Blood Allocation with Replacement Donors: A Theory & Application of Multi-unit Exchange

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Transfusion

- **Blood components**, which include red blood cells, platelets, plasma, and **whole blood** itself, are the most used human body components in medical treatments.
  - They are mostly used to replace or supplement missing components from blood.
  - Whole blood is rarely used in modern transfusion medicine.
- Transfusion is one of the most practiced medical procedures in hospitals.
- There are severe blood shortages in many developing countries and seasonal shortages in developed countries.
  - Millions of deaths each year are associated with lack of blood.

Donation

- World Health Organization (WHO) strongly recommends all blood is supplied by volunteer non-remunerated donors (VNRDs) due to safety and ethics concerns.
- Donating blood components is substantially less costly than any other organ or tissue donation procedure for a donor.
  - A donor can donate red blood cells or whole blood once in every 56 days, while donation of platelets and plasma can be made more often through a procedure called apheresis.
- However,
  - VNRDs are insufficient to meet the demand for blood in many regions of the world.
  - It is costly to screen VNRDs for safety concerns and quality for developing countries, especially in sub-Saharan Africa.

Donation

- WHO'23 reports
  - only in 79 countries (38 high-income, 33 middle-income, 8 low-income) more than 90% of blood component supply comes from VNRDs, and
  - in 53 countries (8 high-income, 36 middle-income, 10 low-income), more than 50% of blood supply comes from replacement donors or paid donors (including populous countries such as Pakistan, Nigeria, Bangladesh and Mexico). Replacement donors are also used unofficially in many other countries (e.g. Turkey, China) making the availability of accurate statistics difficult.
- Moreover, WHO data is inconsistent with other microdata and reports, which show further insufficiency of the VNRD practice in many other countries.

Replacement Donor Programs

- In a replacement donor program, a patient receives the blood she needs by bringing forward a number of replacement donors who are family members or loved ones of the patient.
- Blood banks in different places use different exchange rates that determine how many units are needed for each unit of blood received according to
  - shortages at the blood bank,
  - patients' medical urgency, and
  - other demographics of the patient.

Replacement Donor Programs

- Replacement donor programs are observed in all continents, and especially common in Africa, Latin America, and Central Asia (Allain & Sibinga'16).
- Some experts and local authorities argue that the use of replacement donors is as safe and ethical as VNRDs. Moreover, it is the only ethically acceptable and economically affordable option for mitigating blood shortages in many countries.

Replacement Donor Programs

Table 1: Whole Blood Donations Reported by Countries to WHO (millions)

	Total Donations	VNR Donations	% of VNR Donations	FR Donations	% of FR Donations	Paid Donations	% of Paid Donations	Other (unknown)	% of Other
1998-1999 (n=175)	75.13	55.9	74.404	13.5	17.969	5.73	7.627		
2001-2002 (n=178)	76.27	61.9	81.159	12.1	15.865	2.27	2.976		
2004-2005 (n=154)	64.824	51.52	79.477	11.03	17.015	2.274	3.508		
2008 (n=159)	65.51	54.34	82.949						
2013 (n=178)	88.2	73.471	83.3	14.465	16.4	0.265	0.3		
2018 (n=171)	95.228	78.8	82.749	15.1	15.857	0.16	0.168	1.168	1.227

- The percentage of global blood supply from family replacement donation in 2018 (15.857%) is almost the same as in 2001-2002 (15.865%).

Replacement Donor Programs

- For 53 countries that rely heavily on replacement donation ($>$ 50% of blood supply from replacement donors) in 2018:
  - 78.05% of total blood supply comes from replacement donors, slightly higher than 2011 (77.34%),
  - compared with 2011, total replacement donations increased by 48.52%, and
  - total population of these countries is over 1.5 billion.

Replacement Donor Programs

Existing programs suffer from two major shortcomings:

- They lack optimized inventory management
  - First come first serve: Only exchange with the blood bank, no exchange among patients. This may create bottlenecks in low-inventory settings.
  - No donor screening in general, depending on the needs of the blood bank.
- They use fixed exchange rates between units received and supplied (regardless of blood type), which creates efficiency, fairness, and ethics problems.

  In particular,
  - Certain patients may not be able to recruit the required number of donors.
  - This gives rise to coercion and black markets, through which patients pay others to be their replacement donors.
  - Or rules are bent arbitrarily so that some patients are forgiven their *debts*, while others are not (e.g., Tucuman, Argentina). Trust and transparency of the system are eroded.

Overview of the Paper

- We introduce blood allocation with VNRDs and replacement donors as a novel market design problem.
- We allow for the possibility of endogenous exchange rates beyond the classical one-for-one exchange rate in single- or multi-unit exchange literature.
- To this end, we introduce a new concept, feasible schedule menus of patients, determined depending on the idiosyncratic observable characteristics of the patient.
- We introduce weighted utilitarian mechanisms.

Overview of the Paper

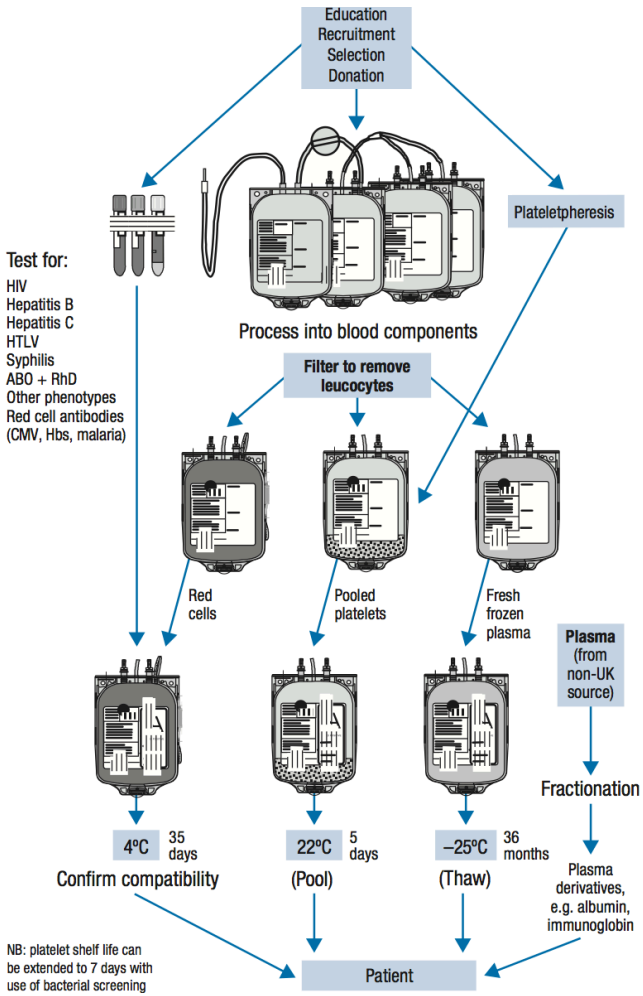
- We show that subclasses of weighted utilitarian mechanisms have desirable incentive properties regarding
  - truthful revelation of replacement donors, and
  - truthful utility revelation

  under some regularity and smoothness assumptions on the feasible schedule menus.
- We give policy recommendations.
- We show that the existing allocation mechanism can be Pareto dominated by incentive-compatible mechanisms using our design, and present simulation results.
- Our results are applicable to general settings of multi-unit exchange of indivisible goods with compatibility-based preferences beyond blood allocation (shift exchange or time banks, etc)
  - Subclasses of our mechanisms also incentivize truthful revelation of compatibility relation and maximal need.

