Coordinated Problem Solving

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In ancient times alchemists believed implicitly in a philosopher's stone which would provide the key to the universe and, in effect, solve all of the problems of mankind. The quest for coordination is in many respects the twentieth century equivalent of the medieval search for the philosopher's stone. If only we can find the right formula for coordination, we can reconcile the irreconcilable, harmonize competing and wholly divergent interests, overcome irrationalities in our government structures, and make hard policy choices to which no one will dissent.

—Harold Seidman: **Politics, Position, and Power**

Coordination is the process of managing interdependencies between activities.

—Tom Malone

Resource Dependencies

Data Dependencies (intermediate or final results)

Distributed Computing vs. Distributed AI Viewpoints

- Distributed Computing
  - Tightly coupled, parallelization, centralized control
  - [Distributed OS] Independent processes
    - Resource coordination: centralized locking, load balancing
  - Total database consistency
- Distributed AI
  - Loose coupling, distributed control
  - Interdependent processes (data coordination)
  - "Functionally Accurate" (often inconsistent)

Key Problem: Coordinating Computational Actions

Managing complex interdependencies between activities

- If there is a choice, then the particular action carried out matters
  - high quality, long duration actions
  - fast, lower quality approximations
- The order in which actions are carried out matters
  - hard precedence constraints
  - soft facilitation opportunities
- The time at which actions are carried out matters
  - hard or soft deadlines
  - time implies ordering across multiple agents

Coordinating Computational Actions

- Primary difficulties in CHOOSING and TEMPORALLY ORDERING actions
  - incomplete view of the problem
  - dynamically changing situation
  - uncertainty in the outcomes of actions

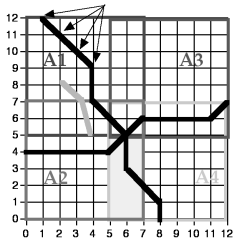
Coordinating Computational Actions

- Overcome difficulties with Coordination Mechanisms
  - schedules, plans, timelines, appointments, commitments
    - Partial views, mostly static situation, often little action uncertainty
  - laws, rules, social behavioral norms
    - Ignore view, possible contingent decisions, reduce uncertainty
  - organizations, roles, negotiated order
    - Allow multiple views, abstract the situation, reduce uncertainty

The Distributed Vehicle Monitoring Problem

[1981–1991]

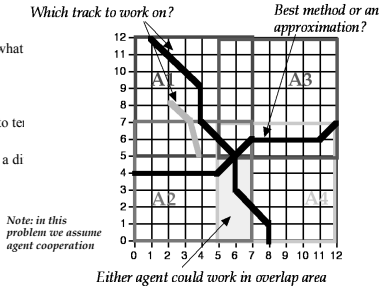
- Acoustic vehicle tracking
  - grammar specifies vehicle's "signature"
  - varying signal strengths
  - uncorrelated noise
  - "ghost tracks"
- Multiple agents with overlapping sensors
  - faulty sensors
- Coordinate processing to terminate as quickly as possible



The Distributed Vehicle Monitoring Problem

[1981–1991]

- Making choices about what do...
  - ...in what order
  - ...and at what time
- Coordinate processing to te quickly as possible
- These choices do make a di



Example Applications & Coordination Problems

- Distributed Sensor Networks
  - when to provide predictive information?
  - DVMT: Distributed Vehicle Monitoring Testbed
- Concurrent HW/SW Engineering
  - which ordering is best for design subtasks done by one agent?
  - Boeing Rotorcraft MADEsmart/RaDEO
- Distributed Scheduling / Agile Manufacturing / Telescope Scheduling
  - How to distribute loads, recover from failures, observe organizational boundaries?
  - Hospital Patient Scheduling, satellite contact scheduling
- Local Area Network Diagnosis
  - How to avoid self-induced packet storms?
  - LODES
- Software Agents for Information Gathering
  - Where to look, how to follow up on leads, integrate feedback from partial results?
  - RETSINA (Warren:finance), DECAF (BioMAS:bioinformatics)

