

# **APPLIED MECHANISM DESIGN FOR SOCIAL GOOD**

**JOHN P DICKERSON**

**Lecture #1 – 01/26/2021**

**CMSC828M**  
**Tuesdays & Thursdays**  
**2:00pm – 3:15pm**



**COMPUTER SCIENCE**  
UNIVERSITY OF MARYLAND

Markets come in many forms ...

... some of which don't conform to conventional notions of markets ...

... and some in which money may play little or no role.

– excerpt from *Who Gets What – and Why*

# AESTHETICALLY-DISPLEASING ONE-SLIDE COURSE SUMMARY

Mechanism design is a field in economics and game theory that takes an engineering approach to designing economic mechanisms or incentives, toward desired objectives, in strategic settings, where players act rationally.

AKA “reverse game theory” – we’re designing the rules of the game, not figuring out how to play it.

**This course:** can we design mechanisms for societal problems that perform well in practice, are computationally tractable, and whose workings and results are understandable by humans?

More info: <https://marketdesign.github.io/>

# PREREQUISITE KNOWLEDGE

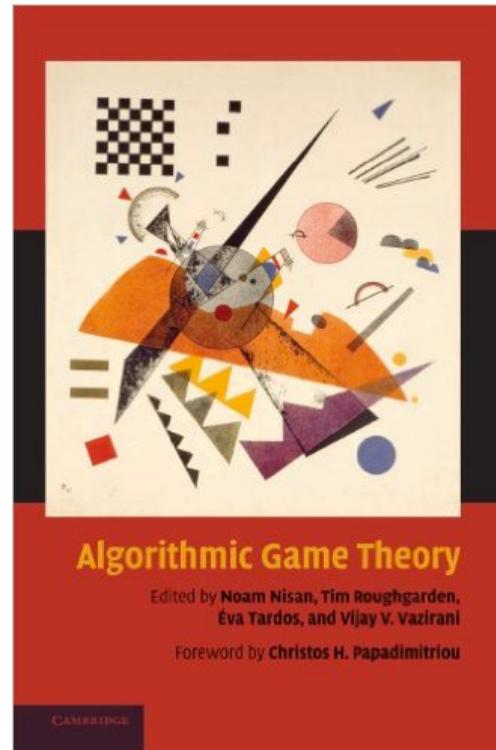
Aimed at **Ph.D. students** – but likely accessible to others with mathematical maturity and interest.

**Assuming:**

- Basic CS undergrad knowledge of theory (correctness proofs, NP-hardness, impossibility results)
- Basic CS/Math undergrad knowledge of optimization
  - Convex optimization, LPs, IPs – one lecture of primer, too
- Basic CS/Math undergrad knowledge of statistics and probability
- Ability to consume scientific papers (CS, Econ, OR)

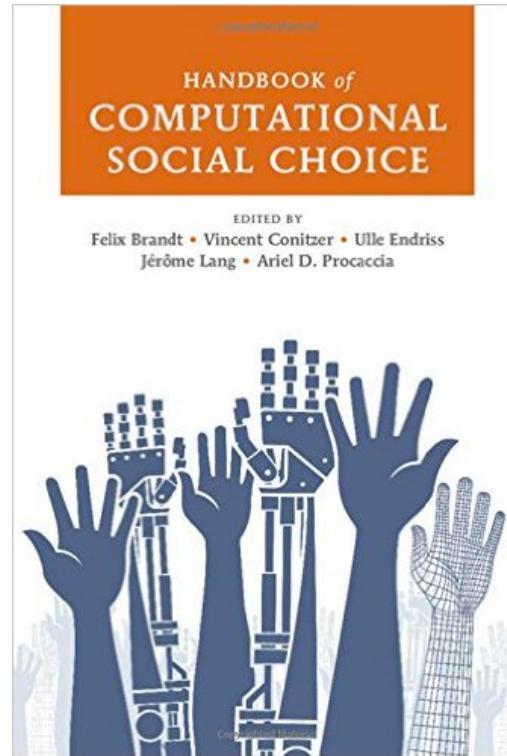
**All of this can be learned on the fly! Recommended books ...**

# BOOK #1: “THE AGT BOOK”



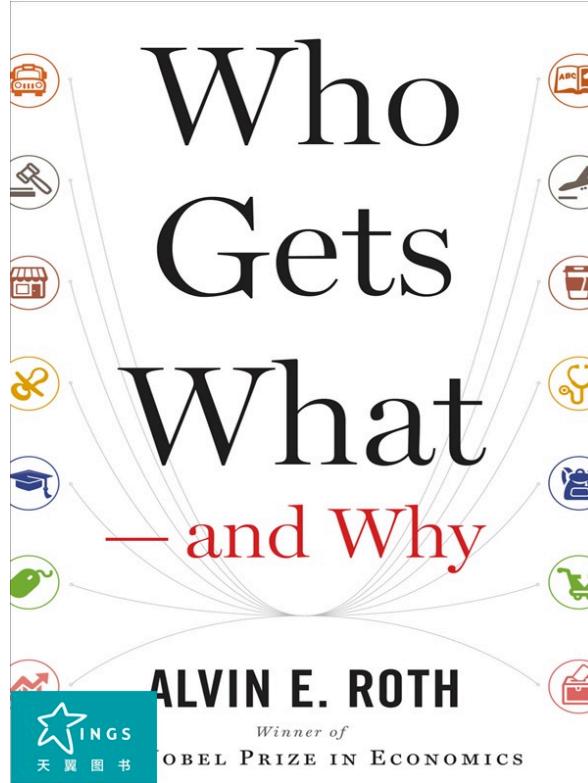
It's **free** online! Check the course webpage.

