# Economic Systems as Locally-Constructive Sequential Games

## The Places We Could Go!


**Leigh Tesfatsion**

Professor of Economics
Courtesy Professor of Mathematics and
Electrical & Computer Engineering
Iowa State University, Ames, Iowa 50011-1054
https://www2.econ.iastate.edu/tesfatsi/
tesfatsi@iastate.edu



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"You have brains in your head. You have feet in your shoes. You can steer yourself any direction you choose. You're on your own. And you know what you know. And YOU are the (one) who'll decide where to go…"

**From:** Dr. Seuss, 1990, *"Oh, the Places You'll Go!"*

# Outline

- What is a "locally constructive sequential game" ?
- What is **A**gent-based **C**omputational **E**conomics (**ACE** ) ?
- **The places we could go: Challenging current issues and edgier explorations**
  - Science-with-practice explorations of critical real-world systems
  - Comprehensive empirical validation
  - Standardized "Design Readiness Levels (DRLs)"
  - Spectrum of experimental approaches to the study of real-world economic systems, from 100% human to 100% agents

# Concerns All Economists Share

Real-world economic systems …

- How do they work ?
- How could they work better ?

# Real-World Economic Systems are Locally-Constructive Sequential Games

1) Heterogeneous interacting participants
2) Open-ended dynamics
3) Human participants are strategic decision-makers.
4) All participants are locally constructive, i.e., their intended actions at any given instant are determined by their own states (data, attributes, and/or methods) at this instant.
5) Actions taken by participants at each given instant affect the states of participants at subsequent instances.

# Real-World Economic Systems …

**A**gent-based **C**omputational **E**conomics (**ACE**) permits the study of real-world systems as *locally-constructive sequential games*.

# Agent-based Computational Economics (ACE)

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

**ACE** is the computational modeling of economic processes (including whole economies) as open-ended dynamic systems of interacting agents.

## Goals:

- Enable modeling of systems for which coordination is a possibility, not a modeler-imposed restriction;
- Let agents be as free to act within their virtual worlds as their empirical counterparts act within the real world.

# ACE Modeling Principles
# (MP1) – (MP7)

**(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.

# ACE Modeling Principles …

- Together, principles (MP1) through (MP7) embody the idea that an ACE model is a *computational laboratory.*
- An ACE model *permits a user to explore* how changes in initial conditions affect subsequent outcomes in modeled systems.
- This exploration process is *analogous to biological experimentation with cultures in Petri dishes*.

# Explorations of Real-World Economic Systems

ACE modeling tools can be used to

- Advance traditional economic goals
- Conduct edgier explorations

# Four Main Strands of ACE Research

1) **Empirical Understanding**
   (possible explanations for empirical regularities)

2) **Normative Design**
   (institutions, policies, regulations …)

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

4) **Method/Tool Advancement** (empirical validation, representation, visualization, presentation protocols, … )

# 1) 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 coherent explanation of several "stylized facts" in combination.
https://www2.econ.iastate.edu/tesfatsi/afinance.htm

# 2) ACE and Normative Design

**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 proposed design.
- Introduce agents with initially configured states appropriate for the purpose at hand. Let the world evolve. Observe and evaluate resulting outcomes.

***Examples:*** Design of auctions, stock exchanges, electricity markets, automated Internet markets (B2B, job markets, eBay,…), policy rules

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

# 3) ACE and Qualitative Analysis

**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.

***ACE Macro Resource Site:*** Annotated pointers to research papers, software, and research groups

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

# 4) Method/Tool Advancement

## *Example:* ACE Permits Comprehensive Empirical Validation

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

**EV1. Input Validation:** Are the exogenous inputs for the model empirically meaningful and appropriate for the purpose at hand?

> **Exogenous Inputs:** Initial state conditions, functional forms, shock realizations, data-based parameter estimates, parameter values imported from other studies, …

**EV2. Process Validation:** How well do modeled physical, biological, institutional, and social processes reflect real-world aspects important for the purpose at hand? Are all process specifications consistent with essential scaffolding constraints, such as physical laws, stock-flow relationships, and accounting identities?

# Comprehensive Empirical Validation …

**EV3. Descriptive Output Validation:**

How well are model-generated outputs able to capture the salient features of the sample data used for model identification? (**in-sample fitting**)

**EV4. Predictive Output Validation:**

How well are model-generated outputs able to forecast distributions, or distribution moments, for sample data withheld from model identification or for data acquired at a later time? (**out-of-sample forecasting**)

# Illustrative ACE Applications

- Combined game & matching models
- Labor market modeling
- Macroeconomic modeling
- Critical infrastructure modeling
- Coupled natural and human system modeling

# Decision-making agents in ACE models can …

- Talk back and forth with each other
- Choose and refuse whom they interact with
- Behave strategically with selected partners
- Evolve their behavioral strategies over time

→ Game Theory + Matching Theory

***Examples:***

***1)*** L. Tesfatsion, "Structure, Behavior, and Market Power in an Evolutionary Labor Market with Adaptive Search, *Journal of Economic Dynamics and Control,* 25(1), 2001, 419-457

