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DISCLAIMER

This a not a textbook. These are lecture notes.
1. Extensive Form Games with Perfect Information

1.1. Chess. We assume the students are familiar with chess. We will choose the following (non-standard) rules for the ending of chess: the game ends either by the capturing of a king, in which case the capturing side wins and the other loses, or else in a draw, which happens when there a player has no legal moves, or more than 100 turns have elapsed.

As such, this game has the following features:

- There are two players, white and black.
- There are (at most) 100 time periods.
- In each time period one of the players chooses an action. This action is observed by the other player.
- The sequence of actions taken by the players so far determines what actions the active player is allowed to take.
- Every sequence of alternating actions eventually ends with either a draw, or one of the players winning.

We say that white can force a victory if, for any moves that black chooses, white can choose moves that will end in its victory. Zermelo showed in 1913 [31] that in the game of chess, as described above, one of the following three holds:

- White can force a victory.
- Black can force a victory.
- Both white and black can force a draw.

We will prove this later.

We can represent the game of chess mathematically as follows.

Let \( N = \{W, B\} \) be the set of players.

Let \( A \) be the set of actions (or moves) that any of the players can potentially take at any stage of the game. E.g., rook from A1 to B3.

A history \( h = (a_1, \ldots, a_n) \) is a finite sequence of elements of \( A \); we denote the empty sequence by \( \emptyset \). We say that \( h \) is legal if each move \( a_i \) in \( h \) is allowed in the game of chess, given the previous moves \( (a_1, \ldots, a_{i-1}) \), and if the length of \( h \) is at most 100. We denote by \( H \) the set of legal histories, including \( \emptyset \).

Let \( Z \subseteq H \) be the set of terminal histories; these are histories of game plays that have ended (as described above, by capturing or a draw). Formally, \( Z \) is the set of histories in \( H \) that are not prefixes of other histories in \( H \).

Let \( O = \{W, B, D\} \) be the set of outcomes of the game (corresponding to \( W \) wins, \( B \) wins and draw). Let \( o: Z \rightarrow O \) be a
function that assigns to each terminal history the appropriate outcome.

- Let \( P : H \setminus Z \to N \) be the player function. \( P \) assigns to each non-terminal history the player whose turn it is to play. Specifically, \( P(h) \) will be \( W \) if the length of \( h \) is even, and \( B \) otherwise.

- Let \( \preceq_W \) and \( \preceq_B \) be the white player’s and the black player’s (obvious) preferences over \( O \).

A strategy of a player is a complete description of what that player would do in her turns, given every possible history. Formally, a strategy \( s \) of \( W \) is a mapping \( s : P^{-1}(W) \to A \) that assigns to each every history \( h \) with \( P(h) = W \) an \( a \in A \) such that \((h, a) \in H\). Here we denote by \( (h, a) \) the strategy \((a_1, \ldots, a_n, a)\), where \( h = (a_1, \ldots, a_n)\).

Let \((s_W, s_B)\) be a pair of strategies, one for each player. Then we can define the history \( h(s_W, s_B) \in H \) to be the terminal history that is reached when the two players choose these strategies. We can also define \( o(s_W, s_B) = o(h(s_W, s_B)) \) to be the resulting outcome of the game.

Given these definitions, we can formally state Zermelo’s Theorem.

**Theorem 1.1** (Zermelo, 1913). In the game of chess, as described above, exactly one of the following three holds:

- There exists a strategy \( s_W^* \) for \( W \) such that, for any strategy \( s_B \) of \( B \), \( o(s_W^*, s_B) = W \).
- There exists a strategy \( s_B^* \) for \( B \) such that, for any strategy \( s_W \) of \( W \), \( o(s_W, s_B^*) = B \).
- There exist strategies \( s_W^* \) for \( W \) and \( s_B^* \) for \( B \) such that, for any strategies \( s_W \) and \( s_B \), \( o(s_W^*, s_B) \neq B \) and \( o(s_W, s_B^*) \neq W \). (It follows that \( o(s_W^*, s_B^*) = D \)).

Note that it is not known which of the three is true.

### 1.2. Definition of extensive form games with perfect information

In general, an extensive form game (with perfect information) \( G \) is a tuple \( G = (N, A, H, O, o, P, \{\preceq_i\}_{i \in N}) \) where

1. \( N \) is the set of players.
2. \( A \) is the set of actions.
3. \( H \) is the set of allowed histories. This is a set of sequences of elements of \( A \) such that if \( h \in H \) then every prefix of \( h \) is also in \( H \).

\( Z \) is the set of sequences in \( H \) that are not subsequences of others in \( H \). Note that we can specify \( H \) by specifying \( Z \); \( H \) is the set of subsequences of sequences in \( Z \).
In general, the sequences in $H$ needn’t be finite. In this case we need an additional requirement, namely that if $H$ contains every subsequence of some infinite sequence then it also contains that infinite sequence. The set $Z$ of terminal histories - those that are not prefixes of others - includes all the infinite ones.

(4) $O$ is the set of outcomes.
(5) $o$ is a function from $Z$ to $O$.
(6) $P$ is a function from $H \setminus Z$ to $N$.
(7) For each player $i \in N$, $\preceq_i$ is a preference relation over $O$. (I.e., a complete, transitive and reflexive binary relation).

We denote by $A(h)$ the actions available to player $P(h)$ after history $h$:

$$A(h) = \{ a \in A : ha \in H \}.$$ 

A game is called a finite horizon game if there is a bound on the length of histories in $H$. A game is called finite if $H$ is finite.

Strategies are defined as for chess. A strategy profile $s = \{ s_i \}_{i \in N}$ constitutes a strategy for each player. We can, as for chess, define $h(s)$ and $o(s)$ as the history and outcome associated with a strategy profile.

1.3. The ultimatum game. In the ultimatum game player 1 makes an offer $a \in \{ 0, 1, 2, 3, 4 \}$ to player 2. Player 2 either accepts or rejects. If player 2 accepts then she receives $a$ dollars and player 1 receives $4 - a$ dollars. If 2 rejects then both get nothing. This is how this game can be written in extensive form:

(1) $N = \{ 1, 2 \}$.
(2) $A = \{ 0, 1, 2, 3, 4, a, r \}$.
(3) $Z = \{ 0a, 1a, 2a, 3a, 4a, 0r, 1r, 2r, 3r, 4r \}$.
(4) $O = \{ (0, 0), (0, 4), (1, 3), (2, 2), (3, 1), (4, 0) \}$. Each pair corresponds to what players 1 receives and what player 2 receives.
(5) For $b \in \{ 0, 1, 2, 3, 4 \}$, $o(ba) = (4 - b, b)$ and $o(br) = (0, 0)$.
(6) $P(\emptyset) = 1$, $P(0) = P(1) = P(2) = P(3) = P(4) = 2$.
(7) For $a_1, b_1, a_2, b_2 \in \{ 0, 1, 2, 3, 4 \}$, $(a_1, a_2) \preceq_1 (b_1, b_2)$ iff $a_1 \leq b_1$, and $(a_1, a_2) \preceq_2 (b_1, b_2)$ iff $a_2 \leq b_2$.

A strategy for player 1 is just a choice among $\{ 0, 1, 2, 3, 4 \}$. A strategy for player 2 is a map from $\{ 0, 1, 2, 3, 4 \}$ to $\{ a, r \}$: player 2’s strategy describes whether or not she accepts or rejects any given offer.

1.4. Equilibria. Given a strategy profile $s = \{ s_i \}_{i \in N}$, we denote by $(s_{-i}, s_i')$ the strategy profile in which $i$’s strategy is changed from $s_i$ to $s'_i$ and the rest remain the same.
A strategy profile $s^*$ is a Nash equilibrium if for all $i \in N$ and strategy $s_i$ of player $i$ it holds that
\[ o(s^*_{-i}, s_i) \preceq_i o(s^*). \]
When $s$ is the equilibrium $h(s)$ is also known as the equilibrium path associated with $s$.

Example: in the ultimatum game, consider the strategy profile in which player 1 offers 3, and player 2 accepts 3 or 4 and rejects 0, 1 or 2. It is easy to check that this is an equilibrium profile.

1.5. The centipede game. In the centipede game there are $n$ time periods and 2 players. The players alternate in turns, and at each turn each player can either stop (S) or continue (C), except at the last turn, where they must stop. Now, there is a piggy bank which initially has in it 2 dollars. If a player decides to stop, she is awarded half of what’s in the bank, plus one dollar, and the other player is awarded the remainder. If a player decides to continue, 2 dollars are added to the bank. Hence, in period $m$, a player is awarded $m + 1$ if she decided to stop, and the other player is given $m - 1$.

Exercise 1.2. Define the centipede game formally, for $n = 6$. How many strategies does each player have?

Exercise 1.3. Show that the strategy profile in which both players play $S$ in every time period is an equilibrium.

Theorem 1.4. In every Nash equilibrium, player 1 plays $S$ in the first period.

Proof. Assume by contradiction that player 1 plays $C$ in the first period under some equilibrium $s$. Then there is some period $m > 1$ in which $S$ is played for the first time on the equilibrium path. It follows that the player who played $C$ in the previous period is awarded $m - 1$. But she could have been awarded $m$ by playing $S$ in the previous period, and therefore $s$ is not an equilibrium. \qed

1.6. Subgames and subgame perfect equilibria. A subgame of a game $G = (N, A, H, O, o, P, \{ \preceq_i \}_{i \in N})$ is a game that starts after a given finite history $h \in H$. Formally, the subgame $G(h)$ associated with $h = (h_1, \ldots, h_n) \in H$ is $G(h) = (N, A, H|_h, O|_h, P|_h, \{ \preceq_i \}_{i \in N})$, where
\[ H|_h = \{(a_1, a_2, \ldots) : (h_1, \ldots, h_n, a_1, a_2, \ldots) \in H\} \]
and
\[ o|_h(h') = o(hh') \quad P|_h(h') = P(hh'). \]
A strategy $s$ of $G$ can likewise used to define a strategy $s|_{h}$ of $G(h)$.

A subgame perfect equilibrium of $G$ is a Nash equilibrium $s^*$ such that for every subgame $G(h)$ it holds that $s^*|_{h}$ is a Nash equilibrium of $G(h)$.

An important property of finite horizon games is the one deviation property. Before introducing it we make the following definition.

Let $s$ be a strategy profile. We say that $s'_i$ is a profitable deviation from $s$ for player $i$ at history $h$ if $s'_i$ is a strategy for $G$ such that

$$o|_h(s_{-i}|_{h}, s'_i|_{h}) \succ_i o|_h(s|_{h}).$$

Note that a strategy profile has no profitable deviations if and only if it is a Nash equilibrium.

**Theorem 1.5** (The one deviation principle). Let $G = (N, A, H, O, o, P, \{\preceq_i\}_{i \in N})$ be a finite horizon, extensive form game with perfect information. Let $s$ be a strategy profile that is not a subgame perfect equilibrium. There there exists some history $h$ and a profitable deviation $s'_i$ for player $i = P(h)$ at history $h$ such that $s'_i(h') = s_i(h')$ for all $h' \neq h$.

**Proof.** Let $s$ be a strategy profile that is not a subgame perfect equilibrium. Then there is a subgame $G(h)$ and a strategy $s'_i$ for player $i = P(h)$ such that $s'_i$ is a profitable deviation for $i$ in $h$. Let $h^*$ be a maximal length history for which there exists a profitable deviation, and let $s'_i$ be a profitable deviation for $G(h^*)$ that minimizes the number of histories by which it differs from $s_i$. It follows that $s'_i(h) = s_i(h)$ for any history $h$ that does not have $h^*$ as a prefix, since otherwise $s'_i$ would not be minimal.

Now, we claim that $s'_i$ differs from $s_i$ only at $h^*$, which will prove the claim. By the definition of $s'_i$, this need only be demonstrated for histories that have $h^*$ as a prefix. Assume by contradiction that $s'_i(h^*h) \neq s_i(h^*h)$ for some non-empty $h$. Then, by the maximality of $h^*$, $s'_i|_{h^*h}$ is not a profitable deviation for $G(h^*h)$. But this then contradicts the minimality of $s'_i$. \qed

### 1.7. Backward induction, Kuhn’s Theorem and a proof of Zermelo’s Theorem

Let $G = (N, A, H, O, o, P, \{\preceq_i\}_{i \in N})$ be an extensive form game with perfect information. Recall that $A(\emptyset)$ is the set of allowed initial actions for player $i = P(\emptyset)$. For each $b \in A(\emptyset)$, let $\sigma(G(b))$ be some strategy profile for the subgame $G(b)$. Given some $a \in A(\emptyset)$, we denote by $a\sigma$ the strategy profile for $G$ in which player $i = P(\emptyset)$ chooses the initial action $a$, and for each action $b \in A(\emptyset)$ the subgame $G(b)$ is played according to $\sigma(G(b))$. That is, $[a\sigma]|_i(\emptyset) = a$ and for every player $j$, $b \in A(\emptyset)$ and $bh \in H \setminus Z$, $[a\sigma]|_j(bh) = [\sigma(G(b))]|_j(h)$. 


Lemma 1.6 (Backward Induction). Let $G = (N, A, H, O, o, P, \{\preceq_i\}_{i \in N})$ be an extensive form game with perfect information. Assume that for each $b \in A(\emptyset)$ the subgame $G(b)$ has a subgame perfect equilibrium $\sigma(G(b))$. Assume also that there is an $a^* \in A(\emptyset)$ that $\preceq_i$-maximizes $o(a^*\sigma)$, where $i = P(\emptyset)$. Then $a^*\sigma$ is a subgame perfect equilibrium of $G$.

Proof. Denote $s^* = a^*\sigma$. Assume by contradiction that $s^*$ is not a subgame perfect equilibrium of $G$. Then some player $j$ has a profitable deviation $s_j$ at some history $h$ for which $j = P(h)$. Let $h$ be a minimal length history at which such a deviation exists.

We first claim that $h = \emptyset$. Otherwise, $h = ah'$ for some $a \in A(\emptyset)$, and so $s_j|_a$ would be a profitable deviation for $j$ in $\sigma(G(a))$ and history $h'$; this is impossible since $\sigma(G(a))$ is a subgame perfect equilibrium.

We have thus shown that $i = P(\emptyset)$ has a profitable deviation $s_i$ at $h = \emptyset$. Denote $b = s_i(\emptyset)$.

Since $s_i$ is profitable then
\[ o(s^* - s_i, s_i) \succ_i o(s^*). \]

The left hand side equals $o|_b(s^* - s_i|_b, s_i|_b)$. As for the right hand side, by the definition of $s^*$ it holds that
\[ o(s^*) \succeq_i o(b) = o|_b(s^* - s_i|_b, s_i|_b). \]

Putting this together yields
\[ o|_b(s^* - s_i|_b, s_i|_b) \succ_i o|_b(s^* - s_i|_b, s_i^*|_b). \]

But $s^*|_b = \sigma(G(b))$, and so we can write this as
\[ o|_b(\sigma(G(b)), s_i|_b) \succ_i o|_b(\sigma(G(b)), s_i^*|_b). \]

Hence $s_i|_b$ is a profitable deviation from $\sigma(G(b))$ for player $i$ in the subgame $G(b)$, in contradiction to the fact that $\sigma(G(b))$ is an equilibrium. \[ \square \]

Kuhn [19] proved the following theorem.

Theorem 1.7 (Kuhn, 1953). Every finite extensive form game with perfect information has a subgame perfect equilibrium.

Proof of Theorem 1.7. We prove the claim by induction on $\ell(G)$. For $\ell(G) = 0$ the claim is immediate, since the trivial strategy profile is an equilibrium, and there are no proper subgames. Assume we have proved the claim for all games $G$ with $\ell(G) < n$. 


Let \( \ell(G) = n \), and denote \( i = P(\emptyset) \). For each \( b \in A(\emptyset) \), let \( \sigma(G(b)) \) be some subgame perfect equilibrium of \( G(b) \). These exist by our inductive assumption, as \( \ell(G(b)) < n \).

Let \( a^* \in A(\emptyset) \) be a \( \preceq_i \)-maximizer of \( o(a^*\sigma) \). Then by the Backward Induction Lemma \( a^*\sigma \) is a subgame perfect equilibrium of \( G \), and our proof is concluded. \( \square \)

Given Kuhn’s Theorem, Zermelo’s Theorem admits a simple proof.

**Proof of Theorem 1.1.** Let \( s^* = (s^*_W, s^*_B) \) be a subgame perfect equilibrium of any finite extensive form game with two players (\( W \) and \( B \)) and outcomes \( \{W, B, D\} \) (e.g., chess). Hence the outcome \( o(s^*) \) is either \( W, B \) or \( D \). Consider these three cases.

If \( o(s^*) = W \) then for any \( s_B \)
\[
o(s^*_W, s_B) \preceq_B o(s^*) = W.
\]
But \( W \) is the unique \( \preceq_B \) minimizer, and so \( o(s^*_W, s_B) = W \). That is, white can force victory by playing \( s^*_W \). The same argument shows that if \( o(s^*) = B \) then black can force victory. Finally, if \( o(s^*) = D \) then for any \( s_B \)
\[
o(s^*_W, s_B) \preceq_B o(s^*) = D,
\]
so \( o(s^*_W, s_B) \) is either \( D \) or \( W \). By the same argument \( o(s_W, s^*_B) \) is either \( D \) or \( B \) for any \( s_W \), and so we have proved the claim. \( \square \)
2. Strategic form games

2.1. Definition. A game in strategic form (or normal form) is a tuple $G = (N, \{S_i\}_{i \in N}, O, o, \{\succeq_i\}_{i \in N})$ where

- $N$ is the set of players.
- $S_i$ is the set of actions or strategies available to player $i$. We denote by $S = \prod_i S_i$ the set of strategy profiles.
- $O$ is the set of outcomes.
- $o : S \rightarrow O$ is a function that assigns an outcome to each strategy profile.
- For each player $i \in N$, $\succeq_i$ is a preference relation over $O$.

Sometimes it is more convenient to define a game by $G = (N, \{S_i\}_{i \in N}, \{u_i\}_{i \in N})$, where for each $i \in N$, the function $u_i : S \rightarrow \mathbb{R}$ is player $i$'s utility (or payoff) for each strategy profile. We say that $G$ is finite if $N$ is finite and $S$ is finite.

2.2. Nash equilibria. Given a strategy profile $s$, a profitable deviation for player $i$ is a strategy $s_i$ such that

$$o(s_{-i}, s_i) \succ_i o(s).$$

A strategy profile $s$ is a Nash equilibrium if no player has a profitable deviation. These are also called pure Nash equilibria, for reasons that we will see later. They are often just called equilibria.

2.3. Examples.

- Extensive form game with perfect information. Let $G = (N, A, H, O, o, P, \{\succeq_i\}_{i \in N})$ be an extensive form game with perfect information. Let $G'$ be the strategic form game given by $G' = (N', \{S_i\}_{i \in N}, O', o', \{\succeq_i'\}_{i \in N})$, where
  - $N' = N$.
  - $S_i$ is the set of $G$-strategies of player $i$.
  - $O' = O$.
  - For every $s \in S$, $o'(s) = o(s)$.
  - $\succeq_i' = \succeq_i$.

We have thus done nothing more than having written the same game in a different form. Note, however, that not every game in strategic form can be written as an extensive form game with perfect information.

Exercise 2.1. Show that $s \in S$ is a Nash equilibrium of $G$ iff it is a Nash equilibrium of $G'$. 


Note that a disadvantage of the strategic form is that there is no natural way to define subgames or subgame perfect equilibria.

**Matching pennies.** In this game, and in the next few, there will be two players: a row player (R) and a column player (C). We will represent the game as a payoff matrix, showing for each strategy profile \( s = (s_R, s_C) \) the payoffs \( u_R(s), u_C(s) \) of the row player and the column player.

\[
\begin{array}{c|cc}
 & H & T \\
\hline
H & 1,0 & 0,1 \\
T & 0,1 & 1,0 \\
\end{array}
\]

In this game each player has to choose either heads (H) or tails (T). The row player wants the choices to match, while the row player wants them to mismatch.

**Exercise 2.2.** Show that matching pennies has no pure Nash equilibria.

**Prisoner’s dilemma.**

Two prisoners are faced with a dilemma. A crime was committed in the prison, and they are the only two who could have done it. Each prisoner has to make a choice between testifying against the other (and thus betraying the other) and keeping her mouth shut. In the former case we say that the prisoner defected (i.e., betrayed the other), and in the latter she cooperated (with the other prisoner, not with the police).

If both cooperate (i.e., keep their mouths shut), they will have to serve the remainder of their sentences, which are 2 years each. If both defect (i.e., agree to testify against each other), each will serve 3 years. If one defects and the other cooperates, the defector will be released immediately, and the cooperator will serve 10 years for the crime.

Assuming that a player’s utility is minus the number of years served, the payoff matrix is the following.

\[
\begin{array}{c|cc}
 & D & C \\
\hline
D & -3,-3 & 0,-10 \\
C & -10,0 & -2,-2 \\
\end{array}
\]

**Exercise 2.3.** Show that the unique pure Nash equilibrium is \((D, D)\).
• **Battle of the sexes**\(^1\). Adam and Steve are a married couple. They have to decide whether to spend the night at the monster truck show (M) or at the opera (O). Adam (the row player) prefers the truck show, while Steve prefers the opera. Both would rather go out then do nothing, which is what would happen if they could not agree. Their payoff matrix is the following.

<table>
<thead>
<tr>
<th></th>
<th>M</th>
<th>O</th>
</tr>
</thead>
<tbody>
<tr>
<td>M</td>
<td>2,1</td>
<td>0,0</td>
</tr>
<tr>
<td>O</td>
<td>0,0</td>
<td>1,2</td>
</tr>
</tbody>
</table>

**Exercise 2.4.** *Find all the equilibria of this game.*

- **Bertrand.** There are \(n\) companies that are selling the same product. There are 1,000 customers who want to buy one product each, but will not buy if the price is more than $1,000. Each company has to set a price, which we will assume has to be an integral amount of dollars.

  All customers buy from the company that set the lowest price (unless all prices are more than $1,000, in which case they buy nothing). If more than one has set the lowest price then the revenue is split evenly between these companies. Therefore, if \(m\) companies chose the lowest price \(p\), then the payoff to each of these companies is \(1000 \cdot p/m\), and the payoff to the rest is zero.

**Exercise 2.5.** *Find all the equilibria of this game.*

Thought experiment: what can the members of the cartel do (in real life) to ensure that all set the price to $1,000?

