COL749: Computational Social Choice

Lecture 7

Cake Cutting

Jan 27, 2025 | Rohit Vaish

Fair Division

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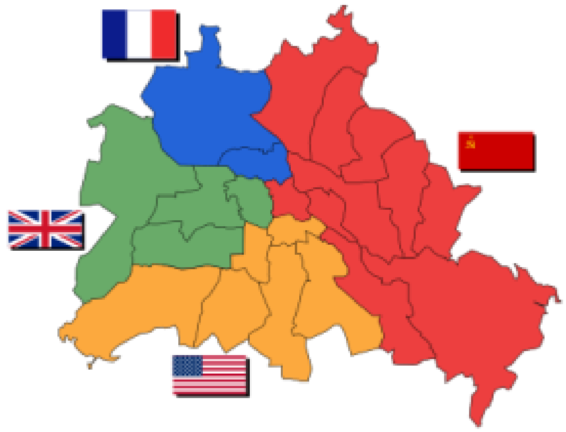

Fair Division

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Divisible

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Cake Cutting

How to fairly divide a cake

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How to fairly divide a cake

among agents with differing preferences?

Why is this problem interesting?

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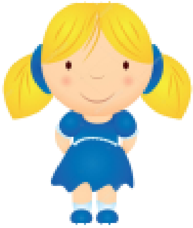

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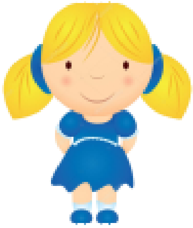

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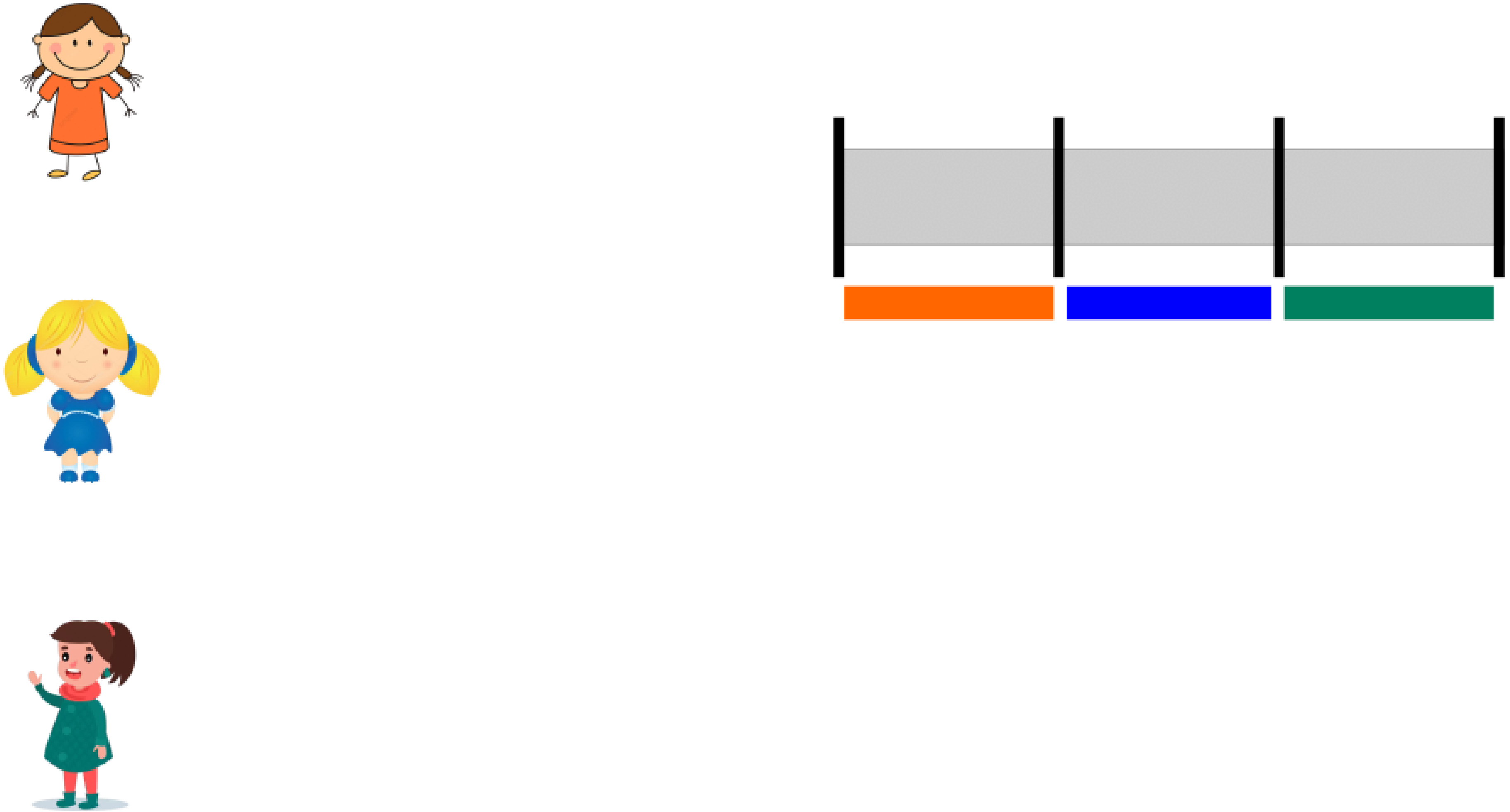

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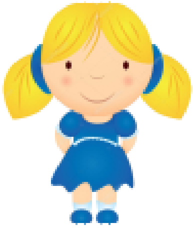

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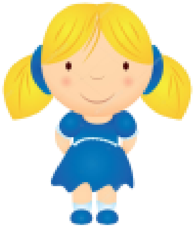

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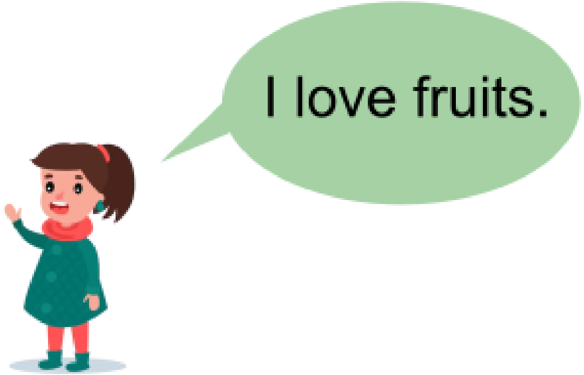

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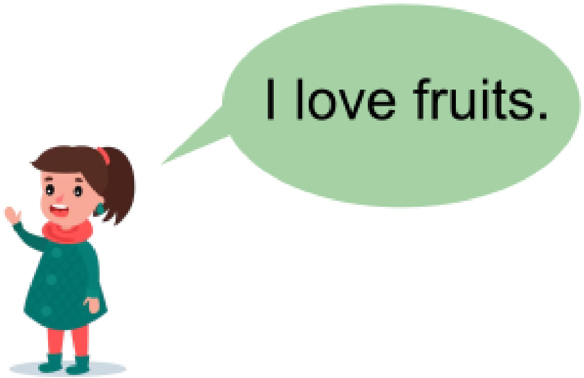

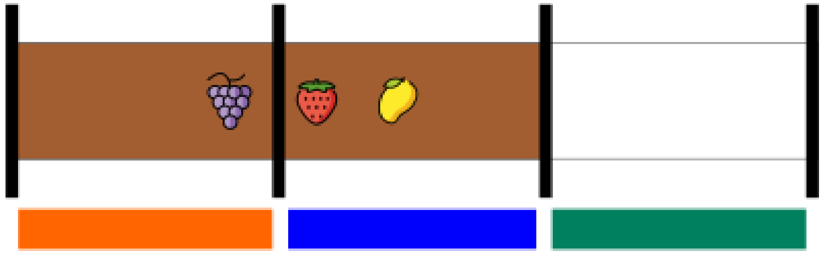

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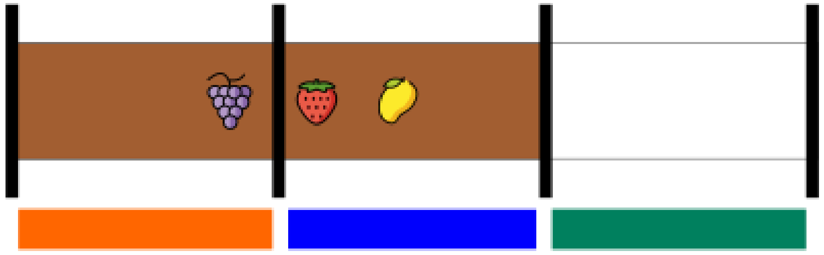

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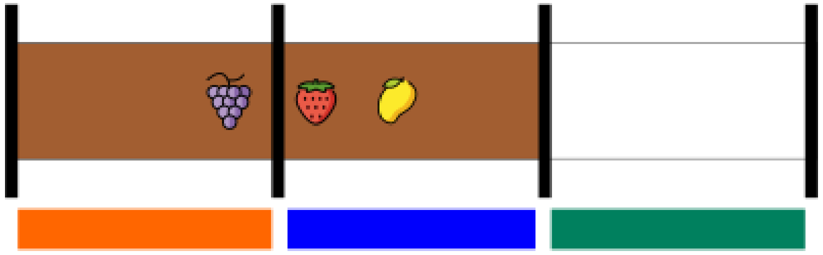

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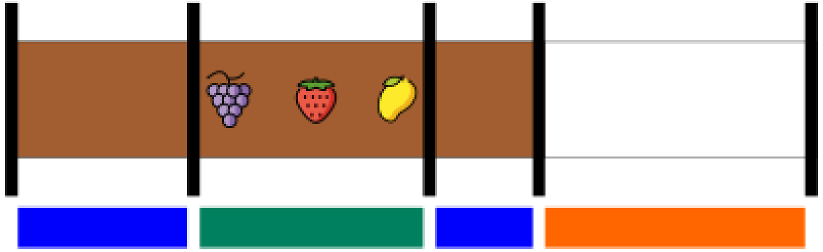

A fairer division 

Why is this problem interesting?

Preferences matter!

The Model

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- The resource: Cake [0,1]

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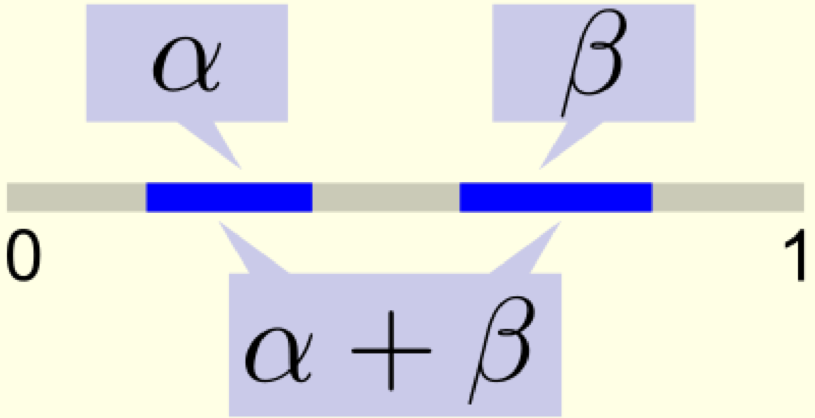

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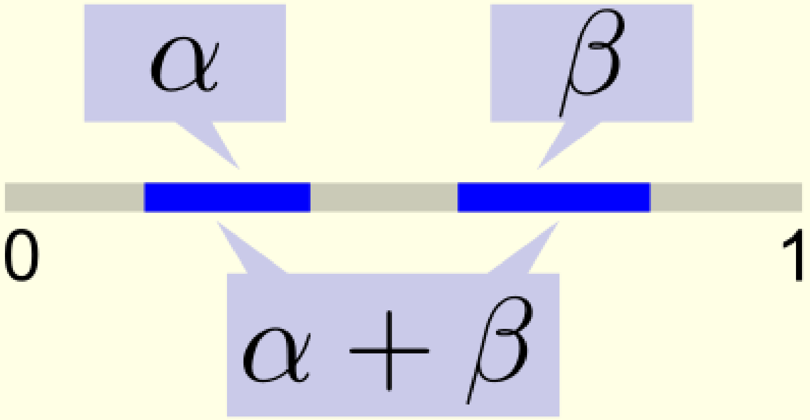

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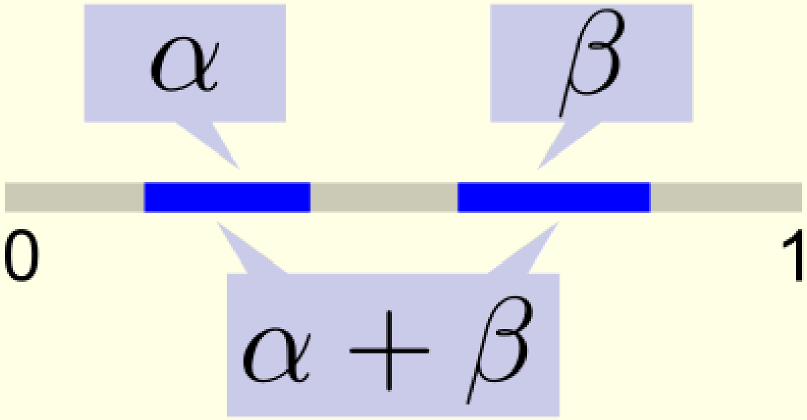

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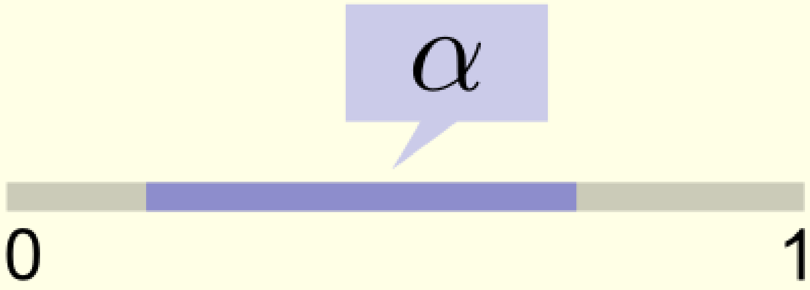

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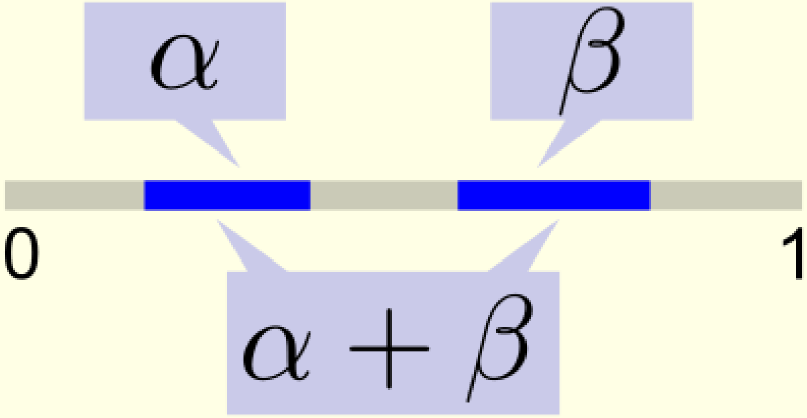

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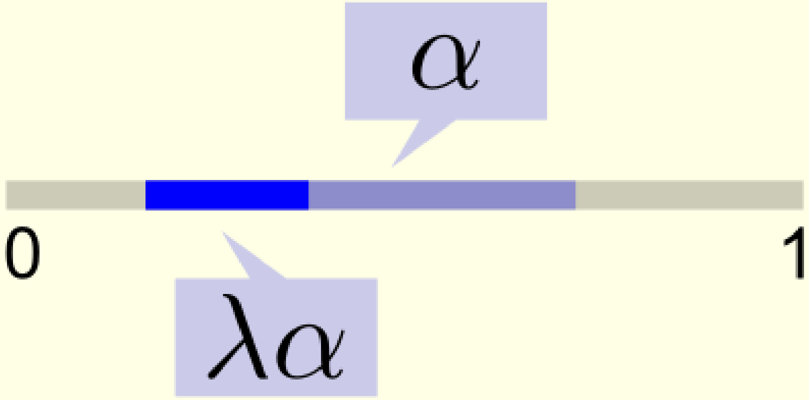

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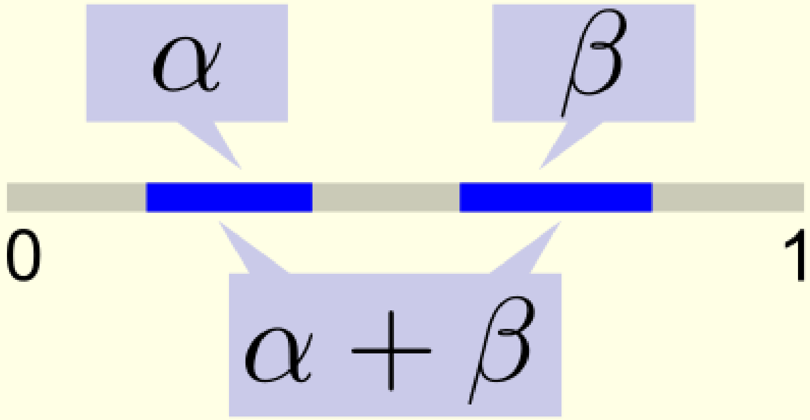

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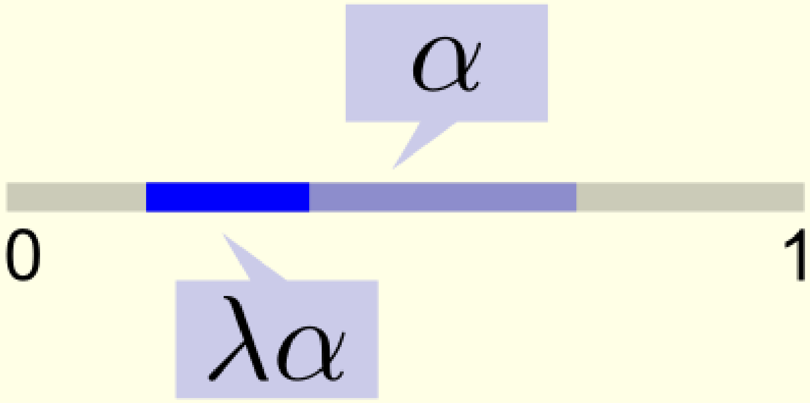

Normalization: for each agent i, $v_i([0,1]) = 1$.

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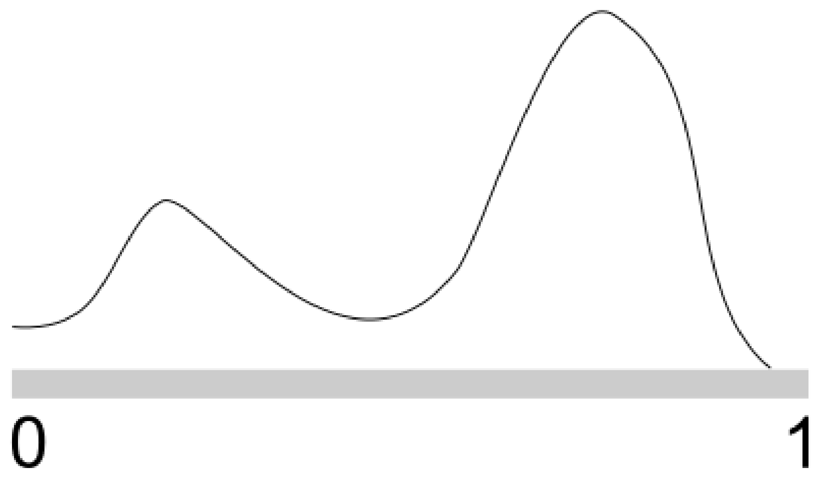
$$v_i(X) = \int_{x \in X} f_i(x)dx$$



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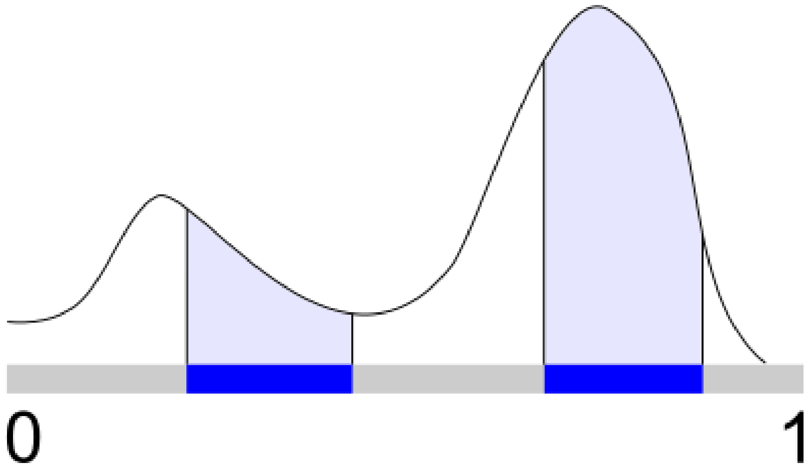
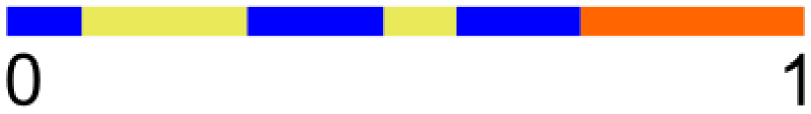


Fairness notions

- *Allocation/Division*: A partition $(A_1, A_2, \ldots, A_n)$ of the cake [0,1] where each A_i is a piece of cake.



