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# A New Methodology for Design and Evaluation of Heterarchical Structures

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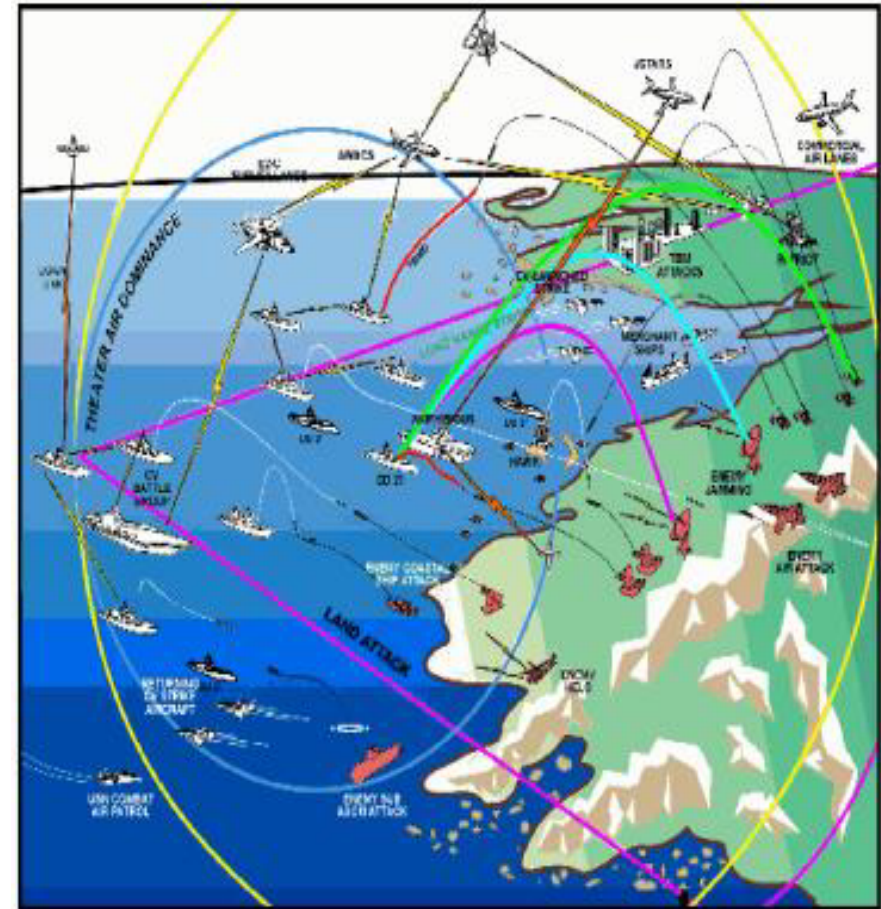
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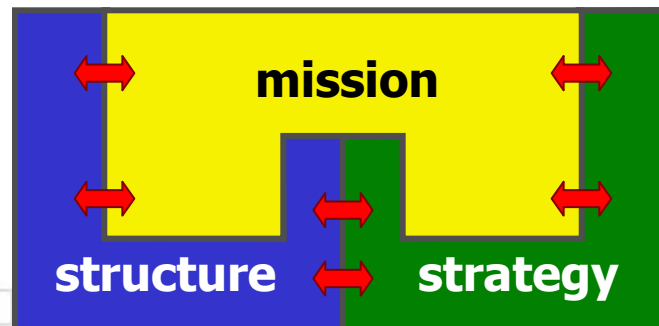
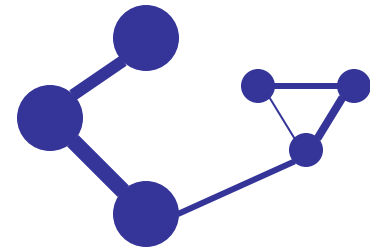
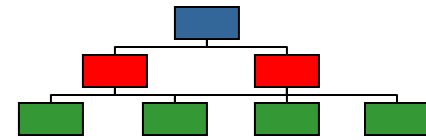
# Basic Notions

- 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

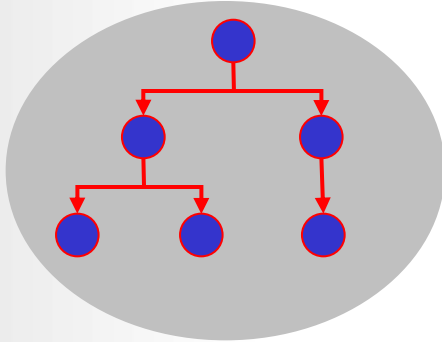
# Why Study Heterarchies?

