Lecture 12: Game Theory // Nash equilibrium

Mauricio Romero

Lecture 12: Game Theory // Nash equilibrium

Dominance

Nash equilibrium

Some examples

Relationship to dominance

Examples

Dominance

Nash equilibrium

Some examples

Relationship to dominance

Examples

Beauty contest

- Consider the following game among 100 people. Each individual selects a number, s_i, between 20 and 60.
- Let a_{-i} be the average of the number selected by the other 99 people. i.e. $a_{-i} = \sum_{j \neq i} \frac{s_j}{99}$.
- The utility function of the individual i is $u_i(s_i, s_{-i}) = 100 - (s_i - \frac{3}{2} a_{-i})^2$

Beauty contest

- Each individual maximizes his utility, FOC:

$$-2(s_i - \frac{3}{2}a_{-i}) = 0$$

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- but $a_{-i} \in [20, 60]$

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- Individuals would prefer to select a number that is exactly equal to 1.5 times the average of the others
- That is they would like to choose $s_i = \frac{3}{2}a_{-i}$
- but $a_{-i} \in [20, 60]$
- Therefore $s_i = 20$ is dominated by $s_i = 30$

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- Playing a number between 30 and 45 (not including) would be strictly dominated by playing 45

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- Knowing this, all individuals believe that everyone else will select a number between 45 and 60 (i.e., $a_{-i} \in [45, 60]$)
- 60 would dominate any other selection and therefore all the players select 60.
- The solution by means of iterated elimination of dominated strategies is $\underbrace{(60, 60, ..., 60)}_{\text{100 times}}$

Dominance
- Weakly dominated strategies

Nash equilibrium

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Examples
- Cournot Competition
- Cartels

	a	b
A	3, 4	4, 3
B	5, 3	3, 5
C	5, 3	4, 3

- There is no strictly dominated strategy

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- However, C always gives at least the same utility to player 1 as B
- It's tempting to think player 1 would never play C
- However, if player 1 is sure that player two is going to play a he would be completely indifferent between playing B or C

Definition

s_i weakly dominates s_i' if for all opponent pure strategy profiles, $s_{-i} \in S_{-i}$,

$$u_i(s_i, s_{-i}) \geq u_i(s_i', s_{-i})$$

and there is at least one opponent strategy profile $s''_{-i} \in S_{-i}$ for which

$$u_i(s_i, s''_{-i}) > u_i(s_i', s''_{-i}).$$

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- Rationality is not enough
- Even so, it sounds “logical” to do so and has the potential to greatly simplify a game
- There is a problem, and that is that the order in which we eliminate the strategies matters

	a	b
A	3, 4	4, 3
B	5, 3	3, 5
C	5, 3	4, 3

- If we eliminate B (C dominates weakly), then a weakly dominates b and we can eliminate b and therefore player 1 would never play A. This leads to the result (C, a).

	a	b
A	3, 4	4, 3
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C	5, 3	4, 3

- If we eliminate B (C dominates weakly), then a weakly dominates b and we can eliminate b and therefore player 1 would never play A. This leads to the result (C, a).

- If on the other hand, we notice that A is also weakly dominated by C then we can eliminate it in the first round, and this would eliminate a in the second round and therefore B would be eliminated. This would result in (C, b).

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Examples

Remember the definition of competitive equilibrium in a market economy.

Definition

A competitive equilibrium in a market economy is a vector of prices and baskets x_i such that: 1) x_i maximizes the utility of each individual given the price vector i.e.

$$x_i = \arg \max_{p \ cdot x_i \leq p \cdot w_i} u(x_i)$$

2) the markets empty.

$$\sum_i x_i = \sum_i w_i$$

- 1) means that given the prices, individuals have no incentive to demand a different amount

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- The idea is to extend this concept to strategic situations

Best response

We denote $BR_i(s_{-i})$ (best response) as the set of strategies of individual i that maximize her utility given that other individuals follow the strategy profile s_{-i}. Formally,

