Vietnam Education Foundation

Distributed Decision Making in Complex Systems

Jose B. Cruz, Jr.

The Ohio State University

Columbus, Ohio, USA

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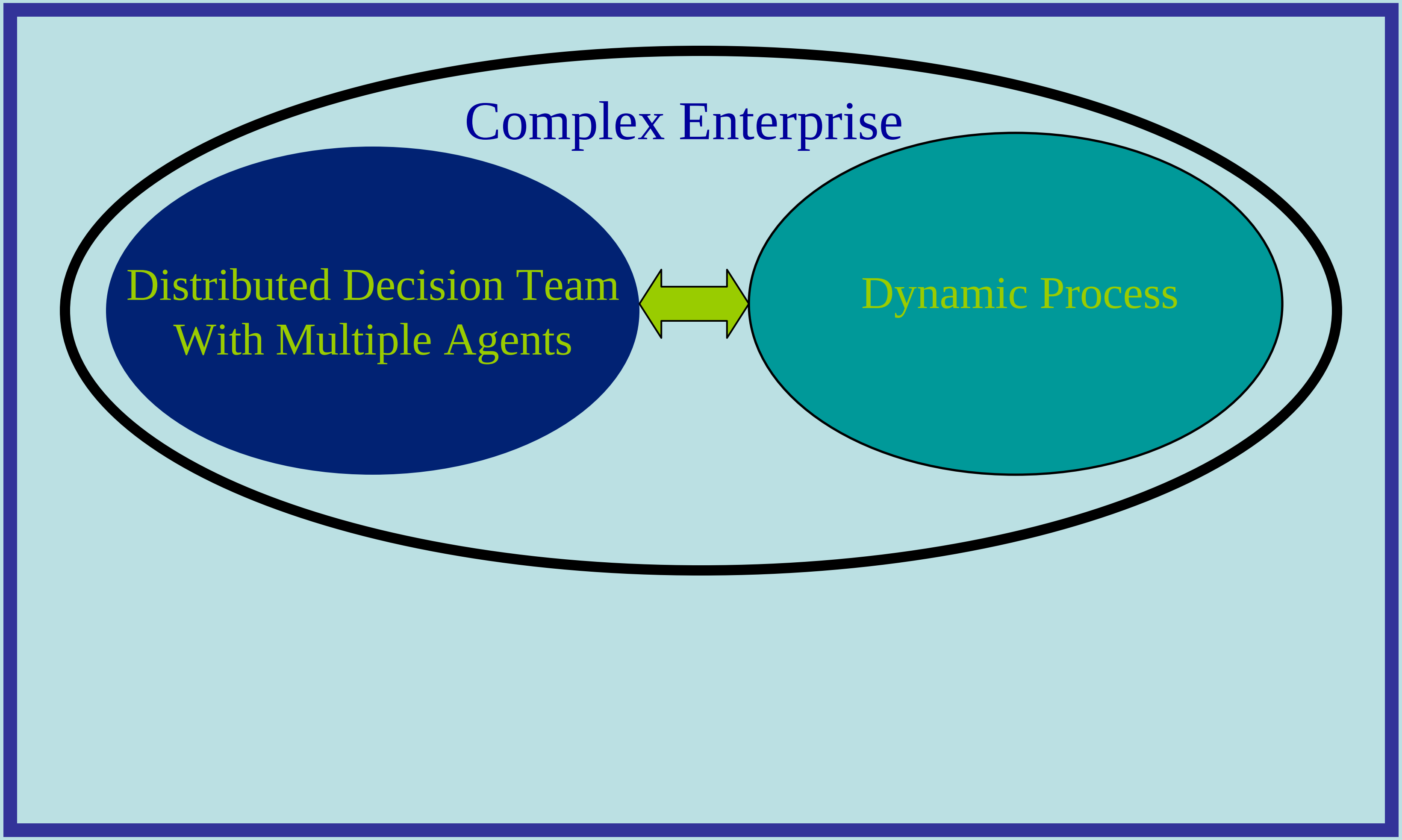
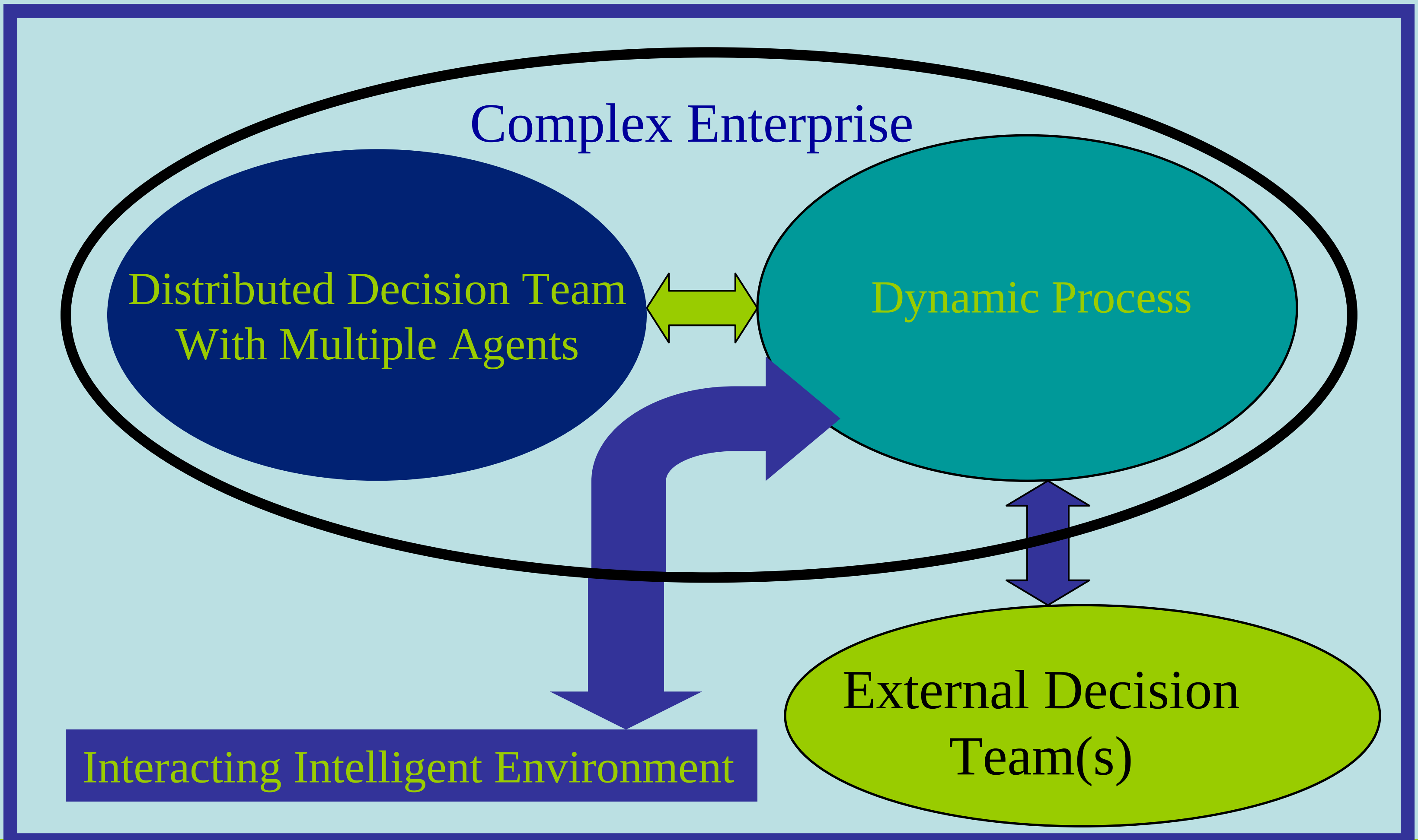
Outline