- **The regulated cartel.** As in the previous game, there are \(n\) companies and 1,000 customers who will buy at $1,000 or less. There is a production cost \(p_{\text{prod}}\) to this product (which is the same for all companies) and the payoff for the company from selling a product is its price minus the production cost. As before, customers are split between the lowest priced companies.

  Regulation dictates that companies must sell at production cost plus $1. However, the regulator does not know the production cost \(p_{\text{prod}}\), which the companies do know.

  Hoping to solve this problem, the regulator has dictated that any company that sets a price \(p\) that is higher than the lowest set price \(p_{\text{min}}\) has to pay a fine of \(p - p_{\text{min}}\).

\(^1\)The name of this game seems archaic in this day and age, but we will keep it, as it is standard in the literature.
Exercise 2.6. *Find the equilibria of this game.*

- **Cournot.** Consider a finite set of companies $N$ that are selling the same product. Each has to decide on a quantity $q_i$ to manufacture. The function $D(p)$ describes the demand as a function of price, and we set denote its inverse by $P = D^{-1}$. Let $c(q)$ be the cost of manufacturing, as a function of quantity. Assuming prices are set so that all the manufactured goods are sold, company $i$'s payoff is

$$u_i(q_1, \ldots, q_n) = q_i \cdot P\left(\sum_i q_i\right) - c(q_i).$$

Exercise 2.7. Let $P(q) = A - B \cdot q$, and let $c(q) = C \cdot q$ (so that the cost per unit is independent of the amount manufactured), and assume $A > C$. Show that there is a Nash equilibrium in which all companies set the same quantity $q$, and calculate this $q$.

2.4. **Dominated strategies.** A strategy $s_i$ of player $i$ in $G = (N, \{S_i\}_{i \in N}, O, o, \{\succeq_i\}_{i \in N})$ is strictly dominated (or just dominated) if there exists another strategy $t_i$ such that, for all choices of strategy $s_{-i}$ of the other players it holds that

$$o(s_{-i}, t_i) \succ_i o(s_{-i}, s_i).$$

That is, regardless of what the other players do, $t_i$ is a better choice for $i$ than $s_i$.

We say that $s_i$ is weakly dominated if there exists another strategy $t_i$ such that for all $s_{-i}$

$$o(s_{-i}, t_i) \succeq_i o(s_{-i}, s_i),$$

and furthermore for some $s_{-i}$

$$o(s_{-i}, t_i) \succ_i o(s_{-i}, s_i).$$

Exercise 2.8. *Does matching pennies have strictly dominated strategies? Weakly dominated strategies? How about the prisoner’s dilemma? How about the regulated cartel?*

2.5. **Repeated elimination of dominated strategies.** It seems unreasonable that a reasonable person would choose a strictly dominated strategy, because she has an obviously better choice. Surprisingly, taking this reasoning to its logical conclusion leads to predictions that sharply contradict observed human behavior.

Consider the regulated cartel game $G$, and assume that $p_{prod} = 0$ and that the set of possible strategies is $\{\$1, \ldots, \$1000\}$. It is easy to
see that $1,000 is a dominated strategy; if all other companies choose $1,000 then $999 is a better strategy. If the lowest price $p_{\text{min}}$ is lower than $1,000, then still $999 is a better strategy, since then the fine is smaller. It is likewise easy to check that $1,000 is the only dominated strategy.

Since no reasonable player would choose $1,000, it is natural to define a new game $G'$ which is identical to $G$, except that the strategy space of every player no longer includes $1,000. Indeed, assuming that we are interested in equilibria, the following theorem guarantees that analyzing $G'$ is equivalent to analyzing $G$.

**Theorem 2.9.** Let $G = (N, \{S_i\}_{i \in N}, O, o, \{\preceq_i\}_{i \in N})$, let $d_j \in S_j$ be a dominated strategy of player $j$, and let $G' = (N, \{S'_i\}_{i \in N}, O, o', \{\preceq_i\}_{i \in N})$, where

$$S'_i = \begin{cases} S_i & \text{for } i \neq j \\ S_j \setminus \{d_j\} & \text{for } i = j \end{cases},$$

and $o'$ is the restriction of $o$ to $S'$.

Then every Nash equilibrium $s \in S$ of $G$ is in $S'$. Furthermore $s \in S'$ is a Nash equilibrium of $G$ if and only if it is a Nash equilibrium of $G'$.

The proof of this Theorem is straightforward and is left as an exercise.

Now, as before, it is easy to see that $999 is a dominated strategy for $G'$, and to therefore remove it from the set of strategies and arrive at a new game, $G''$. Indeed, if we repeat this process, we will arrive at a game in which the single strategy is $1. However, in experiments this is very rarely the chosen strategy\(^2\).

The following theorem of Gilboa, Kalai and Zemel [14] shows that the order of elimination of dominated strategies does not matter, as long as one continues eliminating until there are no more dominated strategies. Note that this is not true for weakly dominated strategies [14].

**Theorem 2.10** (Gilboa, Kalai and Zemel, 1990). Fix a finite game $G$, and let $G_1$ be a game that

- is the result of repeated elimination of dominated strategies from $G$, and
- has no dominated strategies.

Let $G_2$ be a game with the same properties. Then $G_1 = G_2$.

\(^2\)Except in populations of game theory students.
2.6. **Dominant strategies.** A strategy \( s_i \) of player \( i \) in \( G = (N, \{S_i\}_{i \in N}, O, o, \preceq_i) \) is **strictly dominant** if for every other strategy \( t_i \) it holds that
\[
o(s_{-i}, s_i) \succ_i o(s_{-i}, t_i).
\]
That is, regardless of what the other players do, \( t_i \) is a better choice for \( i \) than \( s_i \).

**Exercise 2.11.** Which of the games above have a strictly dominant strategy?

The proof of the following theorem is straightforward.

**Theorem 2.12.** If player \( i \) has a strictly dominant strategy \( d_i \) then, for every pure Nash equilibrium \( s^* \) it holds that \( s^*_i = d_i \).

2.7. **Mixed equilibria and Nash’s Theorem.** Given a finite set \( X \), denote by \( \Delta X \) set of probability distributions over \( X \).

Let \( G = (N, \{S_i\}, \{u_i\}) \) be a finite game. A **mixed strategy** \( \sigma_i \) is an element of \( \Delta S_i \). Given a mixed strategy profile \( \sigma = (\sigma_1, \ldots, \sigma_n) \), we overload notation and let \( o \) be the element of \( \Delta S \) given by the product \( \prod_i \sigma_i \). That is, \( o \) is the distribution over \( \prod_i S_i \) in which we pick independently from each \( S_i \), with distribution \( \sigma_i \).

Define a game \( \hat{G}(N, \{\hat{S_i}\}, \{\hat{u}_i\}) \) as follows:
- \( \hat{S}_i = \Delta S_i \).
- \( \hat{u}_i(\sigma) = \mathbb{E}_{s \sim \sigma}[u_i(s)] \).

That is, \( \hat{G} \) is a game whose strategies are the mixed strategies of \( G \), and whose utilities are the expected utilities of \( G \), taken with respect to the given mixed strategies. A pure Nash equilibrium of \( \hat{G} \) is called a **mixed Nash equilibrium** of \( G \). That is, a mixed strategy profile \( \sigma \in \prod_i \Delta S_i \) is a mixed Nash equilibrium if no player can improve her expected utility by deviating to another mixed strategy. We will often just say “Nash equilibrium” when referring to mixed equilibria. We will use \( u_i \) to also mean \( \hat{u}_i \); that is, we will extend \( u_i \) from a function \( S \to \mathbb{R} \) to a function \( \Delta S \to \mathbb{R} \).

Note that as a function \( \Delta S \to \mathbb{R} \), \( u_i \) is linear. That is,
\[
u_i(\alpha \sigma + (1 - \alpha)\tau) = \alpha u_i(\sigma) + (1 - \alpha)u_i(\tau).
\]

Nash’s celebrated theorem [24] states that every finite game has a mixed equilibrium.

**Theorem 2.13** (Nash, 1950). Every finite game has a mixed Nash equilibrium.

To prove Nash’s Theorem we will need Brouwer’s Fixed Point Theorem.
**Theorem 2.14** (Brouwer’s Fixed Point Theorem). Let $X$ be a compact convex subset of $\mathbb{R}^d$. Let $T: X \rightarrow X$ be continuous. Then $T$ has a fixed point. I.e., there exists an $x \in X$ such that $T(x) = x$.

Corollary: if you are in a room and hold a map of the room horizontally, then there is a point in the map that is exactly above the point it represents.

**Exercise 2.15.** Prove Brouwer’s Theorem for the case that $X$ is a convex compact subset of $\mathbb{R}$.

Consider a “lazy player” who, given that all players are currently playing a mixed strategy profile $\sigma$, has utility for playing some mixed strategy $\sigma'_{i}$ which is given by

$$g^o_{i}(\sigma') = u_i(\sigma_{-i}, \sigma'_{i}) - \lambda \|\sigma'_{i} - \sigma_{i}\|^2$$

for some $\lambda > 0$. That is, her utility has an extra addend which is lower the further away the new strategy is from her current strategy. Analyzing what happens when all players are lazy is the key to the following proof of Nash’s Theorem.

**Proof of Theorem 2.13.** Let $G = (N, \{S_i\}, \{u_i\})$ be a finite game. Let $f: \Delta S \rightarrow \Delta S$ be given by

$$[f(\sigma)]_i = \arg\max_{\sigma'_{i} \in \Delta S_i} g^o_{i}(\sigma')$$

It is straightforward to show that $f$ is continuous, and that this argmax is unique for $\lambda$ high enough.

Since we can think of $\Delta S$ as a convex subset of $\mathbb{R}^{|S|}$, $f$ has a fixed point $\sigma^*$, by Brouwer’s Theorem. We will show that $\sigma^*$ is a mixed Nash equilibrium.

Assume by contradiction that there exists a player $i$ and a $\sigma_i \in \Delta S_i$ such that

$$\delta := u_i(\sigma^*_{-i}, \sigma_i) - u_i(\sigma^*) > 0.$$  

Given any $\varepsilon > 0$, let $\tau_i^\varepsilon = (1 - \varepsilon) \cdot \sigma^*_{i} + \varepsilon \cdot \sigma_i$. Then

$$(2.1) \quad g^o_{i}(\tau_i^\varepsilon) = u_i(\sigma^*_{-i}, \tau_i^\varepsilon) - \lambda \|\tau_i^\varepsilon - \sigma^*_{i}\|^2.$$

Now, by the linearity $u_i$,

$$u_i(\sigma^*_{-i}, \tau_i^\varepsilon) = u_i(\sigma^*_{-i}, (1 - \varepsilon) \cdot \sigma^*_{i} + \varepsilon \cdot \sigma_i)$$

$$= (1 - \varepsilon) \cdot u_i(\sigma^*) + \varepsilon \cdot u_i(\sigma^*_{-i}, \sigma_i)$$

$$= u_i(\sigma^*) + \varepsilon \cdot \delta.$$
By the definition of $\tau_i^\varepsilon$
\[ \|\tau_i^\varepsilon - \sigma_i^*\|^2 = \|\varepsilon \cdot (\sigma_i - \sigma_i^*)\|^2 = \varepsilon^2 \|\sigma_i - \sigma_i^*\|^2. \]
Plugging these expressions back into (2.1) we get
\[ g_i^*(\tau_i^\varepsilon) = u_i(\sigma^*) + \varepsilon \cdot \delta - \varepsilon^2 \lambda \|\sigma_i - \sigma_i^*\|^2, \]
which, for $\varepsilon$ small enough, is greater than $u_i(\sigma^*)$. Hence
\[ \sigma_i^* \neq \arg\max_{\sigma'_i \in \Delta S_i} g_i^*(\sigma'_i), \]
and $\sigma^*$ is not a fixed point of $f$ - contradiction. \hfill \Box

2.8. **Best responses.** Let $G = (N, \{S_i\}, \{u_i\})$ be a finite game, and let $\sigma$ be a mixed strategy profile in $G$. We say that $s_i \in S_i$ is a best response to $\sigma_{-i}$ if, for all $t_i \in S_i$,
\[ u_i(\sigma_{-i}, s_i) \geq u_i(\sigma_{-i}, t_i). \]
This notion can be naturally extended to mixed strategies.

The following proposition is helpful for understanding mixed equilibria.

**Proposition 2.16.** Let $G = (N, \{S_i\}, \{u_i\})$ be a finite game, and let $\sigma^*$ be a mixed Nash equilibrium of $G$. Then any $s_i$ in the support of $\sigma_i^*$ (i.e., any $s_i$ to which $\sigma_i^*$ assigns positive probability) is a best response to $\sigma_{-i}$.

**Proof.** Suppose $s_i \in S_i$ is not a best response to $\sigma_{-i}^*$, and let $t_i \in S_i$ be some best response to $\sigma_{-i}^*$. We will prove the claim by showing that $t_i$ is a profitable deviation for $i$.

Let $C = u_i(\sigma_{-i}^*, t_i)$. Then $u_i(\sigma_{-i}^*, r_i) \leq C$ for any $r_i \in S_i$, and $u_i(\sigma_{-i}^*, s_i) < C$. It follows that
\[ u_i(\sigma^*) = \sum_{r_i \in S_i} \sigma_i^*(r_i) u_i(\sigma_{-i}^*, r_i) < C, \]
and so $t_i$ is indeed a profitable deviation, since it yields utility $C$ for $i$. \hfill \Box

It follows that if $\sigma^*$ is an equilibrium then $u_i(\sigma_{-i}^*, s_i)$ is the same for every $s_i$ in the support of $\sigma_i^*$. That is, $i$ is indifferent between all the pure strategies in the support of her mixed strategy.

The following claim is also useful for calculating mixed equilibria. In its proof we use the fact that if the expectation of a random variable $X$ is lower than $x$ then with positive probability $X < x$. 

Proposition 2.17. Let $G = (N, \{S_i\}, \{u_i\})$ be a finite game, and let $\sigma$ be a mixed strategy profile of $G$. Then $\sigma$ is a mixed equilibrium if and only if, for every player $i$, every $s_i$ in the support of $\sigma_i$ is a best response to $\sigma_{-i}$.

Proof. Assume that $\sigma$ is a mixed equilibrium. Then the claim follows by Proposition 2.16.

Assume now that $\sigma$ is not a mixed equilibrium. Then there exists a player $i$ and a strategy $\sigma'_i$ such that $u_i(\sigma_{-i}, \sigma'_i) > u_i(\sigma)$. Hence there exists a strategy $s'_i$ such that $u_i(\sigma_{-i}, s'_i) > u_i(\sigma)$. Hence there is some $t_i$ in the support of $\sigma_i$ such that $u_i(\sigma_{-i}, s'_i) > u_i(\sigma_{-i}, t_i)$, and we have proved the claim. □

2.9. Correlated equilibria.

2.9.1. Motivating example. Aumann [2] introduced the notion of a correlated equilibrium. Consider the following game, which is usually called “Chicken”. Consider two drivers who arrive at the same time to an intersection. Each one would like to drive on (strategy D) rather than yield (strategy Y), but if both drive then they run the risk of damaging the cars. If both yield time is wasted, but no egos are hurt.

The payoff matrix is the following.

<table>
<thead>
<tr>
<th></th>
<th>Y</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Y</td>
<td>3, 3</td>
<td>0, 5</td>
</tr>
<tr>
<td>D</td>
<td>5, 0</td>
<td>-4, -4</td>
</tr>
</tbody>
</table>

This game has three Nash equilibria: two pure ((Y, D) and (D, Y)) and one mixed, in which each player drives with probability 1/3.

Exercise 2.18. Show that this is indeed a mixed equilibrium.

The players’ expected utilities in these equilibria are (0, 5), (5, 0) and (2, 2).

A natural way to resolve this conflict is by the installation of a traffic light which would instruct each player whether to yield or drive. For example, the light could choose uniformly at random from (Y, D) and (D, Y). It is easy to convince oneself that a player has no incentive to disobey the traffic light, assuming that the other player is obeying it. The players’ utilities in this case become (2, 5, 2.5).

One could imagine a traffic light that chooses from \{ (Y, Y), (Y, D), (D, Y) \}, where the first option is chosen with probability $p$ and the second and third are each chosen with probability $(1 - p)/2$. Now, given that a player is instructed to drive, she knows that the other player has been instructed to yield, and so, if we again assume that the other player is obedient, she has no reason to yield.
Given that a player has been instructed to yield, she knows that the other player has been told to yield with conditional probability \( p_Y = p/(p + (1 - p)/2) \) and to drive with conditional probability \( p_D = ((1 - p)/2)/(p + (1 - p)/2) \). Therefore, her utility for yielding is \( 3p_Y \), while her utility for driving is \( 5p_Y - 4p_D \). It thus follows that she is not better off disobeying, as long as \( 3p_Y \geq 5p_Y - 4p_D \). A simple calculation shows that this is satisfied as long as \( p \leq 1/2 \).

Now, each player’s expected utility is \( 3p + 5(1 - p)/2 \). Therefore, if we choose \( p = 1/2 \), the players’ expected utilities are \( (2.75, 2.75) \). In this equilibrium the sum of the players’ expected utilities is larger than in any Nash equilibrium.

2.9.2. Definition. We now generalize and formalize this idea. Let \( G = (N, \{S_i\}_{i \in N}, \{u_i\}_{i \in N}) \) be a finite game. A distribution \( \mu \in \Delta S \) is a correlated equilibrium if for every player \( i \) and every \( s_i, t_i \in S_i \) it holds that

\[
\sum_{s_{-i}} \mu(s_{-i}, s_i) u_i(s_{-i}, s_i) \geq \sum_{s_{-i}} \mu(s_{-i}, s_i) u_i(s_{-i}, t_i).
\]

Player \( i \)'s expected utility under a correlated equilibrium \( \mu \) is simply \( \mathbb{E}_{s \sim \mu}[u_i(s)] \).

Note that for given \( i \) and \( s_i \), the condition in (2.2) is closed (i.e., if each of a converging sequence \( \{\mu_n\} \) of distributions satisfies it then so does \( \lim_n \mu_n \)). Note also that if \( \mu_1 \) and \( \mu_2 \) satisfy (2.2) then so does any convex combination of \( \mu_1 \) and \( \mu_2 \). These observations immediately imply the following claim.

Claim 2.19. The set of correlated equilibria is a compact, convex subset of \( \Delta S \).

An advantage of correlated equilibria is that they are easier to calculate than Nash equilibria, since they are simply the set of solutions to a linear program. It is even easy to find a correlated equilibrium that maximizes (for example) the sum of the players’ expected utilities, or indeed any linear combination of their utilities. Finding Nash equilibria can, on the other hand, be a difficult problem [15].

2.10. Trembling hand perfect equilibria.

2.10.1. Motivating example. Consider the following “Cuban missile crisis” game. There are two players: the US and the USSR. The USSR has to decide whether to station missiles in Cuba (\( S \)) or not (\( N \)). If the USSR chooses \( N \), the US does nothing. If the USSR chooses \( S \), US has to decide if to start a nuclear war (\( W \)) or forfeit (\( F \)). The payoff matrix in normal form is the following:
There are two equilibria to this game: \((S, F)\) and \((N, W)\). One way to eliminate the \((N, W)\) equilibrium is to consider the extensive form of this game, and to note that it is not subgame perfect. Another approach would be to consider that each player might make a mistake with some very small probability. Assume that the players play \((N, W)\), but that the USSR makes a mistake with some very small probability \(\varepsilon > 0\) and plays \(S\). Then the utility for the US for playing \(F\) is \(-\varepsilon\), whereas the utility for playing \(W\) is \(-10^{10}\varepsilon\). Hence for any \(\varepsilon > 0\), \(W\) is not a best response for \(N\). In a trembling hand perfect equilibrium we require each strategy to be a best response if it still is a best response for some arbitrarily small error. The formal definition follows.

2.10.2. Definition and results. Let \(G = (N, \{S_i\}, \{u_i\})\) be a finite game, and let \(\sigma\) be a mixed strategy profile in \(G\). We say that \(\sigma_i\) is completely mixed if it assigns positive probability to each \(s_i \in S_i\).

A mixed strategy profile \(\sigma\) is called a trembling hand perfect equilibrium [28] if there exists a sequence of completely mixed strategy profiles \(\{\sigma^k\}_{k \in \mathbb{N}}\) that converge to \(\sigma\) and such that, for each \(i \in N\) and \(k \in \mathbb{N}\), \(\sigma_i\) is a best response to \(\sigma^k_{-i}\).

**Exercise 2.20.** Show that every trembling hand perfect equilibrium is a Nash equilibrium.

**Claim 2.21.** Let \(s_i\) be a weakly dominated strategy of player \(i\). Then \(\sigma_i(s_i) = 0\) in any trembling hand perfect equilibrium \(\sigma\).

**Proof.** Let \(\{\sigma^k\}_{k \in \mathbb{N}}\) be a sequence of completely mixed strategy profiles that converge to \(\sigma\), and such that \(\sigma_i\) is a best response to \(\sigma^k_{-i}\) for all \(i\) and \(k\).

Since \(s_i\) is weakly dominated then there exists an \(s_{-i}\) and a \(t_i\) such that

\[ u_i(s_{-i}, s_i) < u_i(s_{-i}, t_i). \]

Since \(\sigma^k(s_{-i}, s_i) > 0\), and since \(u_i(s'_{-i}, s_i) \leq u_i(s'_{-i}, t_i)\) for all \(s'_{-i}\), it follows that \(s_i\) is not a best response to \(\sigma^k_{-i}\), and thus \(\sigma_i(s_i) = 0\). \(\square\)

In fact, for finite two player games, if \(\sigma\) is a mixed Nash equilibrium in which every strategy is not weakly dominated (as a mixed strategy), then \(\sigma\) is trembling hand perfect. In general, this is not true for games with more than two players.

2.11. **Zeros-sum games.**
2.11.1. A motivating example. Consider the following game [25]:

\[
\begin{array}{c|ccc}
J & 1 & 2 & 3 \\
\hline
J & +1, -1 & -1, +1 & -1, +1 \\
1 & -1, +1 & -1, +1 & +1, -1 \\
2 & -1, +1 & +1, -1 & -1, +1 \\
3 & -1, +1 & +1, -1 & -1, +1 \\
\end{array}
\]

Consider the point of view of the row player, and assume that she uses the mixed strategy \( \sigma_R \) in which \( J \) is played with some probability \( q \) and each of 1, 2 and 3 is played with probability \( (1-q)/3 \). Then

\[
u_R(\sigma_R, J) = 2q - 1 \quad \text{and} \quad u_R(\sigma_R, 1) = u_R(\sigma_R, 2) = u_R(\sigma_R, 3) = 1/3 - 4q/3.
\]

If we assume that the column player knows what \( q \) is and would do what is best for her (which here happens to be what is worst for the row player), then the row player would like to choose \( q \) that maximizes the minimum of \{2q - 1, 1/3 - 4q/3\}. This happens when \( q = 2/5 \), in which case the row player’s utility is \(-1/5\), regardless of which (mixed!) strategy the column player chooses.

