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# CS 6001: GAME THEORY AND ALGORITHMIC MECHANISM DESIGN

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## §1. Introduction

In typical linear programming, we have an objective that a *single* individual is trying to maximize (subject to some constraints). In game theory, we typically study systems where there are *multiple* individuals with objectives that they are trying to maximize, but each individual can only set some of the variables (the set of variables is shared). An optimal solution for one individual might not be the optimal solution for another. As a result, it is now better to look at *equilibria* instead of pure black-and-white optimality.

These equilibria are what we shall study.

The course is broadly split in two parts:

- *Game theory*, where we study games, interactions between agents who want to maximize their utilities. This is a predictive approach. We wish to find the most probable outcomes or responses of the agents/players.
- *Mechanism design*, where we try to design a game with desirable outcomes. This is a prescriptive approach. Given a reasonable outcome, we wish to build a game that yields this as a probable outcome.

The above is essentially analysis versus synthesis.

A well-known example of game theory is the *Prisoner's Dilemma*, which we slightly rephrase in the following.

**Example 1** (Neighbouring kingdoms dilemma). Two kingdoms can each decide to dedicate all their resources to either agriculture or warfare. If both kingdoms choose warfare, they each earn one unit of joy. If one chooses agriculture and the other chooses warfare, the former earns nothing while the latter earns six units of joy. Finally, if both choose agriculture, they each earn five units of joy.

This can be represented by the following matrix.

A, B	Agriculture	War
Agriculture	5, 5	0, 6
War	6, 0	1, 1

The above matrix is called a *game matrix*. Each of the two numbers in the cells are referred to as the *utilities* of the respective kingdoms.

Suppose that kingdom A decides to invest in agriculture. In this case, note that irrespective of what the other kingdom decides to choose, A can increase its payoff by switching to investing in warfare. Consequently, it makes more sense to invest in warfare (since the game is symmetric, this is true for both players). Even though both kingdoms heading to war is not the most profitable outcome, it appears to be the most likely outcome.

A *game* is a formal representation of the strategic interaction between multiple agents called *players*. The choices available to the players are called *actions*. A mapping from the state of the game to the set of actions is referred to as a *strategy*.

Depending on the context, games can be represented in different ways, normal form, extensive form, repeated form, stochastic form, etcetera.

*Game theory* is the formal study of the strategic interactions between players who are rational and intelligent.

A player is rational if they pick actions to maximize their payoff.

A player is intelligent if they know the rules of the game perfectly and picks actions assuming that the remaining players are also rational and intelligent. This also assumes that the player has sufficient computational ability to find the “optimal” action.

Let us now look at an example of mechanism design.

**Example 2.** Suppose we want to split a cake in two parts (for two children, say) in an “envy-free” fashion. That is, neither child would prefer the other piece of cake. We do not see the children’s preferences, so we do not even know what a fair division might involve. This well-known problem has a well-known solution – make one child cut the cake and the other choose the piece. Why does this work? The first child splits it in a way that is exactly half from their perspective, and they are indifferent to the two pieces. The second child on the other hand gets a larger piece in their perspective.

While game theory allows us to study existing games, mechanism design helps us design games to attain specific goals.

The reader is no doubt familiar with the rules of chess. It has two players, *White* and *Black*, with 16 pieces each. Each piece has some legal moves (the players’ actions are these moves). The game starts with White and players take alternating turns. White wins if they capture Black’s king, and Black wins they capture White’s king. There are a couple of conditions under which a draw can occur, which we do not detail.

There are numerous natural questions that arise. First and foremost, does White (or Black) have a winning strategy? A winning strategy is a plan of moves such that it wins irrespective of the moves performed by Black. Alternatively, is it possible to guarantee a draw? It is possible for none of these exist.

What is a strategy? Denote a board position by  $x_k$ . A *game situation* is a finite sequence  $(x_0, \dots, x_k)$ , such that  $x_0$  is the opening board position and  $x_k \rightarrow x_{k+1}$  for even (resp. odd)  $k$  is created by a single action of White (resp. Black).

This set of game situations can be naturally represented by a tree, referred to as the *game tree*. The nodes are labelled with board positions  $(x_i)$ , and arrows between nodes are labelled with actions. A *strategy* is a mapping from game situation to action, which describes what action to take at every vertex of this game tree. This is something of a contingency plan for every possible situation.

A strategy pair  $(s_W, s_B)$  which describes strategies for both players determines an outcome, also called a *play* of the game. This describes a path through the game tree.

All leaves in the game tree correspond to either White’s victory, Black’s victory, or a draw.

A *winning strategy* for White is a strategy  $s_W^*$  such that for any strategy  $s_B$ ,  $(s_W^*, s_B)$  ends in a win for White. Similarly, we can define a *strategy guaranteeing at least a draw for White*, denoted  $s_W'$ .

It is not immediately obvious if such strategies exist.

**Theorem 1.1** (von Neumann, 1928). In chess, exactly one of the following statements is true.

- (1) White has a winning strategy.
- (2) Black has a winning strategy.
- (3) Each player has a strategy guaranteeing a draw.

If any such strategy was known, the game would become boring.

*Proof sketch.* Each vertex of the game tree is a game situation. Denote by  $\Gamma(x)$  the subtree rooted at  $x$  (including  $x$  itself) and by  $n_x$  the number of vertices in  $\Gamma(x)$ .  $n_x = 1$  implies that  $x$  is a terminal vertex.

Using induction on  $n_x$ , we prove that one of the three statements must hold at any game situation. The theorem is clearly true for  $n_x = 1$ . Suppose  $x$  is a vertex with  $n_x > 1$ . By the inductive hypothesis, for all  $y \in \Gamma(y) \setminus \{x\}$ , the statement holds ( $n_y < n_x$ ). Let  $C(x)$  be the vertices reachable from  $x$  in one step, and assume wlog that it is White’s turn.

- (a) If there exists  $y_0 \in C(x)$  such that (1) is true, then (1) is true at  $x$  as well.
- (b) If (2) is true for all  $y \in C(x)$ , then Black will win irrespective of White’s move.

- (c) Otherwise, because (a) does not hold, White does not have a winning strategy for any  $y \in C(x)$ . As a result, for every  $y \in C(x)$ , either Black has a winning strategy or both have a draw-guaranteeing strategy. Because (b) does not hold, there is some  $y \in C(x)$  where Black does not have a winning strategy. By the preceding argument, both players must have a draw-guaranteeing strategy at this node. ■

*Remark.* The above proof is technically incorrect since the game tree for chess is infinite, so  $\Gamma(x)$  need not be finite. This issue can be fixed through some clever manipulation of the “cycles” in the game tree to make the graph finite, but we do not go into more detail on this.

## §2. Normal form games

### 2.1. Definitions

Normal form is a representation technique for games.

**Definition 2.1** (Normal form game). A normal form game is a 3-tuple  $\langle N, (S_i)_{i \in N}, (u_i)_{i \in N} \rangle$ , where

1.  $N = \{1, \dots, n\}$  is the set of players.
2.  $S_i$  is the set of *strategies* of player  $i$ . A particular strategy is denoted  $s_i \in S_i$  and the set of *strategy profiles* is  $S := \prod_{i \in N} S_i$ , with specific elements  $s = (s_1, \dots, s_n) \in S$ . A strategy profile without  $i$  is  $s_{-i} = (s_1, \dots, s_{i-1}, s_{i+1}, \dots, s_n)$ .
3.  $u_i : S \rightarrow \mathbb{R}$  is the *utility function* of player  $i$ .

If  $S_i$  is finite for all  $i \in N$ , the game is said to be a *finite game*.

As mentioned earlier, a player is rational if they pick actions that maximize their utility. A player is intelligent if they know the rules of the game perfectly, and pick actions assuming that all other players are rational and intelligent.

A fact is said to be *common knowledge* if

1. all players know the fact,
2. the fact that “all players know the fact” is also common knowledge.

**Example 3** (Propagation of common knowledge). There is an isolated island (with a hundred people, say) where all inhabitants have eye color either blue or black. There is no reflecting surface on the island (people cannot figure out their own eye color) and nobody can communicate with each other.

One day, a truth-telling god comes to the island and declares that all blue-eyed people are bad for the island and must leave as soon as possible. He also says that there is at least one blue-eyed person on the island. The inhabitants, being deeply devout, do listen to him and leave at the end of the day if they discover that their eyes are blue. In this setting, the fact that there is at least one blue-eyed person on the island is common knowledge.

If there was only one blue-eyed person, he would see that all other people have black eyes. Because the god said that there is a blue-eyed person, he infers that he must be the only blue-eyed person and leaves at the end of the first day.

If there were two, then on the second day everyone would notice that all people remain on the island, so they would infer that there are at least two blue-eyed people on the island. If one of the inhabitants sees that exactly one of the other four people is blue-eyed, then he, along with the other blue-eyed person, leaves on the second day.

This goes on, and it is seen that if there are exactly  $n$  blue-eyed people, then all of these  $n$  people leave at the end of the  $n$ th day.

Now, we discuss the concept of *domination* in NFGs. Consider the following game matrix:

1, 2	L	M	R
U	1, 0	1, 3	3, 2
D	-1, 6	0, 5	3, 3

Observe that player 2 has no reason to ever play R. Indeed, no matter what player 1 chooses, they can increase their payoff by switching to M instead. In such a scenario, we say that R is dominated by M.

**Definition 2.2.** A strategy  $s'_i \in S_i$  of player  $i$  is said to be *strictly dominated* if there exists another strategy  $s_i \in S_i$  such that for every strategy profile  $s_{-i} \in S_{-i}$ ,

$$u_i(s_i, s_{-i}) > u_i(s'_i, s_{-i}).$$

A strategy  $s'_i \in S_i$  of player  $i$  is said to be *weakly dominated* if there exists another strategy  $s_i \in S_i$  such that for every strategy profile  $s_{-i} \in S_{-i}$ ,

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

and in addition, there exists some  $\tilde{s}_{-i} \in S_{-i}$  such that

$$u_i(s_i, \tilde{s}_{-i}) > u_i(s'_i, \tilde{s}_{-i}).$$

So, in the earlier example R is strictly dominated and D is weakly dominated.

There is no reason for a rational player to ever play a (weakly or strictly) dominated strategy.

**Definition 2.3.** A strategy  $s_i \in S_i$  is *strictly (weakly) dominant* if it strictly (weakly) dominates all  $s'_i \in S_i \setminus \{s_i\}$ .

Recall Example 1. In this, warfare strictly dominates agriculture, which is precisely what we said there, albeit in more explicit terms.

Let us give another example of this.

**Example 4** (Second price auctions). Suppose there are two players having “values”  $v_1, v_2$  respectively. Each player can choose a number in  $[0, M]$ , where  $M \gg v_1, v_2$ . The player who quotes the larger number wins the object (with ties being broken in favour of player 1, say), and pays the losing player’s chosen number. The utility of the winning player is their value  $v_i$  minus their payment (the amount bid by the other player), and the utility of the losing player is 0.

As a NFG representation,  $N = \{1, 2\}$ ,  $S_1 = S_2 = [0, M]$ , and

$$u_1(s_1, s_2) = \begin{cases} v_1 - s_2, & s_1 \geq s_2, \\ 0, & \text{otherwise,} \end{cases} \text{ and } u_2(s_1, s_2) = \begin{cases} v_2 - s_1, & s_1 < s_2, \\ 0, & \text{otherwise,} \end{cases}$$

It turns out that the strategy  $s_i$  where player  $i$  chooses  $v_i$  is a weakly dominant strategy! Let us check this for player 1.

Suppose that  $s'_1 > v_1$  is in  $S_1$  and  $s_2 \in S_2$ . We would like to show that  $u_1(s_1, s_2) \geq u_1(s'_1, s_2)$ . If  $s_2 > s'_1$ , both payoffs are zero. If  $s_2 \leq s_1 < s'_1$ , then both payoffs are equal to the same value. The remaining case is when  $s_1 \leq s_2 \leq s'_1$ . The payoff for  $s_1$  is zero, but the payoff for  $s'_1$  is non-positive since we are paying more than we value the item.

## 2.2. Some types of equilibria

**Definition 2.4.** A strategy profile  $(s_1^*, s_2^*, \dots, s_n^*)$  is a *strictly (weakly) dominant strategy equilibrium* if each  $s_i^*$  is a strictly (weakly) dominant strategy.

We abbreviate the above as SDSE or WDSE.

No rational player would play dominated strategies, so we can eliminate dominated strategies one-by-one. A point of note here is that after eliminating a strategy, we get a reduced game with fewer strategies, and this game may have dominated strategies that were not there earlier.

For strictly dominated strategies, the order of elimination does not matter. For weakly dominated strategies however, some reasonable outcomes may be eliminated; this is because eliminating one player's weakly dominated strategies may introduce new dominated strategies for another.

