

# *EPICENTER* Spring Course on Epistemic Game Theory

## Chapters 2 and 3: Common Belief in Rationality

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# What is game theory about?

- In **game theory**, we study situations where you must make a choice, but where the **final outcome** also depends on the choices of **others**.
- **Examples** are everywhere:
- **Negotiating** about the price of a car,
- choosing a **marketing strategy** for your firm,
- **bidding** in an auction,
- **discussing** with your partner about what TV program to watch this evening.
- **Key question:** What choice would you make, and why?
- This depends crucially on how you **reason** about the opponent!

## Example: Going to a party

blue	green	red	yellow	same color as Barbara
4	3	2	1	0

### Story

- This evening, you are going to a party together with your friend Barbara.
- You must both decide which color to wear: blue, green, red or yellow.
- Your preferences for wearing these colors are as in the table. These numbers are called utilities.
- You dislike wearing the same color as Barbara: If you both would wear the same color, your utility would be 0.
- What color should you choose, and why?

blue	green	red	yellow	same color as Barbara
4	3	2	1	0

- What color is optimal for you depends on your **belief** about Barbara's choice:
- If you believe that Barbara wears **blue**, then **green** is optimal for you.
- If you believe that Barbara wears **green**, then **blue** is optimal for you.
- If you believe that Barbara wears **red**, then **blue** is optimal for you.
- If you believe that Barbara wears **yellow**, then **blue** is optimal for you.
- We call **blue** and **green** **rational** choices for you, because they are **optimal for some belief** about Barbara's choice.
- Does this mean that **red** and **yellow** are **irrational** for you?

blue	green	red	yellow	same color as Barbara
4	3	2	1	0

- Suppose you believe that, with **probability 0.6**, Barbara chooses **blue**, and that, with **probability 0.4**, she chooses **green**.
- If you would choose **blue**, your **expected utility** would be  $(0.6) \cdot 0 + (0.4) \cdot 4 = 1.6$ .
- If you would choose **green**, your expected utility would be  $(0.6) \cdot 3 + (0.4) \cdot 0 = 1.8$ .
- If you would choose **red**, your utility would be 2.
- If you would choose **yellow**, your utility would be 1.
- So, choosing **red** is **optimal** for you if you hold this **probabilistic belief** about Barbara's choice. In particular, **red** is a **rational** choice for you.

blue	green	red	yellow	same color as Barbara
4	3	2	1	0

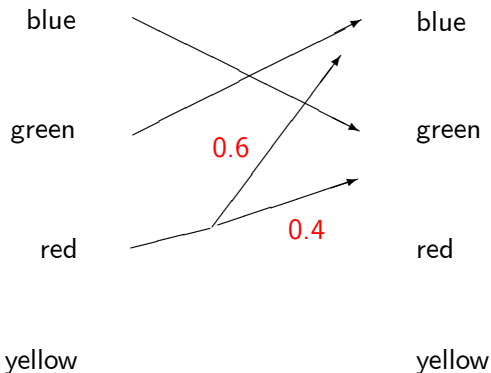
- Choosing **yellow** can **never be optimal** for you, even if you hold a probabilistic belief about Barbara's choice.
- If you assign **probability less than 0.5** to Barbara's choice **blue**, then by choosing **blue** yourself, your expected utility will be at least  $(0.5) \cdot 4 = 2$ .
- If you assign **probability at least 0.5** to Barbara's choice **blue**, then by choosing **green** yourself your expected utility will be at least  $(0.5) \cdot 3 = 1.5$ .
- Hence, whatever your belief about Barbara, you can always guarantee an expected utility of at least 1.5.
- So, **yellow** can **never be optimal** for you, and is therefore an **irrational** choice for you.

# Beliefs diagram

blue	green	red	yellow	same color as Barbara
4	3	2	1	0

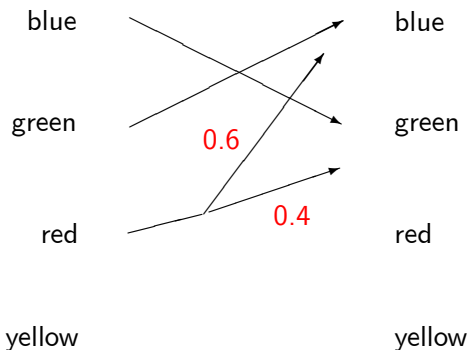
Your choices

Barbara's choices



Your choices

Barbara's choices



- The choices **blue**, **green** and **red** are **rational** for you.
- But are all of these choices also **reasonable**? This depends on **Barbara's** preferences!



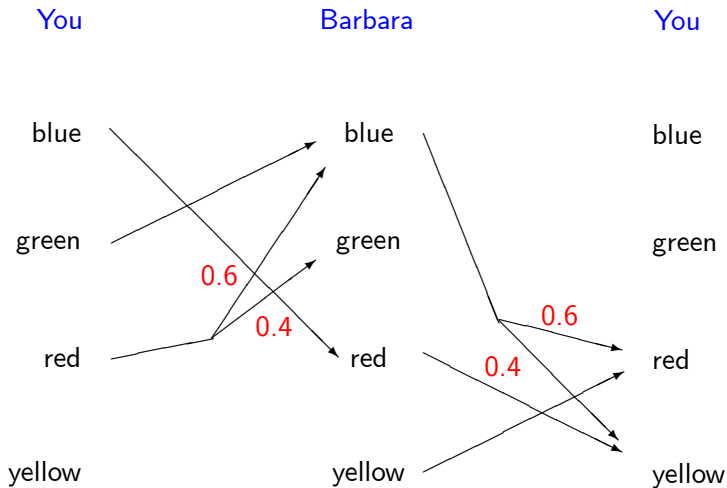
	blue	green	red	yellow	same color as friend
you	4	3	2	1	0
Barbara	2	1	4	3	0

