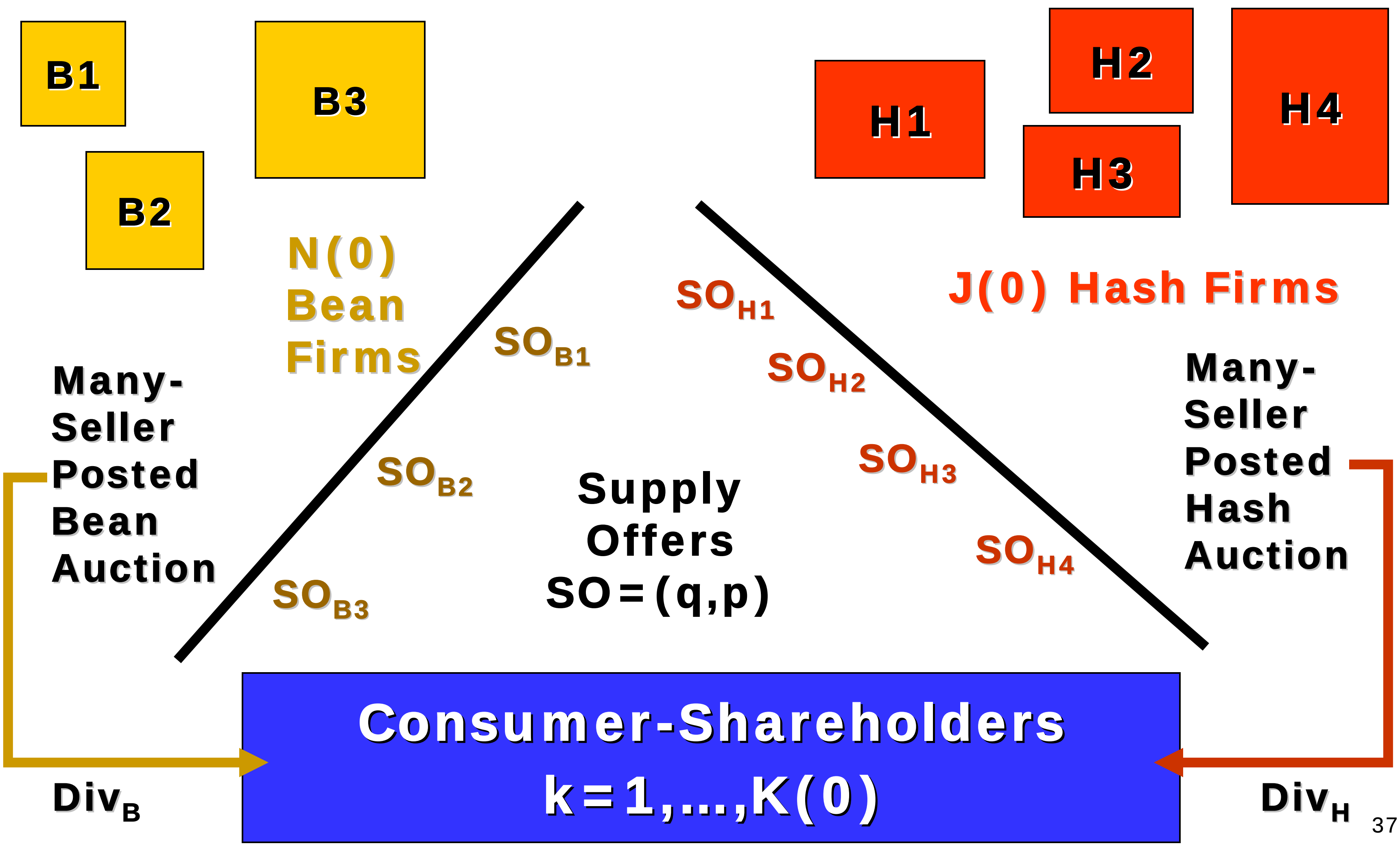


Plucking Out the Fictitious Auctioneer…

Focus must now be procurement processes

- ***Terms of Trade:*** Set production and price levels
- ***Seller-Buyer Matching:***
  - Identify potential suppliers/customers
  - Compare/evaluate opportunities
  - Submit demand bids/supply offers
  - Select suppliers/customers
  - Negotiate supplier/customer contracts
- ***Trade:*** Transactions carried out
- ***Settlement:*** Payment processing and shake-out
- ***Manage:*** Long-term supplier/customer relations

Illustrative Process Model: An ACE Hash-and-Beans Economy



Dynamic Flow of ACE H&B Economy

World Constructed. World configures Markets, Firms, Consumers and starts the clock.

