

# 15-326

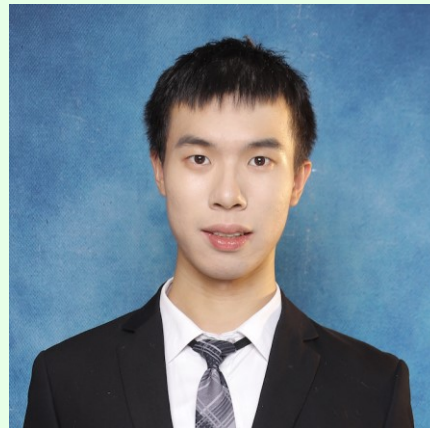
# Computational Microeconomics

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<http://www.cs.cmu.edu/~15326-f24/>

TA: [Jiayuan Liu](#)



# History



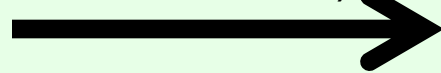
*John von Neumann*

computer architecture  
(von Neumann  
architecture)



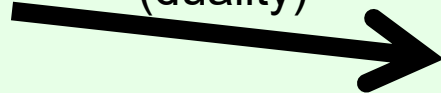
***Computer Science  
& Engineering***

game theory  
(minimax theorem)

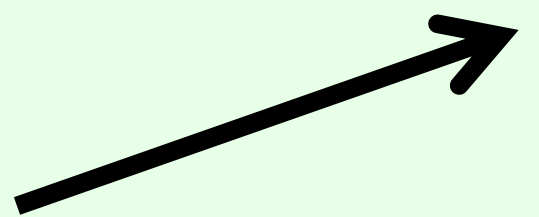
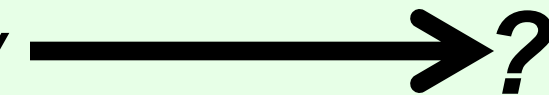
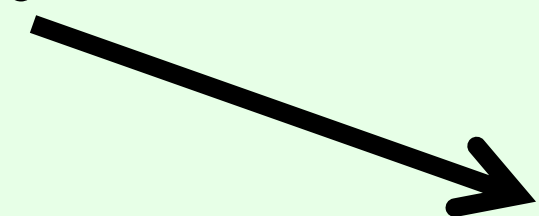


***Economic Theory***

linear programming  
(duality)



***Mathematical  
Optimization &  
Operations  
Research***



?

1900

1950

2000

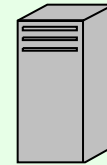


# What is Economics?

- “a social science that studies the production, distribution, and consumption of goods and services.” [[Wikipedia, Aug. 2024](#)]
- Some key concepts:
  - Economic **agents** or **players** (individuals, households, firms, bots, ...)
  - Agents’ current **endowments** of goods, money, skills, ...
  - Possible **outcomes** ((re)allocations of resources, tasks, ...)
  - Agents’ **preferences** or **utility functions** over outcomes
  - Agents’ **beliefs** (over other agents’ utility functions, endowments, production possibilities, ...)
  - Agents’ possible **decisions/actions**
  - **Mechanism** that maps decisions/actions to outcomes

# An economic picture

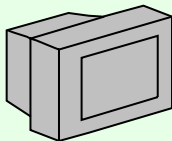
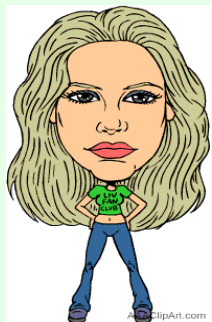
$$v(\text{server}) = 200$$



\$ 800

$$v(\text{monitor}) = 100$$

$$v(\text{laptop}) = 400$$



\$ 600

$$v(\text{laptop}) = 200$$

$$v(\text{server}, \text{monitor}) = 400$$



\$ 200



# After trade (a more efficient outcome)

$$v(\text{server}) = 200$$



\$ 1100

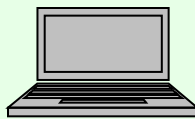
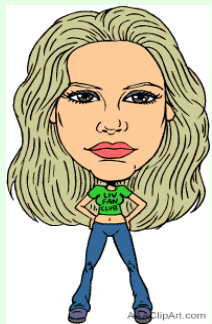
... but how do we get here?  
Unstructured trade?  
Auctions?  
Exchanges?

$$v(\text{television}) = 100$$

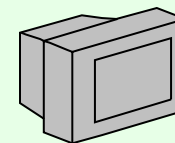
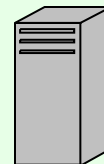
$$v(\text{laptop}) = 400$$

$$v(\text{laptop}) = 200$$

$$v(\text{server}, \text{television}) = 400$$



\$ 400



\$ 100



# Some distinctions in economics

- **Descriptive vs. normative economics**
  - Descriptive:
    - seeks only to describe real-world economic phenomena
    - does not care if this is in any sense the “right” outcome
  - Normative:
    - studies how people “should” behave, what the “right” or “best” outcome is
- **Microeconomics vs. macroeconomics**
  - Microeconomics: analyzes decisions at the level of individual agents
    - deciding which goods to produce/consume, setting prices, ...
    - “bottom-up” approach
  - Macroeconomics: analyzes “the sum” of economic activity
    - interest rates, inflation, growth, unemployment, government spending, taxation, ...
    - “big picture”

# What is Computer Science?

- “Computer science is the study of computation, information, and automation. Computer science spans theoretical disciplines (such as algorithms, theory of computation, and information theory) to applied disciplines (including the design and implementation of hardware and software).” [Wikipedia, Aug. 2024]
- A **computational problem** is given by a function  $f$  mapping inputs to outputs
  - For integer  $x$ , let  $f(x) = 0$  if  $x$  is prime, 1 otherwise
  - For initial allocation of resources + agent utilities  $x$ , let  $f(x)$  be the (re)allocation that maximizes the sum of utilities
- An **algorithm** is a fully specified procedure for computing  $f$ 
  - E.g., sieve of Eratosthenes
  - A **correct algorithm** always returns the **right** answer
  - An **efficient algorithm** returns the answer **fast**
- Computer science is also concerned with building **larger artifacts** out of these building blocks (e.g., personal computers, spreadsheets, the Internet, the Web, search engines, artificial intelligence, ...)