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for each agent i,

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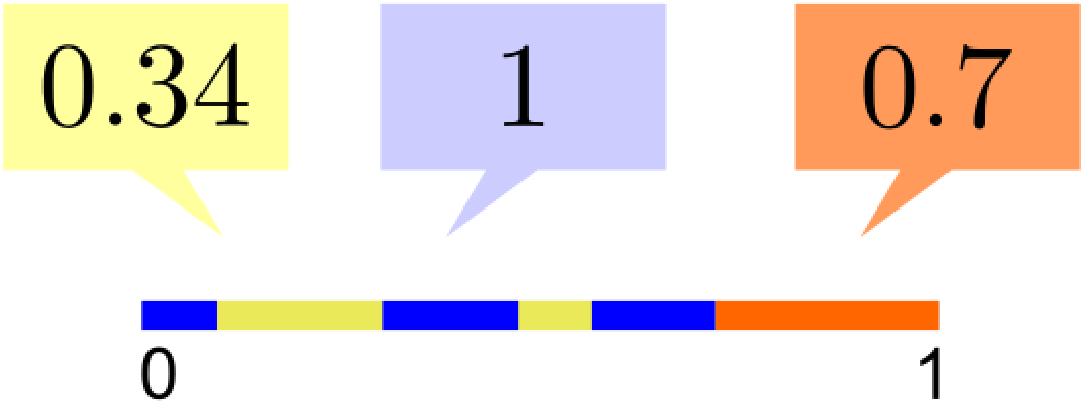

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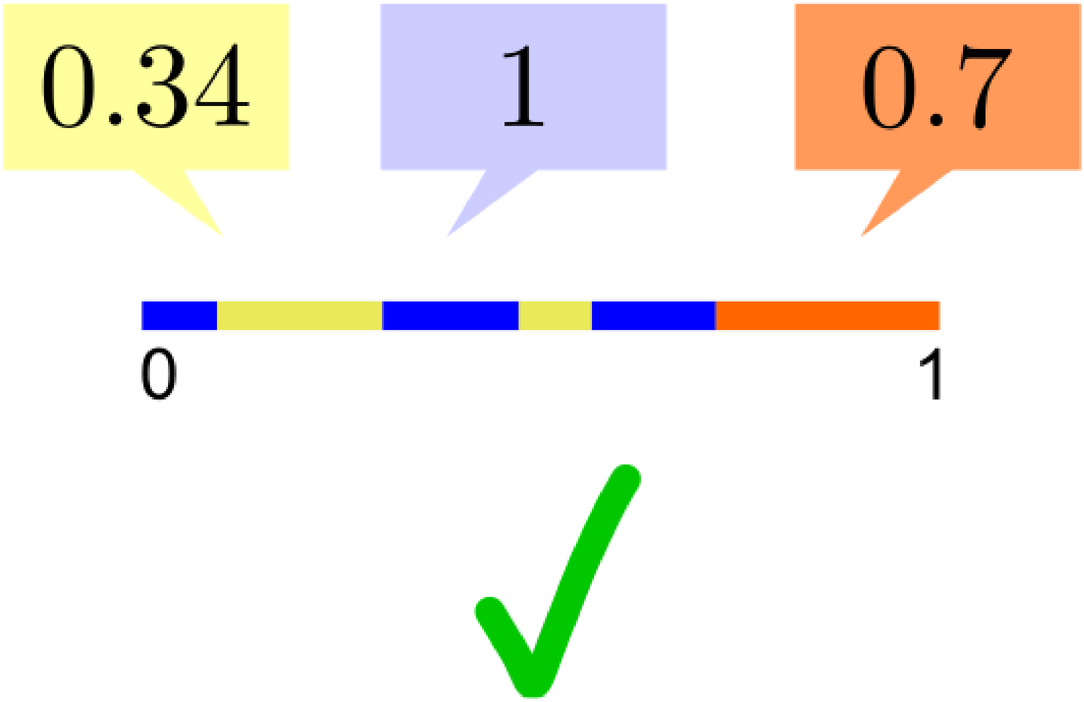

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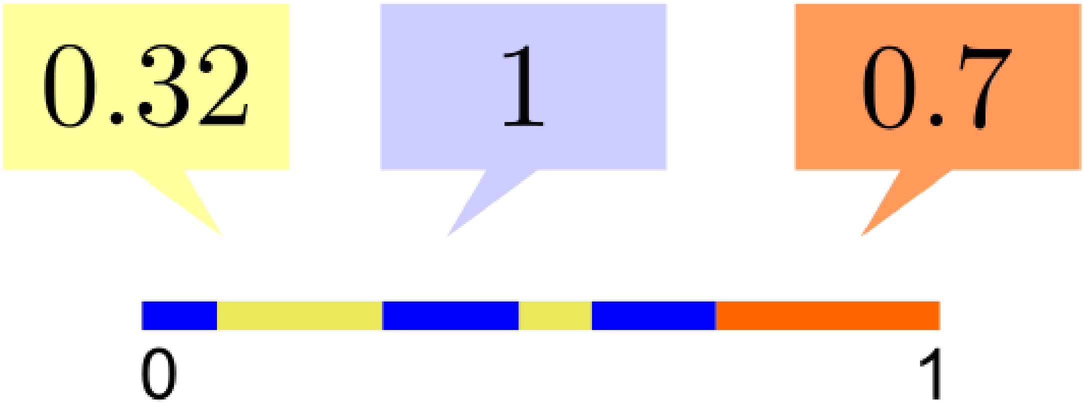

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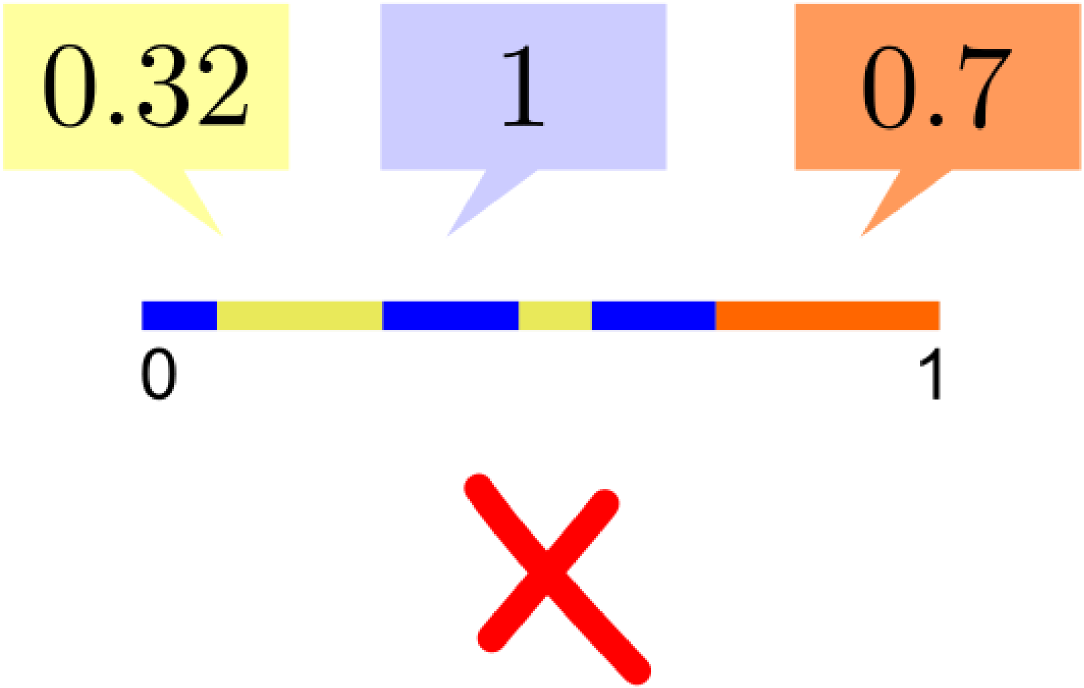

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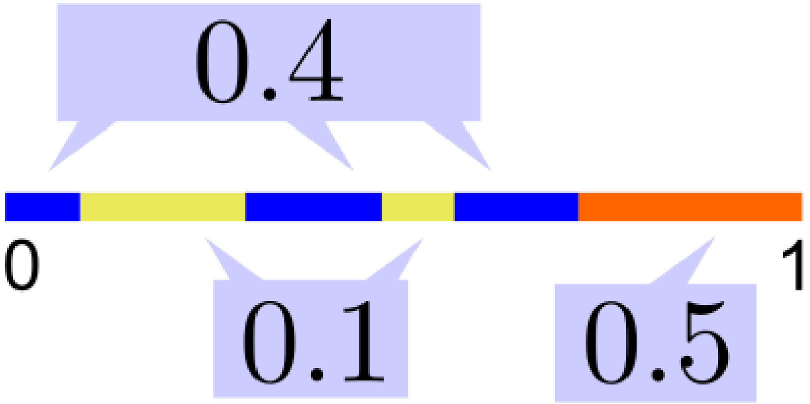

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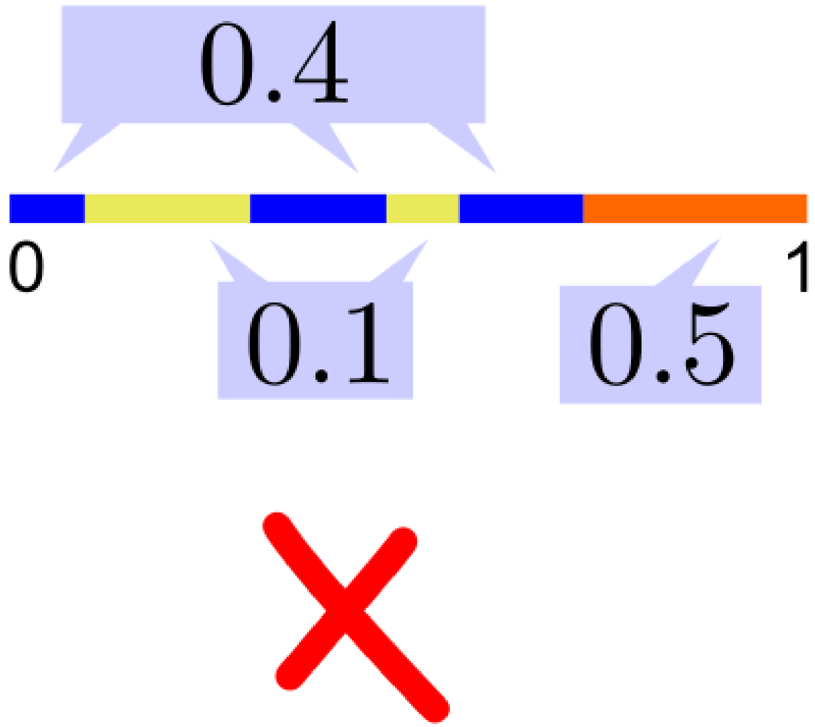

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For two agents (n=2), is one property stronger than the other?

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What about three or more agents?

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EF implies Prop for *any* number of agents

Prop implies EF for *two* agents (but no more)

Robertson-Webb Query Model

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$\texttt{eval}_i(x, y)$: returns $v_i([x, y])$

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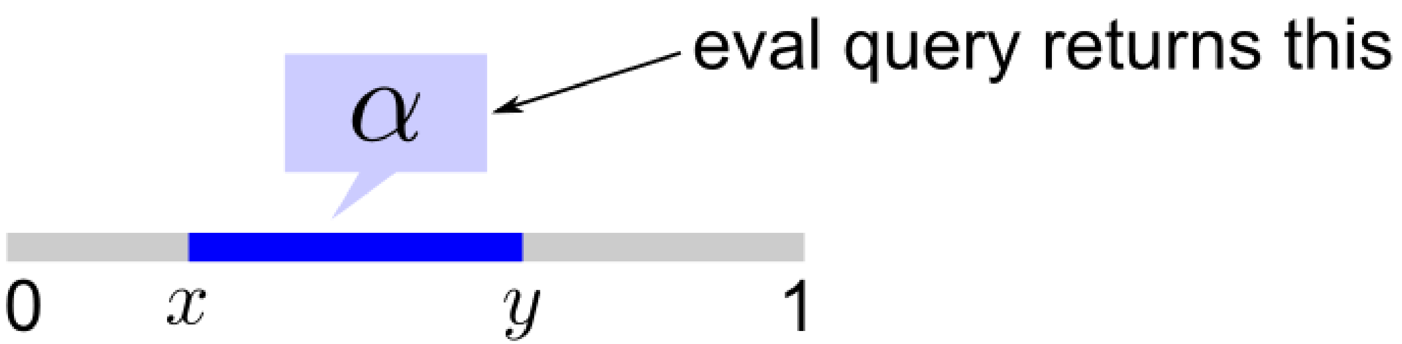

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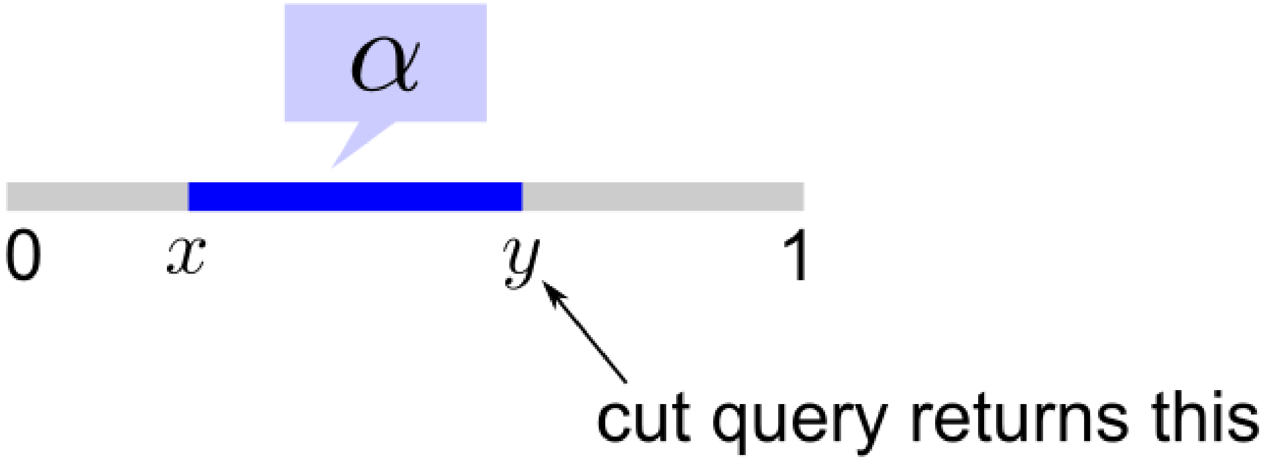

Cake-Cutting Algorithms

Let's start by thinking about proportionality for two agents.

Cut and Choose

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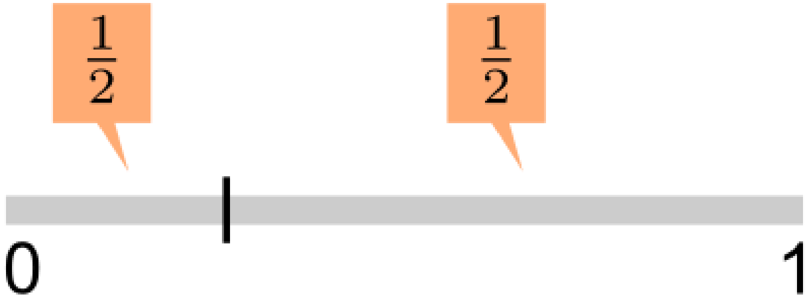

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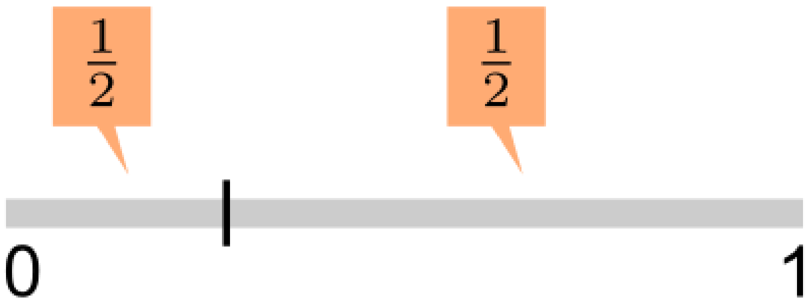

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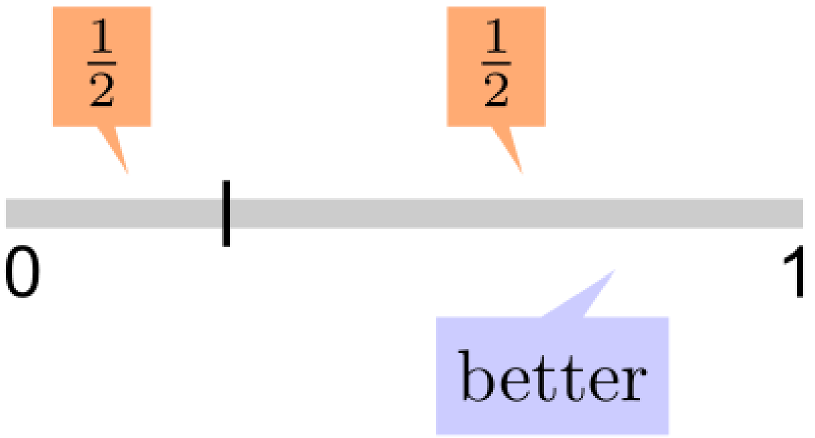

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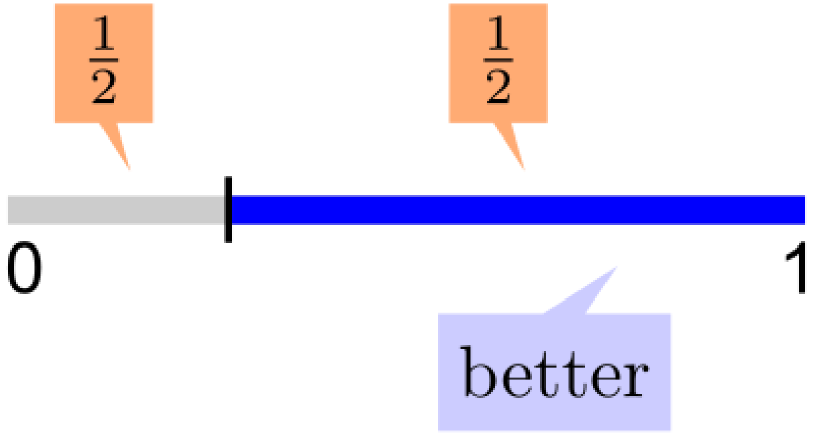

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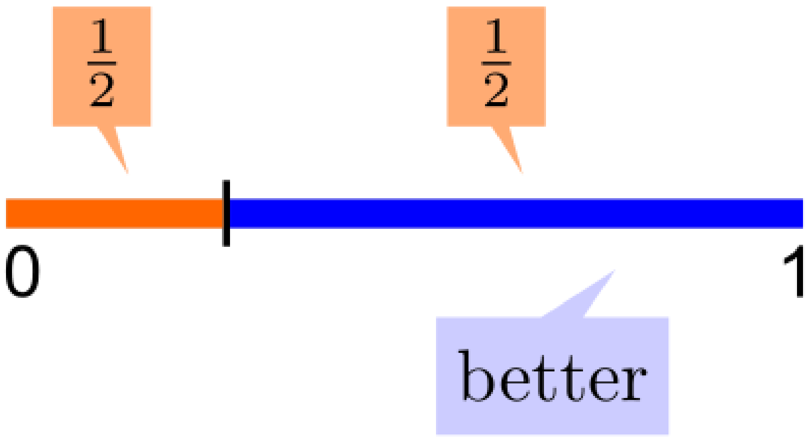

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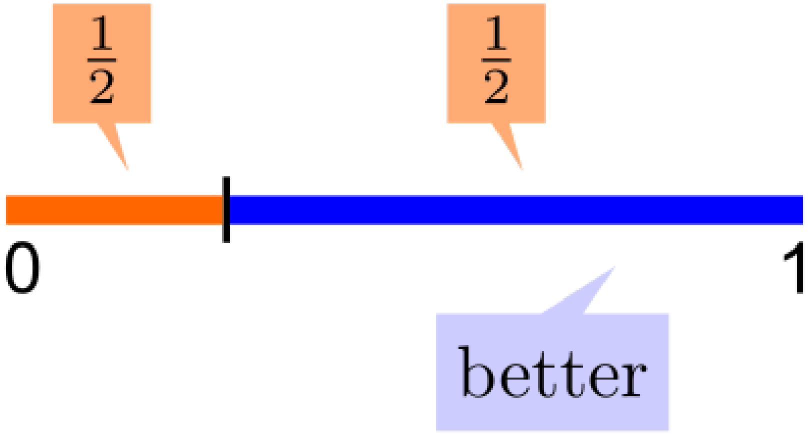

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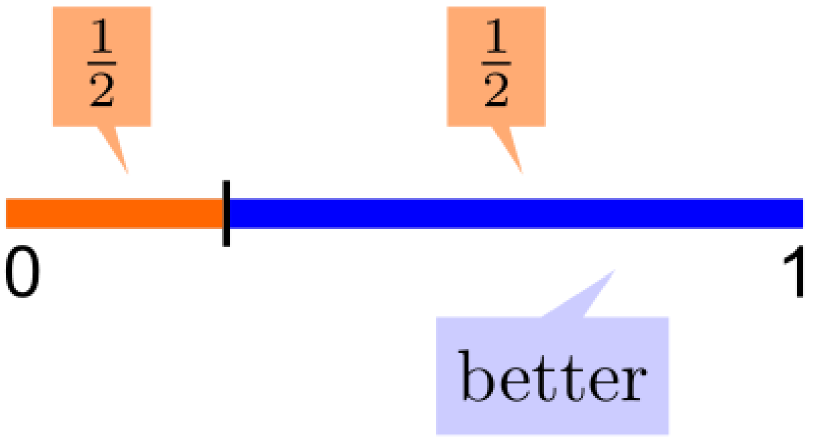

Is the cut-and-choose outcome proportional?

Yes! Agent 2's value is at least 1/2. Agent 1's value is exactly 1/2.

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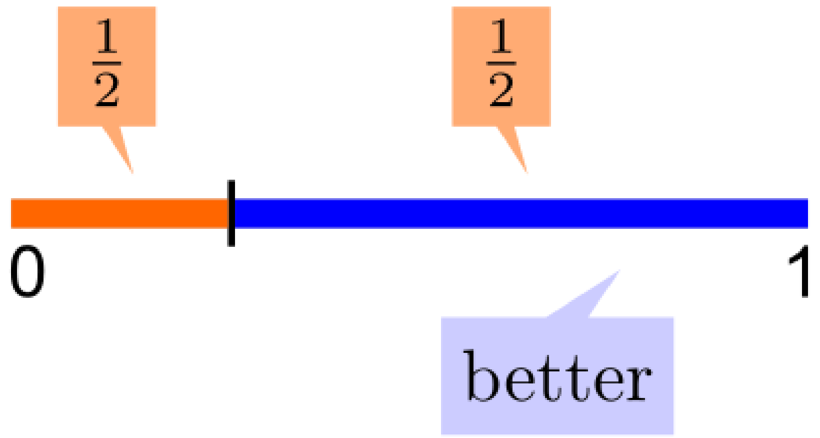

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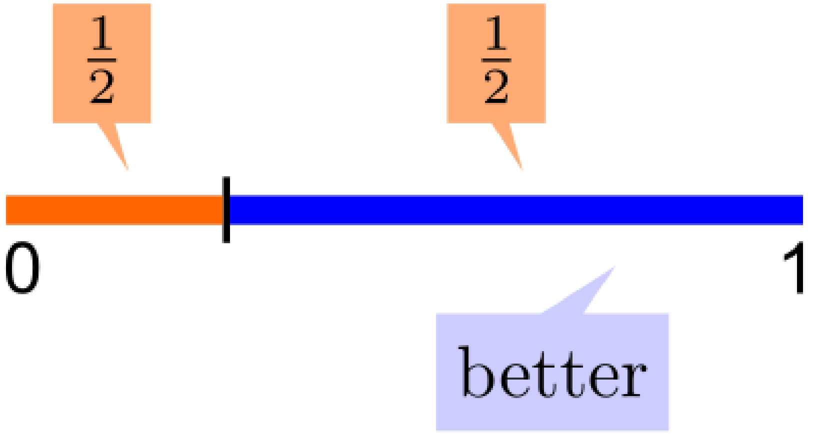

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Yes! EF and Prop are equivalent for two agents.

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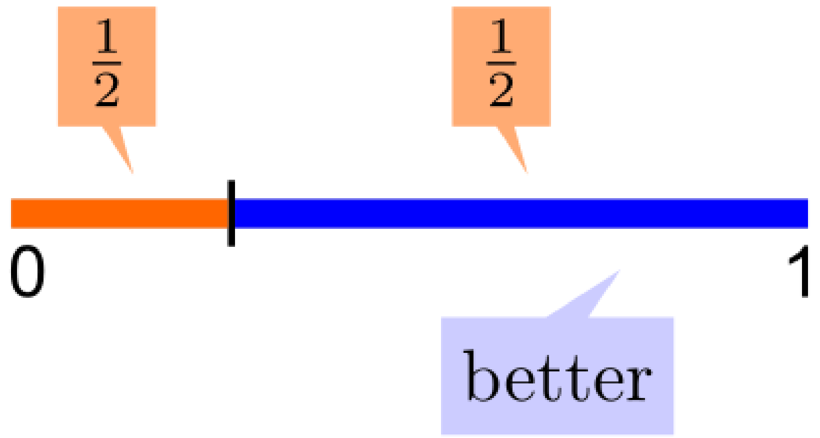
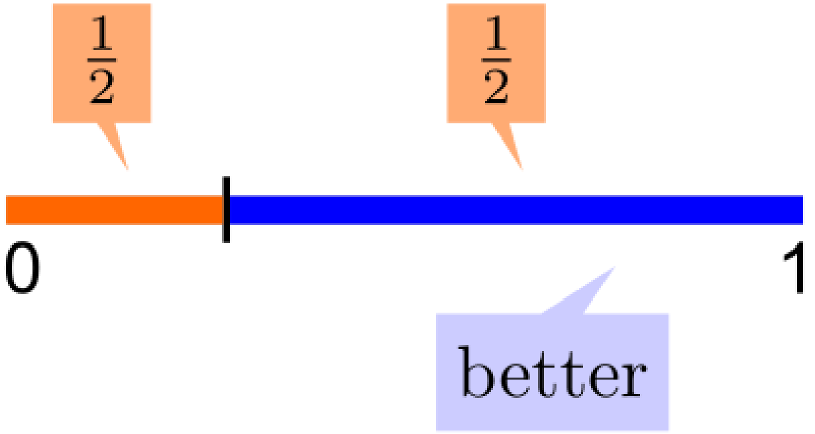


Can cut-and-choose be implemented in the Robertson-Webb model?