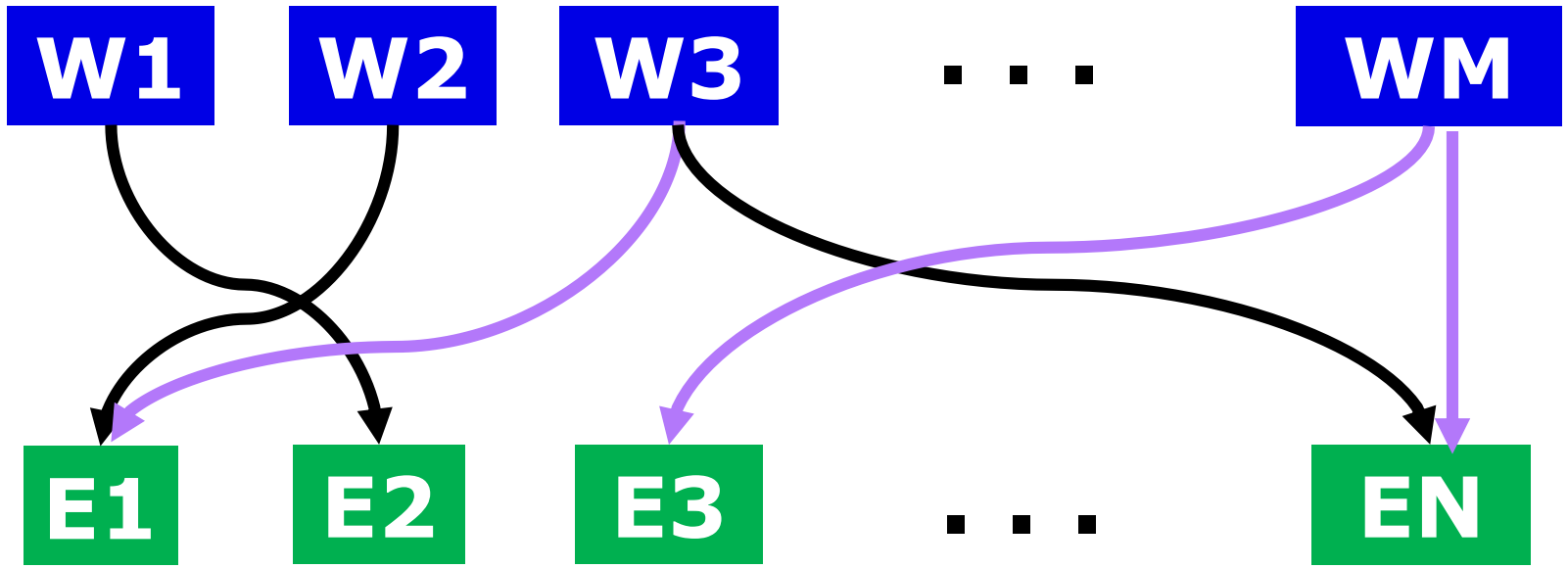
https://www2.econ.iastate.edu/tesfatsi/StructBehMPLabor.JEDC01.LT.pdf

***2)*** The Trade Network Game Laboratory: Homepage

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

# ACE Labor Market Study (Tesfatsion, *JEDC*, 2001)

## Worker-Employer Network Formation Game




**Job search with preferential choice & refusal of worksite partners**

**Purple arrow = Refused work offer; Black arrow = Accepted work offer.**

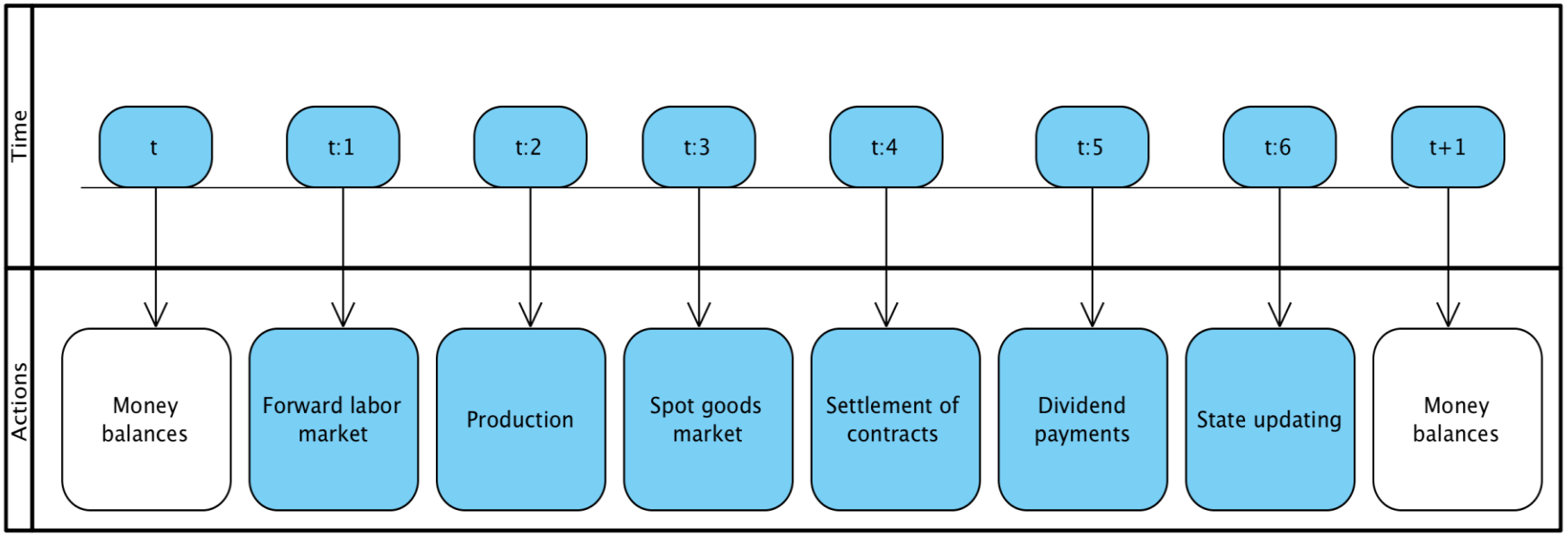
Matched traders play worksite games. Workers use genetic algorithms (GAs) to evolve their game strategies. Hiring, quits, and firings are *endogenously* determined in each work period.

