Approximation and Mechanism Design

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“Game theory has a great advantage in explicitly analyzing the consequences of trading rules that presumably are really common knowledge, it is deficient to the extent it assumes other features to be common knowledge, such as one player’s probability assessment about another’s preferences or information.

“I forsee the progress of game theory as depending on successive reductions in the base of common knowledge required to conduct useful analysis of practical problems. Only by repeated weakening of common knowledge assumptions will the theory approximate reality.”

– Robert Wilson, 1987.

Mechanism Design

Basic Mechanism Design Question: How should an economic system be designed so that selfish agent behavior leads to good outcomes?

Thesis

Informal Thesis: *approximate optimality* is

- more *descriptive* of mechanisms in practice than exact optimality,
- *prescribes* solutions to problems where exact optimality has not, and
- more *conclusive* about salient characteristics of good mechanisms.

Example 1: Gambler's Stopping Game

A Gambler's *Stopping Game*:

- *sequence* of n games,
- *prize* of game i is distributed from F_i,
- *prior-knowledge* of distributions.

On day i, gambler plays game i:

- *realizes* prize $v_i \sim F_i$,
- chooses to keep prize and *stop*, or
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Question: How should our gambler play?

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Discussion:

- *Complicated:* n different, unrelated thresholds.
- *Inconclusive:* what are properties of good strategies?
- *Non-robust:* what if order changes? what if distribution changes?
- *Non-general:* what do we learn about variants of Stopping Game?

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Theorem: *(Prophet Inequality)* For t such that **Pr**["no prize"] $= 1/2$,

$$\mathbf{E}[\text{prize for strategy } t] \geq \mathbf{E}[\max_i v_i]/2.$$

[Samuel-Cahn '84]

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Discussion:

- *Simple:* one number t.
- *Conclusive:* trade-off "stopping early" with "never stopping".
- *Robust:* change order? change distribution above or below t?
- *General:* same solution works for similar games: invariant of "tie-breaking rule"

Prophet Inequality Proof

0. Notation:

- $q_i = \mathbf{Pr}[v_i < t]$.
- $x = \mathbf{Pr}[\text{never stops}] = \prod_i q_i$.

1. Upper Bound on $\mathbf{E}[\max]$:

2. Lower Bound on $\mathbf{E}[\text{prize}]$:

3. Choose $x = 1/2$ to prove theorem.

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  - no, if mech without X is constant approx
  - yes, otherwise.
- Seller can always try ad hoc improvements on approximation.

Overview

1. Single-dimensional Bayesian settings.

   (e.g., single-item auctions)

2. Multi-dimensional Bayesian settings.

   (e.g., multi-item auctions)

3. Prior-free settings.

Part I: Approximation for single-dimensional Bayesian mechanism design

(where agent preferences are given by a private value for service, zero for no service; preferences are drawn from a distribution)

Example 2: Single-item auction

Problem: Bayesian Single-item Auction Problem

- a single item for sale,
- n buyers, and
- a dist. $\mathbf{F} = F_1 \times \cdots \times F_n$ from which the consumers' values for the item are drawn.

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Question: What is optimal auction?

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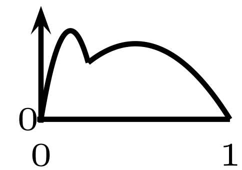
1. **Def:** *revenue curve*: $R_i(q) = q \cdot F_i^{-1}(1-q)$.



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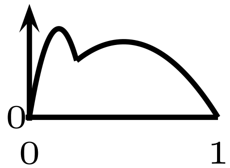

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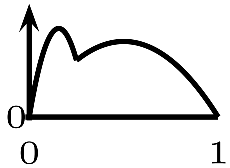

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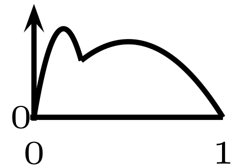

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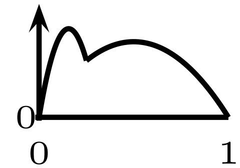

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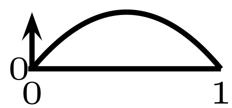

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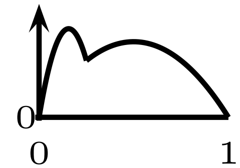

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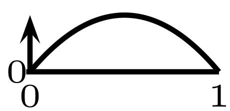

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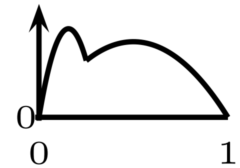

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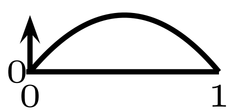

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7. **Cor:** for iid, regular dists, optimal auction is *Vickrey with monopoly reserve price* $\varphi^{-1}(0)$.

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Discussion:

- iid, regular case: seems unlikely in practice.
- general case: nobody runs optimal auction (too complicated?).

