Modern Organ Exchanges:
Designs, Algorithms, and Opportunities

OR

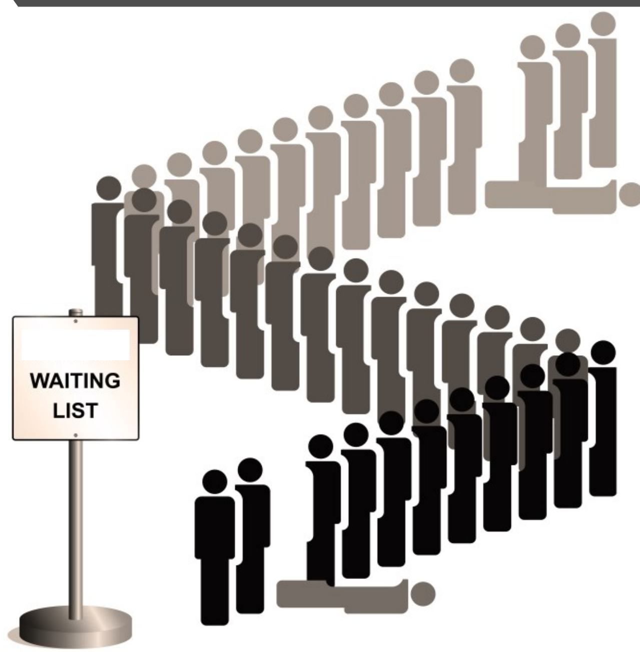
AI Making Life-and-Death Decisions about Humans

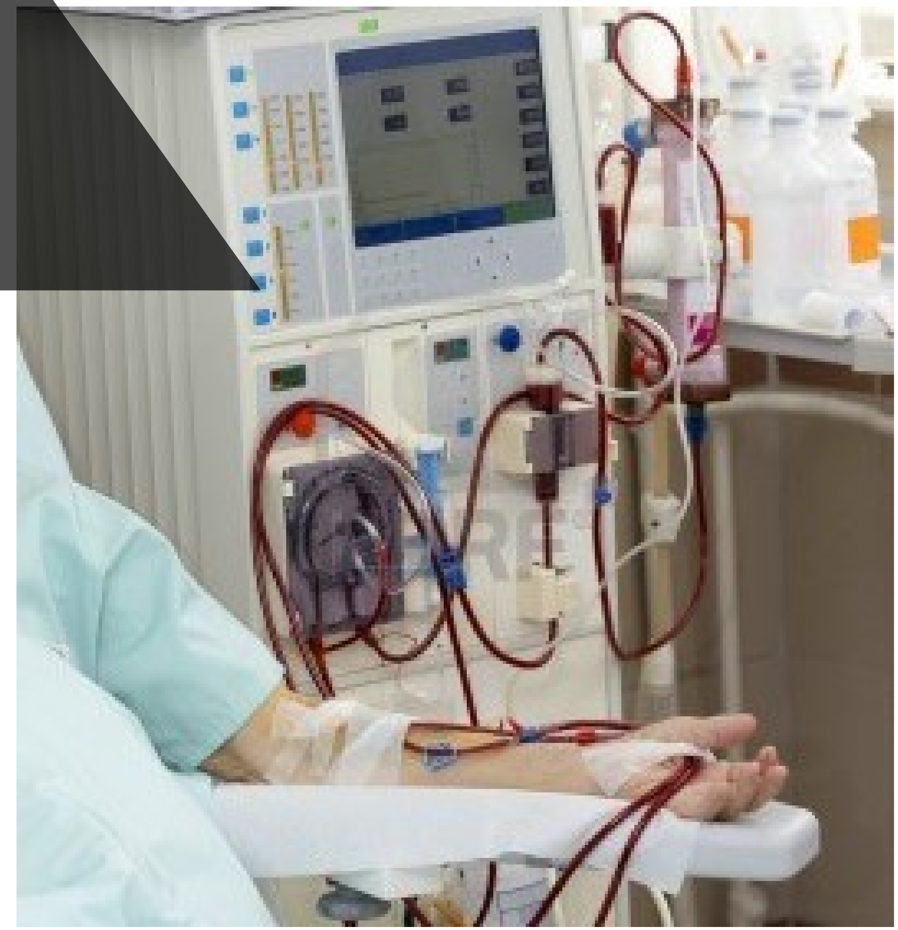
OR

Longest-Running Application of AI for Good?