Cut and Choose

1. Agent 1 cuts the cake into two equally-valued pieces (as per v_1).
2. Agent 2 chooses its preferred piece (as per v_2), and agent 1 gets the remaining piece.



Can cut-and-choose be implemented in the Robertson-Webb model?

$$y = \texttt{cut}_1(0, 1/2)$$

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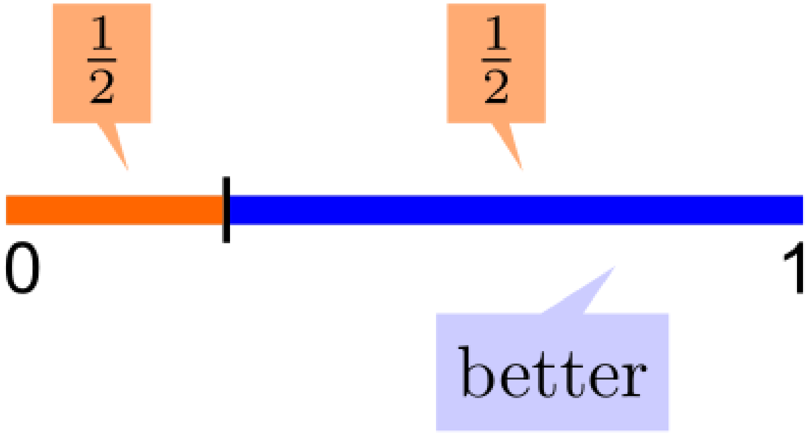

Can cut-and-choose be implemented in the Robertson-Webb model?

$$y = \texttt{cut}_1(0, 1/2)$$

$$\texttt{eval}_2(0, y)$$

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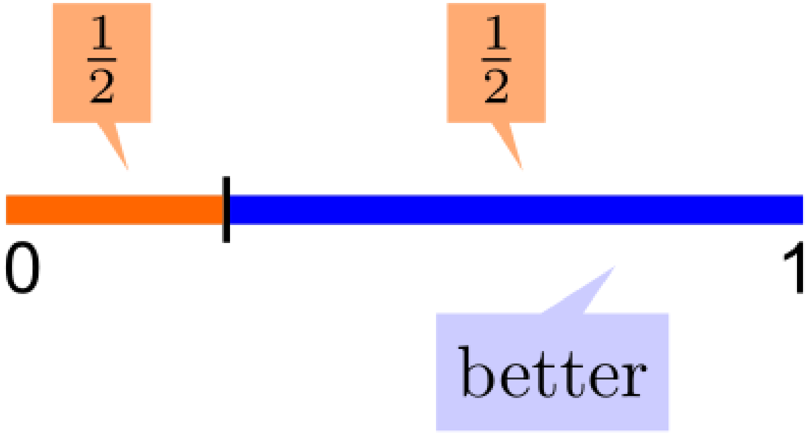

For two agents, an envy-free/proportional cake division can be computed using two queries.

Dubins-Spanier Procedure

A proportional cake division protocol for any number of agents

Dubins-Spanier Procedure

1. A referee gradually moves a knife from left to right.

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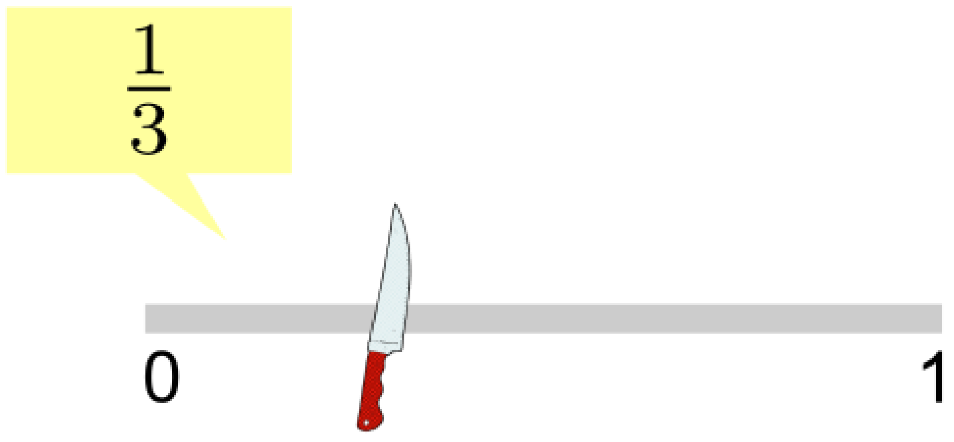

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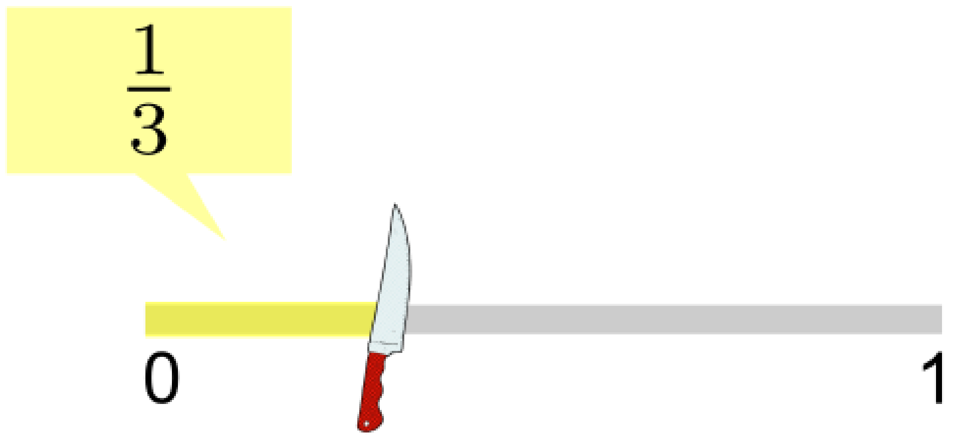

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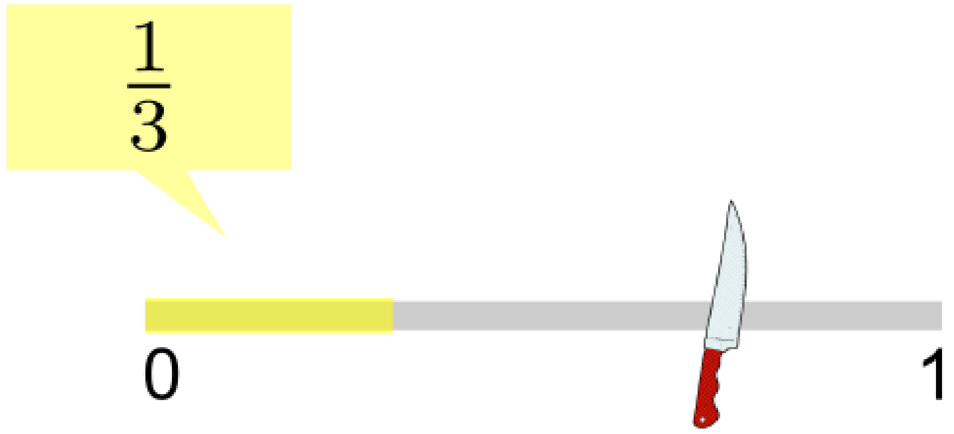

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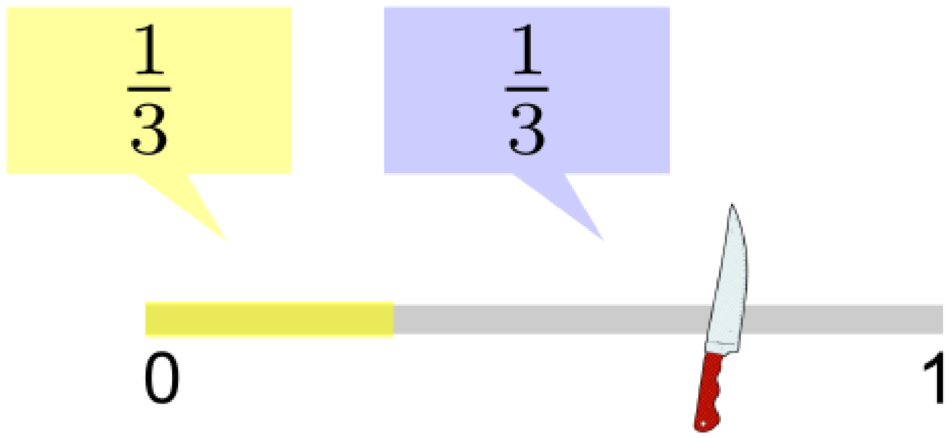

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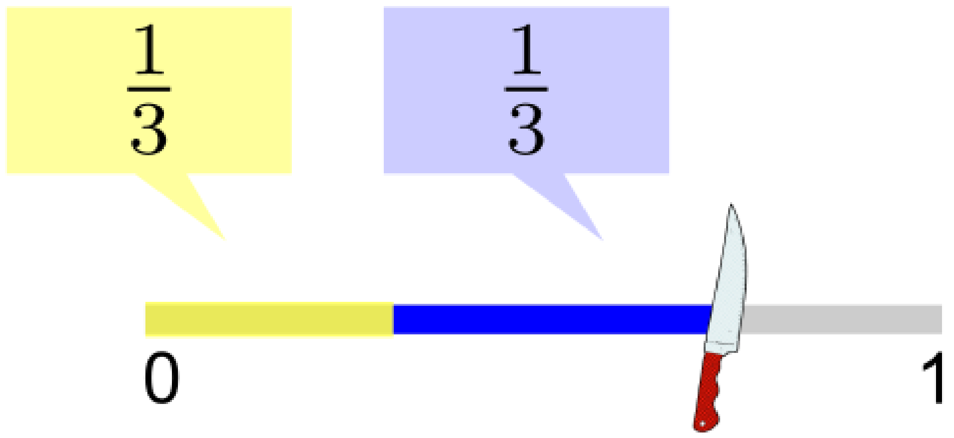

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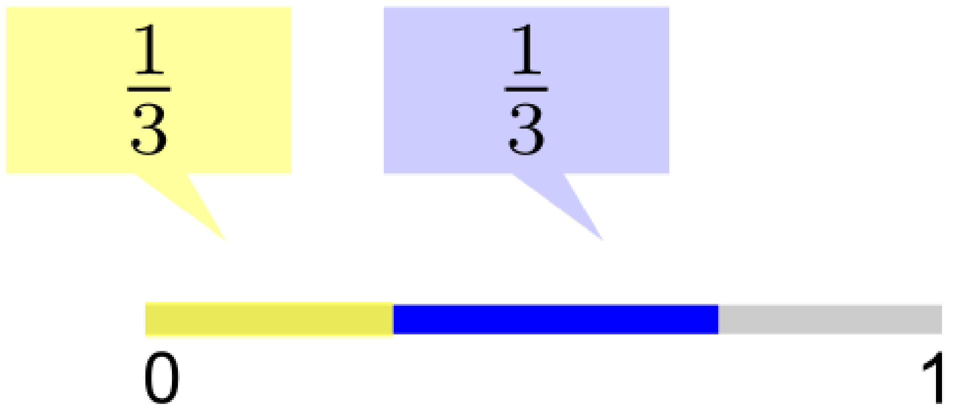

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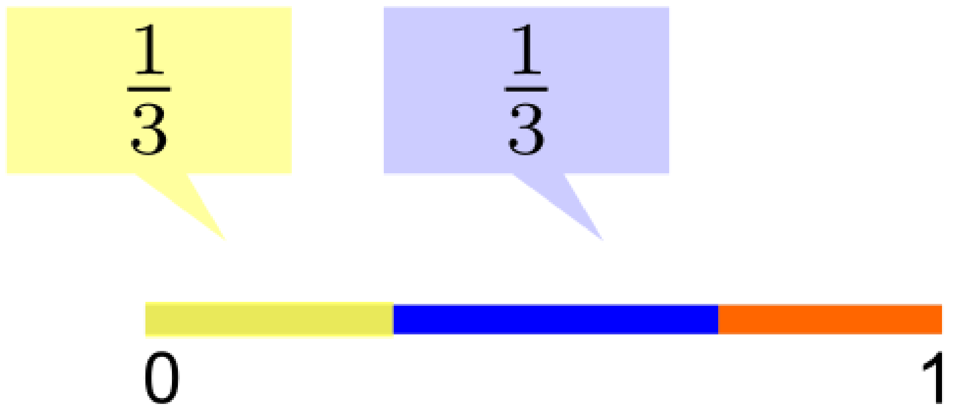

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Why is the resulting allocation proportional?

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Why is the resulting allocation proportional?

Every agent except for the last one gets *exactly* 1/n.
The last agent gets *at least* 1/n.

Dubins-Spanier Procedure

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Can this procedure be implemented in the Robertson-Webb model?

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Can this procedure be implemented in the Robertson-Webb model?

Yes!

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Query complexity in the Robertson-Webb model?

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Query complexity in the Robertson-Webb model?

$\mathcal{O}(n^2)$ queries (Exercise)

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For n agents, a proportional cake division can be computed using $O(n^2)$ queries.

The Story of Proportionality

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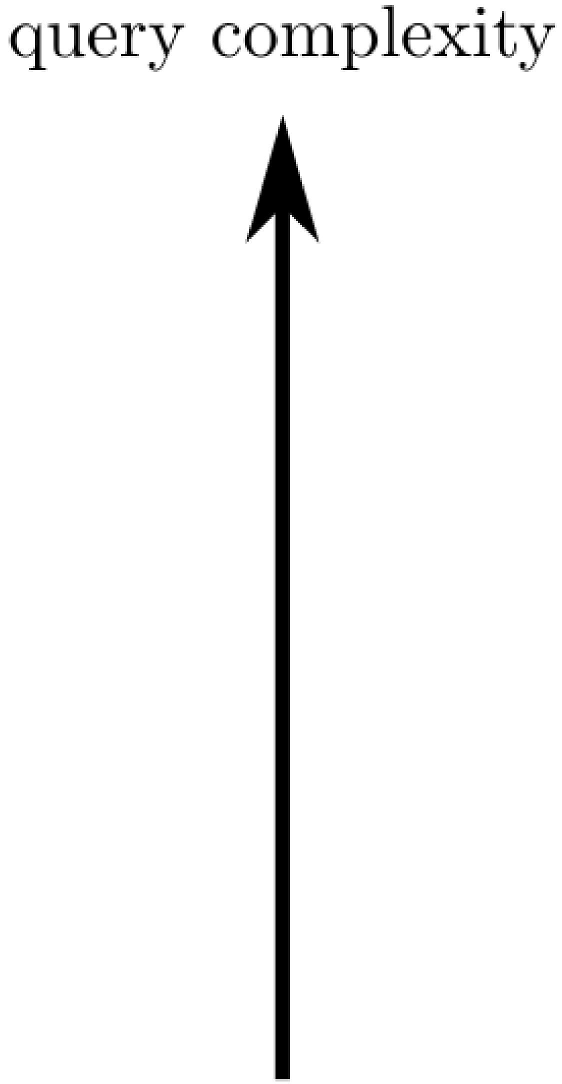

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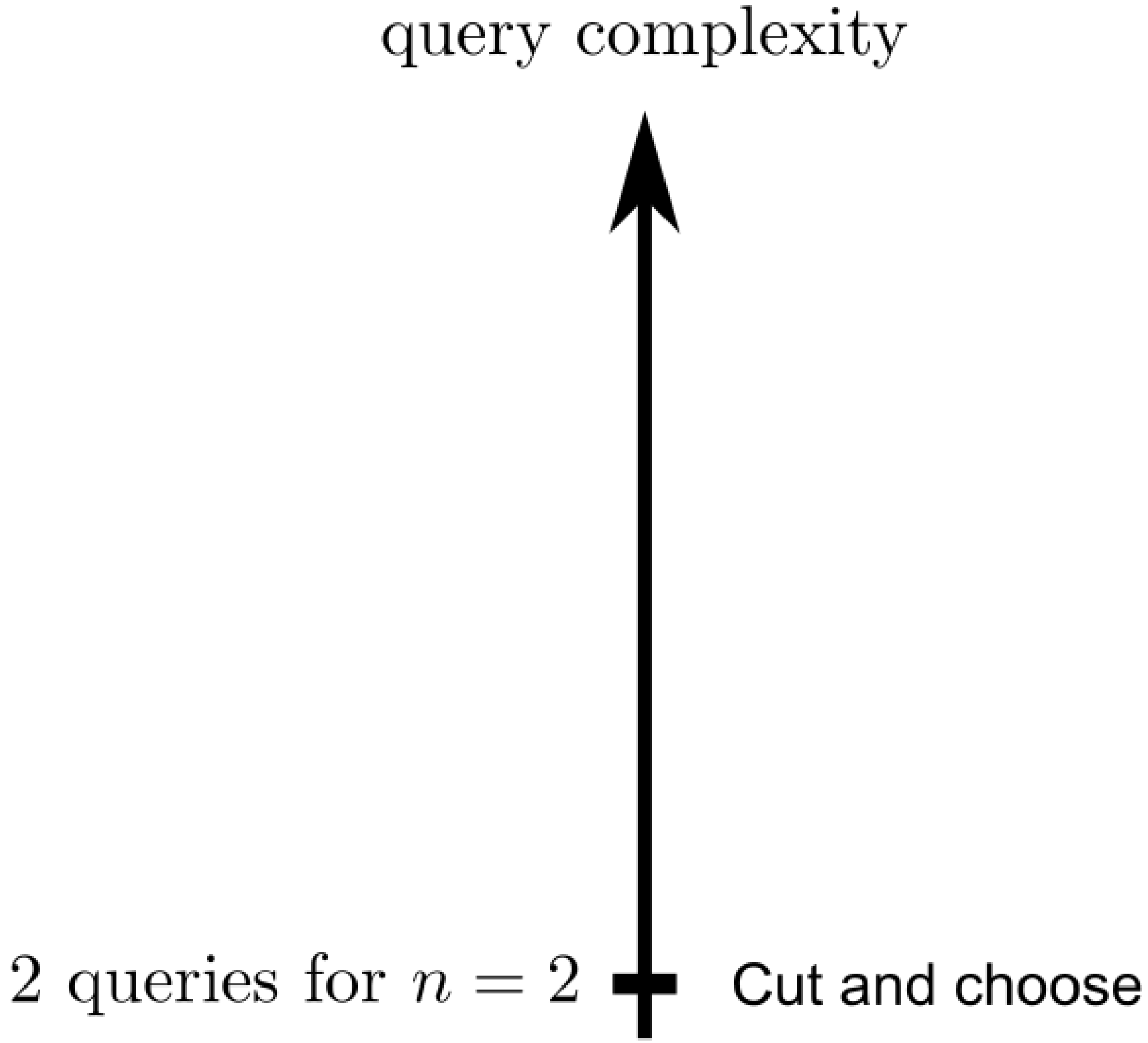

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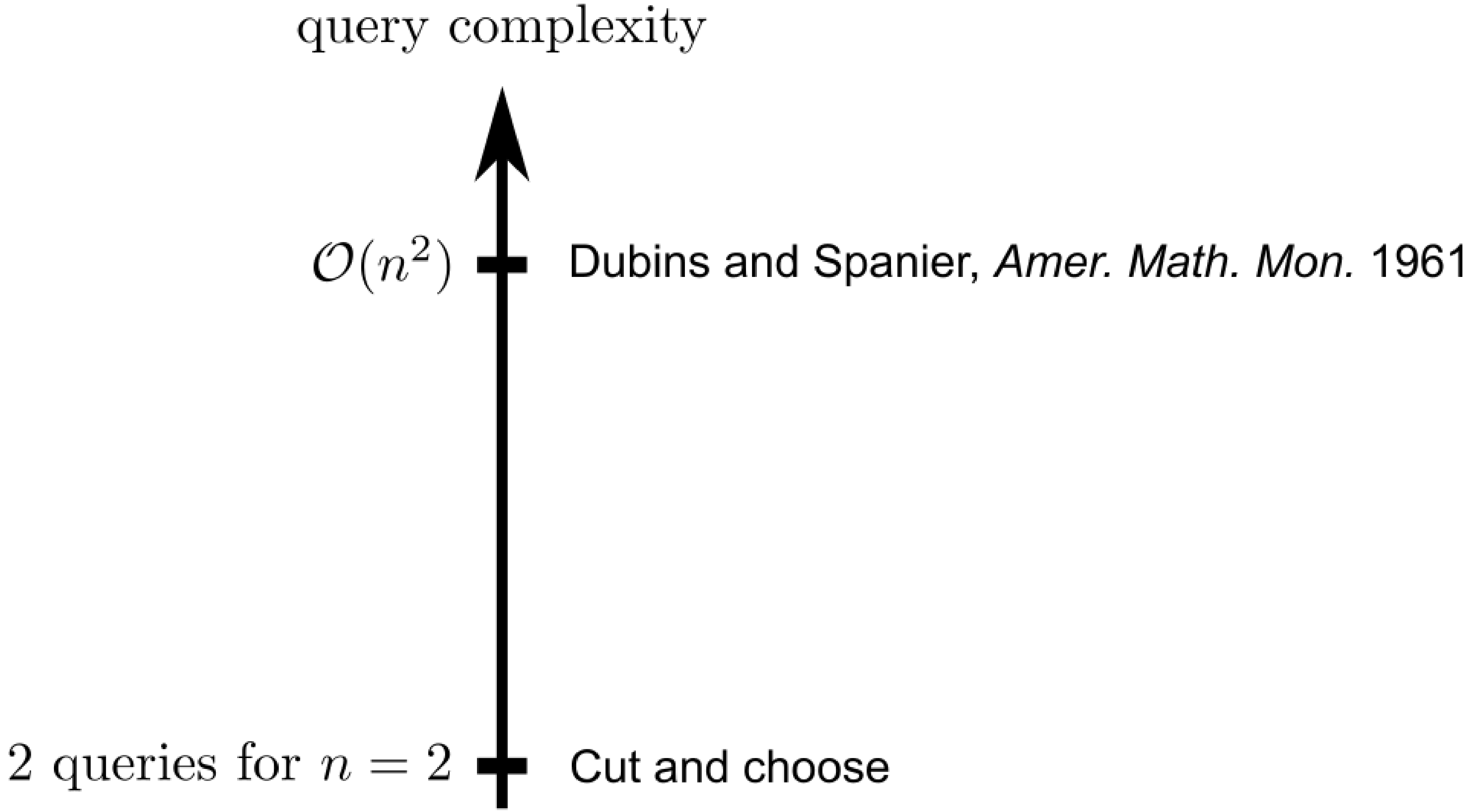

