Agents and Multi-Agent Systems

Multi-Agent Decision Making

Negotiation

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Negotiation Settings

- Auctions are only concerned with the allocation of goods
- The purpose of **negotiation** is to reach an agreement on matters of common interest, in the presence of conflicting goals and preferences

- Negotiation components:
  - Negotiation set: space of possible proposals that agents *can* make
  - Protocol: defines the *legal* proposals, depending on prior negotiation history
  - Strategies: determine what proposals the agents *will* make, and are *private*
  - Deal rule: determines when a deal is agreed, and what it is

- Negotiation proceeds in a series of rounds, in which legal proposals from the negotiation set are made, as determined by the strategies used

Negotiation Attributes

- Single-issue (*e.g.* price)
  - Preferences are symmetric – concession is straightforward (seller lowers price, buyer raises price)
- Multiple-issue: agents negotiate the values of multiple (possibly interrelated) attributes
  - Buying a car: price, length of guarantee, after-sales service, extras, …
  - It is harder to identify concessions
  - Exponential growth in the space of possible deals: m^n, with n attributes and m possible values
  - Assuming attributes are evaluated independently (additive independence), agents typically employ a *multi-attribute utility* function:

$$u_i(x) = \sum_{j=1}^{n} w_{i,j} u_i(x_j), \text{ with } \sum_{j=1}^{n} w_{i,j} = 1$$

Negotiating Agents

- One-to-one negotiation
  - Simplest case: symmetric preferences
  - Everyday example: buying a car
- One-to-many / Many-to-one negotiation
  - A single agent negotiates with a number of other agents
  - ContractNet protocol, procurement, one-sided auctions
  - Concurrent one-to-one negotiations
- Many-to-many negotiation
  - Many agents negotiate with many other agents simultaneously
  - Two-sided auctions

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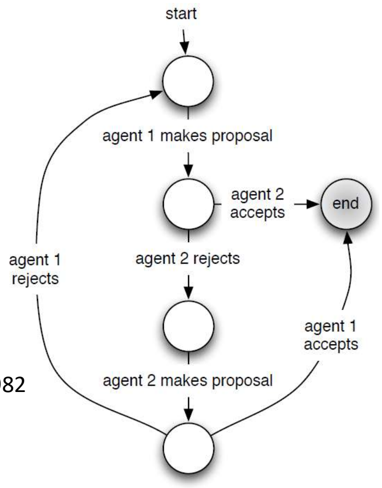
Alternating Offers Protocol

Rubenstein, Israeli, 1951-, economist

- One-to-one
- Sequence of rounds



Rubinstein bargaining model, 1982
- two-person bargaining
- perfect information
- players alternate offers

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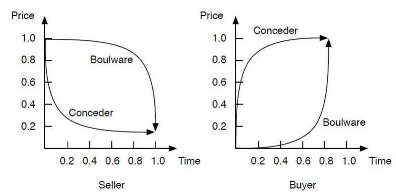
Time in Negotiation

- Time is valuable
  - Agents prefer any outcome x sooner than later
  - We can model agent i's patience using a *discount factor* $\gamma_i \in [0,1]$

    $u_i^0(x) = \gamma_i^0 x = x$ $u_i^2(x) = \gamma_i^2 x$

    $u_i^1(x) = \gamma_i^1 x = \gamma_i x$ $u_i^k(x) = \gamma_i^k x$
  - Larger γ_i (closer to 1) implies *more* patience (indifference to time)
  - Smaller γ_i (closer to 0) implies *less* patience (time matters more)

- Time-dependent negotiation decision functions [Faratin *et al.*, 1998]:



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Behavior in Negotiation

- We can take the negotiation opponent's previous attitude into account
  - *Tit-For-Tat*: equivalent retaliation, reciprocal altruism
- Behavior-dependent tactics [Faratin *et al.*, 1998]
  - *Relative Tit-For-Tat*: reproduce, in percentage terms, the behavior that the opponent performed some steps ago
    - *E.g.*, buyer increases offer in 10%, seller decreases asked price in 10%
  - *Random Absolute Tit-For-Tat*: the same in absolute terms, with some randomization
    - *E.g.*, buyer increases offer in €10, seller decreases asked price in €10±ε
  - *Averaged Tit-For-Tat*: average the percentages of changes in a window
    - If window size is 1, we have *relative Tit-For-Tat*

Task Allocation

- A task-oriented domain (TOD) is a triple $\langle T, Ag, c \rangle$
  - T is a set of tasks
  - Ag is a set of agents
  - $c: 2^T \to \mathbb{R}_+$ is a function that defines the cost of executing a subset of tasks
    - $c(\emptyset) = 0$
    - if $T_1 \subseteq T_2 \subseteq T$, then $c(T_1) \leq c(T_2)$, *i.e.*, c is monotonic
- An encounter is a collection of subsets of tasks $\langle T_1, \ldots, T_n \rangle$, where $T_i \subseteq T$ is the set of tasks assigned to agent i
  - Each agent has an initial set of assigned tasks
  - Agents may reach a deal to *reallocate* the tasks among themselves

