The Revealed Preference Theory of Stable and Extremal Stable Matchings

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Revealed Preference Theory

- Individual behavior: Consumers, General Decision Makers.
- Applications: Consumption, Psychriatic Patients, Kids, Rats, Pigeons...

This paper

Revealed preference theory for matching markets:

When are observed matchings compatible with the theory of two-sided matching?
(*or* what are the empirical implications of matching theory)

Revealed Preference Theory

Why is it useful?

Test the theory of stable matching.

Revealed Preference Theory

Why is it useful?

Test extremal matching.

1. Medical interns & public schools
2. marriage market
3. labor markets

Revealed Preference Theory

Why is it useful?

Test for TU vs. NTU.

1. Marriage in Chicago vs. marriage in Berkeley
2. Other markets w/money but imperfect transfers (utility frontier).

Most work on mkt. design uses NTU.
Econometric work uses TU.

Revealed Preference Theory

Main conceptual difficulty:

- Standard revealed preference:
  Alice buys tomatoes when carrots are available
  $\Rightarrow (T \succ_A C)$.

Revealed Preference Theory

Main conceptual difficulty:

- Standard revealed preference:
  Alice buys tomatoes when carrots are available
  $\Rightarrow (T \succ_A C)$.
- Two sided decision:
  Alice chooses Tomás over Carlos
  $\Rightarrow (T \succ_A C)$ or (C prefers its match to A).

Revealed Preference Theory

Why is it hard?

- Important problem: rationalizing preferences can explain revealed preference and “available sets” (budgets).

Revealed Preference Theory

Why is it hard?

- Important problem: rationalizing preferences can explain revealed preference and “available sets” (budgets).
- Hence direction of revealed preference is affected by the hypothesized rationalizing preferences.
- Literature mostly deals with the problem by assuming transferable utility.

What we do.

Reconcile:

- Theory of stable individual matchings.
- Data on aggregate matchings.

(in the paper, also random matchings)

What we do.

$$\begin{pmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{pmatrix}$$

What we do.

$$\begin{pmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{pmatrix} \qquad \begin{pmatrix} 1 & 8 & 0 & 0 \\ 0 & 4 & 3 & 0 \\ 7 & 3 & 0 & 0 \\ 0 & 0 & 9 & 5 \end{pmatrix}$$

Marriage Data (Michigan)

Age	12-20	21-25	26-30	31-35	36-40	41-50	51-94
12-20	231	47	8	0	0	1	0
21-25	329	798	156	32	11	7	0
26-30	71	477	443	136	27	8	0
31-35	11	148	249	196	83	21	0
36-40	2	41	105	144	114	51	1
41-50	0	15	42	118	121	162	25
51-94	0	2	11	11	35	137	158

Question:

- Given an "aggregate matching table" (data), when are there preferences for individuals s.t. the matching is stable?
- In other words, what are the testable implications of stability for aggregate matchings.

Model:

Primitives: $\langle M, W, P, K \rangle$

- M set of types of men
- W set of types of women
- P a preference profile:
  - P_m a linear order on $W \cup \{m\}$
  - P_w a linear order on $M \cup \{w\}$
- K a list of populations:
  - K_m number of men of type m
  - K_w number of women of type w

Model:

Primitives: $\langle M, W, P, K \rangle$

A *matching* is a $|M| \times |W|$ matrix X s.t.

- $\sum_w x_{m,w} = K_m$
- $\sum_m x_{m,w} = K_w$

Define:

- individual rationality

$$x_{m,w} > 0 \Rightarrow w \; P_m \; m \text{ and } m \; P_w \; w$$

- stability: IR &

$$(w \; P_m \; w' \text{ or } m \; P_w \; m') \Rightarrow x_{m,w'} x_{m',w} = 0$$

Main results

A matching X is *rationalizable* if
$\exists$ a preference profile P s.t. X is stable in $\langle M, W, P, K \rangle$.

