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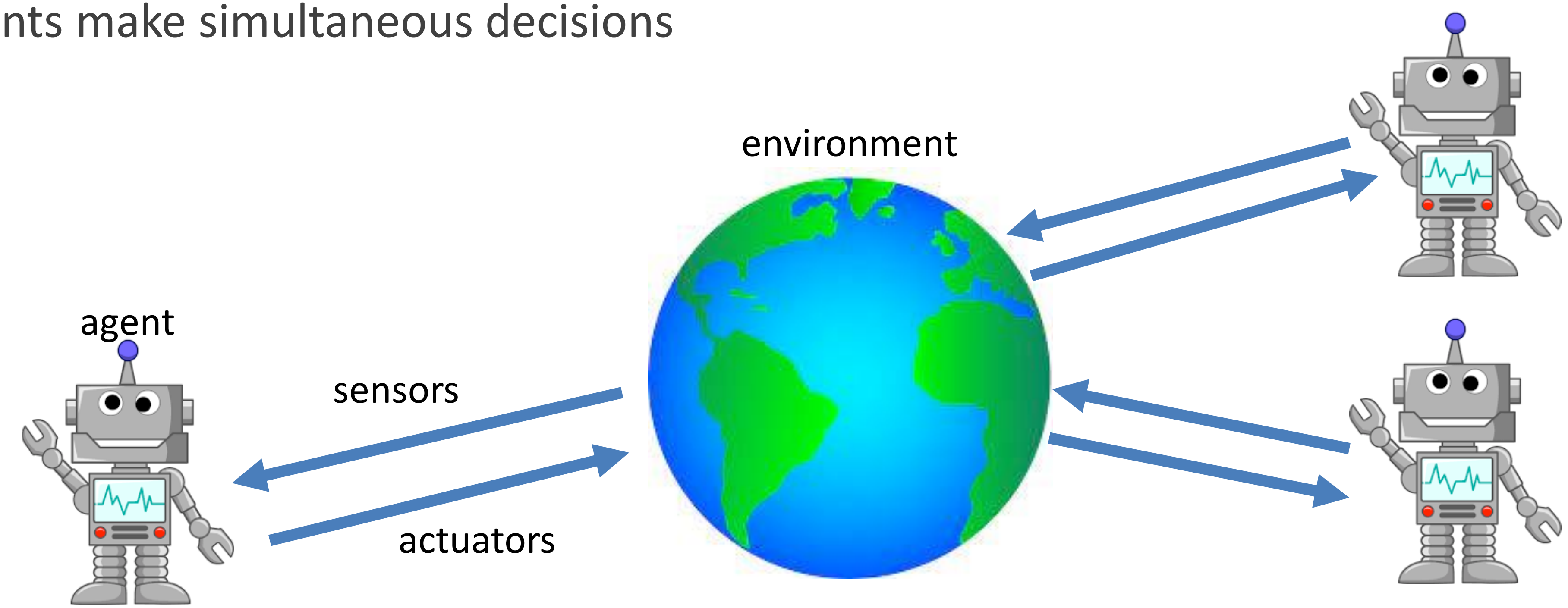
Multiagent decision making and Games in Normal Form

Outline

- **Multiagent decision making with Game theory**
- Normal-form games
  - Example – Prisoner's dilemma
- Strictly dominated action
- Solution Concepts
  - Iterated elimination of strictly dominated actions
  - Nash Equilibrium

Multiagent decision making

- We are now going to study **multiagent decision making**
  - Group of agents coexist within an environment
  - Agents make simultaneous decisions



Game Theory

- What is game theory?
  - Mathematical study of **interactions** among **independent, self-interested agents**
  - It has been **applied in many disciplines**, such as:
    - Economics, political science, biology, psychology, linguistics, and **computer science (multiagent decision making)**

Game Theory

- What is game theory?
  - Agents are considered **self-interested**
    - Each agent has a **description of states (outcomes) it likes**
    - The dominant theory for modeling agent’s interests is **utility theory**

Game Theory

The success of an agent depends on the decisions of <u>all agents</u>

Game Theory

- Game theory was **originally designed for modelling economical interaction**

- Game theory is now an **independent field**
  - Solid mathematical foundation
  - Many applications

Game Theory

- Game theory is based on **two assumptions:**
  - Participating agents are **rational**
  - Agents reason **strategically**
    - They **take into account the other agent’s decision** in their own decision making process