# ACE Macroeconomic Studies

## DSGL = DSGE + Learning Agents

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

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




Sequence of Activities During a Typical Period t

- Consumers and firms have intertemporal utility/profit maximization goals
- Four locally-constructive decision methods are tested for consumers and 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)

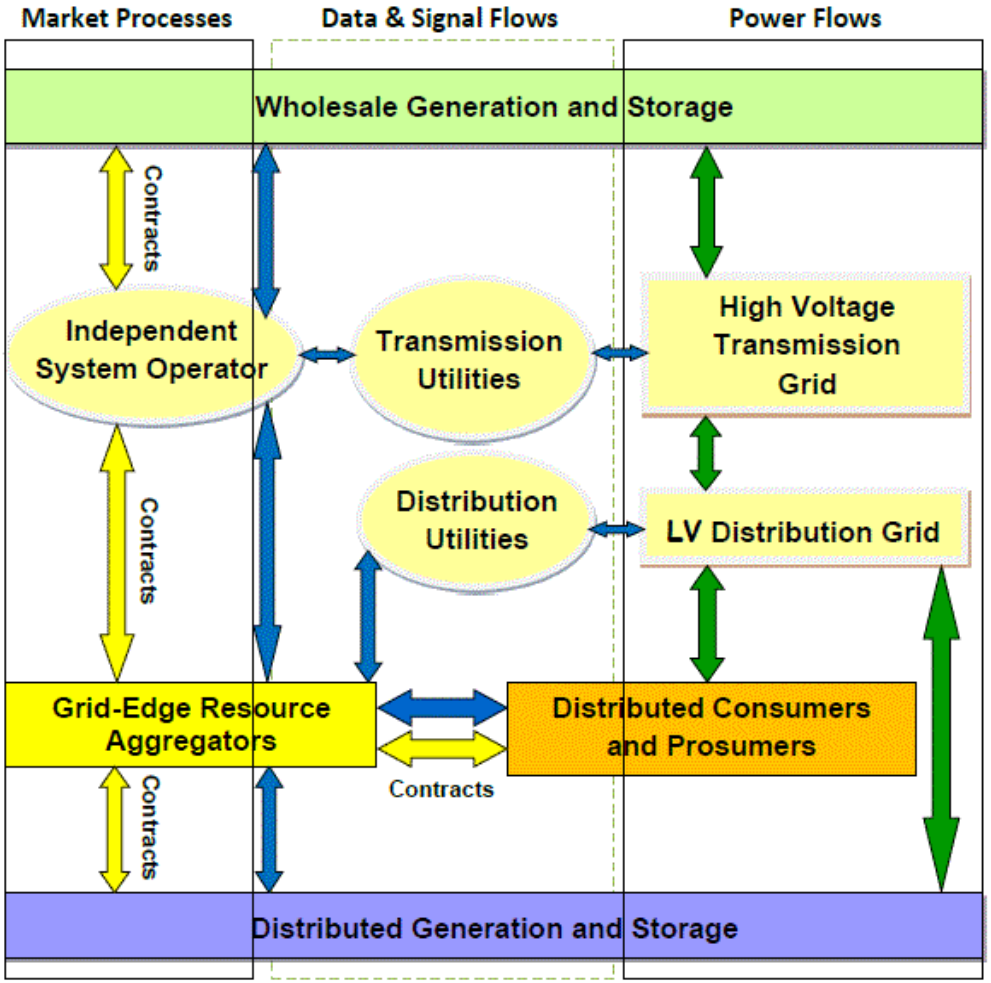
- Good performance requires decision-makers to engage both in the exploitation of their current information and in searches for new information.

- Simpler decision rules with some degree of anticipatory learning can outperform more sophisticated decision rules.