- 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

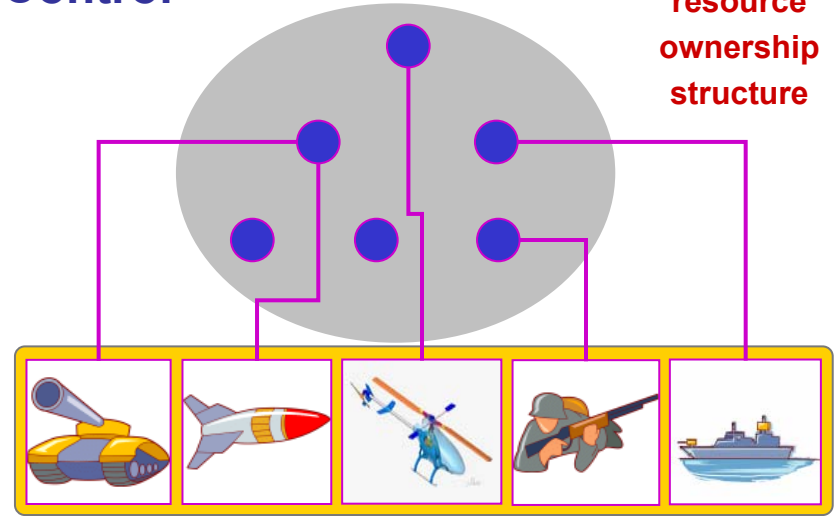
Execution ordering



send  
commands

## Control

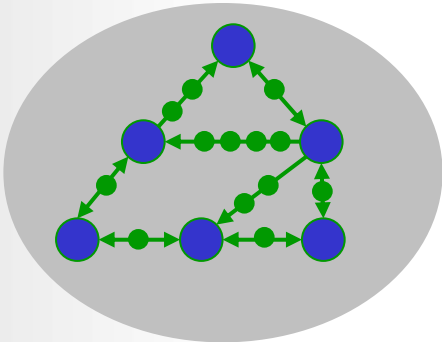
Execution capabilities



resource  
ownership  
structure

## Communication

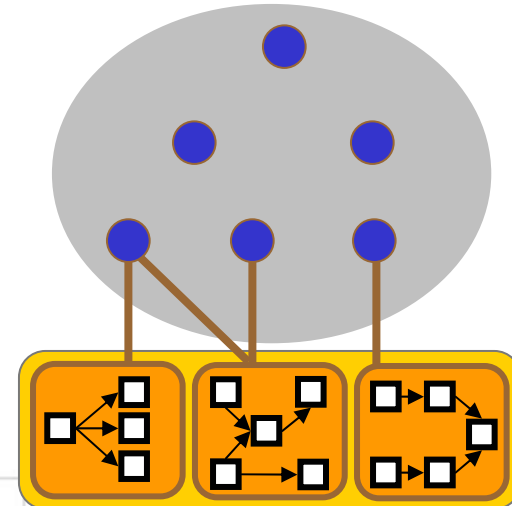
Info propagation



send  
information

## Information

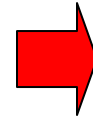
Knowledge/SA



info/event  
access  
structure

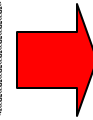
# Design Challenges

**Challenge 1:** Identification of interactions between agents



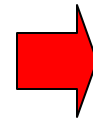
- Use template interaction message library
- Use rule-based reasoning in synthetic environment

**Challenge 2:** Interaction constraints and agent effectiveness

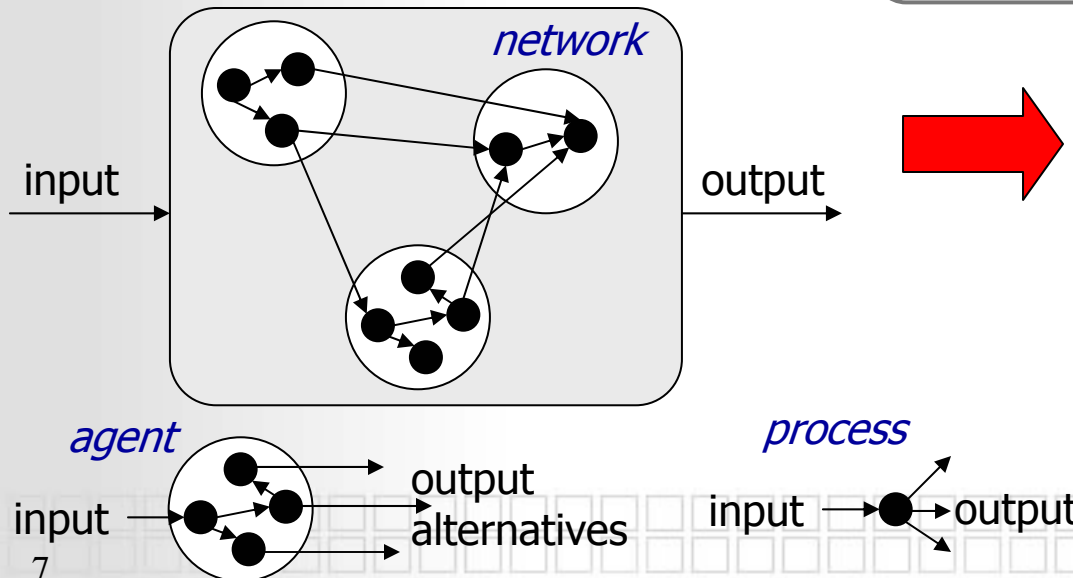


- Study restrictions in information access and flow, workload capacity, processing speed, command flow, etc.
- Study feasibility of structures in military domain