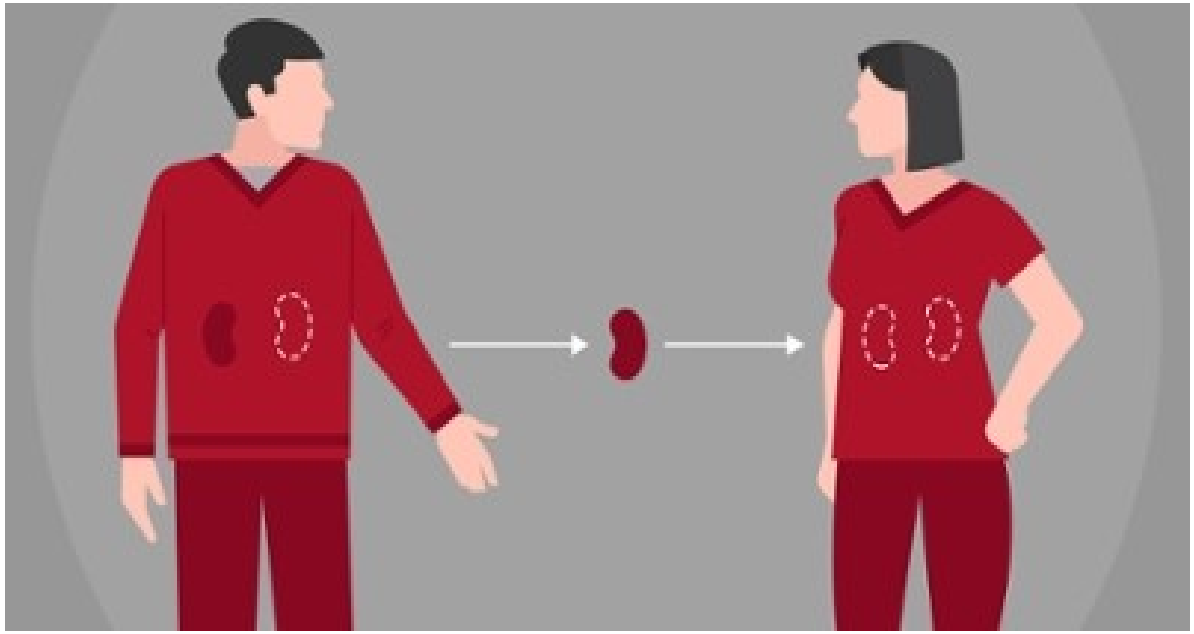
Tuomas Sandholm

90,000+
Waiting for a kidney in the U.S.





