Algorithmic Game Theory
Solution concepts in games

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Solution concepts

Choosing a strategy…

- Given a game, how should a player choose his strategy?
  - Recall: we assume each player knows the other players' preferences but not what the other players will choose

- The most fundamental question of game theory
  - Clearly, the answer is not always clear

- We will start with 2-player games

Prisoner's Dilemma: The Rational Outcome

- Let's revisit prisoner's dilemma

- Reasoning of pl. 1:
  - If pl. 2 does not confess, then I should confess
  - If pl. 2 confesses, then I should also confess

- Similarly for pl. 2

	C	D
C	3, 3	0, 4
D	4, 0	1, 1

- Expected outcome for rational players: they will both confess, and they will go to jail for 3 years each
  - Observation: If they had both chosen not to confess, they would go to jail only for 1 year, each of them would have a strictly better utility

Dominant strategies

- Ideally, we would like a strategy that would provide the best possible outcome, regardless of what other players choose

- <u>Definition</u>: A strategy s_i of pl. 1 is *dominant* if
$$u_1(s_i, t_j) \geq u_1(s', t_j)$$
for every strategy $s' \in S^1$ and every strategy $t_j \in S^2$

- Similarly for pl. 2, a strategy t_j is dominant if
$$u_2(s_i, t_j) \geq u_2(s_i, t')$$
for every strategy $t' \in S^2$ and for every strategy $s_i \in S^1$

Dominant strategies

Even better:

- <u>Definition</u>: A strategy s_i of pl. 1 is *strictly dominant* if
$$u_1(s_i, t_j) > u_1(s', t_j)$$
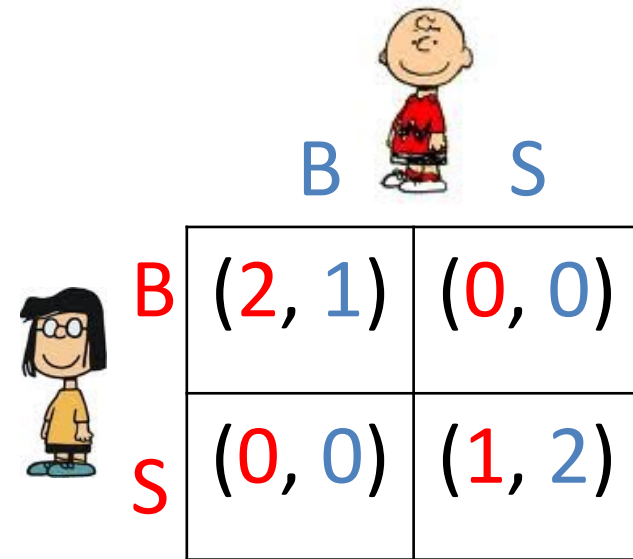for every strategy $s' \in S^1$ and every strategy $t_j \in S^2$

- Similarly for pl. 2

- In prisoner's dilemma, strategy D (confess) is strictly dominant

Observations:

- There may be more than one dominant strategies for a player, but then they should yield the same utility under all profiles

- Every player can have at most one strictly dominant strategy

- A strictly dominant strategy is also dominant

Existence of dominant strategies

- Few games possess dominant strategies

- It may be too much to ask for

- E.g. in the Bach-or-Stravinsky game, there is no dominant strategy:
  - Strategy B is not dominant for pl. 1:
    If pl. 2 chooses S, pl. 1 should choose S
  - Strategy S is also not dominant for pl. 1:
    If pl. 2 chooses B, pl. 1 should choose B

- In all the examples we have seen so far, only prisoner's dilemma possesses dominant strategies

	B	S
B	(2, 1)	(0, 0)
S	(0, 0)	(1, 2)

Back to choosing a strategy...

- Hence, the question of how to choose strategies still remains for the majority of games
- Model of rational choice: if a player knows or has a strong belief for the choice of the other player, then he should choose the strategy that maximizes his utility
- Suppose that someone suggests to the 2 players the strategy profile (s, t)
- When would the players be willing to follow this profile?
  - For pl. 1 to agree, it should hold that
    $$u_1(s, t) \geq u_1(s', t) \text{ for every other strategy } s' \text{ of pl. 1}$$
  - For pl. 2 to agree, it should hold that
    $$u_2(s, t) \geq u_2(s, t') \text{ for every other strategy } t' \text{ of pl. 2}$$

Nash Equilibria

- <u>Definition (Nash 1950)</u>: A strategy profile (s, t) is a (pure) Nash equilibrium, if no player has a unilateral incentive to deviate, given the other player's choice

