Motivation
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.
Definitions
An extensive game with perfect information is a tuple
\[ \Gamma = \langle N, H, P, (u_i)_{i \in N} \rangle \]
that consists of:

- A finite non-empty set \( N \) of players.
- A set \( H \) of (finite or infinite) sequences, called histories, such that
  - it contains 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 \( a^{k+1} \) such that \( \langle a^i \rangle_{i=1}^{k+1} \in H \) are called terminal histories \( Z \). Components of a history are called actions.
Definition (Extensive game with perfect information, ctd.)

- A player function \( P : H \setminus Z \rightarrow N \) that determines which player’s turn it is to move after a given nonterminal history.
- For each player \( i \in N \), a utility function (or payoff function) \( u_i : Z \rightarrow \mathbb{R} \) defined on the set of terminal histories.

The game is called finite, if \( H \) is finite. It has a finite horizon, if the length of histories is bounded from above.

Assumption: All ingredients of \( \Gamma \) are common knowledge amongst the players of the game.

Terminology: In the following, we will simply write extensive games instead of extensive games with perfect information.
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)

- $N = \{1, 2\}$
- $H = \{\langle \rangle, \langle (2, 0) \rangle, \langle (1, 1) \rangle, \langle (0, 2) \rangle, \langle (2, 0), y \rangle, \langle (2, 0), n \rangle, \ldots \}$
- $P(\langle \rangle) = 1, \ P(h) = 2 \text{ for all } h \in H \setminus Z \text{ with } h \neq \langle \rangle$
- $u_1(\langle (2, 0), y \rangle) = 2, \ u_2(\langle (2, 0), y \rangle) = 0, \text{ etc.}$
Notation:

Let \( h = \langle a^1, \ldots, a^k \rangle \) be a history, and \( a \) an action.

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

\[
A(h) = \{ a \mid (h, a) \in H \}.
\]
### Definition (Strategy in an extensive game)

A **strategy** of a player $i$ in an extensive game $\Gamma = \langle N, H, P, (u_i)_{i \in N} \rangle$ 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 $D$. 
Definition (Outcome)

The outcome $O(s)$ of a strategy profile $s = (s_i)_{i \in N}$ is the (possibly infinite) terminal history $h = \langle a^i \rangle_{i=1}^k$, with $k \in \mathbb{N} \cup \{\infty\}$, such that for all $\ell \in \mathbb{N}$ with $0 \leq \ell < k$,

$$s_P(\langle a^1, \ldots, a^\ell \rangle)(\langle a^1, \ldots, a^\ell \rangle) = a^{\ell+1}.$$

Example (Outcome)

$P(\langle \rangle) = 1$

$P(\langle A \rangle) = 2$

$P(\langle A, C \rangle) = 1$

$P(\langle A \rangle) = 2$

$P(\langle A \rangle) = 2$

$O(AF, C) = \langle A, C, F \rangle$

$O(AE, D) = \langle A, D \rangle$. 
Solution Concepts
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 $s_i \in S_i$,

$$u_i(O(s_{-i}^*, s_i^*)) \geq u_i(O(s_{-i}^*, s_i)).$$
Definition (Induced strategic game)

The strategic game $G$ induced by an extensive game $\Gamma = \langle N, H, P, (u_i)_{i \in N} \rangle$ is defined by $G = \langle N, (A'_i)_{i \in N}, (u'_i)_{i \in N} \rangle$, where

- $A'_i = S_i$ for all $i \in N$, and
- $u'_i(a) = u_i(O(a))$ for all $i \in N$.

Proposition

The Nash equilibria of an extensive game $\Gamma$ are exactly the Nash equilibria of the induced strategic game $G$ of $\Gamma$. 

\[ \square \]
Remarks:

- Each extensive game can be transformed into a strategic game, but the resulting game can be exponentially larger.
- The other direction does not work, because in extensive games, we do not have simultaneous actions.
Empty Threats

Example (Empty threat)

Extensive game:

- \( P(\langle \rangle) = 1 \)
- \( P(\langle T \rangle) = 2 \)

Strategic form:

\[
\begin{array}{cc}
  & L & R \\
T & 0,0 & 2,1 \\
B & 1,2 & 1,2 \\
\end{array}
\]

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.

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

Strategies:

- Player 1: \(T\) and \(B\)
- Player 2: \(L\) and \(R\)
Subgames

Idea: Exclude empty threats.

How? Demand that a strategy profile is not only a Nash equilibrium in the strategic form, but also in every subgame.