Coordinating Computational Actions

Other Ways of Thinking About Coordination

- Coordination mechanisms might address different levels of abstraction
  - Specification
    - creating shared goals
  - Planning
    - expressing potential sets of tasks to achieve goals
  - Scheduling
    - task assignment, shared schedules, resource allocation

Coordinating Computational Actions [Specification]

- Work to specify compatible goals, then operate mostly independently
- Robots
  - Goal: don't run into each other
  - Mechanism: externally decided by designers, hard-wired, out of the agent's control
  - [but note that the designers cannot make arbitrary choice: e.g. "pass on right". There is a constraining social context.]
- Small business
  - Goal: select unit product mix for maximum benefit
  - Mechanisms: direct negotiation, selection by CEO, indirect mechanism (budgeting), etc.
- Goverment
  - Goal: allocate scarce resources to some mix of initiatives
  - Mechanisms: direct negotiation, majority voting, coalition formation, etc.

Coordinating Computational Actions [Planning]

- Robots
  - pure preprogrammed reactive behavior, classical AI planning driving low-level behaviors, etc.
- Small business
  - explicitly build and compare plans
- Government
  - simultaneously embark on multiple, partially conflicting plans :-)

Coordinating Computational Actions [Scheduling]

- Robots
  - integrate moving, sensing, seeking goal, avoid obstacles, etc.
- Small Business
  - Assign tasks to people, allocate local resources (money), create explicit schedules
- Government
  - change Standard Operating Procedures, revise decision-making criteria

Coordinating Computational Actions

Yet another view

- Centralized Coordination Mechanisms
  - single locus of data/knowledge and decision-making/authority
  - PROS: easier to show optimality, implement, ignore concurrency issues
  - CONS: central point of failure, human organizational mismatch, difficulties in dynamic environments
- Decentralized Coordination Mechanisms
  - decentralized knowledge/data and decision-makeing
  - PROS: robustness, organizational fit, opportunistic, realistic
  - CONS: rarely optimal compared to centralization, concurrency complexity
- Reality: hybrids (e.g. centralized control of individual resources in a decentralized environment/context)

Coordinating Computational Actions

Yet another view

- Static Coordination Mechanisms
  - designed by programmers at design-time
  - example: rules of the road
- Dynamic Coordination Mechanisms
  - "designed" by agents at run-time
  - parameterized static mechanisms
  - selection between static alternatives

Coordinating Computational Actions

Yet another view

- Implicit Coordination Mechanisms
  - Altering/defining the environment so as to "solve" the coordination problems
  - e.g. Social Conventions/Laws
  - e.g. Organizations
  - e.g. Agent Modeling
  - e.g. Free Market Economics ("the invisible hand")
- Explicit Coordination Mechanisms
  - Agents explicitly "arguing" over who does what, and when
  - e.g. Representing & Exchaning Commitments
  - e.g. Distributed Planning
  - e.g. Distributed Scheduling
- Reality: Hybrids, "open and closed questions"

Searle

Coordination vs. Coherent Action

- Implicit Coordination -/-> coherency
  - Robot 1 observes Robot 2 heading for Exit 2
  - Therefore, Robot 1 decides to use Exit 1
  - However, observation was misleading; Robot 2 also heads for Exit 1
- Coherent Action -/-> explicit coordination
  - Observe many people from all over the place running to a central tree (coherent action)
  - Context:
    - (explict coordination) Dancers in a ballet
    - (implicit coordination) People trying to avoid sudden rain in the park

Coordinating Computational Actions

- Abstraction
  - Goals
  - Plans
  - Schedules
- Location
  - Centralized
  - Decentralized
- Learning
  - Static
  - Dynamic
- Structure
  - Implicit
  - Explicit