- This means that the following conditions should be satisfied:

  1. $u_1(s, t) \geq u_1(s', t)$ for every strategy s' $\in S^1$
  2. $u_2(s, t) \geq u_2(s, t')$ for every strategy t' $\in S^2$

- One of the dominant concepts in game theory from 1950s till now

- Most other concepts in noncooperative game theory are variations/extensions/generalizations of Nash equilibria

Pictorially:

t

(,)	(,)	(x_1,)	(,)	(,)
(,)	(,)	(x_2,)	(,)	(,)
(,)	(,)	(x_3,)	(,)	(,)
(,y_1)	(,y_2)	(x, y)	(,y_4)	(,y_5)
(,)	(,)	(x_5,)	(,)	(,)

s is at the left of the fourth row.

In order for (s, t) to be a Nash equilibrium:
- x must be greater than or equal to any x_i in column t
- y must be greater than or equal to any y_j in row s

Nash Equilibria

- We should think of Nash equilibria as "stable" profiles of a game
  - At an equilibrium, each player thinks that if the other player does not change her strategy, then he also does not want to change his own strategy
- Hence, no player would regret for his choice at an equilibrium profile (s, t)
  - If the profile (s, t) is realized, pl. 1 sees that he did the best possible, against strategy t of pl. 2,
  - Similarly, pl. 2 sees that she did the best possible against strategy s of pl. 1
- Attention: If both players decide to change simultaneously, then we may have profiles where they are both better off

Examples of finding Nash equilibria in simple games

Example 1: Prisoner's Dilemma

In small games, we can examine all possible profiles and check if they form an equilibrium

- (C, C): both players have an incentive to deviate to another strategy
- (C, D): pl. 1 has an incentive to deviate
- (D, C): Same for pl. 2
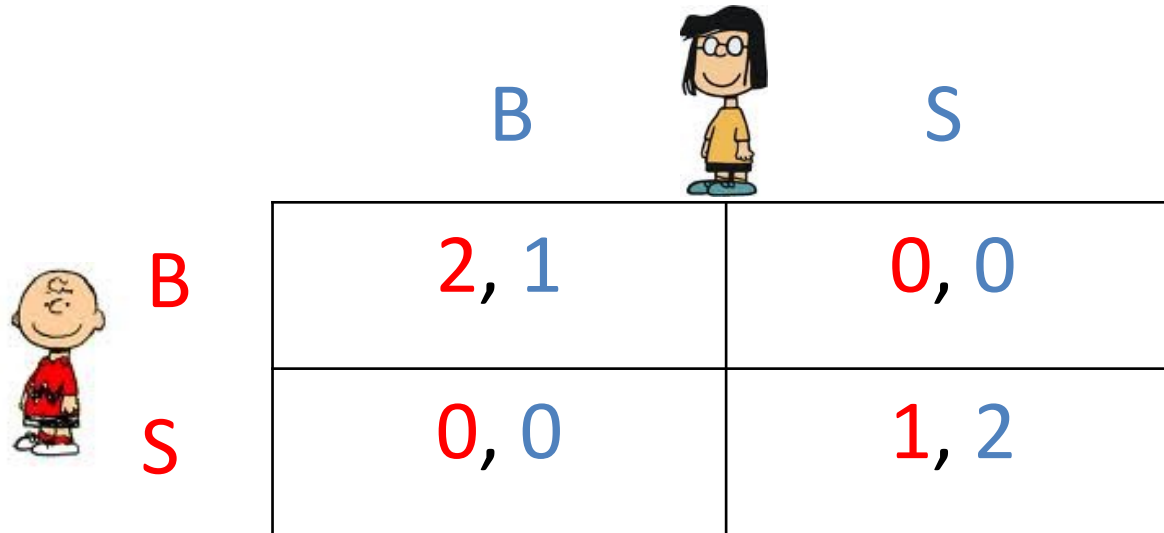- (D, D): Nobody has an incentive to change

	C	D
C	3, 3	0, 4
D	4, 0	1, 1

Hence: The profile (D, D) is the unique Nash equilibrium of this game

- Recall that D is a dominant strategy for both players in this game

Corollary: If s is a dominant strategy of pl. 1, and t is a dominant strategy for pl. 2, then the profile (s, t) is a Nash equilibrium

Example 2: Bach or Stravinsky (BoS)

	B	S
B	2, 1	0, 0
S	0, 0	1, 2

2 Nash equilibria:

- (B, B) and (S, S)
- Both derive the same total utility (3 units)
- But each player has a preference for a different equilibrium