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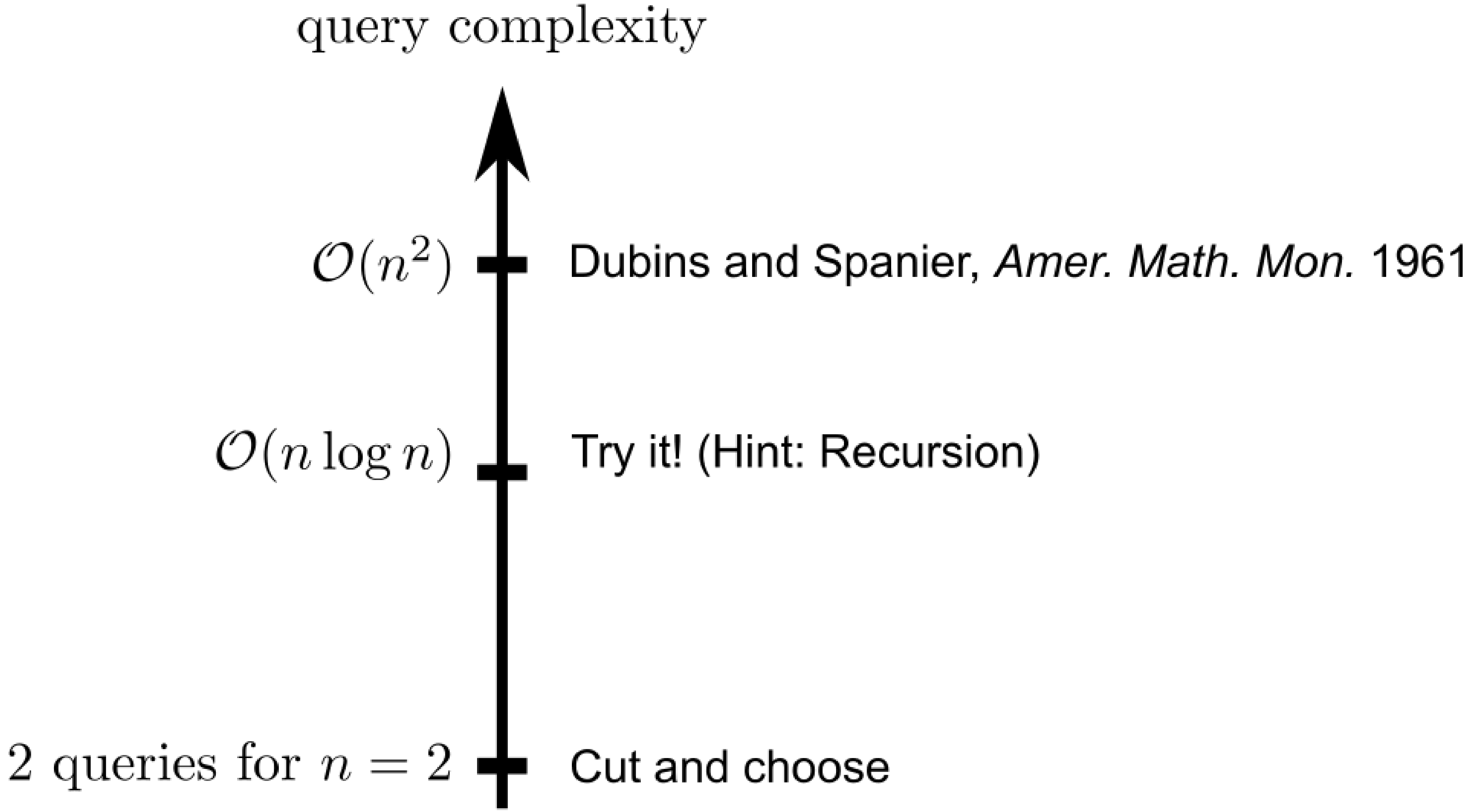

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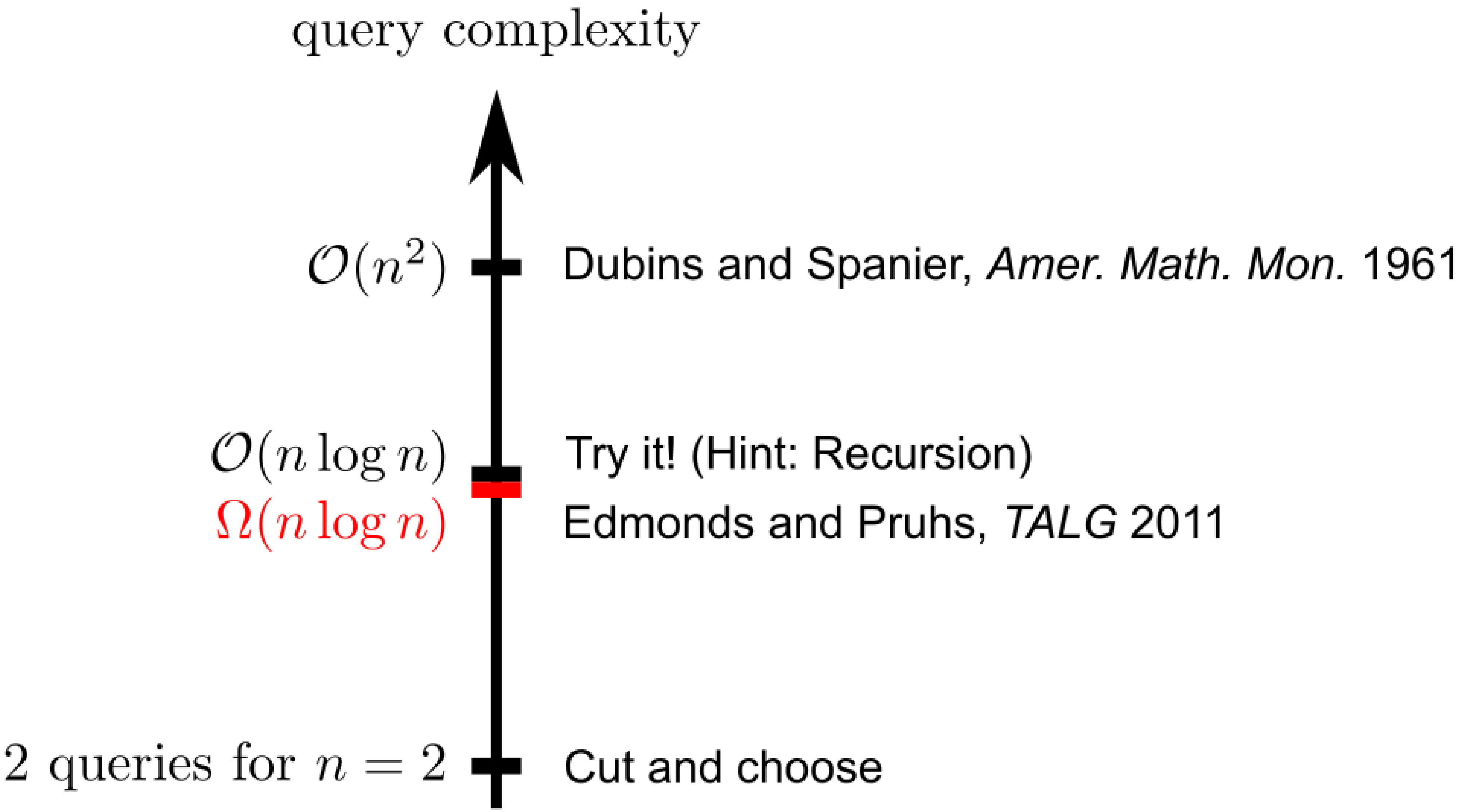


The Story of Envy-freeness

Selfridge-Conway Procedure

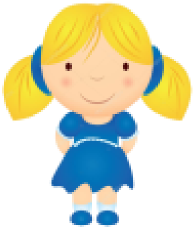
An envy-free cake division protocol for three agents

Envy-free for three

Envy-free for three

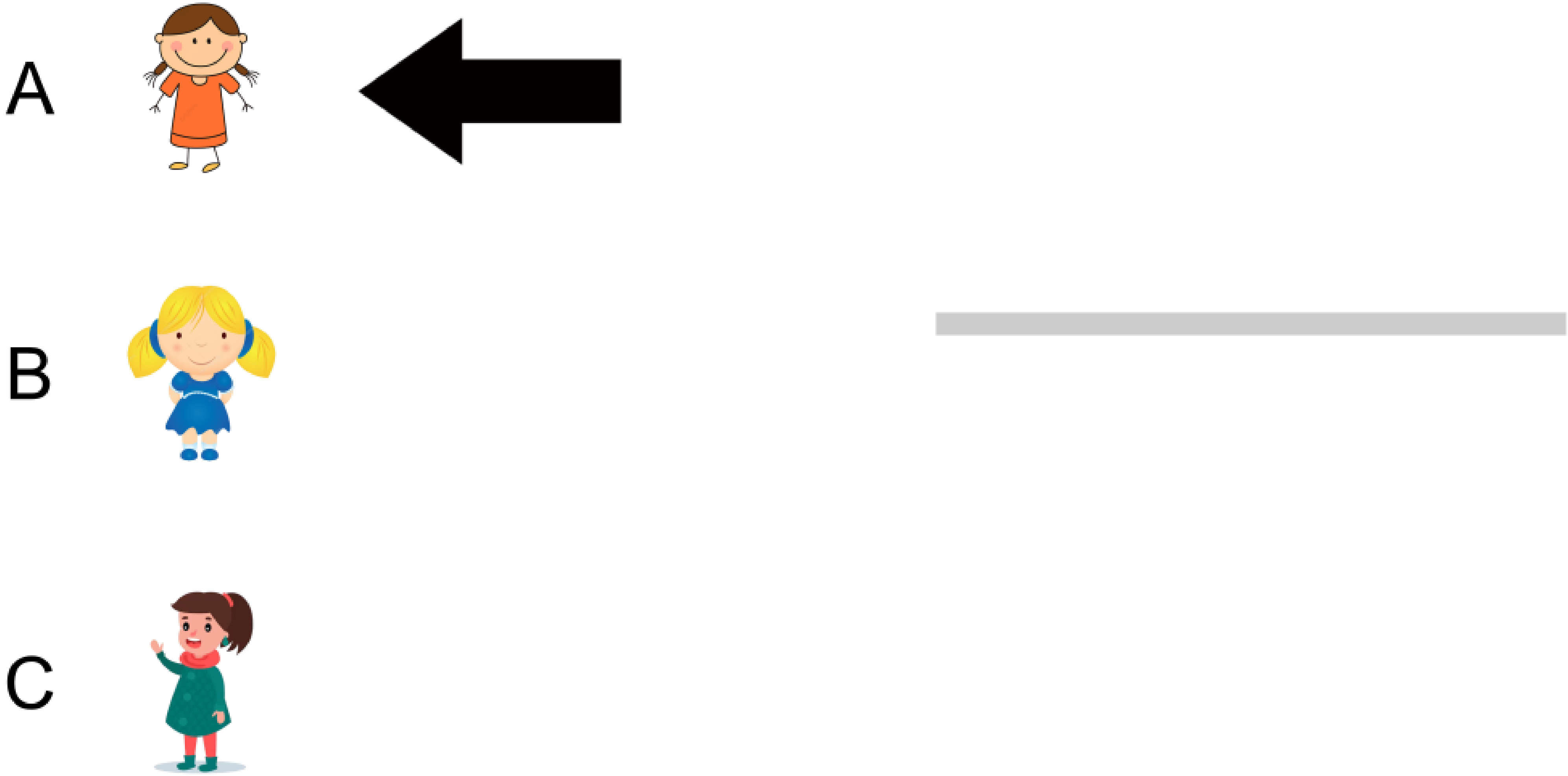
A

B



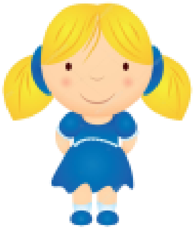
C

Envy-free for three



Envy-free for three

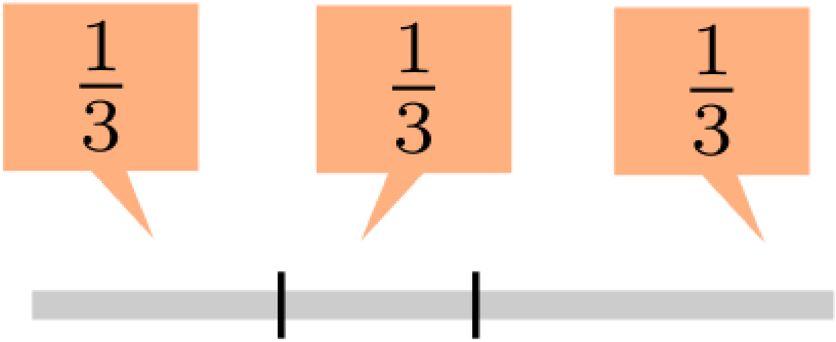
A 

B 

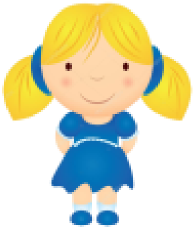
C 

Envy-free for three

A



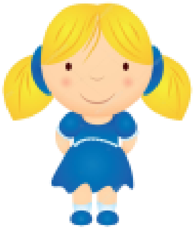
B



C

Envy-free for three

A 

B  

C 

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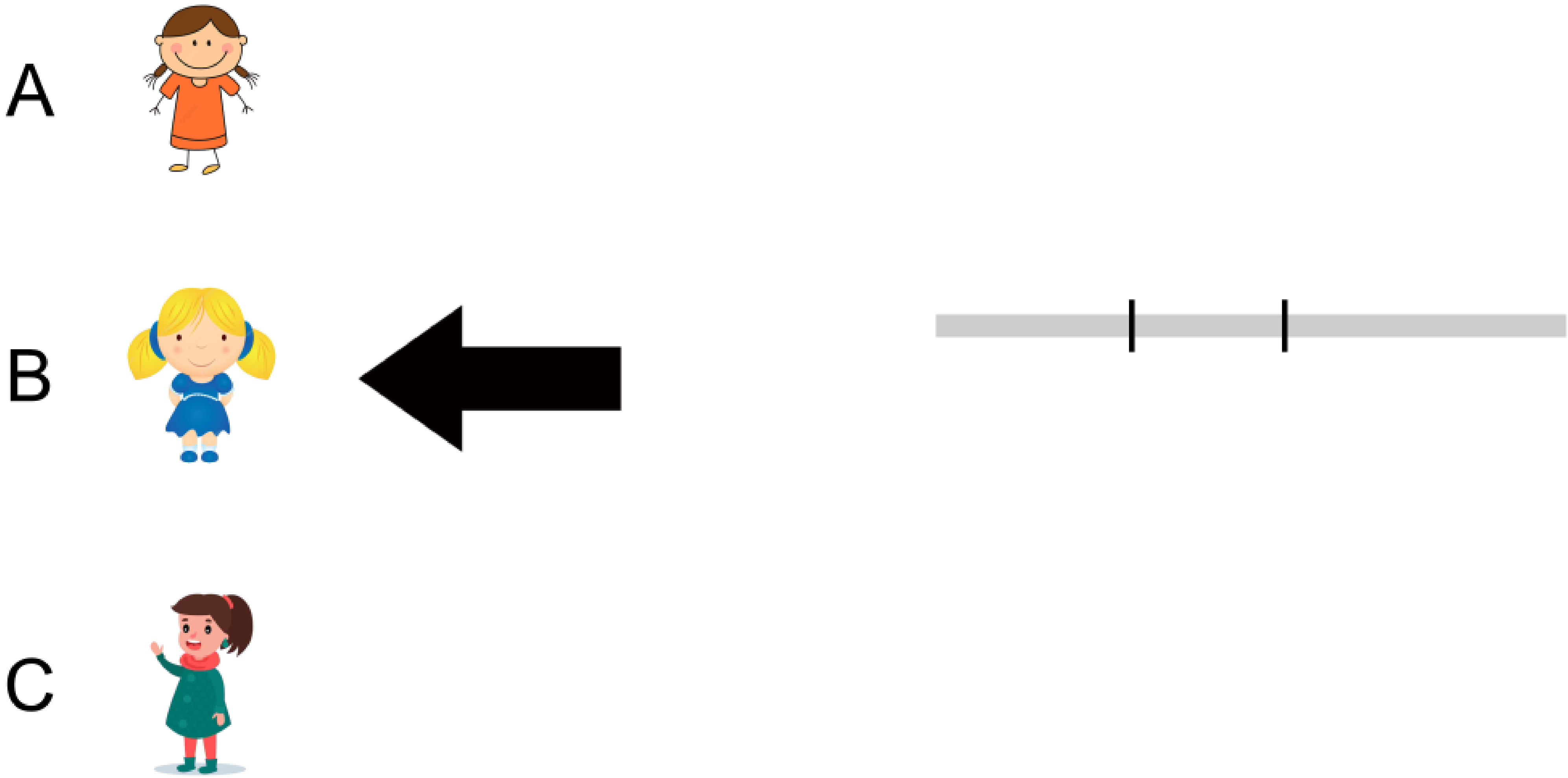
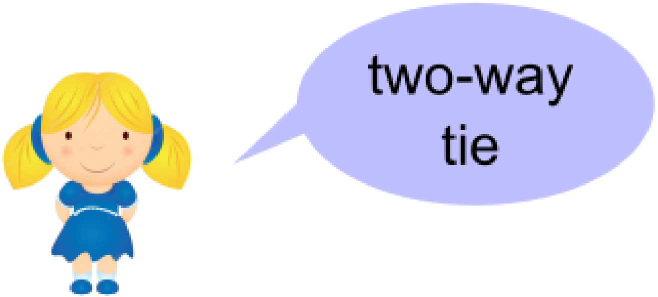


Envy-free for three

A

B

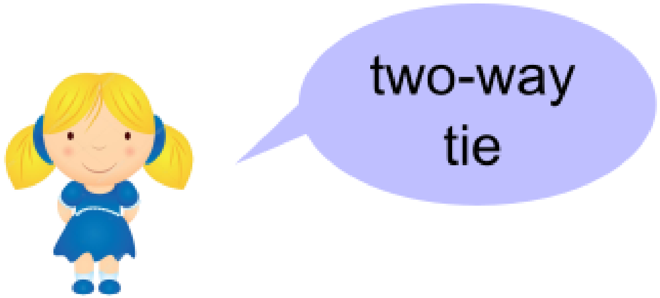


C

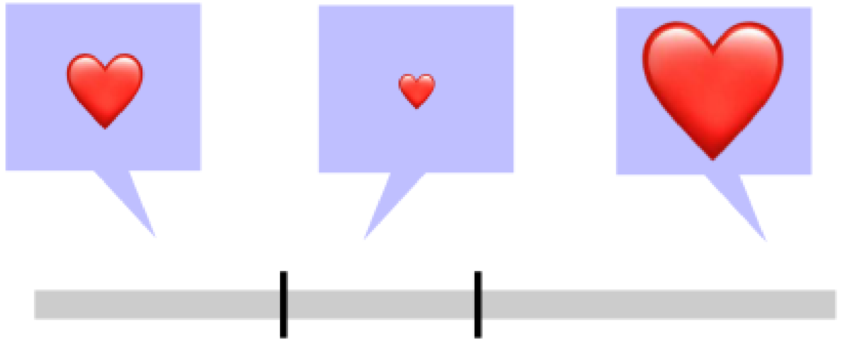
Envy-free for three

A

B



C



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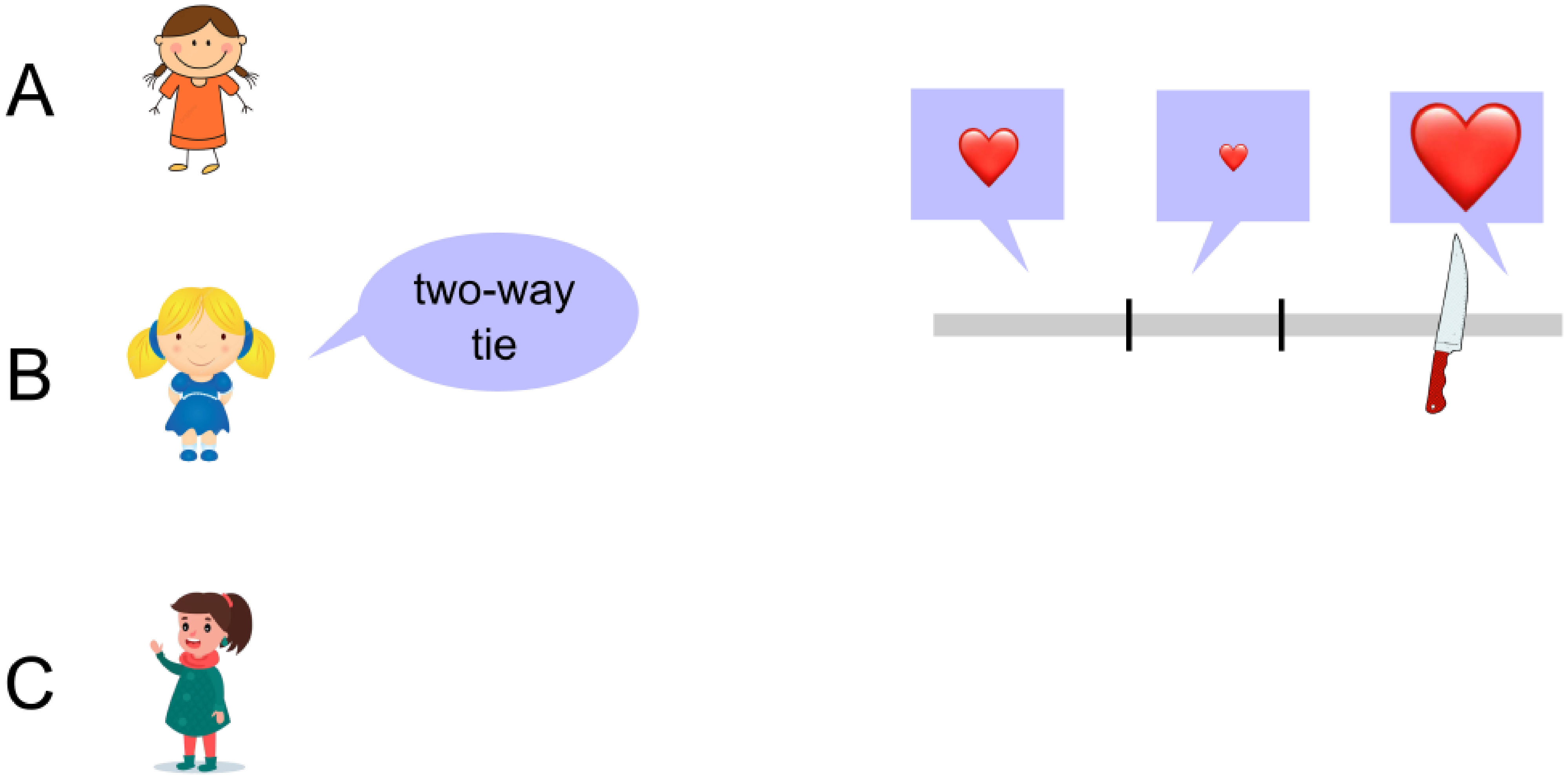