Main results

Given matching X. Graph $G = (V, L)$:

5	3	1
0	7	8
9	4	0

Main results

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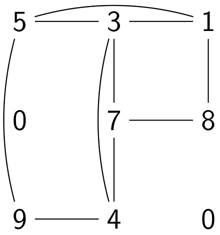


Main results

Theorem

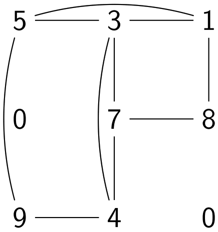
A matching X is rationalizable iff G does not have two connected cycles.

Rationalizable Matchings

Let X be

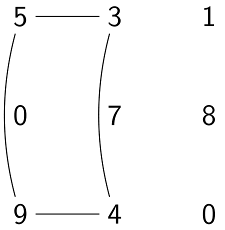
$$\begin{pmatrix} 5 & 3 & 1 \\ 0 & 7 & 8 \\ 9 & 4 & 0 \end{pmatrix}.$$

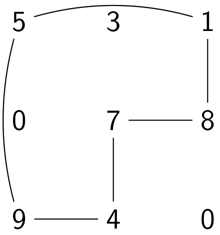
(V, L) is:



Rationalizable Matchings

The following are two minimal cycles that are connected.





Main results

A matching X is *M-optimal rationalizable* if there is P such that X is the M-optimal stable matching in $\langle M, W, P, K \rangle$.

A matching X is *W-optimal rationalizable* if there is P such that X is the W-optimal stable matching in $\langle M, W, P, K \rangle$.

(existence is assured: see below)

Main results

A matching X is *M-optimal rationalizable* if there is P such that X is the M-optimal stable matching in $\langle M, W, P, K \rangle$.

A matching X is *W-optimal rationalizable* if there is P such that X is the W-optimal stable matching in $\langle M, W, P, K \rangle$.

(existence is assured: see below)

A matching X is *unique rationalizable* if there is P such that X is the unique stable matching in $\langle M, W, P, K \rangle$.

Main results

Theorem

Let X be a matching. The following statements are equivalent:

1. *X is rationalizable as a M-optimal stable matching;*

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3. *X is rationalizable as the unique stable matching;*

Main results

Theorem

Let X be a matching. The following statements are equivalent:

1. *X is rationalizable as a M-optimal stable matching;*
2. *X is rationalizable as a W-optimal stable matching;*
3. *X is rationalizable as the unique stable matching;*
4. *the graph G associated to X has no cycles.*

Main results

X is *TU-rationalizable* by a matrix of surplus α if X is the unique solution to the following problem.

$$\begin{aligned} &\max_{\tilde{X}} \textstyle\sum_{m,w} \alpha_{m,w} \tilde{x}_{m,w} \\ &\text{s.t. } \begin{cases} \forall w \ \sum_m \tilde{x}_{m,w} = K_m \\ \forall m \ \sum_w \tilde{x}_{m,w} = K_w \end{cases} \end{aligned} \quad (1)$$

Main results

Theorem

A matching X is TU rationalizable iff the graph G associated to X has no cycles.

Main results

Corollary

Let X be a matching. The following statements are equivalent:

1. *X is rationalizable as a M-optimal stable matching;*
2. *X is rationalizable as a W-optimal stable matching;*
3. *X is rationalizable as the unique stable matching;*
4. *X is TU rationalizable.*

Main results

So:

- Extremal stable matching is observationally equivalent to unique stable matching.

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- Theory of optimal TU matching is embedded (strictly stronger than) theory of stable NTU matching.

Main results

So:

- Extremal stable matching is observationally equivalent to unique stable matching.
- Theory of optimal TU matching is embedded (strictly stronger than) theory of stable NTU matching.
- Optimal TU matching is observationally equivalent to extremal matching.

▸ Proofs

Application: TU vs. NTU

Application: TU vs. NTU

Theorem

A matching X is rationalizable iff G does not have two connected cycles.

Theorem

A matching X is TU rationalizable iff the graph G associated to X has no cycles.

Dating in highschool

Age	School ID: 19				
♂↓, ♀→	-15	16	17	18	19-
-15	0	1	0	0	0
16	1 − − −	5	0	0	0
		|			
17	2 − − −	2	0	0	0
18	0	0	2	0	0
19-	0	0	4 − − −	5 − − −	3

Table: A rationalizable, but not TU/Extremal/Unique-rationalizable matching.