Example 2a: Coordination games

Variation of Bach
or Stravinsky

	B	S
B	2, 2	0, 0
S	0, 0	1, 1

Again 2 Nash equilibria:
- (B, B) and (S, S)
- But now (B, B) is clearly the most preferable for both players
- Still the profile (S, S) is a valid equilibrium, no player has a unilateral incentive to deviate
  - At the profile (S, S), both players could deviate together in order to reach a better outcome

Example 3: The Hawk-Dove game

2, 2	0, 4
4, 0	-1, -1

- The most fair solution (D, D) is not an equilibrium
- 2 Nash equilibria: (D, H), (H, D)
- We have a stable situation only when one population dominates or destroys the other

Example 4: Matching Pennies

	H	T
H	1, -1	-1, 1
T	-1, 1	1, -1

- In every profile, some player has an incentive to deviate
- There is no Nash equilibrium!
- Note: The same is true for Rock-Paper-Scissors

Mixed strategies in games

Existence of Nash equilibria

- We saw that not all games possess Nash equilibria

- E.g. Matching Pennies, Rock-Paper-Scissors, and many others

- What would constitute a good solution in such games?

Example of a game without equilibria: Matching Pennies

	H	T
H	1, -1	-1, 1
T	-1, 1	1, -1

- In every profile, some player has an incentive to change
- Hence, no Nash equilibrium!

Q: How would we play this game in practice?

A: Maybe randomly

Matching Pennies: Randomized strategies

	½ H	½ T
½ H	1, -1	-1, 1
½ T	-1, 1	1, -1

- Main idea: Enlarge the strategy space so that players are allowed to play non-deterministically
- Suppose both players play
  - H with probability 1/2
  - T with probability 1/2
- Then every outcome has a probability of ¼
- For pl. 1:
  - P[win] = P[lose] = ½
  - Average utility = 0
- Similarly for pl. 2

Mixed strategies

- Definition: A mixed strategy of a player is a probability distribution on the set of his available choices
- If S = $(s_1, s_2,..., s_n)$ is the set of available strategies of a player, then a mixed strategy is a vector in the form
  $$\mathbf{p} = (p_1, ..., p_n), \text{ where}$$
  $$p_i \geq 0 \text{ for } i=1, ..., n, \text{ and } p_1 + ... + p_n = 1$$
- p_j = probability for selecting the j-th strategy
- We can write it also as $p_j = p(s_j)$ = prob/ty of selecting s_j
- Matching Pennies: the uniform distribution can be written as
  $\mathbf{p} = (1/2, 1/2)$ or $p(H) = p(T) = \frac{1}{2}$

Pure and mixed strategies

- From now on, we refer to the available choices of a player as *pure strategies* to distinguish them from mixed strategies

- Consider a 2-player game with $S^1 = \{s_1, s_2, ..., s_n\}$ and $S^2 = \{t_1, t_2, ..., t_m\}$

- Every pure strategy can also be represented as a mixed strategy that gives probability 1 to only a single choice

- E.g., the pure strategy s_1 can also be written as the mixed strategy $(1, 0, 0, ..., 0)$

- More generally: each strategy s_i can be written in vector form as the mixed strategy $e^i = (0, 0, ..., 1, 0, ..., 0)$
  - 1 at position i, 0 everywhere else
  - Some times, it is convenient in the analysis to use the vector form for a pure strategy

Utility under mixed strategies

- Suppose that each player has chosen a mixed strategy in a game

- How does a player now evaluate the outcome of a game?

- We will assume that each player cares for his expected utility

  - Justified when games are played repeatedly
  - Not justified for more risk-averse or risk-seeking players

Expected utility (for 2 players)

- Consider a n x m game
- Pure strategies of pl. 1: $S^1 = \{s_1, s_2,..., s_n\}$
- Pure strategies of pl. 2: $S^2 = \{t_1, t_2,..., t_m\}$
- Let **p** = $(p_1, ..., p_n)$ be a mixed strategy of pl. 1

and **q** = $(q_1, ..., q_m)$ be a mixed strategy of pl. 2

- Expected utility of pl. 1:

$$u_1(\mathbf{p}, \mathbf{q}) = \sum_{i=1}^{n} \sum_{j=1}^{m} p_i \cdot q_j \cdot u_1(s_i, t_j) = \sum_{i=1}^{n} \sum_{j=1}^{m} p(s_i) \cdot q(t_j) \cdot u_1(s_i, t_j)$$

- Similarly for pl. 2 (replace u_1 by u_2)

Example

	B	S
B	2, 1	0, 0
S	0, 0	1, 2

- Let p = (4/5, 1/5), q = (1/2, 1/2)
- $u_1(p, q)$ = 4/5 x 1/2 x 2 + 1/5 x 1/2 x 1 = 0.9
- $u_2(p, q)$ = 4/5 x 1/2 x 1 + 1/5 x 1/2 x 2 = 0.6
- When can we have an equilibrium with mixed strategies?

