

# A SURVEY OF MULTI-AGENT ORGANIZATIONAL PARADIGMS

BY: HORLING, B. AND V. LESSER

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# Reference

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- Horling, B. and V. Lesser (2005). A Survey of Multi-Agent Organizational Paradigms, *Knowledge Engineering Review*, **19**(4):281-316.

# Introduction

- The organization of a MAS is the collection of roles, relationships, and authority structures which govern its behavior
- All MASs possess some or all of these characteristics and therefore all have some form of organization
  - ▣ although it may be implicit and informal
- Such agent organizations guide how the members of the population interact with one another
  - ▣ not necessarily on a moment-by-moment basis,
  - ▣ but over the potentially long-term course of a particular goal or set of goals

# Introduction, 2

- The “guidance” can help
  - ▣ groups of simple agents exhibit complex behaviors
  - ▣ Sophisticated agents reduce the complexity of their reasoning
- No single type of organization is suitable for all situations
  - ▣ Some even say no perfect organization exists for any situation, due to the inevitable tradeoffs that must be made and the uncertainty, lack of global coherence and dynamism present in any realistic population

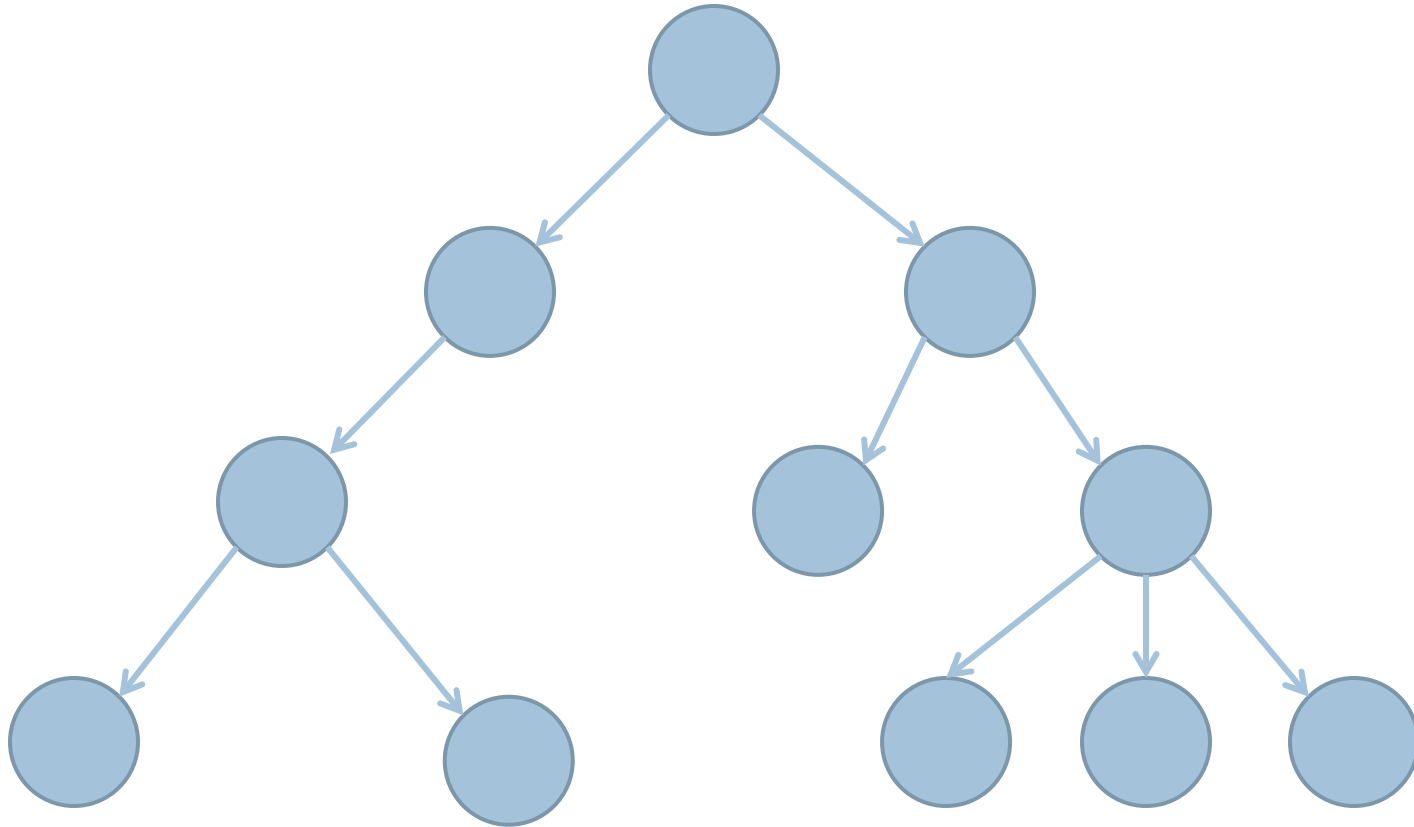
# Introduction, 3

- Organizations can be used to
  - ▣ limit the scope of interactions
  - ▣ Provide strength in numbers
  - ▣ Reduce or manage uncertainty
  - ▣ Reduce or explicitly increase redundancy
  - ▣ Formalize high-level goals which no single agent may be aware of
- Organizations can
  - ▣ Affect adversely computational or communication overhead
  - ▣ Reduce overall flexibility or reactivity
  - ▣ Add additional layer of complexity to the system

# Introduction, 4

- **Hierarchies**
- **Holarchies**
- **Coalitions**
- **Teams**
- **Congregations**
- **Societies**
- **Federations**
- **Markets**
- **Matrix Organizations**
- **Compound Organizations**

# Hierarchies



# Hierarchies: What is it?

- Perhaps the earliest example of structured, organizational design applied to MAS
- Agents higher in the tree have a more global view than those below them
  - ▣ Interactions do not take place across the tree, but only between connected entities
- The *data* produced by lower-level agents typically travels *upwards* to provide a broader view, while *control* flows *downward* as the high level agent provide direction to those below



