

# **APPLIED MECHANISM DESIGN FOR SOCIAL GOOD**

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**Lecture #8 – 02/18/2021**

**CMSC828M**

**Tuesdays & Thursdays**

**2:00pm – 3:15pm**



**COMPUTER SCIENCE**  
UNIVERSITY OF MARYLAND

# **THIS CLASS: SOCIAL CHOICE & MECHANISM DESIGN PRIMER**



A STRANGE GAME.  
THE ONLY WINNING MOVE IS  
NOT TO PLAY.  
  
HOW ABOUT A NICE GAME OF CHESS?

# SOCIAL CHOICE

A mathematical theory that focuses on **aggregation of individuals' preferences** over alternatives, usually in an attempt to collectively choose amongst all alternatives.

- A single alternative (e.g., a president)
- A vector of alternatives or outcomes (e.g., allocation of money, goods, tasks, jobs, resources, etc)

**Agents reveal their preferences to a center**

A **social choice function** then:

- aggregates those preferences and picks outcome

**Voting in elections, bidding on items on eBay, requesting a specific paper/lecture presentation in CMSC828M, ...**

# FORMAL MODEL OF VOTING

Set of **voters**  $N$  and a set of **alternatives**  $A$

Each voter ranks the alternatives

- Full ranking
- Partial ranking (e.g., US presidential election)

A **preference profile** is the set of all voters' rankings

1	2	3	4
<i>a</i>	<i>b</i>	<i>a</i>	<i>c</i>
<i>b</i>	<i>a</i>	<i>b</i>	<i>a</i>
<i>c</i>	<i>c</i>	<i>c</i>	<i>b</i>

# VOTING RULES

A **voting rule** is a function that maps preference profiles to alternatives

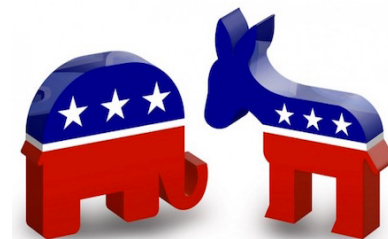
Many different voting rules – we'll discuss more in Nov.

**Plurality**: each voter's top-ranked alternative gets one point, the alternative with the most points wins

1	2	3	4
<i>a</i>	<i>b</i>	<i>a</i>	<i>c</i>
<i>b</i>	<i>a</i>	<i>b</i>	<i>a</i>
<i>c</i>	<i>c</i>	<i>c</i>	<i>b</i>

???????????

*a*: 2 points; *b*: 1 point; *c*: 1 point → ***a* wins**



# SINGLE TRANSFERABLE VOTE

**Wasted votes:** any vote not cast for a winning alternative

- Plurality wastes many votes (US two-party system ...)
- Reducing wasted votes is pragmatic (increases voter participation if they feel like votes matter) and more fair



**Single transferable vote (STV):**

- Given  $m$  alternatives, runs  $m-1$  rounds
- Each round, alternative with fewest plurality votes is eliminated
- Winner is the last remaining alternative

**Ireland, Australia, New Zealand, a few other countries use STV (and coincidentally have more effective “third” parties...)**

- You might hear this called “instant run-off voting”



# STV EXAMPLE

Starting preference profile:

1	2	3	4	5
<i>a</i>	<i>a</i>	<i>b</i>	<i>b</i>	<i>c</i>
<i>b</i>	<i>b</i>	<i>a</i>	<i>a</i>	<i>d</i>
<i>c</i>	<i>c</i>	<i>d</i>	<i>d</i>	<i>b</i>
<i>d</i>	<i>d</i>	<i>c</i>	<i>c</i>	<i>a</i>

1	2	3	4	5
<i>a</i>	<i>a</i>	<i>b</i>	<i>b</i>	<i>c</i>
<i>b</i>	<i>b</i>	<i>a</i>	<i>a</i>	<i>b</i>
<i>c</i>	<i>c</i>	<i>c</i>	<i>c</i>	<i>a</i>

Round 1, *d* has no plurality votes

Round 2, *c* has 1 plurality vote

1	2	3	4	5
<i>a</i>	<i>a</i>	<i>b</i>	<i>b</i>	<i>b</i>
<i>b</i>	<i>b</i>	<i>a</i>	<i>a</i>	<i>a</i>