Nash equilibria with mixed strategies

- Definition: A profile of mixed strategies (**p**, **q**) is a Nash equilibrium if
  - $u_1(\mathbf{p}, \mathbf{q}) \geq u_1(\mathbf{p'}, \mathbf{q})$ for any other mixed strategy **p'** of pl. 1
  - $u_2(\mathbf{p}, \mathbf{q}) \geq u_2(\mathbf{p}, \mathbf{q'})$ for any other mixed strategy **q'** of pl. 2

- Again, we just demand that no player has a unilateral incentive to deviate to another strategy

- How do we verify that a profile is a Nash equilibrium?
  - There is an infinite number of mixed strategies!
  - Infeasible to check all these deviations

Nash equilibria with mixed strategies

- Corollary: It suffices to check only deviations to pure strategies
  - Because each mixed strategy is a convex combination of pure strategies

- Equivalent definition: A profile of mixed strategies (**p**, **q**) is a Nash equilibrium if
  - $u_1(\mathbf{p}, \mathbf{q}) \geq u_1(e^i, \mathbf{q})$ for every pure strategy e^i of pl. 1
  - $u_2(\mathbf{p}, \mathbf{q}) \geq u_2(\mathbf{p}, e^j)$ for every pure strategy e^j of pl. 2

- Hence, we only need to check n+m inequalities as in the case of pure equilibria

Multi-player games

Games with more than 2 players

- All the definitions we have seen can be generalized for multi-player games
  - Dominant strategies, Nash equilibria
- But: we can no longer have a representation with 2-dimensional arrays
- For n-player games we would need n-dimensional arrays (unless there is a more concise representation)

Definitions for n-player games

Definition: A game in normal form consists of

- A set of players $N = \{1, 2, ..., n\}$

- For every player i, a set of available pure strategies S^i

- For every player i, a utility function
  $u_i: S^1 \times ... \times S^n \rightarrow R$

- Let $\mathbf{p} = (\mathbf{p}_1, ..., \mathbf{p}_n)$ be a profile of mixed strategies for the players

- Each $\mathbf{p}_i$ is a probability distribution on S^i

- Expected utility of pl. i under $\mathbf{p}$ =

$$u_i(\mathbf{p}_1, \ldots, \mathbf{p}_n) = \sum_{(s_1, \ldots, s_n) \in S^1 \times \cdots \times S^n} \mathbf{p}_1(s_1) \ldots \mathbf{p}_n(s_n) u_1(s_1, \ldots, s_n)$$

Notation

- Given a vector $s = (s_1, ..., s_n)$,
  we denote by s_{-i} the vector where we have removed the i-th coordinate:

$$s_{-i} = (s_1, ..., s_{i-1}, s_{i+1}, ..., s_n)$$

- E.g., if $s = (3, 5, 7, 8)$, then
  - $s_{-3} = (3, 5, 8)$
  - $s_{-1} = (5, 7, 8)$

- We can write a strategy profile s as $s = (s_i, s_{-i})$

Definitions for n-player games

- A strategy $\mathbf{p}_i$ of pl. i is *dominant* if
$$u_i(\mathbf{p}_i, \mathbf{p}_{-i}) \geq u_i(e^j, \mathbf{p}_{-i})$$
for every pure strategy e^j of pl. i, and every profile $\mathbf{p}_{-i}$ of the other players

- Replace $\geq$ with $>$ for strictly dominant

- A profile $\mathbf{p} = (\mathbf{p}_1, ..., \mathbf{p}_n)$ is a Nash equilibrium if for every player i and every pure strategy e^j of pl. i, we have
$$u_i(\mathbf{p}) \geq u_i(e^j, \mathbf{p}_{-i})$$

  – As in 2-player games, it suffices to check only deviations to pure strategies

Nash equilibria in multi-player games

At a first glance:

- Even finding pure Nash equilibria looks already more difficult than in the 2-player case

- We can try with brute force all possible profiles

- Suppose we have n players, and each of them has m strategies: $|S^i|= m$

- There are m^n pure strategy profiles!

