Advanced Algorithms – COMS31900

Approximation algorithms part one

Constant factor approximations

Raphaël Clifford

Slides by Benjamin Sach

NP-completeness recap

NP is the class of *decision* problems we can check the answer to in polynomial time

A problem A is NP-complete if

A is in NP

Every B in NP has a polynomial time reduction to A

(this second part is the definition of NP-hard)

NP-completeness recap

'yes/no' problems

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we can solve B
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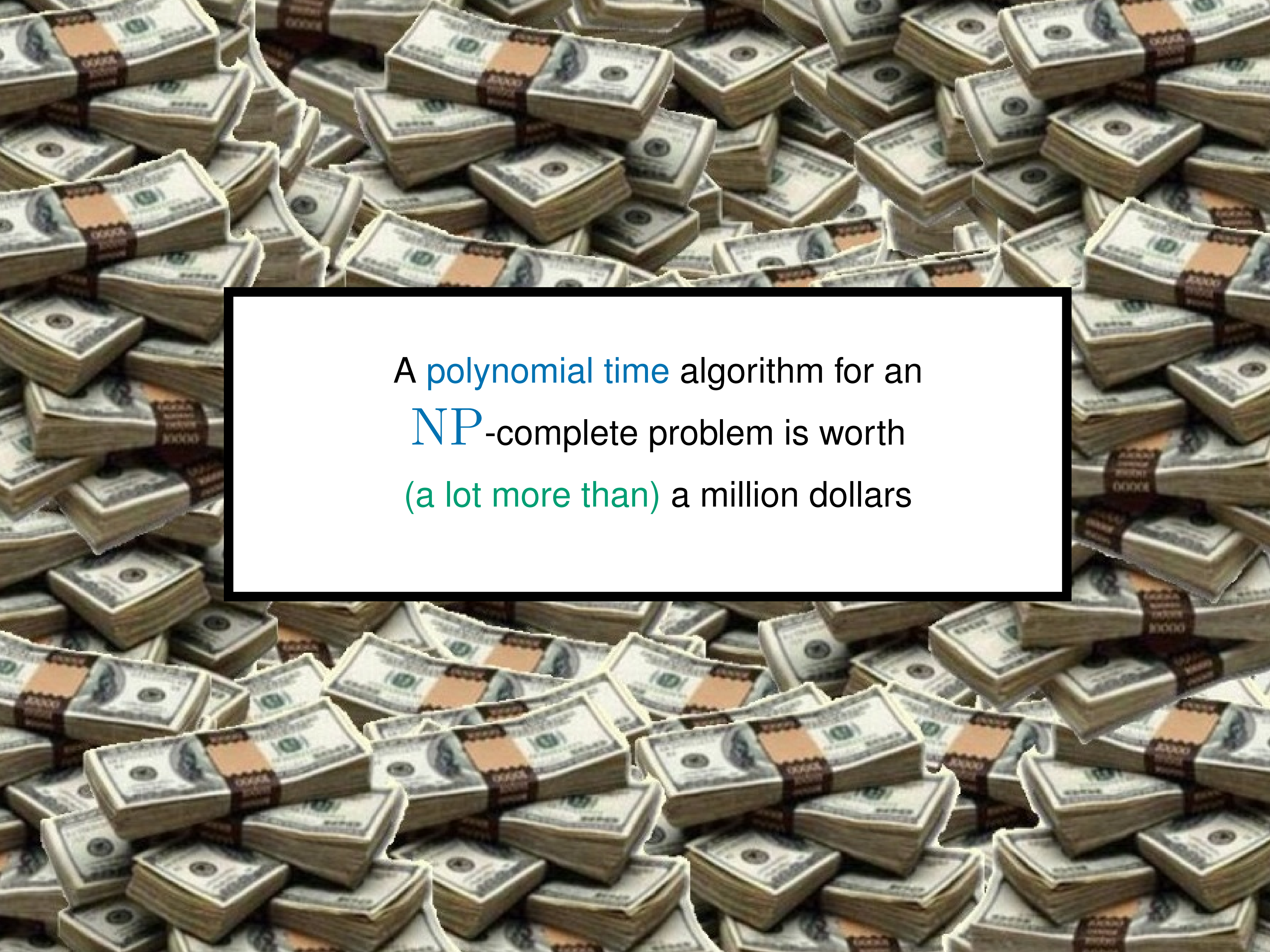
Most computer scientists (I've met) believe
that you can't solve them in polynomial time (i.e. that $\mathrm{P} \neq \mathrm{NP}$)



A polynomial time algorithm for an NP-complete problem is worth (a lot more than) a million dollars

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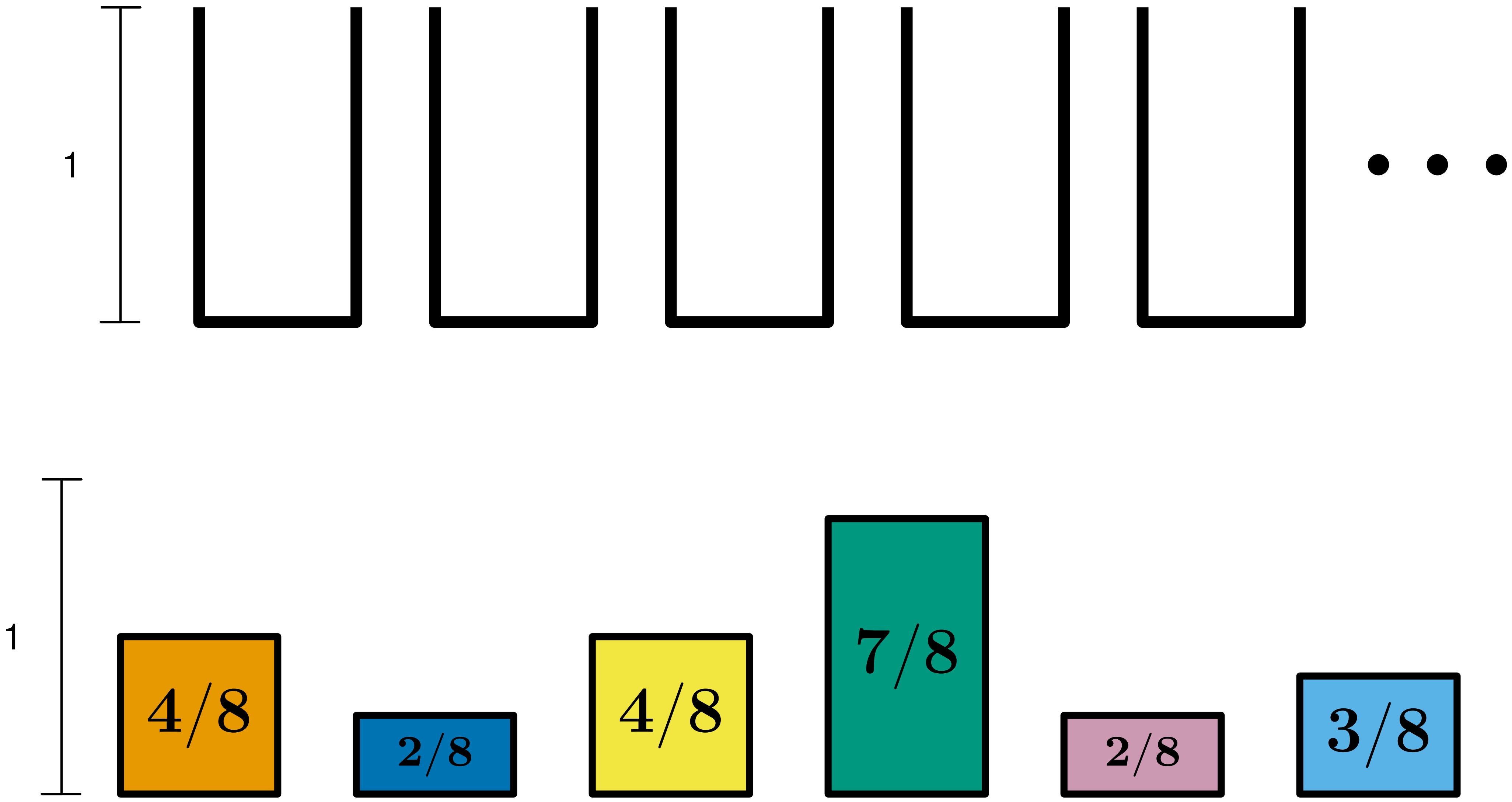
They are the 'hardest' problems in NP

So if a problem is NP-complete, we give up right?

Bin packing



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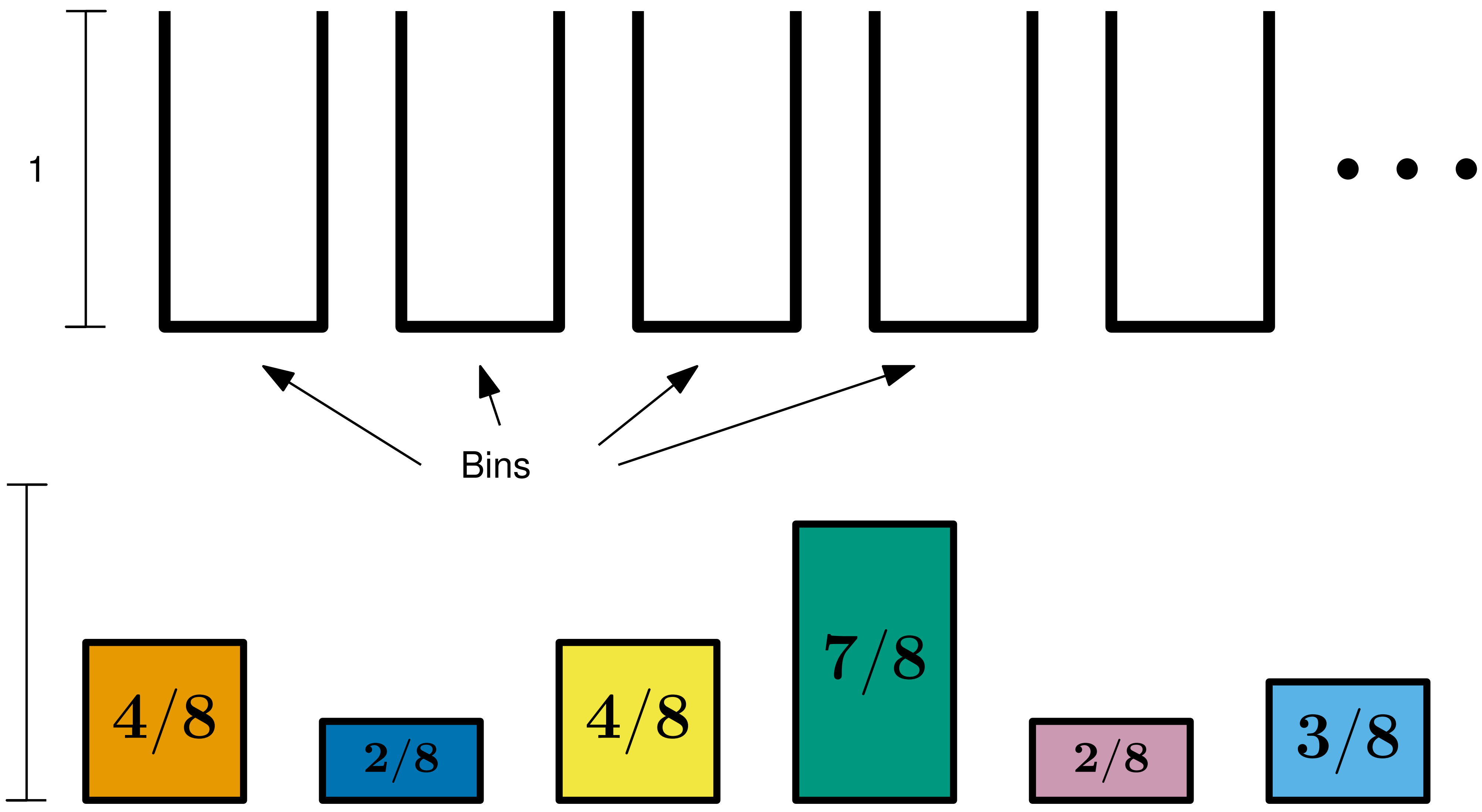

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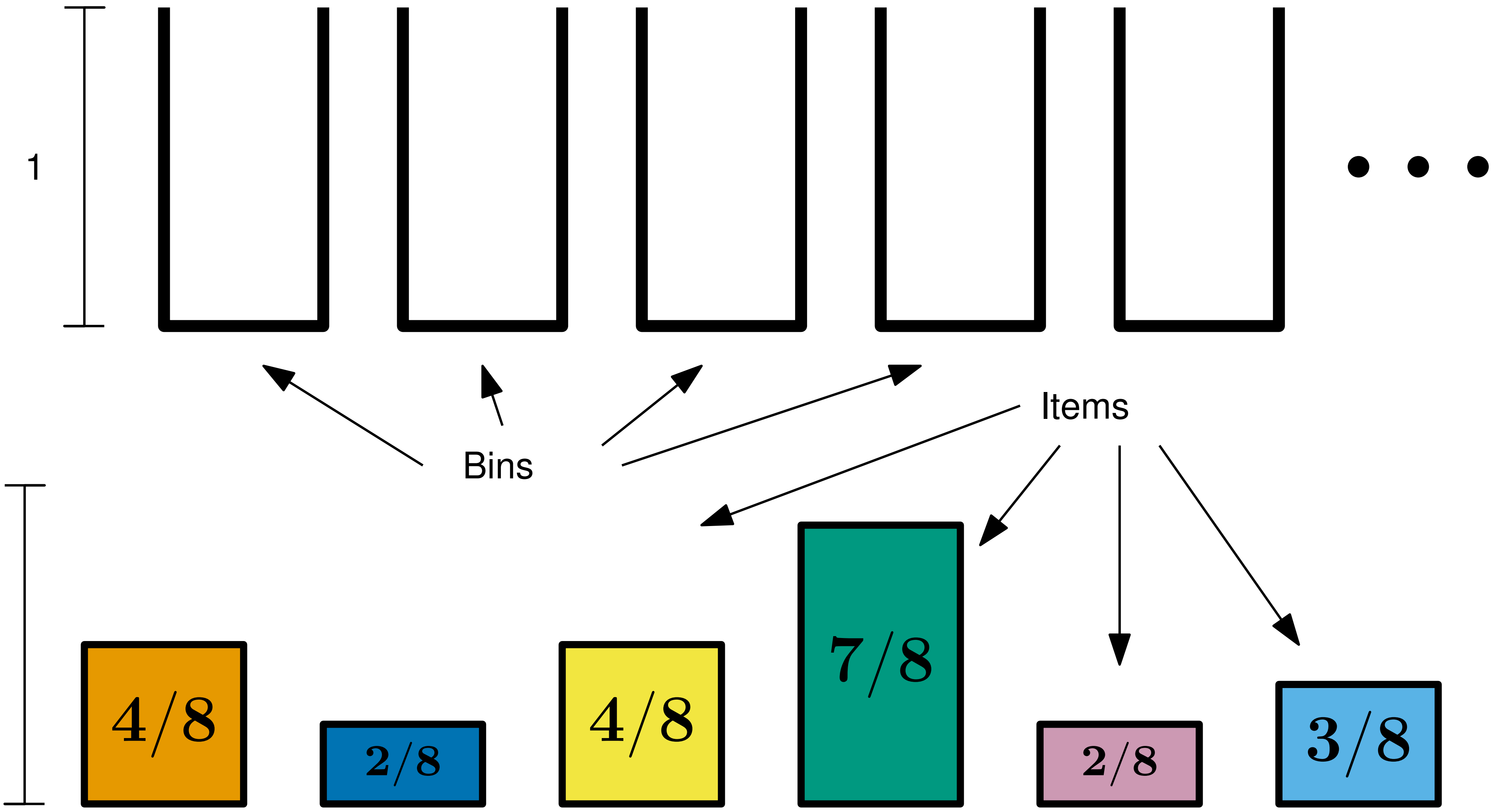

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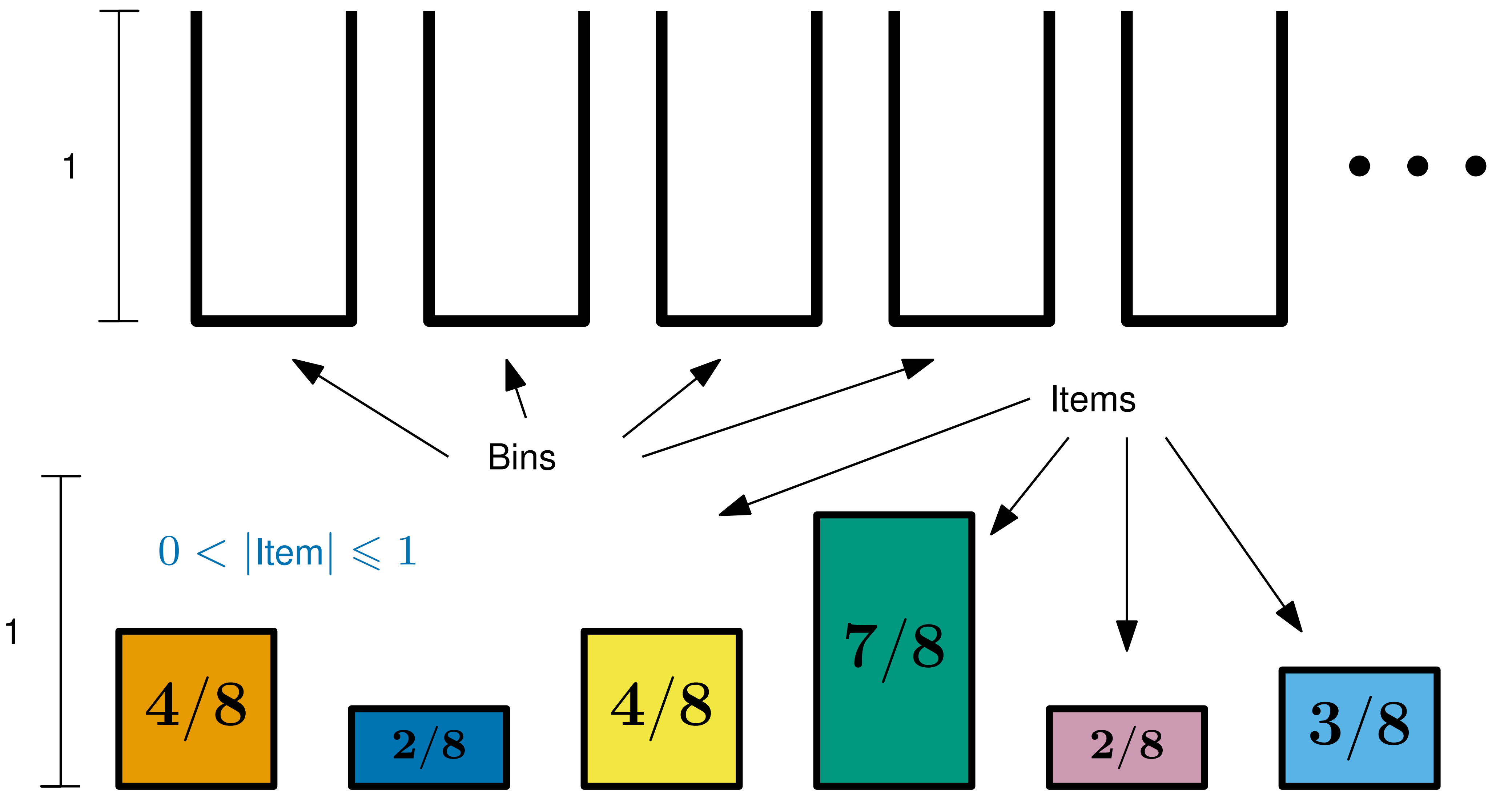

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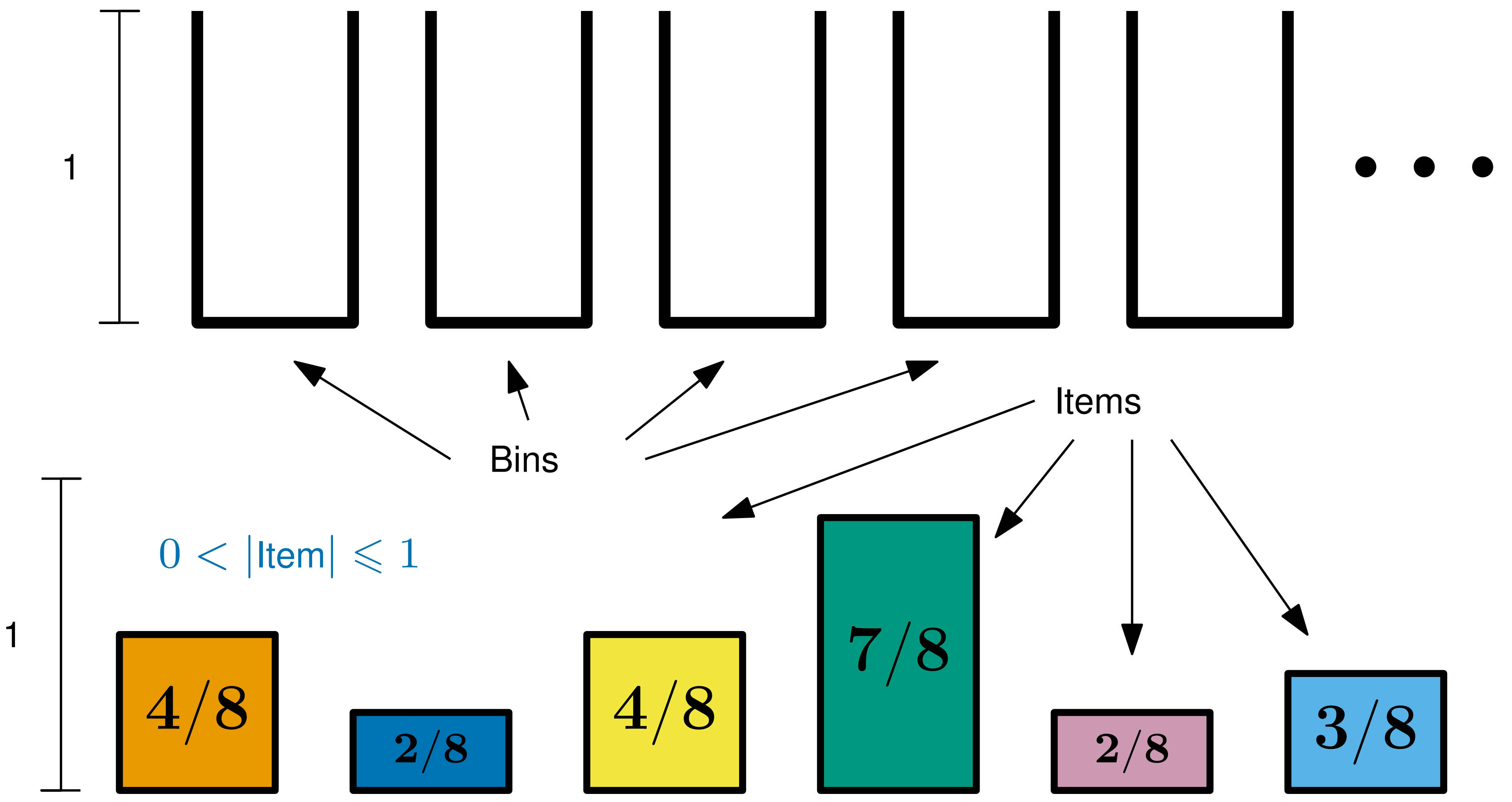
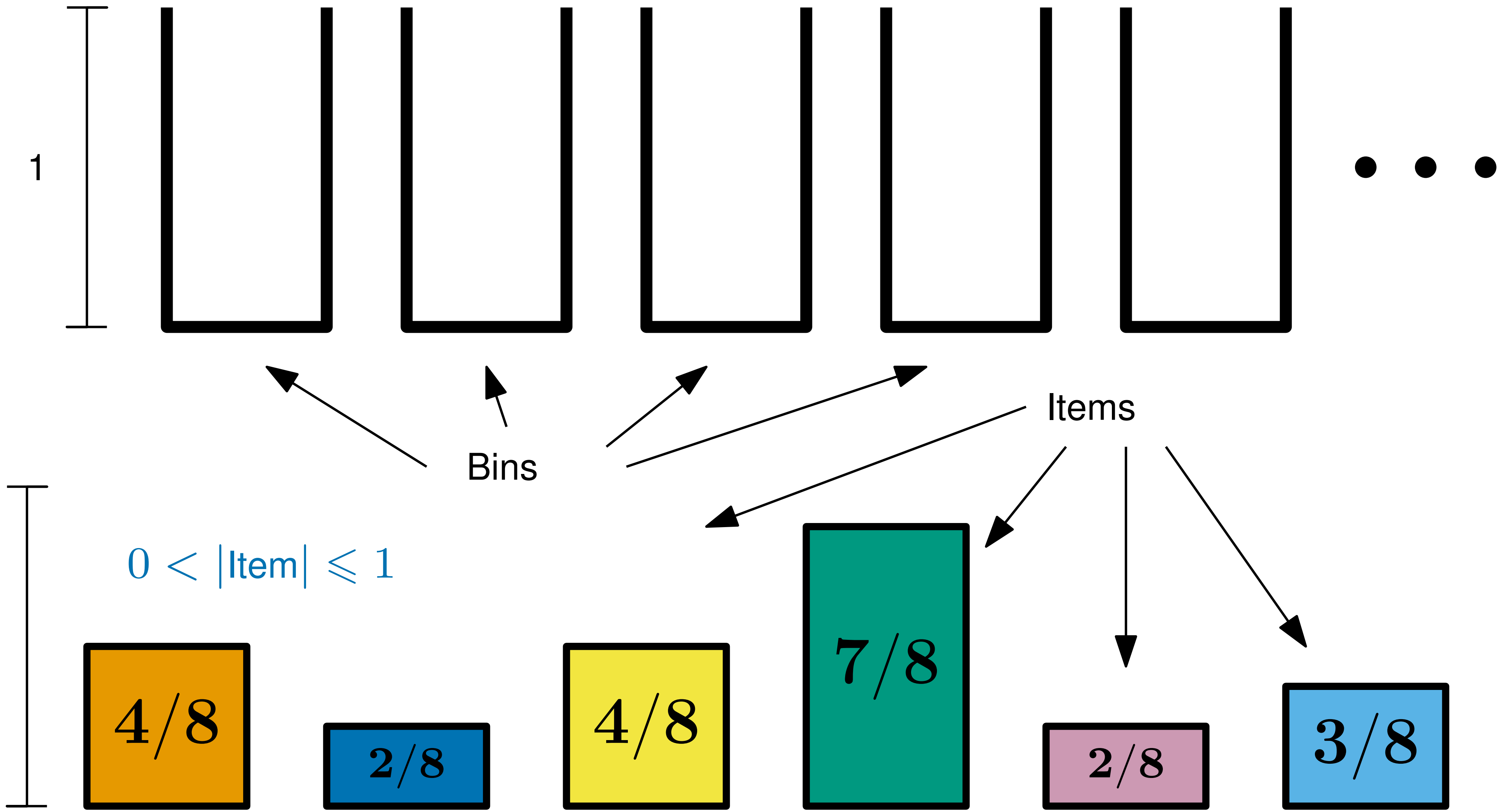


I is the sum of all item sizes

Bin packing

$|\text{Bin}| = 1$ and there is an unlimited number of bins. . .



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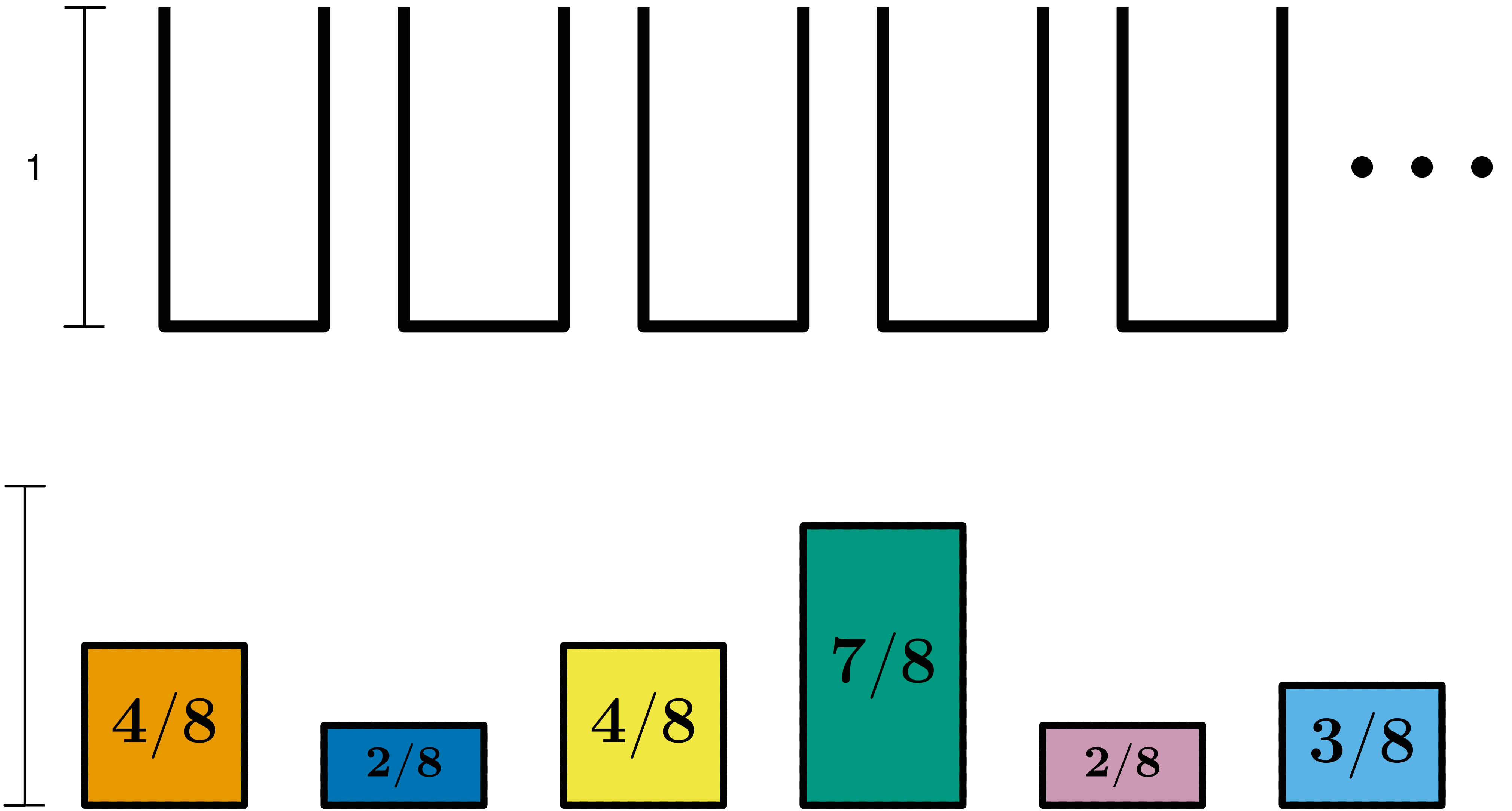
Bin packing

Problem pack all items into the fewest possible bins



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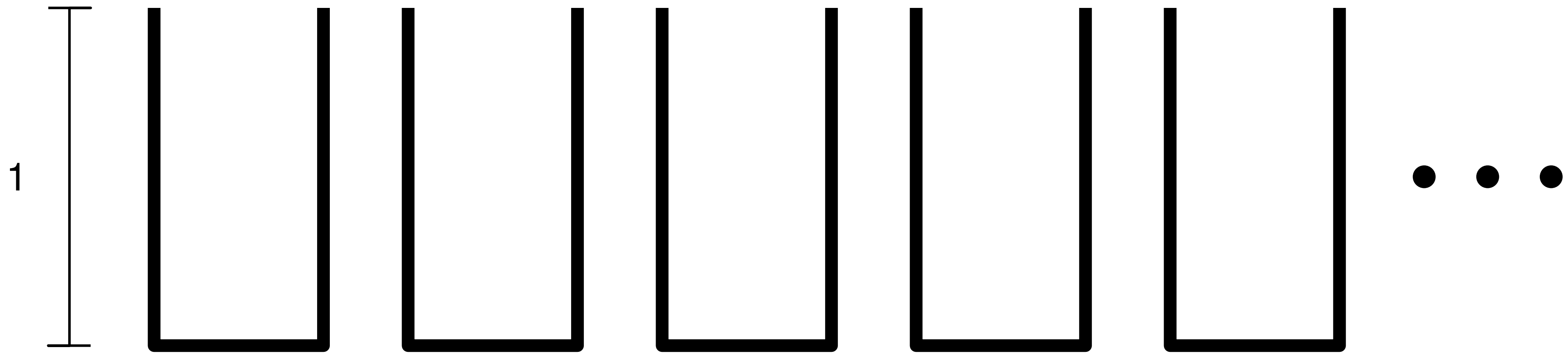
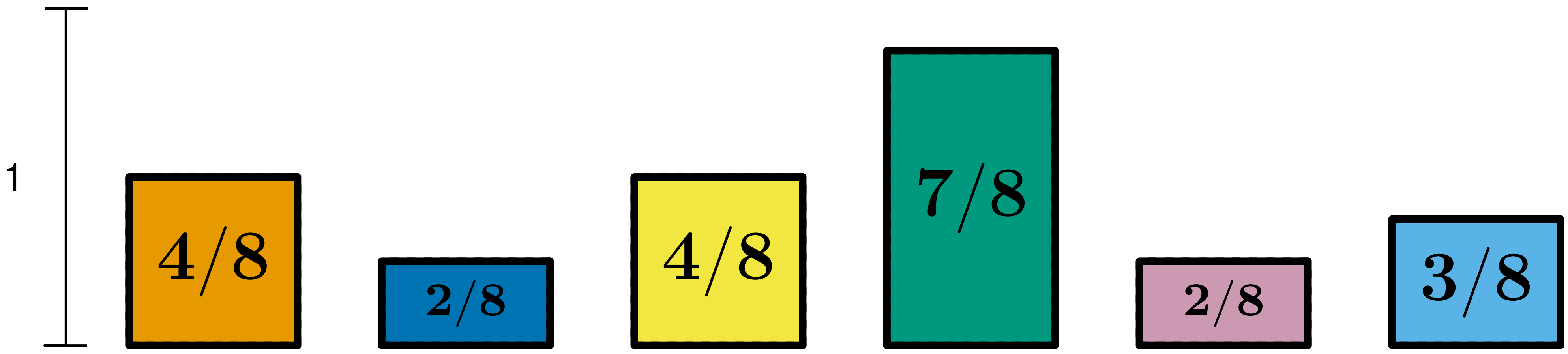


This is an example of an optimisation *problem*



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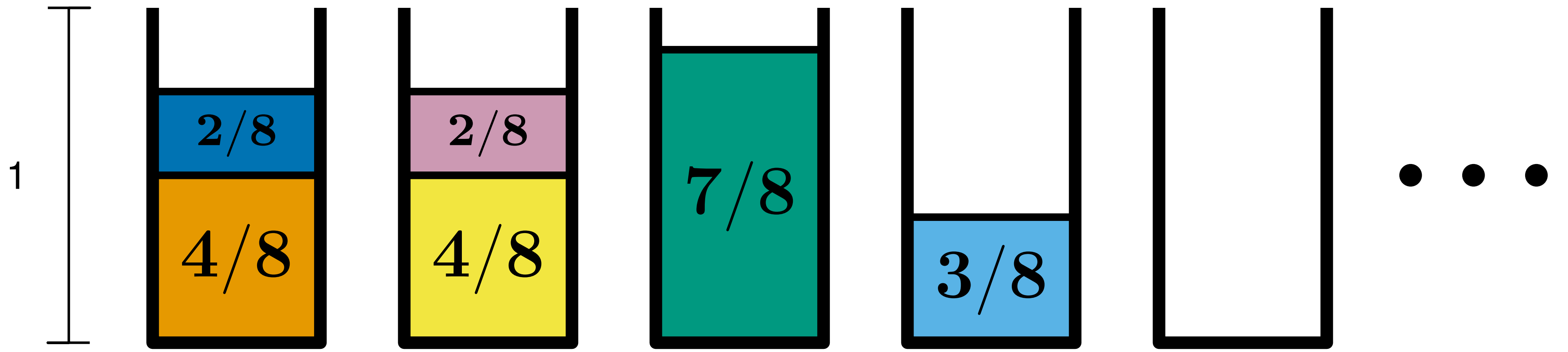

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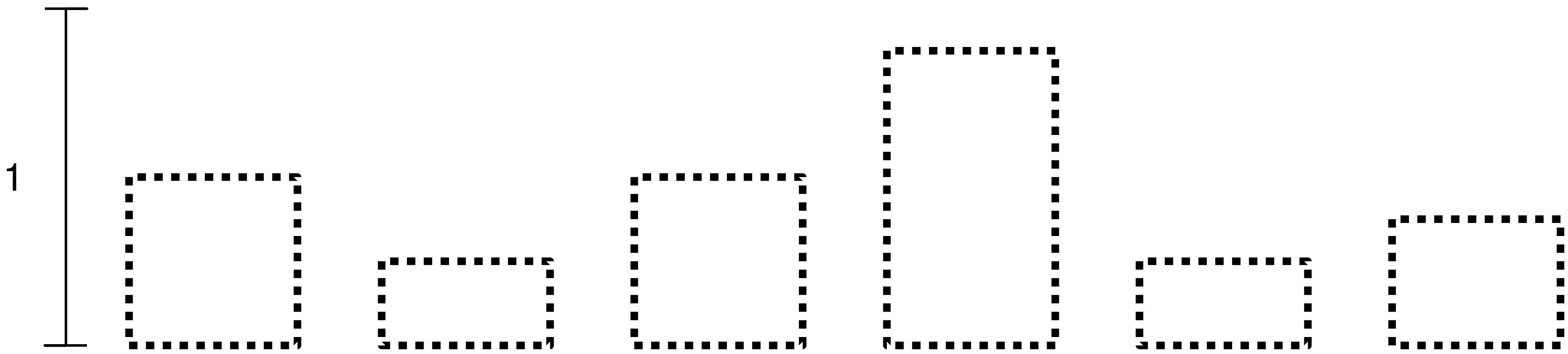

