Why Multiagents?

- Distribute the problem solving.
  - Sometimes no centralized solution will work.
- Complex problems.
  - Geographically distributed
  - Numerous components
  - Large amount of content
  - Broad scope

Multiagent Environments

- Characteristics of multiagent environments.
  - Require communication and interaction protocols.
  - Open with no centralized designer.
  - Contain agents that are distributed and autonomous, while being self-interested or cooperative.

Multiagent Environments

- The environmental characteristics that affect an individual agent are:
  - What does the agent **know** about the environment?
  - Is the agent able to **predict** the environmental changes?
  - Is the agent able to **control** the environment?
  - Does the future state of the environment depend upon a complete **history** or just the current state?

Multiagent Environments

- Are there other agents?
- Does the environment change in **real-time**?

Multiagent Coordination

- **Coordination** amongst multiple agents can be defined as:
  - "A property of a system of agents performing some activity in a shared environment." – Huhns and Stephens
- Coordination can be considered:
  - Cooperation between nonantagonistic agents.
  - Negotiation between competitive or self-interested agents.

Multiagent Coordination

- Coordination requires some level of communication between the agents in the society.
  - Low level communication: swarm behaviors
  - High level communication: intelligent behaviors
    - Can lead to the society being able to better attain its goals.

Multiagent Cooperation

- Successful cooperation between agents requires each agent to:
  - Maintain a representation of the other agents in the system.
  - Create a representation of the future interactions.

Multiagent Coherence

- **Coherence** of a multiagent system represents how well the system of agents behave as a entity.

Communication Meaning

- There exist three aspects of communications:
  - Syntax
  - Semantics
  - Pragmatics – how interpreted

- The **meaning** of communication requires semantics and pragmatics.

Dimensions of Meaning

- Descriptive vs. Prescriptive
  - Descriptions are difficult for agents to represent.
  - Agents primarily communicate about activities and behavior.
- Personal vs. Conventional Meaning
  - Best to create agents that use conventional interpretations.
- Subjective vs. Objective Meaning
  - Best to use messages with objective meanings.

Dimensions of Meaning

- Speaker's vs. Hearer's vs. Society's Perspective
  - Messages should indicate the perspective.
- Semantics vs. Pragmatics
- Contextuality
  - Appropriate context must be provided.
- Coverage
  - Language size

Dimensions of Meaning

- Identity
  - Message meaning is dependent upon the agents involved, their identities and roles.
- Cardinality
  - Interpretation of private messages versus broadcast messages.

Message Types

- Two basic types:
  - Assertions
  - Queries
- The above message types are required for an agent to communicate with other agents.
  - Even if the agent is considered a passive agent.

Message Types vs. Agent Types

	Basic	Passive	Active	Peer
Receives Assertions	X	X	X	X
Receives Queries		X		X
Sends Assertions		X	X	X
Sends Queries			X	X

Message Types

- Table 2.4 on page 86 provides a more detailed list of message types.

Communication Levels

- The protocols typically have various levels.
  - For example:
    - Level 1 (lowest) specifies method of interconnection.
    - Level 2 specifies the syntax.
    - Level 3 (highest) specifies the semantics.

Communication Protocols

- Many communication protocols have been developed.
  - Binary protocols: one sender and one receiver.
  - N-ary protocols: one sender and multiple receivers.

Communication Protocols

- Protocol data structures include:
  - A sender
  - Receiver(s)
  - The protocol language
  - Function for encoding and decoding
  - The actions the receiver(s) is to take.

Speech Acts

- The three aspects of speech acts are:
  - Locution: the speakers actual utterance.
  - Illocution: the meaning the speaker expects.
  - Perlocution: the actions that are a result of the locution.

Speech Acts

- What do the following mean?
  - "I am hungry."
  - "I want to eat an apple."

Illocutionary Force

- Illocutionary force can be classified as:
  - Statements of fact: *assertions* or *declarations*
  - Commands to an individual or agent: *directives*
  - Commitments: *commissives*
  - Emotional expressions: *expressives*
- Illocutionary force constrains the communication semantics and creates clear, well defined messages.