**Example 5** (Order of eliminating weakly dominated strategies matters). Consider the following.

	L	C	R
T	1,2	2,3	0,3
M	2,2	2,1	3,2
B	2,1	0,0	1,0

Right off the bat, it is seen that T, B, and C are weakly dominated strategies. Suppose we start by imposing that player 1 does not play T. If we do this, then R becomes weakly dominated as well, so it makes sense to eliminate it. Similarly, we can go on to eliminate B and C. Finally, the payoff of (M, L) is 2, 2.

On the other hand, if we eliminate strategies in the order of B, L, C, T, then the final remaining strategies are (M, R), which gives a payoff of 3, 2, which is not the same as the previous 2, 2!

Dominant strategies (and dominant strategy equilibria) need not exist in games in general.

**Example 6** (Dominated strategies need not exist). Consider the following game.

	L	R
L	1, 1	0, 0
R	0, 0	1, 1

As a result, dominance is not enough to give a reasonable outcome, so we must give a more refined notion.

**Definition 2.5** (Nash Equilibrium). A strategy profile  $(s_i^*, s_{-i}^*)$  is a *pure strategy Nash equilibrium* (PSNE) if for all  $s_i \in S_i$ ,

$$u_i(s_i^*, s_{-i}^*) \geq u_i(s_i, s_{-i}^*).$$

That is, fixing the remaining players' strategies, no player can increase their payoff by moving to another strategy. More succinctly, unilateral deviation is not beneficial.

In the above example, (L, L) and (R, R) are both PSNEs.

PSNEs need not exist either!

**Example 7** (PSNEs need not exist). The following game has no PSNE.

	L	R
L	-1, 1	1, -1
R	1, -1	1, -1

**Definition 2.6.** A *best response* of player  $i$  against a strategy profile  $s_{-i}$  is a strategy that gives the maximum utility. That is,

$$B_i(s_{-i}) = \{s_i \in S_i : u_i(s_i, s_{-i}) \geq u_i(s'_i, s_{-i}) \text{ for all } s'_i \in S_i\}.$$

So, a PSNE is a strategy profile  $(s_i^*, s_{-i}^*)$  such that  $s_i^* \in B_i(s_{-i}^*)$  for all  $i \in N$ .

A PSNE gives some sort of stability. Once there, no rational player has a reason to change their strategy.

One of our biggest assumptions thus far is that all players are rational and intelligent. There are, however, other types of rationality.

One is risk-aversion, where each player makes pessimistic estimates of others. This worst case optimal choice is called a max-min strategy.

**Definition 2.7.** A strategy  $s_i^{\max\min}$  is a *max-min strategy* for player  $i$  if

$$s_i^{\max\min} \in \arg \max_{s_i \in S_i} \min_{s_{-i} \in S_{-i}} u_i(s_i, s_{-i}).$$

The *max-min value* is defined by

$$\underline{v}_i = \max_{s_i \in S_i} \min_{s_{-i} \in S_{-i}} u_i(s_i, s_{-i}).$$

We have that for any  $t_{-i} \in S_{-i}$ ,

$$u_i(s_i^{\max\min}, t_{-i}) = \underline{v}_i.$$

**Theorem 2.1.** Any dominant strategy is a maxmin strategy.

*Proof.* Let  $s_i^*$  be a dominant strategy for player  $i$ . We have that for any  $s_{-i} \in S_{-i}$  and  $s'_i \in S_i \setminus \{s_i^*\}$ ,

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

In particular, when we set  $s_{-i}$  as any  $s_{-i}^{\min}(s_i^*) \in \arg \min_{s_{-i} \in S_{-i}} u_i(s_i^*, s_{-i})$ , we get

$$\min_{s_{-i} \in S_{-i}} u_i(s_i^*, s_{-i}) = u_i(s_i^*, s_{-i}^{\min}(s_i^*)) \geq u_i(s'_i, s_{-i}^{\min}(s'_i)) \geq \min_{s_{-i} \in S_{-i}} u_i(s'_i, s_{-i})$$

and as a result,

$$s_i^* \in \arg \max_{s_i \in S_i} \min_{s_{-i} \in S_{-i}} u_i(s_i, s_{-i}). \quad \blacksquare$$

**Theorem 2.2.** Every PSNE  $s^* = (s_1^*, \dots, s_n^*)$  of an NFG satisfies

$$u_i(s^*) \geq \underline{v}_i$$

for all  $i \in N$ .

*Proof.* We have

$$\begin{aligned} u_i(s_i^*, s_{-i}^*) &= \max_{s_i \in S_i} u_i(s_i, s_{-i}^*) && \text{(by definition of PSNE)} \\ &\geq \max_{s_i \in S_i} \min_{s_{-i} \in S_{-i}} u_i(s_i, s_{-i}) = \underline{v}_i. && \blacksquare \end{aligned}$$



What happens to stability and security when games are eliminated? Recall that depending on the order in which dominant strategies are eliminated, the final value can change.

**Example 8.** The game matrix involved in this example is very similar to that in Example 5.

	L	C	R
T	1, 2	2, 3	0, 3
M	2, 2	2, 1	3, 2
B	2, 0	0, 0	1, 0

The initial maxmin values for the two players are 2 for player 1 and 0 for player 2, but after we eliminate B, the values go to 2 and 2.

It is not a coincidence that the maxmin value of 2 for player 1 is unchanged.

**Theorem 2.3.** Consider an NFG  $G = \langle N, (S_i)_{i \in N}, (u_i)_{i \in N} \rangle$ . Let  $\hat{s}_j \in S_j$  be a dominated strategy, and  $\hat{G}$  be the residual game after removing  $\hat{s}_j$ . The maxmin value of player  $j$  in  $\hat{G}$  is equal to that in  $G$ .

The idea is that the eliminated strategy cannot be the unique maxmin strategy in  $G$  since it is dominated.

*Proof.* We are done if we show that there is a maxmin strategy in  $G$  in  $S_j \setminus \{\hat{s}_j\}$  (Why?).

Let  $\hat{s}_j$  be dominated by  $t_j \in S_j \setminus \{\hat{s}_j\}$ . Then, for all  $s_{-j} \in S_{-j}$ ,

$$u_j(t_j, s_{-j}) \geq u_j(\hat{s}_j, s_{-j}).$$

We have

$$\min_{s_{-j} \in S_{-j}} u_j(t_j, s_{-j}) \geq \min_{s_{-j} \in S_{-j}} u_j(\hat{s}_j, s_{-j}),$$

so

$$\max_{s_j \in S_j \setminus \{\hat{s}_j\}} \min_{s_{-j} \in S_{-j}} u_j(s_j, s_{-j}) \geq \min_{s_{-j} \in S_{-j}} u_j(\hat{s}_j, s_{-j}),$$

completing the proof – there is another strategy whose value is at least that of  $\hat{s}_j$ . ■

To summarize,

- eliminating strictly dominated strategies has no effect on the PSNEs,
- eliminating weakly dominated strategies may make the set of PSNEs smaller, but does not add new PSNEs, and
- the maxmin value is unaffected by eliminating (strictly or weakly) dominated strategies.

### 2.3. Matrix games

**Definition 2.8.** A *matrix game* or *two player zero-sum game* is a normal form game  $\langle N, (S_i)_{i \in N}, (u_i)_{i \in N} \rangle$  with  $N = \{1, 2\}$  and  $u_1 + u_2 \equiv 0$ .

**Example 9.** Examples of matrix games are the following.

	L	C	R
T	3, -3	-5, 5	-2, 2
M	1, -1	4, -4	1, -1
B	6, -6	-3, 3	-5, 5

	L	R
L	-1, 1	1, -1
R	1, -1	-1, 1

A point of note here that we shall soon examine in more detail is that the first game has PSNEs while the second does not.

A matrix game can be represented by a single *utility matrix*, by considering the utilities of only one of the players, say player 1. Player 2's utilities are then just the negative of the matrix.

Given a utility matrix  $u$ ,  $u_1 \equiv u$  and  $u_2 \equiv -u$ .

What are the PSNEs, if any, of a matrix game?

**Definition 2.9.** A *saddle point* of a matrix  $A$  is an index  $A_{ij}$  that is the largest in the  $i$ th row and the smallest in the  $j$ th column.

**Theorem 2.4.** In a matrix game with utility matrix  $u$ ,  $(s_1^*, s_2^*)$  is a PSNE if and only if it is a saddlepoint.

*Proof.* Indeed,  $(s_1^*, s_2^*)$  is a saddle point iff

$$\begin{aligned} u(s_1^*, s_2^*) &\geq u(s_1, s_2^*) \text{ for all } s_1 \in S_2 \text{ and} \\ u(s_1^*, s_2^*) &\leq u(s_1^*, s_2) \text{ for all } s_2 \in S_2, \end{aligned}$$

which is equivalent to being a PSNE since  $u_1 \equiv u$  and  $u_2 \equiv -u$ . ■

**Definition 2.10.** Given a two player game with utility matrix  $u$ , define the *maxmin* value  $\underline{v}$  by

$$\underline{v} = \max_{s_1 \in S_1} \min_{s_2 \in S_2} u(s_1, s_2)$$

and the *minmax* value  $\bar{v}$  by

$$\bar{v} = \min_{s_2 \in S_2} \max_{s_1 \in S_1} u(s_1, s_2).$$

The above can be slightly rephrased to say

$$\begin{aligned} \underline{v} &= - \min_{s_1 \in S_1} \max_{s_2 \in S_2} u_2(s_1, s_2) \\ \bar{v} &= \min_{s_2 \in S_2} \max_{s_1 \in S_2} u_1(s_1, s_2). \end{aligned}$$

**Lemma 2.5.** For matrix games,  $\bar{v} \geq \underline{v}$ .

*Proof.* Let  $\bar{v}$  and  $\underline{v}$  be attained by  $(s_1, s_2)$  and  $(t_1, t_2)$  respectively. Then,

$$\bar{v} = u(s_1, s_2) \stackrel{(1)}{\geq} u(t_1, s_2) \stackrel{(2)}{\geq} u(t_1, t_2) = \underline{v},$$

where (1) is because  $(s_1, s_2)$  is a minmax strategy and (2) is because  $(t_1, t_2)$  is a maxmin strategy. ■

Going back to Example 9, check that in the first game,  $\bar{v} = 1 = \underline{v}$ , while in the second game,  $\bar{v} = 1$  and  $\underline{v} = -1$ .

**Theorem 2.6.** A matrix game has a PSNE iff  $\bar{v} = \underline{v}$ .

*Proof.* We wish to show that a utility matrix  $u$  has a saddle point iff its maxmin and minmax values are equal.

Suppose that  $(s_1^*, s_2^*)$  is a saddle point. Then,

$$u(s_1^*, s_2^*) \geq \max_{s_1 \in S_1} u(s_1, s_2^*) \geq \min_{s_2 \in S_2} \max_{s_1 \in S_1} u(s_1, s_2) = \bar{v}.$$

An identical argument for player 2 (keeping in mind that  $u_2 \equiv -u!$ ) yields that  $\underline{v} \geq u(s_1^*, s_2^*)$ .

Combining the two,

$$\underline{v} \geq u(s_1^*, s_2^*) \geq \bar{v}.$$

Recalling Lemma 2.5, we must have that  $\bar{v} = \underline{v}$ .

Now, suppose that  $\bar{v} = \underline{v}$ . There is a strategy  $(s_1^*, s_2^*)$  that is both a maxmin and minmax strategy (Why?).

For any  $s_2 \in S_2$ ,

$$u(s_1^*, s_2) \geq \min_{t_2 \in S_2} u(s_1^*, t_2) = \max_{t_1 \in S_1} \min_{t_2 \in S_2} u(t_1, t_2) = \underline{v}.$$

Similarly, for any  $s_1 \in S_1$ ,

$$u(s_1, s_2^*) \leq \max_{t_1 \in S_1} u(t_1, s_2^*) = \min_{t_2 \in S_2} \max_{t_1 \in S_1} u(t_1, t_2) = \bar{v}.$$

The two equations above imply that  $(s_1^*, s_2^*)$  is a saddle point, so we are done. ■

## 2.4. Mixed strategies

So far, one issue is that PSNEs may not exist. We are also limiting ourselves to “pure” strategies, in the sense that there is a certain strategy that we definitely play.

Given a finite set  $A$ , define the set of probability distributions on  $A$

$$\Delta A = \{p \in [0, 1]^A \mid \sum_{a \in A} p_a = 1\}.$$

A *mixed strategy* of player  $i$  is some  $\sigma_i \in \Delta(S_i)$ .

Because we are looking at non-cooperative games, mixed strategies of distinct players are independent.

The utility of the  $i$ th player for a mixed strategy profile  $(\sigma_i, \sigma_{-i})$  is

$$u_i(\sigma_i, \sigma_{-i}) = \sum_{s_1 \in S_1} \cdots \sum_{s_n \in S_n} \left( \prod_{i \in [n]} \sigma_i(s_i) \right) u_i(s_1, \dots, s_n).$$

That is, the utility of a mixed strategy is the expectation of the utility.

