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A New Methodology for Design and Evaluation of Heterarchical Structures

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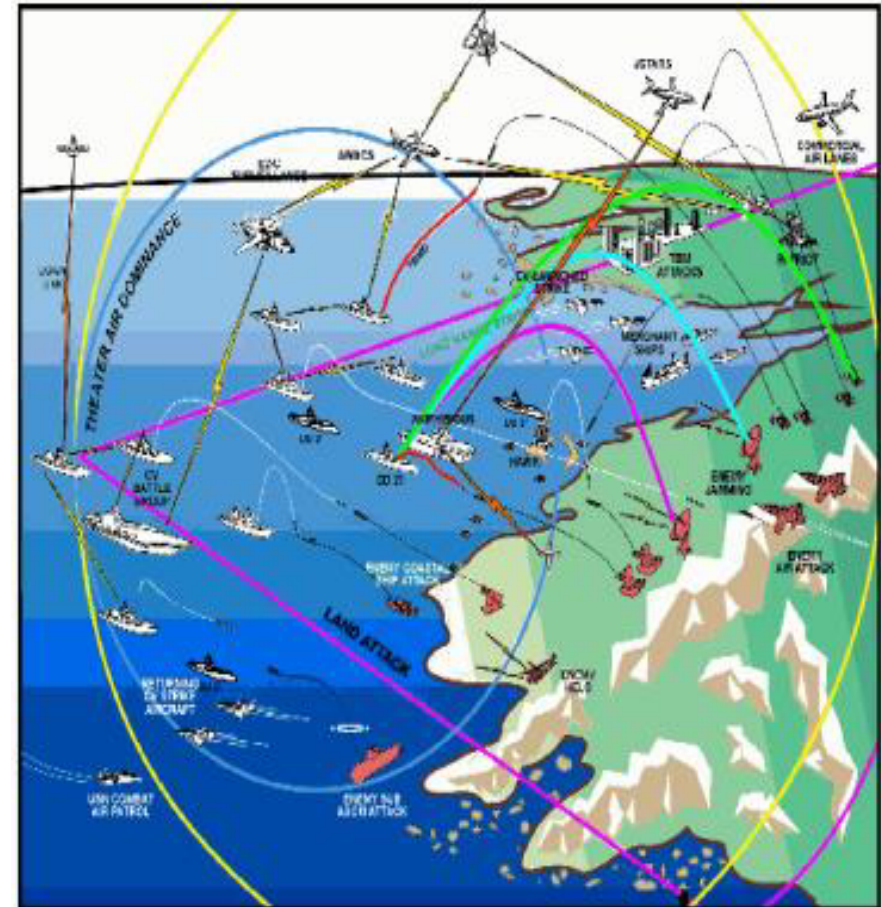
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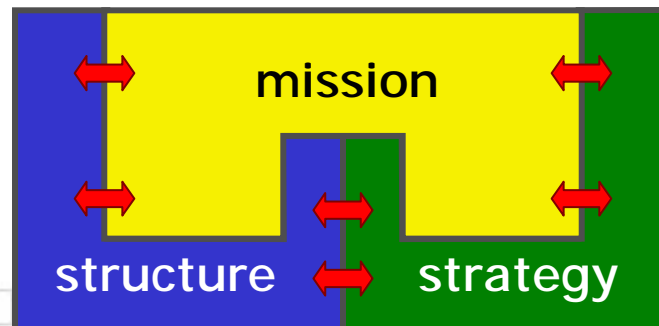
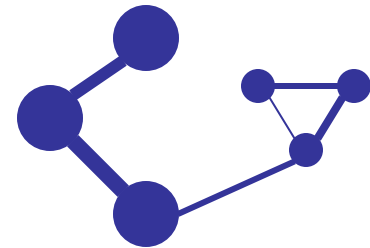
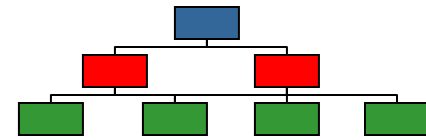
Basic Notions

- Mission
 - Events, activities, tasks to be executed
- Organization
 - Agents
 - ◆ Limited workload capacity
 - ◆ Heterogeneity in effectiveness of observation, command, information fusion, task execution
 - Structure
 - ◆ Access to and *transfer* of **resources**
 - ◆ Access to and *transfer* of **information**
 - ◆ *Generation* and *transfer* of **command**
 - ◆ Structures have **capacity** constraints
 - Strategy
 - ◆ Observation (who sees what)
 - ◆ Information routing and fusion (who communicates to whom)
 - ◆ Command execution and transfer (who commands whom)
 - ◆ Task allocation and execution (who executes what)
 - Resources



Formalization

- What problem are we addressing?
 - Design of organizational structures / networks and strategies
- What is the **structure/network** in our context?
 - Collection of items and rules/constraints of their interactions
 - Collection of nodes, links, channels
- What is the **strategy**?
 - Policy/procedures/rules/guidance to execute a mission
- What is an **issue**?
 - Interactions between mission, structure, and strategy



- Why study heterarchies?
- Types of Structures and Design Challenges
- Research evolution
- Problem identification & constraints
- Process chain
- Agent process graph
- Multi-layer network structure
- Solution approach
- Simulation examples

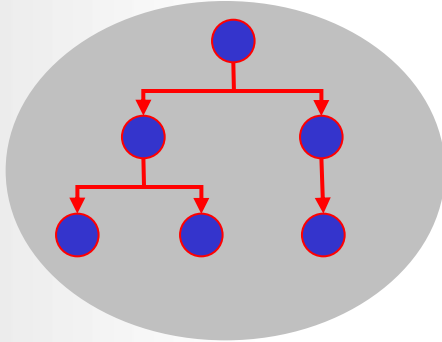
Why Study Heterarchies?

- New technologies – additional **friendly** flexibility to exploit (FORCEnet concept)
- Need to study the **enemy** (e.g., **terrorist networks**)
- Need to study the **environment** (e.g., customer networks, social interactive environments, supply-demand chains, “informal” relationships within hierarchies)
- Heterarchical relationships are “**richer**”, and contain principles and mechanisms that have potential to render *superior performance*
- Thus need to study these relationships in order to:
 - determine how to **influence** other organizations
 - see if concomitant design principles can be **imbedded** into control structures of organizations to *enhance performance*

