

Lecture 21a:
Solving directional dynamic games
for all Markov perfect equilibria
Australian Summer School in Dynamic Structural Econometrics

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ROAD MAP for the next three lectures

1. Collusion of Australian corrugated fibre packaging (CFP) producers
 - ▶ Collusion between Amcor and Visy
 - ▶ Bertrand pricing and investment game
 - ▶ Solution concept: Markov perfect equilibrium (MPE)
2. Experiment with the model
3. State recursion algorithm
 - ▶ Theory of directional dynamic games (DDGs)
4. Recursive lexicographical search (RLS) algorithm
5. Full solution for the leapfrogging game
6. Structural estimation of directional dynamic games with Nested RLS method

Overview of results

- ▶ We extend the standard static textbook model of Bertrand price competition by allowing duopolists to undertake cost-reducing investments in discrete time
- ▶ Technological progress is exogenous and stochastic
- ▶ Each firm has a binary decision to acquire the state of the art production technology
- ▶ Even though this is a small extension of the classic static model of Bertrand price competition, surprisingly little is known about Bertrand competition in the presence of production cost uncertainty, especially in dynamic settings
- ▶ We show how to compute all equilibria of this game and show that this dynamic model of Bertrand price competition has surprisingly rich, complex, and counter-intuitive equilibrium outcomes.

How do you find *all* Markov Perfect Equilibria?

The Markov Perfect Equilibrium (MPE) concept of Maskin and Tirole (1988) is now a widely used in *empirical IO*. However computing MPE remains a daunting computation problem

Quote (Hörner *et. al. Econometrica* 2011)

“Dynamic games are difficult to solve. In repeated games, finding some equilibrium is easy, as any repetition of a stage-game Nash equilibrium will do. This is not the case in stochastic games. The characterization of even the most elementary equilibria for such games, namely (stationary) Markov equilibria, in which continuation strategies depend on the current state only, turns out to be often challenging.”

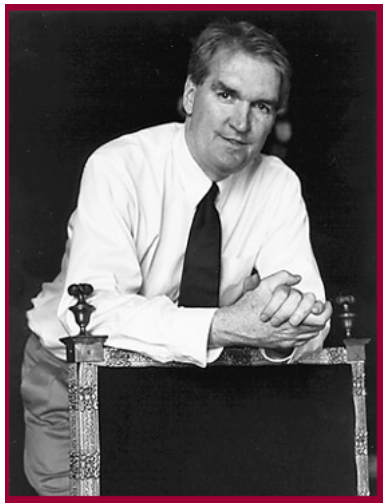
Finding even a single MPE is challenging!

- ▶ How do people “find” MPEs?
- ▶ Theorists: **Guess and Verify**
- ▶ Applied people: **Iterate on the player Bellman equations**
- ▶ Pakes and McGuire (1994): some of the earliest work on computing MPE. Proposed a deterministic, iterative algorithm to compute MPE. Found a curse of dimensionality in trying to solve MPE model of firm dynamics with even moderate numbers of firms
- ▶ Pakes and McGuire (2001): Proposed a *stochastic algorithm* to approximate an MPE, in an attempt to break this curse of dimensionality

Eric Maskin: taught my game theory class at MIT



One of my classmates: Tim Kehoe



Another classmate: David Levine



Another classmate: Drew Fudenberg



Another classmate: Jean Tirole



Motivation: Collusion on the beach



Peter Brown: Amcor Managing Director



Harry Debney: Visy CEO



Russell Jones: Chairman of Amcor



Richard Pratt: Owner of Visy



The Australian cardboard market

- ▶ The Australian market for *cardboard* (CFP) is essentially a duopoly
- ▶ Between 2000 and 2005 the two firms, *Visy* and *Amcor* colluded to raise the price of CFP
- ▶ I was hired to estimate the damage caused by the collusion, which requires predicting what CFP prices would have been in the absence of collusion
- ▶ My opinion was that the “but-for” CFP prices are those predicted by Bertrand price competition in the short run, with *leapfrogging investments* by the two firms over the longer run as they vie for low-cost leadership