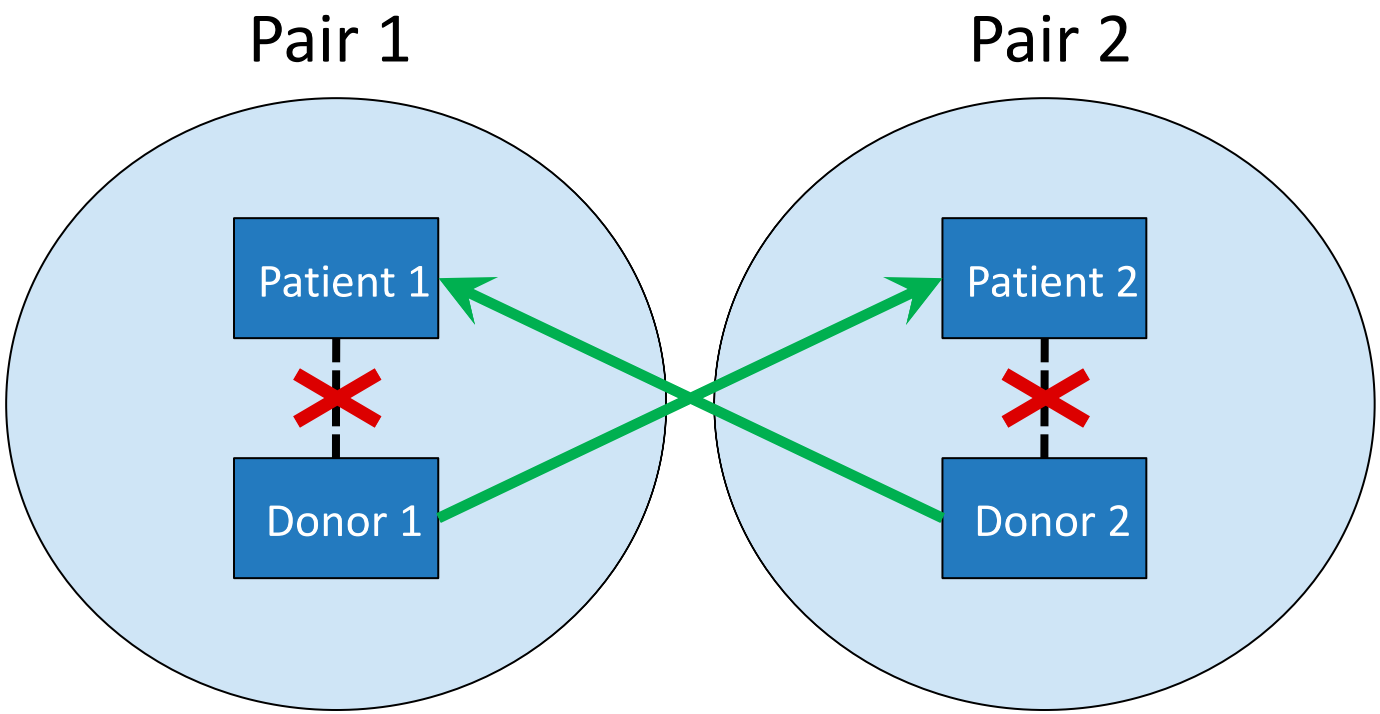
Live donation

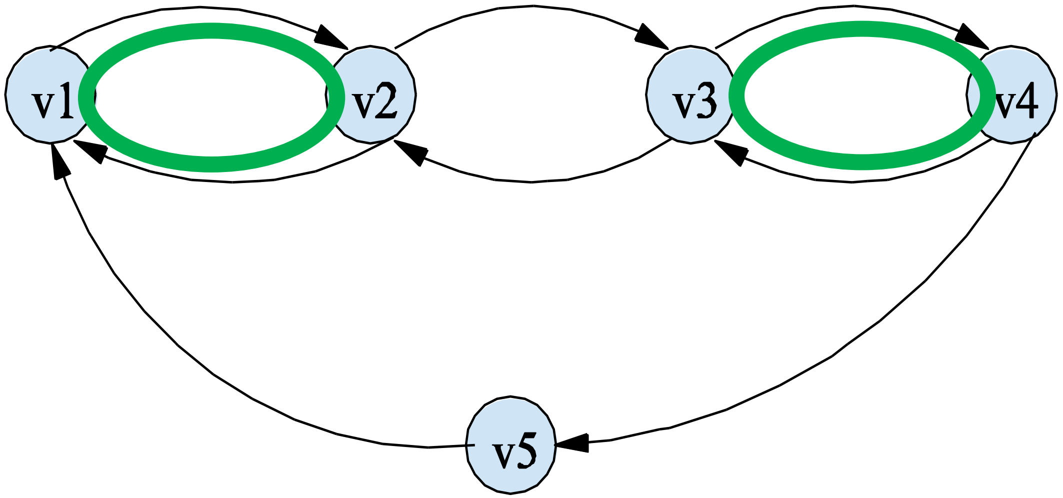


Kidney exchange

Idea introduced in 1986 [Rapaport]

First exchange (NEPKE) started 2003-04 [Roth, Sönmez, Ünver, …]





Objective of the batch problem:

Maximum weight *combination* of short disjoint cycles

Other barter-exchange markets

- Holiday Homes: Intervac
- Books: Read It Swap It
- General used goods: Netcycler / swap.com
- National Odd Shoe Exchange
- Room exchange (e.g. dorm rooms)
- Nurse shift exchange

Cap on cycle length

- Why a cap?
  - Transplants in a cycle must occur simultaneously
  - Cycle may fail
- Cap is typically 3

What if ?