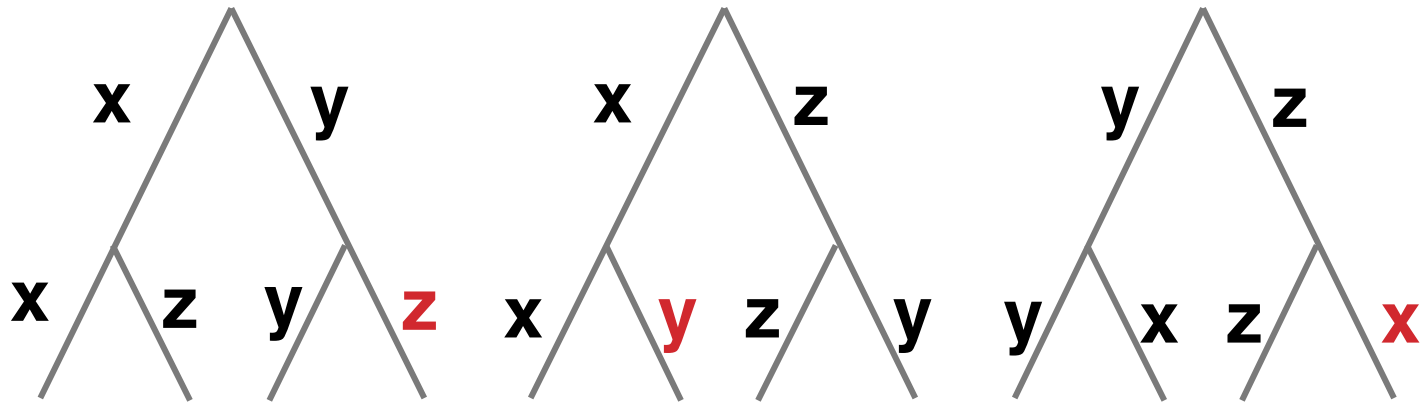
1	2	3	4	5
<i>b</i>	<i>b</i>	<i>b</i>	<i>b</i>	<i>b</i>

Round 3, *a* has 2 plurality votes

# MANIPULATION: AGENDA PARADOX

**Binary protocol** (majority rule), aka “cup”

Three types of agents:



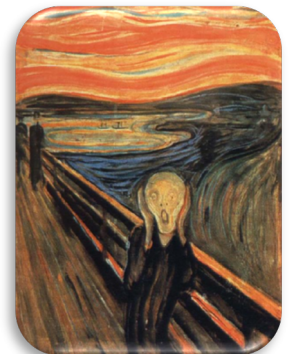
Preference profile:

1.  $x > z > y$  (35%)
2.  $y > x > z$  (33%)
3.  $z > y > x$  (32%)

Power of agenda setter (e.g., chairman)

Under plurality rule, **x** wins

Under STV rule, **y** wins





# HOW SHOULD WE DESIGN VOTING RULES?

Take an **axiomatic** approach!

**Majority consistency:**

- If a majority of people vote for  $x$  as their top alternative, then  $x$  should win the election

**Is plurality majority consistent?**

- Yes

**Is STV majority consistent?**

- No

**Is cup majority consistent?**

- No

# HOW SHOULD WE DESIGN VOTING RULES?



Given a preference profile, an alternative is a **Condorcet winner** if it beats all other alternatives in pairwise elections

- Wins plurality vote against any candidate in two-party election

**Doesn't always exist! Condorcet Paradox:**

1	2	3
x	z	y
y	x	z
z	y	x

$$x > y \text{ (2-1)}; y > z \text{ (2-1)}; z > x \text{ (2-1)} \rightarrow x > y > z > x$$

**Condorcet consistency:** chooses Condorcet winner if it exists

- Stronger or weaker than majority consistency ...?