**Example 10.** Consider the following game.

	U	D
L	-1, 1	1, -1
R	1, -1	-1, 1

Suppose the mixed strategy  $\sigma_1$  chooses L and R with probabilities  $2/3$  and  $1/3$  respectively, and  $\sigma_2$  chooses U and D with probabilities  $4/5$  and  $1/5$  respectively. Then,

$$u_1(\sigma_1, \sigma_2) = \frac{2}{3} \cdot \frac{4}{5} \cdot (-1) + \frac{2}{3} \cdot \frac{1}{5} \cdot 1 + \frac{1}{3} \cdot \frac{4}{5} \cdot 1 + \frac{1}{3} \cdot \frac{1}{5} \cdot (-1) = -1/5.$$

By linearity of expectation, we have

$$u_i(\lambda\sigma_i + (1-\lambda)\sigma'_i, \sigma_{-i}) = \lambda u_i(\sigma_i, \sigma_{-i}) + (1-\lambda)u_i(\sigma'_i, \sigma_{-i}). \quad (2.1)$$

This is referred to as mixing strategies.

**Definition 2.11** (Mixed Strategy Nash Equilibrium). A *mixed strategy nash equilibrium* (MSNE) is a mixed strategy profile  $(\sigma_i^*, \sigma_{-i}^*)$  such that for all  $i \in N$ ,

$$u_i(\sigma_i^*, \sigma_{-i}^*) \geq u_i(\sigma'_i, \sigma_{-i}^*)$$

for any  $\sigma'_i \in \Delta(S_i)$ .

A PSNE is just a special case of a MSNE where all the mixed strategies are degenerate distributions.

**Theorem 2.7.** A mixed strategy profile  $(\sigma_i^*, \sigma_{-i}^*)$  is a MSNE iff

$$u_i(\sigma_i^*, \sigma_{-i}^*) \geq u_i(s_i, \sigma_{-i}^*)$$

for all  $s_i \in S_i$ .

The forward implication is direct on setting the  $\sigma'_i$  appropriately, and the backward implication by an extension of Equation (2.1) to more than two strategies (How?).

Therefore, any PSNE is a MSNE. In any MSNE, there must be some amount of “balance” – in Example 10, the probability distributions that assign  $1/2$  to each strategy together constitute a MSNE (check this!). How do we make this notion of balance more formal?

**Definition 2.12.** Given a mixed strategy  $\sigma_i$ , the *support* of  $\sigma_i$  is

$$\delta(\sigma_i) = \{s_i \in S_i : \sigma_i(s_i) > 0\}.$$

We now characterize MSNEs.

**Theorem 2.8.** A mixed strategy profile  $(\sigma_i^*, \sigma_{-i}^*)$  is a MSNE iff

- (a)  $u_i(s_i, \sigma_{-i}^*)$  is equal for all  $s_i \in \delta(\sigma_i^*)$ , and
- (b)  $u_i(s_i, \sigma_{-i}^*) \geq u_i(s'_i, \sigma_{-i}^*)$  for all  $s_i \in \delta(\sigma_i^*)$ ,  $s'_i \notin \delta(\sigma_i^*)$ .

We encourage the reader to use the above theorem to determine MSNEs in earlier examples.

*Proof.* We have

$$\begin{aligned}
 u_i(\sigma_i^*, \sigma_{-i}^*) &= \max_{\sigma_i \in \Delta(S_i)} u_i(\sigma_i, \sigma_{-i}^*) \\
 &= \max_{s_i \in S_i} u_i(s_i, \sigma_{-i}^*) \quad (\text{similar to Theorem 2.7}) \\
 &= \max_{s_i \in \delta(\sigma_i^*)} u_i(s_i, \sigma_{-i}^*) \\
 &= \sum_{s_i \in \delta(\sigma_i^*)} \sigma_i^*(s_i) u_i(s_i, \sigma_{-i}^*).
 \end{aligned}$$

It is possible for the maximum and weighted average to be equal iff all the utilities are the same, so (a) is proved.

Now, suppose that there is some  $s_i \in \delta(\sigma_i^*)$ ,  $s'_i \notin \delta(\sigma_i^*)$  such that

$$u_i(s_i, \sigma_{-i}^*) < u_i(s'_i, \sigma_{-i}^*).$$

Consider the mixed strategy that is identical to  $\sigma_i^*$  except that the weight that was on  $s_i$  is shifted to  $s'_i$ . This gives a strictly larger utility, contradicting the fact that we have an MSNE and proving (b).

Now, let us prove the backward direction. Let  $u_i(s_i, \sigma_{-i}^*) = m_i(\sigma_{-i}^*)$  for all  $s_i \in \delta(\sigma_i^*)$  (using (a)). Using (b), we have  $m_i(\sigma_{-i}^*) = \max_{s_i \in S_i} u_i(s_i, \sigma_{-i}^*)$ . Then,

$$\begin{aligned}
 u_i(\sigma_i^*, \sigma_{-i}^*) &= \sum_{s_i \in \delta(\sigma_i^*)} \sigma_i^*(s_i) u_i(s_i, \sigma_{-i}^*) \\
 &= m_i(\sigma_{-i}^*) \\
 &= \max_{s_i \in S_i} u_i(s_i, \sigma_{-i}^*),
 \end{aligned}$$

so we are done by Theorem 2.7. ■

We now try to convert the above theorem to an algorithm. Suppose we have an NFG  $G = \langle N, (S_i)_{i \in N}, (u_i)_{i \in N} \rangle$ . The number of possible supports of  $S_1 \times \dots \times S_n$  is  $K = (2^{|S_1|-1})(2^{|S_2|-1}) \dots 2^{|S_n|-1}$ .

For every possible support profile  $X_1 \times \dots \times X_n$ , solve the following feasibility program.

$$\begin{aligned}
 w_i &= \sum_{s_{-i} \in S_{-i}} \left( \prod_{j \neq i} \sigma_j(s_j) \right) u_i(s_i, s_{-i}) \text{ for all } s_i \in X_i, i \in N \text{ and} \\
 w_i &\geq \sum_{s_{-i} \in S_{-i}} \left( \prod_{j \neq i} \sigma_j(s_j) \right) u_i(s_i, s_{-i}) \text{ for all } s_i \in (S_i \setminus X_i), i \in N,
 \end{aligned}$$

where for all  $j \in N$ ,  $\sigma_j(s_j) \geq 0$  for all  $s_j \in S_j$  and  $\sum_{s_j \in S_j} \sigma_j(s_j) = 1$ .

This program is not linear unless there are only two players.

For games in general, there is no polynomial time algorithm known for this. In fact, the problem of finding an MSNE is *PPAD-complete*<sup>1</sup>. The interested reader may see [DGP09] for more details.

The previous algorithm may be applied to a smaller set of strategies by removing dominated strategies. Now, we can even talk about domination by a mixed strategy. As we saw earlier, removing a weak dominated strategy can upset the equilibrium.

**Theorem 2.9.** If a pure strategy  $s_i$  is strictly dominated by a mixed strategy  $\sigma_i \in \Delta(S_i)$ , any MSNE of the game chooses  $s_i$  with probability zero.

<sup>1</sup>PPAD stands for “Polynomial Parity Argument on Directed graphs”.

We can remove strictly dominated strategies without consequences.

**Theorem 2.10** (Nash, [Nas51]). Any finite game has a mixed Nash equilibrium.

Above, “finite” means that the number of players and strategies are finite.

## 2.5. Correlated equilibria

So far, we have worked in the setting where each agent independently picks their own strategy. Now, we look at an alternative approach with a mediating agent or device. This is merely another version of rationality. It may lead to results where the utility of all players is improved, and is computationally tractable.

**Example 11.** Consider the following game, modelling the choices of cars at a crossroads.

	Wait	Go
Wait	0, 0	1, 2
Go	2, 1	−10, −10

It is clear that both Wait, Go and Go, Wait are PSNEs. It can also be seen however that a MSNE can assign some nonzero probability to the event where both players choose Go. In practice, a traffic light guides the players. This trusted third party is called the *mediator*. It randomizes over the strategy *profiles* (and not just strategies like earlier) and suggests the corresponding strategies to the players. If the strategies are enforceable, then it is an equilibrium.

**Definition 2.13.** A *correlated strategy* is a mapping  $\pi \in \Delta S$ .

In the setting of the previous example, an example of a sensible correlated strategy is that which chooses Wait, Go or Go, Wait with equal probability  $1/2$ .

**Definition 2.14.** A *correlated equilibrium* is a correlated strategy  $\pi$  such that

$$\sum_{s_{-i} \in S_{-i}} \pi(s_i, s_{-i}) u_i(s_i, s_{-i}) \geq \sum_{s_{-i} \in S_{-i}} \pi(s_i, s_{-i}) u_i(s'_i, s_{-i})$$

for all  $s_i, s'_i \in S_i$  for all  $i \in N$ .

That is, no player benefits from (unilaterally) changing their strategy. This is largely similar to the definition of an MSNE, but the distribution is over strategy profiles and not strategies.

One massive advantage of correlated equilibria is that they can be computed efficiently! We merely need to find a solution to the set of constraints

$$\begin{aligned} \sum_{s_{-i} \in S_{-i}} \pi(s_i, s_{-i}) u_i(s_i, s_{-i}) &\geq \sum_{s_{-i} \in S_{-i}} \pi(s_i, s_{-i}) u_i(s'_i, s_{-i}) \text{ for all } s_i, s'_i \in S_i \text{ and } i \in N \\ \pi(s) &\geq 0 \text{ for all } s \in S \\ \sum_{s \in S} \pi(s) &= 1. \end{aligned}$$

If  $|S_i| = m$  for all  $i$ , this gives  $O(nm^2)$  inequalities in the first part and  $O(m^n)$  inequalities for the second. All together, they represent a feasibility linear program.

In MSNEs, the total number of support profiles was  $O(2^{mn})$ . Here, we just have  $O(m^n)$  inequalities, which is exponentially smaller.

**Theorem 2.11.** Given a MSNE  $\sigma^*$ , consider the strategy profile distribution  $\pi^*$  defined by

$$\pi^*(s_1, \dots, s_n) = \prod_{i=1}^n \sigma_i^*(s_i).$$

Then,  $\pi^*$  is a correlated equilibrium.

We omit the proof of the above as it is straightforward.

Summarizing much of our discussion thus far, we have that the set of SDSEs is contained in the set of WDSEs, which is contained in the set of PSNEs, which is contained in the set of MSNEs, which is contained in the set of CEs.

### §3. Long-form games

Thus far, we have only looked at “single-step” games in NFGs. Not all games can be represented by this however, with an obvious example that we have discussed being chess.

#### 3.1. Perfect information extensive form games

**Definition 3.1** (Perfect Information Extensive Form Game). A perfect information extensive form game (PIEFG/EFG) is a 7-tuple  $\langle N, A, \mathcal{H}, \mathcal{X}, P, (u_i)_{i \in N} \rangle$  where

- $N$  is the set of players,
- $A$  is the set of all possible actions (of all players)
- $\mathcal{H} \subseteq \bigcup_{k=0}^{\infty} A^k$  is the set of all sequences of actions (*histories*) satisfying
  - $\emptyset \in \mathcal{H}$  and
  - if  $h = (a^{(0)}, a^{(1)}, \dots, a^{(\tau)}) \in \mathcal{H}$ , any subsequence  $h' = (a^{(0)}, a^{(1)}, \dots, a^{(t)})$  of  $h$  (for  $t \leq \tau$ ) starting at the root is in  $\mathcal{H}$ ,
- $Z \subseteq \mathcal{H}$  is called the set of all *terminal histories*, where a history  $h = (a^{(0)}, a^{(1)}, \dots, a^{(\tau-1)})$  is terminal if there exists no  $a^{(\tau)} \in A$  with  $(a^{(0)}, a^{(1)}, \dots, a^{(\tau)}) \in \mathcal{H}$ ,
- $\mathcal{X} : \mathcal{H} \setminus Z \rightarrow 2^A$ , called the *action set selection function*, gives the set of all valid actions given a non-terminal history,
- $P : \mathcal{H} \setminus Z \rightarrow N$  is the *player function* which gives the player who plays at a given non-terminal history, and
- $u_i : Z \rightarrow \mathbb{R}$  is the utility of player  $i$ .

A history is essentially a path from the root in the game tree (recall our discussion of this from the first section). A natural next question is: what is a strategy in a PIEFG?