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prophet inequality	Vickrey with reserves
prizes	virtual values
threshold t	virtual price
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E$[$prize for $t]$	**E**$[$Vickrey revenue$]$

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Discussion:

- constant virtual price $\Rightarrow$ bidder-specific reserves.
- *simple* reserve prices natural, practical, and easy to find.
- *robust* posted pricing with arbitrary tie-breaking works fine too.

Anonymous Reserves

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Discussion:

- theorem is not tight, actual bound is in $[2, 3]$.
- justifies wide prevalence.
- approximation good for *platform design*.

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Proof technique:

- optimal mechanism is a virtual surplus maximizer.
- reserve-price mechanisms are virtual surplus approximators.

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Basic Open Question: to what extent to simple mechanisms approximate (well understood but complex) optimal ones?

Challenges: non-downward-closed settings, negative virtual values.

Part II: Approximation for multi-dimensional Bayesian mechanism design

(where agent preferences are given by values for each available service, zero for no service; preferences drawn from distribution)

Example 3: unit-demand pricing

Problem: Bayesian Unit-Demand Pricing

- a single, unit-demand consumer.
- n items for sale.
- a dist. $\mathbf{F} = F_1 \times \cdots \times F_n$ from which the consumer's values for each item are drawn.

Goal: seller optimal *item-pricing* for $\mathbf{F}$.

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Question: What is optimal pricing?

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Discussion:

- little conceptual insight and
- not generally tractable.

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Problem: Bayesian Unit-demand Pricing (a.k.a., MD-PRICING)	**Problem:** Bayesian Single-item Auction (a.k.a., SD-AUCTION)
• a single, *unit-demand* buyer, • n items for sale, and • a dist. $\mathbf{F}$ from which the consumer's value for each item is drawn.	• a single item for sale, • n buyers, and • a dist. $\mathbf{F}$ from which the consumers' values for the item are drawn.
Goal: seller opt. item-pricing for $\mathbf{F}$.	**Goal:** seller opt. auction for $\mathbf{F}$.

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Note: Same informational structure.

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Proof: prophet inequality. [Chawla, H, Malec, Sivan '10]

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4. *Instantiation:* SD-PRICING $\geq \frac{1}{\beta}$SD-AUCTION

   (virtual surplus approximation)

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- *robust* to agent ordering, collusion, etc.
- *conclusive*: competition not important for approximation.
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Open Question: identify upper bounds beyond unit-demand settings that are

- conceptually tractable and
- approximable.

Part III: Approximation for prior-free mechanism design.

(mechanisms should be good for any set of agent preferences, not just given distributional assumptions)

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Question: can we design good auctions without knowledge of prior-distribution?

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Approach 1: “resource” augmentation.

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- "bicriteria" approximation result.
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- *non-generic*: e.g., for k-unit auctions, need k additional bidders.

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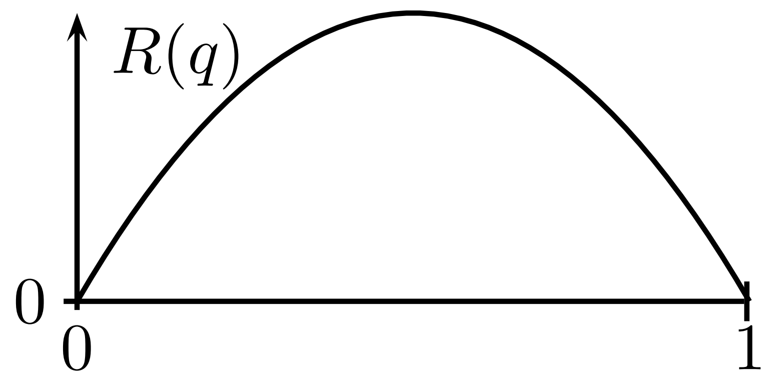

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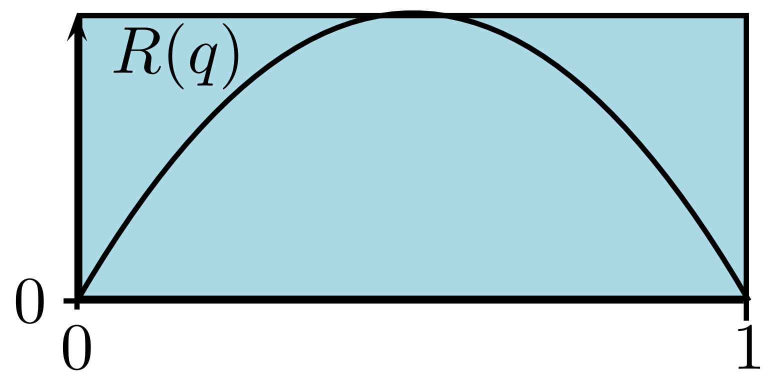

