Game Theory

4. Algorithms

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1 Motivation

Motivation

- We know: In finite strategic games, mixed-strategy Nash equilibria are guaranteed to exist.
- We don't know: How to systematically find them?
- Challenge: There are infinitely many mixed strategy profiles to consider. How to do this in finite time?

This chapter:

- Computation of mixed-strategy Nash equilibria for finite zero-sum games.
- Computation of mixed-strategy Nash equilibria for general finite two player games.

2 Linear Programming

Linear Programming

Digression:

We briefly discuss linear programming because we will use this technique to find Nash equilibria.

Goal of linear programming:

Solving a system of linear inequalities over n real-valued variables while optimizing some linear objective function.

Example

Production of two sorts of items with time requirements and profit per item. Objective: Maximize profit.

	Cutting	Assembly	Postproc.	Profit per item
(x) sort 1	25	60	68	30
(y) sort 2	75	60	34	40
per day	≤ 450	≤ 480	≤ 476	maximize!

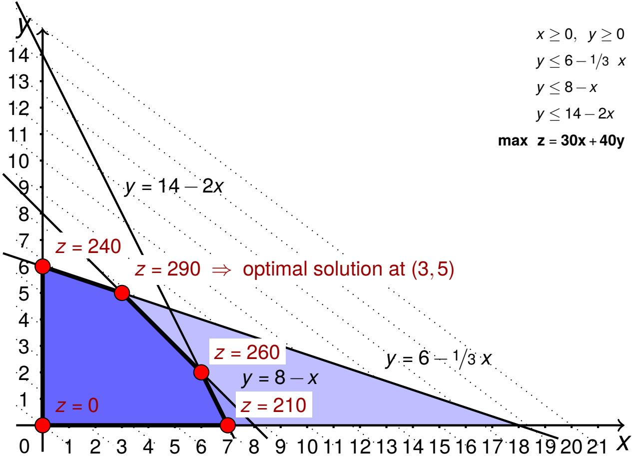
Goal: Find numbers of pieces x of sort 1 and y of sort 2 to be produced per day such that the resource constraints are met and the objective function is maximized.

Example (ctd., formalization)

$$
\begin{aligned}
x \geq 0,\ y \geq 0 & & (1)\\
25x + 75y \leq 450 & \quad (\text{or } y \leq 6 - {}^1\!/_3\, x) & (2)\\
60x + 60y \leq 480 & \quad (\text{or } y \leq 8 - x) & (3)\\
68x + 34y \leq 476 & \quad (\text{or } y \leq 14 - 2x) & (4)\\
\text{maximize } z = 30x + 40y & & (5)
\end{aligned}
$$

- Inequalities (1)–(4): Admissible solutions
  (They form a convex set in $\mathbb{R}^2$.)
- Line (5): Objective function

Example (ctd., visualization)



$x \geq 0, \quad y \geq 0$

$y \leq 6 - {}^1\!/\!_3\ x$

$y \leq 8 - x$

$y \leq 14 - 2x$

max $\mathbf{z = 30x + 40y}$

Definition (Linear program)

A linear program (LP) in standard from consists of

- n real-valued variables x_i; n coefficients b_i;
- m constants c_j; $n \cdot m$ coefficients a_{ij};
- m constraints of the form

$$c_j \leq \sum_{i=1}^{n} a_{ij} x_i,$$

- and an objective function to be minimized ($x_i \geq 0$)

$$\sum_{i=1}^{n} b_i x_i.$$

Solution of an LP:
assignment of values to the x_i satisfying the constraints and minimizing the objective function.

Remarks:

- Maximization instead of minimization: easy, just change the signs of all the b_i's, $i = 1, \ldots, n$.
- Equalities instead of inequalities: $x + y \leq c$ if and only if there is a $z \geq 0$ such that $x + y + z = c$ (z is called a slack variable).

Solution algorithms:

- Usually, one uses the simplex algorithm (which is worst-case exponential!).
- There are also polynomial-time algorithms such as interior-point or ellipsoid algorithms.