Dating in highschool

Age ♂↓, ♀→	School ID: 33					Sch	
	-15	16	17	18	19-	-15	16
-15	(1)	0	0	0	0	0	(2)
16	0	0	(1)	0	0	(2)	7
17	4	3	0	3	0	(3)	(3)
18	(1)	(1)	6	6	4	(4)	(5)
19-	0	0	(1)	6	(1)	(2)	7

Table: Matchings rationalizable only by using thresholds.

Dating in highschool

Across the 39 schools, the median threshold level required to achieve rationalizability is 1 for rationalizability (no two connected minimal cycles), and 2 for TU/Extremal/Unique-rationalizability (no minimal cycles). In percentage scale, the median thresholds are 4.16% for rationalizability, and 4.76% for TU/Extreme/Unique-rationalizability.

Application: Average marriages across 51 states

858	189	30	9	3	1	0
1142	2261	495	121	35	12	1
253	1436	1349	388	111	36	2
56	401	762	560	203	76	4
16	120	303	378	290	142	9
8	54	155	250	325	431	53
2	10	23	45	86	296	461

Application: Average marriages across 51 states

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Application: TU vs. NTU

So. . . with data concentrated on the diagonal,
it's hard to refute TU in favor of NTU.

Strong stability

Let $\langle M, W, > \rangle$ with $M = \{m_1, m_2, m_3\}$, $W = \{w_1, w_2, w_3\}$, and

m_1	m_2	m_3
w_1	w_2	w_3
w_2	w_3	w_1
w_3	w_1	w_2

w_1	w_2	w_3
m_2	m_3	m_1
m_3	m_1	m_2
m_1	m_2	m_3

Model

The following simple matchings are stable:

$$X^1 = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \; X^2 = \begin{pmatrix} 0 & 0 & 1 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \end{pmatrix}$$

Sum of X^1 and X^2:

$$\hat{X} = X^1 + X^2 = \begin{pmatrix} 1 & 0 & 1 \\ 1 & 1 & 0 \\ 0 & 1 & 1 \end{pmatrix}.$$

(m_1, w_2) is a blocking pair.

Existence Extremal Strongly Stable matchings

Let $x, y \in \mathbb{R}_+^{|W|+1}$ $y \leq_m x$ iff

$$\forall w \in W \quad \sum_{i: w_i R_m w} y_i \leq \sum_{i: w_i R_m w} x_i;$$

interpret w_{l+1} as m,

- $X \leq_M Y$ if, for all m, $x_{m,\cdot} \leq_m y_{m,\cdot}$
- $X \leq_W Y$ if, for all w, $x_{\cdot,w} \leq_w y_{\cdot,w}$.

Existence Extremal Strongly Stable matchings

Theorem

$(S(M,W,P,K),\leq_M)$ and $(S(M,W,P,K),\leq_W)$ are nonempty, complete, and distributive lattices; in addition, for $X,Y \in S(M,W,P,K)$

1. *$X \leq_M Y$ iff $Y \leq_W X$;*
2. *for all agents $a \in M \cup W$, either $x_a \leq_a y_a$ or $y_a \leq_a x_a$;*
3. *for all m and w, $\sum_{w\in W} x_{m,w} = \sum_{w\in W} y_{m,w}$ and $\sum_{m\in M} x_{m,w} = \sum_{m\in M} y_{m,w}$.*

Median Matching

Let $S(M, W, P, K) = \{X^1, \ldots, X^k\}$.
Order each row/column for $a \in M \cup W$:

$$x_a^{(1)} \geq_a \ldots \geq_a x_a^{(k)}$$

construct matrices:

$$y_m^{(i)} = x_m^{(i)} \text{ and } y_w^{(i)} = x_a^{(k+1-i)}$$

matrices $Y^{(i)}$ give each agent the ith best stable outcome

Median Matching

Proposition

$Y^{(i)}$ is a stable aggregate matching.