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 $\Gamma(h) = \langle N, H|_h, P|_h, (u_i|_h)_{i \in N} \rangle$, where

- $H|_h = \{ h' \mid (h, h') \in H \}$,
- $P|_h(h') = P(h, h')$ for all $h' \in H|_h$, and
- $u_i|_h(h') = u_i(h, h')$ for all $h' \in H|_h$. 
Definition (Strategy in a subgame)

Let \( \Gamma \) be an extensive game and \( \Gamma(h) \) a subgame of \( \Gamma \) starting after some history \( h \).

For each strategy \( s_i \) of \( \Gamma \), let \( s_i|_h \) be the strategy induced by \( s_i \) for \( \Gamma(h) \). Formally, for all \( h' \in H|_h \),

\[
s_i|_{h}(h') = s_i(h, h').
\]

The outcome function of \( \Gamma(h) \) is denoted by \( O_h \).
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 $h \in H \setminus Z$ with $P(h) = i$,

$$u_i|_h(O_h(s^*_{-i}|_h, s^*_i|_h)) \geq u_i|_h(O_h(s^*_{-i}|_h, s_i))$$

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 \(h = \langle T \rangle\).
Subgame-Perfect Equilibria

Example (Subgame-perfect equilibria in division game)

Equilibria in subgames:
- in $\Gamma(\langle 2, 0 \rangle)$: $y$ and $n$
- in $\Gamma(\langle 1, 1 \rangle)$: only $y$
- in $\Gamma(\langle 0, 2 \rangle)$: only $y$
- in $\Gamma(\langle \rangle)$: $((2, 0), yyy)$ and $((1, 1), nyy)$

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

- **Existence:**
  - Does every extensive game have a subgame-perfect equilibrium?
  - If not, which extensive games do have a subgame-perfect equilibrium?

- **Computation:**
  - If a subgame-perfect equilibrium exists, how to compute it?
  - How complex is that computation?
Positive case (a subgame-perfect equilibrium exists):

- **Step 1**: Show that it suffices to consider local deviations from strategies (for finite-horizon games).
- **Step 2**: Show how to systematically explore such local deviations to find a subgame-perfect equilibrium (for finite games).
Step 1: One-Deviation Property

Definition

Let $\Gamma$ be a finite-horizon extensive game. Then $\ell(\Gamma)$ denotes the length of the longest history of $\Gamma$. 
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 $P(h) = i$,

$$u_i|_h(O_h(s^*_{-i}|_h, s^*_i|_h)) \geq u_i|_h(O_h(s^*_{-i}|_h, s_i))$$

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!
Step 1: One-Deviation Property

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

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Proof (ctd.)

\((\Leftarrow)\) … WLOG, the number of histories \(h'\) with 
\(s_i(h') \neq s^*_i|_h(h')\) is at most \(\ell(\Gamma(h))\) and hence finite (finite horizon assumption!), since deviations not on resulting outcome path are irrelevant.

Illustration: strategies \(s^*_1|_h = AGILN\) and \(s^*_2|_h = CF\) red:

\[
P(h) = 1
\]

\[
A \quad 2
\]

\[
B \quad 2
\]

\[
C \quad 1 \quad D \quad 1
\]

\[
G \quad H \quad I \quad K \quad L \quad M \quad N \quad O
\]
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 $\ell(\Gamma(h))$ and hence finite (finite horizon assumption!), since deviations not on resulting outcome path are irrelevant.

Illustration: strategies $s^*_1|_h = AGILN$ and $s^*_2|_h = CF$ red:

$$P(h) = 1$$
Step 1: One-Deviation Property

Proof (ctd.)

\( (\Leftarrow) \) ... Illustration for WLOG assumption: Assume \( s_1 = BHKMO \) (blue) profitable deviation:

\[
P(h) = 1
\]

Then only \( B \) and \( O \) really matter.
Step 1: One-Deviation Property

Proof (ctd.)

(⇐) ... Illustration for WLOG assumption: And hence

\( \tilde{s}_1 = BGILO \) (blue) also profitable deviation:

\[
P(h) = 1
\]
Step 1: One-Deviation Property

Proof (ctd.)

\[ \leftarrow \rightarrow \ldots \]

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.
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.
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\[(\iff) \ldots\]

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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 1: One-Deviation Property
Remark on Infinite-Horizon Games

The corresponding proposition for infinite-horizon games does not hold.