# HOW SHOULD WE DESIGN VOTING RULES?

1. **Strategyproof**: voters cannot benefit from lying.
2. Is it **computationally tractable** to determine winner?
3. **Unanimous**: if all voters have the same preference profile, then the aggregate ranking equals that.
4. **(Non-)dictatorial**: is there a voter who always gets her preferred alternative?
5. **Independence of irrelevant alternatives (IIA)**: social preference between any alternatives  $a$  and  $b$  only depends on the voters' preferences between  $a$  and  $b$ .
6. **Onto**: any alternative can win

Gibbard-Satterthwaite (1970s): if  $|A| \geq 3$ , then any voting rule that is strategyproof and onto is a dictatorship.

# COMPUTATIONAL SOCIAL CHOICE

There are many strong **impossibility results** like G-S

- We will discuss more of them (e.g., G-S, Arrow's Theorem) during the voting theory lectures in a month and a half

**Computational social choice** creates “well-designed” implementations of social choice functions, with an eye toward:

- Computational tractability of the winner determination problem
- Communication complexity of preference elicitation
- Designing the **mechanism** to elicit preferences **truthfully**

Interactions between these can lead to positive theoretical results and practical circumventions of impossibility results.

# MECHANISM DESIGN: MODEL

Before: we were **given** preference profiles

Reality: agents **reveal** their (private) preferences

- Won't be truthful unless it's in their **individual** interest; but
- We want some **globally** good outcome

**Formally:**

- Center's job is to pick from a set of outcomes  $O$
- Agent  $i$  draws a private type  $\theta_i$  from  $\Theta_i$ , a set of possible types
- Agent  $i$  has a public valuation function  $v_i : \Theta_i \times O \rightarrow \mathbb{R}$
- Center has public objective function  $g : \Theta \times O \rightarrow \mathbb{R}$ 
  - Social welfare max aka efficiency, maximize  $g = \sum_i v_i(\theta_i, o)$
  - Possibly plus/minus monetary payments

# MECHANISM DESIGN WITHOUT MONEY

A (direct) **deterministic mechanism without payments**  $o$  maps  $\Theta \rightarrow O$

A (direct) **randomized mechanism without payments**  $o$  maps  $\Theta \rightarrow \Delta(O)$ , the set of all probability distributions over  $O$

Any mechanism  $o$  induces a Bayesian **game**,  $\text{Game}(o)$

A mechanism is said to **implement** a social choice function  $f$  if, for every input (e.g., preference profile), there is a Nash equilibrium for  $\text{Game}(o)$  where the outcome is the same as  $f$

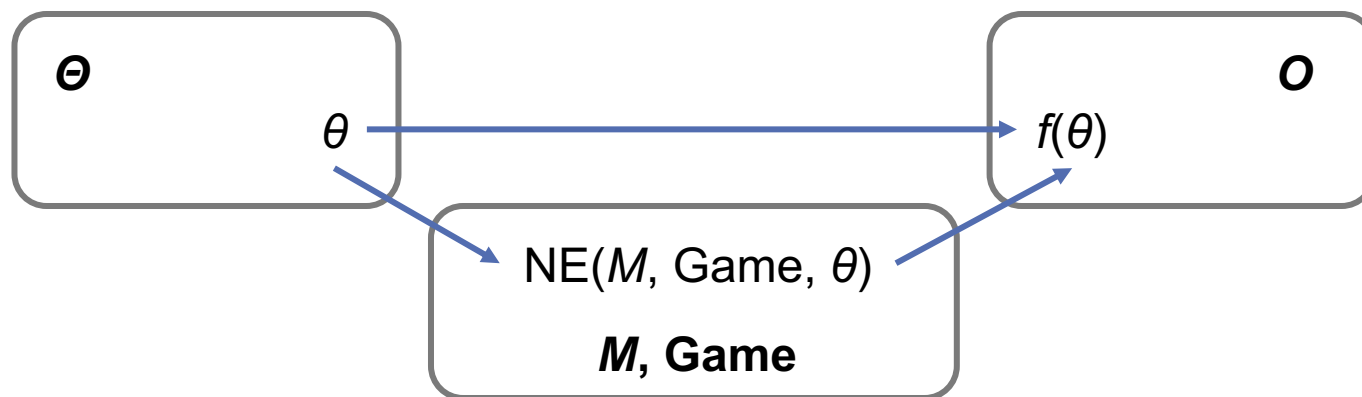
# PICTORIALLY ...