- For Barbara, the choices **red**, **yellow** and **blue** are **rational**, whereas **green** is **irrational**.
- Choosing **red** is optimal for her if she believes that you choose **yellow**.
- Choosing **yellow** is optimal for her if she believes that you choose **red**.
- Choosing **blue** is optimal for her if she believes that, with **probability 0.6**, you choose **red**, and with **probability 0.4** you choose **yellow**.

	blue	green	red	yellow	same color as friend
you	4	3	2	1	0
Barbara	2	×	4	3	0

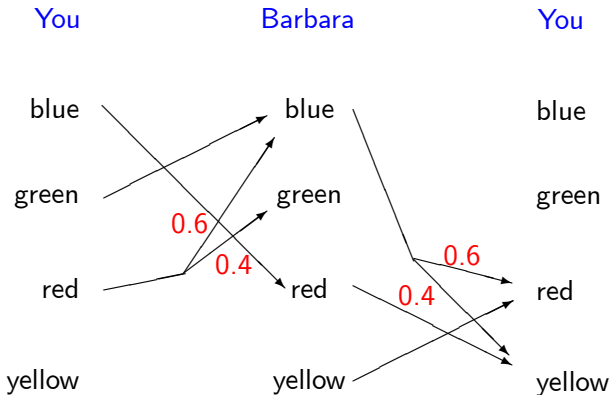
- If you believe that Barbara chooses rationally, you believe that Barbara will choose red, yellow or blue.
- But then, choosing red will no longer be optimal for you, as choosing green will always be better in this case.
- Choosing blue is optimal for you if you believe that Barbara rationally chooses red.
- Choosing green is optimal for you if you believe that Barbara rationally chooses blue.

# Beliefs diagram

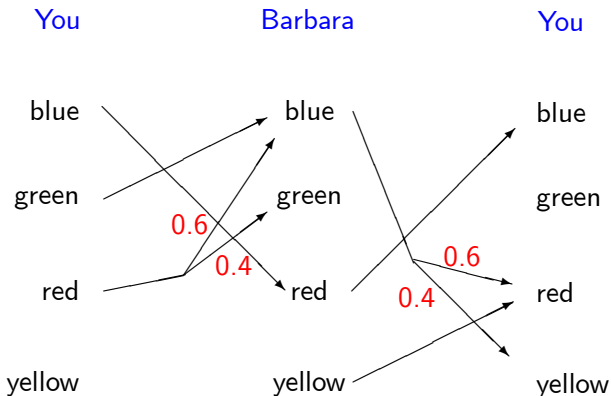


	blue	green	red	yellow	same color as friend
you	4	3	2	1	0
Barbara	2	1	4	3	0

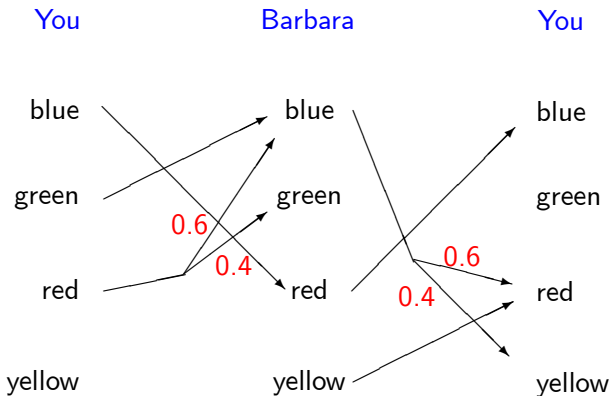
- The color **yellow** is **irrational** for you.
- The color **red** is **rational** for you, but you can **no longer rationally choose it** if you believe that **Barbara chooses rationally**.
- If you believe that **Barbara chooses rationally**, you can still rationally choose the colors **blue** and **green**.
- But are both **blue** and **green reasonable** choices for you?



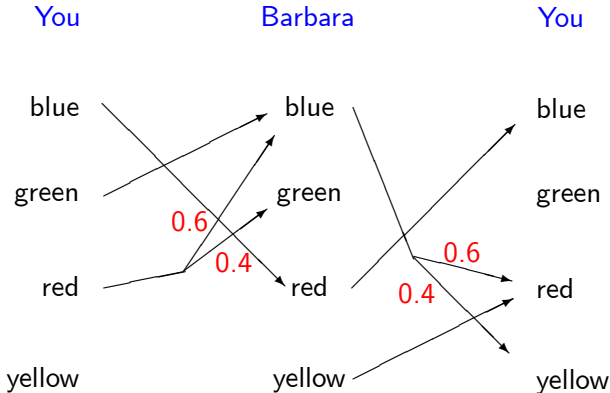
- Consider the **belief hierarchy** that starts at your choice **blue**:
- You believe that Barbara chooses **red**.
- You believe that Barbara believes that you choose **yellow**.
- You believe that Barbara believes that you choose **irrationally (yellow)**, so this belief hierarchy is **not reasonable**.



- In this **alternative beliefs diagram**, consider the belief hierarchy that starts at your choice **blue**.
- You believe that Barbara **rationally** chooses **red**.
- You believe that Barbara believes that you **rationally** choose **blue**.
- You believe that Barbara believes that you believe that Barbara **rationally** chooses **red**. And so on.