- Introduction
- Distributed decisions in complex systems
- Coordination of teams in hierarchical enterprises
- Competitive interaction among enterprises
- Business example of extended enterprise
- Military example of extended enterprise
- Concluding remarks

Complex Enterprise

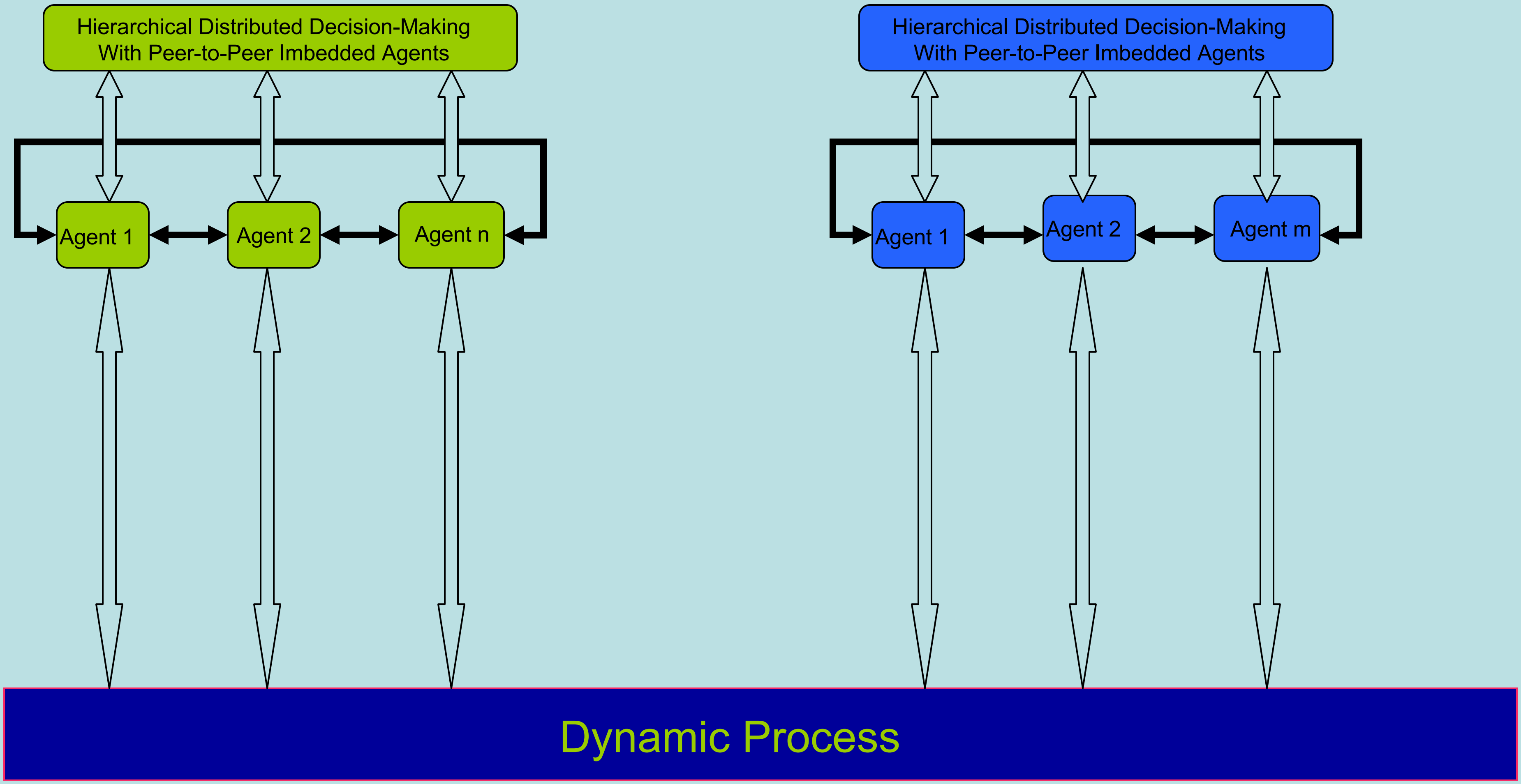


Extended Complex Enterprise



Extended Complex Enterprise: Complex Enterprise Plus External Decision Team(s) and Interacting Intelligent Environment

Interconnected Competitive Enterprises



Examples of Extended Complex Enterprises

- Business enterprises operating in multiple markets with other business enterprises.
- Military forces engaged with other military forces in battles.
- Interconnected electric energy systems.

Business Examples of Complex Enterprises

- Automobile complex enterprise: **General Motors**, with Cadillac, Pontiac, Buick, Chevrolet, others.
- Automobile complex enterprise: **Ford Motor Company**, with Lincoln, Volvo, Mazda, Ford.
- Automobile complex enterprise: **Daimler-Chrysler**, with Chrysler, Mercedes-Benz, Dodge, others.