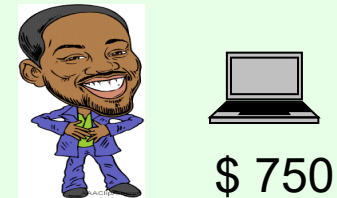
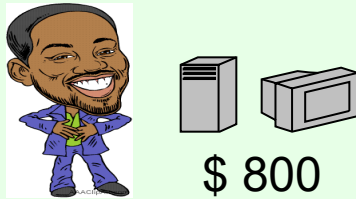
# Resource allocation as a computational problem (*Part 1 of the course*)

*input*

*output*

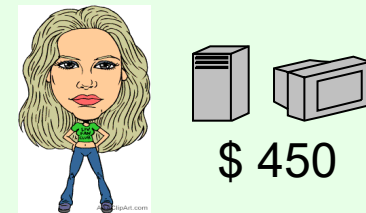
$v(\text{server, monitor}) = \$400$

$v(\text{laptop}) = \$600$



$v(\text{server, monitor}) = \$500$

$v(\text{laptop}) = \$400$



Here, gains from trade (\$300) are divided evenly (not essential)



# Economic mechanisms

**“true” input**

**agents' bids**

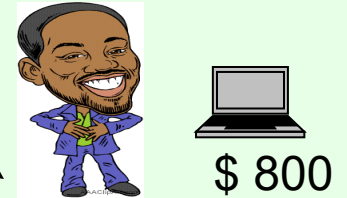
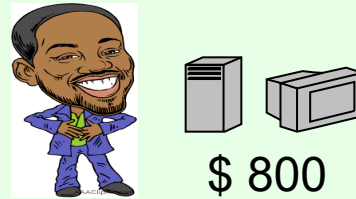
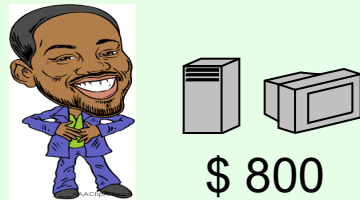
**result**

$$v(\text{server, printer}) = \$400$$
$$v(\text{laptop}) = \$600$$

agent 1's bidding algorithm

$$v(\text{server, printer}) = \$500$$
$$v(\text{laptop}) = \$501$$

exchange mechanism (algorithm)

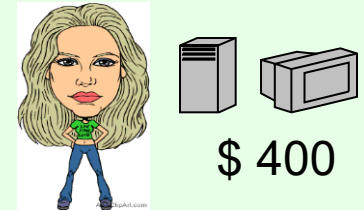
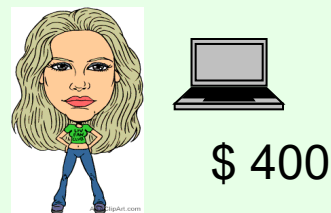


$$v(\text{server, printer}) = \$500$$
$$v(\text{laptop}) = \$400$$

agent 2's bidding algorithm

$$v(\text{server, printer}) = \$451$$
$$v(\text{laptop}) = \$450$$

*Exchange mechanism designer does not have direct access to agents' private information*



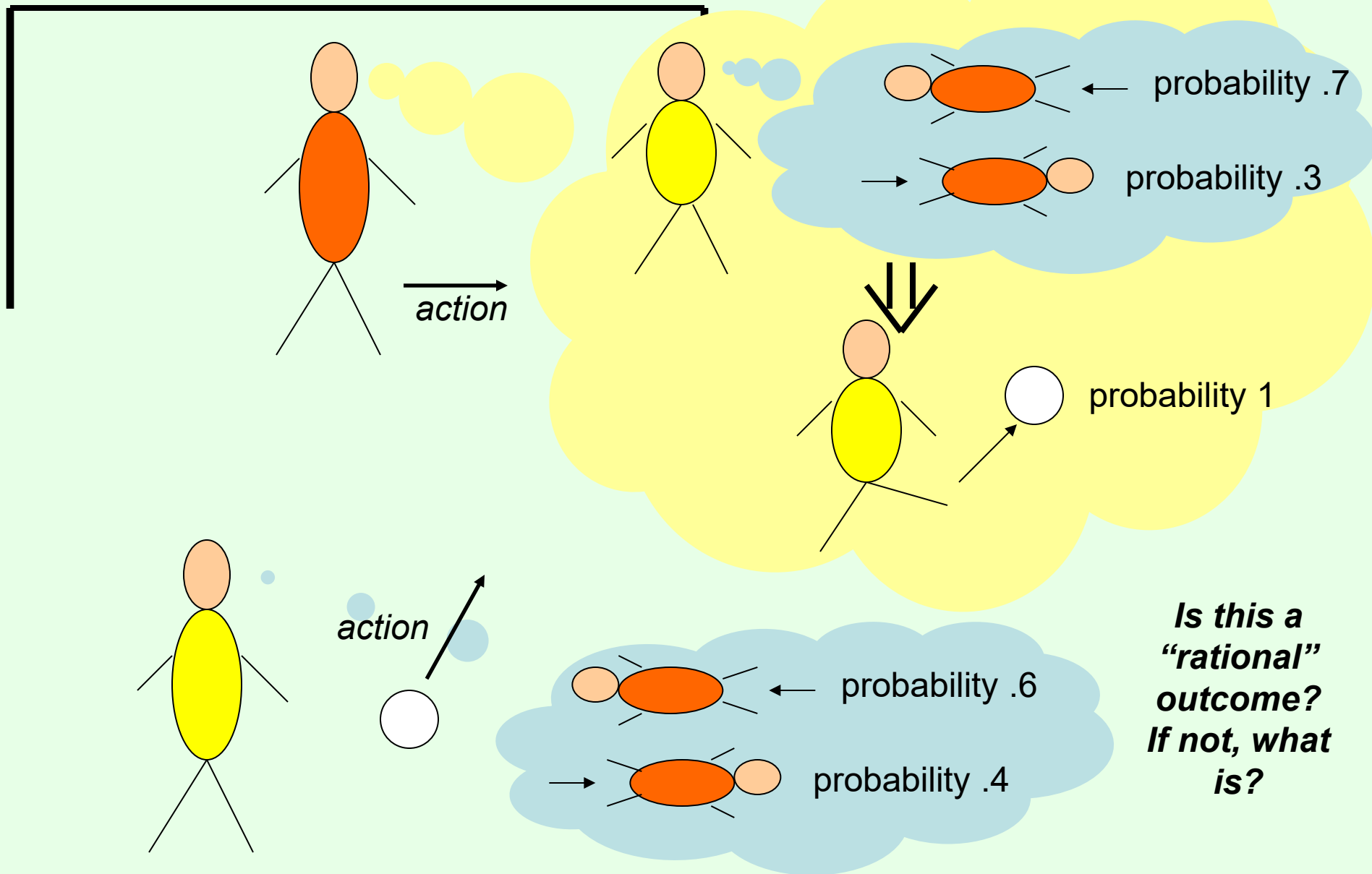
*Agents will selfishly respond to incentives*

