Econ 301: Microeconomic Analysis

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Game Theory

Motivation

- So far in class, have seen only situations where at most one agent can have major impact on outcome
- Now we turn to case where two or more agents interact *strategically*
- We need tools from *game theory*

Setting up the Game

- A game needs several elements:
  - *Players*, usually labelled with names, letters, or numbers
  - *Strategies* for each player
  - *Payoffs* for each player given a combination of strategies (sometimes called an *outcome*)
- To start we will analyze *simultaneous move games*, where each player must select strategy without knowing other's strategy

Payoff Matrix

- We can handily represent all these elements in a *payoff matrix*
- For example, if we have the following game:
  - Players A (row player) and B (column player)
  - A can choose strategy Top or Bottom
  - B can choose strategy Left or Right
  - Payoff function (row player payoff listed first):

    (Top, Left) $\rightarrow (1, 2)$
    (Top, Right) $\rightarrow (0, 1)$
    (Bottom, Left) $\rightarrow (2, 1)$
    (Bottom, Right) $\rightarrow (1, 0)$
- What is payoff matrix?

$$\begin{array}{ccc} & & B & \\ & & \text{Left} & \text{Right} \\ \multirow{2}{*}{A} & \text{Top} & (1, 2) & (0, 1) \\ & \text{Bottom} & (2, 1) & (1, 0) \end{array}$$

Solution Concepts

- The game tells us all the possible outcomes
- A *solution concept* is a rule for narrowing down the possible outcomes
- Which solution concept we apply depends on the type of game and what we want to assume about the players
- Solution concepts we will learn:
  - Dominant/dominated strategies
  - Nash equilibrium
  - Backwards induction/subgame perfect equilibrium

Best Responses

- Suppose that the players have the following strategies
  - $(a_1, a_2, \ldots, a_n)$ for player A
  - $(b_1, b_2, \ldots, b_m)$ for player B
- Define a *best response* for a player as the strategy that maximizes payoffs conditional on a strategy for the other player
  - A's best response is $BR_A(b)$
  - B's best response is $BR_B(a)$

Dominant and Dominated Strategies: Intuition

- Consider the following game:

$$
\begin{array}{cccc}
 & & \multicolumn{2}{c}{B} \\
 & & \textit{Left} & \textit{Right} \\
\text{A} & \textit{Top} & (1, \underline{2}) & (0, 1) \\
 & \textit{Bottom} & (\underline{2}, \underline{1}) & (\underline{1}, 0)
\end{array}
$$

- Note that whether B plays Left or Right, A's optimal choice is to choose Bottom (since $2 > 1$ and $1 > 0$)
- We say that Bottom is a *dominant strategy* for A, and Top is a *dominated strategy*
- Similarly, for player B, Left is dominant and Right is dominated

Dominant Strategies

- The strategy a^D is a *dominant strategy* iff

$$a^D = BR_a(b) \quad \text{for all } b \in b_1, b_2, b_3, \ldots.$$

- That is, a^D is *always* the Player A's best response, regardless of what the other player is doing
- Definition is similar for column player
- Solution concept: if both players have a dominant strategy, then the game has a *dominant strategy solution* where both players play their dominant strategy

Dominated Strategies

- A strategy is *dominated* if it is *never* the best response for a player
  - (Formal definition is a bit messy)
- This gives us another solution concept: players will not play dominated strategies
- Relation to dominant strategies:
  - Possible to have strategies that are neither dominant nor dominated
  - In simple 2-by-2 games: if one strategy is dominant, other will be dominated
  - In more complex games: possible to have strategies that are dominated even if there is no dominant strategy

Prisoner's Dilemma

- Consider the following game, called the Prisoner's Dilemma:
  - Two players are prisoners accused of a joint crime
  - Can either confess (C) to the crime or deny (D)
  - Both confess: both get 4 years in jail
  - Both deny: both get 2 years in jail on lesser charge
  - One confess and one deny: confessor gets 1 year in jail while denier gets 5 years
- What is normal form of game?

