Strategic Games

**Definition (Strategic game)**

A strategic game is a tuple $G = (N, (A_i)_{i \in N}, (u_i)_{i \in N})$ where
- a nonempty finite set $N$ of players,
- for each player $i \in N$, a nonempty set $A_i$ of actions (or strategies), and
- for each player $i \in N$, a payoff function $u_i : A \rightarrow \mathbb{R}$, where $A = \prod_{i \in N} A_i$.

A strategic game $G$ is called finite if $A$ is finite.

A strategy profile is a tuple $a = (a_1, \ldots, a_{|N|}) \in A$.

We can describe finite strategic games using payoff matrices.

**Example:** Two-player game where player 1 has actions $T$ and $B$, and player 2 has actions $L$ and $R$, with payoff matrix

<table>
<thead>
<tr>
<th></th>
<th>$L$</th>
<th>$R$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T$</td>
<td>$w_1, w_2$</td>
<td>$x_1, x_2$</td>
</tr>
<tr>
<td>$B$</td>
<td>$y_1, y_2$</td>
<td>$z_1, z_2$</td>
</tr>
</tbody>
</table>

Read: If player 1 plays $T$ and player 2 plays $L$ then player 1 gets payoff $w_1$ and player 2 gets payoff $w_2$, etc.
Prisoner’s Dilemma

Example (Prisoner’s Dilemma (informally))
Two prisoners are interrogated separately, and have the options to either cooperate (C) with their fellow prisoner and stay silent, or defect (D) and accuse the fellow prisoner of the crime.

Possible outcomes:
- Both cooperate: no hard evidence against either of them, only short prison sentences for both.
- One cooperates, the other defects: the defecting prisoner is set free immediately, and the cooperating prisoner gets a very long prison sentence.
- Both confess: both get medium-length prison sentences.

Hawk and Dove

An anti-coordination game:

Example (Hawk and Dove (informally))
In a fight for resources two players can behave either like a dove (D), yielding, or like a hawk (H), attacking.

Possible outcomes:
- Both players behave like doves: both players share the benefit.
- A hawk meets a dove: the hawk wins and gets the bigger part.
- Both players behave like hawks: the benefit gets lost completely because they will fight each other.
Matching Pennies

A strictly competitive game:

Example (Matching Pennies (informally))
Two players can choose either heads (H) or tails (T) of a coin.

Possible outcomes:
- Both players make the same choice: player 1 receives one Euro from player 2.
- The players make different choices: player 2 receives one Euro from player 1.

Bach or Stravinsky (aka Battle of the Sexes)

A coordination game:

Example (Bach or Stravinsky (informally))
Two persons, one of whom prefers Bach whereas the other prefers Stravinsky want to go to a concert together. For both it is more important to go to the same concert than to go to their favorite one. Let B be the action of going to the Bach concert and S the action of going to the Stravinsky concert.

Possible outcomes:
- Both players make the same choice: the player whose preferred option is chosen gets high payoff, the other player gets medium payoff.
- The players make different choices: they both get zero payoff.

Matching Pennies

Example (Matching Pennies (payoff matrix))

Strategies $A_1 = A_2 = \{H, T\}$. 

<table>
<thead>
<tr>
<th></th>
<th>H</th>
<th>T</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>player 2</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>H</td>
<td>1, -1</td>
<td>-1, 1</td>
</tr>
<tr>
<td><strong>player 1</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T</td>
<td>-1, 1</td>
<td>1, -1</td>
</tr>
</tbody>
</table>

Bach or Stravinsky (aka Battle of the Sexes)

Example (Bach or Stravinsky (payoff matrix))

Strategies $A_1 = A_2 = \{B, S\}$.

<table>
<thead>
<tr>
<th></th>
<th>B</th>
<th>S</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Stravinsky enthusiast</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>2, 1</td>
<td>0, 0</td>
</tr>
<tr>
<td><strong>Bach enthusiast</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S</td>
<td>0, 0</td>
<td>1, 2</td>
</tr>
</tbody>
</table>
Question: What is a “solution” of a strategic game?

Answer:
- A strategy profile where all players play strategies that are rational (i.e., in some sense optimal).
- Note: There are different ways of making the above item precise (different solution concepts).
- A solution concept is a formal rule for predicting how a game will be played.

In the following, we will consider some solution concepts:
- Iterated dominance
- Nash equilibrium
- (Subgame-perfect equilibrium)

Notation: we want to write down strategy profiles where one player’s strategy is removed or replaced.

Let \( a = (a_1, \ldots, a_N) \in A = \prod_{i \in N} A_i \) be a strategy profile.

