Multi-Parameter Mechanism Design

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- In previous lectures, we only consider single-parameter mechanism design problems.
  - The only private parameter of an agent is her valuation.
- In this lecture, we:
  - Introduce multi-parameter environments, where each agent has multiple private parameters.
  - Introduce the Vickrey-Clarke-Groves (VCG) mechanisms.
    - It shows that DSIC welfare maximization is possible in principle in every multi-parameter environments.

Outline

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General Multi-Parameter Design Environment

- n strategic participants/agents.
- a finite set Ω of outcomes.
- each agent i has a private nonnegative valuation $v_i(\omega)$ for each outcome $\omega \in \Omega$.

Single-Item Auction Revisited

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- In a the standard single parameter model,
  - $|\Omega| = n + 1$.
  - The $n + 1$ elements corresponds the winner of the item (if any).

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  - The $n + 1$ elements corresponds the winner of the item (if any).
  - The valuation of a bidder is 0 in all of the n outcomes (in which she doesn't win), leaving only one unknown parameter per bidder.
- In the general multi-parameter framework, a bidder can have a different valuation for each possible outcome (i.e., winner; competitor).

Combinatorial Auctions

- Multiple indivisible items are for sale.
- We have n bidders and a set M of m items.
- Bidders can have preferences between different subsets (bundles) of items.
- The outcome space Ω corresponds to n-vectors $(S_1, \ldots, S_n)$, where $S_i \subseteq M$ is the bundle allocated to bidder i (no item is allocated twice).

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  - 2^m.

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General Mechanism Design Environments

The VCG Mechanism

Remarks

Practical Implementation of Combinatorial Auctions
- Indirect Mechanisms

The General Theorem

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In every general mechanism design environment, there is a DSIC welfare-maximizing mechanism.

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- Note that the computational efficiency is not asserted here.
- Let's discuss the main ideas behind the theorem before proving it.

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- First, assume that the agents truthfully report their private information (i.e., $\boldsymbol{b} = \boldsymbol{v}$).
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- First, assume that the agents truthfully report their private information (i.e., $\boldsymbol{b} = \boldsymbol{v}$).
- Then, figure out which outcome (i.e., allocation) to pick.
- Pick a welfare-maximizing outcome using bids as proxies for the unknown valuations.
- We define the allocation rule

$$\omega^* := \boldsymbol{x}(\boldsymbol{b}) = \arg\max_{\omega \in \Omega} \sum_{i=1}^{n} b_i(\omega).$$

The Second Step

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- Define the payment rule to incentivize the agents!
  - Hopefully we will have a DSIC mechanism.
- However, unlike the single-parameter environments, here:
  - The report is multi-dimensional.
  - Myerson's lemma seems not to hold beyond single-parameter environments.
  - It's unclear how to define "monotonicity", "critical bid", etc.

A Key Idea to the Payment Rule

- Charge the agent the "externality" caused by agent i.
  - The welfare loss inflicted on the other $n-1$ agents by agent i's presence.
- This remains well defined in general mechanism design environments!
- The corresponding payment rule:

$$p_i(\boldsymbol{b}) = \left(\max_{\omega \in \Omega} \sum_{j \neq i} b_j(\omega) \right) - \sum_{j \neq i} b_j(\omega^*),$$

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- You may check that the payment $p_i(\boldsymbol{b}) \geq 0$.

The VCG Mechanism

Definition: VCG Mechanism

A mechanism $(\boldsymbol{x}, \boldsymbol{p})$ with allocation and payment rule as

$$\omega^* := \boldsymbol{x}(\boldsymbol{b}) = \arg\max_{\omega \in \Omega} \sum_{i=1}^{n} b_i(\omega).$$

and

$$p_i(\boldsymbol{b}) = \left(\max_{\omega \in \Omega} \sum_{j \neq i} b_j(\omega) \right) - \sum_{j \neq i} b_j(\omega^*),$$

respectively, is a Vickrey-Clarke-Groves or mechanism.

Another Form of the Payment

$$p_i(\boldsymbol{b}) = \underbrace{b_i(\omega^*)}_{\text{bid}} - \underbrace{\left[\sum_{j=1}^{n} b_j(\omega^*) - \max_{\omega \in \Omega} \sum_{j \neq i} b_j(\omega)\right]}_{\text{rebate}}$$

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- For example, in the second-price auction, say we have two agents with bids $b_1 > b_2$.
  - The highest bidder pays $b_1 - (b_1 - b_2) = b_2$!
- Truthful reporting always guarantees nonnegative utility!

Proof of Theorem 7.3 (1/2)

- Fix an arbitrary general mechanism design environment.
- Let $(\boldsymbol{x}, \boldsymbol{p})$ denote the corresponding VCG mechanism.
- The mechanism maximizes the social welfare whenever the reports are truthful (by definition).
- Next, we have to verify the DSIC condition.
  - We need to show that for every agent i and every set $\boldsymbol{b}_{-i}$, agent i maximizes her utility $v_i(\boldsymbol{x}(\boldsymbol{b})) - p_i(\boldsymbol{b})$ by setting $\boldsymbol{b}_i = \boldsymbol{v}_i$.