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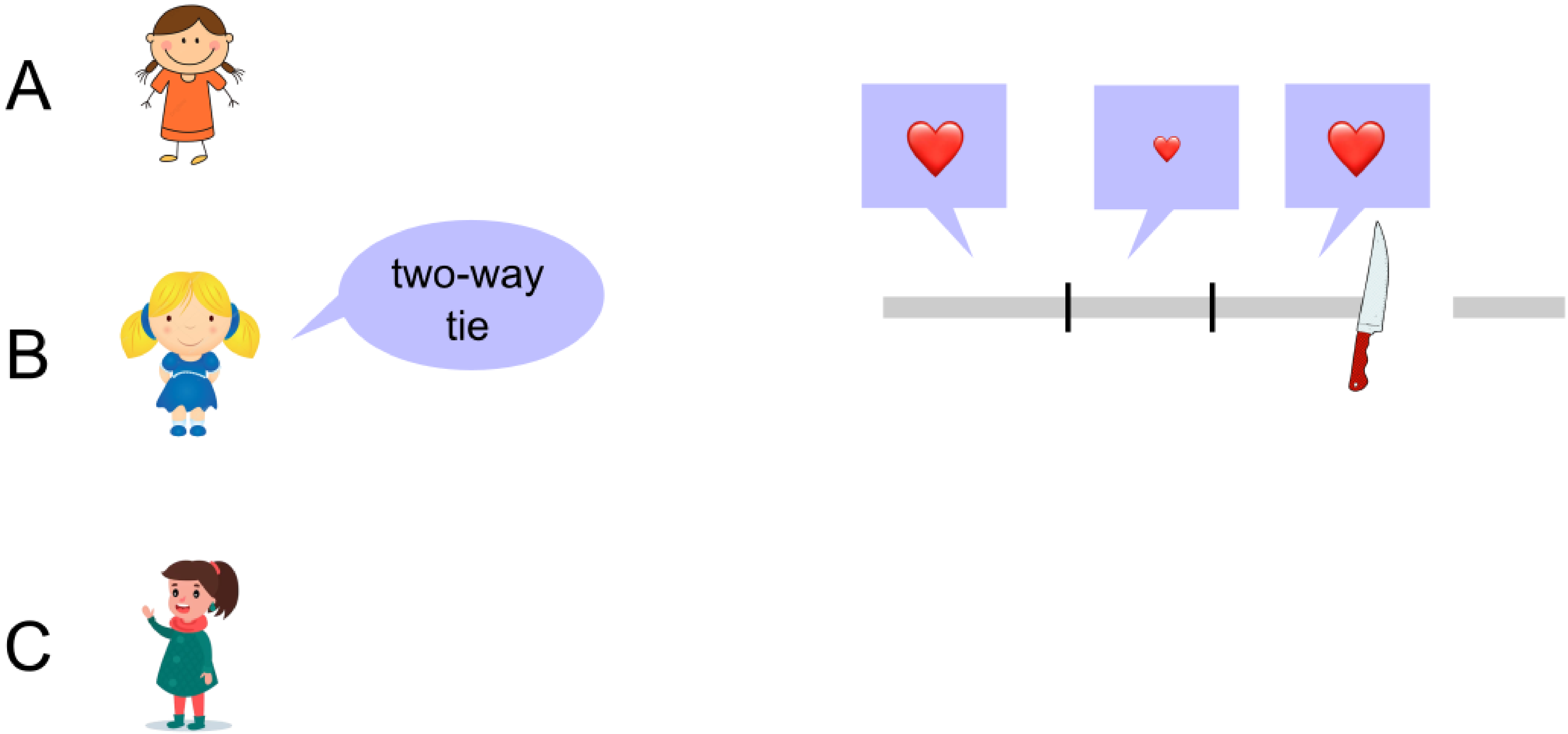

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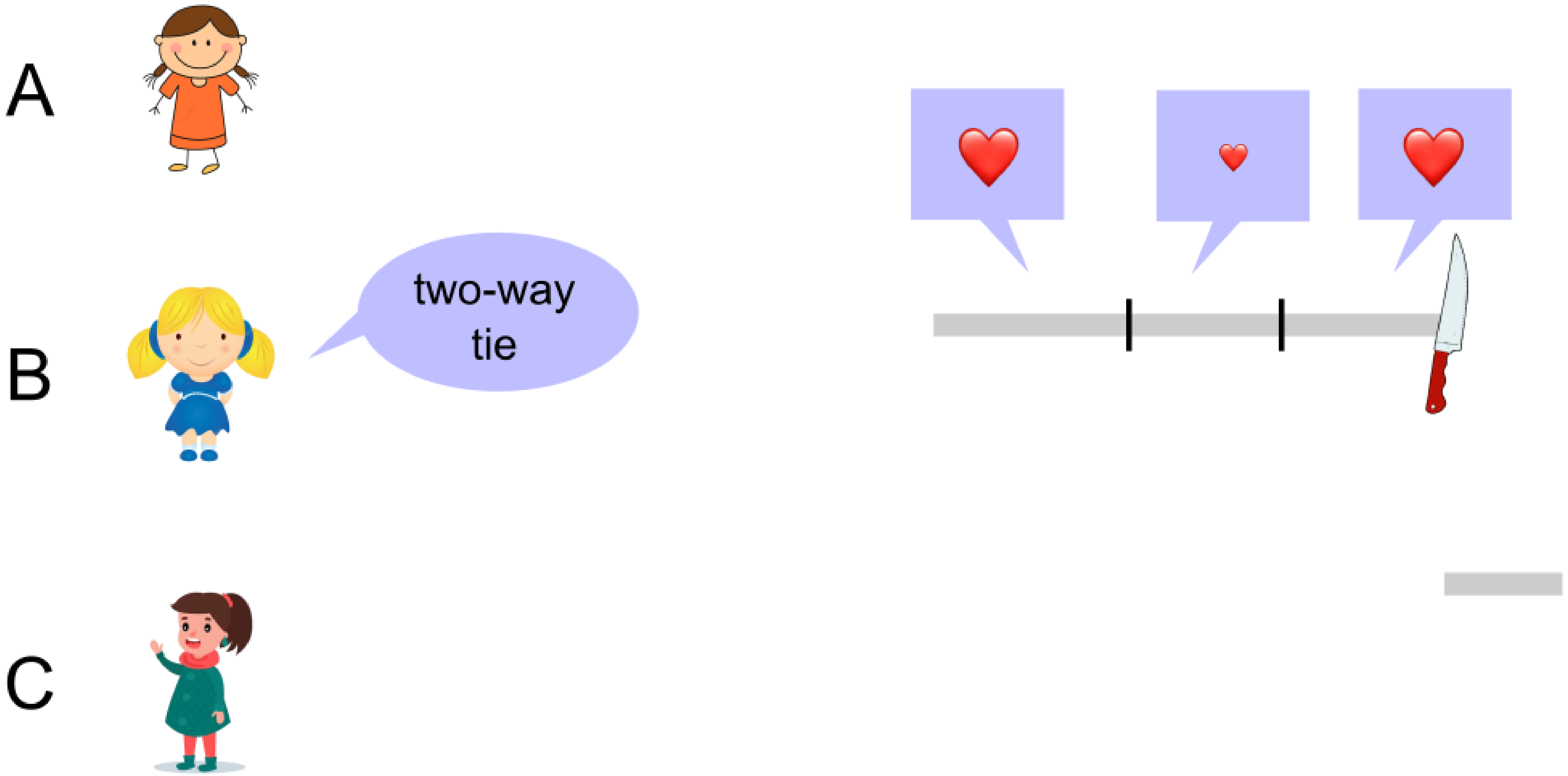

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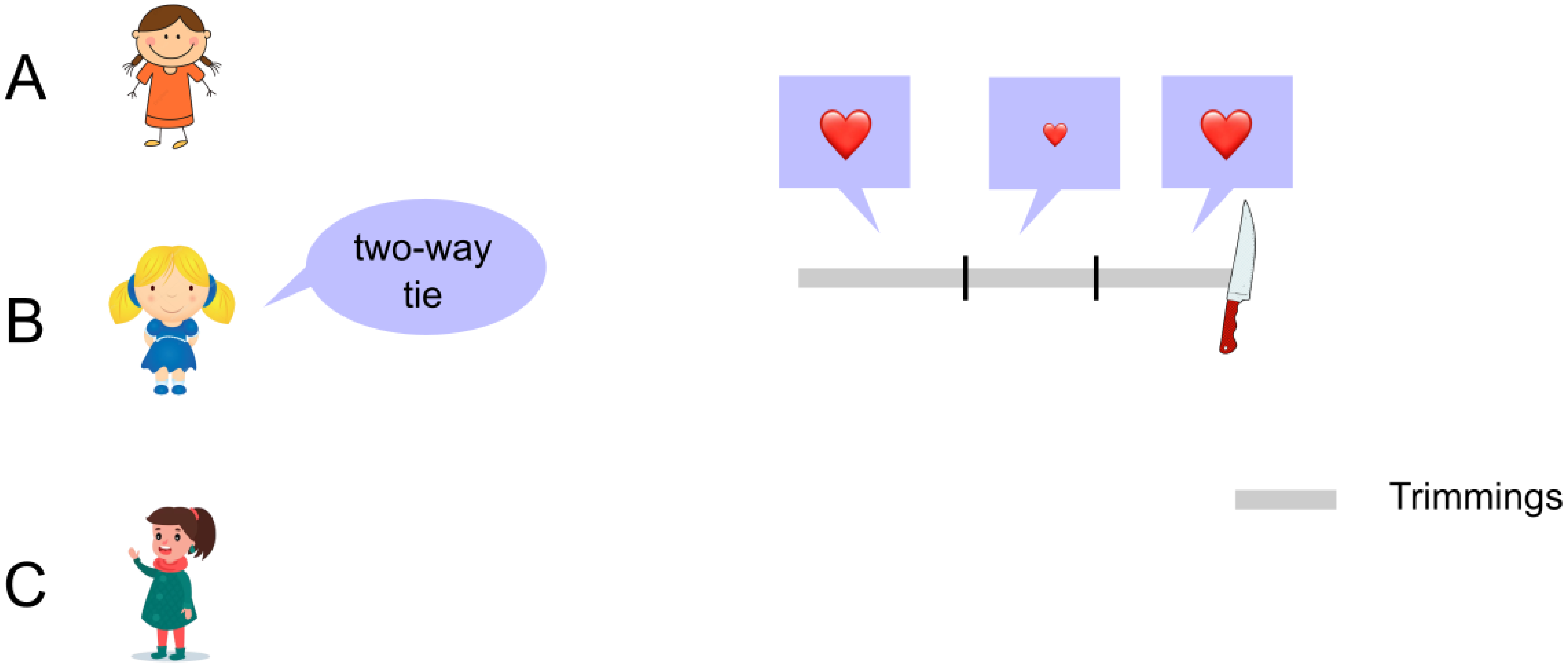

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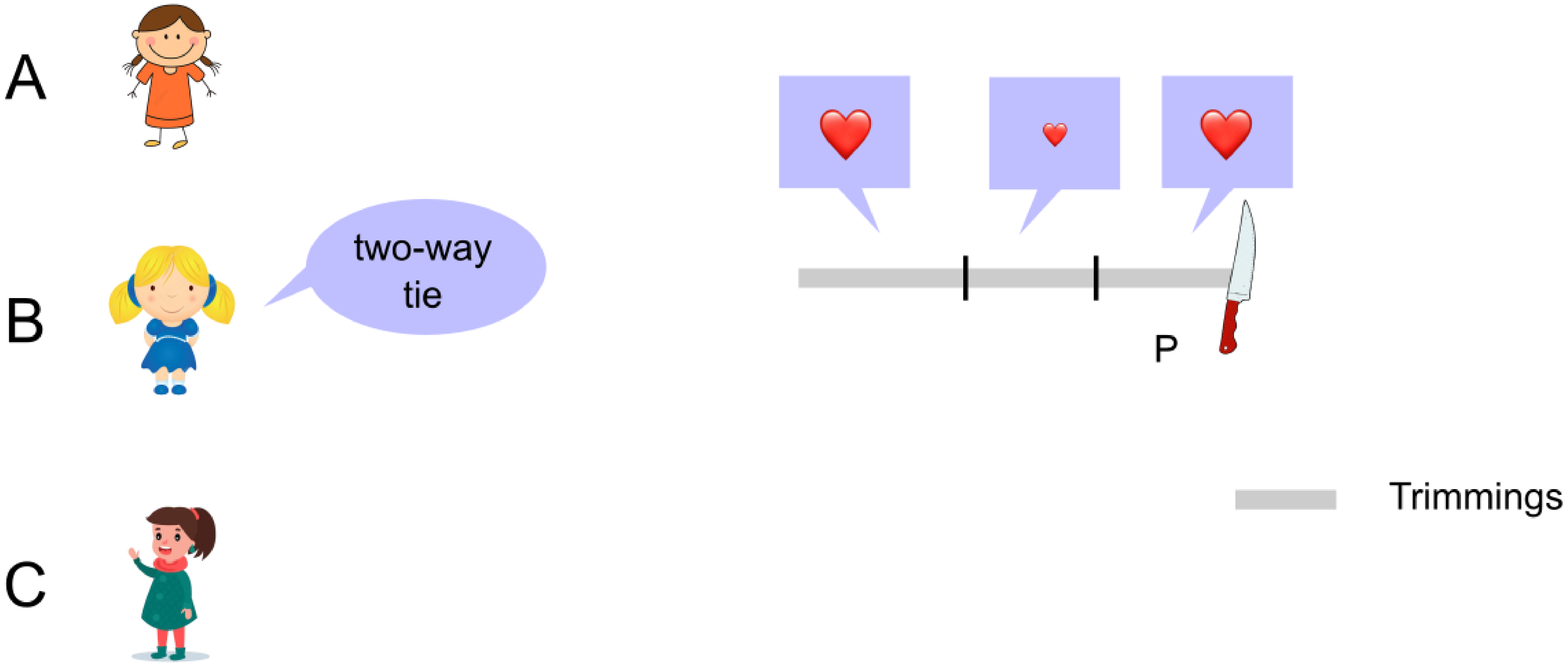
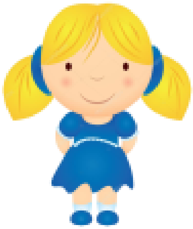
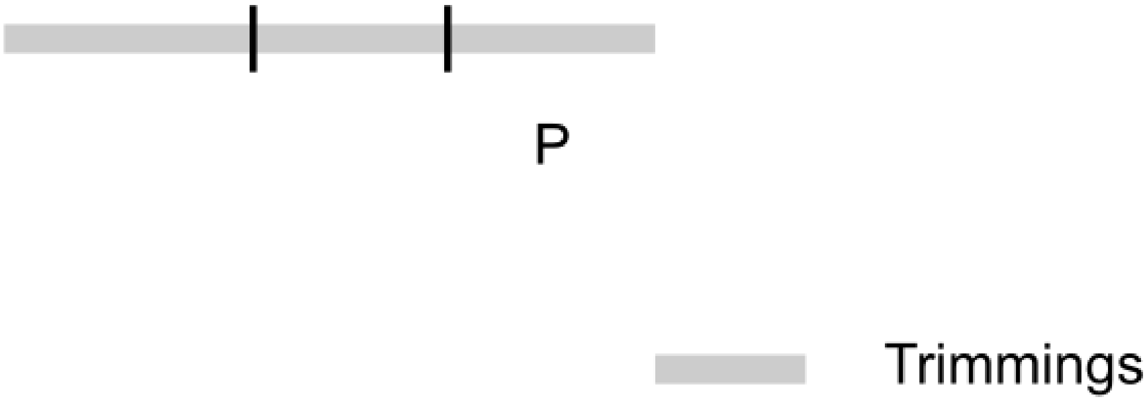


Envy-free for three

A

B





C

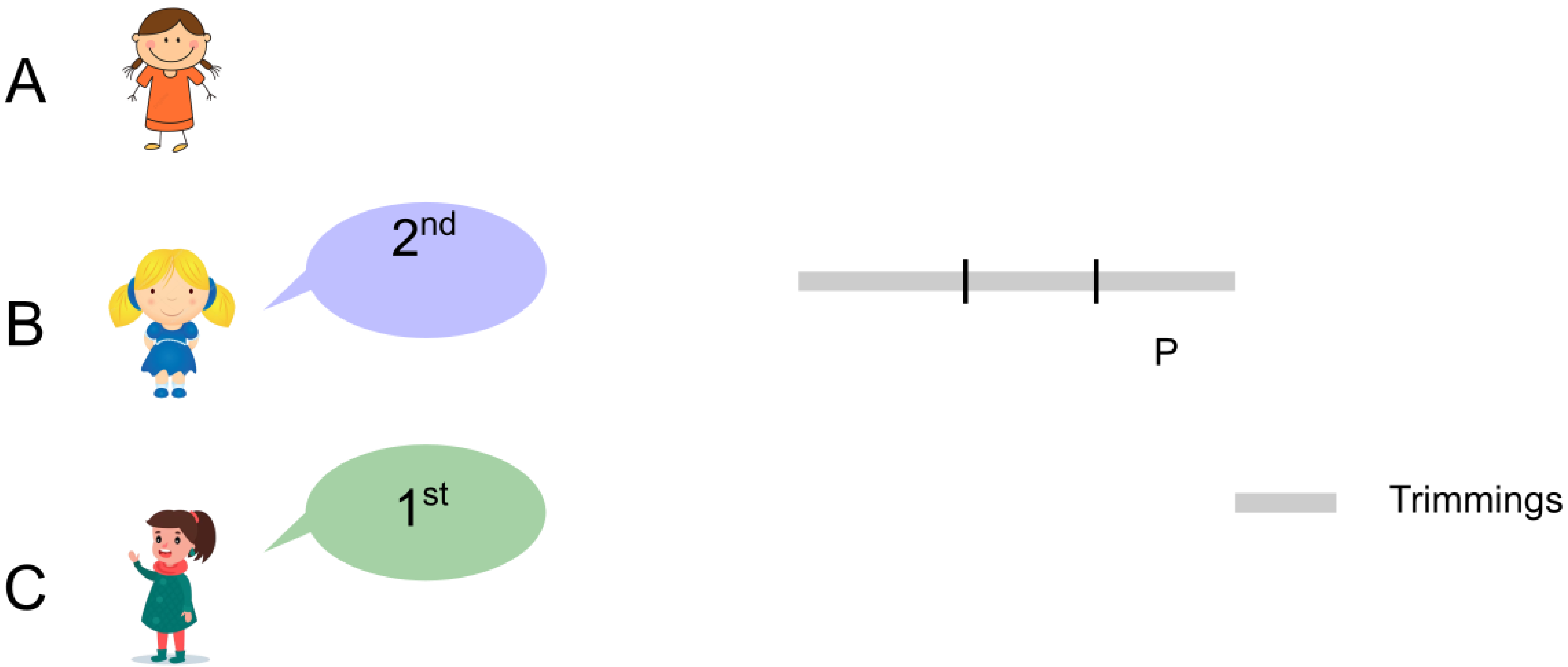
Envy-free for three

A

B

C

Envy-free for three



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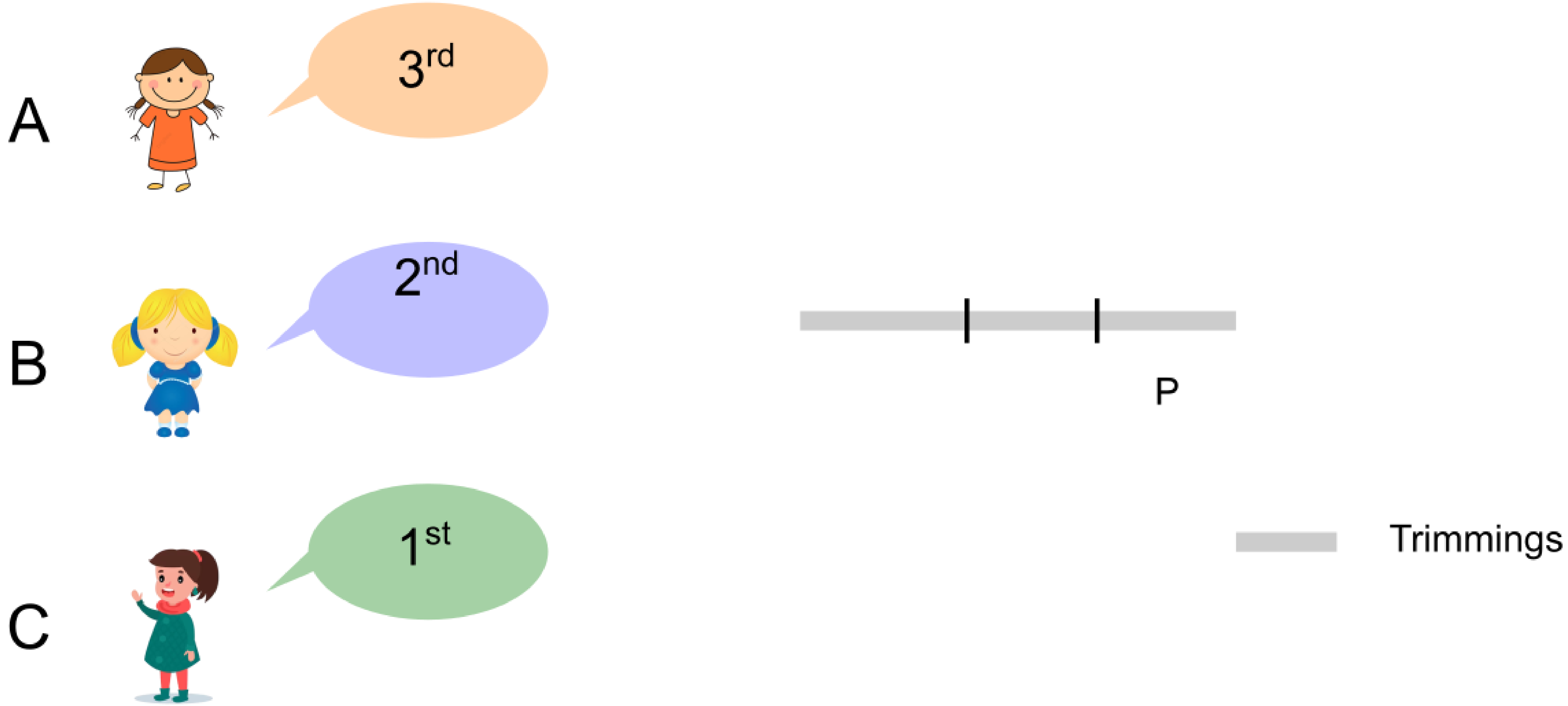