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Normal-Form Games

- Can be viewed as the **multiagent extension** of utility-based decision making

- Also known as **static game or strategic games** in some game theory books

Normal-Form Games

- **Definition (Normal-form game):** *A (finite, n-person) normal-form game is a* ***tuple*** $(\boldsymbol{N}, \boldsymbol{A}, \boldsymbol{u})$***,*** *where:*

  - $\boldsymbol{N}$ *is a* ***finite set of*** $\boldsymbol{n}$ ***players****, indexed by* i*;*

  - $A = A_1 \times \cdots \times A_n$*, where* $\boldsymbol{A_i}$ ***is a finite set of actions available to player/agent*** $\boldsymbol{i}$*. Each vector* $\boldsymbol{a} = (\boldsymbol{a_1}, \dots, \boldsymbol{a_n}) \in \boldsymbol{A}$ ***is called an action profile (or joint action)***

  - $u = (u_1, \dots, u_n)$*, where* $u_i : A \longmapsto \mathbb{R}$ *is a real-valued utility (or payoff) function for player* i*.*

Strategic game

- In summary:
  - **Each agent chooses a single action** and then **receives a payoff that depends on the joint action**
  - The joint action is the **outcome** of the game
  - Although payoffs are common knowledge, an **agent does not know the actions of the other agents**
    - The best an agent can do is to **predict** the actions of others
  - A game's **solution** is a **prediction of the outcome** using the assumptions that all agents are rational and strategic

Notation in Economics

- The **normal-form representation** of a game specifies:
  - *an* $\boldsymbol{n}$**-player game**
  - the **strategies** available to each player
    - Let $s_i \in S_i$ denote a strategy for player i, where S_i is the strategy space
    - Let $(s_1, \dots, s_n)$ denote a combination of strategies
  - the **payoff** received by each player for each combination of strategies that could be chosen by the players
    - Let $u_i(s_1, \dots, s_n)$ denote player i's payoff function
  - Hence, we denote a **game** by $G = \{S_1, \dots, S_n, u_1, \dots, u_n)$

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Prisoner’s dilemma

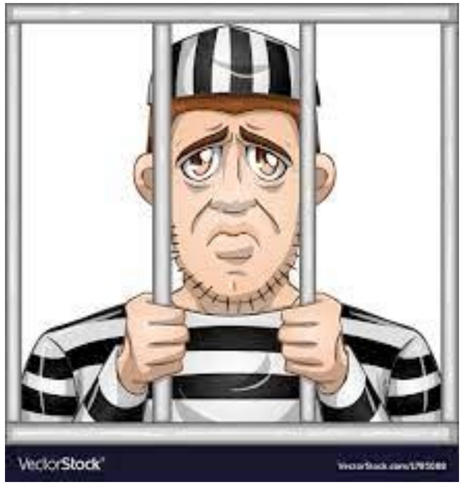
- The **prisoner’s dilemma** is one of the **oldest and most studied model** in game theory

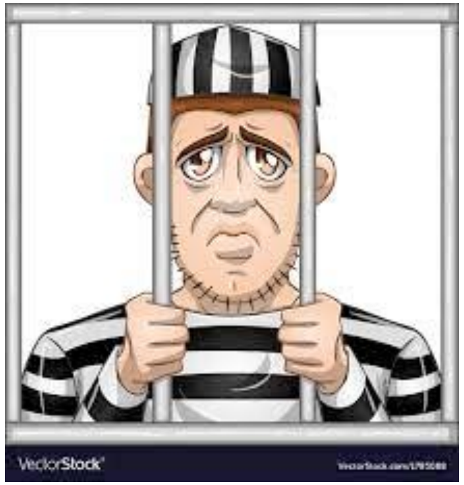
- Information about the game:

  - **Two suspects** are arrested and charged for a crime

  - The **police lack sufficient evidence** to convict the suspects, unless at least one confesses

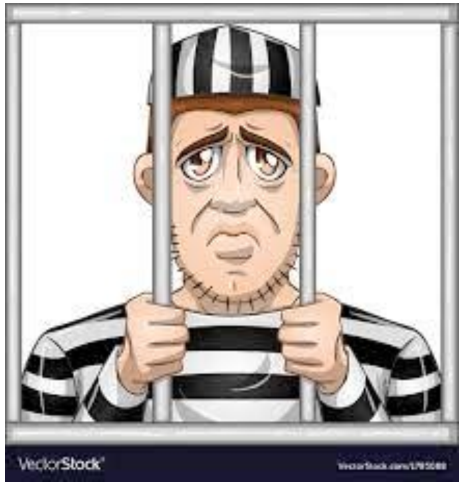
  - The police hold the suspects in **separate cells**

