Plan for Today

So far, our players didn’t know the strategies of the others, but they did know the rules of the game (i.e., how actions determine outcomes) and everyone’s incentives (i.e., their utility functions).

Today we are going to change this and introduce uncertainty:

- Idea: *epistemic types*
- Model: *Bayesian games*
- Solution concept: *Bayes-Nash equilibrium*

This (and more) is also covered in Chapter 7 of the *Essentials*.

Modelling Uncertainty

We are only going to model uncertainty about utility functions.

*Is this not too restrictive?* No! **Example:**

Suppose Rowena is uncertain whether Colin has action \( M \) available. She can simply assume he does, but entertain the possibility that he assigns very low utility to any outcome involving \( M \):

\[
\begin{array}{ccc}
\text{T} & \text{L} & \text{R} \\
\hline
\text{T} & 2 & 8 \\
\text{B} & 1 & 5 \\
\end{array}
\sim
\begin{array}{ccc}
\text{T} & \text{L} & \text{M} & \text{R} \\
\hline
\text{T} & 2 & -100 & 8 \\
\text{B} & 1 & 3 & 5 \\
\end{array}
\]

\[
\begin{array}{ccc}
\text{L} & \text{M} & \text{R} \\
\hline
\text{L} & 11 & 7 \\
\text{R} & 4 & 6 \\
\end{array}
\sim
\begin{array}{ccc}
\text{L} & \text{M} & \text{R} \\
\hline
\text{L} & 11 & 9 \\
\text{R} & 4 & 7 \\
\end{array}
\]
Epistemic Types

The main new concept for today is that of a player's (epistemic) type. This encodes all the private information for that player.

- When the game is played, you know your own type with certainty but only have probabilistic knowledge about the types of the others.
- Your own utility depends on your own type. Still might reason about a game before you observe your type (example: make conditional plan ahead of collecting information).
- Your own utility also depends on the types of others (example: utility of winning an auction depends on knowledgeability of rival bidders).

John C. Harsanyi (1920–2000)

Bayesian Games

A *Bayesian game* is a tuple \( \langle N, A, \Theta, p, u \rangle \), where

- \( N = \{1, \ldots, n\} \) is a finite set of *players*;
- \( A = A_1 \times \cdots \times A_n \), with \( A_i \) the set of *actions* of player \( i \);
- \( \Theta = \Theta_1 \times \cdots \times \Theta_n \), with \( \Theta_i \) the set of possible *types* of player \( i \);
- \( p : \Theta \to [0, 1] \) is a *common prior* (probability distribution) over \( \Theta \);
- \( u = (u_1, \ldots, u_n) \) is a profile of *utility functions* \( u_i : A \times \Theta \to \mathbb{R} \).

We assume that also \( A \) and \( \Theta \) are *finite* (generalisations are possible).

Player \( i \) *knows* \( \Theta \) and \( p \), and *observes* her own type \( \theta_i \in \Theta_i \), but not \( \theta_{-i} \in \Theta_{-i} \). She *chooses* an action \( a_i \), giving rise to the profile \( a \in A \).

Actions are played simultaneously. Player \( i \) receives payoff \( u_i(a, \theta) \).

Remark: If \( |\Theta_i| = 1 \) for all \( i \in N \) (if everyone’s type is unambiguous), this reduces to the familiar definition of a normal-form game.
Knowledge of the State of the World

Let $p(\theta_i)$ denote the probability of player $i$ having type $\theta_i$. Formally:

$$p(\theta_i) = \sum_{\theta' \in \Theta \text{ s.t. } \theta'_i = \theta_i} p(\theta')$$

Let $p(\theta_{-i} | \theta_i)$ denote the probability of the other players having the types as indicated by $\theta_{-i}$, given that player $i$ has type $\theta_i$. Formally:

$$p(\theta_{-i} | \theta_i) = \frac{p(\theta)}{p(\theta_i)}$$

This is all that player $i$ knows upon observing her own type.
Strategies

A *pure strategy* for player \(i\) now is a function \(\alpha_i : \Theta_i \rightarrow A_i\) for picking the action she will play once she observes her own type.

A *mixed strategy* \(i\) is a probability distribution \(s_i \in S_i = \Pi(A_i^{\Theta_i})\) over the space of her pure strategies. Three ways to think about this:

- Mapping pure strategies to probabilities:
  \(s_i : (\Theta_i \rightarrow A_i) \rightarrow [0, 1]\)

- Mapping types to probability distributions over actions:
  \(s_i : \Theta_i \rightarrow (A_i \rightarrow [0, 1])\)

- Mapping pairs of types and actions to probabilities:
  \(s_i : \Theta_i \times A_i \rightarrow [0, 1]\)

Write \(s_i(a_i \mid \theta_i) = \frac{s_i(\theta_i, a_i)}{p(\theta_i)}\) for the probability of player \(i\) playing action \(a_i\) in case she has type \(\theta_i\) and uses strategy \(s_i\).
Three Notions of Expected Utility

Player $i$’s *ex-post expected utility* is her expected utility given everyone’s strategies $s$ and types $\theta$:

$$u_i(s, \theta) = \sum_{a \in A} \left[ u_i(a, \theta) \cdot \prod_{j \in N} s_j(a_j | \theta_j) \right]$$

Player $i$’s *interim expected utility* is her expected utility given everyone’s strategies $s$ and her own type $\theta_i$:

$$u_i(s, \theta_i) = \sum_{\theta_{-i} \in \Theta_{-i}} u_i(s, (\theta_i, \theta_{-i})) \cdot p(\theta_{-i} | \theta_i)$$

Player $i$’s *ex-ante expected utility* is her expected utility given everyone’s strategies $s$, before observing her own type:

$$u_i(s) = \sum_{\theta_i \in \Theta} u_i(s, \theta_i) \cdot p(\theta_i) = \sum_{\theta \in \Theta} u_i(s, \theta) \cdot p(\theta)$$

**Remark:** We again use $u_i$ both for plain utility and for expected utility.
Exercise

Verify that our two alternative definitions of \textit{ex-ante expected utility} indeed coincide. In other words, prove the following for all $s$:

$$
\sum_{\theta_i \in \Theta_i} u_i(s, \theta_i) \cdot p(\theta_i) = \sum_{\theta \in \Theta} u_i(s, \theta) \cdot p(\theta)
$$
Bayes-Nash Equilibria

Consider a Bayesian game $\langle N, A, \Theta, p, u \rangle$ with strategies $s_i \in S_i$.