Amcor's New B9 Paper Mill

Main Mill Site, Botany Bay Road, Botany Bay NSW



Source: Amcor

B9 is an example of leapfrogging

- ▶ Amcor's existing paper plant was over 50 years old
- ▶ "The B9 paper machine, so named as it is the ninth paper machine to operate at the company's Botany site, will produce more than 400,000 tonnes of paper annually when operating at full capacity and will deliver significant environmental benefits."
- ▶ Cost: \$500 million, the largest single investment in Amcor's 144 year history. "Largest and most innovative recycled paper machine of its kind in Australasia"
- ▶ "The machine is 330 metres long, and 22 metres high, and produces 1.6 km of paper per minute and reduces water consumption by 26%, energy usage by 34% and the amount of waste sent to landfill by 75%" (Nigel Garrard, Amcor CEO)

But collusion caused B9 to be abandoned

- ▶ Amcor had planned B9 back in 1999, and at that time internal studies estimated huge rate of return for this investment because it would enable it to leapfrog Visy to become the low-cost producer of CFP in Australia.
- ▶ Amcor and Visy were locked in a price war that started in 1999, around the time the Amcor Board authorized the B9 investment.
- ▶ However when Visy and Amcor started to collude in 2000, the B9 project was curiously scrapped. B9 was not actually started until 2011, well after the end of the collusion in 2005. B9 only came online in February 2013.

Justification for Bertrand pricing

- ▶ cardboard is a highly standardized product
- ▶ the consumers of cardboard are firms that are highly rational and interested in buying inputs at least possible cost
- ▶ further, firms acquire these inputs via *tenders* that create strong incentives for Bertrand-like price cutting
- ▶ In the case, we lacked good data on *aggregate demand* for cardboard facing Amcor and Visy before and after collusion
- ▶ but there was good data on their *costs of production*
- ▶ cardboard is made on production lines with machinery that is well-approximated as constant returns to scale with constant marginal costs

A cardboard corrugator



Technological progress via cost-reducing investments

- ▶ in this industry, Amcor and Visy do minimal amounts of R&D since there is limited scope for new product innovations to replace cardboard
- ▶ however the firms do spend considerable amounts on *cost reducing investments*
- ▶ these investments consist of building new plants or upgrading existing plants with the latest technology and machinery for producing cardboard
- ▶ rather than developing these machines themselves, Amcor and Visy purchase these machines from other companies that specialize in doing the R&D and product development to develop the machines that produce cardboard at the least possible cost

Leapfrogging by Amcor lead to a price war

- ▶ the proximate cause of the collusion between Amcor and Visy was a price war in cardboard
- ▶ a key input to cardboard is *paper* and Amcor had a severe cost disadvantage relative to Visy due to its outdated paper production plant, with machines that had not been replaced/upgraded in decades
- ▶ Visy on the other hand, has aggressively invested in the latest and most cost-efficient technology and maintained a persistent edge as the low cost leader
- ▶ however Amcor planned to invest in a new paper mill, B9, enabling it to produce CFP at substantially lower costs, thereby leapfrogging Visy to become the low cost leader in Australia

Are price wars evidence of tacit collusion?

- ▶ The economic experts defending Amcor and Visy dismissed theory of Bertrand competition and leap frogging investments as naive and out of touch with reality
- ▶ They claim that there is a huge body of research and empirical work in IO that supports a theory *tacit collusion* for repeatedly interacting duopolists
- ▶ In particular, they claimed that duopolists could achieve via tacit collusion the same discounted profits as they could via *explicit collusion*.
- ▶ This implies that the damage is *zero*.
- ▶ But if this is the case, and if tacit collusion is *legal*, why would Amcor and Visy have had any incentive to do illegal explicit collusion?

Paucity of empirical support for tacit collusion

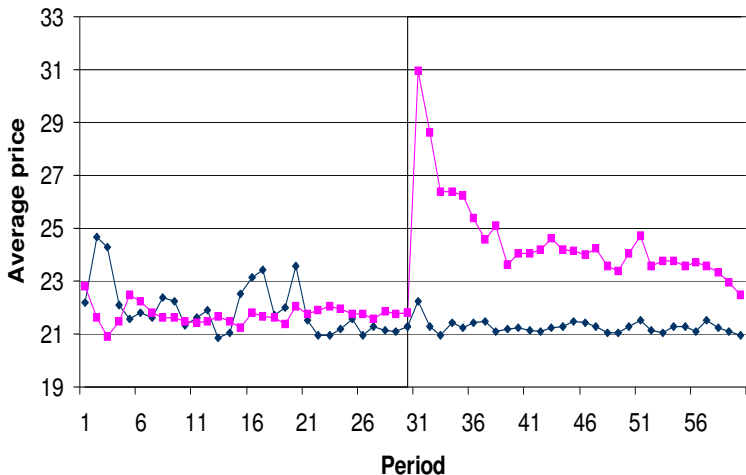
- ▶ Tacit collusion is hard to “observe” by the very fact that it is tacit
- ▶ We need good data on costs and demands to calculate what the cartel price would be
- ▶ Most of the empirical work on tacit collusion comes from laboratory experiments
- ▶ Hundreds of experiments done on tacit collusion have found that it is extremely difficult to “grow” tacit collusion in laboratory settings
- ▶ There are very few “field studies” that find evidence of tacit collusion outside of Breshnahan’s (1987) JIE paper, “Competition and Collusion in the American Automobile Industry: the 1955 Price War”