- The **belief hierarchy** that supports your choice **blue** expresses **common belief in rationality**.
- So, you can rationally choose **blue** under **common belief in rationality**!



- What about your choice **green**? Consider the **belief hierarchy** that starts at your choice **green**.
- You believe that Barbara chooses **blue**.
- You believe that Barbara believes that, with **probability 0.6**, you choose **red**, and with **probability 0.4** you **irrationally** choose **yellow**.
- It does **not** express **common belief in rationality**.



	blue	green	red	yellow	same color as friend
you	4	3	2	×	0
Barbara	2	1	4	3	0

- In fact, you **cannot** rationally choose **green** under **common belief in rationality**:
- If Barbara believes that you choose **rationally**, then she believes that you will **not** choose **yellow**.
- But then, she cannot rationally choose **blue**, as **yellow** would always be better for her.
- So, if you believe that Barbara chooses **rationally**, and that Barbara believes that you choose **rationally**, you must believe that she will only choose **red** or **yellow**.
- But then, you should choose **blue**, and not **green**.

	blue	green	red	yellow	same color as friend
you	4	3	2	1	0
Barbara	2	1	4	3	0

### Summarizing

- Your choice **yellow** is **irrational**.
- Your choice **red** is **rational**, but can **no longer be optimal** if you believe that **Barbara chooses rationally**.
- You can rationally choose **green** if you believe that **Barbara chooses rationally**, but **not** if you believe, in addition, that Barbara believes that **you choose rationally**.
- You can rationally choose **blue** under **common belief in rationality**. In fact, **blue** is the **only** color you can rationally choose under **common belief in rationality**.

- The **idea of common belief in rationality** first appears in **Friedell (1969)**.
- Later, **Armbruster and Böge (1979)** and **Böge and Eisele (1979)** implicitly used the idea of common belief in rationality.
- **Spohn (1982)** explicitly discusses the idea of common belief in rationality.
- **Bernheim (1984)** and **Pearce (1984)** implicitly incorporate the idea of common belief in rationality in their concept of **rationalizability**.
- **Aumann (1987)** uses the idea of common belief in rationality as a foundation for **correlated equilibrium**.
- **Brandenburger and Dekel (1987)** use the idea of common belief in rationality as a foundation for **correlated rationalizability**.
- **Tan and Werlang (1988)** **formally** define common belief in rationality.
- A **historical overview** can be found in **Perea (2014)**.

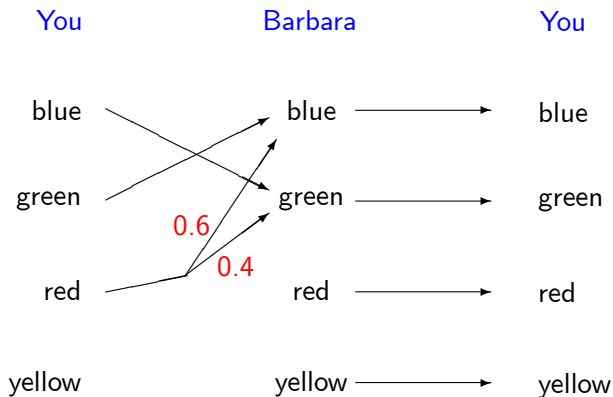
# New Scenario

- Barbara has **same preferences** over colors as you.
- Barbara **likes** to wear the same color as you, whereas you **dislike** this.

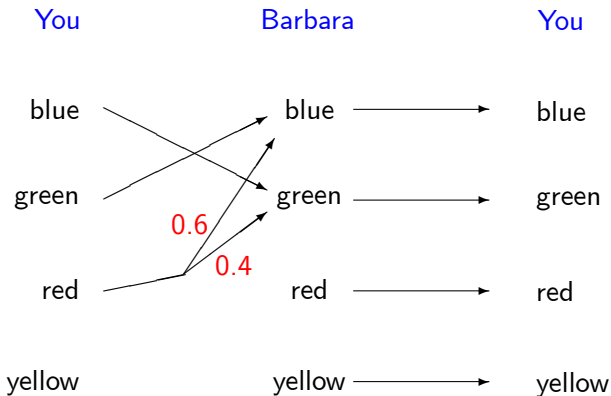
	blue	green	red	yellow	<b>same color</b> as friend
<b>you</b>	4	3	2	1	0
<b>Barbara</b>	4	3	2	1	5

- Which color(s) can you rationally choose under **common belief in rationality**?

# Beliefs diagram



	blue	green	red	yellow	same color as friend
you	4	3	2	1	0
Barbara	4	3	2	1	5



- The **belief hierarchy** that starts at your choice **blue** expresses **common belief in rationality**.
- Similarly, the **belief hierarchies** that start at your choices **green** and **red** also express **common belief in rationality**.
- So, you can rationally choose **blue**, **green** and **red** under **common belief in rationality**.

# Choosing rationally

We will now define **formally** what we mean by a **rational choice**.

- $I = \{1, 2, \dots, n\}$ : set of **players**.
- $C_i$ : set of **choices** for player  $i$ .
- A **choice-combination** for  $i$ 's opponents is a combination  $(c_1, \dots, c_{i-1}, c_{i+1}, \dots, c_n)$ .
- By  $C_{-i}$  we denote the set of all choice-combinations for  $i$ 's opponents.
- A **belief** for player  $i$  about his opponents' choices is a **probability distribution**  $b_i$  over the set  $C_{-i}$  of opponents' choice-combinations.
- For every choice-combination  $c_{-i} \in C_{-i}$ , the number  $b_i(c_{-i})$  specifies the **probability** that player  $i$  assigns to the event that his opponents make precisely this combination of choices.

