CPS 296.1
Bayesian games and their use in auctions

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What is mechanism design?

- In mechanism design, we get to design the game (or mechanism)
  - e.g. the rules of the auction, marketplace, election, …
- Goal is to obtain good outcomes when agents behave strategically (game-theoretically)
- Mechanism design often considered part of game theory
- 2007 Nobel Prize in Economics!
- Before we get to mechanism design, first we need to know how to evaluate mechanisms
Example: (single-item) auctions

- **Sealed-bid** auction: every bidder submits bid in a sealed envelope
- **First-price** sealed-bid auction: highest bid wins, pays amount of own bid
- **Second-price** sealed-bid auction: highest bid wins, pays amount of second-highest bid

```
   0
  /|
  / |
  /  |
bid 3: $1

  /   |
 /     |
/       |
bid 2: $5

first-price: bid 1 wins, pays $10
second-price: bid 1 wins, pays $5
```
Which auction generates more revenue?

- Each bid depends on
  - bidder’s true valuation for the item (utility = valuation - payment),
  - bidder’s beliefs over what others will bid (→ game theory),
  - and... the auction mechanism used

- In a first-price auction, it does not make sense to bid your true valuation
  - Even if you win, your utility will be 0...

- In a second-price auction, (we will see later that) it always makes sense to bid your true valuation

Are there other auctions that perform better? How do we know when we have found the best one?
Bidding truthfully is optimal in the Vickrey auction!

- What should a bidder with value $v$ bid?

**Option 1:** Win the item at price $b$, get utility $v - b$
- Would like to win if and only if $v - b > 0$ – but bidding truthfully accomplishes this!

**Option 2:** Lose the item, get utility $0$

We say the Vickrey auction is strategy-proof
Collusion in the Vickrey auction

- Example: two colluding bidders

\[ v_1 = \text{first colluder’s true valuation} \]

\[ v_2 = \text{second colluder’s true valuation} \]

\[ b = \text{highest bid among other bidders} \]

- Price colluder 1 would pay when colluders bid truthfully.
- Gains to be distributed among colluders.
- Price colluder 1 would pay if colluder 2 does not bid.
Bayesian games

- In a Bayesian game a player’s utility depends on that player’s type as well as the actions taken in the game
  - Notation: $\theta_i$ is player $i$’s type, drawn according to some distribution from set of types $\Theta_i$
  - Each player knows/learns its own type, not those of the others, before choosing action
    - Pure strategy $s_i$ is a mapping from $\Theta_i$ to $A_i$ (where $A_i$ is $i$’s set of actions)
  - In general players can also receive signals about other players’ utilities; we will not go into this

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Converting Bayesian games to normal form

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Row player type 1 (prob. 0.5)

Row player type 2 (prob. 0.5)

Column player type 1 (prob. 0.5)

Column player type 2 (prob. 0.5)

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Type 1: L
Type 2: L
Type 1: R
Type 2: R

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<td>3, 3</td>
<td>4, 3</td>
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<tr>
<td>type 2: U</td>
<td>4, 3.5</td>
<td>4, 3</td>
</tr>
<tr>
<td>type 1: D</td>
<td>2, 3.5</td>
<td>3, 3</td>
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<tr>
<td>type 2: D</td>
<td>3, 4</td>
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Exponential blowup in size
Bayes-Nash equilibrium

- A profile of strategies is a **Bayes-Nash equilibrium** if it is a Nash equilibrium for the normal form of the game
  - Minor caveat: each type should have >0 probability

- Alternative definition: for every i, for every type \( \theta_i \), for every alternative action \( a_i \), we must have:

\[
\sum_{\theta_{-i}} P(\theta_{-i}) u_i(\theta_i, \sigma_i(\theta_i), \sigma_{-i}(\theta_{-i})) \geq \sum_{\theta_{-i}} P(\theta_{-i}) u_i(\theta_i, a_i, \sigma_{-i}(\theta_{-i}))
\]
First-price sealed-bid auction BNE

• Suppose every bidder (independently) draws a valuation from \([0, 1]\)
• What is a Bayes-Nash equilibrium for this?
• Say a bidder with value \(v_i\) bids \(v_i(n-1)/n\)
• Claim: this is an equilibrium!
• Proof: suppose all others use this strategy
• For a bid \(b < (n-1)/n\), the probability of winning is \((bn/(n-1))^{n-1}\), so the expected value is \((v_i-b)(bn/(n-1))^{n-1}\)
• Derivative w.r.t. \(b\) is \(- (bn/(n-1))^{n-1} + (v_i-b)(n-1)b^{n-2}(n/(n-1))^{n-1}\) which should equal zero
• Implies \(-b + (v_i-b)(n-1) = 0\), which solves to \(b = v_i(n-1)/n\)
Analyzing the expected revenue of the first-price and second-price (Vickrey) auctions

- **First-price auction**: probability of there not being a bid higher than $b$ is $(bn/(n-1))^n$ (for $b < (n-1)/n$)
  - This is the cumulative density function of the highest bid
- Probability density function is the derivative, that is, it is $nb^{n-1}(n/(n-1))^n$
- Expected value of highest bid is $\int_{(n-1)/n}^{n/(n-1)} bn^db = (n-1)/(n+1)$