Tools and libraries:

- lp_solve
- CLP
- GLPK
- CPLEX
- gurobi

3 Zero-Sum Games

Mixed-Strategy Nash Equilibria in Finite Zero-Sum Games

We start with finite zero-sum games for two reasons:

- They are easier to solve than general finite two-player games.
- Understanding how to solve finite zero-sum games facilitates understanding how to solve general finite two-player games.

In the following, we will exploit the zero-sum property of a game G when searching for mixed-strategy Nash equilibria. For that, we need the following result.

Proposition

Let G be a finite zero-sum game. Then the mixed extension of G is also a zero-sum game.

Proof.

Homework. $\square$

Mixed-Strategy Nash Equilibria in Finite Zero-Sum Games

Let G be a finite zero-sum game with mixed extension G'.

Then we know the following:

1. Previous proposition implies: G' is also a zero-sum game.
2. Nash's theorem implies: G' has a Nash equilibrium.
3. Maximinimizer theorem + (1) + (2) implies: Nash equilibria and pairs of maximinimizers in G' are the same.

Mixed-Strategy Nash Equilibria in Finite Zero-Sum Games

Consequence:

When looking for mixed-strategy Nash equilibria in G, it is sufficient to look for pairs of maximinimizers in G'.

Method: Linear Programming

Linear Program Encoding

Approach:

- Let $G = \langle N, (A_i)_{i\in N}, (u_i)_{i\in N}\rangle$ be a finite zero-sum game:
  - $N = \{1,2\}$.
  - A_1 and A_2 are finite.
  - $U_1(\alpha,\beta) = -U_2(\alpha,\beta)$ for all $\alpha \in \Delta(A_1), \beta \in \Delta(A_2)$.
- Player 1 looks for a maximinimizer mixed strategy α.
- For each possible α of player 1:
  - Determine expected utility against best response of pl. 2. (Only need to consider finitely many pure candidates for best responses because of Support Lemma).
  - Maximize expected utility over all possible α.

Linear Program Encoding

- Result: maximinimizer α for player 1 in G'
  (= Nash equilibrium strategy for player 1)
- Analogously: obtain maximinimizer β for player 2 in G'
  (= Nash equilibrium strategy for player 2)
- With maximinimizer theorem: we can combine α and β into a Nash equilibrium.

Linear Program Encoding

"For each possible α of player 1, determine expected utility against best response of player 2, and maximize."

translates to the following LP:

$$\alpha(a) \geq 0 \quad \text{for all } a \in A_1$$

$$\sum_{a \in A_1} \alpha(a) = 1$$

$$U_1(\alpha, b) = \sum_{a \in A_1} \alpha(a) \cdot u_1(a, b) \geq u \quad \text{for all } b \in A_2$$

Maximize u.

Example (Matching pennies)

	H	T
H	$1, -1$	$-1, \ \ 1$
T	$-1, \ \ 1$	$1, -1$

Linear program for player 1:

Maximize u subject to the constraints

$$\alpha(H) \geq 0,\ \alpha(T) \geq 0,\ \alpha(H) + \alpha(T) = 1,$$
$$\alpha(H) \cdot u_1(H,H) + \alpha(T) \cdot u_1(T,H) = \alpha(H) - \alpha(T) \geq u,$$
$$\alpha(H) \cdot u_1(H,T) + \alpha(T) \cdot u_1(T,T) = -\alpha(H) + \alpha(T) \geq u.$$

Solution: $\alpha(H) = \alpha(T) = 1/2$, $u = 0$.

Linear Program Encoding

- Remark: There is an alternative encoding based on the observation that in zero-sum games that have a Nash equilibrium, maximinimization and minimaximization yield the same result.
- Idea: Formulate linear program with inequalities

$$U_1(a, \beta) \leq u \qquad \text{for all } a \in A_1$$

and minimize u. Analogously for β.

4 General Finite Two-Player Games

General Finite Two-Player Games

- For general finite two-player games, the LP approach does not work.
- Instead, use instances of the linear complementarity problem (LCP):
  - Linear (in-)equalities as with LPs.
  - Additional constraints of the form $x_i \cdot y_i = 0$ (or equivalently $x_i = 0 \vee y_i = 0$) for variables $X = \{x_1, \dots, x_k\}$ and $Y = \{y_1, \dots, y_k\}$, and $i \in \{1, \dots, k\}$.
  - no objective function.
- With LCPs, we can compute Nash equilibria for arbitrary finite two-player games.