Agents draw private types  $\theta$  from  $\Theta$

If those types were known, an outcome  $f(\theta)$  would be chosen

Instead, agents send *messages*  $M$  (e.g., report their type as  $\theta'$ , or bid if we have money) to the mechanism

Goal: design a mechanism whose Game induces a Nash equilibrium where the outcome equals  $f(\theta)$



# A (SILLY) MECHANISM THAT DOES NOT IMPLEMENT WELFARE MAX

2 agents, 1 item

Each agent draws a private valuation for that item

Social welfare maximizing outcome: agent with greatest private valuation receives the item.

**Mechanism:**

- Agents send a message of  $\{1, 2, \dots, 10\}$
- Item is given to the agent who sends the lowest message; if both send the same message, agent  $i = 1$  gets the item

**Equilibrium behavior:** ??????????

- Always send the lowest message (1)
- Outcome: agent  $i = 1$  gets item, even if  $i = 2$  values it more



# MECHANISM DESIGN WITH MONEY

**We will assume that an agent's utility for**

- her type being  $\theta_i$ ,
- outcome  $o$  being chosen,
- and having to pay  $\pi_i$ ,

can be written as  $v_i(\theta_i, o) - \pi_i$

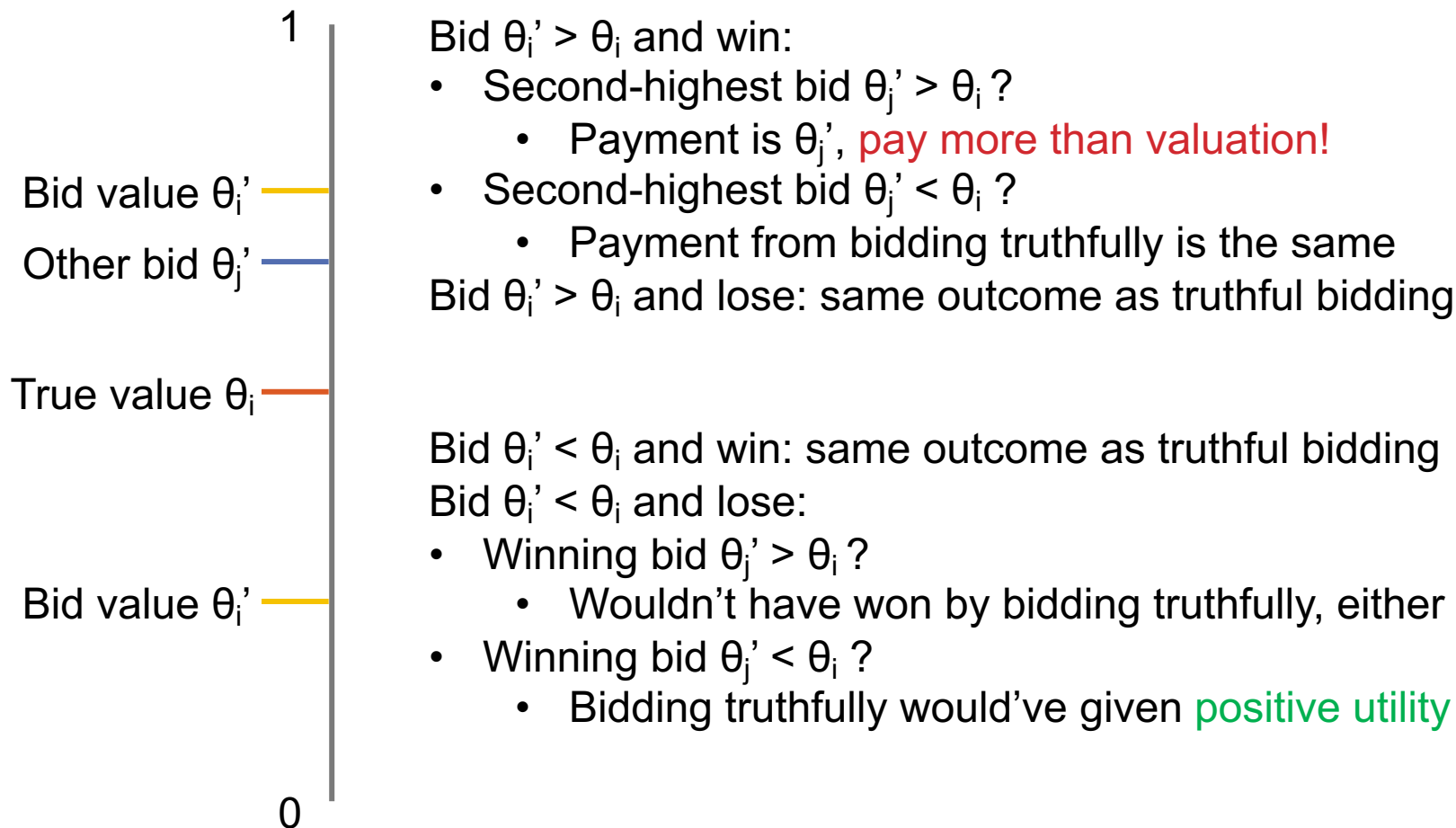
**Such utility functions are called **quasilinear****