- **Best performance is attained** when all consumers and firms use **rolling fixed-horizon (EO-FH) decision rules.** This decision-rule configuration for firms and consumers is
  - ***Pareto efficient***
  - ***A Nash equilibrium***

# ACE Electric Power Market Studies

L. Tesfatsion, **"Electric Power Markets in Transition: Agent-Based Modeling Tools for Transactive Energy Support,"** Ch. 13 (pp. 715-766) in C. Hommes & B. LeBaron (Eds.), Handbook of Computational Economics IV, Elsevier, 2018, https://www2.econ.iastate.edu/tesfatsi/ElectricPowerMarketDesign.TESHandbookChapter.LTesfatsion.pdf

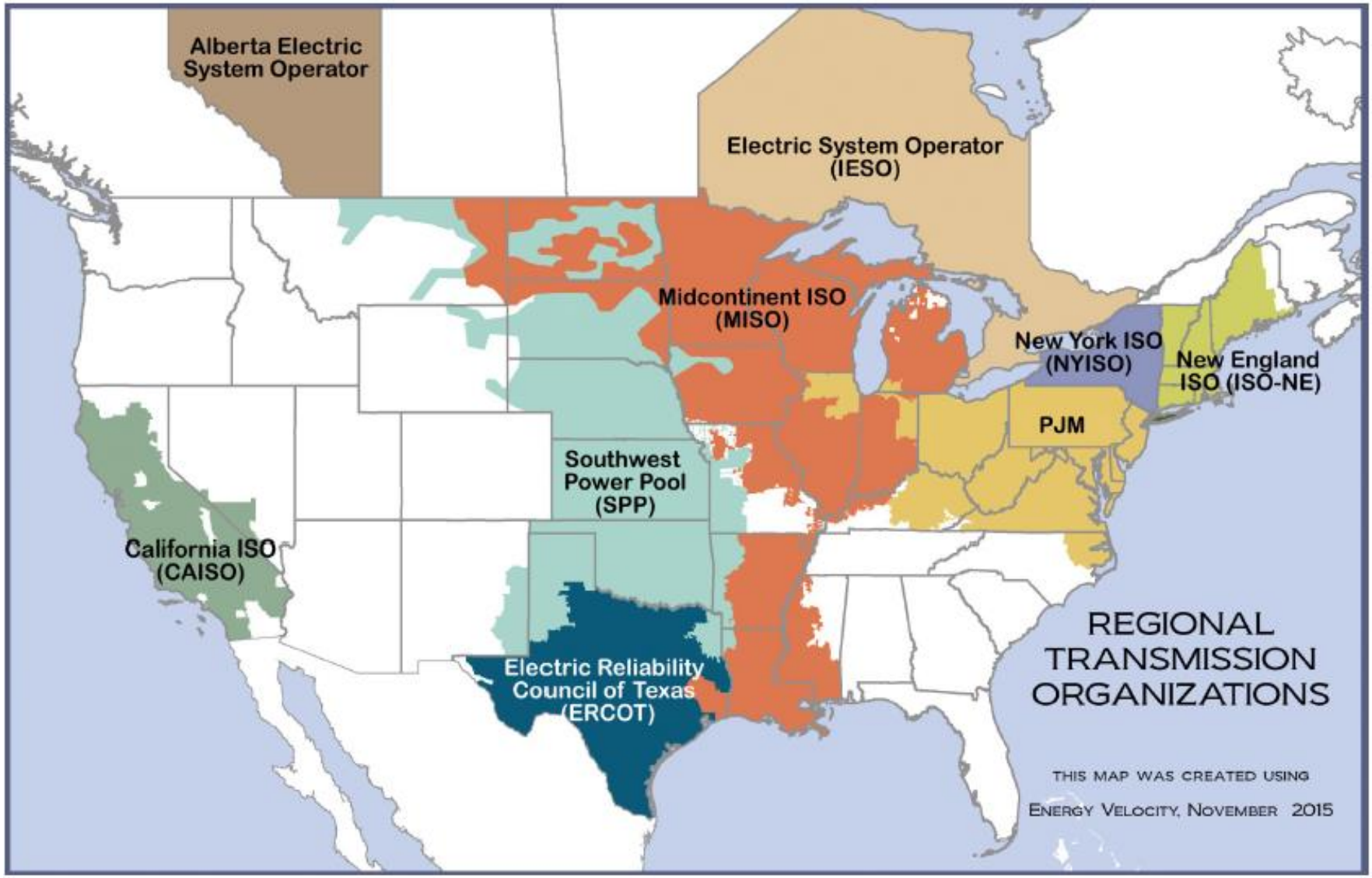



**ACE models** can be used ***to represent*** real-world electric power markets

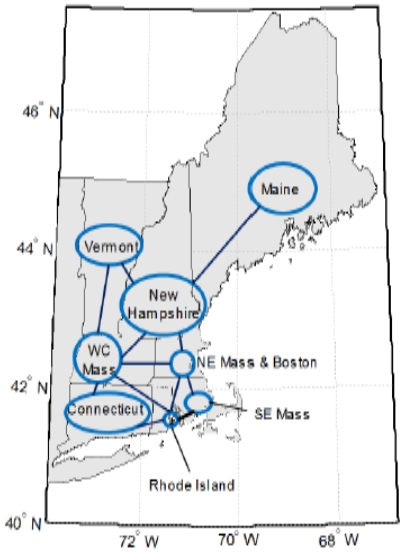
**PLUS**

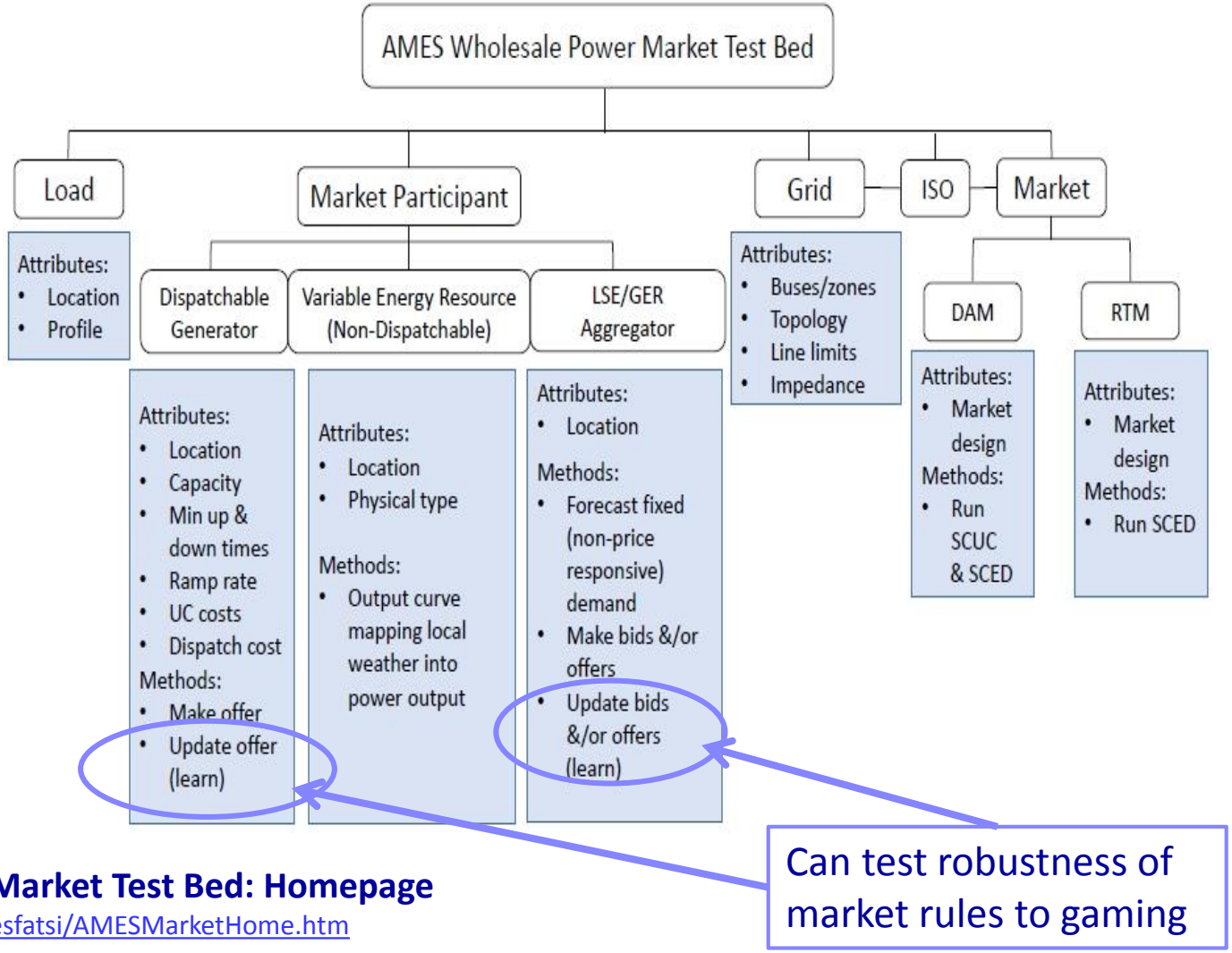
**ACE modeling principles** can be used ***to design*** electric power markets for real-world implementation

