CPS 296.1
Auctions &
Combinatorial Auctions

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A few different 1-item auction mechanisms

- **English auction:**
  - Each bid must be higher than previous bid
  - Last bidder wins, pays last bid

- **Japanese auction:**
  - Price rises, bidders drop out when price is too high
  - Last bidder wins at price of last dropout

- **Dutch auction:**
  - Price drops until someone takes the item at that price

- **Sealed-bid auctions (direct revelation mechanisms):**
  - Each bidder submits a bid in an envelope
  - Auctioneer opens the envelopes, highest bid wins
    - **First-price** sealed-bid auction: winner pays own bid
    - **Second-price** sealed bid (or Vickrey) auction: winner pays second-highest bid
Complementarity and substitutability

- How valuable one item is to a bidder may depend on whether the bidder possesses another item.

- Items a and b are **complementary** if \( v(\{a, b\}) > v(\{a\}) + v(\{b\}) \)

- E.g.

- Items a and b are **substitutes** if \( v(\{a, b\}) < v(\{a\}) + v(\{b\}) \)

- E.g.
Inefficiency of sequential auctions

- Suppose your valuation function is $v(\square) = $200, $v(\square) = $100, $v(\square\square) = $500$
- Now suppose that there are two (say, Vickrey) auctions, the first one for $\square$ and the second one for $\square$
- What should you bid in the first auction (for $\square$)?
- If you bid $200, you may lose to a bidder who bids $250, only to find out that you could have won $\square\square$ for $200$
- If you bid anything higher, you may pay more than $200, only to find out that $\square\square$ sells for $1000$
- Sequential (and parallel) auctions are inefficient
Combinatorial auctions

Simultaneously for sale:  

- $v(\text{server}) = 500$
- $v(\text{monitor}) = 700$
- $v(\text{keyboard}) = 300$

used in truckload transportation, industrial procurement, radio spectrum allocation, …
The winner determination problem (WDP)

- Choose a subset $A$ (the accepted bids) of the bids $B$,
- to maximize $\sum_{b \in A} v_b$,
- under the constraint that every item occurs at most once in $A$
  - This is assuming free disposal, i.e., not everything needs to be allocated
WDP example

- Items A, B, C, D, E
- Bids:
  - ({A, C, D}, 7)
  - ({B, E}, 7)
  - ({C}, 3)
  - ({A, B, C, E}, 9)
  - ({D}, 4)
  - ({A, B, C}, 5)
  - ({B, D}, 5)

- What’s an optimal solution?
- How can we prove it is optimal?
Price-based argument for optimality

- Items A, B, C, D, E
- Bids:
  - ({A, C, D}, 7)
  - ({B, E}, 7)
  - ({C}, 3)
  - ({A, B, C, E}, 9)
  - ({D}, 4)
  - ({A, B, C}, 5)
  - ({B, D}, 5)

- Suppose we create the following “prices” for the items:

  - \( p(A) = 0, \ p(B) = 7, \ p(C) = 3, \ p(D) = 4, \ p(E) = 0 \)

- Every bid bids at most the sum of the prices of its items, so we can’t expect to get more than 14.
Price-based argument does not always give matching upper bound

• Clearly can get at most 2

• Items A, B, C

• If we want to set prices that sum to 2, there must exist two items whose prices sum to < 2

• Bids:
  • ({A, B}, 2)
  • ({B, C}, 2)
  • ({A, C}, 2)

• But then there is a bid on those two items of value 2
  – (Can set prices that sum to 3, so that’s an upper bound)

Should not be surprising, since it’s an NP-hard problem and we don’t expect short proofs for negative answers to NP-hard problems (we don’t expect NP = coNP)
An integer program formulation

- $x_b$ equals 1 if bid $b$ is accepted, 0 if it is not
- maximize $\sum_b v_b x_b$
- subject to
  - for each item $j$, $\sum_{b: j \in b} x_b \leq 1$
- If each $x_b$ can take any value in $[0, 1]$, we say that bids can be partially accepted
- In this case, this is a linear program that can be solved in polynomial time
- This requires that
  - each item can be divided into fractions
  - if a bidder gets a fraction $f$ of each of the items in his bundle, then this is worth the same fraction $f$ of his value $v_b$ for the bundle
Price-based argument **does** always work for partially acceptable bids

- Items A, B, C
- Bids:  
  - (\{A, B\}, 2)
  - (\{B, C\}, 2)
  - (\{A, C\}, 2)
- Now can get 3, by accepting half of each bid
- Put a price of 1 on each item