Some Related Literature

- Incentives and altruism in blood donations: Lacetera, Macis & Slonim'12,'13; Slonim, Wang & Garbarino'14
- Benefits/costs of replacement donors: Allain & Sibinga'16; Sun, Lu & Jin'16
- Covid-19 convalescent blood-plasma donation incentivized by the paying forward and paying backward schemes: Kominers, Pathak, Sönmez & Ünver'20
- Living donor kidney exchange and weighted/maximal/priority mechanisms: Roth, Sönmez & Ünver'05,'07; Andersson & Kratz'19; Kratz'24; dual-organ exchange and maximal mechanisms: Ergin, Sönmez & Ünver'17
- Other mechanisms under compatibility-based preferences: Bogomolnaia & Moulin'04; Nicolò, Yanav & Sen'19; Aziz'20; Echenique, Miralles & Zhang'20; Garg, Tröbst & Vazirani'20; Andersson, Cseh, Ehlers & Erlanson'21; Manjunath & Westkamp'21
- Other multi-unit exchange: Moulin'95; Konishi, Quint & Wako'01; Biró, Klijn & Pápai'22; Feng, Klaus & Klijn'24
- Beyond one-for-one exchange: Budish'11; Agarwal, Ashlagi, Azevedo, Featherstone & Karaduman'19
- Dominating SP mech through SP mech: Erdil'14; Alva & Manjunath'21

Blood Transfusion



- One donor can donate on average
  - ≈500 ml of whole blood (1 unit of red blood cells – once in every 56 days), or
  - up to 2-3 units of platelets through apheresis, once in a week up to 24 times a year, or
  - up to 4 units of plasma through apheresis, twice a week, there can be a limit depending on the purpose of plasma usage.
- Components are processed and then packaged in standard packs.
- A patient typically needs multiple units of compatible blood component for one time use or multiple uses: Idiosyncratic discrete units in some bounded interval are feasible.
- More blood is, in expectation, better for a patient's prognosis (within the interval).
- Different components typically have different (*ABO* and *RhD*) blood type compatibility requirements.

Model

- I: set of patients in need of a given blood component
- $\mathcal{B}$: set of blood types
  - e.g., $\mathcal{B} = \{O+, O-, A+, A-, B+, B-, AB+, AB-\}$
- Each patient $i \in I$
  - has blood type $\beta_i \in \mathcal{B}$,
  - is compatible with blood types in $\mathcal{C}(\beta_i) \subseteq \mathcal{B}$,
  - needs to receive compatible units in $[1, 2, \ldots, \overline{n}_i]$,
  - has a donor set D_i, possibly empty, such that any $d \in D_i$ has blood type $\beta_d \in \mathcal{B}$ and can donate 1 unit.
- b: the blood bank, which has an inventory of v_X units of type X blood, for each $X \in \mathcal{B}$

(Extension of theoretical setup introduced in Andersson, Cseh, Ehlers, Erlanson'21 for time banks and Manjunath and Westkamp'21 for shift exchange)

Preferences and Utilities

- The schedule of a patient i is a pair of integers (r, s).
  - r: the amount received
  - s: the amount supplied (through her donors)
  - $\{0, 1, \ldots, \overline{n}_i\} \times \{0, 1, \ldots, \delta\}$: all possible schedules for i

($r = s$ in Andersson, Cseh, Ehlers & Erlanson'21 and Manjunath & Westkamp'21; more general here)

Preferences and Utilities

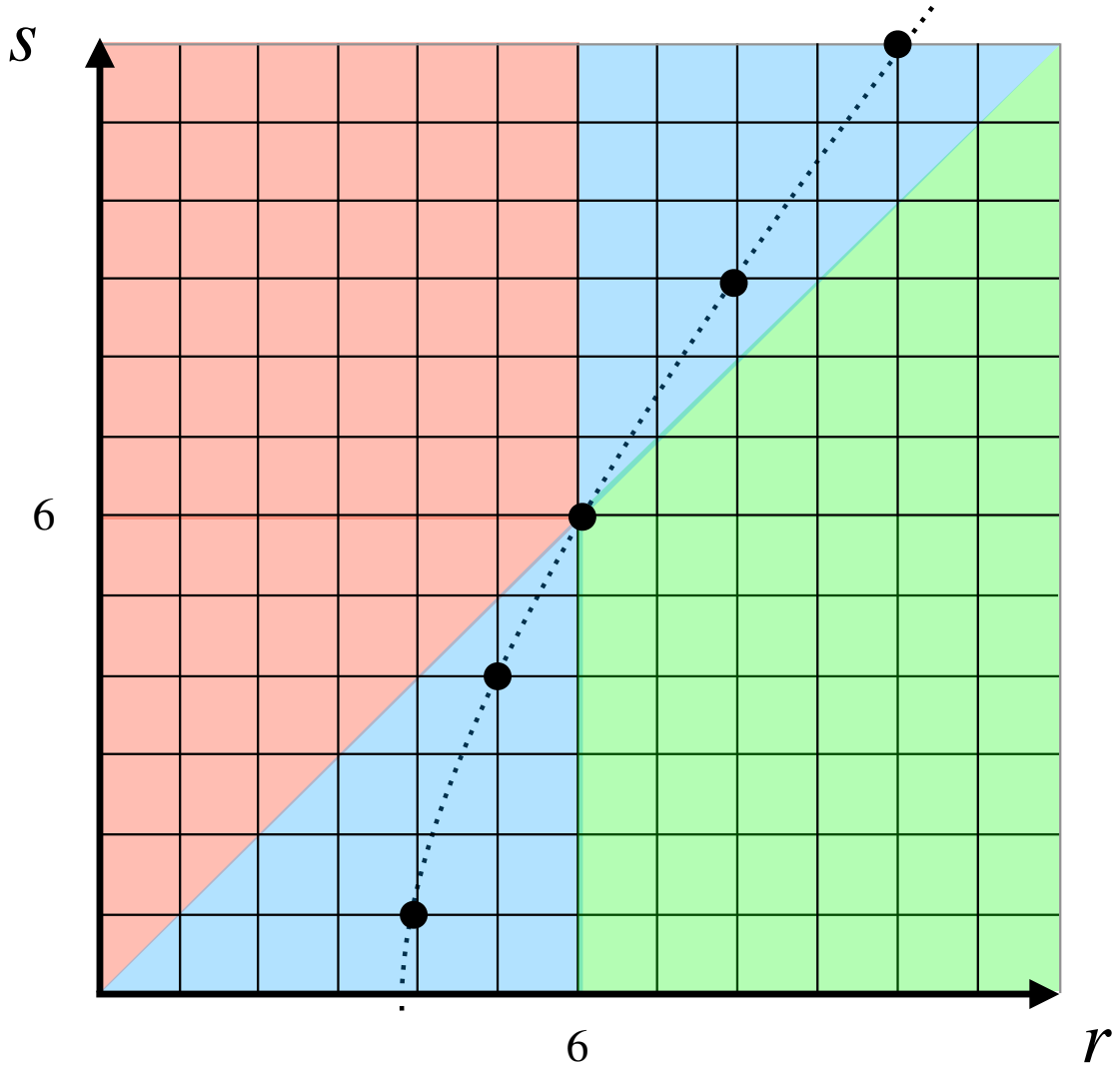
- The patient i has preferences over the schedules, represented by a utility function for her (utility) type $\theta_i = (\rho_i, \sigma_i)$,