- A **utility function** for player  $i$  is a function  $u_i$  that assigns to every combination of choices  $(c_1, \dots, c_n)$  some number  $u_i(c_1, \dots, c_n)$ .
- The number  $u_i(c_1, \dots, c_n)$  indicates how **desirable** player  $i$  finds the outcome induced by  $(c_1, \dots, c_n)$ .
  
- In the example “Going to a party”:
  - $u_1(\text{green}, \text{red}) = 3$ ,
  - $u_1(\text{green}, \text{blue}) = 3$ ,
  - $u_1(\text{green}, \text{green}) = 0$ ,
  - $u_1(\text{blue}, \text{red}) = 4$ .



- Suppose that player  $i$  holds a **belief**  $b_i$  about the opponents' choices.
- The **expected utility** of making choice  $c_i$ , while having the belief  $b_i$ , is

$$u_i(c_i, b_i) = \sum_{c_{-i} \in C_{-i}} b_i(c_{-i}) \cdot u_i(c_i, c_{-i}).$$

- The choice  $c_i$  is **optimal** for player  $i$  given his belief  $b_i$ , if

$$u_i(c_i, b_i) \geq u_i(c'_i, b_i)$$

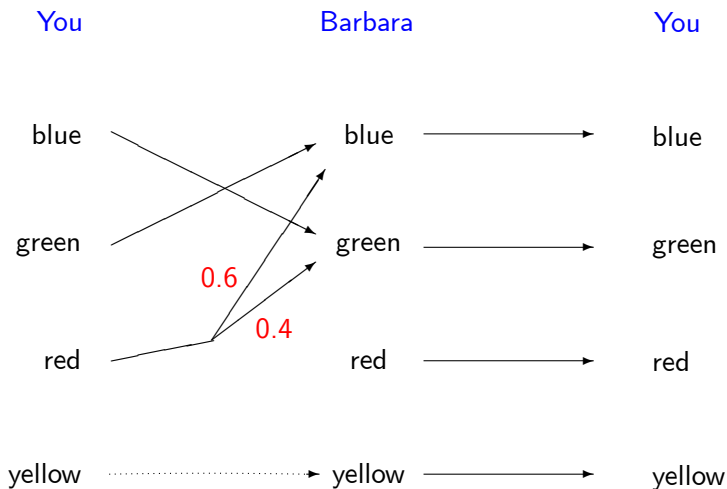
for all other choices  $c'_i \in C_i$ .

- The choice  $c_i$  is **rational** for player  $i$  if it is optimal for **some** belief  $b_i$  about the opponents' choices.

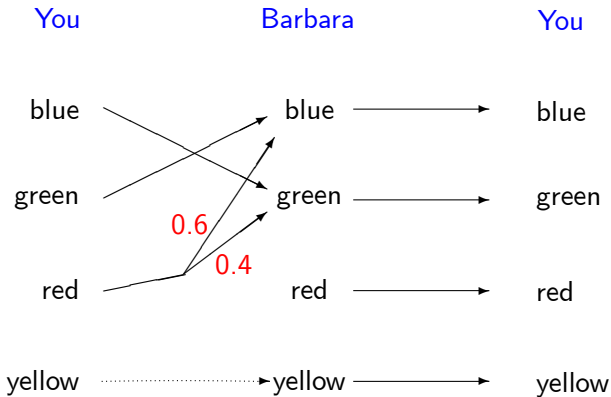
# Belief hierarchies

- A **first-order** belief is a belief about an opponent's choice.
- In order to judge whether a first-order belief about player  $j$ 's choice is **reasonable**, you must also hold
- a belief about what  $j$  believes about his opponents' choices: **second-order** belief.
- In order to judge whether this second-order belief is **reasonable**, you must also hold
- a belief about what  $j$  believes about what the others believe about their opponents' choices: **third-order** belief.
- And so on.
- This yields a **belief hierarchy**. Harsanyi (1962, 1967–1968).
- Belief hierarchies can be constructed from an **extended beliefs diagram**.

# Extended beliefs diagram

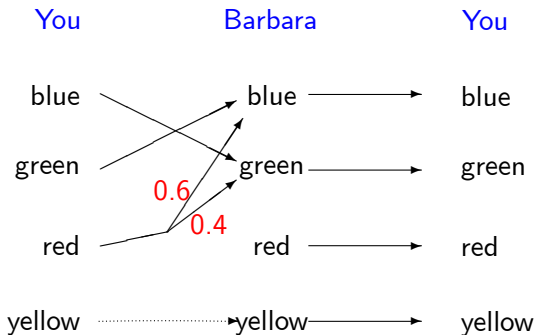


- Writing down a belief hierarchy **explicitly** is **impossible**. You must write down
  - your belief about the opponents' choices
  - your belief about what your opponents believe about their opponents' choices,
  - a belief about what the opponents believe that their opponents believe about the other players' choices,
  - and so on, ad infinitum.
- Is there an **easy** way to **encode** a belief hierarchy?

