

# CPS 296.1

## Mechanism design

Vincent Conitzer  
conitzer@cs.duke.edu

# Mechanism design: setting

- The **center** has a set of outcomes  $O$  that she can choose from
  - Allocations of tasks/resources, joint plans, ...
- Each agent  $i$  draws a **type**  $\theta_i$  from  $\Theta_i$ 
  - usually, but not necessarily, according to some probability distribution
- Each agent has a (commonly known) **valuation function**  $v_i: \Theta_i \times O \rightarrow \mathcal{R}$ 
  - Note: depends on  $\theta_i$ , which is **not** commonly known
- The center has some **objective function**  $g: \Theta \times O \rightarrow \mathcal{R}$ 
  - $\Theta = \Theta_1 \times \dots \times \Theta_n$
  - E.g., efficiency ( $\sum_i v_i(\theta_i, o)$ )
  - May also depend on payments (more on those later)
  - The center does **not** know the types

# What should the center do?

- She would like to know the agents' types to make the best decision
- Why not just ask them for their types?
- Problem: agents might **lie**
- E.g., an agent that slightly prefers outcome 1 may say that outcome 1 will give him a value of 1,000,000 and everything else will give him a value of 0, to force the decision in his favor
- But maybe, if the center is clever about choosing outcomes and/or requires the agents to make some **payments** depending on the types they report, the incentive to lie disappears...

# Quasilinear utility functions

- For the purposes of mechanism design, we will assume that an agent's utility for
  - his type being  $\theta_i$ ,
  - outcome  $o$  being chosen,
  - and having to pay  $\pi_i$ ,can be written as  $v_i(\theta_i, o) - \pi_i$
- Such utility functions are called **quasilinear**
- Some of the results that we will see can be generalized beyond such utility functions, but we will not do so

# Definition of a (direct-revelation) mechanism

- A **deterministic mechanism without payments** is a mapping  $o: \Theta \rightarrow O$
- A **randomized mechanism without payments** is a mapping  $o: \Theta \rightarrow \Delta(O)$ 
  - $\Delta(O)$  is the set of all probability distributions over  $O$
- Mechanisms **with payments** additionally specify, for each agent  $i$ , a payment function  $\pi_i: \Theta \rightarrow \mathcal{R}$  (specifying the payment that that agent must make)
- Each mechanism specifies a **Bayesian game** for the agents, where  $i$ 's set of actions  $A_i = \Theta_i$ 
  - We would like agents to use the truth-telling strategy defined by  $s(\theta_i) = \theta_i$

# Incentive compatibility

- **Incentive compatibility** (aka. **truthfulness**) = there is never an incentive to lie about one's type
- A mechanism is **dominant-strategies** incentive compatible (aka. **strategy-proof**) if for any  $i$ , for any type vector  $\theta_1, \theta_2, \dots, \theta_i, \dots, \theta_n$ , and for any alternative type  $\theta_i'$ , we have

$$v_i(\theta_i, o(\theta_1, \theta_2, \dots, \theta_i, \dots, \theta_n)) - \pi_i(\theta_1, \theta_2, \dots, \theta_i, \dots, \theta_n) \geq v_i(\theta_i, o(\theta_1, \theta_2, \dots, \theta_i', \dots, \theta_n)) - \pi_i(\theta_1, \theta_2, \dots, \theta_i', \dots, \theta_n)$$

- A mechanism is **Bayes-Nash equilibrium (BNE)** incentive compatible if telling the truth is a BNE, that is, for any  $i$ , for any types  $\theta_i, \theta_i'$ ,

$$\sum_{\theta_{-i}} P(\theta_{-i}) [v_i(\theta_i, o(\theta_1, \theta_2, \dots, \theta_i, \dots, \theta_n)) - \pi_i(\theta_1, \theta_2, \dots, \theta_i, \dots, \theta_n)] \geq$$

$$\sum_{\theta_{-i}} P(\theta_{-i}) [v_i(\theta_i, o(\theta_1, \theta_2, \dots, \theta_i', \dots, \theta_n)) - \pi_i(\theta_1, \theta_2, \dots, \theta_i', \dots, \theta_n)]$$

