Motivation

- **So far:** All players move simultaneously, and then the outcome is determined.
- **Often in practice:** Several moves in sequence (e.g., in chess).
 Cannot be directly reflected by strategic games.
- **Extensive games** (with perfect information) reflect such situations by modeling games as **game trees**.
- **Idea:** Players have several decision points where they can decide how to play.
- **Strategies:** Mappings from decision points in the game tree to actions to be played.
Definition (Extensive game with perfect information)

An extensive game with perfect information is a tuple $\Gamma = (N, H, P, (u_i)_{i \in N})$ that consists of:

- A finite non-empty set $N$ of players.
- A set $H$ of (finite or infinite) sequences, called histories, such that
  - the empty sequence $\langle \rangle \in H$.
  - $H$ is closed under prefixes: if $\langle a^1, \ldots, a^k \rangle \in H$ for some $k \in \mathbb{N} \cup \{\infty\}$, and $l < k$, then also $\langle a^1, \ldots, a^l \rangle \in H$, and
  - $H$ is closed under limits: if for some infinite sequence $\langle a^i \rangle_{i=1}^\infty$, we have $\langle a^i \rangle_{i=1}^k \in H$ for all $k \in \mathbb{N}$, then $\langle a^i \rangle_{i=1}^\infty \in H$.

All infinite histories and all histories $\langle a^i \rangle_{i=1}^k \in H$, for which there is no $a^{i+1}$ such that $\langle a^i \rangle_{i=1}^k \in H$ are called terminal histories $Z$. Components of a history are called actions.

Example (Division game)

- Two identical objects should be divided among two players.
- Player 1 proposes an allocation.
- Player 2 agrees or rejects.
  - On agreement: Allocation as proposed.
  - On rejection: Nobody gets anything.

Example (Division game, formally)

- $N = \{1, 2\}$
- $H = \{\langle \rangle, \langle (2, 0) \rangle, \langle (1, 1) \rangle, \langle (0, 0) \rangle, \langle (0, 2) \rangle, \langle (2, 0), n \rangle, \langle (2, 0), y \rangle, \langle (2, 0), y' \rangle, \ldots\}$
- $P(\langle \rangle) = 1, P(h) = 2$ for all $h \in H \setminus Z$ with $h \neq \langle \rangle$
- $u_1(\langle (2, 0), y \rangle) = 2, u_2(\langle (2, 0), y \rangle) = 0$, etc.
Notation:
Let \( h = (a^1, \ldots, a^k) \) be a history, and \( a \) an action.

- Then \((h, a)\) is the history \( (a^1, \ldots, a^k, a)\).
- If \( h' = (b^1, \ldots, b^\ell) \), then \((h, h')\) is the history \( (a^1, \ldots, a^k, b^1, \ldots, b^\ell)\).
- The set of actions from which player \( P(h) \) can choose after a history \( h \in H \setminus Z \) is written as
  \[ A(h) = \{ a \mid (h, a) \in H \}. \]

Strategies

Definition (Strategy in an extensive game)
A strategy of a player \( i \) in an extensive game \( \Gamma = (N, H, P, (u_i)_{i \in N}) \) is a function \( s_i \) that assigns to each nonterminal history \( h \in H \setminus Z \) with \( P(h) = i \) an action \( a \in A(h) \). The set of strategies of player \( i \) is denoted as \( S_i \).

Remark: Strategies require us to assign actions to histories \( h \), even if it is clear that they will never be played (e.g., because \( h \) will never be reached because of some earlier action).

Notation (for finite games): A strategy for a player is written as a string of actions at decision nodes as visited in a breadth-first order.

Example (Strategies in an extensive game)

Strategies for player 1: \( AE, AF, BE \) and \( BF \)
Strategies for player 2: \( C \) and \( D \).