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Given a strategy profile of opponents s_{-i}, we can define the best response of player i:

$$BR_i(s_{-i}) = \arg\max_{s_i' \in S_i} u_i(s_i', s_{-i}).$$

- $s_i \in BR_i(s_{-i})$ if and only if $u_i(s_i, s_{-i}) \geq u_i(s_i', s_{-i})$ for all $s_i' \in S_i$

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Given a strategy profile of opponents s_{-i}, we can define the best response of player i:

$$BR_i(s_{-i}) = \arg\max_{s'_i \in S_i} u_i(s'_i, s_{-i}).$$

- $s_i \in BR_i(s_{-i})$ if and only if $u_i(s_i, s_{-i}) \geq u_i(s'_i, s_{-i})$ for all $s'_i \in S_i$
- There could be multiple strategies in $BR_i(s_{-i})$ but all such strategies give the same utility to player i if the opponents are indeed playing according to s_{-i}

Nash equilibrium

Definition

Suppose that we have a game $(I = \{1, 2, \dots n\}, S_1, \dots, S_n, u_1, \dots, u_n)$. Then a strategy profile $s^* = (s_1^*, \dots, s_n^*)$ is a pure strategy **Nash equilibrium** if for every i and for every $s_i \in S_i$,

$$u_i(s_i^*, s_{-i}^*) \geq u_i(s_i, s_{-i}^*).$$

Nash equilibrium

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- Analogous to that of a competitive equilibrium in the sense that nobody has unilateral incentives to deviate

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- once this equilibrium is reached, nobody has incentives to move from there

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- Analogous to that of a competitive equilibrium in the sense that nobody has unilateral incentives to deviate
- once this equilibrium is reached, nobody has incentives to move from there
- This is a concept of stability, but there is no way to ensure, or predict, that the game will reach this equilibrium

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- Consider the following game among 2 people. Each individual selects a number, s_i, between 20 and 60.

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- Let s_{-i} be the number selected by the other individual.

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- Consider the following game among 2 people. Each individual selects a number, s_i, between 20 and 60.

- Let s_{-i} be the number selected by the other individual.

- The utility function of the individual i is $u_i(s_i, s_{-i}) = 100 - (s_i - \frac{3}{2}s_{-i})^2$

Beauty contest

The best response of an individual is given by

$$s_i(s_{-i})^* = \begin{cases} \frac{3}{2}s_{-i} & \text{if } s_{-i} \leq 40 \\ 60 & \text{if } s_{-i} > 40 \end{cases}$$

The Nash equilibrium is where both BR functions intersect (i.e., when both play 60)

Prisoner's dilemma

	C	NC
C	5,5	0,10
NC	10,0	2,2

Prisoner's dilemma

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C	5,5	0,10
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The best response functions are:

$$BR_i(s_{-i}) = \begin{cases} NC & \text{if } s_{-i} = C \\ NC & \text{if } s_{-i} = NC \end{cases}$$

The Nash equilibrium is where both BR functions intersect (i.e., when both play NC, i.e., (NC, NC))

Prisoner's dilemma – A trick

Best response of 1 to 2 playing C

	C	NC
C	5,5	0,10
NC	<u>10</u>,0	2,2

Prisoner's dilemma – A trick

Best response of 1 to 2 playing NC

	C	NC
C	5,5	0,10
NC	10,0	2,2

Prisoner's dilemma – A trick

Best response of 2 to 1 playing C

	C	NC
C	5,5	0,<u>10</u>
NC	<u>10</u>,0	<u>2</u>,2

Prisoner's dilemma – A trick

Best response of 2 to 1 playing NC

	C	NC
C	5,5	0,$\underline{10}$
NC	$\underline{10}$,0	$\underline{2}$,$\underline{2}$

When underlined for both players, it is a Nash equilibrium (both are doing their BR)

Battle of the sexes

	G	P
G	2,1	0,0
P	0,0	1,2

Battle of the sexes

	G	P
G	$\underline{2},\underline{1}$	0,0
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$$BR_i(s_{-i}) = \begin{cases} G & \text{if } s_{-i} = G \\ P & \text{if } s_{-i} = P \end{cases}$$