# Individual rationality

- A selfish center: “All agents must give me all their money.” – but the agents would simply not participate
  - If an agent would not participate, we say that the mechanism is not **individually rational**
- A mechanism is **ex-post** individually rational if for any  $i$ , for any type vector  $\theta_1, \theta_2, \dots, \theta_i, \dots, \theta_n$ , we have
$$v_i(\theta_i, o(\theta_1, \theta_2, \dots, \theta_i, \dots, \theta_n)) - \pi_i(\theta_1, \theta_2, \dots, \theta_i, \dots, \theta_n) \geq 0$$
- A mechanism is **ex-interim** individually rational if for any  $i$ , for any type  $\theta_i$ ,
$$\sum_{\theta_{-i}} P(\theta_{-i}) [v_i(\theta_i, o(\theta_1, \theta_2, \dots, \theta_i, \dots, \theta_n)) - \pi_i(\theta_1, \theta_2, \dots, \theta_i, \dots, \theta_n)] \geq 0$$
  - i.e., an agent will want to participate given that he is uncertain about others' types (not used as often)

# The **Clarke** (aka. **VCG**) mechanism [Clarke 71]

- The Clarke mechanism chooses some outcome  $o$  that maximizes  $\sum_i v_i(\theta_i', o)$ 
  - $\theta_i'$  = the type that  $i$  reports
- To determine the payment that agent  $j$  must make:
  - Pretend  $j$  does not exist, and choose  $o_{-j}$  that maximizes  $\sum_{i \neq j} v_i(\theta_i', o_{-j})$
  - $j$  pays  $\sum_{i \neq j} v_i(\theta_i', o_{-j}) - \sum_{i \neq j} v_i(\theta_i', o) = \sum_{i \neq j} (v_i(\theta_i', o_{-j}) - v_i(\theta_i', o))$
- We say that each agent pays the **externality** that she imposes on the other agents
- (VCG = Vickrey, Clarke, Groves)

# The Clarke mechanism is strategy-proof

- Total utility for agent  $j$  is
$$v_j(\theta_j, o) - \sum_{i \neq j} (v_i(\theta_i', o_{-j}) - v_i(\theta_i', o)) =$$
$$v_j(\theta_j, o) + \sum_{i \neq j} v_i(\theta_i', o) - \sum_{i \neq j} v_i(\theta_i', o_{-j})$$
- But agent  $j$  cannot affect the choice of  $o_{-j}$
- Hence,  $j$  can focus on maximizing  $v_j(\theta_j, o) + \sum_{i \neq j} v_i(\theta_i', o)$
- But mechanism chooses  $o$  to maximize  $\sum_i v_i(\theta_i', o)$
- Hence, if  $\theta_j' = \theta_j$ ,  $j$ 's utility will be maximized!
  
- Extension of idea: add **any** term to agent  $j$ 's payment that does not depend on  $j$ 's reported type
- This is the family of **Groves** mechanisms [Groves 73]

# Generalized Vickrey Auction (GVA)

(= VCG applied to combinatorial auctions)

- Example:
  - Bidder 1 bids  $(\{A, B\}, 5)$
  - Bidder 2 bids  $(\{B, C\}, 7)$
  - Bidder 3 bids  $(\{C\}, 3)$
- Bidders 1 and 3 win, total value is 8
- Without bidder 1, bidder 2 would have won
  - Bidder 1 pays  $7 - 3 = 4$
- Without bidder 3, bidder 2 would have won
  - Bidder 3 pays  $7 - 5 = 2$
- Strategy-proof, ex-post IR, weakly budget balanced
- Vulnerable to **collusion** (more so than 1-item Vickrey auction)
  - E.g., add two bidders  $(\{B\}, 100)$ ,  $(\{A, C\}, 100)$
  - What happens?
  - More on collusion in GVA in [\[Ausubel & Milgrom 06, Conitzer & Sandholm 06\]](#)