We write:
- \( A_{-i} := \prod_{j \in N \setminus \{i\}} A_j \),
- \( a_{-i} := (a_1, \ldots, a_{i-1}, a_{i+1}, \ldots, a_N) \), and
- \( (a_{-i}, a_i') := (a_1, \ldots, a_{i-1}, a'_i, a_{i+1}, \ldots, a_N) \).

Example
Let \( A_1 = \{T, B\}, A_2 = \{L, R\}, A_3 = \{X, Y, Z\} \), and \( a := (T, R, Z) \).
Then \( a_{-1} = (R, Z) \), \( a_{-2} = (T, Z) \), \( a_{-3} = (T, R) \).
Moreover, \( (a_{-2}, L) = (T, L, Z) \).
3 Dominated Strategies

- Strictly Dominated Strategies
- Weakly Dominated Strategies

Strictly Dominated Strategies

**Definition (Strictly dominated strategy)**

Let $G = \langle (N, (A_i)_{i \in N}, (u_i)_{i \in N} \rangle$ be a strategic game.

A strategy $a_i \in A_i$ is called strictly dominated in $G$ if there is a strategy $a_i^* \in A_i$ such that for all strategy profiles $a_{-i} \in A_{-i}$,

$$u_i(a_{-i}, a_i) < u_i(a_{-i}, a_i^*).$$

We say that $a_i^*$ strictly dominates $a_i$.

If $a_i^* \in A_i$ strictly dominates every other strategy $a_i' \in A_i \setminus \{a_i^*\}$, we call $a_i^*$ strictly dominant in $G$.

**Remark:** Playing strictly dominated strategies is irrational.

Strictly Dominated Strategies

**Question:** What strategy should an agent avoid?

**One answer:**

- Eliminate all obviously irrational strategies.
- A strategy is obviously irrational if there is another strategy that is always better, no matter what the other players do.

This suggest a solution concept:

iterative elimination of strictly dominated strategies:

while some strictly dominated strategy is left:
    eliminate some strictly dominated strategy
if a unique strategy profile remains:
    this unique profile is the solution
### Strictly Dominated Strategies

#### Example (Iterative elimination of strictly dominated strategies for the prisoner’s dilemma)

<table>
<thead>
<tr>
<th></th>
<th>player 1</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>C</td>
<td>D</td>
</tr>
<tr>
<td>C</td>
<td>3,3</td>
<td>0,4</td>
</tr>
<tr>
<td>D</td>
<td>4,0</td>
<td>1,1</td>
</tr>
</tbody>
</table>

**Step 1:** eliminate row C (strictly dominated by row D)

**Step 2:** eliminate column C (strictly dominated by col. D)
Strictly Dominated Strategies

Example (Iterative elim. of strictly dominated strategies)

<table>
<thead>
<tr>
<th></th>
<th>player 1</th>
<th>player 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>M</td>
<td></td>
</tr>
<tr>
<td>T</td>
<td>1,2</td>
<td>2,1</td>
</tr>
<tr>
<td>B</td>
<td>0,0</td>
<td>1,1</td>
</tr>
</tbody>
</table>

Step 1: eliminate row B (strictly dominated by row M)
Step 2: eliminate column R (strictly dominated by col. L)
Strictly Dominated Strategies

Example (Iterative elimination of strictly dominated strategies)

<table>
<thead>
<tr>
<th>player 2</th>
<th>L</th>
<th>R</th>
</tr>
</thead>
<tbody>
<tr>
<td>T</td>
<td>2,1</td>
<td></td>
</tr>
</tbody>
</table>

- Step 1: eliminate row B (strictly dominated by row M)
- Step 2: eliminate column R (strictly dominated by col. L)
- Step 3: eliminate row M (strictly dominated by row T)

Remark
Strict dominance between actions is rather rare. We should identify more constraints on “solutions”, better solution concepts.

Proposition
The result of iterative elimination of strictly dominated strategies is unique, i.e., independent of the elimination order.

Proof.
Homework.
Weakly Dominated Strategies

Definition (Weakly dominated strategy)
Let $G = (N, (A_i)_{i \in N}, (u_i)_{i \in N})$ be a strategic game.
A strategy $a_i \in A_i$ is called weakly dominated in $G$ if there is a strategy $a_i^+ \in A_i$ such that for all profiles $a_{-i} \in A_{-i}$,
$$u_i(a_{-i}, a_i) \leq u_i(a_{-i}, a_i^+)$$
and that for at least one profile $a_{-i} \in A_{-i}$,
$$u_i(a_{-i}, a_i) < u_i(a_{-i}, a_i^+).$$
We say that $a_i^+$ weakly dominates $a_i$.
If $a_i^+ \in A_i$ weakly dominates every other strategy $a_i' \in A_i \setminus \{a_i^+\}$, we call $a_i^+$ weakly dominant in $G$.

