Lecture 13

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Lecture13

Lecture 13: Game Theory // Nash equilibrium

Mauricio Romero

Lecture 13: Game Theory // Nash equilibrium

Examples - Continued

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Examples - Continued
- Cournot - Revisited
- Bertrand Competition
- Bertrand Competition - Different costs
- Bertrand Competition - 3 Firms
- Hotelling and Voting Models

Cournot Competition

- N identical firms competing on the same market

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- Marginal cost is constant and equal to c

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$$p = a - b\sum_{j=1}^{N} q^j$$

Cournot Competition

- N identical firms competing on the same market
- Marginal cost is constant and equal to c
- Aggregate inverse demand is

$$p = a - b\sum_{j=1}^{N} q^j \quad \boxed{\begin{array}{c} Q = \sum_{i=1}^{N} q_i \\ P(Q) = a - bQ \end{array}}$$

- Benefits of firm j are:

$$\Pi^j(q^1, \dots q^N) = \Bigg(\overbrace{a - b\sum_{i=1}^{N} q^i}^{P(Q)}\Bigg) q^j - cq^j.$$

$$= aq^j - b\left(q_1 q^j + q_2 q^j + \dots + q_{j-1} q_j + q_j^2 + q_{j+1} q_j + \dots + q_N q_j\right) - cq^j$$

~~NO DEBEN HACER~~

$$\cancel{\Pi_i = \left(a - b\sum_{i=1}^{N} q_i\right) q_j - c q_j}$$

$$\cancel{\Pi_i = \left(a - b\sum_{i=1}^{N} q^*\right) q^* - c q^*}$$

$$\cancel{\Pi_i = \left(a - bNq^*\right) q^* - c q^*}$$

$$\cancel{\frac{\partial \Pi_i}{\partial q^*} = a - bN2q - c = 0}$$

$$\frac{\partial \Pi_j}{\partial q_j} = a - b(q_1 + q_2 + \dots + q_j + \dots + q_N) - c = 0$$

$$\boxed{= a - b\left(\sum_{i=1}^{N} q_i\right) - bq_j - c = 0}$$

$$\frac{\partial \Pi_1}{\partial q_1} = 0 \Rightarrow MR_1$$

$$\frac{\partial \Pi_2}{\partial q_2} = 0 \Rightarrow MR_2$$

$$\vdots$$

$$\frac{\partial \Pi_N}{\partial q_N} = 0 \Rightarrow MR_N$$

N ECUACIONES

N INCOGNITAS

- Benefits of firm j are:

$$\Pi^j(q^1, \ldots q^N) = \Big(\underbrace{a - b\sum_{i=1}^{N} q^i}_{P(Q)}\Big) q^j - cq^j.$$

$$= aq^j - b\underbrace{\left(q_1 q^j + q_2 q^j + \cdots + q_{j-1} q_j + q_j^2 + q_{j+1} q_j + \cdots + q_N q_j\right)}\, - cq^j$$

$$\frac{\partial \Pi_N}{\partial q_N} = 0 \Rightarrow \text{MIRN}$$

Cournot Competition

- The FOC for a given firm is:

$$a - b\sum_{i=1}^{N} q^i - bq_j - c = 0$$

TRUCO

BUSQUEMOS UN EQ SIMETRICO

$$\boxed{q_1^* = q_2^* = \cdots = q_N^* = q^*}$$

$$a - b\sum_{i=1}^{N} q_i - bq_j - c = 0$$

$$a - b\boxed{\sum_{i=1}^{N} q^*} - bq^* - c = 0 \quad \Big\}\ \begin{array}{l} 1 \text{ EQ.} \\ 1 \text{ INCOGNITA.} \end{array}$$

$$a - b\boxed{N q^*} - bq^* - c = 0$$

$$a - c = bq^*(N+1)$$

$$\boxed{\frac{a-c}{b(N+1)} = q^*}$$

Cournot Competition

- The FOC for a given firm is:

$$a - b\sum_{i=1}^{N} q^i - bq_j - c = 0$$

- The symmetric Nash equilibrium is given by

$$q^* = \frac{a-c}{b(N+1)}$$

Cournot Competition

- The FOC for a given firm is:

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- The symmetric Nash equilibrium is given by

$$q^* = \frac{a-c}{b(N+1)}$$

- Thus

$$\sum_{j=1}^{N} q^j = \frac{N(a-c)}{b(N+1)}$$

$$p = a - N\frac{a-c}{(N+1)} < a$$

$$\Pi^j = \frac{(a-c)^2}{b(N+1)^2}$$

Cournot Competition

$$q^* = \frac{a-c}{b(N+1)}$$

$$\sum_{j=1}^{N} q^j = \frac{N(a-c)}{b(N+1)} = Q$$

$$p = a - N\frac{a-c}{(N+1)} < a = P = a - bQ$$

$$\boxed{\Pi^j = \frac{(a-c)^2}{b(N+1)^2}}$$

$$\boxed{\lim_{N\to\infty} P = \lim_{N\to\infty} a - \frac{N(a-c)}{N+1} = a - \frac{(a-c)}{1} = c = \text{cmg}}$$

$$\boxed{\lim_{N\to\infty} \Pi = \lim_{N\to\infty} \frac{(a-c)^2}{b(N+1)^2} = 0}$$

- As $N \to \infty$ we get close to perfect competition

Cournot Competition

$$\sum_{j=1}^{N} q^j = \frac{N(a-c)}{b(N+1)}$$

$$p = a - N\frac{a-c}{(N+1)} < a$$

$$\Pi^j = \frac{(a-c)^2}{b(N+1)^2}$$

- As $N \to \infty$ we get close to perfect competition
- $N = 1$ we get the monopoly case

$$\boxed{\begin{array}{l} P^{EN} = P^m \\ Q^{EN} = Q^m \\ \Pi^{EN} = \Pi^m \end{array}}$$

Lecture 13: Game Theory // Nash equilibrium

Examples - Continued
Cournot - Revisited
Bertrand Competition
Bertrand Competition - Different costs
Bertrand Competition - 3 Firms
Hotelling and Voting Models

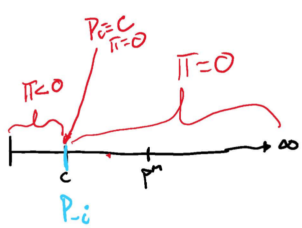
Bertrand Competition

- Consider the alternative model in which firms set prices
- In the monopolist's problem, there was not distinction between a quantity-setting model and a price setting
- In oligopolistic models, this distinction is very important

Bertrand Competition

- Consider two firms with the same marginal constant marginal cost of production and demand is completely inelastic
- Each firm simultaneously chooses a price $p_i \in [0, +\infty)$
- If p_1, p_2 are the chosen prices, then the utility functions of firm i is given by:

$$\pi_i(p_i, p_{-i}) = \begin{cases} 0 & \text{if } p_i > p_{-i}, \text{ (NO VENDO NADA)} \\ \underbrace{(p_i - c)}_{\text{MARGEN POR UNIDAD}} \boxed{\frac{Q(p_i)}{2}} & \text{if } p_i = p_{-i}, \\ (p_i - c)Q(p_i) & \text{if } p_i < p_{-i}. \text{ (i VENDE TODO)} \end{cases}$$



Bertrand Competition

- Assume that the marginal revenue function is strictly decreasing ($MR'(p_i) < 0$):

$$\begin{aligned} R(p_i) &= p_i Q(p_i) && (1)\\ MR(p_i) &= Q(p_i) + p_i Q'(p_i) && (2)\\ &= Q(p_i)\left(1 + \varepsilon_{Q,p}(p_i)\right). && (3) \end{aligned}$$

Bertrand Competition

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- Let $p^m > c \geq 0$ be the monopoly price such that $MR(p^m) = c$.