**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

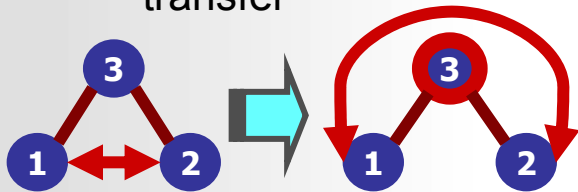


## Modeling approaches:

- 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

## 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

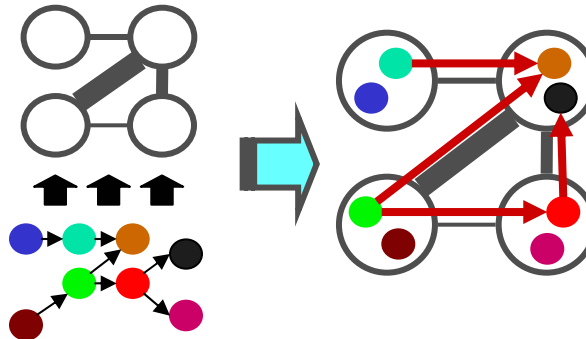


### Cons:

- 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

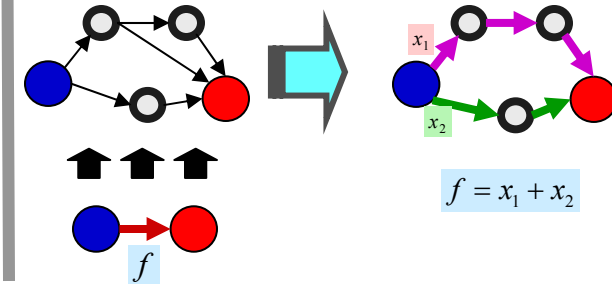


### Cons:

- 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**

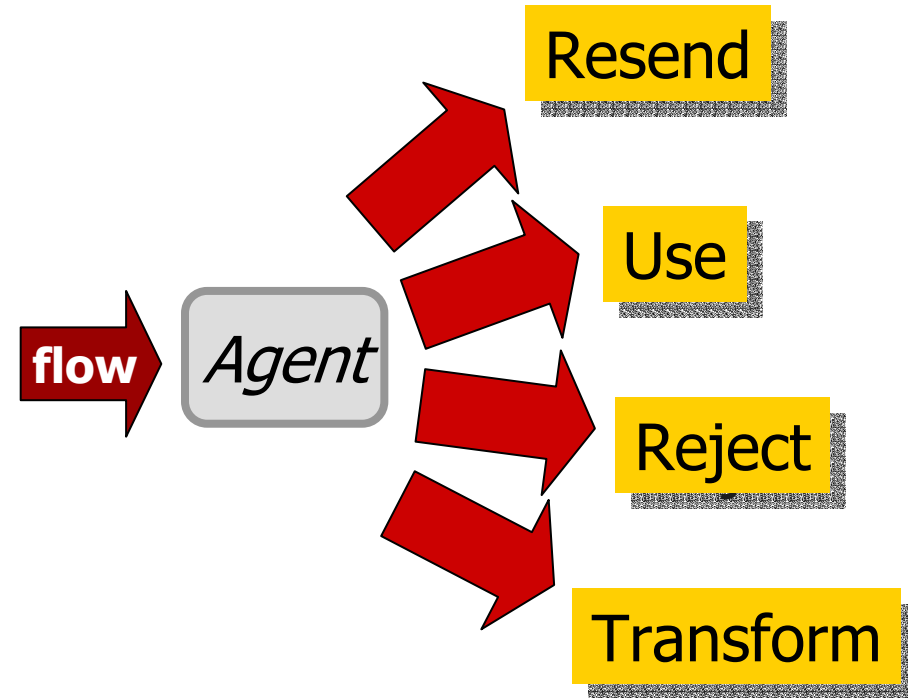


# What is Missing?

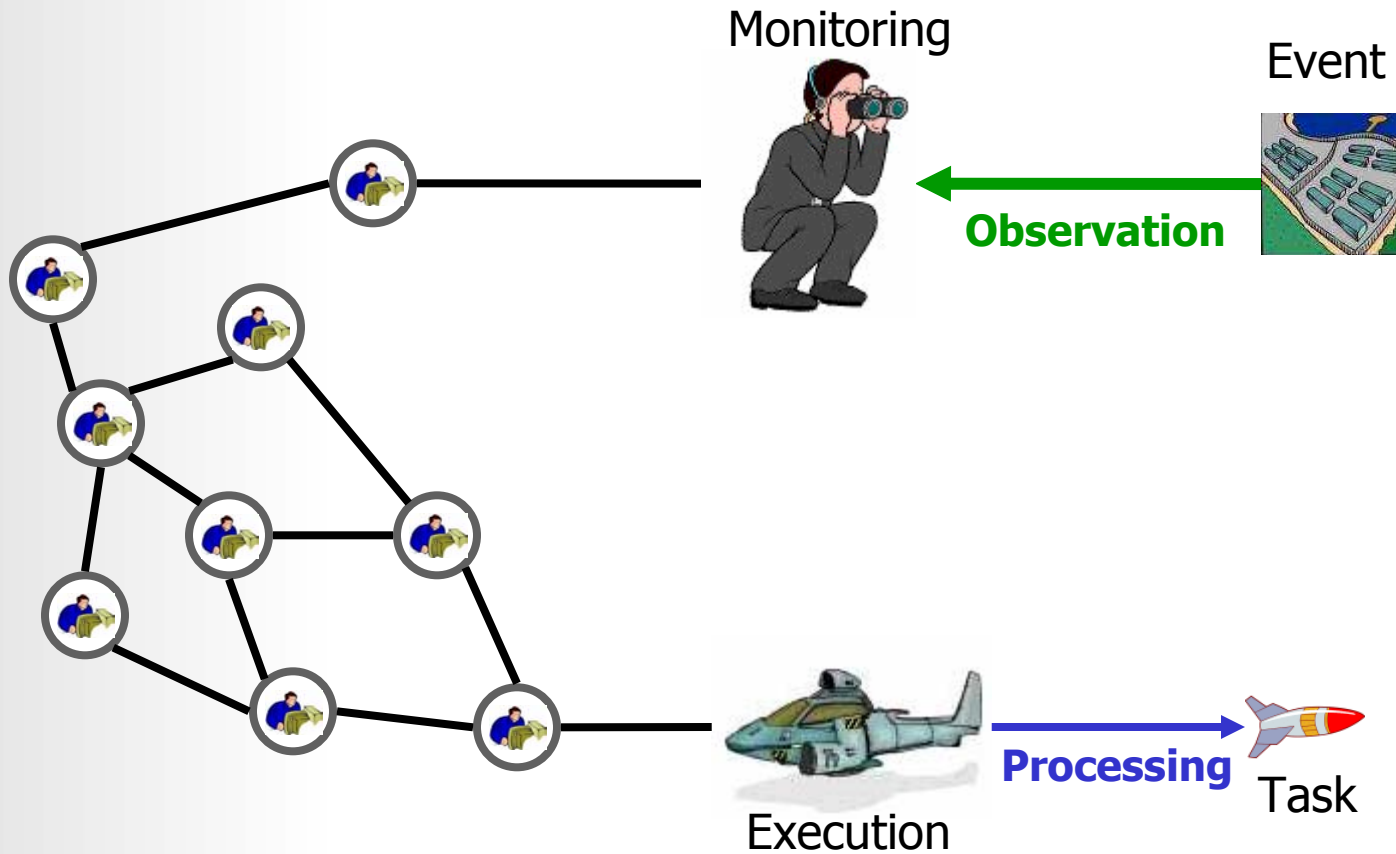
- Strategy-structure-mission interaction/influence
- **Strategy:** how and what is done
- **Structure:** by what means a strategy is accomplished
- **Mission:** what needs to be accomplished

# Problem Identification

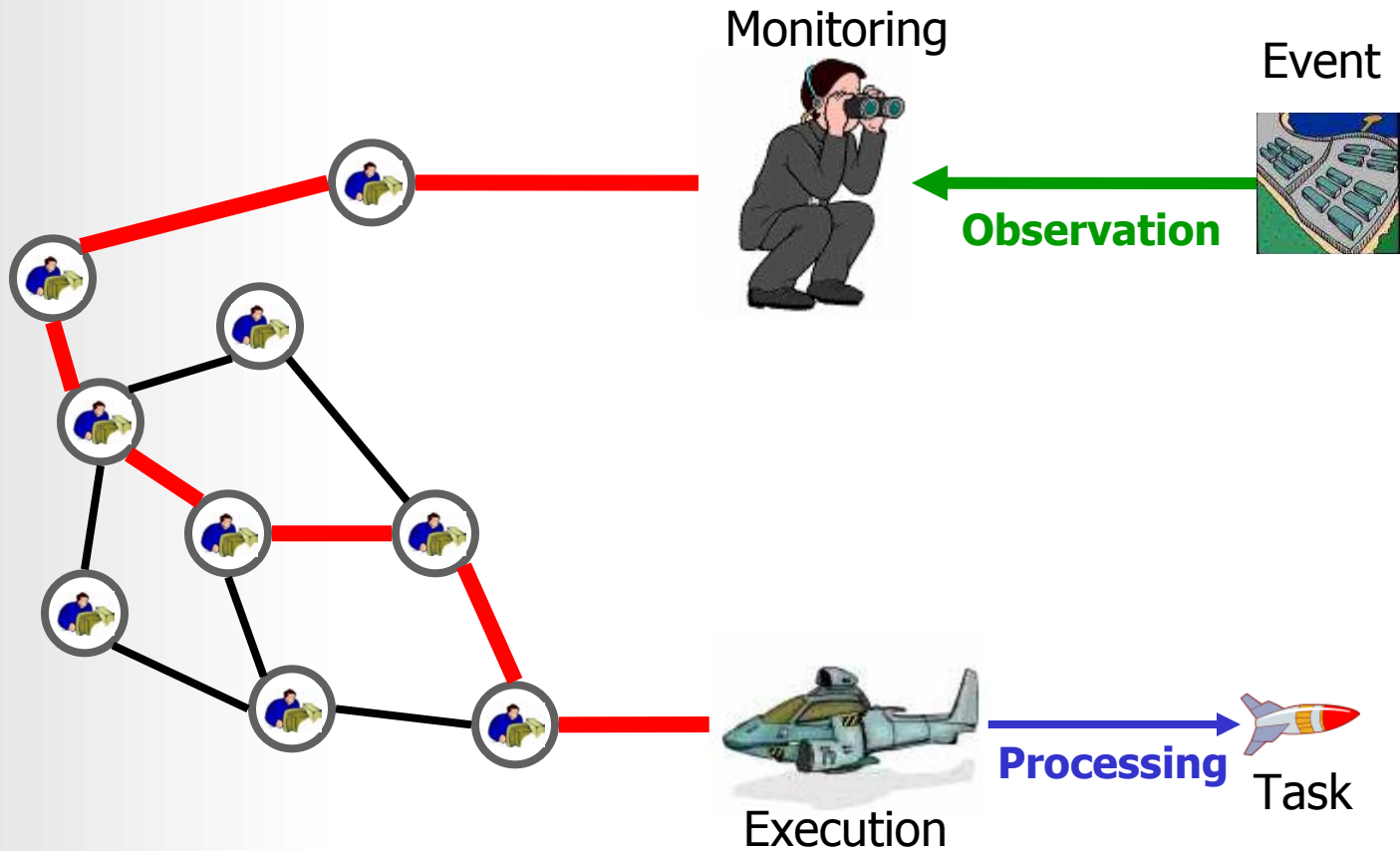
- Agents
  - Observe events
  - Receive/transfer/fuse info
  - Generate/receive/transfer command
  - Receive/transfer/process tasks
- Links/Channels
  - Transfer information
  - Direct command
  - Access observations
- Model agent operations as flow processing
  - Flow of information, command orders,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