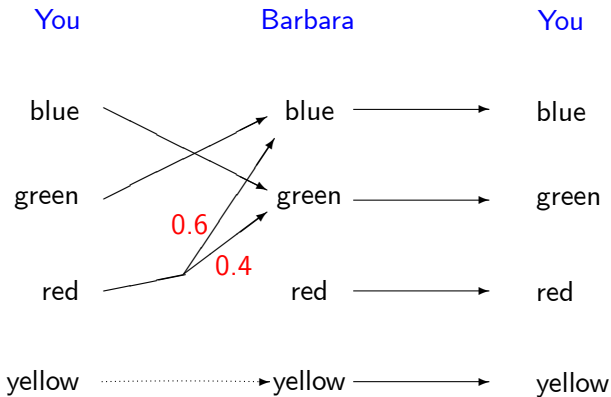


Even writing down the **first three levels** of the belief hierarchy that starts at your choice **red** is a **nightmare!**

- A **belief hierarchy** for you consists of a **first-order** belief, a **second-order** belief, a **third-order** belief, and so on.
- In a **belief hierarchy**, you hold a belief about
- the opponents' **choices**,
- the opponents' **first-order** beliefs,
- the opponents' **second-order** beliefs,
- and so on.
- Hence, in a **belief hierarchy** you hold a belief about
- the opponents' **choices**, and the opponents' **belief hierarchies**.
- Call a belief hierarchy a **type**.
- Then, a **type** holds a belief about the opponents' **choices** and the opponents' **types**.
- Idea goes back to **Harsanyi (1967–68)**.



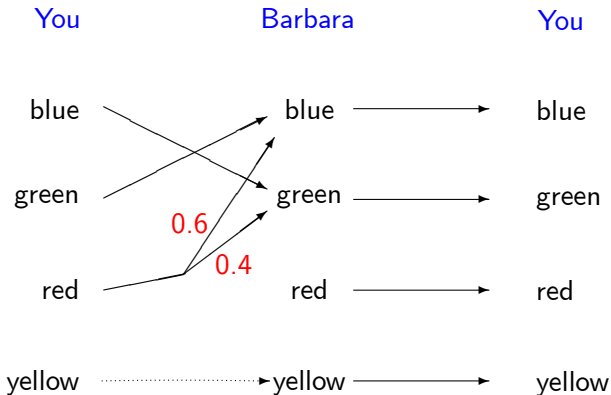
- Denote by  $t_1^{red}$  your **belief hierarchy** that starts at your choice **red**.
- Denote by  $t_2^{blue}$  and  $t_2^{green}$  the **belief hierarchies** for Barbara that start at her choices **blue** and **green**.
- Then,  $t_1^{red}$  believes that, with **prob. 0.6**, Barbara chooses **blue** and has belief hierarchy  $t_2^{blue}$ , and believes that, with **prob. 0.4**, Barbara chooses **green** and has belief hierarchy  $t_2^{green}$ .



- **Formally:** We call the belief hierarchies  $t_1^{red}$ ,  $t_2^{blue}$  and  $t_2^{green}$  types.
- Type  $t_1^{red}$  has belief

$$b_1(t_1^{red}) = (0.6) \cdot (blue, t_2^{blue}) + (0.4) \cdot (green, t_2^{green}).$$





- Also,  $b_1(t_1^{blue}) = (green, t_2^{green})$  and  $b_1(t_1^{green}) = (blue, t_2^{blue})$  and finally  $b_1(t_1^{yellow}) = (yellow, t_2^{yellow})$ .
- We can do the same for Barbara's belief hierarchies. This leads to an **epistemic model**.

# Epistemic model for "Going to a party"

Types	$T_1 = \{t_1^{blue}, t_1^{green}, t_1^{red}, t_1^{yellow}\}$ $T_2 = \{t_2^{blue}, t_2^{green}, t_2^{red}, t_2^{yellow}\}$
Beliefs for player 1	$b_1(t_1^{blue}) = (green, t_2^{green})$ $b_1(t_1^{green}) = (blue, t_2^{blue})$ $b_1(t_1^{red}) = (0.6) \cdot (blue, t_2^{blue}) + (0.4) \cdot (green, t_2^{green})$ $b_1(t_1^{yellow}) = (yellow, t_2^{yellow})$
Beliefs for player 2	$b_2(t_2^{blue}) = (blue, t_1^{blue})$ $b_2(t_2^{green}) = (green, t_1^{green})$ $b_2(t_2^{red}) = (red, t_1^{red})$ $b_2(t_2^{yellow}) = (yellow, t_1^{yellow})$

- In an epistemic model, we can **derive** for every type the **first-order** belief, **second-order** belief, and so on.
- So, we can derive for every type the **complete belief hierarchy** .

Types	$T_1 = \{t_1^{blue}, t_1^{green}, t_1^{red}, t_1^{yellow}\}$ $T_2 = \{t_2^{blue}, t_2^{green}, t_2^{red}, t_2^{yellow}\}$
Beliefs for player 1	$b_1(t_1^{blue}) = (green, t_2^{green})$ $b_1(t_1^{green}) = (blue, t_2^{blue})$ $b_1(t_1^{red}) = (0.6) \cdot (blue, t_2^{blue}) + (0.4) \cdot (green, t_2^{green})$ $b_1(t_1^{yellow}) = (yellow, t_2^{yellow})$
Beliefs for player 2	$b_2(t_2^{blue}) = (blue, t_1^{blue})$ $b_2(t_2^{green}) = (green, t_1^{green})$ $b_2(t_2^{red}) = (red, t_1^{red})$ $b_2(t_2^{yellow}) = (yellow, t_1^{yellow})$

## Definition (Epistemic model)

An **epistemic model** specifies for every player  $i$  a set  $T_i$  of possible **types**.