# Game theory

## *(Part 2 of the course)*

- Game theory studies settings where agents each have
  - different preferences (utility functions),
  - different actions that they can take
- Each agent's utility (potentially) depends on all agents' actions
  - What is optimal for one agent depends on what other agents do
    - Very circular!
- Game theory studies how agents can rationally form beliefs over what other agents will do, and (hence) how agents should act
  - Useful for acting as well as predicting behavior of others

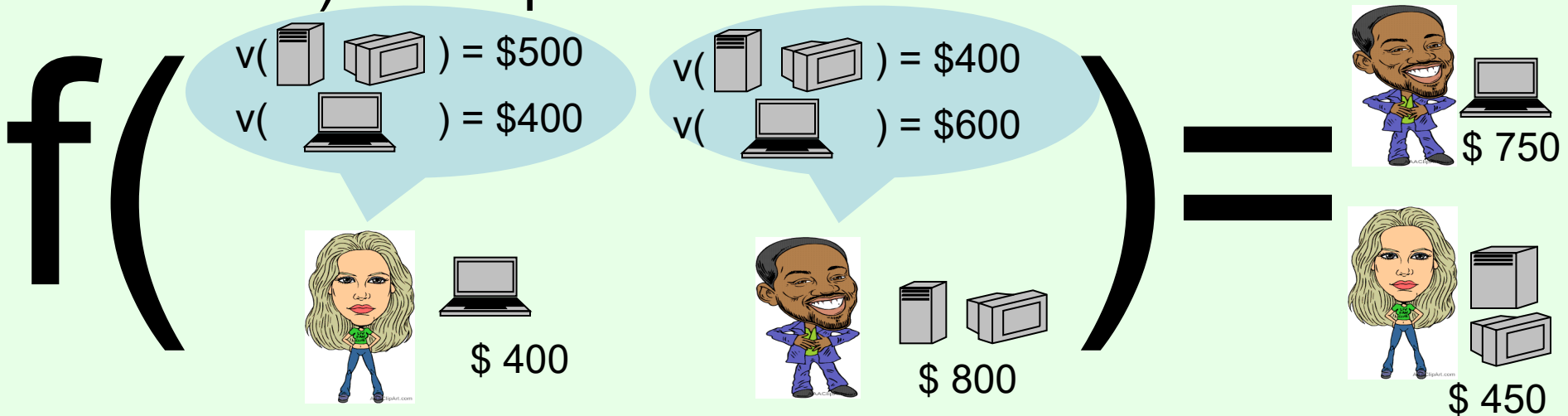
# Penalty kick example



# Mechanism design

## (Part 3 of the course)

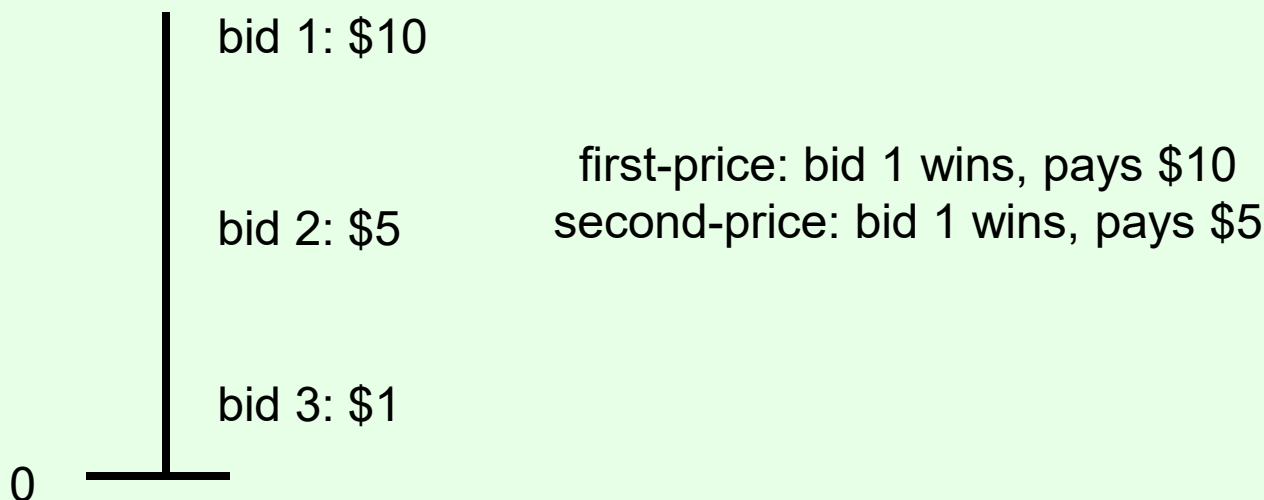
- **Mechanism** = rules of auction, exchange, ...
- A **function** that takes **reported preferences** (bids) as input, and produces **outcome** (allocation, payments to be made) as output



