

# 1 Complexity, Games, Labels, Polytopes, Strings

## 1.1 Some Complexity Classes

## 1.2 Normal Form Games and Nash Equilibria

file: background

## 1.3 Bimatrix Games, Labels and Polytopes

In the rest of this thesis we will focus on two-player normal-form games. For sake of readability, we will use feminine pronouns when referring to player 1 and masculine pronouns when referring to player 2.

Two-player normal-form games are also called *bimatrix games*, since they can be characterized by the  $m \times n$  payoff matrices  $A$  and  $B$ , where  $a_{ij}$  and  $b_{ij}$  are the payoffs of player 1 and 2 when she plays her  $i$ th pure strategy and he plays his  $j$ th pure strategy. We will assume that  $(A, B)$  are non-negative, and that  $A$  and  $B^\top$  have no zero column. This can be easily obtained without loss of generality via an affine transformation that will not affect the equilibria of the game.

The Nash equilibria of bimatrix games can be analysed from a combinatorial point of view using *labels*. This method is due to Shapley [14], in a study building on ideas introduced in a paper by Lemke and Howson [7].

Let  $(A, B)$  be bimatrix game. The mixed-strategy simplices of player 1 and 2 are, respectively

$$X = \{x \in \mathbb{R}^m | x \geq \mathbf{0}, \mathbf{1}^\top x = 1\}, \quad Y = \{y \in \mathbb{R}^n | y \geq \mathbf{0}, \mathbf{1}^\top y = 1\} \quad (1)$$

A *labeling* of the game is then given as follows:

1. the  $m$  pure strategies of player 1 are identified by  $1, \dots, m$ ;
2. the  $n$  pure strategies of player 2 are identified by  $m + 1, \dots, m + n$ ;

3. each mixed strategy  $x \in X$  of player 1 has
  - label  $i$  for each  $i \in [m]$  such that  $x_i = 0$ , that is if in  $x$  player 1 does not play her  $i$ th pure strategy;
  - label  $m + j$  for each  $j \in [n]$  such that the  $j$ th pure strategy of player 2 is a best response to  $x$ ;
4. each mixed strategy  $y \in Y$  of player 2 has
  - label  $m + j$  for each  $j \in [n]$  such that  $y_j = 0$ , that is if in  $y$  player 2 does not play his  $j$ th pure strategy;
  - label  $i$  for each  $i \in [m]$  such that the  $i$ th pure strategy of player 1 is a best response to  $y$ ;

A strategy profile  $(x, y) \in X \times Y$  is *completely labeled* if every label  $1, \dots, m + n$  is a label of either  $x$  or  $y$ . We have the following theorem (Theorem 1 in [14]):

**Theorem 1.** *Let  $(x, y) \in X \times Y$ ; then  $(x, y)$  is a Nash equilibrium of the bimatrix game  $(A, B)$  if and only if  $(x, y)$  is completely labeled.*

*Proof.* The mixed strategy  $x \in X$  has label  $m + j$  for some  $j \in [n]$  if and only if the  $j$ th pure strategy of player 2 is a best response to  $x$ ; this, in turn, is a necessary and sufficient condition for player 2 to play his  $j$ th strategy at an equilibrium against  $x$ . Therefore, at an equilibrium  $(x, y)$  all labels  $m + 1, \dots, m + n$  will appear either as labels of  $x$  or of  $y$ . The analogous holds for the labels  $i \in [m]$ .  $\square$

An useful geometrical representation of labels can be given on the mixed strategies simplices  $X$  and  $Y$ . The outside of each simplex is labeled according to the player's own pure strategies that are *not* played; so, for instance, the outside of  $X$  will have labels  $1, \dots, n$ . The interior of each simplex is subdivided in closed polyhedral sets, called *best-response regions*. These are

labeled according to the other player's pure strategy that is a best response in that set; so, for instance, the inside of  $X$  will have labels  $m+1, \dots, m+n$ .

We give an example of this construction.

page 3–4 of Savani, von Stengel, Unit Vector Games.

*Example 1.1.*

With graphics.

We will now give a description of labeling on polytopes equivalent to the construction based on best-response regions.