$$u_i[r, s, \theta_i] = \rho_i(r) - \sigma_i(s).$$

  - her blood valuation function $\rho_i : \{0, 1, \ldots, \overline{n}_i\} \to \mathbb{R}$ is strictly increasing and concave,
  - her cost function for blood supply $\sigma_i : \{0, 1, \ldots, \delta\} \to \mathbb{R}$ is strictly increasing and convex,
  - for any $0 \leq r < \overline{n}_i$ and $0 \leq s < \delta$,

$$u_i[r + 1, s + 1, \theta_i] > u_i[r, s, \theta_i].$$

Preferences and Utilities



Blood Bank Objectives

- The blood bank cares about the (leftover) blood of each type in its inventory $(r_X)_{X\in\mathcal{B}}$, and possibly the total transfusions to the patients, r_t.

$$o_b\left[(r_X)_{X\in\mathcal{B}}, r_t\right] = \sum_{X\in\mathcal{B}} (\lambda_X \cdot r_X) + \lambda_t \cdot r_t,$$

  where $\lambda_X > 0$ for each $X \in \mathcal{B}$, and $\lambda_t \geq 0$.
  - $(\lambda_X)_{X\in\mathcal{B}}$ can be dynamic optimization weights for the option value of carrying inventory over time for different blood types, depending on the long-term forecasts.
  - λ_t can be interpreted as a social value for transfusing as much blood as possible.

The Blood Allocation Problem

We fix everything except

- the donor profile $D = (D_i)_{i \in I}$ and
- the type profile $\theta = (\theta_i)_{i \in I}$.

A blood allocation problem is represented by a pair (D, θ).

Allocations

- Given a problem (D, θ), an allocation is a non-negative integer vector α such that for every blood type X,

$$\underbrace{\alpha_X(b)}_{\text{leftover}} + \underbrace{\sum_{i \in I : X \in \mathcal{C}(\beta_i)} \alpha_X(i)}_{\text{received by patients}} = \underbrace{v_X}_{\text{inventory}} + \underbrace{\sum_{d \in \cup_{i \in I} D_i : \beta_d = X} \alpha(d)}_{\text{supplied by patients}}$$

  and for every patient i,

$$\sum_{X \in \mathcal{C}(\beta_i)} \alpha_X(i) \leq \overline{n}_i.$$

- The schedule of patient i in α: $\alpha(i) = \big(\alpha_r(i), \alpha_s(i)\big)$
  - received: $\alpha_r(i) = \sum_{X \in \mathcal{C}(\beta_i)} \alpha_X(i)$
  - supplied: $\alpha_s(i) = \sum_{d \in D_i} \alpha(d)$
- The set of all allocations for the problem: $\mathcal{A}(D)$

Design

Two policy levers:

1. Feasible schedule menus
2. Allocation mechanisms

Feasible Schedule Menus

- To accommodate flexible exchange rates, we introduce a new notion to sustain transparency and formalism.
- $\mathcal{F}_i$: feasible schedule menu of patient i:

  A schedule (r, s) is feasible for donor set D_i if $(r, s) \in \mathcal{F}_i(D_i)$.
- For each patient i there is some minimum guarantee $\underline{g}_i$ such that for every D_i,

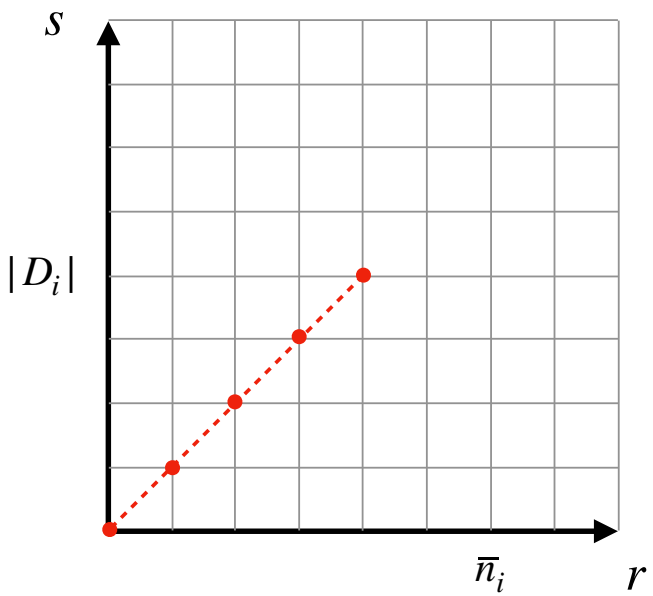
$$\min\left\{r : (r, s) \in \mathcal{F}_i(D_i)\right\} = \underline{g}_i \quad \text{or} \quad \mathcal{F}_i(D_i) = \{(0, 0)\}.$$

- Given a feasible schedule menu profile $\mathcal{F} = (\mathcal{F}_i)_{i \in I}$, for any problem (D, θ), we will only consider allocations in the set

$$\mathcal{A}(\mathcal{F}, D) = \left\{\alpha \in \mathcal{A}(D) : \alpha(i) \in \mathcal{F}_i(D_i), \forall i \in I\right\}.$$