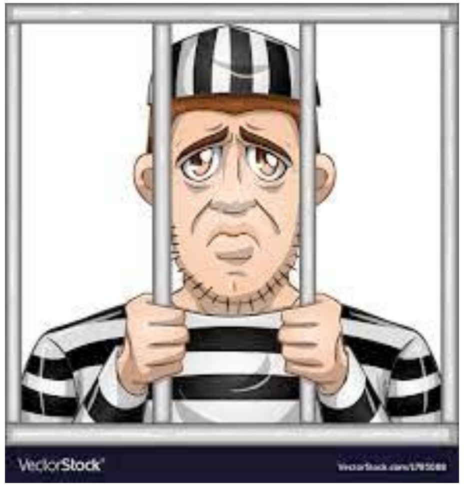




Prisoner’s dilemma

- The **policemen explain the consequences** that will follow from the following actions:
  - **If neither confesses** then **both will be convicted** of a minor offense and sentenced to **one month** in jail
  - **If both confess** then **both will be sentenced** to jail for **six months**
  - **if one confesses but the other does not**, then the **confessor will be released** immediately but the **other will be sentenced** to **nine months** in jail





Prisoner's dilemma

- Elements of this normal-form game:

  - N = **{Prisoner 1, Prisoner 2}** (i.e., there are **2 agents** within the environment)

  - Each agent i can select an **action** a_i (or **strategy**) from his own action set A_i
    - $A_1 = A_2 = \{not\ confess, confess\}$
    - And $a = (a_1, a_2)$ is the **joint action** (or action/strategy profile)
      - e.g., $a = (a_1 = confess, a_2 = not\ confess)$

  - $u = (u_1(a_1, a_2), u_2(a_1, a_2))$, where u_i is the payoff function for each agent (next slide)

Prisoner's dilemma

- Elements of this normal-form game :
  - In the special case of two agents, the normal-form game can be represented by a **payoff matrix**

		Prisoner 2	
		Not confess	***Confess***
Prisoner 1	***Not confess***	-1, -1	-9, 0
	Confess	0, -9	-6, -6

  - E.g.:
    - $u_1(a_1 = confess, a_2 = not\ confess) = 0$
    - $u_2(a_1 = confess, a_2 = not\ confess) = -9$

Prisoner's dilemma

- In its most general form, the Prisoner's Dilemma is any normal-form game as follows:

		Agent 2	
		Cooperate	***Defect***
Agent 1	***Cooperate***	a, a	b, c
	Defect	c, b	d, d

In which: $\boldsymbol{c > a > d > b}$

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- **Strictly dominated action**
- Solution Concepts
  - Iterated elimination of strictly dominated actions
  - Nash Equilibrium

Strictly dominated action

- **In game theory, we assume** that a **rational agent will never choose a suboptimal action** (or play a strictly dominated action/strategy)

- **Suboptimal action** will always result in lower payoffs for the agent than some other action, no matter what the other agents do

Strictly dominated action

- We formalize this concept as follows:

  - **Definition**: *We will say that an action a_i of agent i is* **strictly dominated** *by another action a_i' of agent i if*

$$u_i(a_i', a_{-i}) > u_i(a_i, a_{-i})$$

for all actions a_{-i} of the other agents

Strictly dominated action

- Example in the prisoner's dilemma:
  - **for prisoner 1,** the $not\ confess$ is a **strictly dominated action** by the action $confess$

$$u_1(a_1{}' = confess, a_2 = not\ confess) > u_1(a_1 = not\ confess, a_2 = not\ confess)$$
$$u_1(a_1{}' = confess, a_2 = confess) > u_1(a_1 = not\ confess, a_2 = confess)$$

Prisoner 2

Prisoner 1		***Not confess***	***Confess***
	Not confess	-1, -1	-9, 0
	Confess	0, -9	-6, -6

Strictly dominated action

- Example in the prisoner's dilemma:
  - similarly, **for prisoner 2,** the $not\ confess$ is a **strictly dominated action** by the action $confess$

$$u_2(a_2' = confess, a_1 = not\ confess) > u_2(a_2 = not\ confess, a_1 = not\ confess)$$
$$u_2(a_2' = confess, a_1 = confess) > u_2(a_2 = not\ confess, a_1 = confess)$$

Prisoner 2

Prisoner 1		***Not confess***	***Confess***
	Not confess	-1, -1	-9, 0
	Confess	0, -9	-6, -6

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- **Solution Concepts**
  - Iterated elimination of strictly dominated actions
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Solution Concepts

- Now that we have a defined games in normal form:
  - How can we reason about these games?
  - How can we predict the outcomes of a game?
  - How can we predict the actions of a game?