Types of Structures

Command

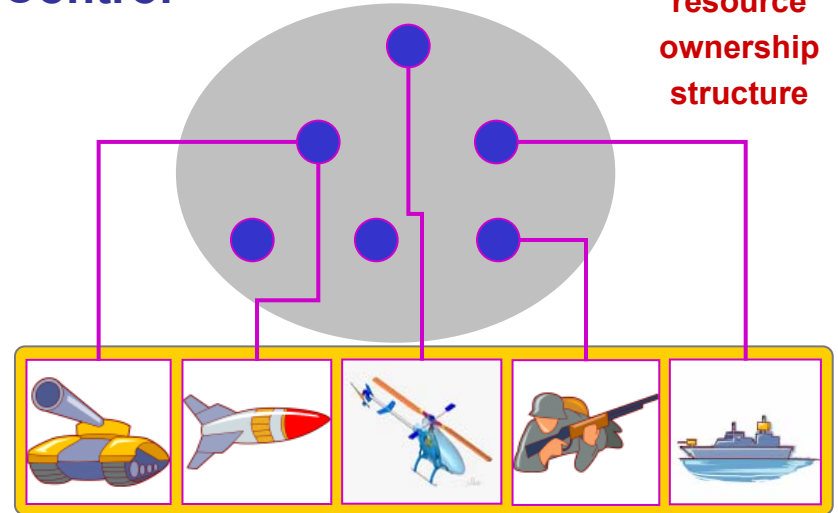
Execution ordering



send
commands

Control

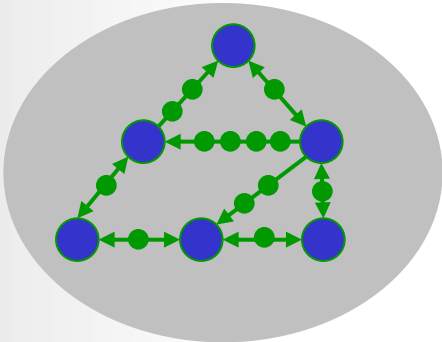
Execution capabilities



resource
ownership
structure

Communication

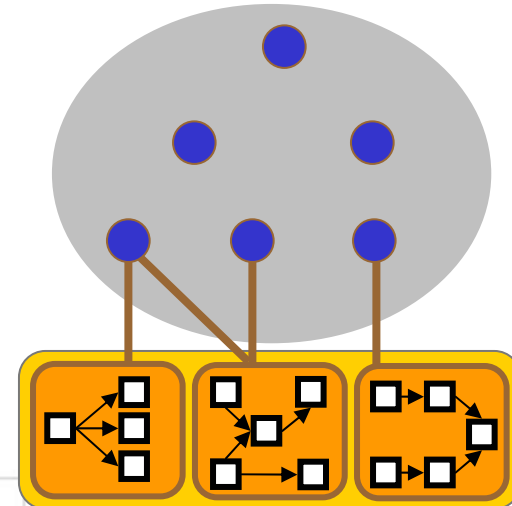
Info propagation



send
information

Information

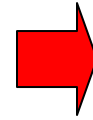
Knowledge/SA



info/event
access
structure

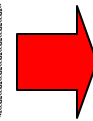
Design Challenges

Challenge 1: Identification of interactions between agents



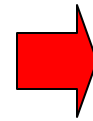
- Use template interaction message library
- Use rule-based reasoning in synthetic environment

Challenge 2: Interaction constraints and agent effectiveness

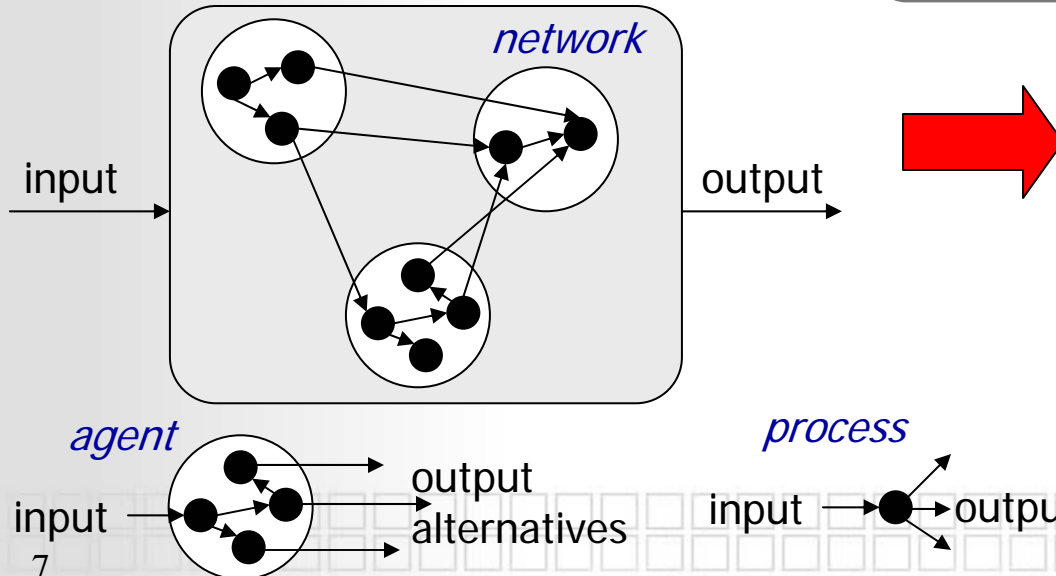


- Study restrictions in information access and flow, workload capacity, processing speed, command flow, etc.
- Study feasibility of structures in military domain

Challenge 3: Complexity & influence of (sub)structures and strategies on each other



- Model how flow is treated in the organization (transfer, consumption, generation, etc.)
- Inter- and intra-agent networks



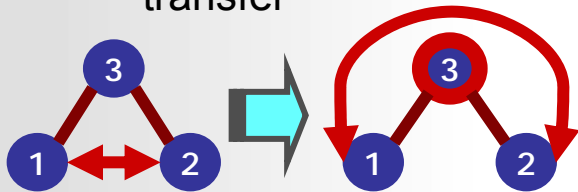
Modeling approaches:

- Use flow model: cost and capacity constraints
- Non-linear function of cost for flow transfer links
- Multi-commodity & non-splittable flow modeling
- Heuristic algorithms to maintain network robustness
- Local / distributed decision making

Research Evolution

Overhead-based design

- Given: **communication requirements**
- Find: a **hierarchy**
- Objective: minimize **communication overhead**
 - Based on exceptions to process, decision-making workload, and load of information transfer

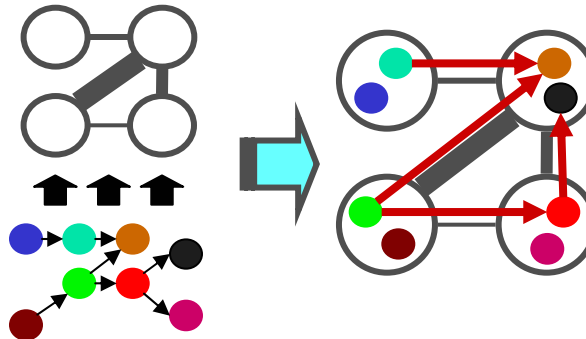


Cons:

- No **effect** of overhead
- No network constraints

Schedule-based design

- Given: **agent network**
- Find: a **task assignment** and **schedule**
- Objective: minimize **mission time**
 - Based task information flow and inter-agent communication

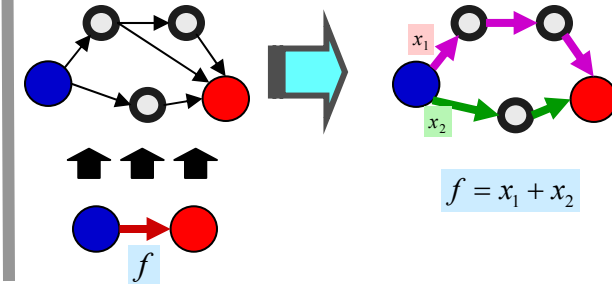


Cons:

- Global controller
- No network design
- Limited routing; no info split

Routing-based design

- Given: **communication requirements**
- Find: a **network** and **info routing**
- Objective: minimize **average delay**
 - Based on information routing & queuing model



Cons:

- No strategy (assignment)-structure allocation
- No multi-structure design

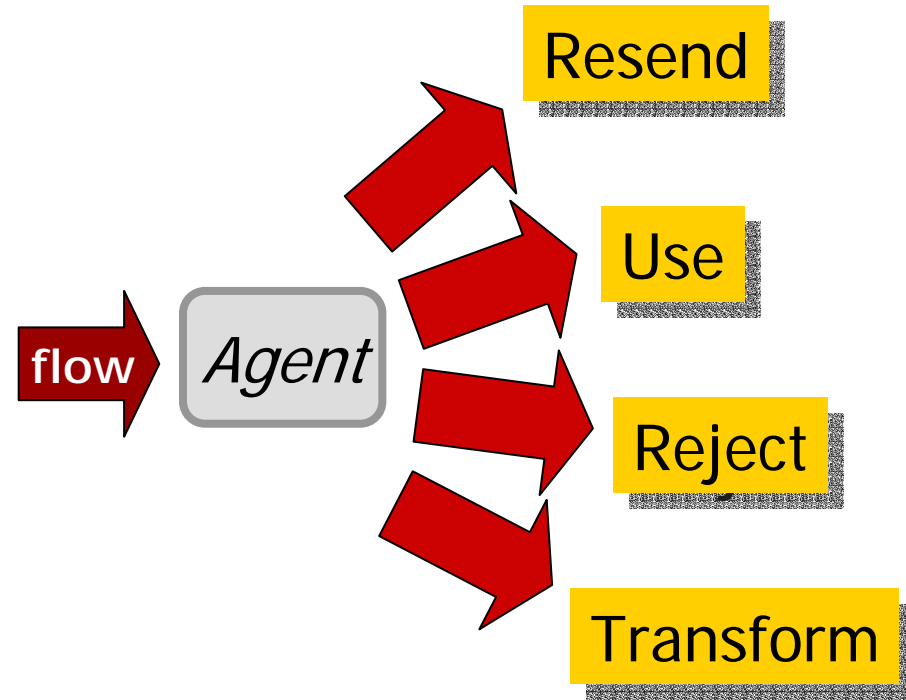
Design Evolution

What is Missing?

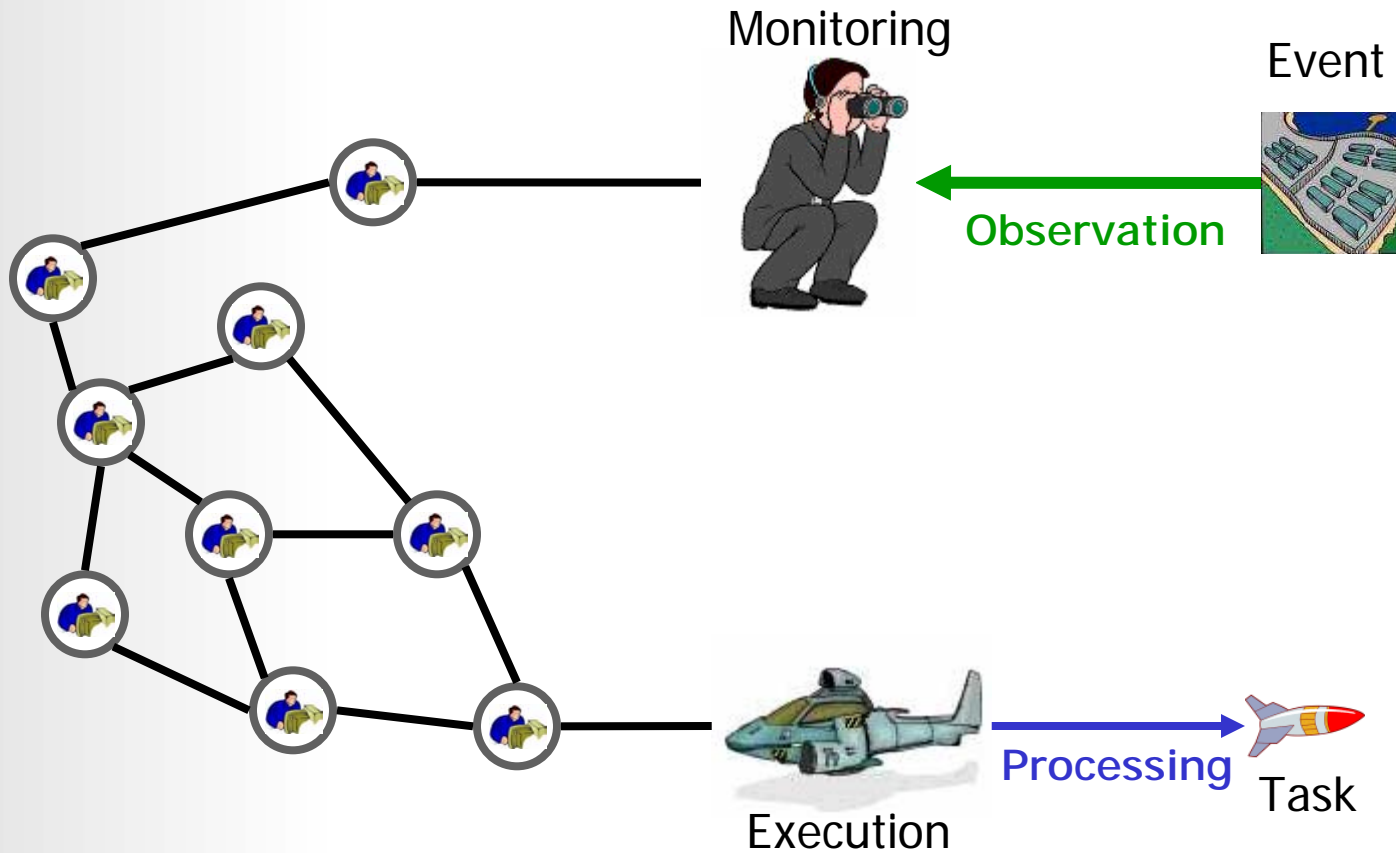
- Strategy-structure-mission interaction/influence
- **Strategy:** how and what is done
- **Structure:** by what means a strategy is accomplished
- **Mission:** what needs to be accomplished