We begin by noticing that the best-response regions can be obtained as projections on  $X$  and  $Y$  of the *best-response facets* of the polyhedra

$$\bar{P} = \{(x, v) \in X \times \mathbb{R} | B^\top x \leq \mathbf{1}v\}, \quad \bar{Q} = \{(y, u) \in Y \times \mathbb{R} | Ay \leq \mathbf{1}u\}. \quad (2)$$

These facets in  $\bar{P}$  are defined as the points  $(x, v) \in X \times \mathbb{R}$  such that  $b_j^\top x = v$ . These points represent the strategies  $x \in X$  of player 1 that give exactly payoff  $v$  to player 2 when he plays strategy  $j$ . The projection of the facet defined by  $b_j^\top x = v$  to  $X$  will have label  $j$ . Analogously, in  $\bar{Q}$ , the facets are the points  $(y, u) \in Y \times \mathbb{R}$  such that  $a_i y = u$ , and their projection to  $Y$  will be the best-response region with label  $i$ .

*Example 1.2.*

cont of ex above, page 4–5, image on page 5 left

Given the assumptions on non-negativity of  $A$  and  $B^\top$ , we can give a change coordinates to  $x_i/v$  and  $y_j/u$  and replace  $\bar{P}$  and  $\bar{Q}$  with the *best-response polytopes*

$$P = \{x \in \mathbb{R}^m | x \geq \mathbf{0}, B^\top x \leq \mathbf{1}\}, \quad Q = \{y \in \mathbb{R}^n | y \geq \mathbf{0}, Ay \leq \mathbf{1}\}, \quad (3)$$

Each one of these polytope is defined by half spaces corresponding to either the player's own strategy that is not being played or the other player's best response; each one of the facets of the polytope is labeled by the strategy corresponding to the relative half-space.

This means that a point in  $P$  has label  $k$  if and only if either  $x_k = 0$  for  $k \in \{1, \dots, m\}$  or  $(B^\top x)_{k-m} = 0$  for  $k \in \{m+1, \dots, m+n\}$ ; analogously, a point in  $Q$  has label  $k$  if and only if either  $y_{k-m} = 0$  for  $k \in \{m+1, \dots, m+n\}$  or  $(Ay)_k$  for  $k \in \{m+1, \dots, m+n\}$ . A point  $(x, y) \in P \times Q$  is *completely labeled* if every  $k \in [m+n]$  is a label of  $x$  or  $y$ . Note that the point  $(\mathbf{0}, \mathbf{0})$  is completely labeled. Rescaling back to  $\bar{P}$  and  $\bar{Q}$ , all the non-zero completely labeled points give exactly all the equilibria of  $(A, B)$ . In this construction, we will call  $(\mathbf{0}, \mathbf{0})$  *artificial equilibrium*.

*Example 1.3.* ex in Savani, von Stengel, image on page 5 right

A characterization of the completely labeled pairs in  $P \times Q$  can be given as follows.

**proposition 1.** *The pair  $(x, y) \in P \times Q$  is completely labeled if and only if one of the following condition holds:*

- (Complementarity condition)

$$x_i = 0 \text{ or } (Ay)_i = 1 \text{ for all } i \in [m], \quad y_j = 0 \text{ or } (B^\top x)_j = 1 \text{ for all } j \in [n] \quad (4)$$

- (Orthogonality condition)

$$x^\top (\mathbf{1} - Ay) = 0, \quad y^\top (\mathbf{1} - B^\top x) = 0 \quad (5)$$

Proposition 1 can be used to prove a useful property: *symmetric games*, that is, games that have payoff matrix of the form  $(C, C^\top)$  for some matrix  $C$ , can be used to study generic bimatrix games without loss of generality. The result is due to Gale, Kuhn and Tucker [6] for zero-sum games; its extension to non-zero-sum games is a folklore result.

**proposition 2.** *Let  $(A, B)$  be a bimatrix game and  $(x, y)$  be one of its Nash equilibria. Then  $(z, z)$ , where  $z = (x, y)$ , is a Nash equilibrium of the symmetric game  $(C, C^\top)$ , where*

$$C = \begin{pmatrix} 0 & A \\ B^\top & 0 \end{pmatrix}.$$

The converse has been proved by McLennan and Tourky ?? in their study of *imitation games*, that is, bimatrix games of the form  $(I, B)$ .

**proposition 3.** *The pair  $(x, x)$  is a symmetric Nash equilibrium of the symmetric bimatrix game  $(C, C^\top)$  if and only if there is some  $y$  such that  $(x, y)$  is a Nash equilibrium of the imitation game  $(I, C^\top)$ .*

*Example 1.4.* Consider the symmetric game  $(C, C^\top)$ , where  $C^\top = B$  in the previous examples.

ex Savani, von Stengel, pg 8

nondegeneracy; ex pg 9; odd no eq, mention homotopy method (find ref) (tie with Nash, again?)

