Introductory Notes on Agent-Based Modeling, Agent-Oriented Programming, & AMES

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https://www2.econ.iastate.edu/tesfatsi/ABMAOPAMES.LT.pdf

Outline

- What is Agent-Based Modeling (ABM)?
- What is Object-Oriented Programming (OOP)?
- Agent-Oriented Programming (AOP) vs. OOP
- ABM via Computational Laboratories
- **Example:**
  AMES Wholesale Power Market Testbed

What is ABM?

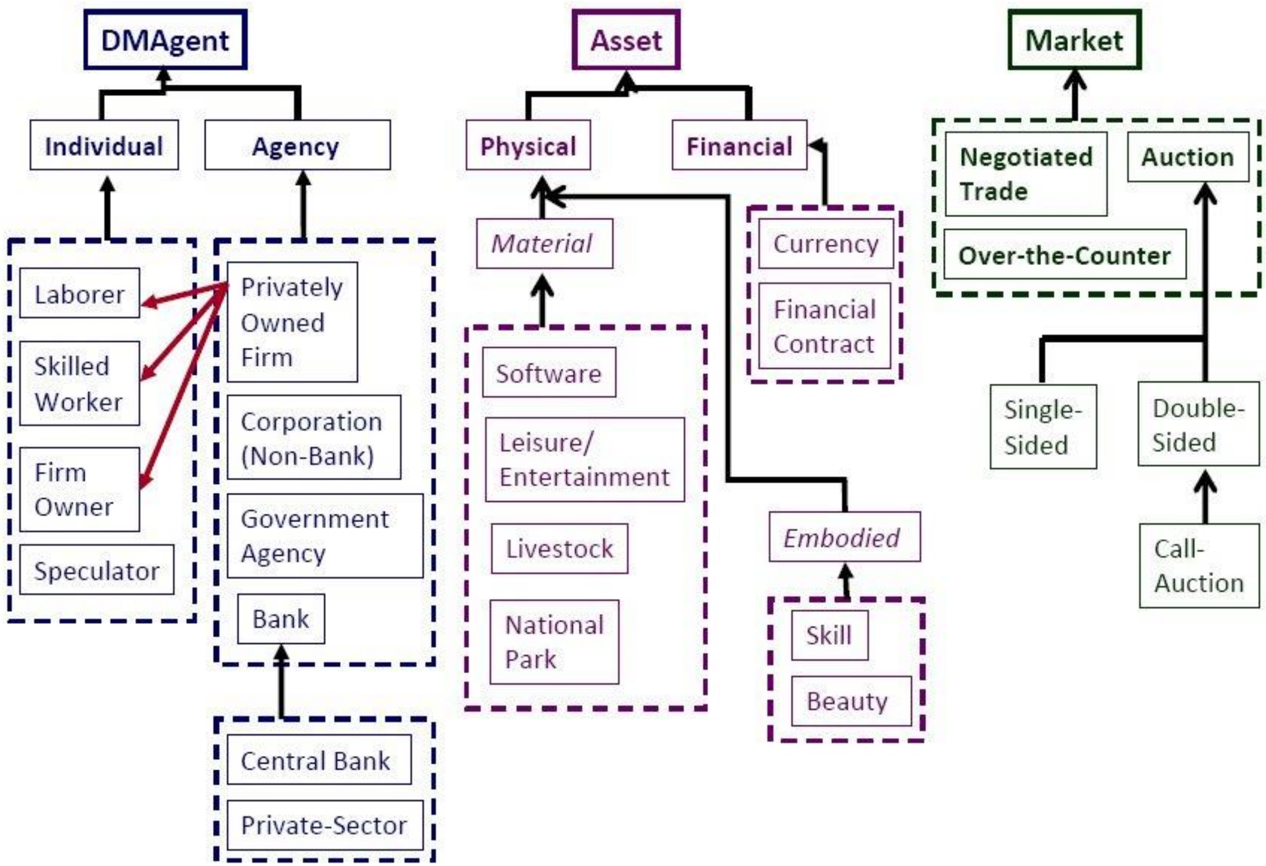
- Classical Approach (Top Down): Model a system by means of parameterized differential equations
  - *Example: Archimedes*, a large-scale system of ODEs modeling pathways of disease spread under alternative possible health care response systems
- ABM Approach (Bottom Up): Model a system as a collection of interacting "agents"
  - Each agent is an entity encapsulating data together with methods that act on this data
  - Global regularities arise from the interactions of distributed agents

Meaning of “Agent” in ABM

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

- 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,…)

Partial depiction of agents for a macroeconomic ABM with "is a" ↑ and "has a" ↓ relations



Meaning of "Agent" in ABM … Continued

Decision-making agents (DMAgents) are capable (in different 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 as well as on external data streams (including from real world)

Importance of Agent Encapsulation

- In the real world, all calculations must be done by entities actually residing in the world.
- ABM forces modelers to respect this constraint.
- Procedures encapsulated into the methods of a particular agent can only be implemented using the particular resources available to that agent.
- This encapsulation achieves a more transparent and realistic representation of real-world systems composed of interacting distributed entities with limited information and computational capabilities.

Constructive Replacement

In principle, as a result of agent encapsulation:

- **Any decision-making agent** interacting within an ABM through a particular input-output public interface can be replaced by a person that interacts with the ABM through this same public interface.

- Since method *implementations* by the decision-making agent and its human replacement need not be the same, the resulting outcomes under replacement could differ.

- The only claim here is the *feasibility* of replacement due to the imposition of agent boundaries in ABMs.

Role of Equations

- Any agent in an ABM can have data and/or methods involving equations.
- These equations can be the basis in part or in whole for the agent's actions.
- ABM world events are driven solely by the **actions** undertaken by the ABM agents within their world.
- ABM world events are ***not*** driven by equations existing ***outside*** of the data and methods of agents. For example, "sky hook" equilibrium conditions are not permitted.

ABM and Institutional Design

Key Issues:

- Will a proposed or actual design promote **efficient, fair, and orderly social outcomes over time**?
- Will the design give rise to **unintended consequences**?

ABM Culture-Dish Approach:

- **Develop a computational world** embodying the design, physical constraints, strategic participants, …
- Set initial world conditions (agent states).
- **Let the world evolve** with no further intervention, and observe and evaluate the resulting outcomes.

Agent-Based Test Bed Development via Iterative Participatory Modeling

- Stakeholders and researchers from multiple disciplines join together in a **repeated looping through four stages of analysis**:

1) Field work and data collection
2) Role-playing games/human-subject experiments
3) Incorporate findings into agent-based test bed
4) Generate hypotheses through intensive computational experiments.

Object-Oriented Programming

The Basic OOP Mindset: Top Down

"One of the best ways to think about objects is as `service providers.' Your goal is to produce…a set of objects that provides the ideal services to solve your problem."

– Bruce Eckel, *Thinking in Java*, 3rd Ed., Prentice Hall, 2003, p. 37.

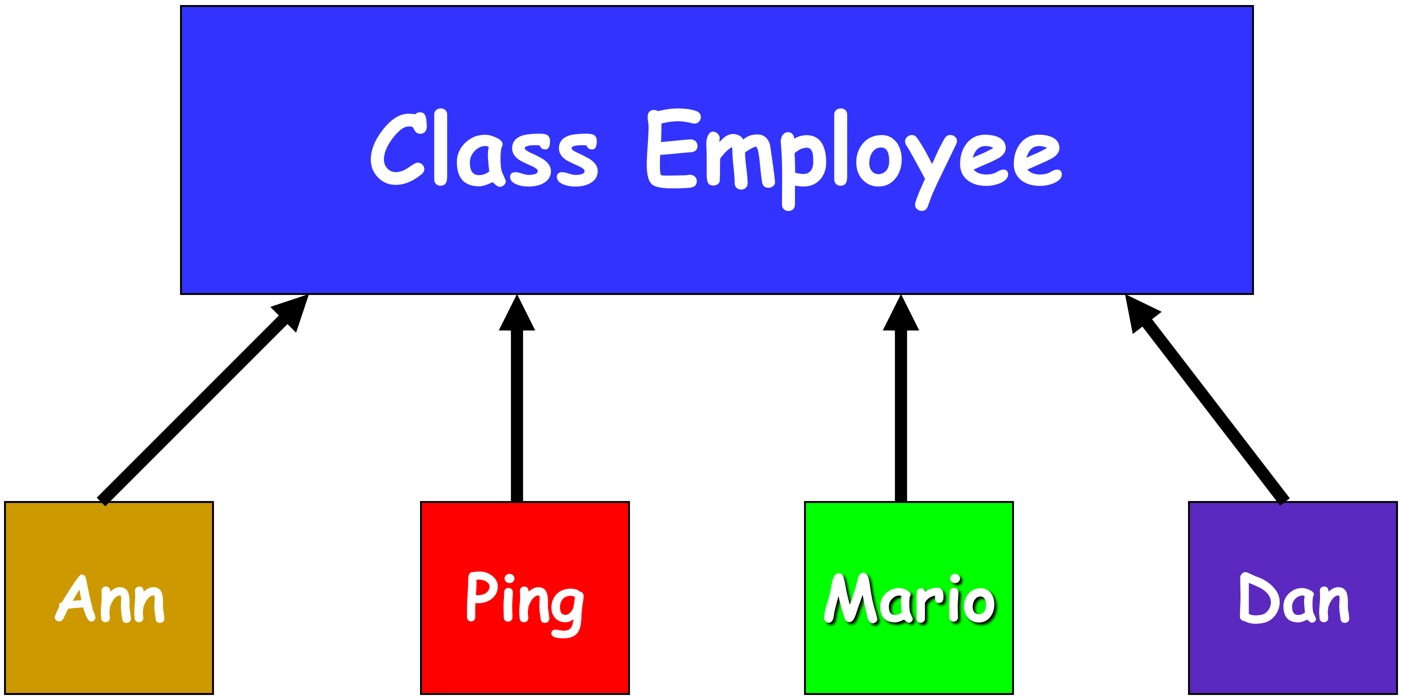
OOP: Key Concepts

- **Object**
  - Methods (operations, functions, procedures,...)
  - Data (attributes, state information,...)
  - Access (public, private, or protected)
- **Class**
- **Interface**
- **Encapsulation**
- **Inheritance (subclass, superclass)**
- **Composition**

OOP: Key Concepts … Continued

- An ***object*** is a software entity that bundles together ***data*** plus ***methods*** that act on these data
- An object controls ***access*** to its data and methods by declaring them
  - public (accessible to all other objects);
  - private (inaccessible to all other objects);
  - or protected (accessible only to certain designated other objects).
- A ***class*** is a blueprint for an object, a template used to create ("instantiate") an object.