We say that strategy $s_i^* \in S_i$ is a best response for player $i$ to the (partial) strategy profile $s_{-i}$ if $u_i(s_i^*, s_{-i}) \geq u_i(s_i', s_{-i})$ for all $s_i' \in S_i$.

We say that profile $s = (s_1, \ldots, s_n)$ is a Bayes-Nash equilibrium, if $s_i$ is a best response to $s_{-i}$ for every player $i \in N$.

Remark: The definitions on this slide are essentially copies of the definitions we had used to introduce mixed Nash equilibria. Only the type of game and the notion of expected utility have changed.

Note: Best responses are defined via ex-ante expected utility ($\rightarrow$).
Discussion

You need to think about what strategy to use after you observe your own type. So why define best responses via *ex-ante* expected utility?

Answer: Keep in mind that strategies $s_i$ are “conditional”. They fix a plan for how to play for any type $\theta_i$ you might end up observing.

So when you optimise to find your best response to $s_{-i}$, you in fact are solving an *independent optimisation problem* for every possible type:

$$s_i^* \in \arg\max_{s_i \in S_i} u_i(s_i, s_{-i}) = \arg\max_{s_i \in S_i} \sum_{\theta_i \in \Theta_i} u_i((s_i, s_{-i}), \theta_i) \cdot p(\theta_i)$$

Thus, in case we have $p(\theta_i) > 0$ for all $i \in N$ and all $\theta_i \in \Theta_i$, we can equivalently define BNE via *ex-interim* expected utility:

$$s \text{ is a BNE iff } s_i \in \arg\max_{s_i \in S_i} u_i((s_i', s_{-i}), \theta_i) \text{ for all } i \in N$$
Example: Fight!

You (Player 1) are considering to have a fight with Player 2, who could be of the weak or the strong type. (Your own type is clear to everyone.)

Let $p$ be the probability (common prior) that Player 2 is weak.

Exercise: Analyse the game for the special cases of $p = 1$ and $p = 0$!
Exercise: Compute the Bayes-Nash Equilibria

So we have $A_1 = A_2 = \{F, \bar{F}\}$, $\Theta_1 = \{\bot\}$, and $\Theta_2 = \{\text{weak, strong}\}$.

A pure strategy is of the form $\alpha_i : \Theta_i \to A_i$. Here they are:

- **Player 1**: fight, don’t-fight
- **Player 2**: always-fight, fight-if-strong, fight-if-weak, never-fight

So there might be up to $2 \times 4 = 8$ pure Bayes-Nash equilibria . . .

Let $p = p(\bot, \text{weak})$ be the probability of Player 2 being weak.

Writing $\theta_2$ for $\theta = (\bot, \theta_2)$, the *ex-ante expected utility* of player $i$ for strategy profile $s$ is $u_i(s) = p \cdot u_i(s, \text{weak}) + (1 - p) \cdot u_i(s, \text{strong})$.

Recall that $s$ is a *Bayes-Nash equilibrium* iff $s_i \in \arg\max_{s_i' \in S_i} u_i(s_i', s_{-i})$.

For any given $p \in (0, 1)$, compute all pure Bayes-Nash equilibria!

For $p = 0$ and $p = 1$ we’ve analysed the game already (previous slide).
**Translation**

Bayesian games are convenient for reasoning about strategic behaviour in the presence of uncertainty, but—in principle—the same reasoning could be carried out using simple normal-form games.

We can translate \( \langle N, A, \Theta, p, u \rangle \) to \( \langle N^*, A^*, u^* \rangle \) as follows:

- \( N^* := N \) — same set of players
- \( A^*_i := \{ a^*_i \mid a^*_i : \Theta_i \rightarrow A_i \} \) — actions are pure Bayesian strategies
- \( u^*_i : a^* \mapsto u_i(a^*) \) — utility is *ex-ante* expected utility

**Remark:** The Bayes-Nash equilibria of the original Bayesian game now correspond to the Nash equilibria of its translation.

**Exercise:** *Express the fighting game for* \( p = \frac{1}{2} \) *as a normal-form game!*
Existence of Bayes-Nash Equilibria

Recall that here we are only dealing with finite games. Thus:

**Corollary 1** Every Bayesian game has a Bayes-Nash equilibrium.

**Proof:** Follows immediately from (i) our discussion of how to translate Bayesian games into normal-form games and (ii) Nash’s Theorem on the existence of Nash equilibria. ✓
Summary

This has been an introduction to games of *incomplete information*, modelled in the form of *Bayesian games*. We have seen:

- definition of the model, based on *epistemic types* $\theta_i$, with utilities based on $(\theta_1, \ldots, \theta_n)$ and a common prior on the full type space
- three notions of *expected utility*: ex-post, ex-interim, ex-ante
- *Bayes-Nash equilibrium*: a solution concept defined in terms of best responses relative to ex-ante expected utility
- *translation* to *complete-information* normal-form games is possible

What next? Modelling sequential actions via games in extensive form.