- “quasi” – linear with respect to one of the raw inputs, in this case payment  $\pi_i$ , as well as a function of the rest (i.e.,  $v_i(\theta_i, o)$ )

**Then, (direct) deterministic and randomized mechanisms with payments additionally specify, for each agent  $i$ , a payment function  $\pi_i : \Theta \rightarrow \mathbb{R}$**

# VICKREY'S SECOND PRICE AUCTION ISN'T MANIPULABLE

(Sealed) bid on single item, highest bidder wins & pays second-highest bid price



# THE CLARKE (AKA VCG) MECHANISM

The Clarke mechanism chooses some outcome  $o$  that maximizes  $\sum_i v_i(\theta_i', o)$

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

- Agent  $i$ 's externality: (social welfare of others if  $i$  were absent) - (social welfare of others when  $i$  is present)

(VCG = Vickrey, Clarke, Groves)

# INCENTIVE COMPATIBILITY

**Incentive compatibility:** there is never an incentive to lie about one's type

A mechanism is **dominant-strategies** incentive compatible (aka **strategyproof**) 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  $\theta_i, \theta_i'$ ,

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

# VCG IS STRATEGYPROOF

Total utility for agent  $j$  is

$$\begin{aligned} v_j(\theta_j, o) - \sum_{i \neq j} (v_i(\theta_i', o_{-j}) - v_i(\theta_i', o)) \\ = v_j(\theta_j, o) + \sum_{i \neq j} v_i(\theta_i', o) - \sum_{i \neq j} v_i(\theta_i', o_{-j}) \end{aligned}$$


But agent  $j$  cannot affect the choice of  $o_{-j}$

$\rightarrow j$  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

# INDIVIDUAL RATIONALITY

A selfish center: “All agents must give me all their money.” – but the agents would simply not participate

- This mechanism is not **individually rational**

A mechanism is **ex-post** individually rational if for any  $i$ , for any known 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  $\theta_i$ ,

$$\sum_{\theta_{-i}} P(\theta_{-i}) [v_i(\theta_i, o(\theta_1, \theta_2, \dots, \theta_i, \dots, \theta_n)) - \pi_i(\theta_1, \theta_2, \dots, \theta_i, \dots, \theta_n)] \geq 0$$

Is the Clarke mechanism individually rational?

# WHY ONLY 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

- 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 STV voting 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.”