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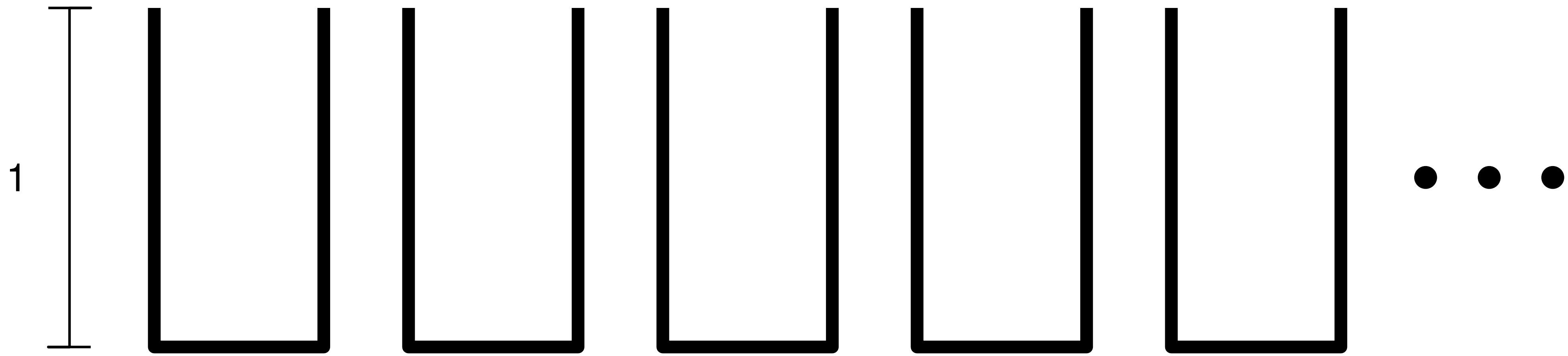

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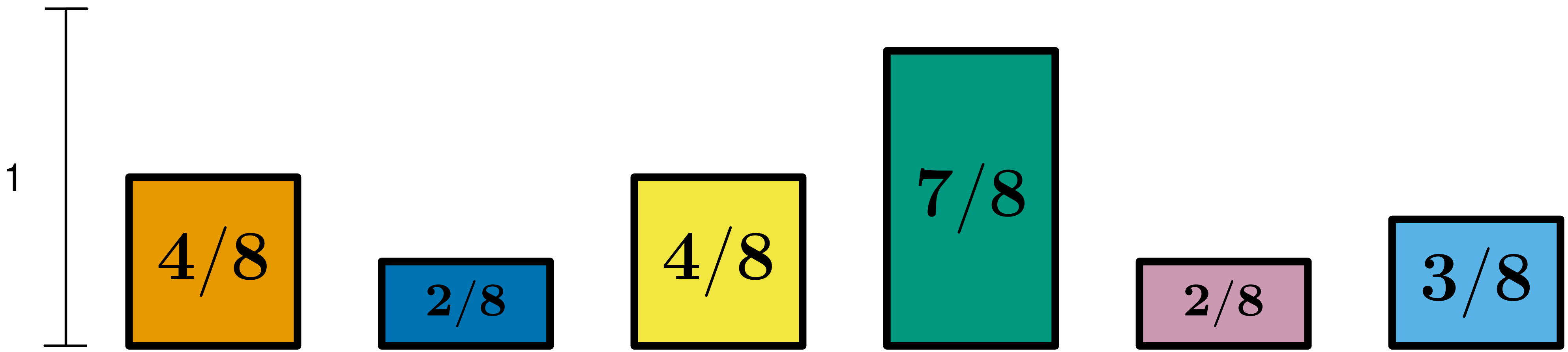

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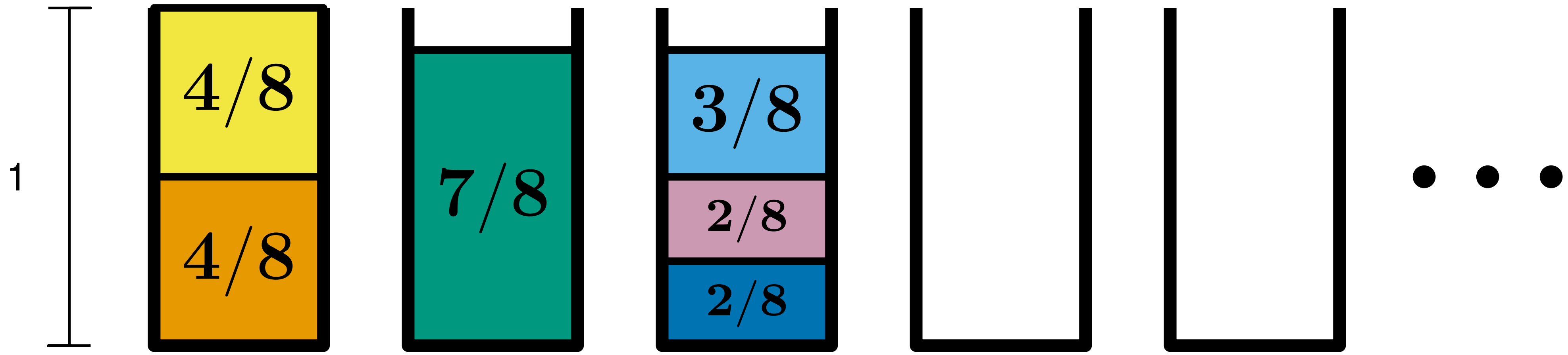

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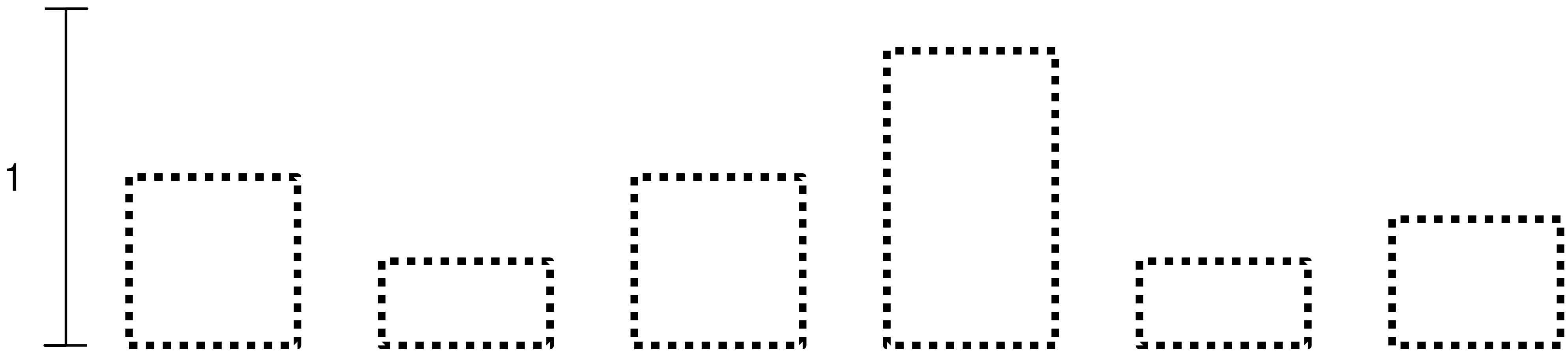

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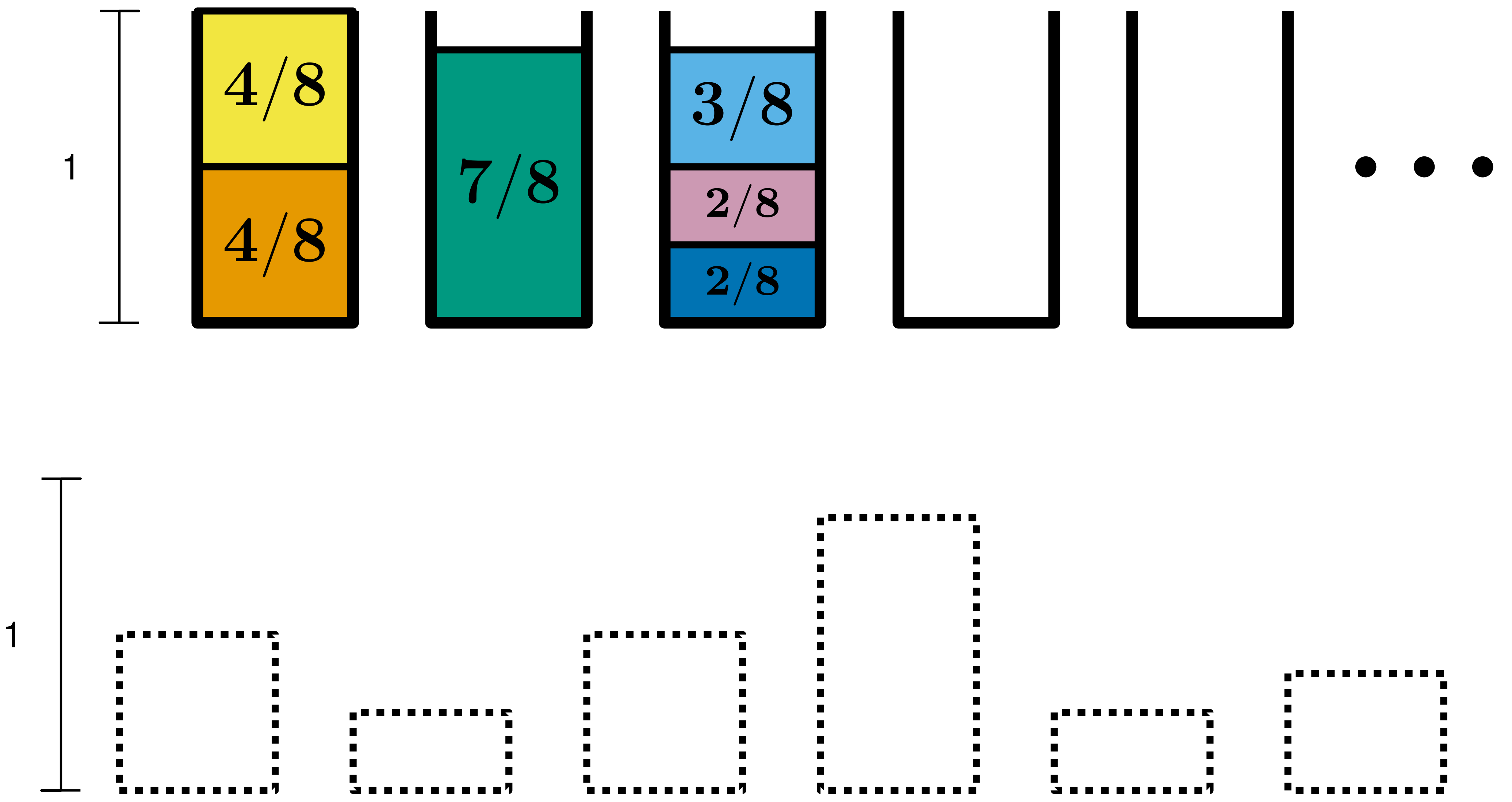

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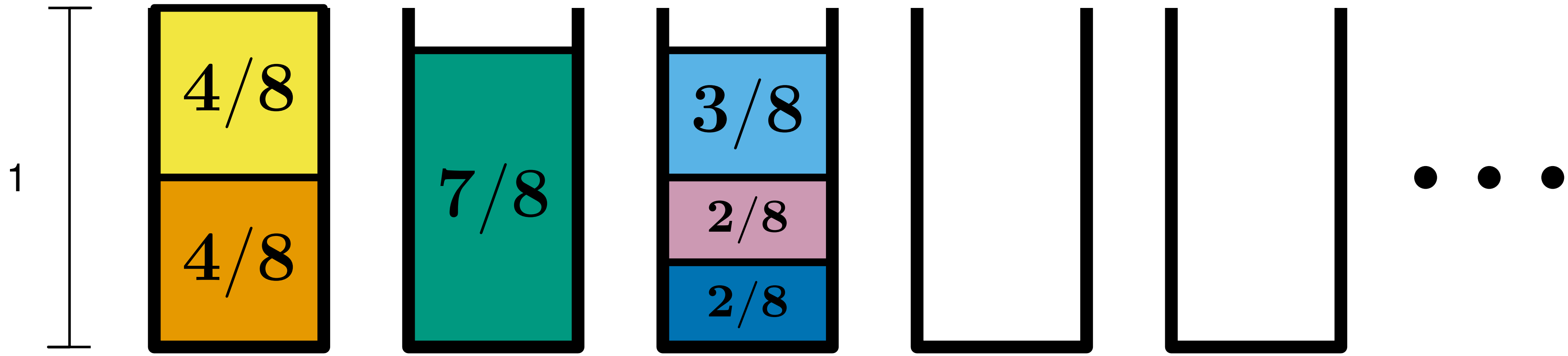
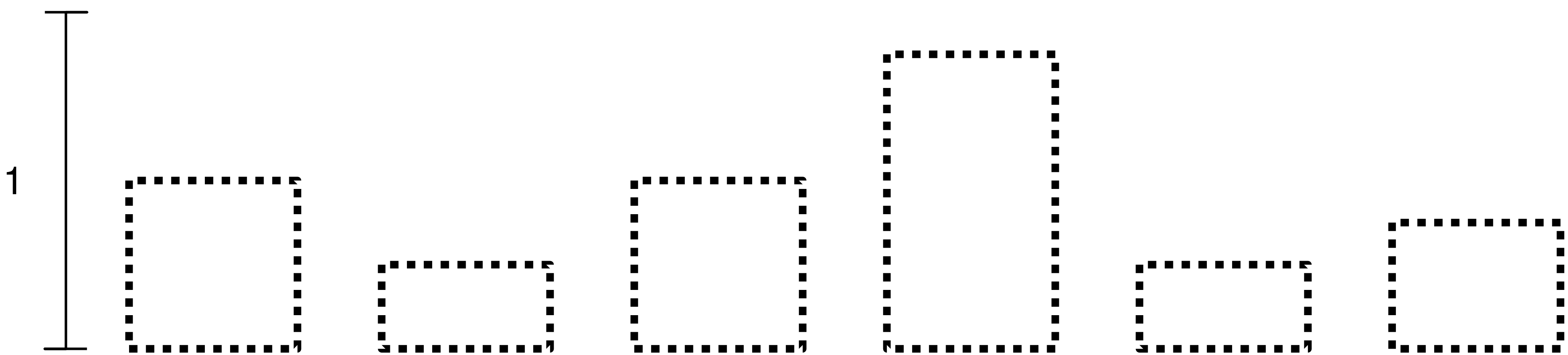


The BinPacking problem is known to be NP-hard



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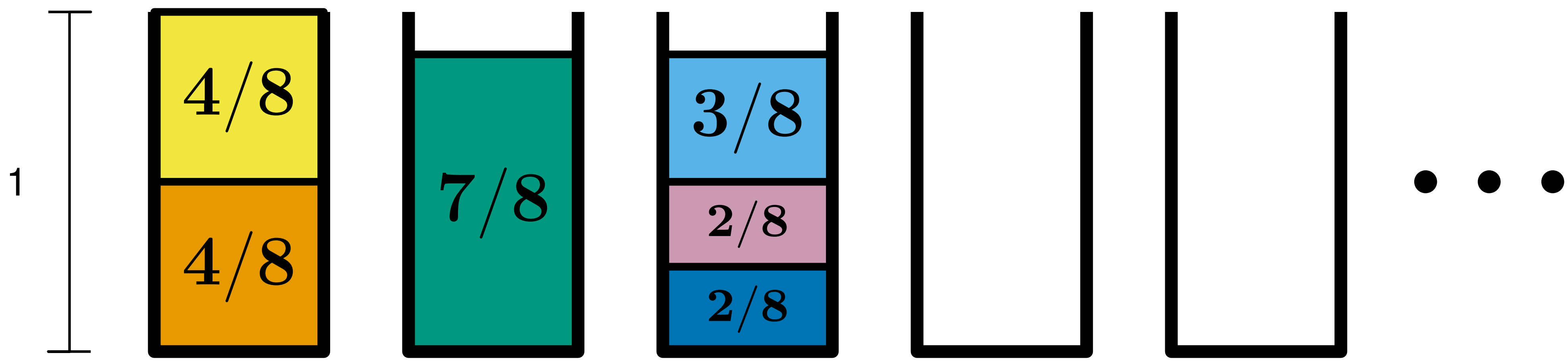


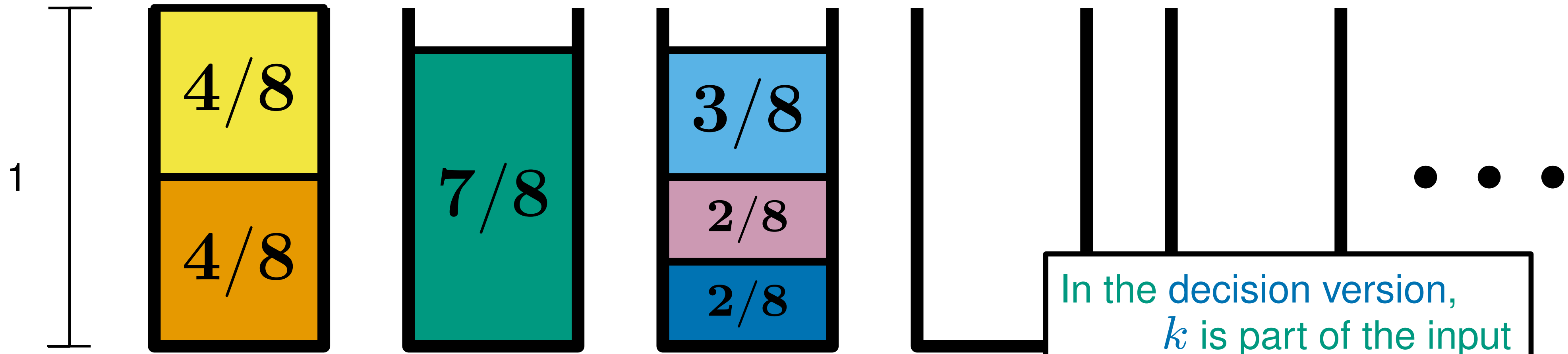
The BINPACKING problem is known to be NP-hard

and the decision version... "Can you pack the items into at most k bins?"

is NP-complete

Bin packing

Problem pack all items into the fewest possible bins



In the decision version,
k is part of the input

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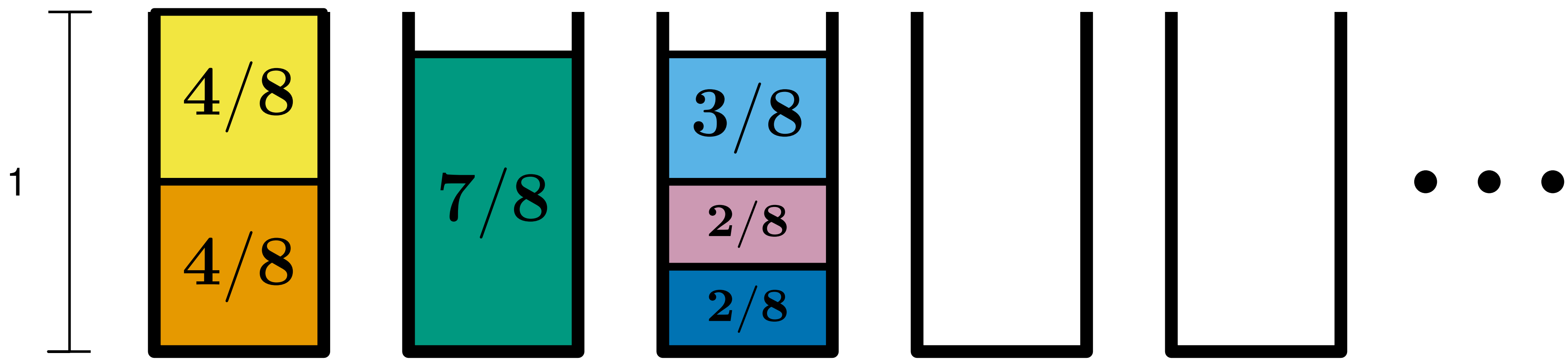

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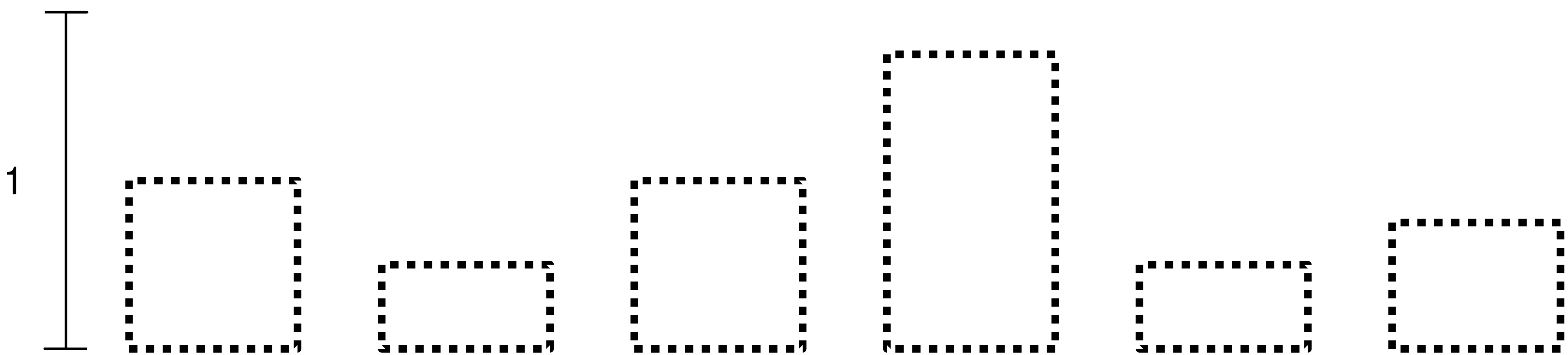

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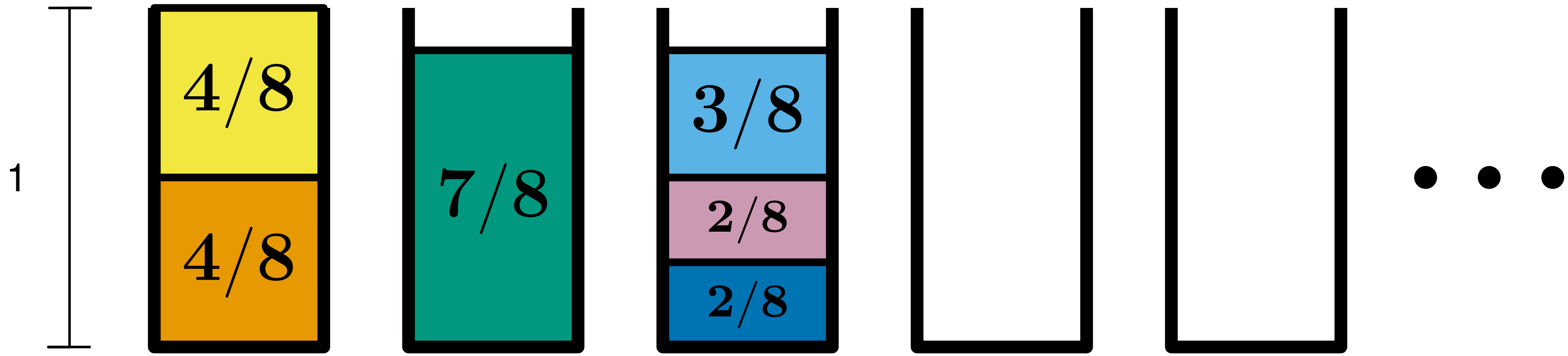
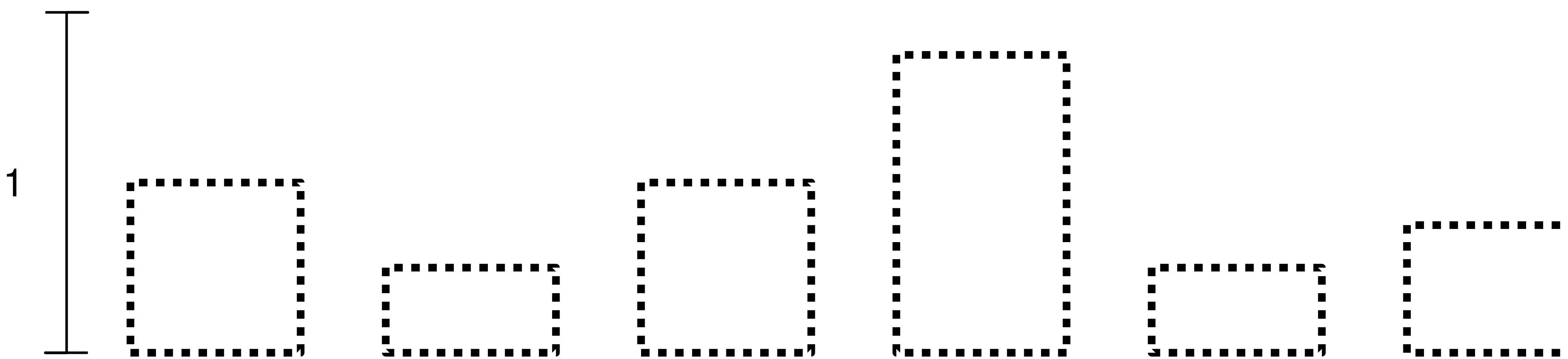
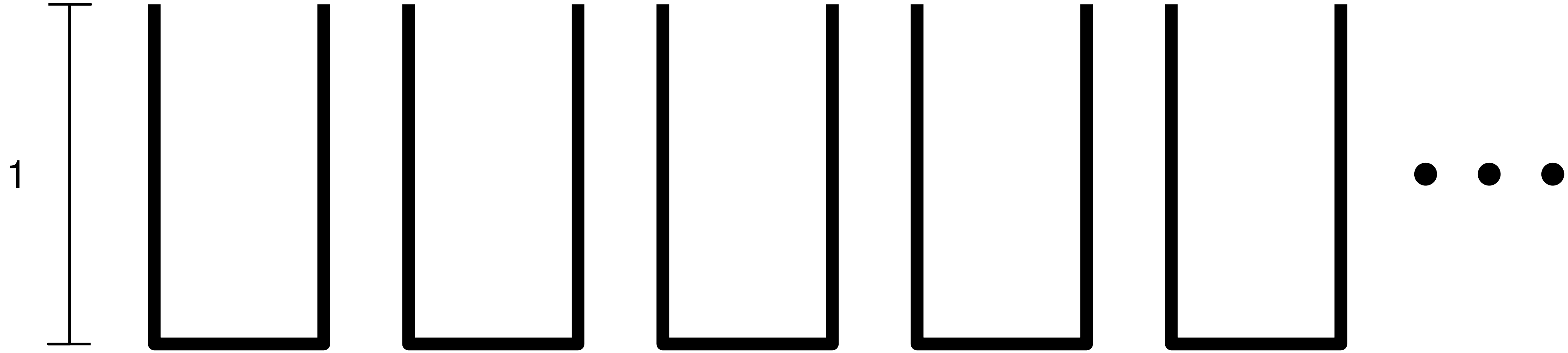


The BinPacking problem is known to be NP-hard

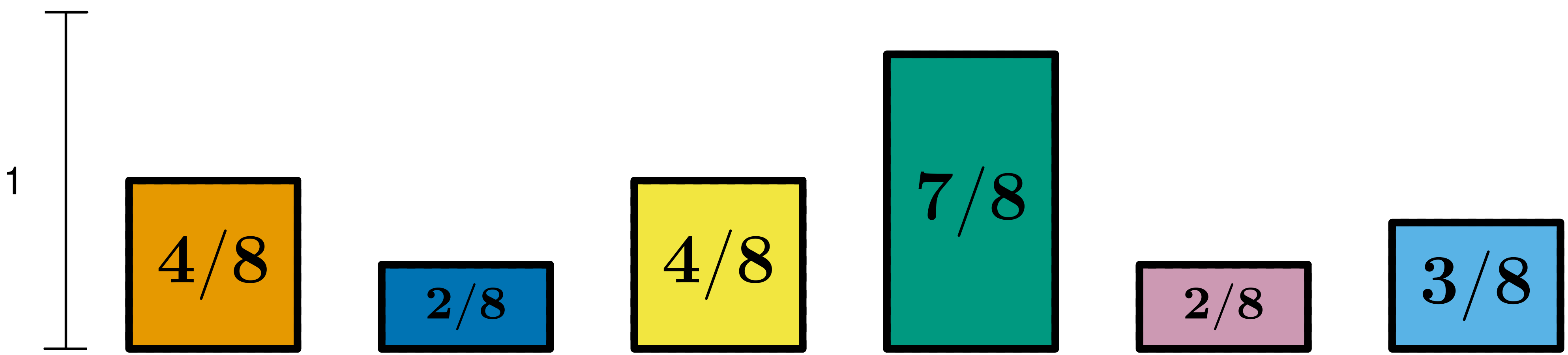
but fortunately we can approximate



Next fit



If item `i` fits into bin `j`: pack it, `i++`; **else** `j++`;



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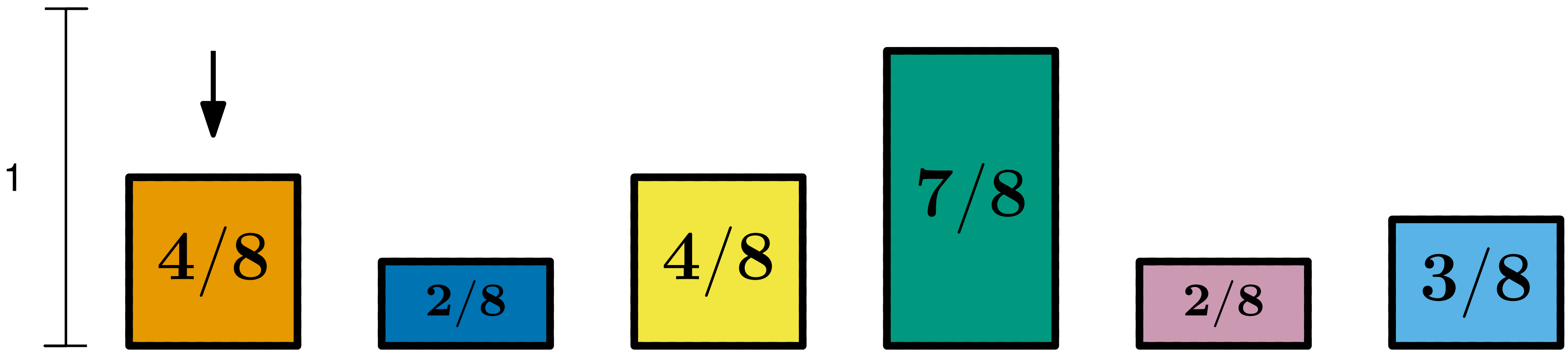

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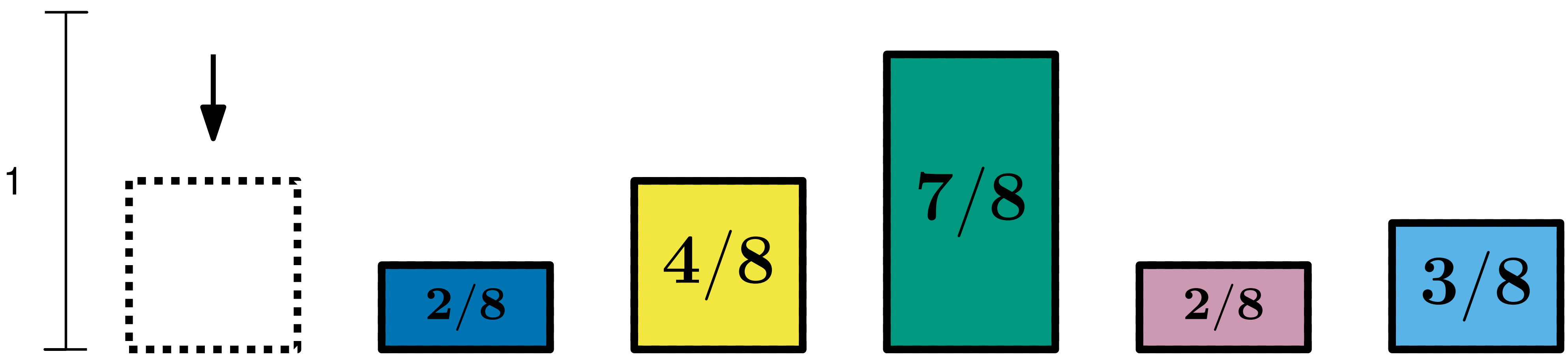

University of BRISTOL

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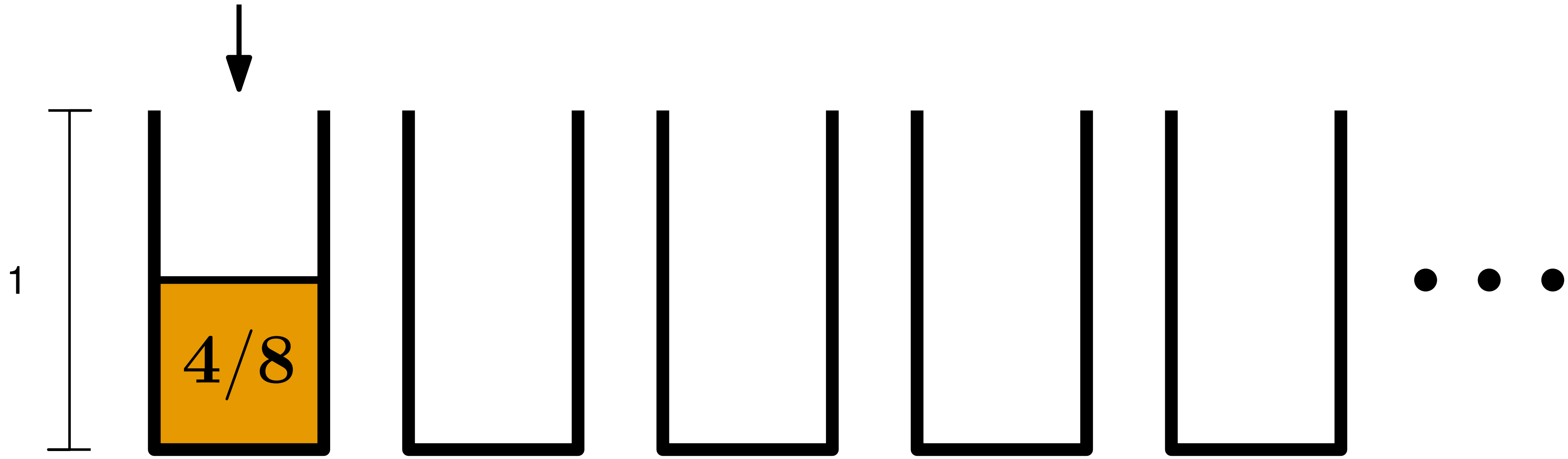

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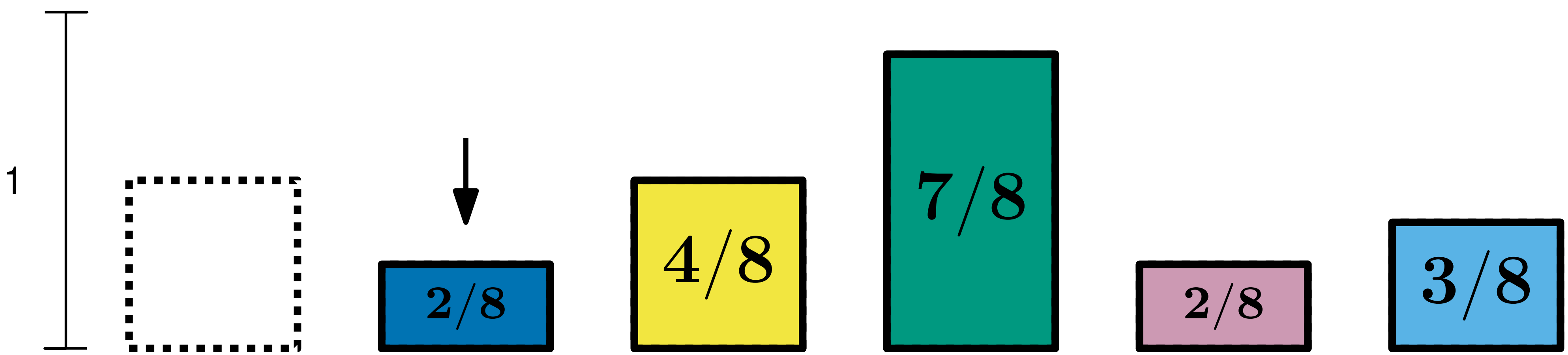