Class = Object Template



Employee Objects (Instances of Employee)

Illustration: Employee Class

Class **EMPLOYEE**

{

Public Access:

Methods:

getSocialSecurityNumber( ) ;

getGender( ) ;

getDateOfBirth( ) ;

Private Access:

Data:

SocialSecurityNumber ;

Gender ;

DateOfBirth ;

Trustworthyness ;

}

OOP: Key Concepts … Continued

- The public methods and public data of an object are called its ***(public) interface***.
- Objects ***communicate*** with each other by activating ("invoking") the public methods of other objects.

OOP: Key Concepts … Continued

- In "good" OOP design, an object should only reveal to other objects what these objects need to know to interact with it.
- Each class specifies interfaces for its instantiated objects
  - Describes how users of these instantiated objects can interact with these instantiated objects.

Illustration: Employee Class

```
Class EMPLOYEE
{
 Public Access:
   Methods:
      getSocialSecurityNumber( ) ;
      getGender( ) ;
      getDateOfBirth( ) ;
 Private Access:
   Data:
      SocialSecurityNumber ;
      Gender ;
      DateOfBirth ;
      Trustworthyness ;
}
```

Illustration: Payroll Class
(invokes public methods in Employee class)

```
Class  PAYROLL
{
 Public Access:
  Methods:
    calculateEmployeePay( );
    payEmployee( );
    Employee.getSocialSecurityNumber( );
    Employee.getGender( );
    Employee.getDateOfBirth( );

Private Access:
 Data:
   CurrentProfits;
   EmployeePayoll;
}
```

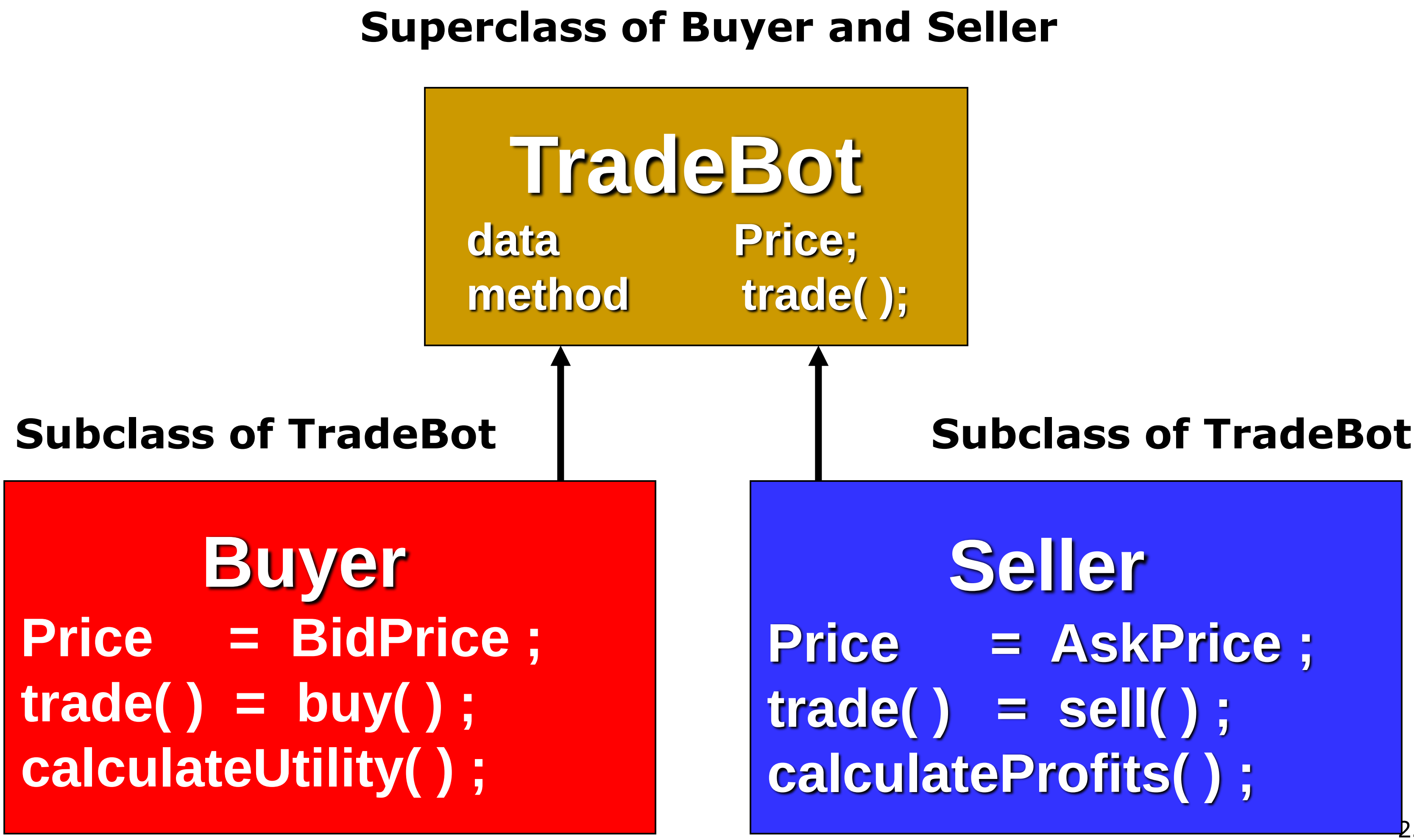
OOP Encapsulation

- *Encapsulation* is the process of determining which aspects of a class are not needed by other classes, and hiding these aspects from other classes.
- More precisely, encapsulation is the process of dividing a class into two distinct parts:
  - (public) interface;
  - private (or protected) stuff that other classes do not need to know about.

Class Inheritance

- A class C can ***inherit*** the data and methods of another class B.
- The class C is then called the ***subclass*** of class B, and class B is called the ***superclass*** of class C.
- A subclass can also include specialized data and methods that are not present in the superclass.

Class Inheritance: Example



Composition vs. Inheritance

- Objects can be built, or "composed", from other objects. This is called ***composition***.

  Example: A firm is composed of employees.

- A ***composition*** relationship between objects is often termed a ***"Has-A" relationship***. A firm "has an" employee.
- An ***inheritance relationship*** between objects is often termed an ***"Is-A" relationship***. A buyer "is a" trader.

Agent-Oriented Programming (AOP) vs. Conventional OOP

- What is an ***agent*** in AOP?
- How does an AOP agent *potentially extend* conventional OOP objects?

What is an *Agent* in AOP?

AOP agent is an object *potentially* capable of ...

- **(Structural) Reactivity:** Changes in internal structure in response to environmental changes
- **Social Ability:** Interaction with other agents through some form of language.
- **Pro-Activity:** Goal-directed actions.
- **Autonomy:** Some degree of control over its own actions ("self-activation").

AOR Agents vs. OOP Objects

- Key distinction is autonomy of AOR Agents
- AOR agents can potentially exercise distributed control, not simply distributed action.
- Conventional OOP objects encapsulate data and methods but do not permit either self-activation or local action choice.

Cf. N. R. Jennings, *Artificial Intelligence*, Vol. 17 (2000), pp. 277-296

Autonomy means...

- Each agent effectively has its own persistent thread of control.
- Each agent decides which actions to perform when, based partly on external conditions ***and partly on private internal aspects*** (private info, beliefs, desires,…).
- Thus, each agent is imperfect predictable from vantage point of other agents due to ***behavioral uncertainty***.

ABM via Comp Laboratories

- ***Computational Laboratory*** = Computational framework for the study of system behaviors by means of controlled & replicable experiments.
- ***Graphical User Interface (GUI)*** permits experimentation by users with no programming background.
- ***Modular/extensible form*** permits framework capabilities to be changed/extended by users who have programming background.

Illustrative Example:

AMES Wholesale Power Market Test Bed

Project Director: **Dr. Leigh Tesfatsion** (Prof of Econ, Courtesy Prof. of Math & ECpE)

Research Assoc: **Dr. Junjie Sun** (Fin. Econ, OCC, U.S. Treasury, Wash, D.C.)

