Pricing Algorithms and Tacit Collusion

Bruno Salcedo

The Pennsylvania State University

January 2016

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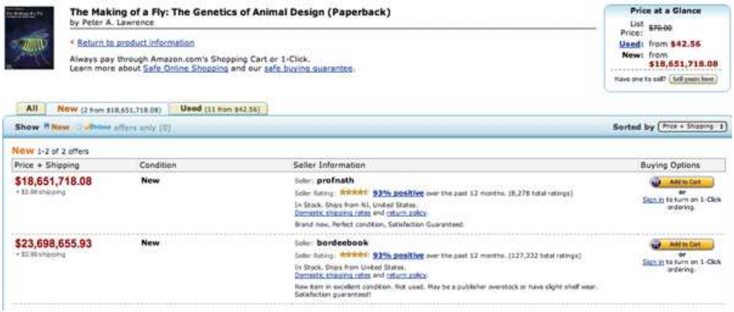
"The Making of the Fly" listed in Amazon for $79.84 on 11/15/15

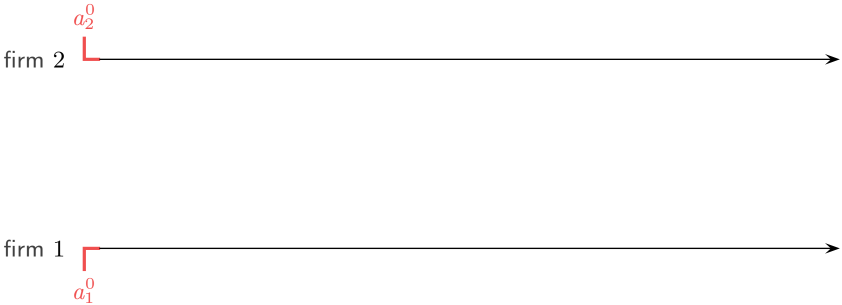


"The Making of the Fly" listed in Amazon for $18,651,718.08 on 4/18/11

- Online retail (Ezrachi & Stucke, 2015)
- Airlines (Borenstein, 2004)
- High-frequency trading (Boehmer, Li & Saar, 2015)
- Online auctions
- Hierarchical firms

"*We will not tolerate anticompetitive conduct, whether it occurs in a smoke-filled room or over the Internet using complex pricing algorithms. American consumers have the right to a free and fair marketplace online, as well as in brick and mortar businesses.*"

— Bill Baer, Department of Justice



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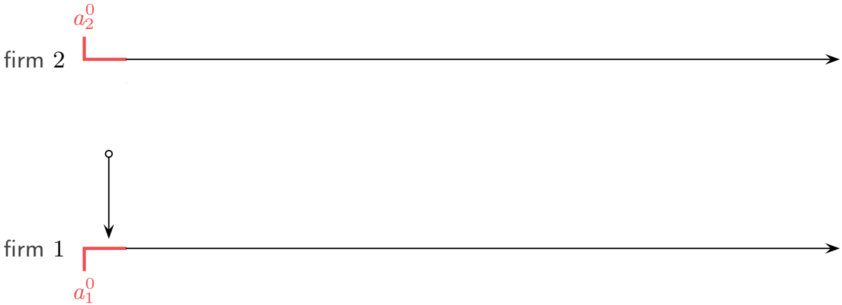

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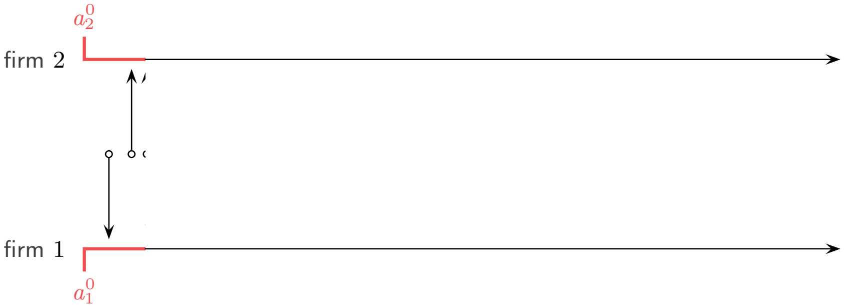
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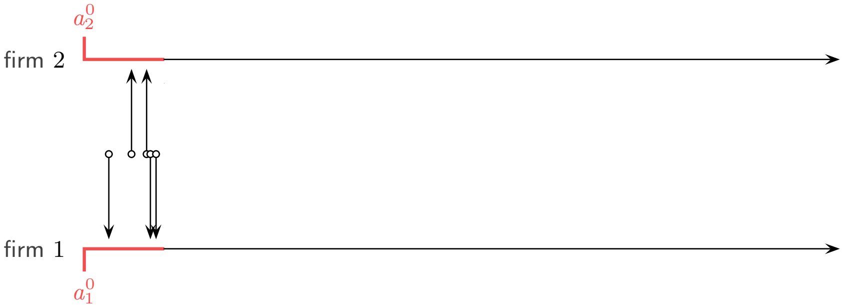

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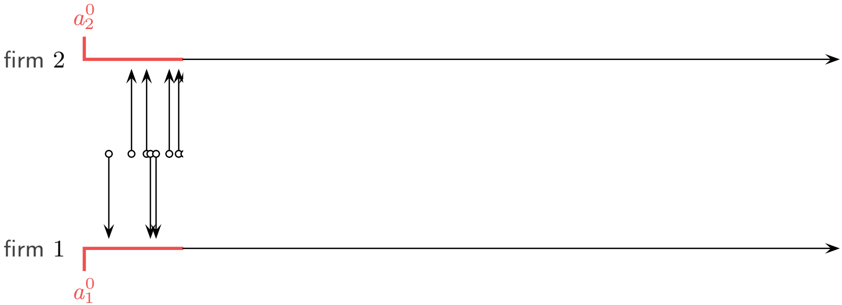
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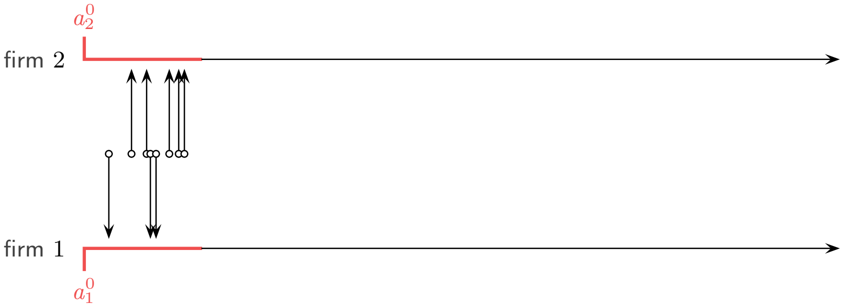

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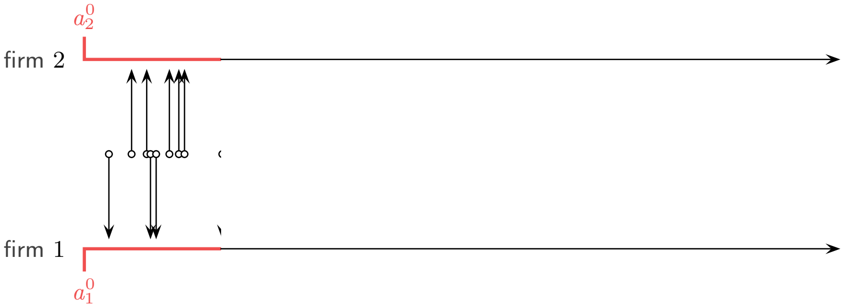
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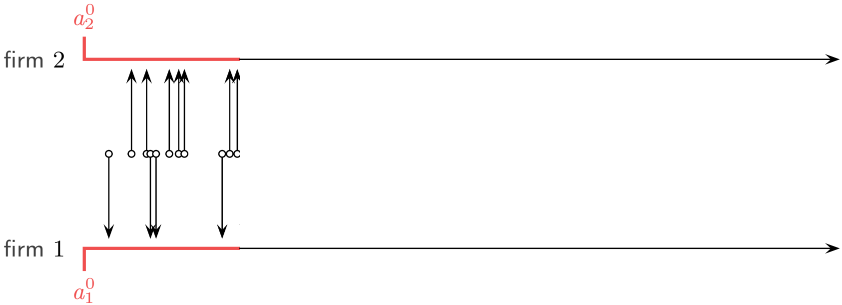
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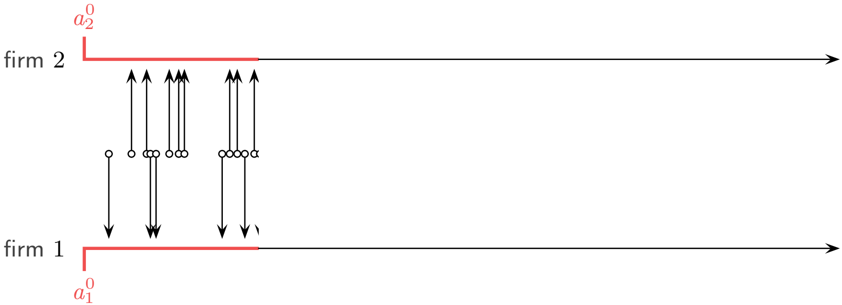