# BOOK #2: “CSC HANDBOOK”



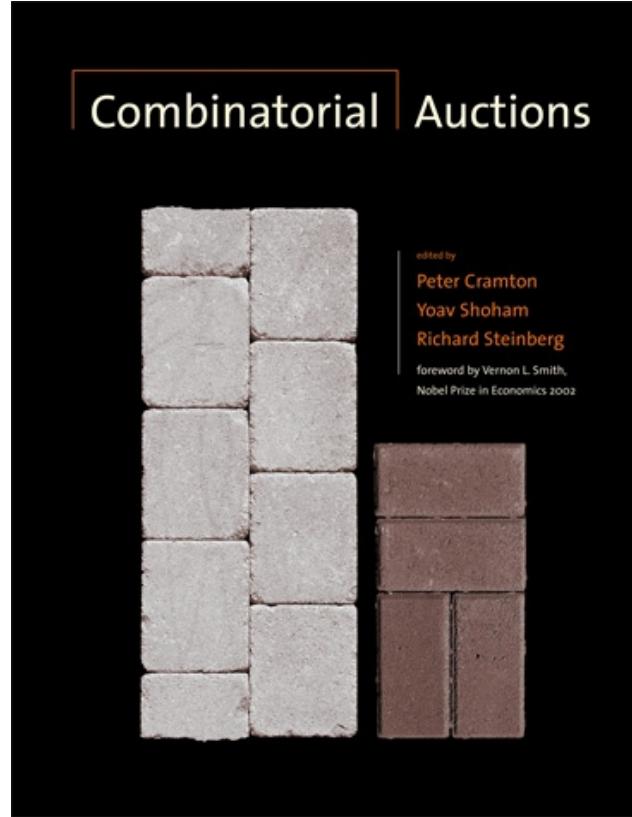
It's **free** online! Check the course webpage.

# BOOK #3: “MATCHING MARKET DESIGN”



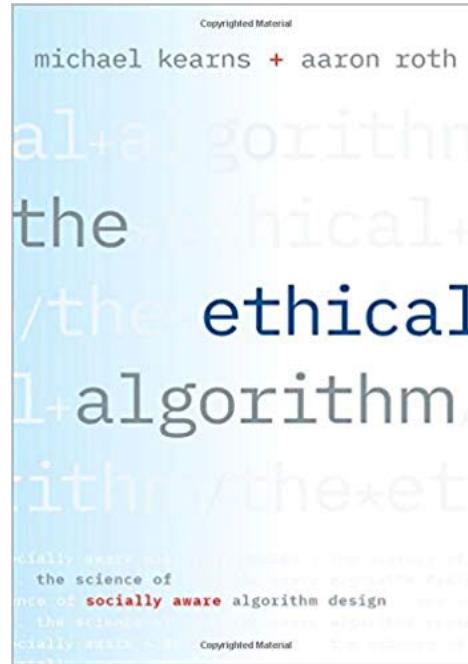
It's **not free** online! UMD has one copy.

# BOOK #4: “COMBINATORIAL AUCTIONS”



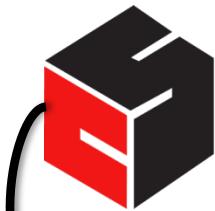
It's **free** online! Check the course webpage.

# BOOK #5: “THE ETHICAL ALGORITHM”



It's **not free** online! UMD might have a copy?

# SINGLE-SLIDE VERSION OF JOHN

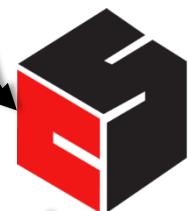


**COMPUTER SCIENCE**  
UNIVERSITY OF MARYLAND

2004 – 2008

**Carnegie Mellon University**  
School of Computer Science

2010 – 2016



**COMPUTER SCIENCE**  
UNIVERSITY OF MARYLAND

2016 – ∞

**facebook research** 2018 – 2020

{ Advisory roles in UMD alumni's startups } 2017 – now

{ Advisory role to a US regulatory agency } Late 2019 +



UNITED NETWORK FOR ORGAN SHARING



**OPTIMIZED**  
MARKETS



**THE DIAN FOSSEY  
GORILLA FUND®  
INTERNATIONAL**

# WHO ARE YOU?

Area?

Interest in this course?

Goals in life? And goals  
for this course?

PhD/MSc/BSc?

Background in: CS, game  
theory, mechanism  
design, HCI?

Advisor?