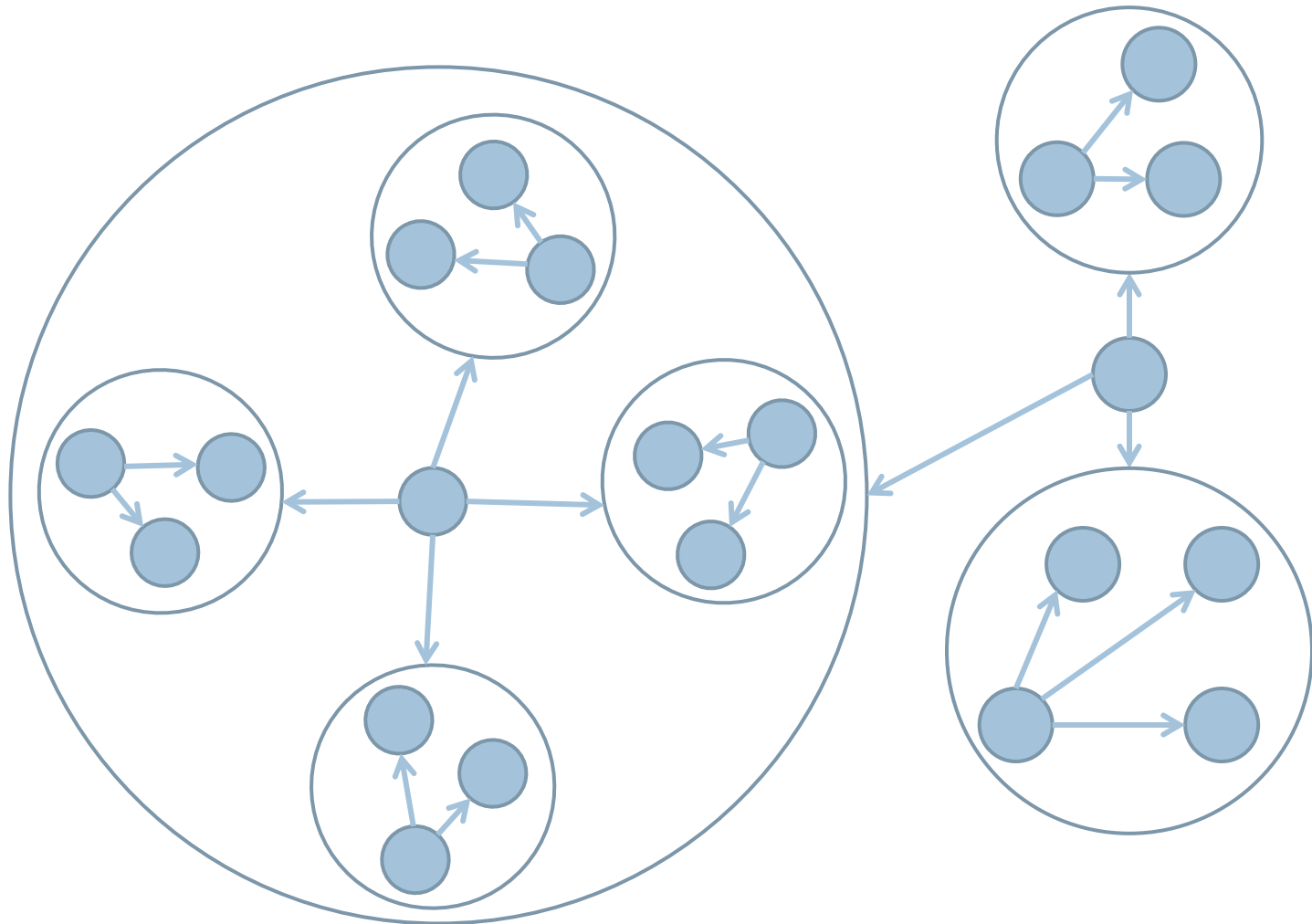
# Hierarchies: Characteristics

- The applicability of hierarchical structuring comes from the natural decomposition possible in many different task environments
- Efficiency derived from decomposition
  - ▣ Divide-and-conquer
  - ▣ Agents constrained to a number of interactions that is small relative to the total population size
    - More tractable control actions and behavior decisions
- Can be overly rigid or fragile
  - ▣ Prone to single-point failures with potentially global impacts
  - ▣ Susceptible to bottleneck effects

# Hierarchies: Formation

- An example approach: *Contract net protocol*
- The shape of the hierarchy can affect the characteristics of both global and local behaviors
  - ▣ A very flat hierarchy where agents have a high degree of connectivity can lead to overloading
  - ▣ A very tall structure may slow the system's performance across multiple levels
  - ▣ Use of *cloning*

# Holarchies



# Holarchies: What is it?

- Each *holon* is composed of one or more subordinate entities, and can be a member of one or more superordinate holons
- The degree of autonomy associated with an individual holon is undefined, and could differ between levels or even between similar holons at the same level
- Within the holarchy, the chain of command generally goes up – that is, subordinate holons follow their superordinate grouping
  - ▣ But, individual holons also determine how to accomplish the tasks they are given, since they are likely the locus of relevant expertise

# Holarchies: What is it?, 2

- If a *hierarchy* allows some amount of cross-tree interactions and local autonomy, then it looks like a holarchy
- If a holarchy is very flat, then it looks like a *federation*

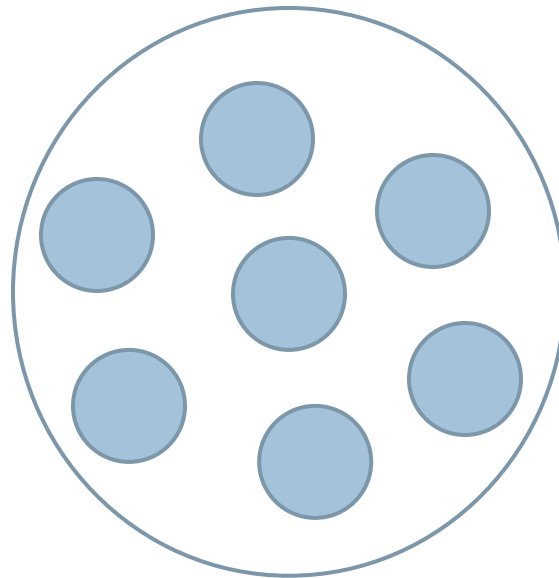
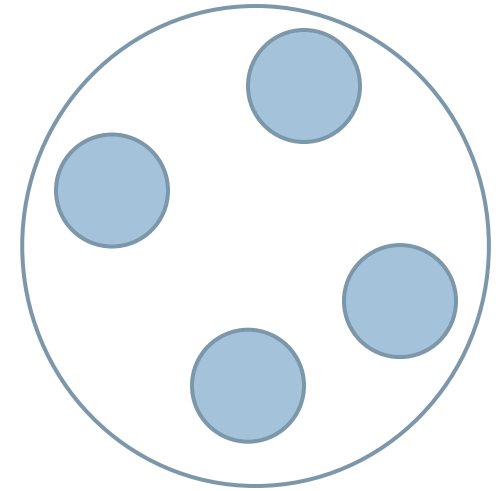
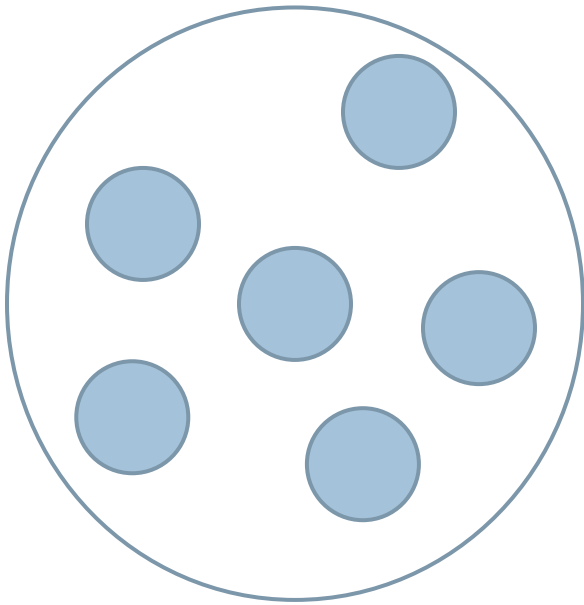
# Holarchies: Characteristics