OUTLINE

- Introduction to Coordination
- Implicit Approaches to Coordination
  - Social Convention
  - Organizations
  - Agent Modeling
- Explicit Approaches to Coordination
  - Commitment
  - Planning
  - Scheduling
- Detailed Example: Generalized Partial Global Planning

Coordination and Social Convention

[Weber, Mintzberg, Scott, Perrow]

- Standardization, Coding
  - negotiating the size of the nuts and bolts VS. using standard sizes
  - standard function/object/service/communication interfaces [WSDL, GridServices]
- Slack
  - Drinks and Dinner at 7pm
  - hard vs. soft deadlines
  - deadlines vs. absolute delivery times
- Rules and Regulations
  - Traffic laws
  - Network Protocols

Coordination and Social Convention

[continued]

- "Social Laws" [Tennenholz]
  - specified as constraints on actions; logical state predicate which PROHIBITS an associated action
  - agents constrained to choose only legal actions
  - learning is NP-complete (but off-line)
- Forecasts / Predictions
  - agents acting on shared information about the future
- Cooperation and CDPS [Cooperative Distributed Problem Solving]; Benevolent Agent Assumption
  - can simplify the construction of many closed or partly closed systems

[Weber, Mintzberg, Scott, Perrow]

Coordination and Organizations

- Hierarchy, Authority
  - [partly] centralized decision-making
  - other assumptions about conventions (can differ between/within orgs)
- Specialization, Professionalization, localization
  - fixed roles (functional/spatial/temporal) avoid redundancy
  - long-term commitments to certain courses of action
    - "I will commit to requests of the form X"
  - example: DVMT "interest areas"
  - example: MAS Matchmakers/Yellow Pages/Directory Services

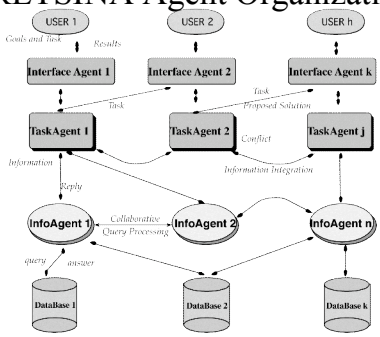
Coordination and Organizations

- Informal Channels [Chisholm]
  - provide extra context, non-local information
  - learn/grow to overcome deficiencies in nominal organization
- Power sharing, Co-optation, Growth
  - one agent/org prepares palette of choices; another chooses
  - boards of directors
  - vertical integration
    - Example: Williamson: Transaction Cost Economics
      - Link 1: Environmental Uncertainty & Bounded/Limited Rationality
      - Link 2: Small Numbers of agents and Opportunism

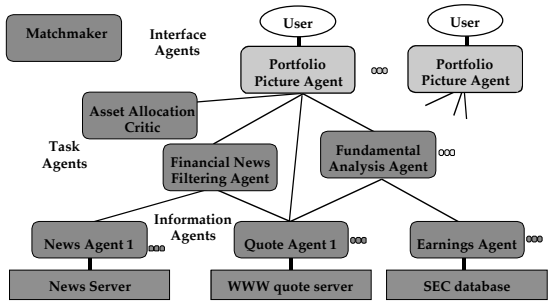
Coordination and Organizations

- Other structured communities
  - Scientific Community metaphor [Hewitt]
  - RETSINA organizations [Sycara & Decker]
  - Teams [Tambe], etc.
- Reorganization: Negotiation and Coalition Formation
  - See Agent Mediated Electronic Commerce lectures
- current structure vs. system to negotiate structure (temporarily open & closed questions [Gasser]
- shared task priorities, shared group utility functions, etc.