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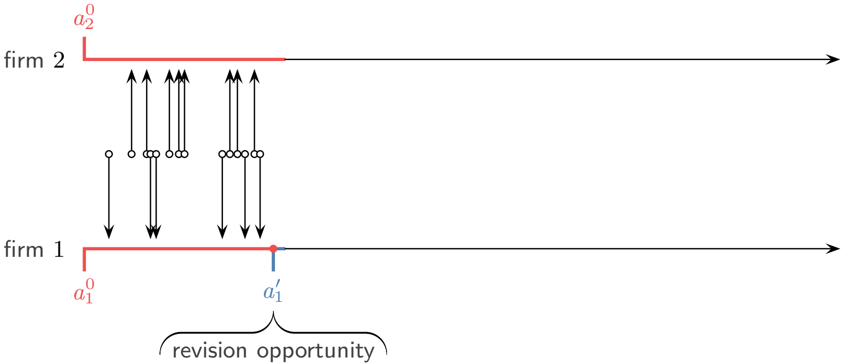
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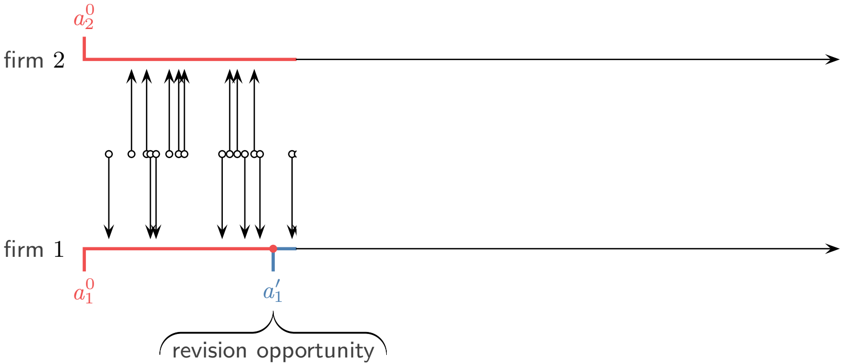
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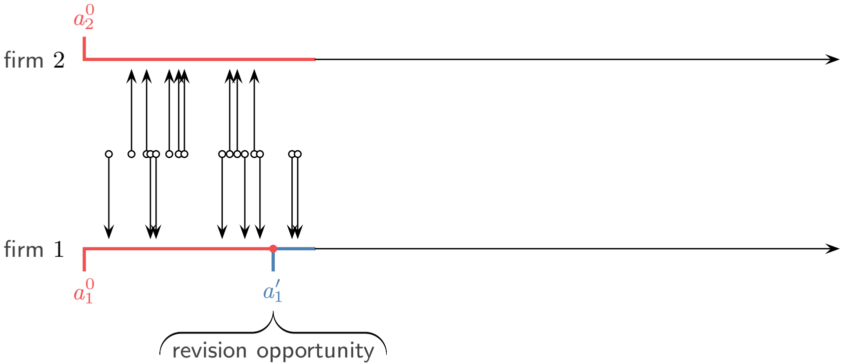
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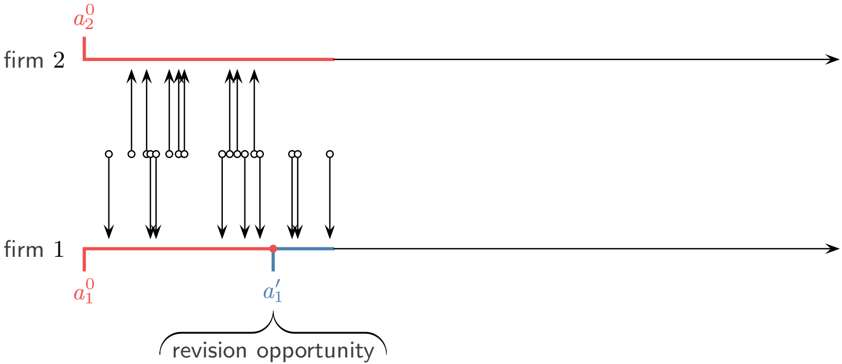

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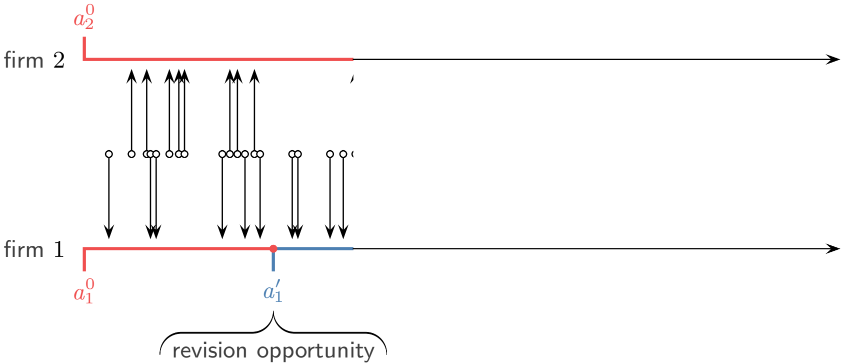
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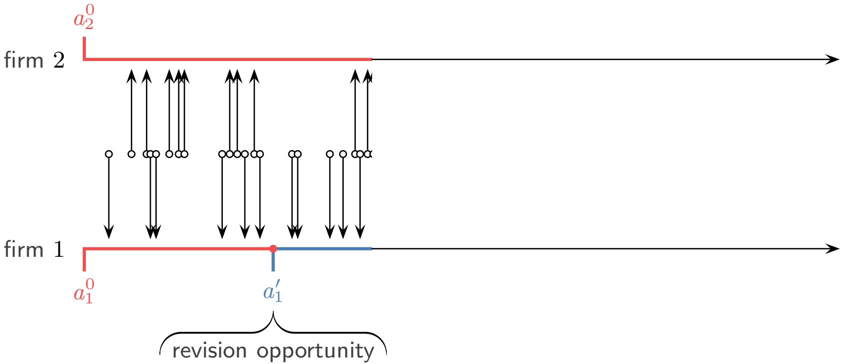

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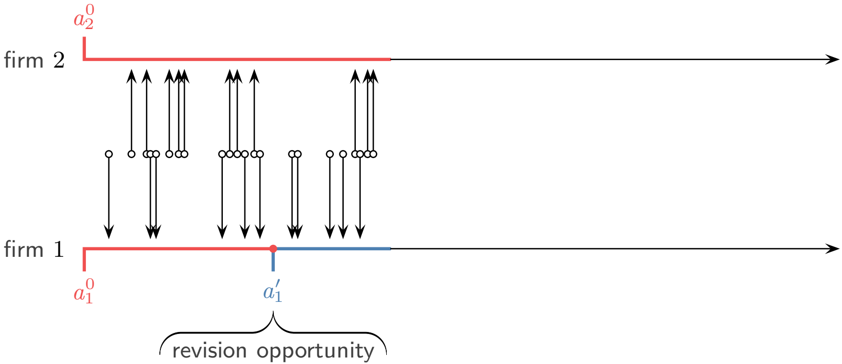
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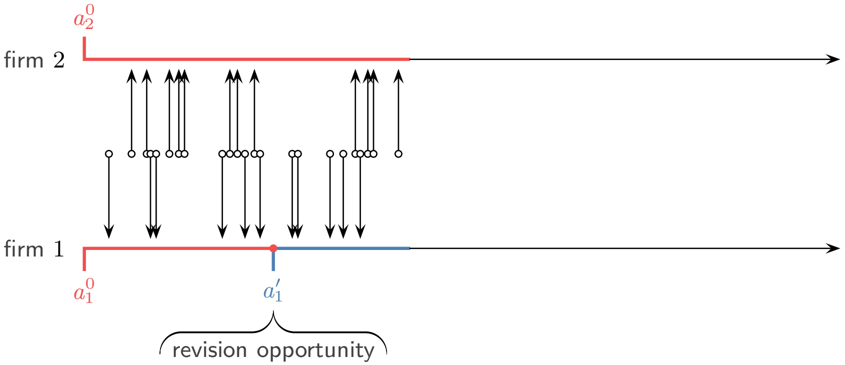