Corollary

The median stable matching exists.

Median Matching

if $\langle v_0, \dots v_N \rangle$ is a cycle, then N is an even number. Say that a cycle c is balanced if

$$\min \{v_0, v_2, \dots, v_{N-2}\} = \min \{v_1, v_3, \dots, v_{N-1}\}.$$

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Theorem

An aggregate matching X is median rationalizable if it is rationalizable and if all cycles of the associated graph (V, L) are balanced.

Median Matching

if $\langle v_0, \ldots v_N \rangle$ is a cycle, then N is an even number. Say that a cycle c is balanced if

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Theorem

An aggregate matching X is median rationalizable if it is rationalizable and if all cycles of the associated graph (V, L) are balanced.

Corollary

A canonical matching X is either not rationalizable or it is median rationalizable.

Other results

Econometric estimation strategy:

- Moment inequalities
- Set identification parameters in “index” utility model.
- Empirical illustration to US marriage data.

Main idea in the proof.

Rationalizable Matchings

Theorem

An aggregate matching X is rationalizable if and only if the associated graph (V, L) has not two connected distinct minimal cycles.

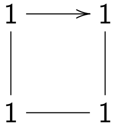
Idea: necessity.

Canonical cycle:

$$\begin{array}{ccc} 1 & \text{------} & 1 \\ | & & | \\ 1 & \text{------} & 1 \end{array}$$

Idea: necessity.

Preferences ⇒ orientation of edges:



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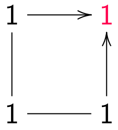

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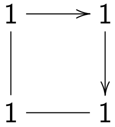

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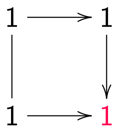

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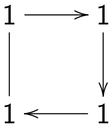

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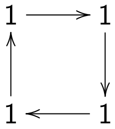
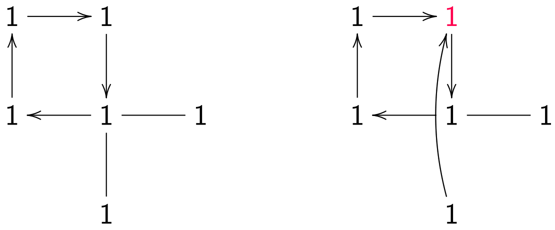


Idea: necessity

So a cycle must be oriented as a flow.

Idea: necessity



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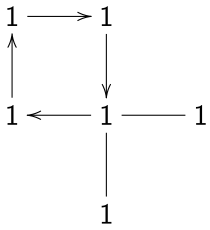

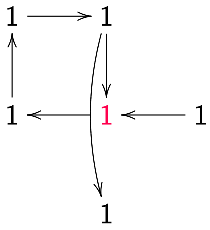

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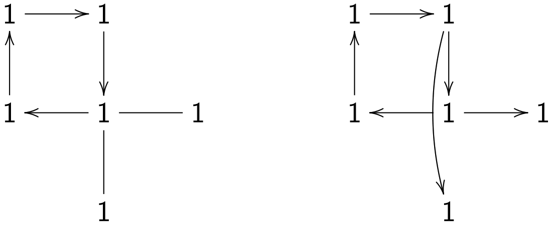


Idea: necessity

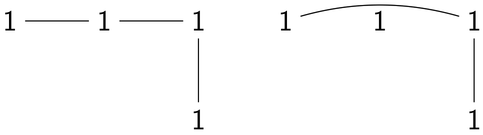
- Orientation of a minimal path must then point away from a cycle.

Idea: necessity

- Orientation of a minimal path must then point away from a cycle.
- Two connected cycles $\Rightarrow$ connecting path must point away from both.

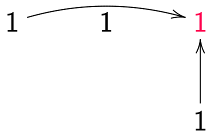
Idea: necessity

Subsequent edges in a minimal path must be at a right angle:



Idea: necessity

Two connected cycles ⇒ connecting path must point away from both.
So connected path does (at some point):



⇒ no two connected cycles.

Idea: sufficiency

- Given X, construct an orientation of (V, L).
- Use orientation to define preferences.