The same reasoning can be used to show that the column player will also choose \( q = 2/5 \). Her expected utility will be be \(+1/5\). Note that this strategy profile (with both using \( q = 2/5 \)) is a mixed Nash equilibrium, since both players are indifferent between all strategies.

2.11.2. Definition and results. A two player game \( G = (\{1, 2\}, \{S_i\}, \{u_i\}) \) is called zero-sum if \( u_1 + u_2 = 0 \). For such games we drop the subscript on the utility functions and use \( u := u_1 \).

A general normal form game may have cooperative components (see, e.g., the battle of the sexes game), in the sense that moving from one strategy profile to another can benefit both players. However, zero-sum games are competitive: whatever one player gains the other loses. Hence a player may want to prepare herself for the worst possible outcome, namely one in which, given her own strategy, her opponent will choose the strategy yielding her the minimal utility. Hence an interesting quantity for a strategy \( \sigma_1 \) for player 1 is the guaranteed utility \( u_g \) when playing \( \sigma_1 \):

\[
u_g(\sigma_1) = \min_{\sigma_2 \in S_2} u(\sigma_1, \sigma_2).
\]

Continuing with this line of reasoning, player 1 will choose a strategy that maximizes her guaranteed utility. She would thus choose an action
Any such strategy is called a maxmin strategy for player 1. It gives her the best possible guaranteed utility, which is

$$\max_{\sigma_1 \in \Delta S_1} \min_{\sigma_2 \in \Delta S_2} u(\sigma_1, \sigma_2).$$

The next theorem shows that maxmin strategies and mixed Nash equilibria are closely related in zero-sum games.

**Theorem 2.22** (Borel, 1921, von Neumann, 1928). Let $G$ be a finite zero-sum game.

1. In every mixed Nash equilibrium $\sigma^*$ each strategy is a maxmin strategy for that player.
2. There is a number $v \in \mathbb{R}$ such that
   $$\max_{\sigma_1 \in \Delta S_1} \min_{\sigma_2 \in \Delta S_2} u(\sigma_1, \sigma_2) = v,$$
   and
   $$\max_{\sigma_2 \in \Delta S_2} \min_{\sigma_1 \in \Delta S_1} -u(\sigma_1, \sigma_2) = -v.$$  

The quantity $v$ is called the value of $G$. It follows that $u(\sigma^*) = v$ for any equilibrium $\sigma^*$.

**Proof of Theorem 2.22.** In this proof we will disencumber notation by shortening $\max_{\sigma_1 \in \Delta S_1}$ to simply $\max_{\sigma_1}$, etc.

1. Let $\sigma^*$ be a mixed Nash equilibrium of $G$. Without loss of generality, it suffices to show that $\sigma^*_1$ is a maxmin strategy for player 1.
   
   Since $\sigma^*_1$ is a best response of player 1,
   $$\max_{\sigma_1} u(\sigma_1, \sigma^*_2) = u(\sigma^*_1, \sigma^*_2).$$
   
   Since $\min_{\sigma_2} u(\sigma_1, \sigma_2) \leq u(\sigma_1, \sigma^*_2)$, we can write
   $$\max_{\sigma_1} \min_{\sigma_2} u(\sigma_1, \sigma_2) \leq u(\sigma^*_1, \sigma^*_2).$$  

   Now, assume by contradiction that $\sigma^*_1$ is not a maxmin strategy, so that $\max_{\sigma_1} u_y(\sigma_1) > u_y(\sigma^*_1)$. I.e.,
   $$\max_{\sigma_1} \min_{\sigma_2} u(\sigma_1, \sigma_2) > \min_{\sigma_2} u(\sigma^*_1, \sigma_2),$$
   
   Since $\sigma^*_2$ is a best response of player 2, it maximizes her utility, which, since this is a zero-sum game, minimizes player 1’s
utility. Hence we have that \( \min_{\sigma_2} u(\sigma_1^*, \sigma_2) = u(\sigma_1^*, \sigma_2^*) \), and we deduce that

\[
\max_{\sigma_1} \min_{\sigma_2} u(\sigma_1, \sigma_2) > u(\sigma_1^*, \sigma_2^*).
\]

But this contradicts (2.3). We have thus shown that \( \sigma_1^* \) is a maximin strategy for player 1.

(2) Let \( \sigma^* \) be an arbitrary mixed equilibrium of \( G \); at least one exists by Nash’s Theorem. We first show that

\[
\max_{\sigma_1} \min_{\sigma_2} u(\sigma_1, \sigma_2) = u(\sigma^*).
\]

Note that

\[
u(\sigma^*) = \min_{\sigma_2} u(\sigma_1^*, \sigma_2),
\]

since, as argued above, \( \sigma_2 \) is a best response for player 2, which by the zero-sum nature of the game minimizes player 1’s utility. But certainly

\[
\max_{\sigma_1} \min_{\sigma_2} u(\sigma_1, \sigma_2) \geq \min_{\sigma_2} u(\sigma_1^*, \sigma_2),
\]

and so we have shown that

\[
\max_{\sigma_1} \min_{\sigma_2} u(\sigma_1, \sigma_2) \geq u(\sigma^*).
\]

By (2.3) the other inequality also holds, and thus

\[
\max_{\sigma_1} \min_{\sigma_2} u(\sigma_1, \sigma_2) = u(\sigma^*).
\]

The same argument applied with the roles of the players reversed shows that

\[
\max_{\sigma_1} \min_{\sigma_2} -u(\sigma_1^*, \sigma_2) = -u(\sigma^*),
\]

and thus our proof is complete, with \( v = u(\sigma^*) \).

\( \square \)

In this proof we used Nash’s Theorem to generate a mixed Nash equilibrium of this game. In fact, the existence of Nash equilibria in zero-sum games can be proved using convex analysis methods, and this was done by Borel [7] and von Neumann [29] long before Nash’s Theorem. Moreover, in zero-sum games equilibria can be found by solving a linear program, which, as observed in the previous section, is easier than the general problem of finding mixed Nash equilibria.
3. Knowledge and Belief

3.1. Knowledge.

3.1.1. The hats riddle. The hats riddle is a motivating example for studying knowledge. Consider \( n \) players, each of which is wearing a hat that is either red (r) or blue (b). The players each observe the others’ hats, but do not observe their own.

An outside observer announces in the presence of all the players that “At least one of you has a red hat.” They now play the following (non-strategic) game: a clock is set to ring every minute. At each ring, anyone who knows the color of their hat announces it, in which case the game ends. Otherwise the game continues.

**Exercise 3.1.** What happens?

We will formally analyze what transpires, after introducing some concepts and notation.

3.1.2. Knowledge spaces. Consider a situation in which there is uncertainty regarding one or more variables of interest. The set of all possible combinations of values of these variables is called the set of *states of the world*, so that knowing the state of the world is equivalent to knowing all there is to know and thus having no uncertainty.

We refer to a player’s *type* as the information (or the type of information) this player has regarding the state of the world. Thus, for example, one player may know one variable of interest, another player may know another variable, and a third could know the sum of the first two variables. A fourth could just know whether the first variable is non-zero.

Formally, a *knowledge space*\(^4\) is a tuple \( (N, (\Omega, \Sigma), \{T_i\}_{i \in N}, \{t_i\}_{i \in N}) \) where

- \( N \) is a set of players.
- \( (\Omega, \Sigma) \) is measurable space of the *states of the world*. For finite \( \Omega \) we will always take \( \Sigma = 2^\Omega \), and sometimes not write \( \Sigma \) explicitly.
- \( T_i \) the space of possible types of player \( i \). In general it will also be equipped with a sigma-algebra, which we suppress here.
- \( t_i : \Omega \to T_i \) is player \( i \)'s *private signal* or *type*.

We naturally require that \( t_i \) be measurable. To facilitate notation, especially in the finite case, we define \( P_i : \Omega \to \Sigma \) by

\[
P_i(\omega) = t_i^{-1}(t_i(\omega)).
\]

\(^4\)This terminology is non-standard.
That is, \( P_i(\omega) \) is the set of states of the world for which player \( i \) has the same type as she does in \( \omega \). It is easy to show that \( \omega \in P_i(\omega) \). The set \( \{ P_i(\omega) \}_{\omega \in \Omega} \) is easily seen to be a partition of \( \Omega \), and is usually called \( i \)'s information partition. A knowledge space can thus be given as \( (N, (\Omega, \Sigma), \{ P_i \}_{i \in N}) \).

As an example, consider two weather forecasters. Each has a computer program to which she feeds the current meteorological data, and which runs a random simulation. The program’s output is either rain (R) or shine (S). Hence we let \( \Omega = \{R, S\}^3 \); the first coordinate is the first forecaster’s program’s output, and the second coordinate is the second’s output. The last coordinate is the “truth” - the actual weather tomorrow. Additionally, a third player just knows whether or not the two forecasters agree (A) or disagree (D).

Each of the players gets to observe her program’s forecast only. Hence \( t_1(\omega_1, \omega_2, \omega_3) = \omega_1 \) and \( t_2(\omega_1, \omega_2, \omega_3) = \omega_2 \) with \( T_1 = T_2 = \{R, S\} \). \( T_3 = \{A, D\} \), with \( t_3(\omega_1, \omega_2, \omega_3) \) equal to \( A \) if \( \omega_1 = \omega_2 \), and to \( D \) otherwise; see Table 3.1.2.

<table>
<thead>
<tr>
<th>( \omega )</th>
<th>( t_1(\omega) )</th>
<th>( t_2(\omega) )</th>
<th>( t_3(\omega) )</th>
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<tbody>
<tr>
<td>RRR</td>
<td>R</td>
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<tr>
<td>RRS</td>
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<td>RSS</td>
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<td>SRR</td>
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<td>SRS</td>
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<tr>
<td>SSR</td>
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<tr>
<td>SSS</td>
<td>S</td>
<td>S</td>
<td>A</td>
</tr>
</tbody>
</table>

Table 1. The forecasters’ knowledge space.

Let us consider the knowledge space associated to the hats riddle, before it is declared that at least one player has a red hat. Here, \( \Omega = \{r, b\}^n \), \( T_i = \{r, b\}^{n-1} \) and \( t_i(\omega) = \omega_{-i} \).

After it is declared that at least one hat is red, we can take the space of states of the world to be \( \Omega = \{r, b\}^n \setminus \{(b, \ldots, b)\} \). Accordingly,

\[
P_i(\omega) = \{(\omega_{-i}, r), (\omega_{-i}, b)\},
\]
unless $\omega_i = (b, \ldots, b)$, in which case
$$P_i(\omega) = \{(\omega_i, r)\} = \{\omega\},$$
since $(b, \ldots, b) \not\in \Omega$.

3.1.3. **Knowledge.** Let $(N, (\Omega, \Sigma), \{T_i\}_{i \in N}, \{t_i\}_{i \in N})$ be a knowledge space. Let $A \in \Sigma$ be an event. We say that player $i$ knows $A$ at $\omega$ if $P_i(\omega) \subseteq A$, or, equivalently, if $t_i(\omega') = t_i(\omega)$ implies that $\omega' \in A$. Intuitively, when $\omega$ occurs, $i$ does not know that - she only knows that $P_i(\omega)$ occurred. She thus knows that $A$ occurred only if $P_i(\omega)$ is contained in $A$.

Given an event $A \in \Sigma$, let $K_iA$ be the set of states of the world in which $i$ knows $A$:
$$K_iA = \{\omega : P_i(\omega) \subseteq A\}.$$ Equivalently,
$$K_iA = \bigcup\{P_i(\omega) : P_i(\omega) \subseteq A\}.$$  

**Theorem 3.2** (Kripke’s S5 system). (1) $K_i\Omega = \Omega$. A player knows that some state of the world has occurred.

(2) $K_iA \cap K_iB = K_i(A \cap B)$. A player knows $A$ and a player knows $B$ if and only if she knows $A$ and $B$.

(3) Axiom of knowledge. $K_iA \subseteq A$. If a player knows $A$ then $A$ has indeed occurred.

(4) Axiom of positive introspection. $K_iK_iA = K_iA$. If a player knows $A$ then she knows that she knows $A$.

(5) Axiom of negative introspection. $(K_iA)^c = K_i(K_iA)^c$. If a player does not know $A$ then she knows that she does not know $A$.

**Proof.** (1) This follows immediately from the definition.

(2) 
$$K_iA \cap K_iB = \{\omega : P_i(\omega) \subseteq A\} \cap \{\omega : P_i(\omega) \subseteq B\}$$
$$= \{\omega : P_i(\omega) \subseteq A, P_i(\omega) \subseteq B\}$$
$$= \{\omega : P_i(\omega) \subseteq A \cap B\}$$
$$= K_i(A \cap B).$$

(3) By definition, if $\omega \in K_iA$ then $P_i(\omega) \subseteq A$. Since $\omega \in P_i(\omega)$, it follows that $\omega \in A$. Hence $K_iA \subseteq A$.

(4) By the previous part we have that $K_iK_iA \subseteq K_iA$.

To see the other direction, let $\omega \in K_iA$, so that $P_i(\omega) \subseteq A$. Choose any $\omega' \in P_i(\omega)$. Hence $P_i(\omega') = P_i(\omega)$, and it follows that $\omega' \in K_iA$. Since $\omega'$ was an arbitrary element of $P_i(\omega)$,
we have shown that $P_i(\omega) \subseteq K_iA$. Hence, by definition, $\omega \in K_iK_iA$.

(5) The proof is similar to that of the previous part.

Interestingly, if a map $L: 2^\Omega \rightarrow 2^\Omega$ satisfies the Kripke S5 system axioms, then it is the knowledge operator for some type: there exists a type space $T$ and a function $t: \Omega \rightarrow 2^\Omega$ such that $L$ is equal to the associated knowledge operator given by

$$KA = \{ \omega : P(\omega) \subseteq A \},$$

where $P(\omega) = t^{-1}(t(\omega))$.

3.1.4. Knowledge in terms of sigma-algebras. A useful way to formulate knowledge is in terms of sigma-algebras. Note this is not the usual choice in this literature.

Let $(N, \Omega, \{ P_i \}_{i \in N})$ be a finite knowledge space. Denote by $\Sigma_i$ the sigma-algebra generated by $i$’s information partition $\{ P_i(\omega) \}_{\omega \in \Omega}$. That is, $\Sigma_i$ is the collection of all sets that are unions of sets of the form $P_i(\omega)$, for some $\omega \in \Omega$.

**Proposition 3.3.** Let $A \in \Sigma$. Then $K_iA \in \Sigma_i$, and in particular

$$K_iA = \cup\{ S \in \Sigma_i : S \subseteq A \}.$$

Since any finite sigma-algebra is closed to unions, it follows that $K_iA$ is the largest element of $\Sigma_i$ that is contained in $A$. The proof of this claim follows immediately from the definition of $K_i$. It is important to note that we can take this to be a definition of $K_i$. The advantage of this definition is that it is entirely in terms of our newly defined sigma-algebras $\{ \Sigma_i \}$. Also, Theorem 3.2 is (more) immediate, using this definition.

We will occasionally define knowledge spaces using these sigma-algebras only. That is, a knowledge space will be given by a tuple $(N, \Omega, \{ \Sigma_i \}_{i \in N})$.

**Exercise 3.4.** Given a finite knowledge space $B = (N, \Omega, \{ \Sigma_i \}_{i \in N})$ find a knowledge space $B' = (N, \Omega, \{ T_i \}_{i \in N}, \{ t_i \}_{i \in N})$ such that each $\Sigma_i$ is the sigma-algebra generated by player $i$’s information partition in $B'$.

3.1.5. Back to the hats riddle. Denote by $\omega^k$ the state of the world in which players 1 through $k$ have a red hat, and the rest have a blue hat.

Assume that the actual state of the world is $\omega^k$ for some $k \geq 1$ (this is without loss of generality, by renaming the players), and consider the situation from the point of view of player $k$. 

If $k = 1$ then initially player 1 already knows her color, since $\omega_1 = (b, \ldots, b)$, and so $P_1(\omega) = \{\omega\}$. No other player knows her color, and hence at time period $t = 1$ player 1 alone will announce it, and the game will end.

If $k > 1$, player $k$’s information partition is $P_k(\omega_k) = \{\omega_k, \omega_k - 1\}$. Hence she knows that there are either $k - 1$ or $k$ red hats, depending on whether or not her hat is red. Denote by $R_{\geq k}$ the event that there are at least $k$ red hats. Then $\omega_k \in K_k R_{\geq k - 1}$ (and of course by symmetry $\omega^k \in K_i R_{\geq k - 1}$ for all $i \leq k$). That is, player $k$ knows that there are at least $k - 1$ red hats. Note that $\omega_k \not\in K_k R_{\geq k - 1}$; that is, player $k$ does not know that there are at least $k$ red hats.

We now make the following crucial observation.

**Claim 3.5.** $\omega^k \not\in K_k K_{k - 1} R_{\geq k - 1}$.

That is, at $\omega^k$ player $k$ does not know that player $k - 1$ also knows that there are at least $k - 1$ red hats.

**Proof.** Note that $\omega^{k - 1} \in P_k(\omega^k)$, but that $\omega^{k - 1} \not\in K_{k - 1} R_{\geq k - 1}$, since player $k - 1$ does not know that there are at least $k - 1$ red hats when the state of the world is $\omega^{k - 1}$. Hence $P_k(\omega^k) \not\subseteq K_k R_{\geq k - 1}$, and so indeed $\omega^k \not\subseteq K_k K_{k - 1} R_{\geq k - 1}$. □

For example, if $k = 100$, then player 100 knows in $\omega^{100}$ that there are at least 99 red hats, but she does not know that player $k - 1$ knows that.

The next claim generalized the previous one.

**Claim 3.6.** For all $1 < k \leq n$ and $i < k$ it holds that

$$\omega^k \not\subseteq K_k K_{k - 1} \cdots K_{k - i} R_{\geq k - i}.$$  

The proof of this claim is essentially a repetition of the argument above.

**Proof.** We prove by induction on $i$. For $i = 0$ and any $1 < k \leq n$ the claim can be restated to say that

$$\omega^k \not\subseteq K_k R_{\geq k}.$$  

This is immediate, by (3.1); intuitively, player 1 observes only $k - 1$ red hats and so does not know that there are at least $k$ red hats.

For general $k$ and $i$, assume that we have proved the claim for $i' = i - 1$ and $k' = k - 1$. Then by the inductive assumption

$$\omega^{k - 1} \not\subseteq K_{k - 1} \cdots K_{k - i} R_{\geq k - i}.$$
But $\omega^{k-1} \in P_k(\omega^k)$, and so

$$P_k(\omega^k) \not\subseteq K_{k-1} \cdots K_{k-i} R^{k-i}.$$  

Thus

$$\omega^k \not\subseteq K_k K_{k-1} \cdots K_{k-i} R^{k-i}.$$  

□

It follows that in particular, for $k > 1$,

$$\omega^k \not\subseteq K_k K_{k-1} \cdots K_2 R^{k-2}.$$  

That is, player $k$ does not know that player $k-1$ knows that player $k-2$ knows... that player 2 knows that there are at least 2 red hats. This holds even when $k$ is (say) 100, and so everyone knows that there are either 99 or 100 red hats!

3.1.6. **Common knowledge.** Let $(N, \Omega, \{T_i\}_{i \in N}, \{t_i\}_{i \in N})$ be a finite knowledge space. An event $A$ is said to be **common knowledge** at $\omega \in \Omega$ if for any sequence $i_1, i_2, \ldots, i_k \in N$ it holds that

$$\omega \in K_{i_1} K_{i_2} \cdots K_{i_k} A.$$  

We will give two characterizations of common knowledge events. In order to introduce these we will need a few definitions.

Let $\Sigma, \Pi$ be two sub-sigma-algebras of some sigma-algebra. We say that $\Sigma$ is a **refinement** of $\Pi$ if $\Pi \subseteq \Sigma$. In this case we also say that $\Pi$ is a **coarsening** of $\Sigma$.

The **meet** of two sigma-algebras is $\Sigma_1, \Sigma_2 \subseteq \Sigma$ is the finest sub-sigma-algebra of $\Sigma$ that is a coarsening of each $\Sigma_i$. Their **join** is the coarsest sub-sigma-algebra of $\Sigma$ that is a refinement of each $\Sigma_i$.

**Exercise 3.7.** Show that the meet of $\Sigma_1$ and $\Sigma_2$ is their intersection $\Sigma_1 \cap \Sigma_2$. Show that their join is the sigma-algebra generated by $\{S_1 \cap S_2 : S_1 \in \Sigma_1, S_2 \in \Sigma_2\}$.

Let $\Sigma_C = \cap_i \Sigma_i$ be the meet of the player’s sigma-algebras.

**Claim 3.8.** If $C \in \Sigma_C$ then $K_i C = C$ for all $i \in N$.

**Proof.** This is an immediate consequence of the sigma-algebraic definition of $K_i$, and the fact that any $C \in \Sigma_C$ is also in $\Sigma_i$. □

We will now define an undirected graph $G$, whose vertices are the elements of $\Omega$, and where there is an edge between $\omega, \omega' \in \Omega$ if there exists a player $i$ such that $P_i(\omega) = P_i(\omega')$. Let $C(\omega)$ be the **connected component** of $\omega$; that is the maximal set of vertices in the graph for which there exists a path from $\omega$. Here, a path from $\omega$ to $\omega'$ is a sequence
of edges \((\omega_1, \omega_2), (\omega_2, \omega_3), (\omega_3, \omega_4), \ldots, (\omega_{k-1}, \omega_k)\) such that \(\omega_1 = \omega\) and \(\omega_k = \omega'\).

**Theorem 3.9.** Given a finite knowledge space \((N, \Omega, \{\Sigma_i\}_{i \in N})\), a state of the world \(\omega \in \Omega\) and an event \(A\), the following are equivalent.

1. \(A\) is common knowledge at \(\omega\).
2. \(C(\omega) \subseteq A\).
3. There exists a \(C \in \Sigma_C\) such that \(\omega \in C\) and \(C \subseteq A\).