- Similar to hierarchies
- Benefits are derived from the *partially autonomous* and *encapsulated nature* of holons
  - ▣ Holons are endowed with sufficient autonomy to determine how best to satisfy the requests they receive
  - ▣ This reduces the knowledge burden placed on the requester
  - ▣ A holon's behavior can adapt dynamically to new conditions without further coordination, so long as the original request's requirements are met

# Holarchies: Formation

- Challenge: selecting the appropriate agents to reside in the individual holons
  - ▣ Purpose of the holon must be useful with respect to the organization's high-level goals
  - ▣ The holon's members must be effective at satisfying that purpose
- Approaches:
  - ▣ Mediator holon – tie holons together
  - ▣ Fuzzy entropy minimization

# Coalitions





# Coalitions: What is it?

- The organizational structure is typically flat
  - ▣ Hierarchical sub-coalition possible
  - ▣ Overlapping coalitions possible
- Generally goal-directed and short-lived
  - ▣ They are formed with a purpose and dissolve when that need no longer exists
  - ▣ They may form in populations of both cooperative and self-interested agents
- Coordination does *not* take place among agents in separate coalitions
  - ▣ except to the degree that their individual goals interact, e.g., agree upon a deadline if their results are dependent

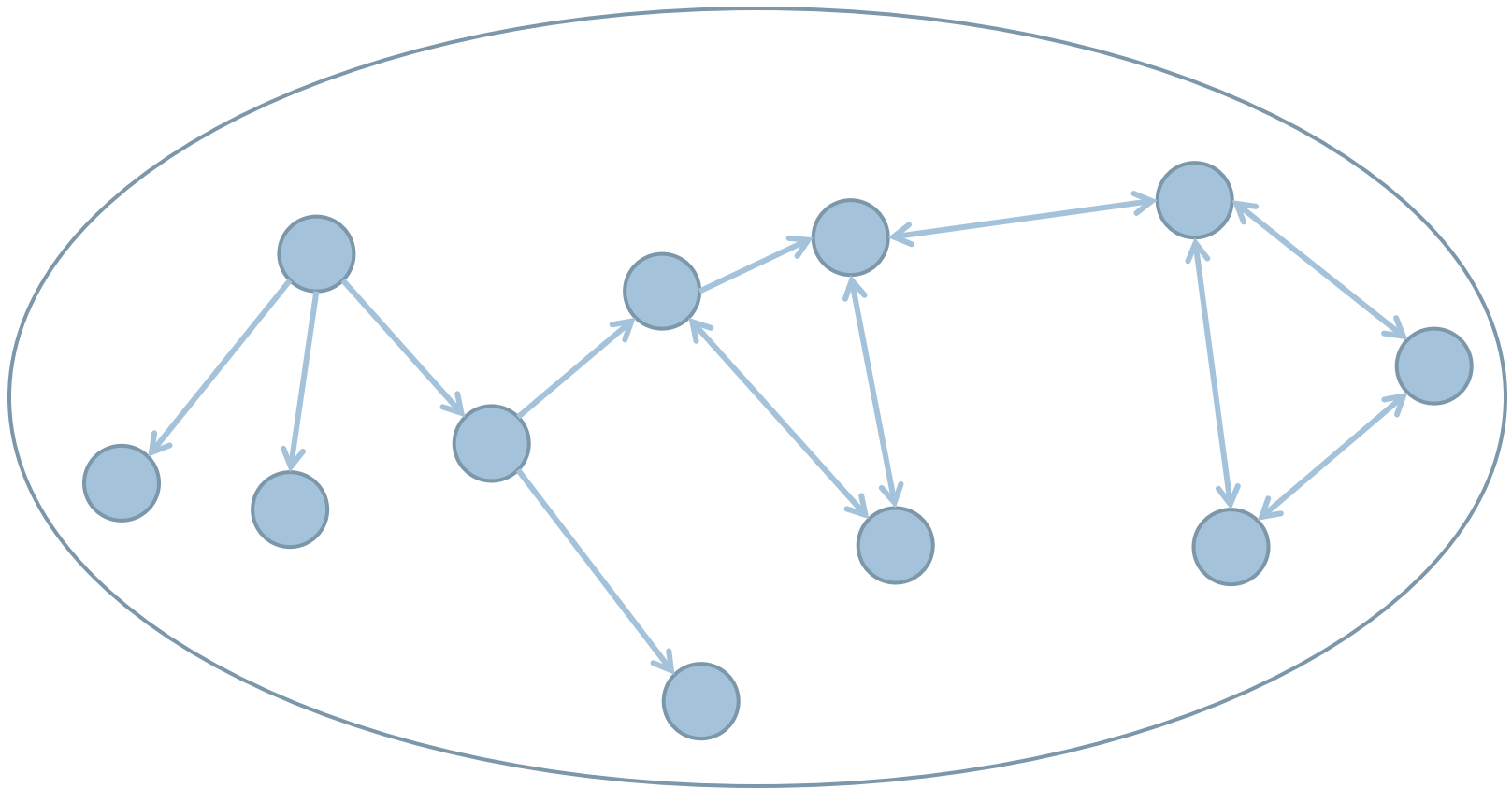
# Coalitions: Characteristics

- Motivation behind the coalition motivation
  - ▣ The value of at least some of the participants may be *superadditive* along some dimension
    - Better rewards, solving more complex tasks, etc.
  - ▣ Analogously, participants' costs may be *subadditive*
    - Task allocation more efficient, etc.
- !!! One could argue that all agents in the system should *always* join to form the *grand coalition* !!!
  - ▣ Since theoretically this would provide the maximum value
  - ▣ **However**, there are costs associated with forming and maintaining such a structure—can be both an impractical and unnecessarily coarse solution

# Coalitions: Formation

- Complexity: depends on the conditions under which the coalitions will exist, and the type of coalitions which are permitted
  - ▣ Operating in dynamic environments is hard
  - ▣ Partitioning of agents is not disjoint
  - ▣ Uncertain rewards, self-interested agents, potential lack of trust while coordinating
- Approaches:
  - ▣ Worst-case performance
  - ▣ Task allocations
  - ▣ Local decision making
  - ▣ Satisficing dynamic coalition formation

# Teams



# Teams: What is it?

- An agent team consists of a number *cooperative* agents which have agreed to work together toward a common goal
- !!! In comparison to *coalitions*, **teams attempt to maximize the utility of the team (goal) itself**, rather than that of the individual agents !!!
- Agents are expected to coordinate in some fashion such that their individual actions are consistent with and supportive of the team's goal
  - ▣ Multiple roles, roles change, etc.