Battle of the sexes

	G	P
G	$\underline{2},\underline{1}$	0,0
P	0,0	$\underline{1},\underline{2}$

$$BR_i(s_{-i}) = \begin{cases} G & \text{if } s_{-i} = G \\ P & \text{if } s_{-i} = P \end{cases}$$

Thus, (G, G) y (P, P) are both Nash equilibrium

Matching pennies (Pares o Nones) – Simultaneous

	1	2
1	(1000,-1000)	(-1000,1000)
2	(-1000,1000)	(1000,-1000)

Matching pennies (Pares o Nones) – Simultaneous

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Matching pennies (Pares o Nones) – Simultaneous

	1	2
1	(<u>1000</u>,-1000)	(-1000,<u>1000</u>)
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$$BR_1(s_2) = \begin{cases} 1 & \text{if } s_2 = 1 \\ 2 & \text{if } s_2 = 2 \end{cases}$$

$$BR_2(s_1) = \begin{cases} 2 & \text{if } s_1 = 1 \\ 1 & \text{if } s_2 = 2 \end{cases}$$

There is no Nash equilibrium in pure strategies

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Nash equilibrium survive IDSDS

Theorem

Every Nash equilibrium survives the iterative elimination of strictly dominated strategies

Proof

By contradiction:

- Suppose it is not true

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- It must have been that

$$u_i(s_i^*, s_{-i}) < u_i(s_i, s_{-i}) \forall s_{-i} \in S_{-i}$$

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- But this means s_i^* is not the best response of individual i to s_{-i}^*
- And this is a contradiction!

Nash equilibrium survive IDSDS

Theorem

If the process of IDSDS comes to a single solution, that solution is a Nash Equilibrium and is unique.

Proof

First let's proof its a Nash Equilibrium. The fact that is unique is trivial by the previous theorem.

Proof.

By contradiction:

- Suppose that the results from IDSDS (s^*) is not a Nash Equilibrium

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Proof

First let's proof its a Nash Equilibrium. The fact that is unique is trivial by the previous theorem.

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By contradiction:

- Suppose that the results from IDSDS (s^*) is not a Nash Equilibrium
- For some individual i there exits s_i such that

$$u_i(s_i, s^*_{-i}) > u_i(s^*_i, s^*_{-i})$$

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- But then s_i could not have been eliminated

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- But then s_i could not have been eliminated
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- Weakly dominated strategies

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Examples
- Cournot Competition
- Cartels

Cournot Competition

- We will apply the concept of pure Nash equilibrium to analyze oligopoly markets

Cournot Competition

- We will apply the concept of pure Nash equilibrium to analyze oligopoly markets
- Suppose that there are two firms that produce the same product have zero marginal cost of production.

Cournot Competition

- We will apply the concept of pure Nash equilibrium to analyze oligopoly markets
- Suppose that there are two firms that produce the same product have zero marginal cost of production.
- If firm 1 and 2 produce q_1 and q_2 units of the commodity respectively, the inverse demand function is given by:

$$P(Q) = 120 - Q, Q = q_1 + q_2.$$

Cournot Competition

- We will apply the concept of pure Nash equilibrium to analyze oligopoly markets
- Suppose that there are two firms that produce the same product have zero marginal cost of production.
- If firm 1 and 2 produce q_1 and q_2 units of the commodity respectively, the inverse demand function is given by:

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- Strategy space is $S_i = [0, +\infty)$

Cournot Competition

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- If firm 1 and 2 produce q_1 and q_2 units of the commodity respectively, the inverse demand function is given by:

$$P(Q) = 120 - Q, Q = q_1 + q_2.$$

- Strategy space is $S_i = [0, +\infty)$
- The utility function of player i is given by:

$$\pi_1(q_1, q_2) = (120 - (q_1 + q_2))q_1,$$
$$\pi_2(q_1, q_2) = (120 - (q_1 + q_2))q_2.$$

