Further Solution Concepts
&
Computational Issues

CMPUT 654: Modelling Human Strategic Behaviour

S&LB §3.4.5, 3.4.7, 4.1, 4.2.3, 4.6

Assignment #1

- **Assignment #1 is released today**
  See the website under Assignments (or on the Schedule)

- Due **February 5** before lecture

Recap: Solution Concepts

- **Maxmin strategies** maximize an agent's **guaranteed payoff**
- **Minmax strategies** minimize the other agent's payoff as much as possible
- The **Minimax Theorem**:
    - Maxmin and minmax strategies are the **only** Nash equilibrium strategies in **zero-sum games**
    - Every Nash equilibrium in a zero-sum game has the **same payoff**
- **Dominated strategies** can be removed **iteratively** without strategically changing the game (too much)
- **Rationalizable** strategies are any that are a **best response** to some **rational belief**

Lecture Outline

1. Recap & Logistics
2. ε-Nash Equilibrium
3. Correlated Equilibrium
4. Linear Programming
5. Computing Nash Equilibrium
6. Computing Correlated Equilbrium

ε-Nash Equilibrium

- In a Nash equilibrium, agents best respond **perfectly**
- What if they are indifferent to **very small** gains in utility?
  - Could reflect modelling error (e.g., unmodelled cost of computational effort)

Definition:
For any $\varepsilon > 0$, a strategy profile s is an **ε-Nash equilibrium** if, for all agents i and strategies $s'_i \neq s_i$,

$$u_i(s_i, s_{-i}) \geq u_i(s'_i, s_{-i}) - \varepsilon.$$

Questions:

For a given ε>0,

1. Is an ε-Nash equilibrium guaranteed to **exist**?
2. Is **more than one** ε-Nash equilibrium guaranteed to exist?

ε-Nash Equilibrium Example

	L	R
U	1, 1	0, 0
D	1+(ε/2), 1	500, 500

Questions:

1. What are the **Nash equilibria** of this game?
2. What are the **ε-Nash equilibria** of this game?

- Every Nash equilibrium is surrounded by a **region** of ε-Nash equilibria
    - Every **numerical algorithm** for computing Nash equilibrium actually computes ε-Nash equilibrium
- However, the reverse is not true! Payoffs from an ε-Nash equilibrium can be **arbitrarily far** from Nash equilibrium payoffs.

Correlated Equilibrium

	Ballet	Soccer
Ballet	2, 1	0, 0
Soccer	0, 0	1, 2

	Go	Wait
Go	-10, -10	1, 0
Wait	0, 1	-1, -1

- In the unique mixed strategy equilibrium of Battle of the Sexes, each player gets a utility of 2/3
- If the players could first observe a coin flip, they could coordinate on **which** pure strategy equilibrium to play
    - Each would get utility of 1.5
    - **Fairer** than either pure strategy equilibrium, and **Pareto dominates** the mixed strategy equilibrium
- **Correlated equilibrium** is a solution concept in which agents get private, potentially-correlated **signals** before choosing their action
    - In both of these example, each agent sees the same signal perfectly, but that is not necessary in general

Correlated Equilibrium

Definition:
Given an n-agent game G=(N,A,u), a **correlated equilibrium** is a tuple (v, π, σ), where

- $v = (v_1, \ldots, v_n)$ is a tuple of random variables with domains $(D_1, \ldots, D_n)$,
- π is a joint distribution over v,
- $\sigma = (\sigma_1, \ldots, \sigma_n)$ is a vector of mappings $\sigma_i : D_i \to A_i$, and
- for every agent i and mapping $\sigma_i' : D_i \to A_i$,

$$\sum_{d \in D_1 \times \cdots \times D_n} \pi(d) u_i(\sigma_1(d_1), \ldots, \sigma_n(d_n)) \geq \sum_{d \in D_1 \times \cdots \times D_n} \pi(d) u_i(\sigma_1(d_1), \ldots, \sigma_i'(d_i), \ldots, \sigma_n(d_n))$$

Correlated Equilibrium Properties

Theorem:
For every **Nash equilibrium**, there exists a corresponding correlated equilibrium in which each action profile appears with the same frequency.

Theorem:
Any **convex combination** of correlated equilibrium payoffs can be realized in some correlated equilibrium.

Linear Programming

Definition:
A **linear program** consists of

- A set of real-valued **variables** $\{x_1, \ldots, x_n\}$
- A linear **objective function** defined by **weights** $\{w_1, \ldots, w_n\}$
- A set of linear **constraints** of the form $\sum_{j=1}^{n} a_j x_j \leq b$

Sample:

$$\text{maximize} \quad \sum_{j=1}^{n} w_j x_j$$

$$\text{subject to} \quad \sum_{j=1}^{n} a_{ij} x_j \leq b_i \qquad \forall 1 \leq i \leq m$$

$$x_j \geq 0 \qquad \forall 1 \leq j \leq n$$

Linear Program Properties

$$\text{maximize} \sum_{j=1}^{n} w_j x_j$$
$$\text{subject to} \sum_{j=1}^{n} a_{ij} x_j \le b_i \qquad \forall 1 \le i \le m$$
$$x_j \ge 0 \qquad \forall 1 \le j \le n$$