**Definition 3.2** (Strategy). A *strategy* of a player in an EFG is a tuple of actions at every history where the player plays. That is, a strategy of a player  $i$  is an element of

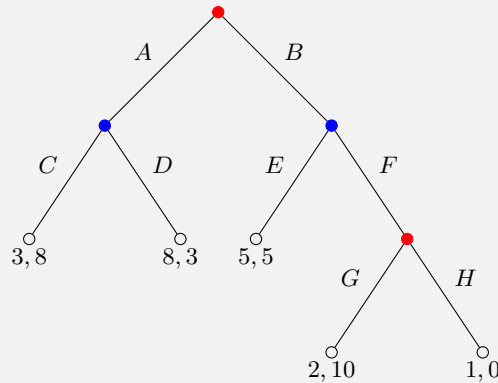
$$S_i = \bigtimes_{h \in \mathcal{H} : P(h)=i} \mathcal{X}(h).$$

We can transform EFGs to NFGs! Indeed, the above definition explicitly describes the strategy set of each player, and associated to any tuple of strategies for all the players, we can determine the payoff.

This conversion has a massive explosion in size however, and equilibria in the converted NFG do not necessarily make sense in the context of the original EFG.



**Example 12** (PSNEs in PIEFGs). Consider the following game with two players, red and blue.



At the node BF, red has no reason to play  $H$  since choosing  $G$  results in a higher payoff. However, it is still seen that  $(AH, CF)$  (at each node, the player chooses whichever of these actions is available) is a PSNE! This is a consequence of the fact that this strategy profile never even reaches the node where red chooses  $G$  or  $H$ , so it never comes into play.

Henceforth, we talk about PSNEs of EFGs as PSNEs of their NFG conversion.

**Definition 3.3.** A *subgame* of a game is the restriction of the game to the descendants of a history.

The idea behind an equilibrium should be *subgame perfection*, where each player chooses the best possible action at each subgame where they play.

**Definition 3.4** (Subgame Perfect Nash Equilibrium). A *subgame perfect nash equilibrium* (SPNE) of an EFG  $G$  is a strategy profile  $s \in S$  such that for any subgame  $G'$  of  $G$ , the restriction of  $s$  to  $G'$  is a PSNE of  $G'$ .

Similar to MSNEs, SPNEs are guaranteed to exist in finite PIEFGs. Observe that any SPNE is a PSNE. As we shall now see, the algorithm to find an SPNE is quite simple.

---

**Algorithm 1:** Backward induction to determine SPNEs

---

**Input:** An EFG  $G$

**Output:** The utility and action to be taken by a given player at a certain history

```

1 backInd(history  $h$ )
2   if  $h \in Z$  then
3     return  $u(h), \emptyset$ 
4   bestUtil $_{P(h)} \leftarrow -\infty$ 
5   foreach  $a \in \mathcal{X}(h)$  do
6     utilAtChild $_{P(h)} \leftarrow \text{backInd}((h, a))$ 
7     if utilAtChild $_{P(h)} > \text{bestUtil}_{P(h)}$  then
8       bestUtil $_{P(h)} \leftarrow \text{utilAtChild}_{P(h)}$ 
9       bestAction $_{P(h)} \leftarrow a$ 
10  return bestUtil $_{P(h)}, \text{bestAction}_{P(h)}$ 
```

---

The idea of subgame perfection is intrinsically tied to the above algorithm.

The issue however is that we are essentially parsing the entire tree, so the algorithm is computationally very expensive. Further, some criticize the idea of SPNEs for assuming that the cognitive limit of the players is infinite (which is not realistic).

It is easy to find an SPNE in simple games such as tic-tac-toe.

**Example 13** (Centipede game). Players 1 and 2 alternate, and each can play a move from {take, push}, with a maximum of  $N$  rounds, say. The game terminates when take is played for the first time or the limit of  $N$  rounds if take is never played.

The game also fixes some quantities  $m_0, m_1$  with  $m_0 > m_1$ . Suppose that the game ends on round  $t \in \{0, \dots, N-1\}$  with player  $p$  making the final move; let  $p'$  be the other player. Then, the payoffs for the two players are as follows:

- if  $p$  played take, then  $p, p'$  have payoffs of  $2^t m_0$  and  $2^t m_1$  respectively.
- if  $p$  played push, then  $p, p'$  have payoffs of  $2^{t+1} m_1$  and  $2^{t+1} m_0$  respectively.

That is, if a player plays push, they increase the size of the pot to be won, and if they play take, the game ends, with them getting a larger amount of money.

Most players except grandmasters play for a few rounds, with some of the reasons claimed for this being altruism, the difference in computational capacity of individuals and incentive difference.

There are some other criticisms of SPNEs as well, such as that it discusses what to do if the game reaches a certain history, but the equilibrium in earlier stages might show that we cannot actually reach this history.

### 3.2. Imperfect information extensive form games

EFGs are perfect information systems, where every player has perfect information about all developments in the game until that round. This is not useful in many practical scenarios, such as card games. EFGs also do not allow the representation of games with simultaneous moves. For example, the neighbouring kingdom dilemma we discussed in Example 1 depends significantly on the fact that both kingdoms move simultaneously.

This can be modeled as a sequential game, where the second player does not know for certain which history the game is in. This is called an *information set*. Such games where players deal with information sets instead of particular histories are called imperfect information extensive form games. When the information sets are singletons, we get back PIEFGs.

**Definition 3.5.** An *imperfect information extensive form games* (IIIEFG) is an 7-tuple  $\langle N, A, \mathcal{H}, \mathcal{X}, P, (u_i)_{i \in N}, (I_i)_{i \in N} \rangle$  where

- $\langle N, A, \mathcal{H}, \mathcal{X}, P, (u_i)_{i \in N} \rangle$  is a PIEFG,
- for every  $i \in N$ ,  $I_i = (I_i^1, I_i^2, \dots, I_i^{k(i)})$  is a partition of  $\{h \in \mathcal{H} \setminus Z : P(h) = i\}$  with the property that  $\mathcal{X}(h) = \mathcal{X}(h')$  and  $P(h) = P(h') = i$  whenever there exists some  $j$  such that  $h, h' \in I_i^j$ . The  $I_i^j$ s are called the *information sets* of player  $i$ , and  $I_i$  the collection of information sets of  $i$ .

At a given information set, the player and all their available actions are the same. The player is not certain which history in the information set the game is at.

Since the actions now depend on the information sets and not the histories, we denote  $\mathcal{X}(I_i^j) := \mathcal{X}(h)$  for any  $h \in I_i^j$ . Strategies are also defined over information sets. The strategy set of player  $i \in N$  is defined by

$$S_i = \prod_{\tilde{I} \in I_i} \mathcal{X}(\tilde{I}).$$

With IIEFGs, NFGs can be represented using EFGs, though this is not very succinct. The representation used is typically chosen on the basis of the game we are working with.

### 3.2.1. Strategies

In NFGs, we had mixed strategies where we randomized over pure strategies. In EFGs, randomization can be done in several ways:

- randomize over the strategies defined at the very beginning of the game, and
- randomize over the actions at a given information set – we call such a strategy a behavioral strategy. This takes advantage of all the information a player has at a certain point of time.

**Definition 3.6.** A *behavioral strategy* of a player in an IIEFG is a function that maps each of their information sets to a probability distribution over the set of actions at that information set.

A couple of questions come to mind seeing this: can a player attain a higher payoff using one type of strategy? Is there any sort of equivalence between mixed and behavioral strategies.

Given a node  $x$ , mixed/behavioral strategy  $\sigma_i$ , and a mixed/behavioral strategy vector  $\xi_{-i}$ , denote by  $p(x; \sigma_i, \xi_{-i})$  the probability of going to the node  $x$  in a game.

**Definition 3.7** (Equivalence of mixed and behavioral strategies). A mixed strategy  $\sigma_i$  and a behavioral strategy  $b_i$  of a player  $i$  in an IIEFG are *equivalent* if for every mixed/behavioral strategy vector  $\xi_{-i}$  of the other players and every vertex  $x$  in the game tree,

$$p(x; \sigma_i, \xi_{-i}) = p(x; b_i, \xi_{-i}).$$

Now, by definition, equivalence implies that the above equality holds at leaf nodes.

In fact, it suffices to check that it holds at leaf nodes! Given an arbitrary non-leaf nodes, the probability of reaching that node is equal to the sum of the probabilities of reaching the leaf nodes in the subtree, so equality at the leaves implies equality at non-leaves.

As a result, we get the following.

**Theorem 3.1** (Utility Equivalence). If  $\sigma_i, b_i$  are equivalent, then for every mixed/behavioral strategy vector of the other players  $\xi_{-i}$  and every  $j \in N$ ,

$$u_j(\sigma_i, \xi_{-i}) = u_j(b_i, \xi_{-i}).$$

**Corollary 3.2.** Let  $\sigma$  and  $b$  be equivalent. Then, for all  $i \in N$ ,  $u_i(\sigma) = u_i(b)$ .

Behavioral strategies are more natural in IIEFGs. Players plan at a given stage (i.e. information set), and don't have a master plan from the very beginning. They are also far simpler computationally, since we only need to deal with fewer variables. For example, if a player has 4 information sets with 2 actions each, a mixed strategy would require  $2^4 - 1$  variables whereas a behavioral strategy requires only 4.

It turns out that behavioral strategies and mixed strategies have incomparable power, as the following two examples demonstrate.

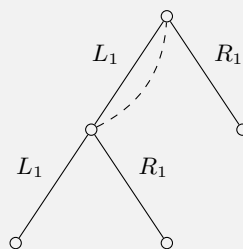
**Example 14** (There exist mixed strategies without equivalent behavioral strategies). Consider the following game tree with a single player.



Observe that there does not exist any behavioral strategy  $b$  for the player such that  $p(b; L_1 R_2) = p(b; R_1 L_2) = 0$ . Indeed, this would require  $b_1(L_2) = b_1(R_2) = 0$ .

On the other hand, there does exist a mixed strategy  $\sigma$  that sets  $\sigma(L_1 R_2) = \sigma(R_1 L_2) = 0$ . This is easily seen on realizing that  $S_1 = \{L_1, L_2\} \times \{R_1, R_2\}$ , so we have complete freedom in assigning probabilities to all four leaf nodes.

**Example 15** (There exist behavioral strategies without equivalent mixed strategies). Consider the following game tree with a single player.



Observe that there exists no mixed strategy that goes to  $L_1 R_1$  with nonzero probability. Indeed, here,  $S_1 = \{L_1, R_1\}$ , so the path  $L_1 R_1$  is not even an option.

On the other hand, the behavioral strategy that picks  $L_1$  or  $R_1$  with equal probability  $1/2$  does go to  $L_1 R_1$  with probability  $1/4$ .

In the first example above, the player remembers that they made a move but does not remember which move they made. In the second, the player does not remember that they made a move.

So, when exactly does a behavioral strategy not have an equivalent mixed strategy?

**Lemma 3.3.** If there exists a path from the root to some vertex  $x$  that passes through the same information set twice, and if the action leading to  $x$  is not the same at each of these vertices, then the player of the information set has a behavioral strategy that has no equivalent strategy.

**Theorem 3.4.** Consider an IIEFG such that every vertex has at least two actions. Every behavioral strategy has an equivalent mixed strategy iff each information set of a player intersects every path emanating from the root at most once.

When does a mixed strategy not have an equivalent mixed strategy?

We need to figure out some way of formalizing the forgetfulness in Example 14.

Let  $X = (x_0, x_1, \dots, x_K)$  and  $\hat{X} = (x_0, \hat{x}_1, \dots, \hat{x}_L)$  be two paths in the game tree and  $I_i^j$  an information set of player  $i$  that intersects the two paths are precisely one vertex, say  $x_k$  and  $\hat{x}_\ell$  respectively where  $k < K$ ,  $\ell < L$ . Then, the two paths choose the same action at  $I_i^j$  if the two actions at these vertices are identical, that is,

$$a_i(x_k \rightarrow x_{k+1}) = a_i(\hat{x}_\ell \rightarrow \hat{x}_{\ell+1}).$$

In general, we also consider  $a_i(x \rightarrow y)$  (where  $y$  is a descendant but not necessarily a child of  $x$ ), defined by the action  $a_i(x \rightarrow x')$ , where  $x'$  is the child of  $x$  on the path from  $x$  to  $y$ .

Player  $i$  is said to have perfect recall if

1. any path from the root to a leaf intersects an information set of player  $i$  at most once, and
2. any two paths that end in the same information set of player  $i$  pass through the same information sets of  $i$  in the same order, and in every such information set, the two paths choose the same action.

Let us state this more formally.

**Definition 3.8** (Perfect recall). Player  $i$  is said to have *perfect recall* if for every  $I_i^j$  and pair of vertices  $x, \hat{x} \in I_i^j$ , if the decision vertices of  $i$  are  $x_i^1, x_i^2, \dots, x_i^L = x$  and  $\hat{x}_i^1, \hat{x}_i^2, \dots, \hat{x}_i^L = \hat{x}$  respectively for the two paths from the root to  $x$  and  $\hat{x}$ , then

1.  $L = \hat{L}$ ,
2. for any  $1 \leq \ell \leq L$ ,  $x_i^\ell, \hat{x}_i^\ell \in I_i^k$  for some  $k$ , and
3. for any  $1 \leq \ell \leq L$ ,  $a_i(x_i^\ell \rightarrow x_i^{\ell+1}) = a_i(\hat{x}_i^\ell \rightarrow \hat{x}_i^{\ell+1})$ .