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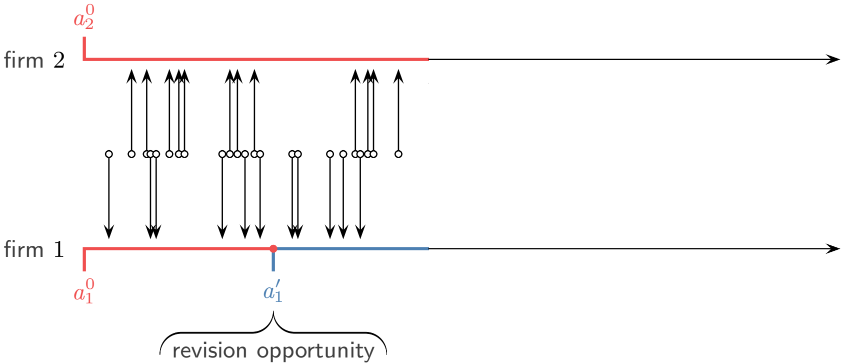
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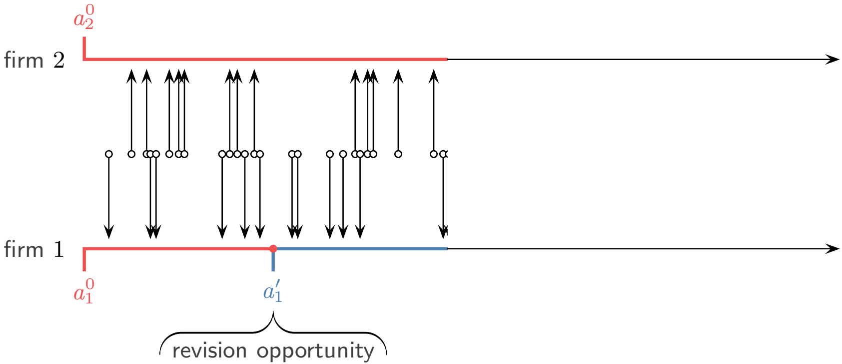
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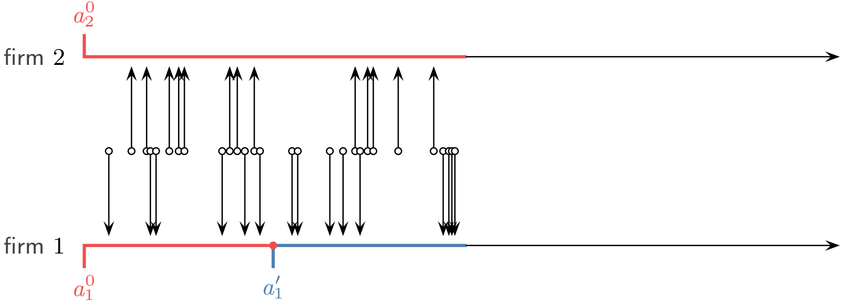
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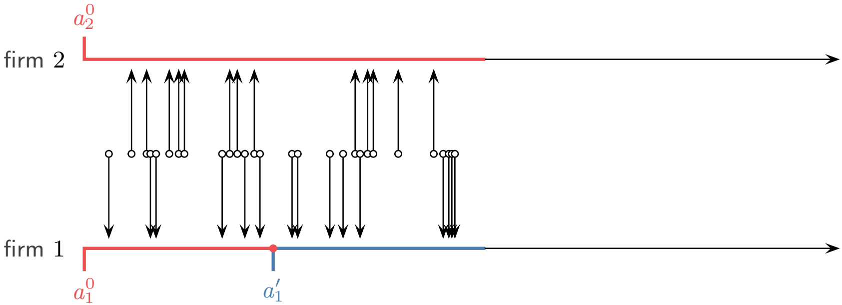

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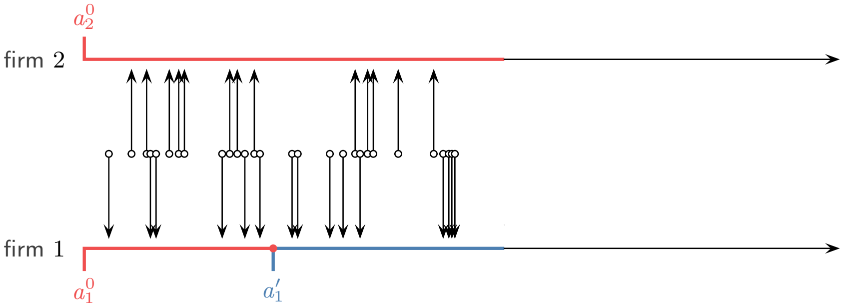
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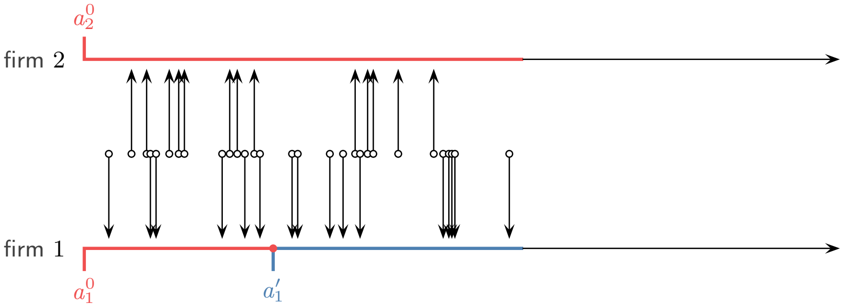

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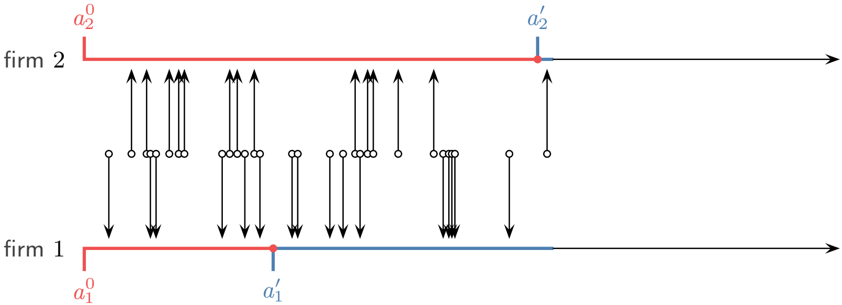
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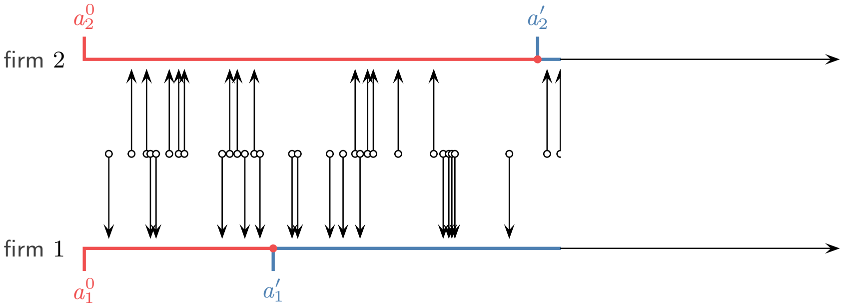
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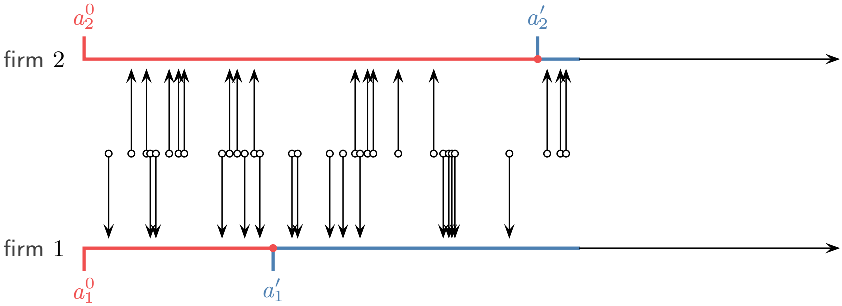