Research Assoc: **Dr. Hongyan Li** (Consulting Eng., ABB, North Carolina)

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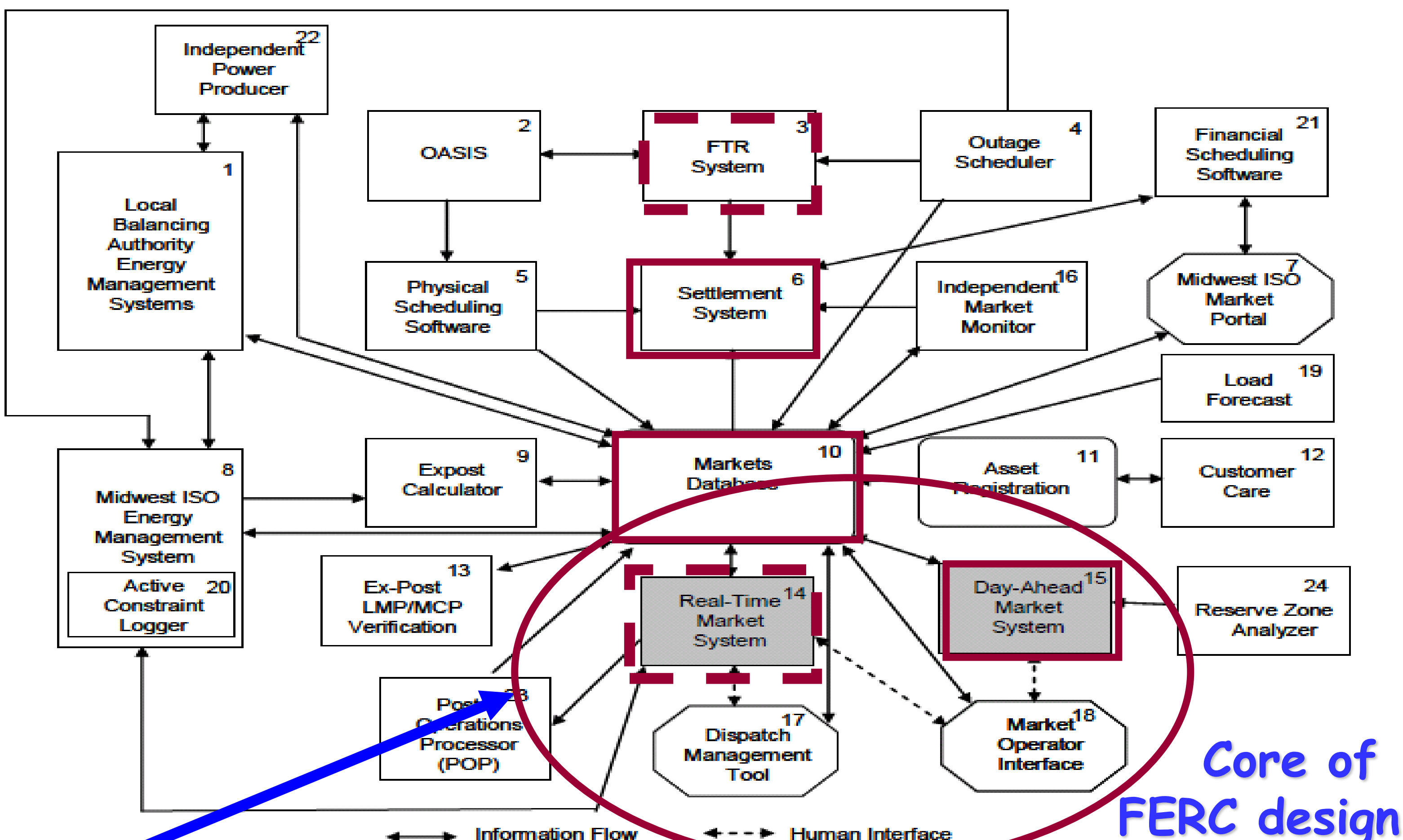
AMES Wholesale Power Market Test Bed Homepage (Code/Manuals/Pubs):
https://www2.econ.iastate.edu/tesfatsi/AMESMarketHome.htm

AMES (V2.05) Wholesale Power Market Testbed

- **Traders**
  - GenCos (sellers)
  - LSEs (buyers)
  - **Learning** capabilities
- **Independent System Operator (ISO)**
  - System reliability assessments
  - Day-ahead scheduling via **bid/offer based optimal power flow (OPF)**
  - Real-time dispatch
- **Two-settlement system**
  - Day-ahead market (double auction, financial contracts)
  - Real-time market (settlement of differences)
- **AC transmission grid**
  - **Generation Companies (GenCos)** & **Load-Serving Entities (LSEs)** located at user-specified transmission buses
  - Grid congestion managed via **Locational Marginal Prices (LMPs)**
  - **LMP at bus k** = Least cost of servicing one additional MW of power at bus k.

Based on MISO Market Organization
Business Practices Manual 001-r1 (1/6/09)

Exhibit 2-3: DART Components Overview



Two-Settlement Power Market System under LMP

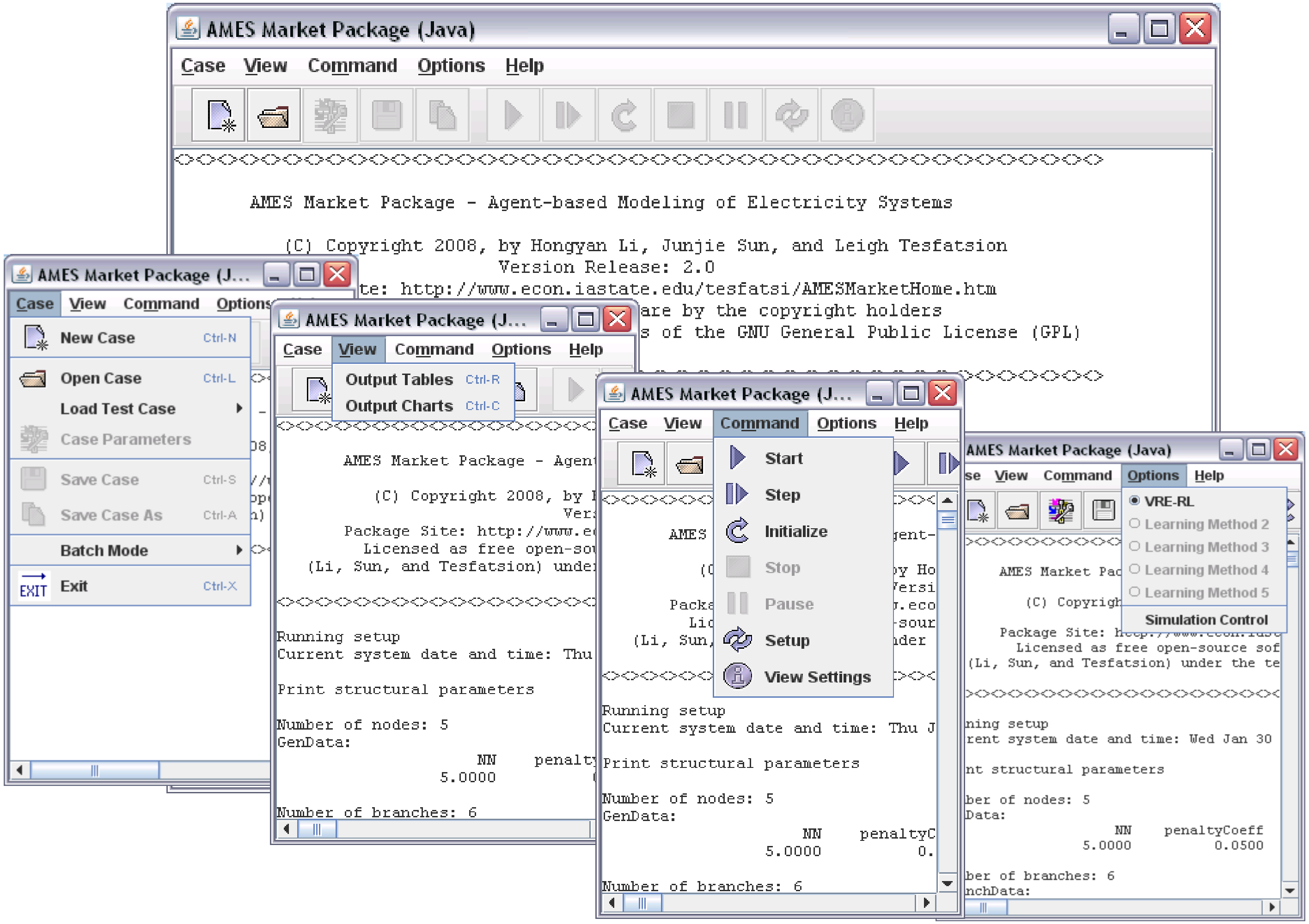
AMES project to date

AMES Modular & Extensible Architecture (Java)