A game is said to be of perfect recall if every player has perfect recall.

Why is the game in Example 14 not of perfect recall?

Observe that perfect recall subsumes the condition in Theorem 3.4.

This effectively says that “every player remembers their choices, as well as whatever they remembered in the past”.

Let us look at some consequences of perfect recall.

Given a node  $x$ , let  $S_i^*(x)$  be the set of pure strategies of player  $i$  at which he chooses the actions leading to  $x$ . This is the intersections of members of  $S_i$  with the paths from the root to  $x$ .

**Theorem 3.5.** If  $i$  is a player with perfect recall and  $x, \hat{x}$  are two vertices in the same information set of  $i$ , then  $S_i^*(x) = S_i^*(\hat{x})$ .

The above conclusion follows because the same information sets are seen and we take the same actions at these sets.

**Theorem 3.6** (Kuhn). In an IIEFG, if  $i$  is a player with perfect recall, then for any mixed strategy of  $i$ , there exists an equivalent behavioral strategy (and vice-versa).

The proof is constructive in nature, with the construction using perfect recall.

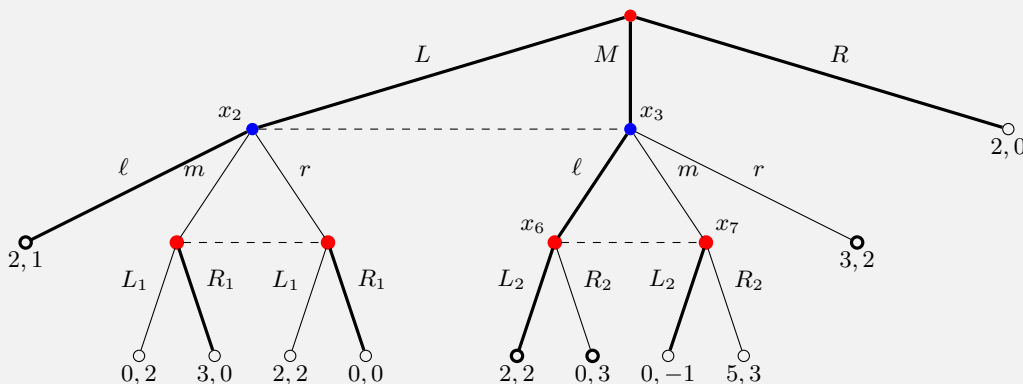
We remark that the converse of this theorem is *not* true, as seen in Example 15.

## 3.2.2. Bayesian equilibria

What are some notions of equilibria in IIEFGs? We could extend the subgame perfection in PIEFGs, but because the histories are uncertain, we are forced to use mixed strategies. Due to the information sets, a best response cannot be defined without the “belief” of each player.

Belief is a conditional probability distribution over the histories in an information set (where the conditioning is done over reaching the information set).

**Example 16.** Consider the following IIEFG, and the behavioral strategy described therein (by thick lines) – in the first round, player 1 plays  $L, M, R$  with probabilities  $5/12, 4/12, 3/12$  respectively.



Now, suppose that player 2 believes that they are at  $x_6, x_7$  with probabilities  $p, 1 - p$  respectively. If it is at  $x_6$ , it makes sense to choose  $L_2$ , and if at  $x_7$ , it makes sense to choose  $R_2$ . So, if the belief was  $> 2/7$  ( $1 - p > 2/7$ ), then the player chooses  $R_2$ . Such an action that maximizes expected utility at each information set is called *sequential rationality*.

Is the behavioral strategy described an equilibrium? Let us check this in the recursive method we did for usual SPNEs.

First of all, as mentioned, we require  $p \geq 5/7$ .

On the left subtree, the choice of  $R_1$  is vacuously rational because we can never reach that subtree.

Now, let the belief of player 2 for the nodes  $x_2, x_3$  be  $q, 1 - q$  respectively. If it plays  $\ell$ , it gets a utility of 1 with probability  $q$  and 2 with probability  $1 - q$ . If it chose  $m$  instead, it would get 0 with probability  $q$  and  $-1$  with probability  $1 - q$ . Finally, if it chose  $r$ , it would get 0 with probability  $q$  and 2 with probability  $1 - q$ . It is seen that the expected utility for the choice of  $\ell$  is always highest. In general, we need to compare it to the expected utilities for other choices. In this case, by nature of the behavioral strategy, the belief corresponds to  $q = 5/9$ .

Therefore, this behavioral strategy is indeed an equilibrium.

This is not a unique equilibrium however. As an exercise, check whether  $(MR_1R_2, m)$  is an equilibrium.

**Definition 3.9.** Let the information sets of player  $i$  be  $I_i = \{I_i^k\}_{k=1}^{k(i)}$ . The *belief* of player  $i$  is a probability distribution  $\mu_i^j$  over  $I_i^j$ .

A belief  $\mu_i = \{\mu_i^j\}_{j=1}^{k(i)}$  of player  $i$  is said to be a *Bayesian belief* wrt the behavioral strategy  $\sigma$  if it is derived from  $\sigma$  using Bayes' rule. That is, for each  $I_i^j$  such that there exists some  $y \in I_i^j$  with  $P_\sigma(y) \neq 0$ ,

$$\mu_i^j(x) = \frac{P_\sigma(x)}{\sum_{y \in I_i^j} P_\sigma(y)}$$

for all  $x \in I_i^j$  and  $j = 1, 2, \dots, k(i)$ .

A strategy  $\sigma_i$  of player  $i$  at information set  $I_i^j$  is said to be *sequentially rational* given  $\sigma_{-i}$  and partial beliefs  $\mu_i^j$  if

$$\sum_{x \in I_i^j} \mu_i^j(x) u_i(\sigma_i, \sigma_{-i} \mid x) \geq \sum_{x \in I_i^j} \mu_i^j(x) u_i(\sigma'_i, \sigma_{-i} \mid x).$$

for all actions  $\sigma'_i$  at  $I_i^j$ .

The tuple  $(\sigma, \mu)$  is sequentially rational if it is sequentially rational for every player at every information set. Such a tuple  $(t, \mu)$  is also called an *assessment*.

Sequential rationality is a refinement of Nash equilibria.

**Proposition 3.7.** In a PIEFG, a behavioral strategy profile  $\sigma$  is an SPNE iff the tuple  $(\sigma, \hat{\mu})$  is sequentially rational.

Above,  $\hat{\mu}$  assigns a degenerate distribution to every node.

**Definition 3.10.** An assessment  $(\sigma, \mu)$  is a *perfect Bayesian equilibrium* (PBE) if for every player  $i \in N$ ,

1.  $\mu_i$  is Bayesian with respect to  $\sigma$ , and
2.  $\sigma_i$  is sequentially rational given  $\sigma_{-i}$  and  $\mu_i$ .

Note that the belief  $\mu_i$  is allowed to be arbitrary on information sets that are never reached. This is often represented with only  $\sigma$ , because  $\mu$  is obtained from  $\sigma$ .

### 3.2.3. Example: peer-to-peer file sharing

In traditional file sharing models, download rate rapidly tapers off as the number of users increases. In peer-to-peer (P2P) models however, the download rate does not change significantly with an increase in users.

P2P models are very scalable and resilient to failures.

1. A *protocol* is the messages that can be sent and the actions that can be taken over the network.
2. A *client* is a particular process for sending messages and taking actions.
3. A *reference client* is a specific implementation of a client.
4. The *peers* are the ones using the protocol, and are the players in the game theoretic version of this problem which we shall discuss.

One of the earliest P2P systems, *Napster*, had a centralized database using which users could download music from one another.

Later, *Gnutella* became more popular. Each peer  $A$  can get a list of IP addresses of peers from a set of known peers (there is no server). To get a file, it broadcasts a query message to known peers, and the query response is sent by a peer  $B$  who has the desired file (this response is routed back to the original requester). Finally,  $A$  directly downloads the file from  $B$ .

Now, in Gnutella, each player can choose to either share, or “free ride” and gain the benefits of downloading without sharing anything. A corresponding game matrix looks something like

	Share	Free
Share	2, 2	-1, 3
Free	3, -1	0, 0

This is very similar to the [neighbouring kingdoms dilemma](#) we have seen. The issue with Gnutella is that it does not take these strategic thoughts into consideration. It does in fact turn out [[AH00](#)] that very few of the peers actually share anything.

In 2005, 85% (!) of the peers were free-riding. By 2013, Gnutella comprised less than 1% of worldwide P2P traffic. Many other P2P systems met the same fate.

We shall look at *BitTorrent*, which now comprises about 85% of P2P traffic in USA. It is used for both file sharing and software distribution (like Linux).

The key innovation is that it breaks files into pieces, and views it as a *repeated* game, with each piece shared separately.

1. First, the user goes to a searchable directory to find a link to a .torrent file corresponding to the desired content.
2. The .torrent file contains metadata about the content, in particular tracker URLs.
3. The tracker provides a list of peers participating in the swarm for the content (that is, their IP address and port).
4. The users BitTorrent client can now contact all these peers to download content.

The tracker is a centralized entity that controls traffic, tracks connection between peers and their speed of upload, download etc.

BitTorrent's algorithm is referred to as the *optimistic unchoking* algorithm. The reference client does as follows.

1. It sets a threshold  $r$  of upload speed.
2. If a peer  $j$  uploaded to  $i$  at a rate  $\geq r$ , unchoke  $j$  in the next period.
3. If a peer  $j$  uploaded to  $i$  at a rate  $< r$ , choke  $j$  in the next period.
4. Some peers who have just appeared may end up being choked because of this because they have not uploaded anything yet. So, every three time periods, optimistically unchoke a random peer from the neighbourhood who is currently choked, and leave them unchoked for three time periods.

This is forcing a repeated game by fragmenting files. The "leecher-seeder" (downloader-uploader) game is a repeated version of the neighbouring kingdoms dilemma, and the strategy of the seeder is just tit-for-tat – it cooperates as long as the leecher does as well.

The reader may find a simulation of the algorithm [here](#).

There are various implementation-related questions and things to consider.

- How often should one contact the tracker?
- Which fragments of the file should be revealed?
- How many upload slots and which peers should be unchoked and at what speed?
- What data should others be allowed to download?
- Possible goals might be to minimize upload speed, maximize download speed, or perhaps some sort of balance.

There are numerous attacks on BitTorrent as well, such as

- BitThief [[LMSW09](#)]. The goal is to download files without uploading. It asks for peers from the tracker very frequently to grow its neighbourhood rapidly. It exploits optimistic unchoking, so never needs to upload. This can be fixed by modifying the tracker to block the IP address.
- Strategic Piece Revealer [[LLSB08](#)]. The reference client tells neighbours about new pieces, and requests the "rarest" piece first. It then tries to set up a monopoly while keeping others interested. Because we have established a monopoly over rare pieces, we can get any piece we desire.



## §4. Bayesian Games

Thus far, we have only discussed non-cooperative games with complete information, where players only aim to maximize their own utilities (as opposed to cooperative games where players form coalitions and utilities are defined over coalitions, and incomplete information games where players do not deterministically know what game they are playing). There are various other types of games, such as repeated games, stochastic games etc.

We shall not discuss cooperative games in this course, but we shall now discuss incomplete information games. In such games, players receive private signals, known as *types*. We shall focus specifically on Bayesian games [Har67].

**Example 17.** Suppose we have a soccer game with two competing teams. Each can choose a game plan, where they either aim to win, or to draw. These two plans are the two possible types, which are private signals caused by external factors such as possibly weather, player injuries etc.

There are four possible type profiles in this example, WW, WD, DW, DD. Given this, we get four possible game matrices (DW is just the opposite of WD).

WW	Attack	Defend	WD	Attack	Defend	WW	Attack	Defend
Attack	1, 1	2, 0	Attack	2, 0	2, 1	Attack	0, 0	1, 0
Defend	0, 2	0, 0	Defend	0, 1	1, 0	Defend	0, 1	-1, -1

The probabilities of choosing each of the four profiles come from a common prior distribution, which is common knowledge.