Bertrand Competition

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- Let $p^m > c \geq 0$ be the monopoly price such that $MR(p^m) = c$.
- Then

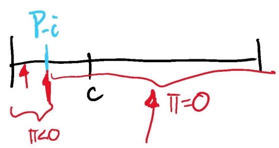
$$MR(p_i) - c > 0 \text{ if } p_i < p^m, MR(p_i) - c < 0 \text{ if } p_i > p^m.$$

Bertrand Competition

- The best response function is:

$$BR_i(p_{-i}) = \begin{cases} p^m & \text{if } p_{-i} > p^m, \\ p_{-i} - \varepsilon & \text{if } c < p_{-i} \leq p^m, \\ [c, +\infty) & \text{if } c = p_{-i} \\ (c, +\infty) & \text{if } c > p_{-i}. \end{cases}$$

- Where ε is the smallest monetary unit

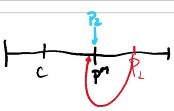


Bertrand Competition

Case 1: $p_1^* > p^m$

X NO EQ!

- $p_2^* = p^m$



Bertrand Competition

Case 1: $p_1^* > p^m$

- $p_2^* = p^m$
- $BR_2(p^m) = p^m - \varepsilon$

Bertrand Competition

Case 1: $p_1^* > p^m$

- $p_2^* = p^m$
- $BR_2(p^m) = p^m - \varepsilon$
- $BR_1(p^m - \varepsilon) = p^m - 2\varepsilon$

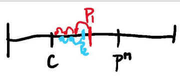
Bertrand Competition

Case 1: $p_1^* > p^m$

- $p_2^* = p^m$
- $BR_2(p^m) = p^m - \varepsilon$
- $BR_1(p^m - \varepsilon) = p^m - 2\varepsilon$
- So this cannot be a Nash equilibrium

Case 2: $p_1^* \in (c, p^m]$

X NO EQ



- $BR_2(p_1^*) = p_1^* - \varepsilon$

Case 2: $p_1^* \in (c, p^m]$

- $BR_2(p_1^*) = p_1^* - \varepsilon$
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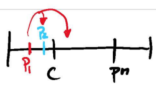
Case 2: $p_1^* \in (c, p^m]$

- $BR_2(p_1^*) = p_1^* - \varepsilon$
- $BR_1(p_1^* - \varepsilon) = p_1^* - 2\varepsilon$
- So this cannot be a Nash equilibrium

Case 3: $p_1^* < c$

NO EQ

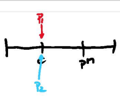


- $BR_2(p_1^*) \in [p_1^* + \varepsilon, \infty)$

Case 3: $p_1^* < c$

- $BR_2(p_1^*) \in [p_1^* + \varepsilon, \infty)$
- So this cannot be a Nash equilibrium

Case 4: $p_1^* = c$



- $BR_2(p_1^*) = (c, +\infty)$

Case 4: $p_1^* = c$

- $BR_2(p_1^*) = (c, +\infty)$
- The unique pure strategy Nash equilibrium is $p_1^* = p_2^* = c$

Thus in contrast to the Cournot duopoly model, in the Bertrand competition model, two firms get us back to perfect competition ($p = c$)

Lecture 13: Game Theory // Nash equilibrium

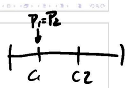
Examples - Continued
Cournot - Revisited
Bertrand Competition
Bertrand Competition - Different costs
Bertrand Competition - 3 Firms
Hotelling and Voting Models

Bertrand Competition - different costs

- Suppose that the marginal cost of firm 1 is equal to c_1 and the marginal cost of firm 2 is equal to c_2 where $c_1 < c_2$.
- The best response for each firm:

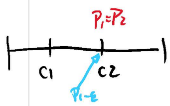
$$BR_i(p_{-i}) = \begin{cases} p_m^i & \text{if } p_{-i} > p_m^i,\\ p_{-i}-\varepsilon & \text{if } c_i < p_{-i} \le p_m^i,\\ [c_i,+\infty) & \text{if } p_{-i}=c_i\\ (p_{-i},+\infty) & \text{if } p_{-i}<c_i. \end{cases}$$