Counterexample (one-player case):

Strategy $s_i$ with $s_i(h) = S$ for all $h \in H \setminus Z$

- satisfies one deviation property, but
- is not a subgame-perfect equilibrium, since it is dominated by $s^*_i$ with $s^*_i(h) = C$ for all $h \in H \setminus Z$. 
Kuhn’s Theorem
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

Example

\[ A \rightarrow B \]
\[ C \rightarrow D \]
\[ E \rightarrow F \]

\((1, 5)\)
\((2, 3)\)
\((3, 4)\)
\((0, 8)\)
Step 2: Kuhn’s Theorem

Example

\[ s_2(\langle A \rangle) = C \quad t_1(\langle A \rangle) = 1 \quad t_2(\langle A \rangle) = 5 \]
Example

\[ s_2(A) = C \quad t_1(A) = 1 \quad t_2(A) = 5 \]
\[ s_2(B) = F \quad t_1(B) = 0 \quad t_2(B) = 8 \]
Step 2: Kuhn’s Theorem

Example

\[
\begin{align*}
  s_2(\langle A \rangle) &= C & t_1(\langle A \rangle) &= 1 & t_2(\langle A \rangle) &= 5 \\
  s_2(\langle B \rangle) &= F & t_1(\langle B \rangle) &= 0 & t_2(\langle B \rangle) &= 8 \\
  s_1(\langle \rangle) &= A & t_1(\langle \rangle) &= 1 & t_2(\langle \rangle) &= 5
\end{align*}
\]
Step 2: Kuhn’s Theorem

A bit more formally:

Proof

Let $\Gamma = \langle N, H, P, (u_i)_{i \in N} \rangle$ be a finite extensive game.

Construct a subgame-perfect equilibrium by induction on $\ell(\Gamma(h))$ for all subgames $\Gamma(h)$. In parallel, construct functions $t_i : H \to \mathbb{R}$ for all players $i \in N$ s.t. $t_i(h)$ is the payoff for player $i$ in a subgame-perfect equilibrium in subgame $\Gamma(h)$.

Base case: If $\ell(\Gamma(h)) = 0$, then $t_i(h) = u_i(h)$ for all $i \in N$.

...
A bit more formally:

**Proof**

Let \( \Gamma = \langle N, H, P, (u_i)_{i \in N} \rangle \) be a finite extensive game.

Construct a subgame-perfect equilibrium by induction on \( \ell(\Gamma(h)) \) for all subgames \( \Gamma(h) \). In parallel, construct functions \( t_i : H \to \mathbb{R} \) for all players \( i \in N \) s.t. \( t_i(h) \) is the payoff for player \( i \) in a subgame-perfect equilibrium in subgame \( \Gamma(h) \).

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**Base case:** If \( \ell(\Gamma(h)) = 0 \), then \( t_i(h) = u_i(h) \) for all \( i \in N \).

...
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

$$s_i(h^*) := \arg\max_{a \in A(h^*)} t_i(h^*, a)$$

and

$$t_j(h^*) := t_j(h^*, s_i(h^*))$$

for all players $j \in N$.

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.
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

$$s_i(h^*) := \arg\max_{a \in A(h^*)} t_i(h^*, a) \quad \text{and} \quad t_j(h^*) := t_j(h^*, s_i(h^*)) \quad \text{for all players } j \in N.$$ 

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Step 2: Kuhn’s Theorem

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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

\[
  s_i(h^*) := \arg\max_{a \in A(h^*)} t_i(h^*,a) 
\]

and

\[
  t_j(h^*) := t_j(h^*,s_i(h^*)) \quad \text{for all players } j \in N. 
\]

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With the one-deviation property lemma it follows that \( s \) is a subgame-perfect equilibrium.
Step 2: Kuhn’s Theorem

- **In principle:** 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 $O(b^m)$. 
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.
Step 2: Kuhn’s Theorem
Remark on Infinite Games

B) infinite horizon, finite branching factor:

\[ u_1(\text{CCC} \ldots) = 0 \text{ and } u_1(\text{CC} \ldots \text{C S}) = n + 1. \]

No subgame-perfect equilibrium.
Step 2: Kuhn’s Theorem

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.
There are 5 *rational* pirates, \( A, B, C, D \) and \( E \). They find 100 gold coins. They must decide how to distribute them.

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 \( E \).

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.
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.
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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.
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Pirates: Formalization

- 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!
Pirates: Analysis by Backward Induction

1. 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!

2. 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.

3. 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.

4. 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).
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Two Extensions
Simultaneous Moves

**Definition**

An **extensive game with simultaneous moves** is a tuple $\Gamma = \langle N, H, P, (u_i)_{i \in N} \rangle$, where

- $N$, $H$, $P$ and $(u_i)$ 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

- **Intended meaning of simultaneous moves**: All players from $P(h)$ move simultaneously.
- **Strategies**: Functions $s_i : h \mapsto a_i$ with $a_i \in A_i(h)$.
- **Histories**: Sequences of vectors of actions.
- **Outcome**: Terminal history reached when tracing strategy profile.
- **Payoffs**: Utilities at outcome history.
Simultaneous Moves
One-Deviation Property and Kuhn’s Theorem

Remark:

- The **one-deviation property still holds** for extensive game with perfect information and simultaneous moves.
- **Kuhn’s theorem does not hold** for extensive game with simultaneous moves.