Example (Iterative elim. of weakly dominated strategies)

Step 1: eliminate row $B$ (weakly dominated by row $M$),
$u_1(M, L) = 2 > 0 = u_1(B, L)$ and $u_1(M, R) = 1 = u_1(B, R)$

Here, two solution profiles remain.
Weakly Dominated Strategies

Example (Iterative elimination of weakly dominated strategies)

- Step 1: eliminate row $B$ (weakly dominated by row $M$), $u_1(M, L) = 2 > 0 = u_1(B, L)$ and $u_1(M, R) = 1 = u_1(B, R)$
- Step 2: eliminate column $R$ (weakly dominated by col. $L$)

Here, two solution profiles remain.

Iterative elimination of weakly dominated strategies:
- leads to smaller games,
- can also lead to situations where only a single solution remains,
- but: the result can depend on the elimination order! (see example on next slide)
Weakly Dominated Strategies

Example (Iterative elim. of weakly dominated strategies)

player 2

\[
\begin{array}{c|c|c}
 & R & \\hline
L & & \\
M & 2,1 & 1,1 \\
B & 0,0 & 1,1 \\
\end{array}
\]

player 1

- **Step 1**: eliminate row \( T \) (weakly dominated by row \( M \))
- **Step 2**: eliminate column \( L \) (weakly dominated by col. \( R \))

Different elimination order, different result, even different payoffs (1,1 vs. 2,1)!  

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We write for a strategy profile

Then a strategy

and

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\[ \mathbf{G} \]

Definition (Best response)

Perspective on Nash equilibria.

Remark: There is an alternative definition of Nash equilibria

One possible profitable deviation is shown (even if there are more).

Remark: In following examples, for non-Nash equilibria, only one possible profitable deviation is shown (even if there are more).

Summary

Games or Zero-Sum

Competitive

Strictly

Equilibria

Nash

Strategies

Dominated

and Notation

Concepts

Solution

Examples

Preliminaries

and

Explanation

Domination

Strategic

Elimination and Nash Equilibria

Strictly Competitive or Zero-Sum Games

Summary

Nash Equilibria

Possible answer:

Strategy profiles where no player benefits from playing a different strategy

Equivalently: Strategy profiles where every player’s strategy is a best response to the other players’ strategies

Such strategy profiles are called Nash equilibria, one of the most-used solution concepts in game theory.

Definition (Nash equilibrium, alternative 2)

A Nash equilibrium of a strategic game \( G = \langle N, (A_i)_{i \in N}, (u_i)_{i \in N} \rangle \) is a strategy profile \( a^* \in A \) such that for every player \( i \in N \),

\[ u_i(a^*) \geq u_i(a^*_{-i}, a_i) \quad \text{for all } a_i \in A_i. \]

Proposition

The three definitions of Nash equilibria are equivalent.

Proof.

Homework.

Homework.

Nash Equilibria

Possible answer:

\[ \mathbf{G} \]

Definition (Nash equilibrium, alternative 1)

A Nash equilibrium of a strategic game \( G = \langle N, (A_i)_{i \in N}, (u_i)_{i \in N} \rangle \) is a strategy profile \( a^* \in A \) such that for every player \( i \in N \),

\[ a_i^* \in B_i(a^*_{-i}). \]

Definition (Nash equilibrium, alternative 2)

A Nash equilibrium of a strategic game \( G = \langle N, (A_i)_{i \in N}, (u_i)_{i \in N} \rangle \) is a strategy profile \( a^* \in A \) such that \( a^* \in B(a^*). \)

Possible answer:

\[ \mathbf{G} \]

Remark: There is an alternative definition of Nash equilibria (which we consider because it gives us a slightly different perspective on Nash equilibria).

Definition (Best response)

Let \( G = \langle N, (A_i)_{i \in N}, (u_i)_{i \in N} \rangle \) be a strategic game, \( i \in N \) a player, and \( a_{-i} \in A_{-i} \) a strategy profile of the players other than \( i \).

Then a strategy \( a_i \in A_i \) is a best response of player \( i \) to \( a_{-i} \) if

\[ u_i(a_{-i}, a_i) \geq u_i(a_{-i}, a'_{i}) \quad \text{for all } a'_i \in A_i. \]

We write \( B_i(a_{-i}) \) for the set of best responses of player \( i \) to \( a_{-i} \).