Conclusions of meta-study of over 500 experiments

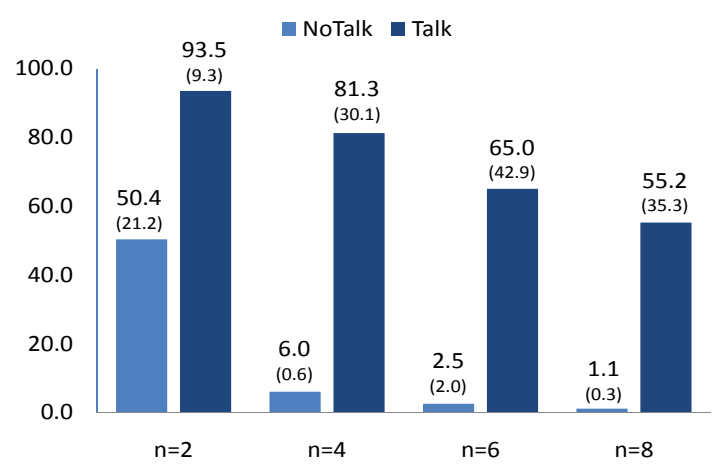
- ▶ Christoph Engel (2007) “Tacit Collusion The Neglected Experimental Evidence”
- ▶ Econometric meta-analysis of 510 laboratory experiments finds no systematic evidence supporting tacit collusion
- ▶ D. Engelmann and W. Müller (2008) “Collusion through price ceilings? A search for a focal point effect”
- ▶ “Note that the Folk Theorem (see for example Tirole, 1988) predicts that infinitely many prices can occur as outcomes of collusive equilibria in infinitely repeated games if the discount factor is sufficiently high. This suggests a coordination problem when firms attempt to collude.” (p. 2)

Results of a laboratory duopoly

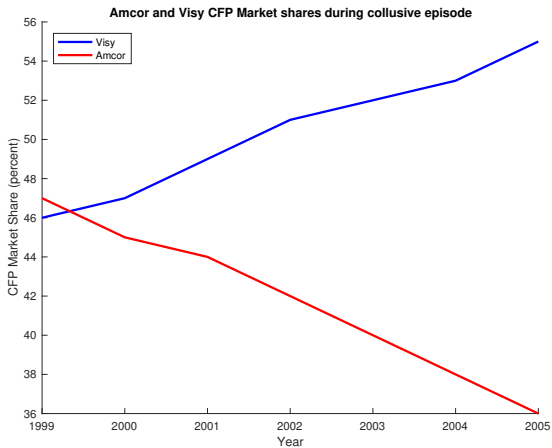
(Note: the Bertrand price is 21, the maximum cartel price is 48 and 28 is the price ceiling)



Explicit communication is necessary for collusion



Amcor and Visy collusive market shares



David Rapson's reanalysis of Bresnahan 1987

- ▶ David Rapson (2009) "Tacit Collusion in the 1950s Automobile Industry? Revisiting Bresnahan (1987)"
- ▶ "This paper reexamines the competitive landscape in the 1950s U.S. automobile industry, and tests the robustness of the famous result from Bresnahan (1987) that firms were engaged in tacit collusion."
- ▶ Rapson uses a random coefficients logit model allows for more realistic demand behavior, including a broad set of possible substitution patterns in characteristic space.
- ▶ This enables firms to engage in a more realistic set of potential actions, including intrabrand or intrafirm, multiproduct strategic pricing.