**Proof.** We first show that (1) implies (2). Choose an arbitrary \(\omega' \in C(\omega)\); we will show that \(\omega' \in A\). Since \(\omega' \in C(\omega)\), there exists a path \((\omega_1, \omega_2), (\omega_2, \omega_3), \ldots, (\omega_{k-1}, \omega_k)\) such that \(\omega_1 = \omega\) and \(\omega_k = \omega'\). There exists therefore a sequence of players \(i_1, \ldots, i_{k-1}\) such that \(P_{i_j}(\omega_j) = P_{i_j}(\omega_{j+1})\).

Now, by the common knowledge assumption

\[
\omega = \omega_1 \in K_{i_1}K_{i_2} \cdots K_{i_{k-1}}A.
\]

Hence

\[
P_{i_1}(\omega_1) \in K_{i_2} \cdots K_{i_{k-1}}A
\]

and in particular

\[
\omega_2 \in K_{i_2} \cdots K_{i_{k-1}}A,
\]

since \(\omega_2 \in P_{i_1}(\omega_1)\). Applying this argument inductively yields \(\omega' = \omega_k \in A\), and thus we have shown that \(C(\omega) \subseteq A\).

To show that (2) implies (3) we show that \(C(\omega) \in \Sigma_C\). To this end it suffices to show that \(C(\omega) \in \Sigma_i\) for all \(i \in N\). Let \(\omega' \in C(\omega)\). Then, by the definition of the graph \(G\), \(P_i(\omega') \subseteq C(\omega)\). Hence \(C(\omega)\) is a union of sets of the form \(P_i(\omega')\), and thus it is an element of \(\Sigma_i\).

Finally, we show that (3) implies (1). Choose \(C \in \Sigma_C\) such that \(\omega \in C\) and \(C \subseteq A\). Let \(i_1, i_2, \ldots, i_k\) be an arbitrary sequence of players. We first prove that

\[
\omega \in K_{i_1}K_{i_2} \cdots K_{i_k}C.
\]

By Claim 3.8

\[
K_{i_1}K_{i_2} \cdots K_{i_k}C = C,
\]

and since \(\omega \in C\) we have shown that

\[
\omega \in K_{i_1}K_{i_2} \cdots K_{i_k}C.
\]

Finally, since \(C \subseteq A\),

\[
K_{i_1}K_{i_2} \cdots K_{i_k}C \subseteq K_{i_1}K_{i_2} \cdots K_{i_k}A
\]
and thus we also have that
\[ \omega \in K_{i_1}K_{i_2} \cdots K_{i_k} A. \]

3.1.7. Back again to the hats riddle. After the declaration that at least one person has a red hat \( R_{\geq 1} \) becomes common knowledge; in fact, by our definition, \( R_{\geq 1} = \Omega \), and the entire space is always common knowledge.

We will denote by \( R^k \) the event that there are exactly \( k \) red hats.

**Theorem 3.10.** At \( \omega \in R^k \) all players with red hats declare their color at round \( k \).

We will prove this theorem using the following lemma:

**Lemma 3.11.** Assume that at some round it holds that \( R_{\geq k} \) is common knowledge at some \( \omega \). If \( \omega \in R^k \) then all the players with red hats will declare their color. Otherwise \( R_{\geq k+1} \) becomes common knowledge.

**Proof.** Assume that \( R_{\geq k} \) is common knowledge at \( \omega \) on some round. If \( \omega \in R^k \) then every player with a red hat observes exactly \( k-1 \) other red hats, and so knows that \( \omega \in R^k \), and hence will declare her color. Thus if no-one declares then \( \omega \notin R^k \), and furthermore this becomes common knowledge. Hence it becomes common knowledge that \( \omega \in R_{\geq k+1} \).

**Proof of Theorem 3.10.** We first prove by induction that \( R_{\geq \ell} \) is common knowledge the beginning of round \( \ell \leq k \). At the beginning of round 1 \( R_{\geq 1} \) is common knowledge, as it was declared. Assume that we have shown the claim for \( \ell - 1 \). Then if player 1 did not declare her color at round \( \ell - 1 \) then, by the inductive assumption \( R_{\geq \ell-1} \) was common knowledge at the beginning of that round, and thus by the lemma \( R_{\geq \ell} \) becomes common knowledge.

Applying this to \( \ell = k \) we get that \( R^k \) is common knowledge at the beginning of round \( k \). Hence, by another application of the lemma, all the players with the red hats will declare their colors.

3.2. Beliefs. Let \( (\Omega, \Sigma) \) be measurable space. A belief of a player over \( (\Omega, \Sigma) \) is a probability measure on \( (\Omega, \Sigma) \).

3.2.1. A motivating example. Beliefs are useful for modeling uncertainty. For example, consider a monopoly seller who would like to sell a single object to a single buyer. The value of the product to the buyer is \( v \). The sellers sets a price \( p \); hence her strategy space is \( \mathbb{R} \). The buyer learns \( p \) and then decides to either buy or not to buy.
her strategies can each be characterized by a set $B \subseteq \mathbb{R}$ of the prices in which she decides to buy.

If the buyer buys then her utility is $v - p$, and the seller’s utility is $p$. Otherwise both have zero utility. Note that this is an (infinite) extensive form game with perfect information.

**Exercise 3.12.** Prove that if the seller knows $v$ then a subgame perfect equilibrium is for the seller to choose $p = v$ and for the buyer to buy if and only if $p \leq v$.

We would like to model the case in which the seller does not know $v$ exactly. One way to do this is to assume that the seller has some belief $\mu$ over $v$. That is, she believes that $v$ is chosen at random from $\mu$. Given this belief, she now has to choose a price $p$. The seller first learns $v$. She then learns $p$ and has to decide whether or not to buy. Thus a strategy of the buyer is a (measurable) set $B \subseteq \mathbb{R}^2$, where she buys at price $p$ iff $(p, v) \in B$. The buyer’s utility is now the expected price that the seller paid, given that she bought, and where expectations are taken with respect to $\mu$. The buyer’s utility is, as before, $v - p$ if she buys and zero otherwise.

Assume that the seller’s belief can be represented by a probability distribution function $f: [0, \infty) \to \mathbb{R}$, so that the probability that $v \in [a, b)$ is $\int_a^b f(v)dv$. Then the seller’s utility for strategy profile $(p, B)$ is

$$u_S(p, B) = p \cdot \int 1_{\{(p, v) \in B\}} f(v)dv.$$ 

Assume that the buyer’s strategy is to buy whenever $p \leq v$ or whenever $p < v$; the following calculation will be the same in both cases, since player 1’s belief is non-atomic. Then the seller’s utility is

$$u_S(p) = p \cdot \int_p^\infty f(v)dv,$$

which we can write as $p \cdot (1 - F(p))$, where $F(x) = \int_0^x f(x)dx$ is the cumulative distribution function associated with $f$. To find the seller’s best response we need to find a maximum of $u_S$. Its derivative with respect to $p$ is

$$\frac{du_S}{dp} = 1 - F(p) - p \cdot f(p).$$

Hence in any maximum it will be the case that

$$p = \frac{1 - F(p)}{f(p)}.$$
It is easy to show that if this equation has a single solution then this solution is a maximum. In this case \( p \) is called the monopoly price.

**Exercise 3.13.** Let

\[
f(v) = \begin{cases} 
0 & \text{if } v < v_0 \\
v_0^2 & \text{if } v \geq v_0
\end{cases}
\]

for some \( v_0 \). Calculate \( u_S(p) \). Under the seller’s belief, what is the buyer’s expected utility as a function of \( p \)?

**Exercise 3.14.** Let \( f(v) = \frac{1}{v_0} \cdot e^{-v/v_0} \) for some \( v_0 > 0 \). Calculate the monopoly price. Under the seller’s belief, what is the buyer’s expected utility as a function of \( p \)?

3.2.2. **Belief spaces.** A belief space is a tuple \((N, (\Omega, \Sigma), \{\mu_i\}_{i \in N}, \{T_i\}_{i \in N}, \{t_i\}_{i \in N})\) where

- \((N, (\Omega, \Sigma), \{T_i\}_{i \in N}, \{t_i\}_{i \in N})\) is a knowledge space.
- \(\mu_i\) is player \(i\)’s belief over \((\Omega, \Sigma)\).

We denote by \(\mu_i(E|t_i)\) the probability, under \(\mu_i\), of the event \(E \in \Sigma\), conditioned on \(t_i\). When \(\Omega\) is finite, this is given by

\[
\mu_i(E|t_i(\omega)) = \frac{\mu_i(E \cap P_i(\Omega))}{\mu_i(P_i(\Omega))}.
\]

(3.2)

If the different \(\mu_i\)’s are equal then we say that the players have a common prior. This will be a common assumption.

Consider again the example of the two weather forecasters. The forecasters believe that half the days have rain and a half do not, that their programs predict the future with some probability \(p > 1/2\), and that the programs fail or succeed independently from each other. This is reflected in the common prior \(\mu\), as detailed in Table 3.2.2.

**Exercise 3.15.** What is the probability that player 1 assigns to the event \(t_2 = R\), conditioned on \(t_1 = R\)? Conditioned on \(t_1 = S\)? What probability does she assign to \(\omega_3 = R\) in each of these cases?

Let \(A \in \Sigma\) be an event. We say that player \(i\) believes \(A\) at some \(\omega \in \Omega\) if \(\mu_i(A|t_i(\omega)) = 1\). As the next claim shows, to believe an event is the same as knowing it, in finite beliefs spaces with fully supported priors. In general, however, this is a different notion.

**Claim 3.16.** Let \(\Omega\) be finite. Then if \(i\) knows \(A\) at \(\omega\) then \(i\) believes \(A\) in \(\omega\). If furthermore \(\mu_i(\theta) > 0\) for all \(\theta \in \Omega\), then the opposite implication holds too.
Proof. Assume first that $P_i(\omega) \subseteq A$. Then

$$\mu_i(A|t_i(\omega)) \geq \mu_i(P_i(\omega)|t_i(\omega)).$$

By (3.2), when $\Omega$ is finite the right hand side is equal to 1, and we have shown the first part of the claim.

Assume now that $\mu_i(A|t_i(\omega)) = 1$ and that $\mu_i(\theta) > 0$ for all $\theta \in \Omega$. Then

$$1 = \mu_i(A|t_i(\omega)) = \frac{\mu_i(A \cap P_i(\omega))}{\mu_i(P_i(\omega))}.$$

Hence

$$\mu_i(A \cap P_i(\omega)) = m\mu_i(P_i(\omega)),$$

which implies that

$$\mu_i(P_i(\omega) \setminus (A \cap P_i(\omega))) = 0.$$

But since $\mu_i$ is supported everywhere we have that the argument to $\mu_i$ in the above display is the empty set, and so $P_i(\omega) \subseteq A$. \hfill \Box

3.3. Agreeing to disagree. Let $(N, \Omega, \{\mu_i\}_{i \in N}, \{\Sigma_i\}_{i \in N})$ be a finite belief space with common priors, so that $\mu_i = \mu$ for all $i$. Given a random variable $X: \Omega \to \mathbb{R}$, we denote by $E[X]$ the expectation of $X$ according to $\mu$. The expectation of $X$ conditioned on player $i$’s information at $\omega$ is

$$E[X|\Sigma_i](\omega) = E[X|P_i(\omega)] = \frac{\sum_{\omega' \in P_i(\omega)} \mu(\omega') X(\omega')}{\sum_{\omega' \in P_i(\omega)} \mu(\omega')}$$

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<th>\omega</th>
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<th>$t_1(\omega)$</th>
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<tr>
<td>RRR</td>
<td>$\frac{1}{2}p^2$</td>
<td>R</td>
<td>R</td>
<td>A</td>
</tr>
<tr>
<td>RRS</td>
<td>$\frac{1}{2}(1-p)^2$</td>
<td>R</td>
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Table 2. The forecasters’ common prior.
Aumann [1] proved the following theorem.

**Theorem 3.17** (Aumann’s Agreement Theorem, 1976). Let $X: \Omega \to \mathbb{R}$ be a random variable. Suppose that at $\omega_0$ it is common knowledge that $E[X|\Sigma_i] = q_i$ for $i = 1, \ldots, n$ and some $(q_1, q_2, \ldots, q_n) \in \mathbb{R}^n$. Then $q_1 = q_2 = \cdots = q_n$.

Note that we implicitly assume that the conditional expectations $E[X|\Sigma_i]$ are well defined everywhere. Before proving the Theorem we will recall the law of total expectation. Let $S$ be an element of a sigma-algebra $\Pi \subseteq 2\Omega$, and let $X: \Omega \to \mathbb{R}$ be a random variable. Then

$$E[X|S] = E[E[X|\Pi]|S].$$

**Exercise 3.18.** Prove the law of total expectation for a finite probability space. Hint: write $C$ as a disjoint union of elements of the partition that generates $\Pi$: $C = \bigcup_j P_j$, with $P_j \in \Pi$ being elements with no proper, non-empty subsets in $\Pi$.

**Proof of Theorem 3.17.** By the common knowledge hypothesis there is for each player $i$ a $C_i \in \Sigma_i$ with $\omega_0 \in C_i$ and such that $E[X|\Sigma_i](\omega) = q_i$ for all $\omega \in C_i$. Let $C = \cap_i C_i$, and note that $\omega_0 \in C_i$. We prove the claim by showing that $q_i = E[X|C]$ for all $i$.

Fix $i$. Since $C \in \Sigma_i$, by the law of total expectation

$$E[X|C] = E[E[X|\Sigma_i]|C].$$

But $E[X|\Sigma_i](\omega) = q_i$ for all $\omega \in C$, and thus

$$E[X|C] = E[q_i|C] = q_i.$$

In his paper, Aumann stated this theorem for the case that $X$ is the indicator of some event:

**Corollary 3.19.** If two players have common priors over a finite space, and it is common knowledge that their posteriors for some event are $q_1$ and $q_2$, then $q_1 = q_2$.

3.3.1. **No trade.** Milgrom and Stokey [21] apply Aumann’s theorem to show that rational agents with common priors can never agree to trade. Here we give a theorem that is less general than their original.

Consider two economic agents. The first one has an indivisible good that she might be interested to sell to the second. This good can be sold tomorrow at an auction for an unknown price that ranges between $0$ and $1,000, in integer increments. Let $\Omega = \Theta_1 \times \Theta_2 \times P$, and let the common prior be some $\mu$. Here $P = \{0, 1, \ldots, 1000\}$ represents the auction price of the good, and $\Theta$ is some finite set that describes many
possible events that may influence the price. Accordingly, \( \mu \) is not a product measure, so that conditioning on different \((\theta_1, \theta_2) \in \Theta_1 \times \Theta_2\) yields different conditional distributions on \( P \). Let the players’ types be given by \( t_i(\theta_1, \theta_2, k) = \theta_i \) for \( i = 1, 2 \). Let \( p: \Omega \to P \) be the auction price \( p(\theta_1, \theta_2, k) = k \).

We denote by \( U_1 \) player 1’s conditional expected utility from trading for a price \( q \):

\[
U_1^q = \mathbb{E}[q - p| t_1] = q - \mathbb{E}[p|t_1].
\]

Analogously,

\[
U_2^q = \mathbb{E}[p - q| t_2] = \mathbb{E}[p|t_2] - q.
\]

For example, let \( \Theta_1 = \Theta_2 = P \) and \( \mu \) be the uniform distribution over \( \{(\theta_1, \theta_2, k) : k = \theta_1 \text{ or } k = \theta_2\} \). Equivalently, pick \( k \) uniformaly at random, and the w.p. 1/2 set \( \theta_1 = k \) and choose \( \theta_2 \) uniformly at random, and w.p. 1/2 set \( \theta_2 = k \) and choose \( \theta_1 \) uniformly at random.

Then

\[
U_1^q = q - \frac{1}{2} (500 + t_1)
\]

and

\[
U_2^q = \frac{1}{2} (500 + t_2) - q.
\]

Thus in any state in which \( t_1 < t_2 \) we have, for \( q = \frac{1}{2}(t_1 + t_2) \), that \( U_1^q > 0 \) and \( U_2^q > 0 \): both players expect a positive return for trading the good for \( q \) dollars. However, note that the players do not know that the other player also has positive expectation. What if they knew that the other person is willing to trade?

**Theorem 3.20** (Milgrom and Stokey, 1982). If at some \( \omega \in \Omega \) it is common knowledge that \( U_1^q(\omega) \geq 0 \) and \( U_2^q(\omega) \geq 0 \) then \( U_1^q(\omega) = U_2^q(\omega) = 0 \).

**Proof.** Let \( E \) be the event that \( U_1^q(\omega) = q - \mathbb{E}[p|\Sigma_1] \geq 0 \) and \( U_2^q(\omega) = \mathbb{E}[p|\Sigma_2] - q \geq 0 \). I.e., \( E \) is the event that \( \mathbb{E}[p|\Sigma_1] \leq q \leq \mathbb{E}[p|\Sigma_2] \). Then \( E \) is common knowledge at \( \omega \), and so there is an event \( \omega \in C \in \Sigma_C \). Hence \( C \in \Sigma_1 \), and so, by (3.3),

\[
\mathbb{E}[p|C] = \mathbb{E}[\mathbb{E}[p|\Sigma_1]|C] \leq \mathbb{E}[q|C] = q.
\]

By the same argument we also get that

\[
\mathbb{E}[p|C] = \mathbb{E}[\mathbb{E}[p|\Sigma_2]|C] \geq \mathbb{E}[q|C] = q.
\]

Hence these are both equalities, and thus, on \( C \) (and therefor at \( \omega \)),

\[
\mathbb{E}[p|\Sigma_1] = \mathbb{E}[p|\Sigma_2] = q.
\]
Exercise 3.21. Construct an example in which $U_1^q(\omega) > 0$ and $U_2^q(\omega) > 0$, player 1 knows that $U_2^q(\omega) > 0$ and player 2 knows that $U_1^q(\omega) > 0$.

3.4. Reaching common knowledge. Geanakoplos and Polemarchakis [12] show that repeatedly communicating posteriors leads agents to convergence to a common posterior, which is then common knowledge. We state this theorem in somewhat greater generality than in the original paper, requiring a more abstract mathematical formulation.

Theorem 3.22 (Geanakoplos and Polemarchakis, 1982). Let $(\Omega, \Sigma, \mathbb{P})$ be a probability space, and fix $A \in \Sigma$. Let $X_1$ and $X_2$ be two random variables on this space. Denote $P_0^1 = \mathbb{P}[A|X_1]$ and $P_0^2 = \mathbb{P}[A|X_2]$. For $t \in \{1, 2, \ldots\}$ let

$$P_t^1 = \mathbb{P}[A|X_1, P_0^2, P_1^2, \ldots, P_{t-1}^2]$$

and

$$P_t^2 = \mathbb{P}[A|X_2, P_0^1, P_1^1, \ldots, P_{t-1}^1].$$

Then $\lim_t P_t^1$ and $\lim_t P_t^2$ almost surely exist and are equal.

To prove this theorem we will need the following classical result in probability.

Theorem 3.23 (Lévy’s Zero-One Law). Let $\{\Pi_n\}$ be a filtration, and let $X$ be a random variable. Let $\Pi_\infty$ be the sigma-algebra generated by $\bigcup_n \Pi_n$. Then $\lim_n \mathbb{E}[X|\Pi_n]$ exists for almost every $\omega \in \Omega$, and is equal to $\mathbb{E}[X|\Pi_\infty]$.

Proof of Theorem 3.22. Note that by Lévy’s zero-one law (Theorem 3.23,

$$P_1^\infty := \lim_t P_1^t = \mathbb{P}[A|X_1, P_0^2, P_1^2, \ldots]$$

and an analogous statement holds for $\lim_t P_2^t$. Let $\Sigma_1$ be the sigma-algebra generated by $\{X_1, P_0^2, P_1^2, \ldots\}$, so that

$$P_1^\infty = \mathbb{P}[A|\Sigma_1].$$

Since $P_2^\infty$ is $\Sigma_1$-measurable, it follows that

$$P_1^\infty = \mathbb{P}[A|\Sigma_1] = \mathbb{P}[\mathbb{P}[A|P_2^\infty]|\Sigma_1] = \mathbb{P}[P_2^\infty|\Sigma_1] = P_2^\infty.$$

3.5. Bayesian games. The buyer-seller game described in Section 3.2.1 is an example of a Bayesian game. In these games there is uncertainty over the payoffs to the players in given pure strategy profiles.

A Bayesian game is a tuple $G = (N, \{A_i\}_{i \in N}, (\Omega, \Sigma), \{\mu_i\}_{i \in N}, \{T_i\}_{i \in N}, \{t_i\}_{i \in N}, \{u_i\}_{i \in N})$ where

- $(N, (\Omega, \Sigma), \{\mu_i\}_{i \in N}, \{T_i\}_{i \in N}, \{t_i\}_{i \in N})$ is a belief space.
• $A_i$ is the set of actions of player $i$.
• $u_i : A \times \Omega \rightarrow \mathbb{R}$ is player $i$’s utility function.

We require that $u_i$ also be measurable.

The set of pure strategies of player $i$ is the set of measurable functions from $T_i$ to $A_i$. That is, a strategy of a player is a choice of action, given her private signal realization. Given a strategy profile $(s_1, \ldots, s_n)$, player $i$’s expected utility is

$$E_{\mu_i, s}[u_i] = \int \Omega u_i(s_1(t_1(\omega)), \ldots, s_n(t_n(\omega)), \omega) d\mu_i(\omega).$$

A Bayes-Nash equilibrium is a strategy profile in which no player can improve her expected utility by changing her strategy. That is, for any player $i$ and strategy $s'_i$ it holds that

$$E_{\mu_i, s}[u_i] \geq E_{\mu_i, (s_{-i}, s'_i)}[u_i]. \tag{3.4}$$

An alternative definition of a Bayes-Nash equilibrium is a strategy profile in which, for each player $i$ and each type $\tau_i \in T_i$ it holds that

$$E_{\mu_i, s}[u_i | t_i = \tau_i] = \int \Omega u_i(s_1(t_1(\omega)), \ldots, s_i(\tau_i), \ldots, s_n(t_n(\omega)), \omega) d\mu_i(\omega | t_i = \tau_i)$$

cannot be improved:

$$E_{\mu_i, s}[u_i | t_i = \tau_i] \geq E_{\mu_i, (s_{-i}, s'_i)}[u_i | t_i = \tau_i]$$

for all $s'_i$ and $\tau_i \in T_i$.

This is not an equivalent definition, but the second is stronger than the first.