# Teams: What is it?, 2

- Nearly any cooperative agent systems has characteristics that are similar to the above, implicit or explicit
- ▣ BUT! MAS with explicit representation of teamwork or joint mental state → can reason more precisely about the consequences of their teamwork decisions → less “scattered”, more “targeted” → more robust to noise, etc.

# Teams: Characteristics

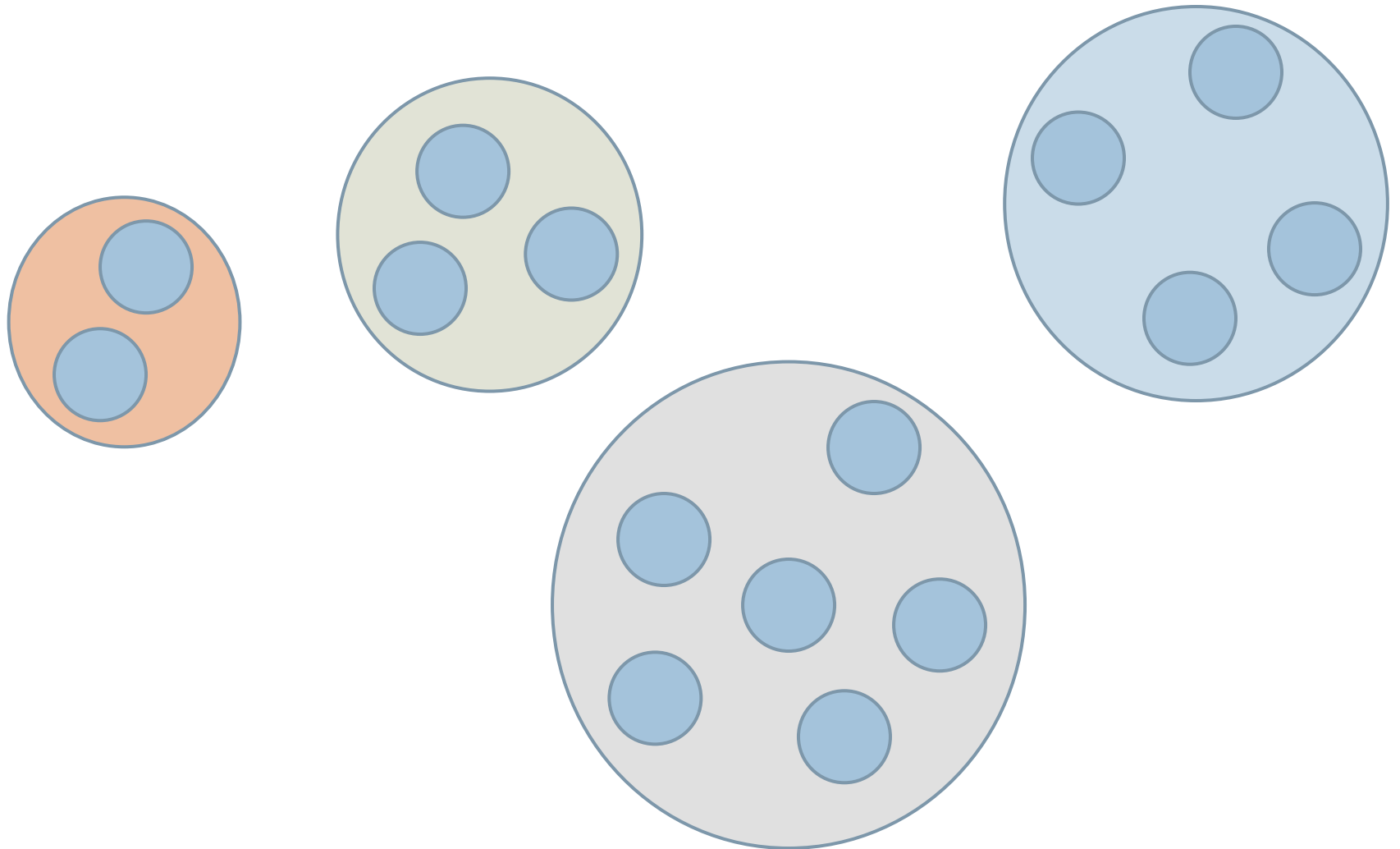
- Primary benefit is acting in concert, the group of agents can address *larger problems* that any individual is capable of
  - ▣ Other benefits: Redundancy
- Ability to reason explicitly about the ramifications of *inter-agent interactions* which gives the team the needed flexibility to work in uncertain environments under unforeseen conditions
  - ▣ Drawbacks: increased communication

# Teams: Formation

- Three main challenges with team formation
  - ▣ Determining how agents will be allocated to address the high-level problem
  - ▣ Maintaining consistency among those agents during execution
  - ▣ Revising the team as the environment or agent population changes
- Approaches
  - ▣ Selection and role assignment (CNP, matchmaking, etc.)
  - ▣ Adapting team behaviors (STEM, SharedPlans, GPDP, etc.)