Bertrand Competition - different costs



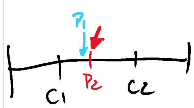
- If $p_2^* = p_1^* = c_1$, then firm 2 would be making a loss

Bertrand Competition - different costs



- If $p_2^* = p_1^* = c_1$, then firm 2 would be making a loss
- If $p_2^* = p_1^* = c_2$, then firm 1 would cut prices to keep the whole market

Bertrand Competition - different costs



- If $p_2^* = p_1^* = c_1$, then firm 2 would be making a loss
- If $p_2^* = p_1^* = c_2$, then firm 1 would cut prices to keep the whole market
- Any pure strategy NE must have $\boxed{p_2^* \le c_1}$. Otherwise, if $p_2^* > c_1$ then firm 1 could undercut p_2^* and get a positive profit

Bertrand Competition - different costs

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- Firm 1 would really like to price at some price p_1^* just below the marginal cost of firm 2, but wherever p_2 is set, Firm 1 would try to increase prices

Bertrand Competition - different costs

- If $p_2^* = p_1^* = c_1$, then firm 2 would be making a loss
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- Any pure strategy NE must have $p_2^* \le c_1$. Otherwise, if $p_2^* > c_1$ then firm 1 could undercut p_2^* and get a positive profit
- Firm 1 would really like to price at some price p_1^* just below the marginal cost of firm 2, but wherever p_2 is set, Firm 1 would try to increase prices
- No NE because of continuous prices

Bertrand Competition - discreet prices

- Suppose $\boxed{c_1 = 0 < c_2 = 10}$

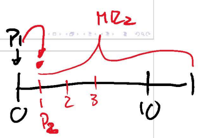
Bertrand Competition - discreet prices

- Suppose $c_1 = 0 < c_2 = 10$
- Firms can only set integer prices.

Bertrand Competition - discreet prices

- Suppose $c_1 = 0 < c_2 = 10$
- Firms can only set integer prices.
- Suppose that (p_1^*, p_2^*) is a pure strategy Nash equilibrium...

Bertrand Competition - discreet prices



Case 1: $\boxed{p_1^* = 0}$

X E.N.

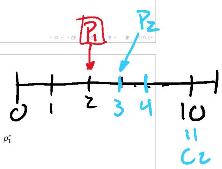
- Best response of firm 2 is to choose some $p_2^* > p_1^*$

Bertrand Competition - discreet prices

Case 1: $p_1^* = 0$

- Best response of firm 2 is to choose some $p_2^* > p_1^*$
- p_1^* cannot be a best response to p_2^* since by setting $p_1 = p_2^*$ firm 1 would get strictly positive profits

Bertrand Competition - discreet prices



Case 2: $p_1^* \in \{1, 2, \ldots, 9\}$

- Best response of firm 2 is to set any price $p_2^* > p_1^*$

Bertrand Competition - discreet prices

Case 2: $p_1^* \in \{1, 2, \ldots, 9\}$

- Best response of firm 2 is to set any price $p_2^* > p_1^*$
- If $p_2^* > p_1^* + 1$, then this cannot be a Nash equilibrium since then firm 1 would have an incentive to raise the price

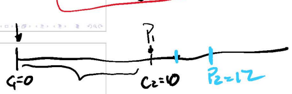
Bertrand Competition - discreet prices

Case 2: $p_1^* \in \{1, 2, \ldots, 9\}$

- Best response of firm 2 is to set any price $p_2^* > p_1^*$
- If $p_2^* > p_1^* + 1$, then this cannot be a Nash equilibrium since then firm 1 would have an incentive to raise the price
- The only equilibrium is $\boxed{(p_1^*, p_1^* + 1)}$