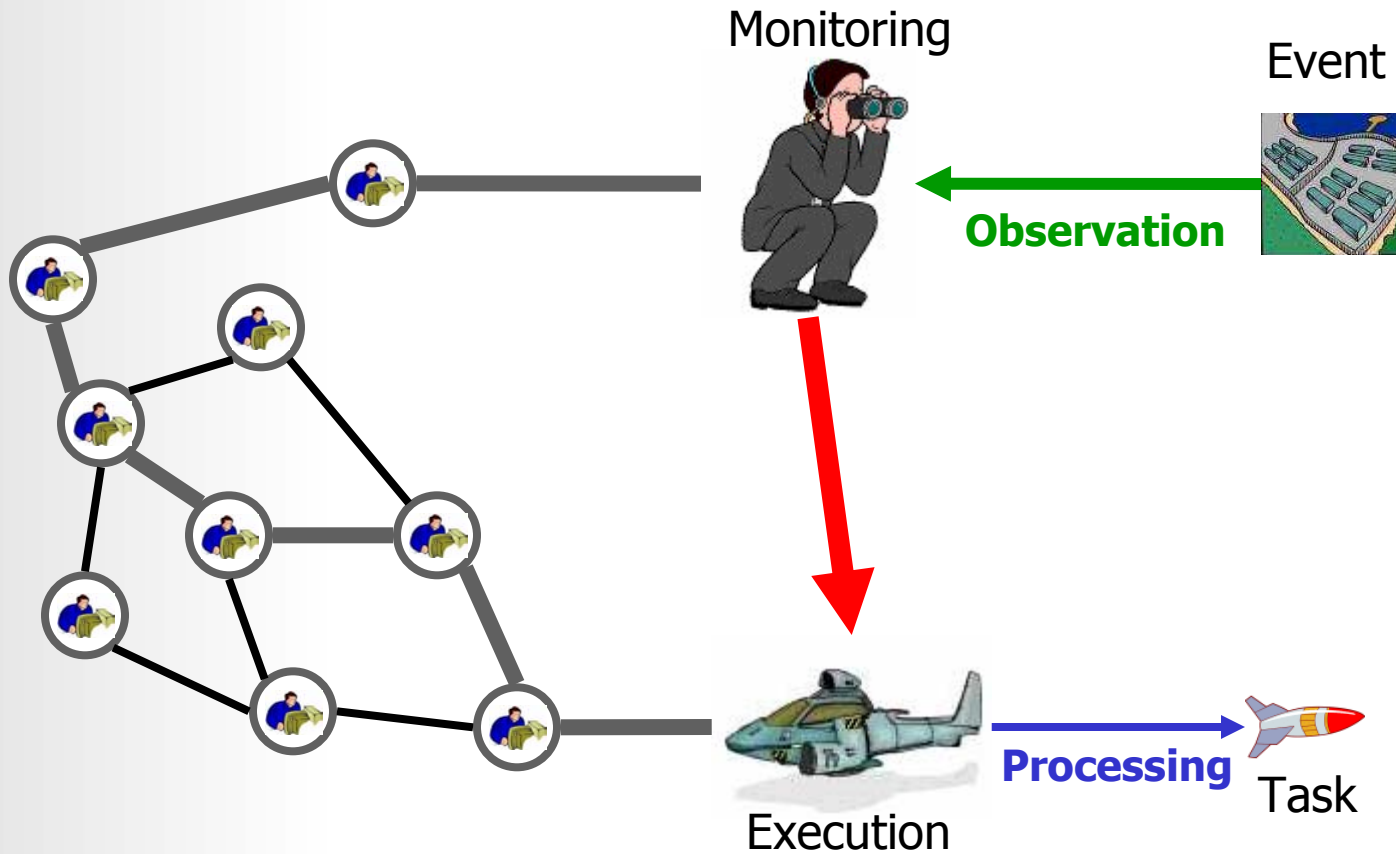
# What Are We Doing?



