Computational aspects of finding Nash Equilibria for 2-player games

Fall 2020

Nash equilibrium

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Let $X = \Delta(A_1)$ and $Y = \Delta(A_2)$.
($\Delta(A)$ is the set of probability distributions over A)

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A Nash equilibrium is a mixed strategy profile $\sigma = (x, y) \in X \times Y$ such that, for every $x' \in X$, $y' \in Y$, it holds

$$U_1(x, y) \geq U_1(x', y) \text{ and } U_2(x, y) \geq U_2(x, y')$$

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A best response can be computed in polynomial time for 2-player games with rational utilities.

1. Linear Algebra formulation
2. Zero-sum games
3. The complexity of finding a NE
4. An exact algorithm to compute NE
5. Other algorithms

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- In terms of matrices we have $C = -R$.

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- Combining both,
$$x^T R\, y^* \leq (x^*)^T R\, y^* \leq (x^*)^T R\, y, \forall x \in X, \forall y \in Y.$$
i.e., (x^*, y^*) is a saddle point
of the function $x^T R\, y$ defined over $X \times Y$.

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Theorem

For any function $\Phi : X \times Y :\rightarrow \mathbb{R}$, *we have*

$$\sup_{x \in X} \inf_{y \in Y} \Phi(x, y) \leq \inf_{y \in Y} \sup_{x \in X} \Phi(x, y).$$

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Taking the supremum over $x' \in X$ on the left hand-side,

$$\sup_{x \in X} \inf_{y \in Y} \Phi(x,y) \leq \inf_{y \in Y} \sup_{x \in X} \Phi(x,y).$$

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We refer to $\inf_{y\in Y} \sup_{x\in X} x^T R\, y$ as the value of the game.

Best response condition and Bimatrix Games

For a fixed $y \in Y$, let u_r the value of the best response of player 1 to y:

$$u_r = \max_{x \in X} x^T R y = \max_{x \in X} \sum_{i=1}^{m} \sum_{j=1}^{n} x_i r_{ij} y_j$$

Let $[Ry]_i = \sum_{j=1}^{n} r_{ij} y_j$

Theorem (Nash)

For a fixed $y \in Y$,

$$u_r = \max_{k=1,\ldots,m} \{[Ry]_k\},$$

and if x is a BR to y, then for all $x_i > 0$, $[Ry]_i = u_r$

Best response condition

Proof.

Let x be a BR to y.

$$u_r = x^T Ry = \sum_{i=1}^{m} x_i [Ry]_i \leq \sum_{i=1}^{m} x_i (\max_{k=1,\dots,m} \{[Ry]_k\})$$

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Hence,

$$u_r \leq \max_{k=1,\dots,m} \{[Ry]_k\}$$

If $[Ry]_i = \max_{k=1,\dots,m}\{[Ry]_k\}$, $x'_i = 1$ and $x'_j = 0$ for all $j \neq i$, then $u_r \geq u_1(x', y) = \max_{k=1,\dots,m}\{[Ry]_k\}$.

(x' is a support of x and a BR to y)

Best response condition

Moreover, if x is a BR to y,

$$x_i > 0 \Rightarrow [Ry]_i = \max_{k=1,\dots,m}\{[Ry]_k\}$$

Assume that $\exists j, x_j > 0$ and

$$[Ry]_j < \max_{k=1,\dots,m}\{[Ry]_k\}. \text{Then,}$$

$$u_r = \sum_{x_i>0} x_i [Ry]_i < \sum_{x_i>0} x_i (\max_{k=1,\dots,m}\{[Ry]_k\}) = \max_{k=1,\dots,m}\{[Ry]_k\} \sum_{x_i>0} x_i = u_r$$

Contradiction!

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- So, both the value of the game and a Nash equilibrium strategy for player 2 can be obtained by solving the linear programming problem:

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$$\min v$$

$$v\mathbf{1}_n \geq Ry, y \in Y.$$

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- LP can be solved efficiently, thus there is a polynomial time algorithm for computing NE for zero-sum games.

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(Papadimitriou 94)
Polynomial Parity Argument on Directed Graphs

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- Such problems are defined by an implicitly defined directed graph G and an unbalanced node u of G
  and the objective is finding another unbalanced node.
- Usually G is huge but implicitly defined as the graphs defining solutions in local search algorithms.

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- But not a clear complexity cut.

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End-of-Line

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- Which guarantees that
  the End-of-Line problem has always a solution.

End-of-Line: graph representation

- G is given implicitly by a circuit C
- C provides a predecessor and successor pair for each given vertex in G, i.e. $C(u) = (v, w)$.
- A special label indicates that a node has no predecessor/successor.

The complexity of finding a NE

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Finding a Nash equilibrium is PPAD-complete even in 2-player games.

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- C. Daskalakis, P-W. Goldberg, C.H. Papadimitriou: The complexity of computing a Nash equilibrium. SIAM J. Comput. 39(1): 195-259 (2009) first version STOC 2006
- X. Chen, X. Deng, S-H. Teng: Settling the complexity of computing two-player Nash equilibria. J. ACM 56(3) (2009) first version FOCS 2006

NE characterization

Theorem

In a strategic game in which each player has finitely many actions a mixed strategy profile σ^* is a NE iff, for each player i,

- *the expected payoff, given σ_{-i}, to every action in the support of σ_i^* is the same*
- *the expected payoff, given σ_{-i}, to every action not in the support of σ_i^* is at most the expected payoff on an action in the support of σ_i^*.*

NE conditions given support

Let $A \subseteq \{1, \ldots n\}$ and $B \subseteq \{1, \ldots m\}$.
The conditions for having a NE on this particular support can be written as follows:

$$\max \lambda_1 + \lambda_2$$

Subject to:

$$\begin{aligned} [R\,y]_i &= \lambda_1, \text{ for } i \in A \\ [R\,y]_i &\leq \lambda_1, \text{ for } i \notin A \\ {}_j[C\,x] &= \lambda_2, \text{ for } j \in B \\ {}_j[C\,x] &\leq \lambda_2, \text{ for } j \notin B \end{aligned}$$

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  Solve the set of simultaneous equations using linear programming.
- This is an exact exponential time algorithm as the number of supports can be exponential.
- The same algorithm can be applied to a multiplayer game. We would be able to compute a NE on rationals if such a NE exists.

Other algorithms

- Lemke-Howson (1964) algorithm defines a polytope based on best response conditions and membership to the support and uses ideas similar to Simplex with a ad-hoc pivoting rule. (See slides by Ethan Kim)
- Lemke-Howson requires exponential time [R. Savani, B. von Stengel, 2004]).