Game Theory
6. Extensive Games

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Motivation

- **So far**: All players move simultaneously, and then the outcome is determined.
- **Often in practice**: Several moves in sequence (e.g. in chess).
  \[\sim\text{cannot be directly reflected by strategic games.}\]
- **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.
2 Definitions
Definition (Extensive game with perfect information)

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
  
  - 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 $\langle a^i \rangle_i^{\infty}$, we have $\langle a^i \rangle_{i=1}^k \in H$ for all $k \in \mathbb{N}$, then $\langle a^i \rangle_i^{\infty} \in H$.

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.
Extensive Games

Example (Division game, formally)

\[ N = \{1, 2\} \]

\[ H = \{\langle \rangle, \langle (2, 0) \rangle, \langle (1, 1) \rangle, \langle (0, 2) \rangle, \langle (2, 0), y \rangle, \langle (2, 0), n \rangle, \ldots \} \]

\[ P(\langle \rangle) = 1, \ P(h) = 2 \text{ for all } h \in H \setminus Z \text{ with } h \neq \langle \rangle \]

\[ u_1(\langle (2, 0), y \rangle) = 2, \ u_2(\langle (2, 0), y \rangle) = 0, \text{ etc.} \]
Motivation

Definitions

Solution

Concepts

One-Deviation

Property

Kuhn’s

Theorem

Two

Extensions

Summary

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)

The diagram illustrates the probability and outcome for the game. The probabilities are:

- \( P(\langle \rangle) = 1 \)
- \( P(\langle A \rangle) = 2 \)
- \( P(\langle A, C \rangle) = 1 \)
- \( P(\langle A, C, F \rangle) = 1 \)

The outcomes are:

- \( O(AF, C) = \langle A, C, F \rangle \)
- \( O(AE, D) = \langle A, D \rangle \).
3 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 $\Gamma$. □
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.
Example (Empty threat)

Extensive game:

\[
\begin{align*}
P(\langle \rangle) &= 1 \\
P(\langle T \rangle) &= 2 \\
L &\quad R \\
T &\quad 0, 0 \quad 2, 1 \\
B &\quad 1, 2 \quad 1, 2
\end{align*}
\]

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.

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

\( H|_h = \{ h' | (h, h') \in H \} \),

\( P|_h(h') = P(h, h') \) 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 $O_h$. 
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 $h \in H \setminus Z$ 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):
- $(2, 0), yyy$, $(2, 0), yyn$, $(2, 0), yny$, $(2, 0), ynn$, $(2, 0), nny$, $(2, 0), nnn$,
- $(1, 1), nyy$, $(1, 1), nyn$,
- $(0, 2), nny$, $(0, 2), nnn$.
4 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 is sufficient 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).
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

Proof (ctd.)

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

Illustration: strategies $s_1^*|_h = AGILN$ and $s_2^*|_h = CF$ red:

$$P(h) = 1$$
Proof (ctd.)

\[(\iff) \ldots \text{Illustration for WLOG assumption: Assume } s_1 = \text{BH}K\text{M}O \text{ (blue)} \text{ profitable deviation:}\]

\[
P(h) = 1
\]

\begin{align*}
A & \quad \quad \quad B \\
C & \quad D & \quad E \quad F \\
G & \quad H & \quad I & \quad K & \quad L & \quad M & \quad N & \quad O
\end{align*}

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.)

\((\Leftarrow)\ldots\)

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.

\(\Box\)
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 $h \in H \setminus Z$.  

```
  C  C  C  C  C  C  C, ...
S  S  S  S  S  S  1
0  0  0  0  0  0  0
```
5 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

\[
\begin{align*}
\langle A \rangle & \quad s_2(\langle A \rangle) = C \quad t_1(\langle A \rangle) = 1 \quad t_2(\langle A \rangle) = 5 \\
\langle B \rangle & \quad s_2(\langle B \rangle) = F \quad t_1(\langle B \rangle) = 0 \quad t_2(\langle B \rangle) = 8 \\
\emptyset & \quad s_1(\emptyset) = A \quad t_1(\emptyset) = 1 \quad t_2(\emptyset) = 5
\end{align*}
\]
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 $i \in N$.

...
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

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

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.
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:

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

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.
6 Two Extensions

- Chance
- Simultaneous Moves
**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

\[ P(\langle A \rangle) = \frac{1}{2} \]
\[ f_c(D|\langle A \rangle) = \frac{1}{2} \]
\[ f_c(E|\langle A \rangle) = \frac{1}{2} \]
\[ f_c(F|\langle B \rangle) = \frac{1}{3} \]
\[ f_c(G|\langle B \rangle) = \frac{2}{3} \]

\[ P(\langle A \rangle) = c \]
\[ P(\langle B \rangle) = c \]

\[ P(\langle B, F \rangle) = 2 \]
\[ (0, 3) \]
\[ (2, 2) \]

\[ P(\langle B, G \rangle) = 2 \]
\[ (0, 3) \]
\[ (3, 3) \]
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.
Simultaneous Moves

Definition

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

- \( N, A, H \) and \((u_i)\) are defined as before, and
- \( P : H \to 2^N \) assigns to each nonterminal history a set of players to move; for all \( h \in H \setminus Z \), there exists a family \((A_i(h))_{i \in \mathcal{P}(h)}\) such that

\[
A(h) = \{ a \mid (h, a) \in H \} = \prod_{i \in \mathcal{P}(h)} A_i(h).
\]
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.
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.

<table>
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<th>H</th>
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<td>1, −1</td>
<td>−1, 1</td>
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<tr>
<td><strong>T</strong></td>
<td>−1, 1</td>
<td>1, −1</td>
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⇝ 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:

\[ N = \{1, 2, 3\} \]
\[ X = \{(x_1, x_2, x_3) \in [0, 1]^3 | x_1 + x_2 + x_3 = 1\} \]
\[ H = \{\langle \rangle\} \cup \{\langle x \rangle | x \in X\} \cup \{\langle x, z \rangle | x \in X, z \in \{y, n\} \times \{y, n\}\} \]
\[ P(\langle \rangle) = \{1\} \]
\[ P(\langle x \rangle) = \{2, 3\} \text{ for all } x \in X \]
\[ u_i(\langle x, z \rangle) = \begin{cases} 0 & \text{if } z \in \{(y, n), (n, y), (n, n)\} \\ x_i & \text{if } z = (y, y). \end{cases} \text{ for all } i \in N \]
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 $s_3$. 
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.