- The **entire function**  $f$  is **one** mechanism
- E.g., the mechanism from part 1: find allocation that maximizes (reported) utilities, distribute (reported) gains evenly
- Other mechanisms choose different allocations, payments

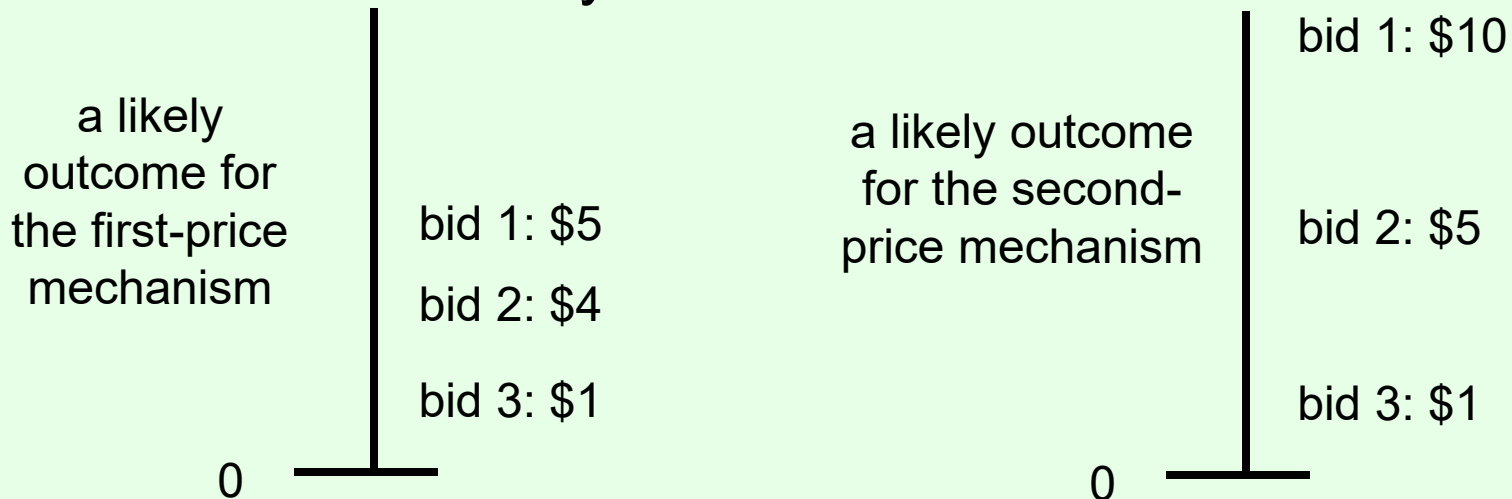
# Example: (single-item) auctions

- **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



# 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 ( $\rightarrow$  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?*

# Mechanism design...

- Mechanism = game
- → we can use game theory to predict what will happen under a mechanism
  - if agents act strategically
- When is a mechanism “good”?
  - Should it result in outcomes that are good for the **reported** preferences, or for the **true** preferences?
  - Should agents ever end up **lying** about their preferences (in the game-theoretic solution)?
  - Should it always **generate the best allocation**?
  - Should agents ever **burn money**?(!?)
- Can we solve for the optimal mechanism?

# How are we going to solve these problems? (*Part 0*)

- This is **not** a programming course
- Will use optimization software
  - GNU Linear Programming Kit (GLPK)
  - Linear programming, mixed integer linear programming

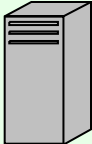
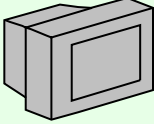
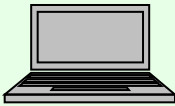


# Uses of LP, MIP in this course

	<b>Linear programming</b>	<b>Mixed integer linear programming</b>
Part 1 (expressive marketplaces)	Winner determination in auctions, exchanges, ... with partially acceptable bids	Winner determination in auctions, exchanges, ... without partially acceptable bids
Part 2 (game theory)	Dominated strategies Minimax strategies Correlated equilibrium Optimal mixed strategies to commit to	Nash equilibrium
Part 3 (mechanism design)	Automatically designing optimal mechanisms that use randomization	Automatically designing optimal mechanisms that do not use randomization

**Other settings/applications**

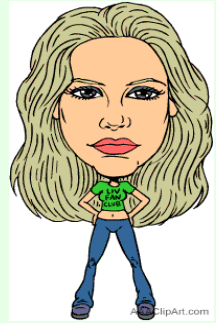
# Combinatorial auctions (in Part 1)

Simultaneously for sale:  ,  , 



*bid 1*

$$v(\text{server rack}, \text{cabinet}) = \$500$$



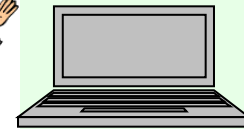
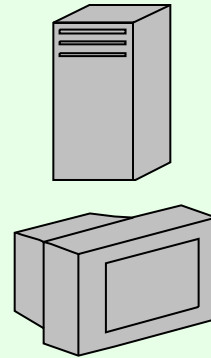
*bid 2*

$$v(\text{laptop}, \text{cabinet}) = \$700$$



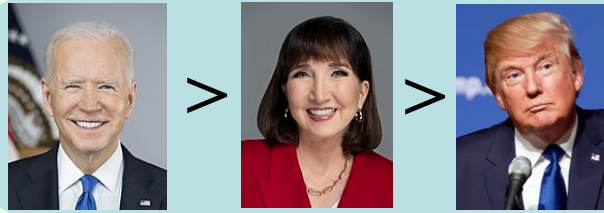
*bid 3*

$$v(\text{laptop}) = \$300$$

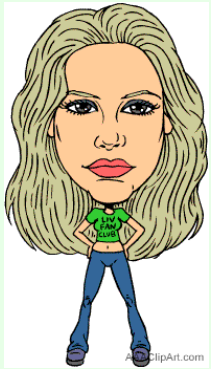


used in truckload transportation, industrial procurement, radio spectrum allocation, ...