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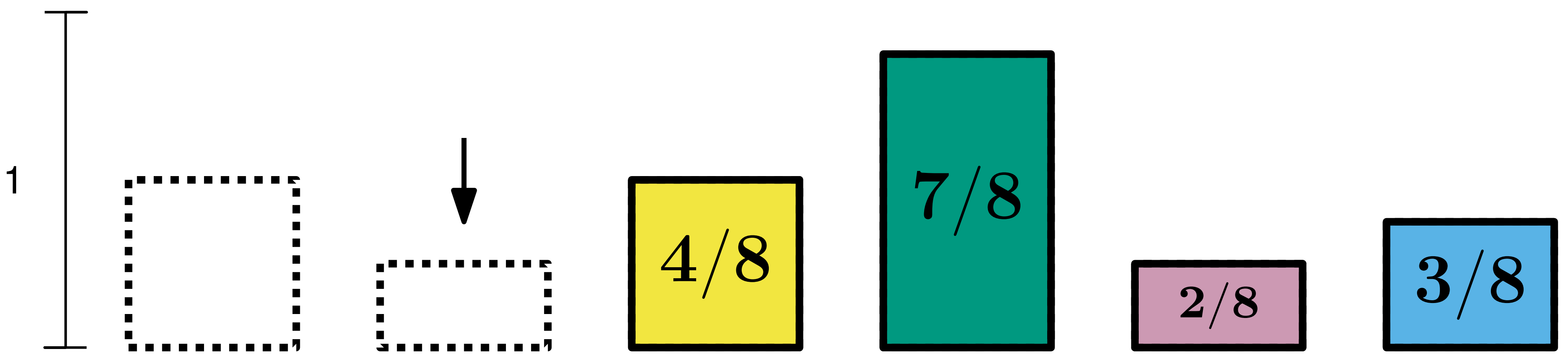

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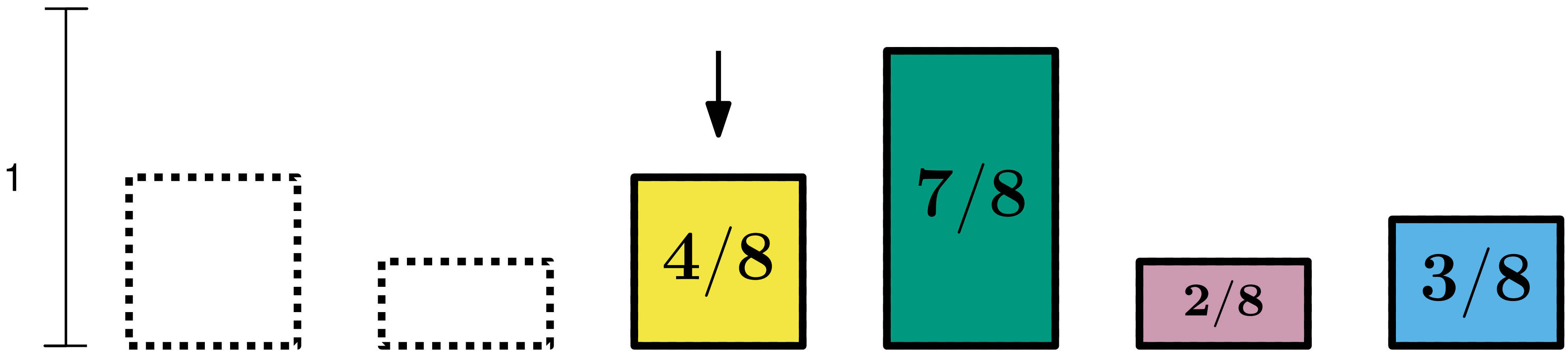

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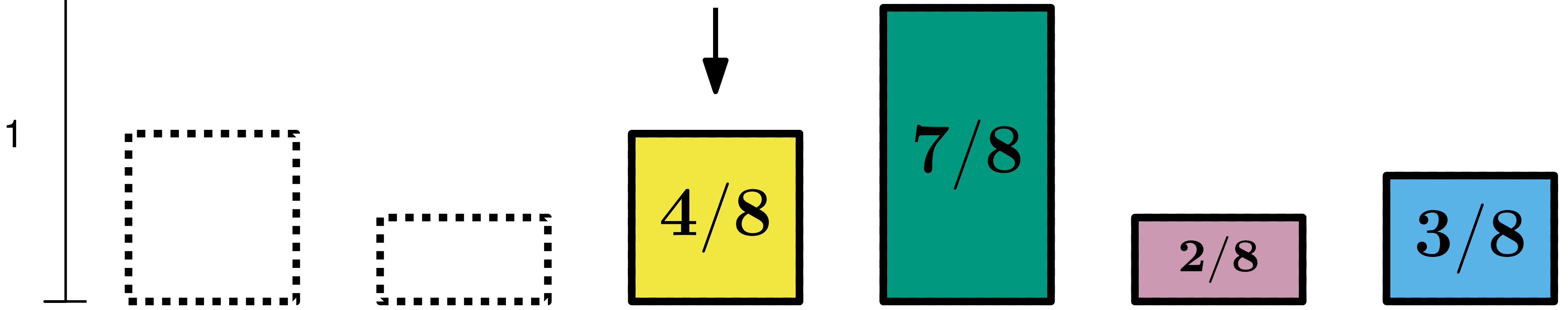

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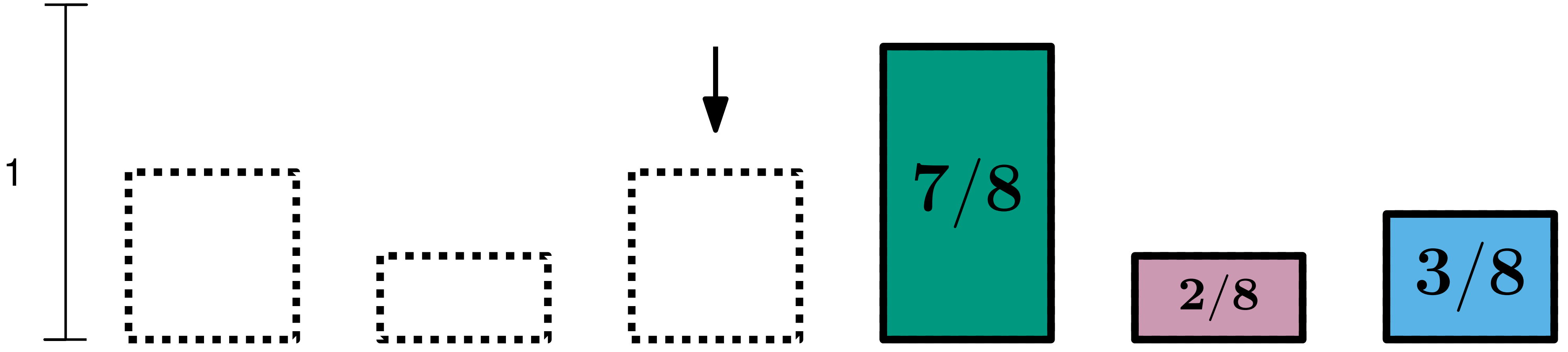

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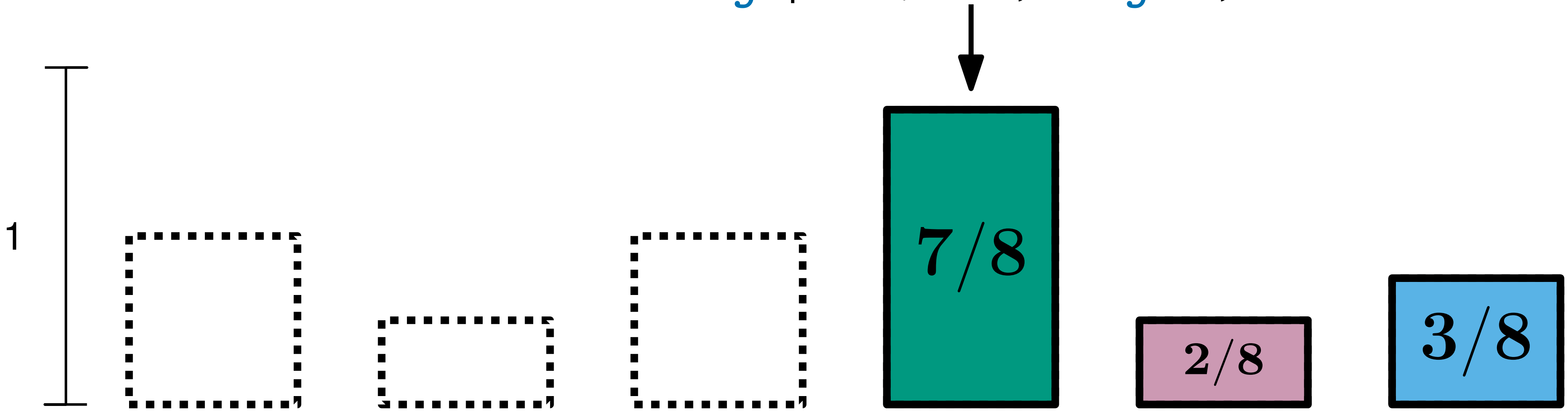

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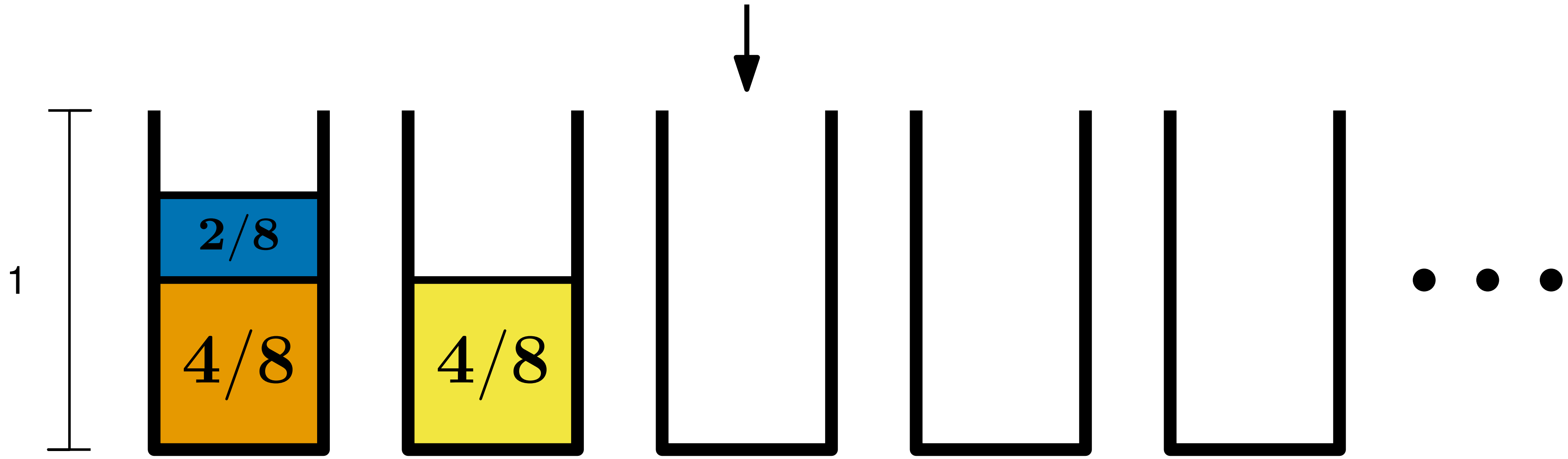

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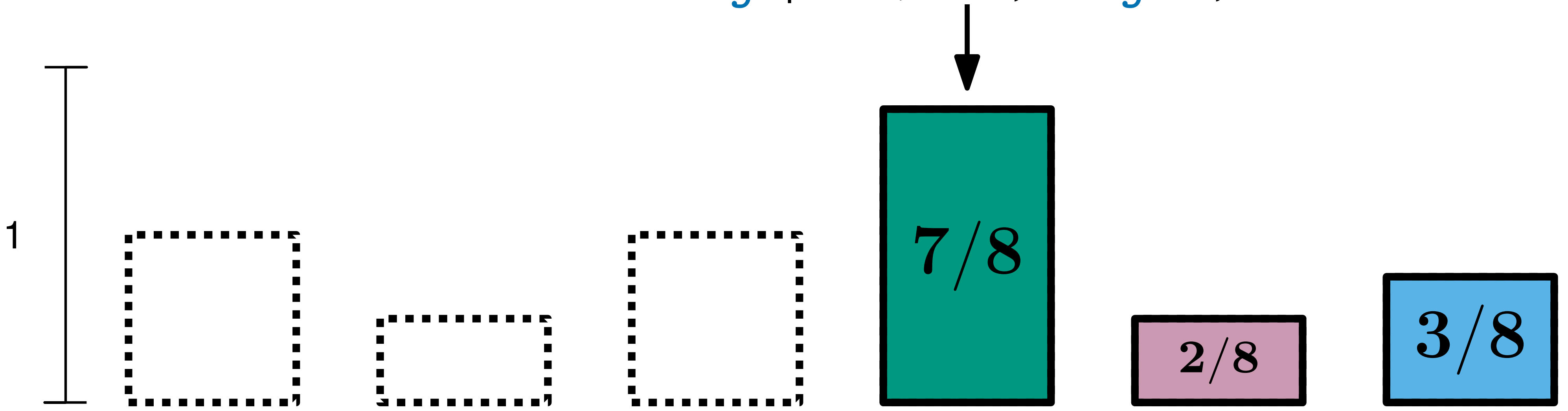

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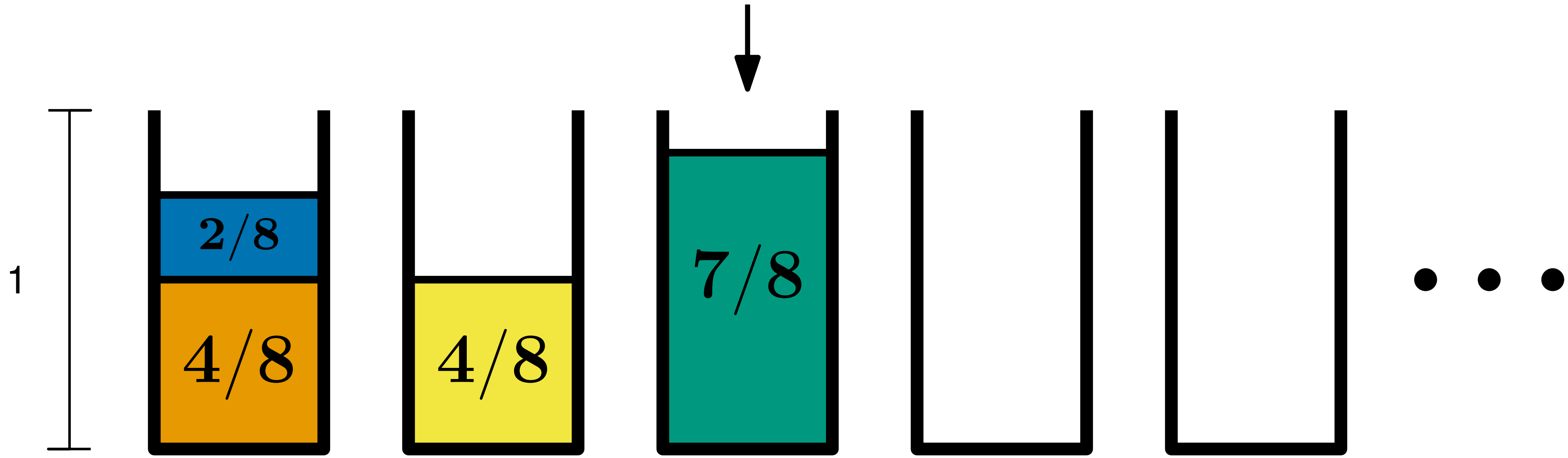

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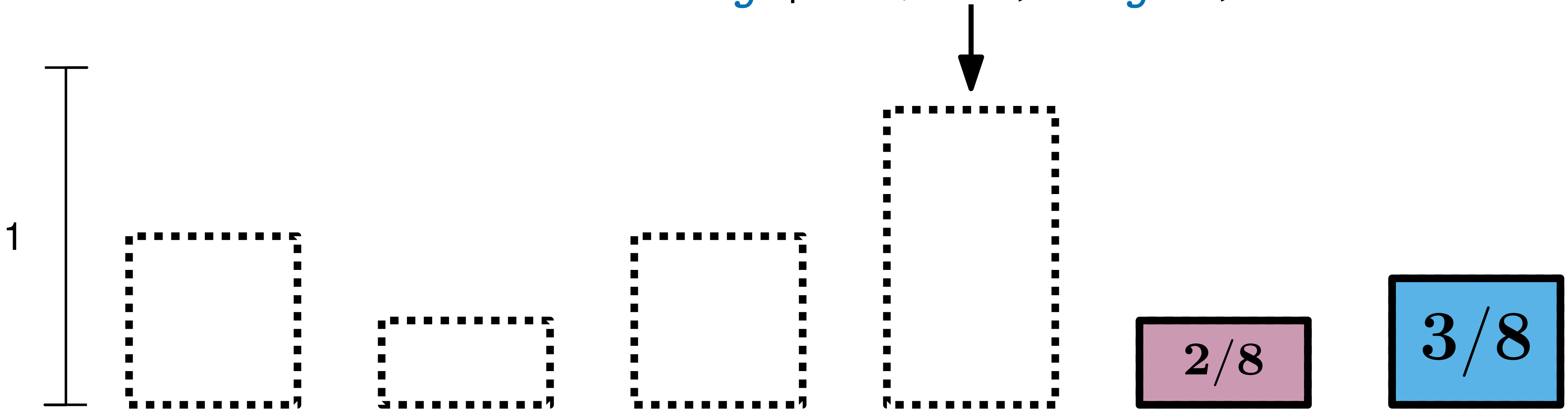

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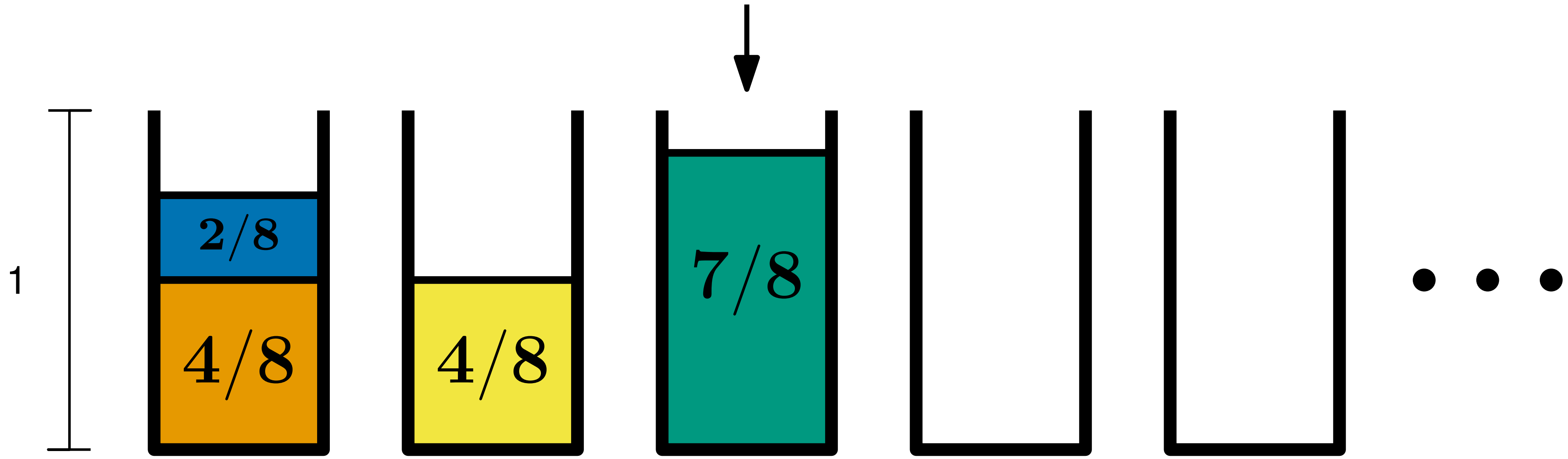

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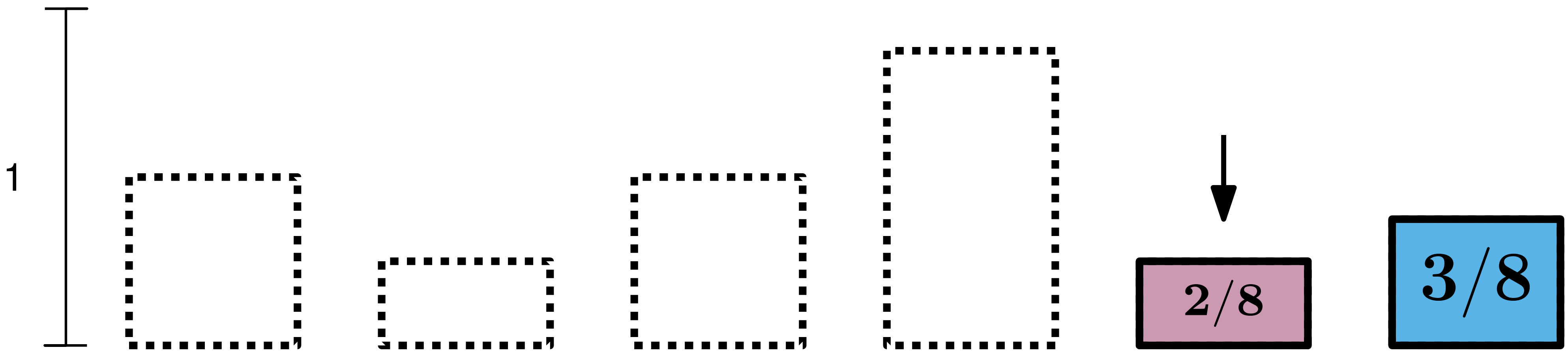

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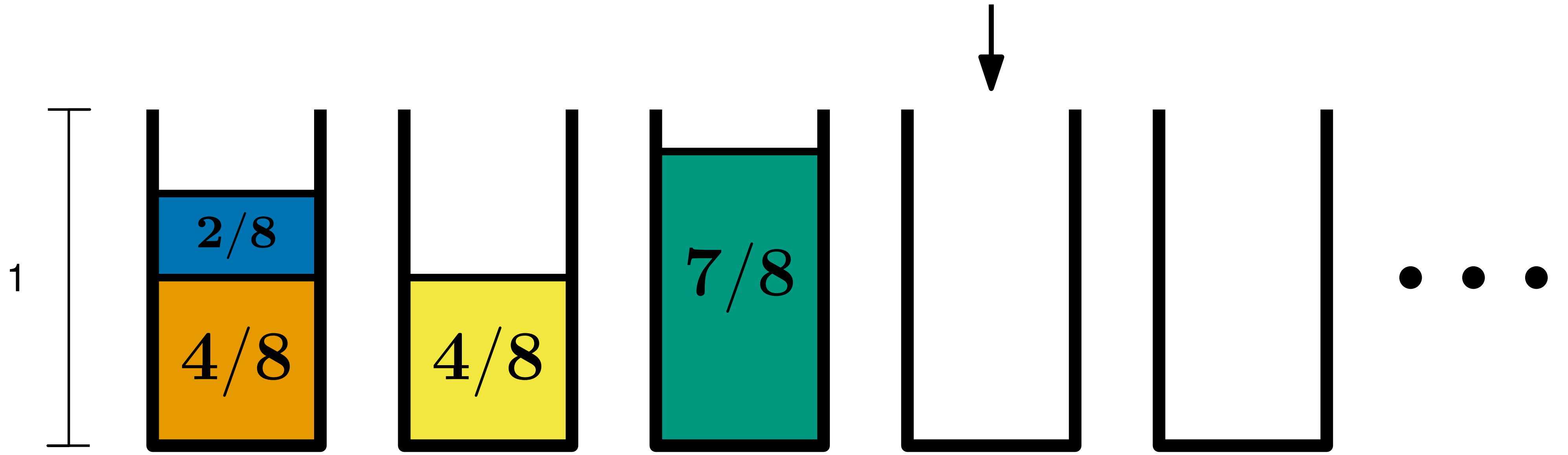

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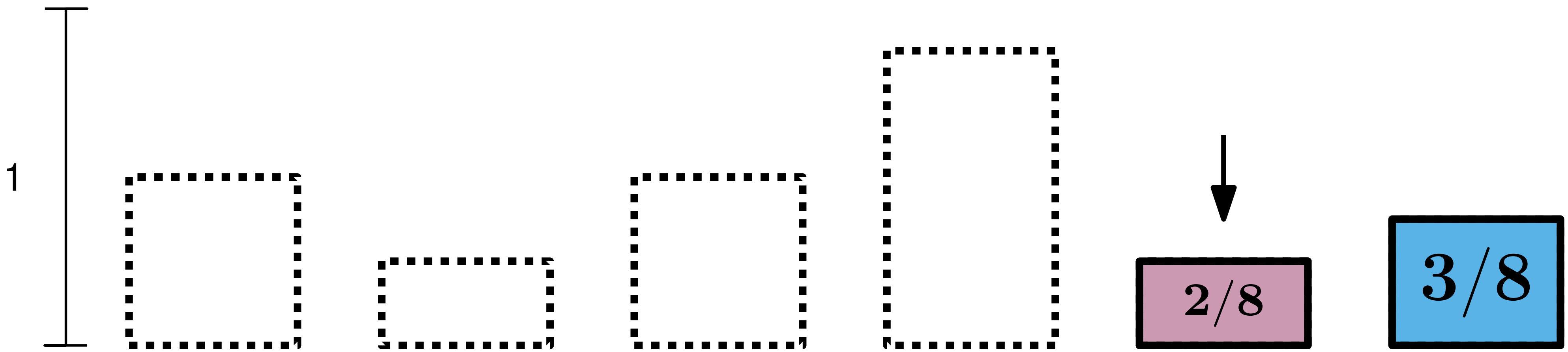

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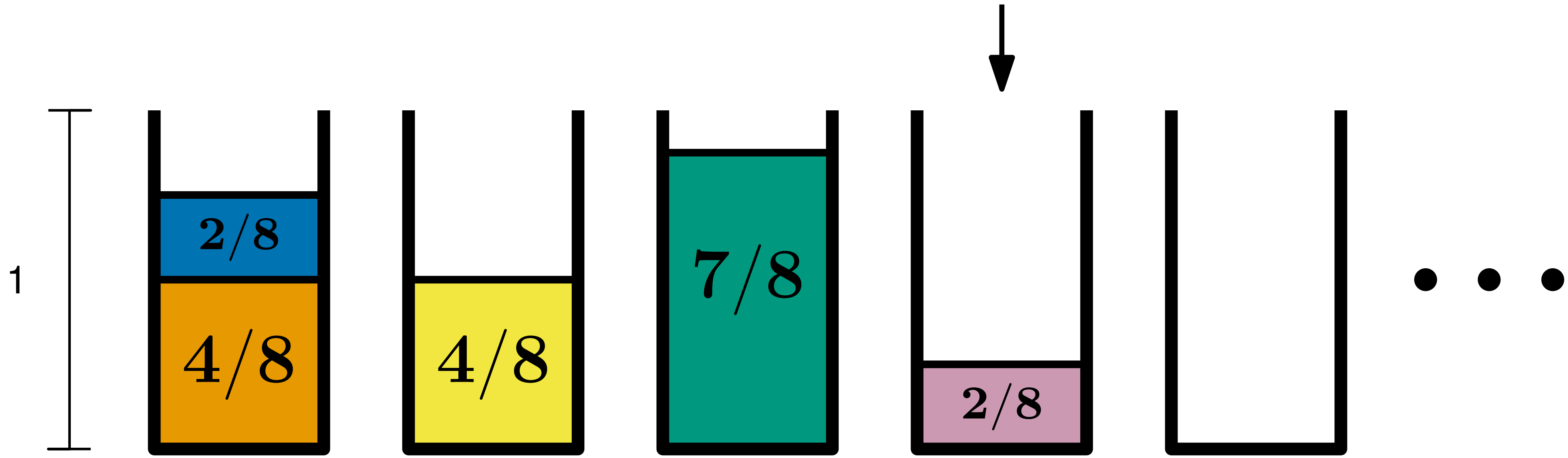

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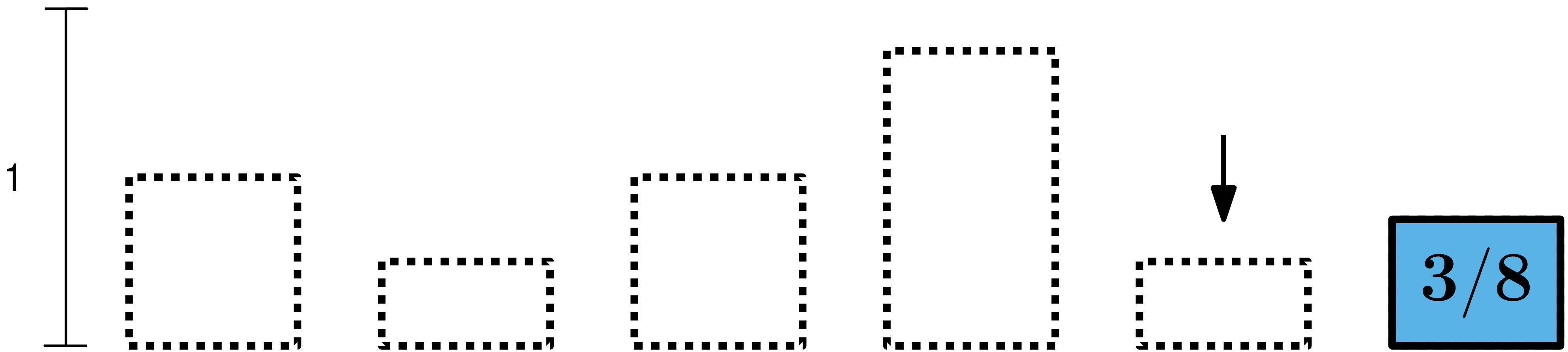

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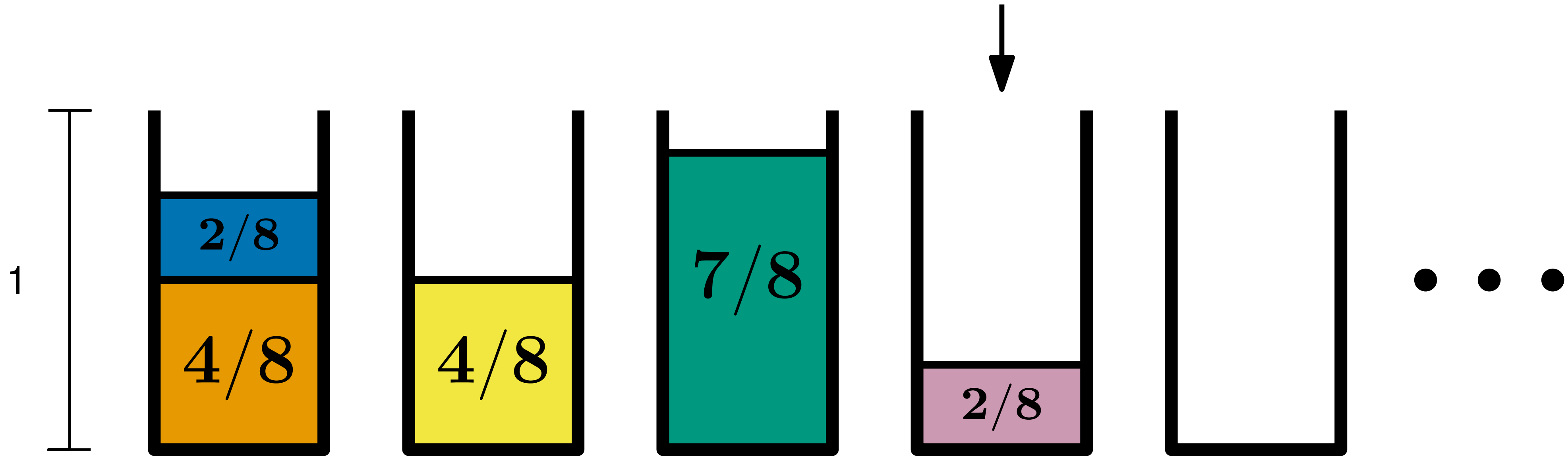

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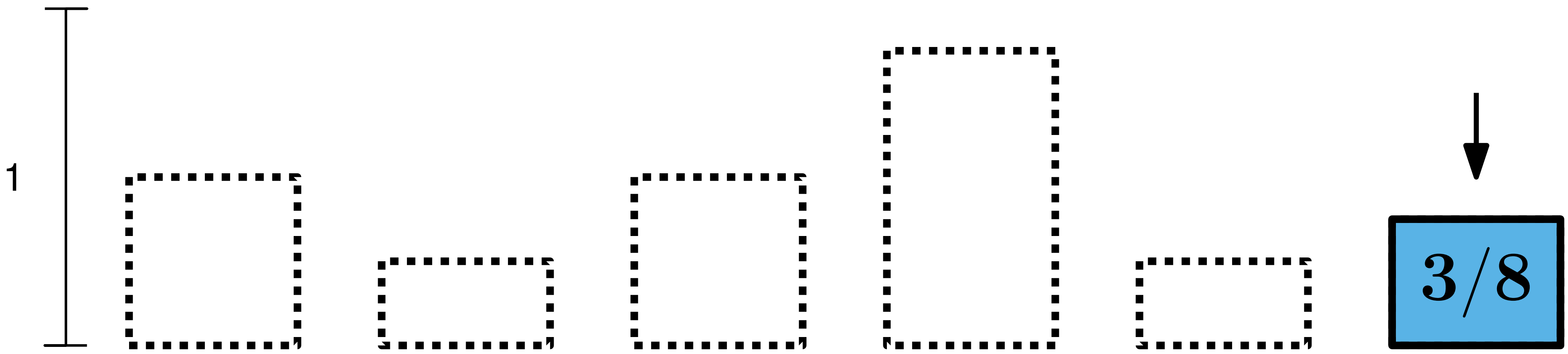

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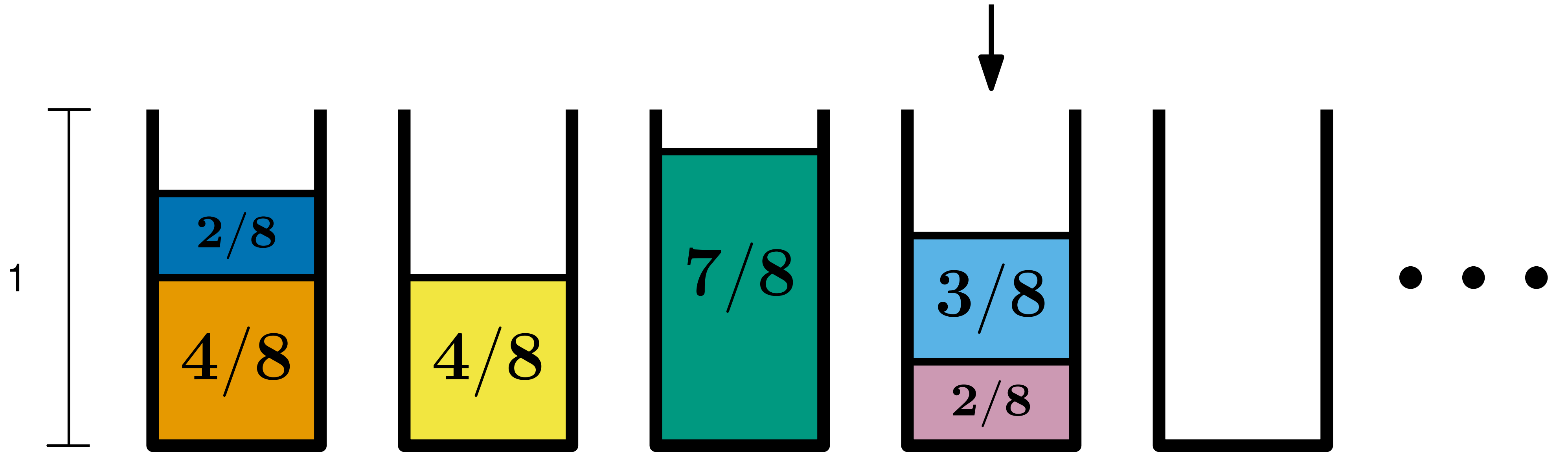

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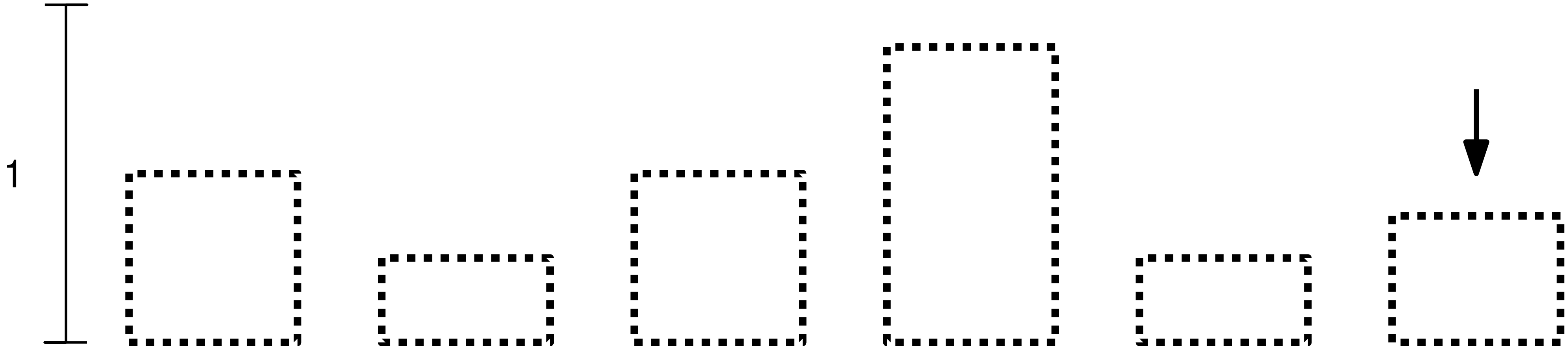