Problem Identification

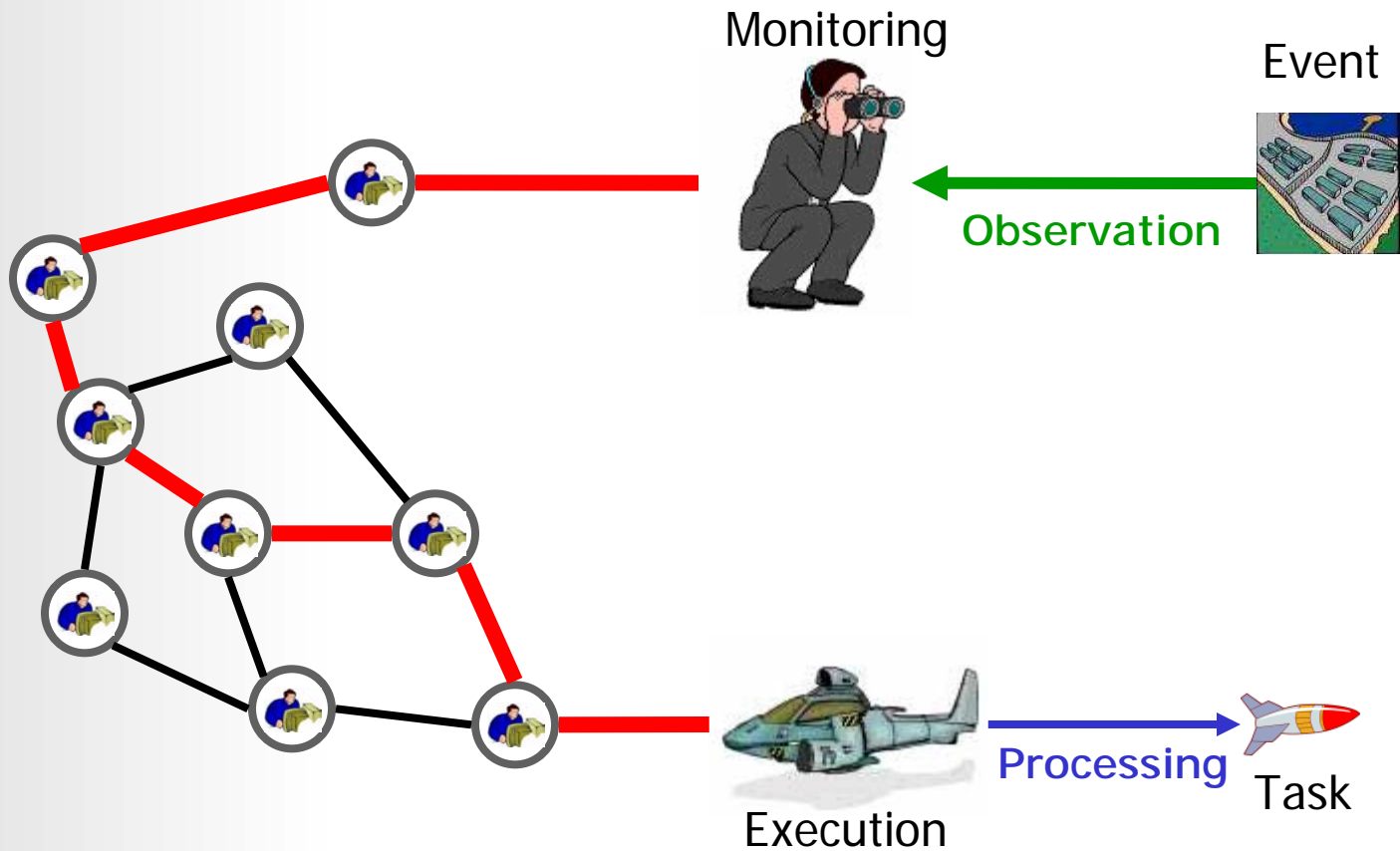
- Agents
 - Observe events
 - Receive/transfer/fuse info
 - Generate/receive/transfer command
 - Receive/transfer/process tasks
- Links/Channels
 - Transfer information
 - Direct command
 - Access observations
- Model agent operations as flow processing
 - Flow of information, command orders, resources, requests for synchronization, exceptions, etc.



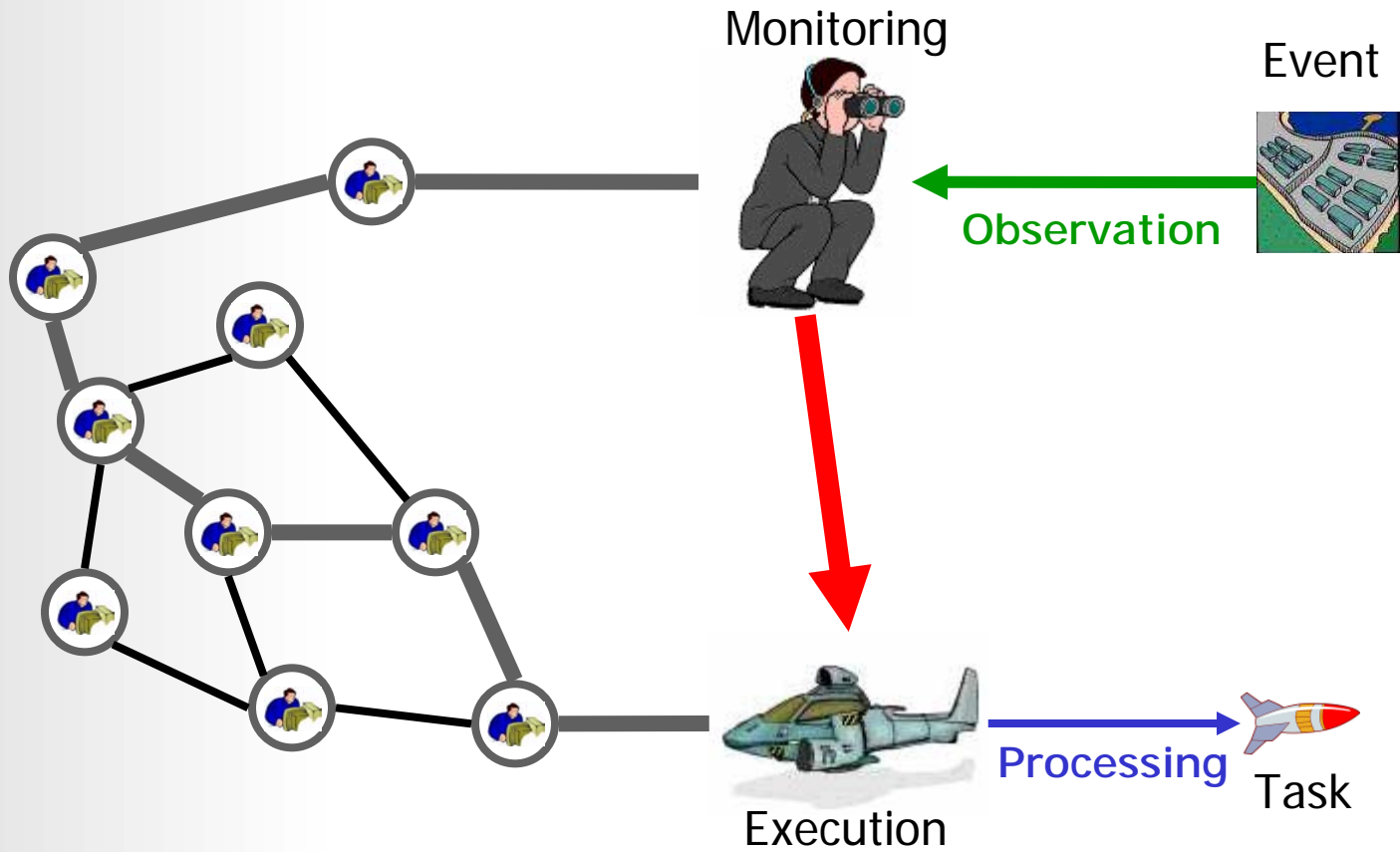
What Are We Doing?