For a strategy profile \( a \in A \), we write \( B(a) = \prod_{i \in N} B_i(a_{-i}) \).
### Preliminaries and Examples

#### Solution Concepts and Notation

- **Dominated Strategies**
- **Nash Equilibria**
  - Definitions and Examples
  - **Example:** Sealed-Bid Auctions
  - Iterative Elimination and Nash Equilibria

#### Strictly Competitive or Zero-Sum Games

#### Summary

### Nash Equilibria

#### Example (Nash Equilibria in the Prisoner’s Dilemma)

<table>
<thead>
<tr>
<th></th>
<th>player 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>C</td>
</tr>
<tr>
<td>player 1</td>
<td>3,3</td>
</tr>
<tr>
<td>D</td>
<td>4,0</td>
</tr>
</tbody>
</table>

- \((C, C)\): No Nash equilibrium (player 1: \(C \rightarrow D\))
- \((C, D)\): No Nash equilibrium (player 1: \(C \rightarrow D\))
- \((D, C)\): No Nash equilibrium (player 2: \(C \rightarrow D\))
- \((D, D)\): Nash equilibrium!

#### Example (Nash Equilibria in Hawk and Dove)

<table>
<thead>
<tr>
<th></th>
<th>player 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>D</td>
</tr>
<tr>
<td>player 1</td>
<td>3,3</td>
</tr>
<tr>
<td>H</td>
<td>4,1</td>
</tr>
</tbody>
</table>

- \((D, D)\): No Nash equilibrium (player 1: \(D \rightarrow H\))
- \((D, H)\): Nash equilibrium!
- \((H, D)\): Nash equilibrium!
- \((H, H)\): No Nash equilibrium (player 1: \(H \rightarrow D\))

#### Example (Nash Equilibria in Matching Pennies)

<table>
<thead>
<tr>
<th></th>
<th>player 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>H</td>
</tr>
<tr>
<td>player 1</td>
<td>1,−1</td>
</tr>
<tr>
<td>T</td>
<td>−1, 1</td>
</tr>
</tbody>
</table>

- \((H, H)\): No Nash equilibrium (player 2: \(H \rightarrow T\))
- \((H, T)\): No Nash equilibrium (player 1: \(H \rightarrow T\))
- \((T, H)\): No Nash equilibrium (player 1: \(T \rightarrow H\))
- \((T, T)\): No Nash equilibrium (player 2: \(T \rightarrow H\))

#### Example (Nash Equilibria in Bach or Stravinsky)

<table>
<thead>
<tr>
<th></th>
<th>Stravinsky enthusiast</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>B</td>
</tr>
<tr>
<td>Bach enthusiast</td>
<td>2,1</td>
</tr>
<tr>
<td>S</td>
<td>0,0</td>
</tr>
</tbody>
</table>

- \((B, B)\): Nash equilibrium!
- \((B, S)\): No Nash equilibrium (player 1: \(B \rightarrow S\))
- \((S, B)\): No Nash equilibrium (player 2: \(S \rightarrow B\))
- \((S, S)\): Nash equilibrium!
Example: Sealed-Bid Auctions

We consider a slightly larger example: sealed-bid auctions

**Setting:**
- An object has to be assigned to a winning bidder in exchange for a payment.
- For each player (“bidder”) \( i = 1, \ldots, n \), let \( v_i \) be the private value that bidder \( i \) assigns to the object. (We assume that \( v_1 > v_2 > \cdots > v_n > 0 \).)
- The bidders simultaneously give their bids \( b_i \geq 0 \), \( i = 1, \ldots, n \).
- The object is given to the bidder \( i \) with the highest bid \( b_i \).
  (Ties are broken in favor of bidders with lower index, i.e., if \( b_i = b_j \) are the highest bids, then bidder \( i \) will win iff \( i < j \).)

**Example (First-price sealed-bid auction)**

Assume three bidders 1, 2, and 3, with valuations and bids

- \( v_1 = 100 \), \( b_1 = 90 \)
- \( v_2 = 80 \), \( b_2 = 85 \)
- \( v_3 = 53 \), \( b_3 = 45 \).

**Observations:**
- Bidder 1 wins, pays 90, gets utility
  \( u_1(b) = v_1 - b_1 = 100 - 90 = 10 \).
- Bidders 2 and 3 pay nothing, get utility 0.
- (Bidder 2 over-bids.)
- Bidder 1 could still win, but pay less, by bidding \( b_1' = 85 \) instead. Then \( u_1 (b_1, b_1') = v_1 - b_1' = 100 - 85 = 15 \).