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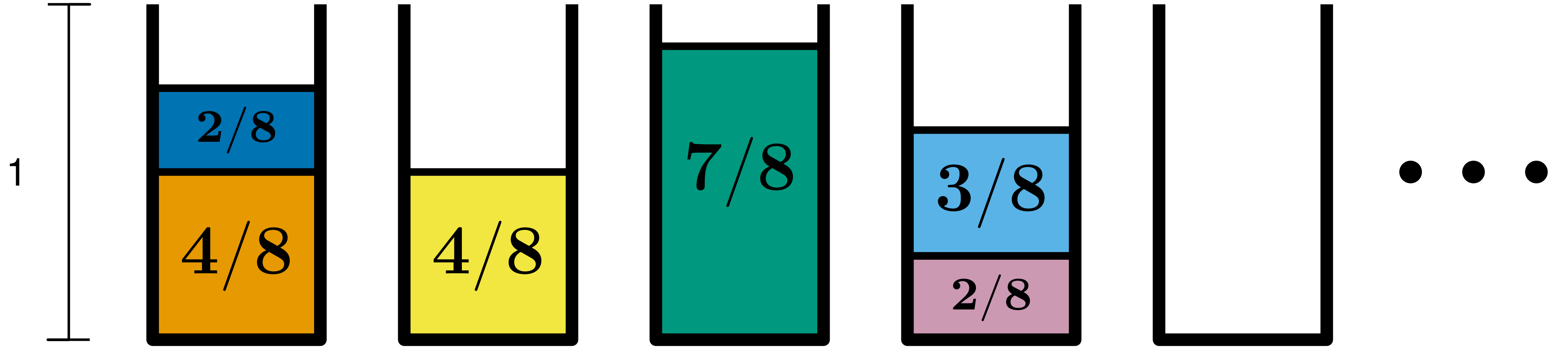

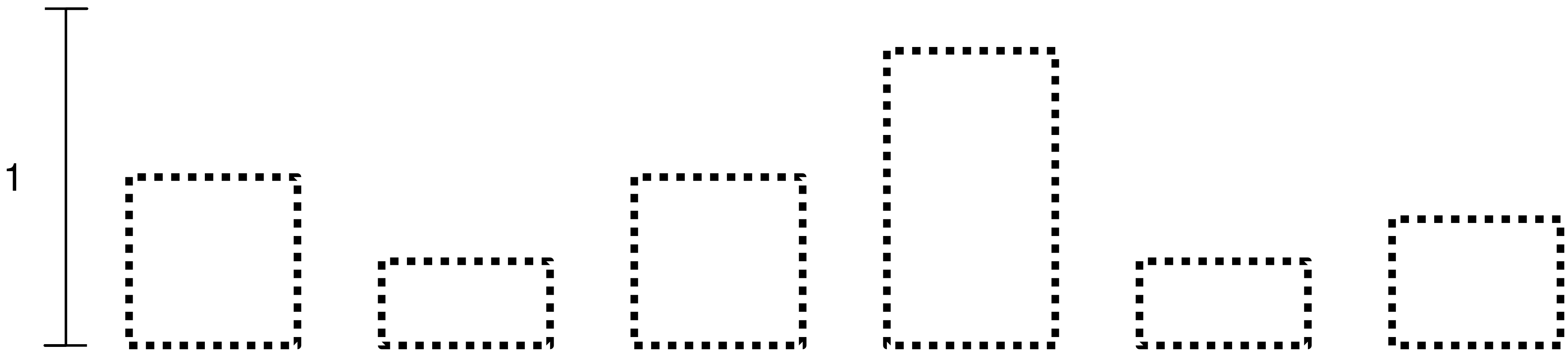

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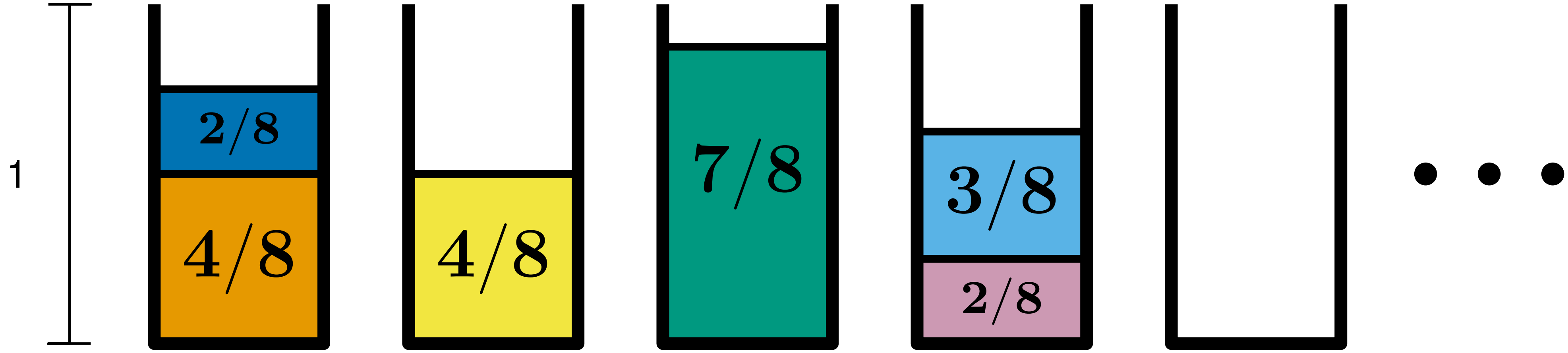
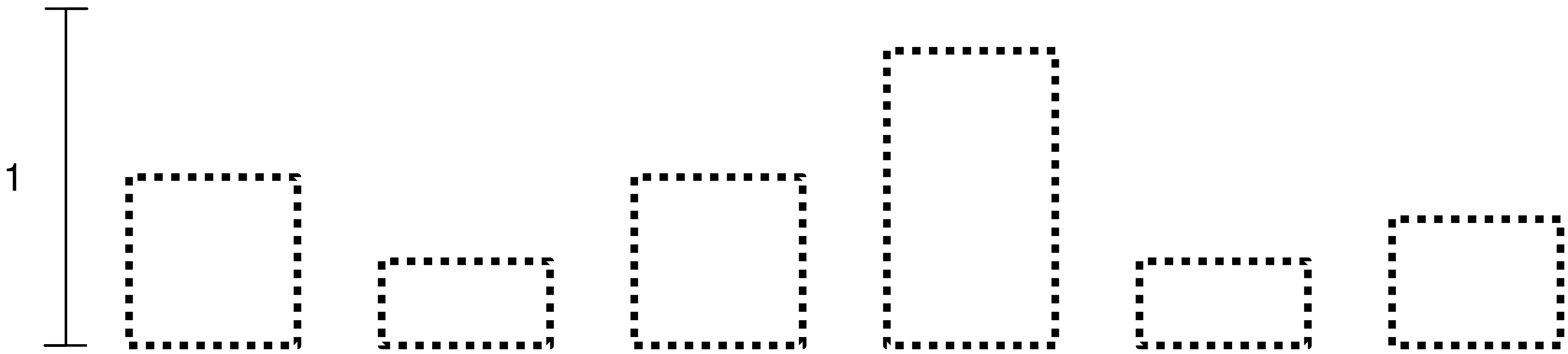


Next fit runs in $O(n)$ time but how good is it?



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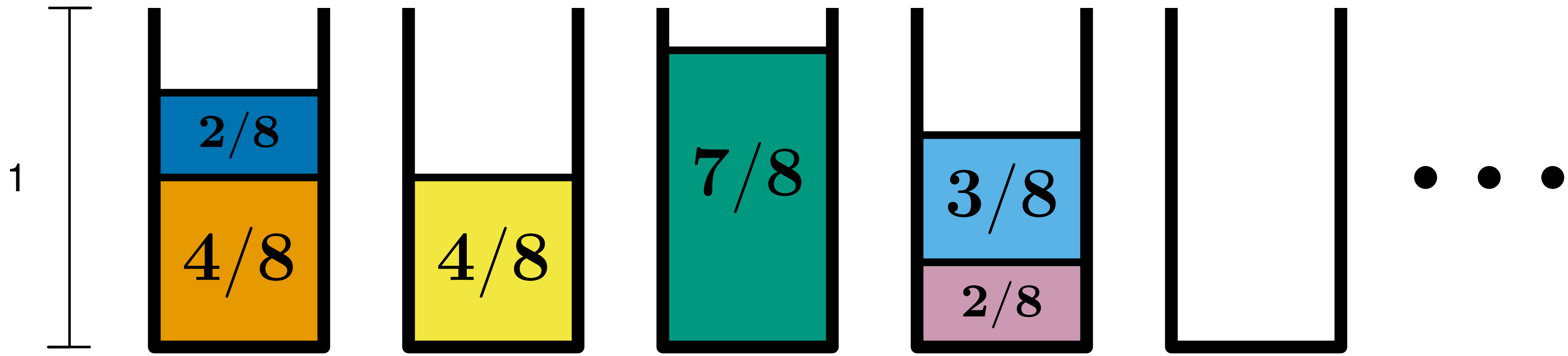
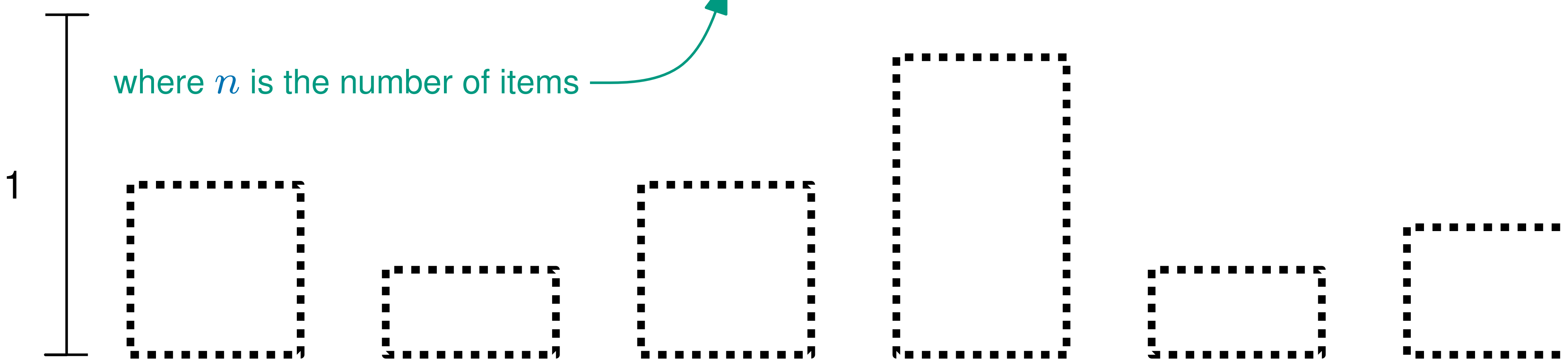


Next fit runs in $O(n)$ time but how good is it?

where n is the number of items



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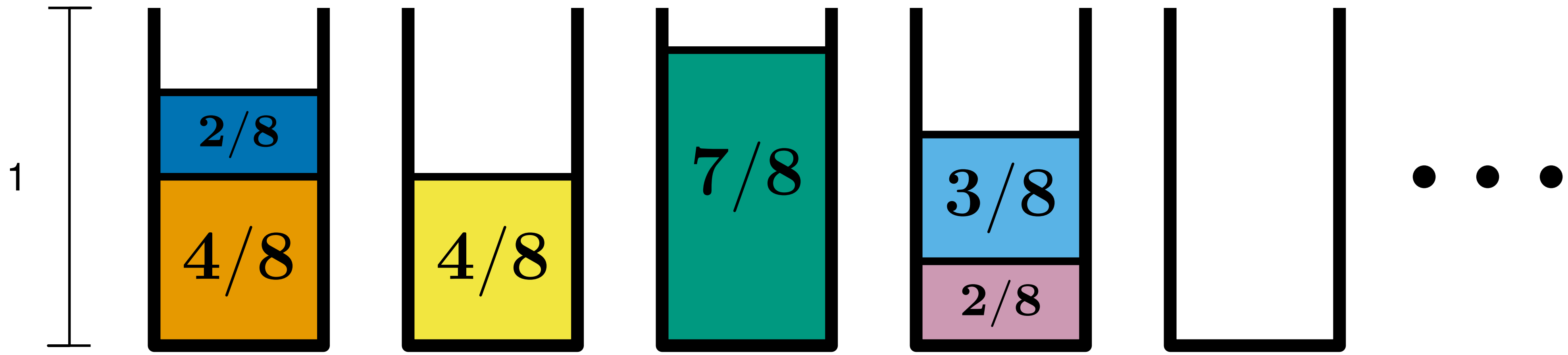

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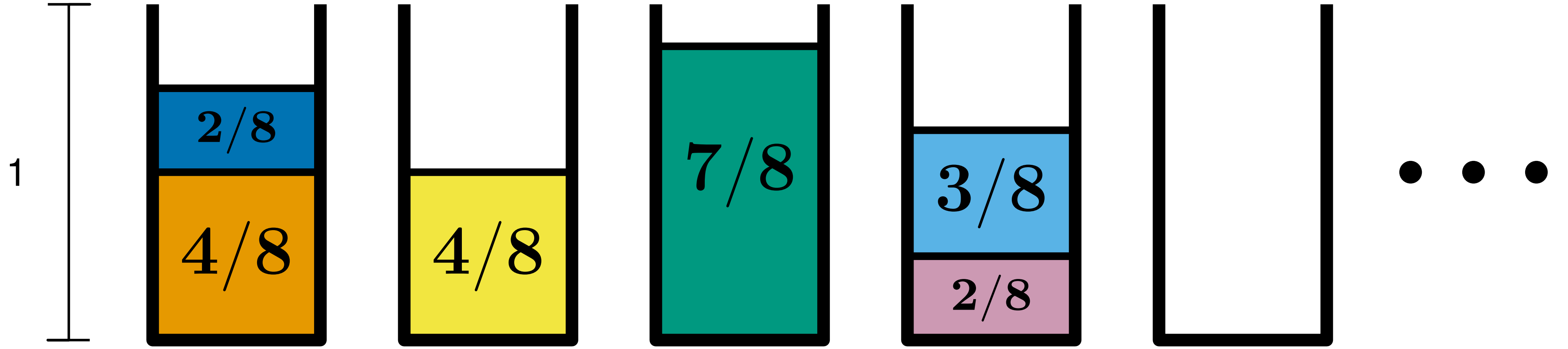
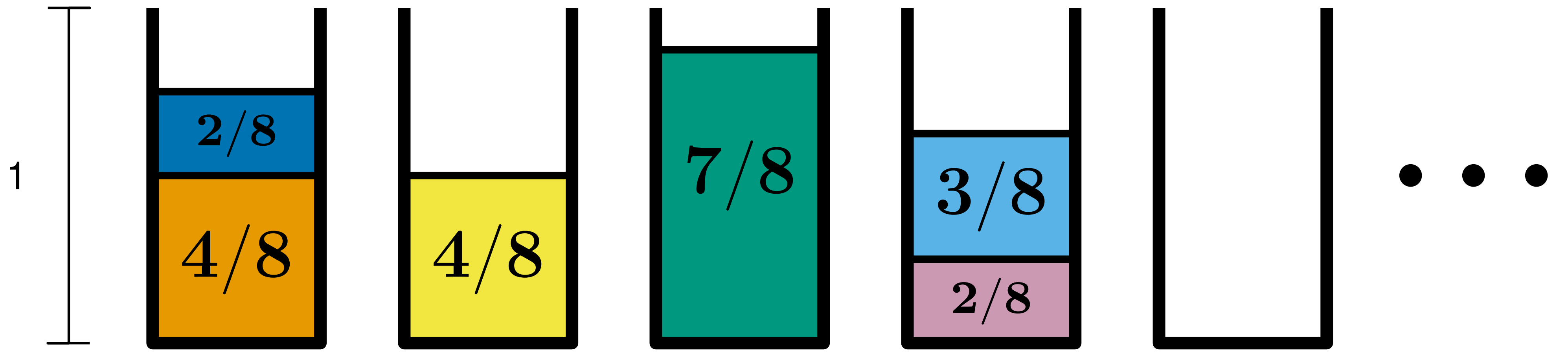


Next fit runs in $O(n)$ time but how good is it?

Let fill(i) be the sum of item sizes in bin i

and s be the number of non-empty bins (using Next fit)

Next fit



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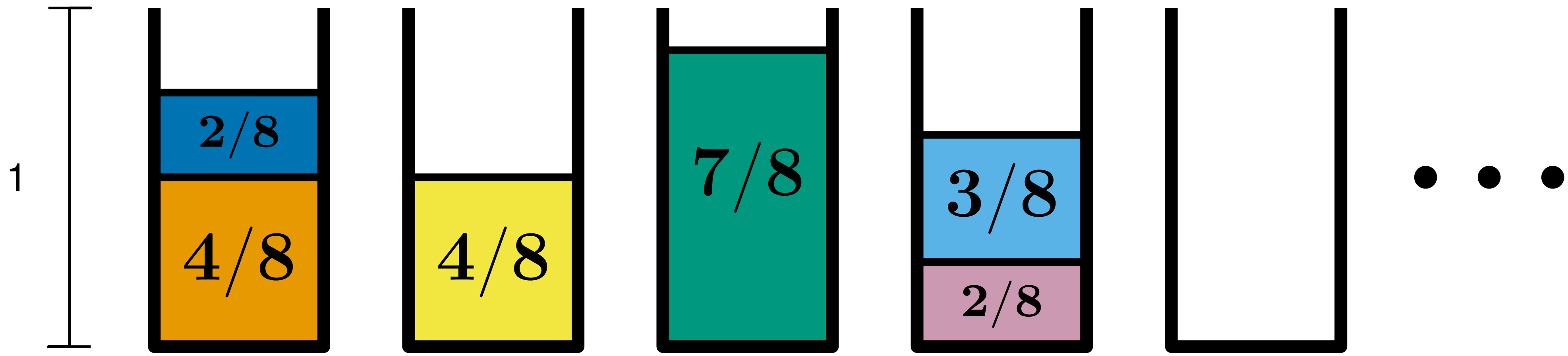

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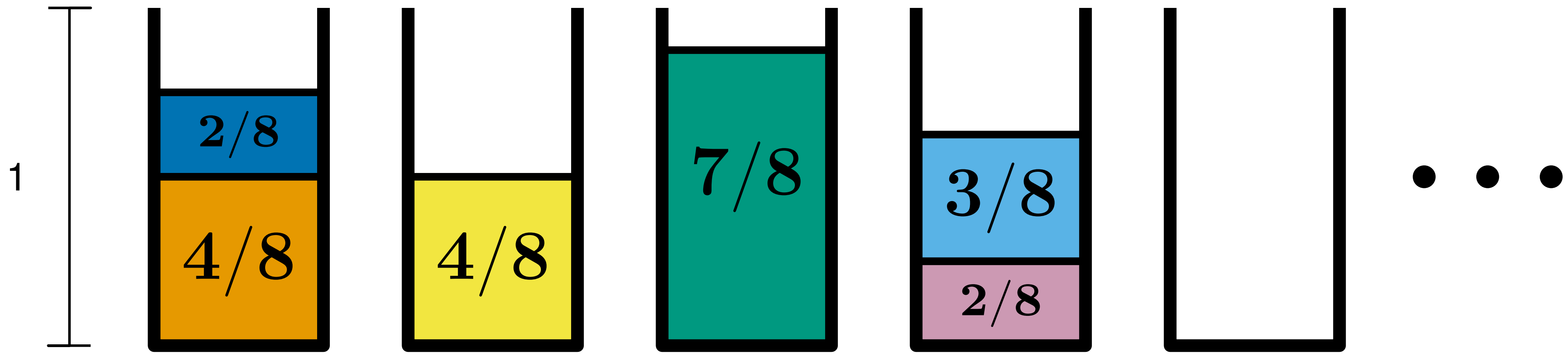

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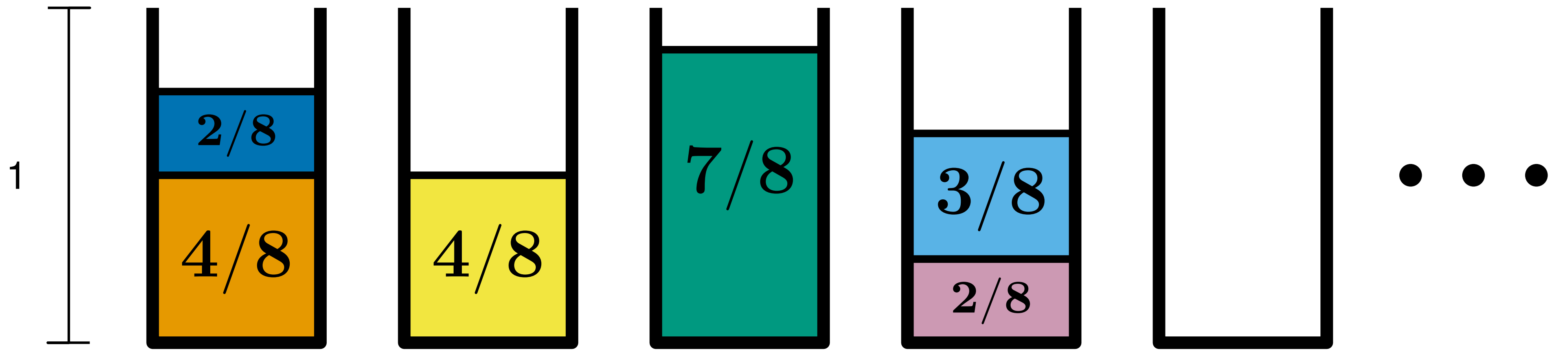

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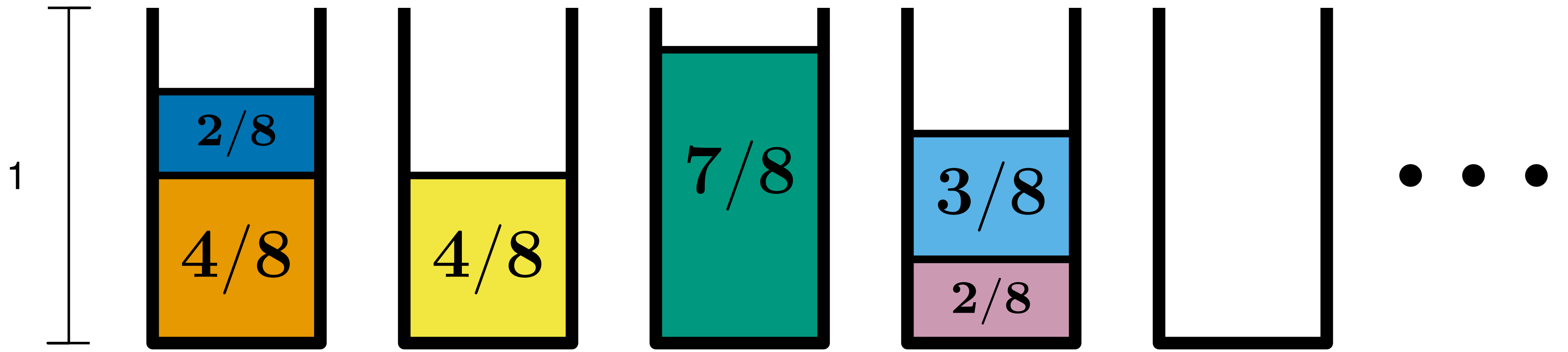

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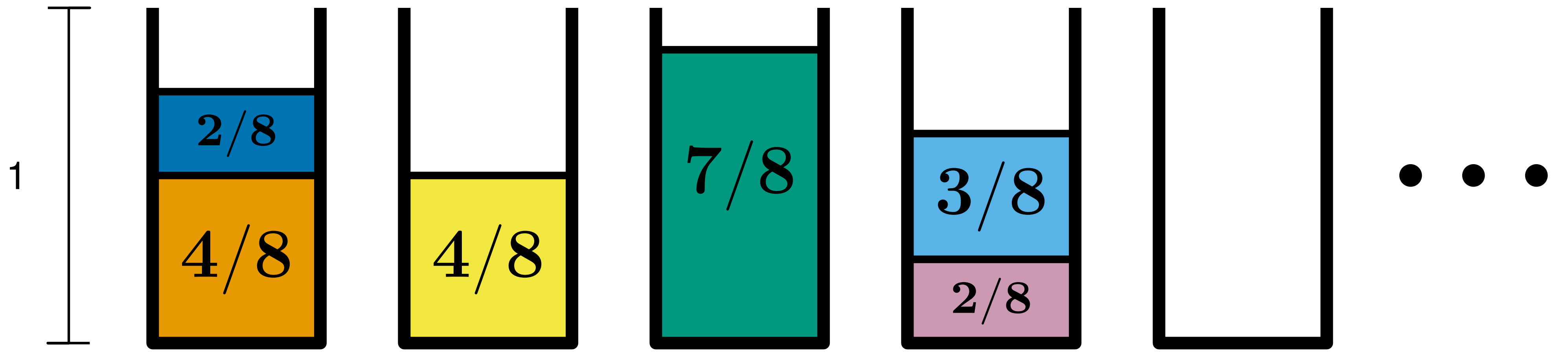

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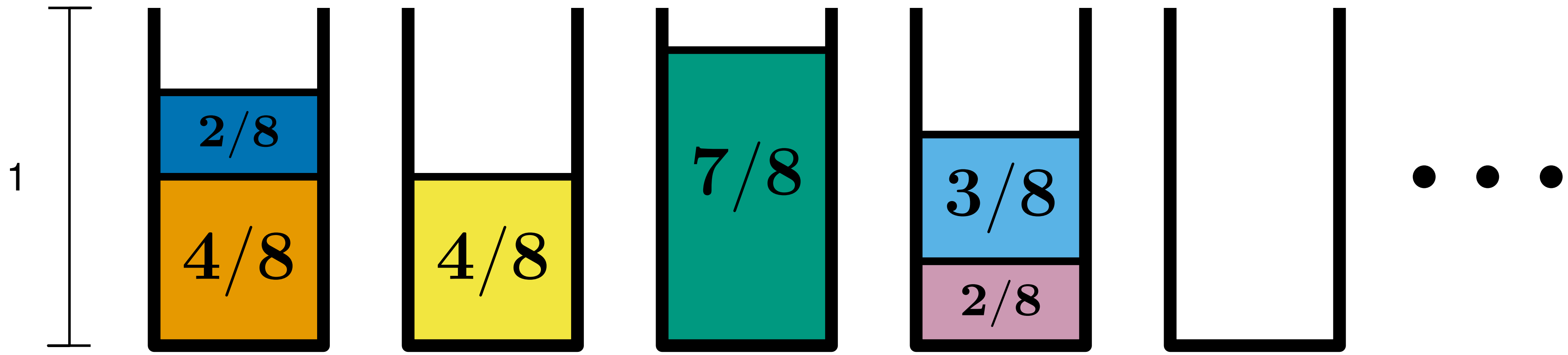
the optimal number of bins

Next fit



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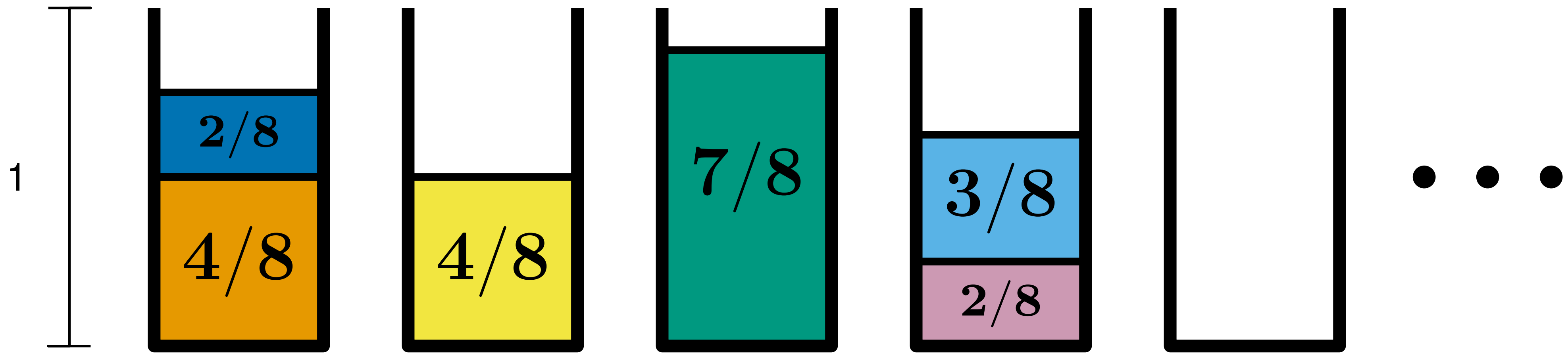

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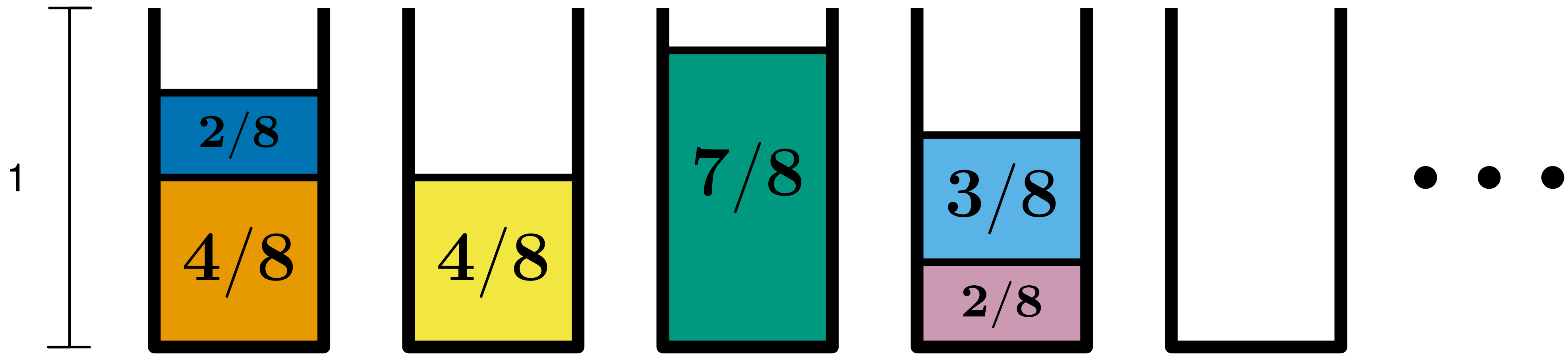

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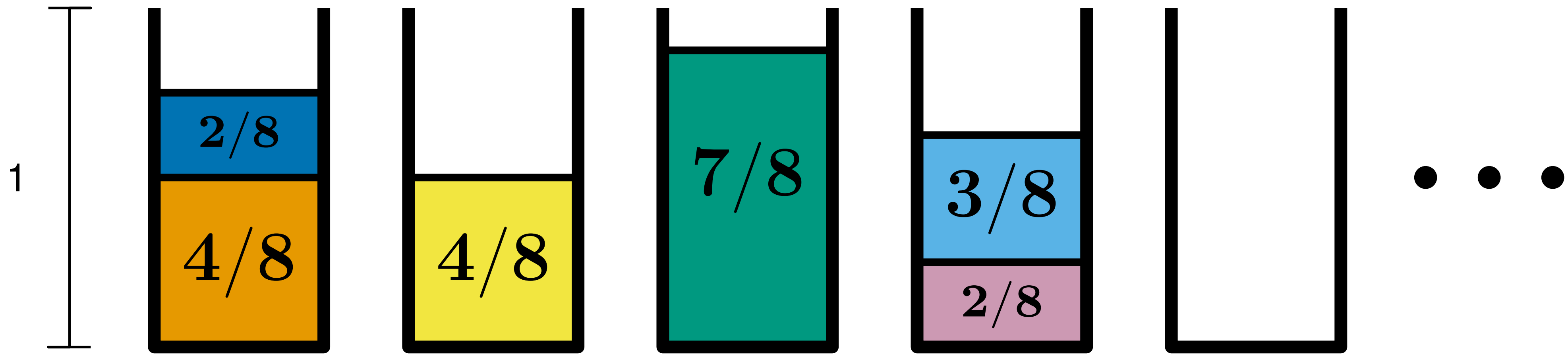
therefore $s \leqslant 2 \cdot \text{Opt}$ *in other words the Next Fit is never worse than twice the optimal*

Next fit



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Approximation Algorithms

An algorithm A is an α-approximation algorithm for problem P if,

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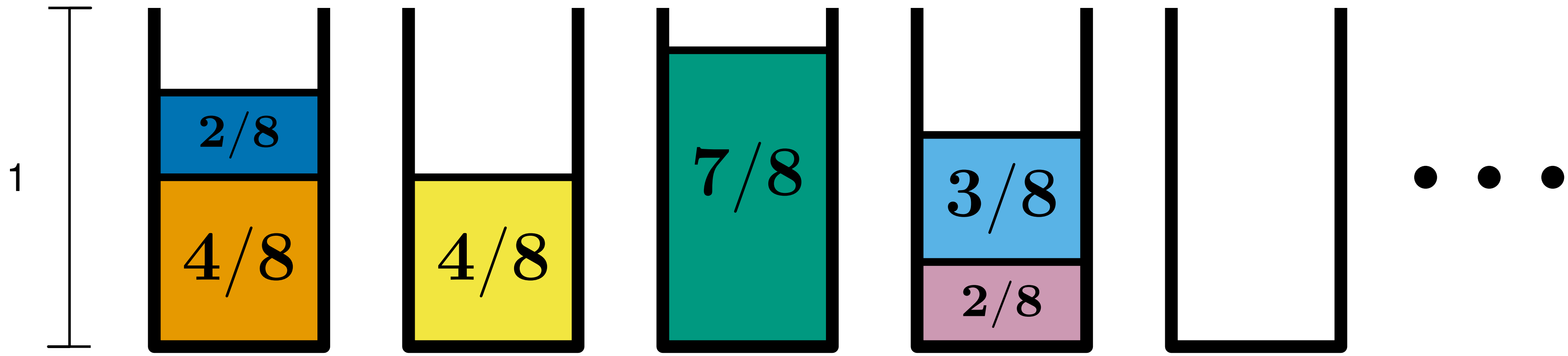
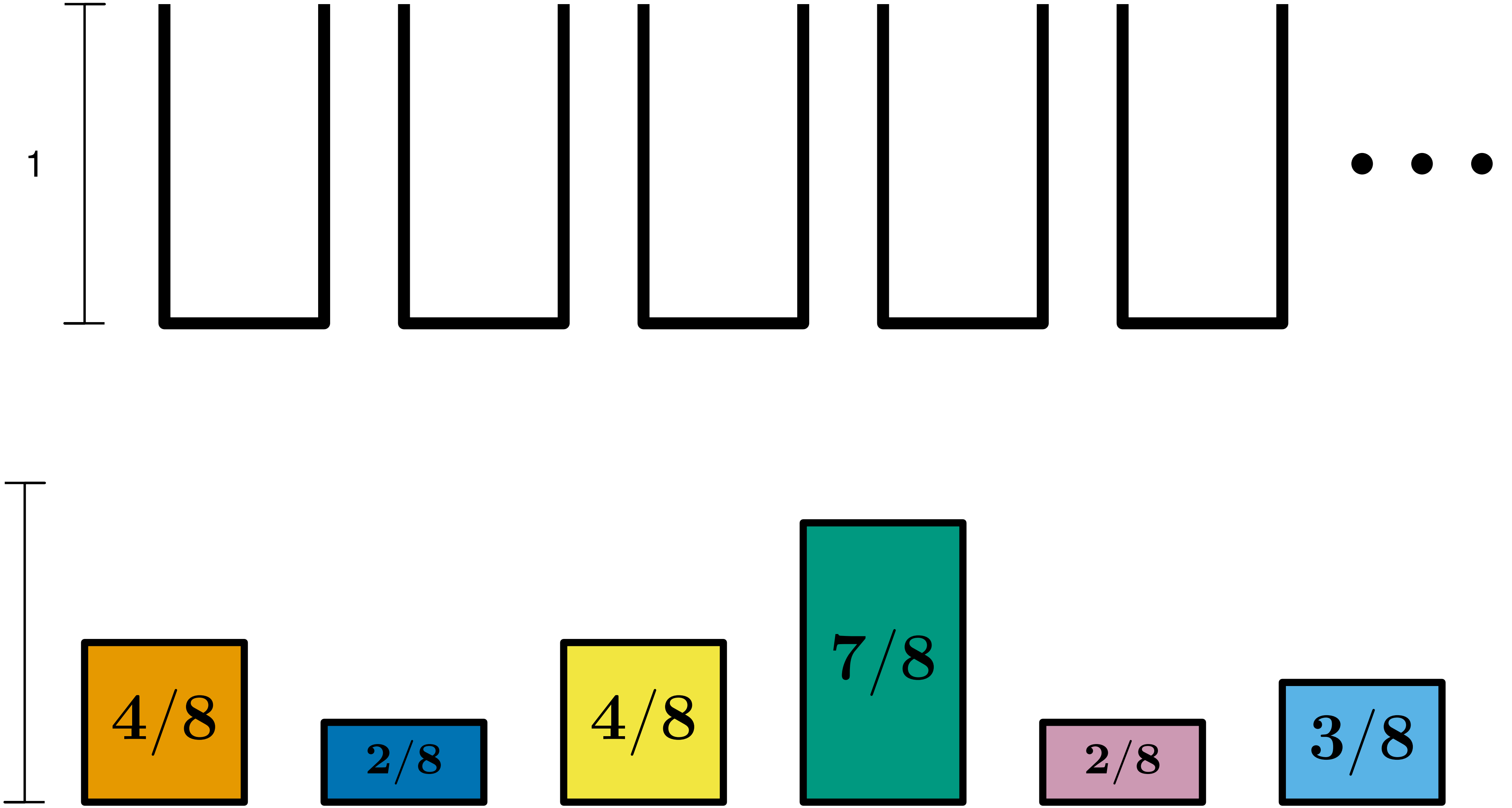
In the examples we consider, α will be a constant but it could depend on n (the input size)



We have seen that Next fit is a 2-approximation algorithm for Bin packing which runs in $O(n)$ time

can we do better?