Never-ending altruist-donor (NEAD) chains

[With Rees *et al. New England Journal of Medicine 2009*]

- First NEAD chain, generated by our algorithm:

		Transplant No.									
		1	2	3	4	5	6	7	8	9	10
Date		July 2007	July 2007	Sept. 2007	Sept. 2007	Feb. 2008	Feb. 2008	Feb. 2008	Feb. 2008	March 2008	March 2008
State		AZ	OH	OH	OH	MD	MD	MD	NC	MD	OH
Recipient's Sex and ABO Type		O	O	A	A	B	A	A	A	A	A
Donor's Sex and ABO Type	O	O	A	A	B	A	A	A	AB	A	AB
Recipient's PRA		62%	0%	23%	0%	82%	78%	64%	3%	100%	46%
Recipient's Race or Ethnic Group		White	White	White	White	White	Hispanic	White	White	White	Black
Recipient–Donor Relationship		Wife–Husband	Daughter–Mother	Mother–Daughter	Brother–Sister	Husband–Wife	Daughter–Father	Wife–Husband	Friend–Friend	Brother–Brother	Mother–Daughter

- NEAD chains have become the main modality of kidney exchange worldwide: >10,000 transplants

30-chain [*New York Times* 2/18/2012]

[National Kidney Registry]

Kidney exchanges use designs, algorithms, and software from my CMU lab

UNOS DONATE LIFE®

UNITED NETWORK FOR ORGAN SHARING

- Technology selected in 2008
- Licensed to UNOS for free
- National exchange went live in 2010
- Now includes 80% of the transplant centers in the US
- Match run every week
- Only US organ exchange that is fully algorithmically run

- Previously:
  - Alliance for Paired Donation
  - Paired Donation Network

Solving the batch problem

- NP-complete (even without chains) [Abraham, Blum, Sandholm, EC-07]
- Novel branch-and-price algorithm enabled nationwide scaling [Abraham, Blum, Sandholm, EC-07]
- …
- Fastest current algorithm: [Dickerson, Manlove, Plaut, Sandholm, Trimble, EC-16]
  - $x_{ij} \rightarrow x_{ijk}$
  - uses the extra constraints:

    “**if an edge is used at position k+1 in chain, there must be an appropriate edge used at position k in that chain**”

"Position-indexed" compact formulation for within-batch chain caps

[Dickerson, Manlove, Plaut, Sandholm & Trimble, EC-16]

$$\max \quad \sum_{(i,j)\in A} \sum_{k\in\mathcal{K}(i,j)} w_{ij} y_{ijk} + \sum_{c\in\mathcal{C}} w_c z_c \tag{3a}$$

$$\text{s.t.} \quad \sum_{j:(j,i)\in A} \sum_{k\in\mathcal{K}(j,i)} y_{jik} + \sum_{c\in\mathcal{C}:i \text{ appears in } c} z_c \le 1 \qquad i \in P \tag{3b}$$

$$\sum_{j:(i,j)\in A} y_{ij1} \le 1 \qquad i \in N \tag{3c}$$

$$\sum_{\substack{j:(j,i)\in A\wedge \\ k\in\mathcal{K}(j,i)}} y_{jik} \ge \sum_{j:(i,j)\in A} y_{i,j,k+1} \qquad \forall\, i \in P,\; k \in \{1,\dots,K-1\} \tag{3d}$$

$$y_{ijk} \in \{0,1\} \qquad (i,j) \in A, k \in \mathcal{K}(i,j) \tag{3e}$$

$$z_c \in \{0,1\} \qquad c \in \mathcal{C} \tag{3f}$$

3a: max weight of edges in chains + weight of cycles

3b: each pair is in at most one chain or cycle

3c: each NDD has at most one used out-edge

3d: if an edge is used at position k+1 in chain, there must be an appropriate edge used at position k in that chain