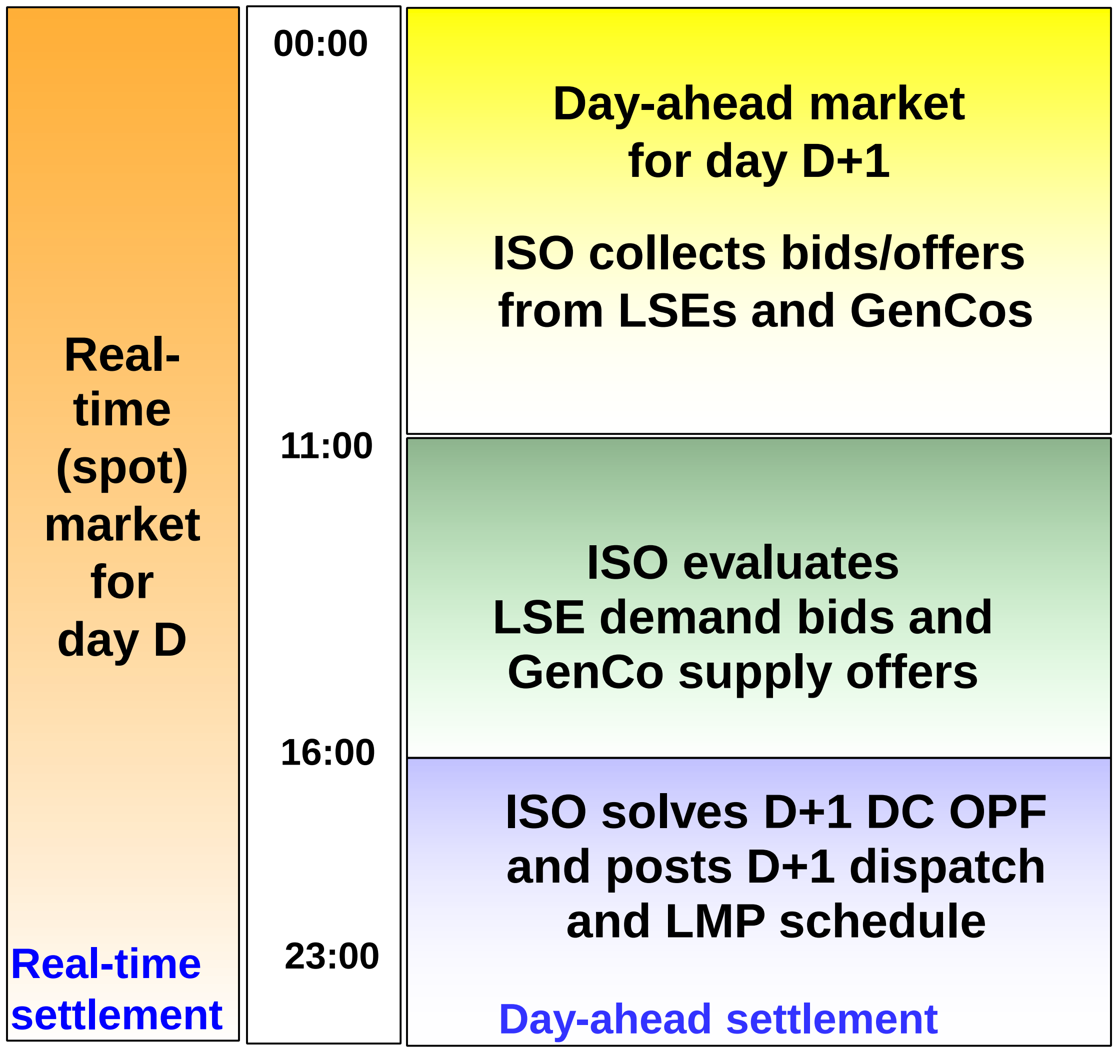
- **Market protocols & AC transmission grid structure**
  - **Graphical user interface (GUI) & modularized class structure** permit easy experimentation with alternative parameter settings and alternative institutional/grid constraints
- **Learning representations for traders**
  - **Java Reinforcement Learning Module (JReLM)**
  - "Tool box" permitting experimentation with a wide variety of learning methods (Roth-Erev, Temp Diff/Q-learning,…)
- **Bid/offer-based optimal power flow formulation**
  - **Java DC Optimal Power Flow Module (DCOPFJ)**
  - Permits experimentation with various DC OPF formulations
- **Output displays and dynamic test cases**
  - Customizable chart/table displays & 5-bus/30-bus test cases

AMES Graphical User Interface (GUI)

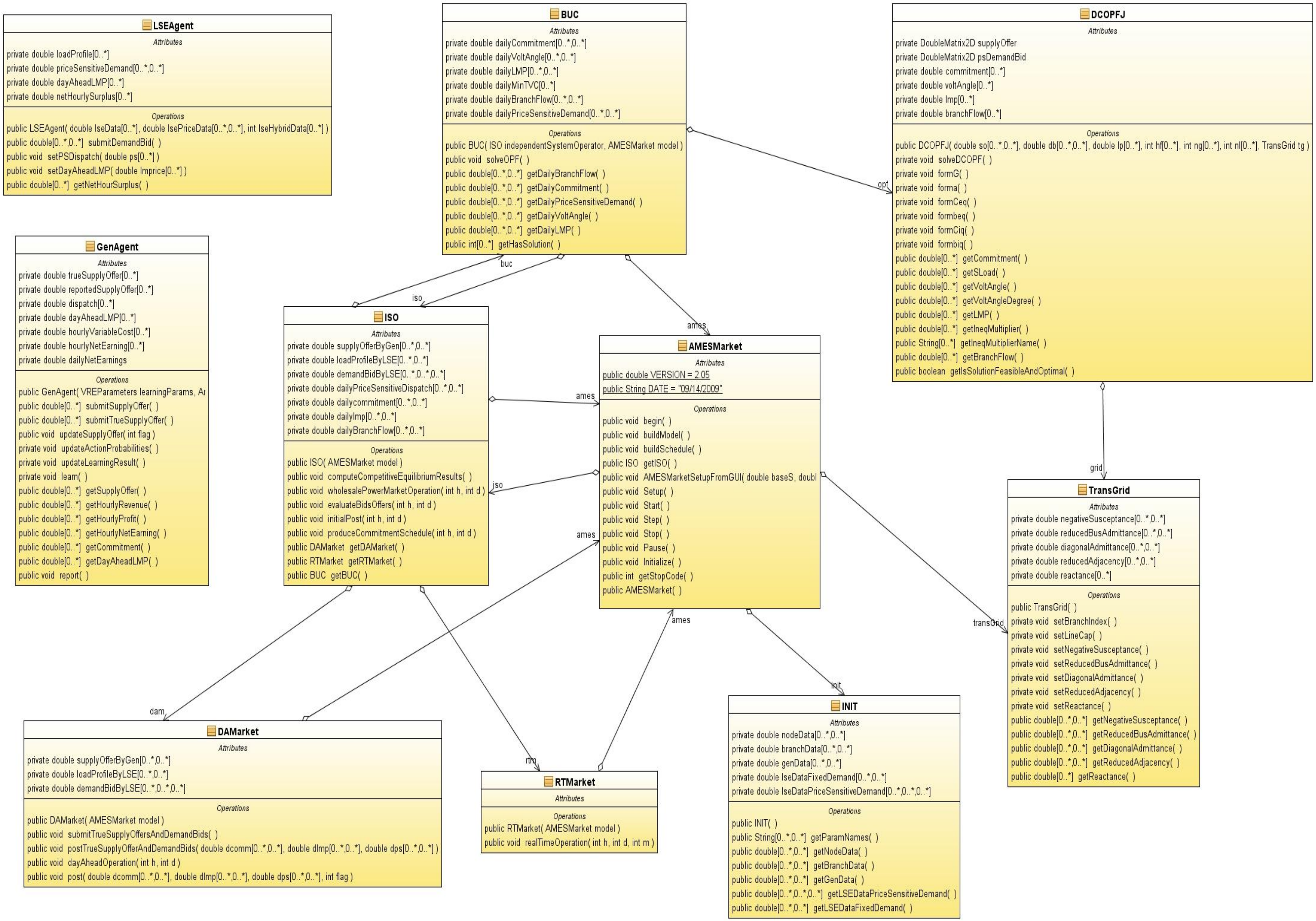
Tool Bar and Menus for Data Input and Output Displays