First fit decreasing (FFD)



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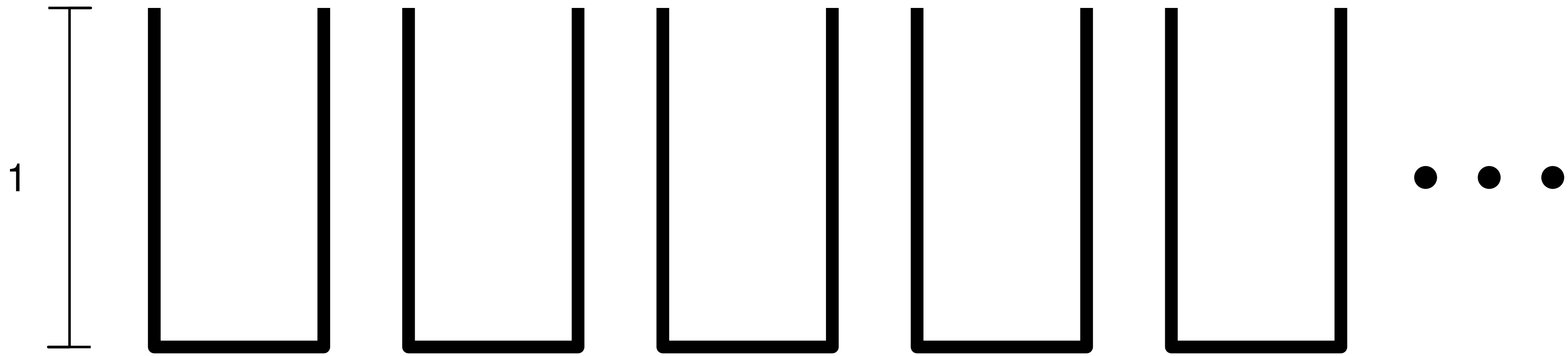
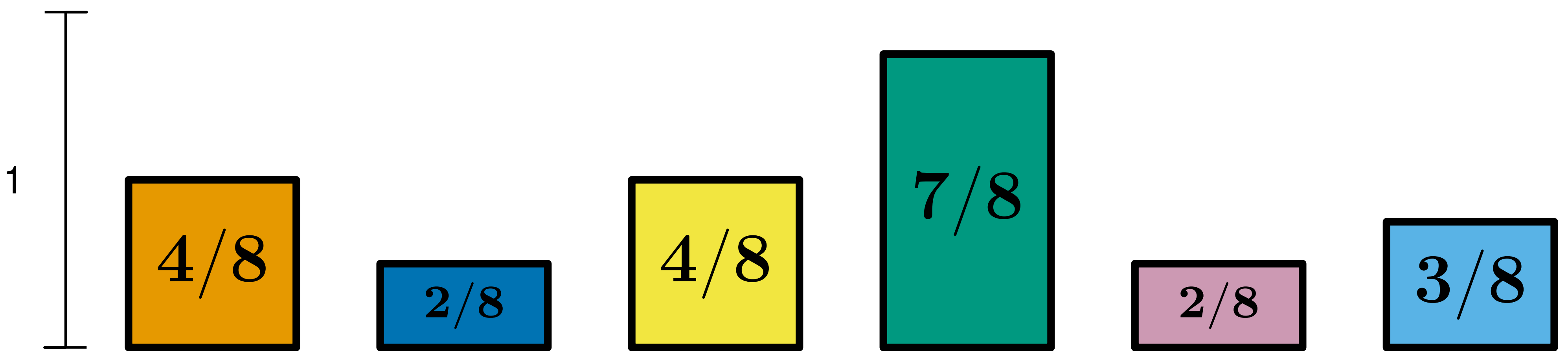


Step 1: Sort the items into non-increasing order



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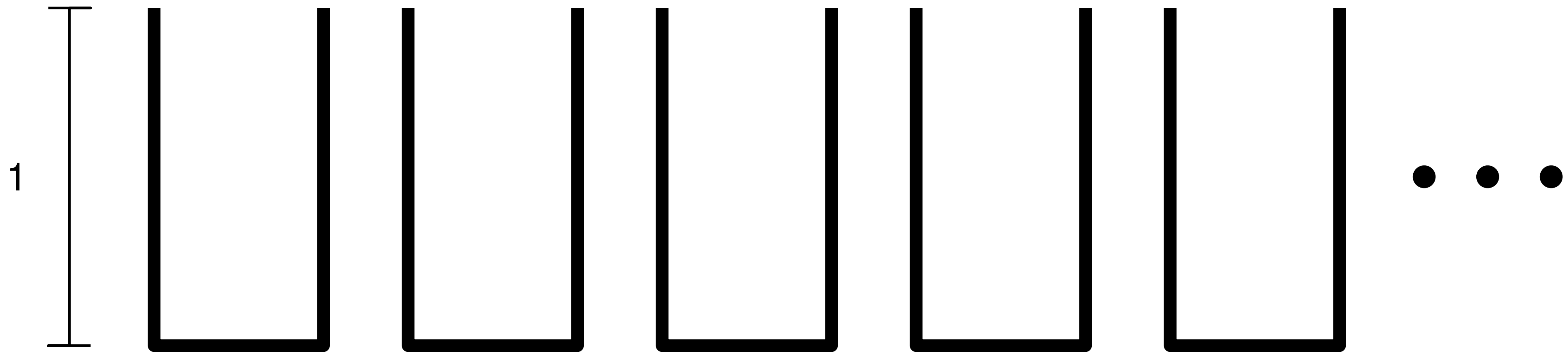

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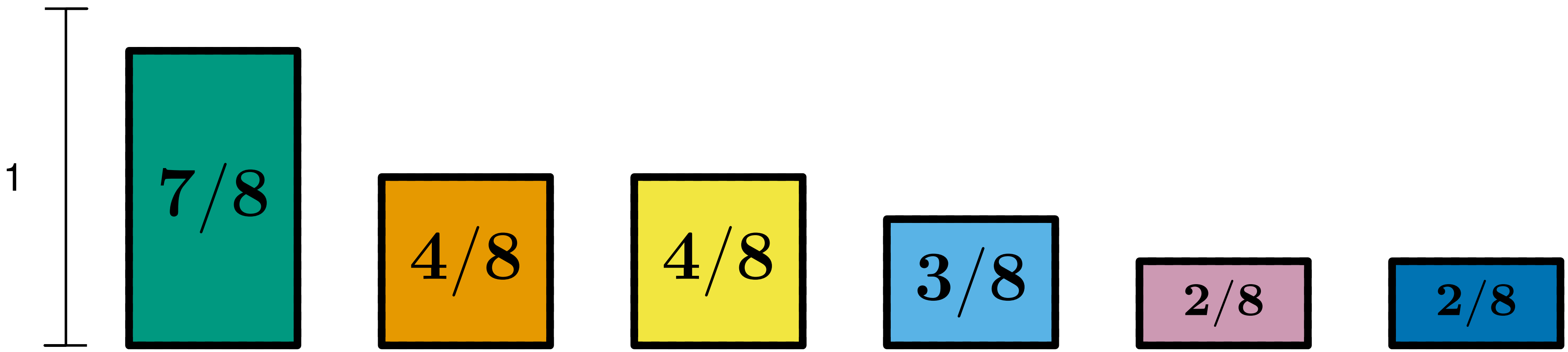

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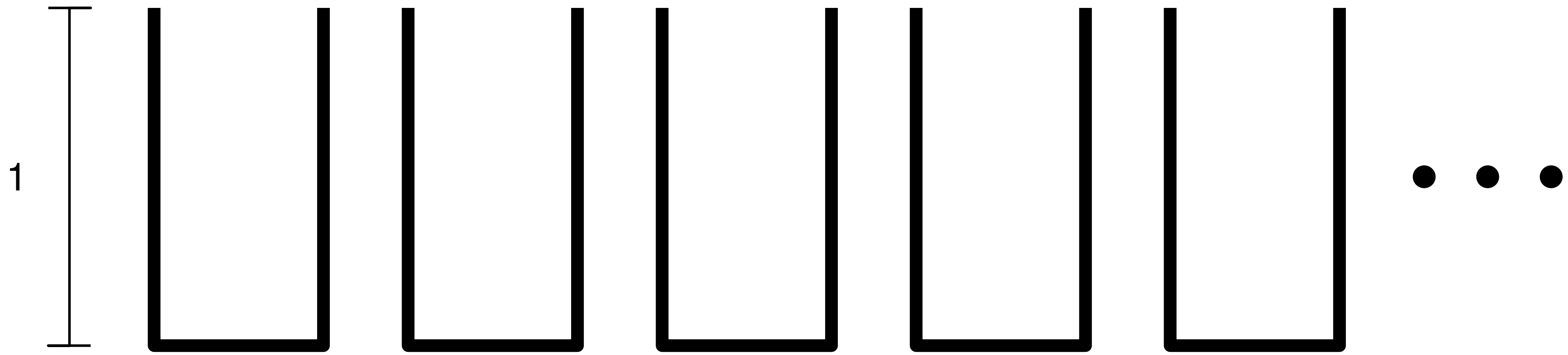
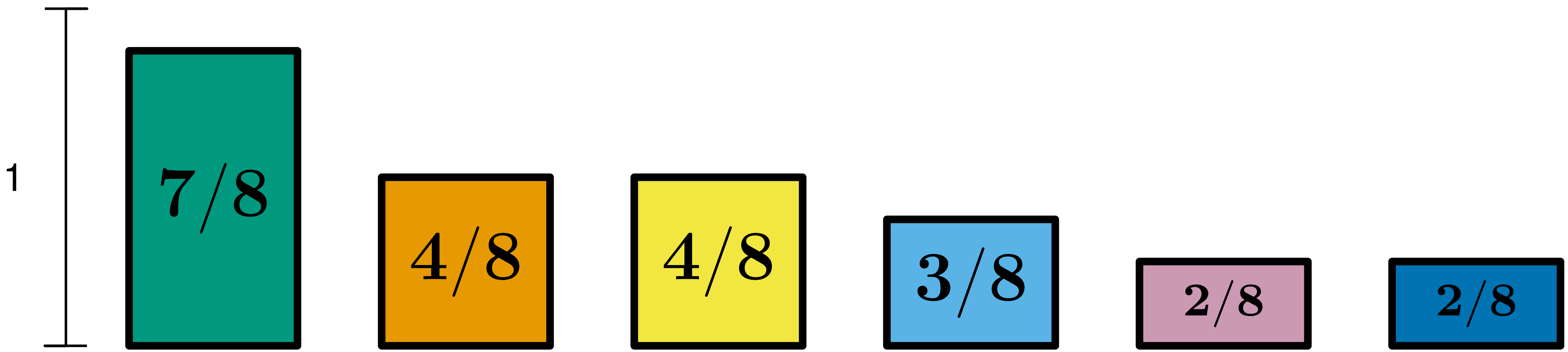


Step 2: Put each item in the first **(left-most)** bin it fits in



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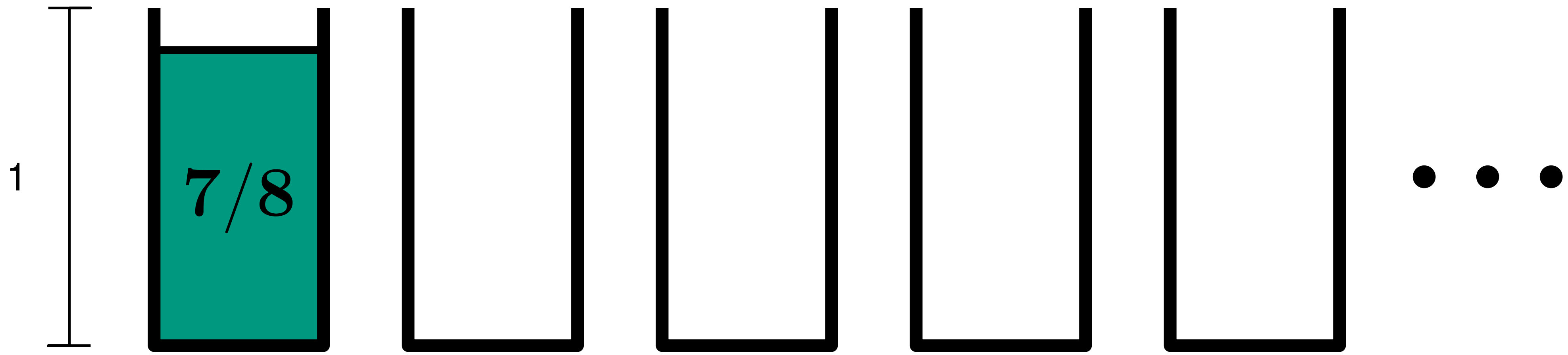

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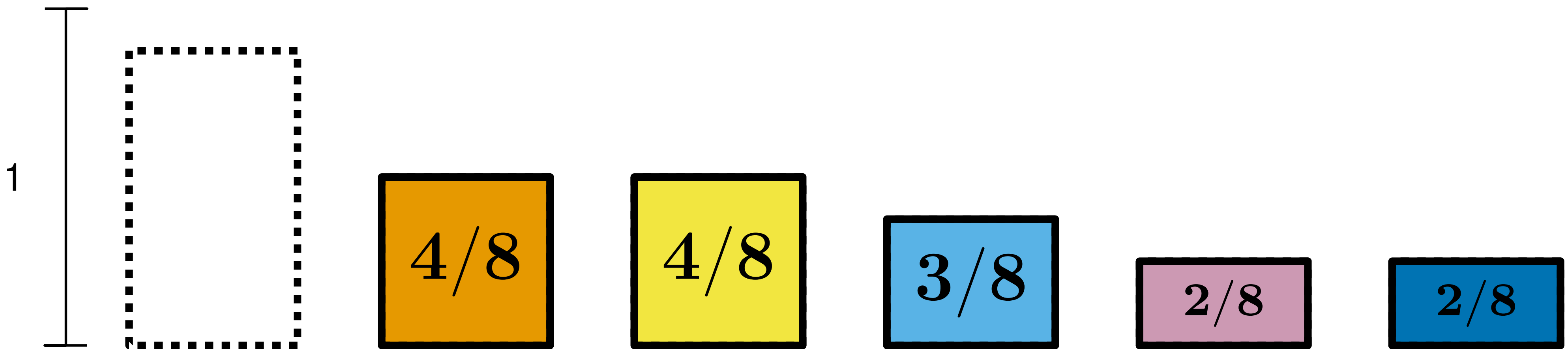

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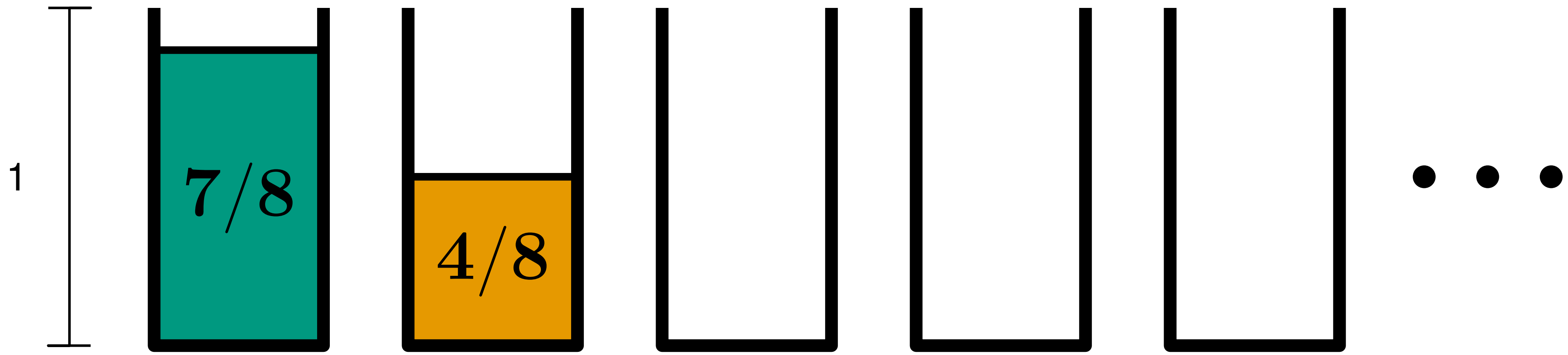

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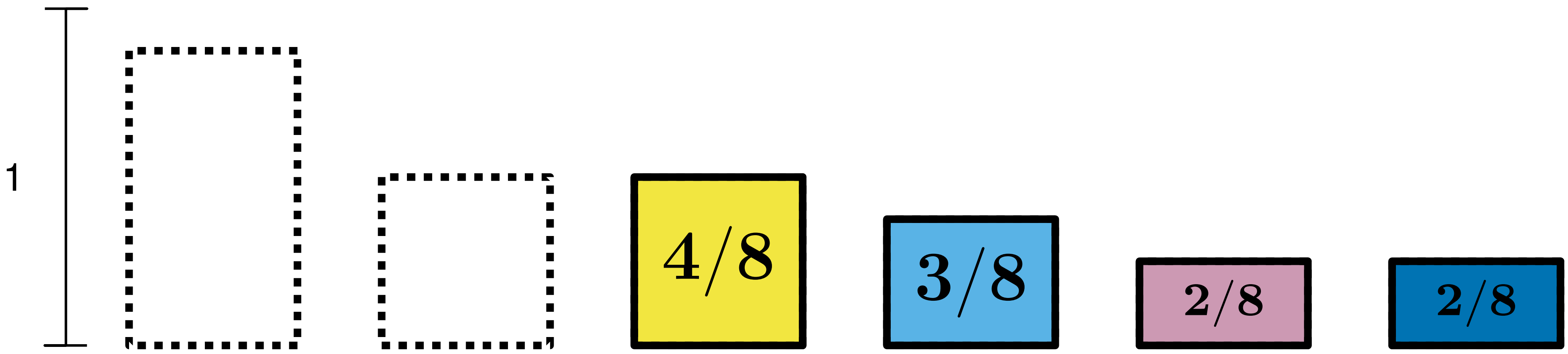

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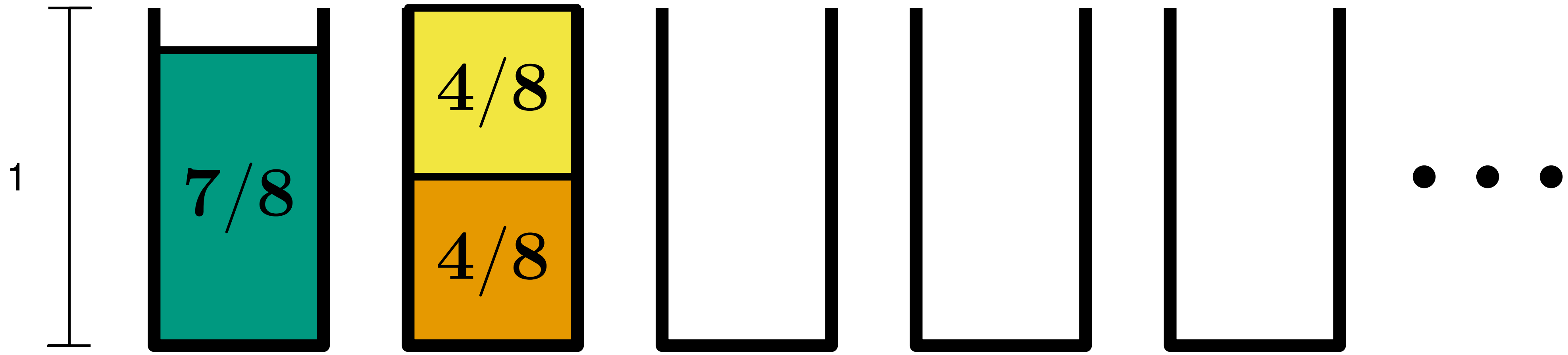

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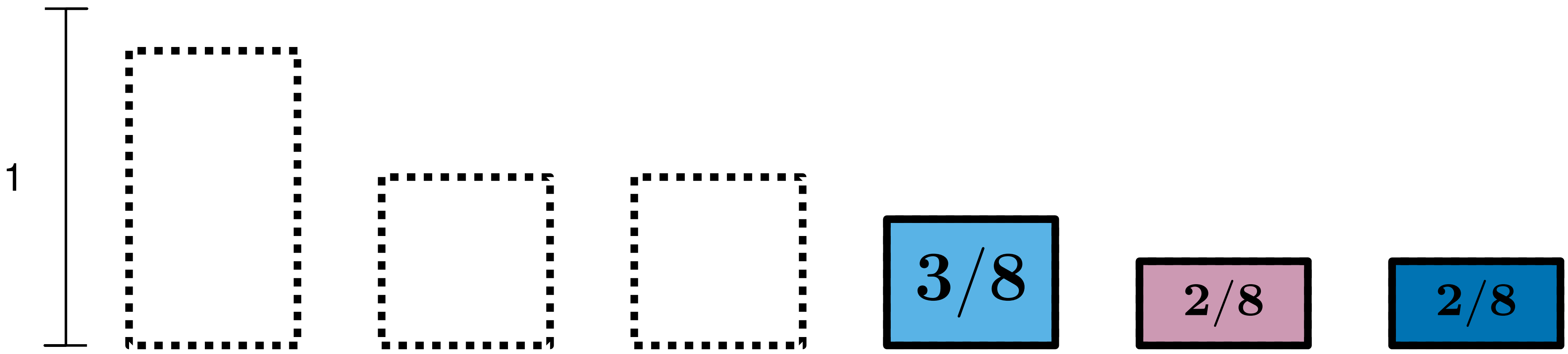

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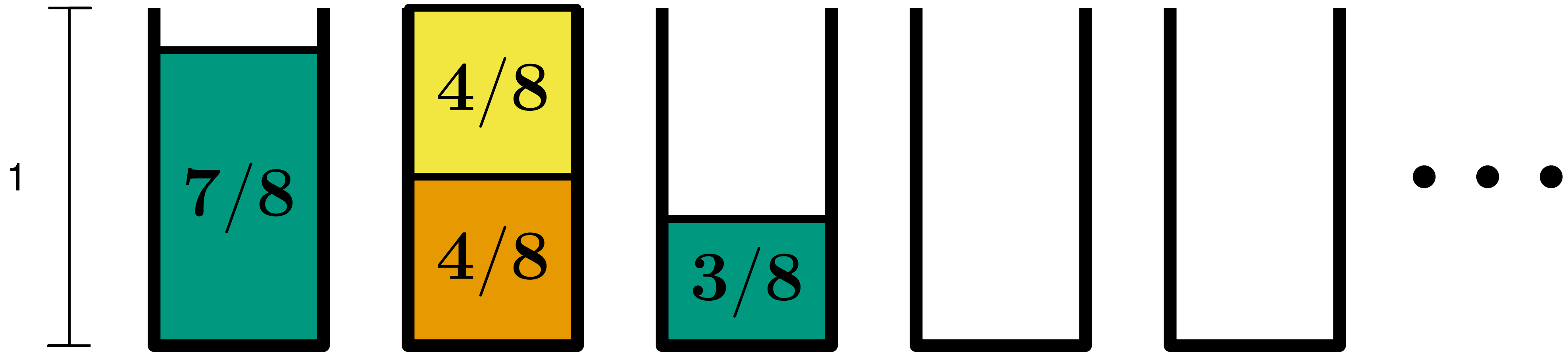

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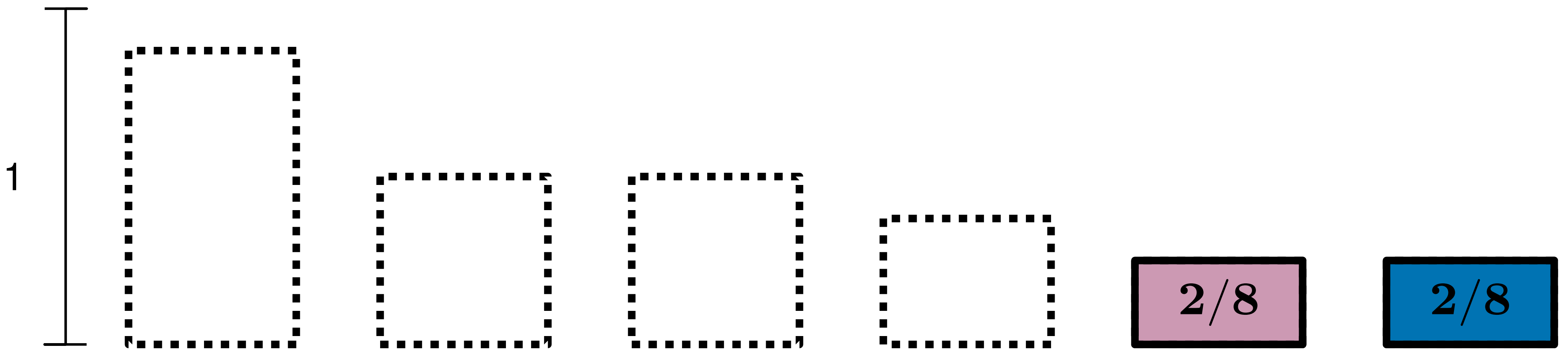

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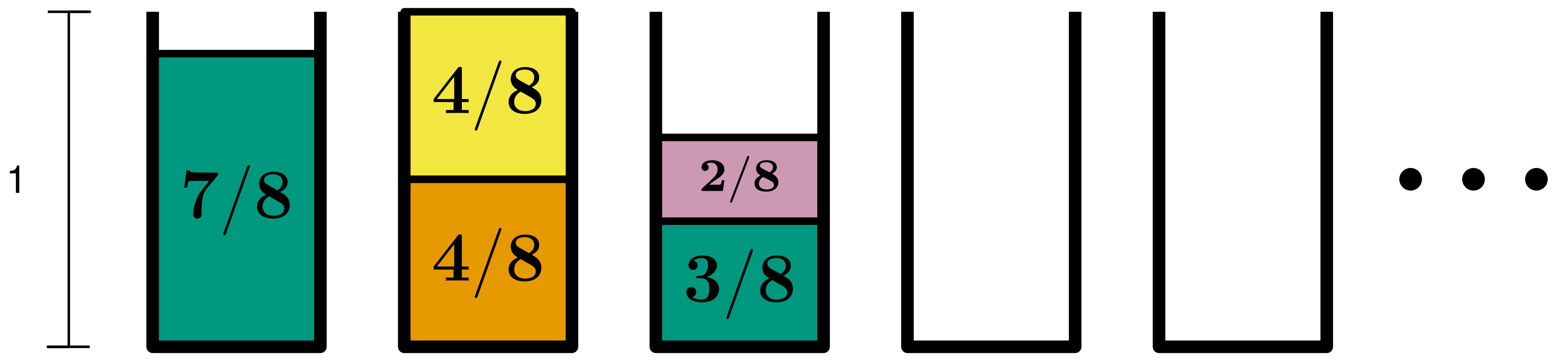

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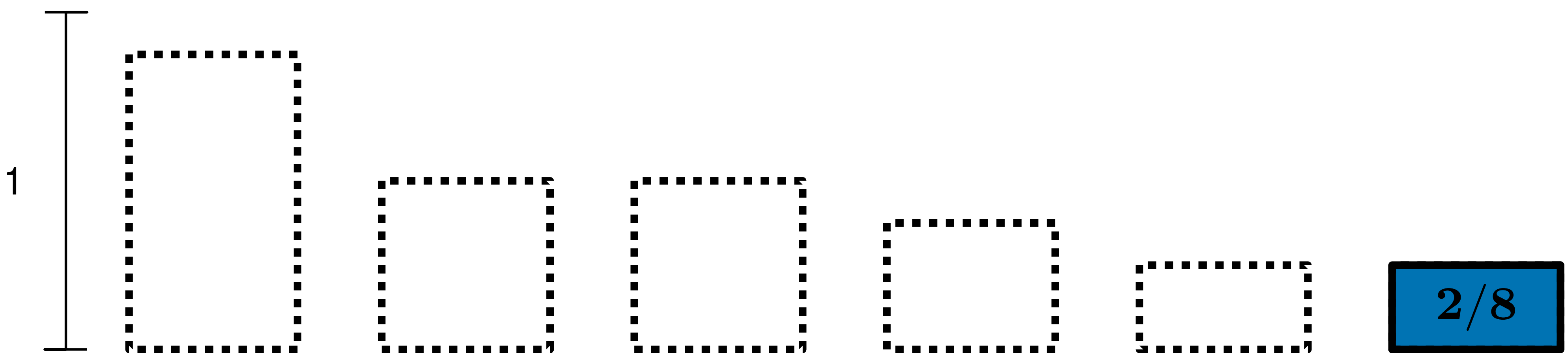

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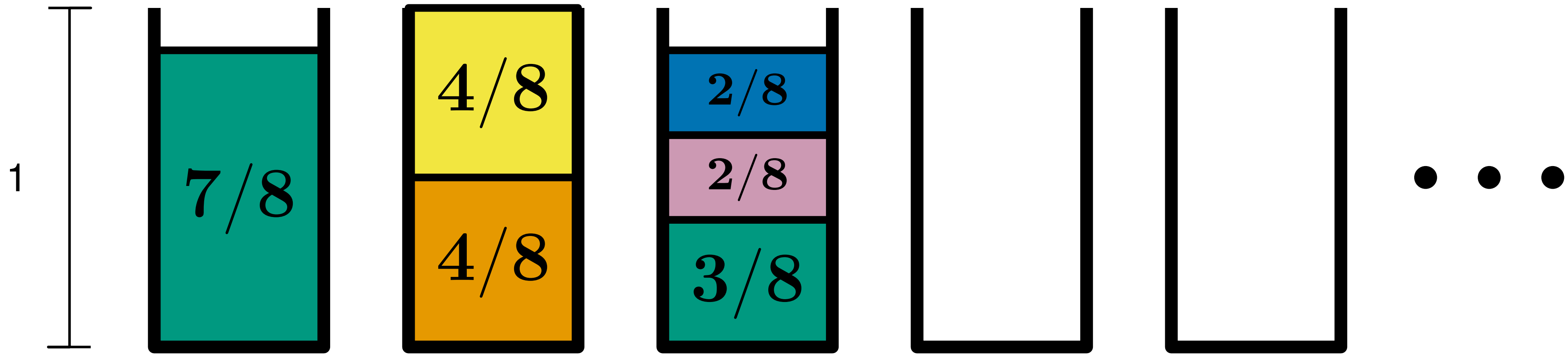

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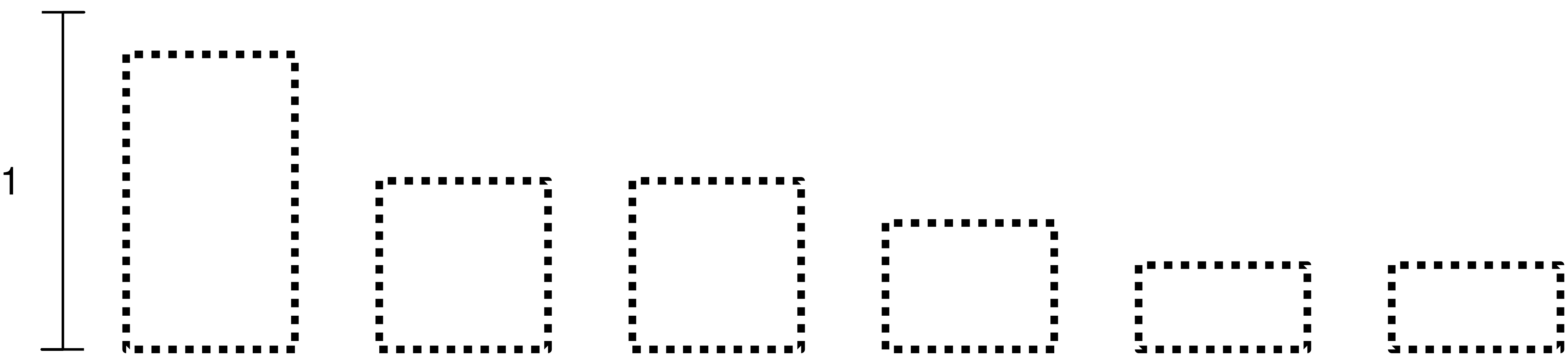

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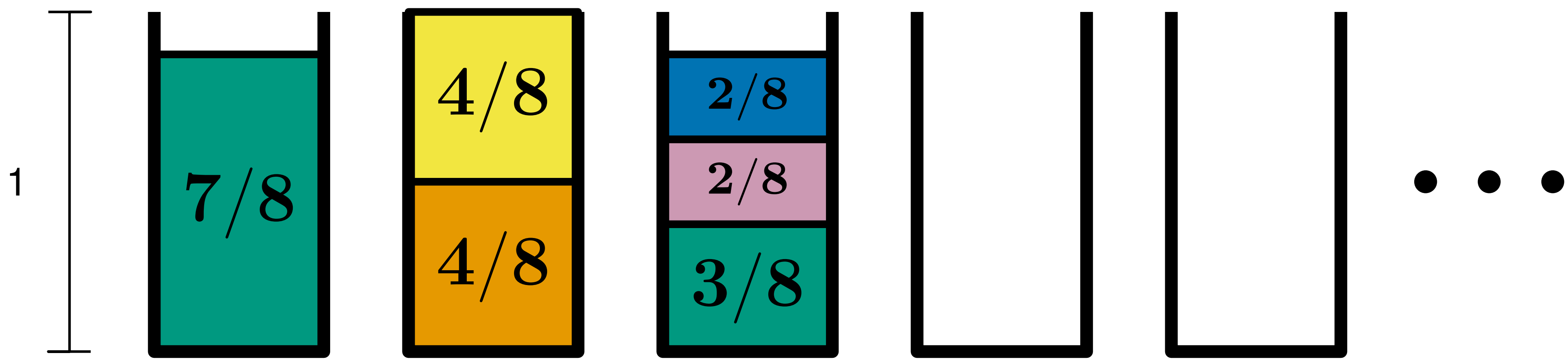

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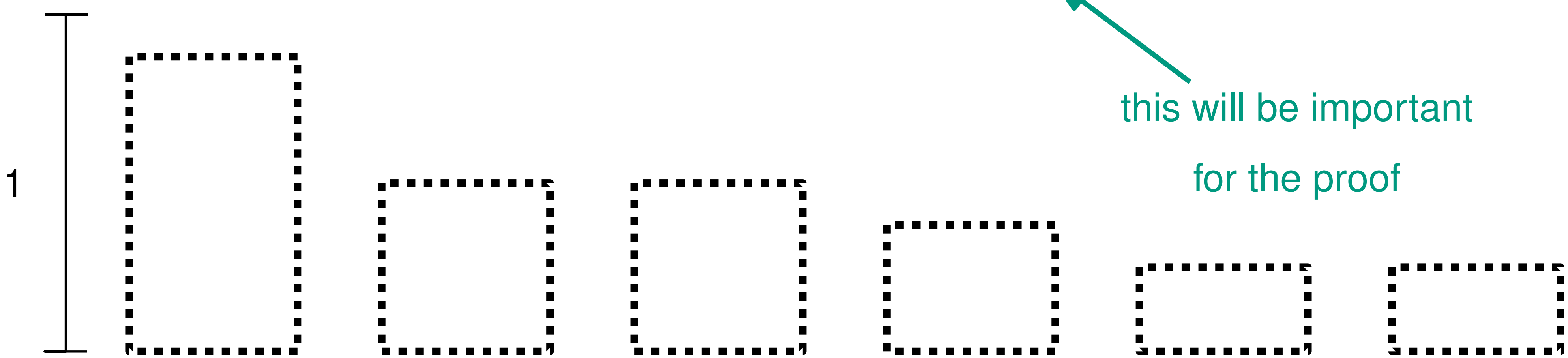
this will be important

for the proof



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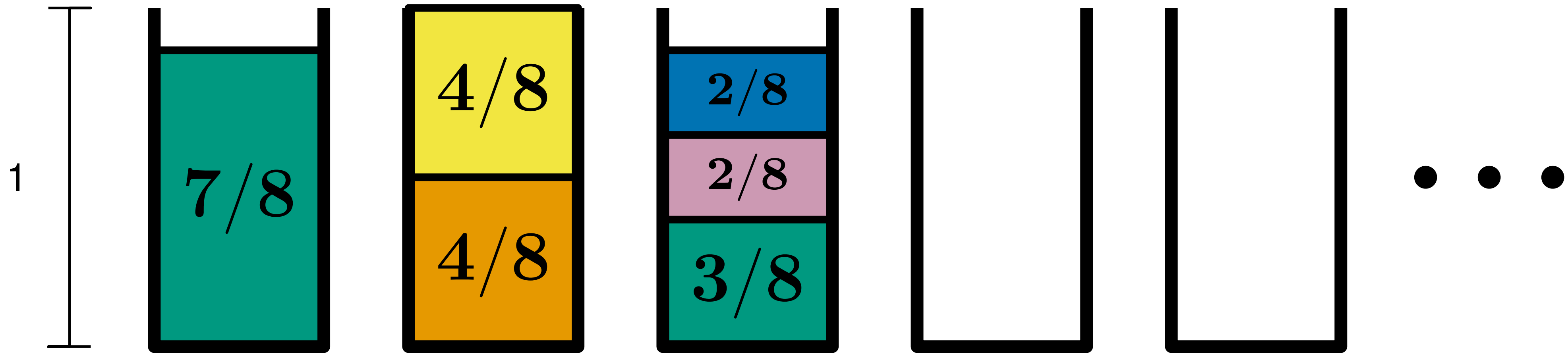

