Does Strategic Ability Affect Efficiency? Evidence from Electricity Markets

Ali Hortaçsu[1] Fernando Luco[2]
Steve Puller[2] Dongni Zhu[3]

[1]University of Chicago [2]Texas A&M University

[3]Shanghai University of Finance and Economics

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	Firm 1	Firm 2
Identity	Split from former vertically integrated utility	Municipal Utility
Physical assets	13 generating units $\approx 18,000$ MW of natural gas, coal and nuclear	2 generating units ≈ 500 MW of natural gas
Trader's previous experience	1y "Director of Energy Trading" 4ys "Energy Trader" 3ys natural gas transportation & exchange firm	2ys trading desk at another firm 10ys "Superv. of System Operations" 8ys "System Operator" 4ys "System Operations Dispatcher" 4ys "Generation Control Operator"

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Efficiency concerns from an antitrust perspective: **large firms**

- Exercise market power
- Mergers and concentration
- Texas market monitor: “small fish swim free” rule.

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Can firms compete in a way that creates inefficiency, in addition to those related to market power? (i.e. prevents least-cost dispatch)

- Can differences in sophistication of pricing strategies cause inefficiencies?

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This paper:

What if all real-world firms were to engage in some strategic thinking, but some “fall short” of playing Nash equilibrium?

- Heterogeneity in level of strategic thinking?

Strategic Sophistication and Efficiency

- (Standard) “Sophisticated” Nash equilibrium bidding leads to inefficiency, aka “market power”.
- (Less Studied) Low level strategic thinking also inefficient
  - Hortaçsu and Puller (2008) study electricity auctions

Rich theory/lab literature on bounded rationality theory: Level-*k*, Cognitive Hierarchy, QRE.

- In I.O., we have seen work on demand but almost nothing on supply.
- More in general, almost no application of level-*k*, CH, and QRE using field data.

Why? Identification.

Strategic Sophistication and Efficiency

Consider the "normal" I.O. approach

- Differentiated product industries: MC $\rightarrow$ prices
- Auctions: valuations $\rightarrow$ bids

Solution: field data on marginal cost

- **Enter electricity markets…**

This paper

- Same context as HP: bidding in the Texas electricity market
- Our strategy
  - Embed a Cognitive Hierarchy (CH) model into a structural model of bidding
  - Exploit a dataset with bids *and marginal costs* to estimate levels of strategic sophistication
- Why? (aka, what is new relative to HP?)
  - How heterogeneous is sophistication?
  - What is the impact of strategic sophistication on efficiency?
  - What are the (private) returns to strategic sophistication?
- Bonus: Ability to calculate counterfactuals
  - In multi-unit auctions, solving for Nash equilibria is difficult/impossible (fixed point in function space)
  - The structure of the CH model makes finding equilibrium “easy” (sequence of best-responses)

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3. Could mergers that increase strategic sophistication, but do not create cost synergies, increase efficiency?
   - Yes, but only if small firms involved; otherwise concentration effect dominates.

Literature

- **Theory and lab**: Costa-Gomez, Crawford and Broseta (2001), Crawford and Iriberri (2007), Camerer et al (2004), McKelvey and Palfrey (1995), Nagel (1995), Stahl and Wilson (1995), Gill and Prowse (2016).
- **Empirical/field**: Hortaçsu and Puller (2008), Gillen (2010), Goldfarb and Xiao (2011), An (2013).
- **Electricity markets**: Doraszelski, Lewis, and Pakes (2016), Fabra and Reguant (2014), Bushnell, Mansur and Saravia (2008), Sweeting (2007), Wolak (2003), Borenstein, Bushnell and Wolak (2002), Wolfram (1998).
- **Productivity differences across firms**: Syverson (2004), Hsieh and Klenow (2009), Bloom and Van Reenen (2007).
- ***Behavioral* supply**: Romer (2006), Massey and Thaler (2013), Ellison, Snyder, and Zhang (2016), DellaVigna and Gentzkow (2017).

Outline

1. Institutional setting
2. A Model of Non-Equilibrium Bidding Behavior
3. Data and Estimation
4. Counterfactuals: Increasing Sophistication

Institutional Setting

Texas Electricity Market - Early Years

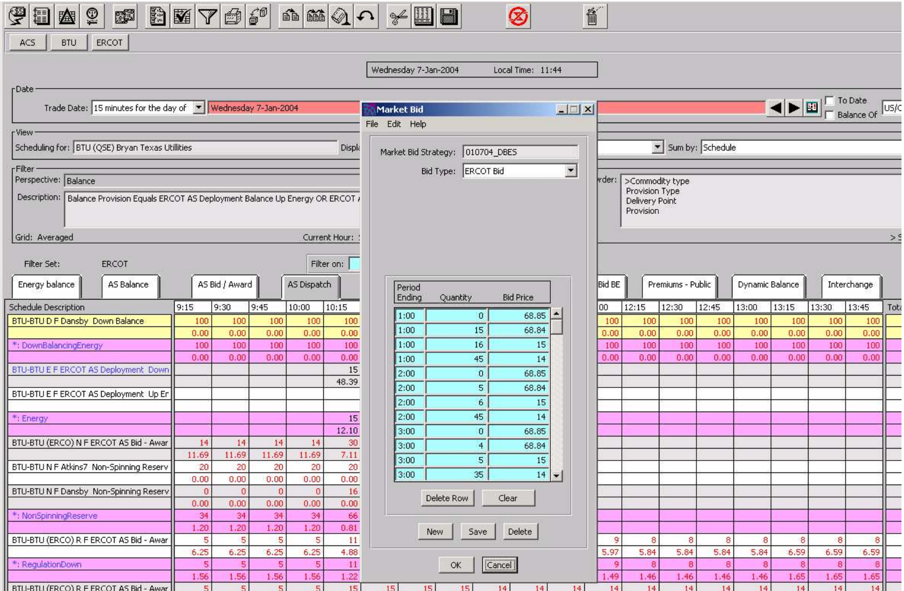
Timeline of Market Operations:

- Generating firms sign bilateral trades with firms that serve customers
- Day-ahead: One day before production and consumption, generating firms schedule a fixed quantity of production for each hour of the following day (‘day-ahead schedule’)
- Day-of: shocks can occur (e.g. hotter July afternoon than anticipated)
- **‘Balancing Market’ to ensure supply and demand balance at every point in time**

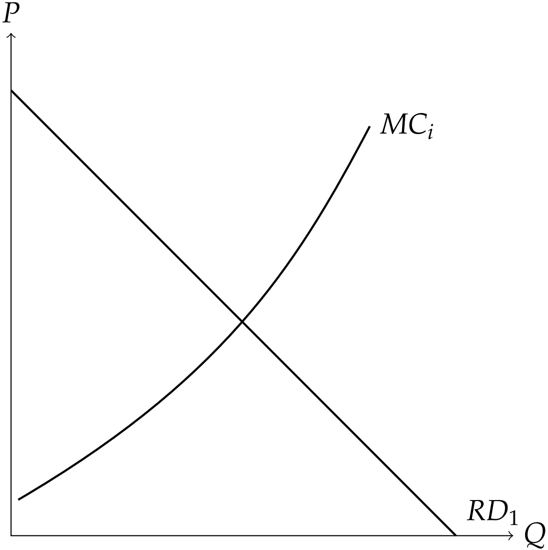
Balancing Market Auction

- Generation firms submit hourly bids to change production relative to their 'day-ahead schedule'
  - Bids are monotonic step functions (up to 40 elbow points) for portfolio of firm's generators
- Demand is perfectly inelastic
- Uniform-price auction that clears every 15-minute interval with hourly bids
- Accounts for 2-5% of all power traded

How do firms do this?



How **should** firms choose price-quantity pairs?



‣ Can firms do this in practice?

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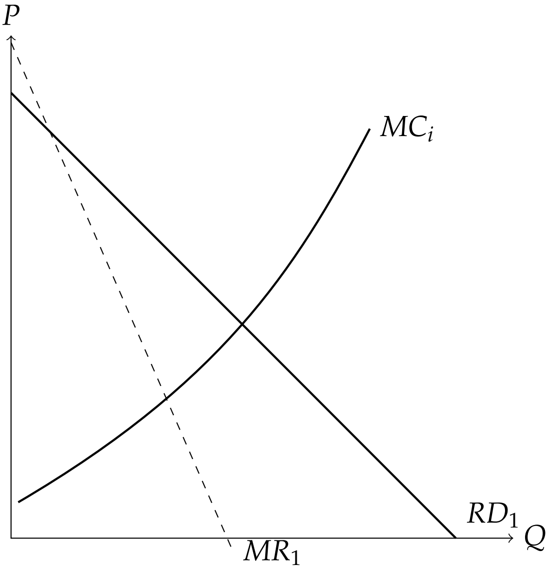

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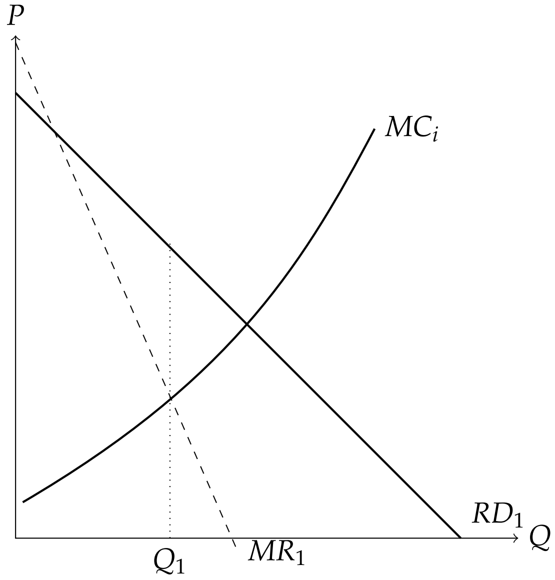

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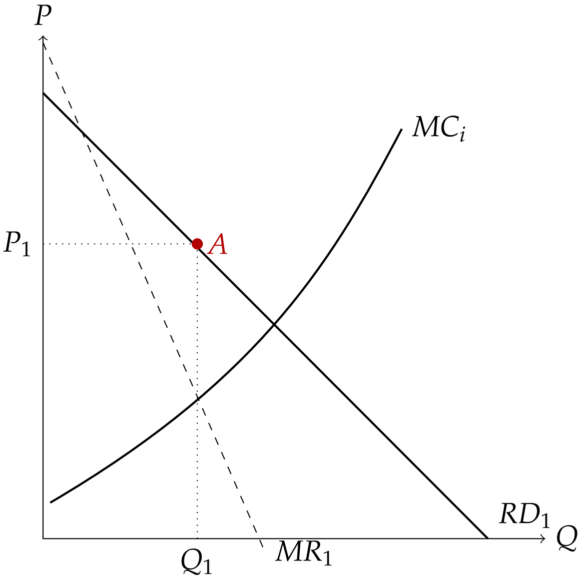

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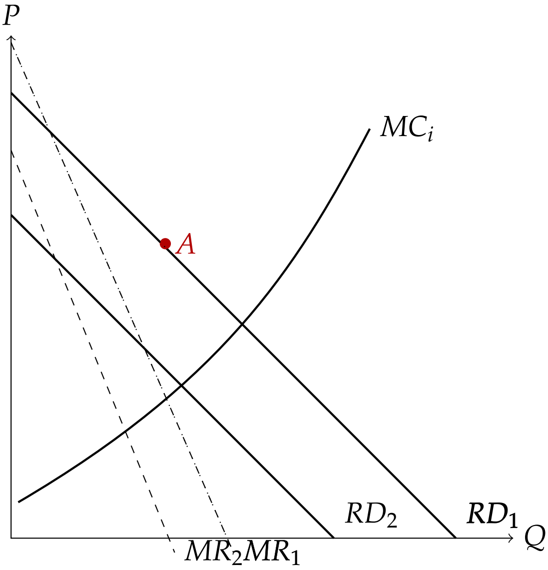