- However, in some cases, we can exploit symmetry or other properties to reduce our search space
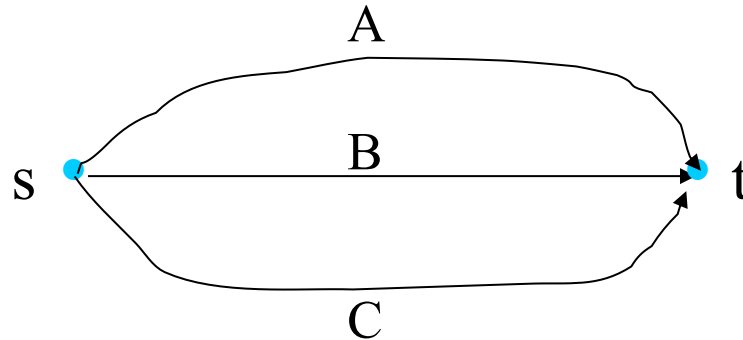
Example: Congestion games
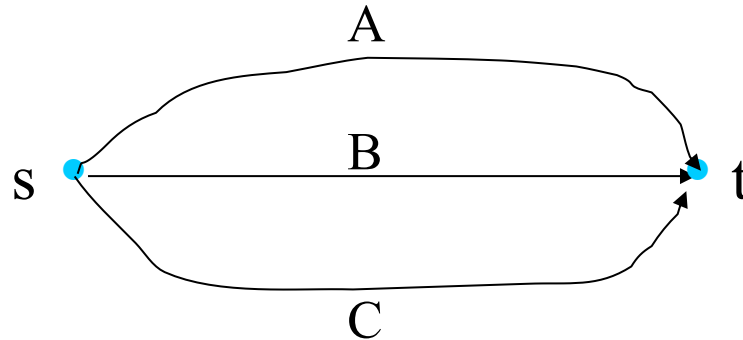

A simple example of a congestion game:

- A set of network users wants to move from s to t

- 3 possible routes, A, B, C

- Time delay in a route: depends on the number of users who have chosen this route

- $d_A(x) = 5x$, $d_B(x) = 7.5x$, $d_C(x) = 10x$,

Example: Congestion games

- Suppose we have n = 5 players

- For each player i, S^i = {A, B, C}

- Number of possible pure strategy profiles: 3^5 = 243

- Utility function of a player: should increase when delay decreases (e.g., we can define it as u = − delay)

- At profile s = (A, C, A, B, A)

  - $u_1(s)$ = -15, $u_2(s)$ = -10, $u_3(s)$ = -15, $u_4(s)$ = -7.5, $u_5(s)$ = -15

Example: Congestion games
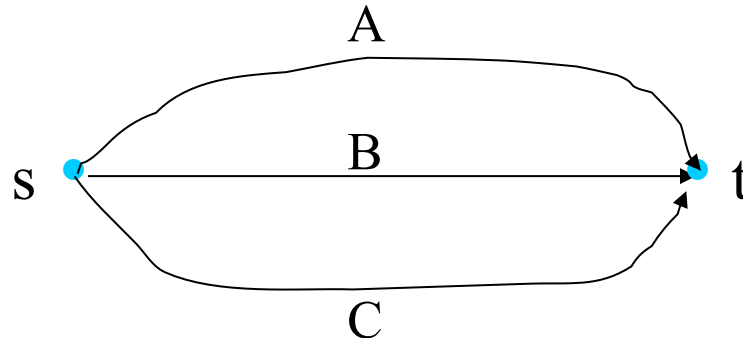
- There is no need to examine all 243 possible profiles to find a pure equilibrium
- Exploiting symmetry:
  - In every route, the delay does not depend on who chose the route but only how many did so
- We can also exploit further properties
  - E.g. There can be no equilibrium where one of the routes is not used by some player

Homework: Find the pure Nash equilibria of this game (if there are any)