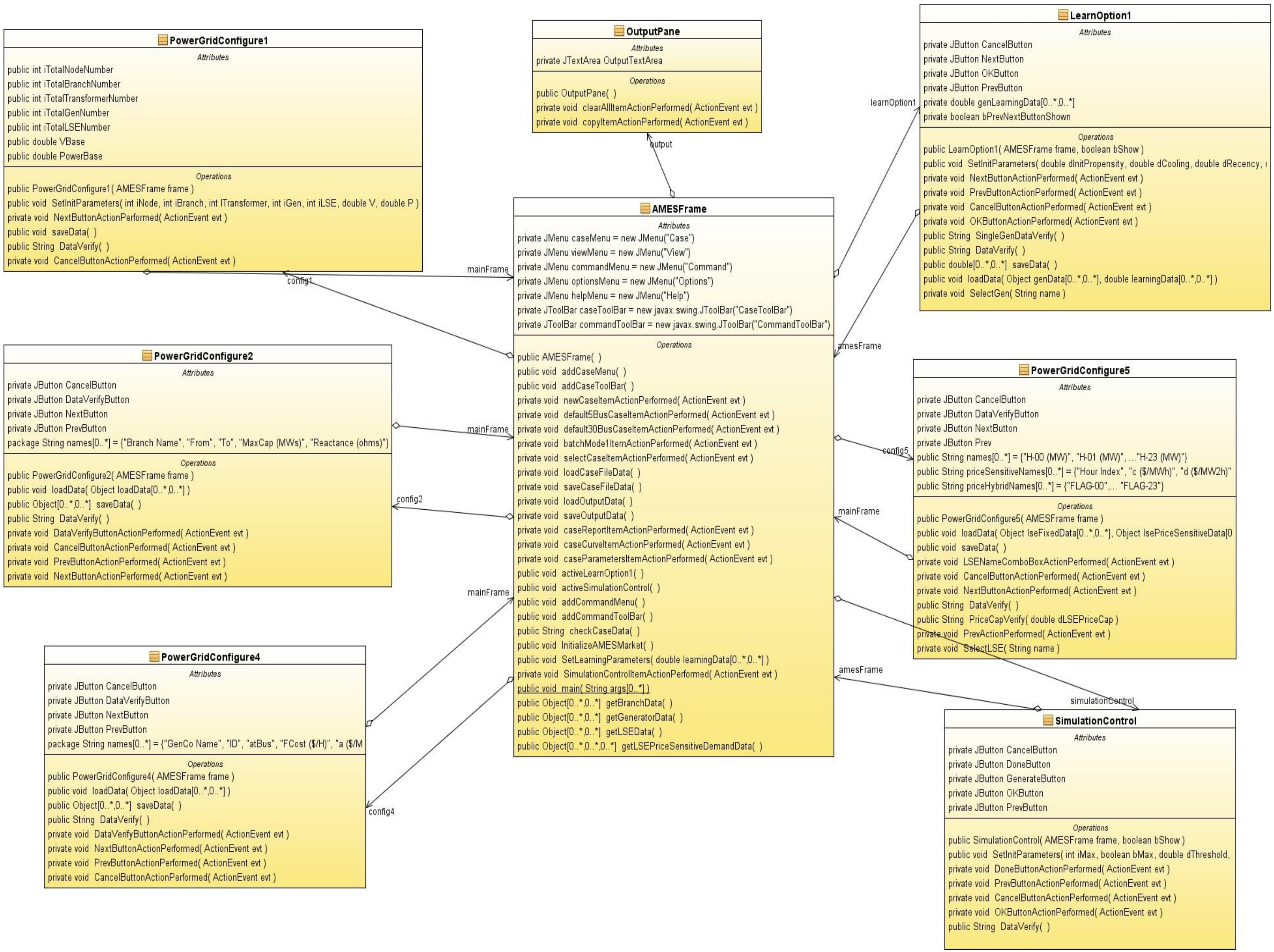
Activities of AMES ISO During Each Operating Day D: Timing Adopted from Midwest ISO (MISO)



Basic AMES Classes:



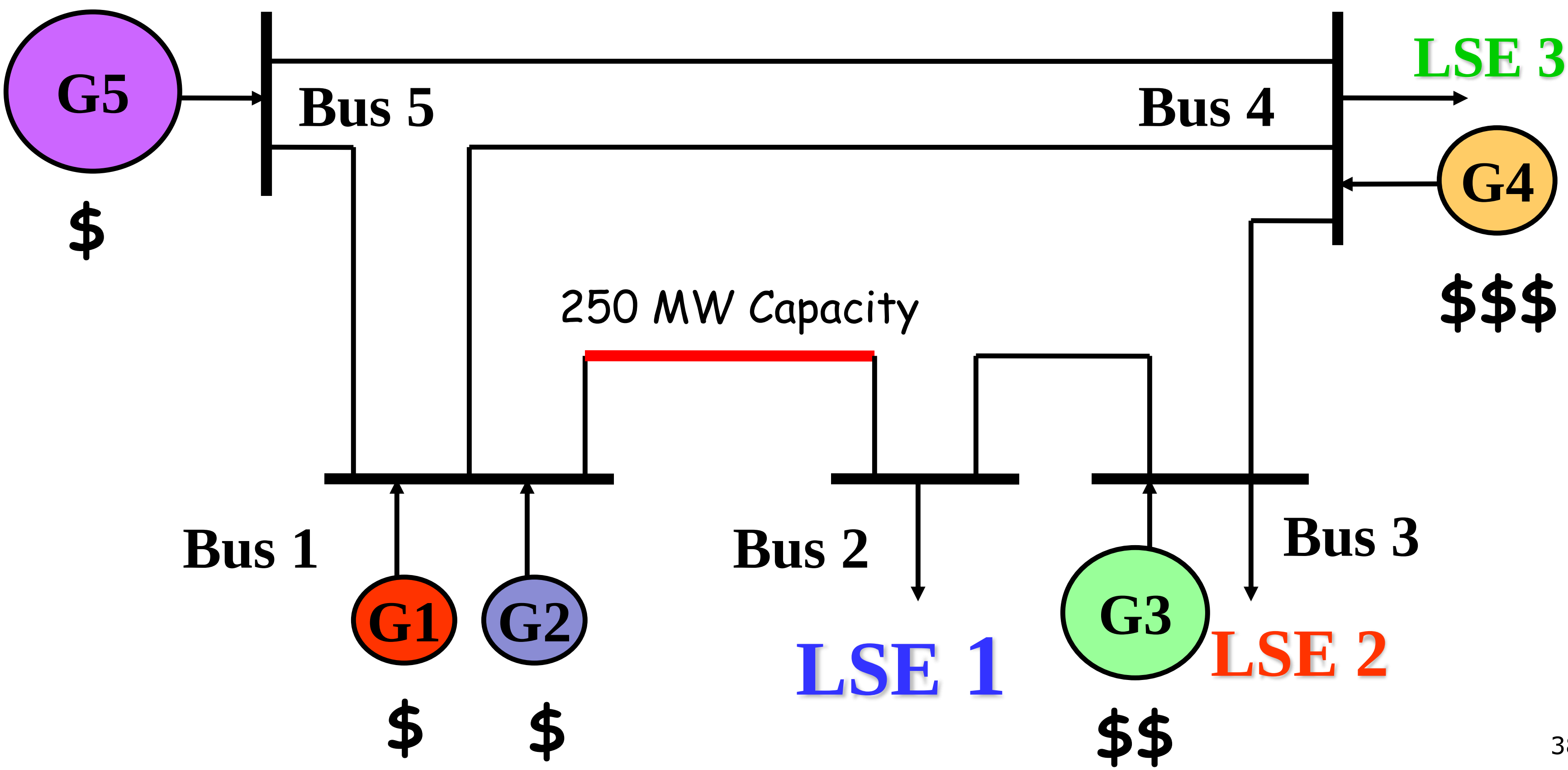
AMESFrame Classes (GUI)



Illustrative 5-Bus Test Case

(Used in many ISO business practice/training manuals)

Five GenCo sellers G1,…,G5 and three LSE buyers LSE 1, LSE 2, LSE 3



Partial depiction of input data for the 5-bus test case:

Base Values[a]	
S_o	V_o
100	10
K^b	π^c
5	0.05

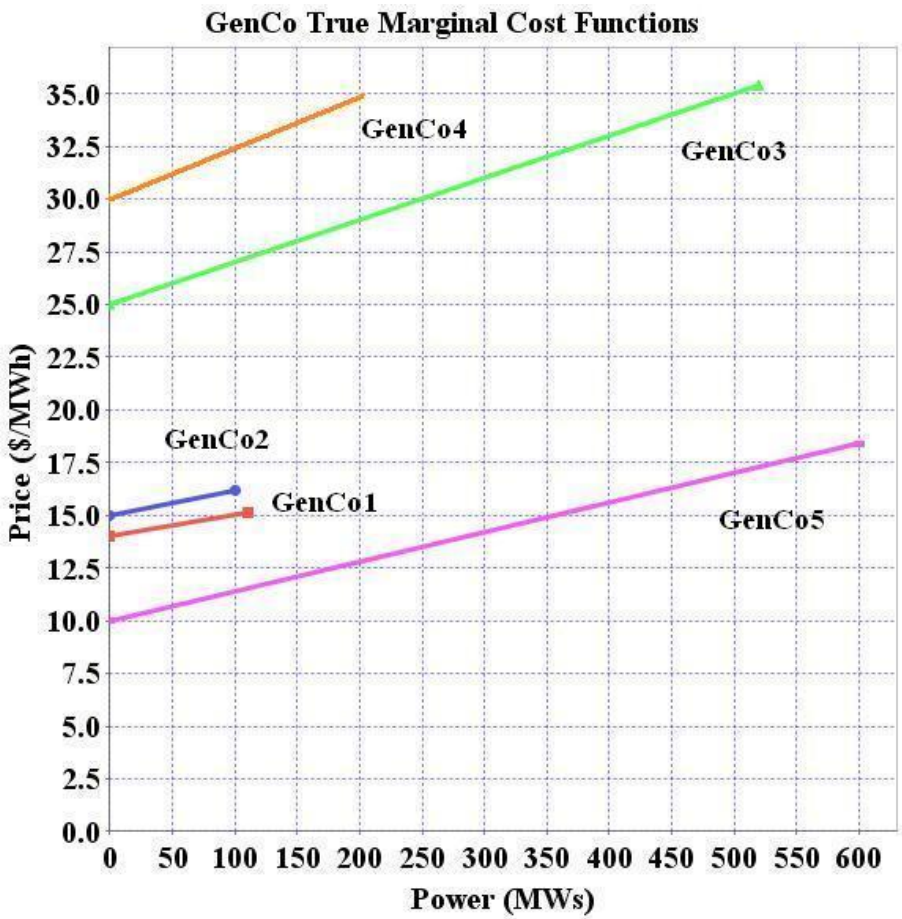
Branch From	To	lineCap[d]	X^e
1	2	250.0	0.0281
1	4	150.0	0.0304
1	5	400.0	0.0064
2	3	350.0	0.0108
3	4	240.0	0.0297
4	5	240.0	0.0297