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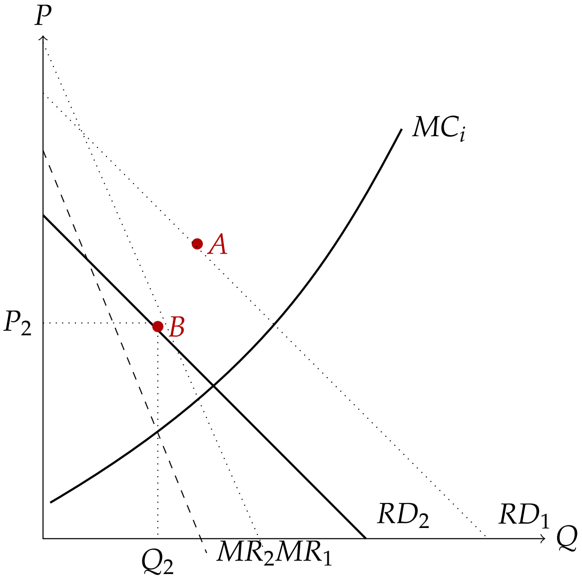

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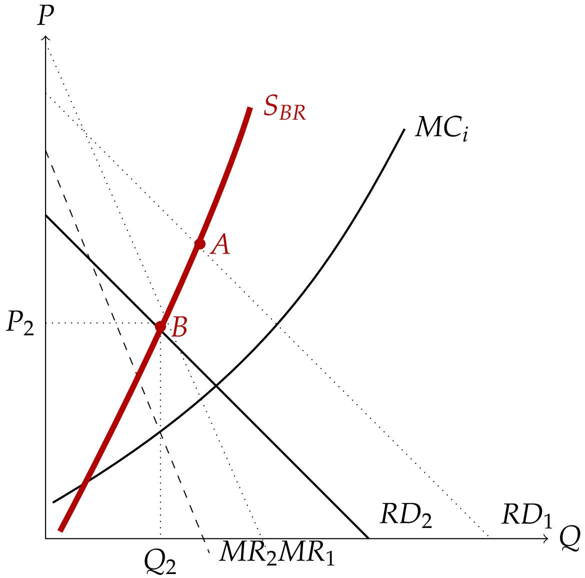

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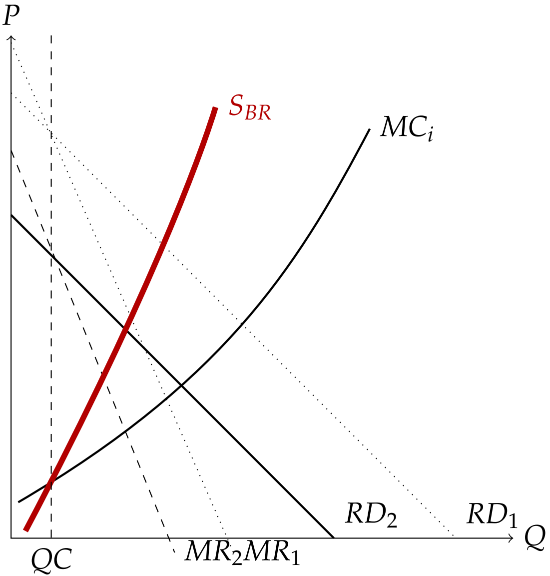

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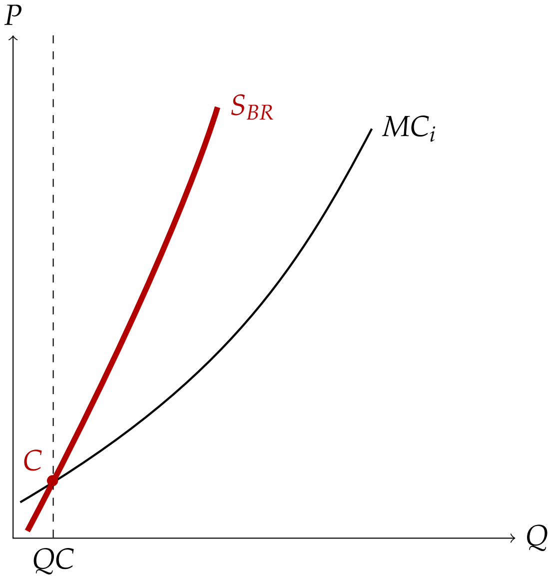

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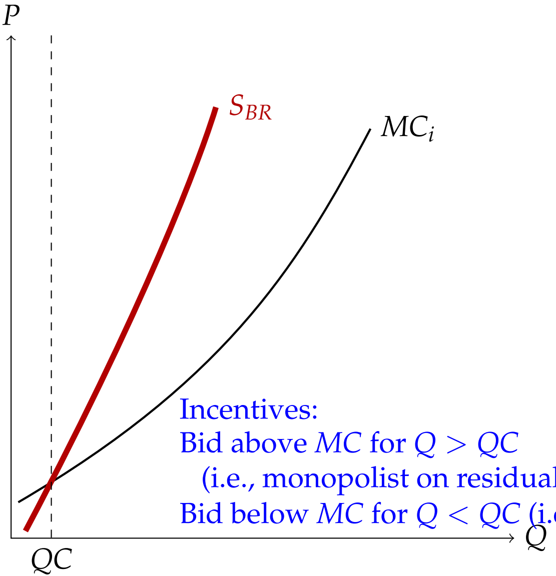
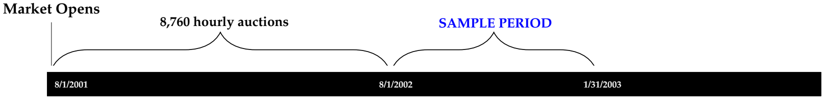


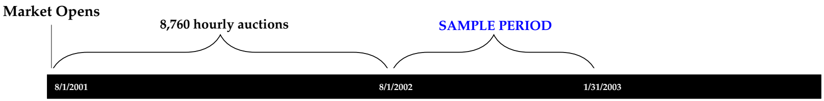
Incentives:
Bid above MC for $Q > QC$
(i.e., monopolist on residual demand)
Bid below MC for $Q < QC$ (i.e., monopsony)

▸ Can firms do this in practice?

Data


Market Opens
8,760 hourly auctions
SAMPLE PERIOD
8/1/2001
8/1/2002
1/31/2003

Data



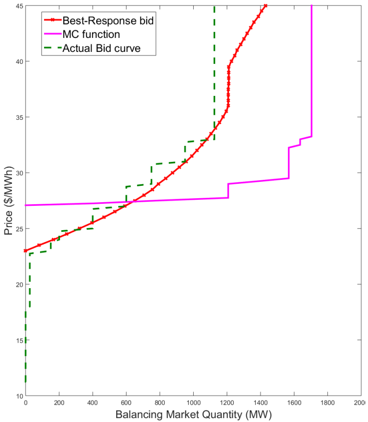
For each hourly auction, we have data on:

- Demand - perfectly inelastic balancing demand
- Bids - each firm's hourly firm-level ("portfolio") bids
- Marginal costs - each firm's hourly MC of supplying balancing power for plants that are "turned on" ▸ MC Details ▸ MC Figure

We focus on the 6–6:15pm periods with no transmission congestion.

What do we observe?

Large firm



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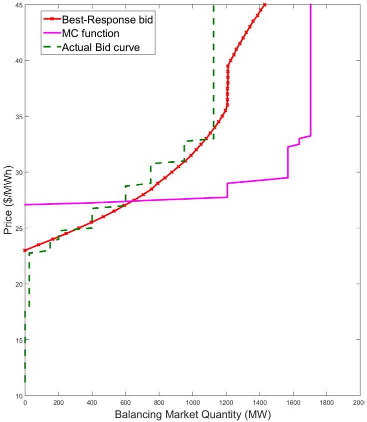
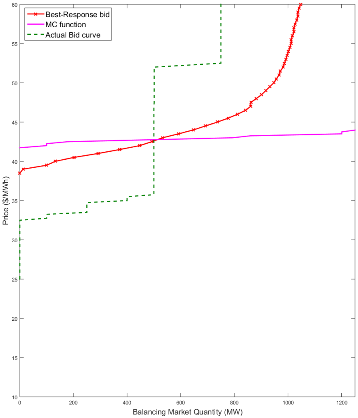


Medium firm



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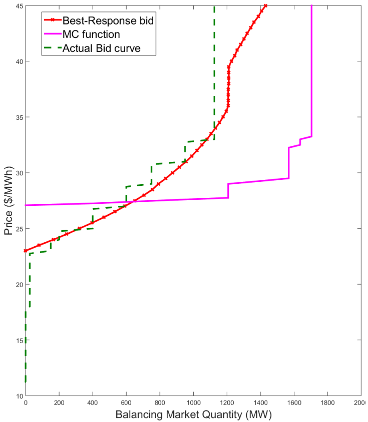

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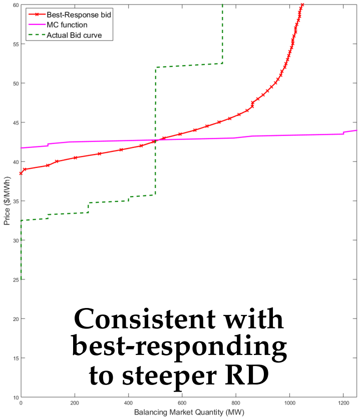
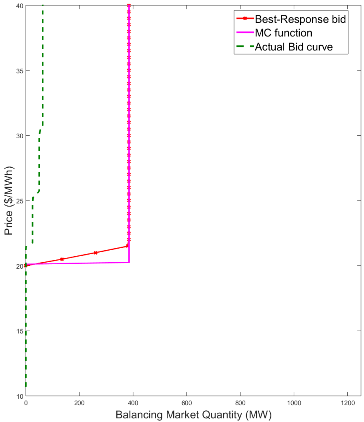


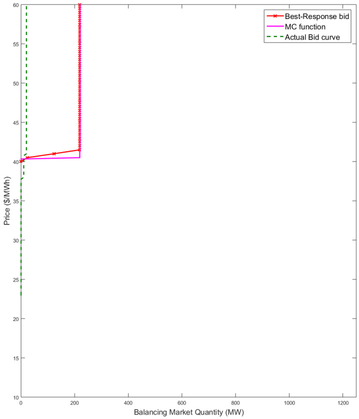
Consistent with best-responding to steeper RD

What do we observe?

Small firm



Very Small firm



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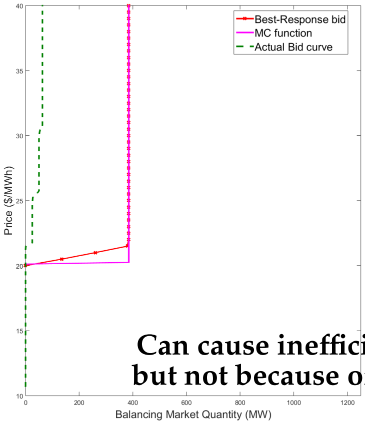

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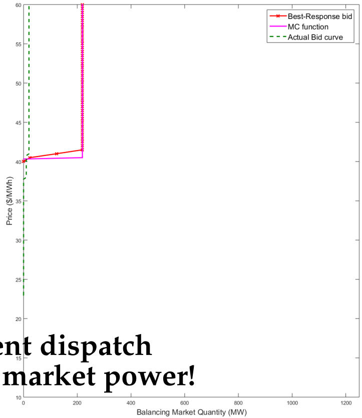

Can cause inefficient dispatch but not because of market power!