Game simplifications:
Strict and weak domination

Strictly dominated strategies

- In Prisoner's dilemma, we saw that strategy D is dominant

- Strategy C is "dominated" by D

- <u>Definition</u>: A (pure or mixed) strategy p_i of pl. i strictly dominates some other strategy p' if for every profile p_{-i} of the other players, it holds that
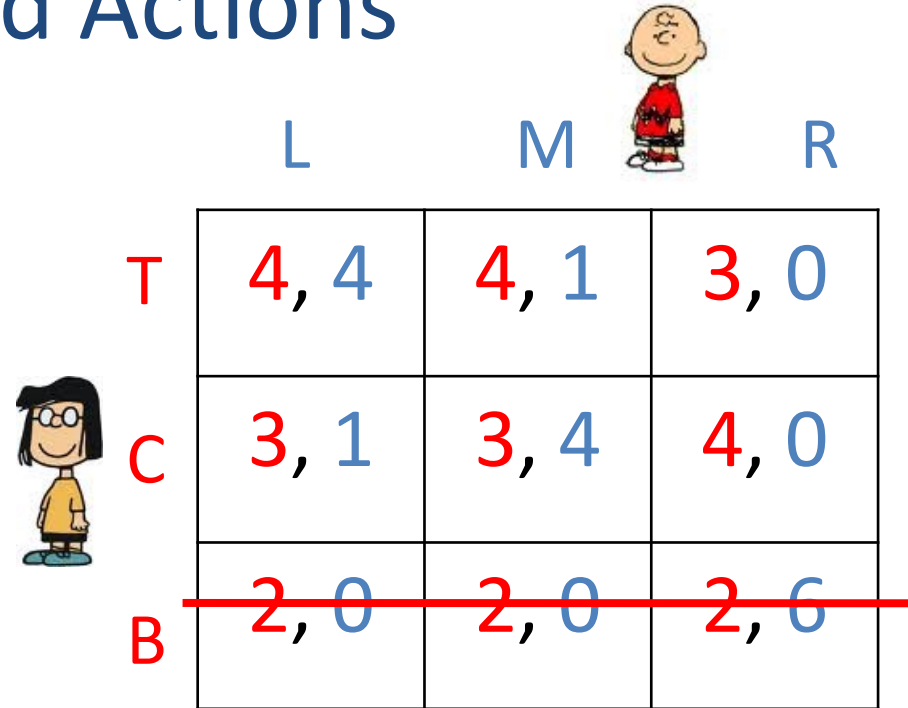
$$u_i(p_i, p_{-i}) > u_i(p', p_{-i})$$

- Strategy p' will be called strictly dominated

- Observation: it suffices to consider only profiles p_{-i} with pure strategies

Strictly dominated strategies

- Strictly dominated strategies cannot be used in any Nash equilibrium

- Hence, we can remove them and reduce the size of the game

- In some cases, this results in much simpler games to analyze

Iterated Elimination of Strictly Dominated Actions

- Action B of player 1 is dominated by T or C

- None of the actions of player 2 is dominated
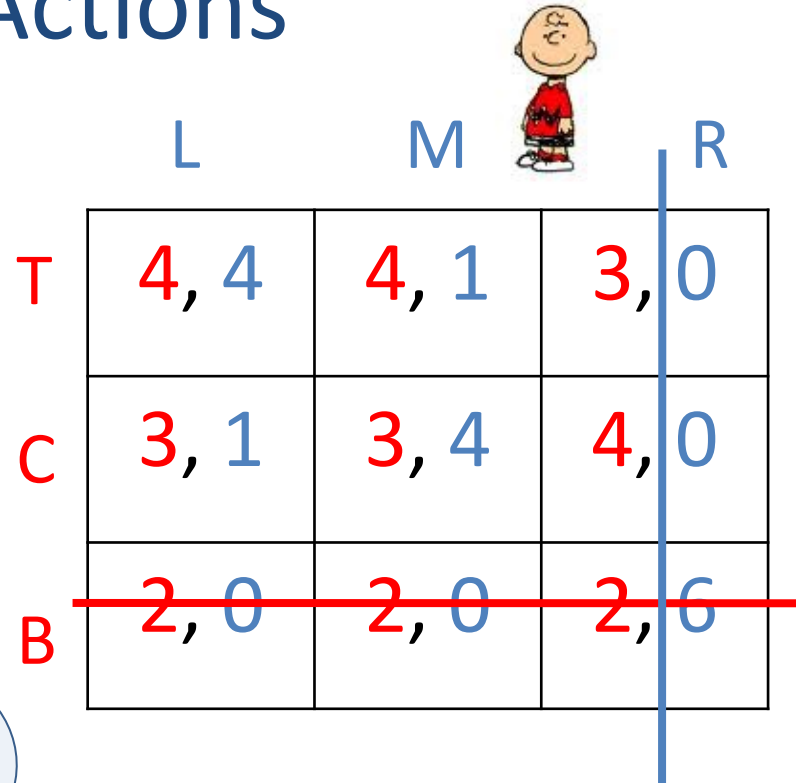
- If player 1 is rational, she would never play B