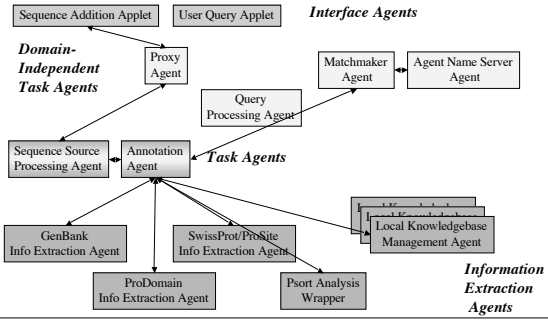
RETSINA Agent Organization



Typical Warren Organization



Part of the BioMAS Organization



[Hewitt & Kornfeld]

Scientific Community Metaphor

- Proposers
  - propose possible solutions
- Proponents
  - collect and present evidence in favor of a solution
- Skeptics
  - collect and present evidence to disprove a solution
- Sponsors
  - evaluate proposals and direct resources toward favorable proposals

Coordination and Agent Modeling

- Game Theory in the Agent Modeling Sense
  - Coordination without communication [Rosenschein and students]
- RMM Recursive Modeling Method [Gymtrawiecz]
- Markets [Wellman, Sandholm, Huberman, Hogg, etc.]
- Other Decision-Theoretic Approaches
- Coordiantion via Observation [Durfee & Huber, Sen]

See also:Game Theory: Agents and Rational Decisions

Game Theory

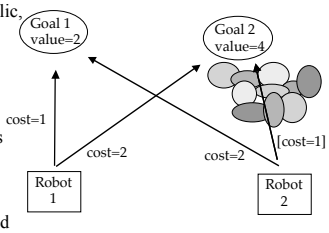
- Coordination and Agent Modeling
- Fixed social conventions:
  - "rules of the game"
  - certain public, shared information
  - rationality assumptions
- Private strategies
- Difficulties
  - large amount of shared knowledge
  - strong assumptions
  - Prisoner's dilemma and iterated games

Agent J \ Agent K	c	d
a	3 / 4	1 / 2
b	4 / 1	2 / 3

Coordination and Agent Modeling

Recursive Modeling Method

- Rather than assume all situational info is public, explicitly model what you believe the other agent believes the situation is (at some likelihood)
- Continue such models until no extra, useful information ("No Information" model)
- Solve game matrix and back up values



Coordination and Agent Modeling

Coordination via Observation

- Plan recognition frameworks
  - fitting observations to possible plans
  - predict future moves based on belief on which plan(s) are being followed, beliefs in possible next actions, etc.

Coordination and Agent Modeling

Markets & Other DT Approaches

- See Agent Mediated Electronic Commerce
- Strong solutions with strong assumptions
  - cookbook of mechanisms indexed by situational assumptions
- Pareto Optimality / Social Welfare

Explicit Coordination

- Increased local capability
  - Reasoning about commitments, plans, schedules, communication
  - meta-level [outside of domain] information exchange
  - Distributed processing

[Jennings, Lesser]

Coordination and Commitment

- Distributed Goal Search
- Commitments & Conventions

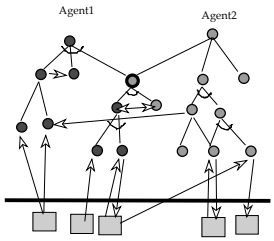
Designing Intelligent Agents & Organizations That:

- operate in environments with uncertainty, deadlines
- have multiple, possibly +/- interacting goals/objectives
- need to satisfice, not optimize
  - produce results that vary in quality depending on time pressure
- interact with other agents
  - non-independent subproblems
  - partially overlapping goals/objectives

Distributed Goal Search

Coordination and Commitment

- Representing
  - action interdependence (positive and negative task interrealtionships)
    - logical formulations, e.g. Favors [von Martial]
    - quantitative formulations, e.g. enables, facilitates, etc. [TAEMS--Decker]
  - global constraints
  - non-homogeneity and/or limited rationality
- Structure
  - AND/OR
  - Weak/Strong dependencies
  - Uni/Bi-directional
- Observations
  - Graph may be elaborated at run-time
  - Elaboration process is itself difficult
  - Entire graph may never exist centrally
- Compare TAEMS, later



[Jennings, Cohen & Levesque, Castelfranchi, Barbuceanu, Grosz & Kraus, Decker & Lesser]

