Ignorance is Strength: Improving Performance of Decentralized Matching Markets by Limiting Information

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Decentralized Matching Markets

In *matching markets*, both buyers and sellers have preferences over the other side

- labor market
- rental housing
- transportation
- dating
- coaching, massage
- kidney exchange
- etc.

In a *decentralized* matching market, participants on one side search for suitable options on the other side

Search Externalities

Two sides: buyers and workers

Cross-side Search Externality

When participants on the one side shop for better options, they waste the other side's time and/or search effort

Same-side (Scheduling Externality)

When a worker rejects offers from buyers, he keeps himself available and decreases other workers' chances of getting good subsequent buyers

▸ Congestion

Examples

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- Airbnb hosts reject 20% of guest inquiries due to screening (Fradkin 2015)
- If Uber drivers were allowed to cherry pick rides, passengers would have to wait longer
- On Upwork (labor platform for freelancers), workers prefer receiving many inquiries from employers, while employers prefer to find a worker in a single interaction session (Horton 2015)

Platform Design

Platform's value proposition is to facilitate matching

- Standard economics literature on two-sided platforms (Rochet-Tirole 2006, Weyl 2010, Armstrong 2006) studies how pricing affects participation and assumes the matching system is fixed
- Wide variety of policies that have economic effects:
  - structured search
  - information structure
  - flexible pricing
  - recommendation systems

Information Disclosure

- We know that information disclosure facilitates trade and exchange (Blackwell 1953, Akerlof 1970, Myerson-Saterthwaite 1983, Lewis 2011)
- However, information availability increases perceived diversity of options -> induces more shopping -> matches take longer to consummate
- Other problems with info disclosure: excessive signaling (Hoppe et al. 2009), failure to share risk (Hirschleifer 1971)

Question

What should be information disclosure policy in matching markets?

Examples

- Passenger attributes on Uber: show/not show destination, gender
- Star ratings: half-star step/10th-of-star step
- Guest's gender, age on Airbnb: show/not show

Conceptual Preview of Results

Important Observation #1

In decentralized matching markets, there is a problem of excessive search which results in negative cross-side and same-side effects

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Important Observation #2

Platform's policy of *coarse* revelation of buyer information alleviates the workers' excessive search problem

Preview of Results

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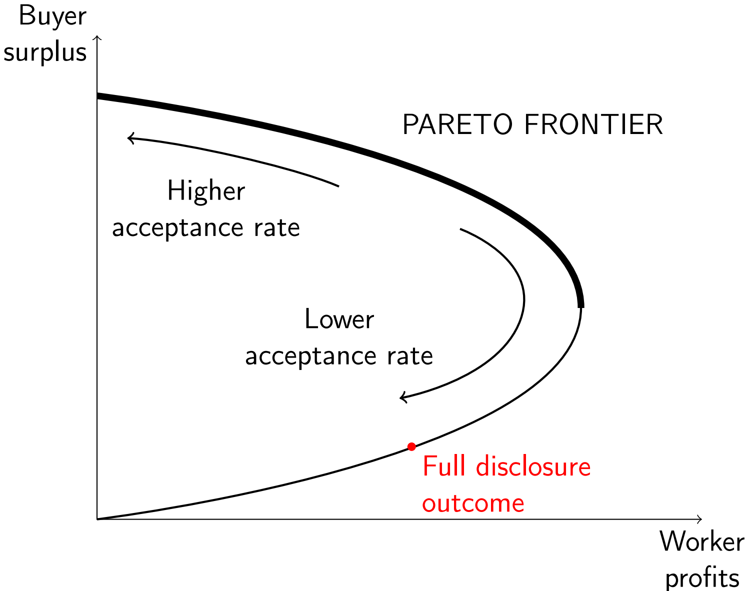
3. Unmediated market -> market outcome is Pareto dominated due to *scheduling externality*
    - Unmediated = full disclosure

Preview of Results



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   - Unmediated = full disclosure

4. Optimal disclosure in linear payoff environment to maximize #matches. Coarsen information if
   - there are more high-skill workers than low-skill workers
   - higher buyer-to-worker ratio
   - capacity constraints are more severe