# Additional nice properties of the Clarke mechanism

- Ex-post individually rational, assuming:
  - An agent's presence never makes it impossible to choose an outcome that could have been chosen if the agent had not been present, and
  - No agent ever has a negative value for an outcome that would be selected if that agent were not present
- **Weak budget balanced** - that is, the sum of the payments is always nonnegative - assuming:
  - If an agent leaves, this never makes the combined welfare of the other agents (not considering payments) smaller

# Clarke mechanism is not perfect

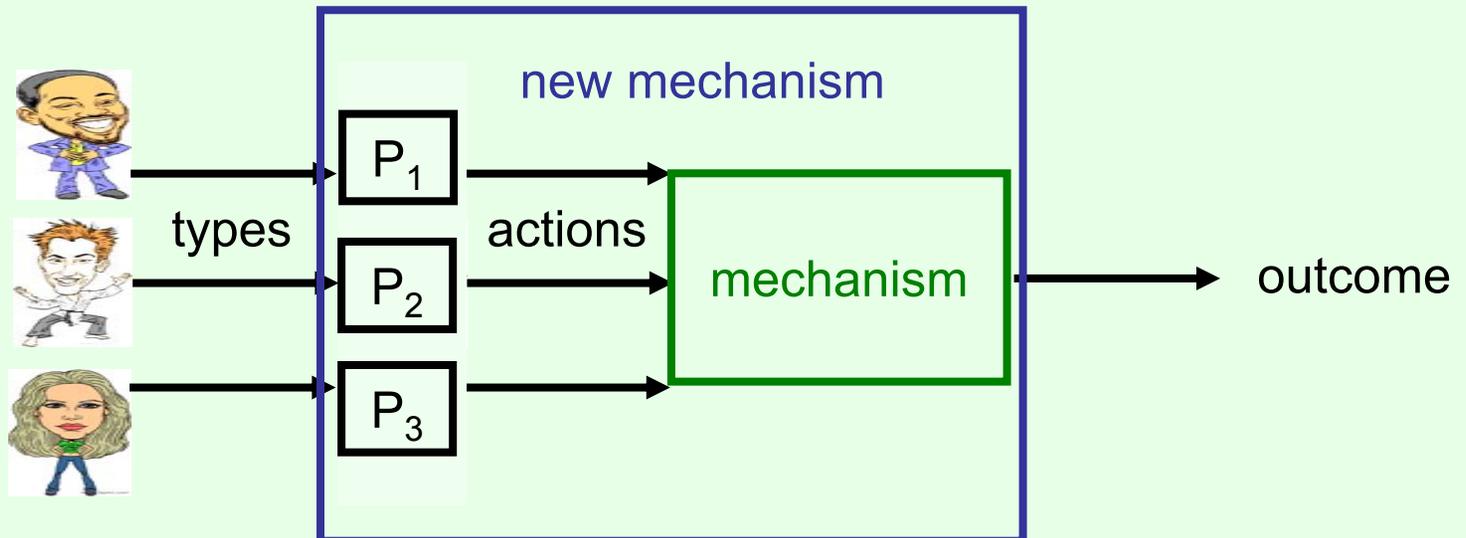
- Requires payments + quasilinear utility functions
- In general money needs to flow away from the system
  - Strong budget balance = payments sum to 0
  - In general, this is impossible to obtain in addition to the other nice properties [Green & Laffont 77]
- Vulnerable to collusion
  - E.g., suppose two agents both declare a ridiculously large value (say, \$1,000,000) for some outcome, and 0 for everything else. What will happen?
- Maximizes sum of agents' utilities (if we do not count payments), but sometimes the center is not interested in this
  - E.g., sometimes the center wants to maximize revenue

# Why restrict attention to truthful direct-revelation mechanisms?

- Bob has an incredibly complicated mechanism in which agents do not report types, but do all sorts of other strange things
- E.g.: Bob: “In my mechanism, first agents 1 and 2 play a round of rock-paper-scissors. If agent 1 wins, she gets to choose the outcome. Otherwise, agents 2, 3 and 4 vote over the other outcomes using the Borda rule. If there is a tie, everyone pays \$100, and...”
- Bob: “The **equilibria** of my mechanism produce better results than any truthful direct revelation mechanism.”
- Could Bob be right?