# Voting (in Part 1)



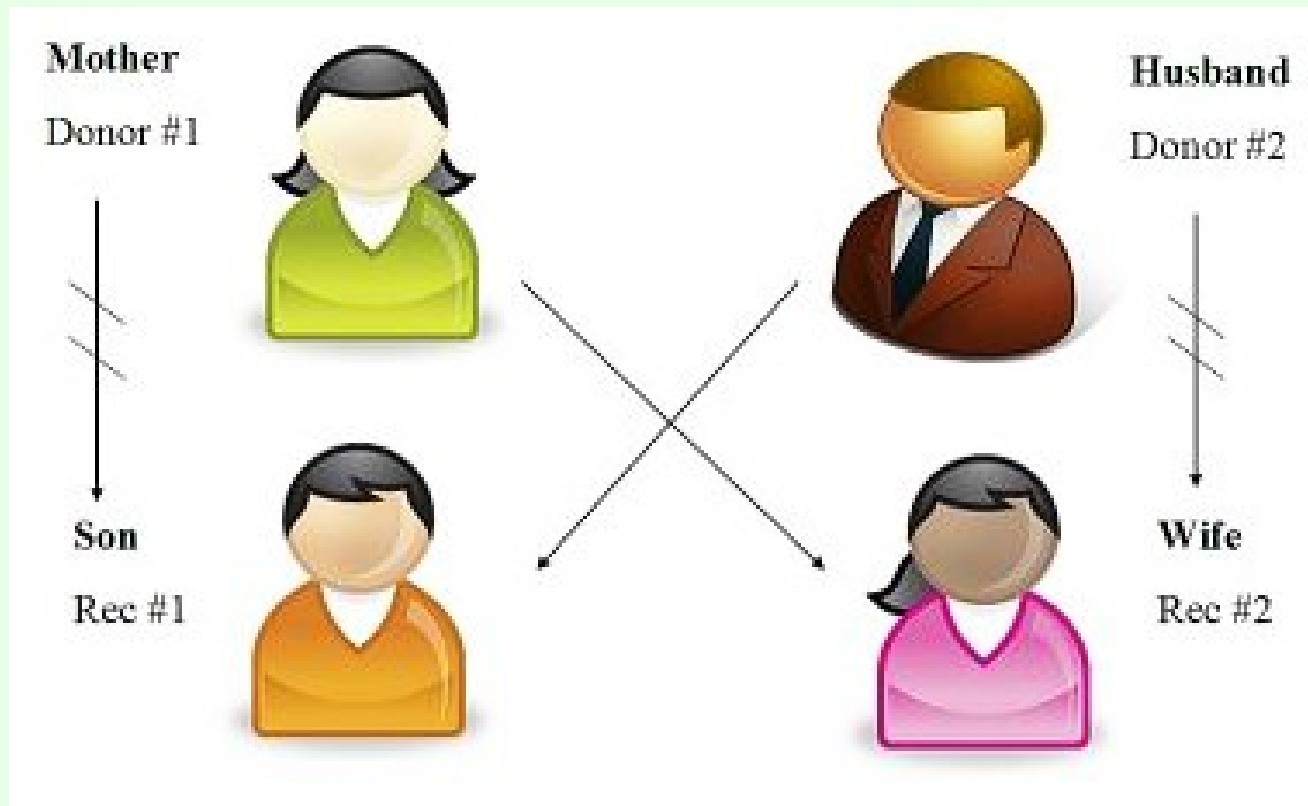
voting rule  
(mechanism)  
determines winner  
based on votes



- Can vote over other things too
  - Where to go for dinner tonight, other joint plans, ...
- Many different rules exist for selecting the winner

# Kidney exchange (in Part 1)

- Kidney exchanges allow patients with willing but incompatible live donors to swap donors



# Kidney exchange (in Part 1)

Q | POPULAR | LATEST | FEATURED

QUARTZ

OBSSESSIONS | EMAILS | EDITIONS | G

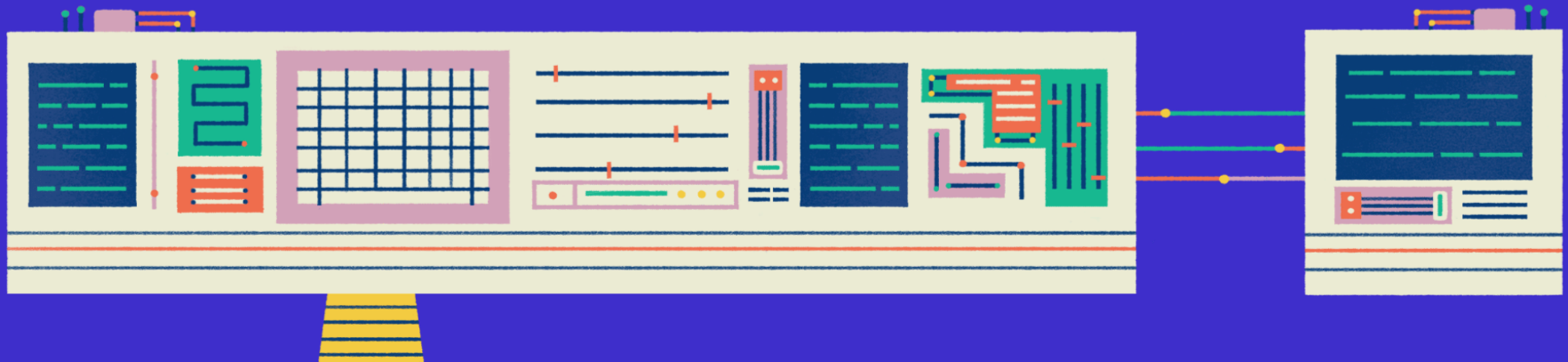
## Prescription AI

This series explores the promise of AI to personalize, democratize, and advance medicine—and the dangers of letting machines make decisions.