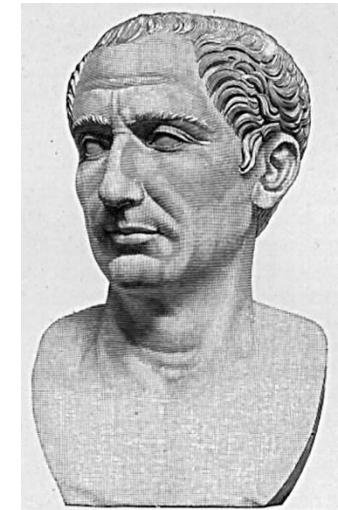
**I'm probably going to use Slack instead of Piazza – thoughts?**

# COURSE STRUCTURE

**First 5-6 lectures: primers in GT/MD and optimization**

**Next 23 lectures: theory + application areas**

- Security games
- Healthcare markets (organ allocation, financing R&D)
- Food allocation
- Learning for mechanism design
- Combinatorial assignment (bidding on courses)
- Incentive auctions (FCC spectrum allocation)
- Fair Division (allocating rooms to schools)
- Voting
- School choice (assigning kids to schools)
- Prediction markets
- 2-3 lectures of “floating topics” – ideas?



Ambitious ...

# GRADE #1: PROJECT

Students will complete a **semester-long course project** on something related to market and mechanism design.

- Individual or small group
- 100% theory, 100% applied, or convex combination

**Goal:** create something **publishable!**

Important dates:

- Project proposals will be due in early March
- ~~Project presentations will be during the last 2-3 lectures~~
- Project writeups—formatted as, say, a NeurIPS conference paper or similar—will be due by the exam date for this course (Monday, May 17 at 10:30AM).

# A FEW PROJECTS FROM RECENT YEARS ...

**Some projects from recent years that have been published:**

- Faez Ahmed: diverse b-matching (IJCAI-17, [arXiv](#))
- Neal Gupta: competition in dynamic matching markets (IJCAI-18)
- Duncan McElfresh: a new fairness metric for kidney exchange (AAAI-18, [arXiv](#))
- Elissa Redmiles: behavioral economics and two-factor authentication (EC-18 & CCS-18, [arXiv](#))
- Candice Schumann: diversity and multi-armed bandits (AAMAS-19 & NeurIPS-19, [arXiv](#) & [arXiv](#))
- Many projects in the works from last year / under submission / I'm sure many that I don't know about!

# **GRADE #2: PRESENT A PAPER (ON ZOOM/YOUTUBE/ETC)**

**Students will pick a paper (or papers, or chapter, or topic, or ...) to present, and will create a small video recording (let's say 15 minutes, but this is flexible) that we can post online!**

- Good for you!
- Good for your fellow classmates!

**Check out the course webpage for topics**

- Also: feel free to suggest a topic you like!

**Logistics:**

- We'll figure this out in second week



# GRADE #3: TAKE-HOME EXAMS

The majority of students want this to be an MSc/PhD qualifier

- So this course is an **AI qualifier** for CMSC grad students

**What this means:**

- "... the courses' written exam(s) which must account for at least 30% of the grade." – *UMD graduate handbook*

**Implementation:**

- One take-home **midterm**; 24 hours to do it
- One take-home **final**; 48 hours to do it
- I'll let you pick when you take exams (within reason; see site)



# **CLASS PARTICIPATION**

**Please please please please please read the paper(s) before coming to class!**

- I want to speak **with** you, not at you ...
- Also, looking forward to your video presentations!

**Participate on Slack, help brainstorm project ideas, ask questions in class, answer questions in class, etc.**

# GRADE BREAKDOWN | QUALIFIER APPROVAL

**55% course project:**

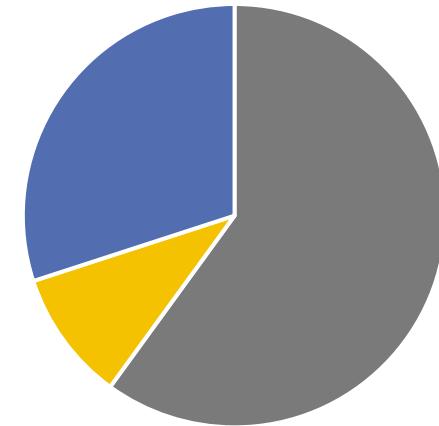
- **5% project proposal (early March)**
- **5% project checkup (April)**
- **45% course project writeup (mid-May)**

**15% presenting/summarizing a paper**

**30% examinations:**

- **Better of 10%/20% or 15%/15% midterm/final**

Your Grade



= A+

■ Project ■ Paper Present ■ Examinations

# **IMPORTANT WALLS OF TEXT**

Common  
Sense!

# ANTI-HARASSMENT

(Adapted from ACM SIGCOMM's policies)

The open exchange of ideas and the freedom of thought and expression are central to our aims and goals. These require an environment that recognizes the inherent worth of every person and group, that fosters dignity, understanding, and mutual respect, and that embraces diversity. For these reasons, we are dedicated to providing a harassment-free experience for participants in (and out) of this class.

