G54DIA:
Designing Intelligent Agents

Lectures 10-11: Multi-Agent Systems I

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Outline of this lecture

- multi-agent systems
- designing multi-agent systems
- example: explorer robots on Mars
- task allocation
- example: contract net protocol
- example: Witness Narrator Agents

Defining “multi-agent system”

- like the notion of an ‘*agent*’, a ‘*multi-agent system*’ is an analysis tool
- it is pointless trying to pin down which systems are *really* multi-agent systems
- the key point is whether we gain by looking at a system as a multi-agent system
- many distributed systems can be viewed as multi-agent systems, but it may not useful to do so

Multi-agent systems

- a *multi-agent system* is a system in which several agents share a common task environment and *cooperate* at least part of the time
- the *agents* can have any of the architectures we have seen so far, e.g., reactive or deliberative or hybrid
- all the agents may have the same architecture or they may have different architectures
- the *environment* may not appear the same to the agents if they are different, e.g., if they have different sensors and actions

Interactions in multi-agent systems

- if the agents are not aware of or simply *ignore* each other, there isn't very much interesting to say
- if they always *compete* with each other, it is more interesting, but the agents don't form a *system* in anything other than the ecological sense (e.g., artificial life)
- for a multi-agent system to be possible the agents must *cooperate* about some things – there must be some overlap in their task environments
- e.g., even if the agents compete for resources, they must cooperate about how the resources are to be allocated

Competition & cooperation in MAS

- the balance between competition and cooperation depends on the degree to which the goals of the agents overlap

- e.g., agents representing different organisations in an electronic market will typically have competing goals (to maximise the profit of their organisation)

- however they must cooperate to ensure that the market (e.g., auction) works fairly

- *mechanism design* is concerned with designing interaction protocols in which the agents have no incentive to cheat

Co-operation in multi-agent systems

- agents are *self-interested* and do not share a common goal
  - e.g., they are designed to represent the interests of different individuals or organisations
  - agents co-operate because it helps them achieve their own goals
- agents implicitly or explicitly share a *common goal*
  - benevolently work to achieve the overall objectives of the system, even when these conflict with the agent's own goals
  - e.g., when the agents are 'owned' by the same organisation or individual

Shared goals

- we will focus on the special case in which all the agents in the MAS cooperate to achieve one or more system or *organisational goals*
- usually the aim in MAS is that agents co-operate to perform some task that a single agent can't do on its own
  - because a single agent doesn't have all the capabilities or knowledge required to perform the task
  - because a single agent would be too slow
- note that there may still be elements of competition, e.g., if the agents compete for the organisation's resources
- mechanisms are still required to ensure that resources and tasks are allocated appropriately

Applications of multi-agent systems

- *distributed problem solving*
  - each agent has only restricted capabilities or knowledge in relation to the (shared) problem to be solved
  - e.g., scheduling meetings, design of industrial products
- *solving distributed problems*
  - the agents have similar capabilities but the problem is distributed
  - e.g., controlling a communications or energy distribution network

Designing multi-agent systems

- more complex than designing a single agent
- the *types* of agents to use: should they be identical or specialised? how many agents should there be of each type (redundancy)?
- what architecture(s) should they have?
- how the agents *communicate* with each other, e.g., by signalling or sending messages

Designing multi-agent systems 2

- what type of organisational structure should be used:
  - *predefined*: relationships are determined in advance by the designer of the system
  - *emergent*: the structure is entirely the result of the interactions between the agents
- how should the organisational structure be implemented:
  - should *control* be hierarchical or distributed?
  - if distributed, what *mechanisms* are there for ensuring co-operation between agents–e.g., sharing tasks and resources, co-ordination of actions, arbitration and negotiation

Specialisation & redundancy

- the degree of *specialisation* indicates the number of actions an agent can perform in relation to the number of actions necessary to perform the task