Summarizing Performance Across Firms

Firm	Percent of Potential Profits Achieved
Reliant	79%
City of Bryan	45%
Tenaska Gateway Partners	41%
TXU	39%
Calpine Corp	37%
Cogen Lyondell Inc	16%
Lamar Power Partners	15%
City of Garland	13%
West Texas Utilities	8%
Central Power and Light	8%
Guadalupe Power Partners	6%
Tenaska Frontier Partners	5%

Ruling Out Alternative Explanations

- Do bidding rules prevent firms from submitting ex post "best response" bids?
  - No! ▸ "Simple bidding rule"

- Are the dollar stakes large enough to justify the fixed costs of submitting the "right" bids?
  - Money-on-the-table: between 3 and 18 million dollars per year.

- Startup costs?
  - All the units we consider in MC are already "on".

- Adjustment costs?
  - Flexible natural gas units often are marginal.
  - Inconsistent with Medium firm's bid for quantities below contract position.
  - "Bid-ask" spread smaller for firms closer to best-response bidding despite having similar technology.

Ruling Out Alternative Explanations

- Is capacity overstated?: No, and even if it did it wouldn't be a problem when *decreasing* generation.
- Transmission constraints: HP find cannot explain deviations.
- Collusion: would be small players; monetary transfers unlikely.

A Model to Explain this Bidding Behavior:

“Cognitive Hierarchy”

What Is “Hierarchical Thinking”?

Imagine the following game:

- Pick a number between 0 and 100
- Winner is player with number closest to $\frac{2}{3}$ of average
- What is your number?

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- Level-2 thinking: If all other players use above reasoning, I should pick 45.

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- Level-3 thinking: If all other players use above reasoning....
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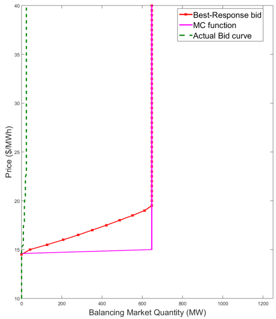
- Level-2 thinking: If all other players use above reasoning, I should pick 45.
- Level-3 thinking: If all other players use above reasoning....
- ...
- Only rational and consistent choice is to choose **0**
- **People playing a game can have different levels of strategic thinking**

Cognitive Hierarchy Applied to this Market

- Relaxes Nash assumption of ‘mutually consistent beliefs’.
- Players differ in level of strategic thinking.
  - $k_i \in \{0, \ldots, K\}$
- Level-0 players are non-strategic (Important assumption, I’ll discuss it in detail in a couple of minutes)

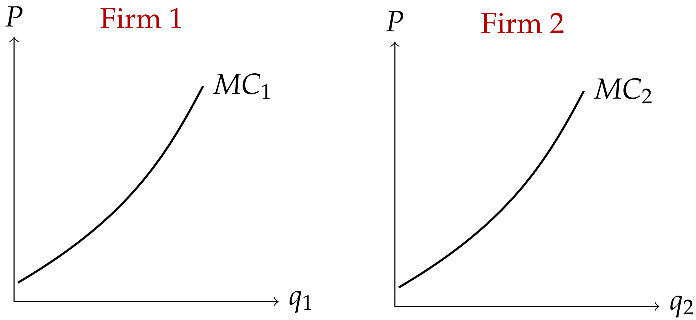


Cognitive Hierarchy Applied to this Market

- Players level-1 to level-k are increasingly more strategic
  - level 1: assume *all* rivals are level 0. Best-respond to these beliefs.
  - level 2: assume rivals are distributed between level 0 and level 1. Best respond to these beliefs.
  - ...
  - level k: assume rivals are distributed between level 0 and level $k-1$. Best respond to these beliefs.

- Firms beliefs about their rivals' level of strategic thinking is a function of characteristics of those rivals (e.g. size)

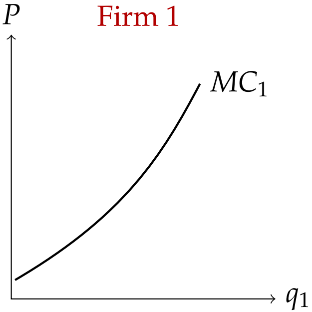
Our model in pictures

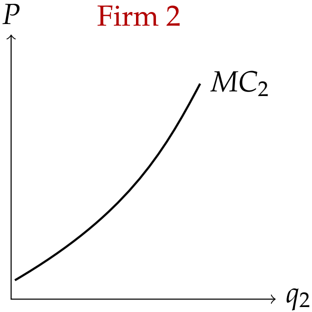


▸ Model in Math

Our model in pictures

Assume F_2 believes F_1 to be type-0





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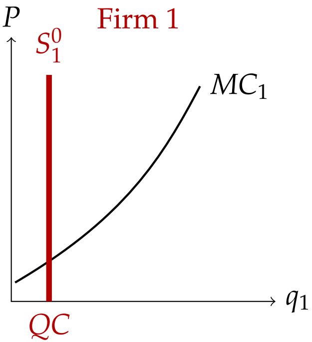

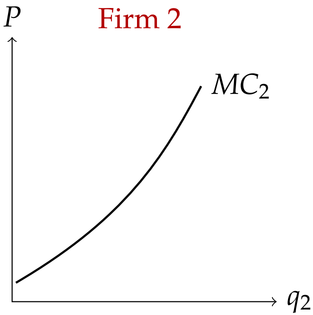

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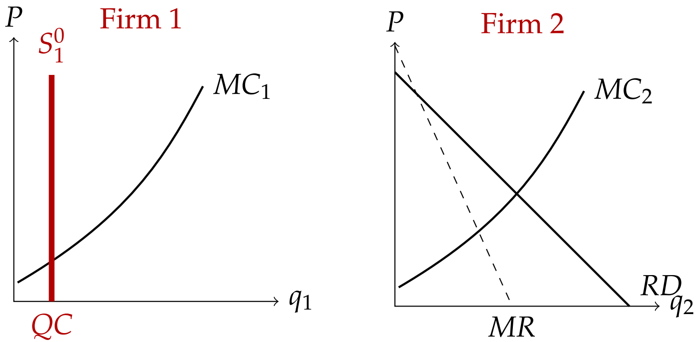

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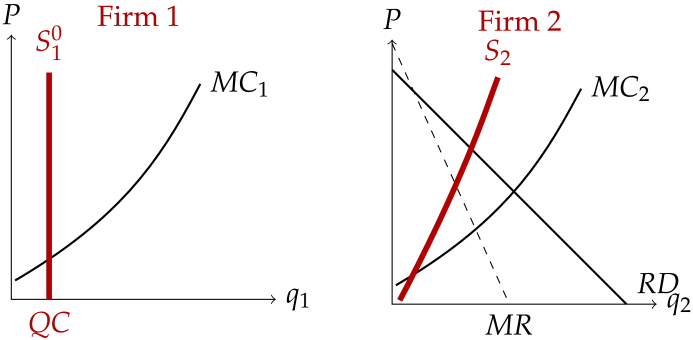

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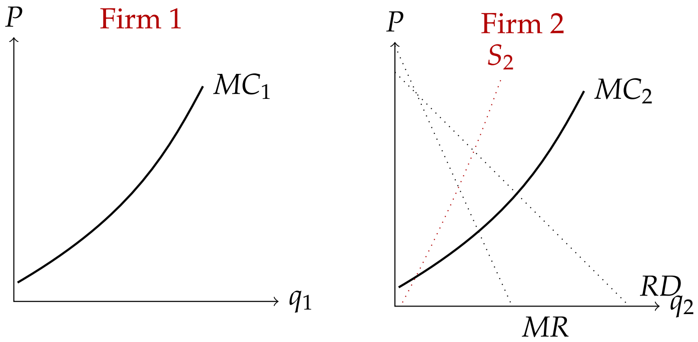
Assume F_2 believes F_1 to be type-1



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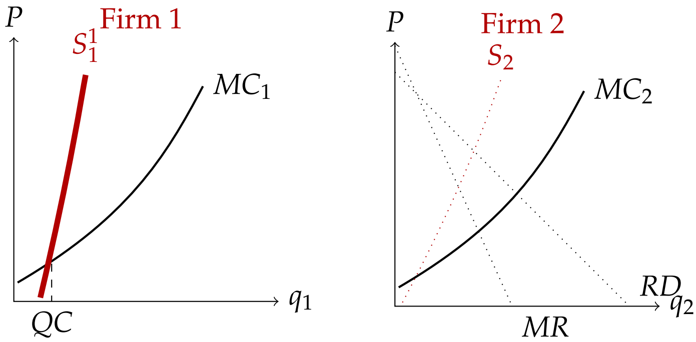

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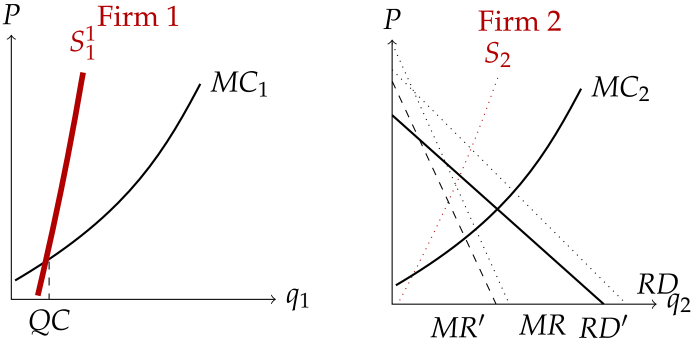

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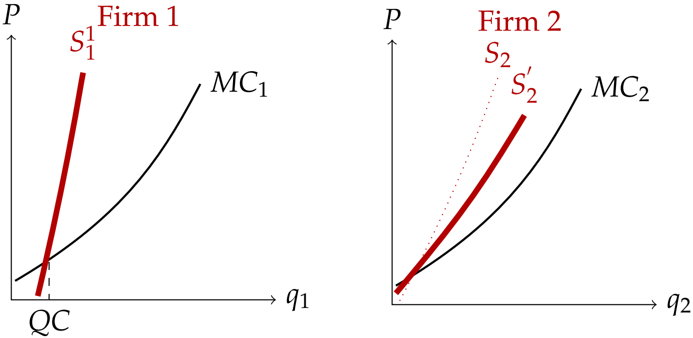

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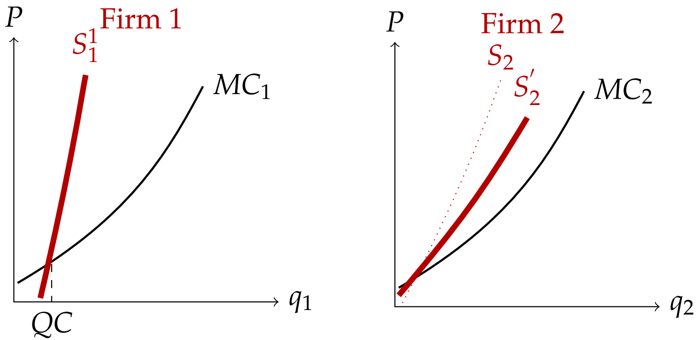
Our model in pictures