**Proposition 3.24.** (3.5) implies (3.4).

**Proof.** Let $s$ satisfy (3.5). Then by the law of total expectation

$$E_{\mu_i, s}[u_i] = E_{\mu_i, s}[E_{\mu_i, s}[u_i | t_i]] \geq E_{\mu_i, s}[E_{\mu_i, (s_{-i}, s'_i)}[u_i | t_i]] = E_{\mu_i, (s_{-i}, s'_i)}[u_i]. \tag{3.5}$$

Conversely, if $\Omega$ is finite and there is a common prior $\mu = \mu_1 = \cdots = \mu_n$ then, if $s$ satisfies (3.4) then there is an $s'$ that satisfies (3.5), and such that the probability (under $\mu$) that $s_i(t_i) \neq s'_i(t_i)$ is zero.

**Exercise 3.25.** Find a finite Bayesian game that has a (pure) strategy profile that satisfies (3.4) but does not have one that satisfies (3.5).
4. AUCTIONS

Auctions have been used throughout history to buy and sell goods. They are still today very important in many markets, including on-line markets that run massive computerized auctions.

4.1. Classical auctions. In this section we will consider $n$ players, each of which have a fixed valuation $v_i$ for some item that is being auctioned. We assume that each $v_i$ is a non-negative integer. Furthermore, to avoid having to deal with tie-breaking, we assume that each $v_i = i + 1 \mod n$. We also assume without loss of generality that $v_1 > v_2 > \cdots > v_n$.

If it is agreed that player $i$ buys the item for some price $p$ then that player’s utility is $v_i - p$. If a player does not buy then she pays nothing and her utility is zero.

We will consider a number of possible auctions.

4.1.1. First price, sealed bid auction. In this auction each player submits a bid $b_i$, which has to be a non-negative integer, congruent to $i \mod n$. Note that this means that a player cannot ever bid her valuation (which is congruent to $i + 1 \mod n$), but can bid one less than her valuation\(^5\).

For example, consider the case that $n = 2$. Then possible valuations are $v_1 = 10$ and $v_2 = 5$, and $b_1$ must be odd while $b_2$ must be even.

The bids $b = (b_1, \ldots, b_n)$ are submitted simultaneously. The player who submitted the highest bid $b_{\text{max}}(b) = \max b_i$ buys the item, paying $b_{\text{max}}$.

Hence player $i$’s utility for strategy profile $b$ is given by

$$u_i(b) = \begin{cases} 
  v_i - b_i & \text{if } b_i = b_{\text{max}}(b) \\
  0 & \text{otherwise} 
\end{cases}.$$

We now analyze this game. We first note that $b_i = v_i - 1$ guarantees utility at least 0. Next, we note that any $b_i > v_i$ is weakly dominated by $b_i = v_i - 1$, since it guarantees utility at most 0, but can result in negative utility if $b_i = b_{\text{max}}$. Furthermore, it is impossible that in a pure equilibrium the winner of the auction bid more than $v_i$, since then she could increase her utility by lowering her bid to $v_i - 1$.

Assume that $b^*$ is an equilibrium.

Claim 4.1. Player 1 wins the auction: $b_1^* = b_{\text{max}}^*$.

\(^5\)Think of this as one cent less.
Proof. Assume by contradiction that player $i > 1$ wins the auction. As we noted above, $b^*_i \leq v_i - 1$. Hence $b^*_{\text{max}} = b^*_i \leq v_i - 1 < v_1 - 1$. Hence player 1 could improve her utility to 1 by bidding $v_1 - 1$ and winning the auction. \hfill \square

We have thus shown that in any equilibrium the first player wins. It thus remains to show that one exists.

**Claim 4.2.** Let $b^*_1$ be the smallest allowed bid\(^6\) that is larger than $v_2 - 1$. Let $b_2 = v_2 - 1$. For $i > 2$ (if there are more than 2 players) let $b^*_i$ be any allowed bid that is less than $v_2$. Then $b^*$ is an equilibrium.

**Exercise 4.3.** Prove Claim 4.2.

We note a few facts about this equilibrium.

- The item was allocated to the player who values it the most.
- The player who won did not base her bid on her own valuation, but on the other players’ valuations, and in particular on the second highest one.

Note that other equilibria exist. For example, if $n = 2$ and $v_1 = 10$ and $v_2 = 5$ then $b_1 = 9$ and $b_2 = 8$ is again an equilibrium. Player 2 gets zero payoff, but can only decrease her utility by raising her price and winning the auction. Player 1 gets positive utility (1), but cannot improve it by lowering her bid.

4.1.2. **Second price, sealed bid auction.** In this auction each player again submits a bid $b_i$, which this time has to be a non-negative integer, congruent to $i + 1 \mod n$; that is, it can be equal to $v_i$. Again, the player who submitted the highest bid $b_{\text{max}}$ wins. However, in this case she does not pay her bid, but rather the second highest bid $b_{\text{nd}}$. Hence

$$u_i(b) = \begin{cases} v_i - b_{\text{nd}} & \text{if } b_i = b_{\text{max}}(b) \\ 0 & \text{otherwise} \end{cases}$$

As in the first price auction, any $b_i > v_i$ is weakly dominated by $b_i = v_i$; when bidding more than $v_i$ the player can at most make 0, but in some cases may have negative utility, which is not possible when bidding $v_i$.

Moreover, in this auction any $b_i < v_i$ is also weakly dominated by $b_i = v_i$. To see this, let $b'$ be the highest bid of the rest of the players. If $b' > v_i$ then in either bid the player loses the auction, and so both strategies yield zero. If $b' < v_i$ then bidding $b_i < v_i$ may either cause

\(^6\)Congruent to 1 \mod n.
the loss of the auction and utility zero (if \( b_i < b' \)) or otherwise gaining \( v_i - b' \). But bidding \( b_i = v_i \) guarantees utility \( v_i - b' \).

Hence \( b_i = v_i \) is a weakly dominant strategy, and so this is an equilibrium. Auctions in which bidding your valuation is weakly dominant are called strategy proof or sometimes truthful.

Note that in this equilibrium the item is allocated to the player who values it the most, as in the first price auction. However, the player based her bid on her own valuation, independently of the other player’s valuations.

4.1.3. English auction. This auction is an extensive form game with complete information. The players take turns, starting with player 1, then player 2 and so on up to player \( n \), and then player 1 again etc. Each player can, at her turn, either leave the auction or stay in. Once a player has left she must choose to leave in all the subsequent turns.

The auction ends when all players but one have left the auction. If this happens at round \( t \) then the player left wins the auction and pays \( t - 1 \).

Claim 4.4. There is a subgame perfect equilibrium of this game in which each player \( i \) stays until period \( t = v_i \) and leaves once \( t > v_i \).

Exercise 4.5. Prove Claim 4.4.

Exercise 4.6. What is the relation between this English auction and the second price auction?

4.1.4. Social welfare. Imagine that the person running the auction is also a player in the game. Her utility is simply the payment she receives; she has no utility for the auctioned object. Then the social welfare, which we will for now define to be the sum of all the players’ utilities, is equal to the utility of the winner — her value minus her payment — plus the utility of the losers (which is zero), plus the utility of the auctioneer, which is equal to the payment. This sum is the value of the object to the winner. Hence social welfare is maximized when the winner is a person who values the object most.

4.2. Bayesian auctions. In this section we will consider auctions in which the players do not know the others’ valuations exactly. Specifically, the auctions will be Bayesian games with common priors.

We will again have \( n \) players. Each player’s type will be her valuation \( v_i \), and the players will have some common prior \( \mathbb{P} \) over \((v_1, \ldots, v_n)\). Formally, the belief space will be \(((\mathbb{R}^+)^n, \Sigma, \mathbb{P})\), where \( \Sigma \) is the Borel sigma-algebra, and \( \mathbb{P} \) is some probability distribution. Player \( i \)’s type \( t_i \) is given by \( t_i(v_1, \ldots, v_n) = v_i \).
As before, if a player does not win the auction she has utility zero. Otherwise, assuming she pays a price $p$, she has utility $v_i - p$. Note that the players' utilities indeed depend on their types in these Bayesian games.

4.2.1. Second price, sealed bid auction. As before, the players will submit bids $b_i$. In this case we do not restrict the bids, and can allow them to take any value in $\mathbb{R}$. Formally, a pure strategy of a player in this game is a measurable function $b_i: \mathbb{R}^+ \to \mathbb{R}$, assigning a bid to each possible type or valuation.

As before, the player with the highest bid $b_{\text{max}}$ wins and pays the second highest bid $b_{\text{nd}}$. Note that despite the fact that two valuations can be never be the same, it still may be the case that two players choose the same bid. For example, the strategy profile could be such that all players always bid 1. Accordingly, we assume that there is some tie-breaking mechanism (e.g., choose at random from all those with the highest bid), but it will not play a role in our analysis.

**Proposition 4.7.** For any joint distribution $\mathbb{P}$, it is weakly dominant for each player to choose $b_i^*(v_i) = v_i$.

The proof of this is identical to the one in the non-Bayesian case.

As an example, consider the case that the valuations are picked i.i.d. from some non-atomic distribution with cumulative distribution function $F$. Then $b_i^*(v_i) = v_i$ is the unique Bayes-Nash equilibrium.

Assume that there are two players. Player 1 wins the auction if she has the highest valuation. Conditioning on her valuations $v_1$, her probability of winning is therefore $F(v_1)$. If she wins then she expects to pay $\mathbb{E}_F [v_2 | v_2 < v_1]$.

4.2.2. First price, sealed bid auction. In this auction, as in the classical one, each player will submit a bid $b_i$, and the player with the highest bid $b_{\text{max}}$ will win and pay $b_{\text{max}}$. We assume here that the valuations are picked i.i.d. from some non-atomic distribution with cumulative distribution function $F$ with derivative $f$. To simplify our calculations we will assume that there are only two players; the general case is almost identical.

**Claim 4.8.** $b_i^*(v_i) = v_i$ is not an equilibrium of this auction.

We will try to construct a Bayes-Nash equilibrium with the following properties:

- Symmetry: there is a function $b: \mathbb{R}^+ \to \mathbb{R}^+$ such that $b_i(v_i) = b(v_i)$ for all players.
- Monotony and differentiability: $b$ is monotone increasing.
Thus, to construct such an equilibrium we assume all players play $b$, and try to calculate $b$ assuming it is some player’s (say player 1’s) best response.

Assume then that player 2 plays $b_2(v_2) = b(v_2)$. Fix $v_1$, and assume that player 1 bids $b_1$. Denote by $G$ the cumulative distribution function of $b(v_2)$, and let $g$ be its derivative. Note that we can write $G$ and $g$ in terms of $F$ and $f$:

\begin{equation}
F(v) = G(b(v))
\end{equation}

and

\begin{equation}
f(v) = g(b(v)) \cdot b'(v).
\end{equation}

The probability that $b_1$ is the highest bid is $G(b_1)$. It follows that player 1’s expected utility (conditioned on $v_1$) is

\[ u_1(v_1, b_1) = G(b_1) \cdot (v_1 - b_1). \]

Therefore, to maximize expected utility, $b_1$ must satisfy

\[ 0 = \frac{du_1(v_1, b_1)}{db_1} = g(b_1) \cdot (v_1 - b_1) - G(b_1), \]

or

\[ G(b_1) = g(b_1) \cdot (v_1 - b_1). \]

Note that $b_1 = v_1$ is a solution only if $G(b_1) = 0$.

Since we are looking for a symmetric equilibrium, we can now plug in $b_1 = b(v)$ to arrive at the condition

\[ G(b(v)) = g(b(v)) \cdot (v - b(v)). \]

Translating back to $F$ and $f$ using (4.1) and (4.2) yields

\[ F(v) = \frac{f(v)}{b(v)} \cdot (v - b(v)). \]

Rearranging, we can write

\[ F(v)b'(v) + f(v) \cdot b(v) = f(v) \cdot v \]

or

\[ \frac{d}{dv} [F(v)b(v)] = f(v) \cdot v. \]

Now, clearly $b(0) = 0$ is weakly dominant, and so we will assume that this is indeed the case. We can therefore solve the above expression to arrive at

\[ b(v) = \frac{1}{F(v)} \int_0^v f(u) \cdot u \, du. \]
Note that this is equal to $E_F[v_2|v_2 < v_1]$, the expectation of $v_2$, conditioned on $v_2$ being less than $v$. It remains to be shown that this strategy profile is indeed a maximum (we only checked the first order condition).

A player’s expected utility, conditioned on having valuation $v$, is simply $F(v)$ (the probability that she wins) times $v - b(v)$. Interestingly, in the second price auction the expected utility is identical: the probability of winning is still $F(v)$, and the expected utility is $v - b(v)$, since, conditioned on winning, the expected payment is the expected valuation of the other player.

4.3. **Truthful mechanisms and the revelation principle.** The revelation principle is important in mechanism design. The basic idea is due to Gibbard [13], with generalizations by others [8, 16, 23].

In this section we will call Bayesian games of incomplete information mechanisms. We will say that a mechanism is truthful if $A_i = T_i$ and $\tilde{s}(t_i) = t_i$ is an equilibrium. Note that sometimes this term is used to describe mechanisms in which the same $\tilde{s}$ is weakly dominant.

**Theorem 4.9.** Let $G = (N, \{A_i\}_{i \in N}, (\Omega, \Sigma), \{\mu_i\}_{i \in N}, \{T_i\}_{i \in N}, \{t_i\}_{i \in N}, \{u_i\}_{i \in N})$ be a mechanism with an equilibrium $s^*$. Then there exists a truthful mechanism $G' = (N, \{A'_i\}_{i \in N}, (\Omega, \Sigma), \{\mu_i\}_{i \in N}, \{T_i\}_{i \in N}, \{t_i\}_{i \in N}, \{u'_i\}_{i \in N})$ such that

$$E_{\mu_i, \tilde{s}}[u'_i|t_i] = E_{\mu_i, s^*}[u_i|t_i].$$

That is, for every game and equilibrium one can design a truthful game in which playing truthfully yields the same conditionally expected utilities as in the original game. The idea of the proof is simple: in the new mechanism, the players reveal their types, the mechanism calculates their equilibrium actions, and then implements the original mechanism on those actions.

**Proof of Theorem 4.9.** Let

$$u'_i(\tau_1, \ldots, \tau_n, \omega) = u_i(s_1^*(\tau_1), \ldots, s_n^*(\tau_n), \omega).$$

Then

$$E_{\mu_i, \tilde{s}}[u'_i|t_i = \tau_i] = \int_{\Omega} u'_i(\tilde{s}_1(t_1(\omega)), \ldots, \tilde{s}_n(t_n(\omega)), \omega)d\mu_i(\omega|t_i = \tau_i)$$

$$= \int_{\Omega} u'_i(t_1(\omega), \ldots, t_n(\omega), \omega)d\mu_i(\omega|t_i)$$

$$= \int_{\Omega} u_i(s_1^*(t_1(\omega)), \ldots, s_n^*(t_n(\omega)), \omega)d\mu_i(\omega|t_i)$$

$$= E_{\mu_i, s^*}[u_i|t_i].$$
To see that this mechanism is truthful, note that for any player $i$ with type $\tau_i \in T_i$ and action $\tau'_i \in A'_i = T_i$ it holds that the utility for playing $\tau'_i$ (instead of $\tau_i$) is

$$\int_\Omega u'_i(\bar{s}_1(t_1(\omega)), \ldots, \tau'_i, \ldots, \bar{s}_n(t_n(\omega)), \omega) d\mu_i(\omega | t_i = \tau_i)$$

$$= \int_\Omega u'_i(t_1(\omega), \ldots, \tau'_i, \ldots, t_n(\omega), \omega) d\mu_i(\omega | t_i = \tau_i)$$

$$= \int_\Omega u_i(s^*_1(t_1(\omega)), \ldots, s^*_i(\tau'_i), \ldots, s^*_n(t_n(\omega)), \omega) d\mu_i(\omega | t_i = \tau_i).$$

But since $s^*$ is an equilibrium this is

$$\leq \int_\Omega u_i(s^*_1(t_1(\omega)), \ldots, s^*_i(\tau_i), \ldots, s^*_n(t_n(\omega)), \omega) d\mu_i(\omega | t_i = \tau_i)$$

$$= \int_\Omega u'_i(\bar{s}_1(t_1(\omega)), \ldots, \bar{s}_n(t_n(\omega)), \omega) d\mu_i(\omega | t_i = \tau_i),$$

which is the utility for playing according to $\bar{s}_i$. $\square$

It follows that when designing auctions we can assume without loss of generality that the players reveal their types to the auctioneer.
5. Repeated games

5.1. Extensive form games with perfect information and simultaneous moves. Recall (Section 1.2) that an extensive form game with perfect information is given as a tuple $G = (N, A, H, O, o, P, \{\preceq_i\}_{i \in N})$, where $N$ is the set of players, $A$ is the set of actions, $H$ is the set of allowed histories (with $Z$ the terminal histories), $O$ is the set of outcomes, $o$ is a function $Z \to O$, $P$ is a function $H \setminus Z \to N$, and for each player $i \in N$, $\preceq_i$ is a preference relation over $O$.

In this section we slightly extend this definition by allowing two or more players to make simultaneous moves. The definitions of $N$ and $A$ remain the same. $P$ will now be a function from $H \setminus Z$ to $2^N$, the power set of the set of players, so that after history $h \in H$ the set of players who play simultaneously is $P(h)$.

Recall that a history was defined to be a finite sequence in $A$; it will now be a sequence of tuples $a_t$ in $A$, with each tuple in the sequences potentially of different size. Specifically, a history $h$ is a sequence $(a_1, a_2, \ldots)$, such that, for each $t$, $a_t \in A^M$ where $M = P(a_1, \ldots, a_{t-1})$. The set of histories will have to satisfy an additional criterion: if $h = (a_1, \ldots, a_n) \in H$ then there must be for each player $i \in P(h)$ a set $A_i(h) \subset A$ such that for any $a \in \prod_i A_i$ the history $(a_1, \ldots, a_n, a)$ is also in $H$. That is, each player has a set of allowed moves, and any combination of allowed moves by the players is allowed.

A strategy in such a game is a function that assigns to each history $h \in H$ and player $i \in P(h)$ an action in $A_i(h)$.

5.1.1. Equilibria. The definitions of a Nash equilibrium, a subgame, and a subgame perfect equilibrium carry unchanged to this new setting.

Note that Kuhn’s Theorem does not apply here: for example, any strategic form game is a one-period extensive form game with perfect information and simultaneous moves. But not every such games has a pure equilibrium. On the other hand, the one deviation principle (Theorem 1.5) still applies; the proof is identical.

5.2. Definition of repeated games. Let $G_0 = (N, \{A_i\}, \{u_i\})$ be a strategic form game, and, as usual, let $A = \prod_i A_i$. We will only consider games in which $A$ is compact and each $u_i$ is continuous.

Let $T$ be the number of periods (or repetitions) of the repeated game. $T$ can be either finite or infinite. A $T$-repeated game of $G_0$ is an extensive form game $G = (N, A', H, O, o, P, \{\preceq_i\}_{i \in N})$, where

- $P(h) = N$ for all $h \in H \setminus Z$.
- The set of histories $H$ has terminal histories $Z = \prod_{t=1}^T A$; recall that $Z$ uniquely determines $H$ as the set of all prefixes of $Z$. 
• $A'$ is likewise determined by $H$.
• $O = Z$ and $o$ is the identity.
• $\preceq_i$ is some preference relation on $Z$ that satisfies the following condition: If $u_i(a^t) \leq u_i(b^t)$ for all $t$ and some $(a^1, a^2, \ldots), (b^1, b^2, \ldots) \in Z$ then
  $$(a^1, a^2, \ldots) \preceq_i (b^1, b^2, \ldots).$$

We call $G_0$ the base game of $G$.

If we assign utilities $\{v_i\}_{i \in N}$ to elements of $Z$, then we call $(v_1(a), \ldots, v_n(a))$ the payoff profile associated with $a$. Given a strategy profile $s$ of $G$, we likewise define the payoff profile associated with $s$ to be the payoff profile associated with the path of play generated by $s$.

When $T$ is finite then a natural choice is to let the players’ utilities in the repeated game be the sum of their base game utilities in each of the periods. When $T = \infty$ we will consider two types of preference relations: discounting and limit of means, or limiting mean. In fact, in both we will define utilities that induce the equivalence relations.

5.2.1. Discounting. We fix some $\delta \in (0, 1)$ and let $v_i : O \to \mathbb{R}$ be given by the discounted sum

$$v_i(a^1, a^2, \ldots) = (1 - \delta) \sum_{t=1}^{\infty} \delta^{t-1} u_i(a^t).$$

These will be the player’s utilities in the repeated game $G$, and $\preceq_i$ will simply be given by these utilities. Note that we chose the scaling of $v_i$ to make it a weighted average of the utilities.

Discounting has the advantage that it is stationary: every subgame of $G$ is isomorphic to $G$.

5.2.2. Limit of means, limiting mean. In the usual definition of “limit of means”, $(a^1, a^2, \ldots) \succ_i (b^1, b^2, \ldots)$ by player $i$ if

$$\liminf_{\tau} \frac{1}{\tau} \sum_{t=1}^{\tau} u_i(a^t) - \frac{1}{\tau} \sum_{t=1}^{\tau} u_i(b^t) > 0.$$ 

Note that, under this definition, a pair $(a^1, a^2, \ldots)$ and $(b^1, b^2, \ldots)$ that differ only in finitely many periods are equivalent.

We will take a slightly different approach to limits of means, using limiting means. Let $\ell^\infty(\mathbb{N}) \subset \mathbb{R}^\mathbb{N}$ denote the bounded real sequences.

A mean $m$ is a map $\ell^\infty(\mathbb{N}) \to \mathbb{R}$ with the following properties

• Linearity:
  $$m(x + y) = m(x) + m(y)$$
and
\[ m(\alpha \cdot x) = \alpha \cdot m(x). \]

- Positivity: if \( x_n \geq 0 \) for all \( n \) then \( m(x) \geq 0 \).
- Unity: \( m(1, 1, \ldots) = 1 \).

For example, if \( \sum_{n=1}^{\infty} \alpha_n = 1 \) then
\[ m(x) = \sum_{n=1}^{\infty} \alpha_n x_n \]
is a mean. However, there are also more interesting examples:

**Theorem 5.1.** There exists a mean \( m \) such that \( m(x) \) is always the limit of some subsequence of \( \{\frac{1}{n} \sum_{i=1}^{n} x_i\}_{n \in \mathbb{N}} \).

In particular, if a pair \( x, y \in \ell^\infty(\mathbb{N}) \) differ in only finitely many coordinates then \( m(x) = m(y) \). Note also that such a mean \( m \) is shift-invariant: \( m(x_1, x_2, x_3, \ldots) = m(x_2, x_3, \ldots) \).