Proof of Theorem 7.3 (2/2)

- Fix i and $\boldsymbol{b}_{-i}$. When the chosen outcome $\boldsymbol{x}(\boldsymbol{b})$ is ω^*, we have

$$
\begin{aligned}
v_i(\omega^*) - p_i(\boldsymbol{b}) &= v_i(\omega^*) - \left(\max_{\omega \in \Omega} \sum_{j \neq i} b_j(\omega) - \sum_{j \neq i} b_j(\omega^*) \right) \\
&= \underbrace{\left[v_i(\omega^*) + \sum_{j \neq i} b_j(\omega^*) \right]}_{(\mathrm{A})} - \underbrace{\left[\max_{\omega \in \Omega} \sum_{j \neq i} b_j(\omega) \right]}_{(\mathrm{B})} .
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- (B) can be viewed as a constant. So we focus on maximizing (A).
- For agent i, assume that ω^* is chosen, setting $b_i = v_i$ makes (A) maximized.
  - $v_i(\omega^*) + \sum_{j \neq i} b_j(\omega^*) = \sum_j b_j(\omega^*)$.
  - Recall that $\omega^* = \arg\max_{\omega \in \Omega} \sum_{i=1}^{n} b_i(\omega)$.

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Practical Considerations (1/3)

- Preference elicitation is a challenge.
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- Preference elicitation is a challenge.
  - Consider getting reports $b_1, \ldots, b_n$ from n agents in a combinatorial auction with m items.
  - Each bidder has 2^m private parameters!
  - It's hard for her to figure out or write down so many numbers.
  - No seller would want to read them.

Practical Considerations (2/3)

- As in single-parameter environments, welfare maximization could be a computationally intractable.
  - Recall the knapsack auction.
- Sometimes even approximate welfare maximization is still computationally intractable.

Practical Considerations (3/3)

- VCG mechanisms can have bad revenue.

Exercise 4 (5%)

1. Consider a combinatorial auction with two bidders and two items A and B. The first bidder only wants both items, so $v_1(\{A, B\}) = 1$ and is 0 otherwise. The second bidder only wants item A, so $v_2(\{A, B\}) = v_2(\{A\}) = 1$ and is 0 otherwise. **Please show that the revenue of the VCG mechanism is 1 in this example.**
2. Now suppose that we add a third bidder who only wants item B, so $v_3(\{A, B\}) = v_3(\{B\}) = 1$. **Please show that the maximum welfare is 2 but the VCG revenue is 0 in this case.**

Recall the issues

- Combinatorial auction: n bidders, m items, bidder i's valuation $v_i(S)$ for each bundle S of items.
- The number of parameters that each bidder reports in the VCG mechanism (or any other direct-revelation mechanism) grows exponentially with m.

Indirect Mechanism

- Learn information about bidders' preferences only on a need-to-know basis.
- The canonical indirect auction: ascending English auction.

- ⋆ An auctioneer asks for takers at successively higher prices.
- ⋆ The auction ends when no one accepts the currently proposed price.
- ⋆ The winner (if any): the bidder who accepted the previously proposed price
  - ✓ This previous price is the final sale price.

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- Empirically, bidders are more likely to play their dominant strategies in this kind of auction than a sealed-bid second-price auction.
  - Bidders: not likely to overbid;
  - Seller: only learns a lower bound on the highest bid.

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- So what's a natural indirect auction format for combinatorial auctions?
  - Eliciting valuations for bundles from each bidder is avoided.
- The simplest way: sell the items separately.
- What's the issue or problem?

Substitutes vs. Complements

For two items A and B,

- substitute condition: $v(AB) \leq v(A) + v(B)$.
  - Spectrum auction: two licenses (the same area & equal-sized frequency ranges).
  - iPhone 13 + iPhone 14 announced together?
  - ⋆ Welfare maximization is computationally tractable.
- complement condition: $v(AB) > v(A) + v(B)$.
  - Spectrum auction: a collection of licenses that are adjacent (geographically or frequency ranges).
  - Two items with additional enhancement when they are both provided.
  - ⋆ Welfare maximization is computationally *intractable*.
- In real world: mixture of substitutes and complements.

Typical mistake #1 of running separate single-item auctions

Hold the single-item auctions sequentially, one at a time.

- The scenario: A sequence of single-item auctions for two identical items.
  - Items are sold via back-to-back second-price auctions.
- Let's say you are a bidder with a VERY HIGH valuation.
- Suppose that every other bidder bid truthfully.

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⋆ If you participate in the first auction, you will win and pay the second-highest valuation.

⋆ If you skip it, the bidder with the second-highest valuation wins the first auction and disappear.

  - Then you would win the second auction at a price equal to the third-highest valuation.

A story from the textbook

- In March 2000, Switzerland auctioned off three blocks of spectrum via a sequence of second-price auctions.
- The first two auctions were for identical items, 28 MHz blocks, and sold for 121 million and 134 million Swiss francs, respectively.
  - This is already more price variation than one would like for identical items.
- But in the third auction, where a larger 56 MHz block was being sold, the selling price was only 55 million francs!
- Some of the bids must have been far from optimal, and both the welfare and revenue achieved by this auction are suspect.

Typical mistake #2 of running separate single-item auctions

Use sealed-bid single-item auctions (simultaneously).

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- Consider that there are 3 bidders and 2 identical items, and each bidder wants only one.
- With simultaneous second-price single-item auctions,
  - if each bidder targets only one item, one of the licenses is likely to have only one bidder and will be given away for free or sold at the reserve price.

A story from the textbook

- In 1990, the New Zealand government auctioned off essentially identical licenses for television broadcasting using simultaneous (sealed-bid) second-price auctions.
- The revenue in the 1990 New Zealand auction was only $36 million, a paltry fraction of the projected $250 million.
  - On one license, the high bid was $100,000 while the second-highest bid (and selling price) was $6!
  - On another, the high bid was $7 million and the second-highest was $5,000.

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- The primary reason that SAAs work better is price discovery.
  - A bidder can abandon the items in the mid-course as she acquires better information about the likely selling prices of the items.
  - Again, bidder only need to determine their valuations on a need-to-know basis.
- Though such kind a mechanisms still has its vulnerabilities (skipped here for further readings).