**Example: Sealed-Bid Auctions**

**Question:** What should the winning bidder have to pay?

One possible answer: The highest bid.

**Definition (First-price sealed-bid auction)**

\[ N = \{1, \ldots, n\} \text{ with } v_1 > v_2 > \cdots > v_n > 0, \]
\[ A_i = \mathbb{R}_0^+ \text{ for all } i \in N, \]
\[ \text{Bidder } i \in N \text{ wins if } b_i \text{ is maximal among all bids } \]
\[ (+ \text{ possible tie-breaking by index}), \text{ and } \]
\[ u_i(b) = \begin{cases} 0 & \text{if player } i \text{ does not win} \\ v_i - b_i & \text{otherwise} \end{cases} \]

where \( b = (b_1, \ldots, b_n) \).

**Example: Sealed-Bid Auctions**

**Question:** How to avoid untruthful bidding and incentivize truthful revelation of private valuations?

Different answer to question about payments: Winner pays the second-highest bid.

**Definition (Second-price sealed-bid auction)**

\[ N = \{1, \ldots, n\} \text{ with } v_1 > v_2 > \cdots > v_n > 0, \]
\[ A_i = \mathbb{R}_0^+ \text{ for all } i \in N, \]
\[ \text{Bidder } i \in N \text{ wins if } b_i \text{ is maximal among all bids } \]
\[ (+ \text{ possible tie-breaking by index}), \text{ and } \]
\[ u_i(b) = \begin{cases} 0 & \text{if player } i \text{ does not win} \\ v_i - \max b_{-i} & \text{otherwise} \end{cases} \]

where \( b = (b_1, \ldots, b_n) \).
Example: Sealed-Bid Auctions

Example (Second-price sealed-bid auction)
Assume three bidders 1, 2, and 3, with valuations and bids

\[
\begin{align*}
v_1 &= 100, & v_2 &= 80, & v_3 &= 53, \\
b_1 &= 90, & b_2 &= 85, & b_3 &= 45.
\end{align*}
\]

Observations:
- Bidder 1 wins, pays 85, gets utility
  \[u_1(b) = v_1 - b = 100 - 85 = 15.\]
- Bidders 2 and 3 pay nothing, get utility 0.
- Bidder 1 has no incentive to bid strategically and guess the other bidders' private valuations.

Proof (ctd.)
Ad (1) [regardless of what the other bidders do, \(b_1^*\) is always a best response]:
- Case I) bidder 1 wins:
  bidder 1 pays \(\max b_{-1} \leq v_1\), gets \(u_1(b_{-1}, b_1^*) \geq 0\).
- Case I.a) bidder 1 decreases bid:
  this does not help, since he might still win and pay the same as before, or lose and get utility 0.
- Case I.b) bidder 1 increases bid:
  bidder 1 still wins and pays the same as before.

Proof (ctd.)
Ad (1) (ctd.):
- Case II) bidder 1 loses:
  bidder 1 pays nothing, gets \(u_1(b_{-1}, b_1^*) = 0\).
- Case II.a) bidder 1 decreases bid:
  bidder 1 still loses and gets utility 0.
- Case II.b) bidder 1 increases bid:
  either bidder 1 still loses and gets utility 0, or becomes the winner and pays more than the object is worth to him, leading to a negative utility.
Example: Sealed-Bid Auctions

Proof (ctd.)
Ad (2) [for each alternative $b_i$ to $b_i^*$, there is an opponent profile $b_{-i}$ against which $b_i^*$ is strictly better than $b_i$]:

Let $b_i$ be some strategy other than $b_i^*$:

- Case I) $b_i < b_i^*$:
  Consider $b_{-i}$ with $b_i < \max b_{-i} < b_i^*$. With $b_i$, bidder $i$ does not win any more, i.e., we have $u_i(b_{-i}, b_i^*) > 0 = u_i(b_{-i}, b_i)$.

- Case II) $b_i > b_i^*$:
  Consider $b_{-i}$ with $b_i > \max b_{-i} > b_i^*$. With $b_i$, bidder $i$ overbids and pays more than the object is worth to him, i.e., we have $u_i(b_{-i}, b_i) = 0 > u_i(b_{-i}, b_i^*)$.

Iterative Elimination and Nash Equilibria

Motivation: We have seen two different solution concepts,
- surviving iterative elimination of (strictly) dominated strategies and
- Nash equilibria.

Obvious question: Is there any relationship between the two?

Answer: Yes, Nash equilibria refine the concept of iterative elimination of strictly dominated strategies. We will formalize this on the next slides.