(P_1, P_2)
$(1, 2)$
$(2, 3)$
$(3, 4)$
$\vdots$
$(9, 10)$
EN

Bertrand Competition - discreet prices



Case 3: $p_1^* = 10$

- Best responses of firm 2 is to set any price $p_2^* \geq p_1^*$

Bertrand Competition - discreet prices

Case 3: $p_1^* = 10$

- Best responses of firm 2 is to set any price $p_2^* \geq p_1^*$
- It cannot be that $p_2^* = p_1^*$ since then firm 1 would rather deviate to a price of 9 and control the whole market:

$$\frac{1}{2}(10) = 5 < 9.$$

Bertrand Competition - discreet prices

Case 3: $p_1^* = 10$

- Best responses of firm 2 is to set any price $p_2^* \geq p_1^*$
- It cannot be that $p_2^* = p_1^*$ since then firm 1 would rather deviate to a price of 9 and control the whole market:

$$\frac{1}{2}(10) = 5 < 9.$$

- We must have $p_2^* = p_1^* + 1$ since otherwise, firm 1 would have an incentive to raise the price higher

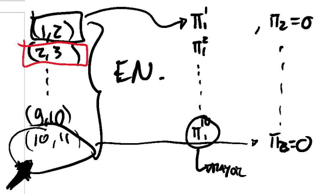
Bertrand Competition - discreet prices

Case 3: $p_1^* = 10$

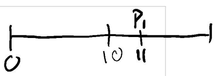
- Best responses of firm 2 is to set any price $p_2^* \geq p_1^*$
- It cannot be that $p_2^* = p_1^*$ since then firm 1 would rather deviate to a price of 9 and control the whole market:

$$\frac{1}{2}(10) = 5 < 9.$$

- We must have $p_2^* = p_1^* + 1$ since otherwise, firm 1 would have an incentive to raise the price higher
- $\boxed{(p_1^*, p_2^*) = (10, 11) \text{ is a Nash equilibrium}}$



Bertrand Competition - discreet prices



Case 4: $p_1^* = 11$

NO EQ

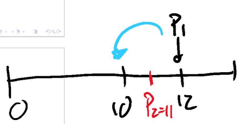
- Best response of firm 2 is to set $p_2^* = 11$

Bertrand Competition - discreet prices

Case 4: $p_1^* = 11$

- Best response of firm 2 is to set $p_2^* = 11$
- Firm 1 would not be best responding since by setting a price of $p_1 = 10$, it would get strictly positive profits

Bertrand Competition - discreet prices



Case 5: $p_1^* \geq 12$

NO EQ

- Firm 2's best response is to set either $p_2^* = p_1^* - 1$ or $p_2^* = p_1^*$

Bertrand Competition - discreet prices

Case 5: $p_1^* \geq 12$

- Firm 2's best response is to set either $p_2^* = p_1^* - 1$ or $p_2^* = p_1^*$
- Firm 1 is not best responding since by lowering the price it can get the whole market.

Lecture 13: Game Theory // Nash equilibrium

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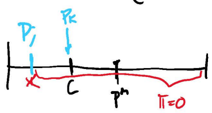
Bertrand Competition - 3 firms

- Symmetric marginal costs model but with 3 firms

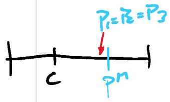
(PRECIOS CONT)



Bertrand Competition - 3 firms

- Symmetric marginal costs model but with 3 firms
- Best response of firm i is given by:

$$BR_1(p_2,p_3)=\begin{cases} p^m & \text{if } \min\{p_2,p_3\}>p^m,\\ \min\{p_2,p_3\}-\varepsilon & \text{if } c<\min\{p_2,p_3\}\le p^m,\\ [c,+\infty) & \text{if } c=\min\{p_2,p_3\},\\ (\min\{p_2,p_3\},+\infty) & \text{if } c>\min\{p_2,p_3\}.\end{cases}$$