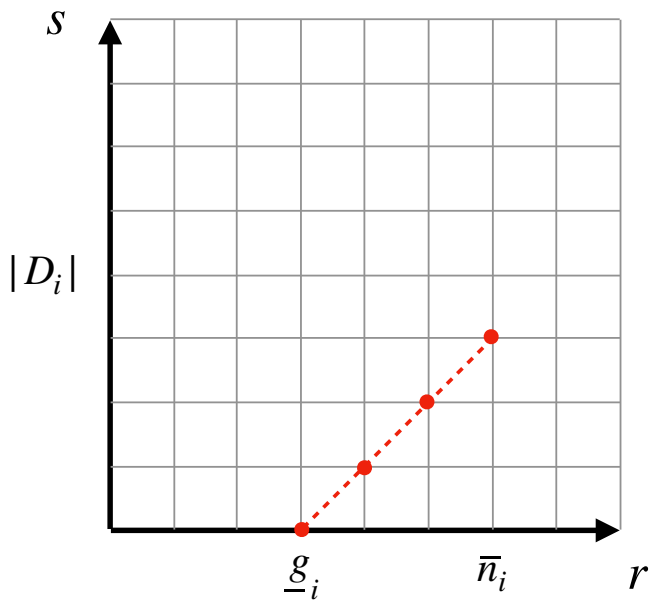
Examples of Feasible Schedule Menus

One-for-one exchange: Used in many countries



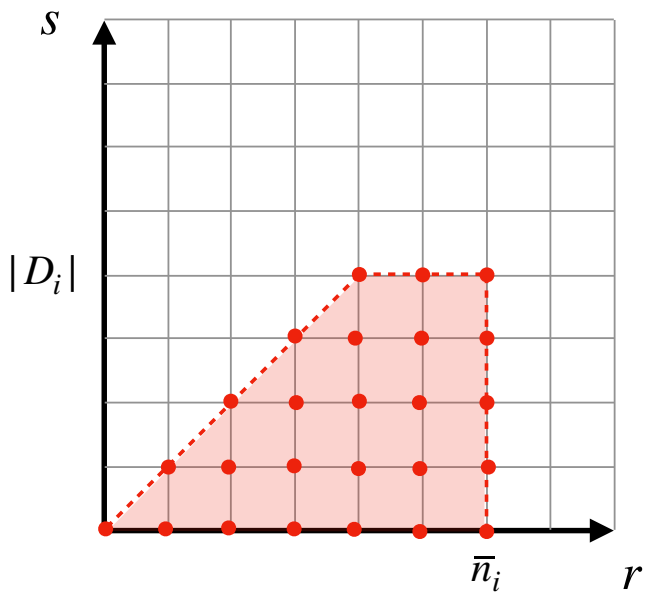
Examples of Feasible Schedule Menus

A minimum guarantee policy: For each unit a patient donated in the past, 3 units are given as a guarantee; additional units are available at the rate one-for-one (Xi'an, China)



Examples of Feasible Schedule Menus

Endogenous exchange rates:



Mechanisms and Incentives

- Given any feasible schedule menu profile $\mathcal{F}$, a mechanism f assigns an allocation $f(\mathcal{F}, D, \theta) \in \mathcal{A}(\mathcal{F}, D)$ to each problem (D, θ).
- A mechanism f is incentive compatible under $\mathcal{F}$ if for any problem (D, θ), patient i, donor subset $D_i' \subseteq D_i$ and type θ_i', we have

$$u_i\big[\alpha(i), \theta_i\big] \geq u_i\big[\alpha'(i), \theta_i\big],$$

where

$$\alpha = f\big(\mathcal{F}, (D_i, D_{-i}), (\theta_i, \theta_{-i})\big)$$

is the outcome of f under true donor set and type revelation of i, and

$$\alpha' = f\big(\mathcal{F}, (D_i', D_{-i}), (\theta_i', \theta_{-i})\big)$$

is the outcome of f when i reveals (D_i', θ_i').

Mechanisms and Incentives

- A mechanism f is incentive compatible with respect to donors under $\mathcal{F}$ if for any problem (D, θ), patient i and donor subset $D_i' \subseteq D_i$, we have

$$u_i\big[\alpha(i), \theta_i\big] \geq u_i\big[\alpha'(i), \theta_i\big],$$

where

$$\alpha = f\big(\mathcal{F}, (D_i, D_{-i}), \theta\big)$$

is the outcome of f under true donor set revelation of i, and

$$\alpha' = f\big(\mathcal{F}, (D_i', D_{-i}), \theta\big)$$

is the outcome of f when i reveals D_i'.

Mechanisms and Incentives

- A mechanism f is donor monotonic under $\mathcal{F}$ if for any problem (D, θ), patient i and donor subset $D_i' \subseteq D_i$,

$$\Big[f\big(\mathcal{F}, (D_i, D_{-i}), \theta\big)\Big]_r(i) \geq \Big[f\big(\mathcal{F}, (D_i', D_{-i}), \theta\big)\Big]_r(i).$$

- Since blood donation is substantially less costly than other organ donation procedures, under lexicographic preferences donor monotonicity is a plausible incentive property.

Weighted Utilitarian Mechanisms

- We study a natural class of mechanisms that choose feasible allocations to maximize the weighted sum of patient utilities and bank objective function.
- Given a collection of positive weights $w = (w_i)_{i \in I}$, f is a weighted utilitarian mechanism with respect to w if

$$f(\mathcal{F}, D, \theta) = \underset{\alpha \in \mathcal{A}(\mathcal{F}, D)}{\arg\max} \sum_{i \in I} \Big(w_i \cdot u_i \big[\alpha(i), \theta_i\big] \Big) + o_b \big[\alpha(b), \sum_{i \in I} \alpha_r(i)\big] + t(\alpha)$$

for every feasible schedule menu profile $\mathcal{F}$ and problem (D, θ) where $t(\cdot)$ is an exogenously fixed tiebreaker function over allocations.

A Special Case of Weighted Utilitarian Mechanisms

- Priority mechanisms: given a priority order over the patients and the blood bank, the priority mechanism lexicographically maximizes their utilities/objectives.
  - A two-way unit-demand priority mechanism for kidney exchange (Roth, Sönmez & Ünver'05, with one-for-one exchange rate).
  - A maximal mechanism with priority tie-breakers for time banks (Andersson, Cseh, Ehlers & Erlanson'21, with one-for-one exchange rate).
  - A priority mechanism for shift exchange (e.g., used in nurse/doctor staffing) (Manjunath & Westkamp'21, with one-for-one exchange rate).

Efficiency

Proposition

Every weighted utilitarian mechanism is Pareto efficient for sufficiently high patient weights w.

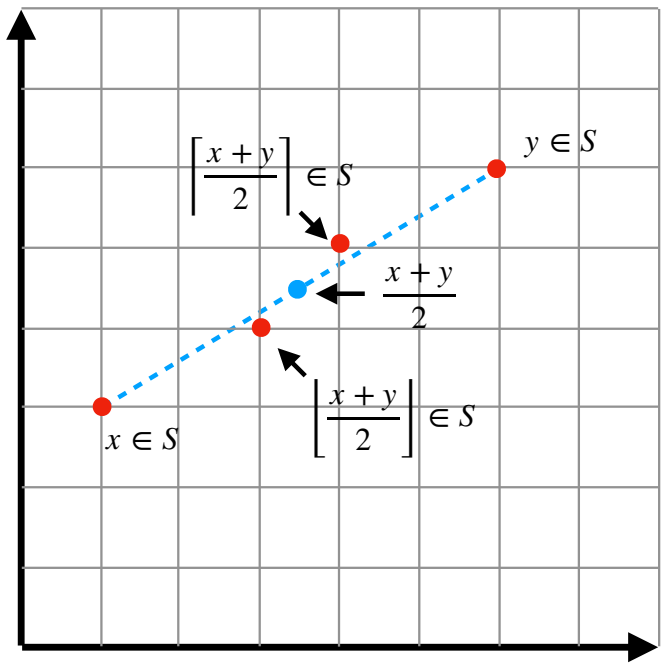
Fairness

- The weighted utilitarian mechanisms can achieve more egalitarian allocations than priority mechanisms, by assigning appropriate weights to patients.
- Moreover, when the valuation function ρ is strictly concave, a weighted utilitarian mechanism tends to assign similar amounts of blood to similar patients.