**Definition 4.1.** A Bayesian game is represented by  $\langle N, (\theta_i)_{i \in N}, P, (\Gamma_\theta)_{\theta \in \times_{i \in N} \Theta_i} \rangle$ , where

1.  $N$  is the set of players,
2.  $\Theta_i$  is the set of types of player  $i$ ,
3.  $P$  is the common prior distribution over  $\Theta := \times_{i \in N} \Theta_i$ , with the restriction that

$$\sum_{\theta_{-i} \in \Theta_{-i}} P(\theta_i, \theta_{-i}) > 0$$

for all  $\theta_i \in \Theta_i$  for all  $i \in N$ . That is, the marginals for every type is positive (because otherwise we can eliminate  $\theta_i$  and prune the type set), and

4.  $\Gamma_\theta$  is an NFG  $\langle N, (A_i(\theta))_{i \in N}, (u_i(\theta))_{i \in N} \rangle$  for the type profile  $\theta \in \Theta$ . We typically assume that  $A_i(\theta) = A_i$  for all  $\theta$ , and set  $A := \times_{i \in N} A_i$ . As a result,  $u$  is a function  $A \times \Theta \rightarrow \mathbb{R}$ .

A Bayesian game is played as follows.

1. First, a profile  $\theta$  is randomly drawn according to  $P$ .
2. Each player observes (only) their own type  $\theta_i$ .
3. Player  $i$  picks an action  $a_i \in A_i$  for all  $i \in N$ .
4. Player  $i$  gets payoff  $u_i(a_i, a_{-i}; \theta)$ .

Now, let us look at strategies in Bayesian games.

**Definition 4.2.** A (pure) strategy in a Bayesian game is a map  $s_i : \Theta_i \rightarrow A_i$  for each  $i$ .

Similarly, a mixed strategy is a map  $\sigma_i : \Theta_i \rightarrow \Delta A_i$ .

**Definition 4.3.**

1. Let  $\sigma$  be a mixed strategy profile of a Bayesian game. The *ex-ante* utility of  $\sigma$  is the expected utility before observing one's own type. It is given by

$$u_i(\sigma) = \sum_{\theta \in \Theta} P(\theta) u_i(\sigma(\theta); \theta).$$

2. After observing the type  $\theta_i$ , we can reevaluate the probabilities of the other players' profiles as

$$P(\theta_{-i} \mid \theta_i) = \frac{P(\theta_i, \theta_{-i})}{\sum_{\tilde{\theta}_{-i} \in \Theta_{-i}} P(\theta_i, \tilde{\theta}_{-i})}.$$

The *ex-interim* utility is the expected utility after observing one's own type  $\theta_i$  is

$$u_i(\sigma \mid \theta_i) = \sum_{\theta_{-i} \in \Theta_{-i}} P(\theta_{-i} \mid \theta_i) u_i(\sigma(\theta); \theta).$$

More explicitly, we have

$$u_i(\sigma) = \sum_{\substack{\theta \in \Theta \\ (a_1, \dots, a_n) \in A}} P(\theta) \left( \prod_{j \in N} \sigma_j(\theta_j)(a_j) \right) u_i(a_1, \dots, a_n; \theta_1, \dots, \theta_n).$$

Observe that when the types are independent, both utilities are the same.

Bayes' rule immediately yields that

$$u_i(\sigma) = \sum_{\theta_i \in \Theta_i} P(\theta_i) u_i(\sigma \mid \theta_i).$$

**Example 18.** Suppose we have a buyer and a seller trying to buy/sell an item. Let their type sets be  $\Theta_1 = \Theta_2 = [100]$  and action sets  $A_1 = A_2 = [100]$ .

If the bid of the seller is less than or equal to that of the buyer, the trade goes through at the average of the two bids. Otherwise, the trade does not happen.

Suppose that type generation occurs independently and uniformly over  $\Theta_1, \Theta_2$ . Then, for all  $\theta_1, \theta_2$ ,

$$P(\theta_2 \mid \theta_1) = P(\theta_1 \mid \theta_2) = \frac{1}{100}.$$

We also have

$$u_1(a_1, a_2; \theta_1, \theta_2) = \begin{cases} \frac{a_1 + a_2}{2} - \theta_1, & a_2 \geq a_1 \\ 0, & \text{otherwise} \end{cases}$$

and

$$u_2(a_1, a_2; \theta_1, \theta_2) = \begin{cases} \theta_2 - \frac{a_1 + a_2}{2} & a_1 \geq a_2 \\ 0, & \text{otherwise.} \end{cases}$$

**Example 19** (Sealed bid auctions I: first price auctions). Suppose we have two players, both willing to buy an object. Their values  $\theta_i$  and bids  $b_i$  lie in  $[0, 1]$ . The allocation functions that indicate the winner are

$$o_1(b_1, b_2) = \mathbb{1}_{b_1 \geq b_2} = \begin{cases} 1, & b_1 \geq b_2, \\ 0, & \text{otherwise} \end{cases} \text{ and } o_2(b_1, b_2) = 1 - o_1(b_1, b_2).$$

Again, suppose that the prior distribution is uniform over  $[0, 1]^2$ . Then,

$$u_i(b_1, b_2; \theta_1, \theta_2) = o_i(b_1, b_2)(\theta_i - b_i).$$

Such a game where we pay the bid in the beginning is called a *first price auction*.

#### 4.1. Equilibria

As discussed, there are two stages to the game, ex-ante before observing the type, and ex-interim after observing the type.

Of course, we have a Nash equilibrium in the ex-ante stage, where  $\sigma^*$  is an equilibrium if

$$u_i(\sigma_i^*, \sigma_{-i}^*) \geq u_i(\sigma_i', \sigma_{-i}^*)$$

for all  $\sigma_i', i \in N$ .

In the ex-interim stage, we have the *Bayesian equilibrium*:

$$u_i(\sigma_i^*(\theta_i), \sigma_{-i}^* | \theta_i) \geq u_i(\sigma_i'(\theta_i), \sigma_{-i}^* | \theta_i)$$

for all  $\sigma_i', \theta_i \in \Theta_i, i \in N$ .

For exactly the same reason as in Theorem 2.7, it suffices to check the right-hand-side for pure strategies  $a_i$ .

**Theorem 4.1.** In finite Bayesian games, a strategy profile is a Bayesian equilibrium iff it is a Nash equilibrium.

*Proof.*

$\Rightarrow$  Suppose that  $(\sigma^*, P)$  is a Bayesian equilibrium. Then,

$$\begin{aligned} u_i(\sigma_i', \sigma_{-i}^*) &= \sum_{\theta_i \in \Theta_i} P(\theta_i) u_i(\sigma_i'(\theta_i), \sigma_{-i}^* | \theta_i) \\ &\leq \sum_{\theta_i \in \Theta_i} P(\theta_i) u_i(\sigma_i^*(\theta_i), \sigma_{-i}^* | \theta_i) = u_i(\sigma_i^*, \sigma_{-i}^*). \end{aligned}$$

$\Leftarrow$  Suppose instead that  $(\sigma^*, P)$  is not a Bayesian equilibrium. That is, there exists some  $i \in N, \theta_i \in \Theta_i, a_i \in A_i$  such that

$$u_i(a_i, \sigma_{-i}^* | \theta_i) > u_i(\sigma_i^*(\theta_i), \sigma_{-i}^* | \theta_i).$$

Consider the strategy  $\hat{\sigma}_i$  defined by

- $\hat{\sigma}_i(\theta_i') = \sigma_i^*(\theta_i')$  for  $\theta_i' \in \Theta_i \setminus \{\theta_i\}$ ,
- $\hat{\sigma}_i(\theta_i)(a_i) = 1$ , and
- $\hat{\sigma}_i(\theta_i)(b_i) = 0$  for  $b_i \in A_i \setminus \{a_i\}$ .

Then,

$$\begin{aligned}
 u_i(\hat{\sigma}_i, \sigma_{-i}^*) &= \sum_{\tilde{\theta}_i \in \Theta_i} P(\tilde{\theta}_i) u_i(\hat{\sigma}_i(\tilde{\theta}_i), \sigma_{-i}^* \mid \tilde{\theta}_i) \\
 &= \sum_{\tilde{\theta}_i \in \Theta_i \setminus \{\theta_i\}} P(\tilde{\theta}_i) u_i(\hat{\sigma}_i(\tilde{\theta}_i), \sigma_{-i}^* \mid \tilde{\theta}_i) + P(\theta_i) u_i(\hat{\sigma}_i(\theta_i), \sigma_{-i}^* \mid \theta_i) \\
 &= \sum_{\tilde{\theta}_i \in \Theta_i \setminus \{\theta_i\}} P(\tilde{\theta}_i) u_i(\sigma_i^*(\tilde{\theta}_i), \sigma_{-i}^* \mid \tilde{\theta}_i) + P(\theta_i) u_i(a_i, \sigma_{-i}^* \mid \theta_i) \\
 &> \sum_{\tilde{\theta}_i \in \Theta_i \setminus \{\theta_i\}} P(\tilde{\theta}_i) u_i(\sigma_i^*(\tilde{\theta}_i), \sigma_{-i}^* \mid \tilde{\theta}_i) + P(\theta_i) u_i(\sigma_i^*(\theta_i), \sigma_{-i}^* \mid \theta_i) \\
 &= u_i(\sigma_i^*, \sigma_{-i}^*),
 \end{aligned}$$

a contradiction. ■

**Theorem 4.2.** Every finite Bayesian game has a Bayesian equilibrium.

A finite Bayesian game is one where the set of players, action set, and type set are finite.

The idea of the proof is that we transform the game to a complete information game treating each type as a player, then we invoke **Nash**.

**Example 20** (Sealed bid auctions II: equilibria in first price auctions). This is a continuation of Example 19. In that example, we looked at *first price auctions*. We claim that the pure strategy profile defined by  $b_1^* = \theta_1/2, b_2^* = \theta_2/2$  is a Bayesian equilibrium. For player 1, for a given  $\theta_1$ , the utility under a unilateral deviation of  $b_1$  is

$$\begin{aligned}
 u_1(b_1, b_2^* \mid \theta_1) &= \int_0^1 f(\theta_2 \mid \theta_1) (\theta_1 - b_1) \mathbb{1}_{b_1 \geq \theta_2/2} d\theta_2 \\
 &= (\theta_1 - b_1) \int_0^1 \mathbb{1}_{\theta_2 \leq 2b_1} d\theta_2. \quad (P \text{ is uniform})
 \end{aligned}$$

If  $b_1 \leq 1/2$ , this is equal to  $(\theta_1 - b_1)2b_1$ , which is maximized for  $b_1 = b_1^* = \theta_1/2$  as desired. When  $b_1 > 1/2$ , this is equal to  $(\theta_1 - b_1) \leq (\theta_1 - 1/2) \leq \theta_1^2/2$ .

Therefore, the payoff is indeed maximized for  $b_1 = b_1^* = \theta_1/2$ . Unilateral deviation for player 2 is similar, and the profile is a Bayesian equilibrium as claimed.

**Example 21** (Sealed bid auctions III: second price auctions). Next, let us look at *second price auctions*. The highest bidder wins as before, but the amount he pays is the second highest bid. Then,

$$u_1(b_1, b_2; \theta_1, \theta_2) = (\theta_1 - b_2) \mathbb{1}_{b_1 \geq b_2}$$

$$u_2(b_1, b_2; \theta_1, \theta_2) = (\theta_2 - b_1) \mathbb{1}_{b_1 < b_2}.$$

Here, we claim that  $b_1^* = \theta_1, b_2^* = \theta_2$  is a Bayesian equilibrium.

Similar to earlier, player 1's payoff under unilateral deviation is

$$\int_0^1 (\theta_1 - \theta_2) \mathbb{1}_{b_1 \geq \theta_2} d\theta_2 = \left( b_1 \theta_1 - \frac{\theta_1^2}{2} \right).$$

This is maximized when  $b_1 = b_1^* = \theta_1$ . Unilateral deviation for player 2 is similar.

It turns out that even in the situation where the distributions of  $\theta_1, \theta_2$  are arbitrary but still independent,  $b_1^* = \theta_1, b_2^* = \theta_2$  is a Bayesian equilibrium. Indeed, for unilateral deviation of player 1,

$$\int_0^{b_1} f(\theta_2)(\theta_1 - \theta_2) d\theta_2 = \theta_1 F(b_1) - \int_0^{b_1} \theta_2 f(\theta_2) d\theta_2.$$

Differentiating with respect to  $b_1$  and setting the derivative to 0 to maximize it, we get

$$\theta_1 f(b_1) - b_1 f(b_1) = 0,$$

so the payoff is maximum when  $b_1 = b_1^* = \theta_1$  (assuming the density is positive everywhere).

For any independent positive prior, bidding the true type is a Bayesian equilibrium of the induced Bayesian game in second price auctions.

## §5. Social Choice

### 5.1. Introduction

Mechanism design is something of an inverse of game theory, given the desired objects/outcomes, our task is to set the rules of the game.

Some common examples of this are elections, resource allocation, matching students to universities, etc.

Let  $N$  be a set of players,  $X$  a set of outcomes, and  $\Theta_i$  a set of private information of each agent  $i$ . Each element  $\theta_i \in \Theta_i$  is called a *type*.

The type manifests in the preferences over the outcomes. We shall look at two ways this can happen.