Coordination and Commitment

- Commitments
  - Concept
    - pledge
    - goal adoption
    - intention-to
    - obligation/role/permission
  - constraints on basic predicate being committed to
    - Beliefs and actions [Jennings; Cohen & Levesque]
    - Action do, deadline, earliest start time, don't [Decker]
    - Actions in support of a goal [Castelfranchi; Barbuceanu]
    - Actions [Grosz & Kraus]

Coordination and Commitment

- temporal constraints
- complex predicates
  - conditional commitment
  - negation (Don't), forbidden actions
  - conjunctions
  - disjunctions (commit to A or B)
- Bundles of commitments; commitment implications (e.g. local --> social)
- Social Commitments
  - committing "To" another agent
  - committing "Before" a witness [Castelfranchi]

Coordination and Commitment

- Joint Commitments [Bratman; Cohen & Levesque; Tambe]
  - commitments shared by more than one agent about something; teamwork models (see Tambe's lectures) (Cohen: traffic vs. convoy)
  - contrast social commitment (from one agent to another, perhaps witnessed by a third)
  - impossibility in practice of shared mental state

Coordination and Commitment

- Conventions
  - Local rules/policies for modifying/reconsidering commitments
  - balance constant reconsideration and terminal stubborness
    - Example: BDI fanatacism vs. relativism
      - Forever, until impossible, until impossible or otherwise a bad idea…
    - Example: GPGP
      - reconsider on new schedule (new task or change in another agent's non-local commitment)

CONVENTION [Cohen & Levesque]

Reasons for re-assessment:
- *commitment satisfied*
- *commitment unattainable*
- *motivation for commitment gone*

Actions:
R1: ***if*** *satisfied*
or unattainable
or motivation gone
then *drop commitment*

Coordination and Commitment

- Social Conventions
  - How commitment reconsideration should impact on other agents

JOINT ACTION CONVENTION: [Cohen & Levesque]
Reasons for re-assessment:
- *[A] status of CMT to joint goal changes*
- *[B] status of CMT to attaining joint goal in current team changes*
- *[C] status of joint CMT of a team member changes*

Actions:
R1: ***if*** *[A] or [B]*
then *inform all other team members of the change*
R2: ***if*** *[C]*
then *determine whether joint CMT is still viable*

Coordination and Planning

- Task-driven planning
- Plan coordination/plan merging
- Syncronization (before, during, after planning)
- Multistage negotiation

Coordination and Planning

- Classic AI Planning:
  - static environment
  - known action outcomes
  - whole plan is made and agreed to before action
- Centralized: factory assembly [Georgeff]
  - separate plans
  - central coordinator
    - identify interactions
    - set up critical regions with semaphore-style communication actions
- Centralized: aircraft flight control [Cammarata]
  - separate intentions/goals/actions
  - central planner adds syncronization/coordination actions (movement)
  - attempt to change only one agent's plan
- Decentralized: Distributed NOAH [Corkill]
  - distributed plan critics propose to distribute conjunctive goals

Coordination and Planning

- Traditional partial order sequence of actions considering goals, capabilities, and environmental constraints
- Distributed: other agents changing the environment (known and unknown); models and commitments to antcipate and be anticipated
- Dynamic environments
  - Assigning roles into existing routine MA plans [Kinney]
  - Cooperative models [GPGP-Decker]
  - Teamwork models [STEAM-Tambe]

Coordination and Planning

- Plan Merging Analyses
  - Given complete plans, look for cross plan threats (dropping or abstracting away independent parts)
- Plan Combination Search [Ephrati & Rosenschein)
  - Refine set of all possible local plans by working through a global state space one step at a time
- Hierarchical Behavior-space Search [Durfee & Montgomery]
  - Work out joint plan at highest level of detail, resolve conflicts at next more specific level

Coordination and Scheduling

- PGP [Durfee]
- GPGP [Decker]
- Distributed Job Shop Scheduling [Sycara/Smith, Hildum/Sadeh]
  - Texture measures (most constrained resource)
  - Poaching

Partial Global Planning [Durfee]

- Assume that tasks are interrelated, but not known a priori
- Develop a local abstract plan in terms of goal sequences
- Communicate to other agents (using meta-level organization)
- Identify partial global goals between abstract plans
- Create new, partial global plans from local plans and send them back to the appropriate agents

Outline from here on...