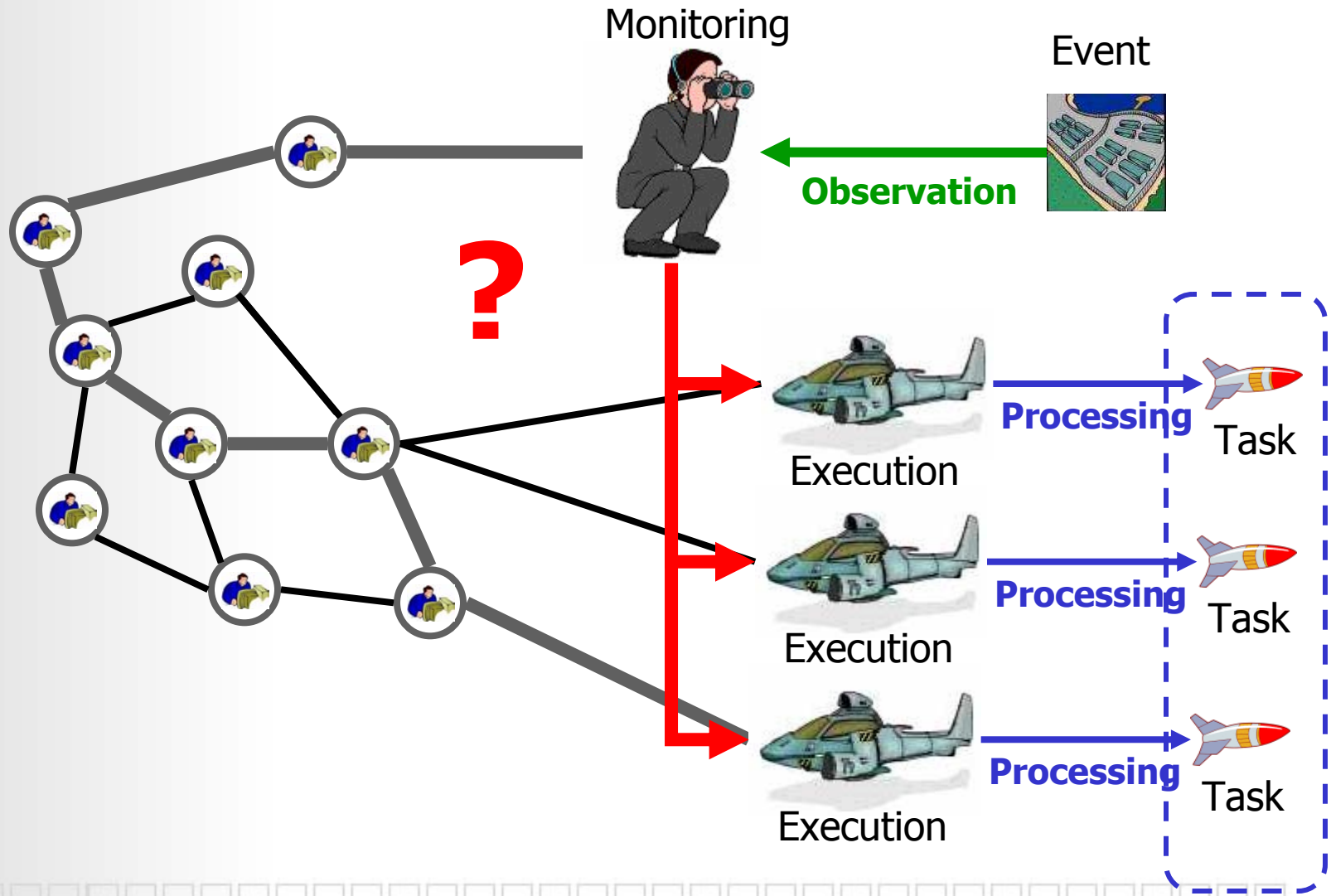
# Getting the Right Info to Right People