Higher-type rivals rotate RD and induce more competitive bidding



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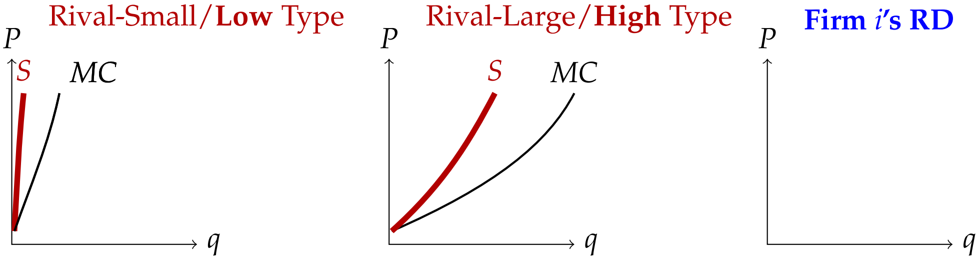
Identification

Suppose larger firms are **higher** types ($\gamma > 0$)



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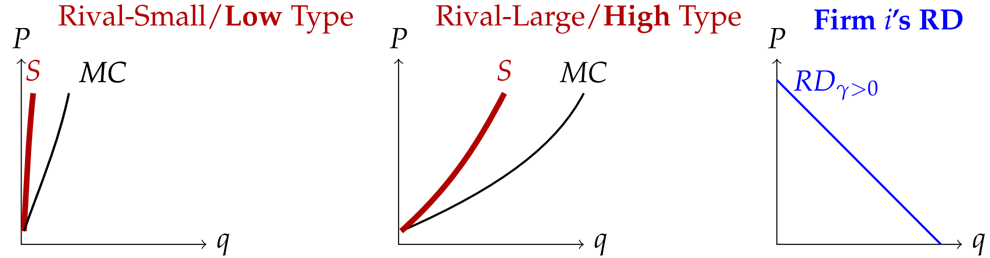

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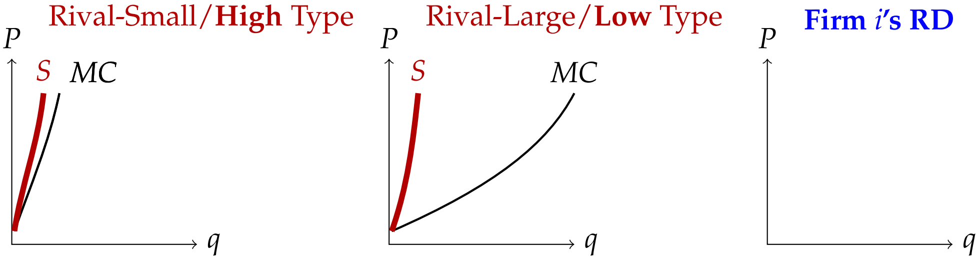

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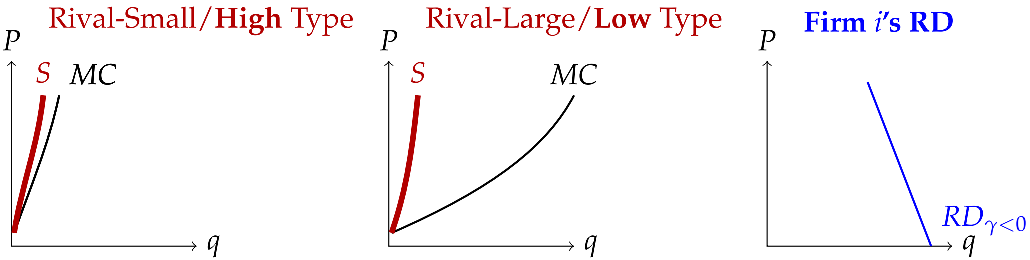

Identification

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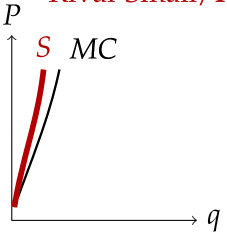
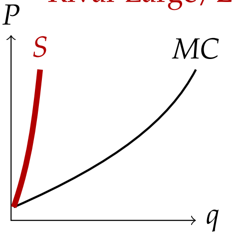
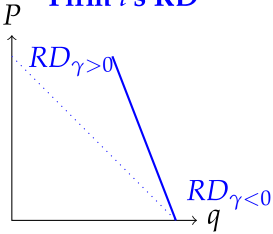
Rival-Small/**High** Type



Rival-Large/**Low** Type



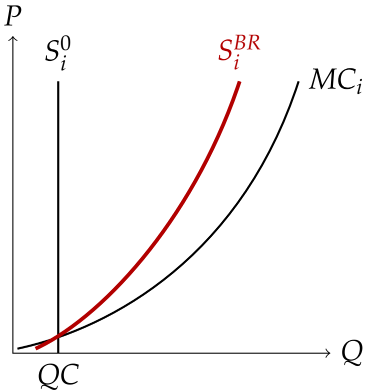
Firm *i*'s RD



Is i's bid more consistent with $RD_{\gamma>0}$ or $RD_{\gamma<0}$?

More on level-0 firms

In general, level-0s are *non-strategic players*. In our setting, this can be



More on level-0 firms

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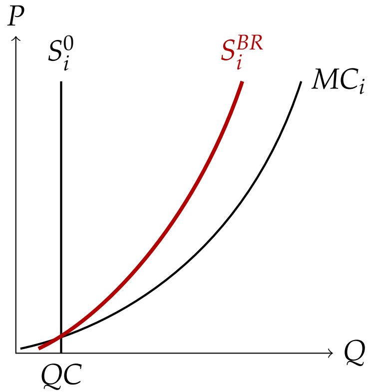

- Bid randomly

More on level-0 firms

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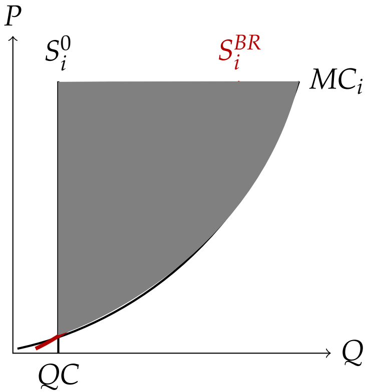

- Bid randomly

More on level-0 firms

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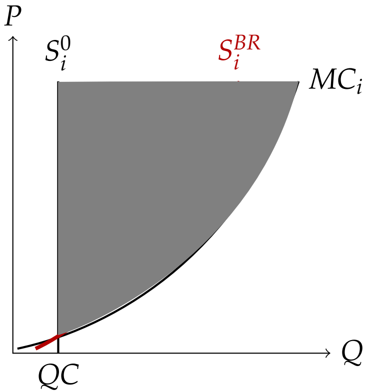

- Bid randomly
  - not observed

More on level-0 firms

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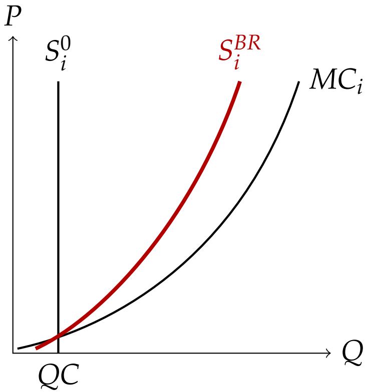

- Bid randomly
  - not observed
- Bid marginal costs

More on level-0 firms

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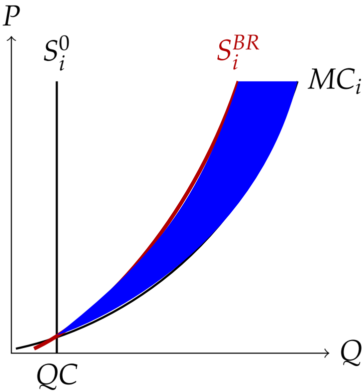

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More on level-0 firms

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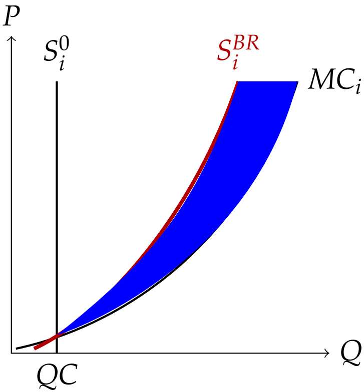
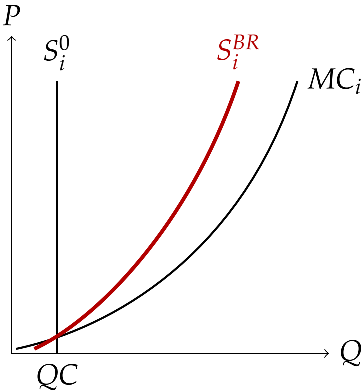


- Bid randomly
  - not observed
- Bid marginal costs
  - bids would have to be flatter than BR, not observed

More on level-0 firms

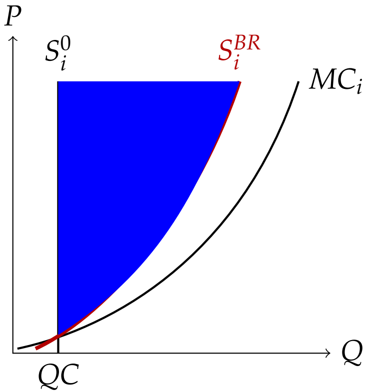
In general, level-0s are *non-strategic players*. In our setting, this can be



- Bid randomly
  - not observed
- Bid marginal costs
  - bids would have to be flatter than BR, not observed
- Bid vertical

More on level-0 firms

In general, level-0s are *non-strategic players*. In our setting, this can be



- Bid randomly
  - not observed
- Bid marginal costs
  - bids would have to be flatter than BR, not observed
- Bid vertical

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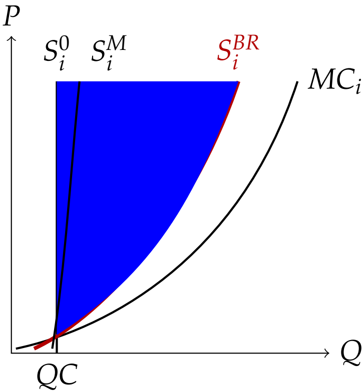

- Bid randomly
  - not observed
- Bid marginal costs
  - bids would have to be flatter than BR, not observed
- Bid vertical

More on level-0 firms

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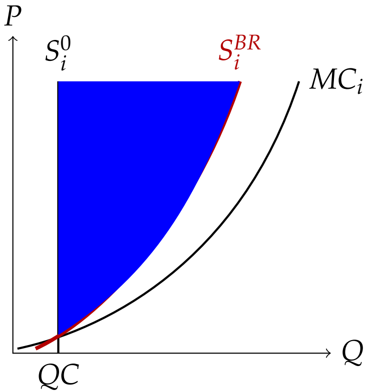


- Bid randomly
  - not observed
- Bid marginal costs
  - bids would have to be flatter than BR, not observed
- Bid vertical
  - higher types would bid flatter and approach BR from the left, as we observe

Estimation

Estimation: Information

Firm type: $k_i \sim Poisson(\hat{\tau}_i)$, $\hat{\tau}_i = \exp(\hat{\gamma}_0 + \hat{\gamma}_1 \text{ size}_i)$.

- k_i is private information
- τ_i is public information.