↓

Firms receive time signal and post quantities/prices in H & B markets

↓

Consumers receive time signal and begin price discovery process

↓

Firms-consumers match, trade, calculate profits/utilities & update wealth levels

↓

Firms update their exp's & prod/price strategies

Dynamic Flow of Activity for H & B Firms

- Each firm f starts out (T=0) with ***money $M_f(0)$*** and a ***production capacity $Cap_f(0)$***
- Firm f's ***fixed cost $FC_f(T)$*** in each $T \geq 0$ 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, and dividend payments.

Dynamic Flow of Activity 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 ≥ 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 ≥ 0, consumer k seeks to secure maximum utility by ***searching*** for beans and hash to buy at ***lowest possible prices***.

- At end of each T ≥ 0, consumer k ***dies*** unless consumption meets subsistence needs (b_k^*, h_k^*).

Experimental Design Treatment Factors

- **Initial size of consumer sector** [K(0)]
- **Initial concentration** [N(0), J(0), Cap(0) values]
- **Firm learning** (supply offers & profit allocations)
- **Firm cost functions**
- **Firm initial money holdings** [$M_f(0)$]
- **Firm rationing protocols** (for excess demand)
- **Consumer price discovery processes**
- **Consumer money endowment profiles** (rich, poor, ↗ , ↘ , life cycle u-shape)
- **Consumer preferences** (θ values)
- **Consumer subsistence needs** (b*,h*)

The Computational World

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 gathering, storing, and sending data;

// **Private Data**

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

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

World inhabitants' methods and data.

A Computational Market

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**

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

A Computational Consumer

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 my budget constraint;
Method for searching for lowest prices.

// **Private Data**

Data about me (history, utility function, current wealth,…);
Data about external world (posted supply offers, …);
Address book (communication links).

A Computational Firm

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:

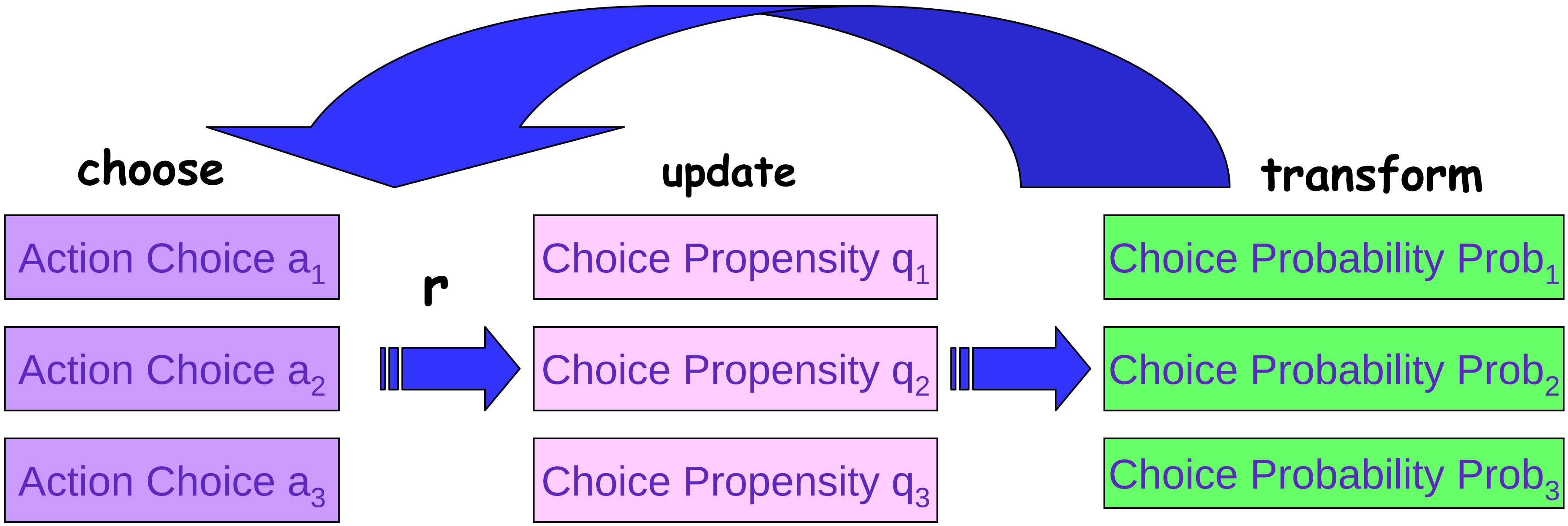
// **Private Methods**

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

// **Private Data**

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

Firms Learn to Select Supply Offers ("Actions") via Modified Roth-Erev RL



- Action choice a_k leads to profits r, followed by updating of action choice propensities q based on these profits, followed by transformation of these propensities into action choice probabilities Prob

Interesting Issues for Exploration

- Initial conditions → **carrying capacity?** (Survival of firms/consumers in long run)
- Initial conditions → **market clearing?** (Walrasian equilibrium benchmark)
- Initial conditions → **market efficiency?** (Walrasian equilibrium benchmark)
- Standard concentration measures at T=0 → **good predictors of long-run market power?**
- Importance of **learning vs. market structure** for market performance? *(Gode/Sunder, JPE, 1993)*

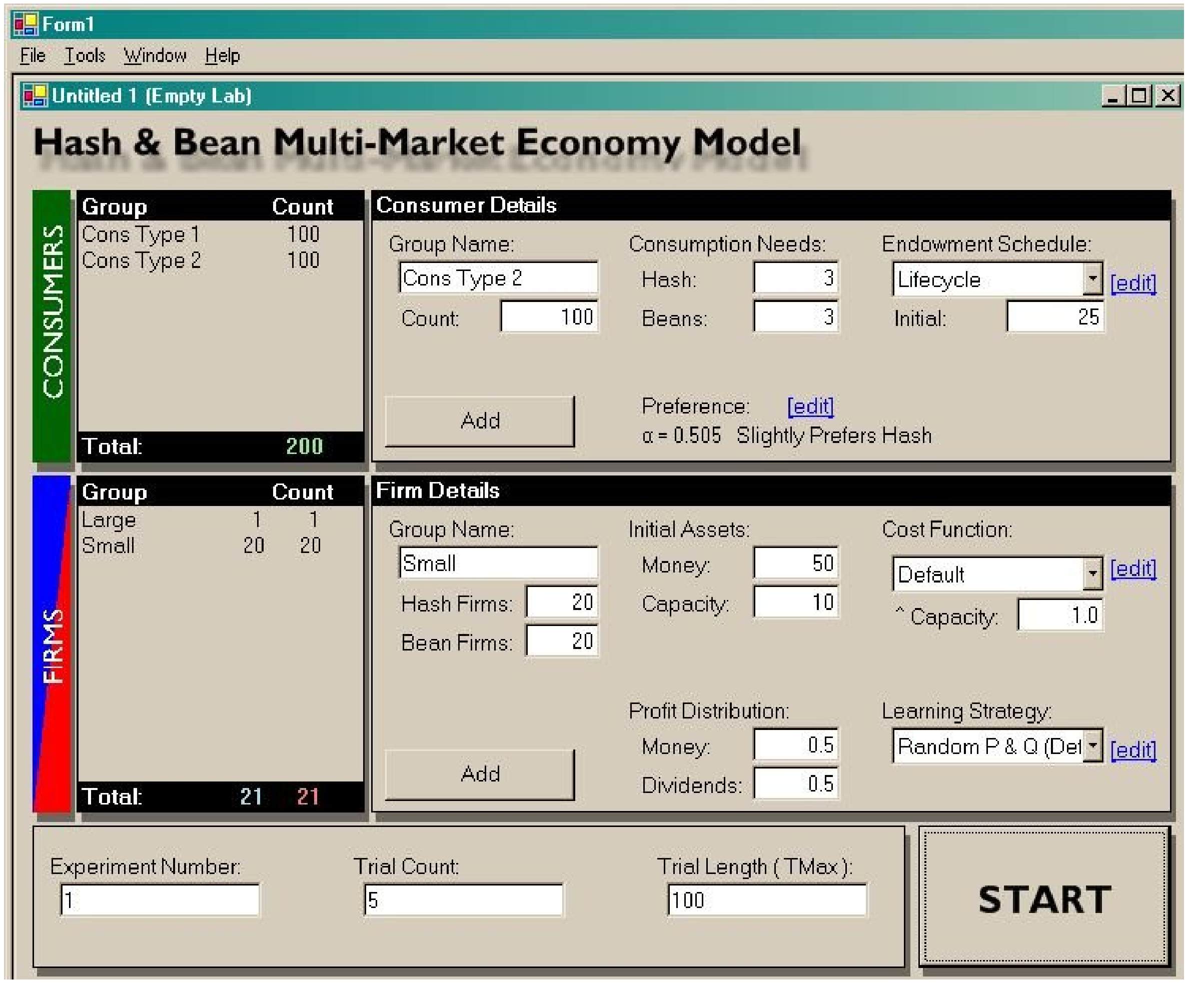
ACE Hash-and-Beans Economy: Comp Lab Implementation