**Example:** **Matching Pennies** can be viewed as extensive game with simultaneous moves. No Nash equilibrium/subgame-perfect equilibrium.

```
player 1
  H   T
H  1, −1  −1, 1
T −1,  1  1, −1
```

⇝ Need more sophisticated solution concepts (cf. mixed strategies). Not covered in this lecture.
Simultaneous Moves
Example: Three-Person Cake Splitting Game

Setting:

- Three players have to split a cake fairly.
- Player 1 suggests a 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).
Simultaneous Moves
Example: Three-Person Cake Splitting Game

Formally:

\[ N = \{1, 2, 3\} \]
\[ X = \{(x_1, x_2, x_3) \in [0, 1]^3 \mid x_1 + x_2 + x_3 = 1\} \]
\[ H = \{\langle\rangle\} \cup \{\langle x \rangle \mid x \in X\} \cup \{\langle x, z \rangle \mid x \in X, z \in \{y, n\} \times \{y, n\}\} \]
\[ P(\langle\rangle) = \{1\} \]
\[ P(\langle x \rangle) = \{2, 3\} \text{ for all } x \in X \]
\[ u_i(\langle x, z \rangle) = \begin{cases} 0 & \text{if } z \in \{(y, n), (n, y), (n, n)\} \\ x_i & \text{if } z = (y, y). \end{cases} \text{ for all } i \in N \]
Simultaneous Moves
Example: Three-Person Cake Splitting Game

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)
Subgame-perfect equilibria (ctd.):

**Entire game:**

Let $s_2$ and $s_3$ be any two strategies of players 2 and 3 such that for all splits $x \in X$ the profile $(s_2(\langle x \rangle), s_3(\langle x \rangle))$ is one of the NEs from above.

Let $X_y = \{x \in X \mid s_2(\langle x \rangle) = s_3(\langle x \rangle) = y\}$ be the set of splits accepted under $s_2$ and $s_3$. Distinguish three cases:

- $X_y = \emptyset$ or $x_1 = 0$ for all $x \in X_y$. Then $(s_1, s_2, s_3)$ is a subgame-perfect equilibrium for any possible $s_1$.
- $X_y \neq \emptyset$ and there are splits $x_{\text{max}} = (x_1, x_2, x_3) \in X_y$ that maximize $x_1 > 0$. Then $(s_1, s_2, s_3)$ is a subgame-perfect equilibrium if and only if $s_1(\langle \rangle)$ is such a split $x_{\text{max}}$.
- $X_y \neq \emptyset$ and there are no splits $(x_1, x_2, x_3) \in X_y$ that maximize $x_1$. Then there is no subgame-perfect equilibrium, in which player 2 follows strategy $s_2$ and player 3 follows strategy $s_3$. 
Definition

An extensive game with chance moves is a tuple \( \Gamma = \langle N, H, P, f_c, (u_i)_{i \in N} \rangle \), where

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

Example

\[
P(\langle \rangle) = \begin{cases} 1 & \text{if } A \\ c(1,4) & \text{if } B \\ \frac{1}{2} & \text{if } D \\ \frac{1}{2} & \text{if } E \\ \frac{1}{3} & \text{if } F \\ \frac{2}{3} & \text{if } G \\ \end{cases}
\]

\[
P(\langle A \rangle) = \begin{cases} c & \text{if } A \\ (1,4) & \text{if } B \\ \frac{1}{2} & \text{if } D \\ \frac{1}{2} & \text{if } E \\ \frac{1}{3} & \text{if } F \\ \frac{2}{3} & \text{if } G \\ \end{cases}
\]

\[
P(\langle B \rangle) = \begin{cases} c & \text{if } A \\ (2,3) & \text{if } B \\ \frac{1}{2} & \text{if } D \\ \frac{1}{2} & \text{if } E \\ \frac{1}{3} & \text{if } F \\ \frac{2}{3} & \text{if } G \\ \end{cases}
\]

\[
P(\langle B, F \rangle) = \begin{cases} 2 & \text{if } A \\ (0,3) & \text{if } B \\ (0,3) & \text{if } D \\ (0,3) & \text{if } E \\ (3,3) & \text{if } F \\ (3,3) & \text{if } G \\ \end{cases}
\]

\[
P(\langle B, G \rangle) = \begin{cases} 2 & \text{if } A \\ (2,3) & \text{if } B \\ (2,3) & \text{if } D \\ (2,3) & \text{if } E \\ (4,1) & \text{if } F \\ (3,3) & \text{if } G \\ \end{cases}
\]
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
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 if 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.