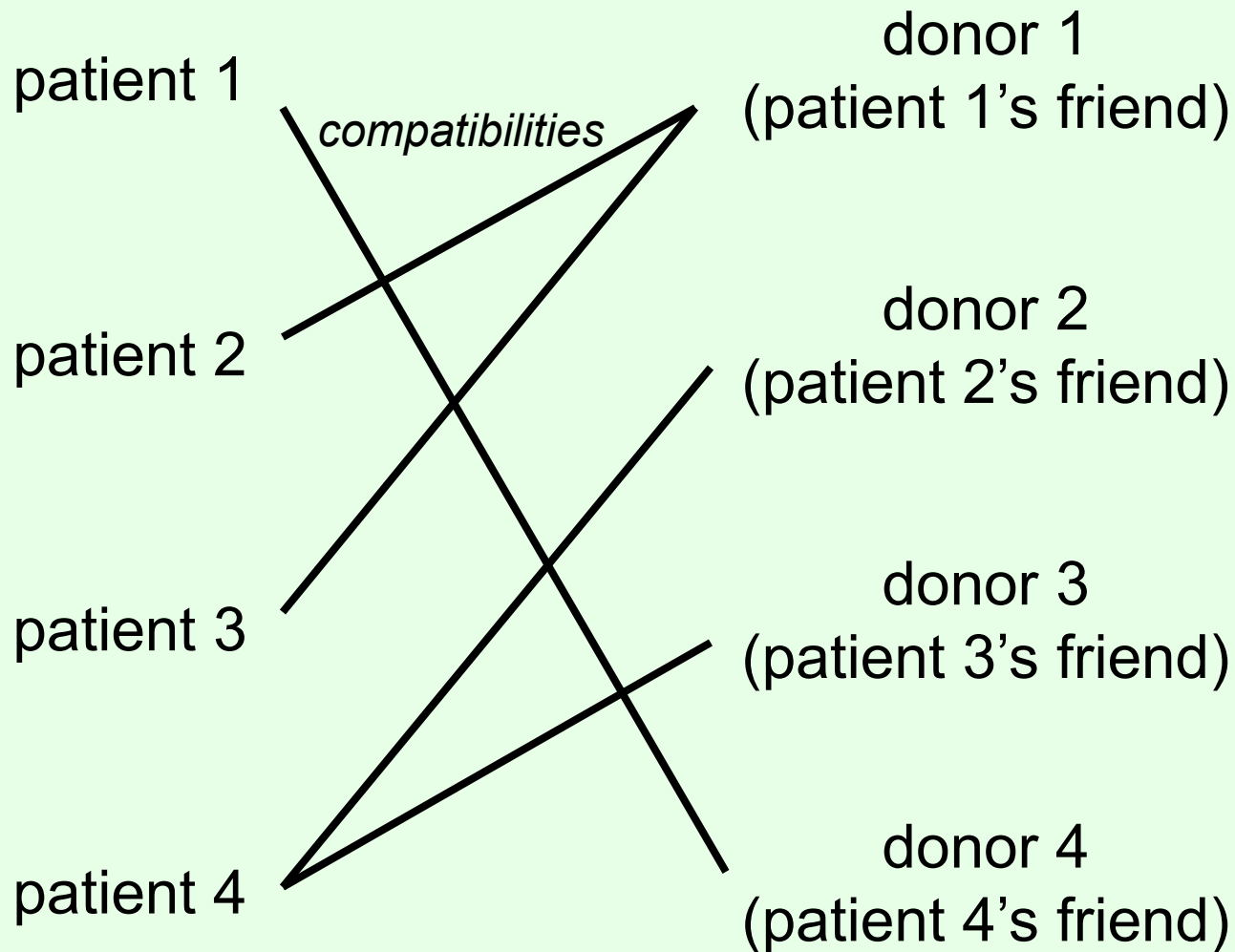
THE BOTPERATING TABLE

# How AI changed organ donation in the US

By [Corinne Purtill](#) · September 10, 2018

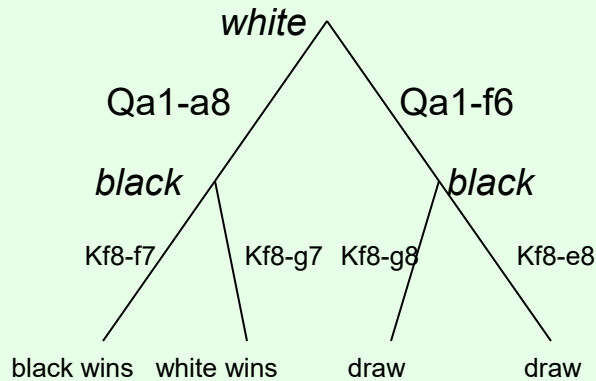


# Kidney exchange (in Part 1)

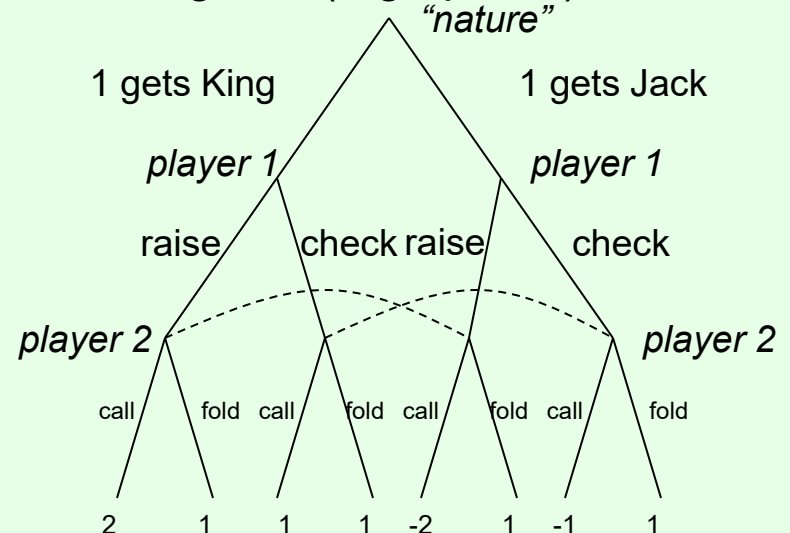


# Game playing & AI (in Part 2)

**perfect information** games:  
no uncertainty about the state of the game (e.g. tic-tac-toe, chess, Go)



**imperfect information** games: uncertainty about the state of the game (e.g., poker)



- Optimal play: value of each node = value of optimal child for current player (**backward induction**, minimax)
- For chess and Go, tree is too large
  - Use other techniques (heuristics, limited-depth search, alpha-beta, deep learning, ...)
- Top computer programs better than humans in chess, ~~not yet in Go~~