David Rapson's reanalysis of Bresnahan 1987

- ▶ “Relative to Bresnahan’s framework, these improvements increase the likelihood that high price-cost markups will be attributed properly to either strategic oligopoly behavior or collusion.” (p. 21).
- ▶ “*For no year can either of the forms of Bertrand competition be rejected in favor of tacit collusion.* This stands in contrast to Bresnahan’s finding that firms were colluding in 1954 and 1956, with a price war in 1955.”
- ▶ “These results accentuate the paucity of empirical evidence in favor of tacit collusion.
- ▶ Bresnahan’s (1987) famous paper is one of the only studies that claim evidence of its occurrence.”

Nicolas de Roos' analysis of the US lysine cartel

- ▶ Theorists model collusion as an incentive-compatible, self-enforcing mechanism where price wars either do not exist in equilibrium, or if they exist, they are on the equilibrium path of a dynamic game of asymmetric information with cost or demand shocks.
- ▶ Papers such as “Cramton and Palfrey (1990) show that efficient collusion is attainable in which the lowest cost firm is allocated full production and the monopoly price is set.”
- ▶ However de Roos argues that these theories may be out of touch with reality “Both price wars contain elements of a bargaining or negotiation problem. Disagreements persisted about the appropriate market shares for the participants as well as the fundamental issue of exactly what form the cartel should take.”

de Roos' analysis of the US lysine cartel, cont.

- ▶ “A second such issue relates to the existence of cheating in the lysine market. It appears that cheating occurred or was at least heavily suspected by cartel participants.” ... “where cheating is a problem for a cartel, this suggests the lack of an incentive compatible enforcement mechanism.”
- ▶ A price war, prior to the cartel, was a result of ADM's leap-frogging: “In 1988, ADM acquired a fermentation technique for lysine and, observed by its incumbent rivals, began production of the world's largest lysine factory in 1989. ADM's plant began production in February 1991, precipitating a severe price war. ”

The Bertrand Investment Paradox

Why should Bertrand competitors undertake cost-reducing investments?

- ▶ Suppose a pair of duopolists simultaneously invest in the state of the art low cost production technology with marginal cost c
- ▶ Bertrand price competition following these investments will lead to a price of $p = c$ and *zero profits for each firm*
- ▶ If each firm earns zero profits *ex post*, why would either have incentive to invest *ex ante*?

The investment stage game is an anti-coordination game. Can the firms dynamically coordinate their investments in equilibrium, in order to avoid "bad" simultaneous investment outcomes?

The Riordan and Salant Conjecture

- ▶ In their 1994 *Journal of Industrial Economics* article, Riordan and Salant proved that in continuous time, if duopolists move alternately and technological progress is deterministic, then **investment preemption is the only possible equilibrium outcome**
- ▶ Further, they show this equilibrium is *completely inefficient* due to the excessively frequent investments of the preempting firm, a result they call **rent dissipation**
- ▶ They conjectured that their result does not depend on the alternating move assumption and that preemption (as opposed to leapfrogging) will be the generic equilibrium outcome in models of Bertrand price competition with cost-reducing investments.

Solution to the Bertrand Investment Paradox

We show:

- ▶ Endogenous coordination is possible in equilibrium
 - ▶ leapfrogging (alternating investments) is possible
 - ▶ We show that the Riordan and Salant conjecture is wrong:
leapfrogging, not preemption, is the generic outcome
- ▶ Price paths are piecewise flat and non-increasing
 - ▶ *Price wars* occur when the high cost firm leapfrogs its rival to become the new low-cost leader
 - ▶ These price wars lead to *permanent* price declines, unlike the conventional interpretation of price wars as punishments for periodic breakdowns in tacit collusion
- ▶ Equilibria are generally inefficient due to overinvestment
 - ▶ duplicative investments
 - ▶ excessively frequent investments

Computing all equilibria

Our findings are based on the computation of all Markov perfect equilibria of this dynamic game

- ▶ New solution approach consisting of:
 1. State recursion algorithm for finding stage equilibria
 2. Recursive Lexicographic equilibrium Search (RLS) algorithm for finding all MPE paths
- ▶ Traditional solution approach (value function iterations, i.e. time recursion) fails in this model due to multiplicity of equilibria
 - ▶ Implementation of the Bellman operator induces an equilibrium selection rule
 - ▶ Not a contraction mapping, convergence is not guaranteed
- ▶ Danger of imposing symmetry
 - ▶ Most of MPE equilibria we find are asymmetric