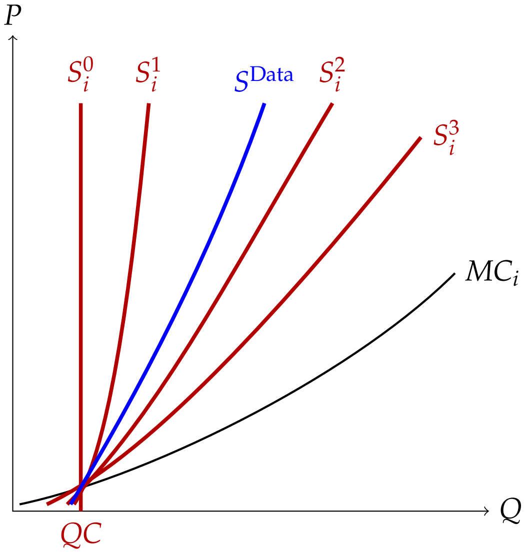
Costs: public information.

k_i and size$_{-i}$ determine i's beliefs about $-i$'s types.

i best-responds to those beliefs.

We compute i's best response for each k and minimize the distance between predicted bids and the data.

Estimation: Minimum-distance approach



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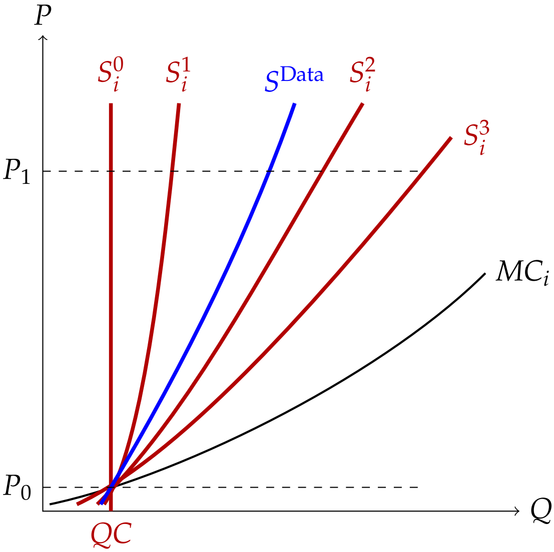
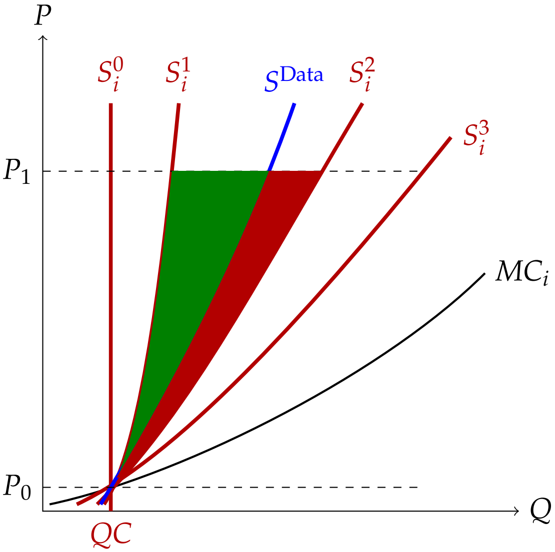


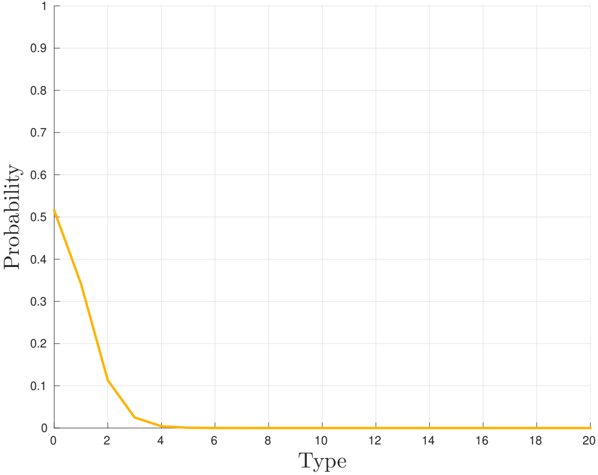
Estimation: Minimum-distance approach



Results

Larger Firms Are Higher Type

$$k_i \sim Poisson(\hat{\tau}_i), \;\; \hat{\tau}_i = \exp(\hat{\gamma}_0 + \hat{\gamma}_1 \, \text{size}_i)$$



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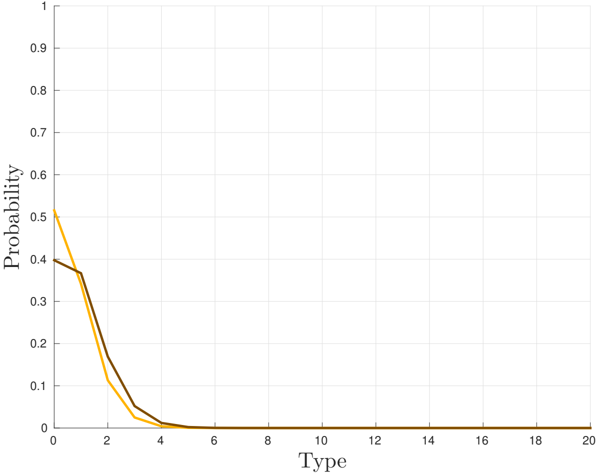

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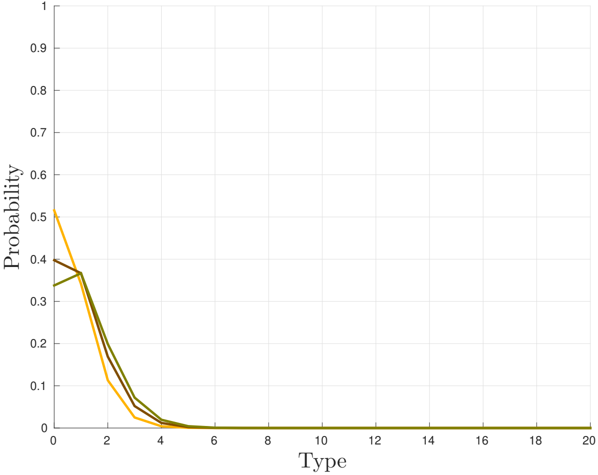

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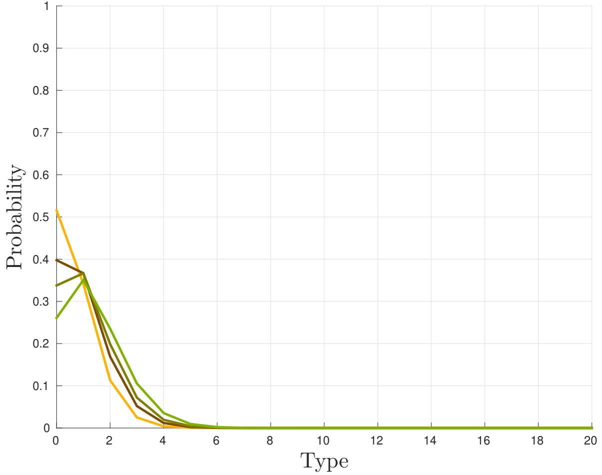

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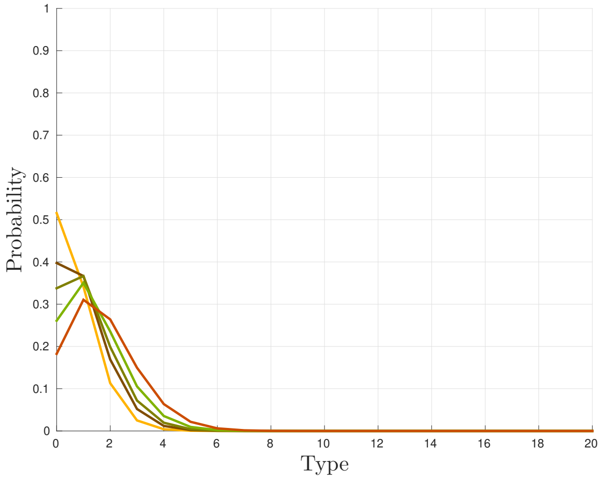

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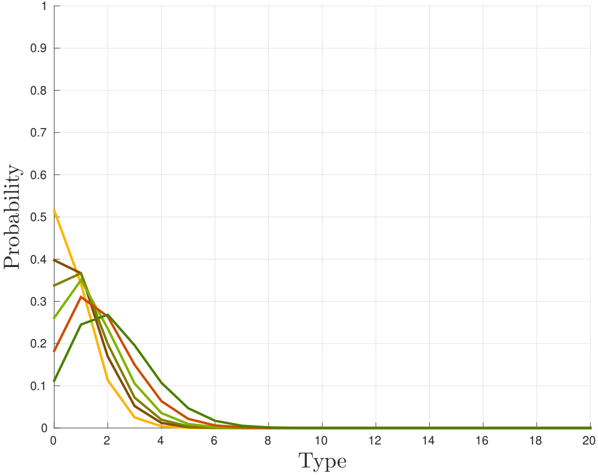

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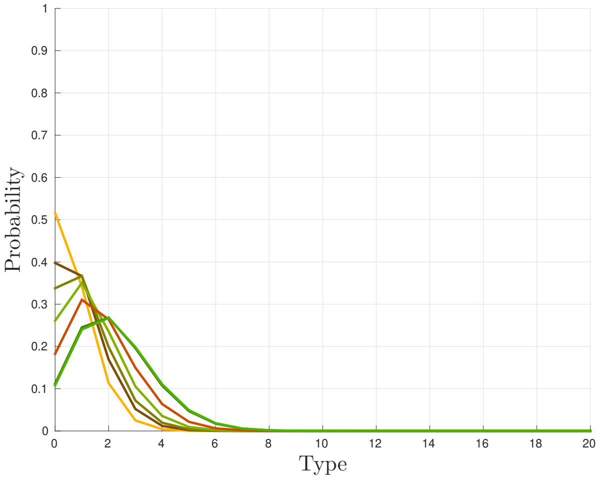

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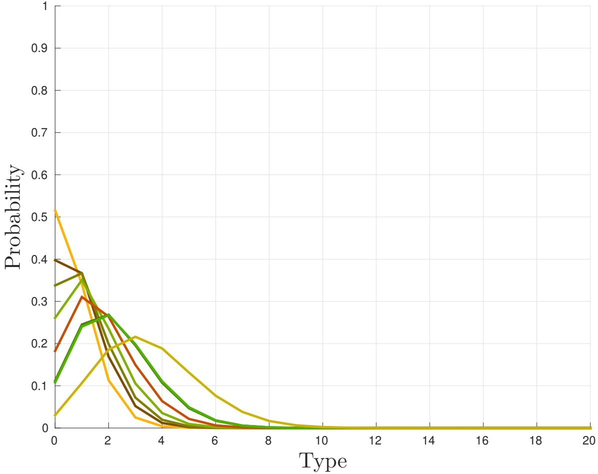

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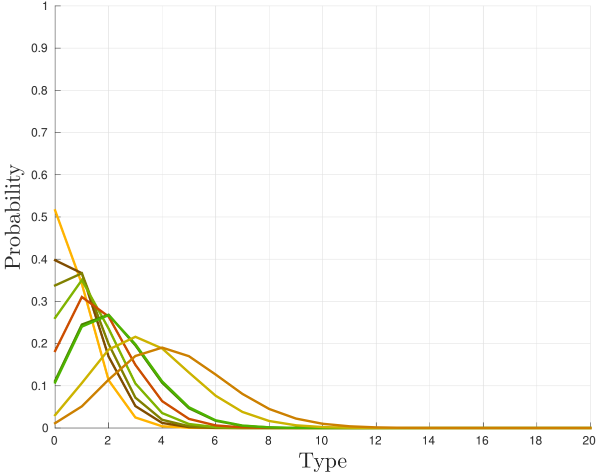