Cournot Competition

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- Are there any strictly dominant strategies? The answer is no, why?
- Are there any strictly dominated strategies?
- The strategies $q_i \in (120, +\infty)$ are strictly dominated by the strategy 0
- Are there any others? given q_{-i},

$$\frac{d\pi_i}{dq_i}(120 - q_i - q_{-i})q_i = 120 - 2q_i - q_{-i}$$

Cournot Competition

- Are there any strictly dominant strategies? The answer is no, why?
- Are there any strictly dominated strategies?
- The strategies $q_i \in (120, +\infty)$ are strictly dominated by the strategy 0
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$$\frac{d\pi_i}{dq_i}(120 - q_i - q_{-i})q_i = 120 - 2q_i - q_{-i}$$

- Therefore 60 strictly dominates any $q_i \in (60, 120]$

Cournot Competition

- $$BR_i(q_{-i}) = \frac{120 - q_{-i}}{2}.$$

Cournot Competition

- $$BR_i(q_{-i}) = \frac{120 - q_{-i}}{2}.$$
- for any $q_i \in [0, 60]$, there exists some $q_{-i} \in [0, +\infty)$ such that $BR_i(q_{-i}) = q_i$

Cournot Competition

- $$BR_i(q_{-i}) = \frac{120 - q_{-i}}{2}.$$
- for any $q_i \in [0, 60]$, there exists some $q_{-i} \in [0, +\infty)$ such that $BR_i(q_{-i}) = q_i$
- Such a q_i can never be strictly dominated

Cournot Competition

- $$BR_i(q_{-i}) = \frac{120 - q_{-i}}{2}.$$
- for any $q_i \in [0, 60]$, there exists some $q_{-i} \in [0, +\infty)$ such that $BR_i(q_{-i}) = q_i$
- Such a q_i can never be strictly dominated
- After one round of deletion of strictly dominated strategies, we are left with: $S_i = [0, 60]$

Cournot Competition

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- $q_{-i} = [0, 60]$

Cournot Competition

- $$BR_i(q_{-i}) = \frac{120 - q_{-i}}{2}.$$
- $q_{-i} = [0, 60]$
- Therefore $q_i \in [0, 30)$ are strictly dominated by $q_i = 30$

Cournot Competition

- $$BR_i(q_{-i}) = \frac{120 - q_{-i}}{2}.$$
- $q_{-i} = [0, 60]$
- Therefore $q_i \in [0, 30)$ are strictly dominated by $q_i = 30$
- After two rounds of deletion of strictly dominated strategies, we are left with: $S_i = [30, 60]$

Cournot Competition

- $$BR_i(q_{-i}) = \frac{120 - q_{-i}}{2}.$$
- $q_{-i} = [30, 60]$
- 45 strictly dominates all strategies $q_i \in (45, 60]$
- After three rounds of deletion of strictly dominated strategies, we are left with: $S_i = [30, 45]$

Cournot Competition

- $$BR_i(q_{-i}) = \frac{120 - q_{-i}}{2}.$$
- $q_{-i} = [30, 45]$
- 37.5 strictly dominates all strategies $q_i \in [30, 37.5]$
- After four rounds of deletion of strictly dominated strategies, we are left with: $S_i = [37.5, 45]$

Cournot Competition

- After (infinitely) many iterations, the only remaining strategies are $S_i = 40$
- The unique solution by IDSDS is $q_1^* = q_2^* = 40$.

Cournot Competition

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Cournot Competition

- There will also be a unique Nash equilibrium
- $$BR_i(q_{-i}) = \frac{120 - q_{-i}}{2}.$$
- At any Nash equilibrium, we must have: $q_1^* \in BR_1(q_2^*)$ and $q_2^* \in BR_2(q_1^*)$.