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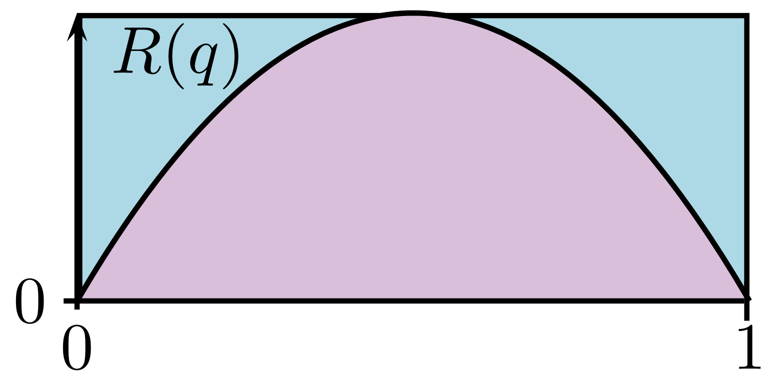

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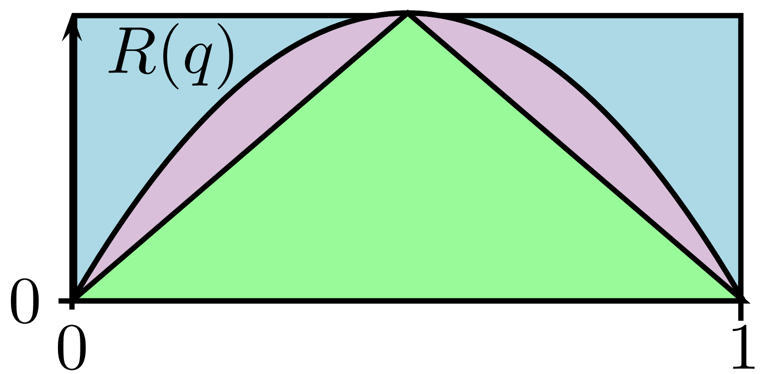

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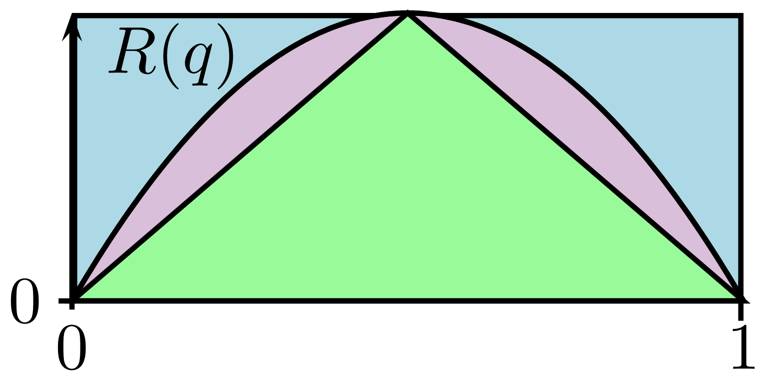

- So Vickrey with two bidders $\geq$ optimal revenue from one bidder.

Example 4: digital goods

Question: how should a profit-maximizing seller sell a *digital good* (n bidder, n copies of item)?

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Discussion:

- optimal,
- simple, but
- not prior-free

Approximation via Single Sample

Single-Sample Auction: (for digital goods)

[Dhangwatnotai, Roughgarden, Yan '10]

1. pick random agent i as sample.
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Discussion:

- *prior-free*.
- *conclusive*, don't need precise distribution, only need single sample for approximation. more samples can improve approximation factor.
- *generic*, applies to general settings.

Average-case vs Worst-case

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Average Case Approximation: $\exists \mathcal{A}, \forall \mathbf{F} \in$ IID,

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Notes:

- worst-case approximation implies average-case approximation.
- $\sup_{\mathbf{F}\in\text{IID}} \mathrm{OPT}_{\mathbf{F}}(\mathbf{v})$ is *prior-free performance benchmark*.
- for digital goods, prior-free benchmark $=$ optimal posted price revenue.

Approximation via Random Sampling

Random Sampling Auction: (for digital goods)

[Goldberg, H, Wright '01]

1. Randomly partition agents into two sets.
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Discussion:

- *conclusive*, market analysis can be done "on the fly"
- *worst-case* is for $n = 2$.
- *practical*, bounds approach 1 in limit with n.
- *generic*, analysis extends beyond digital goods.

Extensions

Prior-free results extend to limited supply, downward-closed settings, non-identical distributions, other objectives, etc.

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Open Questions:

- non-downward-closed settings?
- multi-dimensional settings?
- beyond the *revelation principle*?

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Basic Open Question: attack economic impossibility w. approximation.