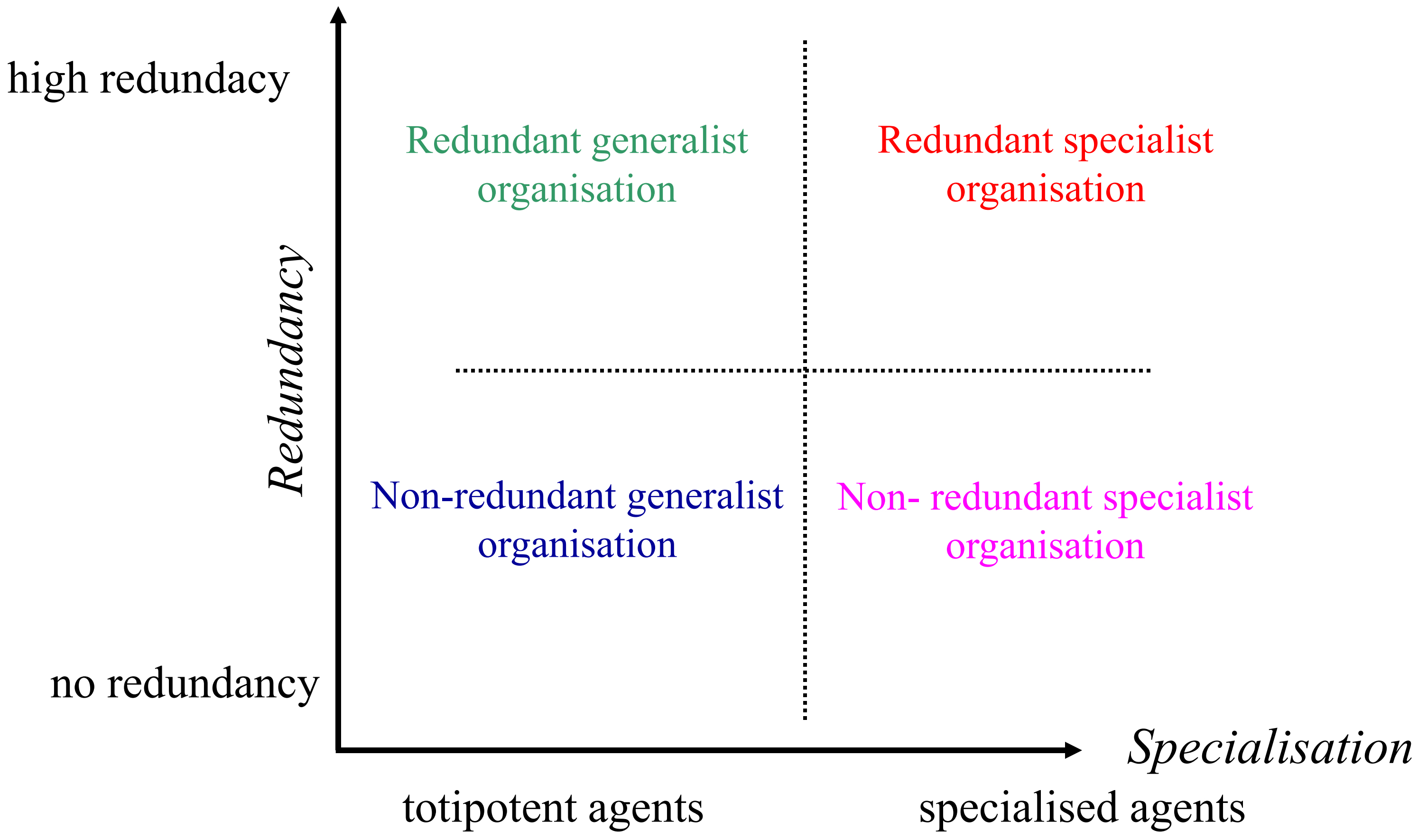
- the degree of *redundancy* indicates the proportion of agents capable of performing a given action

- for simplicity, we assume that all (basic) actions can be carried out by a single agent

Specialisation & redundancy 2

- is it better to to have very specialised agents, each of which can perform only a few actions?
- or is it better to have totipotent agents which can perform all the actions and only the number matters?
- less specialised agents will give a more flexible and reliable system
- but will be more costly and may be less efficient, since more negotiation is required to determine which agent does which task

Specialisation vs redundancy



Specialisation vs redundancy

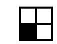
- *non-redundant generalist organisation*: each agent can perform many actions and each action is performed by only a few agents

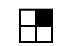
- *redundant specialist organisation*: each agent can perform only a few actions and each action is carried out by many agents

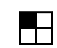
- *redundant generalist organisation*: each agent can perform many actions and each action can be performed by many agents

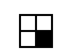
- *non-redundant specialist organisation*: each agent can perform only a few actions and each action is performed by only a few agents

Specialisation vs redundancy 2

- *non-redundant generalist organisation*: in the limit, this reduces to a single agent which can perform all the actions 

- *redundant specialist organisation*: in the limit every agent performs the same single action 