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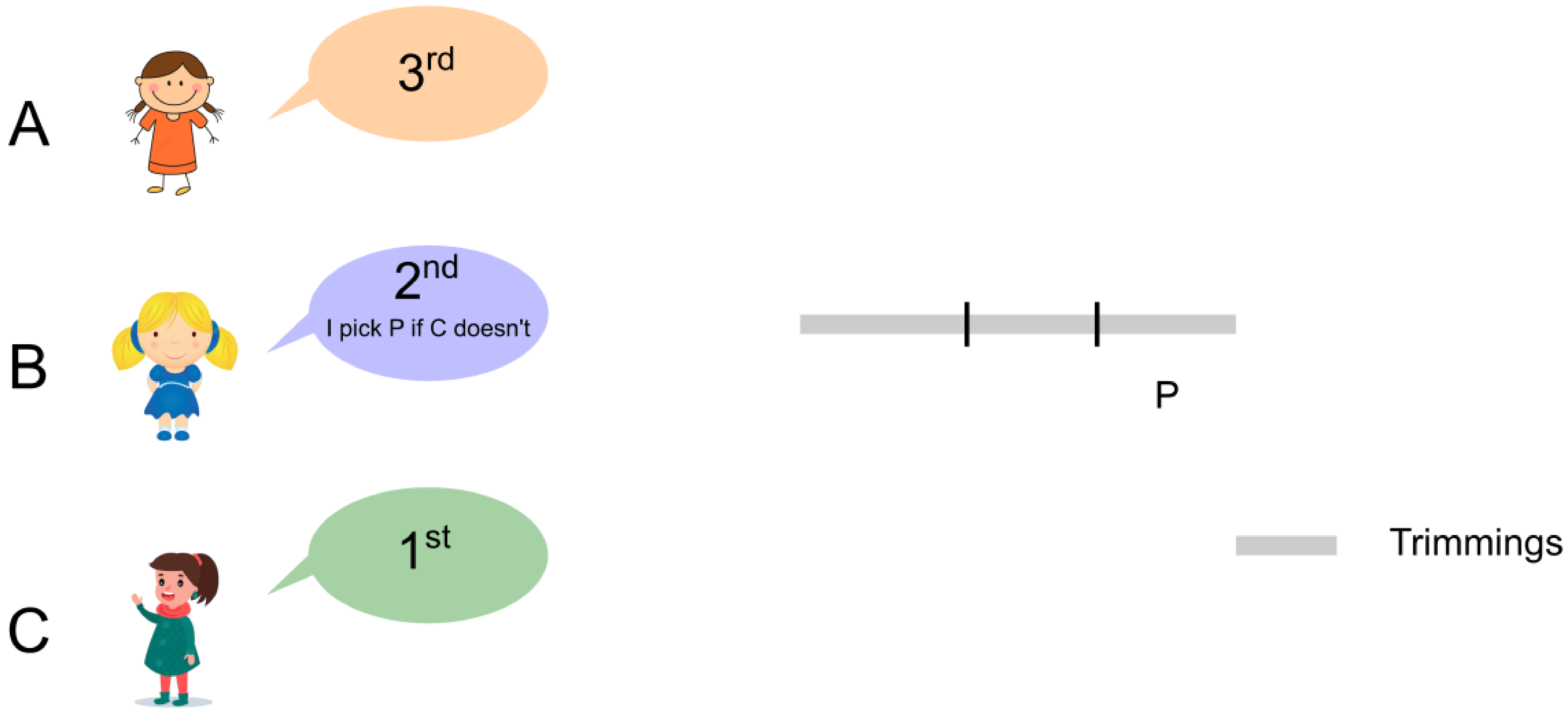


Envy-free for three

A

3rd

B

2nd
I pick P if C doesn't

C

1st

Envy-free for three

A

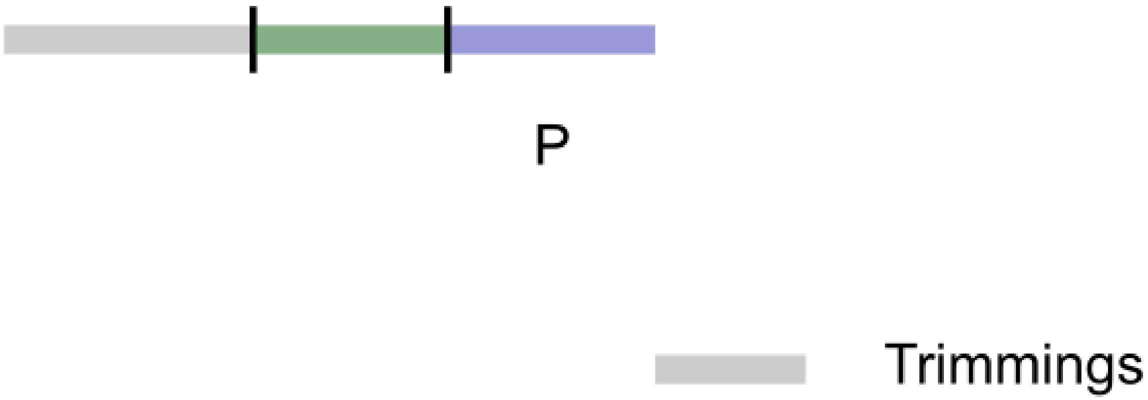
3rd

B

2nd
I pick P if C doesn't

C

1st



Envy-free for three

A

3rd

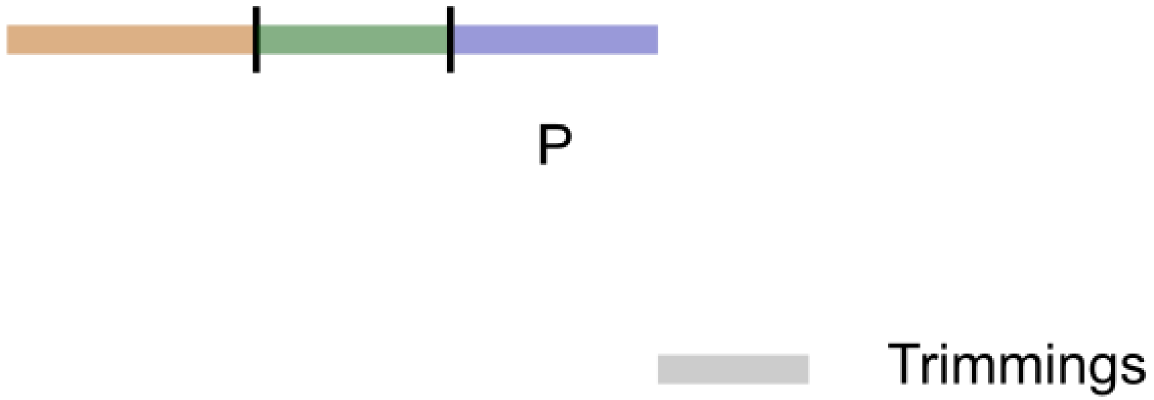
B

2nd

I pick P if C doesn't

C

1st

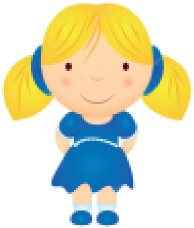


Envy-free for three

A

EF because of equal cuts

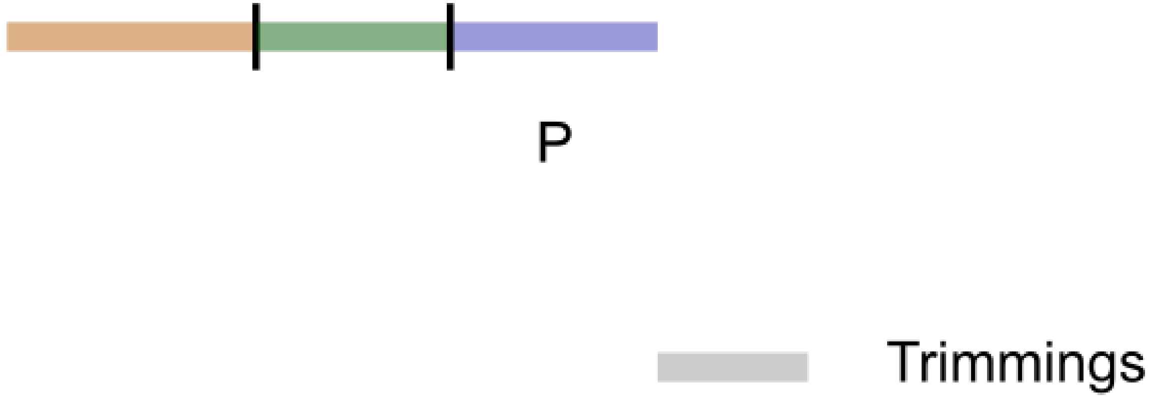
B



EF because of two-way tie

C

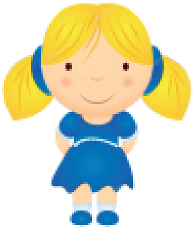
EF because I picked first



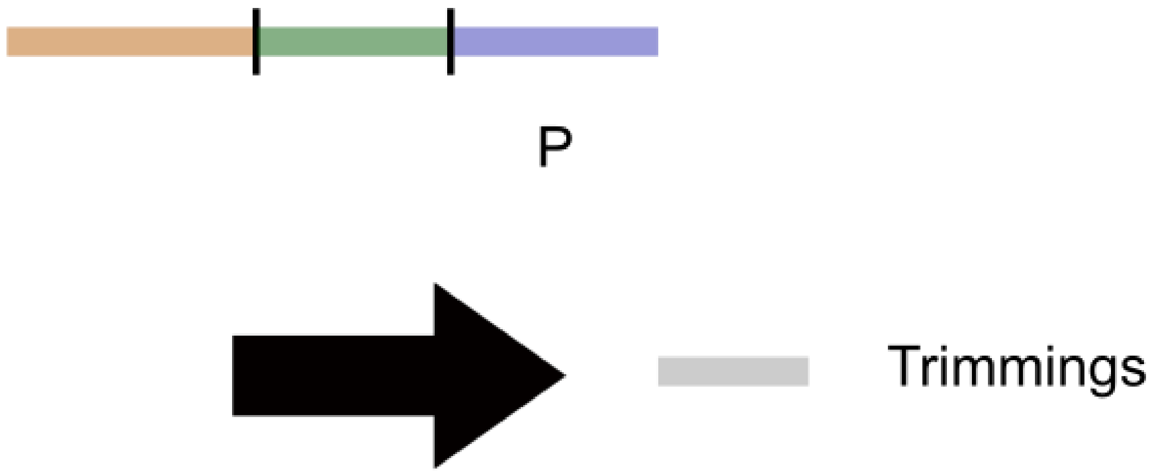
Envy-free for three

A

B



C



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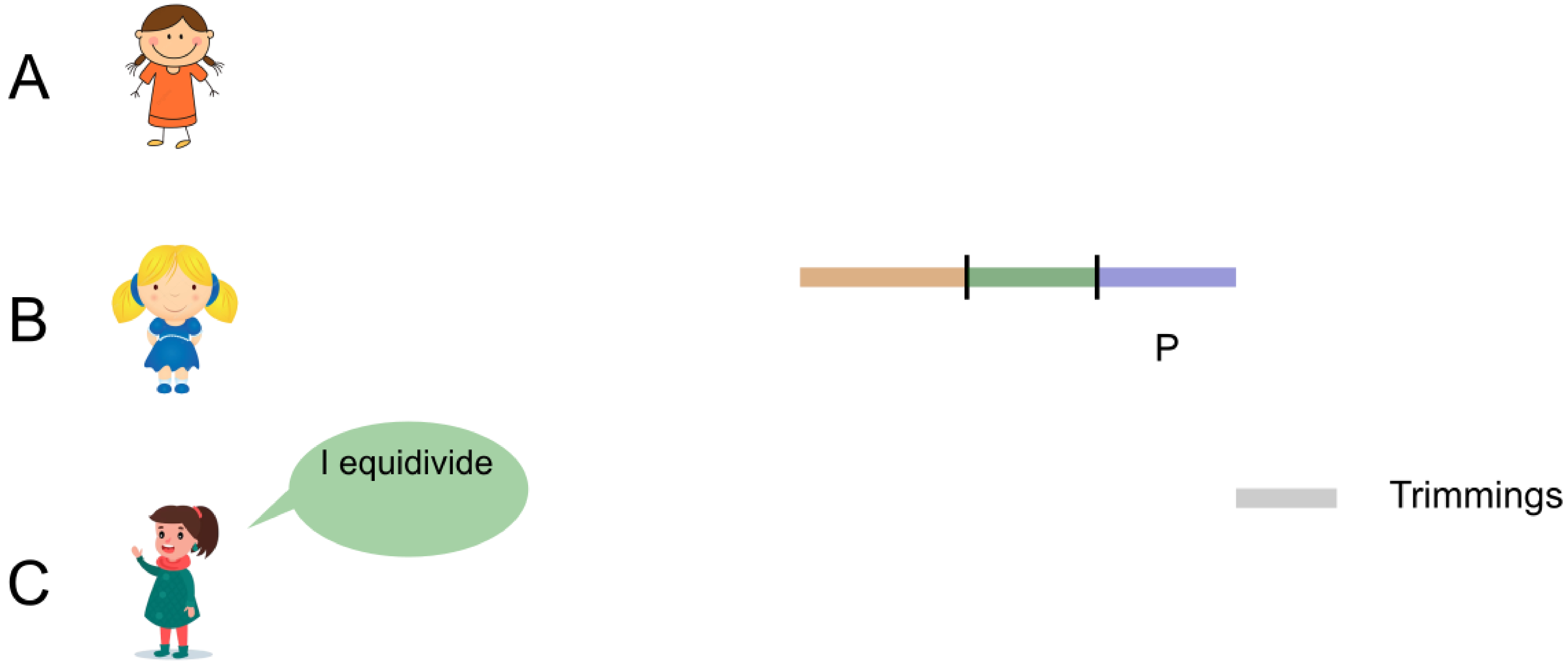
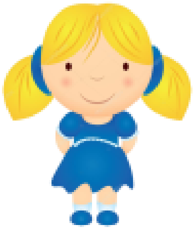