- Player 2 **cannot distinguish** nodes connected by dotted lines
  - Backward induction fails; need more sophisticated game-theoretic techniques for optimal play
- Small poker variants can be solved optimally
- ~~• Humans still better than top computer programs at full-scale poker (at least most versions)~~
- Top computer ~~(heads-up)~~ poker players are based on techniques for game theory



# Science

## 2019 BREAKTHROUGH OF THE YEAR

Darkness made visible

## RUNNERS-UP

- Face to face with the Denisovans
- Quantum supremacy attained
- Microbes combat malnourishment
- A killer impact and its aftermath
- A close-up of a far-out object
- A 'missing link' microbe emerges
- In a first, drug treats most cases of cystic fibrosis

Hope for Ebola patients, at last

Artificial intelligence masters multiplayer poker

## BREAKDOWNS

- The Amazon ablaze
- Measles resurgent
- Bird counts dwindling
- An eleventh hour climate awakening?

## RELATED ITEMS

- Video
- Editorial
- Podcast

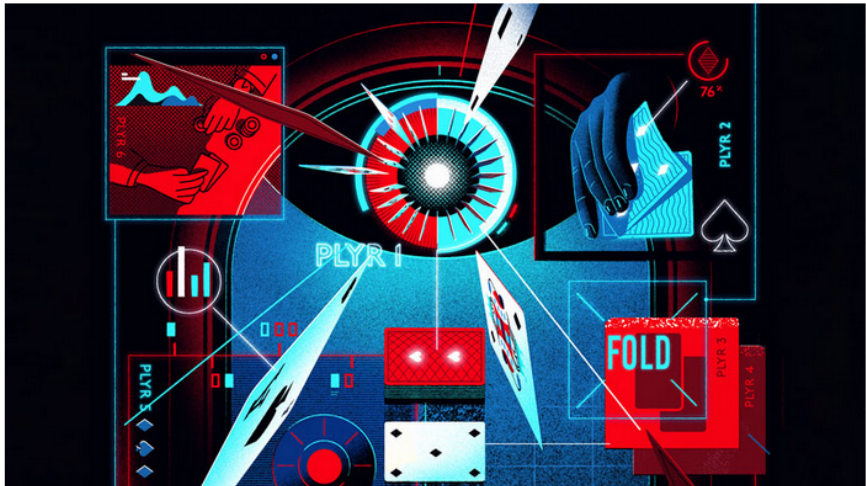
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Required fields are indicated by an asterisk (\*)

# Artificial intelligence masters multiplayer poker



JASON SOLO/THE JACKY WINTER GROUP

This year, an artificial intelligence (AI) program beat some of the world's best players in the most popular version of poker, no-limit Texas Hold 'em. The landmark result marks the first time AI has prevailed in a multiplayer contest in which players have only imperfect information about the state of the game.

AI has been trouncing humans in games at a spectacular rate. In 2007, computer scientists developed a program guaranteed not to lose at checkers. In 2016, another team developed an AI program that defeated the best humans at Go, a board game with vastly more configurations than checkers.

Poker presents a stiffer challenge, as players cannot see their opponents' cards and thus have limited information. In 2017, computer scientists developed an AI program unbeatable at a two-player version of Hold 'em—in which each player forms a hand from five cards laid face up on the table and two more each holds privately.

Now, AI has bested world-class players in the full multiplayer game, as computer scientists at Carnegie Mellon University in Pittsburgh, Pennsylvania, announced in August. By playing 1 trillion games against itself, their program, **Pluribus**, developed a basic strategy for various kinds of situations—say, playing for an inside straight. For each specific hand, it could also think through how the cards would likely play out. In 20,000 hands with six players it outperformed 15 top-level players, as measured by average winnings per hand.



# Real-world security applications (in Part 2)



*Milind Tambe's TEAMCORE group  
(USC → Harvard)*



## Airport security

Where should checkpoints, canine units, etc. be deployed?

## Federal Air Marshals

Which flights get a FAM?



## US Coast Guard

Which patrol routes should be followed?

## Wildlife Protection

Where to patrol to catch poachers or find their snares?





# Global Presence of Security Games Efforts



PHILIP TAMBE'S ARBOR AND ITS MANY ITERATIONS ARE USED AROUND THE WORLD TO PROTECT AGAINST TERRORISM, POACHERS, ILLEGAL FISHING AND OTHER THREATS.

## DEPLOYED

**Paris — PROTECT**  
 PROTECT (initially) was used by U.S. Coast Guard forces to optimize border patrol operations during the 2011 Paris, France and New York, New York terrorist attacks.

**PROTECT is employed at:**  
 Port of New York and New Jersey  
 Port of Seattle  
 Port of Los Angeles  
 Long Beach

**States Island Forre — PROTECT**  
 PROTECT provides protection to the States Island Forre, which is used as a test environment for PROTECT.

**Los Angeles International Airport — ARBOR**  
 ARBOR (initially) was used to optimize operations along the flight paths that lead into the airport.

**U.S. Air Traffic — ARBOR**  
 ARBOR (initially) was used to optimize operations along the flight paths that lead into the airport.