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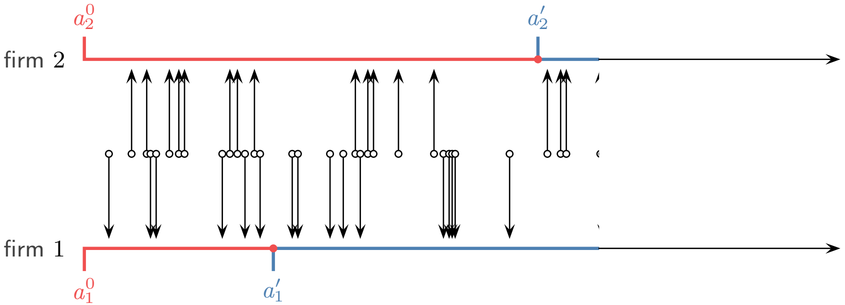

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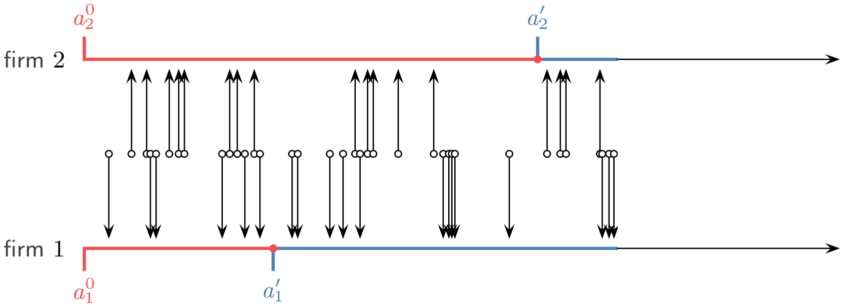

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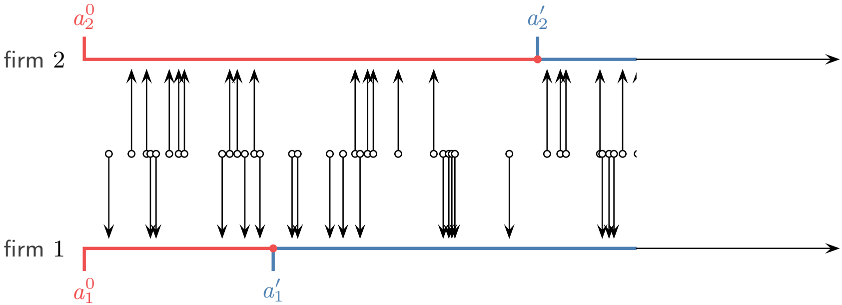
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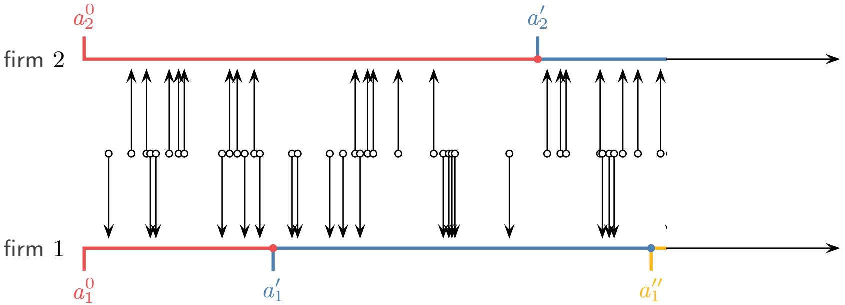

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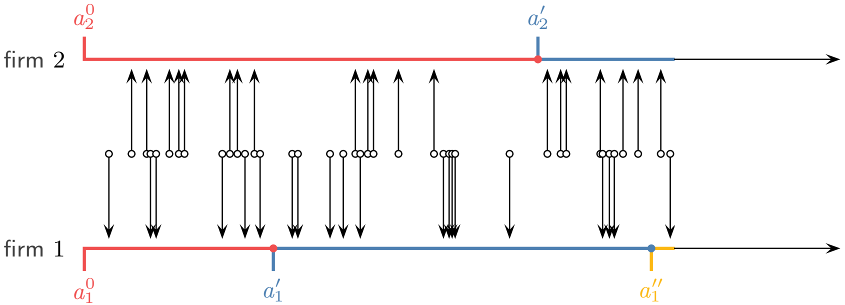
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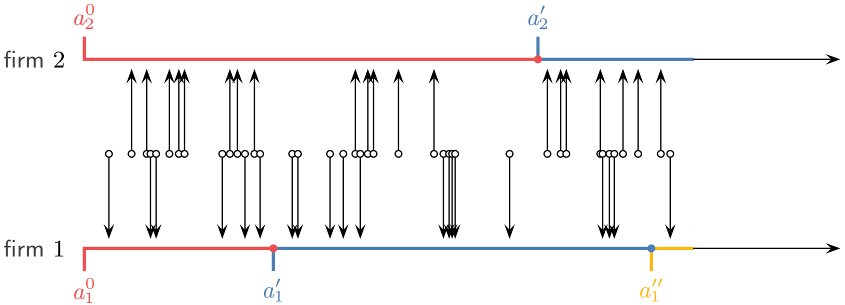

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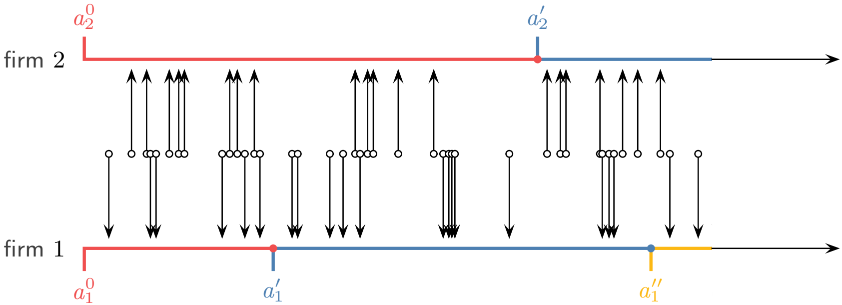

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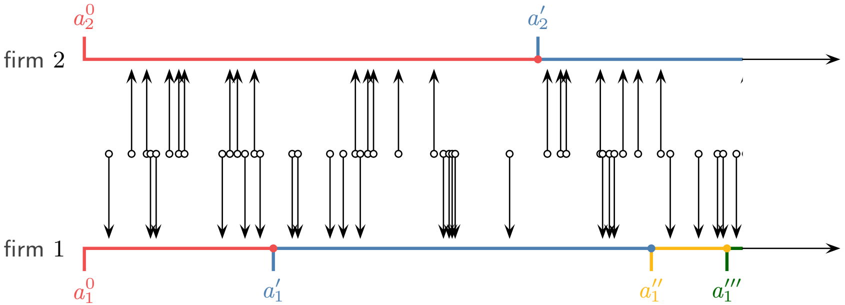

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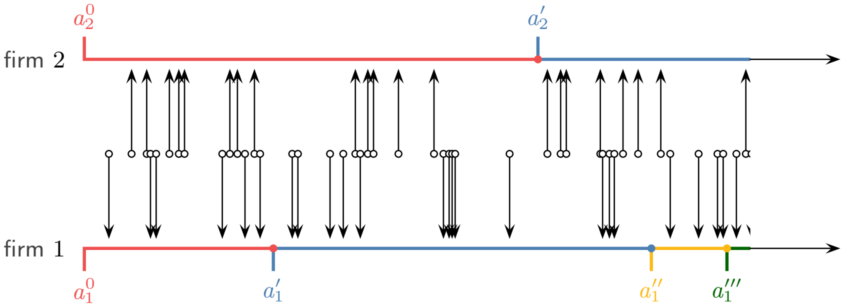

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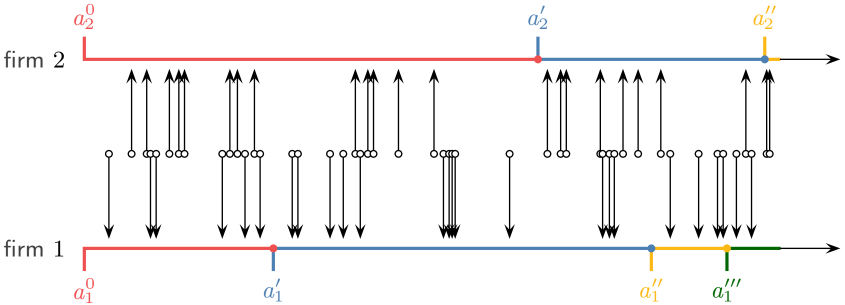
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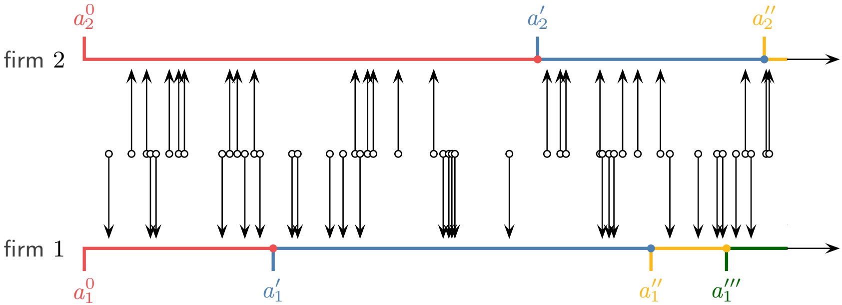