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- Decompose (V, L) in connected components. At most one cycle in each.

Idea: sufficiency

- Given X, construct an orientation of (V, L).
- Use orientation to define preferences.
- Decompose (V, L) in connected components. At most one cycle in each.
- Orient cycle as a "flow," and paths as "flows" pointing away from cycle.
- Uniqueness of cycle within a component ensures transitivity.

Recall

Theorem

Let X be a matching. The following statements are equivalent:

1. *X is rationalizable as a M-optimal stable matching;*
2. *X is rationalizable as a W-optimal stable matching;*
3. *X is rationalizable as the unique stable matching;*
4. *the graph G associated to X has no cycles.*

Idea: necessity.

Canonical cycle:

$$\begin{array}{ccc} 1 & \longrightarrow & 1 \\ \uparrow & & \downarrow \\ 1 & \longleftarrow & 1 \end{array}$$

Idea: necessity.

Canonical cycle:

$$\begin{array}{ccc} 0 & \longrightarrow & 2 \\ \uparrow & & \downarrow \\ 2 & \longleftarrow & 0 \end{array}$$

Idea: sufficiency.

Suppose that (V, L) has no cycles. Fix $v_0 \in V$.
Let $\eta(v) =$ length of path $v_0, \ldots, v$ in (V, L)
Let $\eta(v)$ be utility of match of man and woman in v.

▸ Application

Estimation

Parametrized preferences:

$$u_{ij} = Z_{ij}\beta + \varepsilon_{ij}, \tag{2}$$

$$d_{ijk} \equiv \mathbf{1}(u_{ij} \geq u_{ik}).$$

Recall:

An *antiedge* is a pair $(i,j),(k,l)$ with $i \neq k \in M;\ j \neq l \in W$ s.t. $X_{ij} = X_{kl} = 1$.
Then X is stable iff

$$(ij),(kl) \text{ is anti-edge } \Rightarrow \begin{cases} d_{ilj}d_{lik} = 0 \\ d_{jki}d_{kjl} = 0 \end{cases} \qquad (3)$$

Estimation

$$
\begin{aligned}
Pr((ij),(kl) \text{ antiedge}) &\leq (1 - Pr(d_{ilj}d_{lik} = 1))(1 - Pr(d_{jki}d_{kjl} = 1)) \\
&= Pr(d_{ilj}d_{lik} = 0, d_{jki}d_{kjl} = 0).
\end{aligned}
$$

Estimation

$$\begin{aligned} Pr((ij),(kl) \text{ antiedge}) &\leq (1 - Pr(d_{ilj}d_{lik} = 1))(1 - Pr(d_{jki}d_{kjl} = 1)) \\ &= Pr(d_{ilj}d_{lik} = 0, d_{jki}d_{kjl} = 0). \end{aligned}$$

Gives a moment inequality:

$$\mathbb{E}\underbrace{\left[\mathbb{1}((ij),(kl) \text{ antiedge}) - Pr(d_{ilj}d_{lik} = 0, d_{jki}d_{kjl} = 0; \beta)\right]}_{g_{ijkl}(X_t;\beta)} \leq 0.$$

The identified set is defined as

$$\mathbb{B}_0 = \left\{\beta : \mathbb{E}g_{ijkl}(X_t;\beta) \leq 0,\ \forall i,j,k,l\right\}.$$

Estimation

Sample analog

$$\frac{1}{T}\sum_t \mathbb{1}((ij),(kl) \text{ is antiedge in } X_t) - 1$$

$$+ Pr(d_{ilj}d_{lik} = 0, d_{jki}d_{kjl} = 0; \beta)$$

$$= \frac{1}{T}\sum_t g_{ijkl}(X_t;\beta).$$

Estimation

Problem: condition in the theorem is violated.
Hence no preferences (no betas) rationalize data.

Estimation

Problem: condition in the theorem is violated.
Hence no preferences (no betas) rationalize data.

We relax the model ($\exists$ other solutions).