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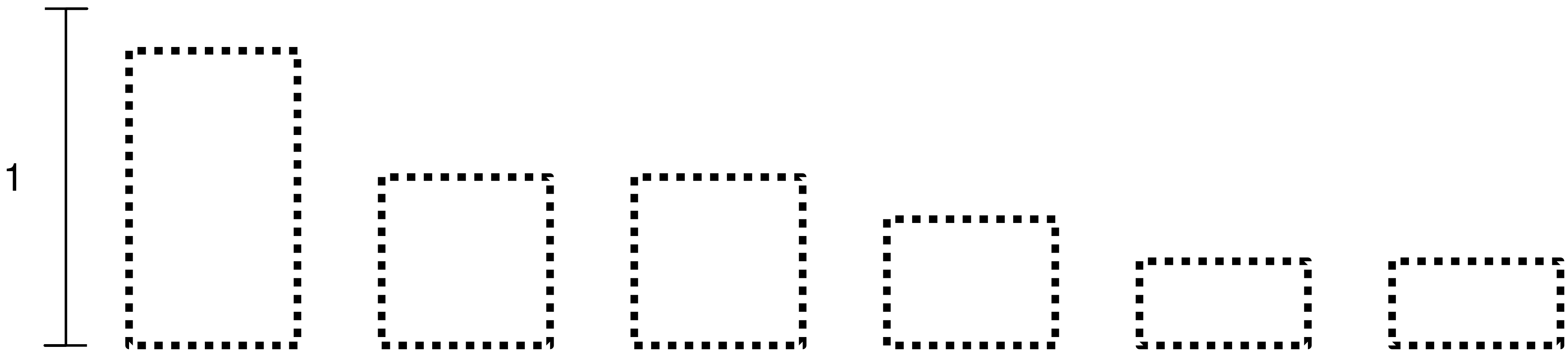

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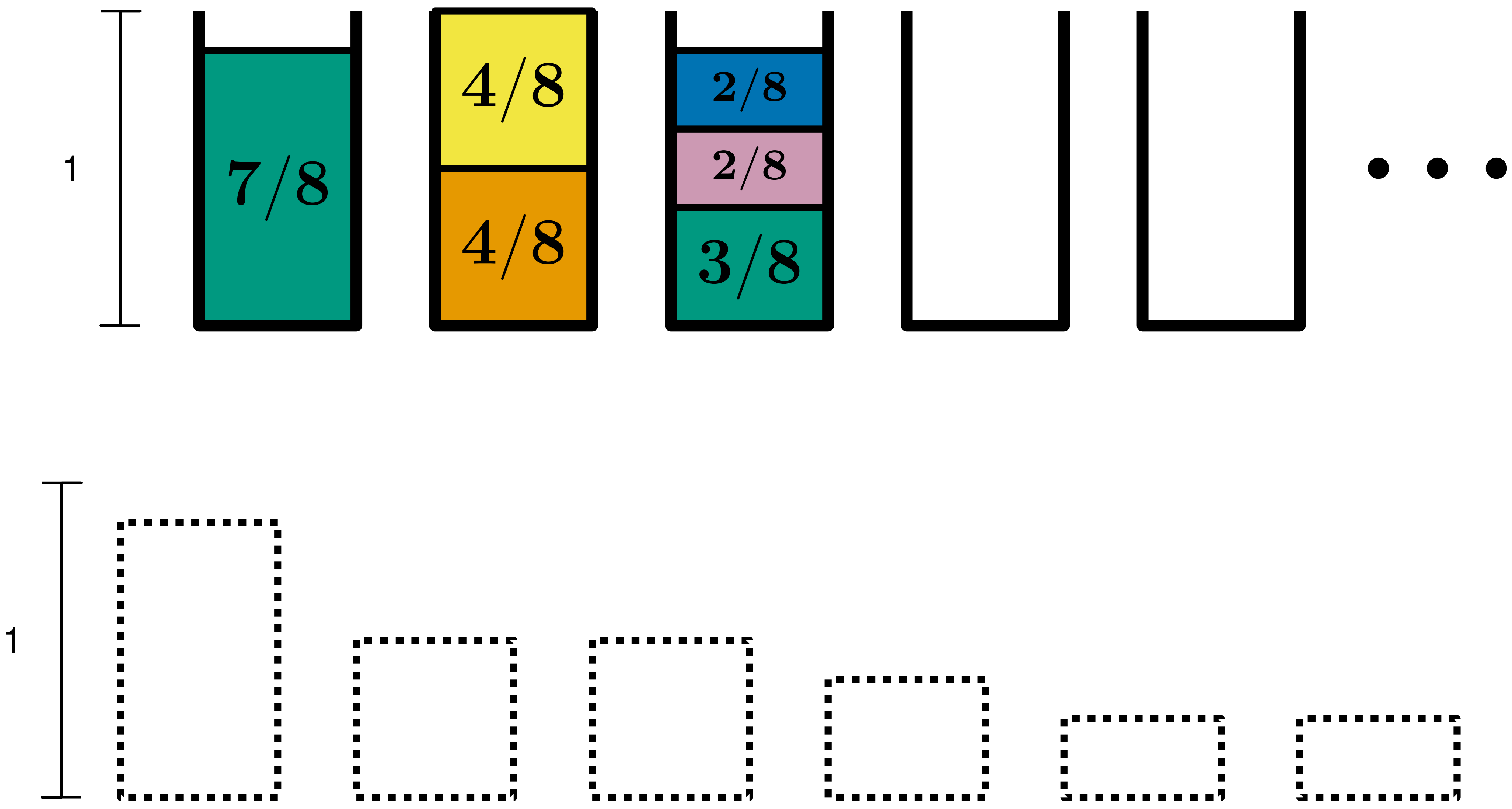

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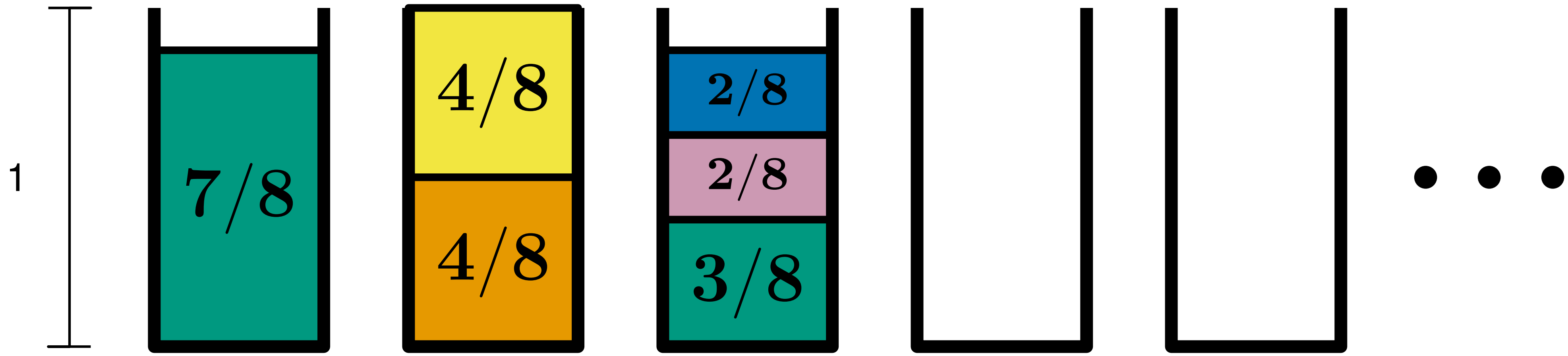

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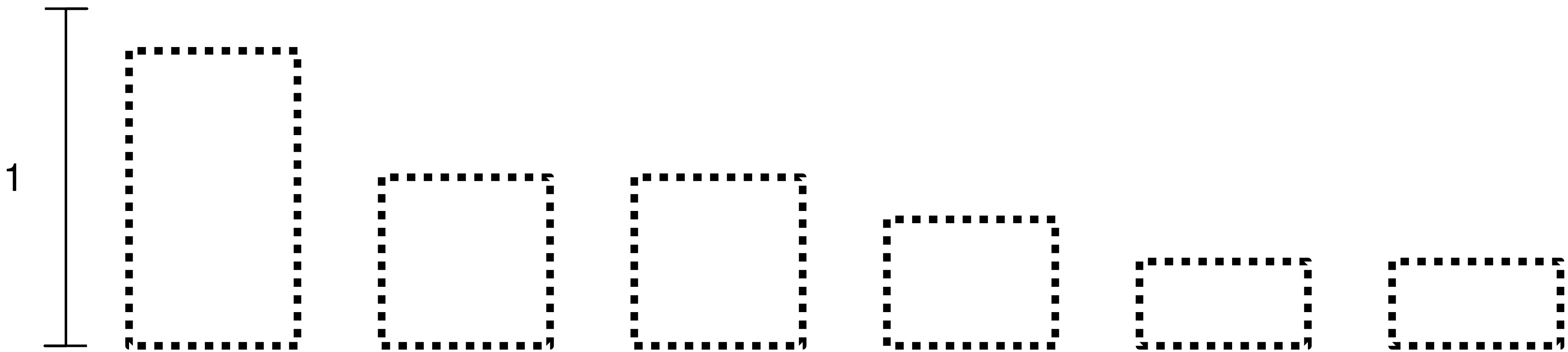

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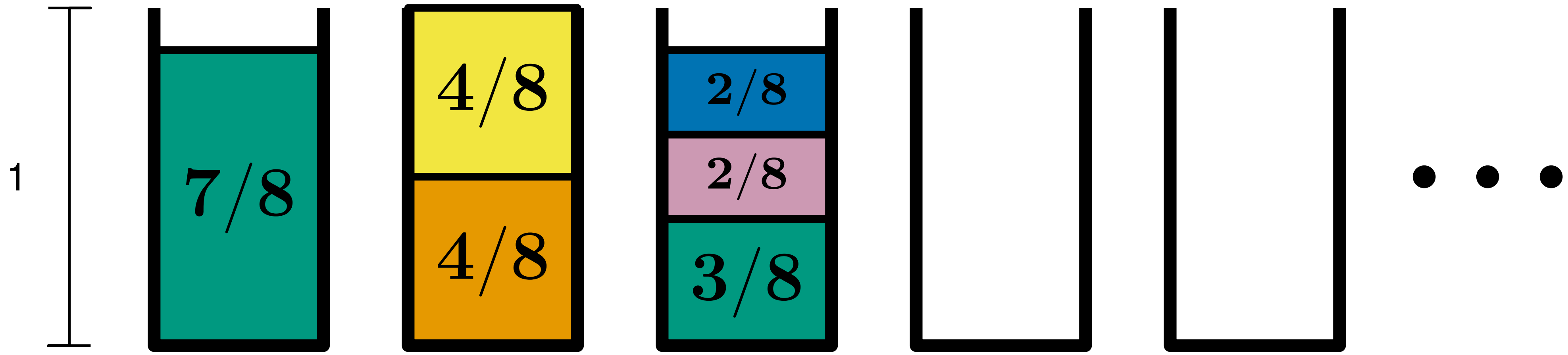

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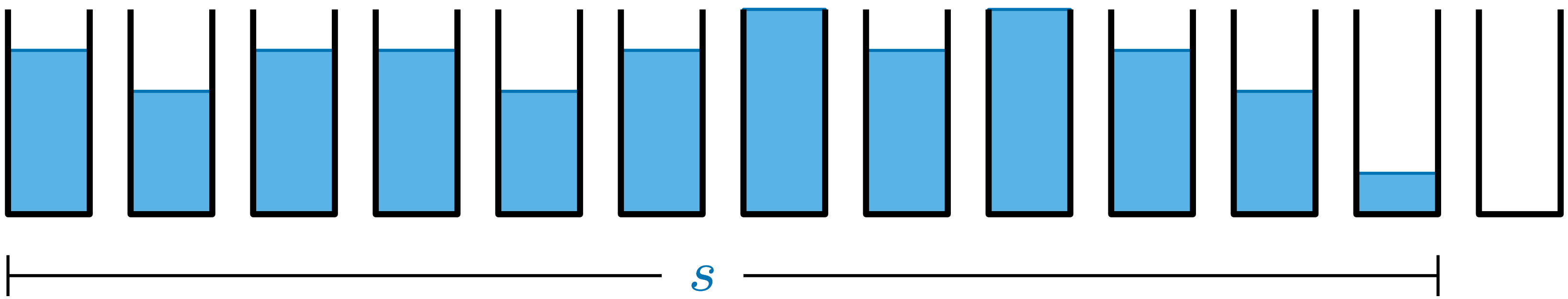

Consider bin $j = \left\lceil \frac{2s}{3} \right\rceil$ (s is the number of bins FFD uses on this input)

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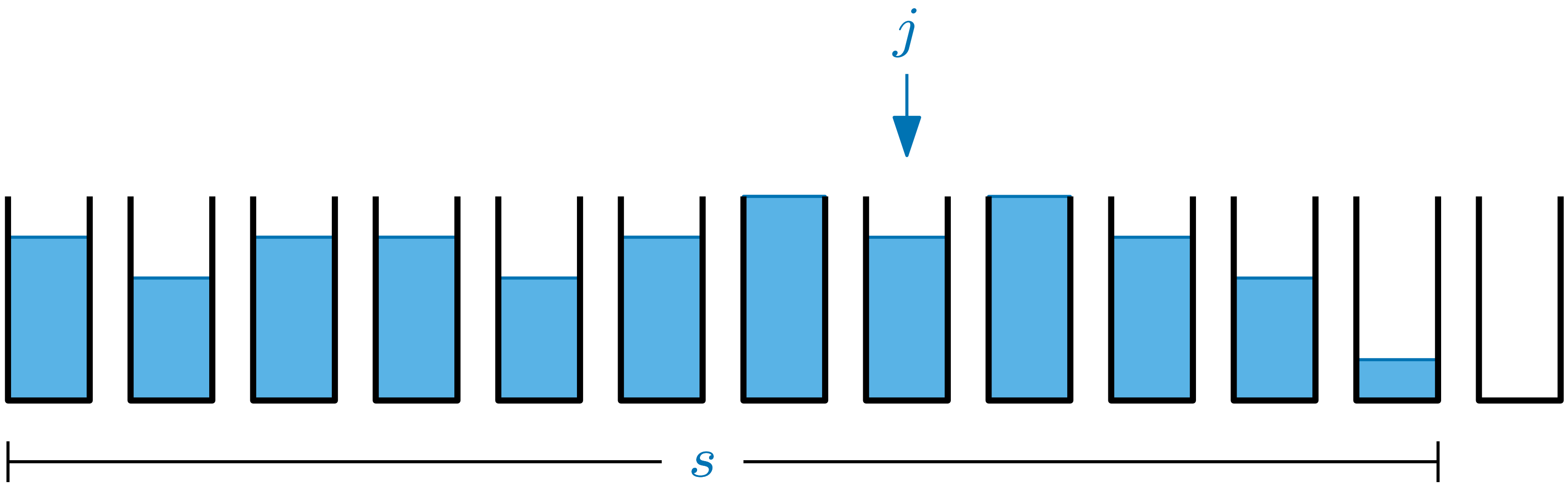

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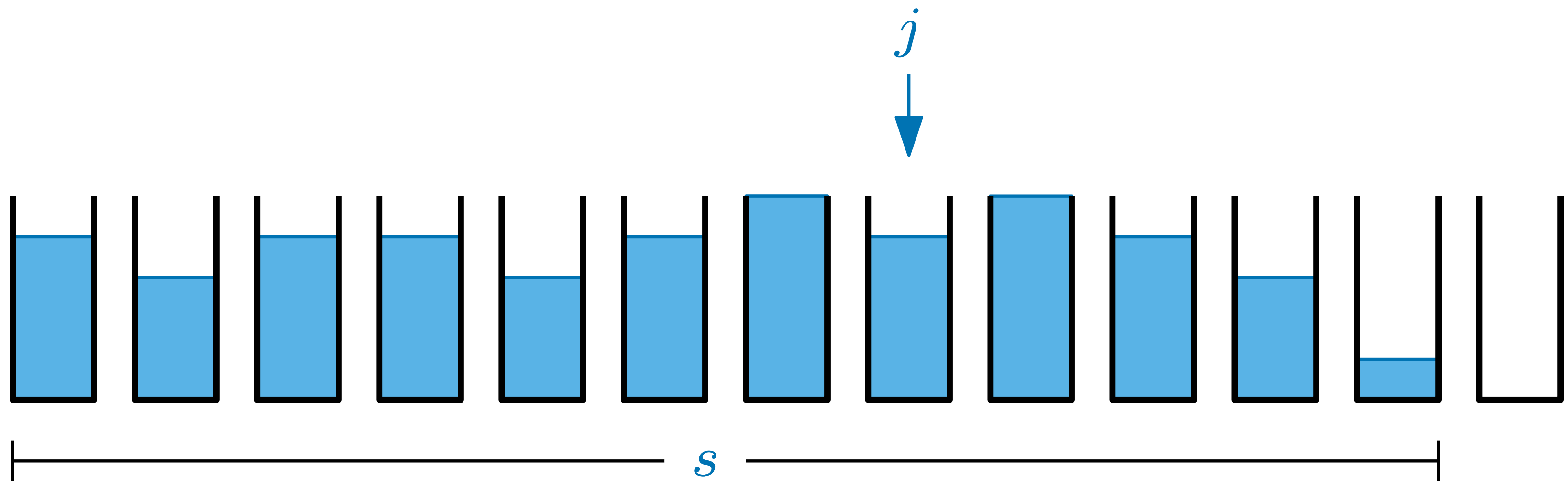

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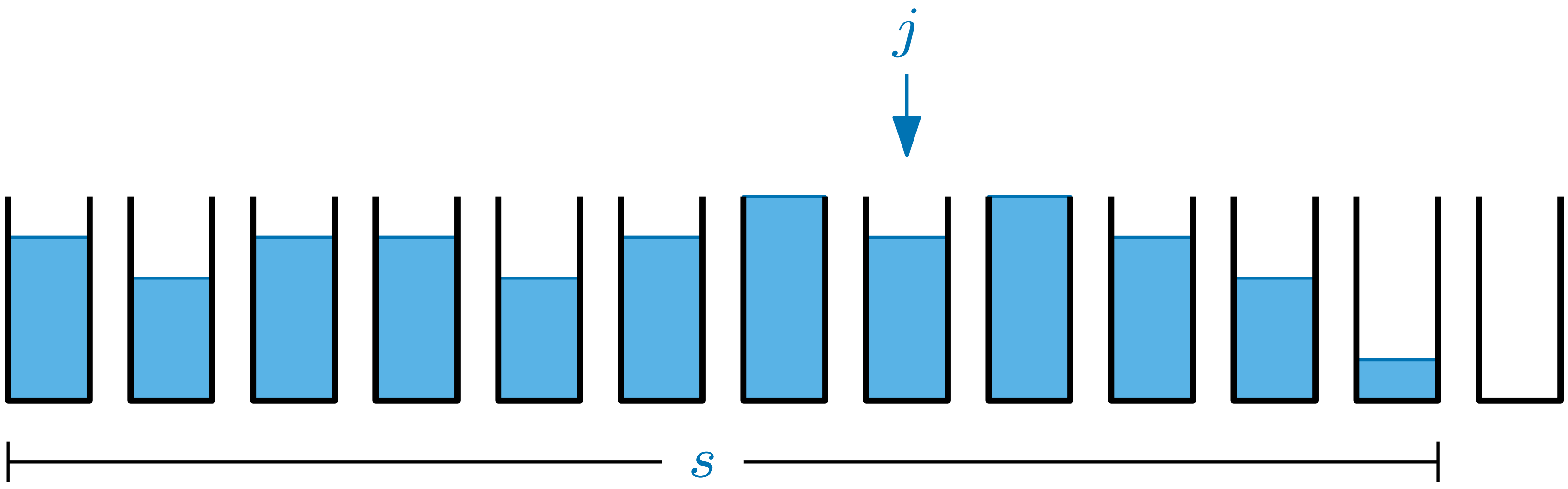

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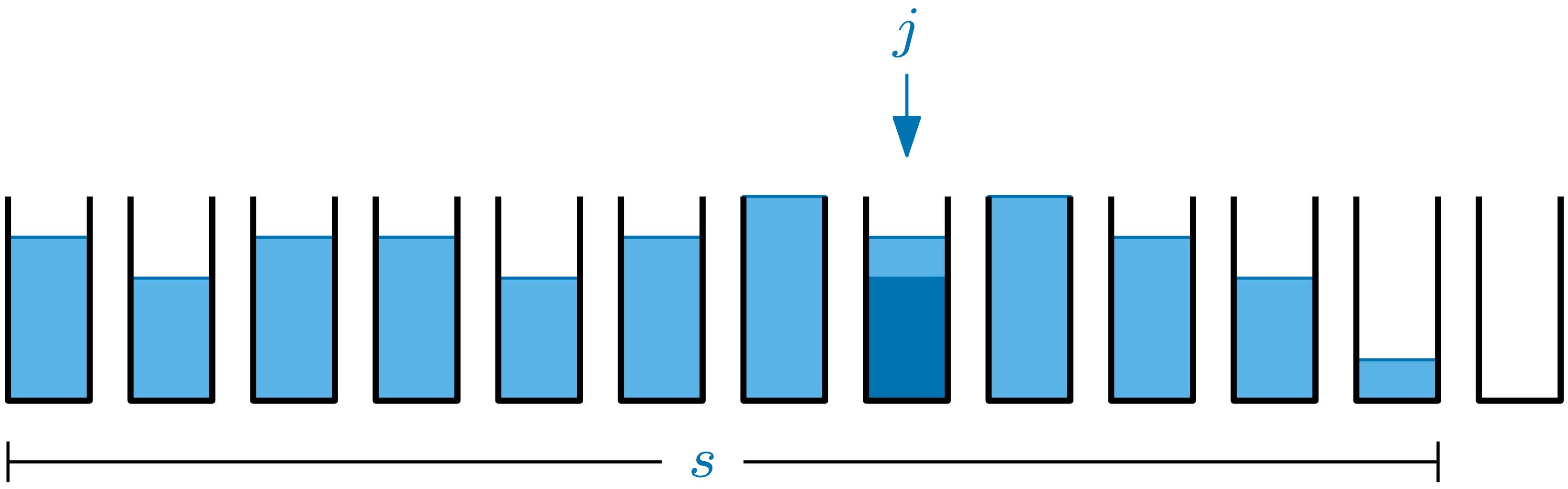

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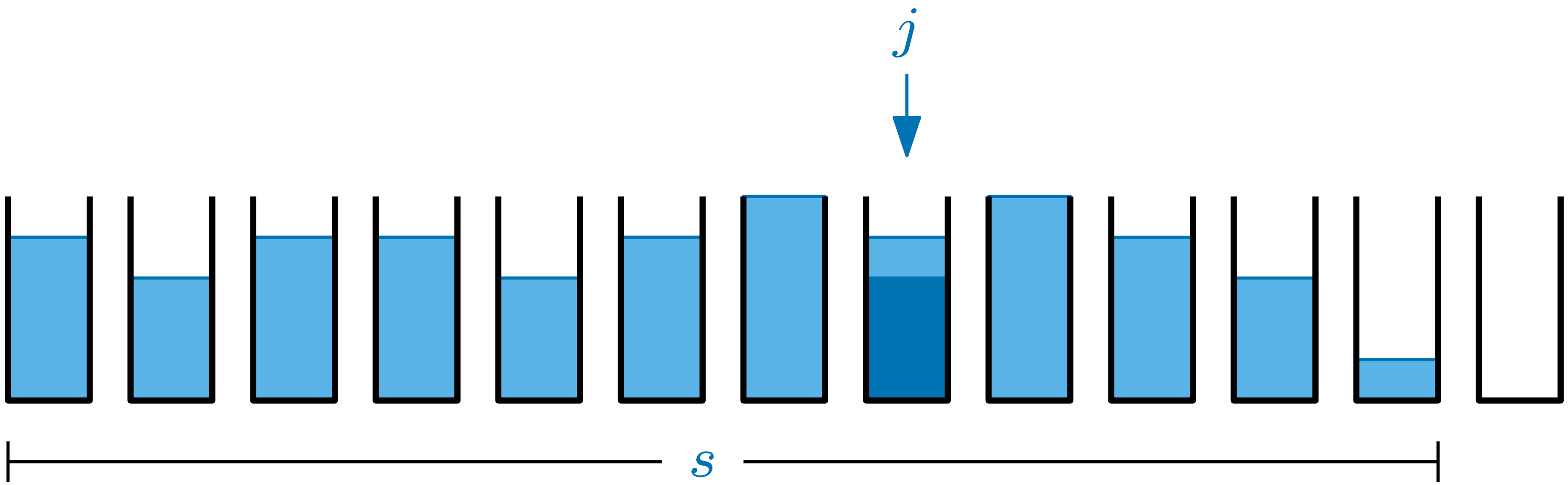

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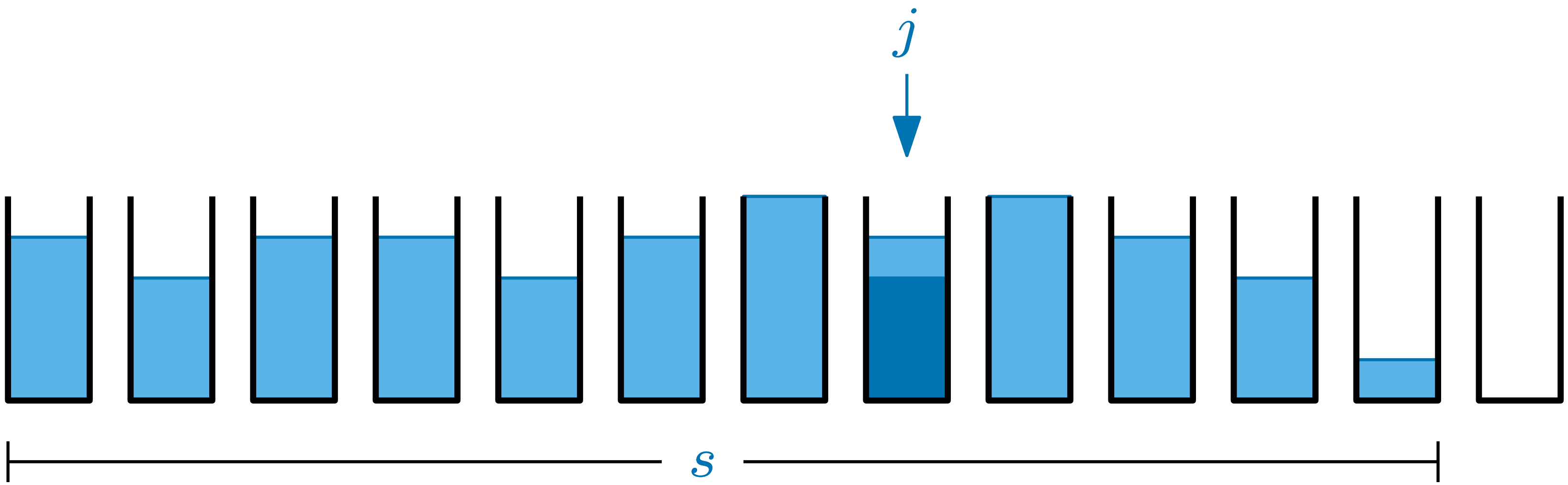

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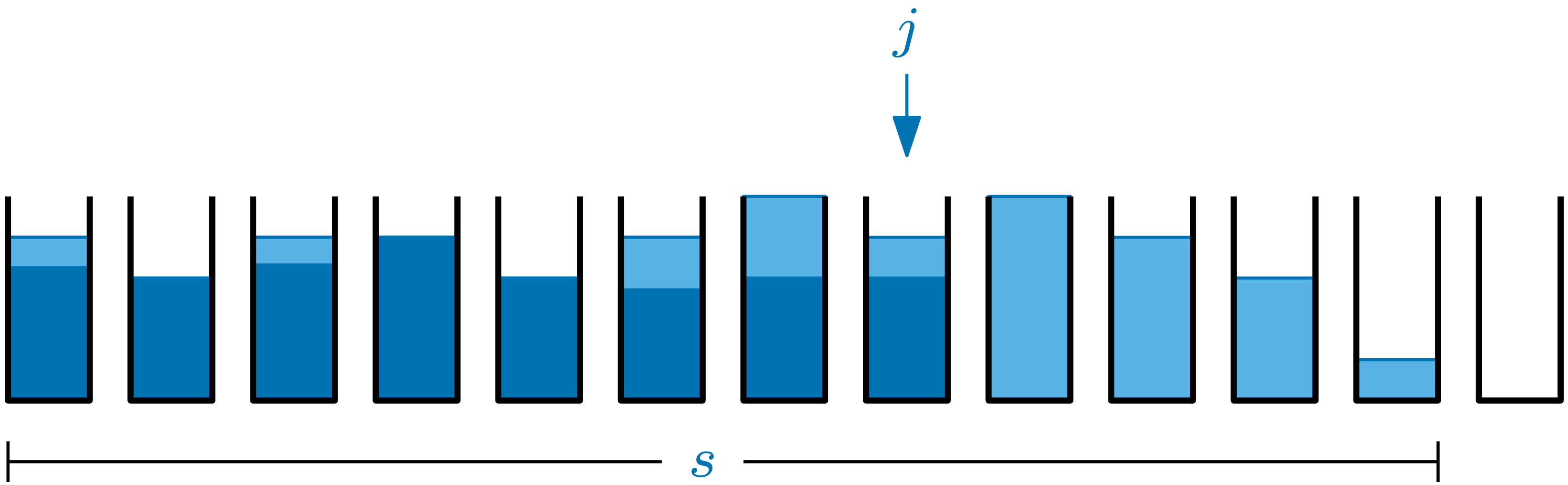

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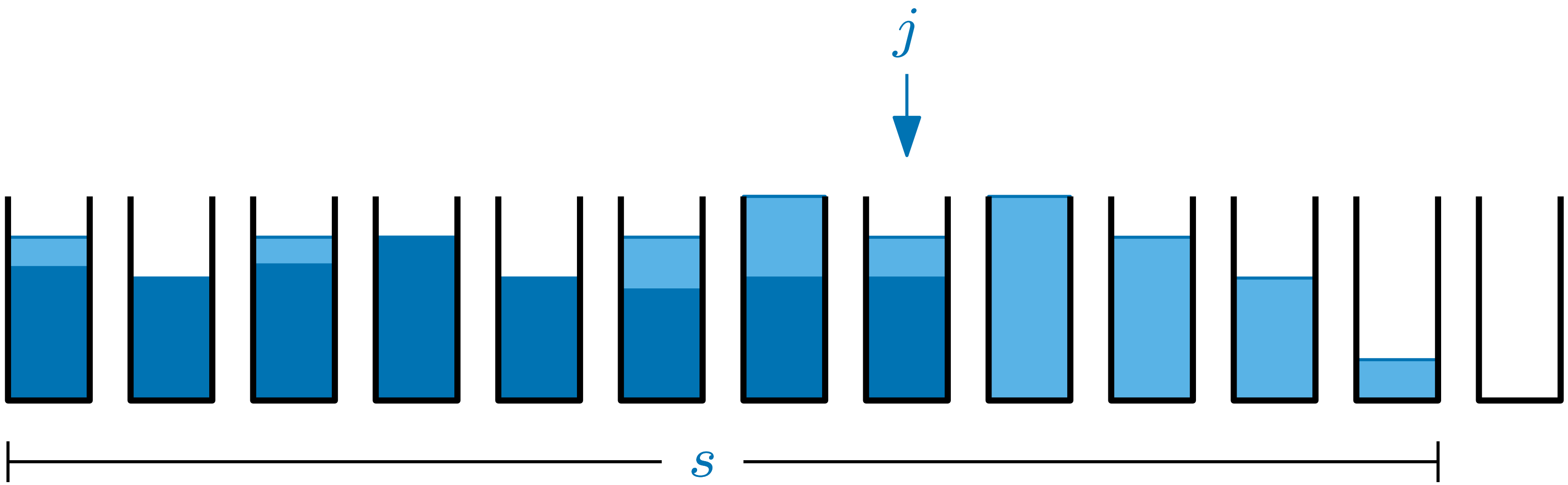
because we packed big things first and each thing was packed in the lowest numbered bin

First fit decreasing (FFD)

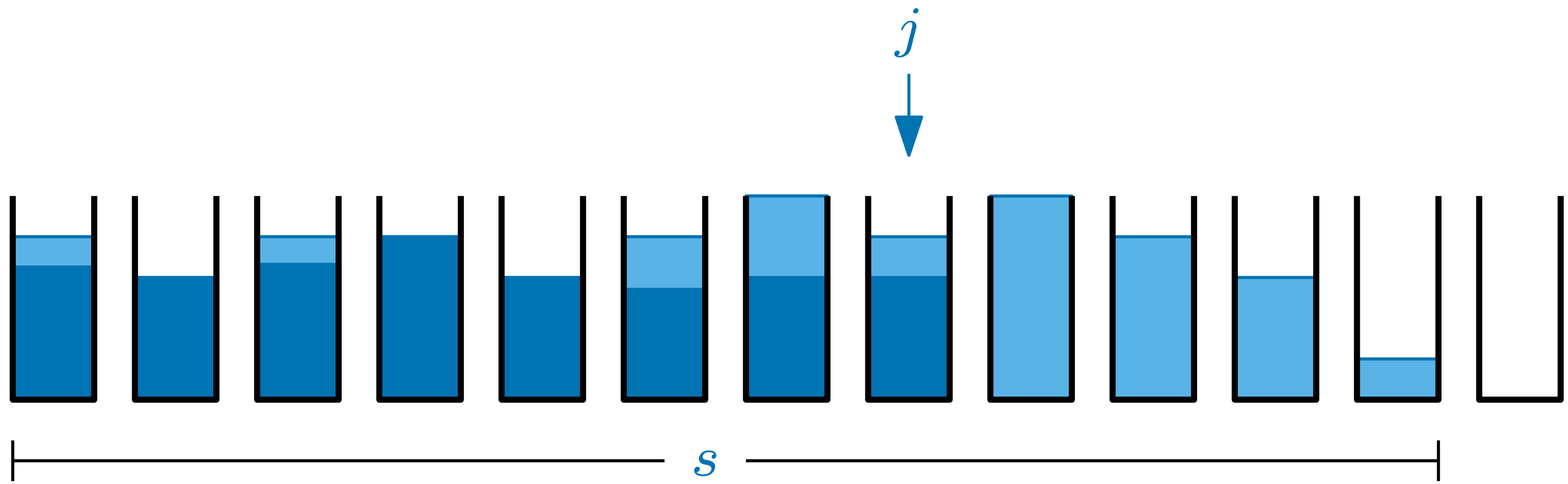


Consider bin $j = \left\lceil \frac{2s}{3} \right\rceil$ (s is the number of bins FFD uses on this input)

Case 1: Bin j contains an item of size $> 1/2$

Every bin $j' \leqslant j$ contains an item of size $> 1/2$

First fit decreasing (FFD)



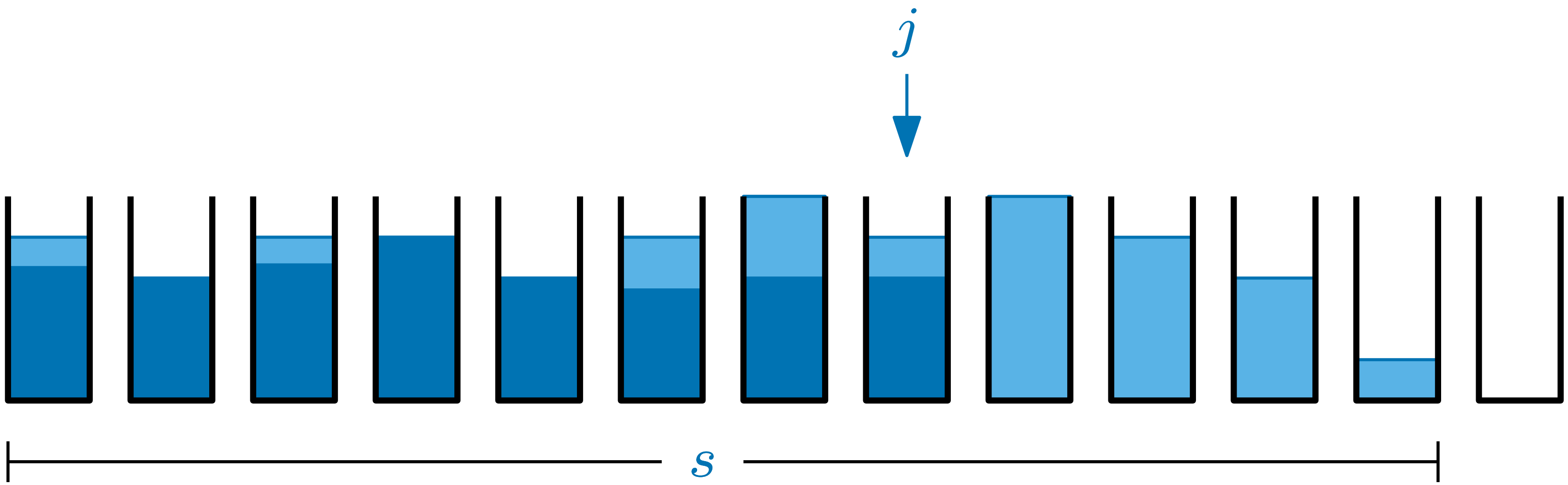
Consider bin $j = \left\lceil \frac{2s}{3} \right\rceil$ (s is the number of bins FFD uses on this input)

Case 1: Bin j contains an item of size $> 1/2$

Every bin $j' \leqslant j$ contains an item of size $> 1/2$

each of these items has to be in a different bin (even in Opt)

First fit decreasing (FFD)



