Recovering Preferences from Finite Data

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This paper

- In a *revealed preference* model: When can we uniquely recover the data-generating preference as the dataset grows large?
- In an *statistical model*: Propose a consistent estimator.
- Unifying framework for both.

Applications:
- Expected utility preferences.
- Intertemporal consumption with discounted utility.
- Choice on commodity bundles.
- Choice over menus.
- Choice over dated rewards.
- ...
Model

Alice (an experimenter)

Bob (a subject)
Alice presents Bob with choice problems:

“Hey Bob would you like x or y?”

Bob chooses one alternative.

Rinse and repeat → dataset of $n$ choices.
Model

- Alternatives: A topological space $X$.
- Preference: A complete and continuous binary relation $\succeq$ over $X$.
- $\mathcal{P}$ a set of preferences.

A pair $(X, \mathcal{P})$ is a preference environment.
Examples

Expected utility preferences:

- There are $d$ prizes.
- $X$ is the set of lotteries over the prizes, $\Delta^{d-1} \subset \mathbb{R}^d$.
- An EU preference $\succeq$ is defined by $v \in \mathbb{R}^d$ such that $p \succeq p'$ iff $v \cdot p \geq v \cdot p'$.
- $\mathcal{P}$ is set of all the EU preferences.

Preferences on commodity bundles:

- There are $d$ commodities.
- $X \equiv \mathbb{R}^d_+$, the $i$-th entry of a vector is quantity consumed of $i$-th good.
- $\mathcal{P}$ is set of all monotone preferences on $X$. 
Alice wants to recover Bob’s preference from his choices.

- Binary choice problem: \( \{x, y\} \subset X \).
- Bob is asked to choose \( x \) or \( y \).
  Behavior encoded by a choice function \( c(\{x, y\}) \in \{x, y\} \).
- Partial observability: indifference is not observable.
Experiment

Alice gets finite dataset.

- Experiment of length $n$: $\Sigma_n = \{B_1, \ldots, B_n\}$ with $B_k = \{x_k, y_k\}$.
- Set of growing experiments: $\{\Sigma_n\} = \{\Sigma_1, \Sigma_2, \ldots\}$ with $\Sigma_n \subset \Sigma_{n+1}$. 
Literature

Afriat’s theorem and revealed preference tests: Afriat (1967); Diewert (1973); Varian (1982); Matzkin (1991); Chavas and Cox (1993); Brown and Matzkin (1996); Forges and Minelli (2009); Carvajal, Deb, Fenske, and Quah (2013); Reny (2015); Nishimura, Ok, and Quah (2017)

Recoverability: Varian (1982); Cherchye, De Rock, and Vermeulen (2011)

Consistency: Mas-Colell (1978); Forges and Minelli (2009); Kübler and Polemarchakis (2017); Polemarchakis, Selden, and Song (2017)

Identification: Matzkin (2006); Gorno (2019)

Econometric methods: Matzkin (2003); Blundell, Browning, and Crawford (2008); Blundell, Kristensen, and Matzkin (2010); Halevy, Persitz, and Zrill (2018)
What’s new?

Unified framework: rev. pref. and econometrics.
What’s new?

- Binary choice
- Finite data
- “Consistency” – Large sample theory
- Unified framework: RP and econometrics.
OK, so far:

- $(X, \mathcal{P})$ preference env.
- $c$ encodes choice
- $\Sigma_n$ seq. of experiments
Rationalization/ Estimation

- Revealed Preference: A preference $\succeq$ rationalizes the observed choices on $\Sigma_n$ if $\{x, y\} \in \Sigma_n$, $c(\{x, y\}) \succeq x$ and $c(\{x, y\}) \succeq y$.
- Statistical model: preference estimate ...
Topology on preferences

Choice of topology: closed convergence topology.

- Standard topology on preferences (Kannai, 1970; Mertens (1970); Hildenbrand, 1970).

- \( \succeq_n \to \succeq \) when:
  1. For all \((x, y) \in \succeq\), there exists a seq. \((x_n, y_n) \in \succ_n\) that converges to \((x, y)\).
  2. If a subsequence \((x_{n_k}, y_{n_k}) \in \succeq_{n_k}\) converges, the limit belongs to \( \succeq \).

- If \(X\) is compact and metrizable, same as convergence under the Hausdorff metric.