Additional functionality for modern kidney exchanges supported by our algorithm and our later enhancements

Multiple willing donors per patient

- All their edges included in input graph
- Solver automatically uses at most one of the donors

Incorporating compatible pairs

- Why?
  - Patient can get a better kidney
  - Others get more/better matches
- Our algorithm supports this
  - Could preprocess so patient can't get worse kidney than her compatible donor brings

Weights on edges

- Algorithm supports weights on edges (thus also on nodes)
- Weights can represent, e.g.,
  - Degrees of compatibility
  - Projected life years (potentially quality-adjusted)
  - Travel distance
  - Wait time
  - Transplanting children
  - Transplanting sensitized, hard-to-match patients

Side constraints

- Algorithm supports certain kinds of side constraints, e.g.,
  - Center A does not want to be in cycles longer than 2
  - Patient x does not want to be in a cycle longer than 2
  - Center B does not want to participate in altruistic donor chains of length greater than 3
  - …

Fielded kidney exchanges

- NEPKE (started 2003-04, now closed)
- United Network for Organ Sharing (UNOS)
- Alliance for Paired Donation
- Paired Donation Network (now closed)
- National Kidney Registry
- San Antonio
- Mayo Clinic
- St. Barnabas Compassionate Share
- Netherlands
- UK
- Canada
- Australia
- Portugal
- Israel
- Sweden
- …

~600 transplants in US per year, mainly via NEAD chains

Only US one that uses purely algorithmic matching

Failure-aware kidney exchange

[Dickerson, Procaccia & Sandholm, EC-13, Management Science 2019]

Failure-aware kidney exchange

[Dickerson, Procaccia & Sandholm, EC-13, Management Science 2019]

- Only 7-12% of planned transplants go into execution
- We propose to find a solution that has maximum ***expected*** weight
  - Each edge has a weight and a success probability
  - Can't just multiply weight and probability
- We needed to develop a different optimal algorithm
  - Based on branch-and-price

Algorithm changes for probabilistic setting

- Use chain extension in pricing problem
  - **Theorem.** Don't need to extend a chain by any #steps if optimistic infinite extension has negative value:

$$\left(\frac{q_{max}}{1-q_{max}}\prod_{i=0}^{k-1} q_i\right) + u(c) + \ell - \left(d_{min} + \sum_{i=0}^{k} d_i\right) \leq 0$$

Optimistic future value of infinite extension

Discounted utility of current chain

Donation to waitlist

Pessimistic sum of LP dual values

  - Ordering heuristics for cycle and chain generation
- Upper bound now hard
  - **Theorem.** Discounted clearing NP-complete (even with no chains or cycle length cap)
  - So, we use looser bound: solve with $w'_e = (1-p_{fail})\, w_e$
- Lower bound still easy
  - **Theorem.** Discounted clearing with 2-cycles polytime