1. *Ordinal*:  $\theta_i$  defines an ordering over the outcomes, which describes a preference order. It does not describe how much something is preferred, however.
2. *Cardinal*: A utility function  $u_i$  maps an outcome/type pair to real numbers. In the *private value model*,  $u_i$  is a map  $X \times \Theta_i \rightarrow \mathbb{R}$ . In the *interdependent value model*,  $u_i$  is a map  $X \times \Theta \rightarrow \mathbb{R}$ .

**Example 22.** Let us look at the example of voting. Here,  $X$  is the set of candidates, and each  $\theta_i$  is a ranking over the candidates. For example,  $(a, b, c)$  means that the voter prefers  $a$  over  $b$  over  $c$ .

Another example is single object allocation. Each outcome is  $x = (a, p) \in X$ , where  $a = (a_1, \dots, a_n)$ , where each  $a_i \in \{0, 1\}$ , and at most one of the  $a_i$ s is 1 and  $p = (p_1, \dots, p_n)$ , where  $p_i$  is the payment charged to  $i$ .  $\theta_i$  is the amount  $i$  values the object. The utility is given by  $u_i(x, \theta_i) = a_i \theta_i - p_i$ .

Now, the designer has a certain objective, captured by a *social choice function* (SCF)  $f : \Theta_1 \times \dots \times \Theta_n \rightarrow X$ . For example, in voting, if there is a candidate who beats everyone else in pairwise contests, we would like him to be chosen as the winner. In public project choice, where  $\theta_i : X \rightarrow \mathbb{R}$  is the value of each project, we should pick  $f(\theta) = \arg \max_{x \in X} \sum_{i \in N} \theta_i(x)$ .

To create a game where  $f(\theta)$  emerges as the outcome as an equilibrium, we require mechanism design.

**Definition 5.1.** A(n indirect) mechanism is a collection of message spaces and a decision rule  $\langle M_1, \dots, M_n, g \rangle$ , where  $M_i$  is the message space of agent  $i$ , and  $g : M_1 \times \dots \times M_n \rightarrow X$ . A direct mechanism is the specific case where  $M_i = \Theta_i$  and  $g \equiv f$ .

We shall see soon that it suffices to look at direct mechanisms.

All subsequent definitions assume cardinal preferences, but they can be replaced with ordinal preferences quite simply.

**Definition 5.2.** In a mechanism  $\langle M_1, \dots, M_n, g \rangle$ , a message  $m_i$  is *weakly dominant* for player  $i$  at  $\theta_i$  if

$$u_i(g(m_i, \tilde{m}_{-i}), \theta_i) \geq u_i(g(m'_i, \tilde{m}_{-i}), \theta_i) \quad (5.1)$$

for all  $\tilde{m}_{-i}, m'_i$ .

**Definition 5.3** (Dominant strategy implementability). An SCF  $f : \Theta \rightarrow X$  is *implemented* in dominant strategies by  $\langle M_1, \dots, M_n, g \rangle$  if

1. there exists a message mapping  $s_i : \Theta_i \rightarrow M_i$  such that  $s_i(\theta_i)$  is a dominant strategy for agent  $i$  at  $\theta_i$ , and

2.  $g(s_1(\theta_1), \dots, s_n(\theta_n)) = f(\theta)$  for all  $\theta \in \Theta$ .

We say that SCF  $f$  is *dominant strategy implementable* (DSI) by  $\langle M_1, \dots, M_n, g \rangle$ .

**Definition 5.4** (Dominant strategy incentive compatibility). A direct mechanism  $\langle \Theta_1, \dots, \Theta_n, f \rangle$  is *dominant strategy incentive compatible* (DSIC) if

$$u_i(f(\theta_i, \tilde{\theta}_{-i}), \theta_i) \geq u_i(f(\theta'_i, \tilde{\theta}_{-i}), \theta_i) \quad (5.2)$$

for all  $\theta_i, \theta'_i, \tilde{\theta}_{-i}, i$ .

To determine if an SCF  $f$  is DSI, it seems that we must search over all possible indirect mechanisms.

**Theorem 5.1** (Revelation principle). If there exists an indirect mechanism that implements  $f$  in dominant strategies, then  $f$  is DSIC.

This means that we can focus on DSIC mechanisms without loss of generality.

*Proof.* Let  $f$  be implemented by  $\langle M_1, \dots, M_n, g \rangle$ , and fix  $s_i : \Theta_i \rightarrow M_i$  as in the definition. Set  $m'_i = s_i(\theta'_i)$ ,  $\tilde{m}_{-i} = s_{-i}(\tilde{\theta}_{-i})$  in Equation (5.1), to get

$$u_i(\underbrace{g(s_i(\theta_i), s_{-i}(\tilde{\theta}_{-i}))}_{f(\theta_i, \tilde{\theta}_{-i})}, \theta_i) \geq u_i(\underbrace{g(s_i(\theta'_i), s_{-i}(\tilde{\theta}_{-i}))}_{f(\theta'_i, \tilde{\theta}_{-i})}, \theta_i),$$

so  $f$  is DSIC. ■

Now, let us look at a Bayesian extension, where agents may have probabilistic information about others' types. Recall **bayesian games**.

**Definition 5.5** (Bayesian implementability). A(n indirect) mechanism  $\langle M_1, \dots, M_n, g \rangle$  implements an SCF  $f$  in *Bayesian equilibrium* if

1. there exists a message mapping profile  $(s_1, \dots, s_n)$  such that  $s_i(\theta_i)$  maximizes the ex-interim utility of agent  $i$ , that is,

$$\mathbb{E}_{\theta_i} [u_i(g(s_i(\theta_i), s_{-i}(\theta_{-i})), \theta_i) \mid \theta_i] \geq \mathbb{E}_{\theta_i} [u_i(g(m'_i, s_{-i}(\theta_{-i})), \theta_i) \mid \theta_i]$$

for all  $m'_i, \theta_i, i \in N$ , and

2.  $g(s_i(\theta_i), s_{-i}(\theta_{-i})) = f(\theta_i, \theta_{-i})$  for all  $i \in N$ .

We say that  $f$  is Bayesian implementable via  $\langle M_1, \dots, M_n, g \rangle$  under the prior  $P$ .

**Proposition 5.2.** If an SCF  $f$  is dominant strategy implementable, it is Bayesian implementable.

Similar to **dominant strategy incentive compatibility**, we have the following.

**Definition 5.6** (Bayesian incentive compatibility). A direct mechanism  $\langle \Theta_1, \dots, \Theta_n, f \rangle$  is *Bayesian incentive compatible* (BIC) if

$$\mathbb{E}_{\theta_{-i}} \left[ u_i(f(\theta_i, \tilde{\theta}_{-i}), \theta_i) \mid \theta_i \right] \geq \mathbb{E}_{\theta_{-i}} \left[ u_i(f(\theta'_i, \tilde{\theta}_{-i}), \theta_i) \mid \theta_i \right]. \quad (5.3)$$

for all  $\theta_i, \theta'_i, \tilde{\theta}_{-i}, i$ .

**Theorem 5.3** (Revelation principle II). If an SCF  $f$  is implementable in Bayesian equilibrium, it is BIC.

The proof is near-identical to that of the first revelation principle.

## 5.2. Arrow's Impossibility Theorem

Consider the setting where we have finite sets  $A = \{a_1, \dots, a_m\}$  of alternatives and  $N = \{1, \dots, n\}$  of players. Each player has a preference order  $R_i$  over  $A$  (a binary relation over  $A$ ) such that

1. Completeness: for every  $a, b \in A$ ,  $aR_i b$  or  $bR_i a$  or both,
2. Reflexivity: for all  $a \in A$ ,  $aR_i a$ , and
3. Transitivity: for  $a, b, c \in A$ , if  $aR_i b$  and  $bR_i c$ , then  $aR_i c$

The set of all such preference orders is denote  $\mathcal{R}$ . An ordering is linear if for  $a, b \in A$ , if  $aR_i b$  and  $bR_i a$ , then  $a = b$ . The set of all such linear orderings is denoted  $\mathcal{P}$ .

Given any ordering  $R_i$ , we can decompose it into an *asymmetric part*  $P_i$  and *symmetric part*  $I_i$ .

**Definition 5.7** (Arrovian Social Welfare Function). An Arrovian Social Welfare Function (ASWF) is a function  $F : \mathcal{R}^n \rightarrow \mathcal{R}$ .

That is, given the preference orders of multiple people, we try to consolidate them into a single preference order. Let  $\hat{F}(R)$  and  $\bar{F}(R)$  be the asymmetric and symmetric parts of  $F(R)$  respectively.

**Definition 5.8** (Pareto). An ASWF  $F$  is said to be *weak Pareto* if for  $a, b \in A$ , if  $aP_i b$  for all  $i \in N$ , then  $a\hat{F}(R)b$  for all  $i \in N$ .

An ASWF  $F$  is said to be *strong Pareto* if for  $a, b \in A$ , if  $aR_i b$  for all  $i \in N$  and for some  $j$ ,  $aP_j b$ , then  $a\hat{F}(R)b$ .

It is not too difficult to see that strong Pareto ASWFs are weak Pareto.

We say that  $R_i, R'_i \in \mathcal{R}$  agree on  $\{a, b\}$  if for agent  $i$ ,  $aP_i b$  iff  $aP'_i b$ ,  $bP_i a$  iff  $bP'_i a$ , and  $aI_i b$  iff  $aI'_i b$ . We use the shorthand  $R_i|_{a,b} = R'_i|_{a,b}$  to denote this. If it holds for every agent  $i$ , we write  $R|_{a,b} = R'|_{a,b}$ .

**Definition 5.9** (Independence of irrelevant alternatives). An ASFW  $F$  is said to satisfy *independence of irrelevant alternatives* (IIA) if for all  $a, b \in A$ , if  $R|_{a,b} = R'|_{a,b}$ , then  $F(R)|_{a,b} = F(R')|_{a,b}$ .



That is, if everyone prefers one option to another, then the final preference order also prefers this option to the other. Note that the dictatorship ASWF, defined by  $F(R) = R_i$  for some fixed  $i$ , is both weak Pareto and IIA.

**Theorem 5.4 (Arrow).** For  $|A| \geq 3$ , if an ASWF  $F$  is weak Pareto and IIA, then it is a dictator.

Over the rest of this section, we prove the above.  
First, we need some notions of “decisiveness”.

**Definition 5.10.** Let  $F : \mathcal{R}^n \rightarrow \mathcal{R}$  be given, and let  $G \subseteq N$  be non-empty.

$G$  is said to be *almost decisive* over  $\{a, b\}$  if if  $aP_i b$  for all  $i \in G$  and  $bP_j a$  for all  $j \notin G$ , then  $a\hat{F}(R)b$ . This is denoted  $\overline{D}_G(a, b)$ .

$G$  is *decisive* over  $\{a, b\}$  if if  $aP_i b$  for all  $i \in G$ , then  $a\hat{F}(R)b$ . This is denoted  $D_G(a, b)$ .

If a group is (almost) decisive over all pairs of coordinates, we say that it is (almost) decisive.  
The proof goes in two parts.

1. Field expansion: If a group is almost decisive over a pair of alternatives, then it is decisive over all pairs of alternatives.
2. Group contraction: If a group is decisive, a strict subset of that group is also decisive.

**Lemma 5.5 (Field expansion).** Let  $F$  be WP and IIA. For all  $a \neq b$  and  $x \neq y$ , and  $G \subseteq N, G \neq \emptyset$ ,  $\overline{D}_G(a, b)$  implies  $D_G(x, y)$ .

*Proof.* There are 6 cases to consider.

1. Case 1.  $x = a$  and  $y \neq a, b$ . Pick arbitrary  $R \in \mathcal{R}^n$  such that  $aP_i y$  for all  $i \in G$ . We wish to show that  $a\hat{F}(R)y$ . Construct another preference  $R'$  as follows. For  $i \in G$ , we have  $aP'_i b$  and  $bP'_i y$ , and on  $N \setminus G$ ,  $bP'_i a$  and  $bP'_i y$ , and between  $a, y$  we retain the same ordering as in  $R_i$ . We ensure that  $R'_i|_{a,y} = R_i|_{a,y}$  for all  $i \in N$ .  $\overline{D}_G(a, b)$  implies that  $a\hat{F}(R')b$ . Weak Pareto over  $b, y$  implies that  $b\hat{F}(R')y$ . So, by transitivity,  $a\hat{F}(R')y$ . Now, use IIA to conclude that  $a\hat{F}(R)y$  as well, completing the proof.
2. Case 2.  $y = b$  and  $x \neq a, b$ . The idea for this is nearly identical to that in case 1.  $R'$  is constructed such that for  $i \in G$ ,  $xP'_i a$  and  $aP'_i b$ , and on  $N \setminus G$ ,  $xP'_i a$  and  $bP'_i a$ , and the ordering of  $a, b$  is the same as that in  $R$ .
3. Case 3.  $x \neq a, b$  and  $y \neq a, b$ . We have  $\overline{D}_G(a, b)$ , so  $D_G(a, y)$  by case 1, so  $\overline{D}_G(a, y)$  by definition, so  $D_G(x, y)$  by case 2.
4. Case 4.  $x \neq a, b$  and  $y = a$ . We have  $\overline{D}_G(a, b)$ , so  $D_G(x, b)$  by case 2, so  $\overline{D}_G(x, b)$  by definition, so  $D_G(x, a)$  by case 1.
5. Case 5.  $x = b$  and  $y \neq a, b$ . We have  $\overline{D}_G(a, b)$ , so  $D_G(a, y)$  by case 1, so  $\overline{D}_G(a, y)$  by definition, so  $D_G(b, y)$  by case 2.
6. Case 6.  $x = a$  and  $y = b$ . This is trivial.
7. Case 7.  $x = b$  and  $y = a$ . This similarly follows from previous parts.