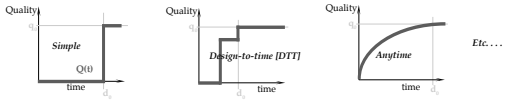
- Representing coordination problems (TÆMS)
- Solving coordination problems (GPGP)
- Building Agents and Multi-Agent Systems (DECAF)

TÆMS Task Structure Representation

- Representing complex domains
  - worth-oriented
  - time-oriented
  - distributed
  - uncertain
- Representing quantitative change in characteristics over which agents have preferences
  - quality
  - cost
  - duration vs. deadline
- State-based semantics
- Annotation for HTN style task networks

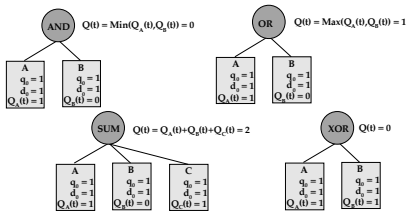
Actions/Executable Methods

- Characteristic Vector
  - maximum possible cost, quality, duration [c0, q0, d0]
  - associated uncertainty
- Execution Profile
  - start, suspend/resume, finish
- Accumulation Function: Characteristics vs execution time
  - Quality Accumulation Function [QAF]



Tasks

- Characteristic Accumulation Functions
  - Quality Accumulation Function [QAF]



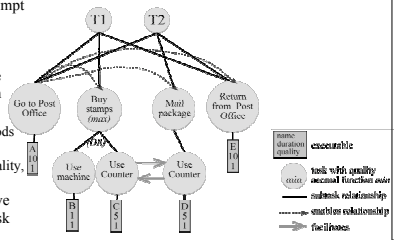
Performance Measure

- Utility function over characteristic vector
  - maximize quality
  - maximize quality - cost
  - minimize duration subject to $Q_{actual} > Q_{min}$
  - etc.

TÆMS Representation Framework

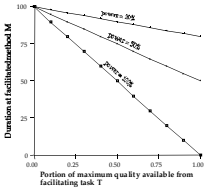
Develop a representation framework to specify the task structure of any computational environment

- Performance is: attempt to maximize quality(worth)
- Representation of structure at multiple levels of abstraction
  - Tasks
  - Executable methods
  - Methods have duration, max quality, QAF
- Explicit, Quantitative representation of task interrelationships



Non-Local Effects & Coordination Relationships

- NLE's are defined when the execution of one method changes the duration or maximum quality of another
- NLE's give an environment its unique characteristics
- A NLE may depend on the communication of information
- A NLE between parts of a task structure known by different agents is called a coordination relationship



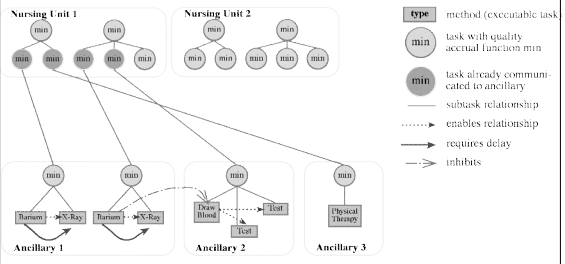
$$\text{facilitates}(T, M, t, d, q, \Box_d, \Box_q) = [d(1 \Box \Box_d R(T, \mathsf{S}(M))), q(1 + R(T, \mathsf{S}(M)))]$$

$$R(T, s) = \frac{Q_{avail}(T, s)}{\mathbf{q}_0(T, s)}$$

TÆMS Usage

- TÆMS can be used for environment modeling, algorithm analysis, and simulation
  - UMass simulators: TÆMS2, MAS
  - Agents may use any internal representation; but if task structure is created dynamically must translate
- However, can use TÆMS to build domain independent reasoning capability into an agent architecture that represents task structures internally
  - Planning, Scheduling, Coordination