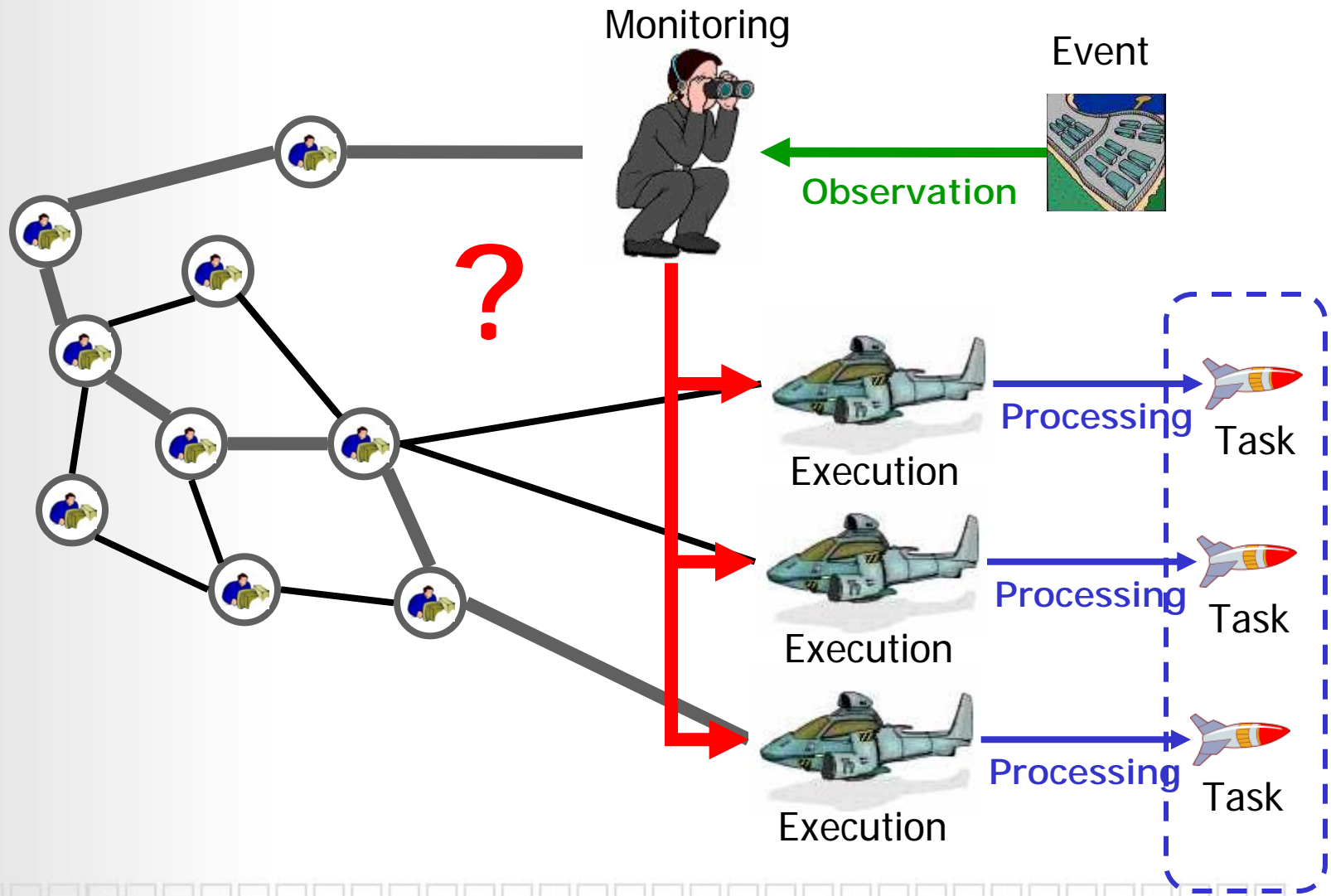
Getting the Right Info to Right People



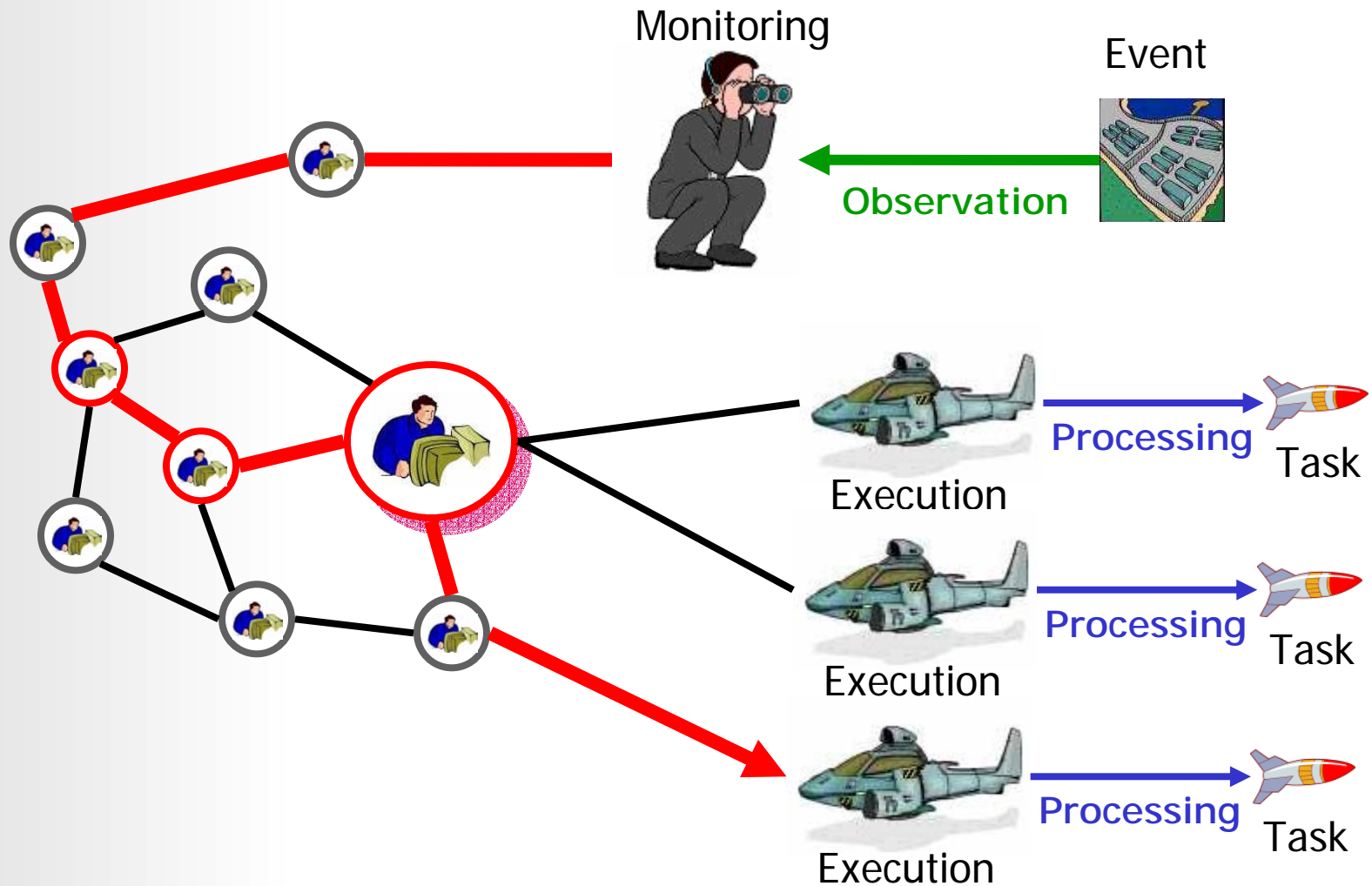
Direct Info Access



Info Conflict



Command as a Resolution



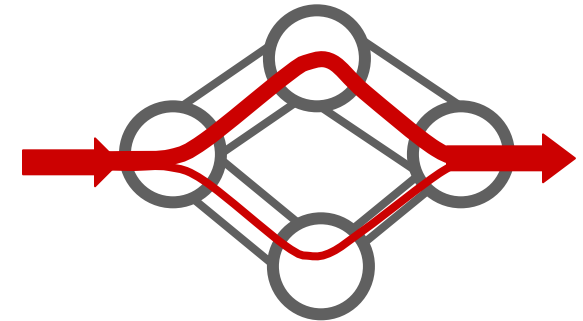
- Agents:
 - Workload capacity
 - ◆ Limit amount of operational and cognitive load
 - ◆ Include load of observations, communication, decision-making, task execution
 - Operation efficiency
 - ◆ Different expertise for observation, command, task processing, transfer
 - ◆ Based on agent expertise
 - Multiple types of expertise assessed; grading each
 - Multi-type expertise capability ⇒ generalists
 - Single-type expertise capability ⇒ specialists
- Links/channels:
 - Cost of maintenance
 - Use simple linear function of flow amount