# North American Centrally-Managed Wholesale Electric Power Markets



# *Example:* **AMES** = **A**gent-based **M**odeling of **E**lectricity **S**ystems




**AMES Wholesale Power Market Test Bed: Homepage**
https://www2.econ.iastate.edu/tesfatsi/AMESMarketHome.htm

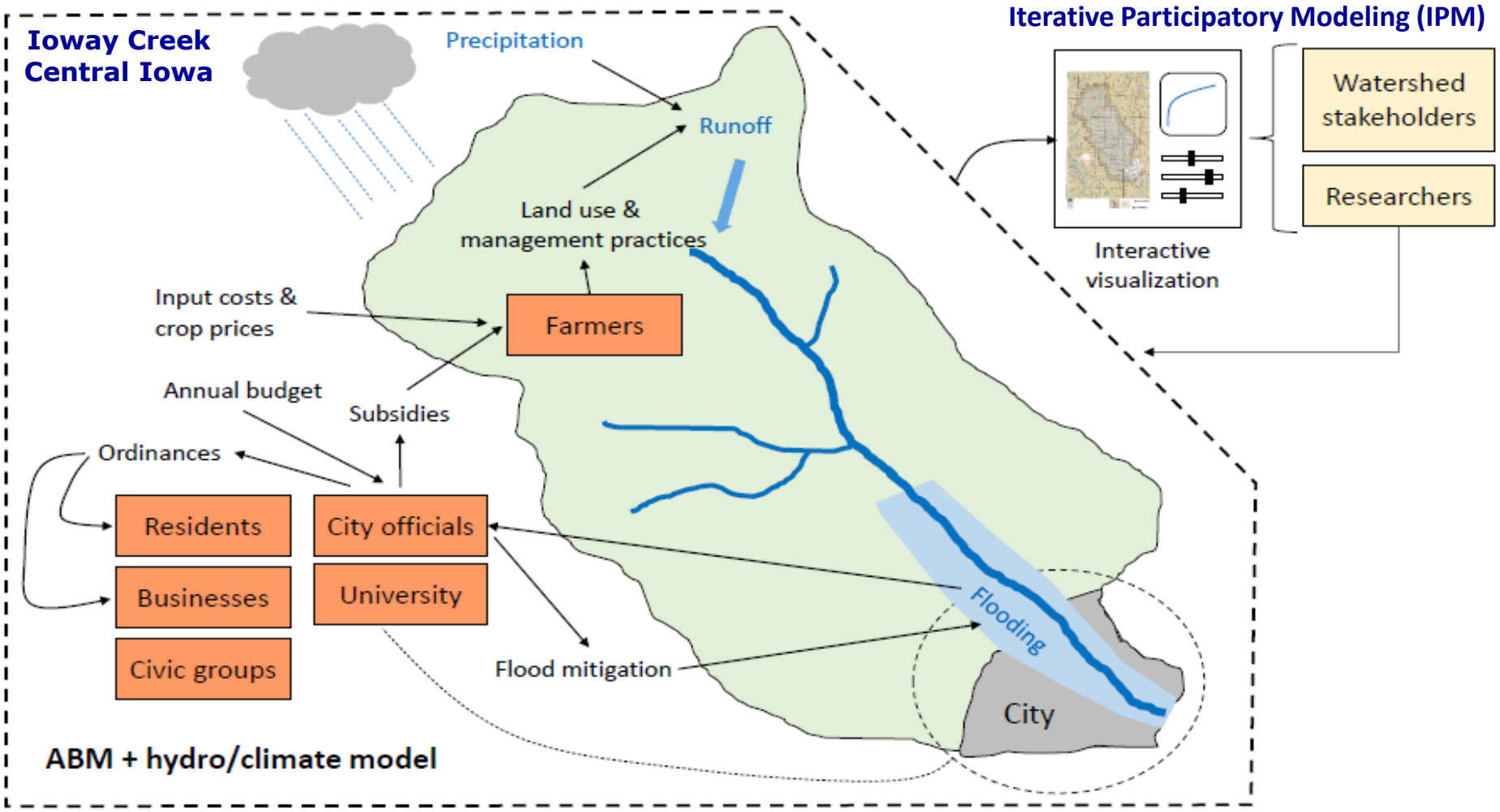
D. Krishnamurthy, W. Li, and L. Tesfatsion, **An 8-Zone Test System based on ISO New England Data: Development and Application**, *IEEE Transactions on Power Systems* 31(1), 2016, 234-246.
https://www2.econ.iastate.edu/tesfatsi/8ZoneISONETestSystem.RevisedAppendix.pdf

# ACE Studies of Coupled Natural and Human Systems

- ACE permits modeling of economic processes as critical components of **Coupled Natural & Human (CNH) systems**
- CNH systems can be dynamic & spatial

→ **Broader ranges of possibly-correlated causal factors can be <u>jointly</u> considered**