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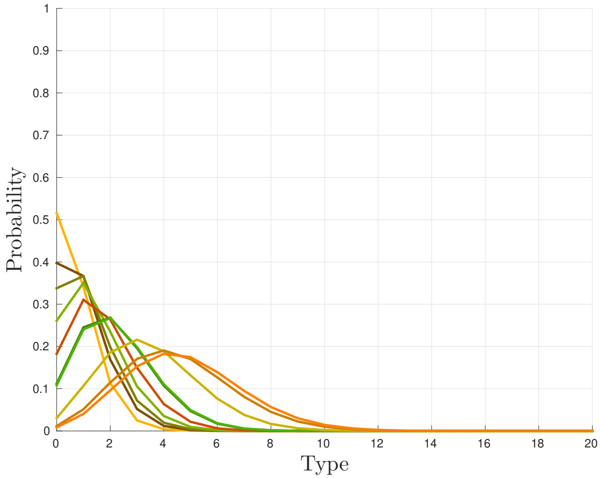

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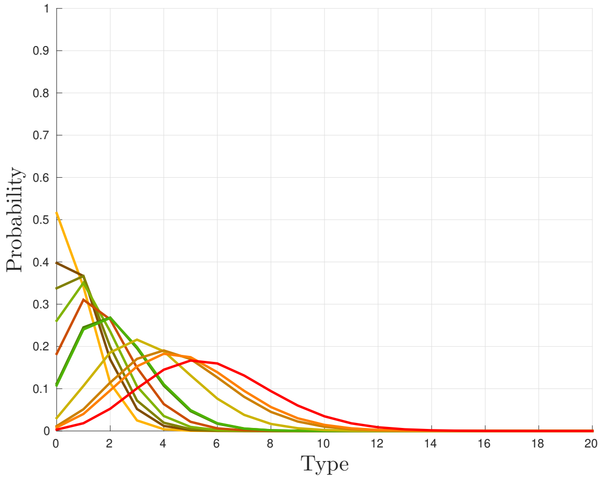

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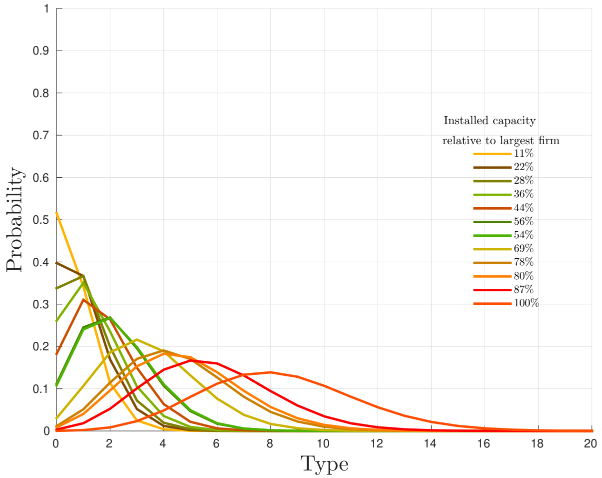


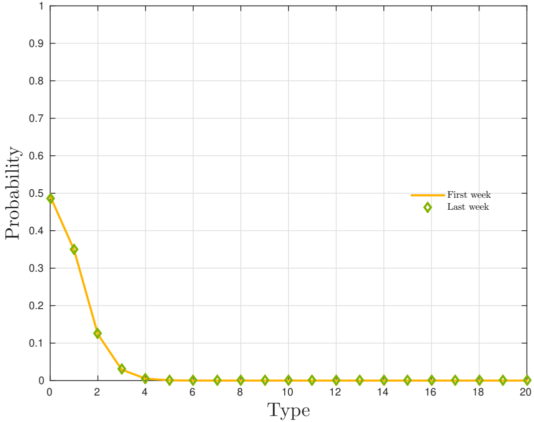
Manager Training Matters

	(1)	(2)	(3)
Constant	-0.726	-0.749	-3.493
	(0.087)	(0.106)	(0.414)
Size	14.594	13.619	3.090
	(1.027)	(1.188)	(0.755)
AAU School		0.376	
		(0.065)	
Econ/Business/Finance degree			5.626
			(1.188)
Number of auctions		99	

Note: Bootstrapped standard errors using 250 samples.

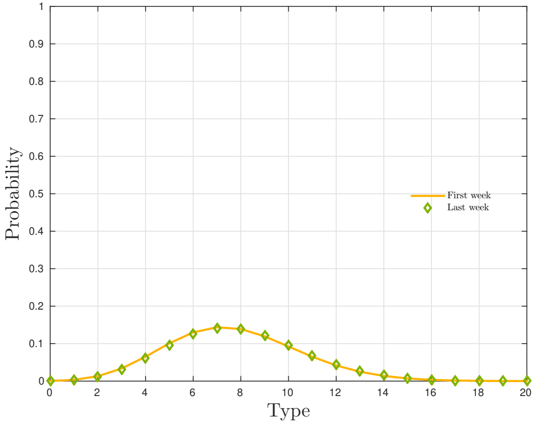
▸ Model fit

Learning?



Small Firm - Estimated Type Distribution with Learning (*Size* and time trend specification)

Learning?



Big Firm - Estimated Type Distribution with Learning (*Size* and time trend specification)

▸ More on learning: Quantity offered did not change over time

Out-of-sample prediction

	Dependent variable: Realized profits		
	(1)	(2)	(3)
Unilateral BR	0.263***		0.061
	(0.052)		(0.091)
CH		0.703***	0.642**
		(0.136)	(0.211)
Constant	-64.484	-248.599**	-264.619**
	(156.308)	(101.941)	(97.348)
Observations	426	426	426
R^2	0.248	0.561	0.570

Simulations of Changes in Sophistication

1. “Consulting Firm”

2. Merger

Increasing Sophistication Decreases Costs

Changes in average generating costs:

	INC side		DEC side	
Counterfactual	Public	Private	Public	Private
Small firms to median				
Above median firms to highest				
Three smallest to median				

Increasing Sophistication Decreases Costs

Changes in average generating costs:

	INC side		DEC side	
Counterfactual	Public	Private	Public	Private
Small firms to median	-6.95%			
Above median firms to highest				
Three smallest to median				

Increasing Sophistication Decreases Costs

Changes in average generating costs:

	INC side		DEC side	
Counterfactual	Public	Private	Public	Private
Small firms to median	-6.95%			
Above median firms to highest	-2.71%			
Three smallest to median				

Increasing Sophistication Decreases Costs

Changes in average generating costs:

	INC side		DEC side	
Counterfactual	Public	Private	Public	Private
Small firms to median	-6.95%			
Above median firms to highest	-2.71%			
Three smallest to median	-4.67%			

Increasing Sophistication Decreases Costs

Changes in average generating costs:

	INC side		DEC side	
Counterfactual	Public	Private	Public	Private
Small firms to median	-6.95%	-6.22%		
Above median firms to highest	-2.71%	-1.96%		
Three smallest to median	-4.67%	-3.75%		

Increasing Sophistication Decreases Costs

Changes in average generating costs:

	INC side		DEC side	
Counterfactual	Public	Private	Public	Private
Small firms to median	-6.95%	-6.22%	-18.4%	-17.6%
Above median firms to highest	-2.71%	-1.96%	-13.42%	-12.46%
Three smallest to median	-4.67%	-3.75%	-14.24%	-13.64%

Mergers that Increase Sophistication

Mergers only reduce generation costs when small firms are involved

	INC side	DEC side
Smallest and largest firms	-2.62%	-6.49%
Median and largest firms	+10.29%	+10.37%
Two largest firms	+18.34%	+48.72%

Conclusions and Takeaway Messages

Does heterogeneity in strategic sophistication affect market performance?

- Context: bidding into electricity auctions in Texas.
- First paper using field data to study pricing decisions.
- To model pricing decisions, we embed a CH model into a structural model of bidding.

Takeaways:

1. Significant heterogeneity in sophistication. Larger firms are more sophisticated than smaller firms.
2. Does sophistication matter? Yes!
   - Increasing sophistication improves efficiency.
   - Most of the gains come from smaller firms.
3. Could mergers that increase sophistication, but do not create cost synergies, increase efficiency?
   - Yes, but only if small firms are involved.

Thank you

Appendix

Main players in generation

Firm	% of installed capacity
TXU	24
Reliant	18
City of San Antonio	8
Central Power & Light	7
City of Austin	6
Calpine	5
Lower Colorado River Authority	4
Lamar Power Partners	4
Guadalupe Power Partners	2
West Texas Utilities	2
Midlothian Energy	2
Dow Chemical	1
Brazos Electric Power Cooperative	1
Others	16

◂ Back

Can Firms Do This in Practice?

- Grid operator reports aggregate bid function with a 2 day lag
- Simple trading rule
  - Download bid data from 2 days ago
  - Assume rivals do not change their bids
  - Calculate best response to lagged rivals' bids
- Does this outperform actual bidding?
- Answer: Yes and it yields almost the same profits as best response to *current* rivals' bids

◂ Back

Firm performance relative to best-responding

	Percent achieved by	
	Actual bids	BR to lagged bids
Reliant	79%	98.5%
City of Bryan	45%	100%
Tenaska Gateway	41%	99.6%
TXU	39%	96.7%
Calpine	37%	97.9%
Cogen Lyondell	16%	100%
Lamar Power Partners	15%	99.6%
City of Garland	13%	99.6%
West Texas Utilities	8%	100%
Central Power and Light	8%	98.7%
Guadalupe Power Partners	6%	99%
Tenaska Frontier	5%	99.3%

Source: Hortaçsu and Puller (2008). Back

Measuring Marginal Cost

- Each unit's daily capacity & day-ahead schedule

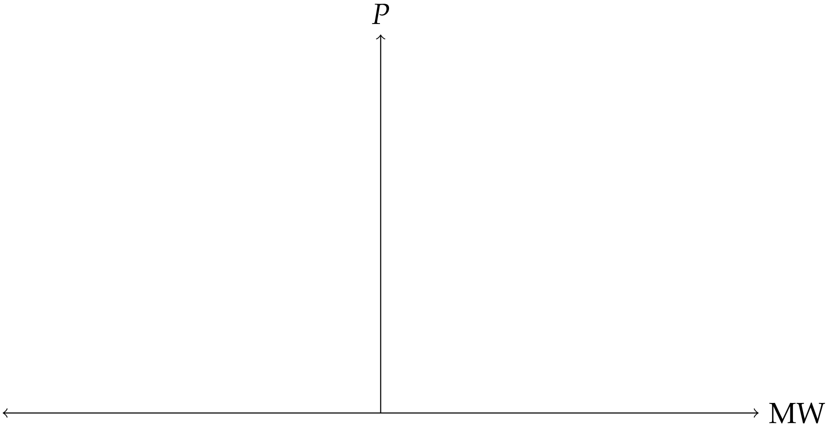
- Marginal Costs for each fossil fuel unit
  - Fuel costs – daily natural gas spot prices (NGI) & monthly average coal spot price (EIA)
  - Fuel efficiency – average "heat rates" (Henwood)
  - Variable O&M (Henwood)
  - SO2 permit costs (EPA)