KQML

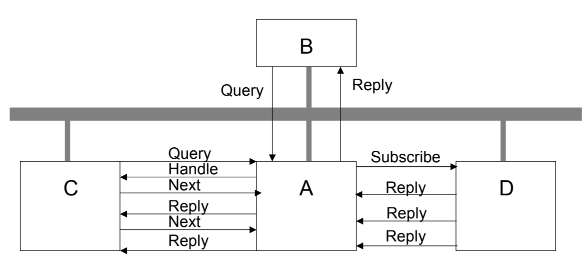
- **K**nowledge **Q**uery and **M**anipulation **L**anguage – KQML
  - An information and knowledge exchange protocol.
  - A message format and message-handling protocol designed to provide real-time communication between agents.
  - Developed by the ARPA supported Knowledge Sharing Effort.

KQML Pragmatics

- The primary concern in KQML is with pragmatics.
  - Pragmatics of computer processes includes:
    - Determining who to communicate with and locating that entity.
    - Determining how to initiate and maintain the communication.
- The secondary concern is semantics.

KQML

- KQML supports both synchronous and asynchronous communication. (Assumes asynchronous)



Preformatives

- KQML employees preformatives as the communication data structure.
  - Agents are able to express the message content in any language which resides inside a KQML message.

Preformatives

- KQML messages are list based (LISP).
  - The first element in the list is the preformative.
  - The remaining elements are pairs containing a keyword and an associated value.

```
(KQML-preformative
  :sender <word>
  :receiver <word>
  :language <word>
  :ontology <word>
  :content <expression>
  … )
```

Preformative Example

- An example message querying the price of a share of IBM stock might look like:

```
(ask-one
  :content PRICE IBM ?price
  :receiver stocker-server
  :language LPROLOG
  :ontology NYSE-TICKS)
```

  - Messages may also be nested.

Reserved Preformative Names

- There are a number of reserved preformative names.
  - Basic queries
  - Multiple response queries
  - Response
  - Generic information
  - Generators
  - Capability-definition
  - Networking

KQML Issues

- As always there are issues:
  - The two agents communicating must understand the content language.
  - The ontology must be created, and maintained while also being accessible to the communicating agents.
  - The communication infrastructure must support KQML so that the agents can locate one another.

Languages

- Any language may be used with KQML but the **K**nowledge **I**nterchange **F**ormat (KIF) has been developed for KQML.
  - KIF is a standard knowledge representation syntax that also includes a semantics specification.
  - It is primarily based upon first-order predicate calculus but also contains extensions that permit non-monotonic reasoning and definitions.

KIF

- KIF is not intended to be used as a language to communicate with humans.
- http://www.csee.umbc.edu/kse/kif/

Other Languages

- **C**hoice **C**onstraint **L**anguage (CCL): Communication about choice.
- P3P: A language that represents privacy practices of a web site.

KIF Syntax

- The KIF syntax can be described as three layers.
  - – The basic characters of the language.
  - – The basic characters are combined to create lexemes.
  - – The lexemes are combined to form expressions.

  - – KIF Documentation.

Ontologies

- An **Ontology** provides the specification of objects, concepts, and relations within an area of interest.
  - – In Philosophy the word ontology refers to “the subject of existence.”
  - – T. Gruber defines an ontology as “a description (like a formal specification of a program) of the concepts and relationships that can exist for an agent or a community of agents.”
    - “A statement of a logical theory.”

Why create an Ontology?

- Why do we need ontologies?
  - – To enable agents to share and reuse knowledge.
  - – An ontology provides a standard vocabulary for agents to communicate queries and assertions.

Ontology Representations

- Ontologies are commonly represented as classes in a hierarchy.
  - – Ontologies also must describe the relationships.
  - – Ontologies do not have to represent the class instances.
  - – Think of an ontology as a database schema rather than the data stored in the database.

Ontology

- Figure 2.4 on page 96 represents an example ontology.
- A couple of available ontology editors:
  - Ontolingua from Stanford.
  - Java Ontology Editor

Interaction Protocols

- Interaction protocols permit agents to maintain a conversation.
  - Coordination
  - Cooperation
  - Negotiation
  - Belief maintenance

Coordination Protocols

- It is common that agents will need to coordinate their activities and resources to attain their goals.
  - Coordination is required because:
    - There are dependencies between agents' actions.
    - There are requirements to meet global constraints.
    - Of the need to share competence, resources, and information to attain the system goals.
      - Information and resources are distributed across the system.

Key Structures

- *Commitments* represent an agent's agreement to complete a specified course of action.
  - Provide predictability.
  - Commitments should be internally consistent while being consistent with the agent's beliefs.

Key Structures

- *Conventions* represent the ability to manage commitments in changing circumstances.
  - Conventions help manage an agents commitments.
  - Conventions do not specify the manner in which agents should behave towards the other agents when the agent modifies its commitments.
  - Conventions represent the degree of support of all involved to the goal.