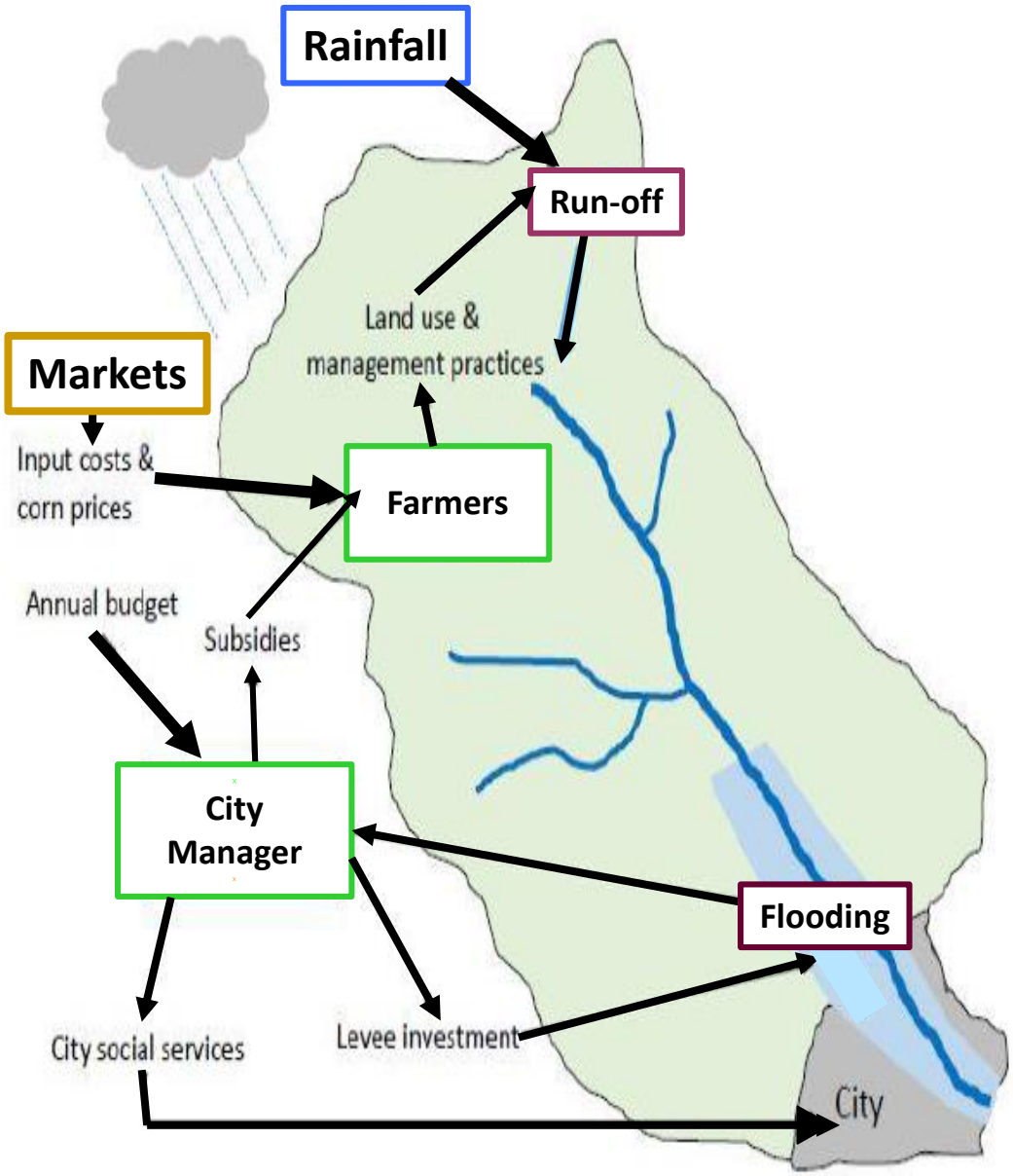
# *Example:* ACE Watershed Local Governance Study




L. Tesfatsion, C.R. Rehmann, D.S. Garcia, Y. Jie, and W.J. Gutowski, **An Agent-Based Platform for the Study of Watersheds as Coupled Natural and Human Systems,** *Environmental Modelling & Software,* Vol. 89 (March), 2017, pp. 40-60

https://www2.econ.iastate.edu/tesfatsi/WACCShedPlatform.RevisedWP15022.pdf

# ACE Watershed World:




## Decision-Making "Human" Agents

**Corn Farmers** (annual allocation of land, corn planting & harvesting, and consumption & savings);

**City Manager** (annual allocation of budget, Farmer subsidy payouts).

## Physical Agents (Data Driven)

**Basin** (population, land attributes, …)

**Climate** (20-year hourly rainfall pattern)

**Hydrology** (HEC-HMS, Feldman et al. 2000)

Maps farmer land allocations
+ land attributes (e.g., curve numbers)
+ rainfall (hourly depth in inches)

→ Water discharge rate into city (which affects extent of city flood damage)

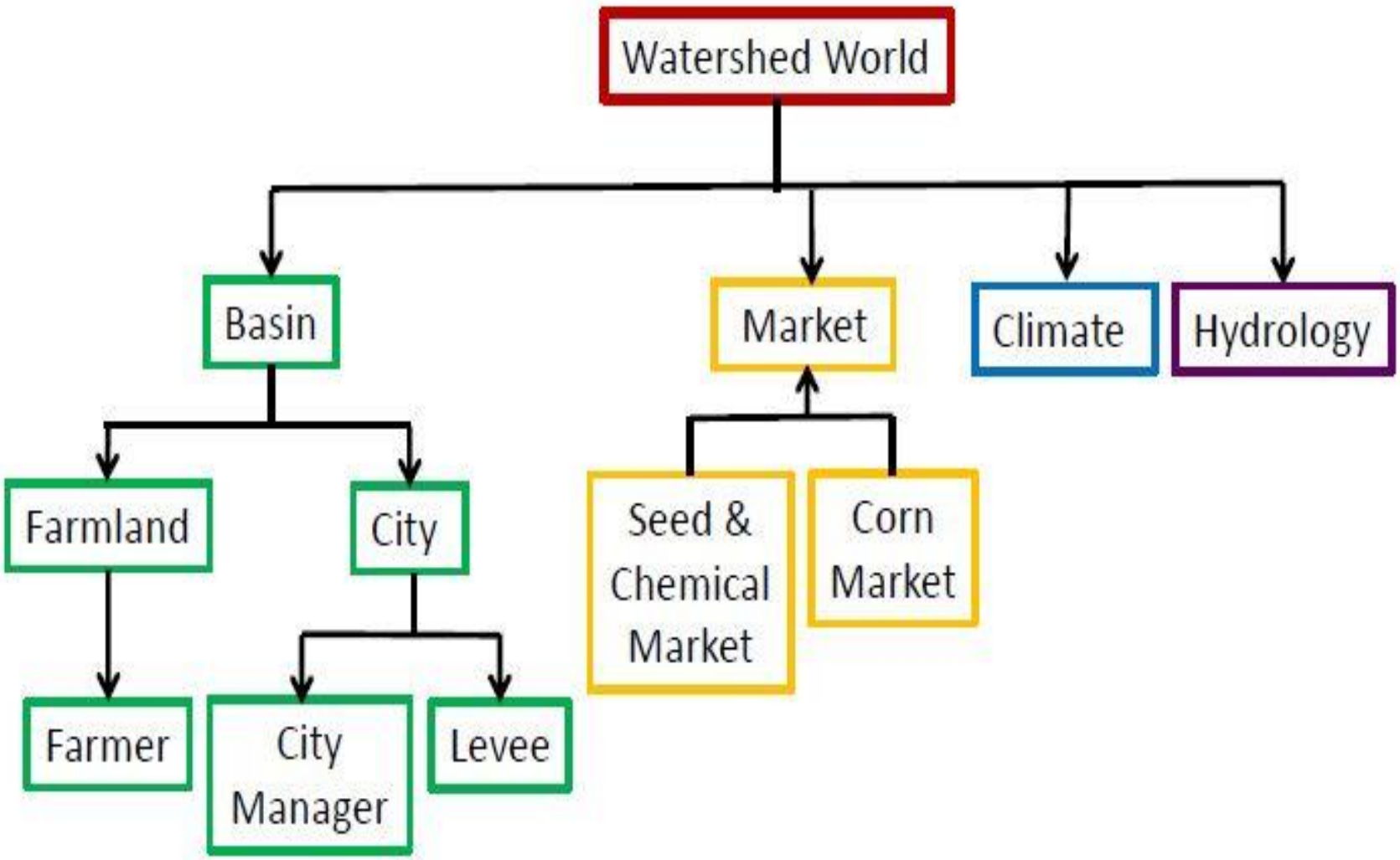
## Institutional Agents (Data Driven)