Related Literature

Two-sided markets: Rochet-Tirole 2006, Armstrong 2006, Weyl 2010

Communication games: Blackwell 1953, Aumann-Maschler 1995, Kamenica-Gentzkow 2011, Kolotilin et al. 2015, Bergemann et al. 2015

Information disclosure in markets: Akerlof 1970, Hirshleifer 1971, Anderson-Renault 1999, Hoppe et al. 2009, Athey-Gans 2010, Bergemann-Bonatti 2011, Tadelis-Zettelmeyer 2015, Board-Lu 2015

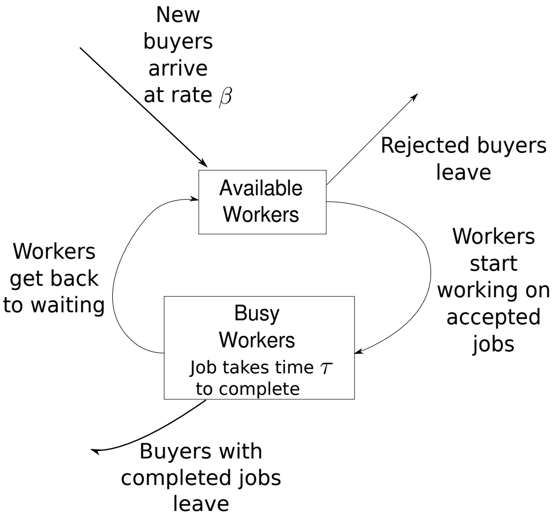
Matching in Labor: Becker 1973, Shimer-Smith 2000, Kircher 2009

Market Design: Roth 2008, Milgrom 2010, Akbarpour et al. 2016

Peer-to-peer markets: Fradkin 2015, Horton 2015

Platforms in OR: Ashlagi et al. 2013, Arnosti et al. 2014, Taylor 2016

Spot Matching Process



Spot Matching Process, ctd

- Continuous time
- Mass 1 of workers, stay on the platform
  - presented with a sequence of job offers at Poisson rate
  - decides to accept or reject
- Accepted job takes time τ to complete
  - during which the worker cannot accept new jobs
- Continuum of potential buyers, short-lived
  - gradually arrive at rate β
  - one buyer - one job
- Buyer search is costly:
  - job accepted -> buyer stays until the job is completed
  - rejected -> leave

Heterogeneity and Payoffs

	Buyers	Workers
Type	$x \in X \subset \mathbb{R}^n$	$y \in Y \subset \mathbb{R}^m$
Cdf, pdf	$F,\ f > 0$	$G,\ g > 0$
1-match net payoff (net of prices)	$u(x, y) \geq 0$	$\pi(x, y) \gtrless 0$
Outside option	0	0

- X, Y – convex subsets of Euclidean spaces
- $F(x)$ and $G(y)$ have full support
- $\pi(x, y)$ continuous
- $\min_x \pi(x, y) < 0 < \max_x \pi(x, y)$ for all y
- $u(x, y) \geq 0$ for any x, y

Spot Matching Process, ctd

τ – time to complete any job
β – buyer arrival rate (mass of buyers per unit of time)

Assumption (Buyer Search is Perfectly Frictional)

Buyers contact an available worker chosen uniformly at random

- Relaxed in an extension in the paper

Assumption (No Excess Demand)

Collectively, it is physically possible for workers to complete every buyer job: $\beta\tau < 1$

- Simplifies the notation, otherwise deal with queues
- Easy extension in the paper

Intermediary: Information Disclosure

Information structure:

- Platform observes buyer type x but not worker type y
- Worker observes his y but not x

Platform chooses how to reveal x to workers

- $S = \Delta(X)$ set of all possible signals
  - $s \in S$ is posterior distribution of x
- $\mu \in \Delta(S)$ disclosure policy
  $=$ distribution of posteriors
- Platform does not elicit y

Steady State of the Matching Process

State of the matching system:

1. $\alpha(y) \in [0, 1]$ *acceptance rate*
   - fraction of jobs accepted by available type-y worker, $\alpha(y) = \mu(s \text{ is accepted by } y | y \text{ is available})$
2. $\rho(y) \in [0, 1]$ fraction of time type-y worker is busy
   - capacity *utilization rate* of type-y workers
   - Worker's constrained resource is time
     - capacity $= 1$
     - capacity utilization rate – proportion of capacity which is actually realized

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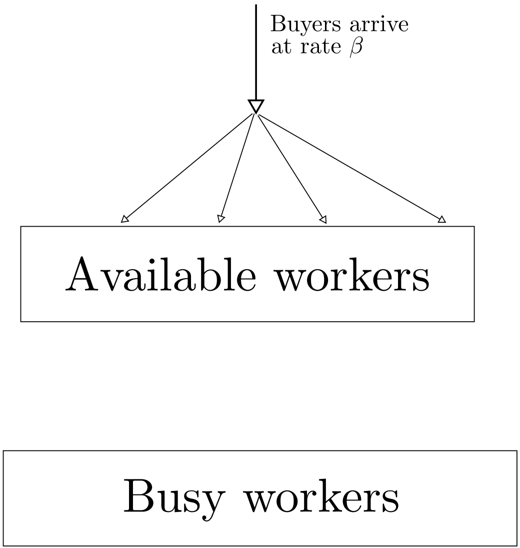
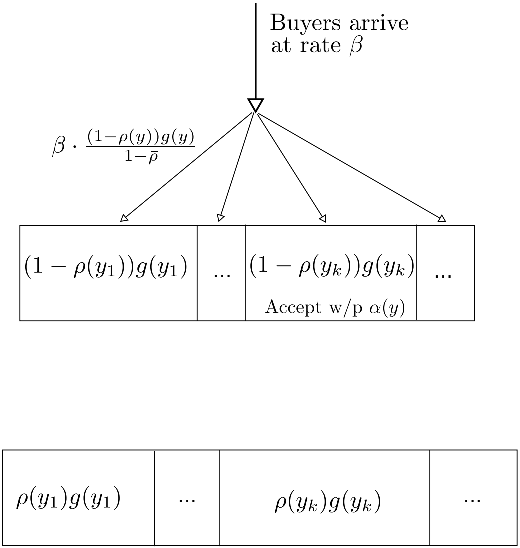


Steady State of the Matching Process

- $g(y)$ mass of y-workers
- $\rho(y)$ utilization rate of y
- $\bar{\rho}$ average utilization



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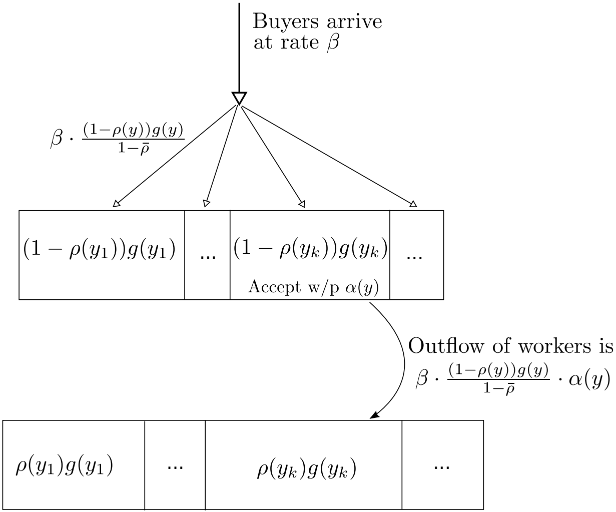

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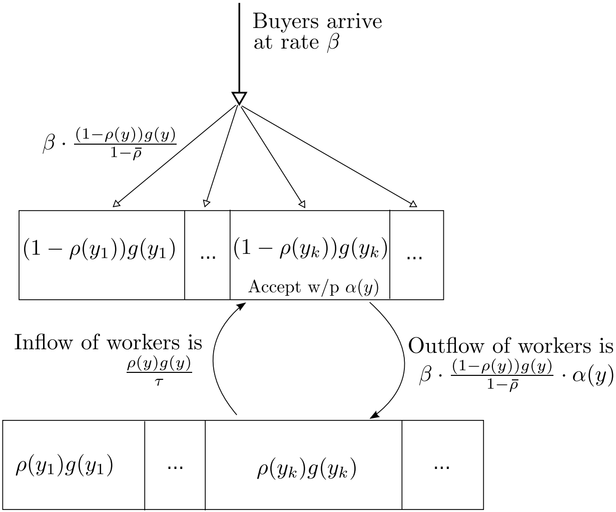