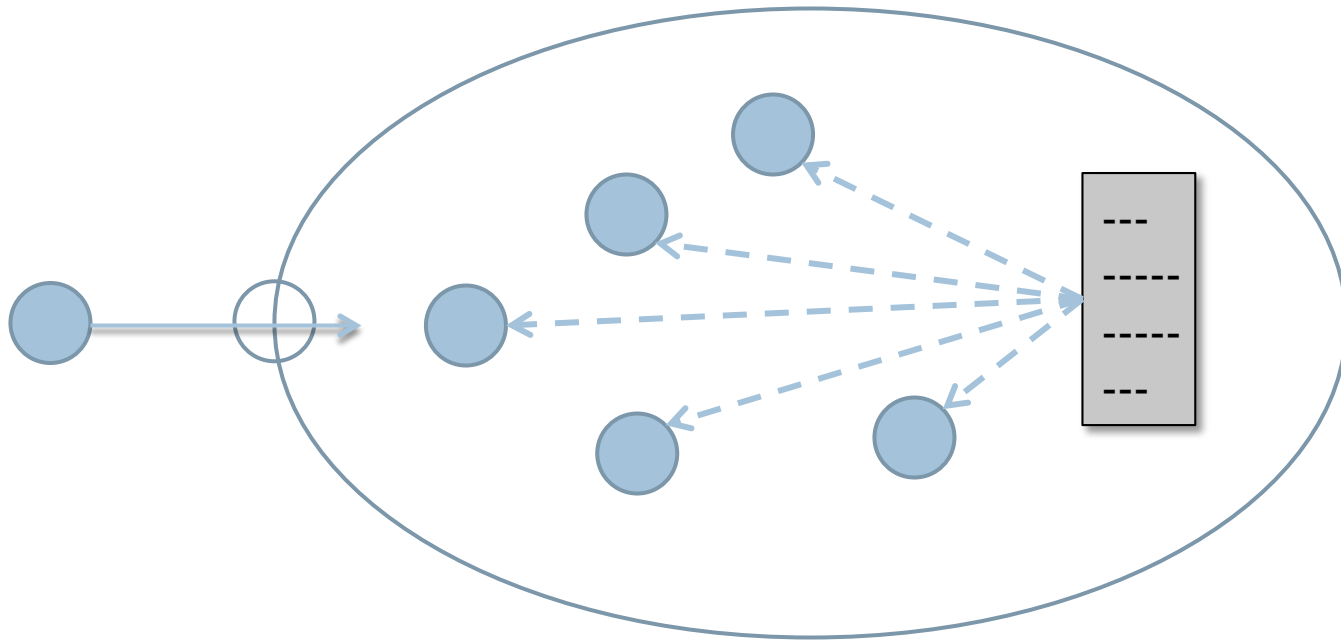
# Congregations



# Congregations ...

- Similar to coalitions and teams, agent congregations are groups of individuals who have banded together in a typically flat organization in order to derive additional benefits
  - ▣ But, they are assumed to be *long-lived* and *are not formed with a single specific goal in mind*
  - ▣ Analogous to clubs, support groups, academic departments, religious groups, etc.
- Agents are expected to be *individually rational*, by maximizing their local long-term utility
  - ▣ Group or global rewards are not used
  - ▣ Agents choose which congregation to join driven by their own utility

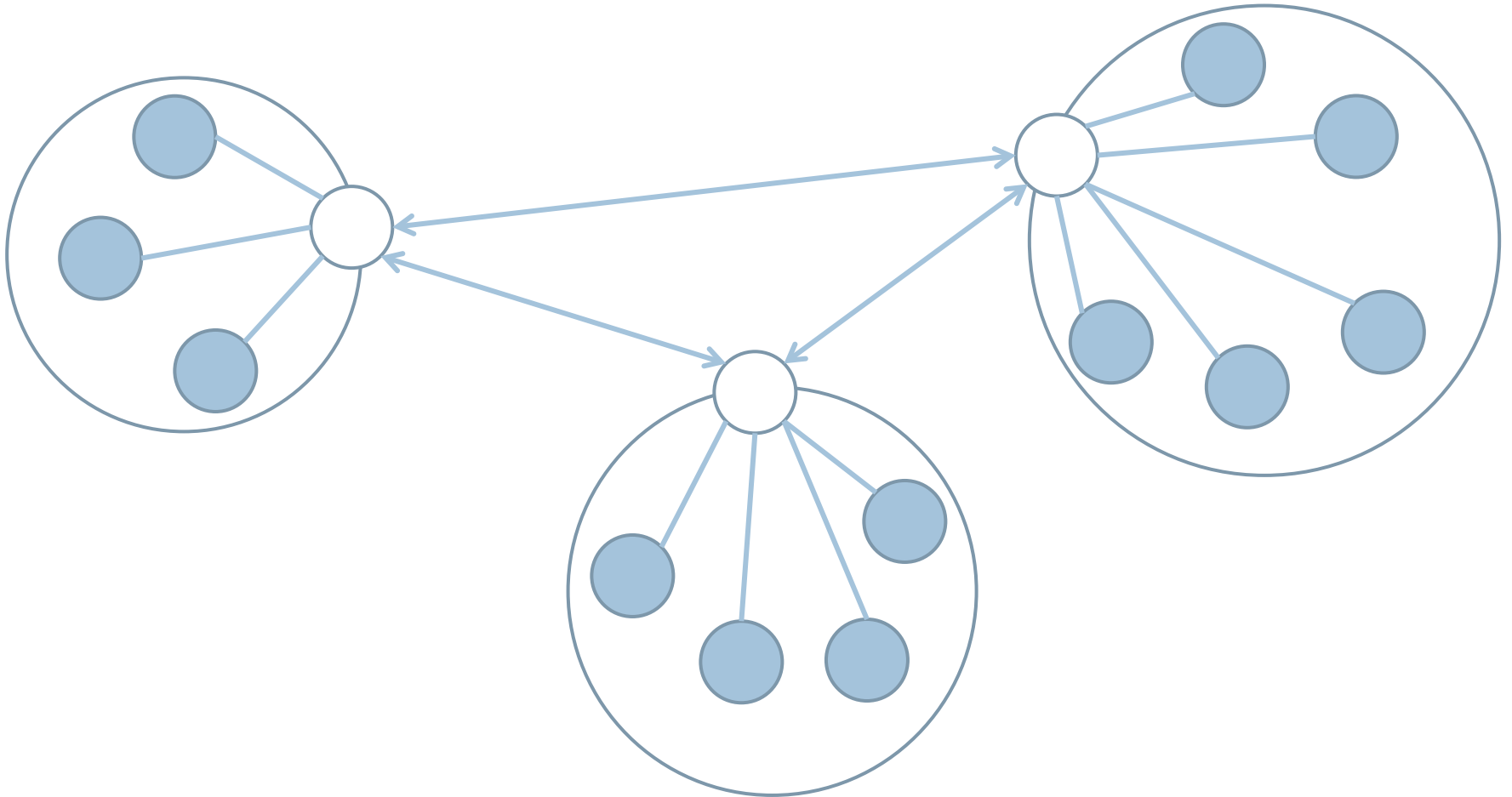
# Societies



# Societies ...

- A society of agents is a long-lived, social construct
- Unlike some other organizational paradigms, agent societies are inherently open systems
  - ▣ Agents may come and go while the society persists (e.g., electronic marketplace)
  - ▣ Agents are very diverse: goals, rationality, capabilities
  - ▣ Societies *impose structure and order*, but the specific arrangement of interactions can be quite flexible
- Societies impose a set of constraints on the behavior of the agents
  - ▣ *Social laws, social norms, or social conventions*
  - ▣ Rules or guidelines by which agents must act, which provides a level of consistency of behavior and interface intended to facilitate co-existence among very diversified agents

# Federations



# Federations: What is it?

- A group of agents which have ceded some amount of autonomy to a single delegate which represents the group
- The delegate is a distinguished member of the group, sometimes called a facilitator, mediator, or a broker
- Group members interact only with this agent, which acts as an intermediary between the group and the outside world
  - ▣ The facilitator accepts skill and need descriptions from the local agents, interacts with other facilitators, and match skills/needs to needs/skills.