Solution Concepts

- The problem of **reasoning about games** and **identifying certain subsets of outcomes** is called

Solution Concept

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  - Nash Equilibrium

Iterated elimination of strictly dominated actions

- The **iterated elimination of strictly dominated actions** is a **first solution concept** for games
  - This solution concept is based on the **assumption** that a **rational agent will never choose a suboptimal action** (or play a strictly dominated action/strategy)

Iterated elimination of strictly dominated actions

- The **iterated elimination of strictly dominated actions** is a solution technique that:
  - **iteratively eliminates strictly dominated actions** from all agents, until no more actions are strictly dominated
- This technique is based on **two assumptions**:
  - A rational agent would never take a strictly dominated action
  - It is *common knowledge* that all agents are rational

Iterated elimination of strictly dominated actions

- Example (**Game 2**):
  - **Imagine 2 agents with the following payoff matrix**
  - **Are there strictly dominated actions?**

Agent 2

Agent 1		***Left***	***Middle***	***Right***
	Up	1, 0	1, 2	0, 1
	Down	0, 3	0, 1	2, 0

Iterated elimination of strictly dominated actions

- Example (**Game 2**):
  - Let us first check agent 1
  - For agent 1, **neither Up nor Down is strictly dominated**

Agent 2

Agent 1		***Left***	***Middle***	***Right***
	Up	1, 0	1, 2	0, 1
	Down	0, 3	0, 1	2, 0

Iterated elimination of strictly dominated actions

- Example (**Game 2**):
  - Let us now check agent 2
  - For agent 2, ***Right*** **is strictly dominated by** ***Middle***

Agent 2

Agent 1		***Left***	***Middle***	***Right***
	Up	1, 0	1, 2	0, 1
	Down	0, 3	0, 1	2, 0

Iterated elimination of strictly dominated actions

- Example (**Game 2**):
  - A **rational** agent 2 will **not choose *Right***
  - Thus, if agent 1 knows that agent 2 is rational, then agent 1 can **eliminate *Right* from the action set**

Agent 2

Agent 1		***Left***	***Middle***	~~***Right***~~
	Up	1, 0	1, 2	~~0, 1~~
	Down	0, 3	0, 1	~~2, 0~~

Iterated elimination of strictly dominated actions

- Example (**Game 2**):
  - Hence, if agent 1 knows that agent 2 is rational, then **agent 1 can play the game as if it were the following:**

Agent 2

Agent 1		***Left***	***Middle***
	Up	1, 0	1, 2
	Down	0, 3	0, 1

Are there strictly dominated actions?

Iterated elimination of strictly dominated actions

- Example (**Game 2**):
  - ***Down* is now strictly dominated by *Up*** for agent 1.

		Agent 2	
		Left	***Middle***
Agent 1	***Up***	1, 0	1, 2
	Down	0, 3	0, 1

Iterated elimination of strictly dominated actions

- Example (**Game 2**):
  - If **agent 1 is rational** (and agent 1 knows that agent 2 is rational, so that the game below applies) then **agent 1 will not choose *Down***
  - if agent 2 knows that agent 1 is rational, then **agent 2 can eliminate *Down* from agent 1's action set**
    - Note that we assume that agent 2 knows that agent 1 knows that agent 2 is rational (so that agent 2 knows that the game below applies)

		Agent 2	
		Left	***Middle***
Agent 1	***Up***	1, 0	1, 2
	~~***Down***~~	~~0, 3~~	~~0, 1~~

Iterated elimination of strictly dominated actions

- Example (**Game 2**):
  - Hence, considering the rationality assumption, **the agents can play the game as if it were the following:**

		Agent 2	
		Left	***Middle***
Agent 1	***Up***	1, 0	1, 2

Are there strictly dominated actions?