L-convexity

Generally, a set $S \subseteq \mathbb{Z}_+^2$ is L-convex (where L stands for lattice) if for every $x, y \in S$, we have

$$\left\lfloor \frac{x+y}{2} \right\rfloor, \left\lceil \frac{x+y}{2} \right\rceil \in S.$$



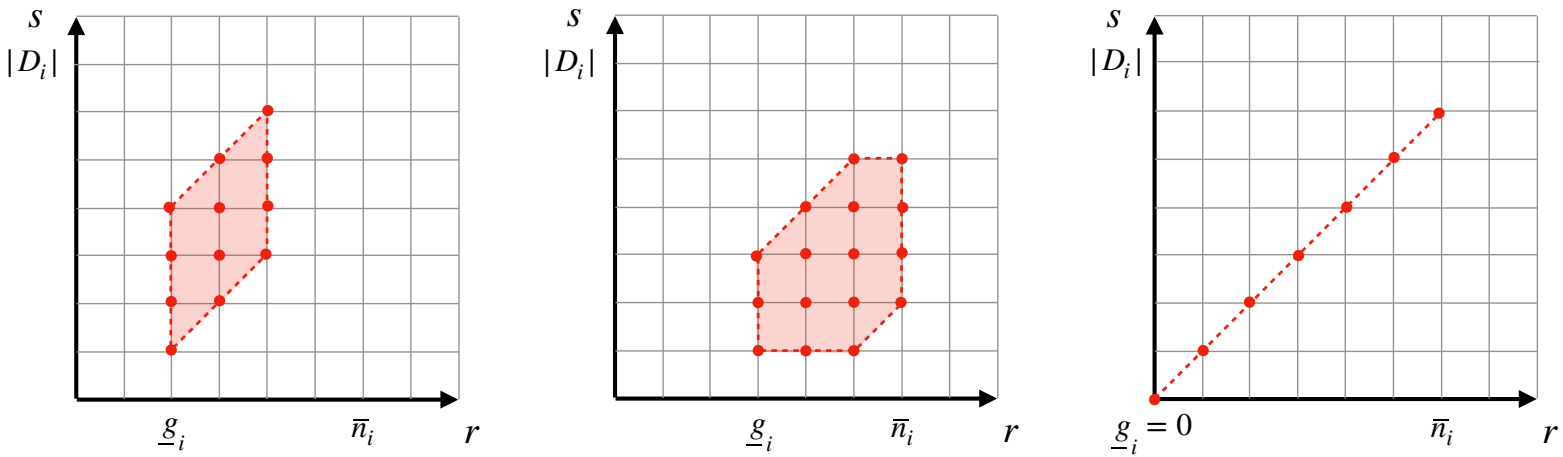
L-convexity

Definition

A feasible schedule menu profile $\mathcal{F}$ satisfies L-convexity if $\mathcal{F}_i(D_i)$ is L-convex for every patient i and her donor set D_i.

L-convexity

Examples:



- L-convex feasible schedule set: Integral points of an at-most-6-sided convex polygon with side slopes of 1, 0, or ∞.

Fairness

Proposition

Assume each ρ_i is strictly concave. There is a weighted utilitarian mechanism such that for any L-convex feasible schedule menu profile and any problem, the amounts of blood received by two identical patients differ by at most one unit.

- It is a discrete and approximate version of "equal (medical) treatment of equals"

Incentive Properties

- We start to analyze the incentives under weighted utilitarian mechanisms by considering donor monotonicity.
- This will serve as the foundation for the other incentive compatibility results later.
- For weighted utilitarian mechanisms to be donor monotonic, we need to make 3 regularity assumptions on the feasible schedule menus.

L-convexity

- The first one is L-convexity, introduced before for allocative fairness.
- The key role of this property in establishing donor monotonicity is that it prevents hidden complementarities between units of blood received.
  - The concavity of blood valuation function ρ_i plays a similar role as the L-convexity of feasible schedule sets in incentives.

Feasibility of Positive Price

Definition

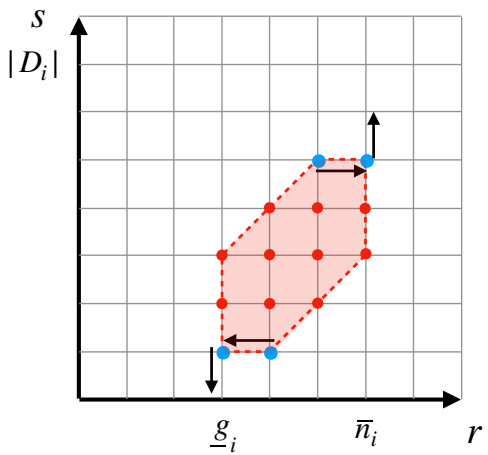
A feasible schedule menu profile $\mathcal{F}$ satisfies feasibility of positive price if for every patient i and her donor set D_i, the following holds:

- if $(r, s), (r', s') \in \mathcal{F}_i(D_i)$, $r' > r$ and $s < |D_i|$, then there exists $s'' > s$ such that $(r', s'') \in \mathcal{F}_i(D_i)$; and
- if $(r, s), (r', s') \in \mathcal{F}_i(D_i)$, $r' < r$ and $s > 0$, then there exists $s'' < s$ such that $(r', s'') \in \mathcal{F}_i(D_i)$.

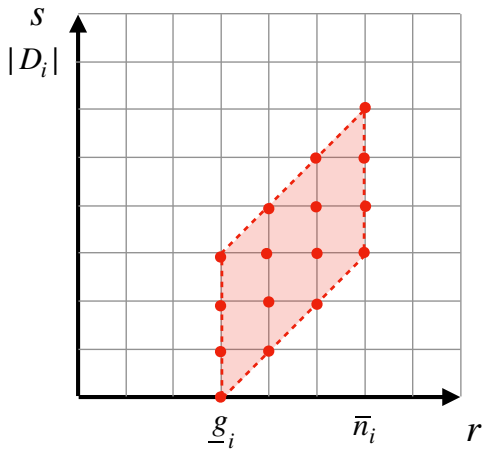
- If the patient can potentially receive a larger (or smaller) amount of blood, then she can potentially receive this amount by supplying more (or less).
- This is the analogue of each unit of blood has a positive "price".

Feasibility of Positive Price

Examples: both satisfy L-convexity



violates feasibility of positive price



satisfies feasibility of positive price

- A "flat bottom" or a "flat top" is ruled out (whenever possible).
  - They can be flat only at feasibility boundaries, i.e., at $s = 0$ and $s = |D_i|$.