Envy-free for three

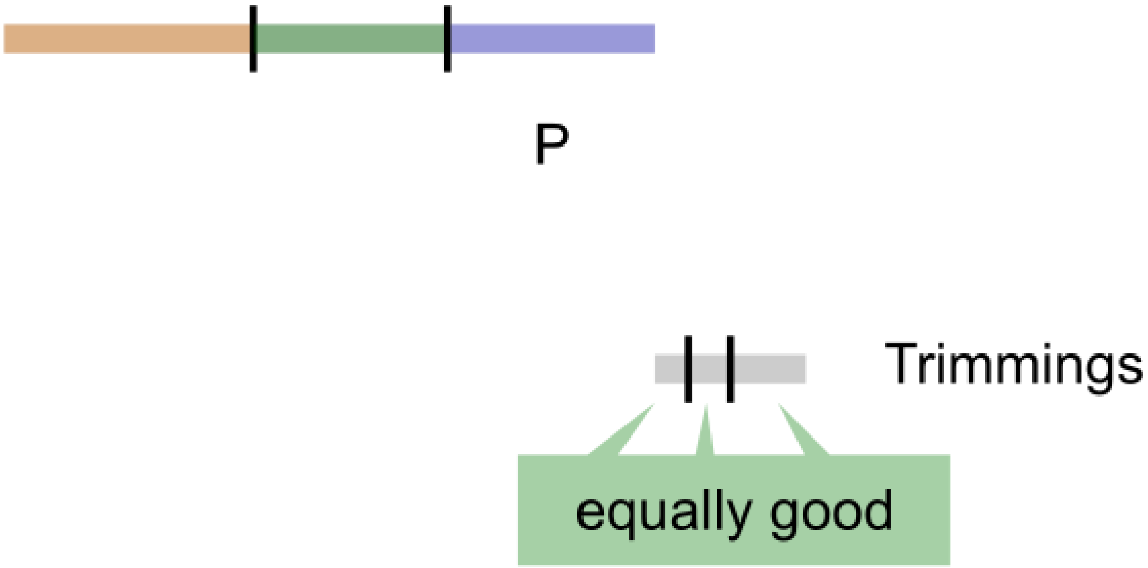
A

B



C

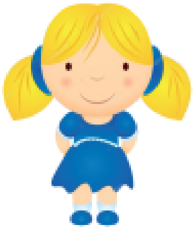
I equidivide



Envy-free for three

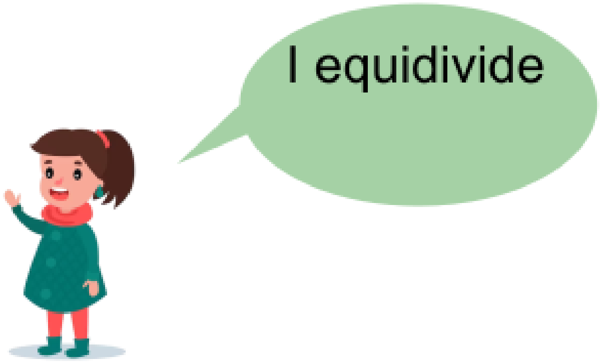
A

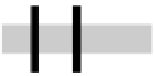
B



P

C





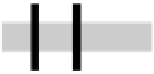
Trimmings

Envy-free for three

A

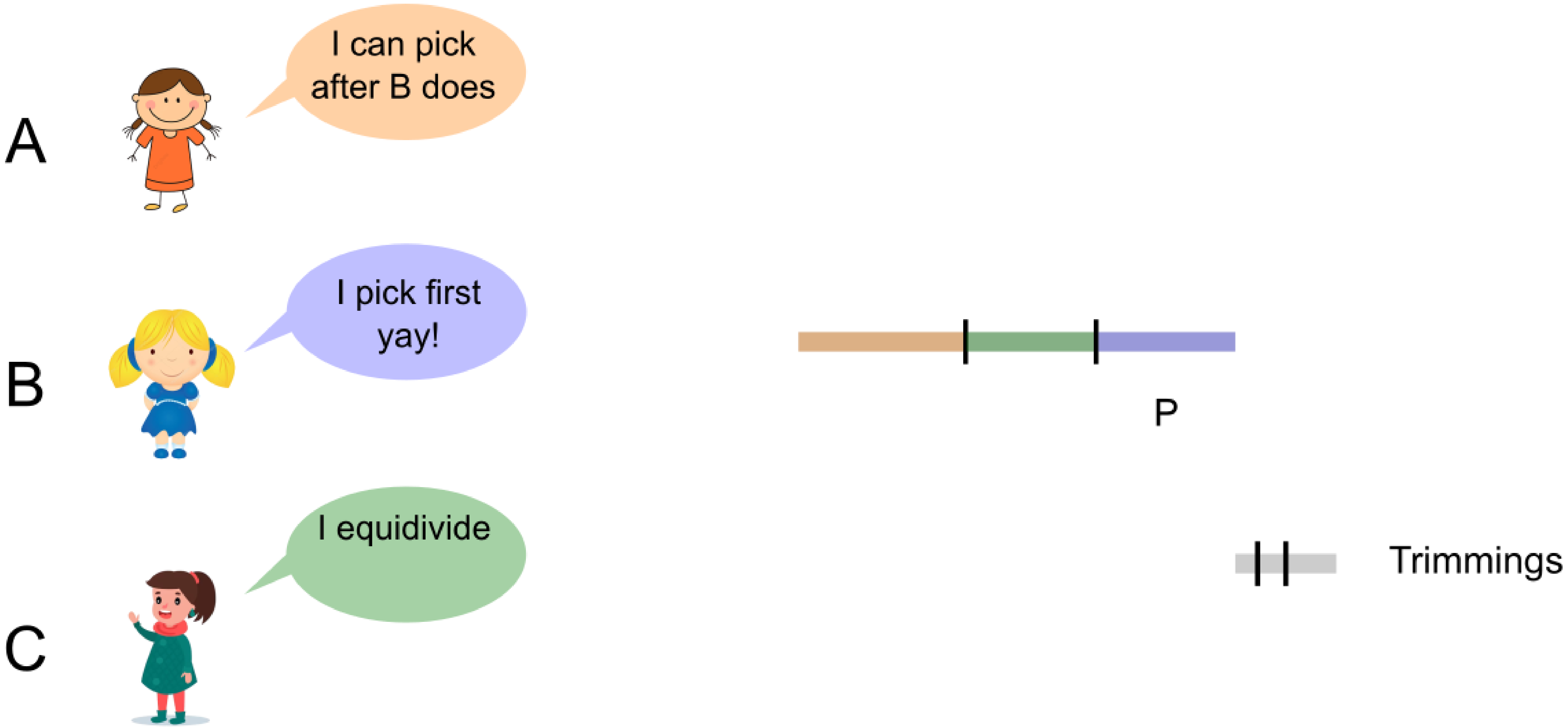
B

C



Trimmings

Envy-free for three



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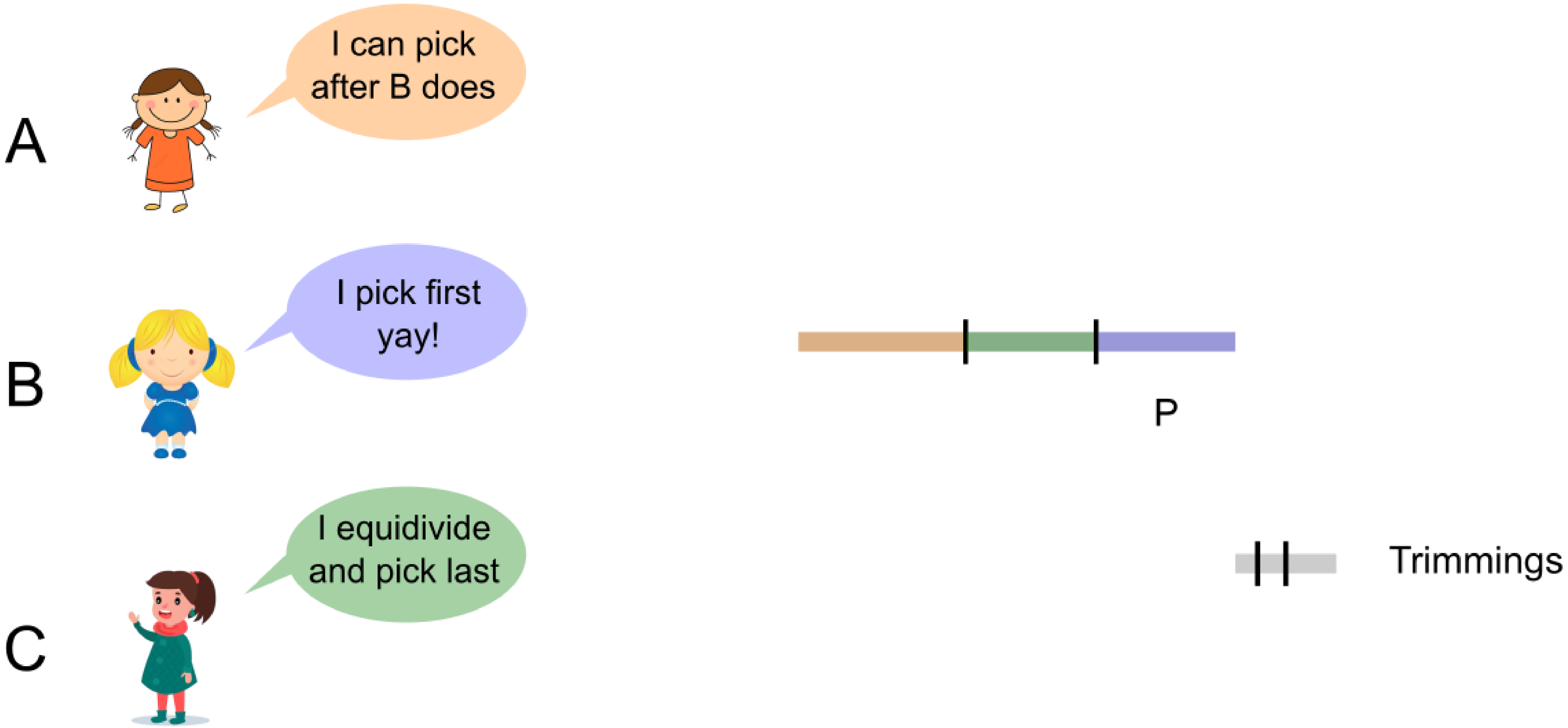
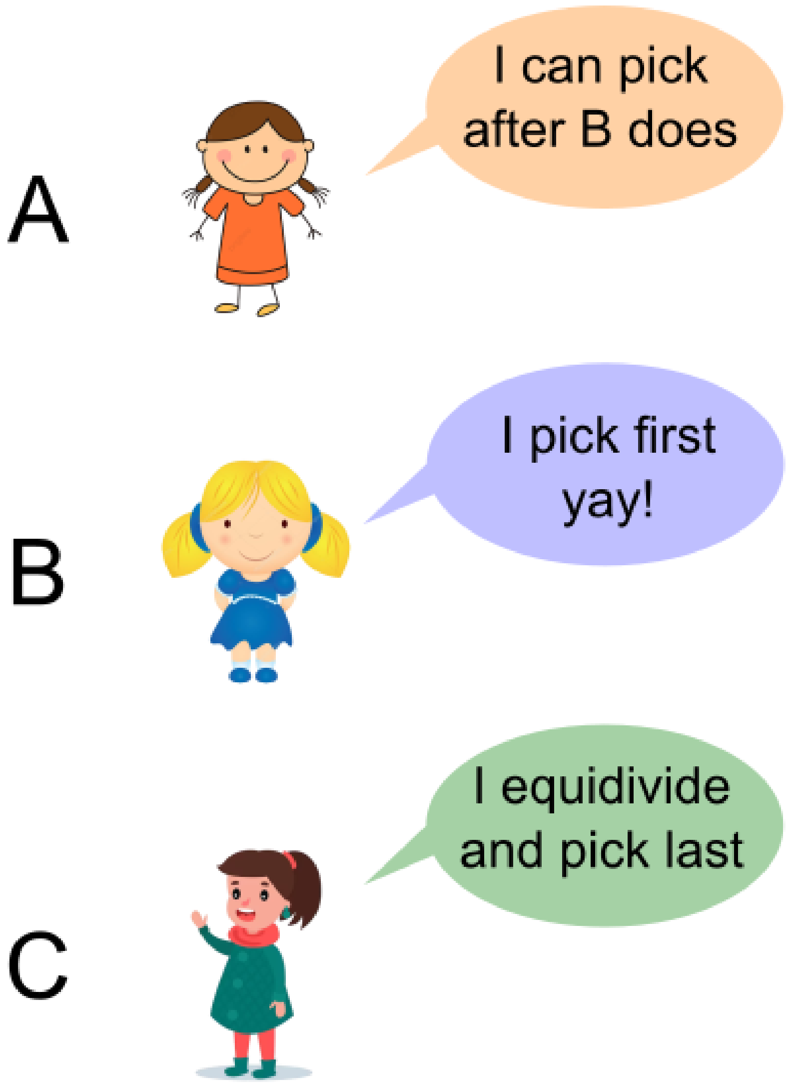
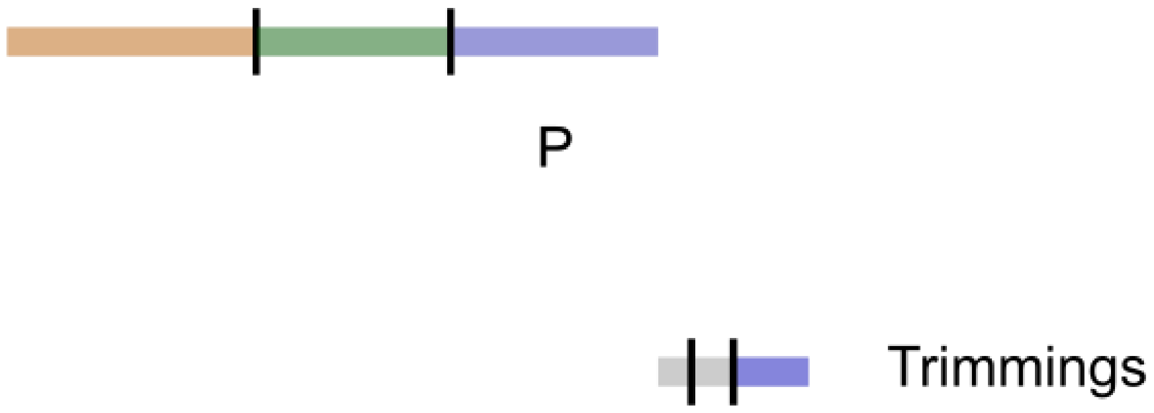
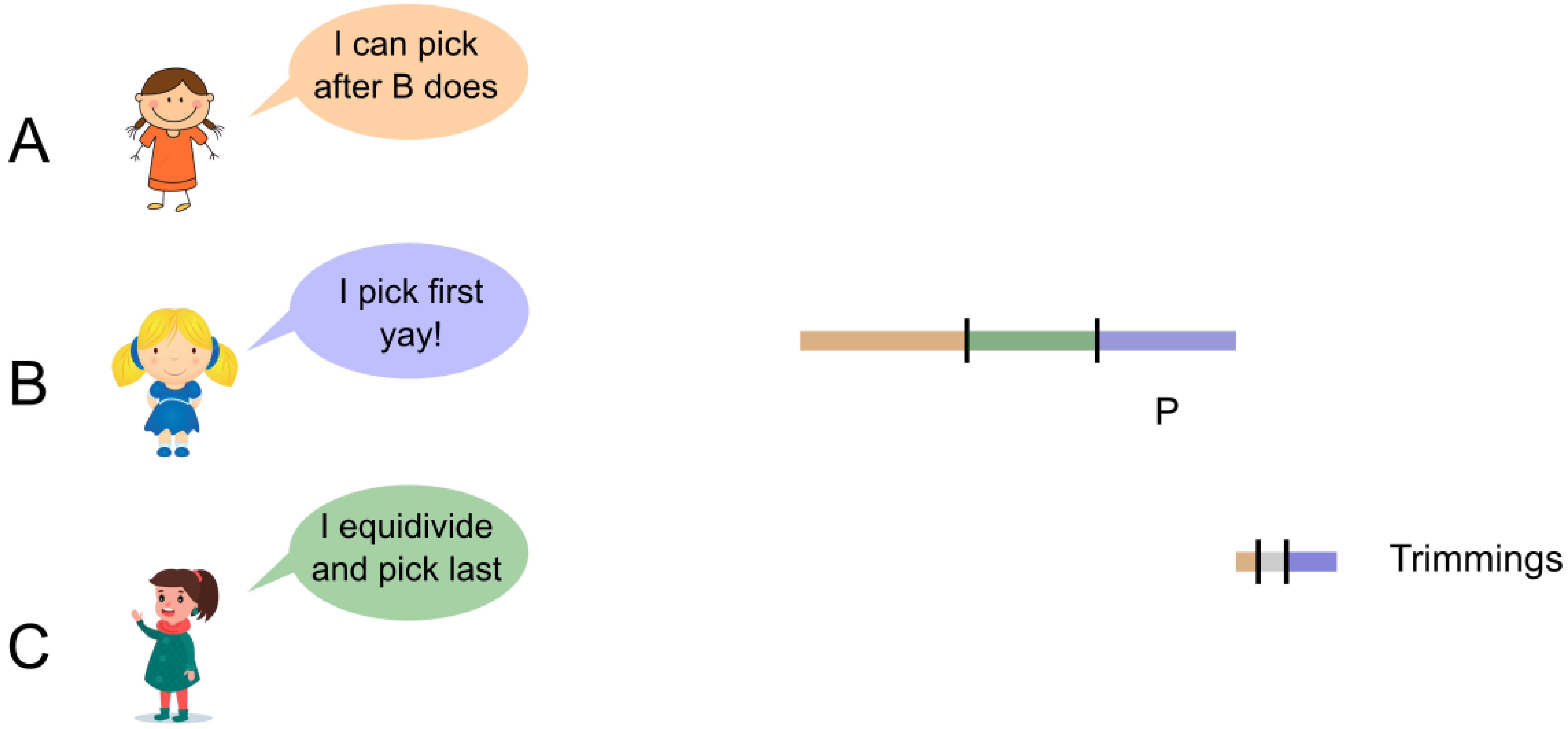


Envy-free for three

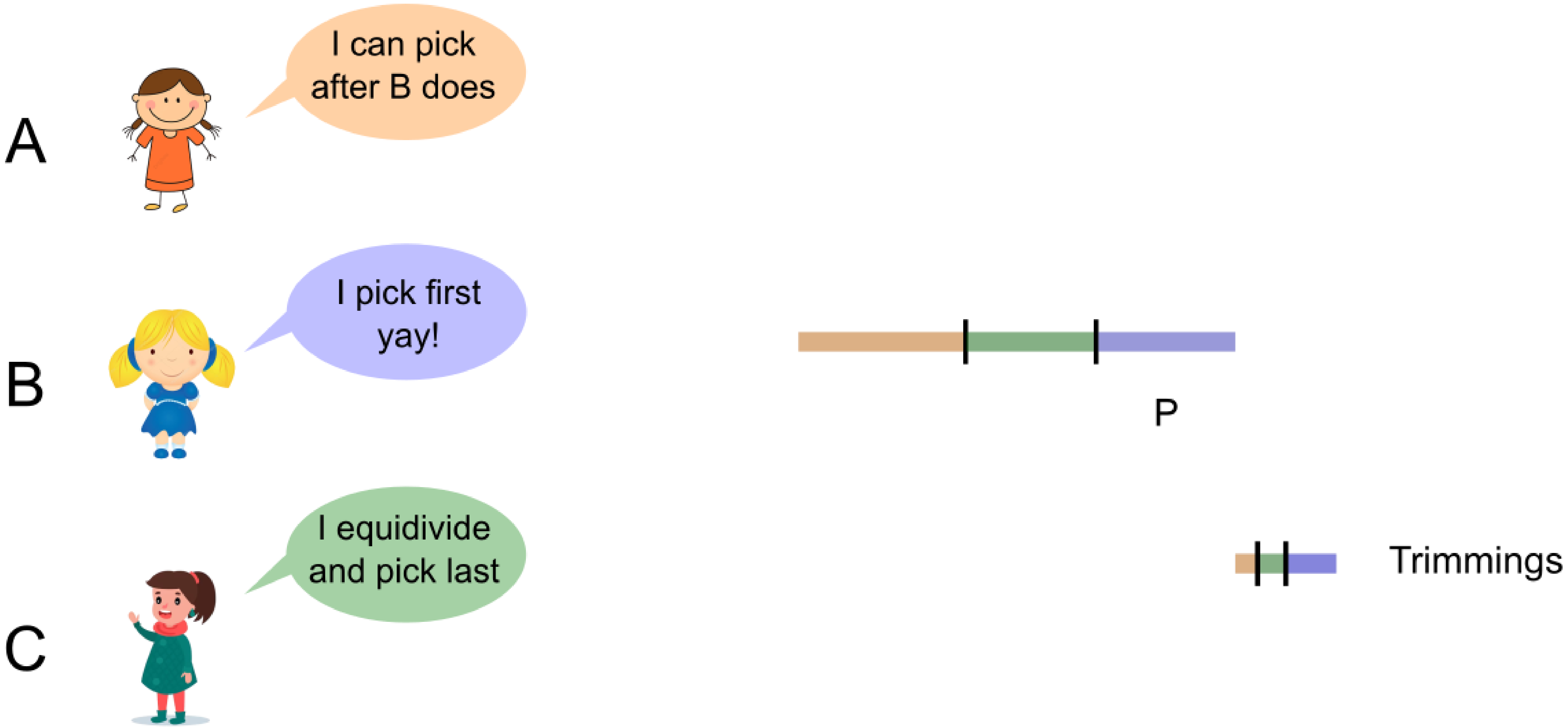




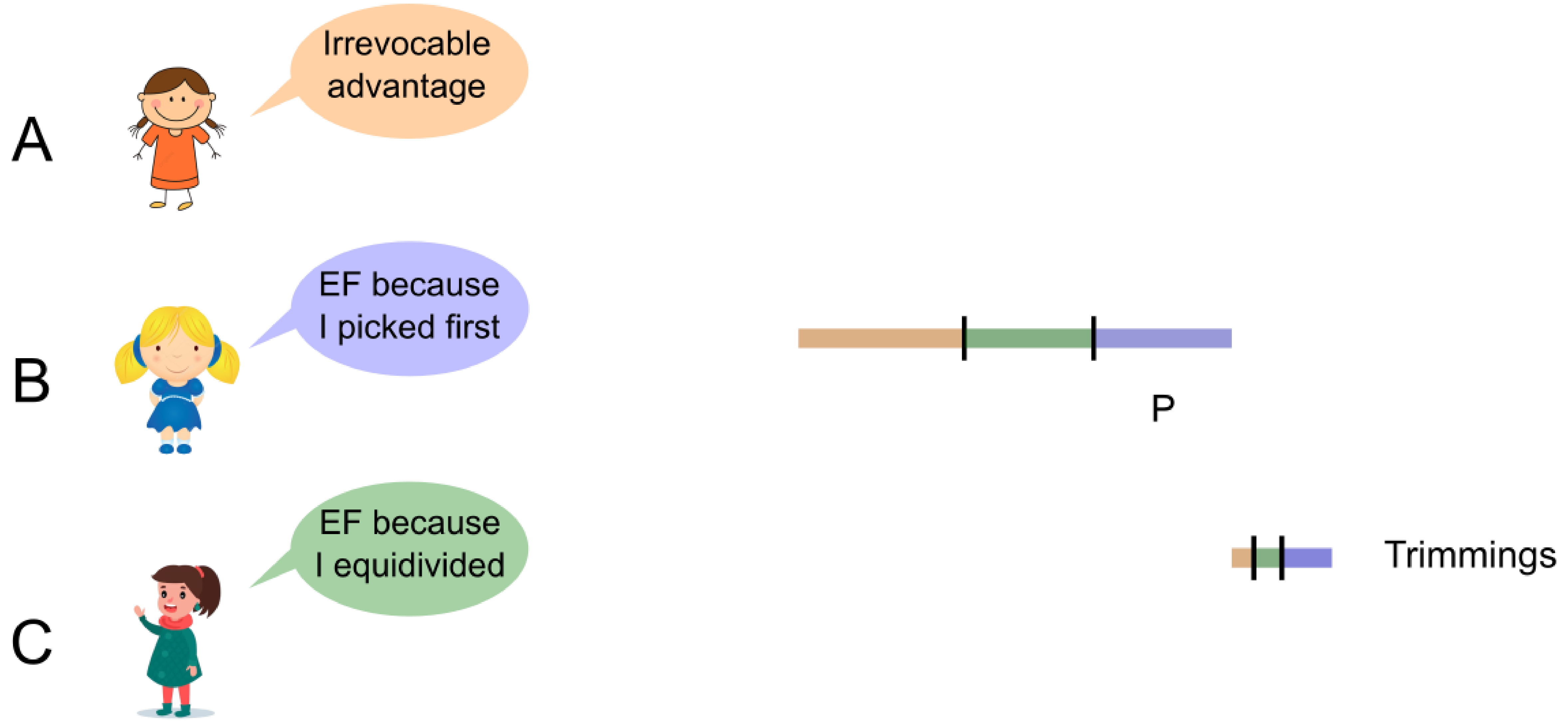
Envy-free for three



Envy-free for three



Envy-free for three

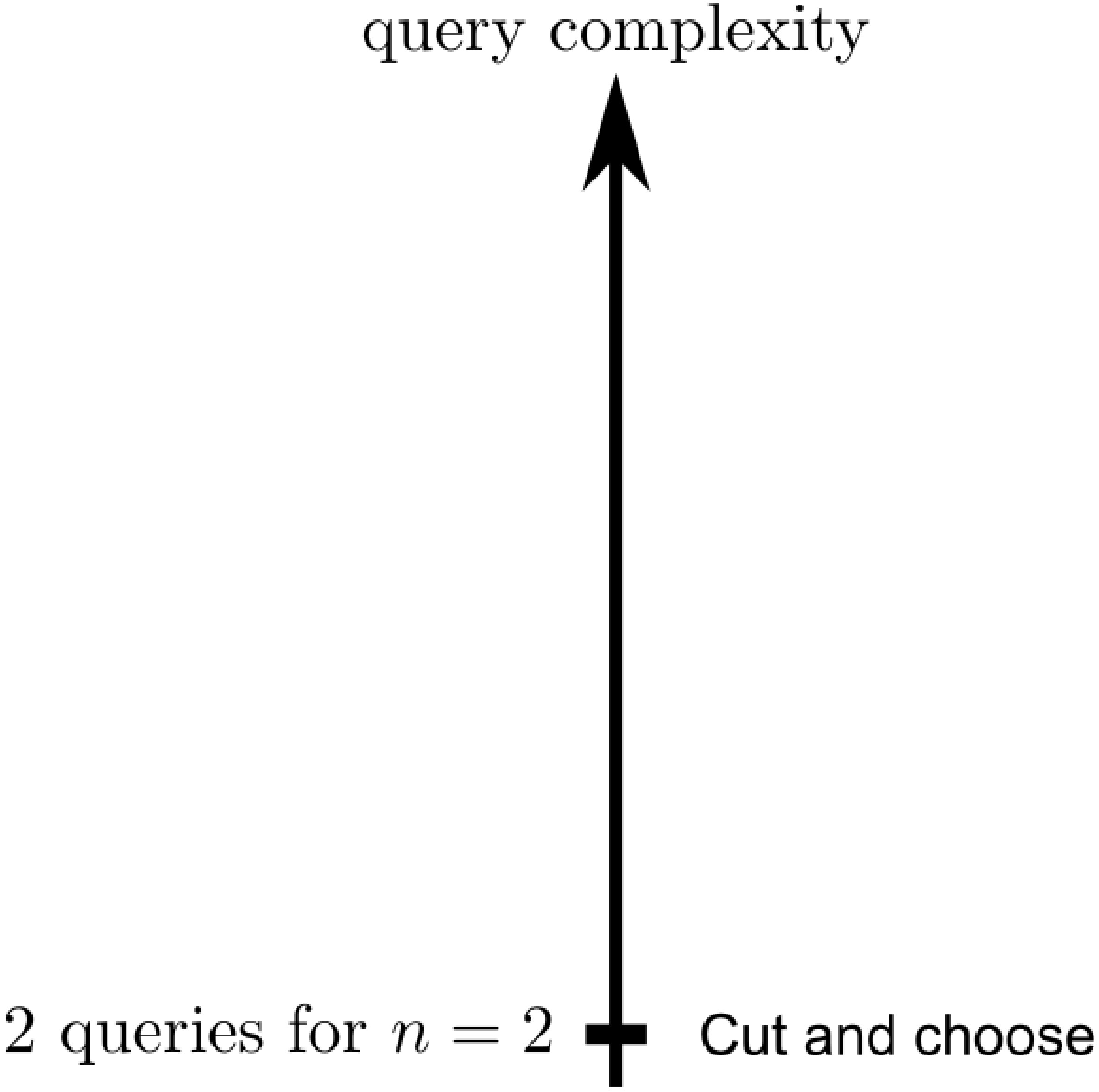


Exercise

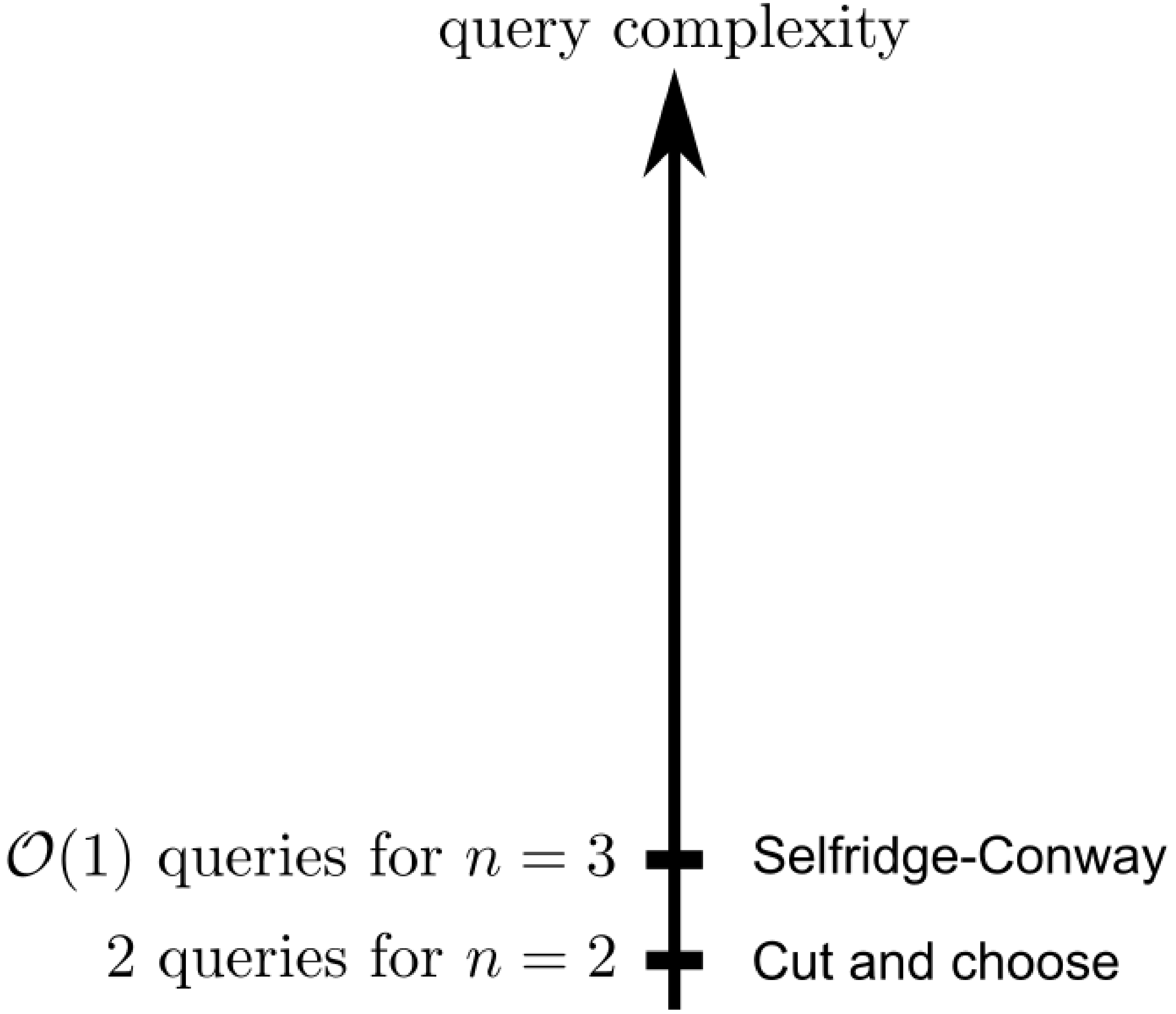
How many queries does the three-person EF protocol require?