Outcome

Definition (Outcome)
The outcome \( O(s) \) of a strategy profile \( s = (s_i)_{i \in N} \) is the (possibly infinite) terminal history \( h = (a^i_\ell)_{i = 1}^k \), with \( k \in \mathbb{N} \cup \{\infty\} \), such that for all \( \ell \in \mathbb{N} \) with \( 0 \leq \ell < k \),
\[ s_{P((a^1_1, \ldots, a^i_\ell))}(a^1_1, \ldots, a^i_\ell) = a^i_{\ell+1}. \]

Example (Outcome)
\[ O(AF, C) = (A, C, F) \]
\[ O(AE, D) = (A, D). \]
Definition (Nash equilibrium in an extensive game)
A Nash equilibrium in an extensive game \( \Gamma = \langle N, H, P, (u_i)_{i \in N} \rangle \) is a strategy profile \( s^* \) such that for every player \( i \in N \) and for all strategies \( s_i \in S_i \),
\[
    u_i(O(s^*_{-i}, s_i)) \geq u_i(O(s^*_{-i}, s))
\]
**Empty Threats**

**Example (Empty threat)**

**Extensive game:**

![Extensive Game Diagram](image)

**Strategic form:**

<table>
<thead>
<tr>
<th></th>
<th>L</th>
<th>R</th>
</tr>
</thead>
<tbody>
<tr>
<td>T</td>
<td>0.0</td>
<td>2.1</td>
</tr>
<tr>
<td>B</td>
<td>1.2</td>
<td>1.2</td>
</tr>
</tbody>
</table>

**Nash equilibria:** \((B,L)\) and \((T,R)\).

However, \((B,L)\) is not realistic:

- Player 1 plays \(B\), “fearing” response \(L\) to \(T\).
- But player 2 would never play \(L\) in the extensive game.

\(~\) \((B,L)\) involves “empty threat”.

**Subgames**

**Definition (Subgame)**

A **subgame** of an extensive game \(\Gamma = \langle N,H,P,\{(u_i)_{i\in N}\}\rangle\), starting after history \(h\), is the game \(\Gamma(h) = \langle H|_h,P|_h,(u|_h)_{i\in N}\rangle\), where

- \(H|_h = \{h'| (h,h') \in H\}\),
- \(P|_h(h') = P(h,h')\) for all \(h' \in H|_h\), and
- \(u_i|_h(h') = u_i(h,h')\) for all \(h' \in H|_h\).

**Subgame-Perfect Equilibria**

**Definition (Subgame-perfect equilibrium)**

A strategy profile \(s^*\) in an extensive game \(\Gamma = \langle N,H,P,\{(u_i)_{i\in N}\}\rangle\) is a **subgame-perfect equilibrium** if and only if for every player \(i \in N\) and every nonterminal history \(h \in H \setminus \{H\}\) with \(P(h) = i\),

\[
u_i|_h(O_i(s^*|_h,s^*|_h)) \geq u_i|_h(O_i(s^*|_h,s_i))
\]

for every strategy \(s_i \in S_i\) in subgame \(\Gamma(h)\).
Two Nash equilibria:
- \((T, R)\): subgame-perfect, because:
  - In history \(h = \langle T \rangle\): subgame-perfect.
  - In history \(h = \langle \rangle\): player 1 obtains utility 1 when choosing \(B\) and utility of 2 when choosing \(T\).
- \((B, L)\): not subgame-perfect, since \(L\) does not maximize the utility of player 2 in history \(h = \langle T \rangle\).

Nash equilibria (red: empty threat):
- \(((2,0), yyy)\), \(((2,0), yyn)\), \(((2,0), yny)\), \(((2,0), ynn)\), \(((2,0), nny)\), \(((2,0), nnn)\),
- \(((1,1), nyy)\), \(((1,1), nyn)\),
- \(((0,2), nny)\), \(((0,2), nnn)\).
Step 1: One-Deviation Property

Definition (One-deviation property)
A strategy profile \( s^* \) in an extensive game \( \Gamma = \langle N, H, P, (u_i)_{i \in N} \rangle \) satisfies the one-deviation property if and only if for every player \( i \in N \) and every nonterminal history \( h \in H \setminus Z \) with \( P(h) = i \),

\[
    u_i|_h(O_h(s^*|_h, s^*_i|h)) \geq u_i|_h(O_h(s^*|_h, s_i))
\]

for every strategy \( s_i \in S_i \) in subgame \( \Gamma(h) \) that differs from \( s^*_i|h \) only in the action it prescribes after the initial history of \( \Gamma(h) \).