Cournot Competition

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- $$BR_i(q_{-i}) = \frac{120 - q_{-i}}{2}.$$
- At any Nash equilibrium, we must have: $q_1^* \in BR_1(q_2^*)$ and $q_2^* \in BR_2(q_1^*)$.
- $$q_1^* = \frac{120 - q_2^*}{2}, q_2^* = \frac{120 - q_1^*}{2}.$$

Cournot Competition

- There will also be a unique Nash equilibrium
- $$BR_i(q_{-i}) = \frac{120 - q_{-i}}{2}.$$
- At any Nash equilibrium, we must have: $q_1^* \in BR_1(q_2^*)$ and $q_2^* \in BR_2(q_1^*)$.
- $$q_1^* = \frac{120 - q_2^*}{2}, q_2^* = \frac{120 - q_1^*}{2}.$$
- We can solve for q_1^* and q_2^* to obtain:

$$q_1^* = 40, q_2^* = 40, Q^* = 80, \Pi_1^* = \Pi_2^* = 1600.$$

Cournot Competition vs Monopoly (cartel)

- In a perfectly competitive market, price equals marginal cost and the total quantity produced will be $Q = 120$.

Cournot Competition vs Monopoly (cartel)

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$$\max_{q_i} p(q_i + Q_{-i})q_i - c_i(q_i)$$

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$$\max_{q_i} p(q_i + Q_{-i})q_i - c_i(q_i)$$

- First order condition implies:

$$q_i \frac{dP}{dQ}(q_i + Q_{-i}) + P(q_i + Q_{-i}) = \frac{dc_i}{dq_i}(q_i)$$

$$q_i \frac{dP}{dQ}(Q) + P(Q) = \frac{dc_i}{dq_i}(q_i)$$

$$P(Q) - \frac{dc_i}{dq_i}(q_i) = -q_i \frac{dP}{dQ}(Q)$$

$$\frac{P(Q) - \frac{dc_i}{dq_i}(q_i)}{P(Q)} = -\frac{q_i}{Q}\frac{Q}{P(Q)}\frac{dP}{dQ}(Q)$$

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Cournot Competition - General case

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- Therefore in a pure strategy Nash equilibrium $(q_1^*, q_2^*, \ldots, q_n^*)$ with $Q^* = q_1^* + q_2^* + \cdots q_n^*$, we must have:

$$\frac{P(Q^*) - \frac{dc_1}{dq_1}(q_1^*)}{P(Q^*)} = -\frac{q_1^*}{Q^*}\frac{1}{\varepsilon_{Q,P}(Q^*)},$$

$$\frac{P(Q^*) - \frac{dc_2}{dq_2}(q_2^*)}{P(Q^*)} = -\frac{q_2^*}{Q^*}\frac{1}{\varepsilon_{Q,P}(Q^*)},$$

$$\vdots$$

$$\frac{P(Q^*) - \frac{dc_n}{dq_n}(q_n^*)}{P(Q^*)} = -\frac{q_n^*}{Q^*}\frac{1}{\varepsilon_{Q,P}(Q^*)}.$$

Cournot Competition - General case

- Suppose that all firms have exactly the same cost function c

$$
\begin{aligned}
\frac{P(Q^*) - \frac{dc}{dq_1}(q_1^*)}{P(Q^*)} &= -\frac{q_1^*}{Q^*}\frac{1}{\varepsilon_{Q,P}(Q^*)}, \\
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&\vdots \\
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- Rewriting

$$P(Q^*) = \frac{1}{1 + \frac{1}{n}\frac{1}{\varepsilon_{Q,P}(Q^*)}}\frac{\partial c}{dq}\left(\frac{Q^*}{n}\right).$$

Dominance
Weakly dominated strategies

Nash equilibrium

Some examples

Relationship to dominance

Examples
Cournot Competition
Cartels

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- In a Nash equilibrium we must have:

$$q_1^* = \frac{1 - q_2^* - q_3^*}{2}$$
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- $q_1^* = q_2^* = q_3^* = \frac{1}{4}$
- Price is $p^* = 1/4$ and all firms get the same profits of $1/16$

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- Therefore

$$q_A^* = \frac{1 - q_B^*}{2}$$
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- Firm 3 is obtaining a disproportionate share of the joint profits (more than $1/3$)

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- Firm 3 clearly wants to stay out

Cartels

There are many ifficulties associated with sustaining collusive agreements (e.g., the OPEC cartel)