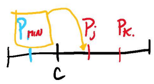


Bertrand Competition - 3 firms

- Symmetric marginal costs model but with 3 firms
- Best response of firm i is given by:

$$BR_1(p_2,p_3)=\begin{cases} p^m & \text{if } \min\{p_2,p_3\}>p^m,\\ \min\{p_2,p_3\}-\varepsilon & \text{if } c<\min\{p_2,p_3\}\le p^m,\\ [c,+\infty) & \text{if } c=\min\{p_2,p_3\},\\ (\min\{p_2,p_3\},+\infty) & \text{if } c>\min\{p_2,p_3\}.\end{cases}$$

- (c,c,c) is indeed a pure strategy Nash equilibrium as in the two firm case

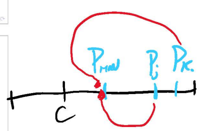


Bertrand Competition - 3 firms

- If (p_1,p_2,p_3) was a pure strategy Nash equilibrium, it can never be the case that $\min\{p_1,p_2,p_3\}<c$

Bertrand Competition - 3 firms

- If (p_1,p_2,p_3) was a pure strategy Nash equilibrium, it can never be the case that $\min\{p_1,p_2,p_3\}<c$
- If (p_1,p_2,p_3) was a pure strategy Nash equilibrium, it can never be the case that $\min\{p_1,p_2,p_3\}>c$



Bertrand Competition - 3 firms

- If (p_1,p_2,p_3) was a pure strategy Nash equilibrium, it can never be the case that $\min\{p_1,p_2,p_3\}<c$
- If (p_1,p_2,p_3) was a pure strategy Nash equilibrium, it can never be the case that $\min\{p_1,p_2,p_3\}>c$
- We must have $\min\{p_1,p_2,p_3\}=c$

$P_1=P_2=P_3=C$

$P_1=C,\ P_2,P_3>C$

Bertrand Competition - 3 firms

- If (p_1,p_2,p_3) was a pure strategy Nash equilibrium, it can never be the case that $\min\{p_1,p_2,p_3\}<c$
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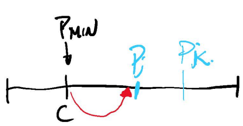
- We must have $\min\{p_1,p_2,p_3\}=c$
- Can there be a pure strategy Nash equilibrium in which just one firm sets price equal to c?



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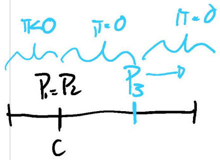

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- Set of all pure strategy Nash equilibria are given by:

$$\boxed{\{(c, c, c+\varepsilon) : \varepsilon \geq 0\} \cup \{(c, c+\varepsilon, c) : \varepsilon \geq 0\} \cup \{(c+\varepsilon, c, c) : \varepsilon \geq 0\}.}$$ E.N. (INFINITOS)

Lecture 13: Game Theory // Nash equilibrium

Examples - Continued
Cournot - Revisited
Bertrand Competition
Bertrand Competition - Different costs
Bertrand Competition - 3 Firms
Hotelling and Voting Models

Hotelling

- Two firms $i = 1, 2$ decide to produce heterogeneous products $x_1, x_2 \in [0, 1]$

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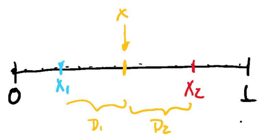
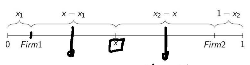
- The game consists of the two players $i = 1, 2$, each of whom chooses a point $x_1, x_2 \in [0, 1]$ simultaneously.



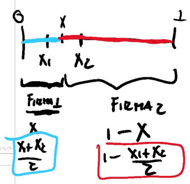
Hotelling

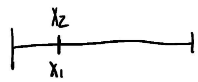


$$x - x_1 = x_2 - x$$

$$2x = x_2 + x_1$$

$$\boxed{x = \frac{x_1 + x_2}{2}}$$





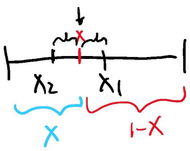
Hotelling

Then the profits that accrue to firm 1 is given by the mass of consumers that are closest to firm 1:

$$u_1(x_1, x_2) = \begin{cases} \frac{x_1+x_2}{2} & \text{if } x_1 < x_2, \\ \frac{1}{2} & \text{if } x_1 = x_2, \\ 1 - \frac{x_1+x_2}{2} & \text{if } x_1 > x_2. \end{cases}$$