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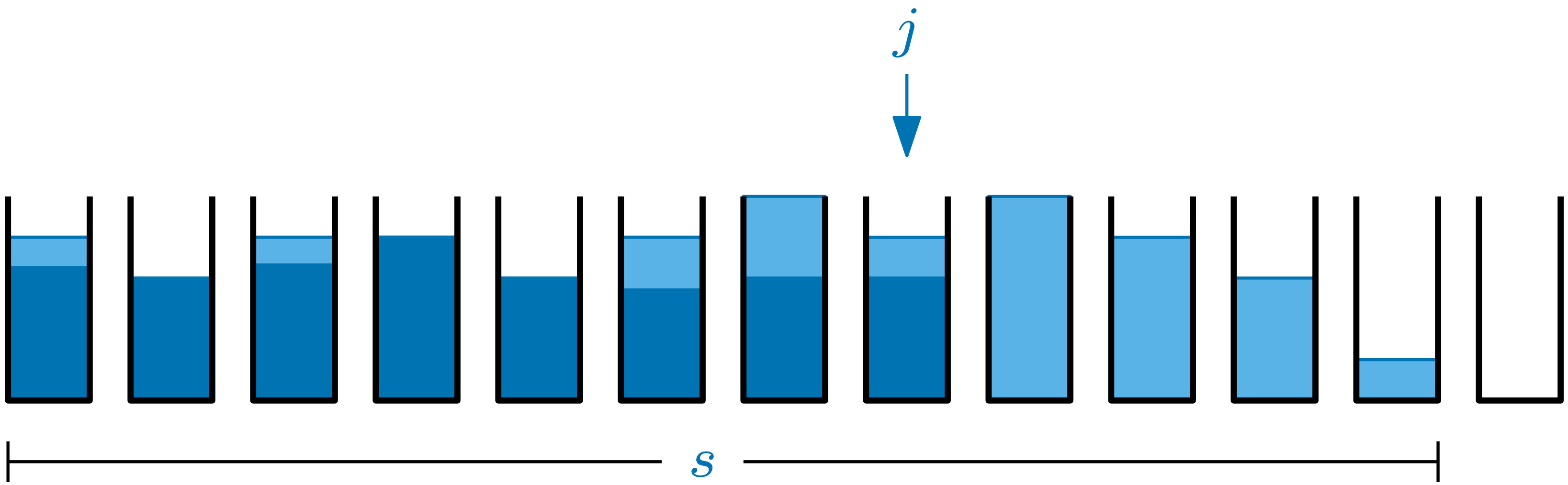
Case 1: Bin j contains an item of size $> 1/2$

Every bin $j' \leqslant j$ contains an item of size $> 1/2$

each of these items has to be in a different bin (even in Opt)

So Opt uses at least $\frac{2s}{3}$ bins

First fit decreasing (FFD)



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each of these items has to be in a different bin (even in Opt)

So Opt uses at least $\frac{2s}{3}$ bins

or... $s \leqslant \frac{3\mathrm{Opt}}{2}$

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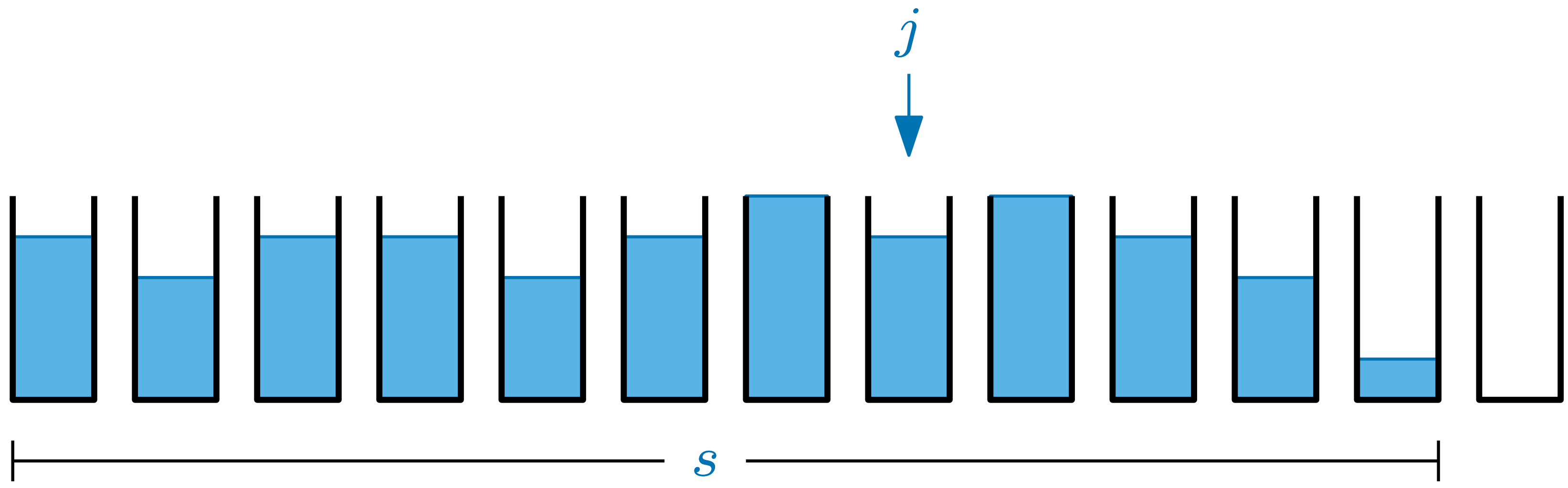

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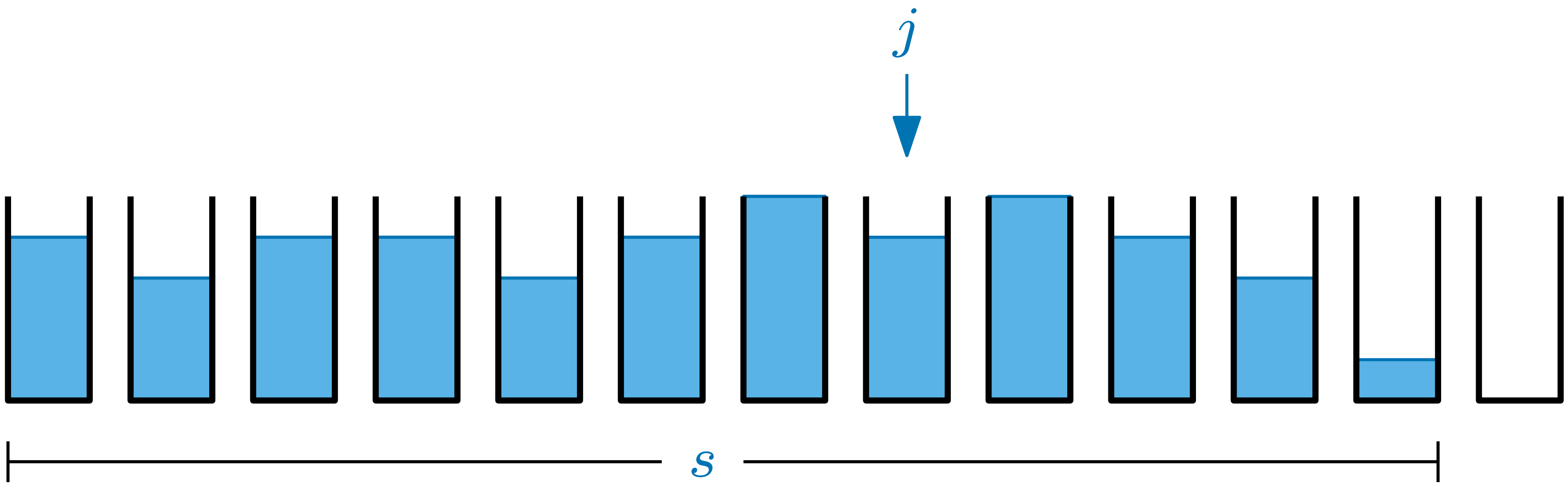
Case 2: Bin j contains only items of size $\leqslant 1/2$

First fit decreasing (FFD)



Consider bin $j = \left\lceil \frac{2s}{3} \right\rceil$ (s is the number of bins FFD uses on this input)

Case 2: Bin j contains only items of size $\leqslant 1/2$

when FFD packed the first item into bin j,

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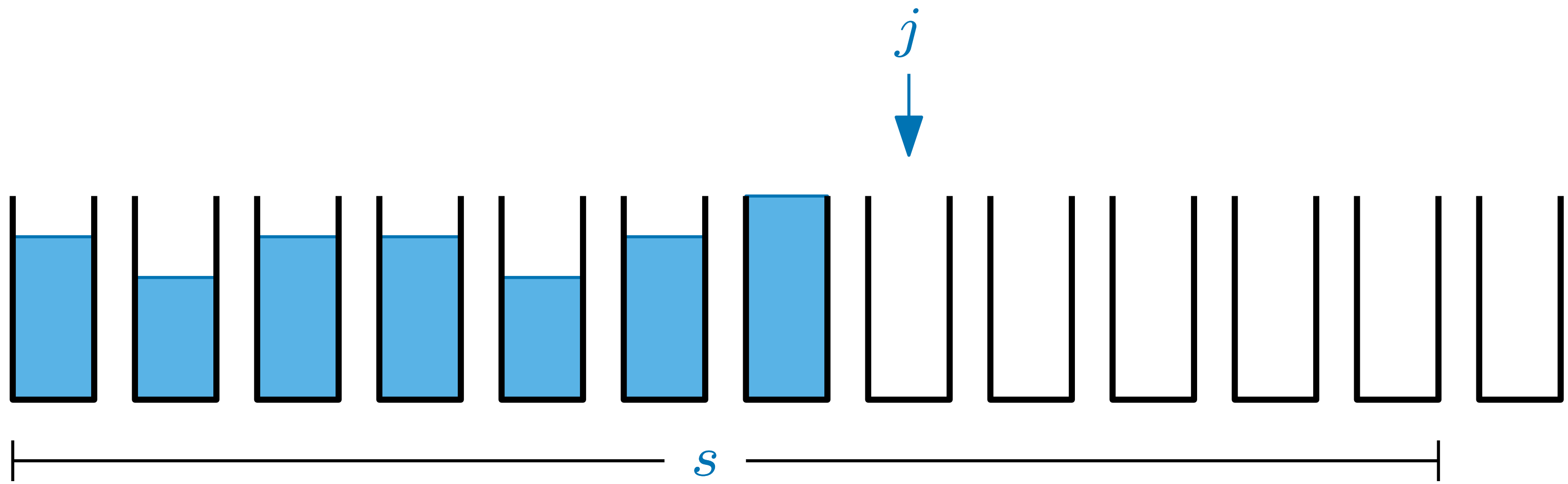

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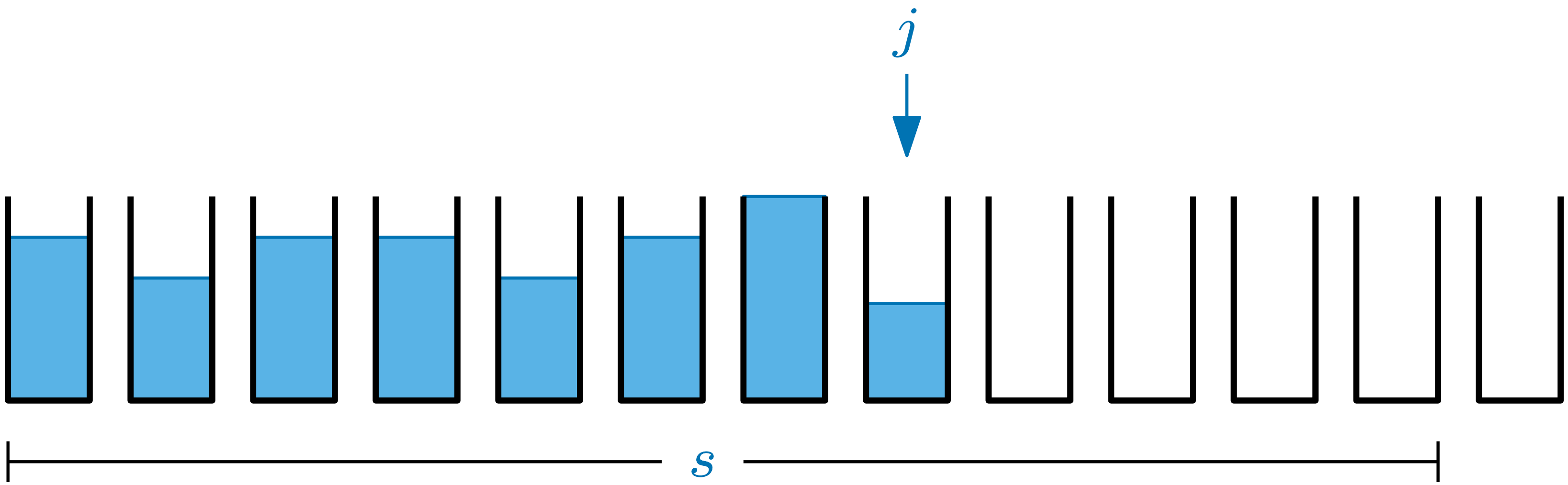

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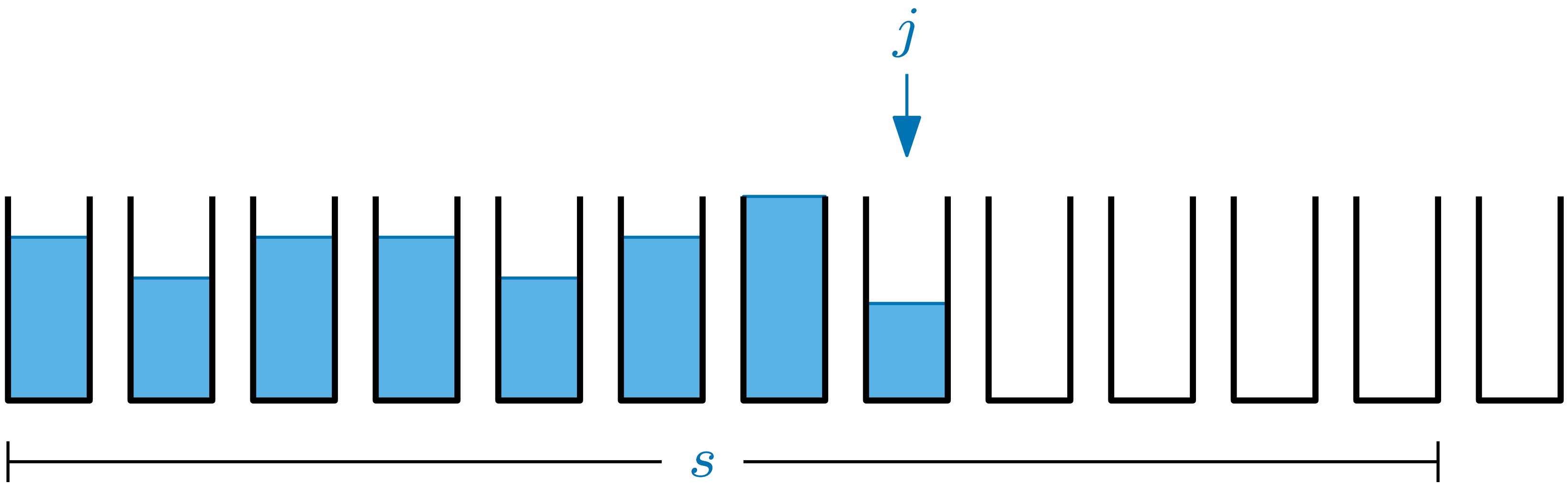

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Case 2: Bin j contains only items of size $\leqslant 1/2$

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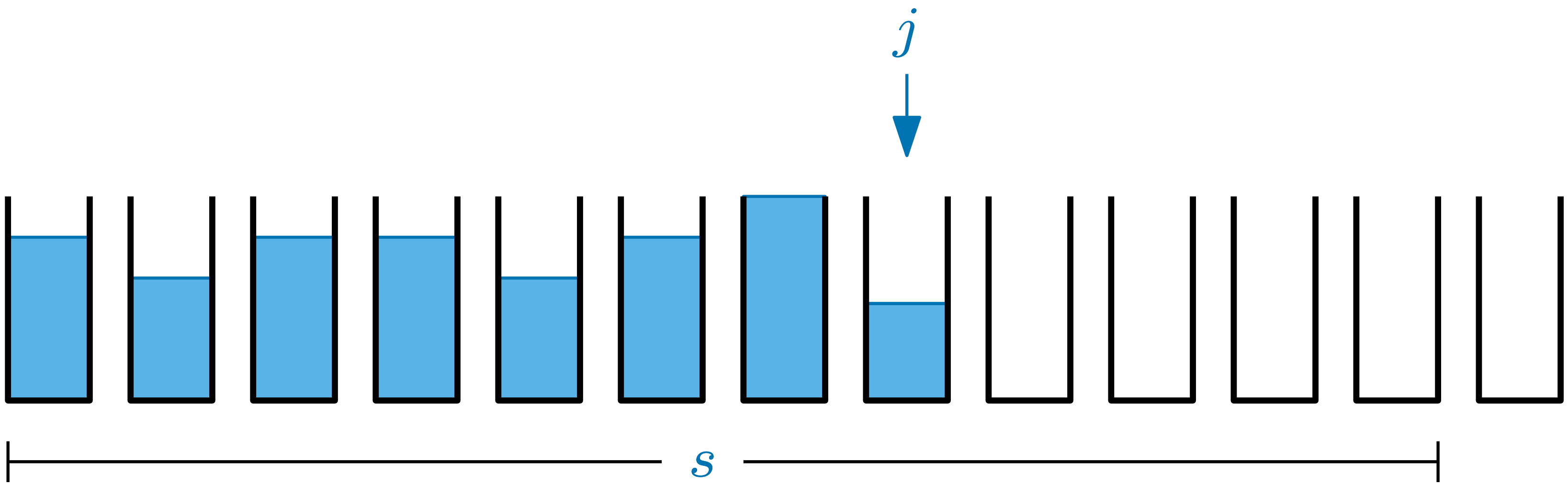

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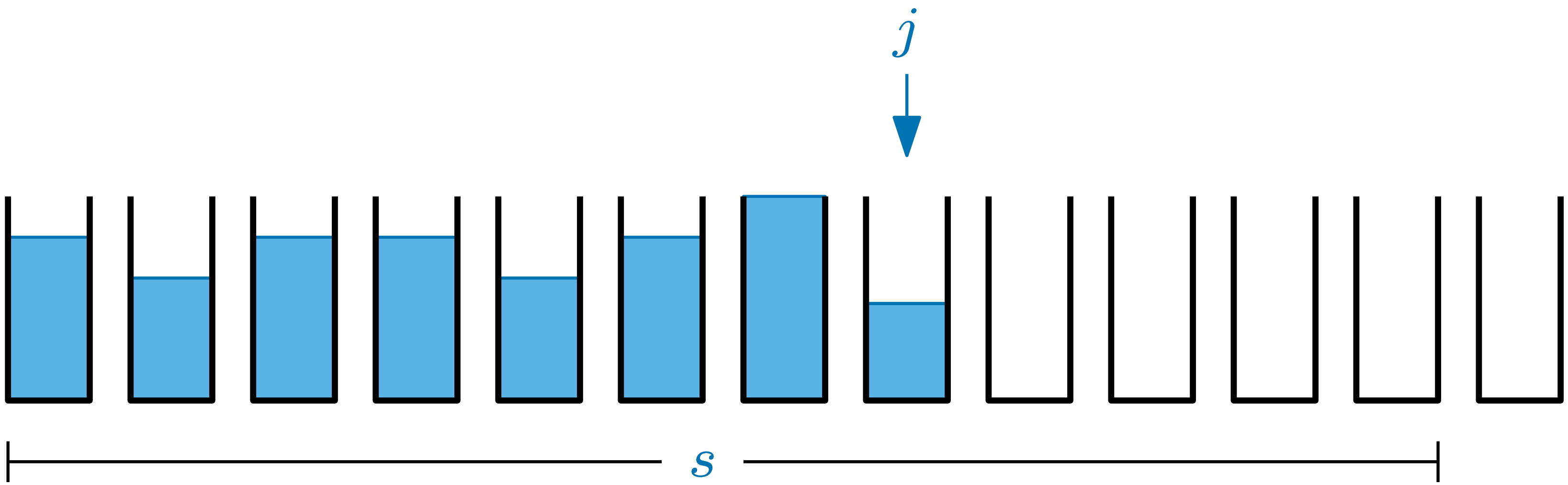
when FFD packed the first item into bin j,

1. all bins $j, (j+1), \ldots, (s-2), (s-1)$ were empty
2. and all unpacked items had size $\leqslant 1/2$

(because we pack in non-increasing order)

First fit decreasing (FFD)



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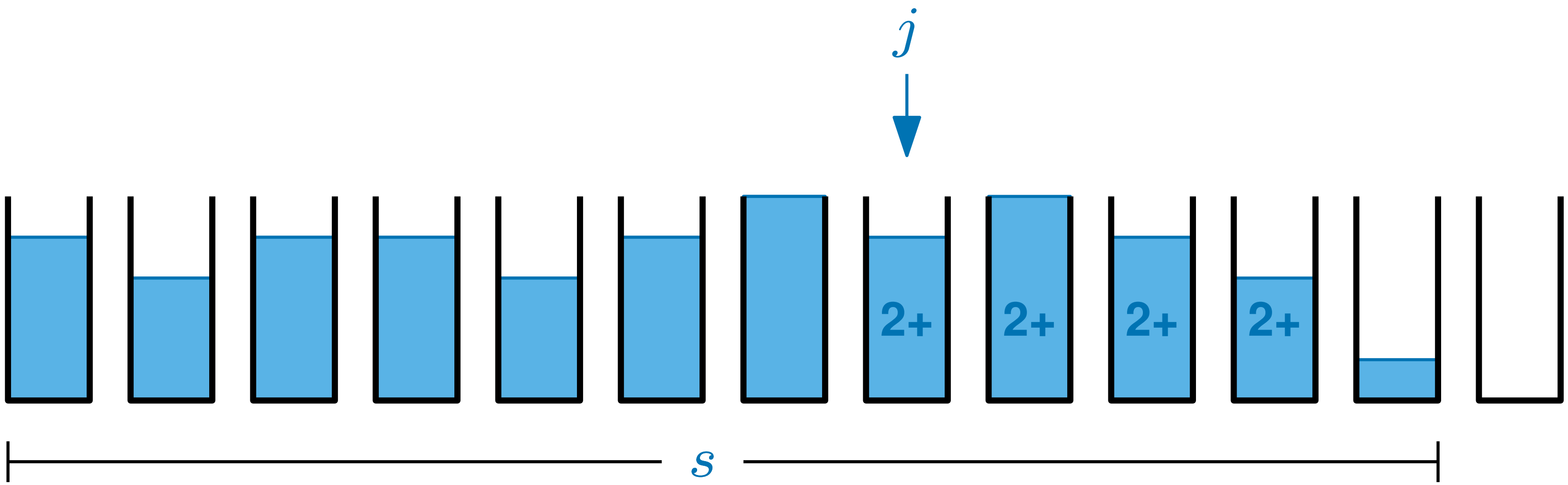

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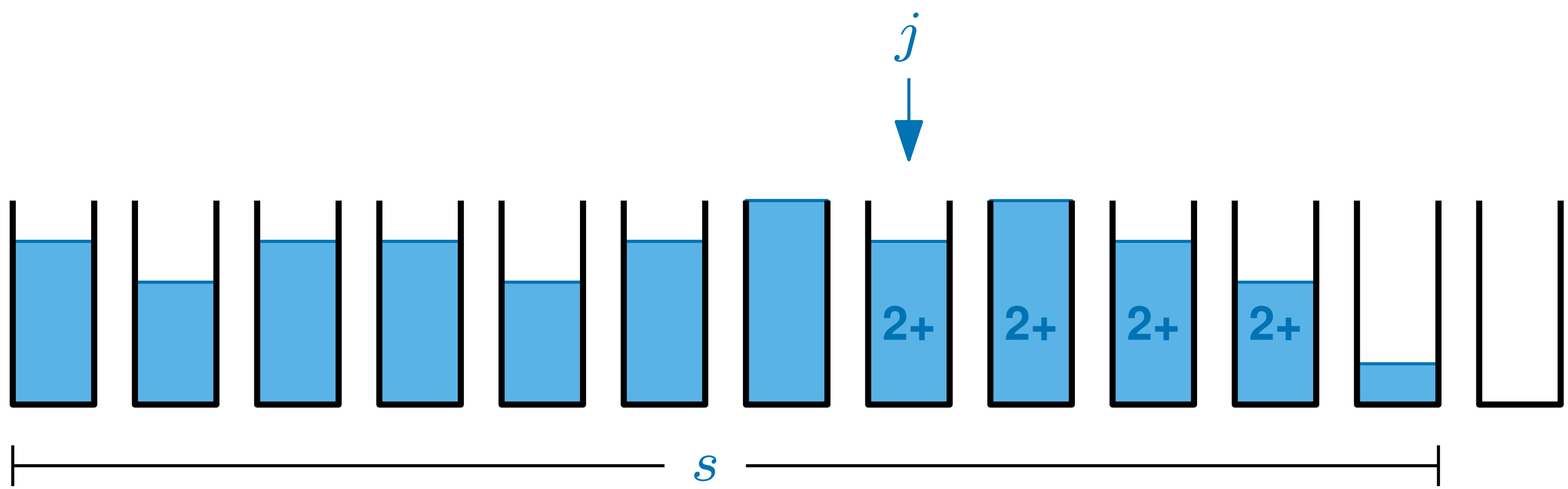

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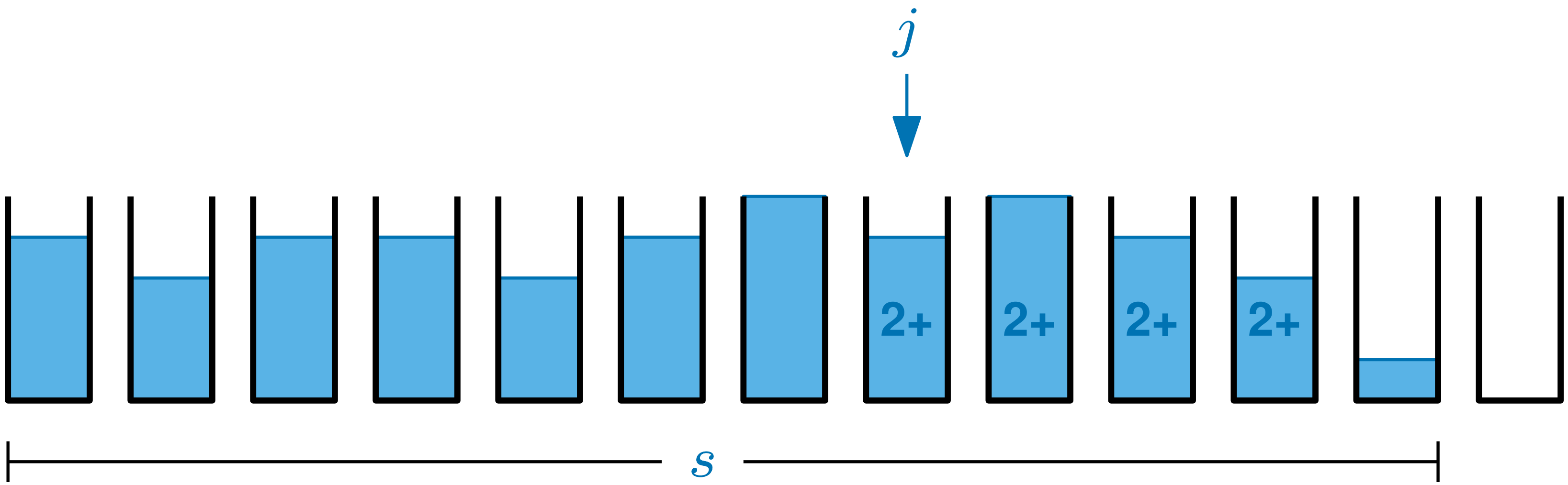
2. and all unpacked items had size $\leqslant 1/2$

(because we pack in non-increasing order)

so Bins $j, (j+1), \ldots, (s-2), (s-1)$ each contain at least two items

(we only use a new bin when the item won't fit in any previous bin)

First fit decreasing (FFD)



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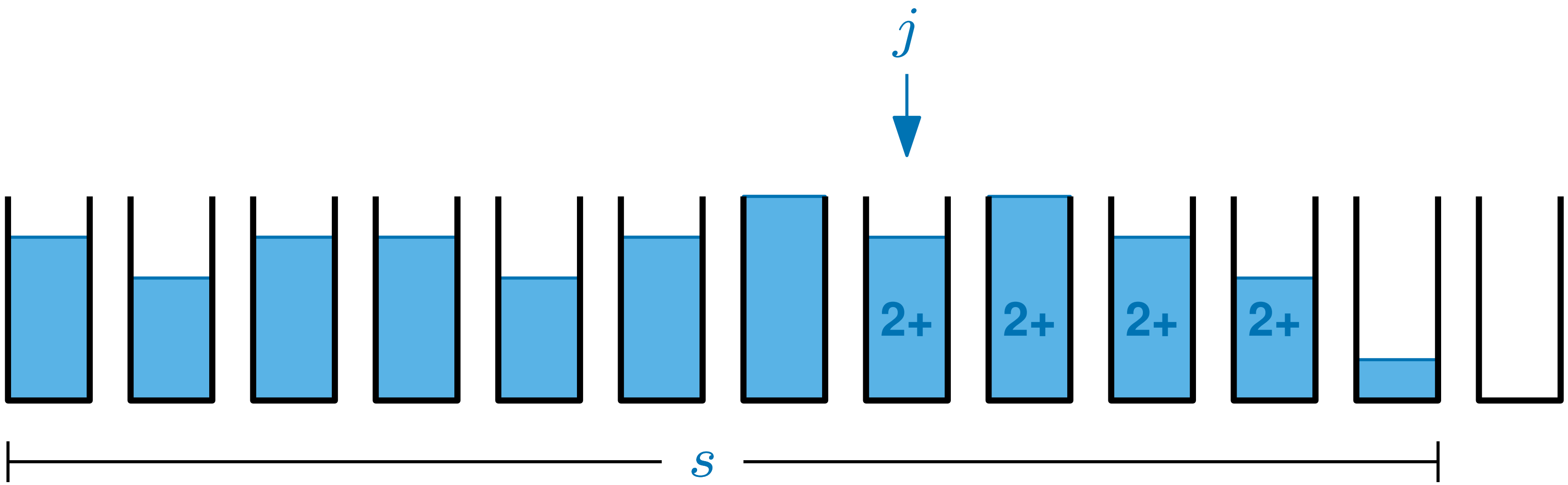

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and bin s contains at least one item

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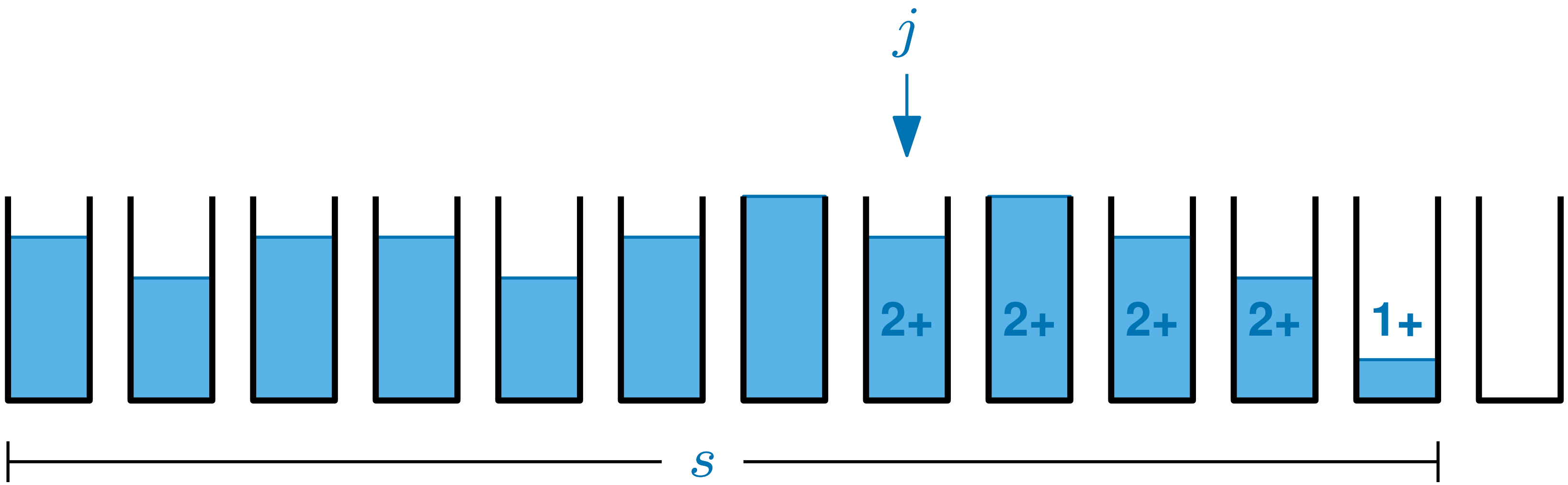

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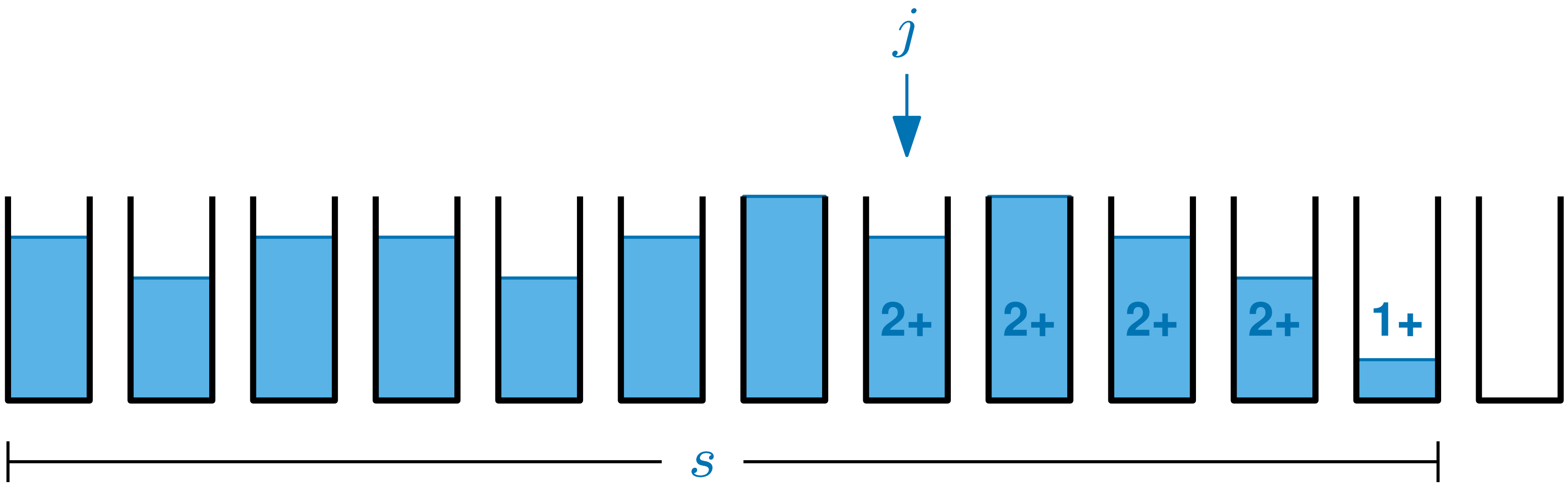

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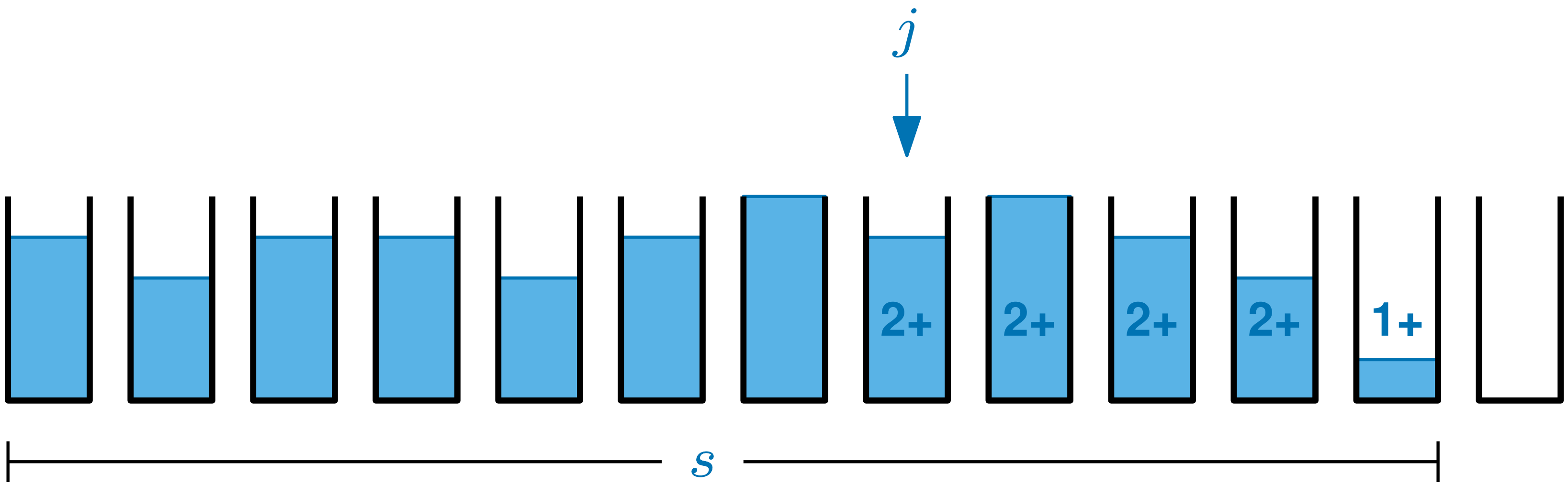