- *redundant generalist organisation*: in the limit, every agent can perform all actions (so the problem is how to distribute the actions among the agents) 

- *non-redundant specialist organisation*: in the limit, each agent can perform only one action and each action is performed by only one agent 

Control

- control structure determines the way in which agents can cause other agents to perform certain tasks:
  - *hierarchical structures*: control is organised around a branching tree, with agents nearer the leaves subordinate to those nearer the root of the tree
  - *distributed structures*: any agent can ask any other agent to carry out a task which it may or may not agree to perform

Example: explorer robots on Mars

- from a fixed base several mobile robots explore an unknown environment in order to find and recover ore and transport it back to the base
- the agents must perform three actions to gather ore:
  - find some ore
  - drill down to bring it to the surface
  - transport the ore back to base
- each action can be accomplished independently of the others by a single agent
- robots can be rendered inoperative for various reasons, e.g., being hit by a meteorite, breakdown etc.

Designing the robots

To solve the problem we have to determine:

- the *types* of robots to use: should they be identical or specialised?
- the *architecture(s)* of the agents: should all the agents have the same architecture or should they have different architectures? should they be reactive or deliberative or hybrid?
- the kind of *communication* to use: signals or messages? (this interacts with the architecture(s) of the agents)
- the *co-operation mechanisms* and *interaction protocols* to use: what happens when two robots discover a deposit ofore at the same time?
- the *organisation* of the agents: should they work as a group or on their own? are the teams fixed or dynamic? can agents ask for assistance?

Solution 1

- *hierarchical*, *predefined* organisational structure
- each agent performs a single action (detecting, drilling and transporting), and several agents can perform the same action
- agents are organised into fixed teams with a hierarchical subordination structure
- each detector robot commands a (fixed) set of driller robots and each driller commands a (fixed) set of transporter robots

Solution 1 analysis

- not very adaptable: if a detector agent finds a very large ore deposit, it can't do anything useful
- central point of failure: if an essential agent breaks down, the whole team is lost
- the performance is low: if a detector takes a long time to find ore, the drillers and transporters in the team remain unused

Solution 2

- *egalitarian*, *predefined* organisational structure:
- robots can be *totipotent* or *specialised*
- one way to do this is the *contract net protocol*:
  – an agent with a task to perform sends a request for bids
  – agents which are interested respond with bids
  – the originating agent decides which bid(s) to accept

Solution 2 analysis

- more flexible than solution 1
- each agent can ask the others for help as the need arises–e.g. drillers can ask detectors to find some ore
- but how do totipotent agents decide which of the 3 actions to perform at each timestep?
- maybe better if the agents are more specialised, since then the agents don’t have to worry about which actions to perform
- but still: which requests for help do specialised agents respond to?

Solution 3

- *egalitarian*, *emergent* organisational structure:
- each robot can detect, drill and gather ore on its own
- the system has a great deal of redundancy, but can be inefficient
- to improve performance, the robots can start to specialise while they are working
- e.g., those who have transported ore become more likely to transport ore in the future

Solution 3 analysis

- one problem with a totipotent MAS is to make the agents capable of cooperating so that if one finds ore, the others can benefit from this discovery
- would it be more efficient if the ‘correct’ number of robots adopt each role, so that they no longer need to deliberate on which action to perform next?
- many ant species have distinct worker roles optimised by natural selection, presumably to increase colony efficiency
  – large workers specialise in defence, and small ones in cutting fruit

Task sharing

- *task sharing* is the problem of determining how tasks are allocated to individual agents in a multi-agent system
- for homogeneous (e.g., totipotent) agents this is straightforward–only concern is load balancing
- if the agents are heterogeneous (have differing capabilities) and/or are autonomous (can refuse tasks), then task sharing involves reaching agreements between agents

Contract net protocol

- *contract net protocol* is a way of achieving efficient co-operation through task sharing in networks of (possibly heterogeneous, autonomous) agents
  - *task announcement*: an agent which generates (or receives) a task broadcasts a description of the task to some or all of the agents
  - *bid response*: agents respond to the task announcement with a bid
  - *task allocation*: the agent which announced the task allocates it to one or more of the bidding agents
  - *expediting*: the agent to which the task was allocated carries it out

Task announcement

- *task manager* sends a task announcement to some or all agents
- task announcement contains information about the task to be performed:
  - *eligibility specification*: the criteria an agent must meet in order to be eligible to submit a bid
  - *task abstraction*: brief description of the task to allow potential bidders to evaluate level of interest
  - *bid specification*: description of the expected form of a bid for the announced task

Bidding

- on receipt of a task announcement, an agent determines if it is *eligible* for the task based on:
  - the task's eligibility specification
  - the agent's hardware and software resources
  - its current commitments
- eligible agents send a *bid* to the task manager containing the information in the bid specification, e.g., when they will be able to complete the task, how much it will cost, etc.