**General proof that with partially acceptable bids, prices always exist to give a matching upper bound is based on linear programming duality**
Weighted independent set

- Choose subset of the vertices with maximum total weight,
- Constraint: no two vertices can have an edge between them
- NP-hard (generalizes regular independent set)
The winner determination problem as a weighted independent set problem

- Each bid is a vertex
- Draw an edge between two vertices if they share an item

\[
\begin{align*}
\text{v( } & \text{bid 1} \text{ } = \$500 \\
\text{v( } & \text{bid 2} \text{ } = \$700 \\
\text{v( } & \text{bid 3} \text{ } = \$300
\end{align*}
\]

- Optimal allocation = maximum weight independent set
- Can model any weighted independent set instance as a CA winner determination problem (1 item per edge (or clique))
- Weighted independent set is NP-hard, even to solve approximately [Håstad 96] - hence, so is WDP
  - [Sandholm 02] noted that this inapproximability applies to the WDP
Dynamic programming approach to WDP \cite{Rothkopf98}

- For every subset $S$ of $I$, compute $w(S) =$ the maximum total value that can be obtained when allocating only items in $S$
- Then, $w(S) = \max \{ \max_i v_i(S), \max_{S': S' \text{ is a subset of } S, \text{ and there exists a bid on } S'} w(S') + w(S \setminus S') \}$
- Requires exponential time
Bids on connected sets of items in a tree

• Suppose items are organized in a tree

item A
  └── item B
  └── item C
      └── item D
  ┌─ item E
  │   └── item F
  └── item G
      └── item H

• Suppose each bid is on a connected set of items
  – E.g. \{A, B, C, G\}, but not \{A, B, G\}

• Then the WDP can be solved in polynomial time (using dynamic programming) [Sandholm & Suri 03]

• Tree does not need to be given: can be constructed from the bids in polynomial time if it exists [Conitzer, Derryberry, Sandholm 04]

• More generally, WDP can also be solved in polynomial time for graphs of bounded treewidth [Conitzer, Derryberry, Sandholm 04]
  – Even further generalization given by [Gottlob, Greco 07]
Maximum weighted matching
(not necessarily on bipartite graphs)

- Choose subset of the edges with maximum total weight,
- Constraint: no two edges can share a vertex
- Still solvable in polynomial time
Bids with few items [Rothkopf et al. 98]

- If each bid is on a bundle of at most two items,
- then the winner determination problem can be solved in polynomial time as a maximum weighted matching problem

  - 3-item example:

    - If each bid is on a bundle of three items, then the winner determination problem is NP-hard again
Variants [Sandholm et al. 2002]: combinatorial reverse auction

- In a combinatorial reverse auction (CRA), the auctioneer seeks to buy a set of items, and bidders have values for the different bundles that they may sell the auctioneer.

  - minimize $\sum_b v_b x_b$
  - subject to
    - for each item $j$, $\sum_{b: i \in b} x_b \geq 1$
WDP example (as CRA)

- Items A, B, C, D, E
- Bids:
  - ({A, C, D}, 7)
  - ({B, E}, 7)
  - ({C}, 3)
  - ({A, B, C, E}, 9)
  - ({D}, 4)
  - ({A, B, C}, 5)
  - ({B, D}, 5)
Variants: multi-unit CAs/CRAs

- **Multi-unit** variants of CAs and CRAs: multiple units of the same item are for sale/to be bought, bidders can bid for multiple units

- Let $q_{bj}$ be number of units of item $j$ in bid $b$, $q_j$ total number of units of $j$ available/demanded

  - maximize $\sum_b v_b x_b$
  - subject to
    - for each item $j$, $\sum_b q_{bj} x_b \leq q_j$
  - minimize $\sum_b v_b x_b$
  - subject to
    - for each item $j$, $\sum_b q_{bj} x_b \geq q_j$
Multi-unit WDP example (as CA/CRA)

- Items: 3A, 2B, 4C, 1D, 3E
- Bids:
  - ({1A, 1C, 1D}, 7)
  - ({2B, 1E}, 7)
  - ({2C}, 3)
  - ({2A, 1B, 2C, 2E}, 9)
  - ({2D}, 4)
  - ({3A, 1B, 2C}, 5)
  - ({2B, 2D}, 5)
Variants: (multi-unit) combinatorial exchanges

- **Combinatorial exchange (CE):** bidders can simultaneously be buyers and sellers
  - Example bid: “If I receive 3 units of A and -5 units of B (i.e., I have to give up 5 units of B), that is worth $100 to me.”