Moreover, for every type  $t_i$  it specifies a **probabilistic belief**  $b_i(t_i)$  over the set  $C_{-i} \times T_{-i}$  of opponents' **choice-type combinations**.

- Here,  $C_{-i} \times T_{-i}$  is the set of combinations

$$((c_1, t_1), \dots, (c_{i-1}, t_{i-1}), (c_{i+1}, t_{i+1}), \dots, (c_n, t_n))$$

of opponents' **choices** and opponents' **types**.

- For every such combination  $(c_{-i}, t_{-i}) \in C_{-i} \times T_{-i}$ , the **probability**

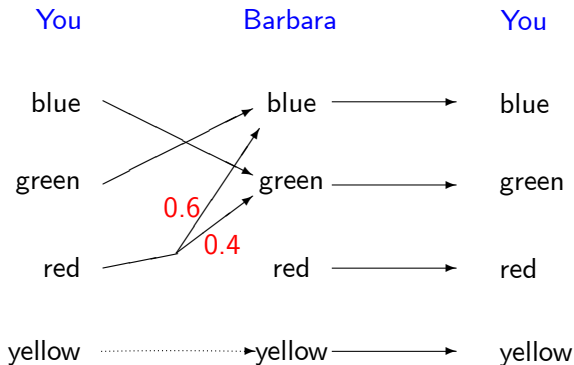
$$b_i(t_i)(c_{-i}, t_{-i})$$

represents the probability that type  $t_i$  assigns to the event that the opponents **choose**  $c_{-i}$  and that the opponents' **belief hierarchies** are given by  $t_{-i}$ .

- Belief hierarchies can also be encoded by **Kripke-structures** (Kripke, 1963) and **Aumann-structures** (Aumann, 1974, 1976).

# Common belief in rationality

- Intuitively, **common belief in rationality** means that
- you believe that your **opponents choose rationally**,
- you believe that your opponents believe that their **opponents choose rationally**,
- and so on, ad infinitum.
- How can we state **common belief in rationality formally**, within an epistemic model?



- Your type  $t_1^{red}$  has belief  $b_1(t_1^{red}) = (0.6) \cdot (blue, t_2^{blue}) + (0.4) \cdot (green, t_2^{green})$ .
- For Barbara, **blue** is optimal for type  $t_2^{blue}$ , and **green** is optimal for type  $t_2^{green}$ .
- So, type  $t_1^{red}$  **only assigns positive probability** to choice-type pairs for Barbara where the **choice is optimal** for the type.
- We say that  $t_1^{red}$  **believes in Barbara's rationality**.

## Definition (Belief in the opponents' rationality)

Type  $t_i$  **believes in the opponents' rationality** if his belief  $b_i(t_i)$  only assigns **positive probability** to choice-type combinations

$$((c_1, t_1), \dots, (c_{i-1}, t_{i-1}), (c_{i+1}, t_{i+1}), \dots, (c_n, t_n))$$

where choice  $c_1$  is **optimal** for type  $t_1, \dots$ , choice  $c_n$  is **optimal** for type  $t_n$ .

## Definition (Common belief in rationality)

Type  $t_i$  expresses **1-fold** belief in rationality if  $t_i$  **believes in the opponents' rationality**.

Type  $t_i$  expresses **2-fold** belief in rationality if  $t_i$  only assigns **positive probability to opponents' types** that express **1-fold** belief in rationality.

Type  $t_i$  expresses **3-fold** belief in rationality if  $t_i$  only assigns **positive probability to opponents' types** that express **2-fold** belief in rationality.

And so on.

Type  $t_i$  expresses **common belief in rationality** if  $t_i$  expresses  $k$ -fold belief in rationality for all  $k$ .

- This definition is similar to **Tan and Werlang (1988)**.
- In the literature, this concept is also known as **correlated rationalizability**. (**Brandenburger and Dekel (1987)**)



## Definition (Common belief in rationality)

Type  $t_i$  expresses **1-fold** belief in rationality if  $t_i$  **believes in the opponents' rationality**.

Type  $t_i$  expresses **2-fold** belief in rationality if  $t_i$  only assigns **positive probability to opponents' types** that express **1-fold** belief in rationality.

Type  $t_i$  expresses **3-fold** belief in rationality if  $t_i$  only assigns **positive probability to opponents' types** that express **2-fold** belief in rationality.

And so on.

Type  $t_i$  expresses **common belief in rationality** if  $t_i$  expresses  $k$ -fold belief in rationality for all  $k$ .

- **Rationalizability** (Bernheim (1984), Pearce (1984)) is obtained if in games with **three players or more** we impose the following additional condition:
- Player  $i$ 's belief about opponent  $j$ 's choice must be **independent** from his belief about opponent  $k$ 's choice.

## Definition

Player  $i$  can **rationally make choice  $c_i$  under common belief in rationality** if there is some epistemic model, and some type  $t_i$  within this epistemic model, such that

type  $t_i$  expresses **common belief in rationality**, and

choice  $c_i$  is **optimal** for type  $t_i$ .

## Theorem (Sufficient condition for common belief in rationality)

Consider an epistemic model in which all types *believe in the opponents' rationality*.

Then, all types in the epistemic model *express common belief in rationality*.