## 1.4 Some Geometrical Notation

so results in labels section - after this - don't get lost in boredom, and each section in background is about 150-200 lines (see: getting lost). Maybe turn this into an appendix? It would make sense if something more about proof of Nash

We denote the transpose of a matrix  $A$  as  $A^\top$ . We consider vectors  $u, v \in \mathbb{R}^d$  as column vectors, so  $u^\top v$  is their scalar product. A vector in  $\mathbb{R}^d$  for which all components are 0's will be denoted as  $\mathbf{0}$ ; similarly, a vectors for which all components are 1's will be denoted as  $\mathbf{1}$ . The *unit vector*  $e_i$  is the vector that has  $i$ -th component  $e_{ii} = 1$  and  $e_{ij} = 0$  for all other components. When writing an inequality of the form  $u \geq v$  (and analogous), we mean that it holds for every component; that is,  $u_i \geq v_i$  for all  $i \in [d]$ .

An *affine combination* of points in an Euclidean space  $z_1, \dots, z_n$  is

$$\sum_{i=1}^n \lambda_i z_i \quad \text{where } \lambda_i \in \mathbb{R} \text{ such that } \sum_{i=1}^n \lambda_i = 1$$

The points  $z_1, \dots, z_n$  are *affinely independent* if none of them is an affine combination of the others.

A *convex combination* of points  $z_1, \dots, z_n$  is an affine combination where  $\lambda_i \geq 0$  for all  $i \in [n]$ . Note that such  $\lambda_i$ 's can be seen as a probability distribution over the  $z_i$ 's.

def simplex: here?

A set of point  $Z$  is *convex* if it is closed under forming convex combinations, that is, if  $\bar{z} = \sum_{i=1}^n \lambda_i z_i$ , where  $z_i \in Z$ ,  $\lambda_i \geq 0$  and  $\sum_{i=1}^n \lambda_i = 1$ , then  $\bar{z} \in Z$ . A convex set has *dimension*  $d$  if it has exactly  $d + 1$  affinely independent points.

def simplex: here?

convex hull; pow hyperplanes; polyhedron, polyopes; needed? yes, for cyclic poly!

from here: notes - copy-paste

A ( $d$ -dimensional) *simplicial polytope*  $P$  is the convex hull of a set of at least  $d + 1$  points  $v$  in  $\mathbb{R}^d$  in general position, that is, no  $d + 1$  of them are on a common hyperplane.

If a point  $v$  cannot be omitted from these points without changing  $P$  then  $v$  is called a *vertex* of  $P$ . A *facet* of  $P$  is the convex hull  $\text{conv } F$  of a set  $F$  of  $d$  vertices of  $P$  that lie on a hyperplane  $\{x \in \mathbb{R}^d \mid a^T x = a_0\}$  so that  $a^T u < a_0$  for all other vertices  $u$  of  $P$ ; the vector  $a$  (unique up to a scalar multiple) is called the *normal vector* of the facet. We often identify the facet with its set of vertices  $F$ .

this from VvS

The following theorem, due to Balthasar and von Stengel [?, ?], establishes a connection between general labeled polytopes and equilibria of certain  $d \times n$  bimatrix games  $(U, B)$ .

**Theorem 2.** *Consider a labeled  $d$ -dimensional simplicial polytope  $Q$  with  $\mathbf{0}$  in its interior, with vertices  $-e_1, \dots, -e_d, c_1, \dots, c_n$ , so that  $F_0 = \text{conv}\{-e_1, \dots, -e_d\}$  is a facet of  $Q$ . Let  $-e_i$  have label  $i$  for  $i \in [d]$ , and let  $c_j$  have label  $l(j) \in [d]$  for  $j \in [n]$ . Let  $(U, B)$  be the  $d \times n$  bimatrix game with  $U = [e_{l(1)} \cdots e_{l(n)}]$  and  $B = [b_1 \cdots b_n]$ , where  $b_j = c_j / (1 + \mathbf{1}^\top c_j)$  for  $j \in [n]$ . Then the completely labeled facets  $F$  of  $Q$ , with the exception of  $F_0$ , are in one-to-one correspondence to the Nash equilibria  $(x, y)$  of the game  $(U, B)$  as follows: if  $v$  is the normal vector of  $F$ , then  $x = (v + \mathbf{1})\mathbf{1}^\top(v + \mathbf{1})$ , and  $x_i = 0$  if and only if  $-e_i \in F$  for  $i \in [d]$ ; any other label  $j$  of  $F$ , so that  $c_j$  is a vertex of  $F$ , represents a pure best reply to  $x$ . The mixed strategy  $y$  is the uniform distribution on the set of pure best replies to  $x$ .*

In the preceding theorem, any simplicial polytope can take the role of  $Q$  as long as it has one completely labeled facet  $F_0$ . Then an affine transformation, which does not change the incidences of the facets of  $Q$ , can be used to map  $F_0$  to the negative unit vectors  $-e_1, \dots, -e_d$  as described, with  $Q$  if necessary expanded in the direction  $\mathbf{1}$  so that  $\mathbf{0}$  is in its interior.