- \(X\) Euclidean and \(B\) the strict parts of cont. weak orders. Then it’s the smallest topology for which the set

\[
\{(x, y, \succ) : x \in X, y \in X, \succ \in B \text{ and } x \succ y\}
\]

is open.
Examples

Set of alternatives $X = [0, 1]$.

- Left: the subject prefers $x$ to $y$ iff $x \geq y$.
- Right: the subject is completely indifferent.
Preference

n=1
Preference

n=2
Preference

\( n = 8 \)
Discipline matters.
Non-closed $\mathcal{P}$
Non-closed $\mathcal{P}$
$P$ must be closed, and some standard models are *not* closed.
Assumption 1: $X$ is a locally compact, separable, and completely metrizable space.
Topology on preferences

**Lemma**
The set of all continuous binary relations on $X$ is a compact metrizable space.
Assumption on the class of preferences

\( \preceq \) is locally strict if

\[
x \succeq y \implies \text{ in every nbd. of } (x, y), \text{ there exists } (x', y') \text{ with } x' \succ y'
\]

(Border and Segal, 1994).
Assumption on the class of preferences

Assumption 2: $\mathcal{P}$ is a closed set of locally strict preferences.
Assumption on the set of experiments

A set of experiments $\{\Sigma_n\}$, with $\Sigma_n = \{B_1, \ldots, B_n\}$, is exhaustive when:

1. $\bigcup_{k=1}^{\infty} B_k$ is dense in $X$.
2. For all $x, y \in \bigcup_{k=1}^{\infty} B_k$ with $x \neq y$, there exists $k$ such that $B_k = \{x, y\}$.

Assumption 3 : $\{\Sigma_n\}$ is an exhaustive growing set of experiments.
To sum up:

Assumption 1: \( X \) is a locally compact, separable, and completely metrizable space.

Assumption 2: \( \mathcal{P} \) is a closed set of locally strict preferences.

Assumption 3: \( \{\Sigma_n\} \) is an exhaustive growing set of experiments.
First main result

Theorem 1
Suppose $c$ is an arbitrary choice function. When Assumptions (1), (2) and (3) are satisfied:

1. If, for every $n$, the preference $\succeq_n \in \mathcal{P}$ rationalizes the observed choices on $\Sigma_n$, then there exists a preference $\succeq^* \in \mathcal{P}$ such that $\succeq_n \rightarrow \succeq^*$.

2. The limiting preference is unique: if, for every $n$, $\succeq'_n \in \mathcal{P}$ rationalizes the observed choices on $\Sigma_n$, then the same limit $\succeq'_n \rightarrow \succeq^*$ obtains.

So, if the subject chooses according to some preference $\succeq^* \in \mathcal{P}$, then $\succeq_n \rightarrow \succeq^*$. 
Ideas behind the thm

Lemma

The set of all continuous binary relations on $X$ is a compact metrizable space.

Lemma

If $A \subseteq X \times X$, then $\{ \succeq \in X \times X : A \subseteq \succeq \}$ is closed.
Lemma

Consider an exhaustive set of experiments with binary choice problems \( \{x_k, y_k\}, \ k \in \mathbb{N} \). Let \( \succeq \) be any complete binary relation, and \( \succeq_A \) and \( \succeq_B \) be locally strict preferences. If, for all \( k \), \( x_k \succeq_A y_k \) and \( x_k \succeq_B y_k \) whenever \( x_k \succeq y_k \), then \( \succeq_A = \succeq_B \).
Statistical model

Given \((X, \mathcal{P})\). We change:

- How subjects make choices: they do not exactly follow a preference, but randomly deviate from it.
- How experiments are generated.
1. In a choice problem, alternatives drawn iid according to sampling distribution $\lambda$.

2. Subjects make “mistakes.”
   Upon deciding on $\{x, y\}$, a subject with preference $\succeq$ chooses $x$ over $y$ with probability $q(\succeq; x, y)$ (error probability function).

3. Only assumption: if $x \succ y$ then $q(\succeq; x, y) > 1/2$.

4. “Spatial” dependence of $q$ on $x$ and $y$ is arbitrary.
Estimator

**Kemeny-minimizing estimator**: find a preference in $\mathcal{P}$ that minimizes the number of observations inconsistent with the preference.