	L	M	R
T	4, 4	4, 1	3, 0
C	3, 1	3, 4	4, 0
B	2, 0	2, 0	2, 6

I should not play B

Iterated Elimination of Strictly Dominated Actions

- If player 2 knows player 1 is rational, he can assume player 1 does not play B
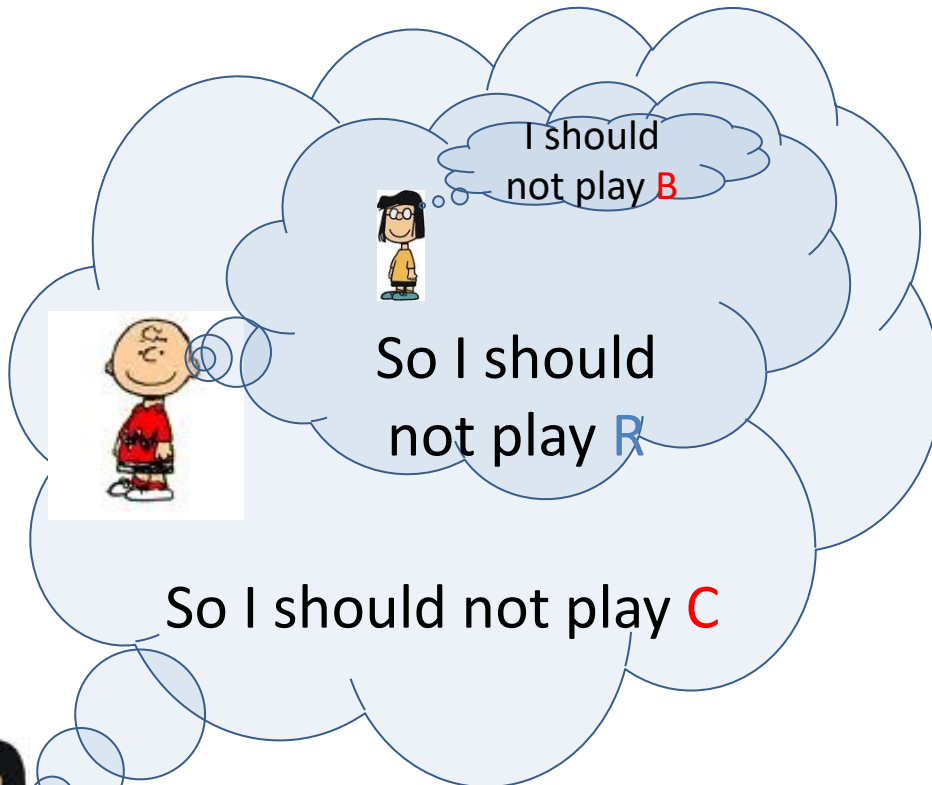 - then player 2 should not play R

I should not play B

So I should not play R

	L	M	R
T	4, 4	4, 1	3, 0
C	3, 1	3, 4	4, 0
B	2, 0	2, 0	2, 6

Iterated Elimination of Strictly Dominated Actions

I should not play B

So I should not play R

So I should not play C

	L	M	R
T	4, 4	4, 1	3, 0
C	3, 1	3, 4	4, 0
B	2, 0	2, 0	2, 6

Unique Nash equilibrium: (T, L)

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Strict domination by mixed strategies

	L	R
T	5, 5	0, 0
C	0, 0	5, 5
B	2, 0	2, 0

- **Attention:** It is possible that some strategy is not strictly dominated by a pure strategy but it is dominated by a mixed strategy

- Strategy B of pl. 1 is not strictly dominated neither by T nor by C

- But, it is strictly dominated by the mixed strategy (1/2, 1/2, 0), i.e., 0.5T + 0.5C:
  - Proof: Consider some arbitrary strategy of pl. 2 $q = (q_1, 1-q_1)$
  - $u_1(B, q) = 2$
  - $u_1((1/2, 1/2, 0), q) = 1/2 \times q_1 \times 5 + 1/2 \times (1-q_1) \times 5 = 2.5 > 2$

Strict domination by mixed strategies

- Consider a 2-player game with $S^1 = \{s_1, s_2, ..., s_n\}$, $S^2 = \{t_1, t_2, ..., t_m\}$
- How can we check if the pure strategy s_i of pl. 1 is strictly dominated by some other (possibly mixed) strategy?
- We have to check if there exist probabilities $p_1, ..., p_n$ such that
  - For every $t_j \in S^2$ (for every column), $u_1(s_i, t_j) < p_1 u_1(s_1, t_j) + ... + p_n u_1(s_n, t_j)$
  - also, $p_1 + p_2 + ... + p_n = 1$, $p_i \geq 0$ for $i = 1, ..., n$
- System with linear inequalities, it has a solution iff s_i is strictly dominated