Steady State of the Matching Process

In a steady state, the flows to and from the pool of busy workers are equal:

$$\beta \frac{(1-\rho(y))g(y)}{1-\bar{\rho}} \alpha(y) = \frac{\rho(y)g(y)}{\tau}, \quad \forall y \in Y.$$

Solution

Average utilization rate $\bar{\rho} \in [0,1]$ is a solution to

$$1 = \int \frac{dG(y)}{1-\bar{\rho}+\beta\tau\alpha(y)}$$

$\bar{\rho}$ increases in $\alpha(y)$ for any $y \in Y$, in β and in τ

Worker Repeated Search Problem

- β_A – buyer Poisson arrival rate when a worker is available
  - β_A is endogenous b/c mass of available workers is endogenous
- $\pi(s, y) := \int_X \pi(x, y)\, s(dx)$ expected profit for worker y of job with signal s
- Every time a job with signal s arrives, worker y gets $v(s, y)$
  - $v(s, y)$ includes option value of rejecting and opportunity cost of being unavailable
- $V(y)$ per-moment value of being available, in the optimum

Worker optimization problem

$$\begin{cases} v(s, y) = \max\{0, \pi(s, y) - \tau V(y)\} \\ V(y) = \beta_A \int v(s, y)\, \mu(ds) \end{cases}$$

- No discounting

Impatient Workers

- $\sigma(s, y)\colon S \to [0, 1]$ acceptance strategy

Steady-State Equilibrium

$(\sigma, \bar{\rho})$ is a *steady-state equilibrium* if

1. [Optimality] Every available worker takes as given Poisson arrival rate $\beta_A = \beta/(1 - \bar{\rho})$ and acts optimally –> σ
2. [SS] σ induces acceptance rates $\alpha(\cdot)$ –> utilization $\bar{\rho}$ arises in a steady state

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Proposition (1)

Steady-state equilibrium exists and is unique.

Market Design: Information Disclosure

Equilibrium $(\sigma, \bar{\rho})$ is a function of disclosure policy μ

How does equilibrium welfare of each side depend on μ?

Pareto Optimality and Implementability

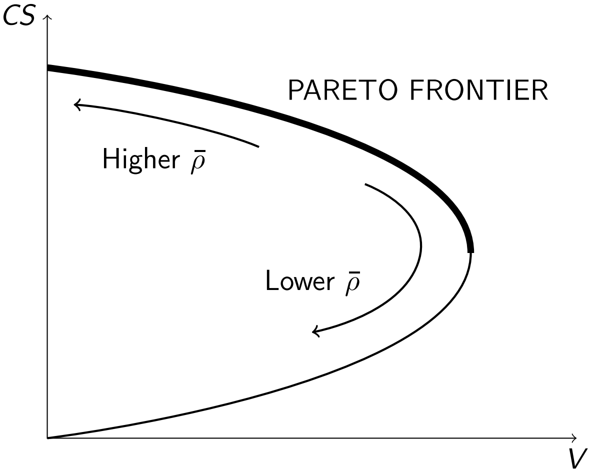
- Market outcome $O = (\{V(y)\}, CS)$ is a combination of worker profits and consumer surplus
- Market outcome is *feasible* if
  1. there are acceptance strategies for workers that generate it, and
  2. $V(y) \geq 0$ for all y
- A feasible O is *Pareto optimal* if there is no other feasible O' such that $V(y)' > V(y)$ for all y, and $CS' > CS$
- O is *implementable* if there is a disclosure μ such that the equilibrium outcome is O

Implementability for Identical Workers

Proposition (2)

Suppose workers are identical. Then any point on the Pareto frontier is implementable by information disclosure.