- “Model free:” to compute estimator don’t need to assume a specific $q$ or $\lambda$.
- May be computationally challenging (depending on $\mathcal{P}$).
Assumption 3' : $\lambda$ has full support and for all $\succeq \in \mathcal{P}$, 
$\{(x, y) : x \sim y\}$ has $\lambda$-probability 0.
Second main result

**Theorem 2 (Part A)**

Under Assumptions (1), (2), (3’), if the subject’s preference is $\succeq^* \in \mathcal{P}$ and $\succeq_n$ is the Kemeny-minimizing estimator for $\Sigma_n$, then, $\succeq_n \rightarrow \succeq^*$ in probability.
Finite data

- Our paper is about finite data.
- Finite data but large samples
- How large?
Convergence rates: Digression

The VC dimension of $\mathcal{P}$ is the largest cardinality of an experiment that can always be rationalized by $\mathcal{P}$.

A measure of how flexible $\mathcal{P}$; how prone it is to overfitting.
Think of a game between Alicia and Roberto
Alicia defends $P$; Roberto questions it.
Given is $k$
Alicia proposes a choice experiment of size $k$
Roberto fills in choices adversarially.
Alicia wins if she can rationalize the choices using $P$.
The VC dimension of $P$ is the largest $k$ for which Alicia always wins.
Convergence rates

Let $\rho$ be a metric on preferences.

\[ N(\eta, \delta) \leq \frac{2}{r(\eta)^2} \left( \sqrt{2/\delta} + C \sqrt{\text{VC}(\mathcal{P})} \right)^2 \]
Convergence rates

- Let $\rho$ be a metric on preferences.
- $N(\eta, \delta)$: smallest value of $N$ such that for all $n \geq N$, and all subject preferences $\succeq^* \in \mathcal{P}$,

$$\Pr(\rho(\succeq_n, \succeq^*) < \eta) \geq 1 - \delta.$$ 

Theorem 2 (Part B)
Under the same conditions as in Part A,

$$N(\eta, \delta) \leq \frac{2}{r(\eta)^2} \left( \sqrt{2/\delta} + C \sqrt{\text{VC}(\mathcal{P})} \right)^2$$
Convergence rates

- Let \( \rho \) be a metric on preferences.
- \( N(\eta, \delta) \): smallest value of \( N \) such that for all \( n \geq N \), and all subject preferences \( \succeq^* \in \mathcal{P} \),

\[
\Pr(\rho(\succeq_n, \succeq^*) < \eta) \geq 1 - \delta.
\]

- \( \mu(\succeq'; \succeq) \): probability that the choice of a subject with preference \( \succeq \) is consistent with preference \( \succeq' \).

\[
r(\eta) = \inf \left\{ \mu(\succeq; \succeq) - \mu(\succeq'; \succeq) : \succeq, \succeq' \in \mathcal{P}, \rho(\succeq, \succeq') \geq \eta \right\}.
\]

**Theorem 2 (Part B)**

Under the same conditions as in Part A,

\[
N(\eta, \delta) \leq \frac{2}{r(\eta)^2} \left( \sqrt{2/\delta} + C \sqrt{\text{VC}(\mathcal{P})} \right)^2
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Convergence rates

- Let $\rho$ be a metric on preferences.
- $N(\eta, \delta)$: smallest value of $N$ such that for all $n \geq N$, and all subject preferences $\succeq^* \in \mathcal{P}$,

$$\Pr(\rho(\succeq_n, \succeq^*) < \eta) \geq 1 - \delta.$$  

- $\mu(\succeq'; \succeq)$: probability that the choice of a subject with preference $\succeq$ is consistent with preference $\succeq'$. 

$$r(\eta) = \inf \left\{ \mu(\succeq; \succeq) - \mu(\succeq'; \succeq) : \succeq, \succeq' \in \mathcal{P}, \rho(\succeq, \succeq') \geq \eta \right\}.$$  

- $\text{VC}(\mathcal{P})$ the VC dimension of the class $\mathcal{P}$.

Theorem 2 (Part B)

Under the same conditions as in Part A,

$$N(\eta, \delta) \leq \frac{2}{r(\eta)^2} \left( \sqrt{2/\delta} + C \sqrt{\text{VC}(\mathcal{P})} \right)^2$$
Expected utility

1. $X$ is the set of lotteries over $d$ prizes.