- **Proof:** Show that every type expresses *k-fold* belief in rationality, for all *k*.
- Every type expresses *1-fold* belief in rationality.
- Since a type can only assign positive probability to other types in the *same* model, every type expresses *2-fold* belief in rationality.
- But then, every type also expresses *3-fold* belief in rationality.
- And so on.
- Hence, all types express *common belief in rationality*. ■

	blue	green	red	yellow	same color as friend
you	4	3	2	1	0
Barbara	4	3	2	1	5

Types	$T_1 = \{t_1^{blue}, t_1^{green}, t_1^{red}\}$ $T_2 = \{t_2^{blue}, t_2^{green}, t_2^{red}\}$
Beliefs for player 1	$b_1(t_1^{blue}) = (green, t_2^{green})$ $b_1(t_1^{green}) = (blue, t_2^{blue})$ $b_1(t_1^{red}) = (0.6) \cdot (blue, t_2^{blue}) + (0.4) \cdot (green, t_2^{green})$
Beliefs for player 2	$b_2(t_2^{blue}) = (blue, t_1^{blue})$ $b_2(t_2^{green}) = (green, t_1^{green})$ $b_2(t_2^{red}) = (red, t_1^{red})$

- Every type believes in the opponent's rationality.
- Hence, every type expresses common belief in rationality.

- We look for an **algorithm** that helps us find those choices you can rationally make under **common belief in rationality**.
- Start with more **basic question**: Can we characterize those choices that are **rational** – that is, optimal for **some** belief?

- Consider the example “Going to a party”.

blue	green	red	yellow	same color as Barbara
4	3	2	1	0

- Only your choice **yellow** is **irrational**.
- Your choice **yellow** is **strictly dominated** by the **randomized choice** in which you choose **blue** and **green** with probability 0.5.

	blue	green	red	yellow
yellow	1	1	1	0
<b>randomized choice</b>	1.5	2	3.5	3.5

- In the example "Going to a party " we see the following:
- A choice is **irrational** precisely when it is **strictly dominated** by another choice, or **strictly dominated** by a **randomized choice**.
- In fact, this is always true!

### Theorem (Pearce's Lemma)

*A choice is **irrational**, if and only if, it is **strictly dominated** by another choice, or strictly dominated by a randomized choice.*

- Due to **Pearce (1984)**.
- Or, equivalently:

### Theorem (Pearce's Lemma)

*A choice is **rational**, if and only if, it is **not strictly dominated** by another choice, nor strictly dominated by a randomized choice.*

- Formally, a choice  $c_i$  is **strictly dominated by a choice**  $c'_i$  if

$$u_i(c_i, c_{-i}) < u_i(c'_i, c_{-i})$$

for every opponents' choice-combination  $c_{-i}$ .

- A **randomized choice** for player  $i$  is a probability distribution  $r_i$  over his set of choices  $C_i$ .
- A choice  $c_i$  is **strictly dominated by a randomized choice**  $r_i$  if

$$u_i(c_i, c_{-i}) < u_i(r_i, c_{-i})$$

for every opponents' choice-combination  $c_{-i}$ .



## Step 1: 1-fold belief in rationality

- Which choices are rational for a type that expresses 1-fold belief in rationality?
- If you believe in the opponents' rationality, then you assign positive probability only to opponents' choices that are rational.
- **Remember:** A choice is rational precisely when it is not strictly dominated.
- So, if you believe in the opponents' rationality, then you assign positive probability only to opponents' choices that are not strictly dominated.

## Step 1: 1-fold belief in rationality

- So, if you believe in the opponents' rationality, then you assign positive probability only to opponents' choices that are not strictly dominated.
- In a sense, you eliminate the opponents' strictly dominated choices from the game, and concentrate on the reduced game that remains.
- The choices that you can rationally make if you believe in your opponents' rationality, are exactly the choices that are optimal for you for some belief within this reduced game.
- But these are exactly the choices that are not strictly dominated for you within this reduced game.
- Hence, these are the choices that survive 2-fold elimination of strictly dominated choices.

## Step 2: Up to 2-fold belief in rationality

- Which choices are rational for a type that expresses up to 2-fold belief in rationality?
- Consider a type  $t_i$  that expresses up to 2-fold belief in rationality. Then,  $t_i$  only assigns positive probability to opponents' choice-type pairs  $(c_j, t_j)$  where  $c_j$  is optimal for  $t_j$ , and  $t_j$  expresses 1-fold belief in rationality.
- So, type  $t_i$  only assigns positive probability to opponents' choices  $c_j$  which are optimal for a type that expresses 1-fold belief in rationality.
- Hence, type  $t_i$  only assigns positive probability to opponents' choices  $c_j$  which survive 2-fold elimination of strictly dominated choices.

## Step 2: Up to 2-fold belief in rationality

- Hence, type  $t_i$  only assigns **positive probability** to opponents' choices  $c_j$  which survive **2-fold elimination** of strictly dominated choices.
- Then, every choice  $c_i$  which is **optimal** for  $t_i$  must be **optimal** for **some belief within the reduced game** obtained after **2-fold elimination** of strictly dominated choices.
- So, every choice  $c_i$  which is **optimal** for  $t_i$  must **not be strictly dominated** within the reduced game obtained after **2-fold elimination** of strictly dominated choices.
- **Conclusion:** Every choice that is **optimal** for a type that expresses **up to 2-fold** belief in rationality, must survive **3-fold elimination** of strictly dominated choices.