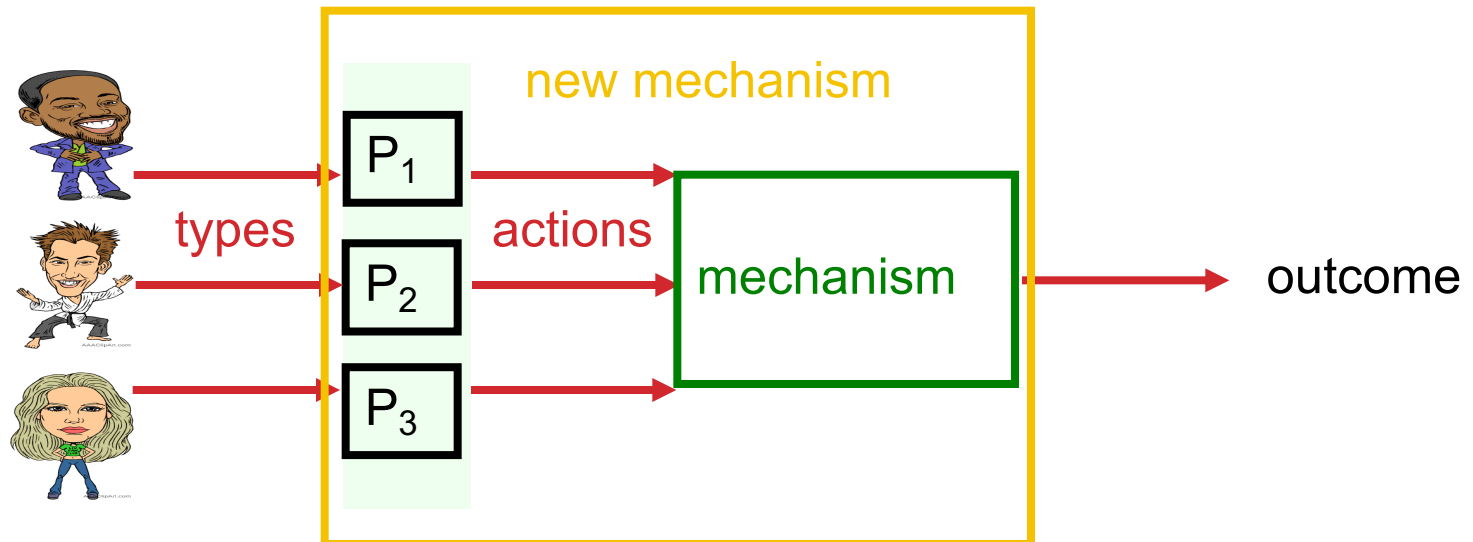
- Could Bob be right?



# 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!





# REVELATION PRINCIPLE IN PRACTICE

## “Only direct mechanisms needed”

- But: strategy formulator might be complex
  - Complex to determine and/or execute best-response strategy
  - Computational burden is pushed on the center (i.e., assumed away)
  - Thus the revelation principle might not hold in practice if these computational problems are hard
  - This problem traditionally ignored in game theory
- But: even if the indirect mechanism has a unique equilibrium, the direct mechanism can have additional bad equilibria

# REVELATION PRINCIPLE AS AN ANALYSIS TOOL

**Best direct mechanism gives tight upper bound on how well any indirect mechanism can do**

- Space of direct mechanisms is smaller than that of indirect ones
- One can analyze all direct mechanisms & pick best one
- Thus one can know when one has designed an optimal indirect mechanism (when it is as good as the best direct one)

# 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); ...) – many good project ideas here ☺.**

# **RUNNING EXAMPLE: MECHANISM DESIGN FOR KIDNEY EXCHANGE**

# THE PLAYERS AND THEIR INCENTIVES

**Clearinghouse cares about global welfare:**

- How many patients received kidneys (over time)?