Problem Specifics

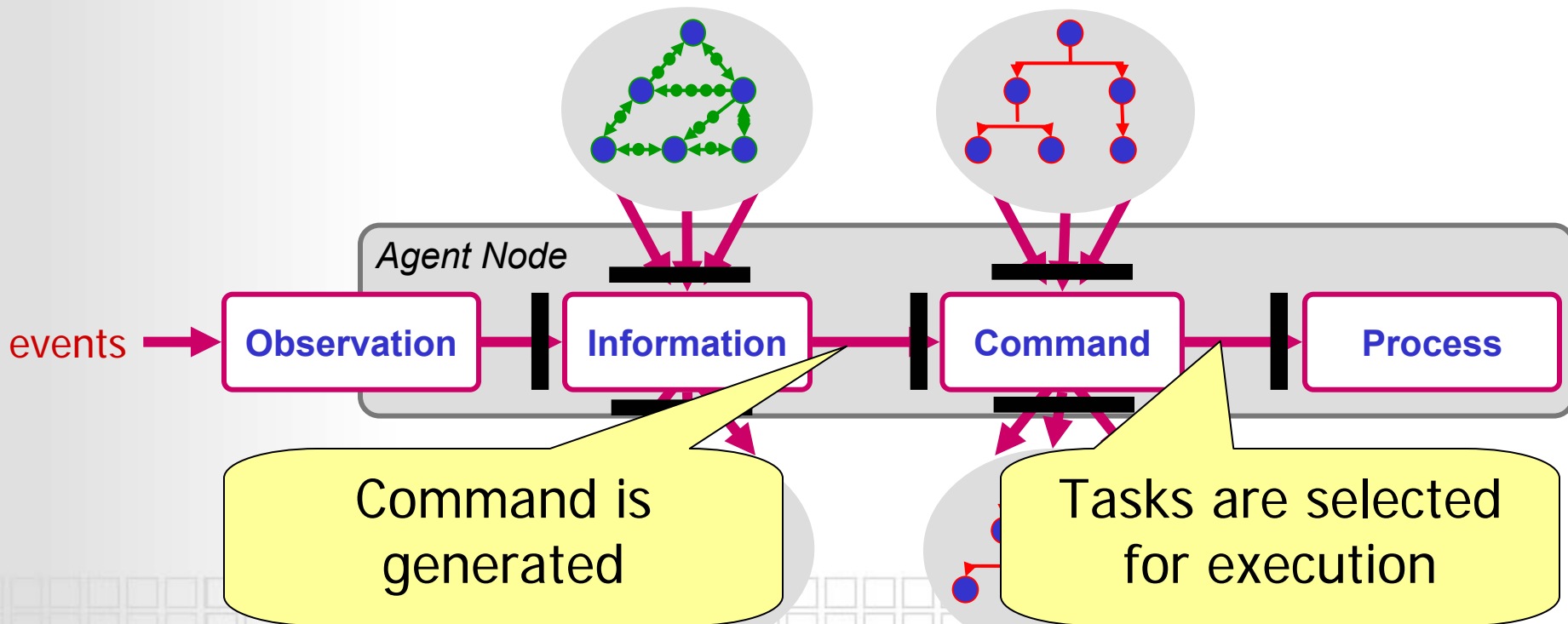
Flow chain:



splitting allowed



Agent process graph:



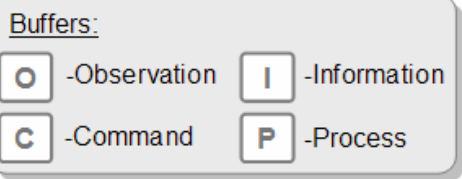
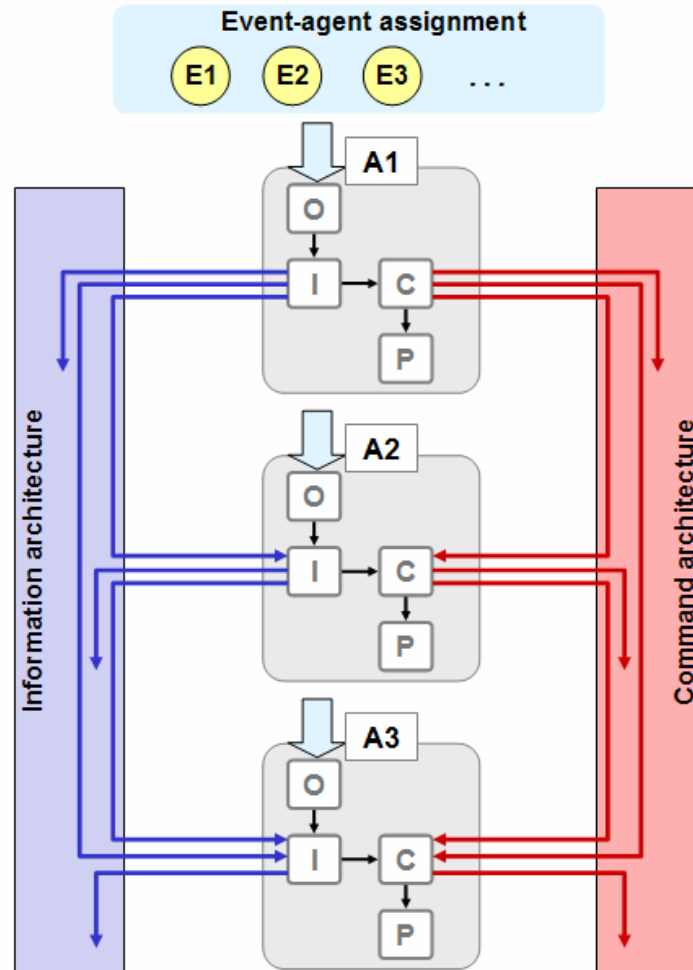
■ Capacity

- Identifies the threshold of volume
- At agent process nodes & links: agents constraints
- At links/channels: structure constraints