- Use coal and gas-fired generating units that are "on" that hour and the daily capacity declaration (Nukes, Wind, Hydro may not have ability to adjust)

- Calculate how much generation from those units is already scheduled == Day-Ahead Schedule

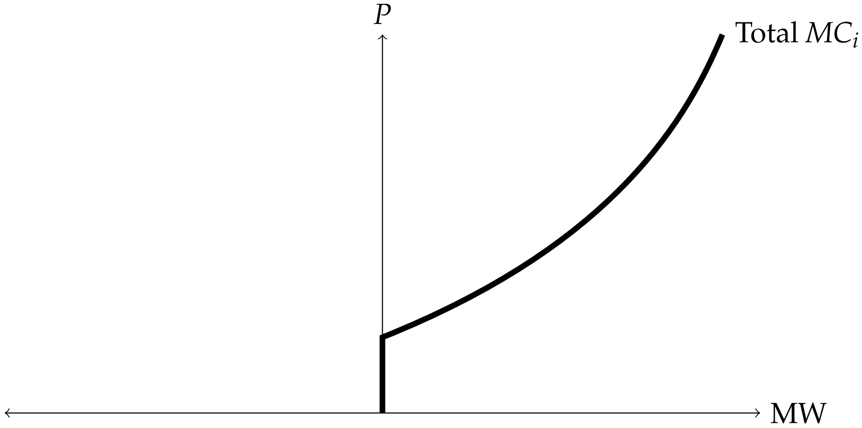
◂ Back

Measuring Marginal Cost



▸ Back

Measuring Marginal Cost



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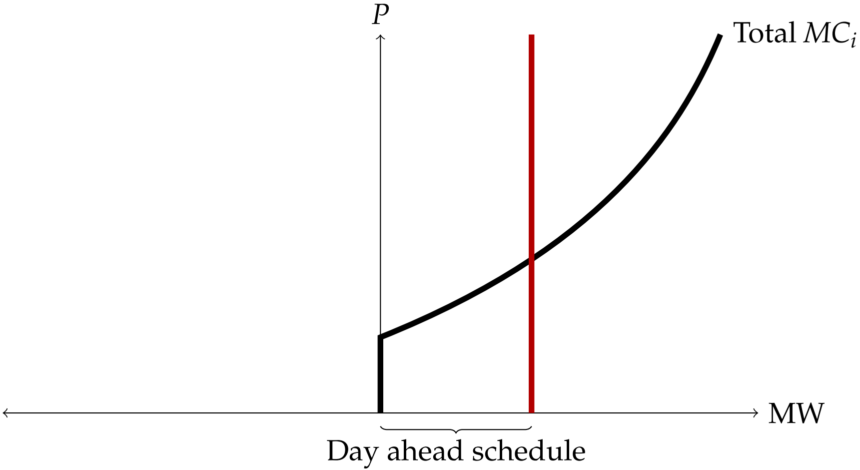
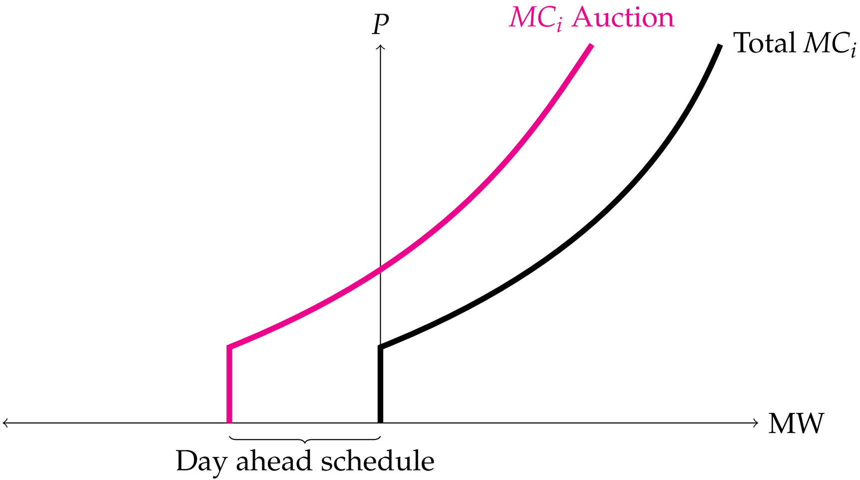
Measuring Marginal Cost



Back

Measuring Marginal Cost



Back

Model: Details

- Market clearing price p_t^c:

$$\sum_{i=1}^{N} S_{it}(p_t^c, QC_{it}) = D_t(p_t^c) + \varepsilon_t \quad (1)$$

- Three sources of uncertainty
  - Demand shock (ε_t)
  - Rival Contract positions (QC_{-it})
  - Rival Types (k_{-i})

$$H_{it}(p, \hat{S}_{it}(p); k_i, QC_{it}) \equiv Pr(p_t^c \leq p | \hat{S}_{it}(p), k_i, QC_{it}) \quad (2)$$

Back

Model: Details

- Market clearing price p_t^c:

$$\sum_{i=1}^{N} S_{it}(p_t^c, QC_{it}) = D_t(p_t^c) + \varepsilon_t \tag{1}$$

- Three sources of uncertainty
  - Demand shock (ε_t)
  - Rival Contract positions (QC_{-it})
  - Rival Types (k_{-i})

$$H_{it}(p, \hat{S}_{it}(p); k_i, QC_{it}) \equiv Pr(p_t^c \leq p | \hat{S}_{it}(p), k_i, QC_{it}) \tag{2}$$

◂ Back

Model: Details

Combining (1) and (2) and denoting i's private information $\Omega_{it} \equiv \{k_i, QC_{it}\}$:

$$H_{it}(p, \hat{S}_{it}(p); \Omega_{it}) =$$

$$\int_{\boldsymbol{QC}_{-it}, \boldsymbol{l}_{-i}, \varepsilon_t} 1 \left[\overbrace{\sum_{j \neq i} S^l_{jt}(p, QC_{jt}; k_i) + \hat{S}_{it}(p)}^{\text{aggregate supply}} \geq D_t(p) + \varepsilon_t \right] dF(\boldsymbol{QC}_{-it}, \boldsymbol{l}_{-i}, \varepsilon_t | \hat{S}_{it}(p), \Omega_{it})$$

$F(\boldsymbol{QC}_{-it}, \boldsymbol{l}_{-i}, \varepsilon_t | \hat{S}_{it}(p), \Omega_i)$: the joint density of each source of uncertainty from the perspective of firm i.

Let $\theta_i \equiv \sum_{j \neq i} S^l_{jt}(\cdot; k_i) - \varepsilon \sim \Gamma_i$. Back

Model: Details

The firm's problem

$$\max_{\hat{S}_{it}(p)} \int_{\underline{p}}^{\overline{p}} \left(U\left(p \cdot \hat{S}_{it}(p) - C_{it}\left(\hat{S}_{it}(p)\right) - (p - PC_{it})QC_{it}\right)\right) dH_{it}\left(p, \hat{S}_{it}(p); \Omega_{it}\right)$$

Necessary condition for optimality:

$$p - C'_{it}\left(S^*_{it}(p)\right) = \left(S^*_{it}(p) - QC_{it}\right) \frac{H_s\left(p, S^*_{it}(p); k_i, QC_{it}\right)}{H_p\left(p, S^*_{it}(p); k_i, QC_{it}\right)} \tag{3}$$

◂ Back

Model: Details

The firm's problem

$$\max_{\hat{S}_{it}(p)} \int_{\underline{p}}^{\overline{p}} \left(U \left(p \cdot \hat{S}_{it}(p) - C_{it} \left(\hat{S}_{it}(p) \right) - (p - PC_{it}) QC_{it} \right) \right) dH_{it} \left(p, \hat{S}_{it}(p); \Omega_{it} \right)$$

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$$p - C'_{it} \left(S^*_{it}(p) \right) = \left(S^*_{it}(p) - QC_{it} \right) \frac{H_s \left(p, S^*_{it}(p); k_i, QC_{it} \right)}{H_p \left(p, S^*_{it}(p); k_i, QC_{it} \right)} \tag{3}$$

◂ Back

Why is Assumption 1 important?

1. It implies that residual demand is flatter for higher type.
2. No more assumptions needed about how private information enters the bid functions.

Why? Consider a level-1 bidder

where $\theta_{it} \equiv \sum_{j \neq i} QC_{jt} - \varepsilon_t$. Back

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2. No more assumptions needed about how private information enters the bid functions.

Why? Consider a level-1 bidder

$$H_{it}(p, \hat{S}_{it}(p); k = 1, QC_{it}) = \int_{\boldsymbol{QC}_{-it}, \boldsymbol{l}_{-i}, \varepsilon_t} 1(\sum_{j \neq i} S^0_{jt}(p, QC_{jt}) + \hat{S}^1_{it}(p) \geq D_t(p) + \varepsilon_t) dF(\boldsymbol{QC_{-it}}, \boldsymbol{l_{-i}}, \varepsilon_t | \hat{S}^1_{it}(p), k_i = 1, QC_{it})$$

where $\theta_{it} \equiv \sum_{j \neq i} QC_{jt} - \varepsilon_t$. ◂ Back

Why is Assumption 1 important?

1. It implies that residual demand is flatter for higher type.
2. No more assumptions needed about how private information enters the bid functions.

Why? Consider a level-1 bidder

$$H_{it}(p,\hat{S}_{it}(p);k=1,QC_{it}) = \int_{\boldsymbol{QC}_{-it},\boldsymbol{l}_{-i},\varepsilon_t} 1(\sum_{j\neq i} S^0_{jt}(p,QC_{jt}) + \hat{S}^1_{it}(p) \geq D_t(p)+\varepsilon_t)dF(\boldsymbol{QC_{-it}},\boldsymbol{l_{-i}},\varepsilon_t|\hat{S}^1_{it}(p),k_i=1,QC_{it})$$

$$= \int_{\boldsymbol{QC}_{-it},\boldsymbol{l}_{-i},\varepsilon_t} 1(\sum_{j\neq i} \overbrace{QC_{jt}}^{\text{Assumption 1}} - \varepsilon_t \geq D_t(p) - \hat{S}^1_{it}(p))dF(\boldsymbol{QC_{-it}},\boldsymbol{l_{-i}},\varepsilon_t|\hat{S}^1_{it}(p),k_i=1,QC_{it})$$

where $\theta_{it} \equiv \sum_{j\neq i} QC_{jt} - \varepsilon_t$. Back

Why is Assumption 1 important?