Task allocation

- bids are stored by the task manager until a deadline is reached
- if no (acceptable) bids are received by the deadline, task is re-announced
- otherwise the manager then awards the task to one or more bidders
- bidders who have been awarded the task confirm that they are still able to undertake it (situation may have changed between bid and award)
- otherwise part or all of the task is re-announced

Task processing

- award messages contain a complete specification of the task to be executed
- successful bidder(s) (contractors) must attempt to expedite the task
- this may result in the generation of new *sub-tasks* which the bidder then manages ...
- when the task is complete, contractors send their manager a report message containing the result of the task

Applications

- contract net has become one of the most popular frameworks for task sharing in multi-agent systems (e.g., FIPA-OS)
  - originally used to allocate tasks over a distribute network of sensors (benevolent agents)
  - later extended to self-interested agents in electronic markets
- many variants—e.g., agents respond with offers of tasks to *swap* for the announced task

Handling inconsistency

- a group of agents may have inconsistencies in their beliefs, goals or intentions (Wooldridge)
- inconsistent beliefs arise because agents have different views of the world
  - may be due to sensor faults or noise or just because they can't see everything
- inconsistent goals may arise because agents are built by different people with different objectives

Handling inconsistency 2

- three ways to handle inconsistency (Durfee at al.)

- do not allow it
  - in the contract net, perhaps the only view that matters is that of the task manager agent

- resolve inconsistency
  - agents argue about the inconsistent information/goals until the inconsistency goes away

- build systems that degrade gracefully in the face of inconsistency

Coordination

- perhaps the defining problem in cooperative working is that of coordination (Wooldridge)
- i.e., managing inter-dependencies between the activities of agents
- we both want to leave the room through the same door: what do we do to ensure we can both get through the door?
  - activities need to be coordinated because there is only one door
- I intend to submit a request for annual-leave, but in order to do this, I need a signature from my manager
  - my activity depends upon my manager’s

Coordination 2

- interactions between activities could he either *positive* or *negative* (Von Martial)
- negative interactions should be recognised and avoided, but positive ones may yield some benefit if actions/plans are combined
- positive coordination may be *requested*: I explicitly ask you for help with my activities
- or it may be *non-requested*: it so happens that by working together we can achieve a solution that is better for at least one of us, without making the other any worse off

Coordination 3

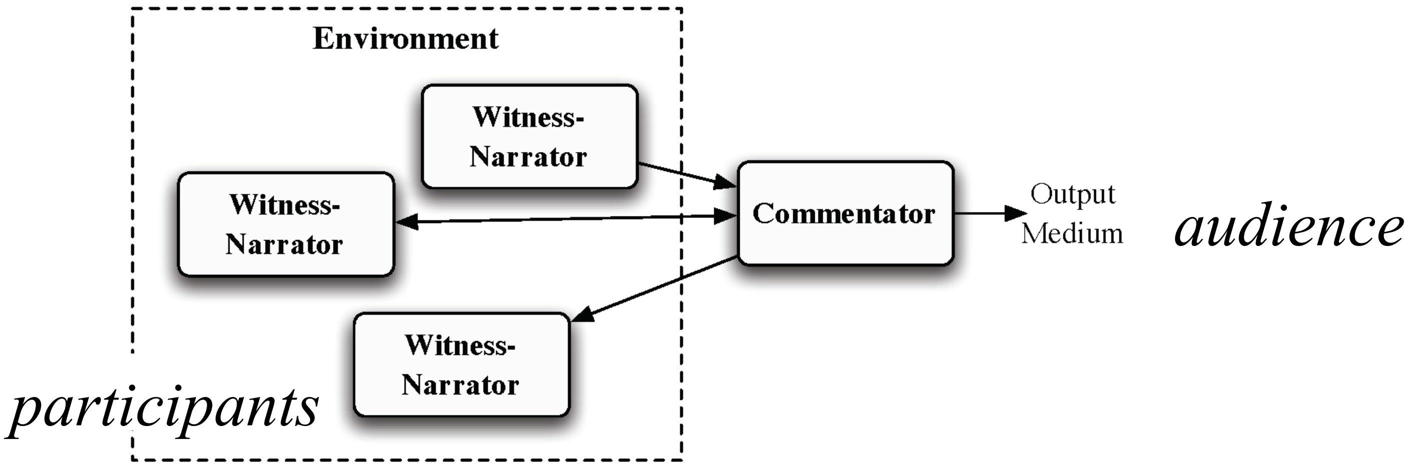
- there are three types of non-requested (implicit) coordination
- *action equality*: we both plan to do something, and by recognizing this one of us can be saved the effort
- *consequence*: what I plan to do will have the side-effect of achieving something you want to do
- *favor*: what I plan to do will make it easier for you to do what you want to do