Iterated Elimination of Strictly Dominated Actions

- Given: an n-player game
  - pick a player i that has a strictly dominated pure strategy (dominated either by a pure or mixed strategy)
  - Remove one of the strictly dominated strategies of pl. i
  - repeat until no player has a strictly dominated pure strategy

- <u>Facts:</u>
  - the set of surviving actions is independent of the elimination order, i.e., which player was picked at each step
  - Iterated elimination of strictly dominated actions cannot destroy Nash equilibria

Weakly dominated strategies

- <u>Definition</u>: A (pure or mixed) strategy $\mathbf{p}_i$ of pl. i weakly dominates some other strategy $\mathbf{p}'$ if for every profile $\mathbf{p}_{-i}$ of the other players, it holds that

$$u_i(\mathbf{p}_i, \mathbf{p}_{-i}) \geq u_i(\mathbf{p}', \mathbf{p}_{-i})$$

and for at least one profile $\mathbf{p}_{-i}$ we have

$$u_i(\mathbf{p}_i, \mathbf{p}_{-i}) > u_i(\mathbf{p}', \mathbf{p}_{-i})$$

- Strategy $\mathbf{p}'$ will be called weakly dominated

Weakly dominated strategies

	L	R
T	1, 1	0, 0
B	0, 0	0, 0

	L	R
T	2, 2	3, 0
B	0, 3	3, 3

- When we remove weakly dominated strategies, we may lose some Nash equilibria
- In the above games:
  - Strategy T weakly dominates B
  - Strategy L weakly dominates R
  - but (B, R) is an equilibrium
- Observation: In the 2ⁿᵈ game, we even have a better value for both players when they choose weakly dominated strategies

Iterated Elimination of Weakly Dominated Actions and Nash Equilibria

- The elimination order matters in iterated deletion of weakly dominated strategies

- Each order may eliminate a different subset of Nash equilibria

- Can we lose all equilibria of the original game?

- **<u>Theorem:</u>** For every game where each player has a finite strategy space, there is always at least one equilibrium that survives iterated elimination of weakly dominated strategies
  - thus: if we care for finding just one Nash equilibrium, no need to worry about elimination order

Exercise

	t_1	t_2
s_1	3, 2	2, 2
s_2	1, 1	0, 0
s_3	0, 0	1, 1

Execute all the possible ways of doing iterated elimination of weakly dominated strategies. Do we lose equilibria with this process?

Existence of Nash equilibria

Nash equilibria: Recap

Recall the problematic issues we have identified for pure Nash equilibria:

1. Non-existence: there exist games that do not possess an equilibrium with pure strategies

2. Non-uniqueness: there are games that have many Nash equilibria

3. Welfare guarantees: The equilibria of a game do not necessarily have the same utility for the players

Have we made any progress by considering equilibria with mixed strategies?

Existence of Nash equilibria

- <u>Theorem</u> [Nash 1951]: Every finite game possesses at least one equilibrium when we allow mixed strategies
  - Finite game: finite number of players, and finite number of pure strategies per player
- Corollary: if a game does not possess an equilibrium with pure strategies, then it definitely has one with mixed strategies
- One of the most important results in game theory
- Nash's theorem resolves the issue of non-existence
  - By allowing a richer strategy space, existence is guaranteed, no matter how big or complex the game might be

Examples

- In Prisoner's dilemma or Bach-or-Stravinsky, there exist equilibria with pure strategies
  - For such games, Nash's theorem does not add any more information. However, in addition to pure equilibria, we may also have some mixed equilibria

- Matching-Pennies: For this game, Nash's theorem guarantees that there exists an equilibrium with mixed strategies
  - In fact, it is the profile we saw: ((1/2, 1/2), (1/2, 1/2))

- Rock-Paper-Scissors?
  - Again the uniform distribution: ((1/3, 1/3, 1/3), (1/3, 1/3, 1/3))

Nash equilibria: Computation

- Nash's theorem only guarantees the existence of Nash equilibria
  - Proof reduces to using Brouwer's fixed point theorem
- Brouwer's theorem: Let f:D→D, be a continuous function, and suppose D is convex and compact. Then there exists x such that f(x) = x
  - Many other versions of fixed point theorems also available

Nash equilibria: Computation

- So far, we are not aware of efficient algorithms for finding fixed points [Hirsch, Papadimitriou, Vavasis '91]
  - There exist exponential time algorithms for finding approximate fixed points
- Can we design polynomial time algorithms for 2-player games?
  - After all, it seems to be only a special case of the general problem of finding fixed points
- For games with more players?
- To be discussed in the next lectures…