**Harassment** is unwelcome or hostile behavior, including speech that intimidates, creates discomfort, or interferes with a person's participation or opportunity for participation, in a conference, event or program.

Common  
Sense!

# ACADEMIC INTEGRITY

(Text unironically stolen from Hal Daumé III)

Any assignment or exam that is handed in must be your own work (unless otherwise stated). However, talking with one another to understand the material better is strongly encouraged. Recognizing the distinction between cheating and cooperation is very important. If you copy someone else's solution, you are cheating. If you let someone else copy your solution, you are cheating (this includes *posting solutions online in a public place*). If someone dictates a solution to you, you are cheating.

Everything you hand in must be in your own words, and based on your own understanding of the solution. If someone helps you understand the problem during a high-level discussion, you are not cheating. We strongly encourage students to help one another understand the material presented in class, in the book, and general issues relevant to the assignments. When taking an exam, you must work independently. Any collaboration during an exam will be considered cheating. Any student who is caught cheating will be given an F in the course and referred to the University Office of Student Conduct. Please don't take that chance – if you're having trouble understanding the material, please let me know and I will be more than happy to help.

# **EXAMPLE APPLICATION AREAS**

***MANY OF WHICH WE'LL COVER IN FUTURE CLASSES***

# EXAMPLE: MATCHING MARKETS

In matching problems, prices do not do all – or any – of the work

Agents are **paired** with other (groups of) agents, transactions, or contracts

- Workers to firms
- Children to schools
- Residents to hospitals
- Patients to deceased donors
- Advertisements to viewers
- Riders to rideshare drivers



# UNCERTAINTY IN MATCHING MARKETS

- Does a matched edge truly exist?
- How valuable is a match?
- Will a better match arrive in the future?

**Upwork™**  
formerly oDesk



# COMPETITION IN MATCHING MARKETS

Rival matching markets compete over the same agents

- How does this affect global social welfare?
- How to differentiate?



# CADENCE OF MATCHING MARKETS

How quickly do new edges form?

How frequently does a market clear?

Is clearing centralized or decentralized?

Can agents reenter the market?



# EXAMPLE: RESIDENT-HOSPITAL ASSIGNMENT

1940s: decentralized resident-hospital matching

- Market “unraveled”, offers came earlier and earlier, quality of matches decreased

1950s: NRMP introduces hospital-proposing **deferred acceptance algorithm**

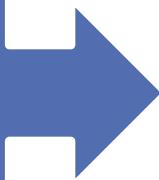
1970s: couples increasingly don't use NRMP

1998: matching with couple constraints

- (**Stable matching** may not exist anymore ...)

Take-home message

Looks like: M.D.s aren't the only type of doctor who help people!



# EXAMPLE: COMBINATORIAL COURSE ALLOCATION

[IMAGES FROM BUDISH ET AL. WORKING PAPER 2016]

## BIDDING

### COURSE MATCH

#### UTILITY SELECTION

Dept	Instructor	Day	Time	Cu	Qtr	Show Positive
Course	Detail			Credit	Qtr	Utility
MGMT691408 LGST806408 OPIM691408	NEGOTIATIONS DIAMOND S R 3:00 PM - 6:00 PM (8/27/14 - 12/9/14) This course CANNOT be taken Pass/Fail.	1.00	S	80	LGST806408	
MGMT7721001	CORP DEV: MERG & ACQUIS FELDMAN E MW 9:00 AM - 10:30 AM (8/27/14 - 12/9/14) This course CANNOT be taken Pass/Fail.	1.00	S	80		
MGMT7721002	CORP DEV: MERG & ACQUIS FELDMAN E MW 12:00 PM - 1:30 PM (8/27/14 - 12/9/14) This course CANNOT be taken Pass/Fail.	1.00	S	80		
OPIM673002	GLOBAL SUPPLY CHAIN MGMT FISHER M TR 1:30 PM - 3:00 PM (10/18/14 - 12/9/14)	0.50	2	85		
LGST611002	RESP IN GLOBAL MGMT PETKOSKI D M 3:00 PM - 6:00 PM (10/20/14 - 12/4/14) This course CANNOT be taken Pass/Fail.	0.50	2	90		
LGST612003	RESP IN PROFL SERVICES ZARING D MW 10:30 AM - 12:00 PM (8/27/14 - 10/8/14) This course CANNOT be taken Pass/Fail.	0.50	1	90		
MGMT778001	GOV & MGMT. OF CHIN FRMS ZHAO M TR 10:30 AM - 12:00 PM (8/27/14 - 12/9/14)	1.00	S	90		
OPIM614001	INNOVATION TERWIESCH C	0.50	1	90		

Search:

My Settings

My Utility Distribution

My Adjustments

My Top Schedules

“Funny money” used for bidding

## DYNAMIC EXCLUSIONS

COURSE MATCH

Course Match closing: Mon Aug 17 12:00 PM

FALL 2015 MBA Courses

MY TOP SCHEDULES

Schedule Value: 392.5

Sun	Mon	Tue	Wed	Thu	Fri	Sat
SAM						
10AM						
11AM			FNCS T23001	FNCS T23001		
12PM		ACCT T23001	ACCT T23002			
1PM		REAL T23001	REAL T23002			
2PM		REAL T23041	REAL T23041			
3PM						
4PM						
5PM						
6PM						
7PM						
8PM						