Let A_1 and A_2 be finite and let (α, β) be a Nash equilibrium with payoff profile (u, v). Then consider this LCP encoding:

$$u - U_1(a, \beta) \geq 0 \quad \text{for all } a \in A_1 \tag{6}$$

$$v - U_2(\alpha, b) \geq 0 \quad \text{for all } b \in A_2 \tag{7}$$

$$\alpha(a) \cdot (u - U_1(a, \beta)) = 0 \quad \text{for all } a \in A_1 \tag{8}$$

$$\beta(b) \cdot (v - U_2(\alpha, b)) = 0 \quad \text{for all } b \in A_2 \tag{9}$$

$$\alpha(a) \geq 0 \quad \text{for all } a \in A_1 \tag{10}$$

$$\sum_{a \in A_1} \alpha(a) = 1 \tag{11}$$

$$\beta(b) \geq 0 \quad \text{for all } b \in A_2 \tag{12}$$

$$\sum_{b \in A_2} \beta(b) = 1 \tag{13}$$

Remarks about the encoding:

- In (8) and (9): for instance,

$$\alpha(a) \cdot (u - U_1(a, \beta)) = 0$$

  if and only if

$$\alpha(a) = 0 \qquad \text{or} \qquad u - U_1(a, \beta) = 0.$$

  This holds in every Nash equilibrium, because:
  - if $a \notin supp(\alpha)$, then $\alpha(a) = 0$, and
  - if $a \in supp(\alpha)$, then $a \in B_1(\beta)$, thus $U_1(a, \beta) = u$.
- With additional variables, the above LCP formulation can be transformed into LCP normal form.

Theorem

A mixed strategy profile (α, β) *with payoff profile* (u, v) *is a Nash equilibrium if and only if it is a solution to the LCP encoding over* (α, β) *and* (u, v)*.*

Proof.

- Nash equilibria are solutions to the LCP: Obvious because of the support lemma.
- Solutions to the LCP are Nash equilibria: Let (α, β, u, v) be a solution to the LCP. Because of (10)–(13), α and β are mixed strategies.

Proof (ctd.)

- Solutions to the LCP are Nash equilibria (ctd.): Because of (6), u is at least the maximal payoff over all possible pure responses, and because of (8), u is exactly the maximal payoff.

  If $\alpha(a) > 0$, then, because of (8), the payoff for player 1 against β is u.

  The linearity of the expected utility implies that α is a best response to β.

  Analogously, we can show that β is a best response to α and hence (α, β) is a Nash equilibrium with payoff profile (u, v).

□

Solution Algorithm for LCPs

Naïve algorithm:

Enumerate all $(2^n - 1) \cdot (2^m - 1)$ possible pairs of support sets.

For each such pair $(supp(\alpha), supp(\beta))$:

- Convert the LCP into an LP:
  - Linear (in-)equalities are preserved.
  - Constraints of the form $\alpha(a) \cdot (u - U_1(a, \beta)) = 0$ are replaced by a new linear equality:
    - $u - U_1(a, \beta) = 0$, if $a \in supp(\alpha)$, and
    - $\alpha(a) = 0$, otherwise,

    Analogously for $\beta(b) \cdot (v - U_2(\alpha, b)) = 0$.
  - Objective function: maximize constant zero function.
- Apply solution algorithm for LPs to the transformed program.

Solution Algorithm for LCPs

- Runtime of the naïve algorithm: $O(p(n+m) \cdot 2^{n+m})$, where p is some polynomial.
- Better in practice: Lemke-Howson algorithm.
- Complexity:
  - unknown whether $\textsc{LcpSolve} \in \mathbf{P}$.
  - $\textsc{LcpSolve} \in \mathbf{NP}$ is clear (naïve algorithm can be seen as a nondeterministic polynomial-time algorithm).

5 Summary

Summary

- Computation of mixed-strategy Nash equilibria for finite zero-sum games using linear programs.
  $\rightsquigarrow$ polynomial-time computation
- Computation of mixed-strategy Nash equilibria for general finite two player games using linear complementarity problem.
  $\rightsquigarrow$ computation in **NP**.