- maximize $\sum_b v_b x_b$
- subject to
  - for each item $j$, $\sum_b q_{b,j} x_b \leq 0$
CE WDP example

- Bids:
  - (\{-1A, -1C, -1D\}, -7)
  - (\{2B, 1E\}, 7)
  - (\{2C\}, 3)
  - (\{-2A, 1B, 2C, -2E\}, 9)
  - (\{-2D\}, -4)
  - (\{3A, -1B, -2C\}, 5)
  - (\{-2B, 2D\}, 0)
Variants: no free disposal

- Change all inequalities to equalities
(back to 1-unit CAs) Expressing valuation functions using bundle bids

• A bidder is **single-minded** if she only wants to win one particular bundle
  – Usually not the case
• But: one bidder may submit multiple bundle bids
• Consider again valuation function $v(\text{book} ) = $200, $v(\text{underwear}) = $100, $v(\text{book} , \text{underwear} ) = $500
• What bundle bids should one place?
• What about: $v(\text{underwear}) = $300, $v(\text{book} ) = $200, $v(\text{book} , \text{underwear} ) = $400?
Alternative approach: report entire valuation function

• I.e., every bidder $i$ reports $v_i(S)$ for every subset $S$ of $I$ (the items)
• Winner determination problem:
• Allocate a subset $S_i$ of $I$ to each bidder $i$ to maximize $\sum_i v_i(S_i)$ (under the constraint that for $i \neq j$, $S_i \cap S_j = \emptyset$)
  – This is assuming free disposal, i.e., not everything needs to be allocated
Exponentially many bundles

- In general, in a combinatorial auction with set of items $I$ ($|I| = m$) for sale, a bidder could have a different valuation for every subset $S$ of $I$
  - Implicit assumption: no externalities (bidder does not care what the other bidders win)
- Must a bidder communicate $2^m$ values?
  - Impractical
  - Also difficult for the bidder to evaluate every bundle
- Could require $v_i(\emptyset) = 0$
  - Does not help much
- Could require: if $S$ is a superset of $S'$, $v(S) \geq v(S')$ (free disposal)
  - Does not help in terms of number of values
Bidding languages

- **Bidding language** = a language for expressing valuation functions
- A good bidding language allows bidders to *concisely* express natural valuation functions
- Example: the **OR** bidding language [Rothkopf et al. 98, DeMartini et al. 99]
- Bundle-value pairs are ORed together, auctioneer may accept any number of these pairs (assuming no overlap in items)
- E.g. ({a}, 3) OR ({b, c}, 4) OR ({c, d}, 4) implies
  - A value of 3 for {a}
  - A value of 4 for {b, c, d}
  - A value of 7 for {a, b, c}
- Can we express the valuation function $v({a, b}) = v({a}) = v({b}) = 1$ using the OR bidding language?
- **OR** language is good for expressing complementarity, bad for expressing substitutability
**XORs**

- If we use XOR instead of OR, that means that only one of the bundle-value pairs can be accepted.
- Can express any valuation function (simply XOR together all bundles).
- E.g. ({a}, 3) XOR ({b, c}, 4) XOR ({c, d}, 4) implies
  - A value of 3 for {a}
  - A value of 4 for {b, c, d}
  - A value of 4 for {a, b, c}
- Sometimes not very concise.
- E.g. suppose that for any S, \( v(S) = \sum_{s \in S} v(\{s\}) \)
  - How can this be expressed in the OR language?
  - What about the XOR language?
- Can also combine ORs and XORs to get benefits of both [Nisan 00, Sandholm 02]
- E.g. ((({a}, 3) XOR ({b, c}, 4)) OR ({c, d}, 4)) implies
  - A value of 4 for {a, b, c}
  - A value of 4 for {b, c, d}
  - A value of 7 for {a, c, d}
WDP and bidding languages

• **Single-minded bidders** bid on only one bundle
  – Valuation is \( v \) for any subset including that bundle, 0 otherwise

• If we can solve the WDP for single-minded bidders, we can also solve it for the OR language
  – Simply pretend that each bundle-value pair comes from a different bidder

• We can even use the same algorithm when XORs are added, using the following trick:
  – For bundle-value pairs that are XORed together, add a dummy item to them [Fujishima et al 99, Nisan 00]
  – E.g. \( (\{a\}, 3) \) XOR \( (\{b, c\}, 4) \) becomes \( (\{a, \text{dummy}_1\}, 3) \) OR \( (\{b, c, \text{dummy}_1\}, 4) \)

• So, we can focus on single-minded bids