Hospital Scheduling

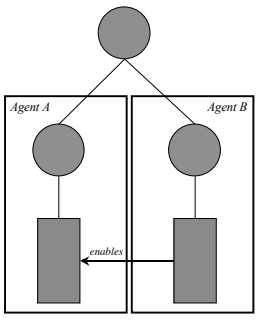


Generalized Partial Global Planning

- Domain-independent, coordinated scheduling of agent actions
  - Action choice, order, and timing
- Generalizes and extends Durfee's PGP algorithm, and von Martial's work on task relationships
  - Deadlines
  - Heterogeneous agent capabilities
  - Communicate less info, and at multiple levels of abstraction
- Individual Coordination Mechanisms
  - Recognize certain task structure patterns
  - Re-write the agent's HTN
  - Respond via instantiating a protocol for communicating commitments, non-local task structure information, and partial results.
- Works in conjunction with agent's local task scheduler to remove uncertainty
  - (DTC — Wagner; DTT — Garvey, DRU — Graham)

GPGP: The Idea

- Have A wait and see (poll)
- Have A ask B
  - "If"
  - "When"
- Have B tell A
  - B sends result when available
  - B commits to a deadline by which it will send the result
- Etc.



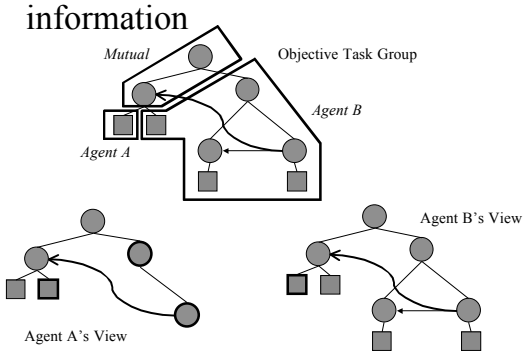
Some Coordination Mechanisms for Enablement

- Avoidance (with/without quality sacrifice);
- Reservation schemes;
- Simple predecessor-side commitments (to do in future time point, do by deadline, do after EST);
- Simple successor-side commitments;
- Polling approachs (busy querying, timetabling, constant headway);
- Shifting task dependencies by learning or mobile code (promotion/demotion shift);
- More complex multi-stage negotiation strategies;

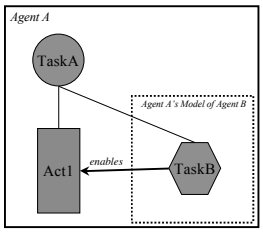
Other Coordination Mechanisms

- Redundant tasks (more than one agent under an OR node)
  - Avoidance
  - Load balancing
- Soft Facilitation
  - Predecessor commitment
- Mutual Exclusive Resources
  - Simple bidding

Minimizing non-local information

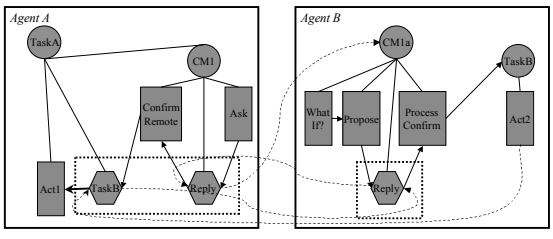


Example: Coordination by Reservation



What is Act1's Quality, Cost, Duration?
Does Agent B even know I need Act2?

Example: Coordination by Reservation

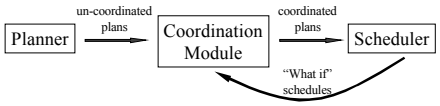


1. When can you finish TaskB? [GPGP Reservation CM Protocol]
2. Commit TaskB finish at time t1, quality 34, cost 6.
3. Agreed.
4. Here is TaskB's result.