A  $d \times n$  bimatrix game  $(U, B)$  is a *unit vector game* if all columns of  $U$  are unit vectors. For such a game  $B$  with  $B = [b_1 \cdots b_n]$ , the columns  $b_j$  for  $j \in [n]$  can be obtained from  $c_j$  as in Theorem 2 if  $b_j > \mathbf{0}$  and  $\mathbf{1}^\top b_j < 1$ . This is always possible via a positive-affine transformation of the payoffs in  $B$ , which does not change the game. The unit vectors  $e_{l(j)}$  that constitute the columns of  $U$  define the labels of the vertices  $c_j$ . The corresponding polytope with these vertices is simplicial if the game  $(U, B)$  is nondegenerate [?], which here means that no mixed strategy  $x$  of the row player has more than  $|\{i \in [d] \mid x_i > 0\}|$  pure best replies. Any game can be made nondegenerate by a suitable “lexicographic” perturbation of  $B$ , which

can be implemented symbolically.

until here

## 1.5 Cyclic Polytopes and Gale Strings

file: gale-def

## References

- [1] M. M. Casetti, J. Merschen, B. von Stengel (2010). “Finding Gale Strings.” *Electronic Notes in Discrete Mathematics* 36, pp. 1065–1082.
- [2] X. Chen, X. Deng (2006). “Settling the Complexity of 2-Player Nash Equilibrium.” *Proc. 47th FOCS*, pp. 261–272.
- [3] C. Daskalakis, P. W. Goldberg, C. H. Papadimitriou (2006). “The Complexity of Computing a Nash Equilibrium.” *SIAM Journal on Computing*, 39(1), pp. 195–259.
- [4] J. Edmonds (1965). “Paths, Trees, and Flowers.” *Canad. J. Math.* 17, pp. 449–467.
- [5] D. Gale (1963). “Neighborly and Cyclic Polytopes.” *Convexity, Proc. Symposia in Pure Math.*, Vol. 7, ed. V. Klee, American Math. Soc., Providence, Rhode Island, pp. 225–232.
- [6] D. Gale, H. W. Kuhn, A. W. Tucker (1950). “On Symmetric Games.” *Contributions to the Theory of Games I*, eds. H. W. Kuhn and A. W. Tucker, *Annals of Mathematics Studies* 24, Princeton University Press, Princeton, pp. 81–87.
- [7] C. E. Lemke, J. T. Howson, Jr. (1964). “Equilibrium Points of Bimatrix Games.” *J. Soc. Indust. Appl. Mathematics* 12, pp. 413–423.
- [8] A. McLennan, R. Tourky (2010). “Imitation Games and Computation.” *Games and Economic Behavior* 70, pp. 4–11.
- [9] N. Megiddo, C. H. Papadimitriou (1991). “On Total Functions, Existence Theorems and Computational Complexity.” *Theoretical Computer Science* 81, pp. 317–324.
- [10] J. Merschen (2012). “Nash Equilibria, Gale Strings, and Perfect Matchings.” PhD Thesis, London School of Economics and Political Science.
- [11] J. F. Nash (1951). “Noncooperative games.” *Annals of Mathematics*, 54, pp. 289–295.
- [12] C. H. Papadimitriou (1994). “On the Complexity of the Parity Argument and Other Inefficient Proofs of Existence.” *J. Comput. System Sci.* 48, pp. 498–532.
- [13] R. Savani, B. von Stengel (2006). “Hard-to-solve Bimatrix Games.” *Econometrica* 74, pp. 397–429.

better other article, “Exponentially many steps for finding a NE in a bimatrix game.” In the 45th Annual IEEE Symposium on Foundations of Computer Science, FOCS 2004.?

- [14] L. S. Shapley (1974). “A Note on the Lemke-Howson Algorithm.” *Mathematical Programming Study 1: Pivoting and Extensions*, pp. 175–189
  - [15] L. Végh, B. von Stengel “Oriented Euler Complexes and Signed Perfect Matchings.” [arXiv:1210.4694v2 \[cs.DM\]](#)
- textbooks - papad, ziegler, sth gth