Christopher Cook and Leigh Tesfatsion, **"Agent-Based Computational Laboratories for the Experimental Study of Complex Economic Systems,"** Working Paper, ISU Department of Economics, in progress.

- Computational laboratory under construction for the ACE Hash-and-Beans Economy
- Programming language C#/.Net (all WinDesktops)
- Under development for Econ 308 (ACE course)

www.econ.iastate.edu/classes/econ308/tesfatsion/

ACE Hash-and-Beans Economy: Comp Lab Main Screen



Potential Disadvantages of ACE for Social Science Modeling

- **Intensive experimentation is often needed**
  (fine sweeps of parameter ranges to attain robust findings)
- **Multi-peaked rather than central-tendency outcome distributions can arise**
  (strong path dependence possible)
- **Can be difficult to ensure platform robustness**
  (i.e., results that are independent of the hardware and/or software implementation of a model)
- **Effort needed to gain computer modeling skills can be significant** (creative computer modeling as opposed to use of existing comp labs requires good programming knowledge)

Potential Advantages of ACE for Social Science Modeling

- **Permits systematic experimental study** of empirical regularities, institutions, and dynamic behaviors of complex socio-economic systems .

- **Facilitates creative experimentation with realistically rendered economic processes:**

  - Using ACE comp labs, researchers/students can evaluate interesting conjectures of their own devising, with immediate feedback and no original programming required