Iterated elimination of strictly dominated actions

- Example (**Game 2**):
  - ***Left* is strictly dominated by *Middle* for agent 2**
  - **Thus, the solution (outcome) of this game is (*Up, Middle*)**

		Agent 2	
		~~***Left***~~	***Middle***
Agent 1	***Up***	~~1, 0~~	1, 2

Iterated elimination of strictly dominated actions

Can we use this solution concept to find the outcome in the Prisoner's Dilemma?

Iterated elimination of strictly dominated actions

- Example with the Prisoner's Dilemma:

  - **Are there strictly dominated actions? Yes!**

  - For prisoner 1, ***Not confess*** **is strictly dominated by** ***Confess***

Prisoner 2

Prisoner 1		***Not confess***	***Confess***
	Not confess	-1, -1	-9, 0
	Confess	0, -9	-6, -6

Iterated elimination of strictly dominated actions

- Example with the Prisoner's Dilemma:
  - A **rational** prisoner 1 will **not choose *Not confess***
  - Thus, if prisoner 2 knows that prisoner 1 is rational, then prisoner 2 can **eliminate *Not confess* from the action set**

		Prisoner 2	
		Not confess	***Confess***
Prisoner 1	***Not confess***	~~-1, -1~~	~~-9, 0~~
	Confess	0, -9	-6, -6

Iterated elimination of strictly dominated actions

- Example with the Prisoner's Dilemma:
  - Hence, if prisoner 2 knows that prisoner 1 is rational, then **prisoner 2 can play the game as if it were the following:**

		Prisoner 2	
		Not confess	***Confess***
Prisoner 1	***Confess***	0, -9	-6, -6

Are there strictly dominated actions?

Iterated elimination of strictly dominated actions

- Example with the Prisoner's Dilemma:
  - ***Not confess*** **is strictly dominated by** ***Confess*** **for prisoner 2**
  - **Thus, the solution (outcome) of this game is (*Confess*, *Confess*)**

		Prisoner 2	
		Not confess	***Confess***
Prisoner 1	***Confess***	~~0, -9~~	-6, -6

Iterated elimination of strictly dominated actions

- Does the order matter in this algorithm?
- Will we end up with different outcomes if we change the order?

Iterated elimination of strictly dominated actions

- Example with the Prisoner's Dilemma:
  - **Recall that we started with this:**
    - For prisoner 1, ***Not confess*** **is strictly dominated by** ***Confess***

		Prisoner 2	
		Not confess	***Confess***
Prisoner 1	***Not confess***	-1, -1	-9, 0
	Confess	0, -9	-6, -6

Iterated elimination of strictly dominated actions

- Example with the Prisoner’s Dilemma:
  - **However, we could have started with this:**
    - For prisoner 2, ***Not confess*** **is strictly dominated by** ***Confess***

		Prisoner 2	
		Not confess	***Confess***
Prisoner 1	***Not confess***	-1, -1	-9, 0
	Confess	0, -9	-6, -6

Iterated elimination of strictly dominated actions

- Example with the Prisoner's Dilemma:
  - A **rational** prisoner 2 will **not choose *Not confess***
  - Thus, if prisoner 1 knows that prisoner 2 is rational, then prisoner 1 can **eliminate *Not confess* from the action set**

		Prisoner 2	
		Not confess	***Confess***
Prisoner 1	***Not confess***	-1, -1	-9, 0
	Confess	0, -9	-6, -6

Iterated elimination of strictly dominated actions

- Example with the Prisoner's Dilemma:
  - Hence, if prisoner 1 knows that prisoner 2 is rational, then **prisoner 1 can play the game as if it were the following:**

		Prisoner 2
		Confess
Prisoner 1	***Not confess***	-9, 0
	Confess	-6, -6

Iterated elimination of strictly dominated actions

- Example with the Prisoner's Dilemma:
  - ***Not confess* is strictly dominated by *Confess* for prisoner 1**
  - **Thus, the solution (outcome) of this game is (*Confess*, *Confess*)**

		Prisoner 2
		Confess
Prisoner 1	***Not confess***	~~-9, 0~~
	Confess	-6, -6

Iterated elimination of strictly dominated actions

- **Appealing idea** that rational agents do not play strictly dominated actions
- **First drawback:**
  - Each step requires a further assumption about what the agents know about each other's rationality
    - We need to assume that it is ***common knowledge*** that the **agents are rational**

Iterated elimination of strictly dominated actions

- **Second drawback:**
  - the process often produces a **very imprecise prediction** about the play of the game
    - For instance, if no actions are eliminated then anything could happen