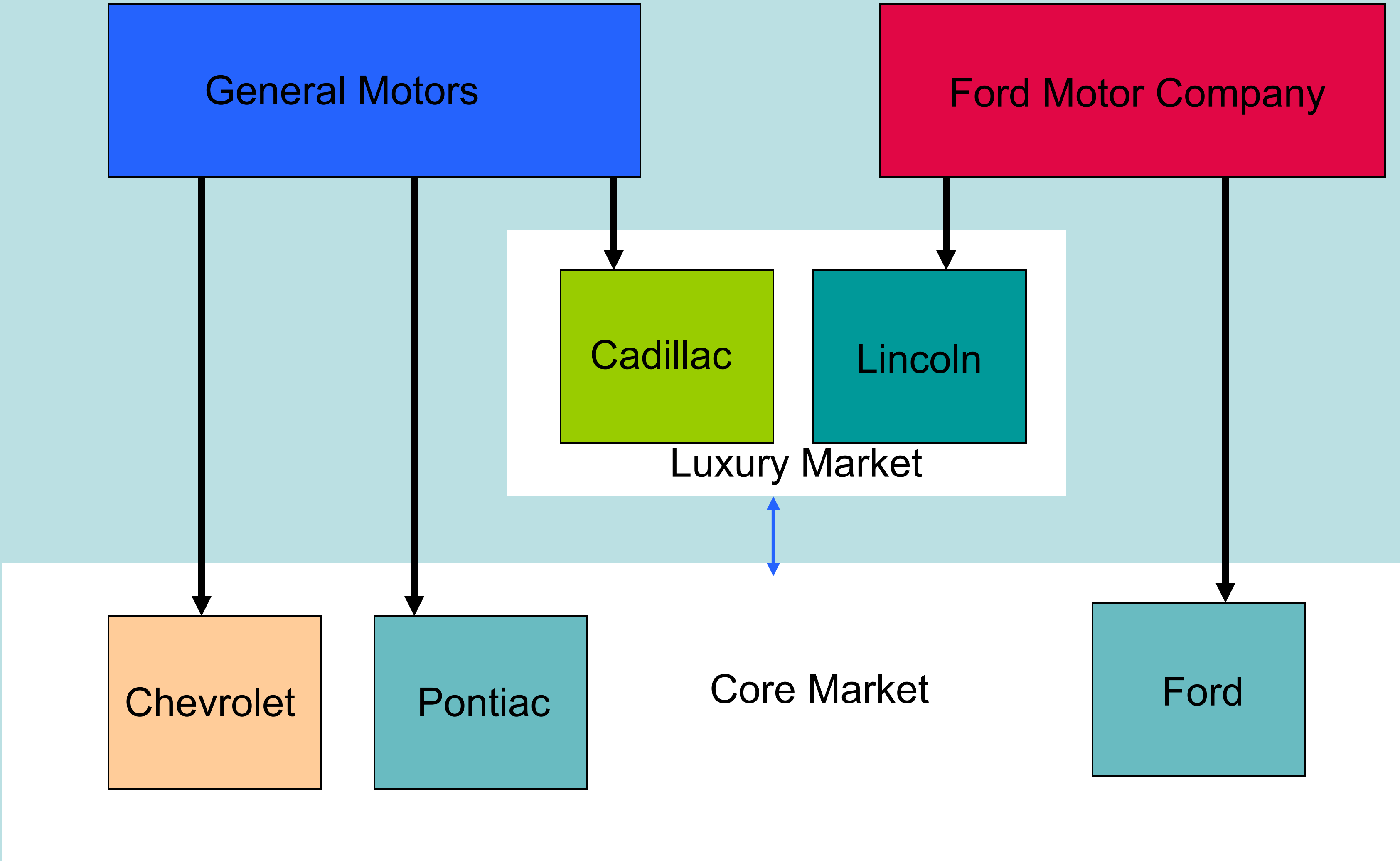
GM Complex Enterprise

- Management team of **Cadillac** is an agent of the GM management team.
- Management team of **Pontiac** is an agent of the GM management team.
- Management team of **Chevrolet** is an agent of the GM management team.
- The various agents are peer decision makers of the GM control authority.

Extended Complex Enterprises

- Each of the complex enterprises, GM, FMC, Daimler-Chrysler, in isolation, is a subsystem in a larger system.
- Each participates in multiple markets, in competition with other complex enterprises.
- Each complex enterprise is imbedded in an extended complex enterprise.

Automobile Extended Complex Enterprise



Competition Between Hierarchical Companies

Consider two hierarchical enterprises, A and B.

Enterprise A owns n companies $A_1,\ A_2,\ldots,\ A_n$.

Enterprise B owns m companies, $B_1,\ B_2,\ldots,B_m$.

A_i and B_j compete in e different markets $M_1,\ M_2,\ldots,M_e$.

Two mappings associate a specific market to each company:

$\varsigma: [1,n] \to [1,e],\ i \to \varsigma(i).$ A_i affects market $M_{\varsigma(i)}$.

$\xi: [1,m] \to [1,e],\ j \to \xi(j).$ B_j affects market $M_{\xi(j)}$.

Simple Model of Competition

A_i chooses it own output production q_{A_i}.

B_j chooses it own output production q_{B_j}.

Market $(M_k)_{k\in[1,e]}$ has a total production Q_k

$$Q_k = \sum_{\Phi_k} q_{A_i} + \sum_{\Psi_k} q_{B_j}$$

where $\Phi_k = \{i \mid \varsigma(i) = k\}$, and $\Psi_k = \{j \mid \xi(j) = k\}$

Objective Functions

Price: $p_{A_i} = f_{A_i}(Q_{\varsigma(i)}, a_i)$, $p_{B_j} = f_{B_j}(Q_{\xi(j)}, b_j)$

Price decreases with Q and increases with a or b.