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$$
\begin{aligned}
H_{it}(p, \hat{S}_{it}(p); k = 1, QC_{it}) = & \int_{\boldsymbol{QC}_{-it}, \boldsymbol{l}_{-i}, \varepsilon_t} 1(\sum_{j \neq i} S^0_{jt}(p, QC_{jt}) + \hat{S}^1_{it}(p) \geq \\
& D_t(p) + \varepsilon_t) dF(\boldsymbol{QC}_{-it}, \boldsymbol{l}_{-i}, \varepsilon_t | \hat{S}^1_{it}(p), k_i = 1, QC_{it}) \\
= & \int_{\boldsymbol{QC}_{-it}, \boldsymbol{l}_{-i}, \varepsilon_t} 1(\sum_{j \neq i} \overbrace{QC_{jt}}^{\text{Assumption 1}} - \varepsilon_t \geq \\
& D_t(p) - \hat{S}^1_{it}(p)) dF(\boldsymbol{QC}_{-it}, \boldsymbol{l}_{-i}, \varepsilon_t | \hat{S}^1_{it}(p), k_i = 1, QC_{it}) \\
= & \int_{\boldsymbol{QC}_{-it}, \boldsymbol{l}_{-i}, \varepsilon_t} 1(\theta_{it} \geq \\
& D_t(p) - \hat{S}^1_{it}(p)) dF(\boldsymbol{QC}_{-it}, \boldsymbol{l}_{-i}, \varepsilon_t | \hat{S}^1_{it}(p), k_i = 1, QC_{it})
\end{aligned}
$$

where $\theta_{it} \equiv \sum_{j \neq i} QC_{jt} - \varepsilon_t$. Back

We can do the same for type 2

But now

$$H_{it}(p, \hat{S}_{it}(p); k_i = 2, QC_{it}) = \int_{\boldsymbol{QC}_{-it} \times \boldsymbol{l}_{-i} \times \varepsilon_t} 1\Big(\sum_{j \neq i \in \boldsymbol{l_0}} QC_{jt} + \sum_{j \neq i \in \boldsymbol{l_1}} S^1_{jt}(p, QC_{jt}) - \varepsilon_t \geq D_t(p) - \hat{S}^2_{it}(p)\Big) dF(\boldsymbol{QC_{-it}}, \boldsymbol{l_{-i}}, \varepsilon_t | \hat{S}^2_{it}(p), k_i = 2, QC_{it})$$

$$= \int_{\boldsymbol{QC}_{-it} \times \boldsymbol{l}_{-i} \times \varepsilon_t} 1(\theta_{it} \geq D_t(p) - \hat{S}^2_{it}(p)) dF(\boldsymbol{QC_{-it}}, \boldsymbol{l_{-i}}, \varepsilon_t | \hat{S}^2_{it}(p), k_i = 2, QC_{it}) \quad (4)$$

where, $\theta_{it} = \sum_{j \neq i \in \boldsymbol{l_0}} QC_{jt} + \sum_{j \neq i \in \boldsymbol{l_1}} S^1_{jt}(p, QC_{jt}) - \varepsilon_t$.

We can do this recursively for all types. Back

Model: Details

Let

$\Gamma(\cdot)$: the conditional distribution of θ_{it} (conditional on $N-1$ type draws).

$\Delta(l_{-i})$: the marginal distribution of the vector of rival firm types.

Then $H(\cdot)$ becomes

$$H_{it}(p, \hat{S}_{it}(p); k_i, QC_{it}) = \int_{l_{-i}} \left[1 - \Gamma\left(D_t(p) - \hat{S}^k_{it}(p)\right)\right] \cdot \Delta(l_{-i})$$

And $\frac{H_S}{H_p}$ becomes

$$\frac{H_s\left(p, S^*_{it}(p); k_i, QC_{it}\right)}{H_p\left(p, S^*_{it}(p); k_i, QC_{it}\right)} = \frac{\int_{l_{-i}} \gamma\left(D_t(p) - \hat{S}^k_{it}(p)\right) \cdot \Delta(l_{-i})}{-\int_{l_{-i}} \gamma\left(D_t(p) - \hat{S}^k_{it}(p)\right) D'_t(p) \Delta(l_{-i})}.$$

◂ Back

Model: Details

Assumption 2: $\Delta(\cdot)$ is an independent multivariate Poisson distribution truncated at $k-1$, as given by Poisson Cognitive Hierarchy model.

Assumption 3: Γ_i is a uniform distribution. (We can relax but adds to computational burden)

First-order condition simplifies to the "inverse elasticity rule":

$$p - C'_{it}\left(\hat{S}^k_{it}(p)\right) = \frac{1}{-D'_t(p)} * \left[\hat{S}^k_{it}(p) - QC_{it}\right] = \frac{1}{-RD'_t(p)} * \left[\hat{S}^k_{it}(p) - QC_{it}\right],$$

where the second equality follows from the fact that $RD(p) = D(p) + \varepsilon - \sum_{j \neq i} S_{jt}(p) = D(p) + \varepsilon - \sum_{j \neq i} QC_{jt}$. Hence, $RD'(p) = D'(p)$ for all p.

◂ Back

Objective function

$$\omega(\hat{\gamma}) = \sum_i \sum_t \left[\sum_k \Big[\sum_p \Big(\frac{b_{it}^{\text{data}}(p) - b_{it}^{\text{model}}(p|k)}{b_{it}^{\text{model}}(p|K) - b_{it}^{\text{model}}(p|0)} \Big)^2 \times \mathbb{P}(p) \Big] \mathbb{P}_i(k|\, |K|, \hat{\gamma}) \right]$$

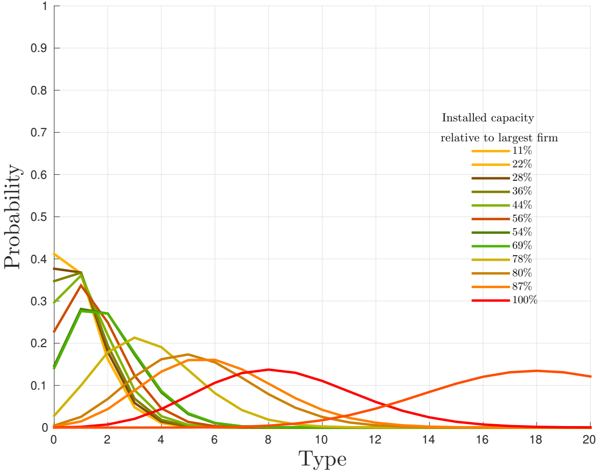
$\mathbb{P}(p) \rightarrow$ price points weighted by triangular distribution centered at market-clearing price

$\mathbb{P}_i(k|\, |K|, \hat{\gamma}) \rightarrow$ weight by probability of a firm being each type

◂ Back

Estimated Type Distributions

$$k_i \sim Poisson(\hat{\tau}_i), \;\; \hat{\tau}_i = \exp(\hat{\gamma}_0 + \hat{\gamma}_1 \, \text{size}_i + \hat{\gamma}_2 \, \text{size}_i^2)$$



Model fit: CH vs. Unilateral Best-Response

Dependent Variable: Profits from Actual Bids

	(1) CH Model	(2) Best-Response	(3)
Profits under Cognitive Hierarchy	0.803	–	0.642
	(0.069)	–	(0.127)
Profits under Best-Response	–	0.428	0.137
	–	(0.044)	(0.062)
Constant	-328.17	-241.74	-374.167
	(141.976)	(120.722)	(125.785)
Observations	1058	1058	1058
R^2	0.67	0.49	0.69

Note: This table reports results from a regression of observed profits from actual bidding behavior on either firm profits as predicted by the Cognitive Hierarchy model (column 1), firm profits that would be achieved from a model of unilateral best-response to rival bids (column 2), or both. An observation is a firm-auction. Standard errors clustered at the firm-level are reported in parentheses.

◂ Back

More evidence on no learning

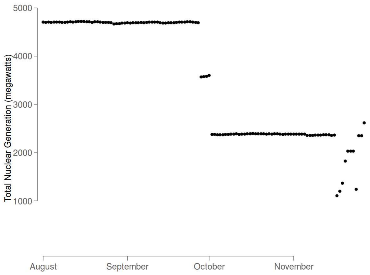
Offered Quantities into Market in Year 2 vs Year 1

	All Firms	All Firms	All Firms	Small Firms
	(1)	(2)	(3)	(4)
Year 2	-34.76	-15.85	-16.15	1.52
	(42.42)	(34.24)	(34.70)	(2.90)
Firm Fixed Effects	Yes	Yes	Yes	Yes
INC Fixed Effects	No	Yes	Yes	Yes
Day of Week Fixed Effects	No	No	Yes	Yes
Observations	2264	2264	2264	1029
R^2	0.01	0.03	0.04	0.09

$^{+}$p$<$0.05; *p$<$0.01. The dependent variable *Participation Quantity*$_{it}$ is the megawatt quantity of output bid at the market-clearing price relative to the firm's contract position in auction t, i.e. $|S_{it}(p^{mcp}) - QC_{it}|$. The sample period is the first 1.5 years of the market and *Year 2* is a dummy variable for the second year. Standard errors clustered at the firm-level are reported in parentheses.

Corroborating "Reduced-Form" Evidence of Non-strategic Behavior

Publicly Observable Shock – Nuclear Generator Went Off-line



Descriptive regressions find:

- Large firms respond to own cost shocks *and* cost shocks of competitors
- Small firms only respond to own cost shocks

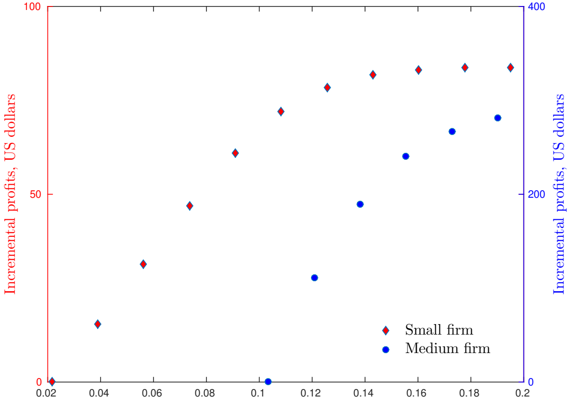
Corroborating "Reduced-Form" Evidence of Non-strategic Behavior

	Largest Six	Smallest Six	Largest Six	Smallest Six	Largest Six	Smallest Six
Outage	-26.27*	-0.64	-9.80*	0.4	-8.40*	-0.03
	(4.69)	(0.42)	(2.92)	(0.38)	(2.05)	(0.25)
Own MC			0.27*	0.18*	0.30*	0.11*
			(0.03)	(0.02)	(0.03)	(0.02)
Constant	40.28*	3.75*	2.82	0.19	-21.13*	0.76*
	(4.49)	(0.32)	(2.41)	(0.37)	(6.55)	(0.21)
Bidder Fixed Effects	No	No	No	No	Yes	Yes
N	378	378	378	378	378	378
R^2	0.09	0.01	0.40	0.31	0.67	0.68

Note: Each column reports estimates from a separate regression of the slope of a firm's bid function on an indicator variable that the auction occurred during the fall 2002 nuclear outage. An observation is a firm-auction. The dependent variable is the slope ($\frac{\partial S_{it}}{\partial p}$) of firm i's bid in auction t where the slope is linearized plus and minus \$10 around the market-clearing price. Own MC is the slope of the firm's own marginal cost function linearized plus and minus \$10 around the market-clearing price. White standard errors are reported in parentheses. + $p<0.05$, * $p<0.01$

Diminishing Returns to Sophistication

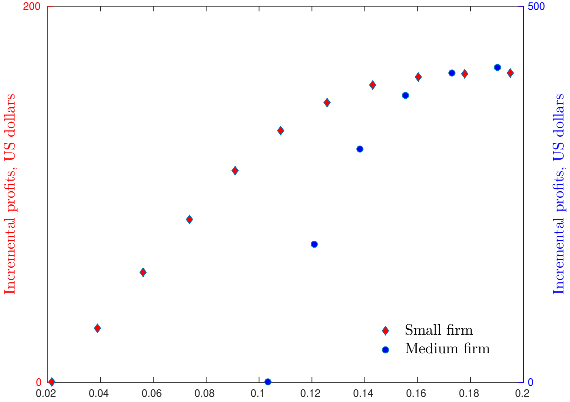
INC side



x-axis includes range from smallest to largest firm

Diminishing Returns to Sophistication

DEC side



x-axis includes range from smallest to largest firm