Iterated elimination of strictly dominated actions

- **Second drawback:**
  - Does the game (i.e., **Game 3**) below **have any strictly dominated actions?**

	L	***C***	***R***
T	0, 4	4, 0	5, 3
M	4, 0	0, 4	5, 3
B	3, 5	3, 5	6, 6

Iterated elimination of strictly dominated actions

- **Second drawback:**

	L	C	R
T	0, 4	4, 0	5, 3
M	4, 0	0, 4	5, 3
B	3, 5	3, 5	6, 6

	L	C	R
T	0, 4	4, 0	5, 3
M	4, 0	0, 4	5, 3
B	3, 5	3, 5	6, 6

	L	C	R
T	0, 4	4, 0	5, 3
M	4, 0	0, 4	5, 3
B	3, 5	3, 5	6, 6

For agent 1, there are no strictly dominated actions

Iterated elimination of strictly dominated actions

- **Second drawback:**

	L	*C*	*R*
T	0, 4	4, 0	5, 3
M	4, 0	0, 4	5, 3
B	3, 5	3, 5	6, 6

	L	*C*	*R*
T	0, 4	4, 0	5, 3
M	4, 0	0, 4	5, 3
B	3, 5	3, 5	6, 6

	L	*C*	*R*
T	0, 4	4, 0	5, 3
M	4, 0	0, 4	5, 3
B	3, 5	3, 5	6, 6

For agent 2, there are no strictly dominated actions

Iterated elimination of strictly dominated actions

- **Second drawback:**
  - Hence, **Game 3** (below) **does not have any strictly dominated actions**
    - And the technique **does not produce a prediction whatsoever about this game, thus we are unsure about the outcome**

	L	***C***	***R***
T	0, 4	4, 0	5, 3
M	4, 0	0, 4	5, 3
B	3, 5	3, 5	6, 6

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  - **Nash Equilibrium**

Nash equilibrium

- The **Nash equilibrium** is a **stronger solution concept** than the iterated elimination of strictly dominated actions
- Hence, it produces **more accurate predictions in a wider class of games**

Nash equilibrium

- **Defintion**: *A* ***Nash equilibrium*** *is a joint action* a^* *with the property that the following holds for every agent* i*:*

$$u_i(a_i^*, a_{-i}^*) \geq u_i(a_i, a_{-i}^*)$$

for all action $a_i \in A_i$

- In other words, a Nash equilibrium is a **joint action from where no agent can *unilaterally* improve his payoff**
  - Hence, **no agent has any incentive to deviate**

Nash equilibrium

- Note that:
  - The **iterated elimination of strictly dominated actions** produces a solution of a game by means of an **algorithm**
  - However, the previous definition of **Nash equilibrium** describes a solution in terms of the **conditions that hold at that solution**

Nash equilibrium

- An alternative for the previous definition makes use of the **best-response function**

- **Definition:** *The **best-response function** for agent i is*

$$B_i(a_{-i}) = \{a_i \in A_i\colon u_i(a_i, a_{-i}) \geq u_i(a_i', a_{-i}) \text{ for all } a_i' \in A_i\}$$

- Note that $B_i(a_{-i})$ can be a set containing many actions

Nash equilibrium

- For instance, in the prisoner's dilemma:

  - If **prisoner 2** takes the action ***Not confess***

  - The **best response** of **prisoner 1** is the action ***Confess***
    - $B_1(a_2 = Not\ confess) = Confess$

Prisoner 2

Prisoner 1

	Not confess	***Confess***
Not confess	-1, -1	-9, 0
Confess	0, -9	-6, -6

Nash equilibrium

- We can compute the **best-response function for each agent**:
  - $B_1(a_2 = Not\ confess) = Confess$
  - $B_1(a_2 = Confess) = Confess$
  - $B_2(a_1 = Not\ confess) = Confess$
  - $B_2(a_1 = Confess) = Confess$

Prisoner 2

Prisoner 1		***Not confess***	***Confess***
	Not confess	-1, -1	-9, <u>0</u>
	Confess	<u>0</u>, -9	<u>-6</u>, <u>-6</u>

Nash equilibrium

- Using the definition of best-response function, we can now formulate an **equivalent definition** (to the first definition):