Objective functions:

$$J_{A_i} = p_{A_i} q_{A_i} - h_{A_i}(q_{A_i})$$

$$J_{B_j} = p_{B_j} q_{B_j} - h_{B_j}(q_{B_j})$$

$$J_A = \sum_{i=1}^{n} J_{A_i} - \overline{a}^T \Gamma_a \overline{a}, \quad J_B = \sum_{j=1}^{m} J_{B_j} - \overline{b}^T \Gamma_b \overline{b}$$

Decision Variables

- At the company level, the decision variables are quantity of production q.
- At the enterprise level, the decision variables, a, and b, may be advertising and consumer promotional rebates.
- The enterprise decision variables are designed to provide incentives to the companies.

Design of Incentive Formulas

- The enterprise decision variables are constructed as functions of the company variables.
- The functions or formulas are announced to the companies in advance.
- The challenge to the enterprise is how to construct the formulas so as to induce the companies to choose company decisions that are good for the enterprise.

Incentive Strategies for Enterprises

- Enterprise decisions provide incentives for their companies to choose decisions that lead to a global Nash optimum for the enterprise.
- When companies of an enterprise are in the same market, they are induced by the incentives to choose decisions that are Pareto-optimal.

Game Theory Strategy Concept

- At the enterprise level A and B choose Nash game equilibrium strategies for a and b.
- Enterprises announce their strategies to their lower level companies, as functions of the lower level decisions.
- At the lower level, there are *e games.* In each market the companies incorporate the strategies of the parent enterprise in their objective functions, and engage in competition leading to a Nash equilibrium.

Advantage of Incentive Approach

- Simulations were conducted with and without incentive strategies.
- Enterprise performance was better with incentives, compared to performance without incentives.
- Individual company performance may not be as good when incentives are imposed, but the total enterprise performance was always better.

Dynamic Process

- A system or process (physical or operational) with at least one input and at least one output is *dynamic* if
  - the input and the output are time-series or time-functions, called signals, and
  - the output signal at any specific time depends on the entire input signal for all time.
- A dynamic system is *causal* if the output y at time t, y(t), depends on the input function u(ε) only for ε ≤ t.

Dynamic Process, continued

- A causal dynamic process is called *Markov* if an internal signal called **state** can be defined such that

function

$$x(k+1) = f(x(k), u(k))$$

state at time k+1

state at time k

control input at time k

Dynamic Process, continued

A causal dynamic Markov process is called a *partially observable Markov decision process* (POMDP) if it can be represented by

$$x(k+1) = f(x(k), u(k), w(k))$$

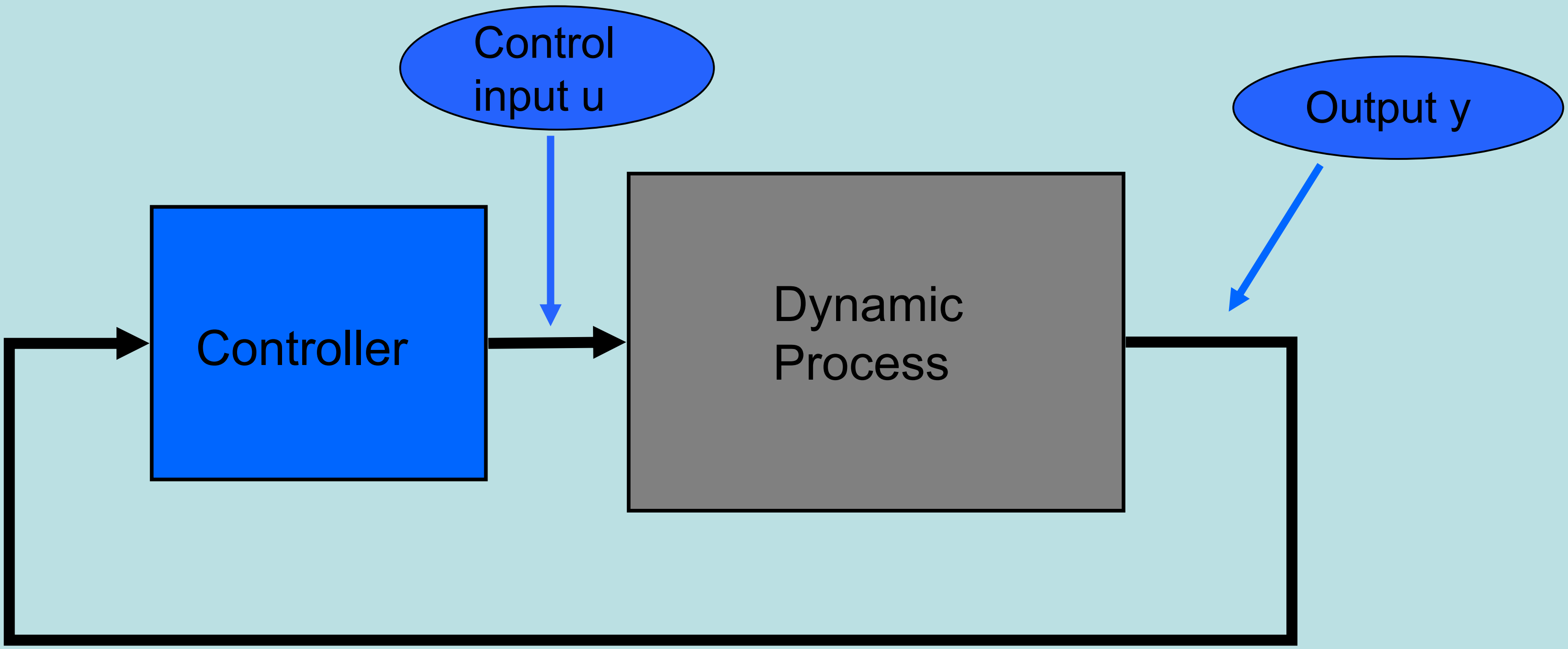
$$y(k+1) = g(x(k+1), u(k), v(k)).$$

The state x, output y, control input u, and the noises w and v may be vectors.

Progression of Control Complexity

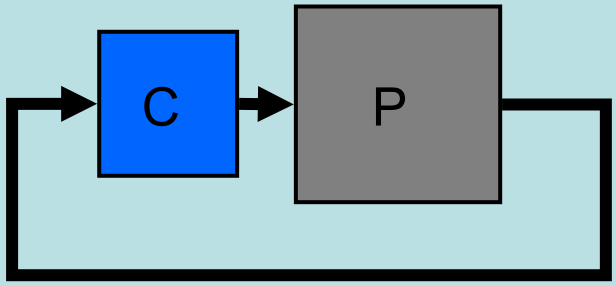
- *Centralized Control*: single controller or single decision maker, choosing or designing all control signals.
  - There may be one or more objective functions to be optimized.
  - The controller may be manual (human) or automatic (imbedded subsystem).
  - The controller is a dynamic process, mapping the observation space (output y) to the control action space (input u).