**Markets** (cost/price data)

→ Annual input planting cost ($/acre) and retail corn price ($/bushel).

# Agent Taxonomy for the ACE Watershed World

depicting “has a” (down-arrow) and “is a” (up-arrow) relations



# Standardized Design Readiness Levels (DRLs)

**DRL-1:** Conceptual design idea

**DRL-2:** Analytic formulation

**DRL-3:** Low-fidelity model

Basic research carried out at universities...

**DRL-4:** Moderate-fidelity small-scale model

**DRL-5:** High-fidelity small-scale model

**DRL-6:** Prototype small-scale model

**Infamous "Valley of Death"**

**DRL-7:** Prototype large-scale model

**DRL-8:** Field study

**DRL-9:** Real-world implementation

Industry, government, regulatory agencies

# ACE Can Help Bridge the "Valley of Death" (DRLs 4-6)

- Infrequency of studies within the "Valley of Death" (DRLs 4-6) hinders development of designs:

  ***Concept*** → ***Implementation***

- ACE is well suited for bridging this valley

- ACE computational platforms permit design performance testing at DRLs 4-6

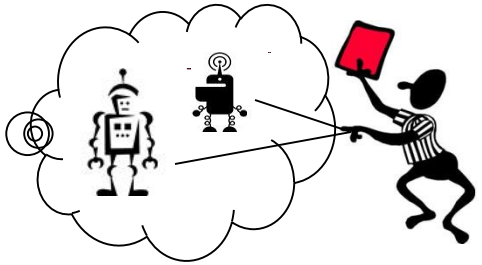
- ***Proof-of-Concept:*** Electricity market research

# ACE is a Limit Point for a Spectrum of Possible Experiment-Based Modeling Methods

100% human

Humans with computer access

Human-controlled computer avatars

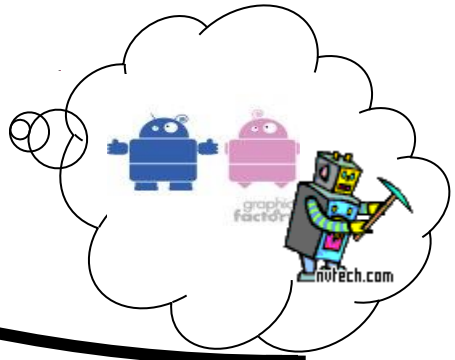


Tethered

Not Tethered

Mix of humans and computer agents

Human-calibrated computer agents



Computer agents with real-world data streaming

100% computer agents evolved from initial conditions (ACE)

# Conclusion

- **A**gent-based **C**omputational **E**conomics (**ACE**) is a useful addition to toolkits of economists studying real-world systems.
- ACE modeling principles have been designed to permit logical rigor, flexibility with regard to choice of model simplifications, and clarity of presentation.
- **But much remains to be done:**

  Empirical validation, Design Readiness Levels (DRLs), presentation protocols, edgier explorations demonstrating value-added for big-time applications, "valley of death" support for design development from concept to practice, …

# On-Line ACE Resource Sites

- **ACE Website: Homepage**

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

- **Online Guide for Newcomers to Agent-Based Modeling**

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

- **Main Background Paper:** L. Tesfatsion (2017), "Modeling Economic Systems as Locally-Constructive Sequential Games," *Journal of Economic Methodology*, Volume 24, Issue 4, pp. 384-409.
  https://lib.dr.iastate.edu/econ_workingpapers/23