Implementability for Identical Workers, ctd



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Proof sketch:

1. 1 worker type, 2 actions -> $X = X_{acc} \cup X_{rej}$ -> binary signaling structure is sufficient
2. With binary signaling structure, worker dynamic problem reduces to static problem
3. Obedience holds because the worker gets V on X_{acc} and $V \geq 0$ by feasibility

Why Information Coarsening Trades off Buyer and Worker Surplus

Intuition for static case with 1 worker

Based on standard information disclosure (Aumann-Maschler 1995, Kamenica-Gentzkow 2011)

-$50	…	-$1	$0	$1	$2	…	$50

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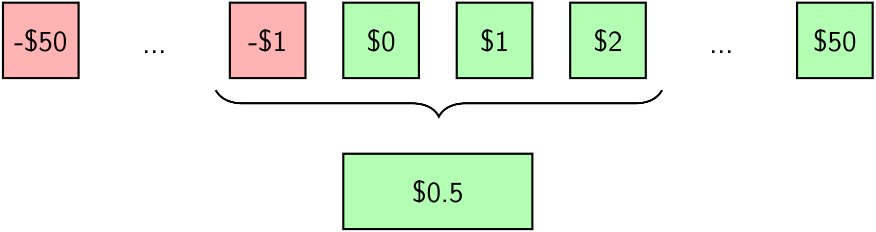


Worker Coordination Problem

- Back to general Y

Worker Coordination Problem

- Back to general Y
- $V^{\sigma}(y)$, $\rho^{\sigma}(y)$, CS^{σ} denote steady-state profits, utilization rates and consumer surplus when strategy profile σ is played

Proposition (3)

Let σ^{FD} be the equilibrium strategy profile under full disclosure. Then there exists $\tilde{\sigma}$ such that for all y:

$$\begin{aligned} \tilde{V}(y) &> V^{FD}(y), \\ \tilde{\rho}(y) &> \rho^{FD}(y), \\ \widetilde{CS} &\geq CS^{FD}. \end{aligned}$$

Worker Coordination Problem, ctd

- Coordination problem, intuitively:
  - a worker keeps his schedule open by rejecting low-value jobs to increase his individual chances of getting high-value jobs
  - as a result in eqm, workers spend a lot of time waiting for high-value jobs
  - collectively, this behavior is suboptimal because all profitable jobs have to be completed
    (feasible by No Excess Demand assumption)

- *Scheduling externality*: by rejecting a job a worker makes himself available and decreases the other workers' chances of getting subsequent jobs.

- Fundamentally, workers jointly are not capacity constrained (in time) while individually, they *are* capacity constrained.e

Proof Sketch

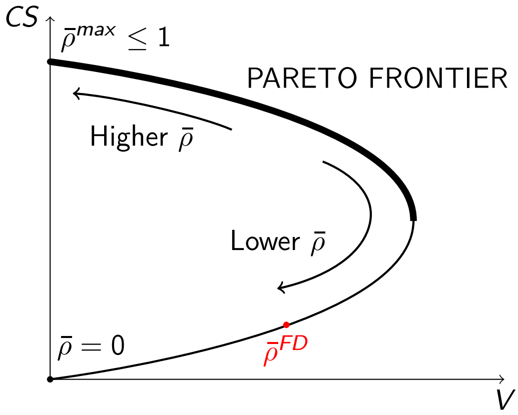
For the case of identical workers

1. X convex, π cts in x –> $V > 0$
2. Individually:
   - Worker's option value of rejecting is

     $$\tau V > 0$$

   - in eqm, accepted jobs have profit $\pi \geq \tau V$
   - all profitable jobs are $\pi \geq 0$
   - so, some profitable jobs are rejected
3. Collectively:
   - no capacity constraint in aggregate => zero option value of rejecting
   - accepted jobs have $\pi \geq 0$

Worker Coordination Problem, Identical Workers



Implement a Pareto improvement with heterogeneous workers?