**Lemma 5.6 (Group contraction).** Let  $F$  be WP and IIA. Let  $G \subseteq N$  with  $|G| \geq 2$  be decisive. Then, there exists non-empty  $G' \subsetneq G$  which is decisive. ■

*Proof.* Let  $G_1 \subsetneq G$  and  $G_2 = G \setminus G_1$ . Let  $a, b, c \in R$ . Consider an ASWF  $R$  which orders  $aP_ibP_ic$  for  $i \in G_1$ ,  $cP_iaP_ib$  for  $i \in G_2$ , and  $bP_icP_ia$  for  $i \in N \setminus G$ . Because  $aP_ib$  for all  $i \in G$  and  $G$  is decisive,  $a\hat{F}(R)b$ .

1. Case 1.  $a\hat{F}(R)c$ . Observe that  $aP_ic$  for all  $i \in G_1$  and  $cP_ia$  for  $i \notin G_1$ . Consider all  $R'$  where this condition holds. By IIA,  $a\hat{F}(R')c$ . Therefore,  $G_1$  is almost decisive over  $\{a, c\}$ . Therefore, by field expansion  $G_1$  is decisive.
2. Case 2.  $c\hat{F}(R)a$ . Recalling that  $a\hat{F}(R)b$ , we have  $c\hat{F}(R)b$ . Observe that  $cP_ib$  for all  $i \in G_2$  and  $bP_ic$  for  $i \notin G_2$ . Considering all  $R'$  where this condition holds again, we get by IIA that  $b\hat{F}(R')c$ , so  $G_2$  is almost decisive over  $\{b, c\}$  and by field expansion,  $G_2$  is decisive. ■

To complete the proof of **Arrow**, note that  $N$  is decisive, so by Lemma 5.6, there is a singleton decisive set and  $F$  is a dictator.

### 5.3. Social Choice

This means the Arrovian social welfare set up is too demanding. It says that achieving a social ordering in a democratic way is impossible. There are two suggestions to mitigate this:

1. consider a social choice setting, where we output an alternative instead of an ordering.
2. put restrictions on the agents' preferences.

**Definition 5.11.** A *social choice function* is a function  $f : \mathcal{P}^n \rightarrow A$ .

Note that we assume strict preferences.

Over the next few examples, we shall look at various voting rules

#### Example 23 (Voting).

1. Scoring rule. Let  $s = (s_1, \dots, s_m)$  be some common score vector. Each voter's  $k$ th preferred alternative is given a score of  $s_k$ . The scores are summed over all candidates, and the candidate with the highest score wins. There are various specific cases depending on  $s$ .
  - Plurality.  $s = (1, 0, 0, \dots, 0)$ .
  - Veto.  $s = (1, 1, \dots, 1, 0)$ .
  - Bonds.  $s = (m-1, m-2, \dots, 1, 0)$ .
  - Harmonic.  $s = (1, 1/2, \dots, 1/m)$ .
  - $k$ -approval.  $s = (1, \dots, 1, 0, \dots, 0)$  with exactly  $k$  1s.
2. Plurality with runoff. This has two phases: in the first, the top 2 highest scoring candidates are retained and everyone else eliminated, and in the second everyone is asked to vote again. This is practiced in the French presidential election.
3. Maximin. This chooses the candidate with the largest margin of victory wins.
4. Copeland. Here we view the set of orderings as a collection of votes for pairwise elections, and choose the candidate who wins the most pairwise elections.

A *Condorcet* winner is a candidate that beats every other candidate in a pairwise election. It is not guaranteed to exist.

A voting rule that returns a Condorcet winner, if it exists, as the winner, is called *Condorcet consistent*. Clearly, Copeland is Condorcet consistent. It turns out that *no* scoring rule is Condorcet consistent (!), even seemingly logical strategies such as plurality.

**Definition 5.12** (Pareto efficiency). An alternative  $a$  is *Pareto dominated* by  $b$  if for all  $i \in N$ ,  $bP_i a$ .  
An SCF  $f$  is *Pareto efficient* if for all preference profiles  $P$  and  $a \in A$ , if  $a$  is Pareto dominated, then  $f(P) \neq a$ .

**Definition 5.13** (Unanimity). An SCF  $f$  is *unanimous* if for a preference profile  $P$  with  $P_1(1) = P_2(1) = \dots = P_n(1) = a$  (where  $P_i(k)$  is the  $k$ th preferred alternative of agent  $i$ ),  $f(P) = a$ .

**Proposition 5.7.** The set of Pareto efficient SCFs is strictly contained in the set of unanimous SCFs.

Indeed, every alternative other than  $a$  is Pareto dominated by it. Further, this containment is strict, as can be seen by considering an SCF which picks a dominated alternative when not all the top alternatives are identical.

**Definition 5.14** (Onto). An SCF  $f$  is *onto* if for all  $a \in A$ , there exists  $P^* \in \mathcal{P}^n$  such that  $f(P^*) = a$ .

**Proposition 5.8.** The set of unanimous SCFs is contained in the set of onto SCFs.

Indeed,  $a$  is chosen by any preference profile which has  $a$  at the top spot everywhere.

**Definition 5.15** (Manipulability). An SCF  $f$  is *manipulable* if there exists  $i \in N$  and a profile  $P$  such that

$$f(P'_i, P_{-i})P_i f(P_i, P_{-i})$$

for some  $P'_i$ .

That is, by falsely reporting a preference, the agent can arrive at an outcome he prefers more.  
Non-manipulability means that on changing the preference you report, the outcome can only become worse.

**Example 24** (Manipulability). Consider a voting system with three candidates  $a, b, c$  (with ties broken in favour of  $a > b > c$ ).

First, suppose we are in the plurality setting, and the three voters have true preference orders  $abc, bac, cba$ . If the third voter reports  $cba$ , then the winner is  $a$ . If he reports  $bca$  on the other hand, the winner is  $b$ , who is preferred to  $a$ .

Next, suppose we are in the Copeland setting, and the three voters have true preference orders  $abc, bca, cab$ . If everyone reports their true preferences,  $a$  is the winner. If the second voter instead reports  $cba$ , then  $c$  becomes the Copeland winner.

**Definition 5.16** (Strategyproofness). An SCF is said to be *strategy-proof* (SP), *truthful*, or *incentive-compatible* if it is not manipulable by any agent at any profile.

Let us look at some implications of strategyproofness.

**Definition 5.17** (Dominated set). For  $a \in A$  and preference  $P_i$ , the *dominated set* of  $a$  at  $P_i$  is

$$D(a, P_i) = \{b \in A : aP_i b\}.$$

**Definition 5.18** (Monotonicity). An SCF  $f$  is *monotone* (MONO) if for any two profiles  $P, P'$  with  $f(P) = a$  and  $D(a, P_i) \subseteq D(a, P'_i)$  for all  $i \in N$ , then  $f(P') = a$ .

That is, the relative position of  $a$  has weakly improved from  $R$  to  $R'$ .

**Lemma 5.9.** An SCF is strategyproof if and only if it is monotone.

*Proof.* Let us look at the forward direction first. Let  $f$  be SP and  $P, P'$  be two profiles with  $f(P) = a$  and  $D(a, P_i) \subseteq D(a, P'_i)$  for all  $i \in N$ . For  $0 \leq k \leq n$ , let  $P^{(k)} = (P'_1, P'_2, \dots, P'_k, P_{k+1}, \dots, P_n)$  – note that  $P^{(0)} = P$  and  $P^{(n)} = P'$ . We shall show inductively that  $f(P^{(k)}) = a$  for each  $0 \leq k \leq n$ . The base case  $k = 0$  is trivial. Suppose that  $f(P^{(k-1)}) = a$  but  $f(P^{(k)}) = b \neq a$  for some  $k \geq 1$ . Now, note that it is not possible that  $bP_k a$  or  $aP'_k b$  as this would violate strategyproofness. This means that  $aP_k b$  and  $bP'_k a$ , but this contradicts  $D(a, P_k) \subseteq D(a, P'_k)$ , so we have a contradiction and are done.

Let us now look at the backward direction. Suppose instead that for some profile  $P, i \in N$ , and  $P'_i, f(P'_i, P_{-i})P_i f(P)$ . Set  $P' = (P'_i, P_{-i})$ ,  $f(P) = a, f(P') = b$ , so  $bP_i a$ . Construct a preference ordering  $P''_i$  with  $P''_i(1) = b$  and  $P''_i(2) = a$ , and let  $P'' = (P''_i, P_{-i})$ .

We clearly have  $D(a, P_j) \subseteq D(a, P''_j)$  for all  $j \in N$ . Monotonicity implies that  $f(P'') = f(P) = a$ . On the other hand,  $D(b, P'_j) \subseteq D(b, P''_j)$  for all  $j \in N$ , so by monotonicity  $f(P'') = f(P') = b$ , resulting in a contradiction. ■

We shall repeatedly see the above proof strategy.

**Lemma 5.10.** If an SCF is monotonic and onto, it is Pareto efficient.

*Proof.* Suppose instead that  $f$  is monotonic and onto, but not PE – let  $P$  be a preference profile and  $a, b \in A$  such that  $bP_i a$  for all  $i \in N$ , but  $f(P) = a$ .

Using ontoness, let  $P'$  be a profile with  $f(P') = b$ , and construct a profile  $P''$  with  $P''_i(1) = b$  and  $P''_i(2) = a$  for all  $i \in N$ . Clearly,  $D(b, P'_i) \subseteq D(b, P''_i)$ , so  $f(P'') = b$ . We also have  $D(a, P_i) \subseteq D(a, P''_i)$ , so  $f(P'') = a$ , yielding a contradiction. ■

**Corollary 5.11.** Let  $f$  be an SCF. The following are equivalent.

1.  $f$  is strategyproof and Pareto efficient.
2.  $f$  is strategyproof and unanimous.
3.  $f$  is strategyproof and onto.

It turns out that even the above requirement is too strict, however.

**Theorem 5.12** (Gibbard-Satterthwaite Theorem). Suppose  $|A| \geq 3$ .  $f$  is strategyproof and onto if and only if it is dictatorial.

The above is untrue when  $|A| = 2$  – plurality with some fixed tie-breaking rule is strategyproof, onto, and non-dictatorial. It may also break down if we place restrictions on the set of alternatives that a voter can report (we assume it to be  $\mathcal{P}$ ).

As long as all ordinal ranks are feasible in the cardinal preference setting, this has an extension to that setting.

The remainder of this section is dedicated to the proof of the Gibbard-Satterthwaite Theorem.

We shall only prove the result for  $n = 2$  (so  $N = \{1, 2\}$ ). It is possible to then apply induction on the number of agents to prove it for an arbitrary  $n$ , but we omit this part – interested readers may consult [Sen01] for more details.

**Claim.** For every preference profile  $P$ ,  $f(P) \in \{P_1(1), P_2(1)\}$ .

If  $P_1(1) = P_2(1)$ , unanimity implies that  $f(P)$  is this common value.

Suppose that  $P_1(1) = a \neq b = P_2(1)$ , and  $f(P) = c \neq a, b$ . Consider a profile  $P'_1$  with  $P'_1(1) = a, P'_1(2) = b$ , and a profile  $P'_2$  with  $P'_2(1) = b, P'_2(2) = a$ . Note that  $f(P_1, P'_2) \in \{a, b\}$ , because every other alternative is Pareto dominated and  $f$  is Pareto efficient. Further,  $f(P_1, P'_2) \neq b$  because this would mean that  $f$  is manipulable (by player 2). Therefore,  $f(P_1, P'_2) = a$ . Similarly, we get that  $f(P'_1, P_2) = b$ . Now, due to monotonicity (because  $f$  is strategyproof),  $D(a, P_1) \subseteq D(a, P'_1)$ , so  $f(P'_1, P'_2) = a$ , but similarly  $D(b, P_2) \subseteq D(b, P'_2)$  so  $f(P'_1, P'_2) = b$ , leading to a contradiction.  $\square$

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