Iterative Elimination and Nash Equilibria

Lemma (preservation of Nash equilibria)
Let $G$ and $G'$ be two strategic games where $G'$ is obtained from $G$ by elimination of one strictly dominated strategy. Then a strategy profile $a^*$ is a Nash equilibrium of $G$ if and only if it is Nash equilibrium of $G'$.

Proof.
Let $G = \langle N, (A_i)_{i\in N}, (u_i)_{i\in N} \rangle$ and $G' = \langle N, (A'_i)_{i\in N}, (u'_i)_{i\in N} \rangle$. Let $a_i'$ be the eliminated strategy. Then there is a strategy $a_i^*$ such that for all $a_{-i} \in A_{-i}$,

$$u_i(a_{-i}, a_i^*) < u_i(a_{-i}, a_i').$$

(1)
Iterative Elimination and Nash Equilibria

Proof (ctd.)

“⇒” Let $a^*$ be a Nash equilibrium of $G$.

- Nash equilibrium strategies are not eliminated: For players $j \neq i$, this is clear, because none of their strategies are eliminated.

For player $i$, action $a^*_i$ is a best response to $a^*_{-i}$, and in particular at least as good a response as $a_i^*$:

$$u_i(a^*_{-i}, a^*_i) \geq u_i(a^*_{-i}, a_i^*).$$

With (1) $u_i(a_{-i}, a^*_i) > u_i(a_{-i}, a_i^*)$, we get $u_i(a^*_i, a^*_i) > u_i(a^*_i, a_i^*)$ and hence $a^*_i \neq a_i^*$. Thus, the Nash equilibrium strategy $a_i^*$ is not eliminated.

Proof (ctd.)

“⇐” Let $a^*$ be a Nash equilibrium of $G$.

- Best responses remain best responses: For all players $j \in N$, $a_j^*$ is a best response to $a^*_{-j}$ in $G$. Since in $G'$, no potentially better responses are introduced ($A'_j \subseteq A_j$) and the payoffs are unchanged, this also holds in $G'$.

Hence, $a^*$ is also a Nash equilibrium of $G'$.

Iterative Elimination and Nash Equilibria

Corollary

If iterative elimination of strictly dominated strategies results in a unique strategy profile $a^*$, then $a^*$ is the unique Nash equilibrium of the original game.

Proof.

Assume that $a^*$ is the unique remaining strategy profile. By definition, $a^*$ must be a Nash equilibrium of the remaining game.

We can inductively apply the previous lemma (preservation of Nash equilibria) and see that $a^*$ (an no other strategy profile) must have been a Nash equilibrium before the last elimination step, and before that step, ..., and in the original game.
5 Strictly Competitive or Zero-Sum Games

Zero-Sum Games

Definition (Zero-sum game)
A strictly competitive game or zero-sum game is a strategic game $G = \langle N, (A_i)_{i \in N}, (u_i)_{i \in N} \rangle$ with $N = \{1, 2\}$ and for all $a \in A$:

$$u_1(a) = -u_2(a).$$

Example (Matching Pennies as a zero-sum game)

<table>
<thead>
<tr>
<th></th>
<th>player 1</th>
<th>player 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H$</td>
<td>1, -1</td>
<td>-1, 1</td>
</tr>
<tr>
<td>$T$</td>
<td>-1, 1</td>
<td>1, -1</td>
</tr>
</tbody>
</table>

Note: Any constant-sum game can be transformed into a zero-sum game with the same set of Nash equilibria.

Playing it Safe (in Two-Player Games)

Motivation: What happens if both players try to “play it safe”?

Question: What does it even mean to “play it safe”?

Answer: Choose a strategy that guarantees the highest worst-case payoff.

Example

<table>
<thead>
<tr>
<th></th>
<th>player 2</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$T$</td>
<td>2, 20</td>
<td></td>
</tr>
<tr>
<td>$M$</td>
<td>3, 0</td>
<td>-10, 1</td>
</tr>
<tr>
<td>$B$</td>
<td>-100, 2</td>
<td>3, 3</td>
</tr>
</tbody>
</table>

Worst-case payoff for player 1:
- if playing $T$: 2
- if playing $M$: -10
- if playing $B$: -100
  $\Rightarrow$ play $T$.

Worst-case payoff for player 2:
- if playing $L$: 0
- if playing $R$: -20
  $\Rightarrow$ play $L$.