# Federations: Characteristics

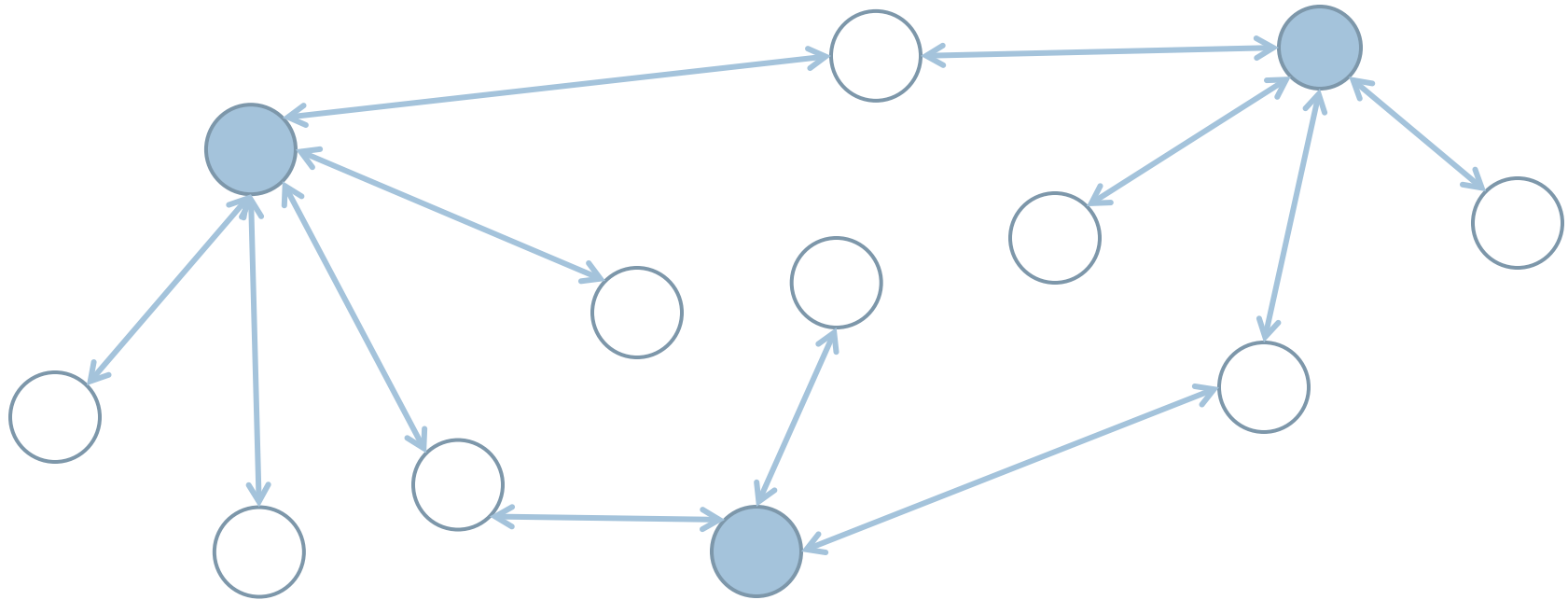
- The facilitators handle the skills and needs, reducing communication and “negotiation”
- Individual local agents do not need to know how to communicate with agents from another federate
- Facilitators can provide translation, security, management, communication, monitoring, notifications/alerts, and other services for their federates

# Federations: Formation

- Agent Communication Language
  - ▣ First-order predicate logic (KIF) and KQML agent messaging language
- Approaches
  - ▣ Yellowpages
- Useful for integrating legacy systems



# Markets



# Markets: What is it?

- In a marketplace
  - ▣ buying agents may request or place bids for a common set of items (e.g., shared resources, tasks, services, or goods)
  - ▣ Agents may also supply items to the market to be sold
  - ▣ Sellers (or sometimes third parties called auctioneers) are responsible for processing bids and determining the winner
  - ▣ Creates a producer-consumer system that can closely model and greatly facilitate real-world market economies
- Markets are similar to *federated systems* in that a group or individuals is responsible for coordinating the activities of a number of other participants
  - ▣ But, market participants are *competitive*
  - ▣ They *do not cede operational authority* to those distinguished individuals
- Markets are also usually open