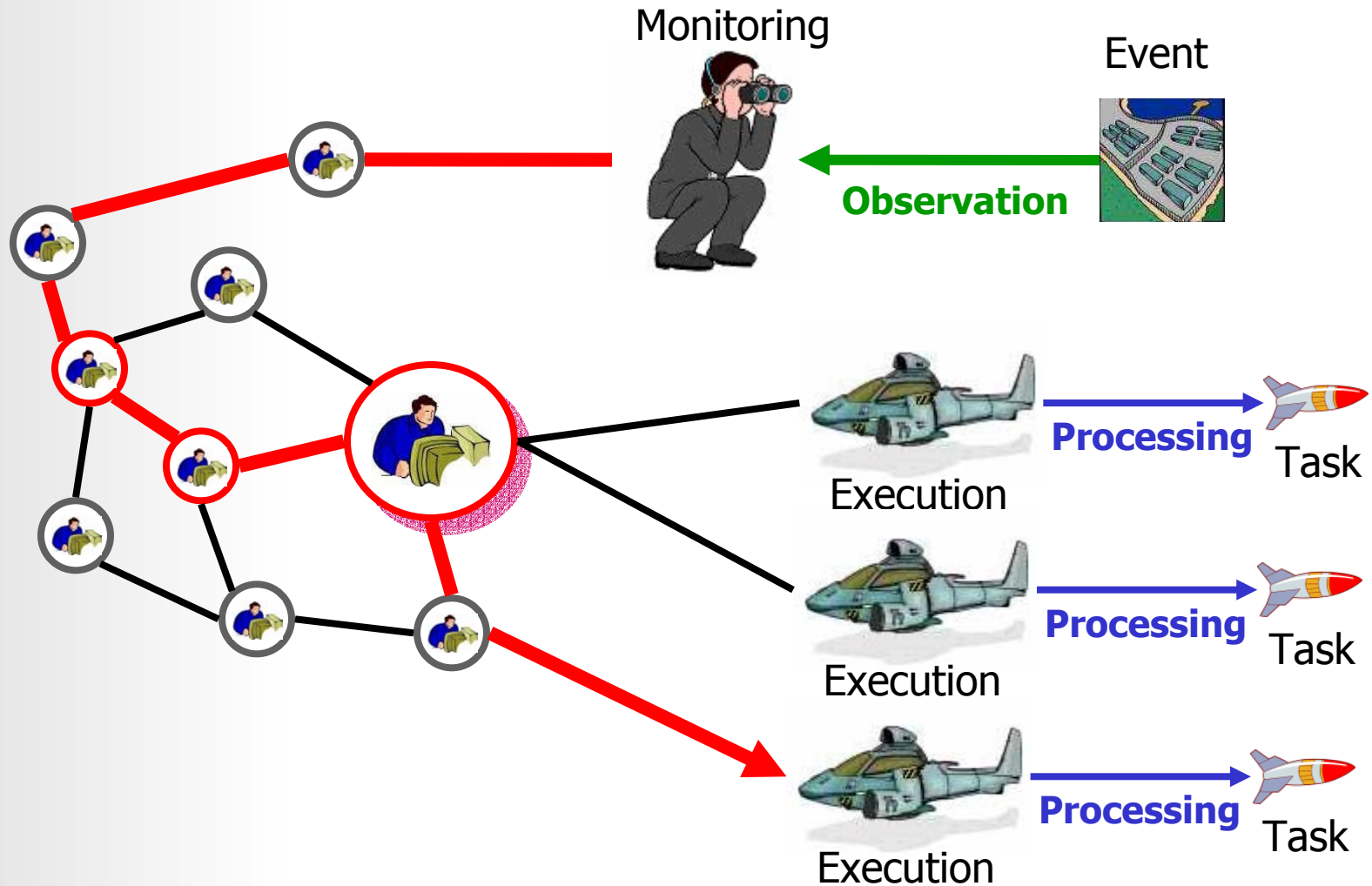
# Direct Info Access



# 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

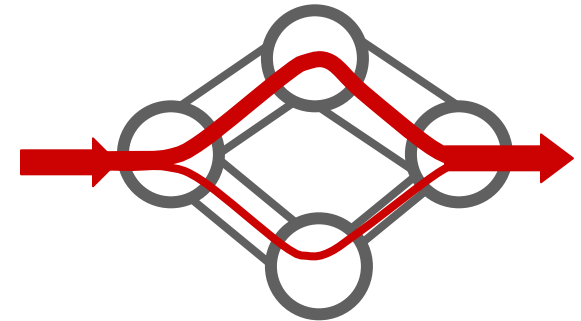


# Problem Specifics

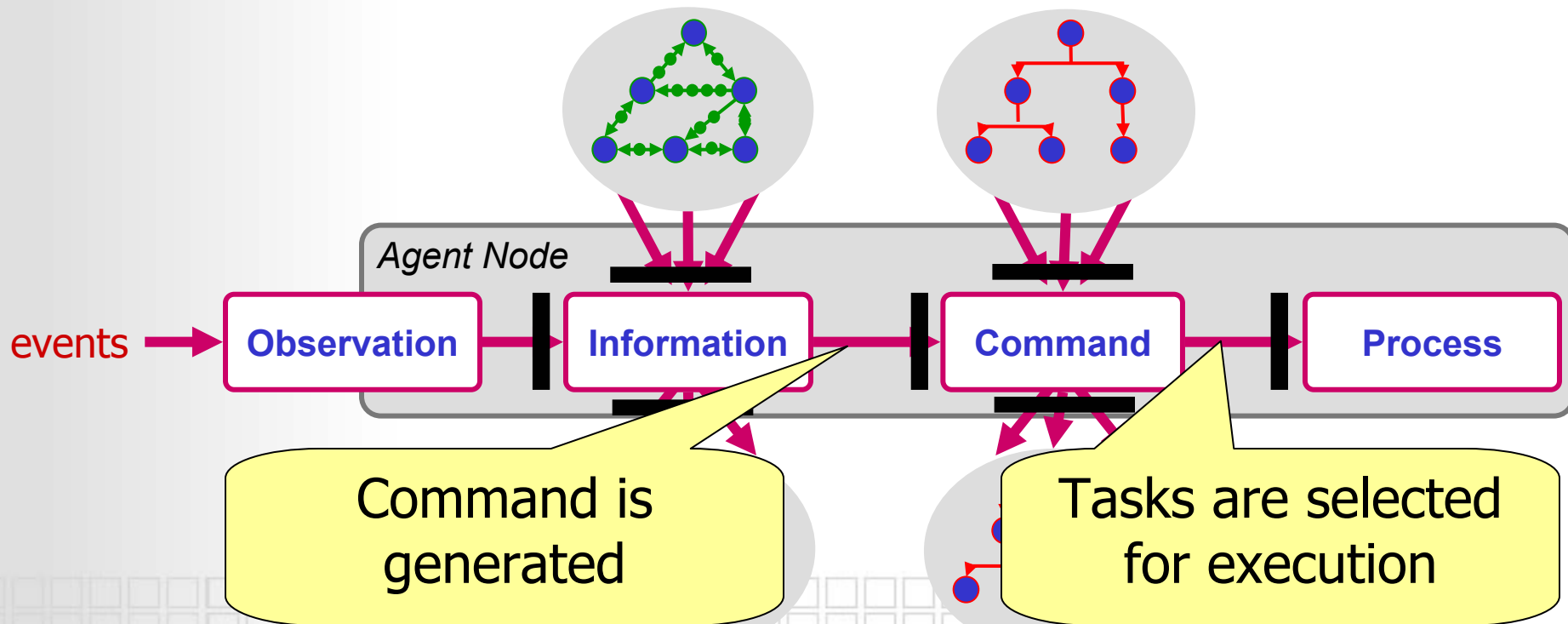
## Flow chain:



splitting allowed



## Agent process graph:



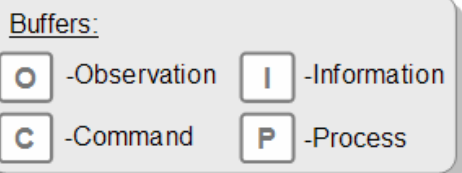
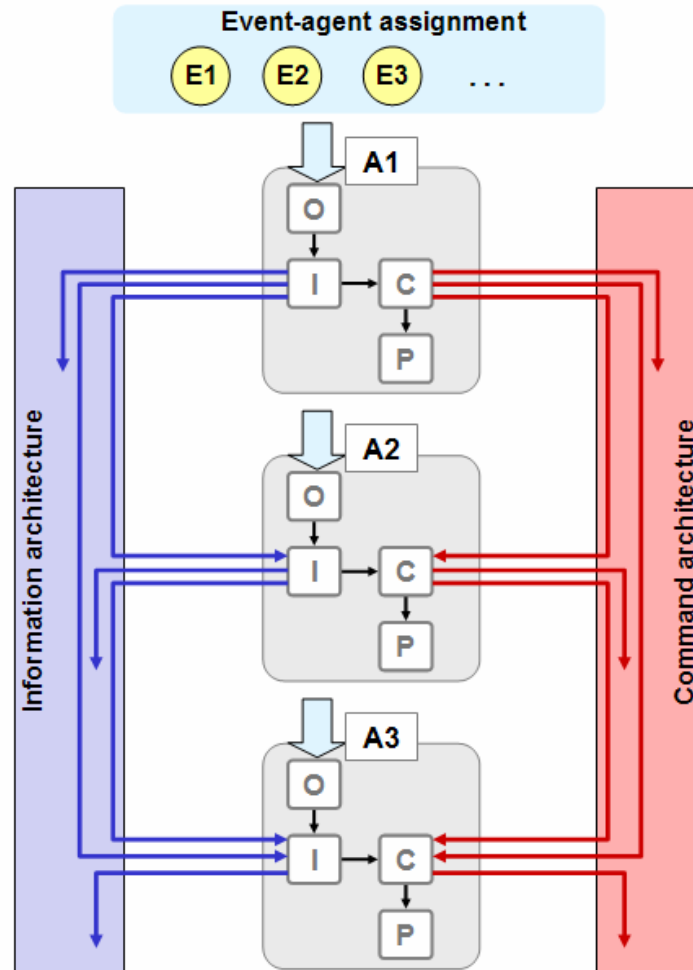
## ■ Capacity