Gen ID	atNode	FCost	a	b	Cap^L	Cap^U	Init$
1	1	1600.0	14.0	0.005	0.0	110.0	$\$1M$
2	1	1200.0	15.0	0.006	0.0	100.0	$\$1M$
3	3	8500.0	25.0	0.010	0.0	520.0	$\$1M$
4	4	1000.0	30.0	0.012	0.0	200.0	$\$1M$
5	5	5400.0	10.0	0.007	0.0	600.0	$\$1M$

LSE ID	atNode	L-00[f]	L-01	L-02	L-03	L-04	L-05	L-06	L-07
1	2	350.00	322.93	305.04	296.02	287.16	291.59	296.02	314.07
2	3	300.00	276.80	261.47	253.73	246.13	249.93	253.73	269.20
3	4	250.00	230.66	217.89	211.44	205.11	208.28	211.44	224.33
ID	atNode	L-08	L-09	L-10	L-11	L-12	L-13	L-14	L-15
1	2	358.86	394.80	403.82	408.25	403.82	394.80	390.37	390.37
2	3	307.60	338.40	346.13	349.93	346.13	338.40	334.60	334.60
3	4	256.33	282.00	288.44	291.61	288.44	282.00	278.83	278.83
ID	atNode	L-16	L-17	L-18	L-19	L-20	L-21	L-22	L-23
1	2	408.25	448.62	430.73	426.14	421.71	412.69	390.37	363.46
2	3	349.93	384.53	369.20	365.26	361.47	353.73	334.60	311.53
3	4	291.61	320.44	307.67	304.39	301.22	294.78	278.83	259.61

[a] For simplicity, the base apparent power S_o (MVA) and base voltage V_o (kV) are chosen so base impedance Z_o satisfies $Z_o = V_o^2/S_o = 1$.
[b] Total number of nodes
[c] Soft penalty weight π for voltage angle differences
[d] Upper limit P_{km}^U (in MWs) on the magnitude of real power flow in branch km
[e] Reactance X_{km} (in ohms) for branch km
[f] L-H: Load (in MWs) for hour H, where H=00,01,...,23

GenCo True Cost & Capacity Attributes for the 5-Bus Test Case



AMES Generation Company (Seller)

Public Access:

// Public Methods

getWorldEventSchedule(clock time,…);
getMarketProtocols(ISO market power mitigation,…);
Methods for receiving data;
Methods for retrieving GenCo data;

Private Access:

// Private Methods

Methods for gathering, storing, and sending data;
Methods for calculating own expected & actual net earnings;
Method for updating own supply offers (**LEARNING**);

// Private Data

Own capacity, grid location, cost function, current wealth… ;
Data recorded about external world (prices, dispatch,…);
Address book (communication links);

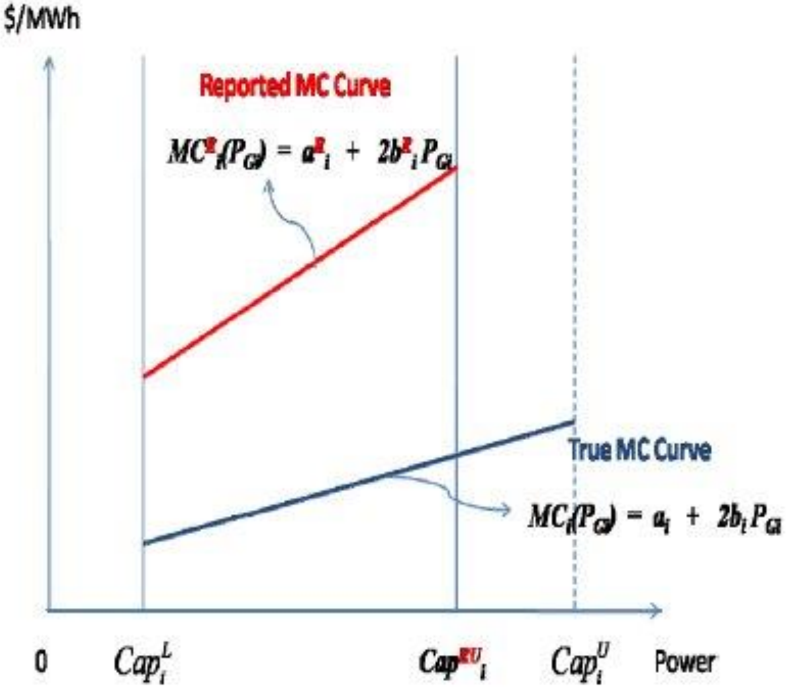
AMES GenCos are learners who report strategic hourly supply offers to ISO

Hourly supply offer for each GenCo i = ***Reported*** linear marginal cost function over a ***reported*** operating capacity interval for real power p_{Gi} (in MWs):

$$MC^{R}_{i}(p_{Gi}) = a^{R}_{i} + 2b^{R}_{i}\, p_{Gi}$$

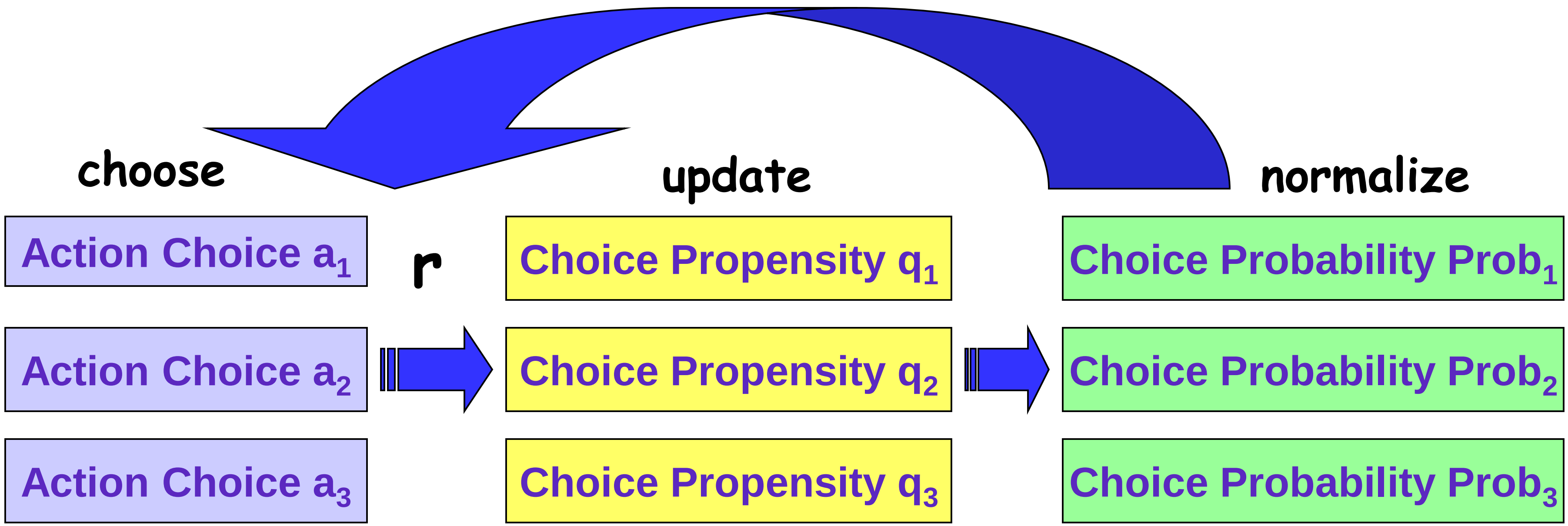
$$Cap_{i}^{L} \leq p_{Gi} \leq Cap_{i}^{RU}$$

GenCos can learn to report ***higher-than-true*** marginal costs and/or to report ***lower-than-true*** maximum capacity.



In 5-bus study, AMES GenCos use VRE learning

(version of Roth-Erev stochastic reinforcement learning)



- Each GenCo maintains action choice propensities q, normalized to choice probabilities Prob, to choose actions (supply offers). *A* good (bad) reward r_k resulting from an action a_k results in an increase (decrease) in both q_k and $Prob_k$.