Centralized Control



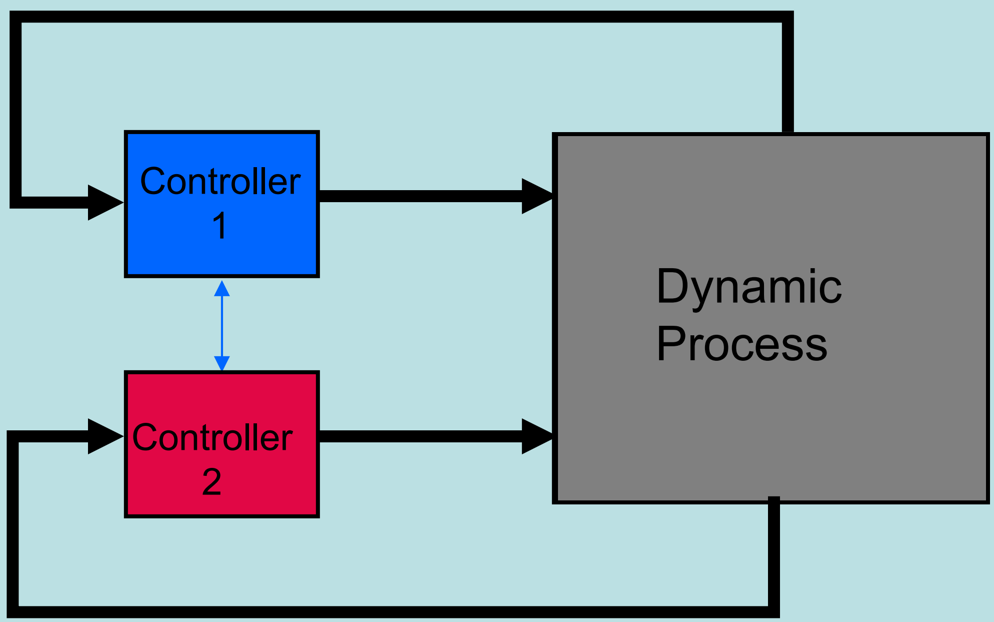
Centralized Control Design in Brief

- Construct a model for the dynamic process P.
- Specify a dynamic mapping C, from output space to control input space,
  - so as to satisfy one or more objectives,
  - to be tolerant to a class of uncertainty and fault conditions.
- There is a single control authority.



Control Complexity, continued

- *Distributed Control:* There may be a single decision maker or control authority, but there are at least two controllers.

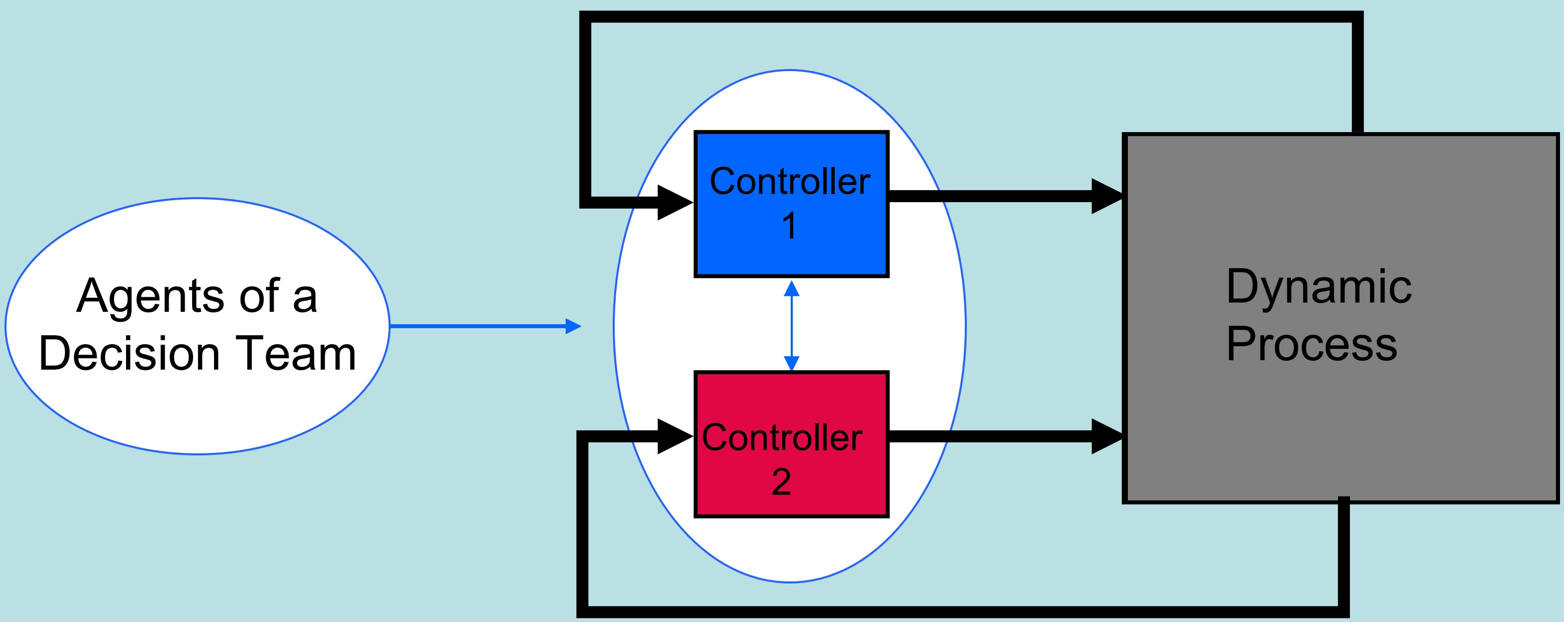


Distributed Control

- Each distributed controller may be a dynamic mapping from a localized output space to a localized control input space.
- There may be limited communication between the distributed controllers.
- Each distributed controller may have a separate objective but it is generally aware of the objectives of the other controllers.
- The distributed controllers are agents of a decision team of a single control authority.