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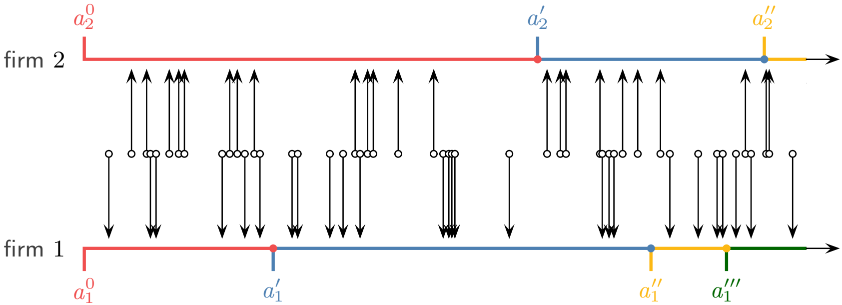

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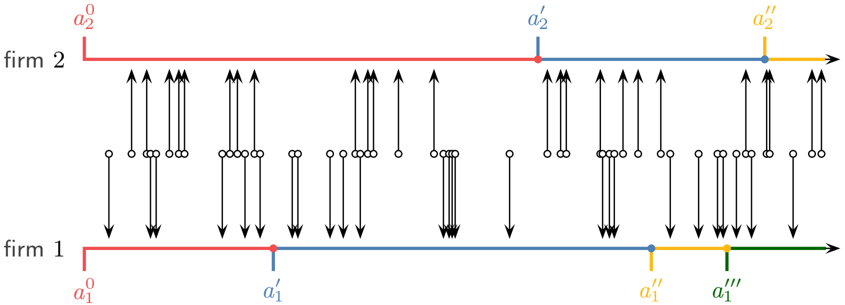
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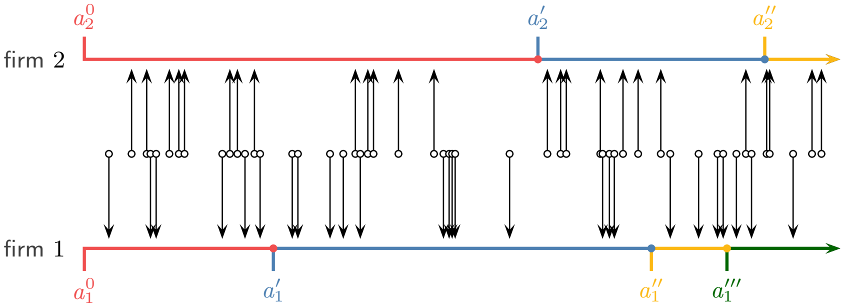
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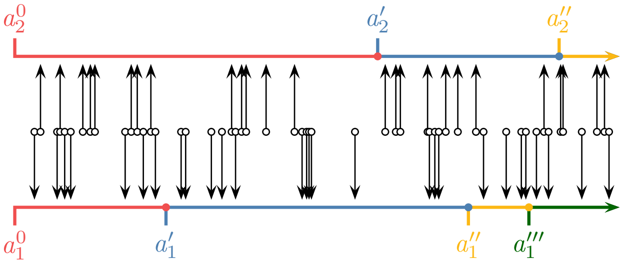
key features



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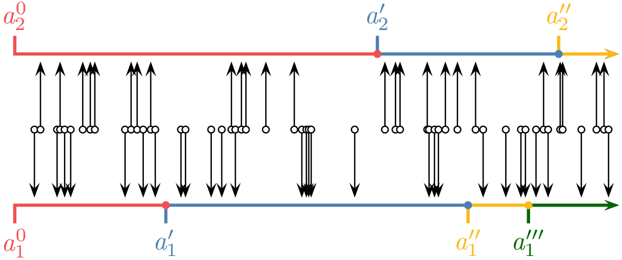
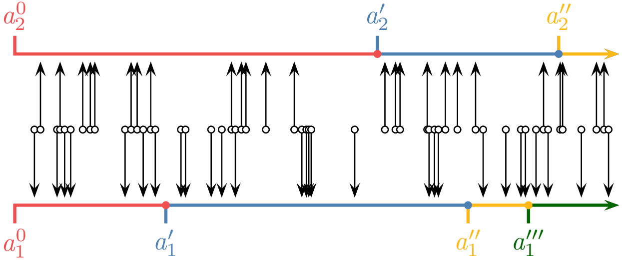


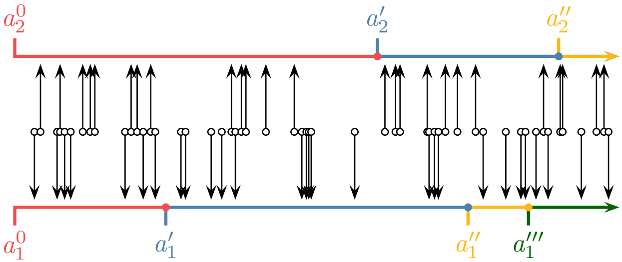
1. *Responsiveness:* algorithms rapidly react to market outcomes



1. *Responsiveness:* algorithms rapidly react to market outcomes

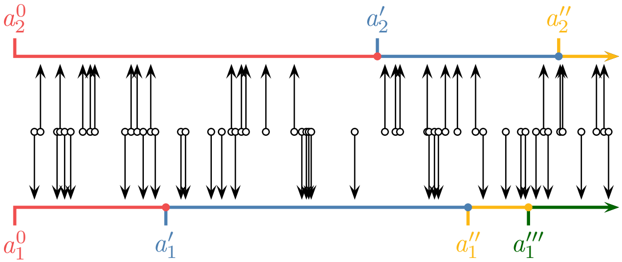
2. *Short-term commitment:* algorithms cannot be revised too often

key features



1. *Responsiveness:* algorithms rapidly react to market outcomes
2. *Short-term commitment:* algorithms cannot be revised too often
3. *Long-term flexibility:* algorithms can be revised over time

key features

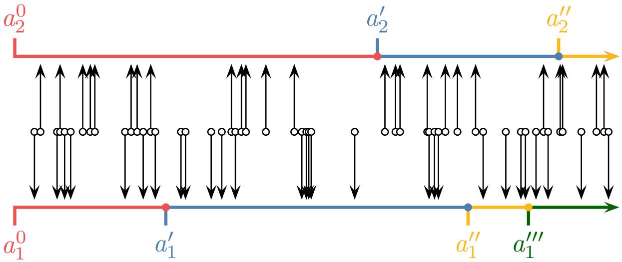


1. *Responsiveness:* algorithms rapidly react to market outcomes

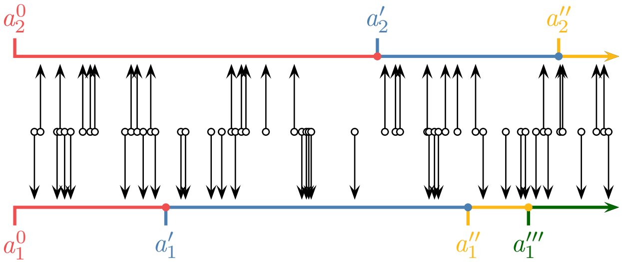
2. *Short-term commitment:* algorithms cannot be revised too often

3. *Long-term flexibility:* algorithms can be revised over time

4. *Observability:* rival's algorithm can be decoded



When demand shocks arrive much more frequently than algorithm revisions, the long-run joint profits from any subgame-perfect equilibrium are close to those of a monopolist



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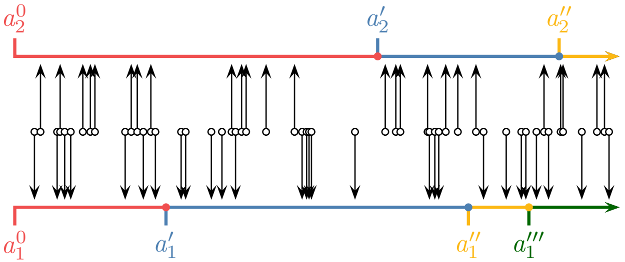
inevitability of collusion



