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Lecture13....

Lecture 13: Game Theory // Nash equilibrium

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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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Cournot Competition

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

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

- Benefits of firm j are:

$$\Pi^j(q^1, \dots q^N) = \left(a - b\overbrace{\sum_{i=1}^{N} q^i}^{?}\right) q^j - cq^j.$$

$$\frac{\partial \pi^j}{\partial q_j} : -bq_j + \left(a - b\sum_{i=1}^{N} q_i\right)(1) - c = 0$$

$$-bq_j + a - b(q_1 + \dots + q_N) - c = 0$$

$$-2bq_j + a - b(\underbrace{Q_{-i}}_{\sum_{i \neq j} q_i}) - c = 0$$

$$\boxed{q_j = MR_j(Q_{-i}) = \frac{a - bQ_{-i} - c}{2b}}$$

En un Eq Simetrico:

$$q_1^* = q_2^* = \dots = q_N^* = q^*$$

$$-2bq^* + a - b\left(\boxed{\sum_{i \neq j} q^*}\right) - c = 0$$

$$-2bq^* + a - b(N-1)q^* - c = 0$$

$$bq^*(-2 - (N-1)) + a - c = 0$$

Cournot Competition

- The FOC for a given firm is:

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

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

Cournot Competition

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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

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Cournot Competition

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

Lecture 13: Game Theory // Nash equilibrium

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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:

$$\pi_i(p_i, p_{-i}) = \begin{cases} 0 & \text{if } p_i > p_{-i}, \\ (p_i - c)\frac{Q(p_i)}{2} & \text{if } p_i = p_{-i}, \\ (p_i - c)Q(p_i) & \text{if } p_i < p_{-i}. \end{cases}$$

Bertrand Competition

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

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

Bertrand Competition

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

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$$= Q(p_i)\left(1 + \varepsilon_{Q,p}(p_i)\right). \quad (3)$$

- 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: $\underline{p_1^* > p^m}$ $\to P_2 = P^m \to P_1 = P^m - \varepsilon$

- $p_2^* = p^m$

Bertrand Competition

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

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

Bertrand Competition

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

- $p_2^* = p^m$

$$bq^*(-2-(N-1)) + a - c = 0$$

$$bq^*(-2-N+1) + a - c = 0$$

$$bq^*(-N-1) + a - c = 0$$

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

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

$$P^{EN} = a - b\left(\sum_{i=1}^{N} q_i\right)$$

$$p^{EN} = a - b\left(\sum_{i=1}^{N} q^*\right) = a - bNq^*$$

$$p^{EN} = a - \cancel{b}\left(\frac{a-c}{\cancel{b}(N+1)}\right)N$$

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

$$p^{EN} = \frac{\cancel{aN} + a - \cancel{aN} + cN}{N+1}$$

$$\boxed{p^{EN} = \frac{a}{N+1} + c\frac{N}{(N+1)}}$$

$$\Pi^{EN} = p^{EN}q^{EN} - cq^{EN} = q^{EN}(P - C)$$

$$\Pi^{EN} = \left(\underbrace{\frac{a}{N+1} + \frac{cN}{(N+1)}}_{P} - c\right)\left(\frac{a-c}{b(N+1)}\right)$$

$$\Pi^{EN} = \left(\frac{a + cN - c(N+1)}{N+1}\right)\left(\frac{a-c}{b(N+1)}\right)$$

$$= \left(\frac{a + \cancel{cN} - \cancel{cN} - c}{N+1}\right)\left(\frac{a-c}{b(N+1)}\right)$$

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

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: $p_1^* > p^m$

- $p_2^* = p^m$
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- So this cannot be a Nash equilibrium

Bertrand Competition

Case 2: $p_1^* \in (c, p^m]$ $\rightarrow P_2 = P_1 - \varepsilon \rightarrow P_1 = P_1 - 2\varepsilon$

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

Bertrand Competition

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

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Bertrand Competition

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

Bertrand Competition

$\boxed{P_1^* < c} \rightarrow P_2 > C \rightarrow P_1 \in (C, P_2)$

$\rightarrow P_2 = C \rightarrow P_1 \in [C, \infty]$

Case 3: $p_1^* < c$

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

Bertrand Competition

Case 3: $p_1^* < c$

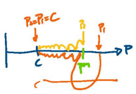
- $BR_2(p_1^*) \in [p_1^* + \varepsilon, \infty)$
- So this cannot be a Nash equilibrium

Bertrand Competition

$P_2 > C \rightarrow P_1 = P_2 - \varepsilon > C$

Case 4: $p_1^* = c$ $\rightarrow P_2 = C \Rightarrow \boxed{EN = (P_1 = C, P_2 = C)}$

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



Bertrand Competition

Case 4: $p_1^* = c$

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

Bertrand Competition

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
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Hotelling and Voting Models

$$\pi^{EN} = \left(\frac{a-c}{N+1}\right)\left(\frac{a-c}{b(N+1)}\right) = \frac{(a-c)^2}{b(N+1)^2}$$

$$\lim_{N \to \infty} P^{EN} = C$$

$$\lim_{N \to \infty} \pi^{EN} = 0$$

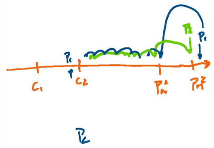
$$\lim_{N \to \infty} q^{EN} = 0$$

$$\lim_{N \to \infty} N q^{EN} = \frac{(a-c)N}{b(N+1)} = \frac{a-c}{b}$$

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:

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



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 $p_2^* \leq c_1$. 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

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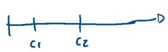
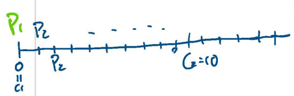
- No NE because of continuous prices



Bertrand Competition - discreet prices

- Suppose $c_1 = 0 < c_2 = 10$



$\boxed{EN = (P_1 = 10, P_2 = 11)}$

$EN = (P_1 = 9, P_2 = 10)$

$EN = (P_1 = 8, P_2 = 9)$

⋮

$EN = (P_1 = 1, P_2 = 2)$

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: $p_1^* = 0$

- 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 $(p_1^*, p_1^* + 1)$

Bertrand Competition - discreet prices

Case 3: $p_1^* = 10$

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

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
- $(p_1^*, p_2^*) = (10, 11)$ is a Nash equilibrium

Bertrand Competition - discreet prices

Case 4: $p_1^* = 11$

- 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: $p_1^* \geq 12$

- 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

Bertrand Competition - 3 firms

- Symmetric marginal costs model but with 3 firms

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- 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

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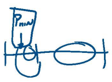
- (c,c,c) is indeed a pure strategy Nash equilibrium as in the two firm case

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 $\min\{p_1,p_2,p_3\}<c$
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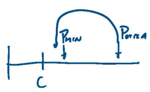
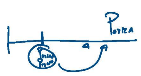


Bertrand Competition - 3 firms

- 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 $\min\{p_1,p_2,p_3\}=c$



Bertrand Competition - 3 firms

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- Can there be a pure strategy Nash equilibrium in which just one firm sets price equal to c?

Bertrand Competition - 3 firms

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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? No since that firm would want to raise his price a bit and get strictly better profits
- There must be at least two firms that set price equal to marginal cost

Bertrand Competition - 3 firms

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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? No since that firm would want to raise his price a bit and get strictly better profits
- There must be at least two firms that set price equal to marginal cost
- Set of all pure strategy Nash equilibria are given by:

$$\{(c,c,c+\varepsilon):\varepsilon\ge 0\}\cup\{(c,c+\varepsilon,c):\varepsilon\ge 0\}\cup\{(c+\varepsilon,c,c):\varepsilon\ge 0\}.$$

Lecture 13: Game Theory // Nash equilibrium

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P

Hotelling

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

Hotelling

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Hotelling

- Two firms $i = 1, 2$ decide to produce heterogeneous products $x_1, x_2 \in [0, 1]$
- x_1, x_2 represents the characteristic of the product
- For example, this could be interpreted as a model in which there is a "linear city" represented by the interval $[0, 1]$
- In this interpretation, the firms are each deciding where to locate on this line

Hotelling

- Two firms $i = 1, 2$ decide to produce heterogeneous products $x_1, x_2 \in [0, 1]$
- x_1, x_2 represents the characteristic of the product
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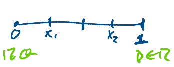
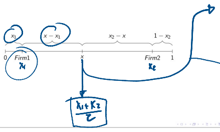
- The game consists of the two players $i = 1, 2$, each of whom chooses a point $x_1, x_2 \in [0, 1]$ simultaneously.



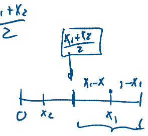
Hotelling



$x - x_1 = x_2 - x$

$2x = x_1 + x_2$

$x = \dfrac{x_1 + x_2}{2}$



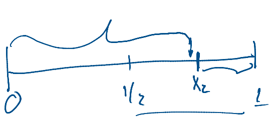
Hotelling

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,

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



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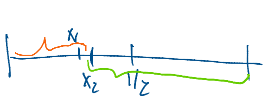

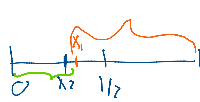

Hotelling

Compute the best response functions

- **Case 1:** Suppose first that $x_2 > 1/2$. Then setting x_1 against x_2 yields a payoff of

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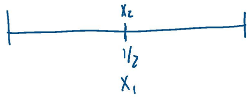
This utility function has a discontinuity at $x_1 = x_2$ and jumps down to $1/2$ at $x_1 = x_2$. There will be no best response for firm 1 (try to set as close to the left the other firm as possible)



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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)
- **Case 3:** Suppose next that $x_2 = 1/2$. Here there will be a best response for firm 1 at $1/2$

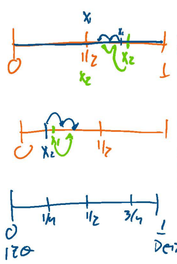
Hotelling

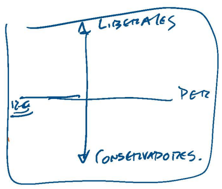
$$BR_1(x_2) = \begin{cases} \emptyset & \text{if } x_2 > 1/2 \\ 1/2 & \text{if } x_2 = 1/2 \\ \emptyset & \text{if } x_2 < 1/2. \end{cases}$$

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





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).