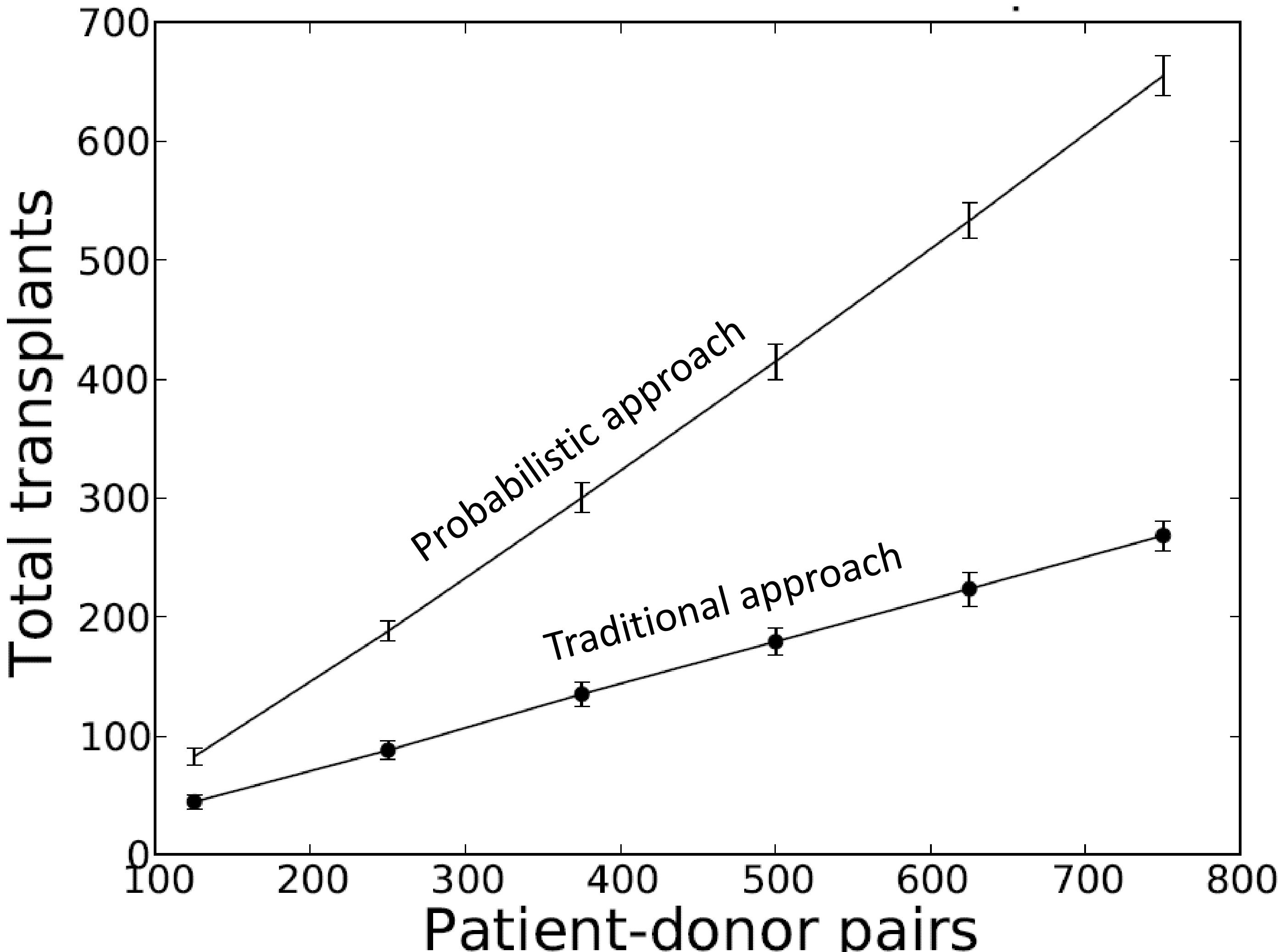
Scalability experiment

Time limit 1 hour; 8GB RAM; Saidman *et al*. generator; p_{fail} = 0.7; #altruists = 0.1*#pairs

	CPLEX (Discounted)		Ours (Discounted)	
$\lvert V \rvert$	Cleared	Time (cleared)	Cleared	Time (cleared)
10	127 / 128	0.044	128 / 128	0.027
25	125 / 128	0.045	128 / 128	0.023
50	105 / 128	0.123	128 / 128	0.046
75	91 / 128	0.180	126 / 128	0.072
100	1 / 128	1.406	121 / 128	0.075
150	0 / 128	–	114 / 128	0.078
200	0 / 128	–	113 / 128	0.135
250	0 / 128	–	94 / 128	0.090
500	0 / 128	–	107 / 128	0.264
700	0 / 128	–	115 / 128	1.071
900	0 / 128	–	38 / 128	2.789
1000	0 / 128	–	0 / 128	–