- **Second-price auction**: probability of there not being two bids higher than $b$ is $b^n + nb^{n-1}(1-b)$
  - This is the cumulative density function of the second-highest bid
- Probability density function is the derivative, that is, it is $nb^{n-1} + n(n-1)b^{n-2}(1-b) - nb^{n-1} = n(n-1)(b^{n-2} - b^{n-1})$
- Expected value is $(n-1) - n(n-1)/(n+1) = (n-1)/(n+1)$
Revenue equivalence theorem

• Suppose valuations for the single item are drawn i.i.d. from a continuous distribution over \([L, H]\) (with no “gaps”), and agents are risk-neutral

• Then, any two auction mechanisms that
  – in equilibrium always allocate the item to the bidder with the highest valuation, and
  – give an agent with valuation \(L\) an expected utility of 0, will lead to the same expected revenue for the auctioneer
(As an aside) what if bidders are not risk-neutral?

• Behavior in second-price/English/Japanese does not change, but behavior in first-price/Dutch does
• Risk averse: first price/Dutch will get higher expected revenue than second price/Japanese/English
• Risk seeking: second price/Japanese/English will get higher expected revenue than first price/Dutch
(As an aside) **interdependent valuations**

- E.g. bidding on drilling rights for an oil field
- Each bidder $i$ has its own geologists who do tests, based on which the bidder assesses an expected value $v_i$ of the field
- If you win, it is probably because the other bidders’ geologists’ tests turned out worse, and the oil field is not actually worth as much as you thought
  - The so-called **winner’s curse**
- Hence, bidding $v_i$ is no longer a dominant strategy in the second-price auction
- In English and Japanese auctions, you can update your valuation based on other agents’ bids, so no longer equivalent to second-price
- In these settings, English (or Japanese) > second-price > first-price/Dutch in terms of revenue
Expected-revenue maximizing ("optimal") auctions [Myerson 81]

- Vickrey auction does not maximize expected revenue
  - E.g. with only one bidder, better off making a take-it-or-leave-it offer (or equivalently setting a reserve price)
- Suppose agent i draws valuation from probability density function $f_i$ (cumulative density $F_i$)
- Bidder’s virtual valuation $\psi_i(v_i) = v_i - (1 - F_i(v_i))/f_i(v_i)$
  - Under certain conditions, this is increasing; assume this
- The bidder with the highest virtual valuation (according to his reported valuation) wins (unless all virtual valuations are below 0, in which case nobody wins)
- Winner pays value of lowest bid that would have made him win
- E.g. if all bidders draw uniformly from $[0, 1]$, Myerson auction = second-price auction with reserve price $\frac{1}{2}$
Vickrey auction without a seller

$v(1) = 2$
$v(2) = 4$
$v(3) = 3$

pays 3
(money wasted!)
Can we redistribute the payment?

Idea: give everyone $1/n$ of the payment

$v(\text{I1}) = 2$
$v(\text{I2}) = 4$
$v(\text{I3}) = 3$

receives 1
pays 3
receives 1

not strategy-proof

Bidding higher can increase your redistribution payment
Incentive compatible redistribution

[Bailey 97, Porter et al. 04, Cavallo 06]

Idea: give everyone $1/n$ of second-highest other bid

\[ v(\text{bid}) = \begin{cases} 2 \\ 4 \\ 3 \end{cases} \]

receives 1
pays 3
receives 2/3

2/3 wasted (22%)

Strategy-proof

Your redistribution does not depend on your bid; incentives are the same as in Vickrey
Bailey-Cavallo mechanism…

• Bids: $V_1 \geq V_2 \geq V_3 \geq \ldots \geq V_n \geq 0$
• First run Vickrey auction
• Payment is $V_2$
• First two bidders receive $V_3/n$
• Remaining bidders receive $V_2/n$
• Total redistributed: $2V_3/n + (n-2)V_2/n$

Is this the best possible?

\[
\begin{align*}
R_1 &= V_3/n \\
R_2 &= V_3/n \\
R_3 &= V_2/n \\
R_4 &= V_2/n \\
\vdots \\
R_{n-1} &= V_2/n \\
R_n &= V_2/n 
\end{align*}
\]
Another redistribution mechanism

- Bids: $V_1 \geq V_2 \geq V_3 \geq V_4 \geq \ldots \geq V_n \geq 0$
- First run Vickrey
- Redistribution:
  Receive $1/(n-2)$ * second-highest other bid,
  - $2/[(n-2)(n-3)]$ third-highest other bid
- Total redistributed:
  $V_2 - 6V_4/[(n-2)(n-3)]$

$$R_1 = V_3/(n-2) - 2/[(n-2)(n-3)]V_4$$
$$R_2 = V_3/(n-2) - 2/[(n-2)(n-3)]V_4$$
$$R_3 = V_2/(n-2) - 2/[(n-2)(n-3)]V_4$$
$$R_4 = V_2/(n-2) - 2/[(n-2)(n-3)]V_3$$
$$\ldots$$
$$R_{n-1} = V_2/(n-2) - 2/[(n-2)(n-3)]V_3$$
$$R_n = V_2/(n-2) - 2/[(n-2)(n-3)]V_3$$

Idea pursued further in Guo & Conitzer 07 / Moulin 07