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

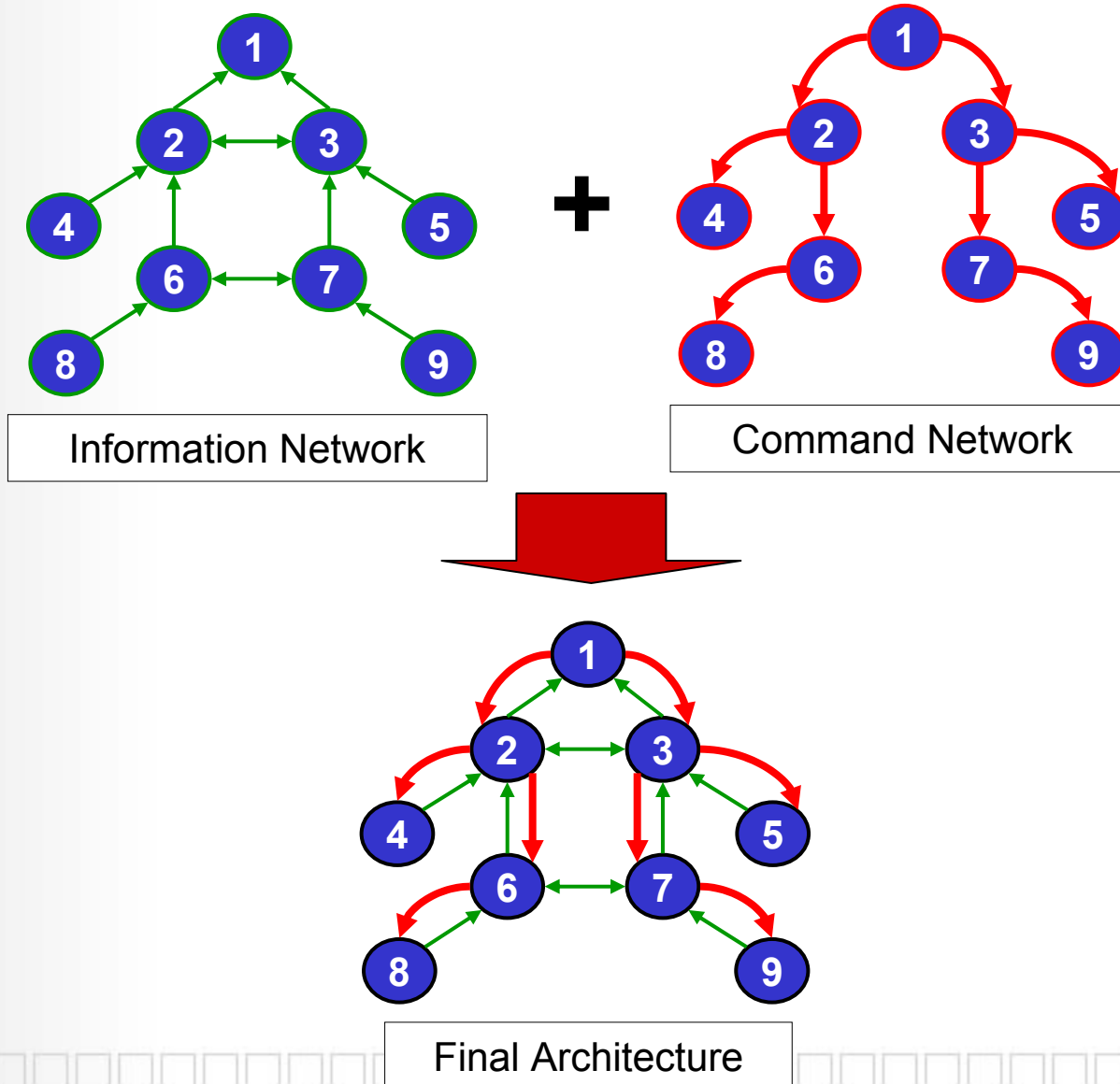
## ■ Mission Gain

- **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

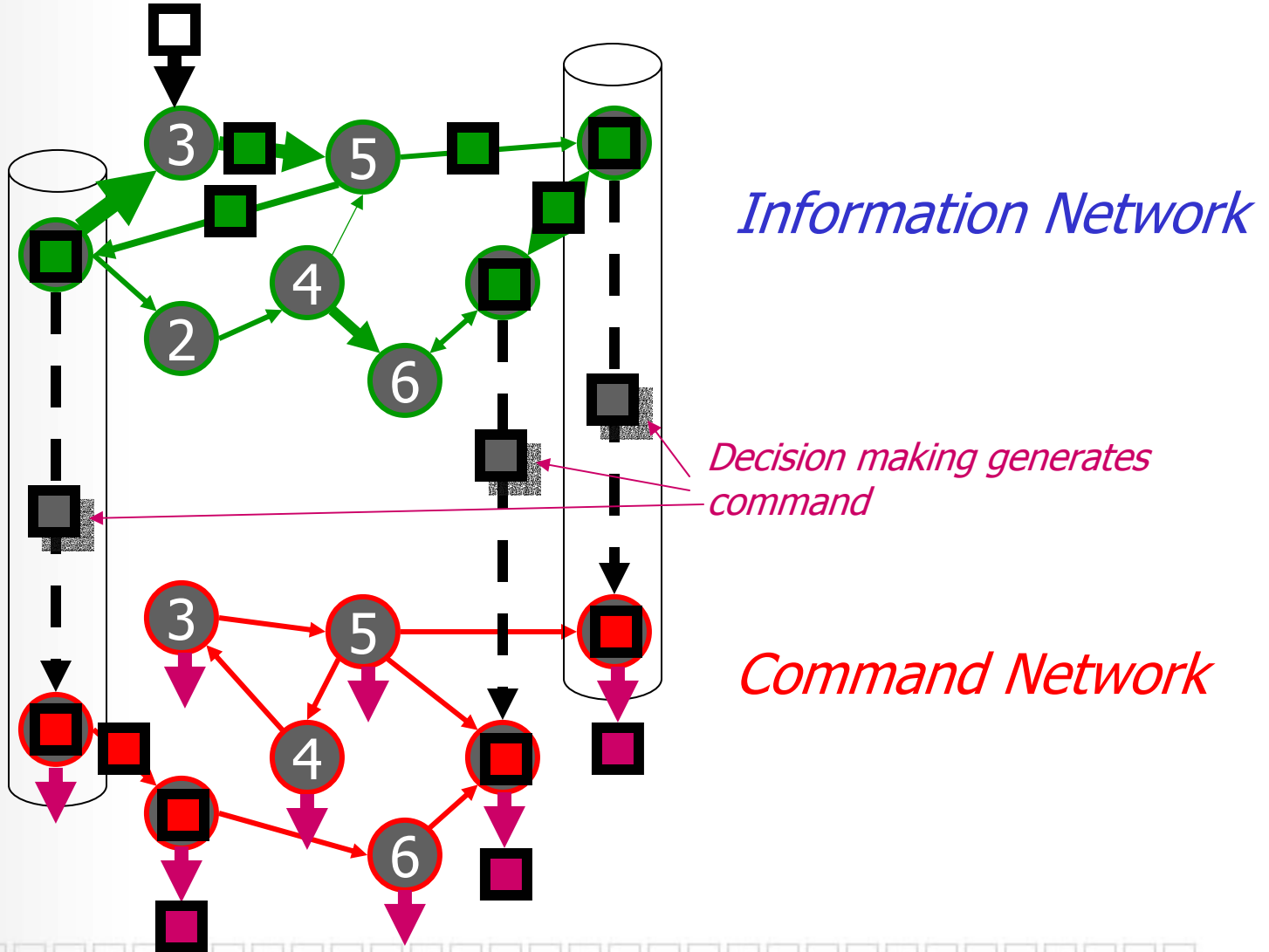


# Example of Hybrid Structure



# Multi-Layer Organization

Event is observed

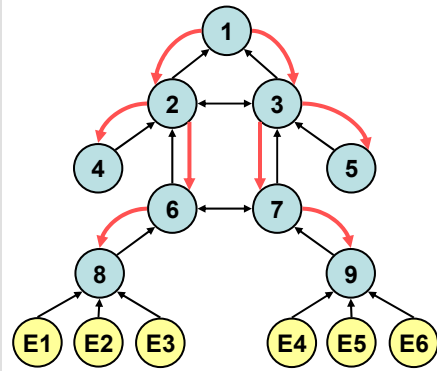


# Solution Approach

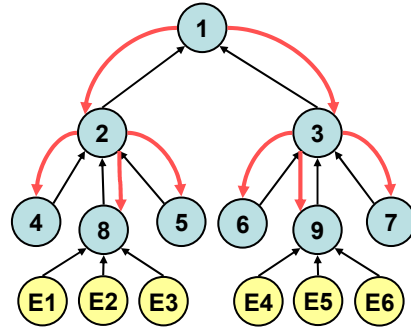
- **Step 1:** Define mission
  - Events volume and expertise requirements
- **Step 2:** Define organization
  - Agent expertise
- **Step 3:** Define agents' process graphs
  - Agent capacities, processing gain