However: Unlike $(B, R)$, the profile $(T, L)$ is not a Nash equilibrium.
Playing it Safe (in Two-Player Games)

Example

<table>
<thead>
<tr>
<th>player 1</th>
<th>player 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>L</td>
</tr>
<tr>
<td>T</td>
<td>2, 1</td>
</tr>
<tr>
<td>M</td>
<td>3, 0</td>
</tr>
<tr>
<td>B</td>
<td>−100, 2</td>
</tr>
</tbody>
</table>

Worst-case payoff for player 1:
- if playing T: 2
- if playing M: −10
- if playing B: −100
← play T.

Worst-case payoff for player 2:
- if playing L: 0
- if playing R: −20
- if playing B: −100
← play L.

However: Unlike (B, R), the profile (T, L) is not a Nash equilibrium.

Observation: In general, pairs of maximinimizers, like (T, L) in the example above, are not the same as Nash equilibria.

Claim: However, in zero-sum games, pairs of maximinimizers and Nash equilibria are essentially the same.

(Tiny restriction: This does not hold if the considered game has no Nash equilibrium at all, i.e., there might exist pairs of maximinimizers which are not Nash equilibrium strategies.)

Reason (intuitively): In zero-sum games, the worst-case assumption that the other player tries to harm you as much as possible is justified, because harming the other is the same as maximizing ones own payoff. Playing it safe is rational.

Maximinimizers

Definition (Maximinimizer)

Let \( G = (\{1, 2\}, (A_i)_{i \in \mathbb{N}}, (u_i)_{i \in \mathbb{N}}) \) be a zero-sum game.

An action \( x^* \in A_1 \) is called maximinimizer for player 1 in \( G \) if
\[
\min_{y \in A_2} u_1(x^*, y) \geq \min_{y \in A_2} u_1(x, y) \quad \text{for all } x \in A_1,
\]
and \( y^* \in A_2 \) is called maximinimizer for player 2 in \( G \) if
\[
\min_{x \in A_1} u_2(x, y^*) \geq \min_{x \in A_1} u_2(x, y) \quad \text{for all } y \in A_2.
\]
Maximinimizers

Example (Zero-sum game with three actions each)

\[
\begin{array}{ccc}
\text{player 1} & \text{player 2} \\
T & L & 8, -8 \\
M & C & 2, -2 \\
B & R & -6, 6 \\
\end{array}
\]

Guaranteed worst-case payoffs:
- \(T: -6, M: -1, B: -6 \Rightarrow \text{maximinimizer } M\)
- \(L: -8, C: -4, R: -8 \Rightarrow \text{maximinimizer } C\)
- Pair of maximinimizers \((M, C)\) with payoffs \((-1, 1)\)
  (not a Nash equilibrium; this game has no Nash equilibrium.)

Maximinimizers

Lemma

Let \(G = (\{1, 2\}, (A_i)_{i \in N}, (u_i)_{i \in N})\) be a zero-sum game. Then

\[
\max_y \min_x u_2(x, y) = -\min_x \max_y u_1(x, y). \quad (2)
\]

Proof.

For any real-valued function \(f\), we have

\[
\min_z -f(z) = -\max_z f(z). \quad (3)
\]

Maximinimizers

Example (Maximinimization vs. minimaximization)

\[
\begin{array}{ccc}
\text{player 1} & \text{player 2} \\
T & L & 1, -1 \\
M & C & 2, -2 \\
B & R & -2, 2 \\
\end{array}
\]

Worst-case payoffs (player 2):
- \(L: -1, R: -2\)

Best-case payoffs (player 1):
- \(L: +1, R: +2\)

Maximize: \(-1\)

Minimize: \(+1\)

Observation: Results identical up to different sign.
Proof.

Let \((x^*, y^*)\) be a Nash equilibrium. Then
\[
    u_2(x^*, y^*) \geq u_2(x^*, y) \quad \text{for all } y \in A_2.
\]

With \(u_1 = -u_2\), this implies
\[
    u_1(x^*, y^*) \leq u_1(x^*, y) \quad \text{for all } y \in A_2.
\]

Thus
\[
    u_1(x^*, y^*) = \min_{y \in A_2} u_1(x^*, y) \leq \max_{x \in A_1} \min_{y \in A_2} u_1(x, y). \tag{4}
\]

Furthermore, since \((x^*, y^*)\) is a Nash equilibrium, also
\[
    u_1(x^*, y^*) \geq u_1(x, y^*) \quad \text{for all } x \in A_1.
\]

Hence
\[
    u_1(x^*, y^*) \geq \max_{x \in A_1} u_1(x, y^*). \tag{5}
\]

This implies
\[
    u_1(x^*, y^*) \geq \max_{x \in A_1} \min_{y \in A_2} u_1(x, y). \tag{5}
\]
Nash Equilibria in Zero-Sum Games

Proof (ctd.)