The Story of Envy-freeness

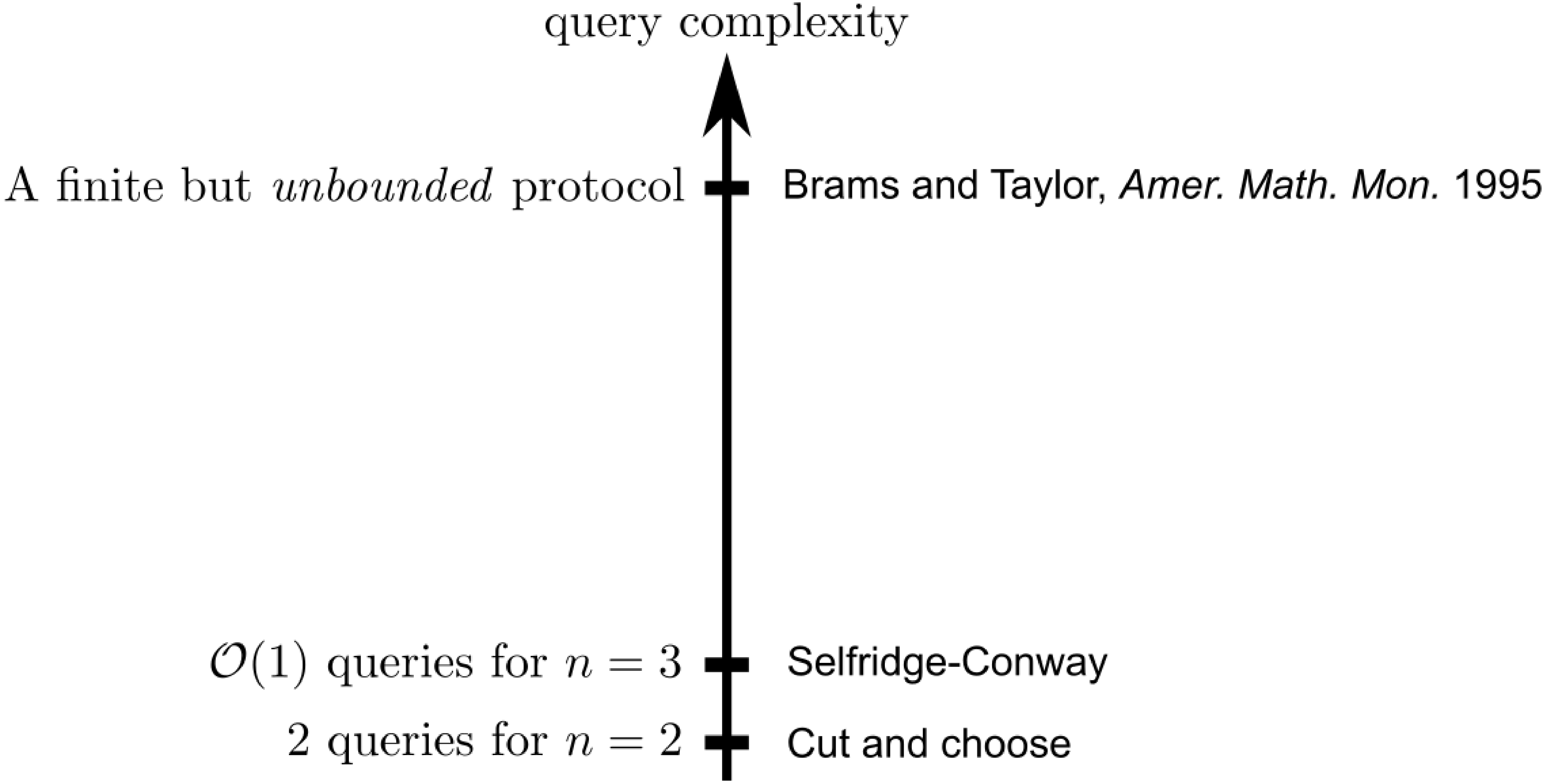
The Story of Envy-freeness



The Story of Envy-freeness



The Story of Envy-freeness



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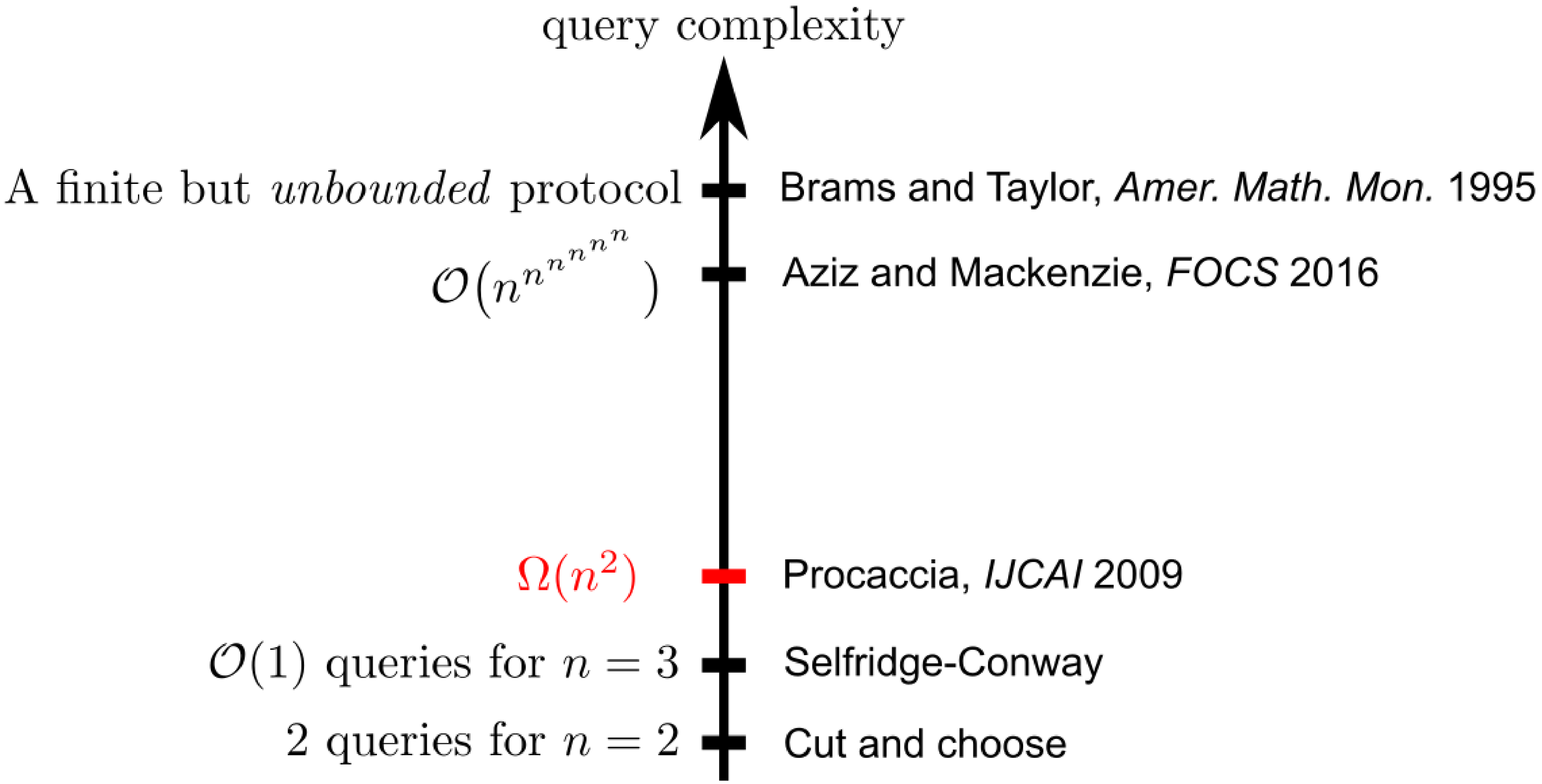
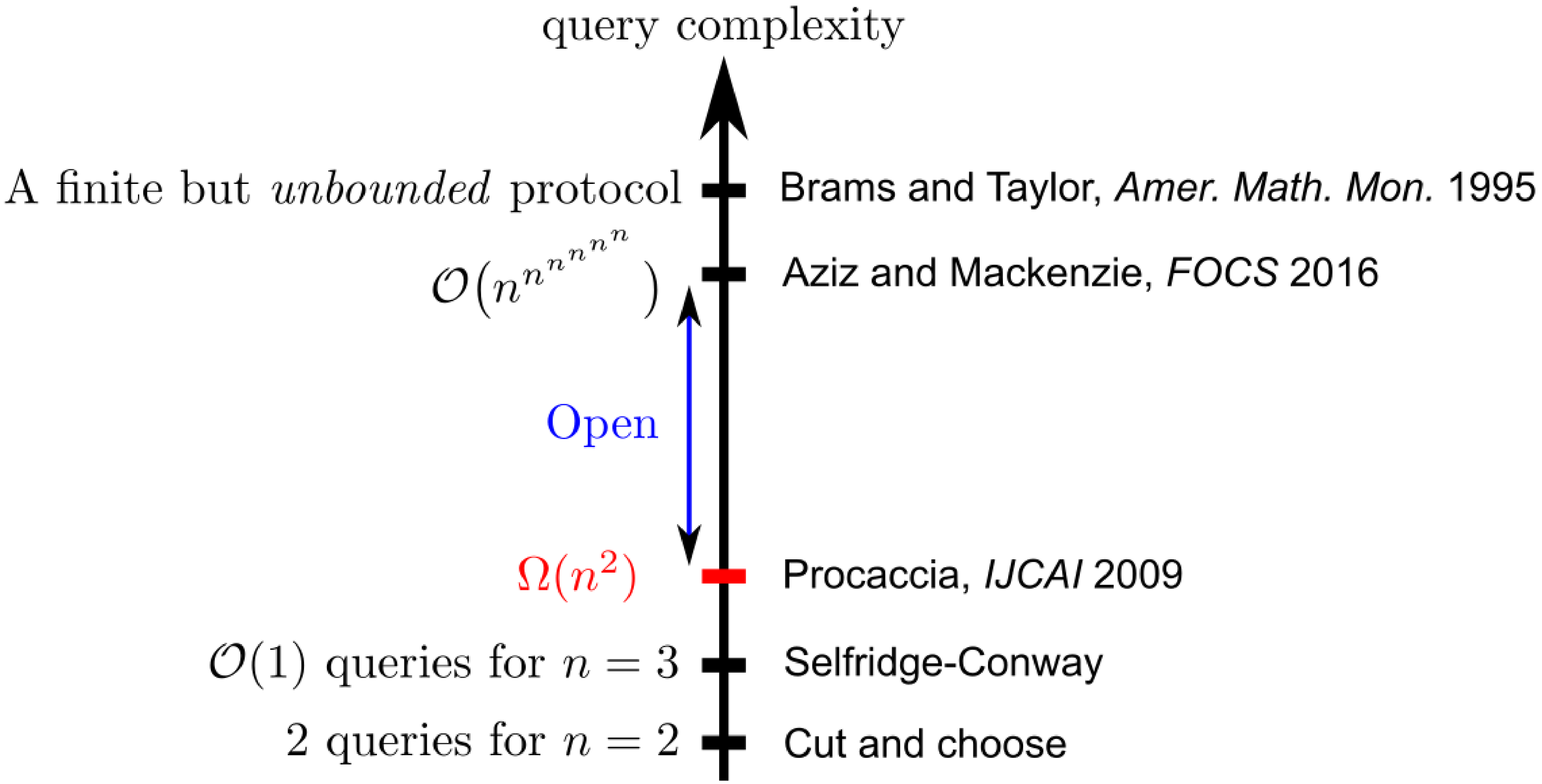


The Story of Envy-freeness



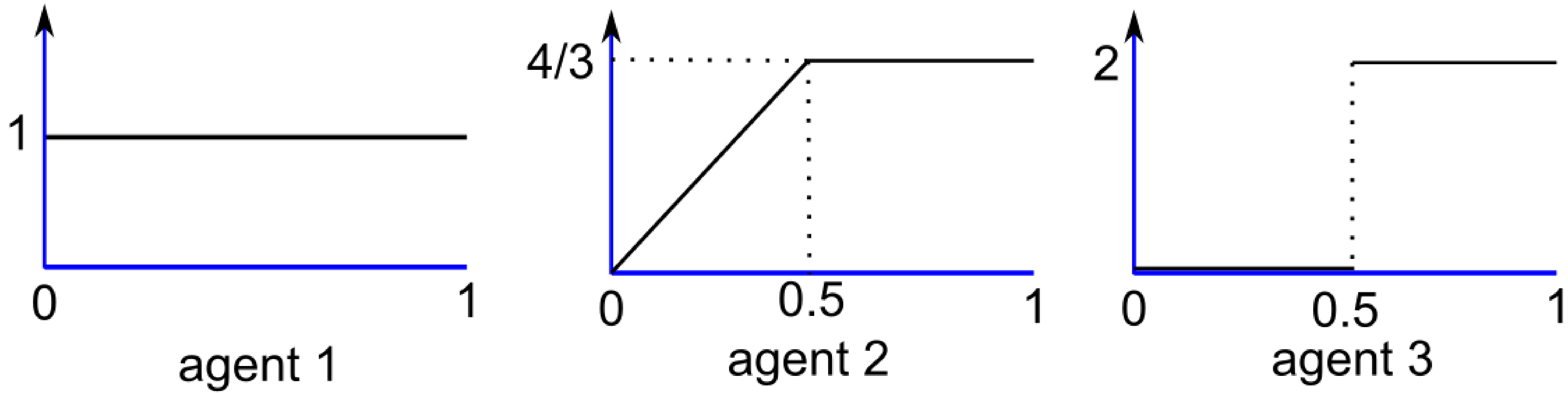
Next Time

Fair Division of Indivisible Items

Quiz

Quiz

Consider a three-agent instance with the following value density functions:



Identify any envy-free division in this instance.

References

- Introduction to cake-cutting algorithms.

  Ariel Procaccia
  "*Cake Cutting Algorithms*"
  Chapter 13 in Handbook of Computational Social Choice

- Lecture by Ariel Procaccia on "Cake cutting" in the *Optimized Democracy* course.
  https://sites.google.com/view/optdemocracy/schedule

Selfridge-Conway Procedure

Phase 1

Selfridge-Conway Procedure

Phase 1

1. Agent A divides the cake into three equal pieces (as per v_A).

Selfridge-Conway Procedure

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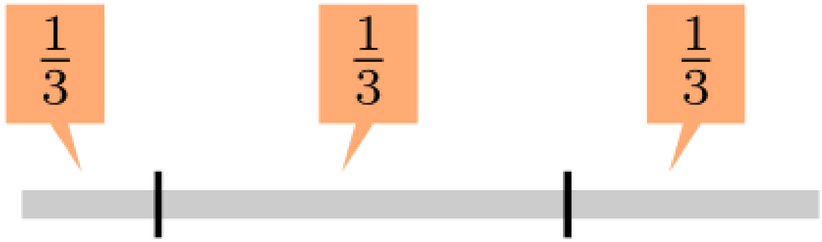

Selfridge-Conway Procedure

Phase 1

1. Agent A divides the cake into three equal pieces (as per v_A).

Selfridge-Conway Procedure

Phase 1

1. Agent A divides the cake into three equal pieces (as per v_A).
2. Agent B trims its favorite piece to create a two-way tie with second-favorite.

Selfridge-Conway Procedure

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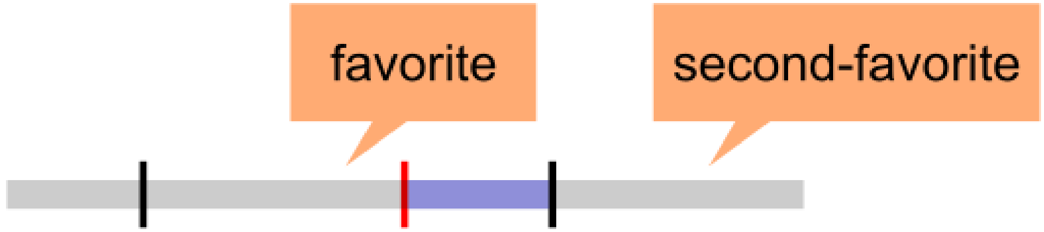

Selfridge-Conway Procedure

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1. Agent A divides the cake into three equal pieces (as per v_A).
2. Agent B trims its favorite piece to create a two-way tie with second-favorite.

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   - Trimmings = S; Main cake M; Original cake = M∪S

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3. Agent C, then B, then A, in that order, pick a piece each from main cake M.

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   - Agent B must pick the trimmed piece if agent C does not.

Let T = owner of the trimmed piece (T = B or C); let T' = {B,C} \ T.

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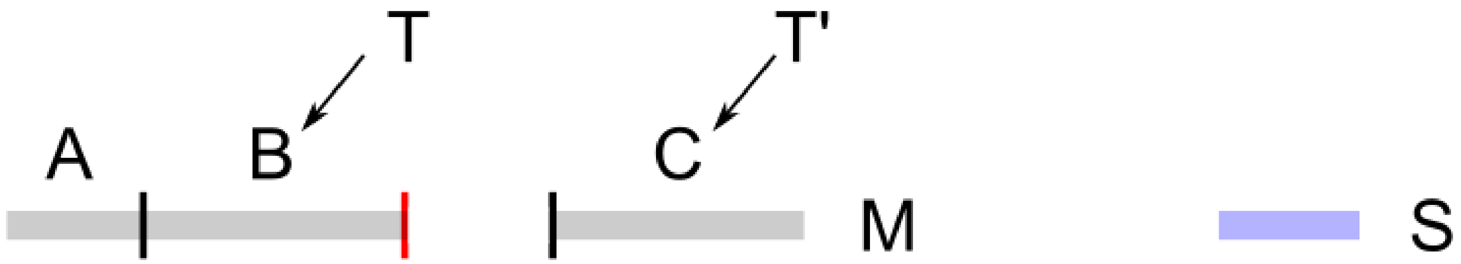

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2. Agent B trims its favorite piece to create a two-way tie with second-favorite.
   - Trimmings = S; Main cake M; Original cake = M∪S
3. Agent C, then B, then A, in that order, pick a piece each from main cake M.
   - Agent B must pick the trimmed piece if agent C does not.

Let T = owner of the trimmed piece (T = B or C); let T' = {B,C} \ T.

Phase 2

Selfridge-Conway Procedure

Phase 1

1. Agent A divides the cake into three equal pieces (as per v_A).
2. Agent B trims its favorite piece to create a two-way tie with second-favorite.
   - Trimmings = S; Main cake M; Original cake = M∪S
3. Agent C, then B, then A, in that order, pick a piece each from main cake M.
   - Agent B must pick the trimmed piece if agent C does not.

Let T = owner of the trimmed piece (T = B or C); let T' = {B,C} \ T.

Phase 2

4. Agent T' divides the trimmings S into three equal pieces (as per $v_{T'}$).

Selfridge-Conway Procedure

Phase 1

1. Agent A divides the cake into three equal pieces (as per v_A).
2. Agent B trims its favorite piece to create a two-way tie with second-favorite.
   - Trimmings = S; Main cake M; Original cake = M∪S
3. Agent C, then B, then A, in that order, pick a piece each from main cake M.
   - Agent B must pick the trimmed piece if agent C does not.

Let T = owner of the trimmed piece (T = B or C); let T' = {B,C} \ T.

Phase 2

4. Agent T' divides the trimmings S into three equal pieces (as per $v_{T'}$).

Selfridge-Conway Procedure

Phase 1

1. Agent A divides the cake into three equal pieces (as per v_A).
2. Agent B trims its favorite piece to create a two-way tie with second-favorite.
   - Trimmings = S; Main cake M; Original cake = M∪S
3. Agent C, then B, then A, in that order, pick a piece each from main cake M.
   - Agent B must pick the trimmed piece if agent C does not.

Let T = owner of the trimmed piece (T = B or C); let T' = {B,C} \ T.

Phase 2

4. Agent T' divides the trimmings S into three equal pieces (as per $v_{T'}$).
5. Agent T, then A, then T', in that order, pick a piece each from trimmings S.

Selfridge-Conway Procedure

Phase 1

1. Agent A divides the cake into three equal pieces (as per v_A).
2. Agent B trims its favorite piece to create a two-way tie with second-favorite.
   - Trimmings = S; Main cake M; Original cake = M∪S
3. Agent C, then B, then A, in that order, pick a piece each from main cake M.
   - Agent B must pick the trimmed piece if agent C does not.

Let T = owner of the trimmed piece (T = B or C); let T' = {B,C} \ T.

Phase 2

4. Agent T' divides the trimmings S into three equal pieces (as per $v_{T'}$).
5. Agent T, then A, then T', in that order, pick a piece each from trimmings S.

Selfridge-Conway Procedure

Selfridge-Conway Procedure

- Is any part of the cake left unassigned in the final allocation?

Selfridge-Conway Procedure

- Is any part of the cake left unassigned in the final allocation? No.

Selfridge-Conway Procedure

- Is the final allocation envy-free from agent C's perspective?

Selfridge-Conway Procedure

- Is the final allocation envy-free from agent C's perspective? Yes.

Selfridge-Conway Procedure

- Is the final allocation envy-free from agent C's perspective? Yes.
  - Within the main cake M, C does not envy A or B because it chooses first.

Selfridge-Conway Procedure

- Is the final allocation envy-free from agent C's perspective? Yes.
    - Within the main cake M, C does not envy A or B because it chooses first.
    - Within the trimmings S, C does not envy A or B because:

Selfridge-Conway Procedure

- Is the final allocation envy-free from agent C's perspective? Yes.
  - Within the main cake M, C does not envy A or B because it chooses first.
  - Within the trimmings S, C does not envy A or B because:
    - If C is T, then it chooses first in S.

Selfridge-Conway Procedure

- Is the final allocation envy-free from agent C's perspective? Yes.
  - Within the main cake M, C does not envy A or B because it chooses first.
  - Within the trimmings S, C does not envy A or B because:
    - If C is T, then it chooses first in S.
    - If C is T', then it divides S into three equal pieces.

Selfridge-Conway Procedure

- Is the final allocation envy-free from agent C's perspective? Yes.
  - Within the main cake M, C does not envy A or B because it chooses first.
  - Within the trimmings S, C does not envy A or B because:
    - If C is T, then it chooses first in S.
    - If C is T', then it divides S into three equal pieces.
  - By additivity across M∪S, C does not envy A or B w.r.t. the entire cake.

Selfridge-Conway Procedure

- Is the final allocation envy-free from agent B's perspective?

Selfridge-Conway Procedure

- Is the final allocation envy-free from agent B's perspective? Yes.

Selfridge-Conway Procedure

- Is the final allocation envy-free from agent B's perspective? Yes.
  - Within the main cake M, B does not envy A or C because of two-way tie.

Selfridge-Conway Procedure

- Is the final allocation envy-free from agent B's perspective? Yes.
  - Within the main cake M, B does not envy A or C because of two-way tie.
  - Within the trimmings S, B does not envy A or C because:

Selfridge-Conway Procedure

- Is the final allocation envy-free from agent B's perspective? Yes.
  - Within the main cake M, B does not envy A or C because of two-way tie.
  - Within the trimmings S, B does not envy A or C because:
    - If B is T, then it chooses first in S.

Selfridge-Conway Procedure

- Is the final allocation envy-free from agent B's perspective? Yes.
  - Within the main cake M, B does not envy A or C because of two-way tie.
  - Within the trimmings S, B does not envy A or C because:
    - If B is T, then it chooses first in S.
    - If B is T', then it cuts S into three equal pieces.

Selfridge-Conway Procedure

- Is the final allocation envy-free from agent B's perspective? Yes.
  - Within the main cake M, B does not envy A or C because of two-way tie.
  - Within the trimmings S, B does not envy A or C because:
    - If B is T, then it chooses first in S.
    - If B is T', then it cuts S into three equal pieces.
  - By additivity across M∪S, B does not envy A or C w.r.t. the entire cake.

Selfridge-Conway Procedure

- Is the final allocation envy-free from agent A's perspective?

Selfridge-Conway Procedure

- Is the final allocation envy-free from agent A's perspective? Yes.

Selfridge-Conway Procedure

- Is the final allocation envy-free from agent A's perspective? Yes.
  - Within the main cake M, A does not envy B or C because it was the cutter and it never gets the trimmed piece.

Selfridge-Conway Procedure

- Is the final allocation envy-free from agent A's perspective? Yes.
  - Within the main cake M, A does not envy B or C because it was the cutter and it never gets the trimmed piece.
  - Within the trimmings S, A does not envy:

Selfridge-Conway Procedure

- Is the final allocation envy-free from agent A's perspective? Yes.
  - Within the main cake M, A does not envy B or C because it was the cutter and it never gets the trimmed piece.
  - Within the trimmings S, A does not envy:
    - T' because it picks before T' does.

Selfridge-Conway Procedure

- Is the final allocation envy-free from agent A's perspective? Yes.
  - Within the main cake M, A does not envy B or C because it was the cutter and it never gets the trimmed piece.
  - Within the trimmings S, A does not envy:
    - T' because it picks before T' does.
    - T because of "irrevocable advantage" from Phase 1.

Selfridge-Conway Procedure

- Is the final allocation envy-free from agent A's perspective? Yes.
  - Within the main cake M, A does not envy B or C because it was the cutter and it never gets the trimmed piece.
  - Within the trimmings S, A does not envy:
    - T' because it picks before T' does.
    - T because of "irrevocable advantage" from Phase 1.
  - By additivity across M∪S, A does not envy B or C w.r.t. the entire cake.