Complex Enterprise

- Distributed decision team of multiple agents.
- Agents are peer (at the same level) controllers



Military Context of Multi-Team Planning and Scheduling

- Force A (red) controls a geographical area with many critical targets for the Force B (blue).
- Blue force composes multiple teams to deal with multiple tasks in battle.
- Blue commander allocates resources to multiple teams and assigns tasks.
- Red force may be organized into several teams.
- During the battle, a commander may decide to reassign tasks, and reallocate assets. Sub-teams may be reassigned to assist other teams.

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Adversarial Hierarchies

- The Blue force has several cooperating teams,

  $T_i^B,\ i = 1,\ 2,\ \ldots\ n_B$

- Each T_i^B consists of several sub-teams, $T_{ij}^B,\ j = 1,\ 2,\ \ldots m_i^B$
- Each sub-team consists of individual assets such as Uninhabited Air Vehicles (UAVs).
- Associated with each T_i^B and T_{ij}^B is an objective function J_i^B or J_{ij}^B to be optimized in cooperative fashion:
- $J^B = \sum_{i=1}^{n_B} \alpha_i J_i^B,\quad J_i^B = \sum_{j=1}^{\mathrm{m}_\mathrm{i}^\mathrm{B}} \alpha_{ij} J_{ij}^B$
- The Red force may have a similar hierarchy.

Team Dynamics and Tactics

- Each Blue team may be engaged with an adversarial Red team.
- Each Blue team or sub-team may be reassigned during battle to join a new team and assume new tasks and new schedules.
- Non-cooperative Nash game strategies are used to deal with an adversary.
- Pareto-optimality strategies are used for peer controller coordination.

Cooperation Among Peer Controllers

- Limited communication among peer controllers.
- Limited communication with higher level decision maker.
- Utilization of Pareto-optimality.

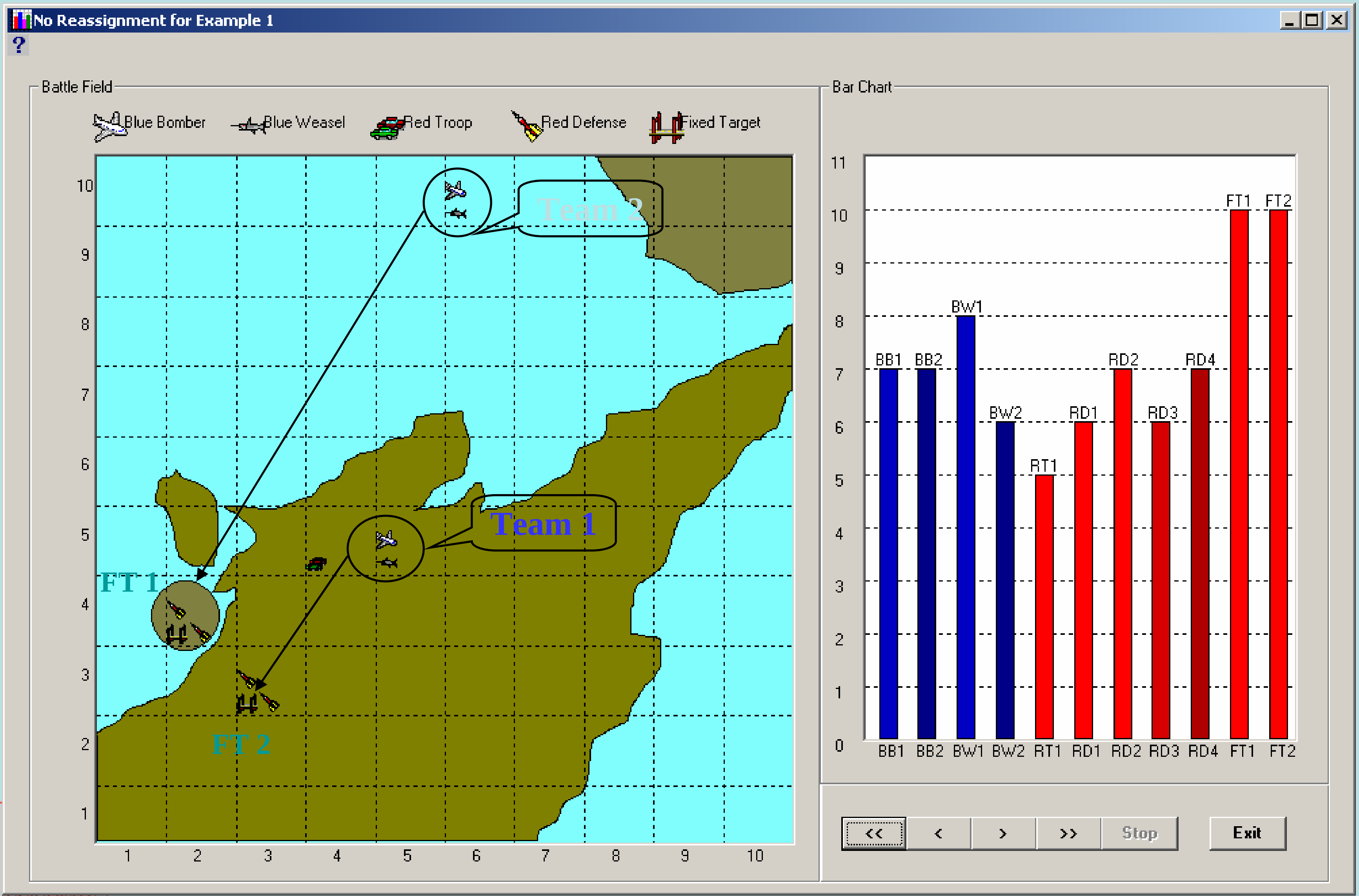
Team Strategies

- Calculate moving horizon, model predictive, two-stage look ahead, dynamic Nash strategies, and implement first stage.
- Repeat calculation for moving horizon, and implement new strategy for first stage only.
- Reallocated sub-teams or teams acquire objectives of teams they are joining.

Dynamics and Objectives Modeling for Teams and Sub-teams

- State variables for sub-teams:
  - Position, platforms, weapons
  - Dynamic state transition is nonlinear and of attrition type
- Control variables:
  - Movement, choice of targets, salvo size
- Objective functions
  - Moving horizon, two-time-stage, linear combination of asset values (blue and red).