Note: Without the highlighted parts, this is just the definition of subgame-perfect equilibria!

Lemma
Let \( \Gamma = \langle N, H, P, (u_i)_{i \in N} \rangle \) be a finite-horizon extensive game. Then a strategy profile \( s^* \) is a subgame-perfect equilibrium of \( \Gamma \) if and only if it satisfies the one-deviation property.

Proof
\( \Rightarrow \) Clear.
\( \Leftarrow \) By contradiction:
Suppose that \( s^* \) is not a subgame-perfect equilibrium. Then there is a history \( h \) and a player \( i \) such that \( s_i \) is a profitable deviation for player \( i \) in subgame \( \Gamma(h) \).

...
Step 1: One-Deviation Property

Proof (ctd.)

(⇐) ... WLOG, the number of histories $h'$ with $s_i(h') \neq s_i^*|_{h(h')}$ is at most $i(\Gamma(h))$ and hence finite (finite horizon assumption!), since deviations not on resulting outcome path are irrelevant.

Illustration: strategies $s_i^*|_h = AGILN$ and $s_i^*|_h = CF$ red:

Then only $B$ and $O$ really matter.

Proof (ctd.)

(⇐) ... Illustration for WLOG assumption: Assume $s_1 = BHKMO$ (blue) profitable deviation:

Choose profitable deviation $s_i$ in $\Gamma(h)$ with minimal number of deviation points (such $s_i$ must exist).

Let $h^*$ be the longest history in $\Gamma(h)$ with $s_i(h^*) \neq s_i^*|_{h(h^*)}$, i.e., “deepest” deviation point for $s_i$.

Then in $\Gamma(h, h^*)$, $s_i|_{h^*}$ differs from $s_i^*|_{(h, h^*)}$ only in the initial history.

Moreover, $s_i|_{h^*}$ is a profitable deviation in $\Gamma(h, h^*)$, since $h^*$ is the longest history in $\Gamma(h)$ with $s_i(h^*) \neq s_i^*|_{h(h^*)}$.

So, $\Gamma(h, h^*)$ is the desired subgame where a one-step deviation is sufficient to improve utility.
Step 1: One-Deviation Property

Example

To show that \( (AHI, CE) \) is a subgame-perfect equilibrium, it suffices to check these deviating strategies:

**Player 1:**
- \( G \) in subgame \( \Gamma(\langle A, C \rangle) \)
- \( K \) in subgame \( \Gamma(\langle B, F \rangle) \)
- \( BHI \) in \( \Gamma \)

**Player 2:**
- \( D \) in subgame \( \Gamma(\langle A \rangle) \)
- \( F \) in subgame \( \Gamma(\langle B \rangle) \)

In particular, e.g., no need to check if strategy \( BGK \) of player 1 is profitable in \( \Gamma \).

Step 2: Kuhn’s Theorem

Theorem (Kuhn)

Every finite extensive game has a subgame-perfect equilibrium.

Proof idea:
- Proof is constructive and builds a subgame-perfect equilibrium bottom-up (aka backward induction).
- For those familiar with the Foundations of AI lecture: generalization of Minimax algorithm to general-sum games with possibly more than two players.
Step 2: Kuhn’s Theorem

Proof (ctd.)

Inductive case: If \( t_i(h) \) already defined for all \( h \in H \) with \( \ell(\Gamma(h)) \leq k \), consider \( h^* \in H \) with \( \ell(\Gamma(h^*)) = k + 1 \) and \( P(h^*) = i \).

For all \( a \in A(h^*) \), \( \ell(\Gamma(h^*, a)) \leq k \), let

\[
\begin{align*}
    s_i(h^*) := \text{argmax}_{a \in A(h^*)} t_i(h^*, a) \\
    t_j(h^*) := t_j(h^*, s_i(h^*)) \quad \text{for all players } j \in N.
\end{align*}
\]

Inductively, we obtain a strategy profile \( s \) that satisfies the one-deviation property.