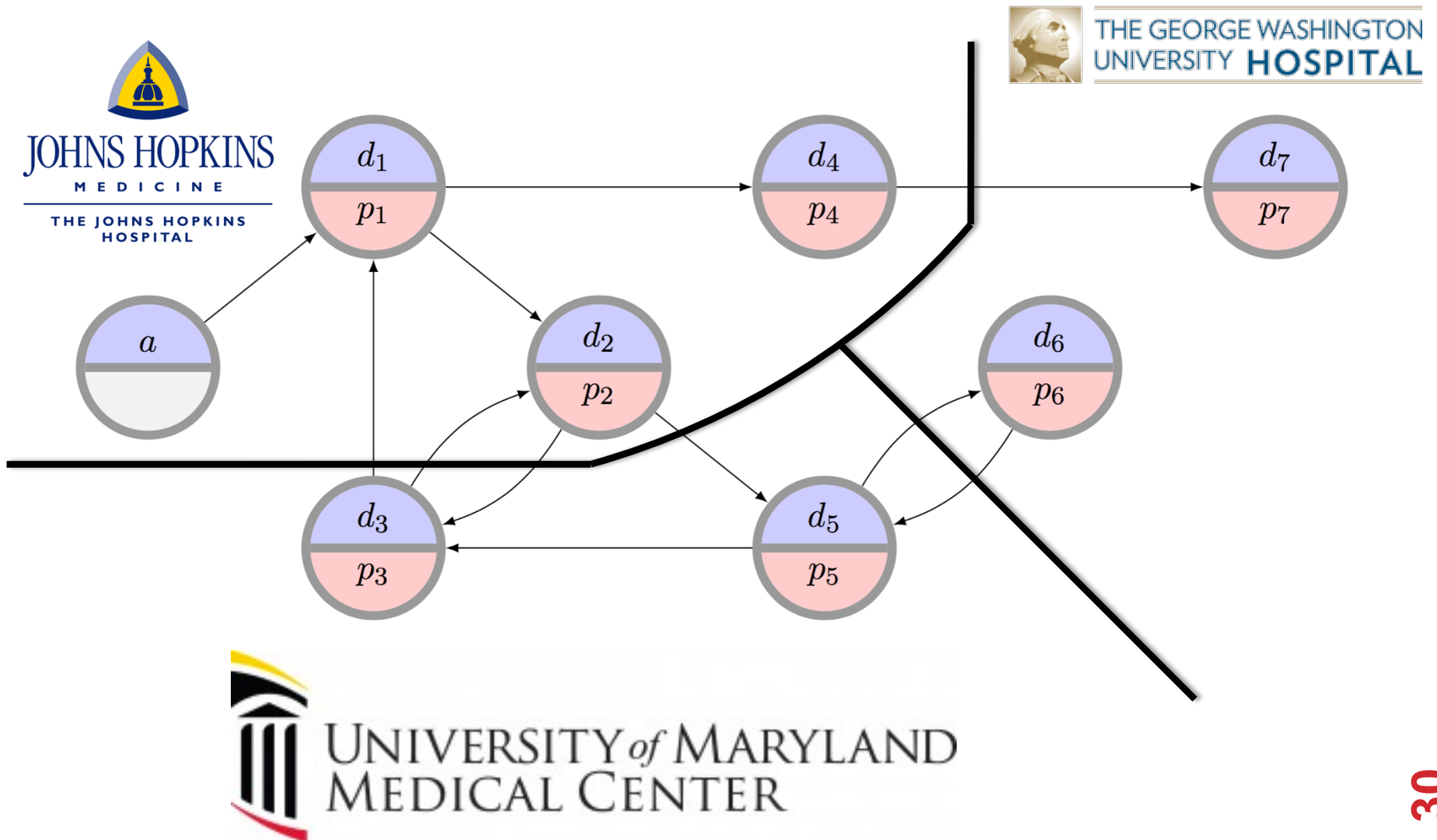
**Transplant centers care about their individual welfare:**

- How many of my own patients received kidneys?

**Patient-donor pairs care about their individual welfare:**

- Did I receive a kidney?
- (Most work considers just clearinghouse and centers)

# PRIVATE VS GLOBAL MATCHING



# MODELING THE PROBLEM

**What is the type of an agent?**

**What is the utility function for an agent?**

**What would it mean for a mechanism to be:**

- **Strategyproof**
- **Individually rational**
- **Efficient**

# KNOWN RESULTS

**Theory** [Roth&Ashlagi 14, Ashlagi et al. 15, Toulis&Parkes 15]:

- Can't have a strategy-proof and efficient mechanism
- Can get “close” by relaxing some efficiency requirements
- Even for the **undirected** (2-cycle) case:
  - No deterministic SP mechanism can give 2-eps approximation to social welfare maximization
  - No randomized SP mechanism can give 6/5-eps approx
- **But!** Ongoing work by a few groups hints at **dynamic models** being both more realistic and less “impossible”!

**Reality: transplant centers strategize like crazy!** [Stewart et al. 13]





# **NEXT CLASS: COMBINATORIAL OPTIMIZATION**