Example
Initial States and Initial Assignments



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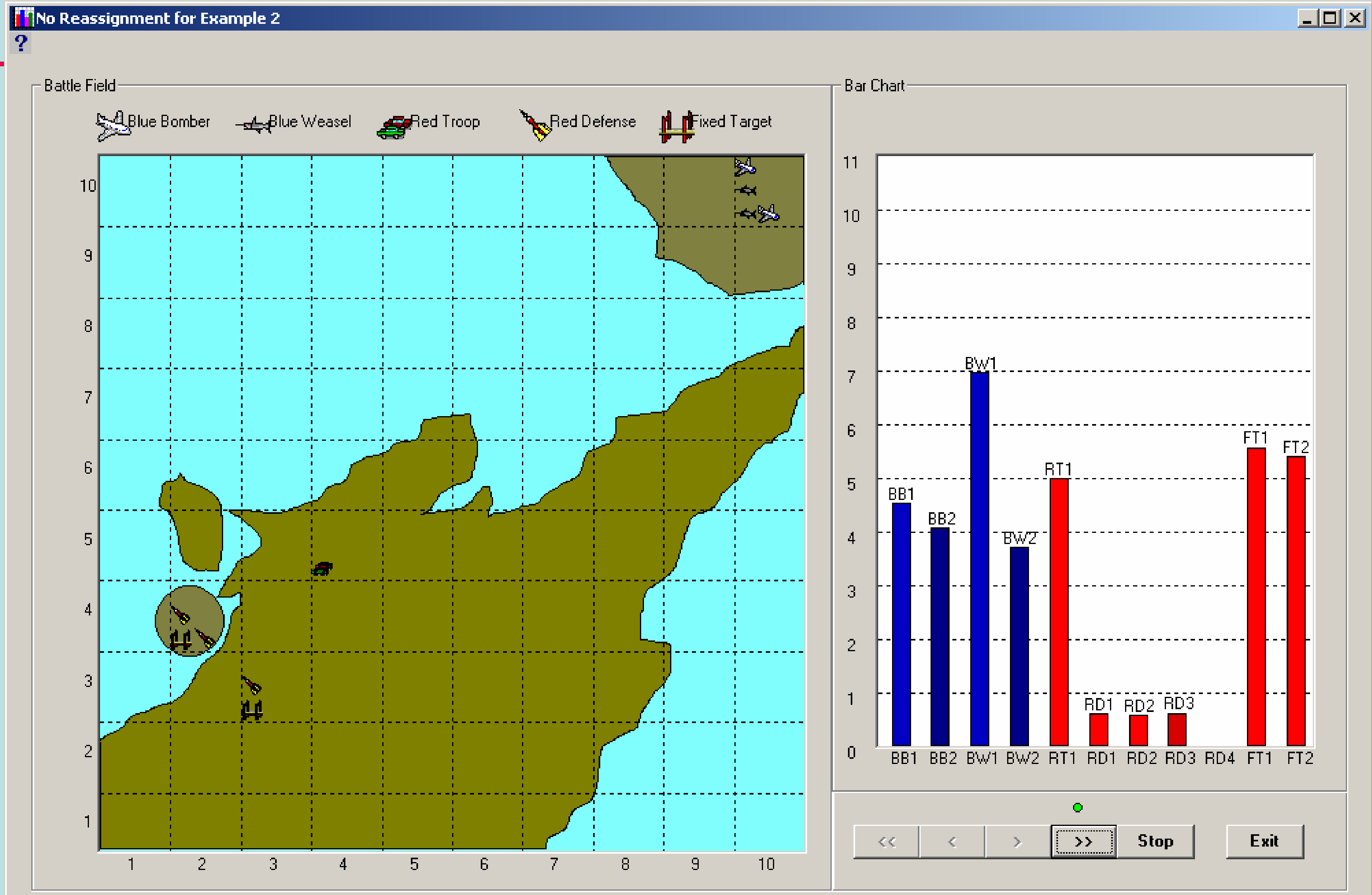
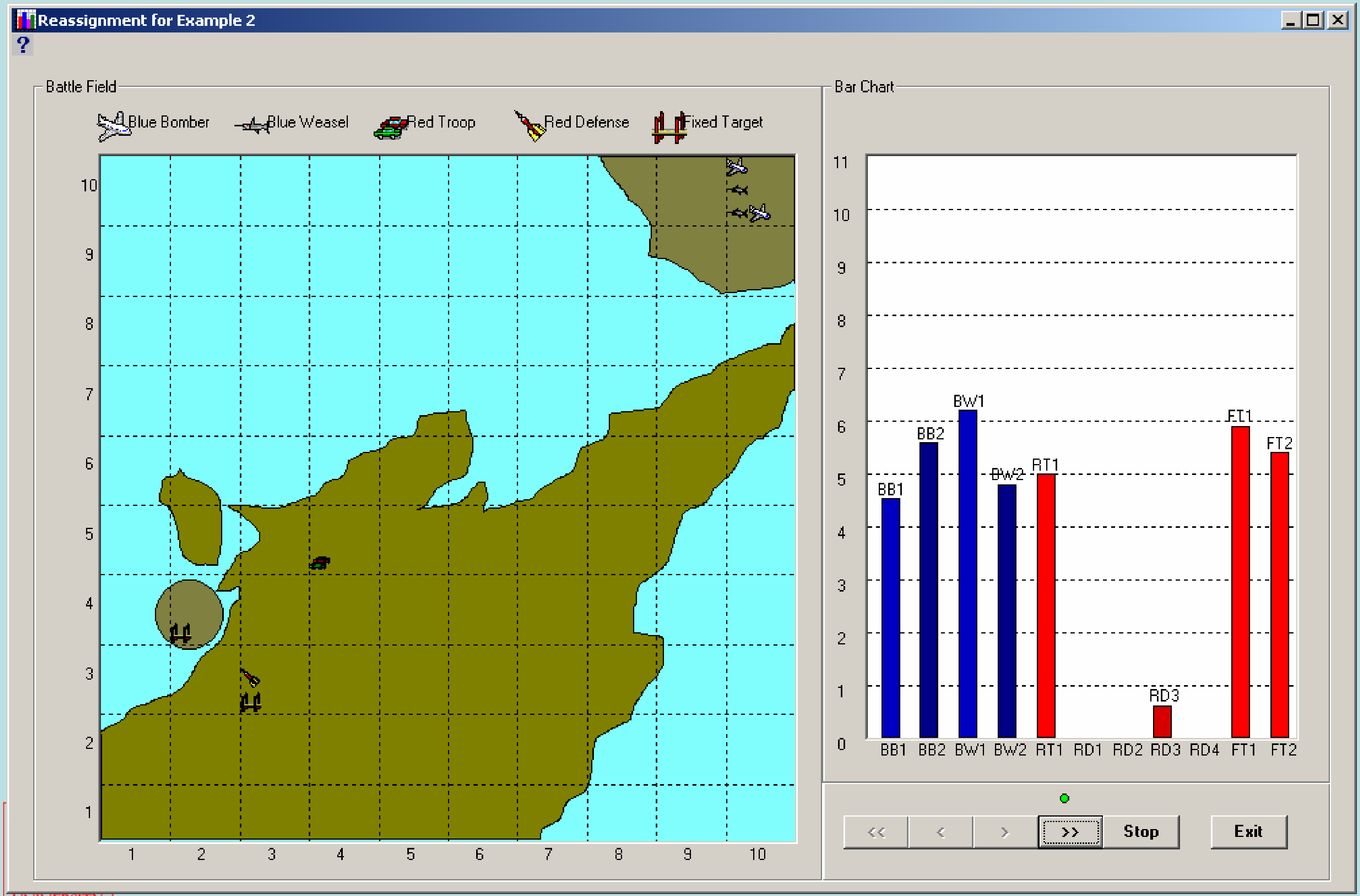
Final Result Without Re-assignment in Example