- Generally not -> next section

Linear Payoff Environment

- $X = [0, 1]$
  - e.g. job difficulty
- $Y = [0, \bar{y}]$
  - e.g. worker skill
- $\pi(x, y) = y - x$
- Platform does not elicit y

Maximal #Matches

- Imagine the platform is growing and wants to maximize #matches
- What is the optimal disclosure policy?
- Equivalent to maximizing capacity utilization:

$$\max_{\mu \in \Delta(S)} \bar{\rho}$$

- Pareto efficient outcome

The problem is not trivial because:

1. workers are heterogeneous
2. disclosure affects workers' option value
3. disclosure alters equilibrium value of arrival rate β_A

Static Case

Benchmark

Suppose $\tau = 0$ (static setting). Then:

- If g is decreasing, then full disclosure is optimal
- If g is increasing, no disclosure is optimal.
- If g is constant, then utilization rate is information neutral

- Appears e.g. in Kolotilin et al. 2015
- The concavification reasoning goes back to Aumann-Maschler 1995 and Kamenica-Gentzkow 2011

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Optimal Disclosure for Uniform Worker Distribution

Definition

Disclosure μ is x^*-*upper-censorship* for $x^* \in [0,1]$ if μ reveals $x < x^*$ and pools all $x > x^*$

Proposition (4)

Assume $G = U[0, \bar{y}]$. Then there is unique $x^* \in X$ such that x^*-upper-censorship is optimal.
Furthermore,

- *if $\beta\tau < 1/2$, then $x^* = 1$ (full disclosure is strictly optimal)*
- *if $\bar{y}$ is large enough, then there is $\chi^* \in (1/2, 1)$ such that if $\beta\tau > \chi^*$, then $x^* < 1$ (some coarsening is strictly optimal)*

Intuition

Additional effects in dynamic matching:

- availability effect
  - high types accept more jobs -> less available -> pdf of available workers is decreasing
  - -> motivation for platform to reveal x
- patience effect
  - high types have larger pool of profitable jobs -> larger opportunity cost of accepting
  - -> motivation for platform to conceal high x's
  - overcomes availability effect when there are very high worker types (large $\bar{y}$) and strong buyer traffic (large β)

Optimality of Information Coarsening: General G

Proposition (5)

There is $\xi^* \in \mathbb{R}$ such that if

$$g'(\bar{y})/g(\bar{y}) > \xi^*,$$

then full disclosure is sub-optimal. Furthermore, if $\bar{y}$ is large enough, then there is $\chi^* \in (1/2, 1)$ such that if

$$\beta\tau > \chi^*,$$

then $\xi^* < 0$.

Worker Optimization Problem

- $Z = \left\{ \int x\, s(dx) \colon s \in S \right\}$ is the set of posterior means of x
- $F^\mu(\zeta) = \mu \left\{ \int x\, s(dx) \leq \zeta \right\}$ is the cdf of posterior means of x under μ

Lemma (1)

For any disclosure policy μ, worker's optimal strategy has a cutoff form. Furthermore, worker cutoff $\hat{z}(y)$ is the solution to:

$$y - \hat{z}(y) = \tau \beta_A W^\mu(\hat{z}(y))$$

where

$$W^\mu(z) := \int_0^z (z - \zeta) dF^\mu(\zeta)$$

is the option value function.

Disclosure Policy Representation

- $\overline{W}$ option value function under full disclosure,

$$\overline{W}(z) := \int_0^z F(\xi)d\xi.$$

- $\underline{W}$ be the option value function under no disclosure,

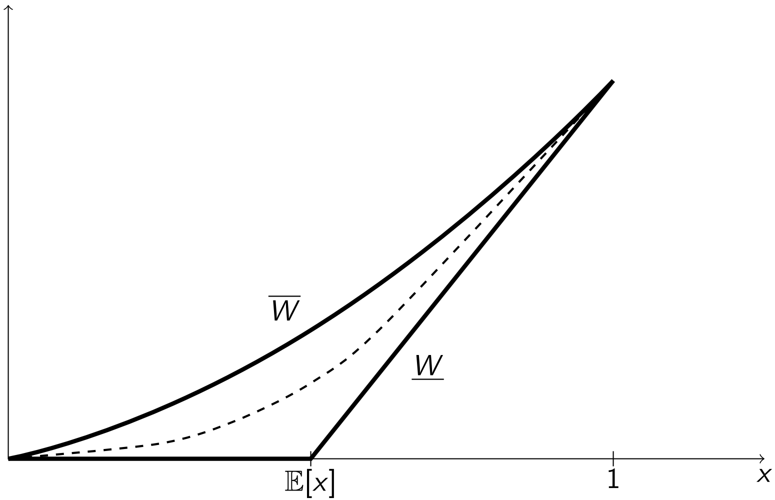
$$\underline{W}(z) := \max\{0, z - \mathbb{E}[x]\}.$$

Lemma (2)

Option value function W is implementable by some disclosure policy if and only if W is a convex function point-wise between $\overline{W}$ and $\underline{W}$.