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Deals and Utilities

- Given an encounter $\langle T_1, \ldots, T_n \rangle$, we define a pure deal as $\delta = \langle D_1, \ldots, D_n \rangle$, where $\bigcup_{i=1}^{n} D_i = \bigcup_{i=1}^{n} T_i$
  - Each agent i is committed to performing tasks D_i
- The cost of deal $\delta = \langle D_1, \ldots, D_n \rangle$ to agent i is $cost_i(\delta)$, or simply $c(D_i)$
- Utility is defined as a cost difference: $u_i(\delta) = c(T_i) - cost_i(\delta)$
  - The utility represents how much the agent *gains* with the deal
  - If negative, then the agent is worse off than if performing the originally assigned tasks
- If agents fail to reach agreement, they fall back to the conflict deal

$$\Theta = \langle T_1, \ldots, T_n \rangle$$

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Dominance

Deal δ_1 dominates deal δ_2 (written $\delta_1 \succ \delta_2$) iff:

1. Deal δ_1 is at least as good as δ_2 for every agent: $\forall_{i \in Ag}\, u_i(\delta_1) \geq u_i(\delta_2)$
2. Deal δ_1 is better than δ_2 for some agent: $\exists_{i \in Ag}\, u_i(\delta_1) > u_i(\delta_2)$

Deal δ_1 is said to *weakly dominate* δ_2 ($\delta_1 \succcurlyeq \delta_2$) if only the first condition holds

- A deal that is not dominated by any other deal is said to be *Pareto optimal*
  - If a deal is *not* Pareto optimal, then there is some other deal in which some agent gets a higher utility without making anyone worse off
- Deal δ is *individually rational* if it weakly dominates the conflict deal: $\delta \succcurlyeq \Theta$
  - If a deal is *not* individually rational, then at least one agent can do better by performing its originally assigned tasks

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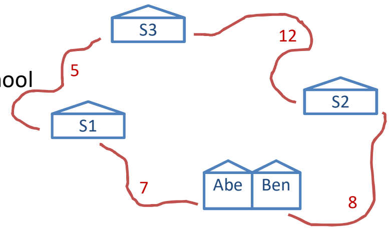
Example: Taking kids to school

- Abe has got 3 children, each attending a different school: $A_i \rightarrow S_i, i \in [1..3]$
- Ben has got 2 children: $B_j \rightarrow S_j, j \in [1..2]$
- Abe and Ben are neighbors and work at home
- Every morning they need to take the kids to school

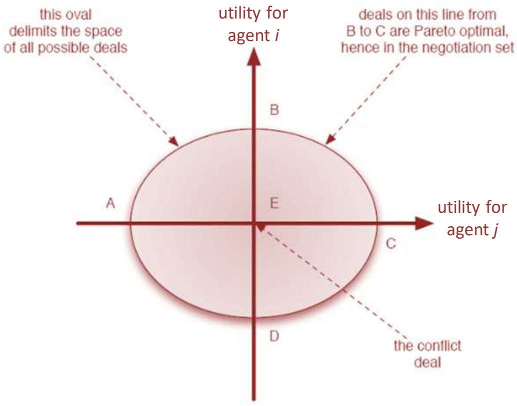


- What are their costs in the conflict deal?
  - $c_{Abe}(\Theta)$, $c_{Ben}(\Theta)$
- Which are the individual rational deals?
  - Assume that kids attending the same school travel together: $A_1 + B_1$ / $A_2 + B_2$
  - $\forall_{k \in \{Abe,Ben\}}\, u_k(\delta) \geq 0$, i.e., $c_k(\delta) \leq c_k(\Theta)$
- Of those, which are Pareto optimal?

Negotiation Set

- The negotiation set consists of the set of deals that are
  - Individually rational and
  - Pareto optimal
- Individually rational
  - There is no purpose in proposing a deal that is worse than the conflict deal for some agent
- Pareto optimal
  - There is no point in making a proposal for which there is a better alternative for some agent at nobody's expense

Negotiation Set



- Deals to the left of line B-D are *not individual rational* for agent *j*
- Deals below line A-C are *not individual rational* for agent *i*

- The negotiation set contains deals in the shaded area B-C-E
- But only those in the line B-C are *Pareto optimal*. This is the negotiation set.

- Typically, agent *i* starts by proposing the deal at point B, and agent *j* starts by proposing the deal at point C

Monotonic Concession Protocol

- Negotiation proceeds in a series of rounds
- On the first round, both agents simultaneously propose a deal from the negotiation set

- Agreement is reached if $u_1(\delta_2) \geq u_1(\delta_1)$ or $u_2(\delta_1) \geq u_2(\delta_2)$
  - Proposal received is at least as good as own proposal
  - Such proposal is the agreement deal (random if both)

- If no agreement is reached, proceed to a new round of simultaneous proposals, under the conditions that $u_1(\delta_2^{t+1}) \geq u_1(\delta_2^t)$ and $u_2(\delta_1^{t+1}) \geq u_2(\delta_1^t)$
  - Agents must concede