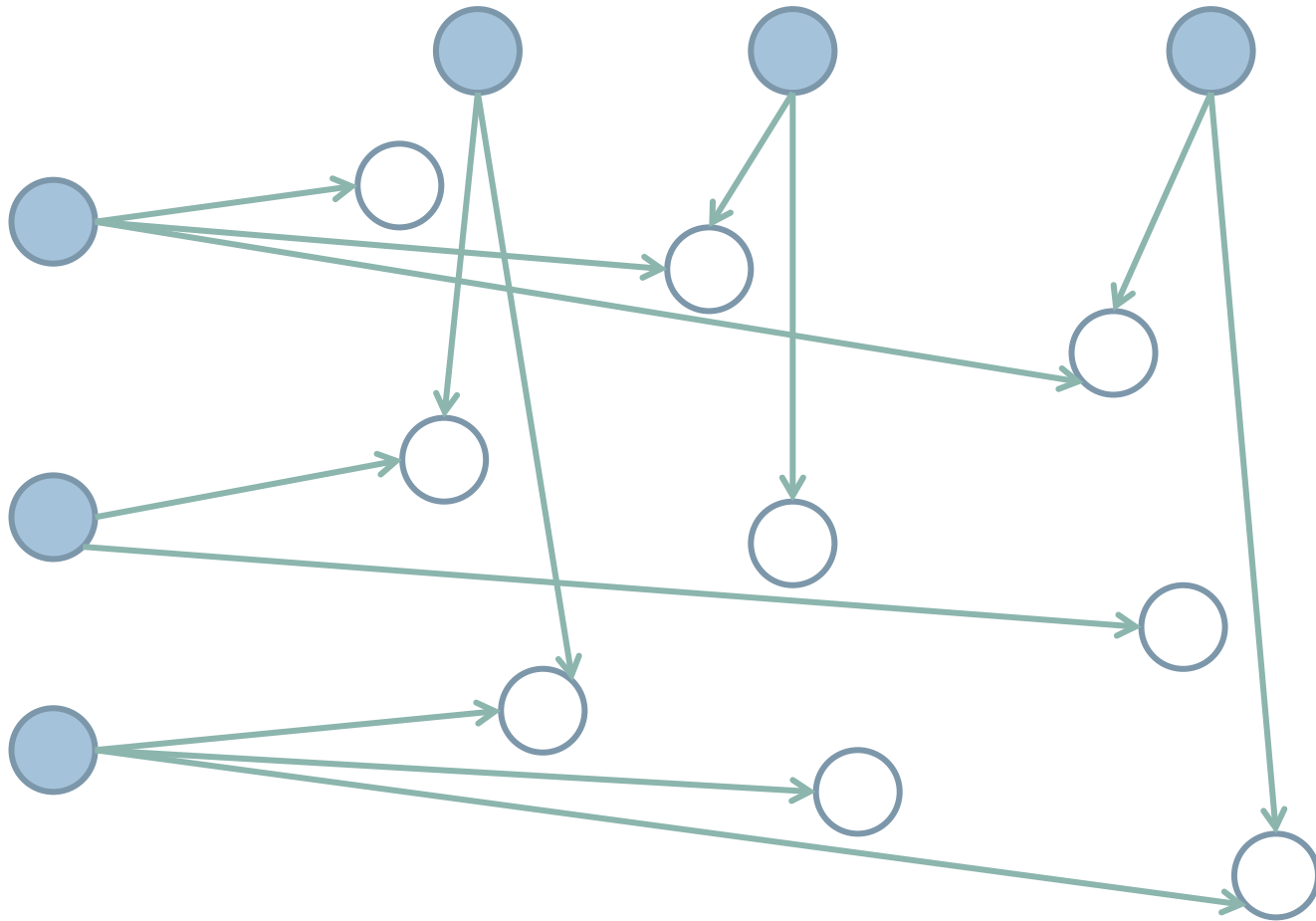
# Markets: Characteristics

- Markets excel at the processes of allocation and pricing
  - ▣ If agents bid correctly (truthfully)
- Intrinsically linked to auctions
  - ▣ Allows for many well-studied auction protocols to be used with guarantee expected outcomes (rationality)
- Two drawbacks
  - ▣ The potential complexity required to both reason about the bidding process and determine the auction's outcome
    - Approximation, counterspeculation, clearing the trade, etc.
  - ▣ Security
    - Network-related, transactions validation, collusion, etc.

# Markets: Formation

- Must maintain *temporal integrity*
  - ▣ The outcome of an auction, for example, depends on the arrival sequence of bids, and its independent of any delays internal to the market itself
- Transactions performed must be *atomic*
  - ▣ They have no effect if they fail or are canceled prior to completion
- Approaches: dynamic formation of markets, virtual organizations, etc.

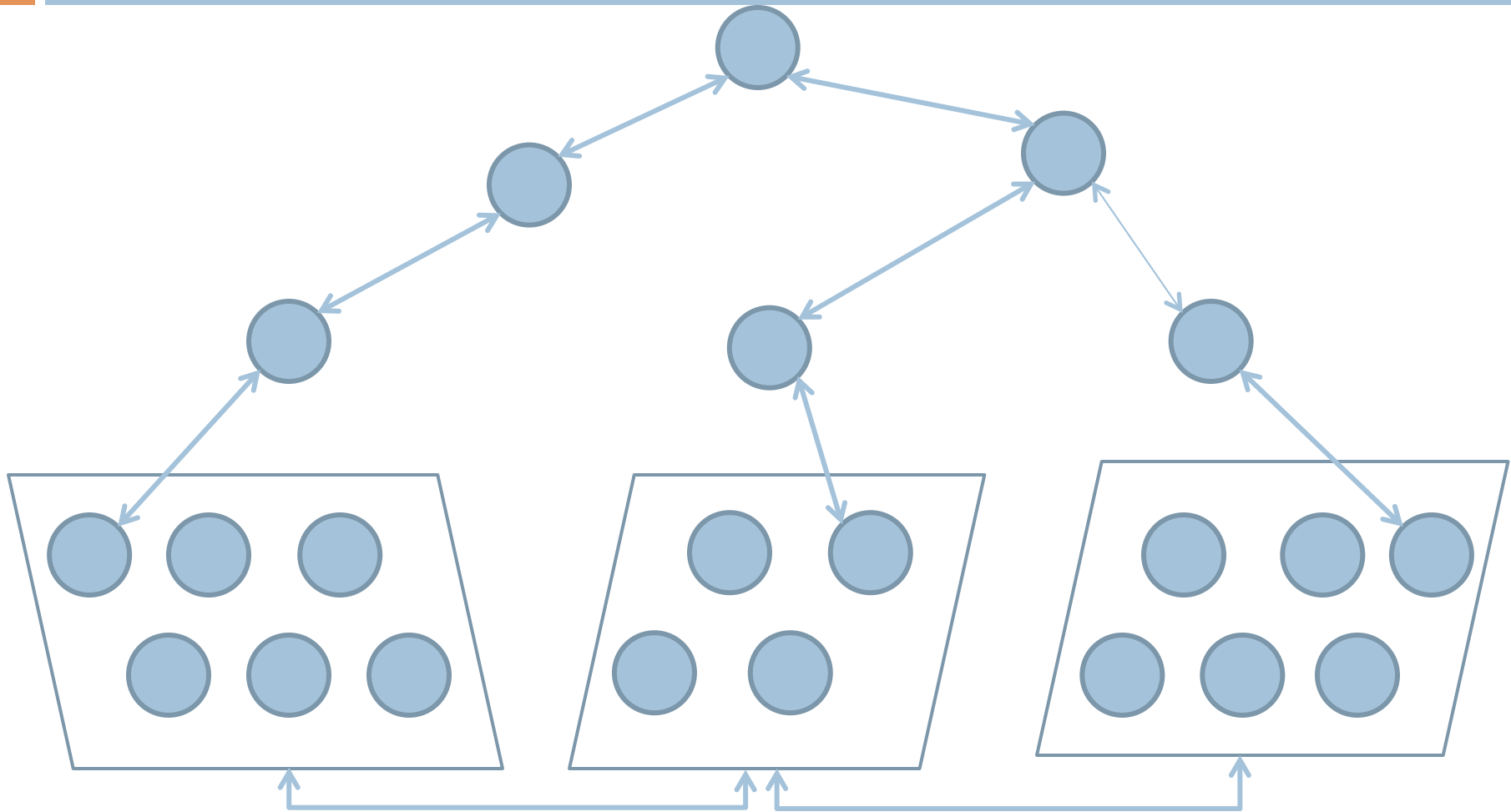
# Matrix Organizations



# Matrix Organizations ...

- Matrix organizations relax the one-agent, one-manager restriction, by permitting many managers or peers to influence the activities of an agent
  - ▣ Multiple lines of authority and rules
- This forms a *mixed-initiative* environment, where successful agents reason about the effects their local actions can have on *multiple* entities
- Agents can share resources for multiple tasks
  - ▣ Resource contention among managers
  - ▣ Need commitment ranking and conflict resolution

# Compound Organizations



# Compound Organizations ...

- A mixture of organizational paradigms
- Structurally, can be nested, overlapping, etc.
- Examples
  - ▣ Distributed sensor networks



# Other Organizational Topics

- Global Organizational Representation
  - ▣ How should we represent or design the system?
- Local Organizational Presentation
  - ▣ How should we represent or design each agent?
- Organizational Performance
  - ▣ As simulations? As solutions? As analytical models?
- Generative Paradigms
  - ▣ Scripted? Controlled? Emergent?
- Organizational Adaptation
  - ▣ Reactive, self-adapting

# Other Organizational Topics, 2

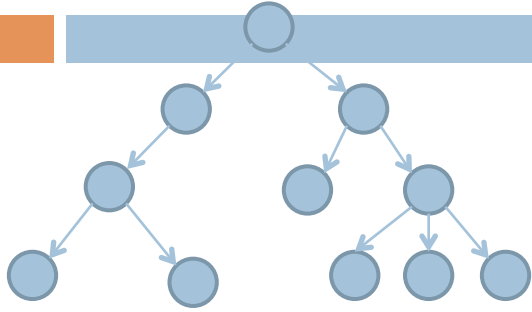
- Coordination and Negotiation
  - ▣ One-to-one, bottom-up
- Autonomy
  - ▣ Ceding authority, autonomy?
- Human Organizational Analogues
  - ▣ Mimicking human organizations?
  - ▣ Benefiting from sociology, biology, anthropology, economics, business management, etc.
- Diversity
  - ▣ Robustness