- e.g. appears in Kolotilin et al. 2015
- Proof idea: Distribution of x is the mean preserving spread of distribution of posterior means of x

Disclosure Policy Representation, ctd



First Order Condition

- Use representation of disclosure policy via W
- Use calculus of variations to write down the optimality condition

Lemma (3: Main lemma)

The first variation of $\bar{\rho}$ with respect to W exists and is proportional to:

$$\frac{\delta\bar{\rho}}{\delta W} \propto -\left(g(y)(1-\rho(y))^2\right)' - g(y)\rho'(y).$$

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Corollary

Suppose $\tau = 0$ (static setting). Then

$$\frac{\delta \bar{\rho}}{\delta W} \propto -g'(y).$$

If G is concave, then full disclosure is optimal. If G is convex, no disclosure is optimal.

Intuition: Uniform Distribution of Worker Skill

- Consider $G = U[0,1]$
- In statics ($\tau = 0$),
$$\frac{\delta\bar{\rho}}{\delta W} = 0, \quad \forall W.$$
- If $\tau > 0$,
$$\frac{\delta\bar{\rho}}{\delta W} \propto -(\overbrace{\underbrace{(1-\rho(y))^2}_{\text{availability factor}} + \underbrace{\rho(y)}_{\text{patience factor}}}^{\text{"adjusted density"}})'.$$
- Additional effects:
  - availability effect
  - patience effect

Proof of Proposition 4

Sketch

1. Need to show that at $\overline{W}(y)$, there is deviation $\delta W(y)$ such that $\delta\bar{\rho} > 0$.
2. $\frac{(\rho(y)-\rho(y)^2)'}{(1-\rho(y))^2} < \frac{g'(y)}{g(y)}$ for some interval of y's
3. LHS decreasing in y so take $\delta W(y)$ such that $\delta W(\bar{y}) < 0$

Optimality of Full Disclosure

Proposition (6: Sufficient condition for local optimality of full disclosure)

If G is concave, and $\beta\tau < 1/2$, then it's impossible to improve upon full disclosure by "local coarsening".

Optimality of No Disclosure

Proposition (7: Necessary condition for optimality of no disclosure)

If

$$g'(y) < g(\mathbb{E}x)\tau\beta(1-\beta\tau)^2, \quad \forall y,$$

then no disclosure is suboptimal.

Conclusion

Summary

- In decentralized matching markets, there is a problem of excessive search
  - one side does not internalize time value and search efforts of the other side
  - workers compete for the best jobs by ignoring other valuable jobs
- Full disclosure -> workers are under-utilized and welfare is lost
- Information coarsening can be Pareto improving and increase benefits of participation on both sides of the market
  - when workers are homogenous
  - there are more high-skill workers than low-skill workers
  - higher buyer-to-worker ratio
  - capacity constraints are more severe

Further Directions

- Optimal pricing and disclosure to maximize revenue
- Non-information design
  - Limits on acceptance rate
  - Ranked workers

Congestion?

1. Roth 2008: "a situation in which the participants do not have time to consider multiple alternative options because they disappear from the market too fast"
2. In congested markets, participants send more applications than is desirable
3. Same-side effect: as application costs are lowered, the increase in applications leads to the situation that many applications that are sent are never even screened
4. Cross-side effect: employers find that suitable applicants have been already matched (AJK14)

Back

Impatient Workers

Results generalize to the case when the worker has discount rate ρ by changing τ to

$$\tau_\rho = \frac{1 - e^{-\rho\tau}}{\rho}$$

Back