Fixed Core / Preferred

Schedule Value: 382.5

Sun	Mon	Tue	Wed	Thu	Fri	Sat
SAM						
10AM						
11AM			FNCS T23001	FNCS T23001		
12PM		LGST T23041	LGST T23041			
1PM		REAL T23041	REAL T23041			
2PM		REAL T23041	REAL T23041			
3PM						
4PM						
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7PM						
8PM						

Fixed Core / Preferred

Schedule Value: 345

Sun	Mon	Tue	Wed	Thu	Fri	Sat
SAM						
10AM						
11AM			FNCS T23001	FNCS T23001		
12PM		ACCT T23001	ACCT T23002			
1PM		REAL T23041	REAL T23041			
2PM		REAL T23041	REAL T23041			
3PM						
4PM						
5PM						
6PM						
7PM						
8PM						

Fixed Core / Preferred

Schedule Value: 342.5

Sun	Mon	Tue	Wed	Thu	Fri	Sat
SAM						
10AM						
11AM			FNCS T23001	FNCS T23001		
12PM		LGST T23041	LGST T23041			
1PM		REAL T23041	REAL T23041			
2PM		REAL T23041	REAL T23041			
3PM						
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7PM						
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Fixed Core / Preferred

Schedule Value: 324.5

Sun	Mon	Tue	Wed	Thu	Fri	Sat
SAM						
10AM						
11AM			FNCS T23001	FNCS T23001		
12PM		ACCT T23001	ACCT T23002			
1PM		REAL T23041	REAL T23041			
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Fixed Core / Preferred

Schedule Value: 322.5

Sun	Mon	Tue	Wed	Thu	Fri	Sat
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8PM						

Fixed Core / Preferred

28

# EXAMPLE: VOTING

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

{Hillary Clinton, The Donald, Gary Johnson}

Each voter ranks the candidates:

$v_1$ : The Donald > HRC > Gary Johnson

$v_2$ : HRC > Gary Johnson > The Donald

...

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

Can we choose a **voting rule** – that is, a function that takes preference profiles and returns a winning alternative – that:

- “Behaves well”
- Isn’t manipulable by strategic agents



# EXAMPLE: FAIR ALLOCATION

Divisible goods:

- Splitting land, cutting cake

Indivisible goods:

- Splitting up assets after divorce (house, cars, pets)



<http://spliddit.org>

**A chief concern:** defining and guaranteeing the fairness of the final allocation

An allocation is **envy free** if each player values her own allocated set of goods at least as highly as any other player's allocated set

*When do envy-free allocations exist? How can we compute them? What can we do when they don't exist?*

# EXAMPLE: FOOD BANK ALLOCATION

Food banks supply nutrition to the needy for free or at a reduced cost

- Much of that food comes from donors (e.g. supermarkets, manufacturers)

Distribution is overseen by a large non-profit organization, Feeding America

- Previously: **centralized allocation** based on perceived need of food banks
- Currently: food banks bid in an **online auction** using a fake currency for loads of donated food.



# EXAMPLE: SECURITY GAMES

**Where should we deploy security forces (checkpoints, cop cars, dogs, troops), assuming a rational adversary who can observe our deployment strategy?**

- Checkpoints at airports
- Patrol routes on the water on the borders
- Anti-poacher teams near big game

How do we compute these strategies?

What if the adversary isn't rational?

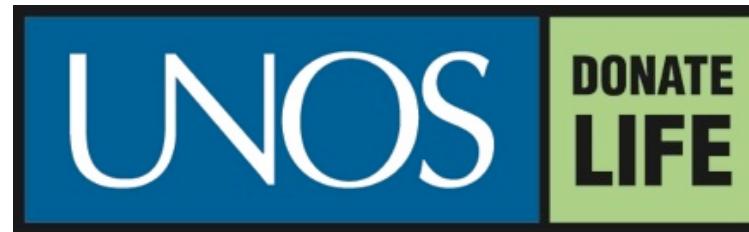
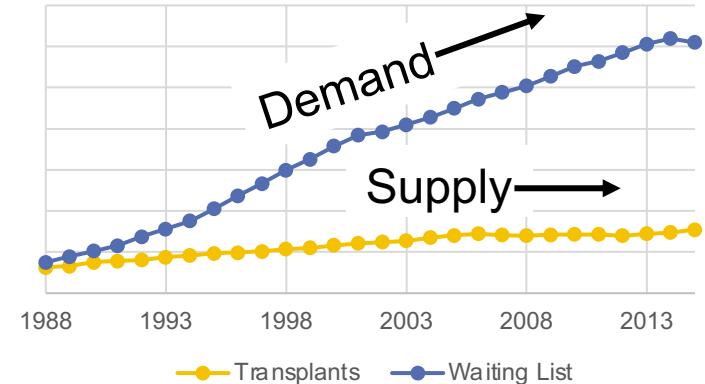
Rangers Use Artificial Intelligence to Fight Poachers

Emerging technology may help wildlife officials beat back traffickers.