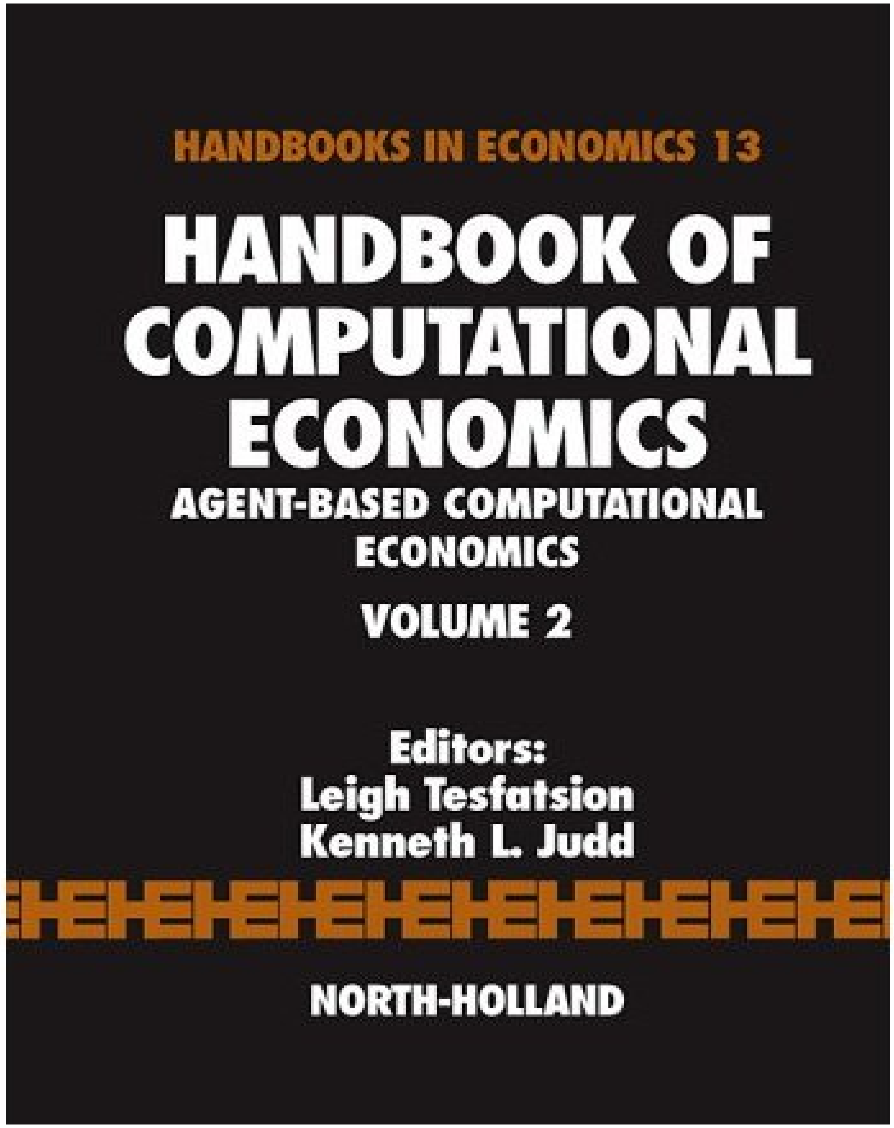
  - Modular form of ACE software permits relatively easy modification/extension of features.

BE and ACE Resources

- Colin Camerer, George Loewenstein, and Matthew Rabin, eds., **Advances in Behavioral Economics**, Princeton U Press, 2004. Preprint of Chapter 1 available:

www.econ.iastate.edu/tesfatsi/CamererIntroChapter.AdvancesBE.pdf

- Colin F. Camerer, **Behavioral Game Theory: Experiments in Strategic Interaction,** Russell Sage Foundation and Princeton University Press, 2003.
- ACE Website **www.econ.iastate.edu/tesfatsi/ace.htm**
- ACE Handbook (Leigh Tesfatsion & Kenneth L. Judd, Handbooks in Economics Series, North-Holland, 2006. **www.econ.iastate.edu/tesfatsi/hbace.htm**


HANDBOOKS IN ECONOMICS 13
HANDBOOK OF COMPUTATIONAL ECONOMICS
AGENT-BASED COMPUTATIONAL ECONOMICS
VOLUME 2
Editors:
Leigh Tesfatsion
Kenneth L. Judd
NORTH-HOLLAND

Current ACE Research Areas

(http://www.econ.iastate.edu/tesfatsi/aapplic.htm)

- Learning and embodied cognition
- Network formation
- Evolution of norms
- Specific market case studies (labor, electricity, finance…)
- Industrial organisation
- Technological change and growth
- Multiple-market economies
- Market design
- Automated markets and software agents
- Development of computational laboratories
- Experiments with real and computational agents
- Empirical validation…. ***and many more areas as well!***