Non-diminishing Favorability in Donors

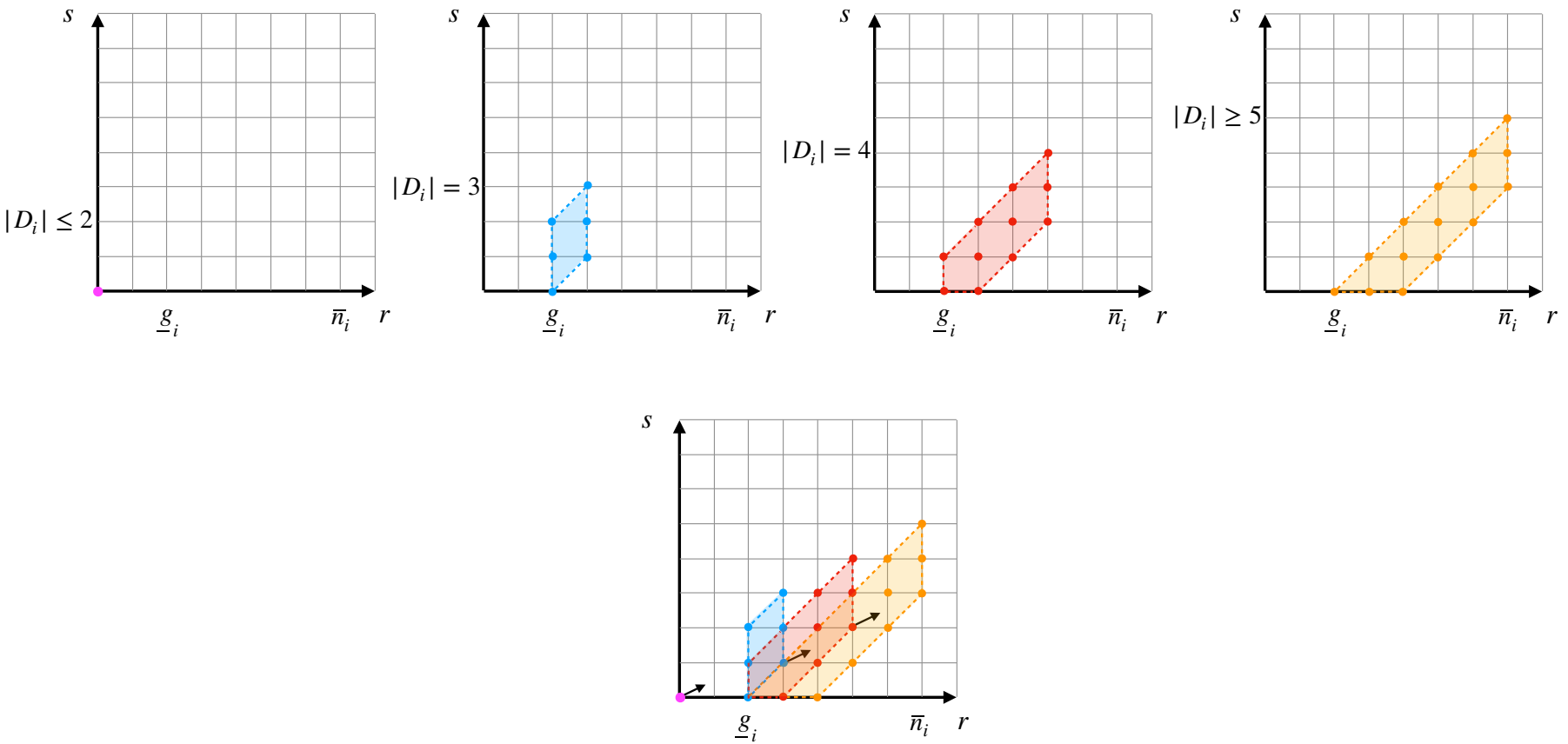
Definition

A feasible schedule menu profile $\mathcal{F}$ satisfies non-diminishing favorability in donors if for every patient i and pair of her donor sets D_i, D_i' such that $D_i' \subseteq D_i$, we have:

- if $(r, s) \in \mathcal{F}_i(D_i')$ and $r \geq \underline{g}_i$, then there exists $s' \leq s$ such that $(r, s') \in \mathcal{F}_i(D_i)$; and
- if $(r, s) \in \mathcal{F}_i(D_i)$, $s \leq |D_i'|$ and $(r, s') \in \mathcal{F}_i(D_i')$, then there exists $s'' \geq s$ such that $(r, s'') \in \mathcal{F}_i(D_i')$.

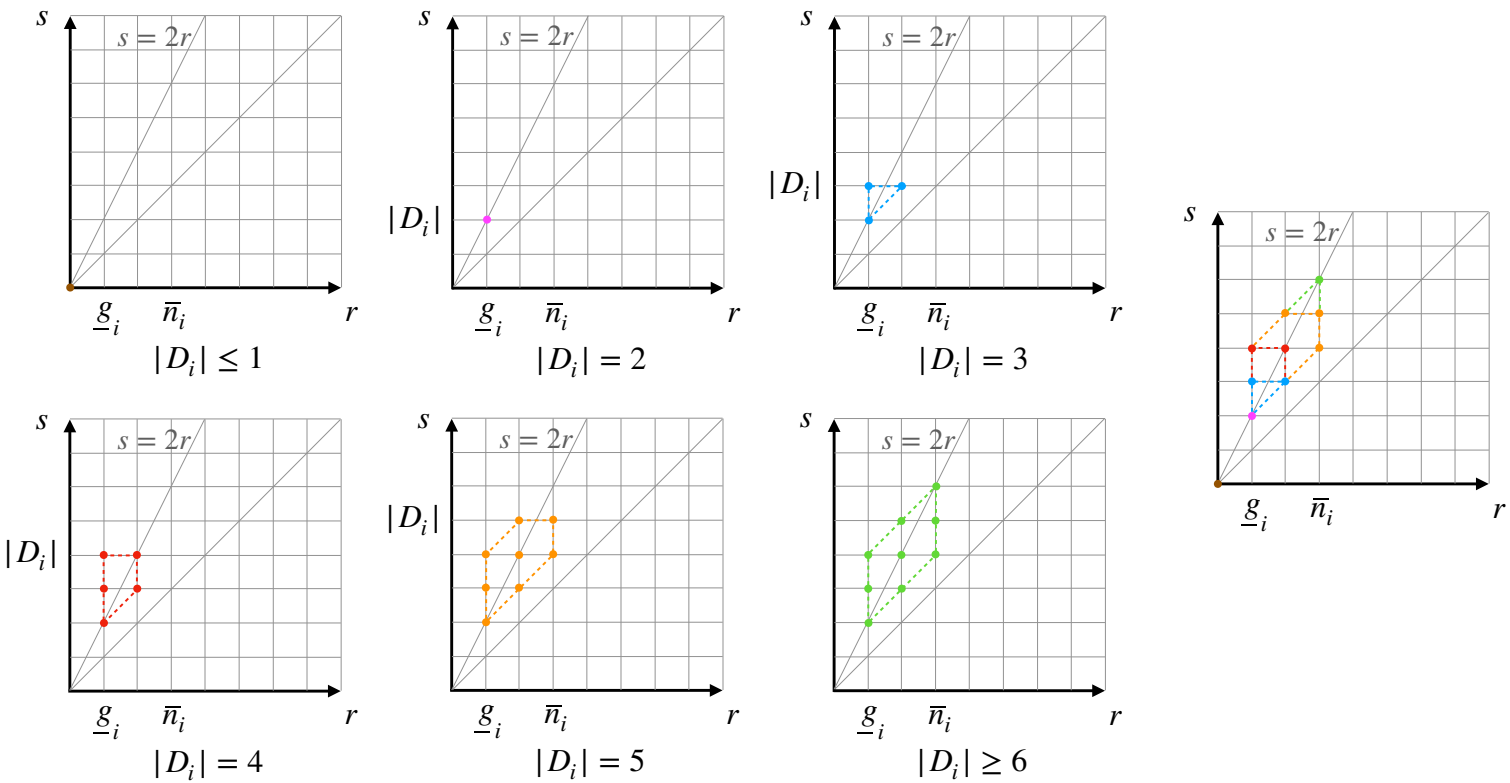
- Non-diminishing favorability in donors manifests itself geometrically as $\mathcal{F}_i(D_i)$ being an expansion of $\mathcal{F}_i(D_i')$ in the direction of receiving more blood or a downward shift of $\mathcal{F}_i(D_i')$.
- One-for-one exchange satisfies all properties.