It follows that \( m(x_1, x_2, \ldots) > m(y_1, y_2, \ldots) \) whenever
\[ \liminf_n \frac{1}{n} \sum_{i=1}^{n} x_i - \frac{1}{n} \sum_{i=1}^{n} y_i > 0. \]

Therefore, if we choose such an mean \( m \) and let
\[ v_i(a^1, a^2, \ldots) = m(u_i(a^1), u_i(a^2), \ldots) \]
then \( v_i(a) > v_i(b) \) whenever \( a \succ_i b \). That is, the preference relation induced by \( v_i \) has all the strict preferences that \( \succeq_i \) has, and perhaps also additional ones.

Limiting means utilities, like discounting utilities, are stationary.

**5.3. Folk theorems.**

**5.3.1. Example.** What payoffs profiles are achievable in Nash equilibria of infinite repeated games? It turns out that the answer is: more or less all of them. To get some intuition as to how this is done, consider the following example. Let \( G_0 \) be the following prisoner's dilemma game:

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

Consider the following symmetric strategy profile, called “grim trigger”: start with \( C \), and keep on playing \( C \) until the other person plays \( D \). Then play \( D \) henceforth. It is easy to see that this is an equilibrium under both limiting means and discounting, for \( \delta \) close enough to one.

\[7\] For a “real life” example: [https://www.youtube.com/watch?v=y6GhbT-zEfc](https://www.youtube.com/watch?v=y6GhbT-zEfc).
5.3.2. **Enforceable and feasible payoffs.** We fix an infinitely repeated game $G$ with base game $G_0$. Define the minmax payoff of player $i$ in the base game $G_0$ as the lowest payoff that the rest of the players can force on $i$:

$$u_i^{mm} = \min_{a_{-i}} \max_{a_i} u_i(a_{-1}, a_i).$$

Equivalently, this is the payoff that player one can guarantee for herself, regardless of the other player’s actions.

We say that a payoff profile $w \in \mathbb{R}^n$ is enforceable if $w_i \geq u_i^{mm}$ for all $i \in N$. It is strictly enforceable if $w_i > u_i^{mm}$ for all $i \in N$.

**Claim 5.2.** Let $s^*$ be a Nash equilibrium of $G$, under either discounting or limiting means. Then the payoff profile associated with $s$ is enforceable.

**Proof.** Since player $i$ can guarantee a stage utility of $u_i^{mm}$, she can always choose a strategy such that her stage utilities will each be at least $u_i^{mm}$. Hence under both discounting and limiting means her payoff will be at least $u_i^{mm}$ in $G$. □

We say that a payoff profile $w$ is feasible if it is a convex combination of utilities achievable in $G_0$. That is, if for all $i \in N$

$$w_i = \sum_{a \in A} \alpha_a \cdot u_i(a)$$

for some $\{\alpha_a\}$ that sum to one. Clearly, every payoff profile in $G$ is feasible.

**Exercise 5.3.** Consider the game

<table>
<thead>
<tr>
<th></th>
<th>$D$</th>
<th>$C$</th>
<th>$F$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D$</td>
<td>0,0</td>
<td>1,0</td>
<td>0,1</td>
</tr>
<tr>
<td>$C$</td>
<td>0,1</td>
<td>2,2</td>
<td>−2,3</td>
</tr>
<tr>
<td>$F$</td>
<td>1,0</td>
<td>2,−3</td>
<td>−2,−2</td>
</tr>
</tbody>
</table>

Draw a diagram of the feasible and enforceable profiles.

5.4. **Nash folk theorems.** Aumann and Shapley [3] proved the Nash folk theorem for limit of means. We state it for limiting means.

**Theorem 5.4.** For every feasible, enforceable payoff profile $w$ there exists a Nash equilibrium of $G$ with limiting means utilities whose associated payoff profile is $w$.

The construction of these equilibria involves *punishing*: players all play some equilibrium, and if anyone deviates the rest punish them.
Proof of Theorem 5.4. Let $w_i = \sum_{a \in A} \alpha_a \cdot u_i(a)$. Let $(a_1, a_2, \ldots)$ be a sequence in $A$ such that $m(\mathbb{1}_{\{a_1 = a\}}, \mathbb{1}_{\{a_2 = a\}}, \ldots) = \alpha_a$. Such a sequence exists since (for example) if we choose each $a^t$ independently at random to equal $a$ with probability $\alpha_a$ then with probability one the sequence has this property. If the coefficients $\alpha_a$ are rational then one can simply take a periodic sequence with period equal to the lowest common denominator.

Let $s^*$ be the following strategy profile. For each player $i$ let $s^*_i$ be the strategy in which she chooses $a^t_i$, unless in some previous period $\tau$ some player $j$ did not choose $a^\tau_j$, in which case she chooses a strategy $b_i$, where

$$b_{-j} \in \arg\min_{a_{-j}} \max_{a_j} u_j(a_{-j}, a_j).$$

Hence the stage utilities of a player $i$ who deviates will be, from the point of deviation on, at most $u^{mm}_i$. Therefore her utility will be at most $u_i^{mm}$, since utilities do not depend on any finite set of stage utilities. Since $w$ is enforceable, it follows that $w_i \geq u_i^{mm}$, and so no deviation is profitable, and $s^*$ is an equilibrium. □

A similar proof technique can be used to show the following theorem, which is due to Fudenberg and Maskin [10], with an earlier, weaker version by Friedman [9].

Theorem 5.5. For every feasible, strictly enforceable payoff profile $w$ and $\varepsilon > 0$ there is a $\delta_0 > 0$ such that for all $\delta > \delta_0$ there exists a Nash equilibrium of $G$ with $\delta$-discounting utilities whose associated payoff profile $w'$ satisfies $|w'_i - w_i| < \varepsilon$ for all $i \in N$.

The discount factor needs to be large enough to make eternal punishment pose more of a loss than can be gained by a single deviation. It also needs to be large enough to allow for the discounted averages to approximate a given convex combination of the base game utilities.

5.5. Perfect folk theorems. Consider the following base game (taken from Osborne and Rubinstein [26]):

$$
\begin{array}{c|cc}
  & D & C \\
\hline
D & 0,1 & 1,5 \\
C & 0,1 & 2,3 \\
\end{array}
$$

Here, an equilibrium built in Theorems 5.4 and 5.5 that achieves payoff profile $(2,3)$ has the players playing $(C,C)$ on the equilibrium path, and punishing by playing $D$ forever after a deviation. Note, however, that for the row player, action $D$ is strictly dominated by $C$. Hence this equilibrium is not a subgame perfect equilibrium: regardless of
what the column player does, the row player can increase her subgame utility by at least 1 by always playing C rather than D. It is therefore interesting to ask if there are subgame perfect equilibria that can achieve the same set of payoff profiles.

5.5.1. Perfect folk theorem for limiting means. The following theorem is due to Aumann and Shapley [3], as well as Rubinstein [27].

**Theorem 5.6.** For every feasible, strictly enforceable payoff profile $w$ there exists a subgame perfect Nash equilibrium of $G$ with limiting means utilities whose associated payoff profile is $w$.

The idea behind these equilibria is still of punishing, but just for some time rather than for all infinity.

**Proof of Theorem 5.6.** As in the proof of Theorem 5.4, let $w_i = \sum_{a \in A} \alpha_a \cdot u_i(a)$, and let $(a^1, a^2, \ldots)$ be a sequence in $A$ such that $m(\mathbb{1}_{\{a^1 = a\}}, \mathbb{1}_{\{a^2 = a\}}, \ldots) = \alpha_a$. Likewise, for each player $i$ let $s^*_i$ be the strategy in which she chooses $a^t_i$, unless in some previous period $\tau$ some player $j$ deviated and did not choose $a^\tau_j$. In the latter case, we find for each such $\tau$ and $j$ a $\tau'$ large enough so that, if all players but $j$ play

$$b_{-j} \in \arg\min_{a_{-i}} \max_{a_i} u_i(a_{-1}, a_i),$$

in time periods $(\tau + 1, \ldots, \tau')$ then the average of player $j$’s payoffs in periods $(\tau, \tau + 1, \ldots, \tau')$ is lower than $w_j$. Such a $\tau'$ exists since the payoffs in periods $(\tau + 1, \ldots, \tau')$ will all be at most $u_{ij}^{mm}$, and since $w_j > u_{ij}^{mm}$. We let all players but $j$ play $b_{-j}$ in time periods $\tau + 1, \ldots, \tau'$. We do not consider these punishments as punishable themselves, and after period $\tau'$ all players return to playing $a^t_i$ (until the next deviation).

To see that $s^*$ is a subgame perfect equilibrium, we consider two cases. First, consider a subgame in which no one is currently being punished. In such a subgame anyone who deviates will be punished and lose more than they gain for each deviation. Hence a deviant $j$’s long run average utility will tend to at most $w_j$, and there is no incentive to deviate.

Second, consider a subgame in which someone is currently being punished. In such a subgame the punishers have no incentive to deviate, since the punishment lasts only finitely many periods, and thus does not affect their utilities; deviating from punishing will not have any consequences (i.e., will not be punished) but will also not increase utilities, and therefore there is again no incentive to deviate.

\[\square\]
5.5.2. Perfect folk theorems for discounting. We next turn to proving perfect folk theorems for discounted utilities. An early, simple result is due to Friedman [9].

**Theorem 5.7.** Let $G_0$ have a pure Nash equilibrium $s^*$ with payoff profile $z$. Let $w$ be a payoff profile of some strategy profile $a \in A$ of $G_0$ such that $w_i > z_i$ for all $i \in N$. Then there is a $\delta_0 > 0$ such that for all $\delta > \delta_0$ there exists a subgame perfect equilibrium of $G$ under discounting, with payoff profile $w$.

The idea behind this result is simple: the players all play $a$ unless someone deviates. Once anyone has deviated, they all switch to playing $s^*$. Given that $\delta$ is close enough to 1, the deviant’s utility from playing $s^*$ henceforth will trump any gains from the deviation. Since $s^*$ is an equilibrium, there is no reason for the punishers to deviate from the punishment.

A harder result is due to Fudenberg and Maskin [10] who, for the two player case, extend the Nash folk theorem 5.5 to a perfect Nash folk theorem.

**Theorem 5.8.** Assume that $|N| = 2$. For every feasible, strictly enforceable payoff profile $w$ and $\varepsilon > 0$ there is a $\delta_0 > 0$ such that for all $\delta > \delta_0$ there exists a perfect Nash equilibrium of $G$ with $\delta$-discounting utilities whose associated payoff profile $w'$ satisfies $|w'_i - w_i| < \varepsilon$ for all $i \in N$.

Before proving this theorem will we state the following useful lemma. The proof is straightforward.

**Lemma 5.9.** Let $G$ be a repeated game, with $\delta$-discounted utilities. Let $G$ have a subgame $G'$ that starts after the players play some action profile $a \in A$. Let $(a^1, a^2, \ldots)$ be a sequence of action profiles for $G'$, and define the $G'$ utilities by

$$v'_i(a^1, a^2, \ldots) = (1 - \delta) \sum_{t=1}^{\infty} \delta^{t-1} \cdot u_i(a^t).$$

Then the $G$ utilities for playing $(a, a^1, a^2, \ldots)$ are given by

$$v_i(a, a^1, a^2, \ldots) = (1 - \delta)u_i(a) + \delta v'_i(a^1, a^2, \ldots).$$

We prove Theorem 5.8 for the particular case that $(w_1, w_2) = (u_1(a), u_2(a))$ for some feasible and strictly enforceable $a \in A$; in this case we can take $\varepsilon = 0$. The proof of the general case uses the same idea, but requires the usual technique of choosing a sequence of changing action profiles.
We assume that \( u_i^{mm} = 0 \). This is without loss of generality, since otherwise we can define a game \( G'_0 \) in which the utilities are \( u'_i = u_i - u_i^{mm} \). The analysis of the \( G'_0 \)-repeated game will be identical, up to an additive constant for each player’s utility.

Fix

\[
b_1 \in \text{argmin} \max_a u_2(a_1, a_2)
\]

and

\[
b_2 \in \text{argmin} \max_a u_1(a_1, a_2)
\]

Note that \( u_1(b_1, b_2) \leq 0 \) and likewise \( u_2(b_1, b_2) \leq 0 \), since we assume that \( u_i^{mm} = 0 \).

As an example, consider the following base game:

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

With \( a = (C, C) \). It is easy to see that \( u_1^{mm} = u_2^{mm} = 0 \) and that necessarily \( b = (F, F) \).

Consider the following strategy profile \( s^* \) for the repeated game. Recall that \( (w_1, w_2) = (u_1(a), u_2(a)) \) for some feasible and strictly enforceable \( a \in A \). In \( s^* \), the game has two “modes”: on-path mode and punishment mode.

- In on-path mode each player \( i \) plays \( a_i \).
- In punishment mode each player \( i \) plays \( b_i \).

Both players start in the on-path mode. If any player deviates, the game enters punishment mode for some fixed number of \( \ell \) rounds. This also applies when the game is already in punishment mode: if a player deviates when in punishment mode (i.e., stops punishing and does not play \( b_i \)), the game re-enters punishment mode for \( \ell \) rounds.

Player \( i \)'s utility on path is given by

\[
v_i(s^*) = (1 - \delta) \sum_{t=1}^{\infty} \delta^{t-1} u_i(a) = w_i.
\]

Denote by \( \bar{u}_i = \max_{a \in A} u_i(a) \) the maximal utility achievable by player \( i \) in \( G_0 \). Denote the punishment utility penalty by \( p_i = -u_i(b_1, b_2) \geq 0 \).

In the example above, \( w_1 = w_2 = 2 \) and \( u_1(b_1, b_2) = u_2(b_1, b_2) = -2 \).

To show that \( s^* \) is a subgame perfect equilibrium, we consider the \( \ell + 1 \) types of possible subgames: those that start in punishment mode
(and consider separately the number of punishment periods left), and those that start in on-path mode. We begin with the former.

Let the subgame $G^k$ start in punishment mode, with $k$ punishment periods left. Then on the (subgame) equilibrium path, player $i$’s utility is given by

$$v^k_i = (1 - \delta) \sum_{t=1}^{k} \delta^{t-1} \cdot u_i(b_1, b_2) + (1 - \delta) \sum_{t=k+1}^{\infty} \delta^{t-1} \cdot w_i$$

$$= -(1 - \delta^k) p_i + \delta^k w_i.$$ 

In particular

$$v^\ell_i = \delta^\ell w_i - (1 - \delta^\ell) p_i.$$

Let $k$ be the highest number ($\leq \ell$) for which it is profitable to deviate on the first round of $G^k$. If no such $k$ exists then we are done with the punishing mode subgames. Otherwise, if a player decides to deviate, she will again and again find it profitable to deviate when arriving at the subgame $G^k$, and so the game will always be in punishment mode. Hence her utility will be at most 0. It follows that it is profitable to already deviate at the first opportunity, which is $G^\ell$, and thus ensure a utility of 0. Hence, under our assumption that it is profitable to deviate, a utility of zero is preferable to $v^\ell_i$, or, equivalently, $v^\ell_i < 0$. Therefore, if we choose $\delta$ and $\ell$ in such a way that $v^\ell_i \geq 0$, player $i$ will have no incentive to deviate in punishment mode. Since $w_i > 0$, this is always possible, by choosing $\delta^\ell$ close enough to 1.

Now, consider any subgame that starts in on-path mode. Player $i$’s utility from playing $s^*$ is $w_i$. Her utility from deviating in the first round is at most

$$(1 - \delta) \bar{u}_i + \delta v^\ell_i,$$

since after the deviation she will enter punishment mode, and there we have ensured that $v^\ell_i$ is the best utility she can achieve. Hence if we can choose $\delta$ and $\ell$ in such a way that

$$(5.1) \quad w_i - (1 - \delta) \bar{u}_i - \delta v^\ell_i \geq 0$$

then she will have no reason to deviate in the first round of any subgame that starts in on-path mode, and will therefore never deviate.

Consider the sequences $\{\delta_m\}$ and $\{\ell_m\}$ given by

$$\delta_m = e^{-1/m^2}$$

and

$$\ell_m = m,$$
so that
\[ \delta_m^{\ell} = e^{-1/m}. \]
Since \( \delta_m^{\ell} \) tends to 1, it follows that \( v^\ell_i \) is positive for large enough \( m \), and so player \( i \) has no incentive to deviate on the first rounds of subgames that start in punishing mode. So see that (5.1) is also satisfied — and so player \( i \) has no incentive to deviate in on-path mode — we calculate:

\[
w_i - (1 - \delta_m)\bar{u}_i - \delta_m v^\ell_i = w_i - (1 - \delta_m)\bar{u}_i - \delta_m(\delta_m^{\ell} w_i - (1 - \delta_m^{\ell})p) \\
= w_i - (1 - e^{-1/m^2})\bar{u}_i - e^{-1/m^2}(e^{-1/m} w_i - (1 - e^{-1/m^2})p) \\
\geq w_i - (1 - e^{-1/m^2})\bar{u}_i - e^{-1/m^2-1/m} w_i \\
= (1 - e^{-1/m^2-1/m})w_i - (1 - e^{-1/m^2})\bar{u}_i.
\]

Now, \( 1 - e^{-x} = x + O(x^2) \), and so this expression is equal to

\[
\frac{1}{m} w_i - \frac{1}{m^2} \bar{u}_i + O\left(\frac{1}{m^2}\right),
\]

and in particular is positive for large enough \( m \). Hence, for large enough \( m \), it will be positive for both \( i = 1 \) and \( i = 2 \).

We have thus shown that for an appropriate choice of \( \delta \) and \( \ell \) it holds that both players have no incentive to deviate in any subgame, and so \( s^* \) is a subgame perfect equilibrium. This completes the proof of Theorem 5.8.

The picture is a little more complicated once the number of players is increased beyond 2. Consider the following 3 player base game: the actions available to each player are \( A_i = \{0, 1\} \), and the utility to each player is 1 if all players choose the same action, and 0 otherwise. Clearly, the minmax utilities here are \( u_i^{mm} = 0 \).

If we try to implement the idea of the two person proof to this game we immediately run into trouble, since there is no strategy profile \((b_1, b_2, \ldots, b_n)\) such that, for every player \( i \), \( b_{-i} \) satisfies

\[ b_{-i} \in \text{argmin}_{a_{-i}} \max_{a_i} u_i(a_{-i}, a_i). \]

To see this, assume that the above is satisfied for \( i = 3 \); that is, that \( b_{-3} \) is a minmax strategy for player 3. Then \( b_1 \neq b_2 \). Hence either \( b_3 = b_1 \) or \( b_3 = b_2 \). In the first case \( b_{-2} \) is not a minmax strategy for player 2, while in the second case \( b_{-1} \) is not a minmax strategy for player 1. In other words, for any strategy profile \( b \) there is a player who can guarantee a payoff of 1, either by playing \( b \) or by deviating from it.
In fact, it can be shown [10] that in this repeated game there are no perfect equilibria in which all players have utility less than 1! Fix a discount factor \( \delta \in (0, 1) \), and let

\[ \alpha = \inf \{ w : \exists \text{ a subgame perfect equilibrium with utility } w \text{ for all players} \} . \]

By the above observation, in any subgame there will be a player who can, by perhaps deviating, guarantee a payoff of at least \((1 - \delta) + \delta \alpha\).

Now, for every \( \varepsilon > 0 \) there is a subgame perfect equilibrium in which the utility for each player is at most \( \alpha + \varepsilon \). Hence

\[ (1 - \delta) + \delta \alpha \leq \alpha + \varepsilon . \]

Since this holds for every \( \varepsilon \) we have that

\[ (1 - \delta) + \delta \alpha \leq \alpha \]

and thus \( 1 \leq \alpha \).

Note that in this game the set of feasible, enforceable payoff profiles is \( \{(w, w, w) : w \in [0, 1]\} \), which is one dimensional. It turns out that in base games in which this set has full dimension — i.e., dimension that is equal to the number of players — a folk theorem does apply. This result is also due to Fudenberg and Maskin [10].

**Theorem 5.10.** Assume that the set of feasible, enforceable payoff profiles has dimension \( n \). For every feasible, strictly enforceable payoff profile \( w \) and \( \varepsilon > 0 \) there is a \( \delta_0 > 0 \) such that for all \( \delta > \delta_0 \) there exists a perfect Nash equilibrium of \( G \) with \( \delta \)-discounting utilities whose associated payoff profile \( w' \) satisfies \( |w'_i - w_i| < \varepsilon \) for all \( i \in N \).

Before proving this theorem we will state and prove a one-deviation principle for repeated game with discounting.

**Theorem 5.11.** Let \( G \) be a repeated game with \( \delta \)-discounting. Let \( s^* \) be a strategy profile that is not a subgame perfect equilibrium. Then there is a subgame \( G' \) of \( G \) and a player \( i \) who has a profitable deviation in \( G' \) that differs from \( s^*_i \) only in the first period of \( G' \).

**Proof.** Let \( s_i \) be a profitable deviation from \( s^*_i \), which, among \( i \)'s profitable deviations, has a minimal last period in which it can differ from \( s^*_i \). Of course, it could a-priori be that \( s_i \) differs from \( s^*_i \) in infinitely many periods.

If there is a finite maximum period \( t \) in which \( s_i \) differs from \( s^*_i \), let \( G' \) be a subgame that starts in period \( t \) and in which, under \( s_i \), \( i \) chooses a different action that she does in \( s^*_i \). Then, by the minimality of \( s \), \( s_i \) is a profitable deviation for \( G' \), and furthermore, as a \( G' \) strategy, differs from \( s^* \) only in the first period. Therefore, if we let \( s_i \) be the strategy
that is equal to \( s^*_i \) everywhere but in the first period of \( G' \) where it equals \( s_i \), then we have found a profitable one-deviation for \( G \).

We are left with the case that there is no finite maximum period in which \( s_i \) differs from \( s^*_i \). Let \( u_i(s^*_i, s_i) = u_i(s^*) + \varepsilon \). Let \( \tilde{s}_i \) be the strategy for player \( i \) which is equal to \( s_i \) up to some time period \( \ell > \log(\varepsilon/2) / \log(\delta) \), and thereafter is equal to \( s^* \). Then \( \delta^\ell < \varepsilon/2 \), and so \( |u_i(s^*_i, s_i) - u_i(s^*_i, \tilde{s}_i)| < \varepsilon/2 \). In particular, \( u_i(s^*_i, s_i) > u_i(s^*) + \varepsilon/2 \), and thus \( \tilde{s}_i \) is a profitable deviation. It furthermore has a finite maximum period in which it differs from \( s^*_i \), in contradiction to the minimality of \( s_i \).