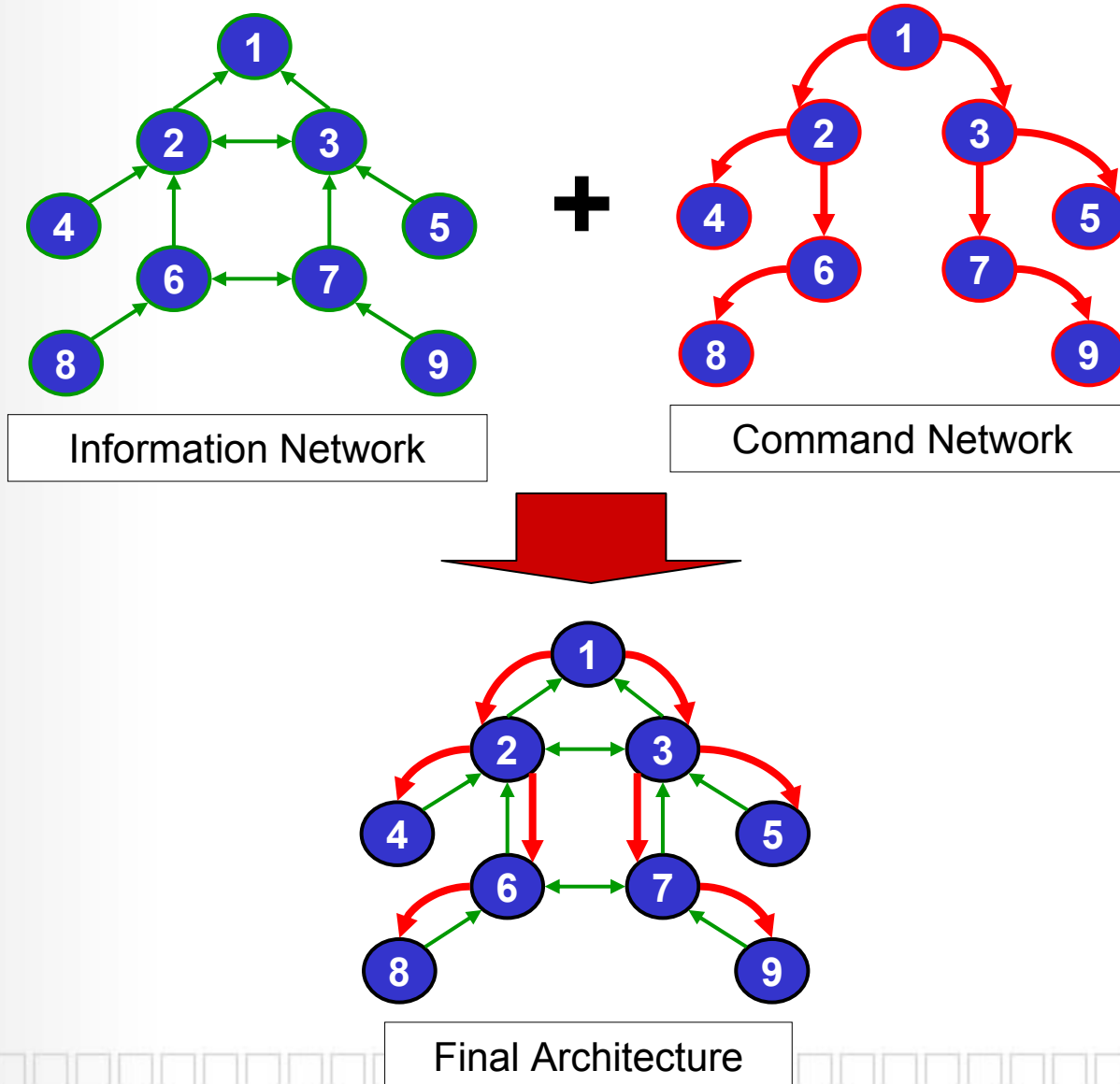
■ Mission Gain

- **Positive – task execution gain:** from the efficiency/accuracy of agents to observe, conduct decision making, execute tasks, communicate
- **Negative – transfer cost:** info/tasking through network
 - ◆ Network maintenance
 - ◆ Information loss
 - ◆ Interpretation loss
 - ◆ Noisy transmission