# Conclusions

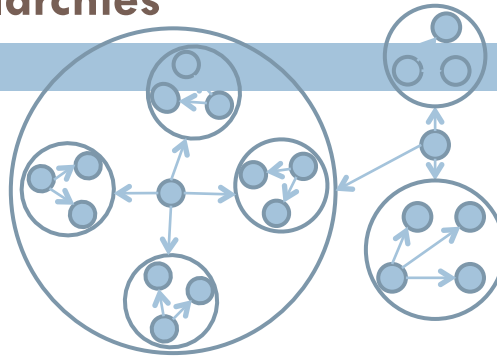
- Scale, real-time constraints, and bounded rationality all conspire to create challenging environments to operate in
- Organizations should be a critical part of any comprehensive, multi-agent solution, because of their ability to regulate the increased complexity of the local problem solving process required in such domains

# Recap

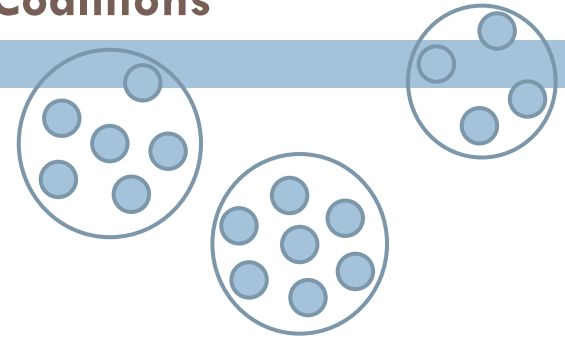
**Hierarchies**



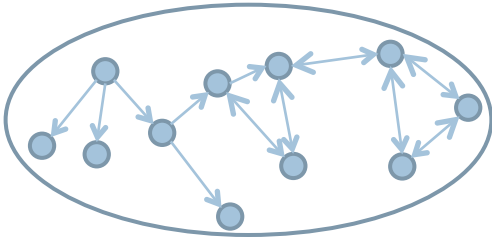
**Holarchies**



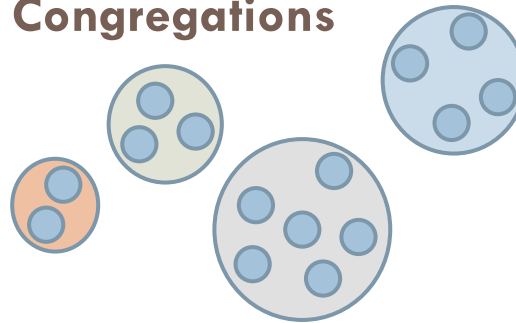
**Coalitions**



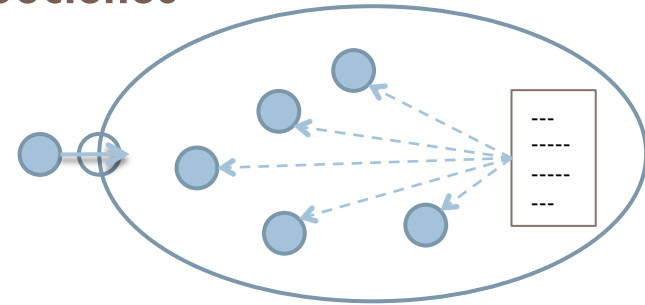
**Teams**



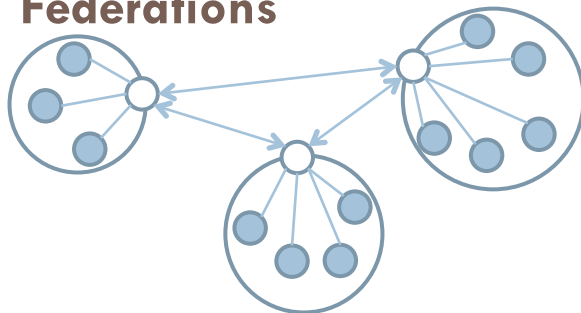
**Congregations**



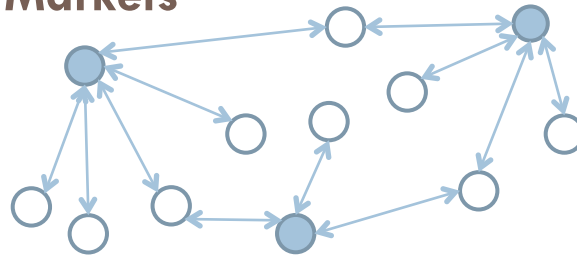
**Societies**



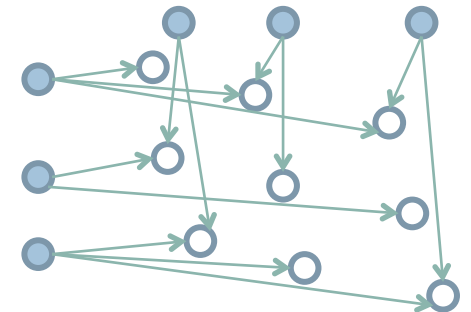
**Federations**



**Markets**



**Matrix Organizations**



# Recap, 2

Paradigm	Key Characteristic	Benefits	Drawbacks
Hierarchy	Decomposition	Maps to many common domains; handles scale well	Potentially brittle; can lead to bottlenecks or delays
Holarchy	Decomposition with autonomy	Exploit autonomy of functional units	Must organize holons; lack of predictable performance
Coalition	Dynamic, goal-directed	Exploit strength in numbers	Short term benefits may not outweigh organization construction costs
Team	Group level cohesion	Address larger grained problems; task-centric	Increased communication
Congregation	Long-lived, utility-directed	Facilitates agent discovery	Sets may be overly restrictive

# Recap, 3

Paradigm	Key Characteristic	Benefits	Drawbacks
Society	Open system	Public services; well defined conventions	Potentially complex, agents may require additional society-related capabilities
Federation	Middle-agents	Matchmaking, brokering, translation services; facilitates dynamic agent pool	Intermediaries become bottlenecks
Market	Competition through pricing	Good at allocation; increased utility through centralization; increased fairness through bidding	Potential for collusion, malicious behavior; allocation decision complexity can be high

# Recap, 3

Paradigm	Key Characteristic	Benefits	Drawbacks
Matrix	Multiple managers	Resource sharing; multiply-influenced agents	Potential for conflicts; need for increased agent sophistication
Compound	Concurrent organizations	Exploit benefits of several organizational paradigms	Increased sophistication; drawbacks of several organizational paradigms