Similarly,

$$u_2(x_1, x_2) = \begin{cases} \boxed{1 - \frac{x_1+x_2}{2}} & \text{if } x_1 < x_2, \\ \frac{1}{2} & \text{if } x_1 = x_2, \\ \frac{x_1+x_2}{2} & \text{if } x_1 > x_2. \end{cases}$$



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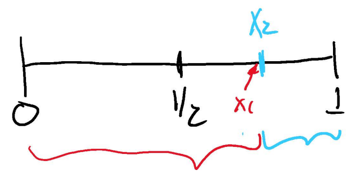

Hotelling

Compute the best response functions

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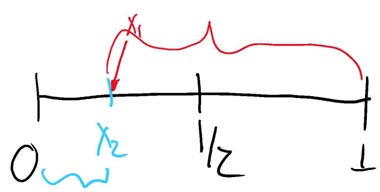
This utility function has a discontinuity at $x_1 = x_2$ and jumps down to $1/2$ at $x_1 = x_2$. There will be no best response for firm 1 (try to set as close to the left the other firm as possible)



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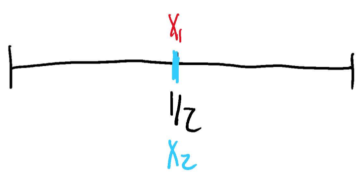
- **Case 2:** Suppose next that $x_2 < 1/2$. Again there will be no best response for firm 1 (try to set as close to the right the other firm as possible)



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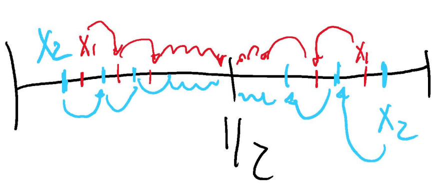
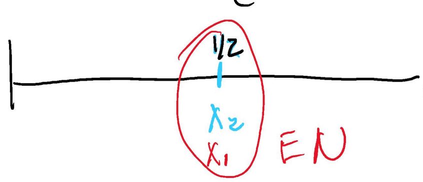
- **Case 2:** Suppose next that $x_2 < 1/2$. Again there will be no best response for firm 1 (try to set as close to the right the other firm as possible)
- **Case 3:** Suppose next that $x_2 = 1/2$. Here there will be a best response for firm 1 at $1/2$





Hotelling

VACIO

$$\boxed{BR_1(x_2) = \begin{cases} \emptyset & \text{if } x_2 > 1/2 \\ 1/2 & \text{if } x_2 = 1/2 \\ \boxed{\emptyset} & \text{if } x_2 < 1/2. \end{cases}}$$

Symmetrically, we have:

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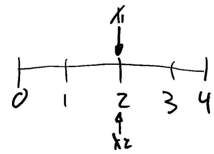
Symmetrically, we have:

$$BR_2(x_1) = \begin{cases} \emptyset & \text{if } x_1 > 1/2 \\ 1/2 & \text{if } x_1 = 1/2 \\ \emptyset & \text{if } x_1 < 1/2. \end{cases}$$

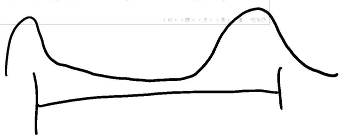
The unique Nash equilibrium is for each firm to choose $(x_1, x_2) = (1/2, 1/2)$. Each firm essentially locates in the same place

x_2
x_1
EN



Hotelling

- Hotelling can also be done in a discreet setting
- Hotelling can be applied to a variety of situations (e.g., voting)
- But this predicts the opposite of polarization
- With three candidates, predictions are quite different
- All candidates picking $\frac{1}{2}$ is no longer a Nash equilibrium
- What are the set of pure strategy equilibria here? (this is a difficult problem).



CDMX