Joint Graph

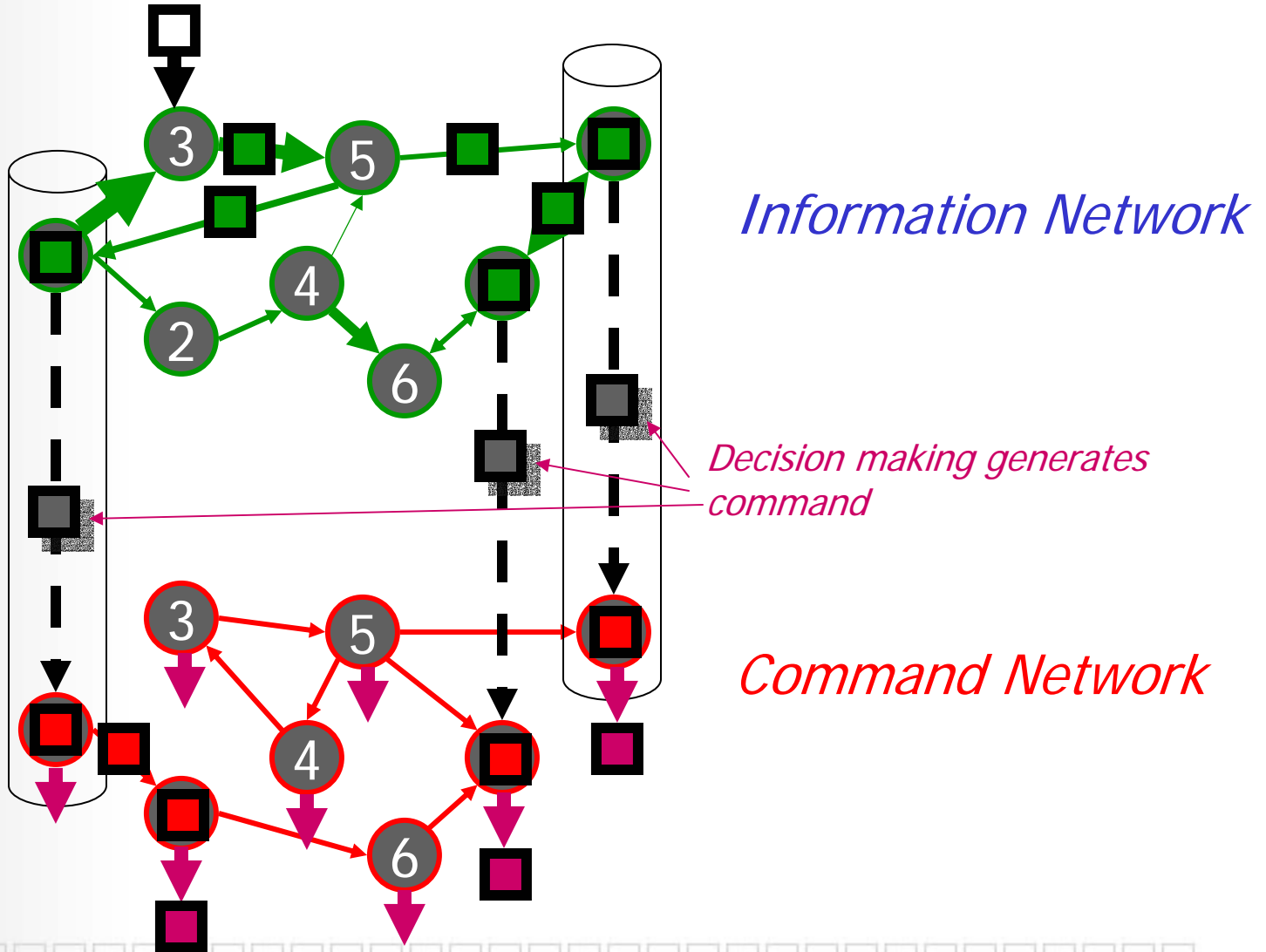


Example of Hybrid Structure



Multi-Layer Organization

Event is observed

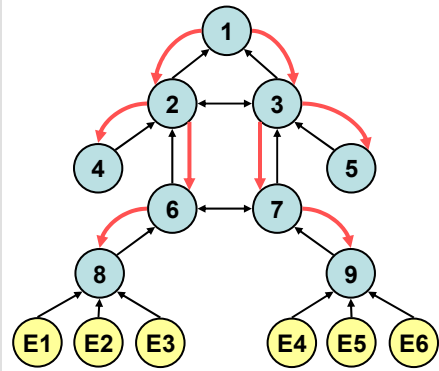


Solution Approach

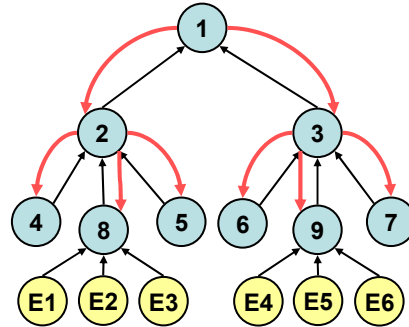
- **Step 1:** Define mission
 - Events volume and expertise requirements
- **Step 2:** Define organization
 - Agent expertise
- **Step 3:** Define agents' process graphs
 - Agent capacities, processing gain
- **Step 4:** Define structure constraints
 - Link/channel capacities for different-type networks
- **Step 5:** Expand the aggregate network
 - Replace node capacity and gain constraints with link capacities and cost
- **Step 6:** Apply minimum cost maximum flow algorithm

- **Structure:** specification of load for sub-networks
 - Can use to design network bandwidth and architecture
- **Strategy:** specification of who does what
 - Observation, fusion, communication, transfer, execution

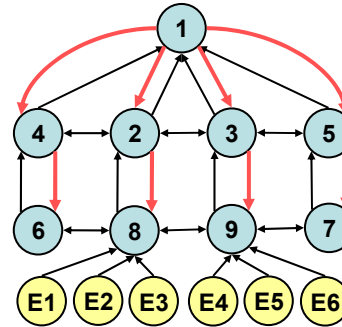
Sample Results



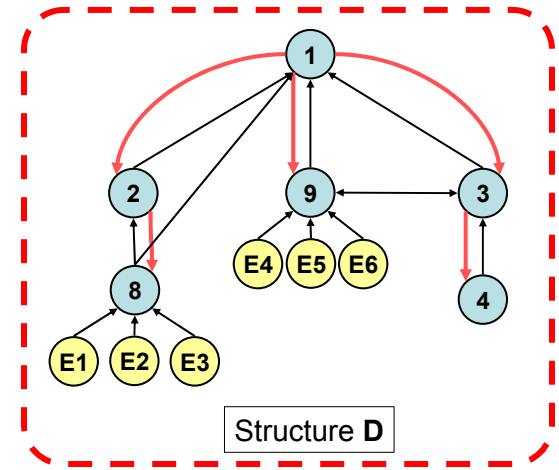
Structure A



Structure B

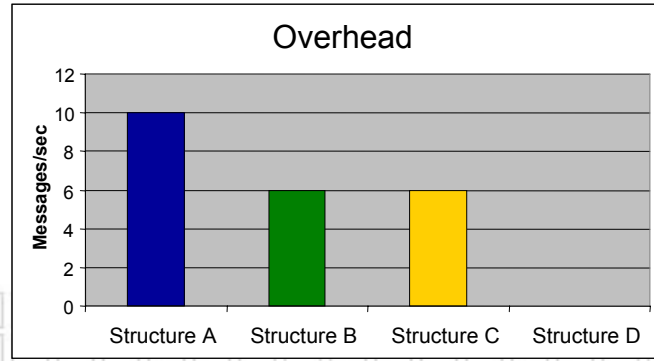
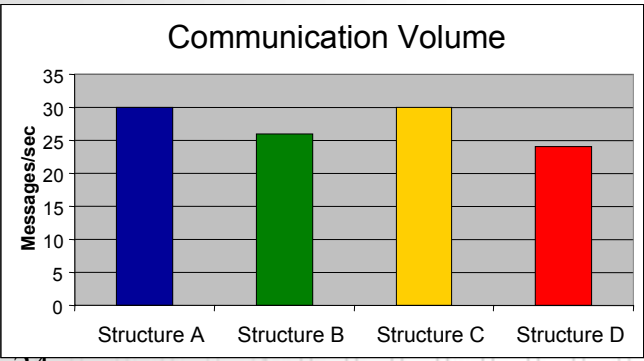
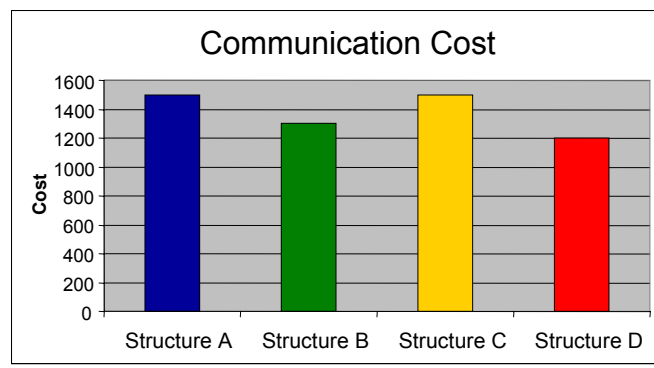
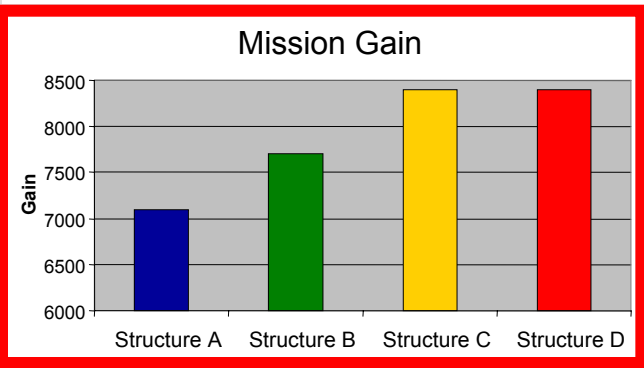


Structure C



Structure D

● - Agent node
● - Event/observation node
→ - Command network
→ - Information network



- Increase the accumulated mission execution effectiveness (gain) while decreasing the communication overhead, cost and volume
- **Optimal network allows better access to efficient nodes**

Future Directions

- Consider network robustness constraints
- Implement **multi-commodity** problem formulation
 - Currently we implemented single-type events
- Consider problem of **unsplittable** or partially splittable flows
 - An item can only be transferred through **single path**, without splitting
- Consider flow **transfer** and generation
 - Flow volume change
- Consider error propagation
- Consider local autonomous agent strategy based on partial information

Accomplishments:

- Developed methodology to design inter-dependent organizational sub-structures (command, observation, communication, information)
- Utilize the benefits and constraints of hierarchical, heterarchical, and hybrid structures
- Integrated structure-strategy optimization

Applications:

- Will provide innovative strategy and structure solutions for various levels and nodes of the FORCEnet