We now return to the proof of Theorem 5.10 Let \( w \) be a feasible, strictly enforceable payoff profile. Then there is some payoff profile \( z \) so that \( z_j < w_j \) for all \( j \). Furthermore, because of the full dimensionality assumption, for each \( i = 1, \ldots, n \) there is a payoff profile \( z^i \) such that

- \( z^i_i = z_i \).
- For \( j \neq i \), \( z_j < z^i_j < w_j \).

As in the two-player case, we will prove Theorem 5.10 for the case that there are action profiles \( a^0, a^1, \ldots, a^n \) for \( G_0 \) that, respectively, realize the payoff profiles \( w, z^1, \ldots, z^n \).

For each player \( i \) let \( b^i \) be the profile given by

\[
 b^i_{-i} \in \arg\min_{a_{-i}} u_i(a_{-i}, a_i),
\]

with \( b^i_i \) a best response to \( b^i_{-i} \). We consider the strategy profile \( s^* \) with the following modes.

- In on-path mode the players play \( a^0 \).
- In \( i \)-punishment mode, the players play \( b^i \).
- In \( i \)-reconciliation mode the players play \( a^i \).

The game starts in on-path mode. Assuming it stays there, the payoff profile is indeed \( w \). If any player \( i \) deviates, the game enters \( i \)-punishment mode for some number of \( \ell \) rounds. After these \( \ell \) rounds the game enters \( i \)-reconciliation mode, in which it stays forever. A deviation by player \( j \) in \( i \)-reconciliation model or \( i \)-punishment mode are likewise met with entering \( j \)-punishment mode for \( \ell \) periods, followed by \( j \)-reconciliation mode.

As in the two player case, denote by \( \bar{u}_i = \max_{a \in A} u_i(a) \) the maximal utility achievable by player \( i \) in \( G_0 \).

For \( s^* \) to be an equilibrium we have to verify that there are no profitable deviations in any of the possible subgames. By Theorem 5.11 it suffices to check that no one-shot profitable deviation exists in them.
Note that the possible subgames correspond to one-path mode, \(i\)-punishment mode with \(k\) periods left, and \(i\)-reconciliation mode.

The equilibrium path utility for player \(j\) is \(w_j\) in on-path mode. In \(i\)-punishment mode with \(k\) periods left it is
\[
(1 - \delta^k)u_j(b^i) + \delta^k z^i_j,
\]
which we will denote by \(v^{i,k}_j\). Note that \(u_i(b^i) = 0\) by the definition of \(b^i\), and so
\[
v^{i,k}_i = \delta^k z^i_i.
\]
In \(i\)-reconciliation mode the utility on equilibrium path for player \(j\) is \(z^i_j\).

For a deviation of player \(j\) in on-path mode to not be profitable it suffices to ensure that
\[
(1 - \delta)\bar{u}_j + \delta v^{i,\ell}_j \leq w_j.
\]
Substituting \(v^{i,\ell}_j\) yields
\[
(1 - \delta)\bar{u}_j + \delta^{\ell+1} z^j_j \leq w_j.
\]
Since \(z^j_j < w_j\) this holds for all \(\delta\) close enough to 1. Similarly, in \(i\)-reconciliation mode it suffices that
\[
(1 - \delta)\bar{u}_j + \delta^{\ell+1} z^j_j \leq z^i_j,
\]
which holds for all \(\delta\) close enough to 1 and \(\ell\) large enough, since \(z^j_j \leq z^i_j\).

In \(i\)-punishment mode with \(k\) periods left there is clearly no profitable deviation for \(i\), who is already best-responding to her punishment \(b_{-i}\). For there to not be a profitable deviation for \(j \neq i\), it must hold that
\[
(1 - \delta)\bar{u}_j + \delta v^{j,\ell}_j \leq v^{i,k}_j.
\]
Substituting yields
\[
(1 - \delta)\bar{u}_j + \delta^{\ell+1} z^j_j \leq (1 - \delta^k)u_j(b^i) + \delta^k z^i_j.
\]
By again choosing \(\delta\) close enough to 1 we can make the left hand side smaller than \(\delta^k z^i_j\), since \(z^j_j < z^i_j\) (recall that \(j \neq i\)), and thus smaller than the right hand side. This completes the proof of Theorem 5.10, for the case that the relevant payoff profiles can be realized using pure strategy profiles.
5.6. **Finitely repeated games.** In this section we consider a finitely repeated game with $T$ periods. The utility will always be the sum of the stage utilities:

$$v_i(a^1, a^2, \ldots, a^T) = \sum_{t=1}^{T} u_i(a^t).$$

5.6.1. **Nash equilibria and folk theorems.** A simple but important first observation about finitely repeated games is the following.

**Claim 5.12.** In every Nash equilibrium of a finitely repeated game, the last action profile played on path is a Nash equilibrium of the base game.

In general finitely repeated games one cannot hope to prove a folk theorem that is as strong as those available in infinitely repeated games, as the following example illustrates.

Let $G_0$ be the following prisoner’s dilemma:

<table>
<thead>
<tr>
<th></th>
<th>D</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>D</td>
<td>−3</td>
<td>−10</td>
</tr>
<tr>
<td>C</td>
<td>−10</td>
<td>−2</td>
</tr>
</tbody>
</table>

**Claim 5.13.** In every Nash equilibrium of $G$ both players play $D$ in every period on the equilibrium path.

**Proof.** Let $s^*$ be a Nash equilibrium of the repeated game. Assume by contradiction that, when playing $s^*$, some player plays $C$ on some period, and let $t_\ell$ be the last such period. Say player $i$ plays $C$ on $t_\ell$.

Let $s_i$ be the strategy for player $i$ that is identical to $s^*_i$ in all periods $t < t_\ell$, and under which, for periods $t \geq t_\ell$, player $i$ always plays $D$. We claim that $s_i$ is a profitable deviation: the stage utilities for $i$ in periods $t < t_\ell$ are the same under $s_i$ and $s^*_i$. In period $t_\ell$ the utility is strictly larger, since $D$ is a strictly dominant strategy. In periods $t > t_\ell$ both players played $D$ under $s^*$ (by the definition of $t_\ell$), and so the utility for player $i$ under $s_i$ is either the same (if the other player still plays $D$) or greater than the utility under $s^*$ (if the other player now plays $C$ in some of the periods). \(\Box\)

Hence the payoff profile in every Nash equilibrium (subgame perfect or not) is $(-10, -10)$. This is in stark contrast to the infinitely repeated case.

This result can be extended to any game in which every equilibrium achieves minmax payoff profiles. In contrast we consider games in which there is a Nash equilibrium in which every player’s payoff is
larger than her minmax payoff. In such games we again have a strong folk theorem [17].

**Theorem 5.14.** Assume that $G_0$ has a Nash equilibrium $a^*$ whose associated payoff profile $w^*$ satisfies $w^*_i > u^*_i$. Let $a$ be an action profile in $G_0$ whose payoff profile $w$ is strictly enforceable. Then for any $\varepsilon > 0$ and $T$ large enough there is a Nash equilibrium of $G$ with payoff profile $w'$ such that $|w_i - w'_i| < \varepsilon$ for all $i$.

Consider a strategy profile $s^*$ with the following modes:

- In on-path mode, players play $a$ in all periods except the last $\ell$ periods, in which they play $a^*$.
- In $i$-punishment mode the players play $b^i$ where

$$b^i \in \arg\min_{a_{-i}} \max_{a_i} u_i(a_{-i}, a_i)$$

and $b^i_i$ a best response to $b^i_{-i}$.

The game starts in on-path mode, and switches to $i$-punishment mode for the rest of the game if $i$ deviates.

**Exercise 5.15.** Prove Theorem 5.14 using $s^*$.

5.6.2. Perfect Nash equilibria and folk theorems.

**Claim 5.16.** In every subgame perfect Nash equilibrium of a finitely repeated game, the last action profile played after any history is a Nash equilibrium of the base game.

**Exercise 5.17.** Show that if the base game has a unique Nash equilibrium $a^*$ then the payoff profile of any subgame perfect equilibrium of the repeated game is the same as that of $a^*$.

When there are sufficiently many diverse equilibria of the base game it is possible to prove a perfect folk theorem for the finite repeated game.
6. EXTENSIVE FORM GAMES WITH CHANCE MOVES AND IMPERFECT INFORMATION

6.1. Definition. In this section we introduce two new elements to extensive form games: chance moves and imperfect information. The idea behind chance moves is to model randomness that is introduced to the game by an outside force ("nature") that is not one of the players. Imperfect information models situations where players do not observe everything that happened in the past. We will restrict ourselves to games of perfect recall: players will not forget any observations that they made in the past. To simplify matters we will not allow simultaneous moves.

In this section, an extensive form game will be given by $G = (N, A, H, I, P, \sigma_c, \{u_i\})$ where $N$, $A$ and $H$ are as in games of perfect information (Section 1.2), $Z$ are again the terminal histories, and

- $I$ is a partition of the non-terminal histories $H \setminus Z$ such that, for all $J \in I$ and $h_1, h_2 \in J$, it holds that $A(h_1) = A(h_2)$. We therefore define can define $A: I \to A$ by $A(J) = A(h)$ where $h \in J$ is arbitrary. We denote by $J(h)$ the partition element $J \in I$ that contains $h \in H \setminus Z$.
- $P: I \to N \cup \{c\}$ assigns to each non-terminal history either a player, or $c$, indicating a chance move. We sometimes think of the chance moves as belonging to a chance player $c$. When $P(J) = i$ we say that $J$ is an information set of player $i$. The collection of the information sets of player $i$ is denoted by $I_i = P^{-1}(i)$ and is called $i$'s information partition.
- $A_c = \prod_{J \in P^{-1}(c)} A(J)$ be the product of all action sets available to the chance player. $\sigma_c$ is a product distribution on $A_c$. That is,

$$\sigma_c = \prod_{J \in P^{-1}(c)} \sigma_c(\cdot|J),$$

where $\sigma_c(\cdot|J)$ is a probability distribution on $A(J)$, the set of actions available at information set $J$.
- For each player $i$, $u_i: Z \to \mathbb{R}$ is her utility for each terminal history.

We will assume that $G$ is a game of perfect recall: For each player $i$ and each $h = (a^1, a^2, \ldots, a^n)$ that is in some information set of $i$, let the experience $X(h)$ be the sequence of $i$'s information sets visited.

---

\[8\] This is (almost) without loss of generality, since simultaneous moves are equivalent to sequential moves that are not observed by others until later.
by prefixes of \( h \), and the actions \( i \) took there. That is, \( X(h) \) is the sequence
\[
((J^1, b^1), (J^2, b^2), \ldots, (J^k, b^k))
\]
where each \( J^m \) is an element of \( \mathcal{I}_i \), each \( b^m \) is an element of \( A(J^m) \), and \( (b^1, \ldots, b^m) \) is the subsequence of \( h \) which includes the actions taken by \( i \).

Perfect recall means that for each \( J \in \mathcal{I} \) and \( h_1, h_2 \in J \) it holds that \( X(h_1) = X(h_2) \). That is, there is only one possible experience of getting to \( J \), which we can denote by \( X(J) \). In particular, in a game of perfect recall each information set is visited at most once along any play path.

6.2. Pure strategies, mixed strategies and behavioral strategies. A pure strategy of player \( i \) in \( G \) is a map \( s_i \) that assigns to each \( J \in \mathcal{I}_i \) an action \( a \in A(J) \). We can think of \( s_i \) as an element of \( A_i := \prod_{J \in \mathcal{I}_i} A(J) \). A mixed strategy \( \sigma_i \) of a player in an extensive form game is a distribution over pure strategies. Given a \( J \in \mathcal{I}_i \), we denote by \( \sigma_i(\cdot|J) \) the distribution over \( A(J) \) given by \( \sigma_i \), conditioned on the experience \( X(J) \). That is, \( \sigma_i(a|J) \) is the probability, if we choose \( s_i \) according to \( \sigma_i \), that \( s_i(J) = a \) conditioned on \( s_i(J^1) = b^1, \ldots, s_i(J^k) = b^k \), where \( ((J^1, b^1), (J^2, b^2), \ldots, (J^k, b^k)) \) is the unique experience that terminates in \( J \). Of course, it could be that this conditional probability is not well defined, in the case that \( s_i(J^1) = b^1, \ldots, s_i(J^k) = b^k \) occurs with zero probability.

Recall that \( A_i = \prod_{J \in \mathcal{I}_i} A(J) \) is the product of all action sets available to player \( i \). A behavioral strategy \( \sigma_i \) of player \( i \) is a product distribution on \( A_i \):
\[
\sigma_i = \prod_{J \in \mathcal{I}_i} \sigma_i(\cdot|J),
\]
where \( \sigma_i(\cdot|J) \) is a distribution on \( A(J) \). Note that \( \sigma_c \), the chance player’s distribution, is a behavioral strategy. Note also that each element of \( \prod_{J \in \mathcal{I}_i} A(J) \) can be identified with a function that assigns to each element \( J \in \mathcal{I}_i \) an element of \( A(J) \). Therefore, by our definition of behavioral strategies, every behavioral strategy is a mixed strategy.

Given a strategy profile \( \sigma \) of either pure, mixed or behavioral strategies (or even a mixture of these), we can define a distribution over the terminal histories \( Z \) by choosing a random pure strategy for each player (including the chance player), and following the game path to its terminal history \( z \). A player’s utility for \( \sigma \) is \( u_i(\sigma) = \mathbb{E}[u_i(z)] \), her expected utility at this randomly picked terminal history.
Proposition 6.1. Under our assumption of perfect recall, for every mixed (resp., behavioral) strategy $\sigma_i$ there is a behavioral (resp., mixed) strategy $\sigma_i'$ such that, for every mixed $\sigma_{-i}$ it holds that $u_i(\sigma_{-i}, \sigma_i) = u_i(\sigma_{-i}, \sigma_i')$.

We prove this proposition for finite games. Note that our definition of behavioral strategies as a special case of mixed strategies is designed for games in which each information set is visited only once. In the general case, behavioral strategies are defined differently: they are simply a distribution on each information set, with the understanding that at each visit a new action is picked independently.

Proof of Proposition 6.1. By our definition of behavioral strategies, every behavioral strategy is a mixed strategy, and so if $\sigma_i$ is a behavioral strategy we can simply take $\sigma_i' = \sigma_i$.

To see the other direction, let $\sigma_i$ be a mixed strategy. For $J \in I_i$ and $a \in A(J)$, let

$$
\sigma_i'(a|J) = \sigma_i(a|J),
$$

provided the conditioned event of reaching $J$ has positive probability; otherwise let $\sigma_i'(a|J)$ be arbitrary.

Fix $\sigma_{-i}$ and let $h = (a^1, \ldots, a^k)$ be a history. We denote by $\mathbb{P}[a^1, \ldots, a^k]$ the probability that this history is played when using the strategy profile $(\sigma_{-i}, \sigma_i)$. Assume by induction that this probability is the same whether we calculate it using $\sigma_i$ or $\sigma_i'$, for all histories of length $< k$.

Note that

$$
\mathbb{P}[a^1, \ldots, a^k] = \mathbb{P}[a^k|a^1, \ldots, a^{k-1}] \cdot \mathbb{P}[a^1, \ldots, a^{k-1}].
$$

Now, by our inductive assumption $\mathbb{P}[a^1, \ldots, a^{k-1}]$ takes the same value if we calculate it using $\sigma_i'$ rather than $\sigma_i$. If $h = (a^1, \ldots, a^{k-1})$ is a history in an information set $J$ that does not belong to $I_i$ then clearly $\mathbb{P}[a^k|a^1, \ldots, a^{k-1}]$ does not depend on whether we use $\sigma_i$ or $\sigma_i'$, and hence $\mathbb{P}[a^1, \ldots, a^k]$ does not either.

Otherwise $J \in I_i$. In this case, let $s_i$ be a strategy that is picked according to $\sigma_i$. Then

$$
\mathbb{P}[a^k|(a^1, \ldots, a^{k-1})] = \mathbb{P}[s_i(J) = a^k|a_1, \ldots, a^{k-1}]
$$

$$
= \mathbb{P}[s_i(J) = a^k|s_i(J^1) = b^1, \ldots, s_i(J^\ell) = b^\ell]
$$

$$
= \sigma(a^k|J),
$$

where $((J^1, b^1), \ldots, (J^\ell, b^\ell))$ is player $i$'s experience at $J$, the partition element of $h$. This holds since the other players' choices are independent of $i$'s and hence can be left out. Hence, by our definition of $\sigma_i'$,
\( \mathbb{P} \left[ a^k | a^1, \ldots, a^{k-1} \right] \) is the same under \( \sigma_i \) and \( \sigma'_i \). Therefore the same applies to \( \mathbb{P} \left[ a^1, \ldots, a^k \right] \), and in particular to any terminal history. Thus the distribution on terminal histories is identical, and hence so are the expected utilities. \( \square \)

6.3. **Belief systems and assessments.** Let \( G = (N, A, H, I, P, \sigma_c, \{ u_i \}) \) be a finite extensive form game. A belief system \( \{ \mu(\cdot | J) \} \) is a collection of probability measures, with \( \mu(\cdot | J) \) a probability measure over \( J \).

Fix a mixed strategy profile \( \sigma \), and for a history \( h = (a^1, \ldots, a^k) \) denote, as above, by \( \mathbb{P}_\sigma[h] \) the probability of the event that the path of play includes \( h \). We likewise denote by \( \mathbb{P}_\sigma[J] \) the probability that an information set \( J \) is visited. We say that \( \mu(\cdot | J) \) is derived from \( \sigma \) if for any history \( h \in J \) such that \( \mathbb{P}_\sigma[J] > 0 \) it holds that \( \mu(h | J) = \mathbb{P}_\sigma[h | J] \).

For \( J \) with \( \mathbb{P}_\sigma[J] = 0 \), \( \mu(\cdot | J) \) can take any value.

An assessment is a pair \((\sigma, \mu)\) such that \( \mu \) is derived from \( \sigma \).

Recall that we say that \( \sigma \) is completely mixed if for all \( i, J \in \mathcal{I}_i \) and \( a \in A(J) \) it holds that \( \sigma_i(a | J) > 0 \). That is, in every information set every allowed action has positive probability. In this case \( \mathbb{P}_\sigma[J] > 0 \) for every information set \( J \), and so there is only one belief system \( \mu \) that is derived from \( \sigma \). Hence for completely mixed \( \sigma \) there is only one assessment \((\sigma, \mu)\).

6.4. **Sequential rationality and sequential equilibria.** In this section we introduce a concept that is a natural adaptation of subgame perfection to games with incomplete information.

Given a strategy profile \( \sigma \) and a belief system \( \mu \), we can naturally extend each \( \mu(\cdot | J) \) to a distribution over all terminal histories that can be reached from \( J \): given a terminal history \( z = (a^1, \ldots, a^k, a^{k+1}, \ldots, a^\ell) \) such that \( h = (a^1, \ldots, a^k) \in J \), denote by \( J^m := J(a^m) \) the information set to which \( a^m \) belongs, and let

\[
\mu_\sigma(z | J) = \mu(h | J) \cdot \prod_{m=k}^{\ell-1} \sigma_{P(J^m)}(a^{m+1} | J^m).
\]

Note that \( \mu_\sigma(z | J) \) is well defined since for any terminal history that passes through \( J \) there is, by perfect recall, a unique prefix \( h \) that ends in \( J \).

Recall from the previous section that an assessment \((\sigma, \mu)\) induces, for each \( J \in \mathcal{I} \), a distribution \( \mu(\cdot | J) \) on the terminal histories reachable.
from $J$. We say that $(\sigma^*, \mu^*)$ is sequentially rational if for each player $i$ and $J \in \mathcal{I}_i$ it holds that
\[ E_{\mu^*_{\sigma^*}(|J)} [u_i(z)] \geq E_{\mu^*_{\sigma}(|J)} [u_i(z)] \]
for any $\sigma = (\sigma^*_{-i}, \sigma_i)$. Intuitively, sequential rationality corresponds to subgame perfection: there are no profitable deviations for any player at any information set.

**Exercise 6.2.** Show that this notion of subgame perfection reduces to the usual notion in the case of games of perfect information.

Recall that for completely mixed $\sigma$ there is a unique assessment $(\sigma, \mu)$. However, when $\sigma$ is not completely mixed, there can be excessive freedom in choosing $\mu$, which can result in “strange” belief updates following deviations. For example, consider the three player game in which players 1 and 2 choose among \{a, b\}, and player 3 only observes player 1’s choice, so that her information sets are $J_a$ and $J_b$, corresponding to player 1’s choice. Player 3 then chooses among \{a, b\}. Let $\sigma_1(a) = \sigma_2(a) = \sigma_3(a) = 1$, and let $\mu(aa|J_a) = 1$, $\mu(bb|J_b) = 1$; the rest of the information sets are singletons and therefore have trivial beliefs. The fact that $\mu(bb|J_a) = 1$ means that if player 3 learns that 1 deviated then she assumes that 2 also deviated. See also the game in [30, Figure 4].

A common way to restrict $\mu$ is to require consistency: We say that an assessment $(\sigma, \mu)$ is consistent if there exists a sequence \{$(\sigma^m, \mu^m)$\}$_{m \in \mathbb{N}}$ that converges to $(\sigma, \mu)$ and such that each $\sigma^m$ is completely mixed. We say that $(\sigma, \mu)$ is a sequential equilibrium [18] if it is consistent and sequentially rational.

**Exercise 6.3.** Show that if $G$ has perfect information then $(\sigma, \mu)$ is a sequential equilibrium iff it is subgame perfect.

6.5. **Trembling hand perfect equilibrium.** In extensive form games one could define trembling hand equilibria as simply the trembling hand equilibria of the strategic form game. However, this leads to equilibria that are not subgame perfect (see, e.g., [26, Figure 250.1]).

We therefore define a different notion for extensive form games. To this end, given a behavioral strategy $\sigma_i = \prod_{J \in \mathcal{I}_i} \sigma_i(\cdot|J)$, we think of each decision made at each information set as being made by a different agent. This is sometimes called the agent form of the game. Here the set of agents is the set of information sets (except those that belong to the chance player) and the strategy of player $J \in \mathcal{I}_i$ is $\sigma_i(\cdot|J)$.

An extensive form trembling hand perfect equilibrium of $G$ is a behavior strategy profile $\sigma$ that is a trembling hand perfect equilibrium of the agent form of $G$ (in strategic form).
6.6. **Perfect Bayesian equilibrium.** An assessment that is sequentially rational is said to be a *weak perfect Bayesian equilibrium*. As we mentioned above, this seems to be a problematic notion (see [30, Figure 4]).