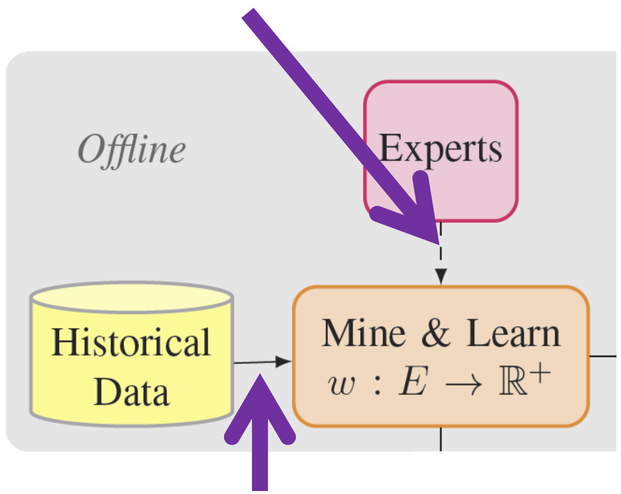
Dynamic experiment with failures

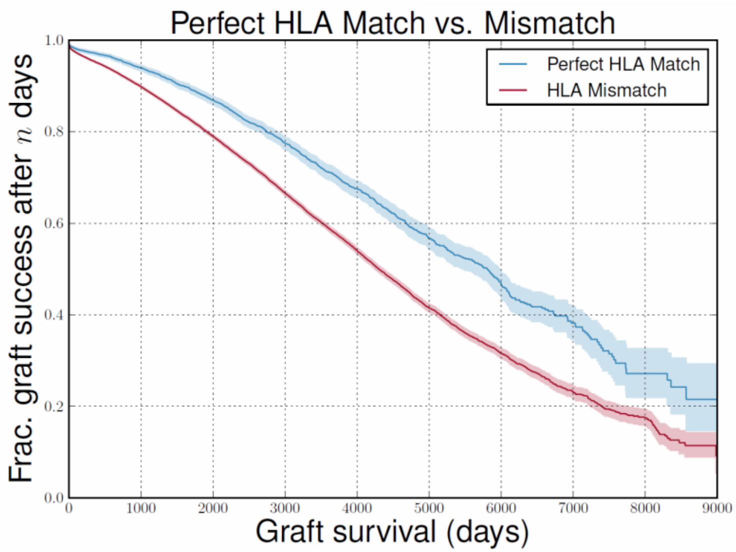
24 weeks; Bimodal failure probability; #altruists = 0.1 * #pairs



FutureMatch: Combining human value judgments, ML, and integer programming for automatically generating the best policy for large-scale dynamic problems [Dickerson & S., AAAI-15]

Experiments with 3 objectives: max-graft-survival, max-cardinality, max-β-weighted-cardinality





E.g., for β=2, improves over myopic in both #transplants and #sensitized transplants

Preference elicitation from multiple experts

- To extract the value system from the multiple expert stakeholders, I designed a careful questionnaire with questions comparing small-case solutions