Example: Witness-narrator framework

- agent-based approach
- agents embodied in the environment generate narrative from observations of participant's actions
- narrative is published to external audiences, e.g., community websites, SMS messages
- or fed back into the environment in real-time to embellish the ongoing experience

Narrative production

- ***participants*** are the subject of the narrative—interact with *witness narrator agents* in the environment
- external ***audience*** are not (currently) embodied in the world but read accounts of the action—interact with non-embodied *commentator agents*
- both participants and audience make requests for information about past, present or future events



Example output

Dragon slain in Etum Castle District

An ancient dragon was slain in Etum Castle District within the last hour. Lance Bannon, a powerful mage, delivered the fatal blow by casting a fireball at the dragon.

It all started when Jim Fingers, a young rogue, attacked the dragon with a sword. The ancient dragon slashed Jim Fingers with its talons. Lance Bannon, a powerful mage, cast invisibility. Oliver Ranger, a fighter, stabbed the dragon with a dagger. The dragon cast a fireball at Jim Fingers. Lance Bannon cast a fireball at the dragon. Finally, the ancient dragon died.

Embodiment & control

- witness narrator agents are embodied in the environment and have (approximately) the same capabilities as a human participant
- participants can determine when they are being observed and the information an agent can obtain given its position
- can also try to avoid agents or modify their behaviour when they are around
- allows participants (some) control over what gets reported
- important when reporting events to an external audience

Embodiment as interface

- provides an interface to the narrative system which is seamlessly integrated with the virtual environment
- participants interact with WNAs in the same way as with other NPCs (via menus & text):
  - ask for information about current events elsewhere in the environment
  - ask an agent accompany them as they progress through the game to share reports of their activities with others
  - ask an agent to go away

Embodiment & PoV

- WNAs embodiment (first-person view of events) explains the ultimate source of the narrative
- makes explicit the limitations of what is knowable about the actions of other participants
- view of events is limited to actions of players and speculation about their thoughts, feelings or motives
- agents are ‘witnesses’ rather than protagonists—do not actively play a part in the activities of the game beyond their presence and the narration they provide

User requests

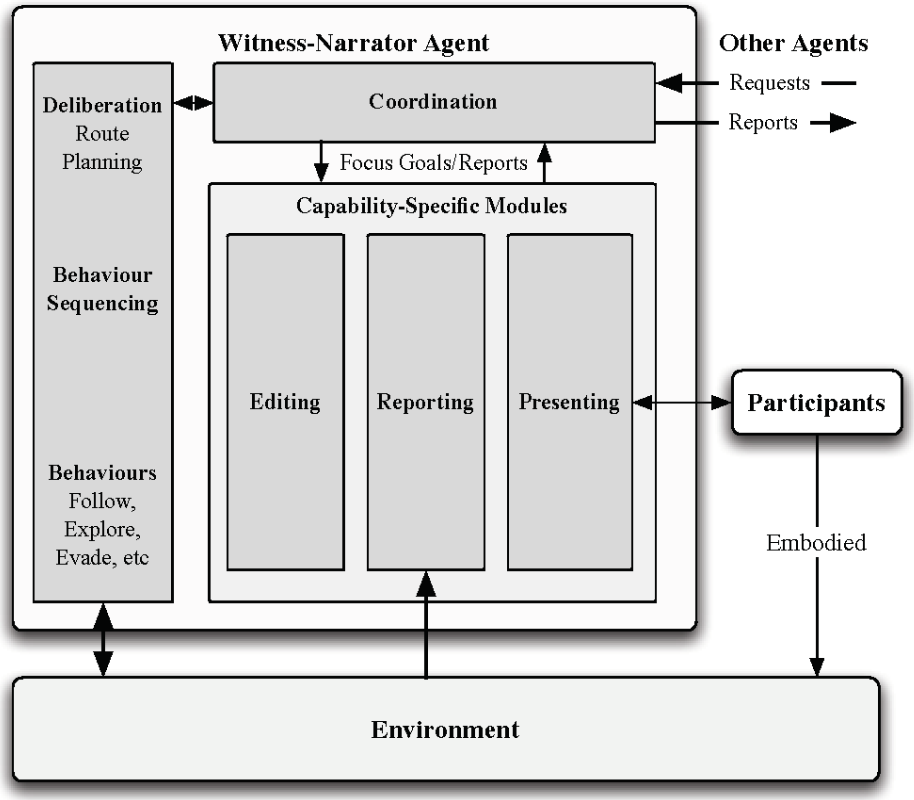
- information requests give rise to *focus goals* which direct the activities of the witness-narrator agents:
  - partial description of events (e.g., what are my friends doing now)
  - area of the environment and the time(s) at which the events occur (e.g., what happened at this location in the past)
  - interval specifying how frequently to generate reports
- focus goals determine which events observed by the agents are considered 'interesting'