- **Step 4:** Define structure constraints
  - Link/channel capacities for different-type networks
- **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

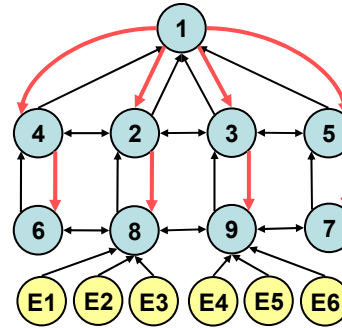
# Sample Results



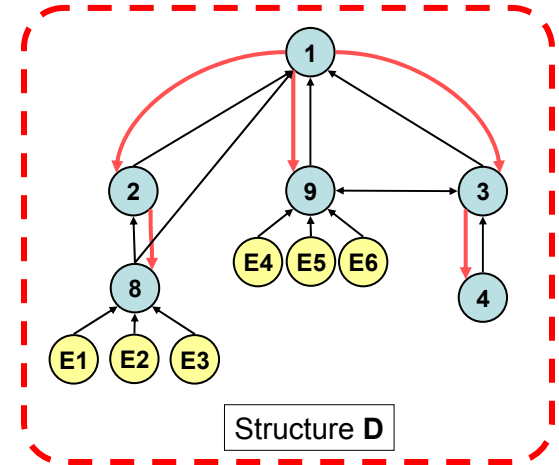
Structure A



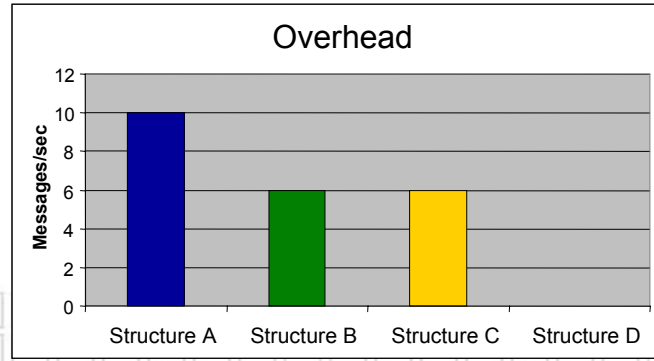
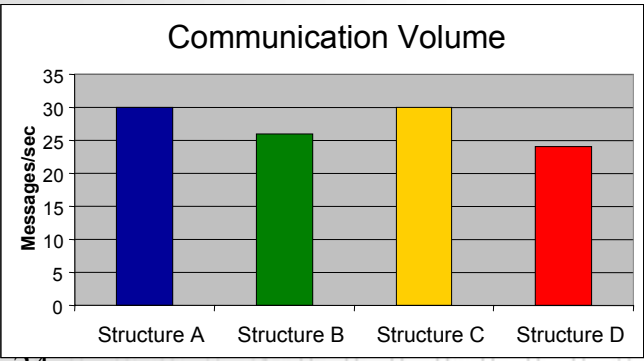
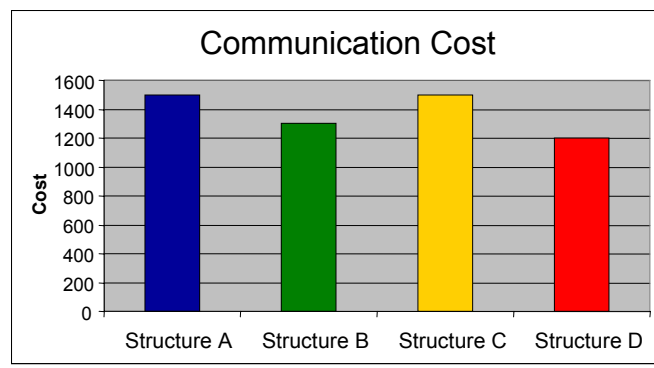
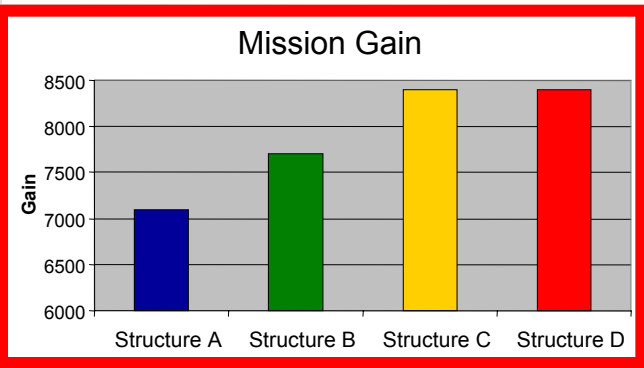
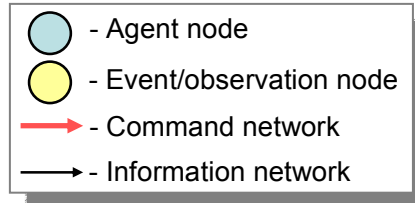
Structure B



Structure C



Structure D



- 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