# EXAMPLE: KIDNEY TRANSPLANTATION

- US waitlist: over **100,000**
  - 36,157 added in 2014
- **4,537 people died while waiting**
- **11,559 people received a kidney from the deceased donor waitlist**
- **5,283 people received a kidney from a living donor**
  - Some through **kidney exchanges** [Roth et al. 2004]
  - (We work extensively with the UNOS exchange.)



# EXAMPLE: DECEASED-DONOR ALLOCATION

**Online bipartite matching problem:**

- Set of patients is known (roughly) in advance
- Organs arrive and must be dispatched **quickly**

**Constraints:**

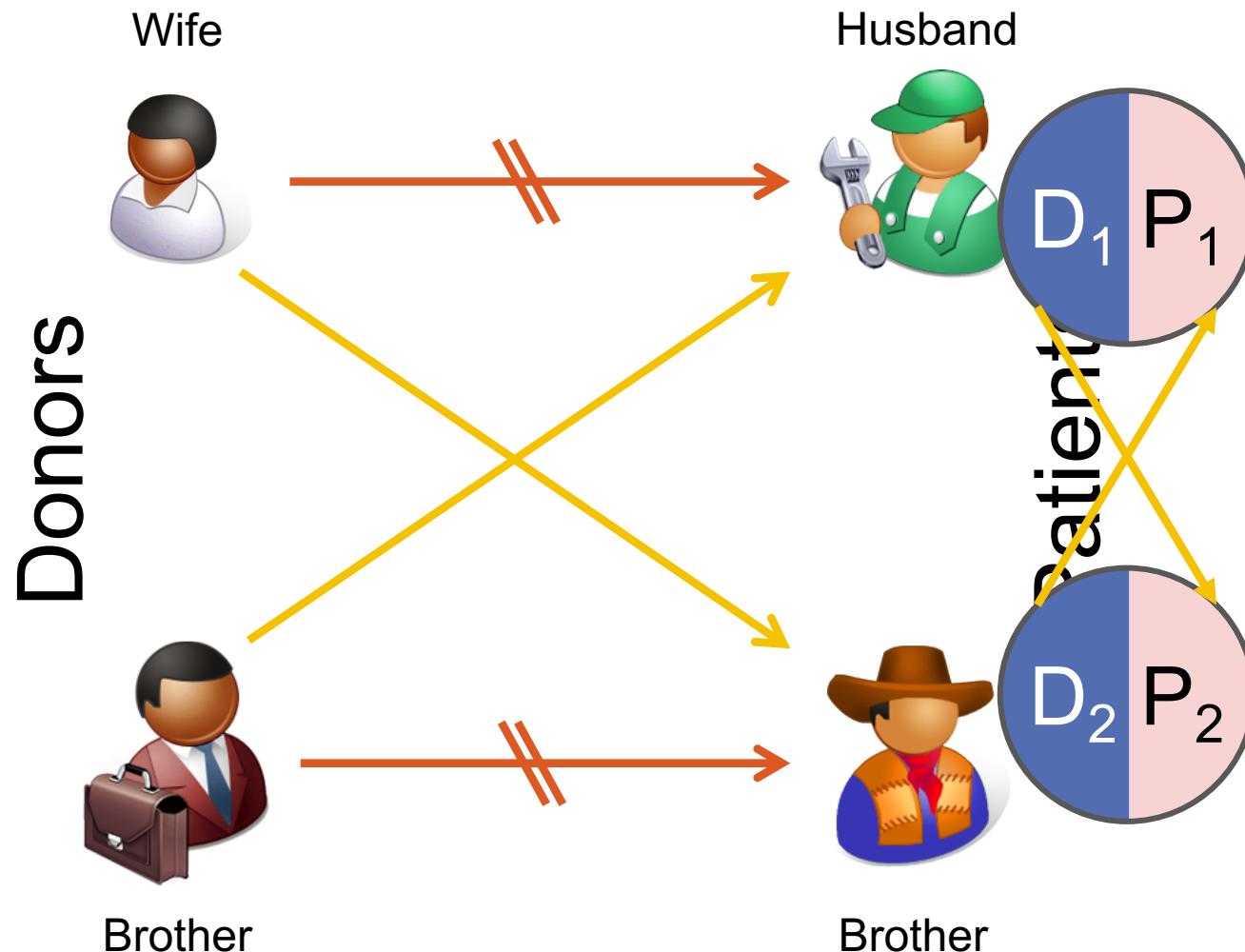
- Locality: organs only stay good for 24 hours
- Blood type, tissue type, etc.

**Who gets the organ? Prioritization based on:**

- Age?
- QALY maximization?
- Quality of match?
- Time on the waiting list?