An Example Satisfying All Properties



Example: Beyond One-for-one Exchange

- Strict two-for-one exchange rate as used in Sub-saharan Africa and Mexico is not L-convex.
- Instead, use the smallest L-convex envelope satisfying other properties:



Donor Monotonicity

Theorem

Let $\mathcal{F}$ be a feasible schedule menu profile that satisfies

- *L-convexity,*
- *feasibility of positive price, and*
- *non-diminishing favorability in donors.*

1. *When every patient has a quasi-linear utility function ($u_i[r, s, \theta_i] = \rho_i(r) - \theta_i \cdot s$), all weighted utilitarian mechanisms are donor monotonic under $\mathcal{F}$.*
2. *When every patient has a general separable utility function, all priority mechanisms, including the maximal mechanisms, are donor monotonic under $\mathcal{F}$.*

- Two special cases of $\mathcal{F}$ that satisfy the three assumptions:
  1. one-for-one exchange 2. whole consumption space

⏩ Skip Proof Sketch

Proof Sketch

- Define an auxiliary matching market isomorphic to the original problem.
- A patient is matched with the donors who donate to her and also those of her own donors who do not donate to anyone.
- Consider two extended problems: $D \supset D'$ such that i conceals exactly one of her donors.
- Consider matching M of D and M' of D' s.t. i receives more under M'.

Lemma

There exists a cycle or chain C, from M to M' s.t. each j points to a donor in $M'(j) \setminus M(j)$, each d points to $M^{-1}(d)$ except that in a chain head does not point and tail is not pointed. Moreover, $M' - C$ of D' and $M + C$ of D are well-defined matchings under three conditions of $\mathcal{F}$.

Proof Sketch

- Suppose f is weighted utilitarian with weights w, $f(D) = M$, $f(D') = M'$ and i receives more under M' (recall $D \supset D'$ with only i concealing 1 donor). Let $U(\cdot)$ denote the overall w-weighted sum of utilities.
- Show $M + C$ and M are "welfare" equivalent (for quasi-linearity):
  1. Suppose not: then $U(M) > U(M + C)$.
  2. A patient receives or supplies one more (less) unit under $M + C$ wrt $M \iff$ the same happens under M' wrt $M' - C$ (Lemma). By concavity of value functions and overall quasi-linearity of utility functions, $U(M) - U(M + C) \leq U(M' - C) - U(M')$.
  3. Therefore, $U(M' - C) > U(M')$, where $M' = f(D')$ and $M' - C$ is a feasible matching for D', a contradiction.
- Repeat cycle/chain addition to $M + C$, welfare equivalence continues. Every repetition ensures we get closer to M'.
- Eventually, we reach M' and then M and M' should be welfare equivalent, a contradiction $\implies$ f is donor monotonic. QED

Incentive Compatibility w.r.t. Donors

Definition

A feasible schedule menu profile $\mathcal{F}$ satisfies individual rationality if for every patient i and her donor set D_i, we have $r \geq s$ for any $(r, s) \in \mathcal{F}_i(D_i)$.

Incentive Compatibility w.r.t. Donors

Definition

A feasible schedule menu profile $\mathcal{F}$ satisfies strong non-diminishing favorability in donors if for every patient i and pair of donor sets D_i, D_i' such that $D_i' \subseteq D_i$, we have:

- if $(r, s') \in \mathcal{F}_i(D_i')$ and $r \geq \underline{g}_i$, then there exists s such that $(r, s) \in \mathcal{F}_i(D_i)$; and
- if $(r, s) \in \mathcal{F}_i(D_i)$ and $(r, s') \in \mathcal{F}_i(D_i')$, then $s \leq s'$.

Incentive Compatibility w.r.t. Donors

Theorem

Suppose every patient has a general separable utility function. If a feasible schedule menu profile $\mathcal{F}$ satisfies

- *L-convexity,*
- *feasibility of positive price,*
- *strong non-diminishing favorability in donors,*
- *individual rationality*

then every weighted utilitarian mechanism is incentive compatible with respect to donors under $\mathcal{F}$.

Incentive Compatibility

Theorem

Suppose every patient has a general separable utility function. If a feasible schedule menu profile $\mathcal{F}$ satisfies

- *L-convexity,*
- *feasibility of positive price,*
- *strong non-diminishing favorability in donors,*
- *individual rationality*

then all priority mechanisms, including the maximal mechanisms, are incentive compatible under $\mathcal{F}$.

⏩ Skip Policy

"Hybrid Implementation" with VNRDs: Red Blood Cells

Blood bank/hospital determines

- Policy variables
  - For non-urgent patients, feasible menus.

    Easy to explain: Example,

    > "Your donors will be recruited to donate no more than x units and no less than y units with respect to the units you receive."
    >
    > (This may depend on patient's blood type, minimum guarantees, etc; can be shown to satisfy the desired properties)

  - For urgent patients feasible menus with forgiving policies.
- The weighted utilitarian mechanism
  Urgent patients are prioritized almost always over non-urgent patients.

"Hybrid Implementation" with VNRDs: Red Blood Cells

A possible timeline of implementation:

1. Prioritize urgent patients in the system over non-urgent patients.
   - Always serve urgent patients using inventory if possible: A dynamic priority mechanism as soon as they arrive,
   - if not possible, bundle urgent patients with the existing non-urgent patients and run the mechanism that prioritizes urgent patients immediately, and serve them as soon as possible.
   - Urgent patients' designated replacement donors, if any, can be processed later.