- Experts are reluctant to answer, and even ask

Edge testing

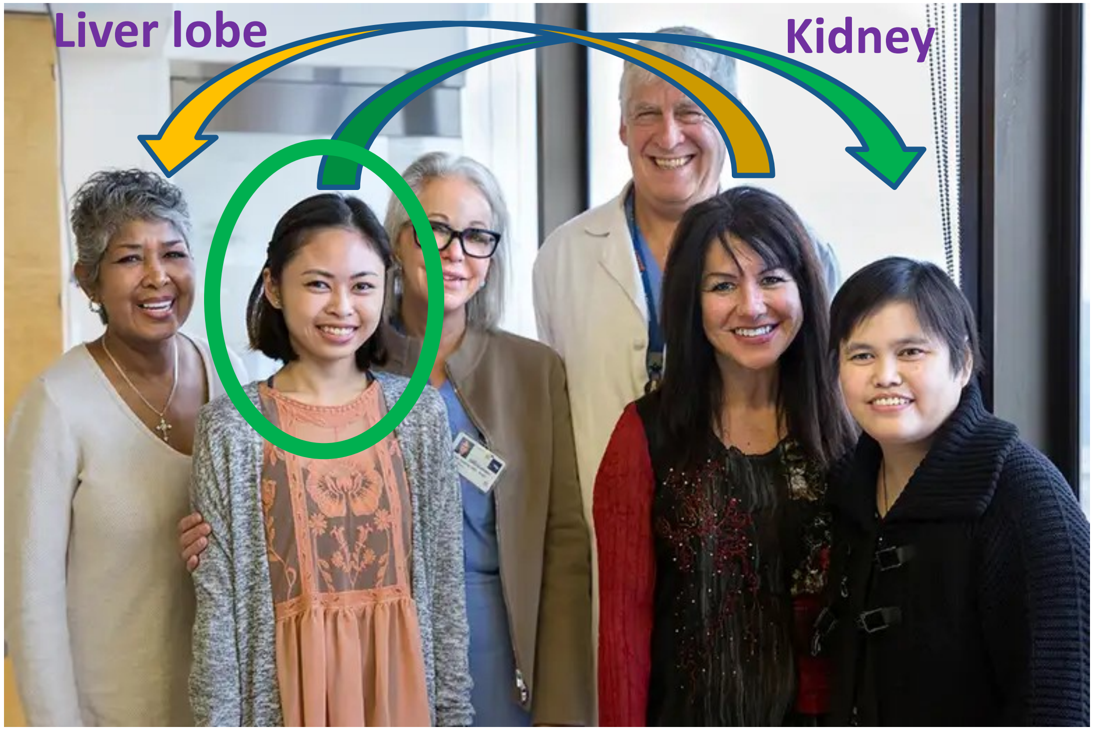
- Algorithms for better edge testing policies
  - Blum, Dickerson, Haghtalab, Procaccia & Sandholm EC-15, Operations Research 2019
  - McElfresh, Curry, Sandholm & Dickerson NeurIPS-20
- Ongoing pilot with UNOS for prioritizing queries in UNOS's donor pre-select tool

Transplant centers hide pairs and NDDs from exchange(s)

- Why do centers do this?
  - Logistical benefit
  - Money
- What fraction of locally matchable pairs/NDDs do centers hide?
  - A: 100% [Stewart, Leishman, Sleeman, Monstello, Lunsford, Maghirang, Sandholm, Gentry, Formica, Friedewald, Andreoni. 2013. American Transplant Congress]
- No mechanism design solution possible in static setting
  [Roth, Sönmez, Ünver (2007a); Ashlagi, Fischer, Kash, Procaccia, GEB-13; Ashlagi & Roth (2014)]
- Incentive-compatible, efficient, long-term-IR credit mechanism
  [Hajaj, Dickerson, Hassidim, Sandholm, Sarne, AAAI-15]
  - Matching favors centers that reveal more than their expected number of pairs/NDDs, and disfavors those who reveal fewer than that
  - Supports chains and long cycles
  - Assumes pairs and NDDs last for only one matching period

Liver lobe and cross-organ exchanges

- Invented liver lobe and cross-organ exchange [Sandholm, UMass DLS-10]
- Merging kidney and liver lobe exchanges produces a large benefit in theory and simulation [Dickerson & Sandholm, JAIR-17]
- Fielding has started in the small, with manual matching, as it started with kidneys
  - A few liver lobe swaps per year in the US
  - First liver lobe - kidney swap took place in 2019



Our ongoing research on organ exchange

- Better algorithms that handle the dynamic problem with arrivals & departures
- Better edge testing policies
- Matching cadence: Race to bottom among exchanges [Das, Dickerson, Li, Sandholm, AMMA-15]
  - Why allow multiple kidney exchanges in a country?
- Better incentive schemes for transplant centers to reveal pairs
- Multi-donor kidney exchange
  - Current practice allows multiple donors listed, only one used
  - Our new approaches allow multiple donors to be used in various ways [Sandholm, Farina, Dickerson, Leishman, Stewart, Formica, Thiessen, Kulkarni ATC-17; Farina, Dickerson, Sandholm IJCAI-17, AGT-17]
- "Operation frames" [Farina, Dickerson, Sandholm IJCAI-17, AGT-17]
- Other organs
  - Liver & cross-organ exchange [Dickerson & Sandholm, GREEN-COPLAS-13, AAAI-14, JAIR-17]
  - Lung "components" [Ergin, Sönmez, Ünver, draft 2014-15; Tang et al. 2015]
- International exchanges

Some more of my future research on organ donation