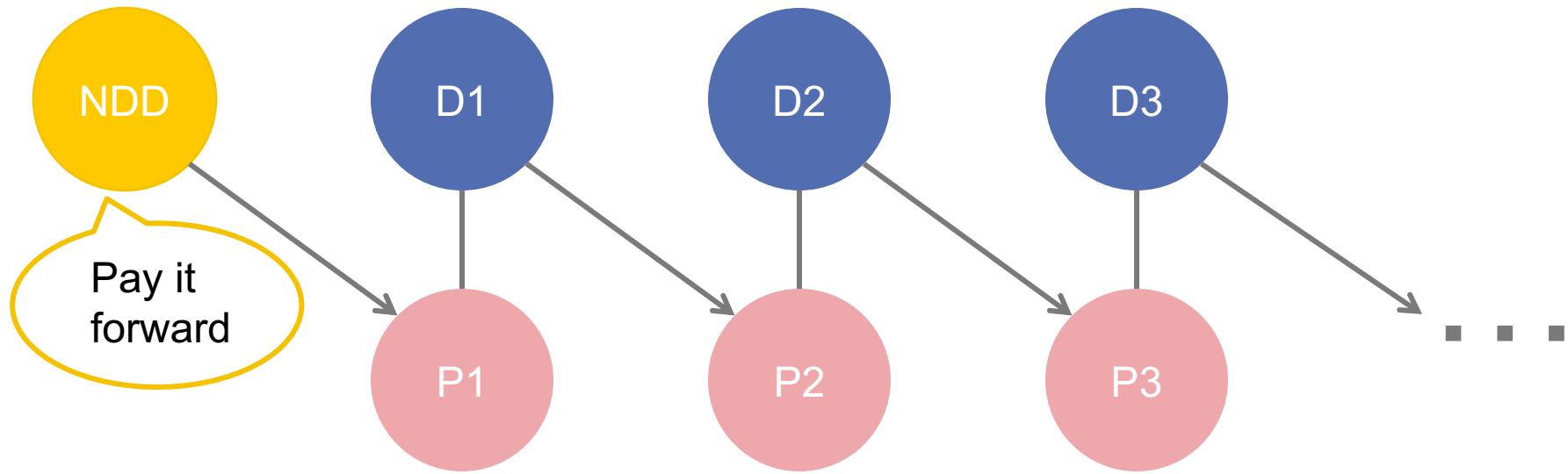
# EXAMPLE: KIDNEY EXCHANGE



(2- and 3-cycles, all surgeries performed simultaneously)

# NON-DIRECTED DONORS & CHAINS

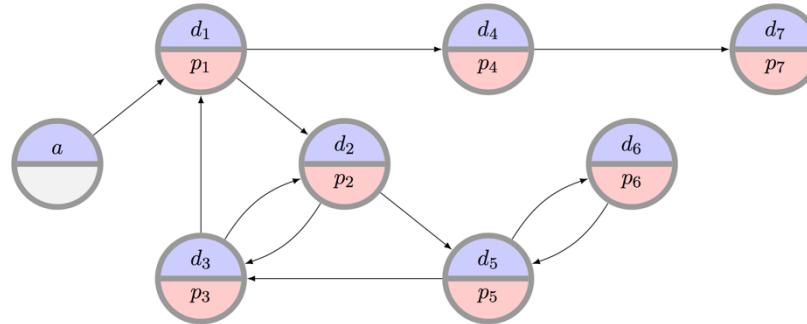
[Rees et al. 2009]



*Not executed simultaneously, so no length cap required based on logistic concerns ...*

**... but in practice edges fail, so some finite cap is used!**

# EXAMPLE: KIDNEY EXCHANGE



What is the “best” matching objective?

- Maximize matches right now or over time?
- Maximize transplants or matches?
- Prioritization schemes (i.e. fairness)?
- Modeling choices?
- Incentives? Ethics? Legality?

Can we design a mechanism that **performs well in practice**, is **computationally tractable**, and is **understandable by humans**?

# **TECHNIQUES WE'LL USE**

*(NEXT THREE LECTURES WILL COVER THESE,  
IN THE CONTEXT OF MECHANISM DESIGN)*

# COMBINATORIAL OPTIMIZATION

Combinatorial optimization lets us select the “best element” from a set of elements.

Some PTIME problems:

- Some forms of matching
- 2-player zero-sum Nash
- Compact LPs

Some PPAD- or NP-hard problems:

- More complex forms of matching
- Many equilibrium computations

Some > NP-hard problems:

- Randomizing over a set of all feasible  $X$ , where all feasible  $X$  must be enumerated (#P-complete)

# C.O. FOR KIDNEY EXCHANGE: THE EDGE FORMULATION

[Abraham et al. 2007]

Binary variable  $x_{ij}$  for each edge from  $i$  to  $j$

**Maximize**

$$u(M) = \sum w_{ij} x_{ij} \quad \text{Flow constraint}$$

**Subject to**

$$\sum_j x_{ij} = \sum_j x_{ji}$$

for each vertex  $i$

$$\sum_j x_{ij} \leq 1$$

for each vertex  $i$

$$\sum_{1 \leq k \leq L} x_{i(k)i(k+1)} \leq L-1$$

for paths  $i(1)\dots i(L+1)$

(no path of length  $L$  that doesn't end where it started – cycle cap)