Autonomous goal generation

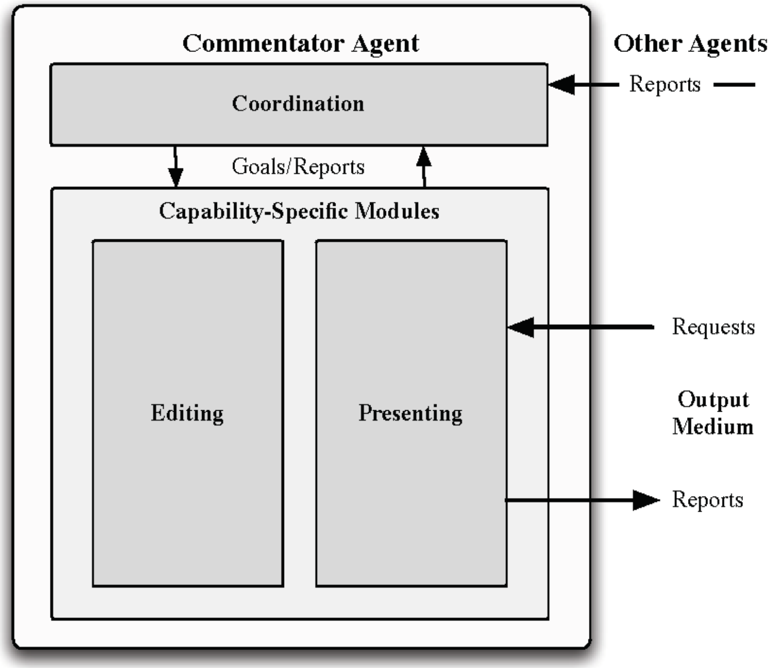
- witness-narrator agents can generate focus goals autonomously in response to observed events
  - always refer to current or future events
  - always specialisations of existing focus goals
- WNAs have *a priori* high-level goals which are used as a basis for autonomous goal generation, e.g., death of a player

Agent architecture

Witness-Narrator Agent



Commentator Agent



Agent coordination

- a focus goal specifying past or current events which cannot be satisfied by the agent that generated it is *broadcast* to all WNAs, e.g.
  - "what happened yesterday"
  - "what are my friends doing right now"
- reports matching the focus goal are forwarded to the originating agent

Team formation

- focus goals which specify future events result in the formation of a *team of agents* coordinated by the agent which generated the goal
- coordinator broadcasts a call for participation which includes the focus goal
- agents which can attend to a focus goal at any point during the time it is active will offer to join the team, stating when they are available
- coordinator assigns roles to team members based on a set of ideal role requirements, so as to ensure the maximum coverage of the goal
- team formation is on a best-effort basis

Implementation

- agents are implemented in AgentSpeak (Jason)—each module is a collection of Jason plans and rules
- event ontologies are developed in OWL-DL using Protégé and compiled into Jason rules
- coordination layer builds on Jason's contract net implementation
- also draws on a number of other Jason extensions (multiagent communication, persistent database etc)
- NWN gameserver plugin for sensing

The next lecture

Multi-Agent Systems II

Suggested reading:

- Ferber (1999), chapter 1