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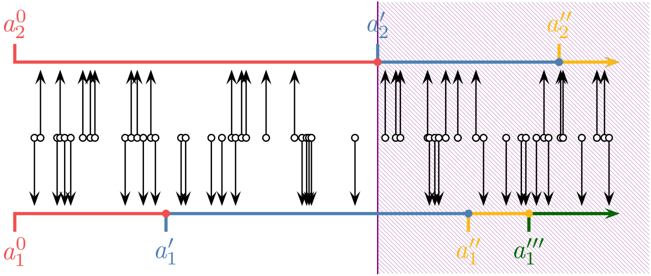

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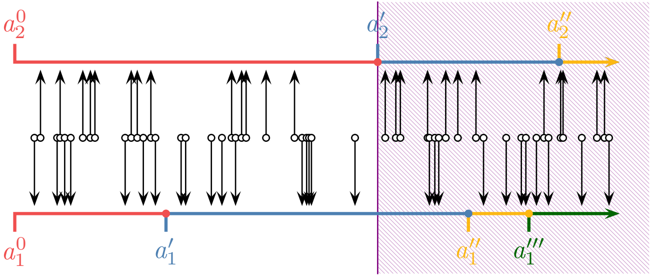


When demand shocks arrive much more frequently than algorithm revisions, the long-run joint profits from any subgame-perfect equilibrium are close to those of a monopolist

outline

1. introduction
2. example
3. model
4. main result
5. closing remarks

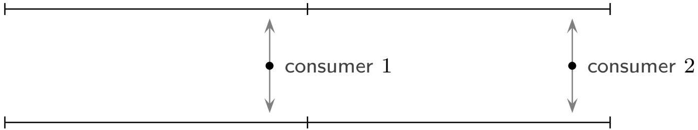
1. introduction

2. **example**

3. model

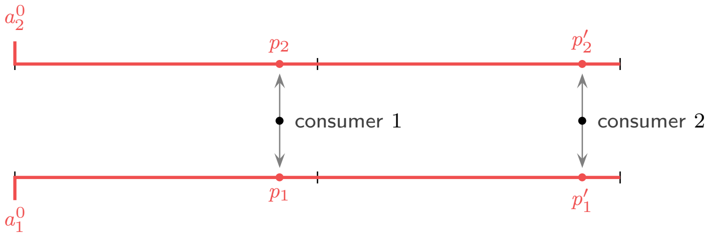
4. main result

5. closing remarks

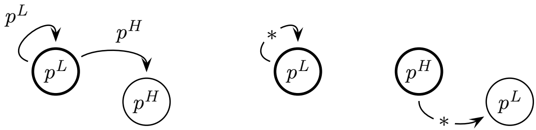


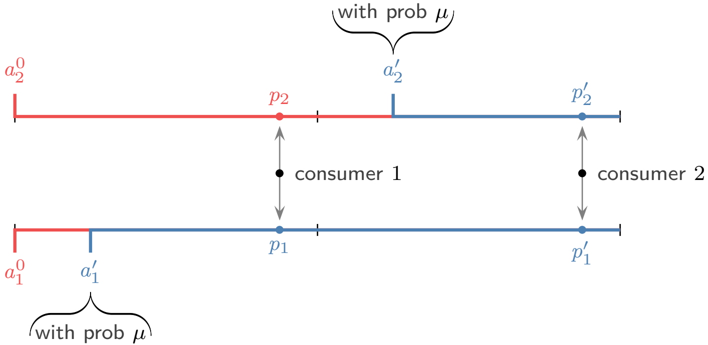
- One consumer tonight and one consumer tomorrow night
- Stage game is a prisoner's dilemma

	p^H	p^L
p^H	$2, 2$	$0, 3$
p^L	$3, 0$	$1, 1$



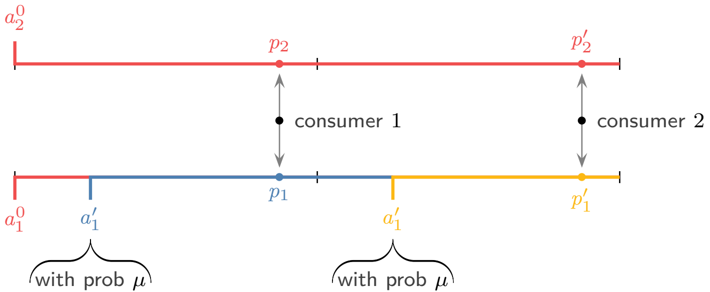
- At the beginning of the game firm simultaneously choose pricing algorithms
  - a price for tonight p_j
  - a contingent price for tomorrow night $p_j'(p_{-j})$





- Exogenous stochastic revision opportunities each morning

	revision	no revision
revision	0	μ
no revision	μ	$1-2\mu$



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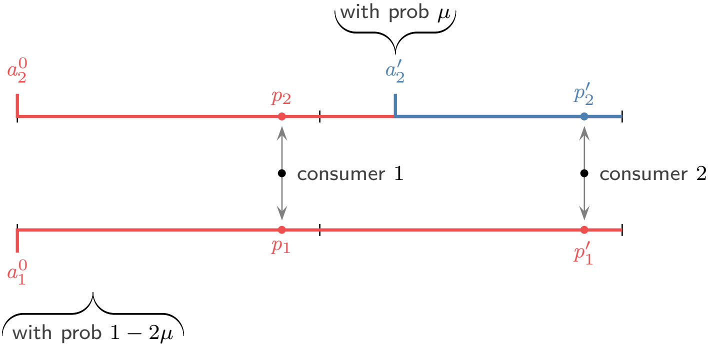

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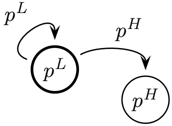
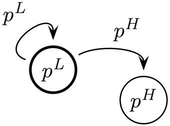


	p^H	p^L
p^H	$2, 2$	$0, 3$
p^L	$3, 0$	$1, 1$

- Suppose firm 1 uses "tit for tat" and firm 2 has a revision on the first day

lower bound on profits



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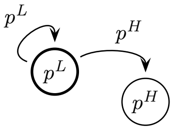
- Suppose firm 1 uses "tit for tat" and firm 2 has a revision on the first day
  - 2's profits from choosing p^L on day 1 are bounded above by

$$\hat{v}_2^L = \underbrace{1}_{\text{day } 1} + \underbrace{(1-\mu)1}_{\substack{\text{day } 2 \\ 1 \text{ doesn't revise}}} + \underbrace{\mu 3}_{\substack{\text{day } 2 \\ 1 \text{ revises}}} = 2 + 2\mu$$

lower bound on profits



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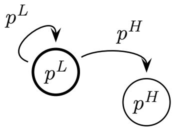
  - 2's profits from choosing p^H on day 1 and p^L on day 2 are bounded below by

$$\underline{v}^H = \underbrace{0}_{\text{day 1}} + \underbrace{(1-\mu)3}_{\substack{\text{day 2} \\ \text{1 doesn't revise}}} + \underbrace{\mu 1}_{\substack{\text{day 2} \\ \text{1 revises}}} = 3 - 2\mu$$

lower bound on profits



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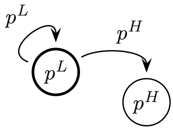
  - If $\mu < 1/4$ then $\underline{v}_2^H > \hat{v}_2^L$

lower bound on profits



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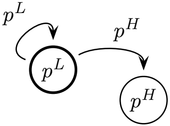
- Suppose firm 1 uses "tit for tat" and firm 2 has a revision on the first day
  - If $\mu < 1/4$ then firm 2 chooses p^H on day 1
- If $\mu < 1/4$, firm 1 can guarantee profits above 2 by using "tit for tat"
  - If firm 2 sets p^L on both days, firm 1 makes 2 in profits
  - If firm 2 sets p^M on at least one day, firm 1 makes at least 3 in profits
  - If firm 2 has a revision on day 1 it sets p^H

lower bound on profits



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> If revisions are sufficiently unlikely, joint profits in any subgame-perfect equilibrium are strictly greater than 4