## Algorithm (Iterated elimination of strictly dominated choices)

**Step 1.** Within the *original game*, *eliminate* all choices that are *strictly dominated*.

**Step 2.** Within the *reduced game* obtained after step 1, *eliminate* all choices that are *strictly dominated*.

**Step 3.** Within the *reduced game* obtained after step 2, *eliminate* all choices that are *strictly dominated*.

⋮

*Continue in this fashion until no further choices can be eliminated.*

## Theorem (Algorithm “works”)

(1) For every  $k \geq 1$ , the choices that are *optimal* for a type that expresses *up to  $k$ -fold belief in rationality* are exactly those choices that survive  *$(k + 1)$ -fold elimination* of strictly dominated choices.

(2) The choices that can rationally be made under *common belief in rationality* are exactly those choices that survive *iterated elimination* of strictly dominated choices.

- Based on Theorems 5.1, 5.2 and 5.3 in [Tan and Werlang \(1988\)](#).
- [Adam Brandenburger \(2014\)](#) calls it the **Fundamental Theorem of Epistemic Game Theory**.

# Properties of the algorithm

## Algorithm (Iterated elimination of strictly dominated choices)

**Step 1.** Within the *original* game, *eliminate* all choices that are *strictly dominated*.

**Step 2.** Within the *reduced game* obtained after step 1, *eliminate* all choices that are *strictly dominated*.

**Step 3.** Within the *reduced game* obtained after step 2, *eliminate* all choices that are *strictly dominated*.

⋮

*Continue in this fashion until no further choices can be eliminated.*

- This algorithm always **stops after finitely many steps**.
- It always yields a **nonempty output** for every player.
- The **order** and **speed** by which you **eliminate** choices is **not relevant** for the eventual output.

## Theorem (Algorithm “works”)

(1) For every  $k \geq 1$ , the choices that are *optimal* for a type that expresses *up to  $k$ -fold belief in rationality* are exactly those choices that survive  *$(k + 1)$ -fold elimination* of strictly dominated choices.

(2) The choices that can rationally be made under *common belief in rationality* are exactly those choices that survive *iterated elimination* of strictly dominated choices.

- **Proof of part (2):**
- We have shown: If a choice can rationally be made under **common belief in rationality**, then it must survive **iterated elimination of strictly dominated choices**.



- We now show the **converse**: If a choice survives **iterated elimination** of strictly dominated choices, then it can rationally be made under **common belief in rationality**.
- Assume **two players**. Suppose that the algorithm **terminates after  $K$  steps**. Let  $C_i^K$  be the set of **surviving choices** for player  $i$ .
- Then, every choice in  $C_i^K$  is **not strictly dominated** within **reduced game  $\Gamma^K$** . Hence, every choice  $c_i$  in  $C_i^K$  is **optimal** for some belief  $b_i^{c_i} \in \Delta(C_j^K)$ .
- Define set of **types**  $T_i = \{t_i^{c_i} : c_i \in C_i^K\}$  for both players  $i$ .
- Every type  $t_i^{c_i}$  **only deems possible** opponents' choice-type pairs  $(c_j, t_j^{c_j})$ , with  $c_j \in C_j^K$ , and

$$b_i(t_i^{c_i})(c_j, t_j^{c_j}) := b_i^{c_i}(c_j).$$

- Then, every type  $t_i^{c_i}$  **believes in the opponents' rationality**.
- Hence, every type expresses **common belief in rationality**. ■

Corollary (Common belief in rationality is always possible)

*We can always construct an epistemic model in which **all types** express **common belief in rationality**.*

# Other classes of games

- **Common belief in rationality**, and an associated **algorithm**, have also been defined for **other classes of games**:
- **games with incomplete information**: Battigalli and Siniscalchi (1999, 2002, 2007), Battigalli (2003), Battigalli, Di Tillio, Grillo and Penta (2011), Battigalli and Prestipino (2011), Bach and Perea (2016)
- **games with unawareness**: Perea (2017)
- **psychological games**: Battigalli and Dufwenberg (2009), Bjorndahl, Halpern and Pass (2013), Jagau and Perea (2017), Mourmans (2017)
- **Research question**: Simple algorithms for (certain classes of) psychological games?
- **Research question**: Application of common belief in rationality to models in economics?







# Example: Guessing two-thirds of the average

## Story

- Is also known as the “Guessing Game”, or “Beauty Contest”.
- Has been studied experimentally in Nagel (1995).
- All students in this room must write a number on a piece of paper, between 1 and 100.
- The closer you are to two-thirds of the average of all numbers, the higher your prize money.







- What number(s) could you have rationally written down under **common belief in rationality**?
- Apply the algorithm of “**iterated elimination of strictly dominated choices**”.
- **Step 1:** What numbers are **strictly dominated**?
- **Two-thirds of the average** can never be above 67.
- Hence, every number above 67 is **strictly dominated** by 67.
- **Eliminate** all numbers above 67.






- **Step 2:** Consider the **reduced game**  $\Gamma^1$  in which only the numbers 1, ..., 67 remain for all students.
- Which numbers are **strictly dominated** in  $\Gamma^1$  ?
- **Two-thirds of the average** of all numbers in  $\Gamma^1$  can never be above  $\frac{2}{3} \cdot 67 \approx 45$ .
- All numbers above 45 are **strictly dominated** in  $\Gamma^1$ .
- **Eliminate** all numbers above 45.
- And so on.
- Only the **number 1** remains at the end.
- Under **common belief in rationality**, you must choose number 1.
- Would you really choose this number? Why?







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