Final Result With Re-assignment in Example



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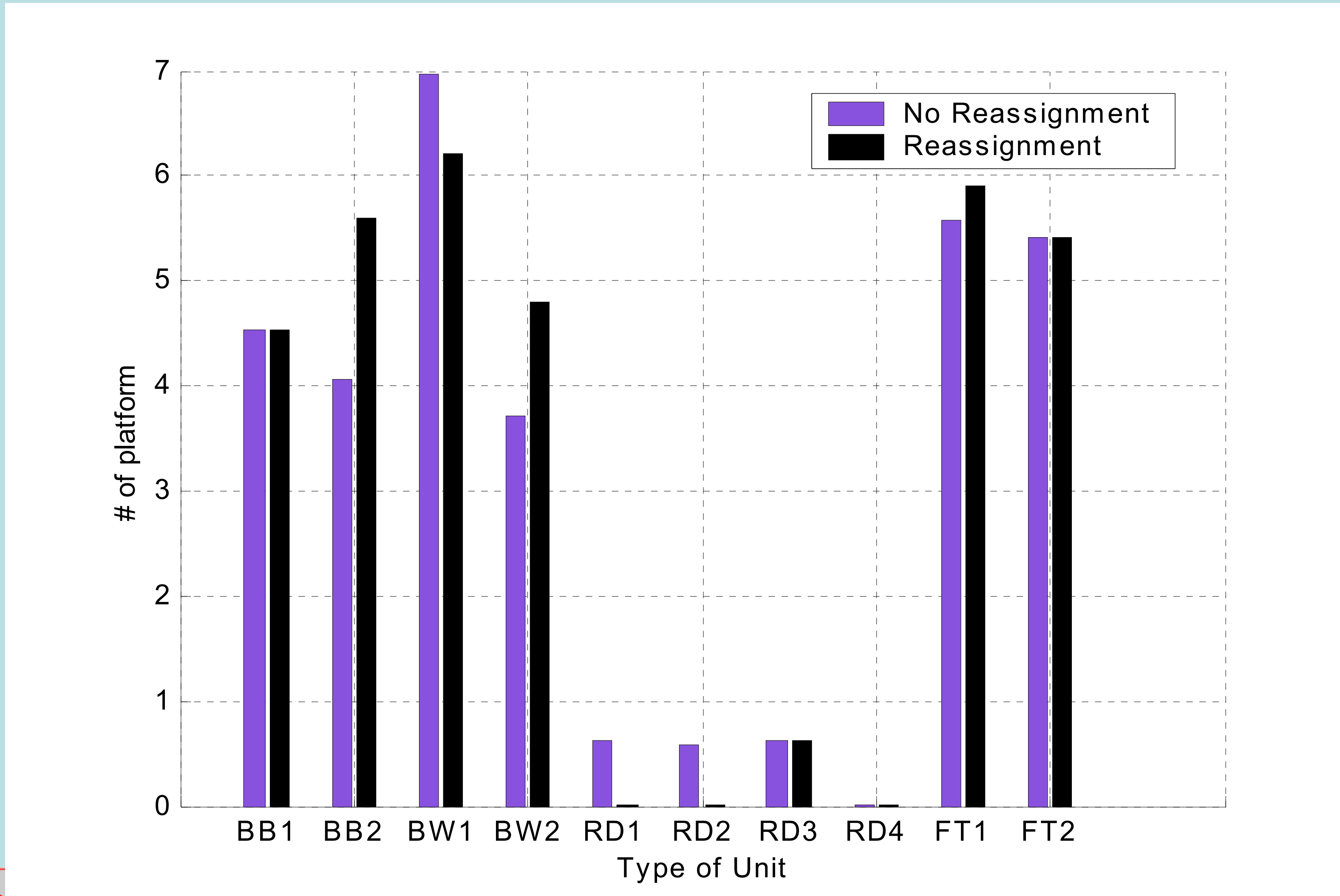
Comparison of battle damage in Example



Open Problems

- Game theory assumes that the players know the objectives of the other players. For agents of the same enterprise this is not a problem. For competitive or adversarial players, there is a need to estimate intent of the other players. This is preferable to ignoring them or assuming that their effects are like noise.

Open Problems, continued

- When the links to the enterprise are weak or absent, the agents become semi-autonomous.
- The agents need limited communication with their peers to maintain collaboration and coordination.

Concluding Remarks

- Decision-making in extended complex enterprises is very challenging.
- Hierarchical incentive strategies offer potential benefits that are not achievable without incentives.
- Modeling extended enterprises pose new challenges not present in isolated enterprises.