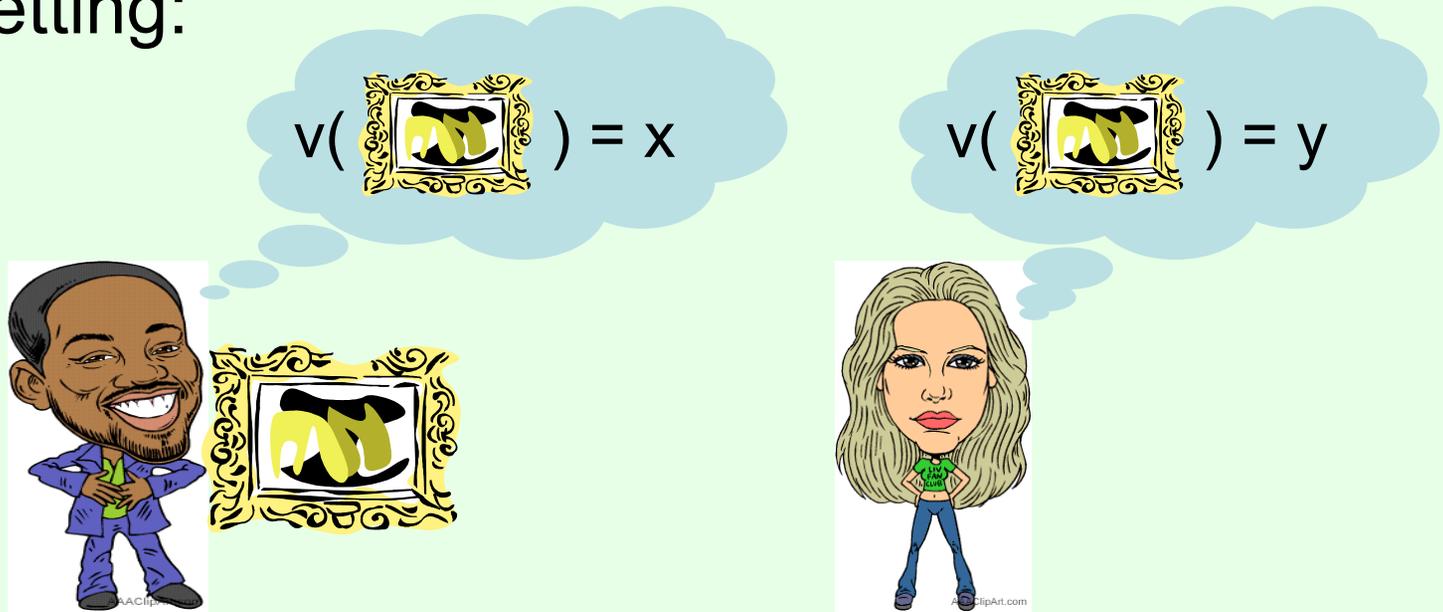
# The revelation principle

- For any (complex, strange) mechanism that produces certain outcomes under strategic behavior (dominant strategies, BNE)...
- ... there exists a (dominant-strategies, BNE) incentive compatible direct revelation mechanism that produces the same outcomes!



# Myerson-Satterthwaite impossibility [1983]

- Simple setting:



- We would like a mechanism that:
  - is efficient (trade if and only if  $y > x$ ),
  - is budget-balanced (seller receives what buyer pays),
  - is BNE incentive compatible, and
  - is ex-interim individually rational
- This is impossible!

# A few computational issues in mechanism design

- **Algorithmic** mechanism design
  - Sometimes standard mechanisms are too hard to execute computationally (e.g., Clarke requires computing optimal outcome)
  - Try to find mechanisms that are easy to execute computationally (and nice in other ways), together with algorithms for executing them
- **Automated** mechanism design
  - Given the specific setting (agents, outcomes, types, priors over types, ...) and the objective, have a **computer** solve for the best mechanism for this particular setting
- When agents have **computational limitations**, they will not necessarily play in a game-theoretically optimal way
  - Revelation principle can collapse; need to look at nontruthful mechanisms
- Many other things (computing the outcomes in a **distributed** manner; what if the agents come in over time (**online** setting); ...)