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5. closing remarks

- Two symmetric firms $j \in \{1, 2\}$
- Continuous time $t \in [0, \infty)$
- Consumers arrive randomly
  - Poisson process with parameter $\lambda > 0$
  - (y_n) denotes sequence of arrival times
  - A single consumer arrives at each y_n

stage game

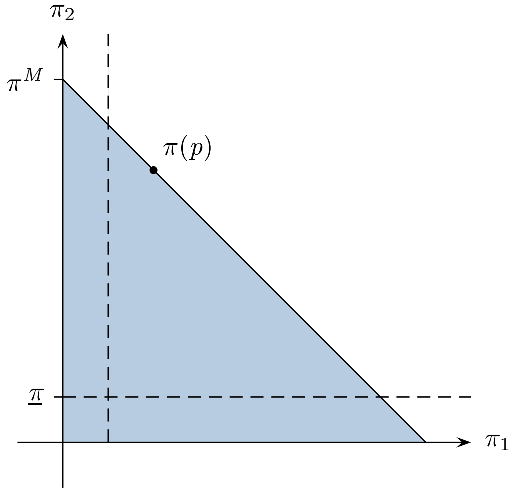
$P = \mathbb{R}_+$

stage game

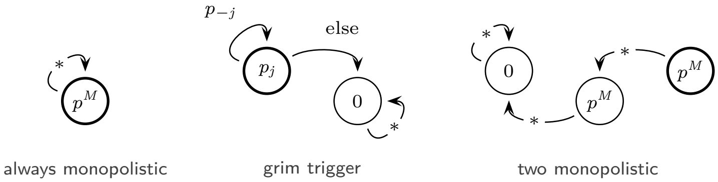
$$P = \mathbb{R}_+ \qquad \pi_j : P^2 \to \mathbb{R}_+$$

stage game

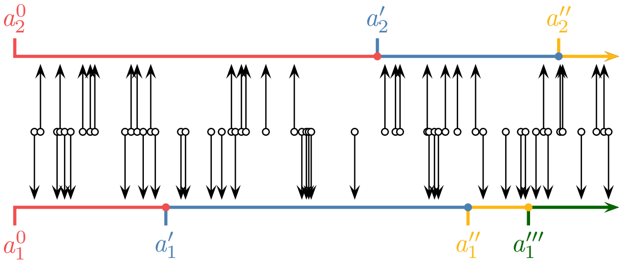
$$P = \mathbb{R}_+ \qquad \pi_j : P^2 \to \mathbb{R}_+ \qquad \Pi = \left\{ \pi(p) \;\middle|\; p \in P^2 \right\}$$



- Pricing algorithms set current prices contingent on the history of past prices
- Finite automata $a = (\Omega, \omega_0, \theta, \alpha)$
  - Finite set of states Ω
  - Initial state ω_0
  - Pricing rule $\alpha : \Omega \to P$
  - Measurable transition function $\theta : \Omega \times P \to \Omega$

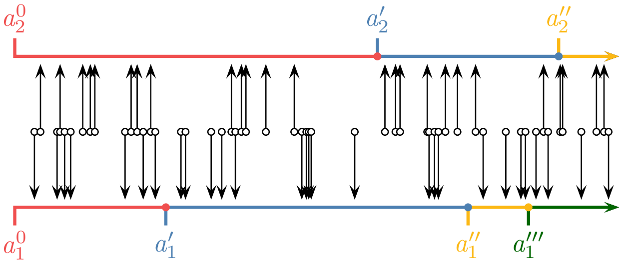


dynamic game



- Firms simultaneously set algorithms at time $t = 0$ and can revise them at exogenous stochastic times
  - Poisson process with parameter $\mu > 0$
  - Arrival of revision is independent across firms and independent of consumer-arrival times

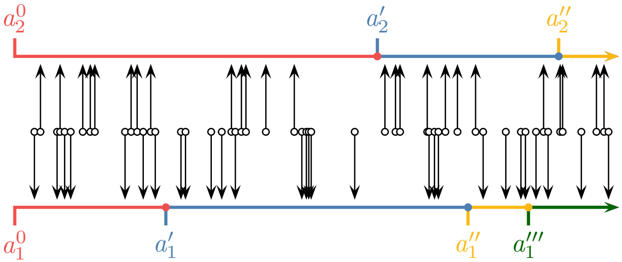
dynamic game



- Firms simultaneously set algorithms at time $t = 0$ and can revise them at exogenous stochastic times

- A strategy $s_j : H_j \to \Delta(A)$ for firm j chooses algorithms
  - As a function of past algorithms, prices, and number of past consumers

dynamic game



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- A strategy $s_j : H_j \to \Delta(A)$ for firm j chooses algorithms
  - As a function of past algorithms, prices, and number of past consumers
  - In this talk, not as a function of clock time of consumer and revision arrivals

- Firms maximize (normalized) expected discounted profits

$$v_j = \frac{r}{\lambda + r} \times \mathbb{E}\left[\sum_{n=1}^{\infty} \exp(-r y_n) \pi_j(p_n) \right]$$

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- Sub-game perfect Nash equilibria $s \in S^*$
- Using Levy (2015) and Mertens and Parthasarathy (1987)

If the profit function π is bounded (and Borel measurable), then the dynamic game has an equilibrium

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- Fix any interest rate r and any constant $\varepsilon > 0$

inevitability of collusion

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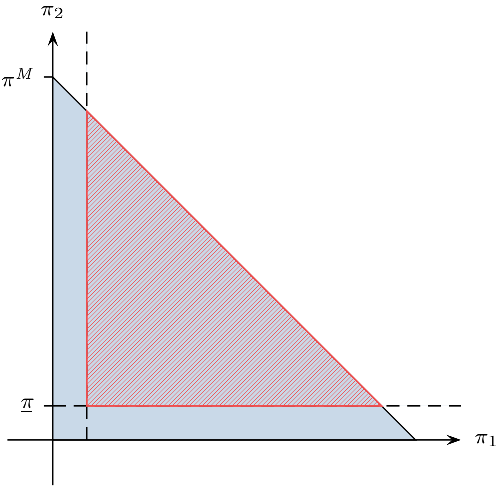
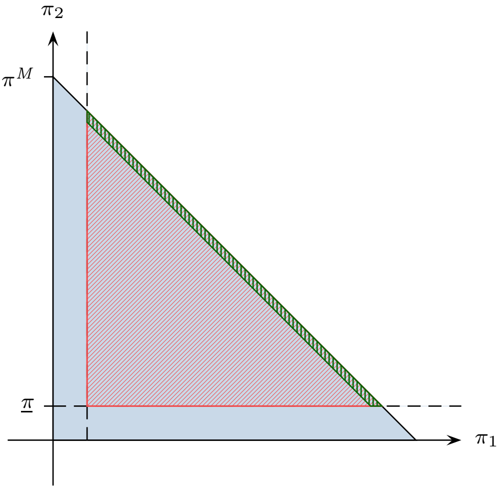
- If costumers arrive frequently $\lambda > r\underline{\lambda}$
- And revisions are infrequent $0 < \mu < r\bar{\mu}(\varepsilon, \lambda)$
- For any date $\tau \geq t_0$ the joint continuation profits are closer than ε from the joint monopolistic profits with probability greater than $(1 - \varepsilon)$ in any equilibrium, i.e.

$$\inf_{s \in S^*} \Pr{}_s \Big(\bar{v}_\tau > \bar{\pi}^M - \varepsilon \Big) > 1 - \varepsilon$$

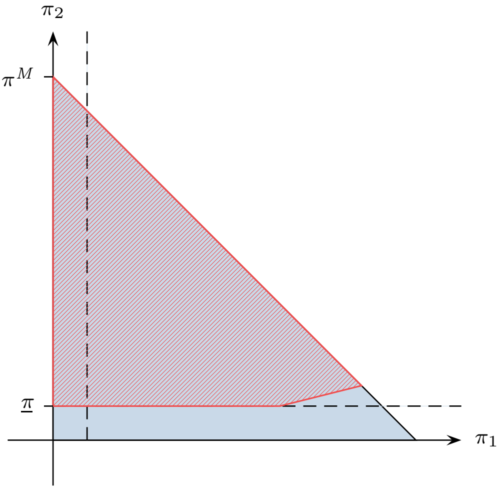
inevitability of collusion



inevitability of collusion

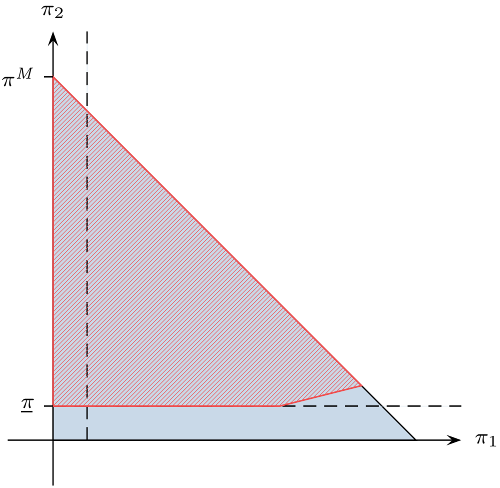


step 1



$$\Pi^j = \left\{ v(a) \;\middle|\; a_{-j} \in \mathrm{BR}(a_j) \right\}$$

step 1



If $\dfrac{\lambda}{r} > \underline{\lambda}$, then Π^j intersects the Pareto frontier

step 2

- Suppose current algorithms induce a sequence of profits π^n
- Expected discounted profits can be decomposed as

$$v_j = \mathbb{E}\left[\underbrace{\exp(-rz_1)}_{\substack{\text{discounting}\\ \text{to first event}}}\left(\underbrace{\mathbb{1}_0 \cdot \left(\frac{r}{\lambda}\pi_j^1 + w^0\right)}_{\text{consumer}} + \underbrace{\mathbb{1}_1 \cdot w_j^1 + \mathbb{1}_2 \cdot w_j^2}_{\text{revisions}}\right)\right]$$