Estimation – Relaxation of the model

A blocking pair may not form.

$$\delta_{ijkl} = P(\text{types } (i,j), (k,l) \text{ communicate}).$$

Idea: a BP forms only when types (i,j), (k,l) communicate.
Then stability condition becomes:

$$\begin{pmatrix} (ij),(kl) \text{ is anti-edge} \\ (ij),(kl) \text{ meet} \end{pmatrix} \Rightarrow \begin{cases} d_{ilj}d_{lik} = 0 \\ d_{jki}d_{kjl} = 0 \end{cases}$$

Modified moment inequality:

$$Pr((ij),(kl) \text{ antiedge}) * \delta_{ijkl} \leq Pr(d_{ilj}d_{lik} = 0, d_{jki}d_{kjl} = 0; \beta)$$

Assume: two events are independent.

Estimation – Relaxation of the model

We put some structure on "communication probabiliites". We allow δ_{ijkl} to vary across antiedges $(ij),(kl)$, depending on the number of (ij) and (kl) couples:

$$\delta_{ijkl} = \min\left\{2 \cdot \gamma \frac{|X_{T_i^M, T_j^W}|}{|X|} \cdot \frac{|X_{T_k^M, T_l^W}|}{|X|}, 1\right\}.$$

where $\gamma > 0$ is a tuning parameter (higher is more restrictive).
δ^t_{ijkl} set to the number of potential blocking pairs which can form between (ij) and (kl) couples, as a proportion of total number of potential couples in the population $|X|^2$.
Essentially: we weigh/smooth anti-edges by # agents involved.

Specification of Utilities

Men:

$$Utility^{m,w} = \beta_1 |Age^m - Age^w|^- + \beta_2 |Age^m - Age^w|^+ + \varepsilon^{m,w}$$

Women:

$$Utility^{w,m} = \beta_3 |Age^m - Age^w|^- + \beta_4 |Age^m - Age^w|^+ + \varepsilon^{w,m}$$

Intepretation of preference parameters:

- $\beta_1(\beta_3) > 0$: when wife older, men (women) prefer larger age gap; men prefer older women, women prefer younger men
- $\beta_2(\beta_4) > 0$: when husband older, men (women) prefer larger age gap; men prefer younger women, women prefer older men

Results: Identified set.

We describe the identified set for different values of γ.

if γ is too high $\Rightarrow$ identified set $= \emptyset$.
if γ is too low $\Rightarrow$ identified set is everything.

Idea: choose high γ to "discipline" our estimates:

Table: Unconditional Bounds of β.

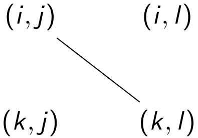
	β_1		β_2		β_3		β_4	
γ	min	max	min	max	min	max	min	max
25	-2.00	2.00	-2.00	2.00	-2.00	2.00	-2.00	2.00
28	-2.00	1.60	-2.00	2.00	-2.00	1.60	-2.00	2.00
29	-2.00	0.40	-2.00	1.80	-2.00	0.40	-2.00	1.80
30	-2.00	-0.80	-2.00	0.60	-2.00	-0.85	-2.00	0.60

Joint identified sets

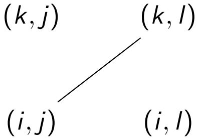
Some guidance for interpreting identified sets

- More anti-edges below the diagonal, where $age^m > age^w$. So focus on β_2, β_4 (lower triangular preferences)
- More "downward-sloping" anti-edges than "upward-sloping"

Downward-sloping anti-edge:



Upward-sloping anti-edge:



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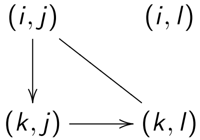

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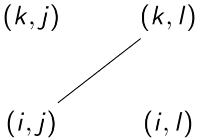

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if women prefer younger men, then men prefer younger women
Do we see this in identified sets? Consider slices of identified set

Related Literature (empirical – field data)

- TU: Choo-Siow (2006), Fox (2007), Galichon-Salanié (2009), Chiappori-Salanié-Weiss (2010)
- NTU: Dagsvik (2000), Echenique (2008)

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- econometric approach: moment inequalities derived from stability.