- If neither agent concedes, negotiation terminates with the conflict deal

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Zeuthen Strategy

- What should be an agent's first proposal?
  - Its most preferred deal
- On a given round, who should concede?
  - The agent *least willing to risk conflict*: the one for which the difference between its current proposal and the conflict deal is highest
    - intuitively, such agent has conceded less so far
- How much should an agent concede?
  - Just enough to change the balance of risk
    - If it does not concede enough, it will be the one to concede again
    - If it concedes too much, it may 'waste' some utility

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Zeuthen Strategy

$$risk_i^t = \frac{utility\ i\ loses\ by\ conceding\ and\ accepting\ j's\ offer}{utility\ i\ loses\ by\ not\ conceding\ and\ causing\ conflict}$$

$$risk_i^t = \begin{cases} 1 & \text{if } u_i(\delta_i^t) = 0 \\ \dfrac{u_i(\delta_i^t) - u_i(\delta_j^t)}{u_i(\delta_i^t)} & \text{otherwise} \end{cases}$$

- Until an agreement is reached, $risk_i^t \in [0,1]$
  - Higher values indicate that i has less to lose from conflict, lower values indicate that i has more to lose
  - When $risk_i^t = 1$, agent i is completely willing to risk conflict by not conceding (its proposal is as good as the conflict deal Θ)

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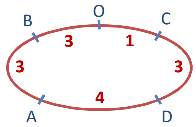
Example: Pizza delivery

- A couple of pizza deliverers
  - P1 starts in O and must deliver at A and C
  - P2 starts in O and must deliver at B and D



- Consider these deals and show they are individually rational and Pareto optimal:

  $\delta_1 = \langle\{C, D\}, \{A, B\}\rangle$ $\delta_3 = \langle\{A, C, D\}, \{B\}\rangle$

  $\delta_2 = \langle\{A, B\}, \{C, D\}\rangle$ $\delta_4 = \langle\{B\}, \{A, C, D\}\rangle$

- Following the Zeuthen strategy, which is the first proposal of each agent?
- Which agent should concede in the following negotiation round, and which proposal should it make?
- What is the outcome of this negotiation?

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Properties

- The monotonic concession protocol:
  - Does not guarantee success, but guarantees termination
  - Does not guarantee social welfare maximization
  - Guarantees that if agreement is reached, it is Pareto optimal and individually rational
- The Zeuthen strategy is in Nash equilibrium
  - If one agent uses it, the other can do no better than use it too
- Deception: agents may benefit from not being truthful
  - *Phantom and decoy tasks*: are announced tasks verifiable?
  - *Hidden tasks*: not mentioning some task may be beneficial

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Resource (Re)Allocation

- How can agents reallocate resources for mutual benefit?
- As with combinatorial auctions, we have:
  - A set of resources $Z = \{z_1, \dots, z_m\}$
  - Valuation functions $v_i: 2^Z \longrightarrow \mathbb{R}$
  - An allocation is a partition $Z_1, \dots, Z_n$ of Z
- Agents negotiate to move from an *initial allocation* to another that is collectively *more beneficial*, given their *individual* valuation functions
- Negotiating a change from an allocation P_i to Q_i
  - $v_i(P_i) < v_i(Q_i)$ — i is better off after the exchange
  - $v_i(P_i) = v_i(Q_i)$ — i is indifferent between P_i and Q_i
  - $v_i(P_i) > v_i(Q_i)$ — i is worse off after the exchange

Side Payments

- Agent i has some good z_1, $v_i(\{z_1\}) = 5$ and $v_j(\{z_1\}) = 10$
  - How can agent j persuade i to transfer the item?
  - Make a side payment, sufficient to compensate i's resulting loss in utility (≥5)
  - Any side payment must be funded by value received (≤10)
- A payment vector $\bar{p} = \langle p_1, \dots, p_n \rangle$ is a tuple of side payments, one for each agent, such that $\sum_{i=n}^{n} p_i = 0$
  - If $p_i < 0$, agent i receives $-p_i$
  - If $p_i > 0$, agent i contributes p_i
- A deal is a triple $\delta = \langle (Z_1, \dots, Z_n), (Z'_1, \dots, Z'_n), \bar{p} \rangle$
  - Allocation $(Z_1, \dots, Z_n)$ is replaced by allocation $(Z'_1, \dots, Z'_n)$ and payments specified in $\bar{p}$ are made

Side Payment Deal properties

- Deal δ is individually rational if

$$v_i(Z_i') - p_i \geq v_i(Z_i), \quad \text{for every agent } i$$

  - p_i can be 0 if $Z_i = Z_i'$
  - even without payments, there may be deals where some agents are better off

- Deal δ is Pareto optimal if every other deal that makes some agent strictly better off makes some other agent strictly worse off

Further Reading

- Wooldridge, M. (2009). *An Introduction to MultiAgent Systems*, 2nd ed., John Wiley & Sons: Chap. 15

- Faratin, P., Sierra, C. and Jennings, N. R. (1998). *Negotiation Decision Function for Autonomous Agents*. Robotics and Autonomous Systems 24, 159-182.
- Rosenschein, J. S. and Zlotkin, G. (1994). *Rules of Encounter: Designing Conventions for Automated Negotiation among Computers*. MIT Press.