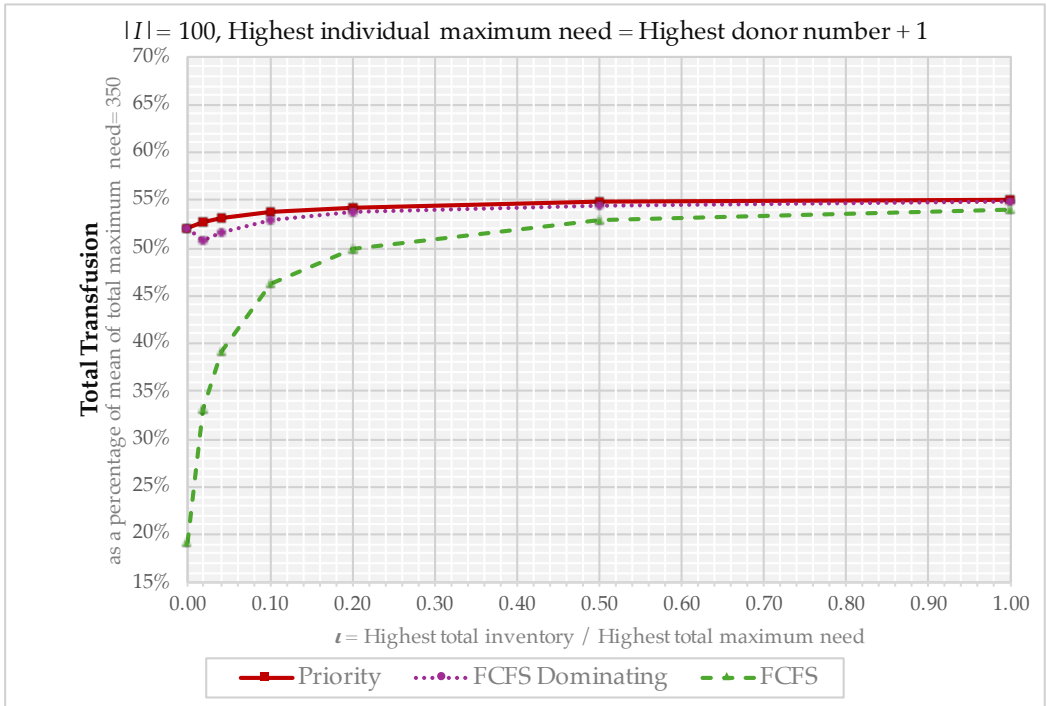
"Hybrid Implementation" with VNRDs: Red Blood Cells

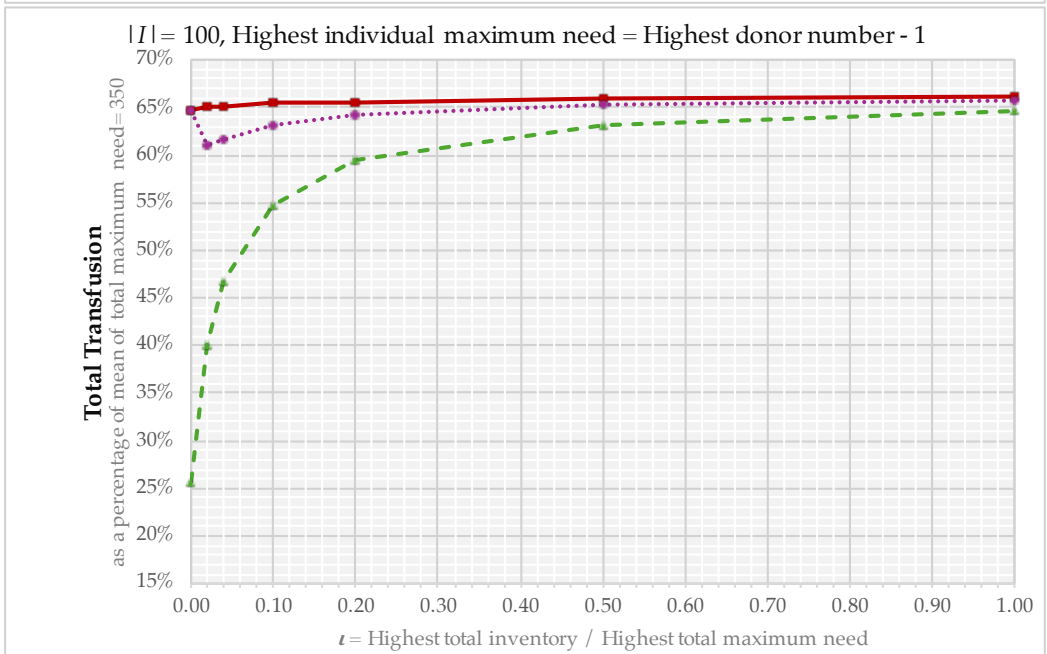
2. Non-urgent patients submit their requests and register the set of their possible replacement donors when they arrive.
   - Blood bank/hospital determines allocation at the end of the day using the mechanism chosen.
   - Designated donors donate, donated blood is tested and processed.
   - Blood is distributed to designated patients.

   (If the blood bank can run at a high inventory level (VNRDs), the last two steps can be done simultaneously.)

Simulations

- Donor number $|D_i| \in \{0, 1, \ldots, 6\}$ uniform iid
- Maximum need $\overline{n}_i \in \{1, 2, \ldots, 6 \pm 1\}$ uniform iid
- Max blood-bank inventory $= k \in \{0, \frac{1}{50}, \frac{1}{25}, \frac{1}{10}, \frac{1}{5}, \frac{1}{2}, 1\}$ times total max demand, and inventory is uniform between 0 and max.
- Blood-type distribution: India
- Allocation methods under fixed one-for-one exchange rate:
  - Most common current mechanism First Come First Serve: Exchange only with the blood bank
  - One-for-one Priority Mechanism: prioritized based on "time" and bundled to be processed together
  - An FCFS-dominating IC mechanism


|I| = 100, Highest individual maximum need = Highest donor number + 1
Total Transfusion
as a percentage of mean of total maximum need= 350
70%
65%
60%
55%
50%
45%
40%
35%
30%
25%
20%
15%
0.00
0.10
0.20
0.30
0.40
0.50
0.60
0.70
0.80
0.90
1.00
ι = Highest total inventory / Highest total maximum need
Priority
FCFS Dominating
FCFS


|I| = 100, Highest individual maximum need = Highest donor number - 1
Total Transfusion
as a percentage of mean of total maximum need= 350
70%
65%
60%
55%
50%
45%
40%
35%
30%
25%
20%
15%
0.00
0.10
0.20
0.30
0.40
0.50
0.60
0.70
0.80
0.90
1.00
ι = Highest total inventory / Highest total maximum need

Extensions

- Suppose compatibility relation $\mathcal{C}_i$ is unknown by others.
  (E.g., assume each patient has a different blood type, her compatibility relation is over donor blood types, and her compatibility relation is not observable by others; while donor blood types, which are distinct from patients', are observable.)
  - Some applications: time banks (Andersson, Cseh, Ehlers & Erlanson'21) and shift exchange (Manjunath & Westkamp'21).
  - Focus on one-for-one exchange as in these papers.
- Extend the definition of incentive compatibility to include truthful $\mathcal{C}_i$ by the agents, in addition to utility function (redundant now) and donor set (endowment) revelation: full incentive compatibility.

Proposition

Under one-for-one exchange, all priority mechanisms, including the maximal mechanisms, are fully incentive compatible.

(Extends Andersson, Cseh, Ehlers & Erlanson'21 and Manjunath & Westkamp'21 results)

Conclusions

- We introduce a new application to the market design literature with multi-unit demand for indivisible goods and present how practical blood exchange and allocation policies can be implemented in real life.
- We introduce a new class of mechanisms with good efficiency, fairness and incentive compatibility properties.
- We go beyond classical one-for-one exchange paradigm in previous literature on incentive compatible exchange mechanisms.