	Confess	*Deny*
Confess	$(-4, -4)$	$(-1, -5)$
Deny	$(-5, -1)$	$(-2, -2)$

Prisoner's Dilemma

- Does the Prisoner's dilemma have any dominant or dominated strategies?
  - Confess is a dominant strategy for both players
  - Deny is a dominated strategy for both players
  - Thus the only possible outcome according to both solution concepts is (Confess, Confess)

Nash Equilibrium: Definition

Definition

A Nash equilibrium of a two-person game is a pair of strategies (a^*, b^*) such that

$$a^* = BR_A(b^*)$$
$$b^* = BR_B(a^*)$$

- Note that player's actions and beliefs are *mutually consistent*
  - That is, all players are best responding to each other
- If all other players are playing NE, no player will want to deviate

Nash Equilibrium: Another Definition

- Suppose that more generally we have N players, indexed by i
- The strategy chosen by player i is noted as s_i
- The strategy chosen by player i's opponents is noted as s_{-i}
- The payoff for player i given her strategy and opponents' strategies is $U_i(s_i, s_{-i})$
  - Note $BR_i(s_{-i}) = \max_{s_i} U_i(s_i, s_{-i})$
- Using this notation, we get another definition for Nash equilibrium:

Definition

A Nash equilibrium of a N-person game is a vector of strategies $s_1^*, s_2^*, \ldots, s_N^*$ such that

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

for all s_i and for all $i \in (1, \ldots, N)$

Nash Equilibrium of Prisoner's Dilemma

	Confess	*Deny*
Confess	$(-4, -4)$	$(-1, -5)$
Deny	$(-5, -1)$	$(-2, -2)$

- What is/are the Nash equilibrium/a of the Prisoner's Dilemma?
  - If your opponent is choosing Deny, your best response to choose Confess, since $(-1 > -2)$
  - If your opponent is choosing Confess, your best response to choose Confess, since $(-4 > -5)$
  - Thus NE is (Confess, Confess)
  - Note that NE occurs whenever both entries in a cell are best responses
- Note that when describing NE, we give strategies, not payoffs

Another Example: Stag Hunt

	Stag	*Hare*
Stag	$(7, 7)$	$(0, 1)$
Hare	$(1, 0)$	$(2, 2)$

- Are there any dominant or dominated strategies?
  - No dominant or dominated strategies for either player in the above game
- Are there any NE?
  - Note that for outcome (Stag, Stag)
    - A is choosing optimal response to B's strategy
    - B is choosing optimal response to A's strategy
  - We call an outcome with mutual best response a *Nash equilibrium*
  - (Hare,Hare) is a Nash equilibrium as well

Mixed Strategies

$$\begin{array}{ccc} & L & R \\ T & (0, \underline{0}) & (\underline{0}, -1) \\ B & (\underline{1}, 0) & (-1, \underline{3}) \end{array}$$

- This game has no Nash equilibrium in *pure strategies*
- However, we have not yet considered *mixed strategies*
  - Players may randomize between two or more strategies
  - For example, player A could play 50% T, 50% B while player B could play 33% L, 67% R
- If we allow for mixed strategies, then every game has at least one Nash Equilbrium

Mixed Strategies: Definition

- Suppose a player has *pure* strategies $(a_1, a_2, \ldots, a_n)$
- We then define a *mixed strategy* as a vector $p = (p_1, p_2, \ldots, p_n)$ s.t.
  - $p_i \geq 0$ for all i
  - $\sum_{i=1}^{n} p_i = 1$
- Interpretation: p_i is probability of playing a_i
- Best response: given mixed strategy for opponent and return the optimal mixed strategey for the player
- We can modify our definition of Nash to include mixed strategies:

Definition

A Nash Equilibrium of a two-person game is a pair of mixed strategies (p^*, q^*) such that

$$p^* = BR_A(q^*)$$
$$q^* = BR_B(p^*)$$

Finding Mixed Strategy Solutions

- Suppose Player A is mixing between strategies Top and Bottom in equilibrium
- Suppose that playing Top gives greater expected payoff than playing Bottom
- Then mixing cannot be a best response, since would do better to play pure strategy Top
- By similar logic, playing Bottom cannot give higher payoff than playing Top
- Therefore, if a player is mixing in equilibrium, she must be indifferent between all pure strategies she is mixing over

Finding Mixed Strategies: Example

	Left	*Right*
Top	$(2, 1)$	$(0, 0)$
Bottom	$(0, 0)$	$(1, 2)$

- Suppose players are playing mixed strategies:
  - Player A is putting weight p on Top, $1 - p$ on Bottom
  - Player B is putting weight q on Left and $1 - q$ on Right
- Player A plays Top: payoff is $2q + 0(1 - q) = 2q$
- Player A plays Bot: payoff is $0q + 1(1 - q) = 1 - q$
- Player A must be indifferent for mixing:

$$2q = 1 - q \rightarrow q = \frac{1}{3}$$

- Note that A's indifference condition determines B's mixing probability!