- **Definition 2**: *A **Nash equilibrium** is a joint action a^* with the property that the following holds for every agent i:*

$$a_i^* \in B_i(a_{-i}^*)$$

- In other words, in a Nash equilibrium, **each agent's actions is an optimal response to the other agents' actions**

Nash equilibrium

- We can compute the **best-response function for each agent**:

  - $B_1(a_2 = Not\ confess) = Confess$
  - $B_1(a_2 = Confess) = Confess$
  - $B_2(a_1 = Not\ confess) = Confess$
  - $B_2(a_1 = Confess) = Confess$

		Prisoner 2	
		Not confess	***Confess***
Prisoner 1	***Not confess***	-1, -1	-9, 0
	Confess	0, -9	-6, -6

Nash Equilibrium

Nash equilibrium

- In the prisoner's dilemma, note that:

		Prisoner 2	
		Not confess	***Confess***
Prisoner 1	***Not confess***	-1, -1	-9, 0
	Confess	0, -9	-6, -6

No incentives to deviate

Nash equilibrium

- So, we could use a **brute-force algorithm** to finding a game's **Nash equilibria** (NE):
  - Check whether each possible joint action satisfies the condition in the definition

Nash equilibrium

- Let us try this approach in **Game 2**:

		Agent 2		
		Left	***Middle***	***Right***
Agent 1	***Up***	1, 0	1, 2	0, 1
	Down	0, 3	0, 1	2, 0

Nash equilibrium

- In a two-agent game, this approach has the following steps:
  - for each agent and for each action of that agent, **determine the other agent's best response** to that action

Agent 2

Agent 1

	Left	***Middle***	***Right***
Up	1, 0	1, 2	0, 1
Down	0, 3	0, 1	2, 0

Nash equilibrium

- In a two-agent game, this approach has the following steps:
  - A **pair of actions satisfies condition in the definition of a NE** if each agent's action is a best response to the other's
    - Thus, we have **NE if both payoffs are underlined in the corresponding cell of the payoff matrix**

Agent 2

Agent 1		***Left***	***Middle***	***Right***
	Up	<u>1</u>, 0	<u>1</u>, <u>2</u>	0, <u>1</u>
	Down	0, <u>3</u>	0, 1	<u>2</u>, 0

Nash equilibrium

Nash equilibrium

- Let us try this approach in **Game 3**:

		Agent 2		
		L	***C***	***R***
	T	0, 4	4, 0	5, 3
Agent 1	***M***	4, 0	0, 4	5, 3
	B	3, 5	3, 5	6, 6

Nash equilibrium

- In a two-agent game, this approach has the following steps:
  - for each agent and for each action of that agent, **determine the other agent's best response** to that action

		Agent 2		
		L	***C***	***R***
	T	0, 4	4, 0	5, 3
Agent 1	***M***	4, 0	0, 4	5, 3
	B	3, 5	3, 5	6, 6

Nash equilibrium

- In a two-agent game, this approach has the following steps:
  - A **pair of actions satisfies condition in the definition of a NE** if each agent's action is a best response to the other's
    - Thus, we have **NE if both payoffs are underlined in the corresponding cell of the payoff matrix**

		Agent 2		
		L	***C***	***R***
	T	$0, \underline{4}$	$\underline{4}, 0$	$5, 3$
Agent 1	***M***	$\underline{4}, 0$	$0, \underline{4}$	$5, 3$
	B	$3, 5$	$3, 5$	$\underline{6}, \underline{6}$

Nash equilibrium

Final remarks

- Although the two definitions suggest **a brute-force method** for finding the **Nash equilibrium** of a game
  - the **cost** of such an algorithm **is exponential in the number of agents**

Final remarks

- Addressing the **relation** between **Nash equilibrium (NE)** and **iterated elimination of strictly dominated actions (IESDA)**

  - Recall the **NE joint actions** in the Prisoners' Dilemma (*Confess, Confess*) and Game 2 (*Up, Middle*)
    - These are the only joint actions that ***"survived"*** **IESDA**

  - In fact, this **result can be generalized:**

    - If IESDA eliminates all but a single joint action a, then this joint action is the unique NE of the game

Final remarks

- Addressing the **relation** between **NE** and **IESDA:**
  - Since IESDA **frequently does not eliminate** all but a single joint action
    - We say that the **Nash equilibrium is a stronger solution concept** than iterated elimination of strictly dominated actions
  - For example in Game 3:
    - any outcome is possible with IESDA
    - while NE gives a unique prediction

Thank You

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