Information Level

- In order for agents to agree to a common goal there is a minimal level of information required.
  - The status of each agent's commitment to the goal.
  - The status of each agent's commitment to the suggested team framework.

  - Any change to either of the above for any agent requires all other agents be updated.

Cooperation Protocols

- Cooperation protocols provide a mechanism for distributing the tasks amongst the agents.
  - Indicate how an overall goal is decomposed and distributed.
    - Simple divide-and-conquer.
    - Spatial decomposition according to the agents' expertise.
    - Functional decomposition.

Task Distribution

- Tasks can be distributed based upon:
  - Avoiding critical resource overloading.
  - Matching agent capabilities to tasks.
  - Omniscient agents assign tasks to others.
  - Create coherence by assigning overlapping responsibilities to agents.
  - Minimize communication and synchronization overhead by assigning highly interdependent tasks to agents in spatial or semantic proximity.
  - Complete urgent tasks by reassigning other tasks.

Task Distribution

- Common task distribution mechanisms
  - Contract Net
  - Market Mechanisms
  - Multiagent Planning
    - Planning agents assign tasks
  - Organizational structure
    - Each agent has a defined responsibilities for particular tasks.

Contract Net

- The Contract Net protocol permits agents to announce a task, accept bids for task completion, award the task to another agent and await the results.
  - Best known and most commonly applied.
  - Represents how businesses exchange goods and services.

Connection Problem

- The *connection problem* is the problem of locating the appropriate agent for a given task.
  - Contract Nets resolve this issue.

CN Entities

- The agent who announces tasks, accepts bids, etc. is called the **manager**.
- The agent who is selected to complete the task is the **contractor**.
  - Contractors view the process as receiving announcements, determining whether or not to bid, responding, completing the task (if bid accepted) and reporting the results.
- The roles are interchangeable.

Bids

- Bids may not be received if:
  - All potential contractors are busy
  - The proposed task is not important enough to an idle agent.
  - No agents have the capabilities to complete the task.

Blackboard Systems

- A blackboard architecture has three major components:
  - a hierarchically organized global memory or database called a blackboard which saves the solutions generated by the knowledge sources;

Definition from: http://www.primenet.com/pcai/New_Home_Page/ai_info/blackboard_technology.html

Blackboard Technology

- a collection of knowledge sources that generate independent solutions on the blackboard using expert systems, neural networks, and numerical analysis;
- a separate control module or scheduler that reviews the knowledge sources and selects the most appropriate one.

Definition from: http://www.primenet.com/pcai/New_Home_Page/ai_info/blackboard_technology.html

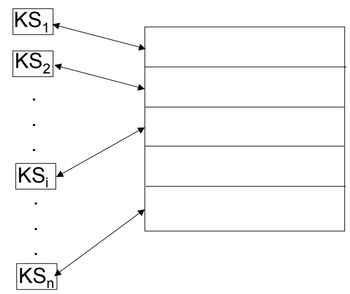
Blackboard Technology

- Additional characteristics include:
  - Flexible representation of the information for placement in/on the blackboard.
  - The internal representation is hidden from the users.
  - It provides a common interaction language.
  - Also, blackboards provide internal solution generation that can lead to contradictions or new lines of reasoning.

Blackboard Technology

- Advantages of blackboards:
  - Permit the separation of knowledge into independent modules therefore permitting each module to use the appropriate technology to arrive at the best and most efficient solution.
  - The independent modules facilitate distributing the modules over multiple processors.

Blackboards



KS = Knowledge Source

A KS retrieves data from the blackboard, processes it, and returns the results to the blackboard for use by other knowledge sources.

Negotiation

- A technique many humans know and understand.
- Should lead to a joint decision that permits all involved to attain their goals and objectives.
- Issues to be concerned with:
  - Permitting productivity
  - Conducting fair negotiations.

Negotiation Mechanism

- Characteristics of a negotiation mechanism:
  - Agents should be able to **efficiently** reach an agreement.
  - The agreed upon strategies should be viewed as **stable** by all agents.
  - The mechanism should provide a **simple** (meaning low computation and bandwidth requirements) negotiation process.

Negotiation Mechanism

- The negotiation mechanism should support **distributed** decision making.
- The mechanism should provide **symmetry**, in other words, treat all agents equally.