VRE Updating of Action Propensities

Parameters:

- $q_j(1)$ 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

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

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

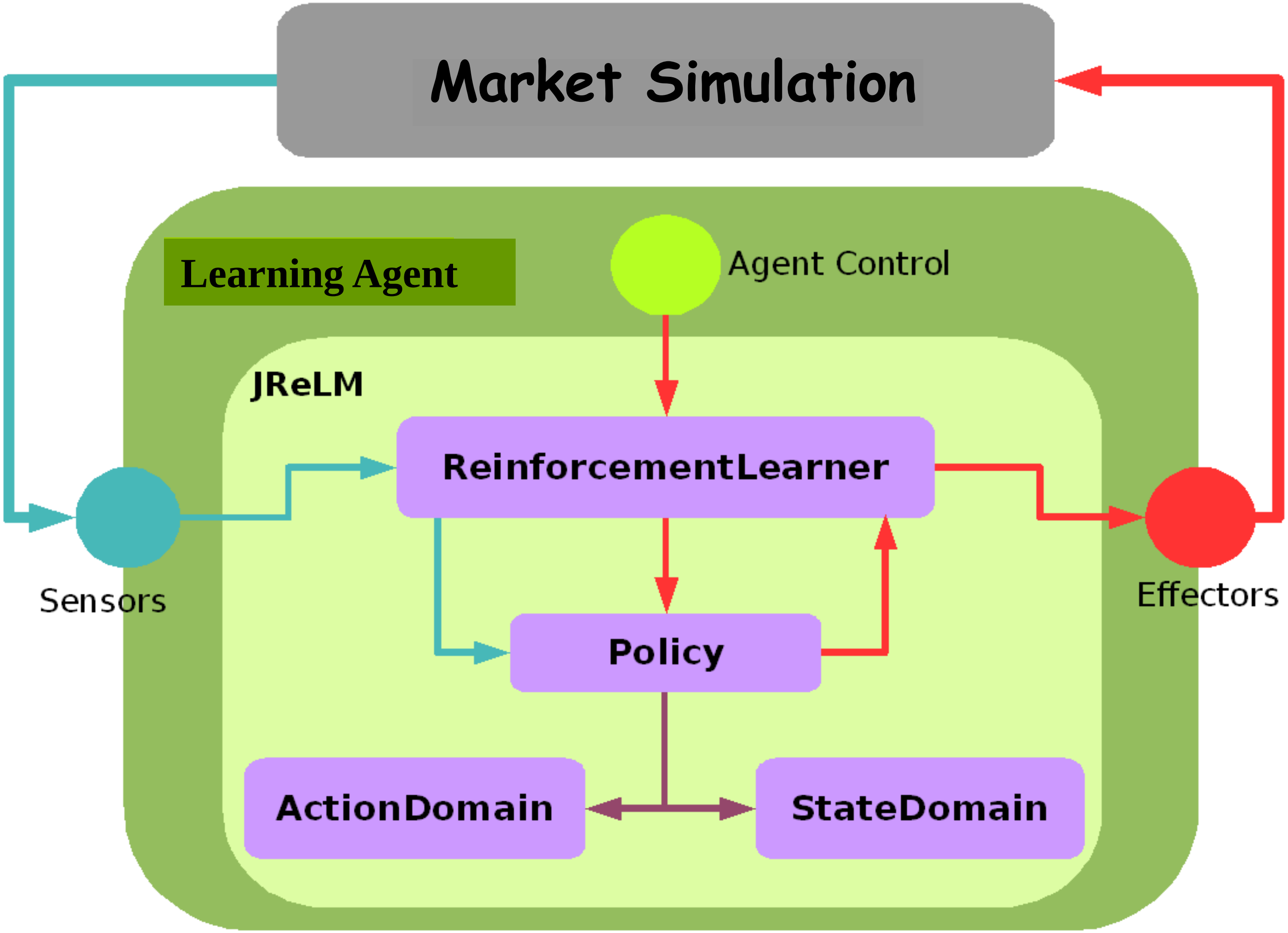
From VRE Propensities to Probabilities
Gibbs-Boltzmann Probability

- $q_j(t)$ = "propensity" to choose action j at time t
- N = Total number of available actions
- T = Temperature ("cooling") parameter
- $Prob_j(t)$ = Probability of choosing action j at time t

$$Prob_j(t) = \frac{e^{q_j(t)/T}}{\sum_{n=1}^{N} e^{q_n(t)/T}}$$

AMES GenCo learning implemented via JReLM module

(Java Reinforcement Learning Module developed by Charles J. Gieseler, Comp Sci M.S. Thesis, 2005)



AMES Load-Serving Entity (Buyer)

Public Access:

// **Public Methods**

getMarketProtocols(posting, trade, settlement);
getMarketProtocols(ISO market power mitigation);
Methods for receiving data;
Methods for retrieving LSE data;

Private Access:

// **Private Methods**

Methods for gathering, storing, and sending data;
Methods for calculating own expected & actual net earnings;

// **Private Data**

Own downstream demand, grid location, current wealth…;
Data recorded about external world (prices, dispatch,…);
Address book (communication links);

AMES LSE Hourly Demand-Bid Formulation

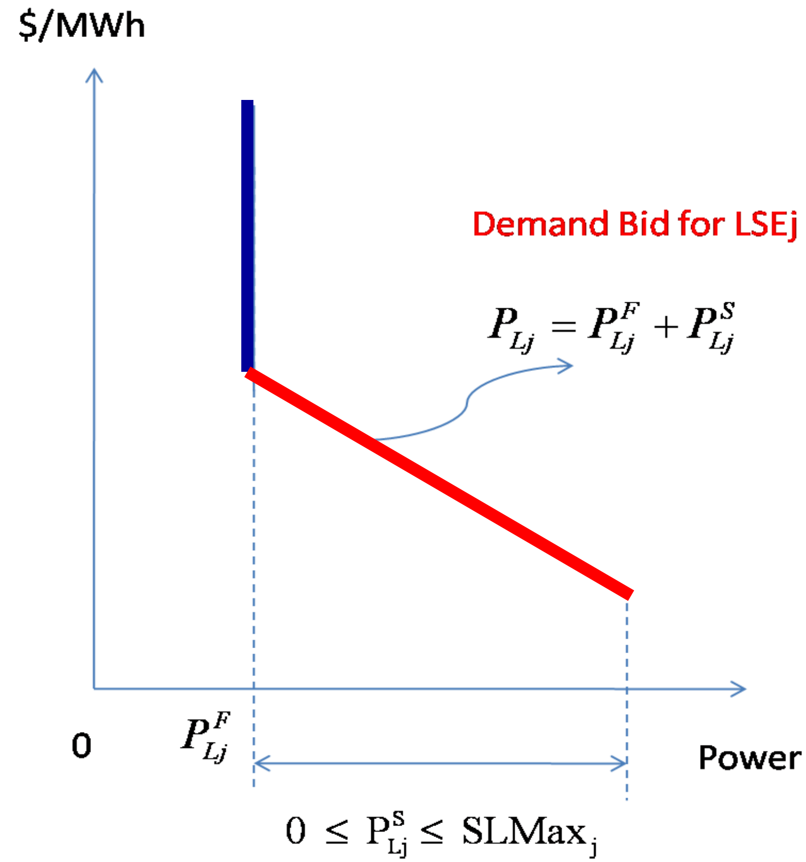
- Hourly demand bid for each LSE j

Fixed* + *Price-Sensitive Demand Bid

- **Fixed** demand bid = p^F_{Lj} (MWs)
- **Price-sensitive** demand bid = Inverse demand function for real power p^S_{Lj} (MWs) over a purchase capacity interval:

$$F_j(p^S_{Lj}) = c_j - 2d_j\, p^S_{Lj}$$

$$0 \le p^S_{Lj} \le SLMax_j$$



AMES ISO (Market Operator)

Public Access:

// Public Methods

getWorldEventSchedule(clock time,…);
getMarketProtocols(bid/offer reporting, settlement,…);
Methods for receiving data;
Methods for retrieving stored ISO data;

Private Access:

// Private Methods

Methods for gathering, storing, posting, & sending data;
Method for solving hourly DC optimal power flow;
Methods for posting schedules and carrying out settlements;
Methods for implementing market power mitigation;

// Private Data

Historical data (e.g., cleared bids/offers, market prices,…);
Address book (communication links);

AMES ISO Solves Hourly DC Optimal Power Flow (OPF)

GenCos report hourly supply offers and LSEs report fixed & price-sensitive hourly demand bids to ISO for day-ahead market

Minimize

$$\sum_{i=1}^{I}[a_i^R p_{Gi} + b_i^R p_{Gi}^2] - \sum_{j=1}^{J}[c_j p_{Lj}^S - d_j {p_{Lj}^S}^2] + \pi \left[\sum_{km \in BR} [\delta_k - \delta_m]^2\right]$$

GenCo-reported total avoidable costs

LSE gross buyer surplus

$$\text{w.r.t.} \quad p_{Gi},\ i = 1, ..., I;\ p_{Lj}^S,\ j = 1, ..., J;\ \delta_k,\ k = 1, ..., K$$