Implementation

- Assume agent has local scheduling capability
  - Attempt to maximize utility (self, shared, whatever) by future action sequence
  - Problem is non-local effects make schedule more uncertain or simply unknown (I can't start my task until Agent B does Task B)
- Other assumptions needed for full range of mechanisms
  - Some way to do "what-if" schedule reasoning
  - Ability to make commitments to do, don't, and do w.r.t earliest start times and deadlines
  - Ability to move code for action promotion/demotion

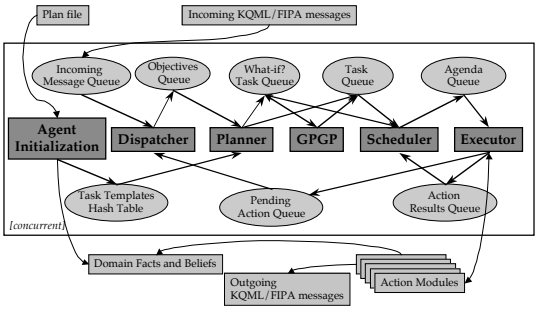
Coordination Module



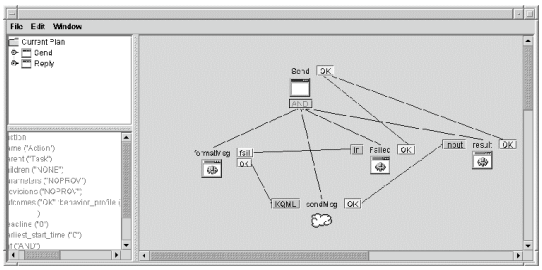
Coordination Module takes advantage of the local scheduler's scheduling ability to evaluate/estimate the features of actions for the remote agents.

http://www.cis.udel.edu/~decaf/

DECAF Architecture



Plan Editor



Summary: Coordination

- Process of managing the interdependencies between activities
  - Choice of actions
  - Ordering of actions
  - Timing of actions
- Difficulties occur because of uncertainties
  - Incomplete view (partly inaccessible state)
  - Dynamic situation
  - Action outcome nondeterminism

Summary: Coordination Mechanisms

- Explicit ly negotiated commitments, schedules, plans
- Explicit or implicit laws, rules, behavioral norms
- Long-term, generalized versions of the above
  - organizations, roles, standard operating procedures

Summary: Mechanism design space

- Abstraction
  - Goals
  - Plans
  - Schedules
- Location
  - Centralized
  - Decentralized
- Learning
  - Static
  - Dynamic
- Structure
  - Implicit
  - Explicit

Summary: (Mostly) Implicit Approaches

- Social Conventions
  - Standardization
  - Slack
  - Rules/Social Laws
  - Forecasting
  - Benevolence
- Agent Modeling
  - Game Theory
  - RMM
  - Markets
  - Observation
- Organizations
  - Authority/ hierarchy
  - Standard Operating Proceedures (Business Processes)
  - Specialization
  - Professionalization
  - Informal channels
  - Vertical Integration
  - Structured Communities
    - Teams

Summary: (Mostly) Explicit Approaches

- Commitments
  - Distributed goal search
  - Types of commitments
    - Concept
    - Related constraints
  - Joint Commitment
  - Conventions
- Planning
  - Centralized
    - Plan merging
    - Plan Syncronization
- Scheduling (continuum w/ planning)
  - Partial Global Planning
  - Other Distributed Scheduling Approaches

Summary

- Coordination: locally choosing and temporally ordering actions
- TÆMS: representing coordination problems
- GPGP: mechanisms for dealing with coordination problems
- DECAF: agent building toolkit [http://www.cis.udel.edu/~decaf]
- Information gathering applications in finance & bioinformatics [http://udgenome.ags.udel.edu/]

http://www.cis.udel.edu/~decker