## SUCCESSFULLY TESTED

**City of Mexico (Near Chapala Channel, Texas) — ARBOR-USA**  
 ARBOR-USA (initially) was used to optimize operations for U.S. Coast Guard in its efforts to detect the illegal fishing of overboarded shark and other poachers. (2011)

**Los Angeles Water — PROTECT**  
 The Los Angeles Water Department, which LA Water uses to optimize operations, used PROTECT to intelligently coordinate and schedule water supply for its various facilities. (2011-2012)

**Malaysia — ARBOR**  
 ARBOR (initially) was used to optimize operations for the Malaysian National Parks to protect the integrity of forests, including forest trails, waterfalls and other forest areas, which are used for ecotourism and other activities. (2011)

## POSSIBLE FUTURE TEST SITES

Vietnam, Cambodia, Bangladesh, Indonesia — ARBOR

**Philippines — PAWS**  
 PAWS (initially) was used to optimize operations for the Philippine National Police (PNP) to detect and prevent illegal logging activities. (2011)

**Fishery Gap (FIC) Region in Indonesia**  
 FIC (initially) was used to optimize operations for the Indonesian National Police (INP) to detect and prevent illegal logging activities. (2011)



# Prediction markets

(Aug. 24, 2024)



Markets

Leaderboards

Support

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Presidency


Congress

Donald Trump

Kamala Harris

## Who will win the 2024 US presidential election?

Contract	Latest Yes Price	Best Offer	Best Offer
 Kamala Harris	55¢ <small>NC</small>	55¢	<input type="button" value="Buy Yes"/> <input type="button" value="Buy No"/> 46¢
 Donald Trump	49¢ <small>NC</small>	49¢	<input type="button" value="Buy Yes"/> <input type="button" value="Buy No"/> 52¢
 Nikki Haley	2¢ <small>NC</small>	2¢	<input type="button" value="Buy Yes"/> <input type="button" value="Buy No"/> N/A
 Ron DeSantis	1¢ <small>NC</small>	1¢	<input type="button" value="Buy Yes"/> <input type="button" value="Buy No"/> N/A
 Joe Biden	1¢ <small>NC</small>	1¢	<input type="button" value="Buy Yes"/> <input type="button" value="Buy No"/> N/A

5 More Contracts 

# Prediction markets

(Aug. 24, 2024)



Markets

Leaderboards

Support

Login

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Presidency

Congress

Donald Trump

Kamala Harris

## PredictIt Announcements

Visit the [PredictIt Status Page](#) for real-time updates

### Notice to Traders

Victoria University of Wellington (“VUW”) has [responded](#) to a [March 2, 2023 preliminary decision](#) from the Commodity Futures Trading Commission (“CFTC”) to withdraw the No Action Letter under which PredictIt operates. The March 2 letter provided an opportunity for VUW, PredictIt’s operator to contest the Commission’s arguments.









VUW issued the following statement in connection with their response to the CFTC:

*“While Te Herenga Waka—Victoria University of Wellington respects the CFTC’s authority as a regulator, it strongly disagrees with the version of events put forward by the Commission in its recent letter proposing to withdraw the “No Action” letter. The University has provided a detailed and robust response to the Commission in relation to all of the points raised. In particular, the University believes it has been transparent and has engaged in good faith regarding the operation of PredictIt and how this has changed over time, including the role of Aristotle International, Inc. The University has made no money from PredictIt, with the only payment being \$US2,000 per month to the University’s subsidiary Wellington UniVentures, to offset costs. The University’s goal in relation to the PredictIt platform has been purely to support its development as a research and educational tool for the international research community of which we are a part.”*

The CFTC’s March 2 letter withdrew an earlier August 4, 2022 withdrawal decision that has been [temporarily enjoined](#). PredictIt traders, university educators, and market servicer, Aristotle International Inc. are challenging the CFTC’s efforts to close PredictIt in a case that is currently pending before that court. VUW is not a party to that legal action.

PredictIt traders may continue to hold and trade existing contracts pending further consideration by the Fifth Circuit Court of Appeals and the CFTC. There remains the possibility that a judicial or administrative decision may require early termination of those contracts. We have no certainty as to the timing of any such decision.

# Financial securities (in Part 1)

- Tomorrow there must be one of   
- Agent 1 offers \$5 for a security that pays off \$10 if  or 
- Agent 2 offers \$8 for a security that pays off \$10 if  or 
- Agent 3 offers \$6 for a security that pays off \$10 if 
- Can we accept some of these at offers **at no risk?**

# How to incentivize a weather forecaster (in Part 3)

$$P(\text{☀}) = .5$$

$$P(\text{☁☔}) = .3$$

$$P(\text{☁⚡}) = .2$$

$$P(\text{☀}) = .8$$

$$P(\text{☁☔}) = .1$$

$$P(\text{☁⚡}) = .1$$



- Forecaster's bonus can depend on
  - Prediction
  - Actual weather on predicted day
- Reporting true beliefs should maximize expected bonus



# Sponsored search / ad auctions (in Part 3)

The screenshot shows a Google search results page for the query "prediction markets proper scoring". The search bar at the top contains the text "prediction markets proper scoring" and a magnifying glass icon. Below the search bar, there are navigation tabs for "All", "News", "Images", "Videos", "Shopping", "More", "Settings", and "Tools". The search results are displayed below, starting with "About 714,000 results (0.43 seconds)". The first result is a sponsored advertisement for "A Political Prediction Market - Join PredictIt Today - predictit.org". This ad is highlighted with a black rectangular box. The ad text includes "Ad www.predictit.org/ ▾", "Buy and sell shares on political outcomes with PredictIt. Let's Play Politics!", "Predict & Trade · Safe and Secure · Unique Platform · Easy to Use", and "About · Markets · Markets Analysis · Blog". Below the ad, there are several organic search results, each with a green checkmark icon to its right. The first organic result is "Scholarly articles for prediction markets proper scoring" with a sub-heading "Prediction markets: Does money matter? - Servan-Schreiber - Cited by 337". The second organic result is "[PDF] Geometric Characterization of Proper Scoring Rules and Hanson ... - ..." with a sub-heading "www.mit.edu/~pengshi/papers/2009-05-csurf-geometry.pdf ▾". The third organic result is "[PDF] Proper Scoring Rules with Additional Properties - MIT" with a sub-heading "www.mit.edu/~pengshi/papers/2009-04-psr-characterization.pdf ▾". The fourth organic result is "[PDF] Logarithmic Market Scoring Rules for Modular ... - Robin Hanson" with a sub-heading "hanson.gmu.edu/mktscore.pdf ▾".

- Choice of ads (if any) to show determined by:
  - Advertiser bid
  - Predicted likelihood of click