Subject to

$$\sum_{i \in I_k} p_{Gi} - \sum_{j \in J_k} (p_{Lj}^F + p_{Lj}^S) - \sum_{km \text{ or } mk \in BR} B_{km} [\delta_k - \delta_m] = 0$$

$$|B_{km} [\delta_k - \delta_m]| \leq P_{km}^U$$

$$Cap_i^L \leq p_{Gi} \leq Cap_i^{RU}$$

$$0 \leq p_{Lj}^S \leq SLMax_j$$

$$\delta_1 = 0$$

Fixed and price-sensitive demand bids for LSE j

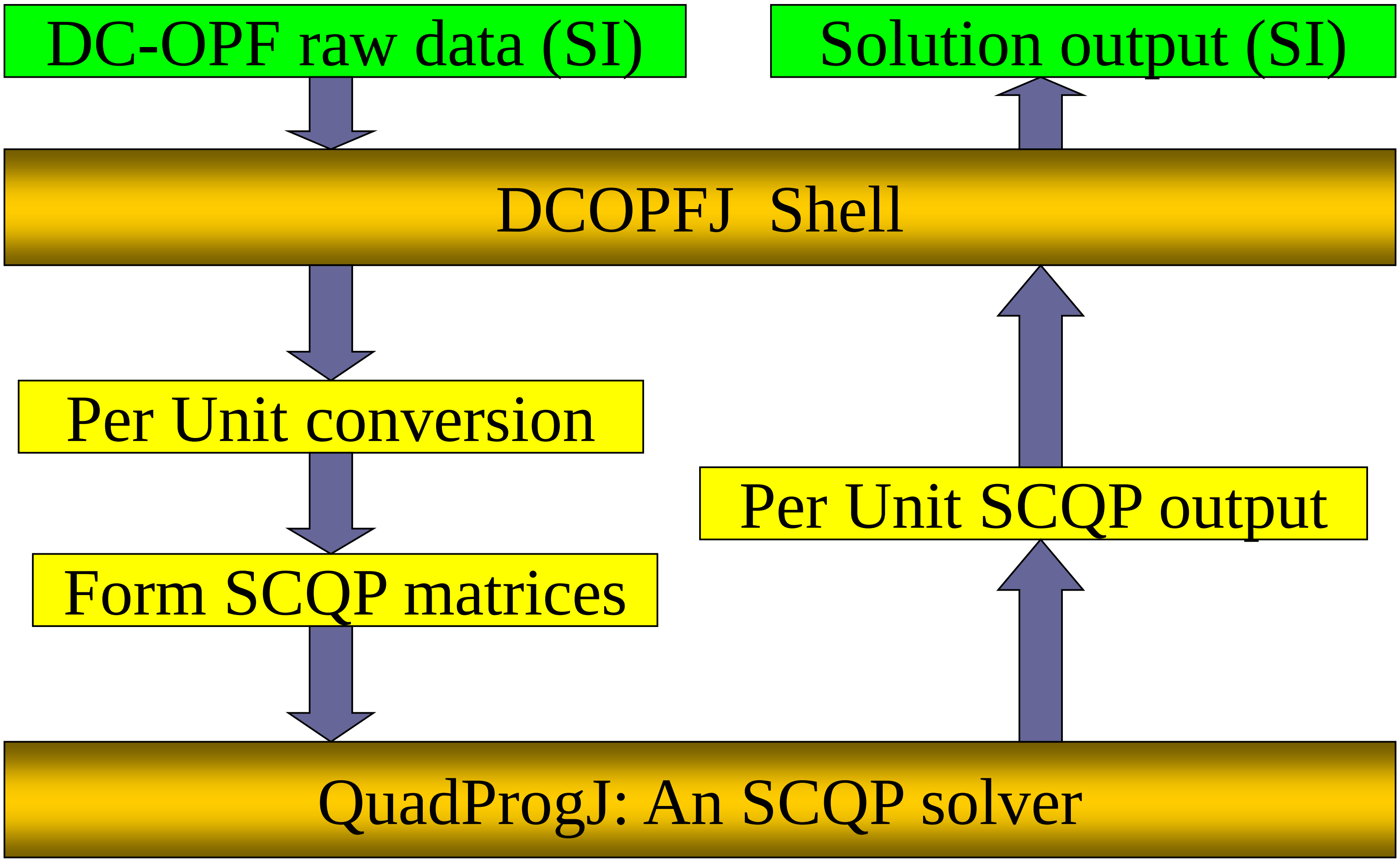
Dual variable for this bus-k balance constraint gives LMP for bus k

Operating capacity interval for GenCo i

Purchase capacity interval for LSE j

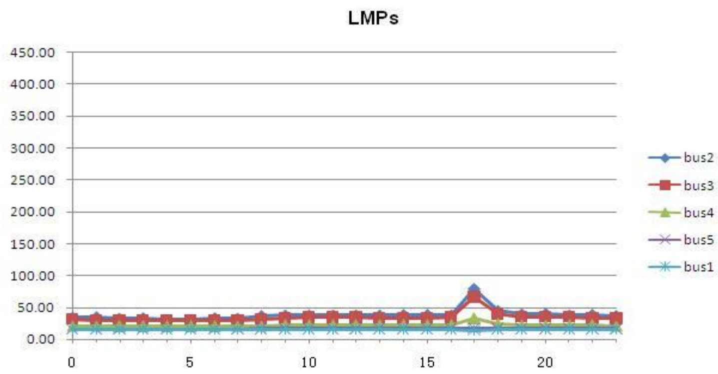
P^U_{km} = Upper limit on branch km

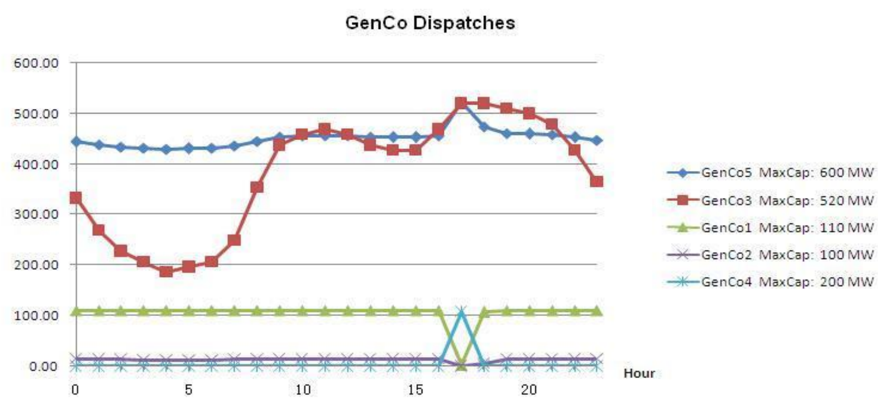
AMES ISO Solves DC-OPF via DCOPFJ Module



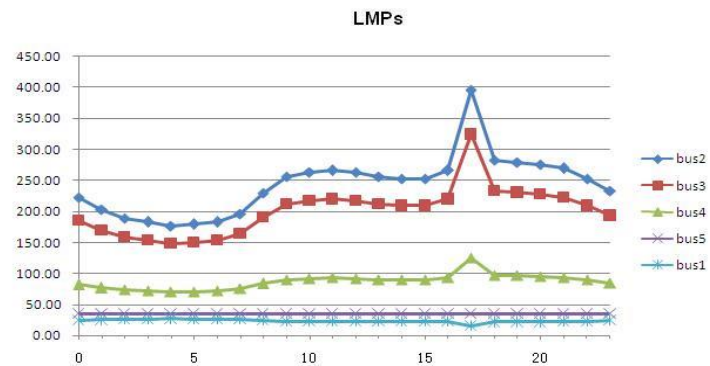
Illustrative 5-Bus Findings for R=0.0 (100% Fixed Demand)

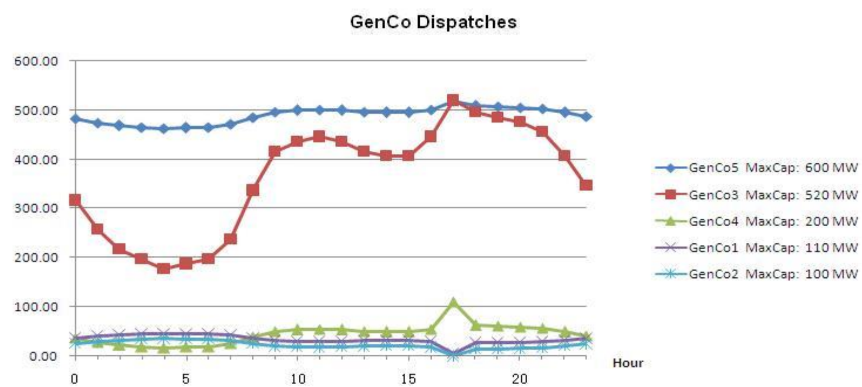
W/O Gen Learning (Day 1000)

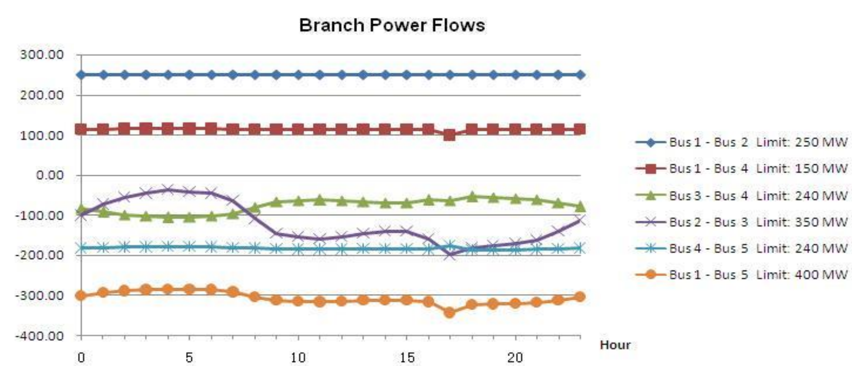




With Gen Learning (Day 1000)







Online Resources

- **Agent-Based Comp Econ Homepage**
  https://www2.econ.iastate.edu/tesfatsi/ace.htm
- **ACE/CAS Comp Labs and Demos**
  https://www2.econ.iastate.edu/tesfatsi/acedemos.htm
- **ACE/CAS: General Software & Toolkits**
  https://www2.econ.iastate.edu/tesfatsi/acecode.htm
- **AMES Wholesale Power Market Testbed**
  https://www2.econ.iastate.edu/tesfatsi/AMESMarketHome.htm
- **Agent-Based Electricity Research**
  https://www2.econ.iastate.edu/tesfati/aelect.htm