With the one-deviation property lemma it follows that \( s \) is a subgame-perfect equilibrium.

In practice: sample subgame-perfect equilibrium effectively computable using the technique from the above proof.

In practice: often game trees not enumerated in advance, hence unavailable for backward induction.

E.g., for branching factor \( b \) and depth \( m \), procedure needs time \( O(b^m) \).
Step 2: Kuhn’s Theorem
Remark on Infinite Games

Corresponding proposition for infinite games does not hold.

Counterexamples (both for one-player case):

A) finite horizon, infinite branching factor:
Infinitely many actions \( a \in A = [0, 1) \) with payoffs \( u_1(\langle a \rangle) = a \) for all \( a \in A \).
There exists no subgame-perfect equilibrium in this game.

B) infinite horizon, finite branching factor:

Uniqueness:
Kuhn's theorem tells us nothing about uniqueness of subgame-perfect equilibria. However, if no two histories get the same evaluation by any player, then the subgame-perfect equilibrium is unique.

Extended Example: Pirate Game

1. There are 5 rational pirates, \( A, B, C, D \) and \( E \). They find 100 gold coins. They must decide how to distribute them.
2. The pirates have a strict order of seniority: \( A \) is senior to \( B \), who is senior to \( C \), who is senior to \( D \), who is senior to \( E \).
3. The pirate world’s rules of distribution say that the most senior pirate first proposes a distribution of coins. The pirates, including the proposer, then vote on whether to accept this distribution (in order from most junior to senior). In case of a tie vote, the proposer has the casting vote. If the distribution is accepted, the coins are disbursed and the game ends. If not, the proposer is thrown overboard from the pirate ship and dies, and the next most senior pirate makes a new proposal to apply the method again.
The pirates do not trust each other, and will neither make nor honor any promises between pirates apart from a proposed distribution plan that gives a whole number of gold coins to each pirate.

Pirates base their decisions on three factors. First of all, each pirate wants to survive. Second, everything being equal, each pirate wants to maximize the number of gold coins each receives. Third, each pirate would prefer to throw another overboard, if all other results would otherwise be equal.

Players \( N = \{A, B, C, D, E\} \);
actions are:
- proposals by a pirate: \( \langle A : x_A, B : x_B, C : x_C, D : x_D, E : x_E \rangle \), with \( \sum_{i \in \{A, B, C, D, E\}} x_i = 100 \);
- votings: \( y \) for accepting, \( n \) for rejecting;
histories are sequences of a proposal, followed by votings of the alive pirates;
utilities:
- for pirates who are alive: utilities are according to the accepted proposal plus \( x/100 \), \( x \) being the number of dead pirates;
- for dead pirates: -100.

Remark: Very large game tree!

Assume only \( D \) and \( E \) are still alive. \( D \) can propose \( \langle A : 0, B : 0, C : 0, D : 100, E : 0 \rangle \), because \( D \) has the casting vote!

Assume \( C, D, \) and \( E \) are alive. For \( C \) it is enough to offer 1 coin to \( E \) to get his vote: \( \langle A : 0, B : 0, C : 99, D : 0, E : 1 \rangle \).

Assume \( B, C, D, \) and \( E \) are alive. \( B \) offering \( D \) one coin is enough because of the casting vote:
\( \langle A : 0, B : 99, C : 0, D : 1, E : 0 \rangle \).

Assume \( A, B, C, D, \) and \( E \) are alive. \( A \) offering \( C \) and \( E \) each one coin is enough: \( \langle A : 98, B : 0, C : 1, D : 0, E : 1 \rangle \) (note that giving 1 to \( D \) instead to \( E \) does not help).
Simultaneous Moves

Definition

An extensive game with simultaneous moves is a tuple \( \Gamma = (N, H, P, (u_i)_{i \in N}) \), where
- \( N \), \( H \), \( P \) and \((u_i)_{i \in N} \) are defined as before, and
- \( P : H \rightarrow 2^N \) assigns to each nonterminal history a set of players to move; for all \( h \in H \setminus Z \), there exists a family \( (A_i(h))_{i \in P(h)} \) such that
\[
A(h) = \{ a \mid (h, a) \in H \} = \prod_{i \in P(h)} A_i(h).
\]