- Linear programs can be solved in **polynomial time** by generic algorithms (e.g., ellipsoid algorithm)
  - So writing a problem as a linear program constitutes a **proof** that it is solvable in polynomial time
- Negating weights w_j allows us to **minimize** the objective
- Negating constraint coefficients a_{ij} allows for **greater-than-or-equal** constraints
- Providing both greater-than-or-equal and less-than-or-equal constraints allows for **equality constraints**
- **Cannot** always express **strict inequalities** (although there are tricks)

Computing Nash Equilibrium

- The problem of computing a Nash equilibrium is known to be **computationally hard** (PPAD-complete)
  - Even for two-player games!
- But there are some **special cases** that we can compute efficiently

Computing Nash Equilibrium: Zero-Sum Games

$$\text{minimize } U_1^*$$

$$\text{subject to } \sum_{a_2 \in A_2} u_1(a_1, a_2) s_2(a_2) \leq U_1^* \qquad \forall a_1 \in A_1$$

$$\sum_{a_2 \in A_2} s_2(a_2) = 1$$

$$s_2(a_2) \geq 0 \qquad \forall a_2 \in A_2$$

- This linear program computes U^*_1, player 1's **minmax value**, and s_2, player 2's **minmax strategy** against player 1
  - By the minimax theorem, this is player 2's **equilibrium strategy**
- Compute player 1's equilibrium strategy analogously

Computing Maxmin Strategies: Two-Player, General-Sum Games

- We can efficiently compute the maxmin strategies for agents in a two-player **zero-sum game**

- The maxmin strategy for an agent in a general-sum game is their best response to an imaginary agent that is **trying to hurt them**

- To compute player 1's maxmin strategy in a general-sum game:

    1. Construct a **zero-sum game** from player 1's payoffs,

    2. Find player 1's minmax strategy in the **constructed game** (using the program from the previous slide)

Computing Nash Equilibrium: Two-Player, General Sum Games

- Finding an equilibrium in general is hard
- But if we already know the **support** of the equilibrium, then we can compute it efficiently in a two-player game:

$$\sum_{a_{-i} \in \sigma_{-i}} s_{-i}(a_{-i}) u_i(a_i, a_{-i}) = v_i \qquad \forall i \in \{1,2\}, a_i \in \sigma_i$$

$$\sum_{a_{-i} \in \sigma_{-i}} s_{-i}(a_{-i}) u_i(a_i, a_{-i}) \leq v_i \qquad \forall i \in \{1,2\}, a_i \notin \sigma_i$$

$$s_i(a_i) \geq 0 \qquad \forall i \in \{1,2\}, a_i \in \sigma_i$$

$$s_i(a_i) = 0 \qquad \forall i \in \{1,2\}, a_i \notin \sigma_i$$

$$\sum_{a_i \in A_i} s_i(a_i) = 1 \qquad \forall i \in \{1,2\}$$

Questions:

1. Why can't we just set $\sigma_i = A_i$ for every agent and solve **once**?
2. Why can't we just try **every possible support**?
3. Why wouldn't this work for ***n*-player** games?

Computing Nash Equilibrium: General-Sum *n*-Player Games

- In theory, computing an equilibrium in *n*-player games and two-player games have **equal computational complexity**
- In practice, **two-player** games tend to be faster to solve:
  - Lemke-Howson pivoting algorithm based on a **linear complementarity program**
- For *n*-player games, **homotopy-following** methods:
  - Construct a family of parameterized **perturbations** of the game, with $t=0$ being a trivial game with a known equilibrium, and $t=1$ being the original game
  - Move t along $[0,1]$, adjusting the equilibrium as you go, until you reach $t=1$

Computing Correlated Equilibrium

- Correlated equilibria can be found efficiently even in general-sum, *n*-player games

- Every correlated equilibrium induces a probability distribution over **action profiles**

  - Corresponds to a correlated equilibrium where Nature randomly chooses an action profile, and the agent's **signals** are their **own actions** in that profile

- So finding a distribution over action profiles in which each agent would always prefer to play their **recommended action** is sufficient to find a correlated equilibrium

Computing Correlated Equilibrium in Polynomial Time

$$\sum_{a \in A | a_i \in a} p(a) u_i(a) \geq \sum_{a \in A | a_i \in a} p(a) u_i(a_i', a_{-i}) \qquad \forall i \in N,\ a_i, a_i' \in A_i$$

$$p(a) \geq 0 \qquad \forall a \in A$$

$$\sum_{a \in A} p(a) = 1$$

- We could find the social-welfare-optimizing correlated equilibrium by adding an **objective function**:

$$\text{maximize} \sum_{a \in A} p(a) \sum_{i \in N} u_i(a)$$

Summary

- **ε-Nash equilibria**: stable when agents have no deviation that gains them more than ε
- **Correlated equilibria**: stable when agents have **signals** from a possibly-correlated randomizing device
- **Linear programs** are a flexible encoding that can always be solved in **polytime**
- Finding a Nash equilibrium is **computationally hard** in general
- **Special cases** are efficiently computable:
  - Nash equilibria in zero-sum games
  - Maxmin strategies (and values) in two-player games
  - Correlated equilibrium