2. $\mathcal{P}$ is the set of nonconstant EU preferences: there are always lotteries $p, p'$ such as $p$ is strictly preferred to $p'$.

This preference environment satisfies Assumptions 1 and 2.

Suppose: there is $C > 0$ and $k > 0$ s.t

$$q(x, y; \succeq) \geq \frac{1}{2} + C(v \cdot x - v \cdot y)^k,$$

when $x \succeq y$ and $v$ represents $\succeq$. 
Under these assumptions, we can bound $r(\eta)$ and $\text{VC}(\mathcal{P})$, which implies

$$N(\eta, \delta) = O \left( \frac{1}{\delta \eta^{4d-2}} \right).$$

Other examples: Cobb-Douglas, CES, and CARA subjective EU preferences, and intertemporal choice with discounted, Lipschitz-bounded utilities.
Monotone preferences

- $K$ be a compact set in $X \equiv \mathbb{R}^d_{++}$, and fix $\theta > 0$.
- $\mathcal{P}$ has finite VC-dimension and is identified on $K$.
- $\lambda$ is the uniform probability measure on $K^{\theta/2}$.
- $q$ satisfies: probability of choosing $y$ instead of $x$ when $x \succ y$ is a function of $\|x - y\|$,.

**Proposition**

The Kemeny-minimizing estimator is consistent and, as $\eta \to 0$ and $\delta \to 0$,

$$N(\eta, \delta) = O \left( \frac{1}{\eta^{2d+2}} \ln \frac{1}{\delta} \right).$$
Applications: preferences from utilities

A set $\mathcal{P}$ is defined from utilities when there is a class $\mathcal{U}$ of utility functions such that for all $\succeq \in \mathcal{P}$

$$x \succeq y \iff U(x) \geq U(y)$$

for some $U \in \mathcal{U}$.

**Proposition 1**

Under Assumption 1, if $\mathcal{U}$ is compact and represents locally strict preferences, then Assumption 2 is met.

Implied by the continuity theorem of Border and Segal (1994).
Revisit the case of expected utility preferences:

1. \( X \) is the set of lotteries over \( d \) prizes.
2. \( \mathcal{P} \) is the set of \textbf{nonconstant} EU preferences: there are always lotteries \( p, p' \) such as \( p \) is strictly preferred to \( p' \).

This preference environment satisfies Assumptions 1 and 2. When the probability of error of choosing \( y \) instead of \( x \) when \( x \succ y \) is a function of \( \|x - y\| \), we can bound \( r(\eta) \) and \( \text{VC}(\mathcal{P}) \), which implies

\[
N(\eta, \delta) = O \left( \frac{1}{\delta \eta^{4d-2}} \right).
\]

Other examples: Cobb-Douglas, CES, and CARA subjective EU preferences, and intertemporal choice with discounted, Lipschitz-bounded utilities.
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Applications: monotone preferences

- Call a dominance relation any binary relation on $X$ that is not reflexive.

- Say that $\succeq$ is strictly monotone wrt $\triangleright$ if $x \triangleright y$ implies $x \succeq y$.

- Say that $\succeq$ is Grodal-transitive if $x \succeq y \succ z \succeq w$ implies $x \succeq w$.

Proposition 2

Take a set of alternatives $X$ that meets Assumption 1, and suppose:

1. $\triangleright$ is a dominance relation that is open,
2. for each $x$, there are $y, z$ arbitrarily close to $x$ such that $y \triangleright x$ and $x \triangleright z$.

Then the class of preferences that are Grodal-transitive and strictly monotone wrt $\triangleright$ meets Assumption 2.
Example: back to preferences over commodity bundles.

- There are $d$ commodities.
- $X \equiv \mathbb{R}^d_{++}$, where for $(x_1, \ldots, x_d) \in X$, $x_i$ is quantity of good $i$ consumed.
- $x \succ y$ iff $x_i > y_i$ for all $i = 1, \ldots, d$.

The set of all preferences that are Grodal-transitive and strictly monotone wrt $\succ$ meets Assumption 2.

Other examples: choice over menus of lotteries, dated rewards, intertemporal consumption, non-EU choice over lotteries.
Conclusion

- Binary choice
- Finite data
- “Consistency” – Large sample theory
- Unified framework: RP and econometrics.

Applicable to:

Large-scale (online) experiments/surveys.

Voting (roll-call data).