Simultaneous Moves

Example: Three-Person Cake Splitting Game

Setting:
- Three players have to split a cake fairly.
- Player 1 suggest split: shares \( x_1, x_2, x_3 \in [0, 1] \) s.t. \( x_1 + x_2 + x_3 = 1 \).
- Then players 2 and 3 simultaneously and independently decide whether to accept (“y”) or reject (“n”) the suggested splitting.
- If both accept, each player \( i \) gets his allotted share (utility \( x_i \)). Otherwise, no player gets anything (utility 0).
Subgame-perfect equilibria (ctd.):

**Example: Three-Person Cake Splitting Game**

Formally:

\[ N = \{1, 2, 3\} \]
\[ X = \{(x_1, x_2, x_3) \in [0, 1]^3 | x_1 + x_2 + x_3 = 1\} \]
\[ H = \{\emptyset\} \cup \{(x) | x \in X\} \cup \{(x, z) | x, z \in \{y, n\} \times \{y, n\}\} \]
\[ P(\emptyset) = \{1\} \]
\[ P(x) = \{2, 3\} \text{ for all } x \in X \]
\[ u_i(x, z) = \begin{cases} 0 & \text{if } z \in \{(y, n), (n, y), (n, n)\} \\ x_i & \text{if } z = (y, y) \end{cases} \text{ for all } i \in N \]

Subgame-perfect equilibria:

- **Subgames after legal split** \((x_1, x_2, x_3)\) by player 1:
  - NE \((y, y)\) (both accept)
  - NE \((n, n)\) (neither accepts)
  - If \(x_2 = 0\), NE \((n, y)\) (only player 3 accepts)
  - If \(x_3 = 0\), NE \((y, n)\) (only player 2 accepts)

**Chance Moves**

**Definition**

An extensive game with chance moves is a tuple
\[ \Gamma = (N, A, H, f, u_i, c) \text{ for all } i \in N \]

- \(N, A, H\) and \(u_i\) are defined as before,
- the player function \(P : H \setminus Z \to N \cup \{c\}\) can also take the value \(c\) for a chance node, and
- for each \(h \in H \setminus Z\) with \(P(h) = c\), the function \(f_c(h)\) is a probability distribution on \(A(h)\) such that the probability distributions for all \(h \in H\) are independent of each other.
**Chance Moves**

- **Intended meaning of chance moves:** In chance node, an applicable action is chosen randomly with probability according to $f_c$.
- **Strategies:** Defined as before.
- **Outcome:** For a given strategy profile, the outcome is a probability distribution on the set of terminal histories.
- **Payoffs:** For player $i$, $U_i$ is the expected payoff (with weights according to outcome probabilities).

**Example**

\[
\begin{align*}
P(\langle \rangle) &= 1, \quad (2, 3) \\
P(\langle A \rangle) &= c, \quad (1, 4) \\
f_c(D|\langle A \rangle) &= \frac{1}{2}, \quad D \\
f_c(E|\langle A \rangle) &= \frac{1}{2}, \quad E \\
f_c(F|\langle B \rangle) &= \frac{1}{3}, \quad F \\
f_c(G|\langle B \rangle) &= \frac{2}{3}, \quad G \\
P(\langle B, F \rangle) &= 2, \quad (2, 2) \\
P(\langle B, G \rangle) &= 2, \quad (0, 3) \\
P(\langle B \rangle) &= c \\
\end{align*}
\]

**Remark:**

The one-deviation property and Kuhn's theorem still hold in the presence of chance moves. When proving Kuhn's theorem, expected utilities have to be used.
Summary

- For finite-horizon extensive games, it suffices to consider local deviations when looking for better strategies.
- For infinite-horizon games, this is not true in general.
- Every finite extensive game has a subgame-perfect equilibrium.
- This does not generally hold for infinite games, no matter is game is infinite due to infinite branching factor or infinitely long histories (or both).

- With chance moves, one deviation property and Kuhn’s theorem still hold.
- With simultaneous moves, Kuhn’s theorem no longer holds.