Let $x^*$ and $y^*$ be minimaximizers for player 1 and 2, respectively, and assume that

$$\max_{x \in A_1} \min_{y \in A_2} u_1(x, y) = \min_{y \in A_2} \max_{x \in A_1} u_1(x, y) =: v^*. \tag{8}$$

With Equation (2) from the previous lemma, we get

$$\min_{y \in A_2} \max_{x \in A_1} u_2(x, y) = -v^*. \tag{9}$$

With $x^*$ and $y^*$ being maximinimizers, (8) and (9) imply

$$u_1(x^*, y) \geq v^* \text{ for all } y \in A_2, \text{ and } \tag{10}$$

$$u_2(x, y^*) \geq -v^* \text{ for all } x \in A_1. \tag{11}$$

Thus, $x^*$ is a maximinimizer for player 1.

Similarly, we can show that $y^*$ is a maximinimizer for player 2.

In particular, it follows that all Nash equilibria share the same payoff profile.

Proof (ctd.)

We only need to put things together:

$$\max_{x \in A_1} \min_{y \in A_2} u_1(x, y) = \min_{y \in A_2} \max_{x \in A_1} u_1(x, y) =: v^*. \tag{6}$$

$$\max_{x \in A_1} \min_{y \in A_2} u_1(x, y) = \max_{x \in A_1} \min_{y \in A_2} u_1(x, y) =: u_1(x^*, y^*). \tag{7}$$

With Equation (2) from the previous lemma, we get

$$\min_{y \in A_2} \max_{x \in A_1} u_2(x, y) = -v^*. \tag{9}$$

With $x^*$ and $y^*$ being maximinimizers, (8) and (9) imply

$$u_1(x^*, y) \geq v^* \text{ for all } y \in A_2, \text{ and } \tag{10}$$

$$u_2(x, y^*) \geq -v^* \text{ for all } x \in A_1. \tag{11}$$

Thus, $x^*$ is a maximinimizer for player 1.

Similarly, we can show that $y^*$ is a maximinimizer for player 2.

In particular, it follows that all Nash equilibria share the same payoff profile.
Nash Equilibria in Zero-Sum Games

Proof (ctd.)
Let $G = \langle \{1, 2\}, (A_i)_{i \in \mathbb{N}}, (u_i)_{i \in \mathbb{N}} \rangle$ be a zero-sum game, and let $(x_1^*, y_1^*)$ and $(x_2^*, y_2^*)$ be two Nash equilibria of $G$.

Then $(x_1^*, y_2^*)$ and $(x_2^*, y_1^*)$ are also Nash equilibria of $G$.

In other words: Nash equilibria of zero-sum games can be arbitrarily recombined.

Proof.
With part (1) of the maximinimizer theorem, we get that $x_1^*$ and $x_2^*$ are maximinimizers for player 1 and that $y_1^*$ and $y_2^*$ are maximinimizers for player 2.

With part (2) of the maximinimizer theorem, we get that $\max_{x \in A_1} \min_{y \in A_2} u_1(x, y) = \min_{y \in A_2} \max_{x \in A_1} u_1(x, y)$.

With this equality, with $x_1^*$, $x_2^*$, $y_1^*$, and $y_2^*$ all being maximinimizers, and with part (3) of the maximinimizer theorem, we get that $(x_1^*, y_2^*)$ and $(x_2^*, y_1^*)$ are also Nash equilibria of $G$. 

Corollary
Let $G = \langle \{1, 2\}, (A_i)_{i \in \mathbb{N}}, (u_i)_{i \in \mathbb{N}} \rangle$ be a zero-sum game, and let $(x_1^*, y_1^*)$ and $(x_2^*, y_2^*)$ be two Nash equilibria of $G$.

Then $(x_1^*, y_2^*)$ and $(x_2^*, y_1^*)$ are also Nash equilibria of $G$.

In other words: Nash equilibria of zero-sum games can be arbitrarily recombined.
Summary

- **Strategic games** are one-shot games of finitely many players with given action sets and payoff functions. Players have perfect information.
- **Solution concepts**: survival of iterative elimination of strictly dominated strategies, Nash equilibria.
- **Relation between solution concepts**: Nash equilibria always survive iterative elimination of strictly dominated strategies.
- In **zero-sum games**, one player's gain is the other player's loss. Thus, playing it safe is rational. Relevant concept: maximinimizers.
- **Relation to Nash equilibria**: In zero-sum games, Nash equilibria are pairs of maximinimizers, and, if at least one Nash equilibrium exists, pairs of maximinimizers are also Nash equilibria.