Negotiation Environments

- **Task-oriented domains**:
  - Represents an environment in which the agents need to complete tasks, the required resources are available and the agents are capable of completing the tasks without interfering with each other.
    - It is possible that the agents could share some of the tasks.
      - Reduces the cost of completing the task.

Negotiation Environments

- **Worth-Oriented environments**
- **State-Oriented environments**

The Question

- The development of many negotiation systems is based on one fundamental question.
  - "Given an environment in which my agent must operate, what is the best strategy for it to follow?"
  - This leads to domain specific solutions.

General Solutions

- One general solution is a negotiation tool based upon speech-act classifiers and the possible world semantics.
  - Chapter 8

General Solutions

- Another general solution is a unified protocol that permits agents to broker deals.
  - A utility measure represents the amount an agent is willing to pay minus the cost of the deal.
    - Objective: maximize utility and minimize cost.
  - There is a negotiation set that represents the agents set of deals that have a positive utility for all agents.

Negotiation Systems

- INSPIRE: Carleton University
- Pleiades Project: CMU

Truth-Maintenance Systems

- The purpose of a truth-maintenance system (TMS) is to protect the integrity of the conclusions created by an inferencing system. Luger and Stubblefield
  - In an agent system the purpose of TMS is to maintain the integrity of the individuals agent's knowledge.

Characteristics of Agent Knowledge

- An agent's knowledge should be:
  - **Stable** in that
    - each piece of data has a valid justification and is believed by the agent.
    - Also that any piece of data that does not have proper justification is not believed.
  - **Well-founded** in that it permits no beliefs to be mutually dependent.
  - **Logically consistent** in that the knowledge contains no contradictions.

Characteristics of Agent Knowledge

- Complete, concise, accurate, and efficient.

JTMS

- Justification based truth maintenance system (Doyle)
  - "JTMS communicates with the problem solver, receiving information about new propositions and justifications and in turn supplying the problem solver with information about which propositions should be believed based on the current existing justifications." Luger and Stubblefield

JTMS

- The primary operations performed by JTMS are:
  - The system reviews the network of justifications.
  - The system modifies the network of dependencies.
    - Modifications are created based upon information provided by the problem solver.
    - Add propositions, add or remove premises, add contradictions, and justify proposition belief.

JTMS

- The system updates the network.
- See Luger and Stubblefield pages 277 – 281 for a typical AI example.

JTMS and Agents

- The extension of JTMS to multiagents requires:
  - Every piece of data has a set of justifications and an associated status.
    - The status can be INTERNAL (believed because of local justification), EXTERNAL (believed because of another agent made the assertion) and OUT (disbelieved).

Multiagent JTMS

- In order to maintain the characteristics
  - The over all knowledge may be stable but each agent maintains a partially-independent set of beliefs.
  - In order for a piece of data to be considered well-founded it must be INTERNAL to at least one agent and INTERNAL or EXTERNAL to the remaining agents.

Multiagent JTMS

- No single agent change change the status of a piece of data, all agents must coordinate to maintain consistency.

Multiagent JTMS

- To maintain system efficiency, as few as possible agents should be involved in resolving changes.
  - Additionally, as few beliefs as possible should be modified to resolve changes.

Market Mechanisms

- The intention is to allow the market to dictate how agents work together to complete their goals.
  - A primary concern is to minimize the amount of direct agent communication required to complete a task.
  - The intention is to use the current prices to represent anything of interest to an agent.

Market Mechanisms

- A **consumer** agent buys goods and a **producer** agent transforms goods into other goods.
- Agents bid for goods at any price, but the actual exchange occurs at the current market price.
  - The agents want to maximize either their profit or their utility.

Creating a Market

- In order to create a market oriented system determine
  - the goods that will be traded
  - Who are the consumers
  - Who are the producers
  - What the bidding and trading behaviors will be.

Market Equilibrium

- The market equilibrium will provide competitiveness such that
  - Consumers bid in order to maximize their utility.
  - Produces bid to maximize their profits.
  - The net demand for all goods is zero.

References

- KQML
  - T. Finin, et. al. KQML as an Agent Communication Language. *The Proceedings of the Third International Conference on Information and Knowledge Management* 1994.
- KIF
  - http://www.csee.umbc.edu/kse/kif/specification.html
- Wiess. *Multiagent Systems*. Chapter 2.
- Ontology
  - http://www-ksl.stanford.edu/kst/what-is-an-ontology.html
- Luger and Stubblefield. Artificial Intelligence. Third Edition. 1998.