The most widely used notion of perfect equilibrium is that of a *perfect Bayesian equilibrium*, due to Fudenberg and Tirole [11]. However, they only define it for a small class of extensive form games with incomplete information, and it is not clear what the (widely used!) definition is for general games. An excellent discussion and two possible notions are presented by Watson [30]. These notions involve two principles:

1. *Bayesian updating*. Whenever possible beliefs are updated using Bayes’ rule. This is obviously possible on path, but also sometimes in updates following a deviation but not immediately after it.

2. *Conservation of independence*. A natural assumption is that if a player deviates then the others update their beliefs regarding her strategy / type, but not the other players’, unless necessary. More generally, if two events are independent before a deviation, and if the deviation is (somehow) independent of one, then beliefs regarding the other should not be updated [5].

6.7. **The Walmart game.** In this section (based on [26, Example 239.1]) we describe a game of perfect information, find its unique subgame perfect equilibrium, and discuss why this seems an unsatisfactory description of reality. We then analyze a Bayesian version of the same game, which seems to have a more attractive solution.

6.7.1. **Perfect information, one round.** A mobster approaches a local grocer and asks for payment in exchange for “protection services”. The grocer has two possible courses of action: comply (C) or refuse (R). In the latter case the mobster has two possible responses: punish (P) or forgive (F). The payoff matrix in strategic form is the following, with the mobster as the row player. Here $a > 1$ and $0 < b < 1$.

<table>
<thead>
<tr>
<th></th>
<th>C</th>
<th>R</th>
</tr>
</thead>
<tbody>
<tr>
<td>P</td>
<td>$a,0$</td>
<td>$-1,b-1$</td>
</tr>
<tr>
<td>F</td>
<td>$a,0$</td>
<td>$0,b$</td>
</tr>
</tbody>
</table>

Alternatively, this can be a model of a game played by Walmart and the same grocer: Walmart opens a store in town. The grocer has two possible courses of action: leave town or stay. In the latter case Walmart has two possible responses: undercut or compete; undercutting refers to the practice of charging below cost in order to bankrupt the competition.
A Nash equilibrium of this game is for the grocer to comply, under threat of punishment by the mobster. However, this is not a credible threat, and in the unique subgame perfect equilibrium of this game the grocer refuses and the mobster forgives.

6.7.2. **Perfect information, many rounds.** Consider now the case that there are \( n \) grocers that the mobster engages, one after the other. Thus this is an \( n + 1 \)-player game, with the game between the mobster and each grocer being the one described above. Note that for the last grocer the unique subgame perfect equilibrium is again \((R, F)\), and therefore, by backward induction, in the unique subgame perfect equilibrium of this game each grocer refuses and the mobster forgives, after any history.

Consider the case that the mobster deviates and punishes the first ten grocers who refuse. Under this (unique) subgame perfect equilibrium, the eleventh grocer will not learn the lesson and will again refuse.

6.7.3. **Imperfect information, one round.** Consider now the case that there are two types of mobsters: the sane mobster \((s)\) and the crazy mobster \((c)\). The former’s utility is as described above. The latter derives sadistic pleasure from punishing, and therefore, when playing with a crazy mobster, the utility matrix is the following.

\[
\begin{array}{ccc}
P & R \\
C & a, 0 & 0, b - 1 \\
F & a, 0 & -1, b \\
\end{array}
\]

Consider now a Bayesian game in which the mobster is crazy with probability \( \varepsilon \) and sane with probability \( 1 - \varepsilon \). The mobster observes his type but the grocer does not. They then play the same game.

The mobster does have complete information here, and so the analysis of the subgame perfect equilibrium is still simple. If the grocer refuses, clearly the sane mobster forgives and the crazy mobster punishes. Hence the grocer’s expected utility for refusing is \( (1 - \varepsilon)b + \varepsilon(b - 1) = b - \varepsilon \) and his utility for complying is 0. If we assume that \( \varepsilon < b \), and so we again have that the grocer refuses.

6.7.4. **Imperfect information, many rounds.** We now expand this Bayesian game to a game with \( n \) rounds, where, as before, in each round the mobster engages a new grocer. We number the rounds \( \{0, 1, \ldots, n - 1\} \). We associate with each round \( k \) the number \( b_k = b^{n-k} \).

The mobster’s type is picked once in the beginning of the game, and is not observed by any of the grocers. We think of \( \varepsilon \) as small but fixed, and of \( n \) of being very large, so that \( b_0 = b^n < \varepsilon \).
We describe an assessment that is sequentially rational, and is in fact a perfect Bayesian equilibrium, according to the definition in Fudenberg and Tirole [11]. In this equilibrium the mobster will (obviously) punish if he is crazy. However, even if he is sane, he will punish (except towards the end), to maintain the grocers’ beliefs that he might be crazy. The result is that the grocers all comply, except for the last few.

Note that the mobster observes his own type and all the grocers’ actions, and so there is no need to define beliefs for him. The grocer’s beliefs are probability distributions over the mobster’s type, and so we denote the belief of grocer $P(h)$ after a history $h$ by $\mu(h)$, which we will take to denote the belief that the mobster is crazy (rather than having it denote the entire distribution).

The game will have two phases. In the first phase, the mobster will always punish any grocer that does not comply. This will last $k^*$ rounds, where

$$k^* = \max\{k \in \mathbb{N} : \varepsilon > b_k\}.$$ 

In the second phase the sane mobster will use a mixed strategy to decide whether to punish or forgive, while the crazy mobster will always punish. Finally, in the last round the sane mobster always forgive (while the crazy still punishes).

The beliefs are defined as follows:

- Initially, $\mu(\emptyset) = \varepsilon$; this must be so if this is indeed to be an assessment (recall that in assessments we require beliefs to be derived from the strategy profile, and in particular from the chance moves).
- When a grocer complies they do not observe any action of the mobster, and thus maintain the same belief. That is, $\mu(hC) = \mu(h)$ for any history $h$.
- If the mobster ever forgives a refusal then the grocers henceforth believe that he is sane. That is, $\mu(h) = 0$ for any history $h$ that contains $F$.
- Given a history $h$ in which the mobster has never forgiven, and which ends in round $k$ in which the mobster punished, the belief $\mu(hP) = \max\{\mu(h), b_k\}$.

The strategies $\sigma$ are defined as follows, where $h$ is a history at round $k$:

- The grocer refuses if $\mu(h) < b_k$. He complies if $\mu(h) > b_k$. If $\mu = b_k$ then he complies with probability $1/a$ and refuses with probability $1 - 1/a$. 

• The mobster has to move only if the grocer refused. If the mobster is crazy then he always punishes. If he is sane then on the last round he always forgives. On other rounds he punishes if $\mu(h) > b_k$. If $\mu(h) \leq b_k$ then he punishes with probability $p_k$ and forgives with probability $1 - p_k$, where

$$p_k = \frac{(1 - b_{k+1})\mu(h)}{b_{k+1}(1 - \mu(h))}.$$ 

We now analyze the game play along the equilibrium path. We assume that $\varepsilon > b^n$, and thus $k^* \geq 1$. Since $\mu(\emptyset) = \varepsilon$, in round 0 we have that $\mu > b_0$, and so the grocer complies. This leaves $\mu$ unchanged, and so, as long as the round $k$ is at most $k^*$, we have that $\mu > b_k$ and the grocers keep complying. This is rational since the mobster (whether sane or not) punishes when $\mu > b_k$. If any of the grocers were to deviate and refuse in this phase, the mobster would punish (again, whether sane or not) and so the grocers would learn nothing and continue complying.

In the second phase, if $\mu(h) = b_k$ then a sane mobster will punish with probability $p_k$. Hence the probability that a mobster will punish is

$$b_k + (1 - b_k)p_k = b_k + (1 - b_k)\frac{(1 - b_{k+1})\mu(h)}{b_{k+1}(1 - \mu(h))}$$

$$= b_k + (1 - b_k)\frac{(1 - b_{k+1})b_k}{b_{k+1}(1 - b_k)}$$

$$= b_k + \frac{(1 - b_{k+1})b_k}{b_{k+1}}$$

$$= b_k + (1 - b_{k+1})b$$

$$= b.$$  

It follows that a grocer’s utility for complying is $(b - 1)b + b(1 - b) = 0$, making him indifferent between complying and refusing. It is therefore rational for him to play any mixed strategy. If $\mu(h) < b_k$ then the mobster punishes with probability less than $b$. In that case the only rational choice of the grocer is to refuse.

In the second phase, we claim that $\mu$ at round $k$ is always at most $b_k$. We prove this by induction; it is true by definition at the first round of the second phase, round $k^*$.

If the grocer refuses and the mobster punishes at round $k > k^*$ (with probability $p_k$), and assuming the he has never forgiven before, Bayes’
law yields that
\[
\frac{\mu(hP)}{1 - \mu(hP)} = \frac{\mu(h)}{(1 - \mu(h)) p_k} = \frac{\mu(h) b_{k+1}(1 - \mu(h))}{(1 - \mu(h))(1 - b_{k+1}) \mu(h)} = \frac{b_{k+1}}{1 - b_{k+1}}.
\]

Hence \(\mu(hP) = b_{k+1}\) at round \(k + 1\). If the grocer refuses and the mobster forgives then the grocers learn that the mobster is sane and \(\mu(hF) = 0\). If the grocer complies then \(\mu\) remains unchanged since no action is observed, and \(\mu(hC) = \mu(h) < b_{k+1}\). Thus in any case it indeed holds that \(\mu\) is at most \(b_k\). Also, it follows that the grocers’ beliefs are derived from \(\sigma\).

Finally, we note (without proof) that the probabilities that the grocers choose in their mixed strategies make the mobster indifferent, and thus this assessment is indeed sequentially rational.
7. Social learning

7.1. Bayesian hypothesis testing. Consider the following single agent Bayesian game. There is a state of nature \( S = \{0, 1\} \), which is initially picked with some probability \( p = \mathbb{P}[S = 1] \). There is an experiment that the agent can carry out repeatedly, and where each execution \( i = 1, \ldots, n \) results in her observing a number \( X_i \). If \( S = 0 \) then the \( X_i \)'s are distributed i.i.d. with some distribution \( \nu_0 \). If \( S = 1 \) then they are distributed i.i.d. with distribution \( \nu_1 \). We say the the private signals \( \{X_i\}_{i=1}^n \) are conditionally independent.

Two common example are the following:

1. \( \nu_0 \) is \( N(-1, 1) \) and \( \nu_1 \) is \( N(1, 1) \).
2. \( \nu_0 \) is \( B(\frac{1}{2} - \varepsilon) \) and \( \nu_1 \) is \( B(\frac{1}{2} + \varepsilon) \).

We will assume (as in these two examples) that \( \nu_0 \) and \( \nu_1 \) are mutually absolutely continuous, so that \( \frac{d\nu_0}{d\nu_1} \) is well defined \( \nu_0 \)-almost everywhere and \( \nu_1 \)-almost everywhere.

Now, after observing her \( n \) signals the agent has to guess whether the state of nature is 0 or 1. That is, she has to take an action \( a \in \{0, 1\} \), and her utility is 1 if \( a = S \) and zero otherwise. Hence the agent’s expected utility is equal to \( \mathbb{P}[a = S] \).

It is easy to see that the only rational choices are to choose \( a = 1 \) if \( \mathbb{P}[S = 1|X_1, \ldots, X_n] \geq \frac{1}{2} \), and to choose \( a = 0 \) if \( \mathbb{P}[S = 1|X_1, \ldots, X_n] \leq \frac{1}{2} \). We will assume for now that \( p, \nu_0, \nu_1 \) are chosen in such a way that we never have equality (i.e., indifference), and so

\[
  a = \arg\max_{s \in \{0, 1\}} \mathbb{P}[s = S|X_1, \ldots, X_n].
\]

Now,

\[
  \mathbb{P}[a = S] = \mathbb{P}[a = 1|S = 1] \cdot p + \mathbb{P}[a = 0|S = 0] \cdot (1 - p).
\]

Let us calculate \( \mathbb{P}[a = 1|S = 1] \). By the remarks above the event \( a = 1 \) is equal to the event \( \mathbb{P}[S = 1|X_1, \ldots, X_n] > \frac{1}{2} \). The latter is equal to the event that

\[
  \frac{\mathbb{P}[S = 1|X_1, \ldots, X_n]}{\mathbb{P}[S = 0|X_1, \ldots, X_n]} > 1.
\]

When \( \nu_0 \) and \( \nu_1 \) are atomic, we can rewrite this as

\[
  \frac{\mathbb{P}[X_1, \ldots, X_n|S = 1]}{\mathbb{P}[X_1, \ldots, X_n|S = 0]} \cdot \frac{p}{1 - p} > 1.
\]
By conditional independence, this is the same as
\[ \sum_{i=1}^{n} \log \frac{P[X_i|S=1]}{P[X_i|S=0]}(X_i) + \ell_0 > 0. \]

In the general (not necessarily atomic) case, this becomes
\[ \sum_{i=1}^{n} \log \frac{d\nu_1}{d\nu_0}(X_i) + \ell_0 > 0, \]
where \( \ell_0 = \log(p/(1-p)) \). Let \( L_i = \log \frac{d\nu_1}{d\nu_0}(X_i) \) be the private log likelihood ratios. Denote \( M_i = \sum_{k=1}^{i} L_k \). Then we have shown that \( a = 1 \) iff \( \ell_0 + M_n > 0 \). To simplify calculations henceforth we assume that \( \ell_0 = 0 \).

Therefore, to estimate \( P[a = 1|S=1] \) we need to estimate the probability that \( M_n > 0 \). To this end we will need a few definitions. First, denote \( L = L_1 \), and let \( \varphi_1 : \mathbb{R} \to \mathbb{R} \) be given by
\[ \varphi_1(t) = -\log E[e^{-tL}|S=1]. \]

We now add an additional assumption that \( \varphi_1(t) \) is finite for all \( t \). This holds, for example, if the supports of \( \nu_0 \) and \( \nu_1 \) are finite. It also holds in the Gaussian example above. Note that \( E[e^{-tL}] \) is called the Laplace transform of \( L \).

**Proposition 7.1.**
1. \( \varphi_1(0) = \varphi_1(1) = 0 \).
2. \( \varphi_1 \) is smooth and concave.

We will not prove this claim here. Note that it follows from it that \( \varphi_1 \) is positive in the interval \((0, 1)\).

Now, the probability of mistake (that is, the probability that \( a = 0 \) conditioned on \( S = 1 \)) is, for any \( t > 0 \),
\[ P[M_n < 0|S=1] = P[e^{-tM_n} > 1|S=1]. \]

Since \( e^{-tM_n} \) is a positive random variable, we can apply Markov’s inequality and write
\[ P[M_n < 0|S=1] \leq E[e^{-tM_n}|S=1]. \]

Now, recall that \( M_n = \sum_i L_i \), and that the \( L_i \)'s are conditionally independent. Hence
\[ P[M_n < 0|S=1] \leq E\left[e^{-t\sum_{i=1}^{n} L_i}|S=1\right] \]
\[ = \prod_{i=1}^{n} E\left[e^{-tL_i}|S=1\right] \]
\[ = e^{-\varphi_1(t)n}. \]
This holds for any $t > 0$, and so we have show that

**Theorem 7.2.** $P[a \neq 1|S = 1] \leq \inf_{t>0} e^{-\varphi_1(t)n}$.

Since $t$ is positive in the interval $(0, 1)$, it follows that $P[a \neq 1|S = 1]$ decreases (at least) exponentially with $n$. It turns out (but will not be proven here) that this estimate is asymptotically tight: if we denote $r = \sup_{t>0} \varphi_1(t)$, then $P[a \neq 1|S = 1] = e^{-r-n+o(n)}$.

### 7.2. Herd behavior.

The text of this section is largely taken from [22].

Banerjee [4] and concurrently Bikhchandani, Hirshleifer and Welch [6], consider the following model: There is a binary state of the world $S \in \{0, 1\}$, conditionally i.i.d. private signals with conditional distributions $\nu_1$ and $\nu_2$. There is an infinite sequence of agents $N = \{1, 2, \ldots\}$, each one with a single private signal $X_i$. For simplicity, we consider the prior $P[S = 1] = P[S = 0] = 1/2$. We assume that $\nu_0$ and $\nu_1$ satisfy the *bounded likelihood ratio* assumption: that is, that there is some $M > 0$ such that, with probability one,

$$L_i = \log \frac{d\nu_1}{d\nu_0}(X_i)$$

is in $(-M, M)$. This is satisfied, for example, when $\nu_0$ and $\nu_1$ have the same finite support.

The agents act sequentially, with agent $i$ having to choose $a_i \in \{0, 1\}$ and receiving utility $u_i(a_i, S) = 1\{a_i = S\}$. Each agent $i$, in addition to her private signal, observes the actions of her predecessors $\{1, 2, \ldots, i-1\}$. Hence

$$a_i = \arg\max_{s \in \{0, 1\}} P[s = S|a_1, \ldots, a_{i-1}, X_i].$$

We assume that $a_i = 1$ whenever the agent is indifferent.

By Theorem 7.2, if agent $i$ had access to the private signals of her predecessors then she should choose the correct action, except with exponentially small probability. It turns out that this is not exactly what happens here.

**Theorem 7.3.** The limit $\lim_i P[a_i \neq S]$ exists and is strictly greater than zero.

To analyze this model it is useful to consider an outside observer $x$ who sees the agents’ actions, but not their private signals. Thus the information available to $x$ at round $i$ is $\{a_1, a_2, \ldots, a_{i-1}\}$. We denote by

$$B^i_x = P[S = 1|a_1, \ldots, a_{i-1}]$$
x’s belief at round i. It follows from Lévy’s zero-one law (Theorem 3.23 that

\[ B_x^\infty := \mathbb{P}[S = 1|a_1, a_2, \ldots] = \lim_{i \to \infty} B_x^i. \]

We also define an action \( a_x^i \) for \( x \) at round \( i \); this is given by

\[ a_x^i = \arg\max_{s \in \{0, 1\}} \mathbb{P}[s = S|a_1, \ldots, a_{i-1}], \]

where, as with the actual players of the game, indifference results in choosing \( a_x^i = 1 \).

**Claim 7.4.** \( a_x^i = a_{i-1} \).

That is, the outside observer simply copies the action of the last agent she observes. The proof is simple, and follows from the fact that at time \( i \), agent \( i-1 \) has more information than \( x \) does. It follows that \( \mathbb{P}[a_i = S] = \mathbb{P}[a_x^i = S] \), which will help us prove Theorem 7.3.

We define agent i’s log-likelihood ratio by

\[ L_a^i = \log \frac{\mathbb{P}[S = 1|a_1, \ldots, a_{i-1}, X_i]}{\mathbb{P}[S = 0|a_1, \ldots, a_{i-1}, X_i]]. \]

As before, by Bayes’ law we can write this as

\[ L_a^i = \log \frac{\mathbb{P}[a_1, \ldots, a_{i-1}, X_i|S = 1]}{\mathbb{P}[a_1, \ldots, a_{i-1}, X_i|S = 0]}, \]

Now, the actions \( a_1, \ldots, a_{i-1} \) are not conditionally independent. However, they are conditionally independent of \( X_i \), and so

\[ L_a^i = \log \frac{\mathbb{P}[a_1, \ldots, a_{i-1}|S = 1]}{\mathbb{P}[a_1, \ldots, a_{i-1}|S = 0]} + \log \frac{\mathbb{P}[X_i|S = 1]}{\mathbb{P}[X_i|S = 0]}. \]

If we denote by

\[ L_x^i = \log \frac{B_x^i}{1 - B_x^i} = \log \frac{\mathbb{P}[a_1, \ldots, a_{i-1}|S = 1]}{\mathbb{P}[a_1, \ldots, a_{i-1}|S = 0]} \]

the outside observer’s log-likelihood ratio then we have that

(7.1) \[ L_a^i = L_x^i + L_i. \]

We observe here without proof (although it is straightforward) that there is a continuous function \( f : [0, 1] \times \{0, 1\} \to [0, 1] \) such that for all rounds \( i \)

(7.2) \[ B_x^{i+1} = f(B_x^i, a_i). \]
That is, to update her belief the outside observer need only know the new action she observes, and this calculation is the same in all rounds. The key observation behind this is that

\[ B^{i+1}_x = \mathbb{P}[S = 1|a_1, \ldots, a_{i-1}, a_i] = \mathbb{P}[S = 1|B^i_x, a_i] = f(B^i_x, a_i). \]

That is, \( B^i_x \) already includes all the \( S \)-relevant information contained in \( a_1, \ldots, a_{i-1} \), and so, given \( B^i_x \), the history before \( a_i \) is irrelevant for making inferences regarding \( S \).

**Theorem 7.5.** The limit \( \lim_i a_i \) exists almost surely.

**Proof.** As we noted above, \( a_i = a^{i+1}_x \), and so it suffices to show that \( \lim_i a^i_x \) exists almost surely.

Assume by contradiction that \( a^i_x \) takes both values infinitely often. Hence \( B^i_x \) is infinitely often above \( 1/2 \), and infinitely often below \( 1/2 \). It therefore converges to \( 1/2 \).

Taking the limit of (7.2), it follows from the continuity of \( f \) that \( f(1/2, 0) = f(1/2, 1) = 1 \). But \( B^0_x = 1/2 \), and so \( B^i_x = 1/2 \) for all \( i \). Hence \( a^i_x = 1 \) for all \( i \), and we have reached a contradiction. \( \square \)

Since \( \lim_i a_i \) exists almost surely we can define a random variable \( a = \lim_i a_i = \lim_i a^i_x \); this is the action that almost all agents choose. To prove Theorem 7.3 it remains to show that \( \mathbb{P}[a = S] \neq 1 \). An important observation is that

\[ \mathbb{P}[a^i_x = S|a_1, \ldots, a_{i-1}] = \max\{B^i_x, 1 - B^i_x\}. \]

It therefore suffices to show that \( \lim_i B^i_x \) is almost surely in \( (0, 1) \).

Since the private signals have bounded log-likelihood ratios (say with bound \( M \)), it follows from (7.1) that when \( L^i_x > M \) then, with probability one, \( L^i_a > 0 \), and hence (again with probability one) \( a_i = 1 \). Thus when \( L^i_x > M \) it is not informative to observe \( a_i \); the outside observer already knew that agent \( i \) would choose \( a_i = 1 \). Hence, in this case, \( B^{i+1}_x = B^i_x \). It follows that, with probability one, \( L^i_x < 2M \), and thus \( B^i_x \) is bounded away from one. An identical argument shows that it is bounded away from zero. This completes a sketch of the proof of Theorem 7.3.
References