Finding Mixed Strategies: Example (cont)

	Left	*Right*
Top	$(2, 1)$	$(0, 0)$
Bottom	$(0, 0)$	$(1, 2)$

- Player B plays Left: payoff is $1p + 0(1 - p) = p$
- Player B plays Right: payoff is $0p + 2(1 - p) = 2 - 2p$
- Player B must be indifferent for mixing:

$$p = 2 - 2p \rightarrow p = \frac{2}{3}$$

- Thus the mixed strategy Nash equilibrium is $(\frac{2}{3}, \frac{1}{3})$
- Notation: since there are just two strategies for each player, we need just one number to indicate each mixed strategy

Best Response Functions

- What is player A's payoff for any mixture q played by B?

$$\begin{aligned}\pi_A &= 2pq + 0(1-p)q + 0p(1-q) + 1(1-p)(1-q)\\ &= (3q-1)p + 1 - q\end{aligned}$$

- Thus the best response for A is
    - Make p as big as possible if $3q - 1 > 0$
    - Make p as small as possible if $3q - 1 < 0$
    - Any p is a best response if $3q - 1 = 0$
- Best response function:

$$p = BR_A(q)\begin{cases} = 1 \text{ if } q > 1/3 \\ \in [0,1] \text{ if } q = 1/3 \\ = 0 \text{ if } q < 1/3 \end{cases}$$

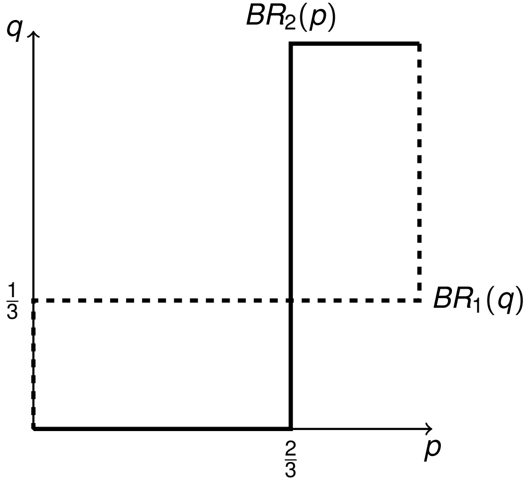
Best Response Functions (cont)

- Similarly, we can write the best response function of B as

$$q = BR_B(p) \begin{cases} = 1 \text{ if } p > 2/3 \\ \in [0,1] \text{ if } p = 2/3 \\ = 0 \text{ if } p < 2/3 \end{cases}$$

- BR functions can also be deduced from indifference conditions
- Graph q vs p for both players: Any place where the best response functions intersect is a Nash equilibrium

Best Responses Graphically



- Each intersection represents one (pure or mixed) NE

Sequential Games

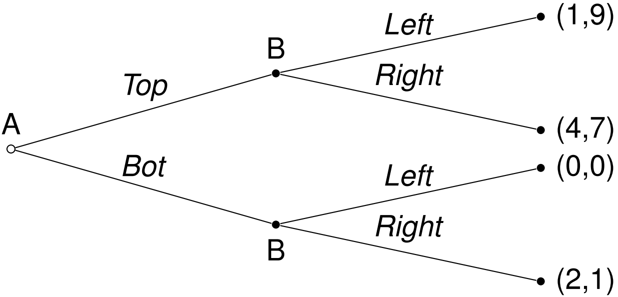
- Consider the following game
  - Player A chooses Top or Bottom
  - Observing A's choice, player B then chooses Left or Right
- This is a *sequential game*, because players move in sequence rather than simultaneously
- Payoff function:

$$\begin{array}{ll} (\text{Top, Left}) & \rightarrow (1,9) \\ (\text{Top, Right}) & \rightarrow (4,7) \\ (\text{Bottom, Left}) & \rightarrow (0,0) \\ (\text{Bottom, Right}) & \rightarrow (2,1) \end{array}$$

- Note Player B really now has more complicated strategies, since must pick what to do after each move player B

Extensive Form

- We analyze such games in *extensive form* with a game tree:



- Note that extensive form has:
  - Every non-terminal node labeled with player who moves at that point
  - Every terminal node labeled with payoffs
  - Every branch labeled with available actions

Solution Concept: Subgame Perfect Nash Equilibrium

- We solve extensive form games with *backwards induction*
  - Start with end of the game tree
  - Determine what last mover will do
  - Take one step backwards in tree and repeat until all decisions have been analyzed
- The solution we arrive at is called the *subgame perfect Nash equilibrium*
- Note that in sequential games, strategies must list action at every node at which the player moves
  - For example, player B's strategy must indicate what B will do if A plays Top *and* what B will do if A plays Top
  - Notation: *RL* means play Right if Top, Left if Bottom, for example

Example

- What is backwards induction solution to game on previous slide?
  - After Top, player B will play Left
  - After Bottom, player B will play Right
  - Given what player B will do, player A will choose to play Bottom
  - SPNE strategies are (B, LR)
  - SPNE outcome is (Bottom, Right)