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$$= \underbrace{\frac{r}{r+\lambda+2\mu}\pi_j^1 + \frac{\lambda}{r+\lambda+2\mu}w_j^0}_{\text{consumer}} + \underbrace{\frac{\mu}{r+\lambda+2\mu}w_j^1 + \frac{\mu}{r+\lambda+2\mu}w_j^2}_{\text{revision}}$$

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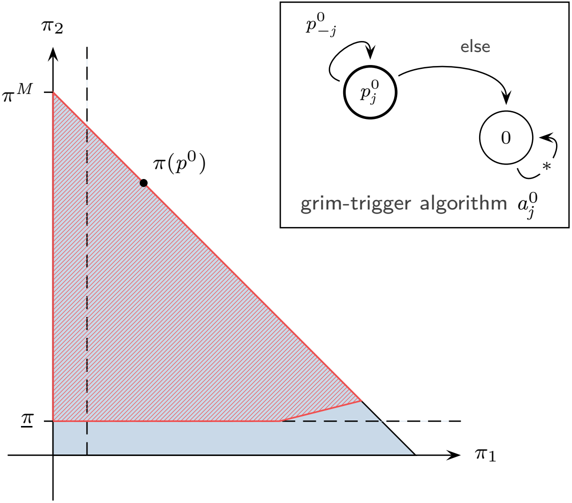
- Iterating this process yields

$$v_j = \frac{r}{r+2\mu}(1-\beta)\sum_{k=0}^{\infty}\beta^k\pi_j^k + \frac{2\mu}{r+2\mu}\tilde{w}_j$$

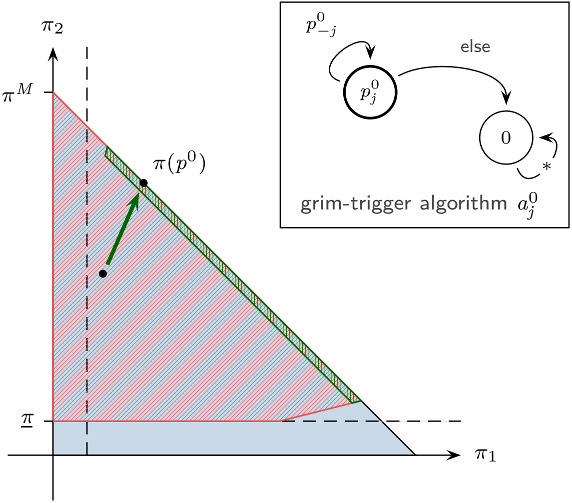
where $\beta = \lambda/(r+\lambda+2\mu)$

step 2



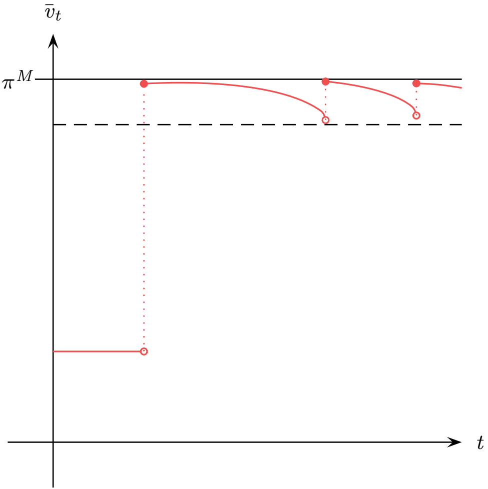
In any equilibrium,if firm $-j$ observes a^0_j, it chooses an algorithm that mimics a^0_{-j} for at least $N = c_1(p^0)\dfrac{r}{\mu} - c_0$ consumers

step 2



If $\dfrac{\mu}{r} < \bar{\mu}(\varepsilon, \lambda)$, then continuation values at the moment of each revision after the first one are close to the Pareto frontier of Π^j

step 3



Revision continuation joint profits after t_0 are close enough to π^M
so that, after the second revision, long run profits remain high

additional results

- The four key features of the model are necessary for the main result ▷
- Firms are willing to make their algorithms transparent and benefit from being less flexible ▷
- Pricing algorithms enable collusion between impatient firms ▷

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- Internal organization of the firm matters
- Pricing algorithms provide predictability and stability
- May not only enable *tacit* collusion, but inevitably lead to it in the long run
- Regulation of transparent/public algorithms and algorithm patterns

efficient renegotiation

- Explicit negotiation protocols leading to efficient outcomes
- Inefficient equilibria exist in repeated games because
  - Strategies are chosen independently
  - There are no opportunities to renegotiate
- The ability to revise initial choices and learn about future intentions of other players can restore efficiency in the long run

work in progress

- Minor extensions
  - Calibration
  - General profit functions
  - Restriction to pure strategies

work in progress

- Minor extensions
  - Calibration
  - General profit functions
  - Restriction to pure strategies
- For the next paper
  - Can learning substitute observability?
  - Can incomplete information substitute commitment?

Thank you for your attention!

paper available at brunosalcedo.com

contact me at bruno@psu.edu

Ü///

tightness

- Responsiveness
- Observability
- Short-term commitment
- Long-term flexibility

tightness

- Responsiveness
  - Suppose firms choose prices instead of algorithms
  - Deviating from the static equilibrium of the stage game would be costly if there are no revisions

- Observability
- Short-term commitment
- Long-term flexibility

- Responsiveness
  - Suppose firms choose prices instead of algorithms
  - Deviating from the static equilibrium of the stage game would be costly if there are no revisions
  - Not necessary for all games (Ambrus & Ishii, 2015)
- Observability
- Short-term commitment
- Long-term flexibility

tightness

- Responsiveness
- Observability
  - If firm 2 cannot decode firm 1's algorithm it cannot react to it
- Short-term commitment
- Long-term flexibility

- Responsiveness
- Observability
  - If firm 2 cannot decode firm 1's algorithm it cannot react to it
  - Might not be necessary under imperfect monitoring (work in progress)
- Short-term commitment
- Long-term flexibility

tightness

- Responsiveness
- Observability
- Short-term commitment
  - If firm 2 believes that firm 1 will change its algorithm back to "always Bertrand" it is optimal to do the same
  - The result hinges on high commitment ($\mu \approx 0$)
- Long-term flexibility

tightness

- Responsiveness
- Observability
- Short-term commitment
- Long-term flexibility
  - If there are no revisions choosing "always Bertrand" is an equilibrium
  - The result hinges on imperfect commitment ($\mu > 0$)

◁

- Fix any any λ and r
- Take limits when firm 1 is completely committed and firm 2 can revise arbitrarily often

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- Take limits when firm 1 is completely committed and firm 2 can revise arbitrarily often
- Firm 1's expected discounted profits in any equilibrium become weakly greater than its dynamic Stackelberg payoff, i.e.,

$$\lim_{\mu_1 \to 0} \lim_{\mu_2 \to \infty} \inf_{s \in S^*} v_1(s) \geq \pi_1^S(\lambda, r)$$

where

$$\pi_1^S(\lambda, r) := \max \left\{ v_j(a) \,\middle|\, \quad a_{-j} \in \arg\max_{a'_{-j}} v_{-j}(aj, a'_{-j}) \right\}$$

impatient firms

- Fix any any λ and r
- Take limits as revision opportunities become arbitrarily frequent

- Fix any any λ and r
- Take limits as revision opportunities become arbitrarily frequent
- There joint profits in the best symmetric equilibrium converge to the joint monopolistic profits, i.e.,

$$\lim_{\mu \to 0} \sup \left\{ v \,\middle|\, (v, v) \in V^*(\lambda, \mu, r) \right\} = \pi^M$$

◁