# C.O. FOR KIDNEY EXCHANGE: THE CYCLE FORMULATION

[Roth et al. 2004, 2005,  
Abraham et al. 2007]

Binary variable  $x_c$  for each feasible cycle or chain  $c$

**Maximize**

$$u(M) = \sum w_c x_c$$

**Subject to**

$$\sum_{c : i \text{ in } c} x_c \leq 1 \text{ for each vertex } i$$

# C.O. FOR KIDNEY EXCHANGE: COMPARISON

Tradeoffs in number of variables, constraints

- IP #1:  $O(|E|^L)$  constraints vs.  $O(|V|)$  for IP #2
- IP #1:  $O(|V|^2)$  variables vs.  $O(|V|^L)$  for IP #2

**IP #2's relaxation is weakly tighter than #1's. Quick intuition in one direction:**

- Take a length  $L+1$  cycle. #2's LP relaxation is 0.
- #1's LP relaxation is  $(L+1)/2$  – with  $\frac{1}{2}$  on each edge

**Recent work focuses on balancing tight LP relaxations and model size** [Constantino et al. 2013, Glorie et al. 2014, Klimentova et al. 2014, Alvelos et al. 2015, Anderson et al. 2015, Mak-Hau 2015, Manlove&O'Malley 2015, Plaut et al. 2016, ...]:

- We will discuss (9/29) new compact formulations, some with tightest relaxations known, all amenable to failure-aware matching

# GAME THEORY & MECHANISM DESIGN

We assume participants in our mechanisms are:

- Selfish utility maximizers
- Rational (typically – sometimes relaxed)

Game theory & M.D. give us the language to describe desirable properties of mechanisms:

- Incentive compatibility
- Individual rationality
- Efficiency

A STRANGE GAME.  
THE ONLY WINNING MOVE IS  
NOT TO PLAY.

HOW ABOUT A NICE GAME OF CHESS?

# MACHINE LEARNING

Predicting supply and demand

Computing optimal matching/allocation policies:

- MDPs
- RL
- POMDPs, if you're feeling brave/masochistic

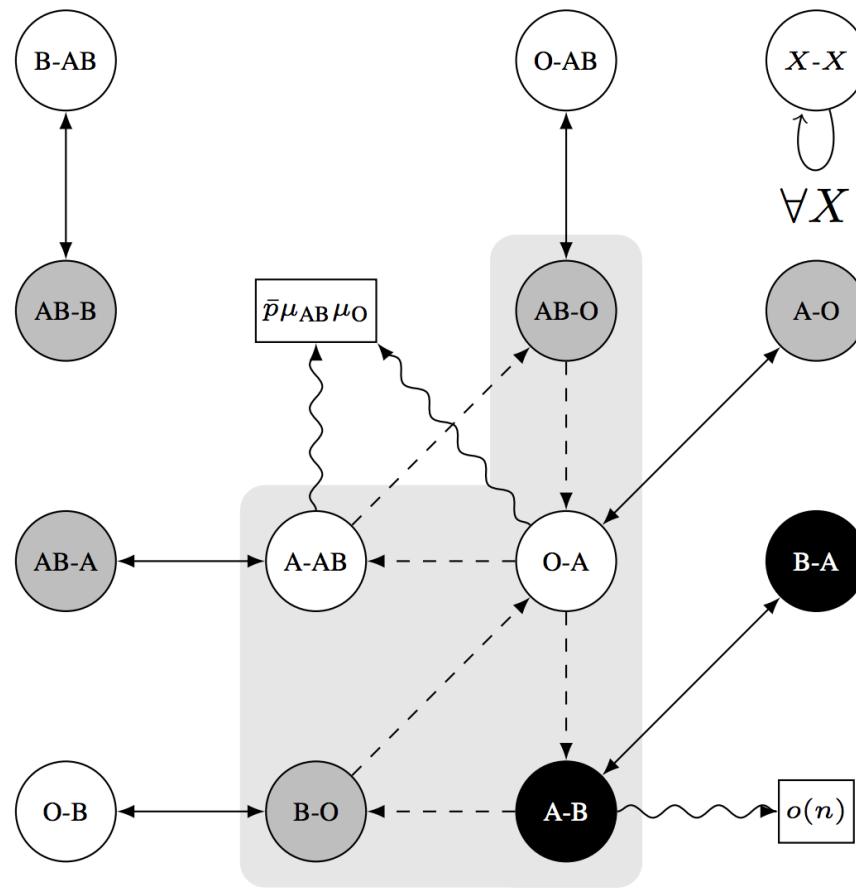
**Aside: recent work looks at fairness and discrimination in machine learning – could be an interesting project.**

- “... when a search was performed on a name that was “racially associated” with the black community, the results were much more likely to be accompanied by an ad suggesting that the person had a criminal record—regardless of whether or not they did.”

**CAN COMPUTERS BE RACIST?**

*Big data, the internet, and the law*

# RANDOM GRAPH THEORY



# **NEXT CLASS: GAME THEORY PRIMER**