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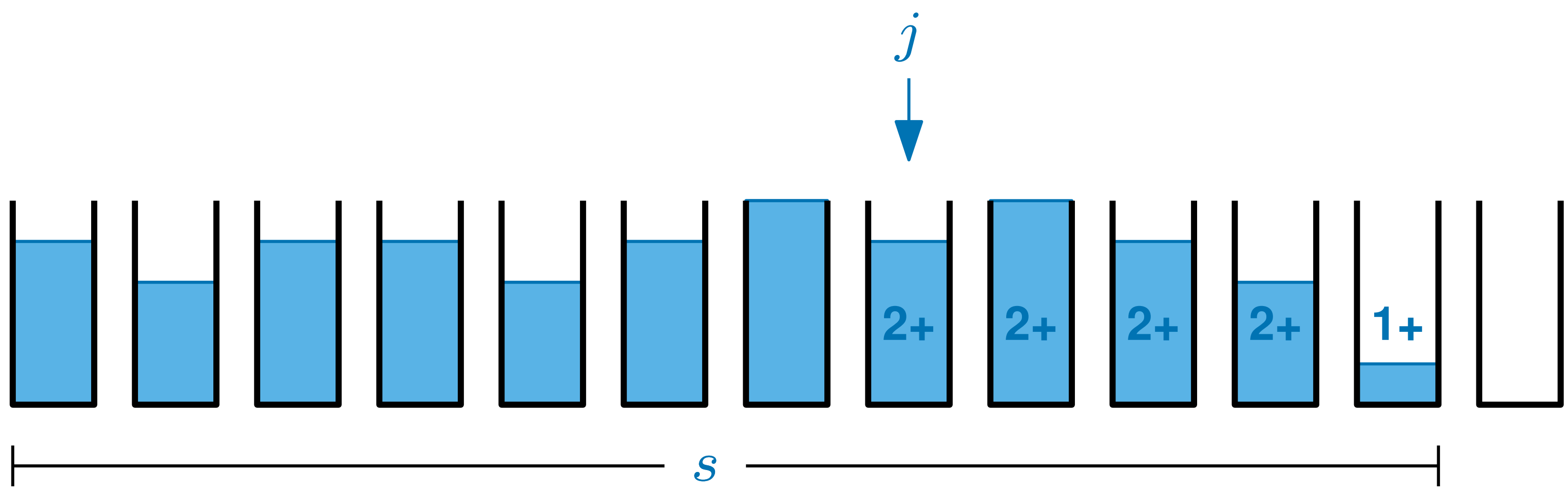

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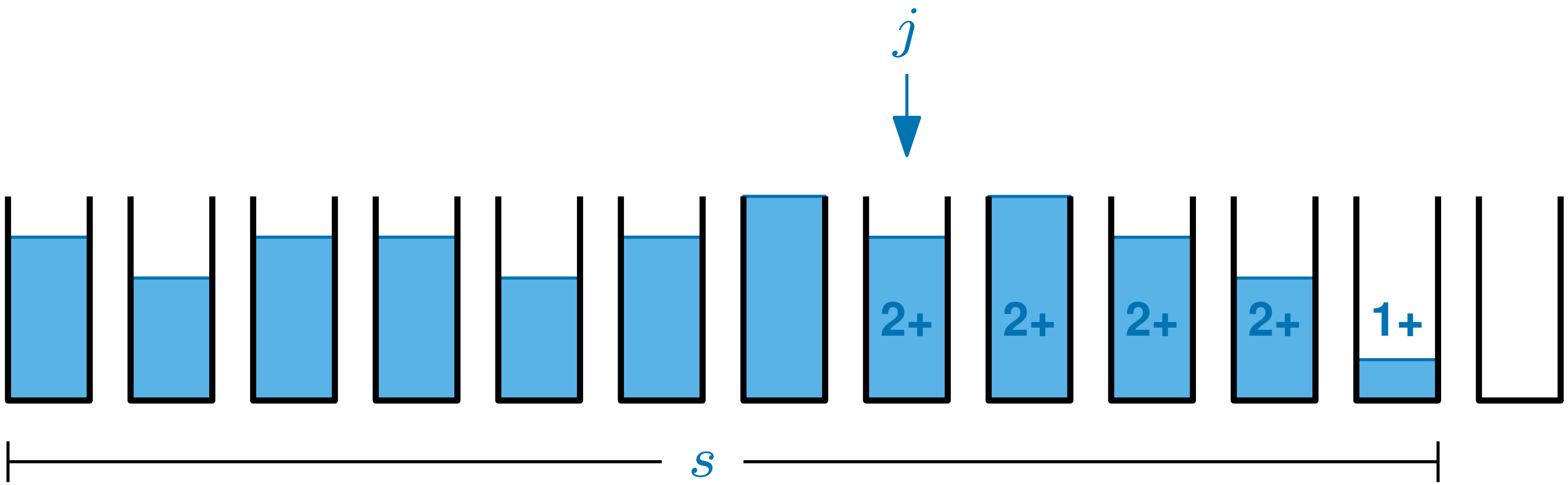

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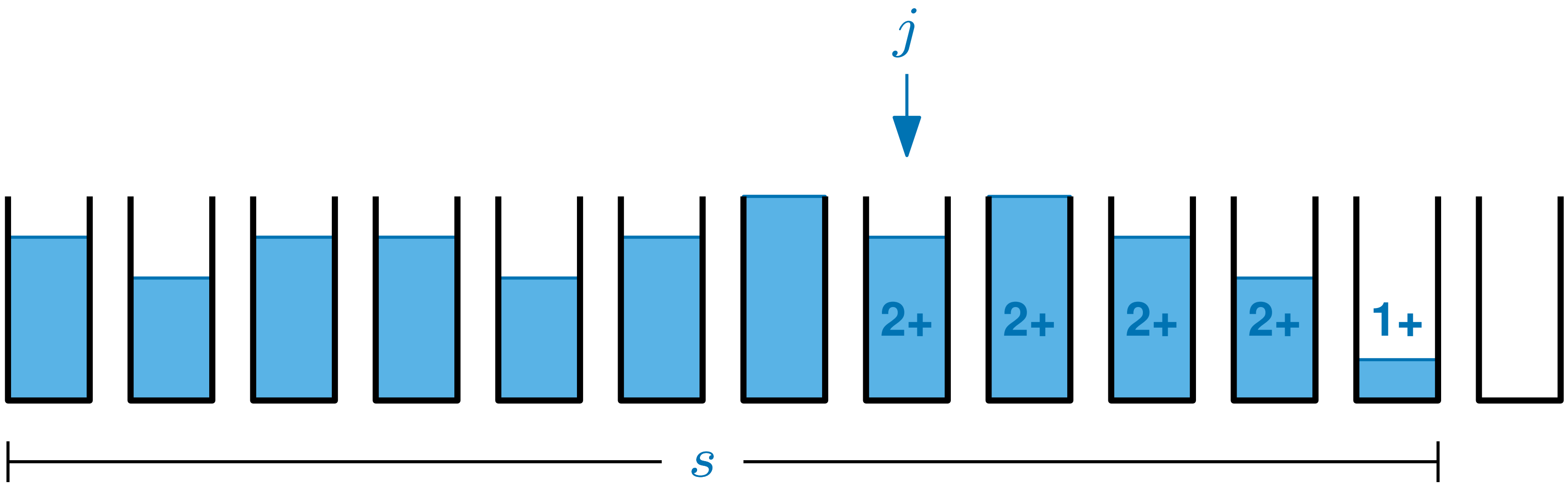
This gives a total of $2(s-j)+1$ items, none of which fits into bins $1, 2, 3, \ldots, (j-1)$

First fit decreasing (FFD)



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otherwise we would have packed them there

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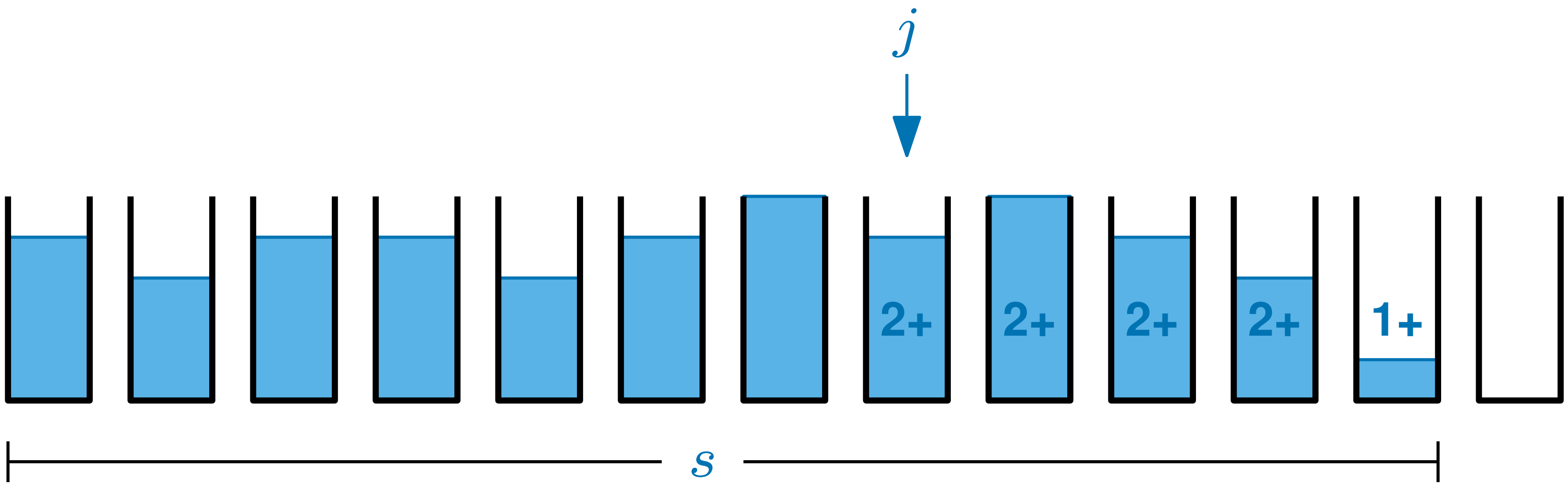

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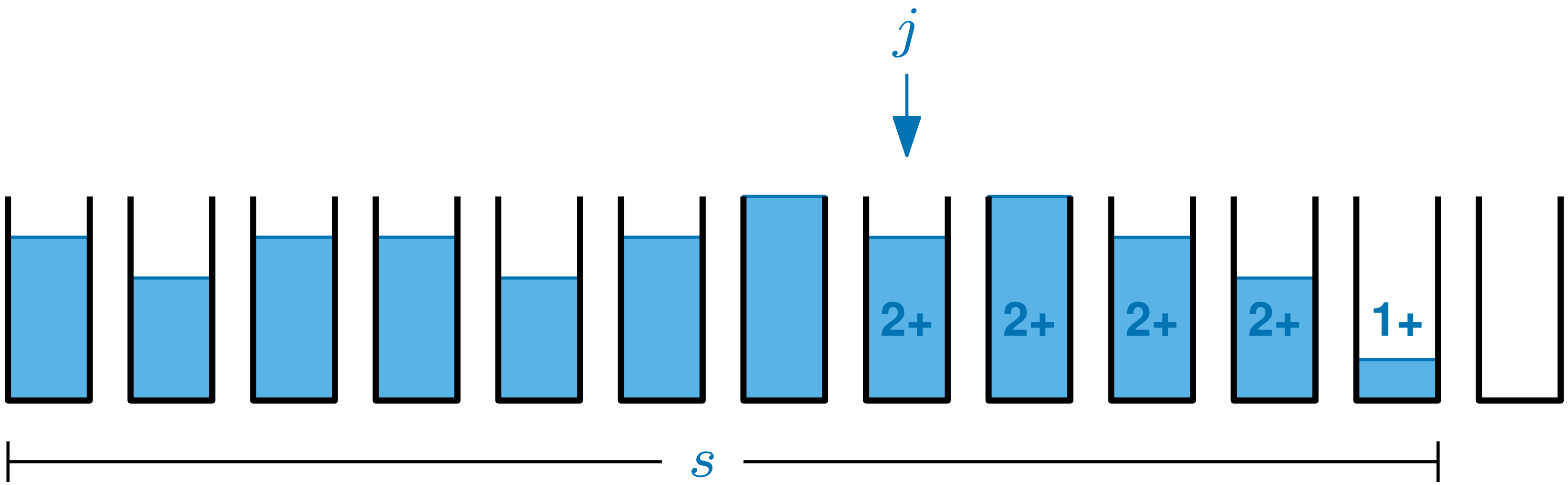

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This gives a total of $2(s-j)+1$ items, none of which fits into bins $1, 2, 3, \ldots, (j-1)$

so $I > \min\{j-1, 2(s-j)+1\}$

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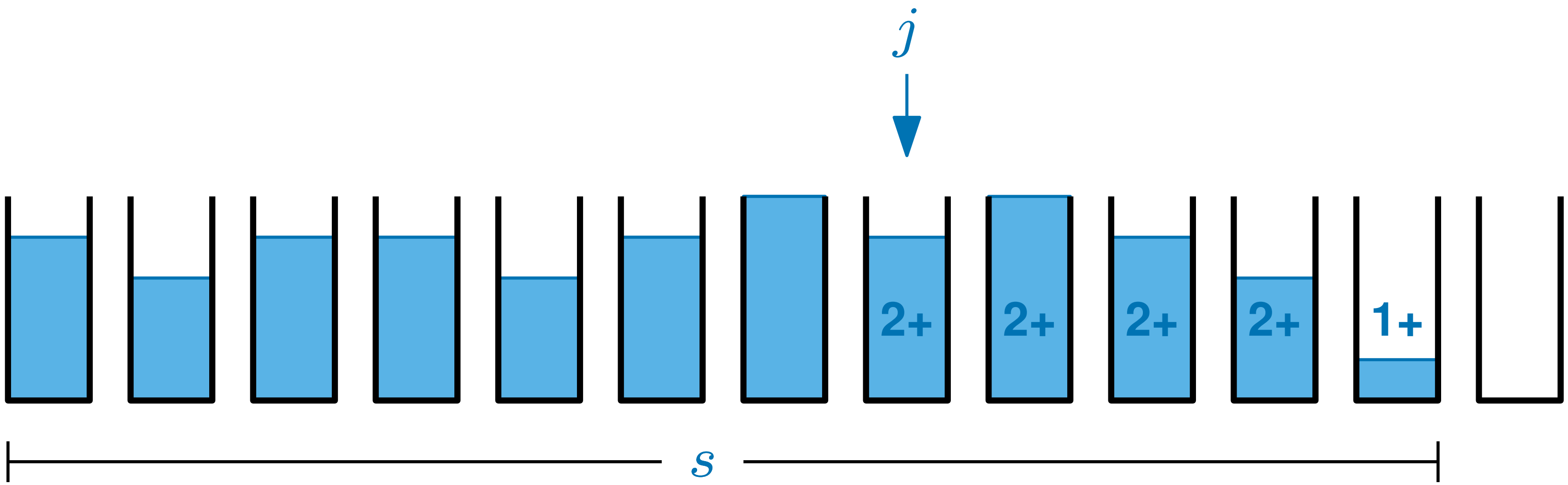

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recall I is the total weight of all items

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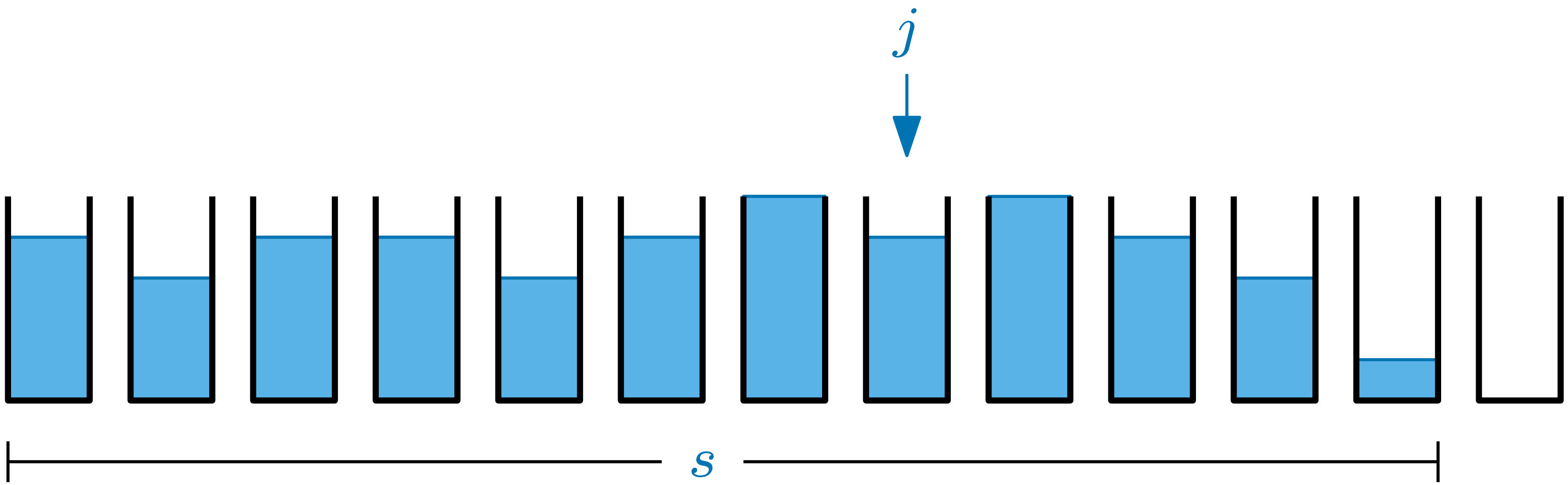

Consider bin $j = \left\lceil \frac{2s}{3} \right\rceil$ (s is the number of bins FFD uses on this input)

consider
pairing **these** with **these**

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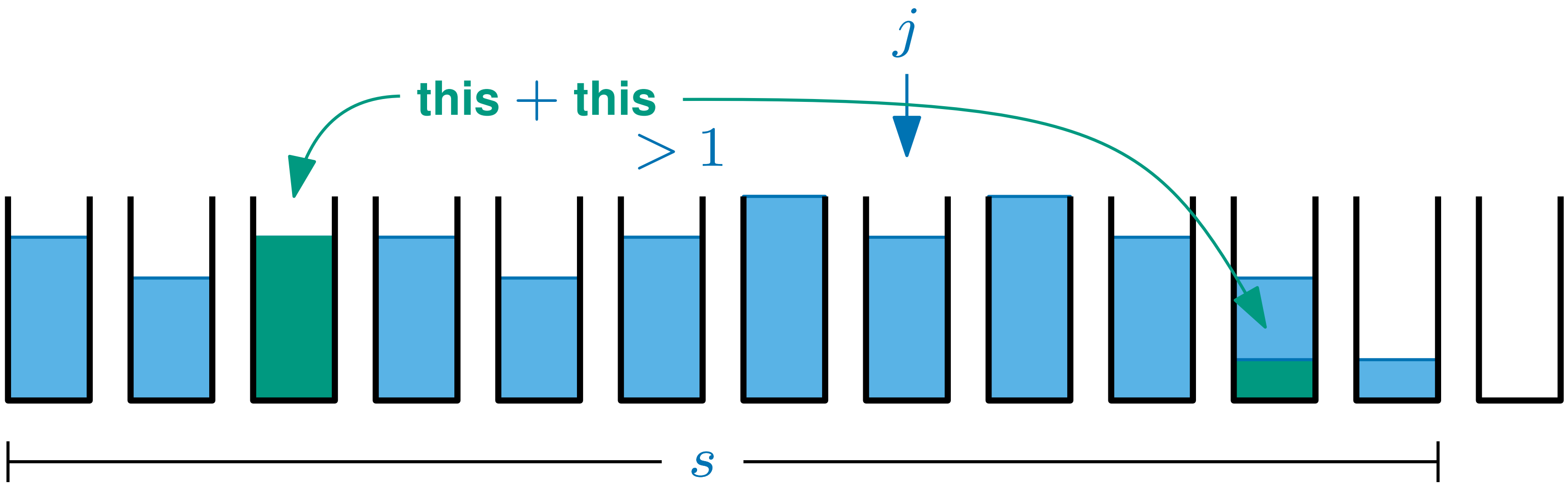

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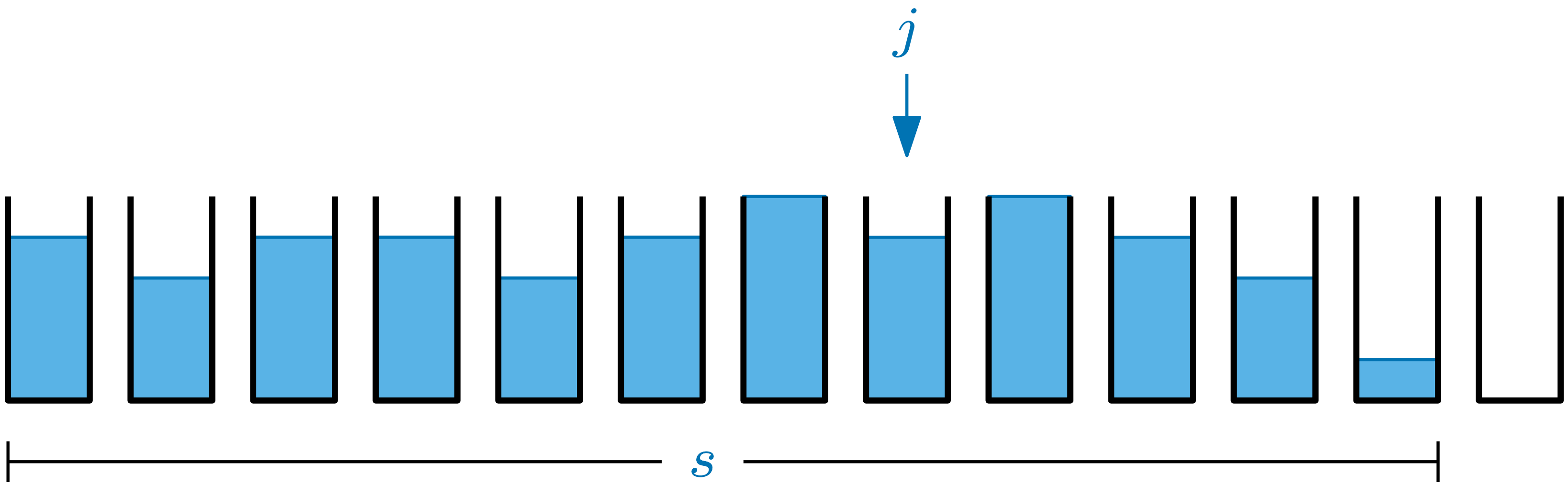

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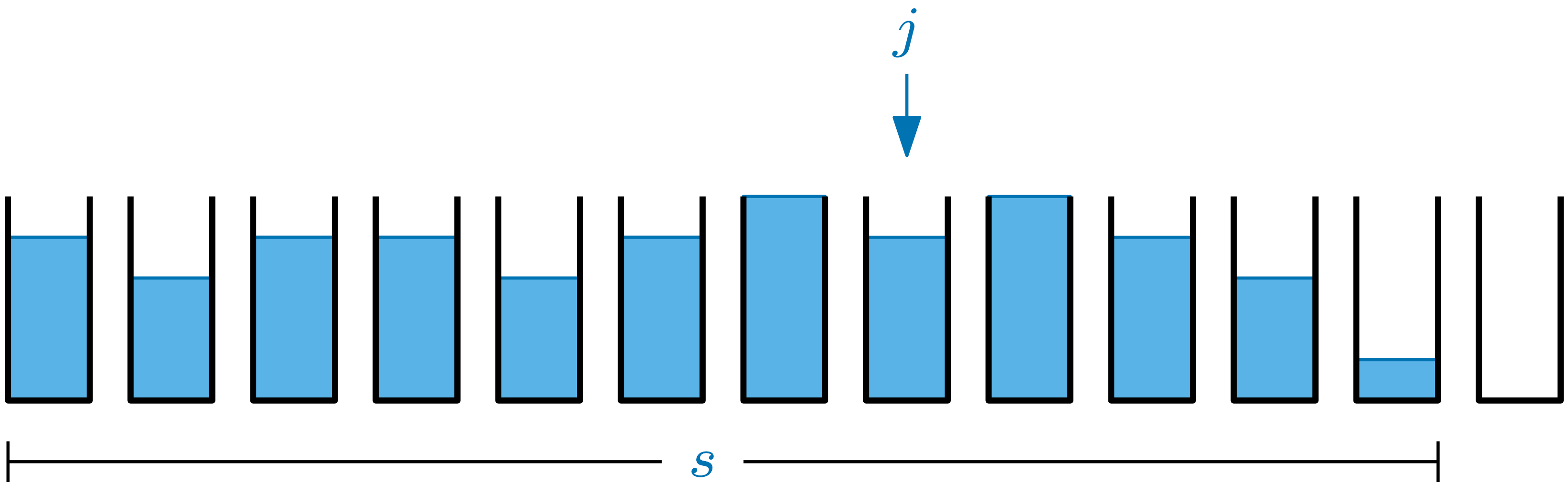

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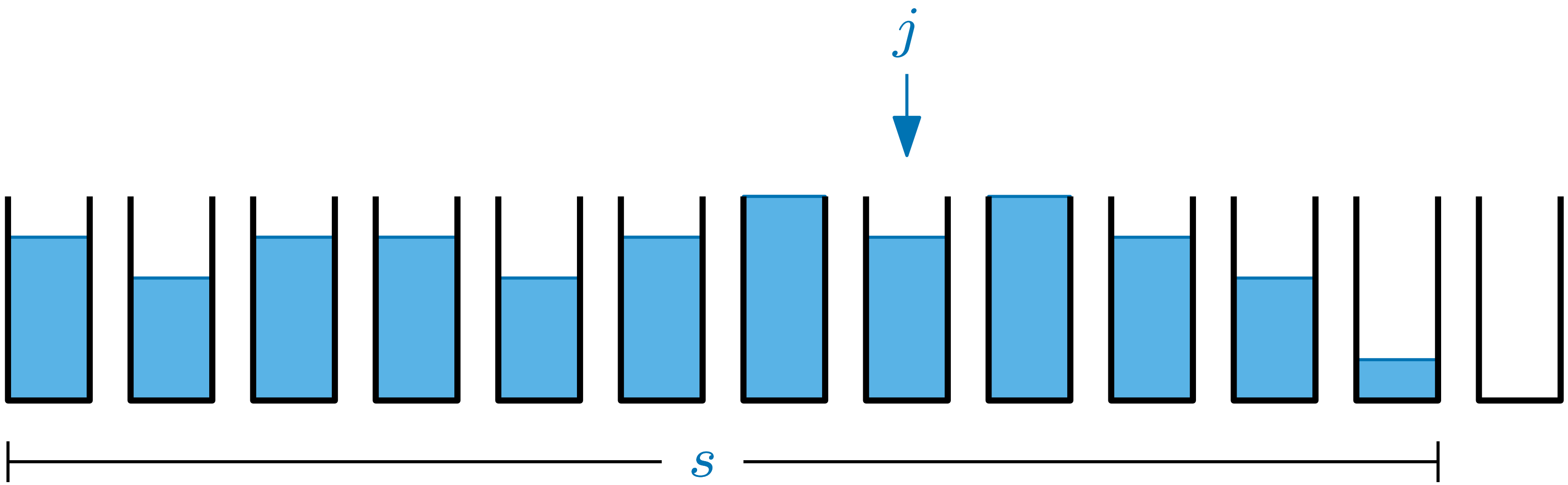

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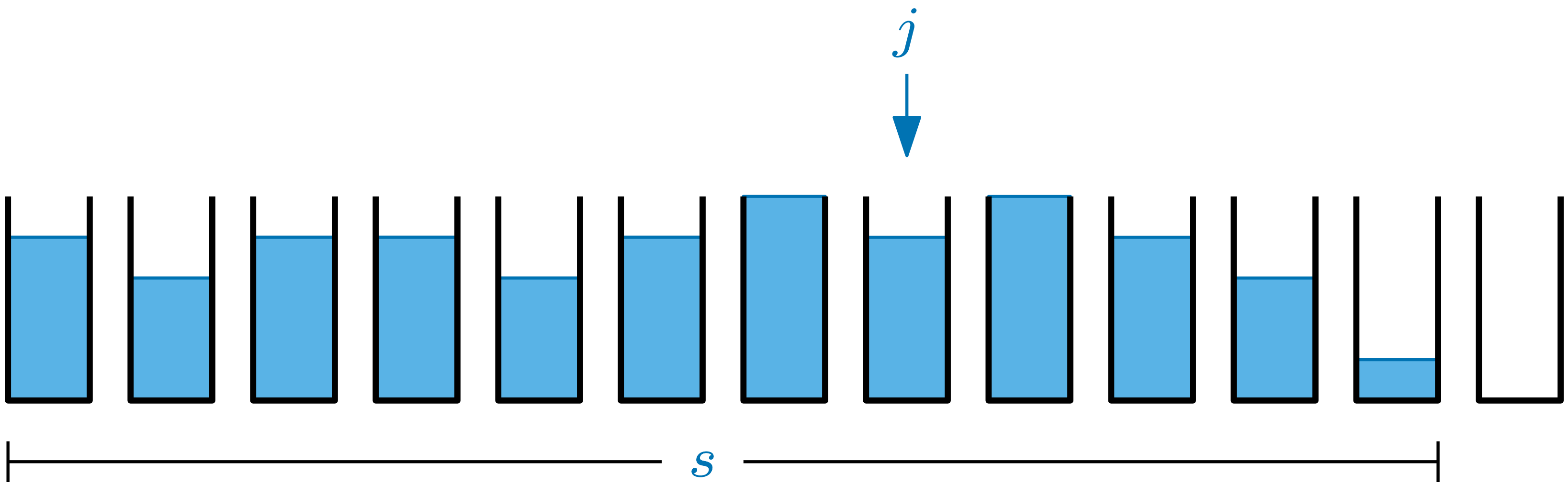

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by plugging in $j = \lceil 2s/3 \rceil$

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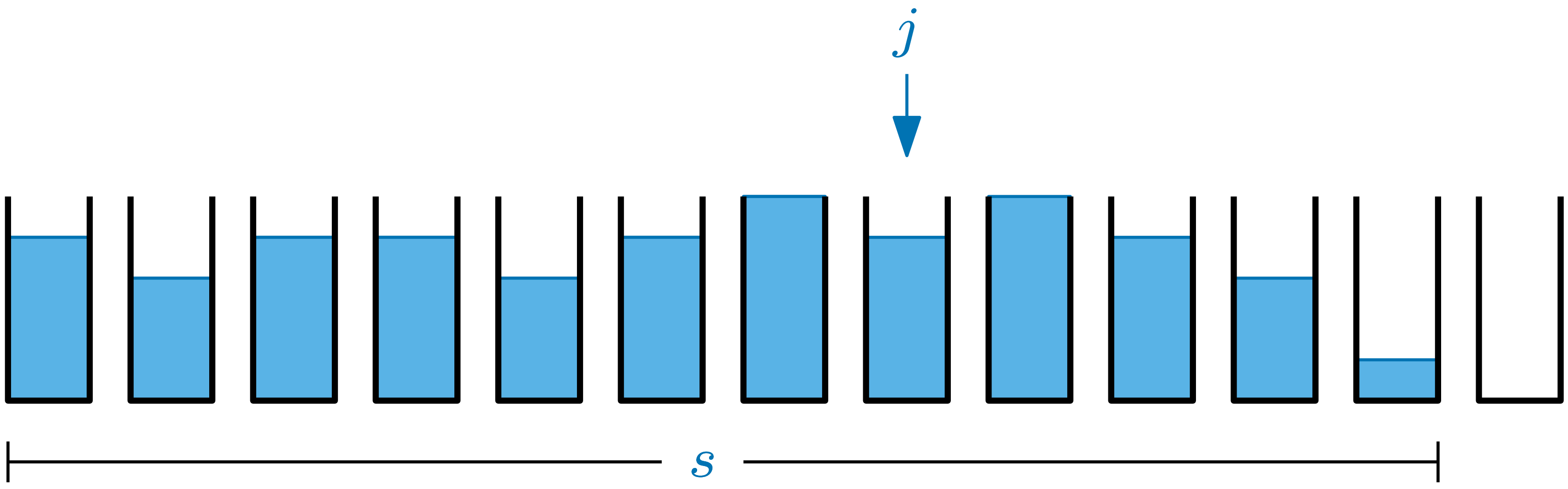

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As $\lceil 2s/3 \rceil - 1 < I$

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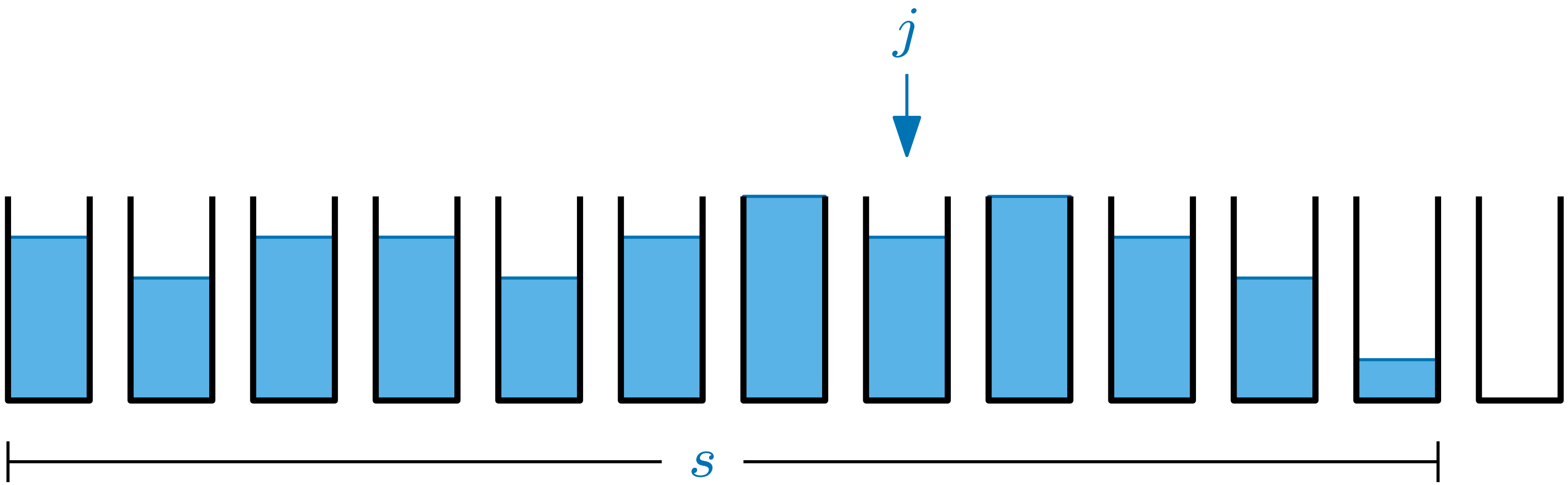

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As $\lceil 2s/3 \rceil - 1 < I$ and $I \leqslant \mathrm{Opt}$

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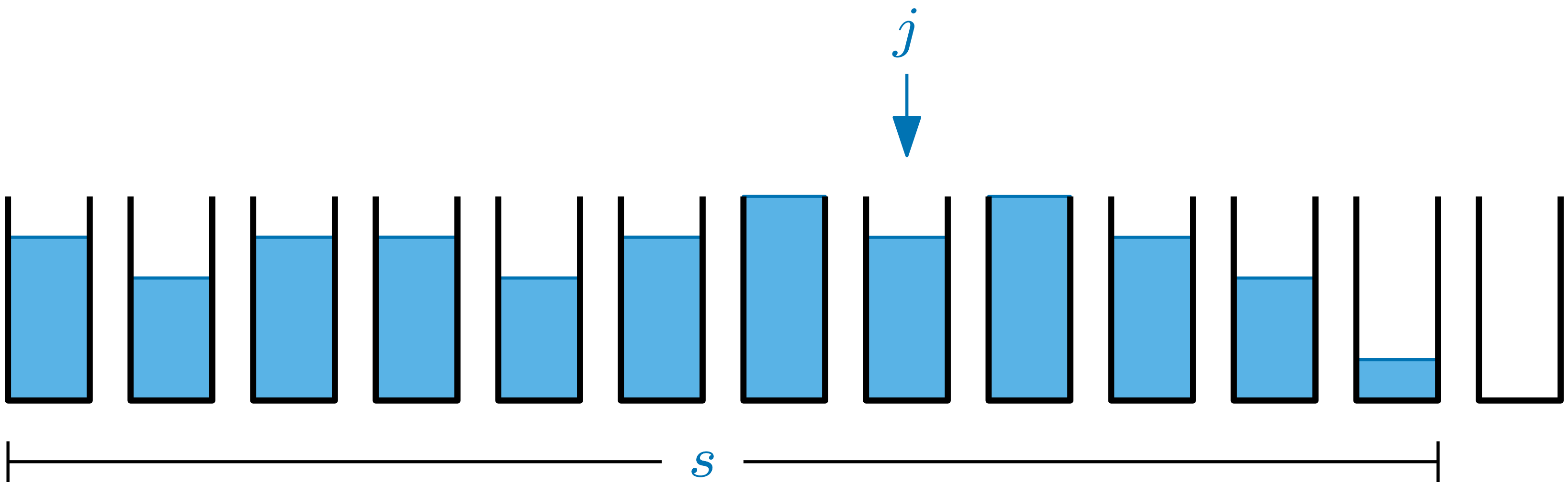

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As $\lceil 2s/3 \rceil - 1 < I$ and $I \leqslant \mathrm{Opt}$

we have that $\lceil 2s/3 \rceil - 1 < \mathrm{Opt}$

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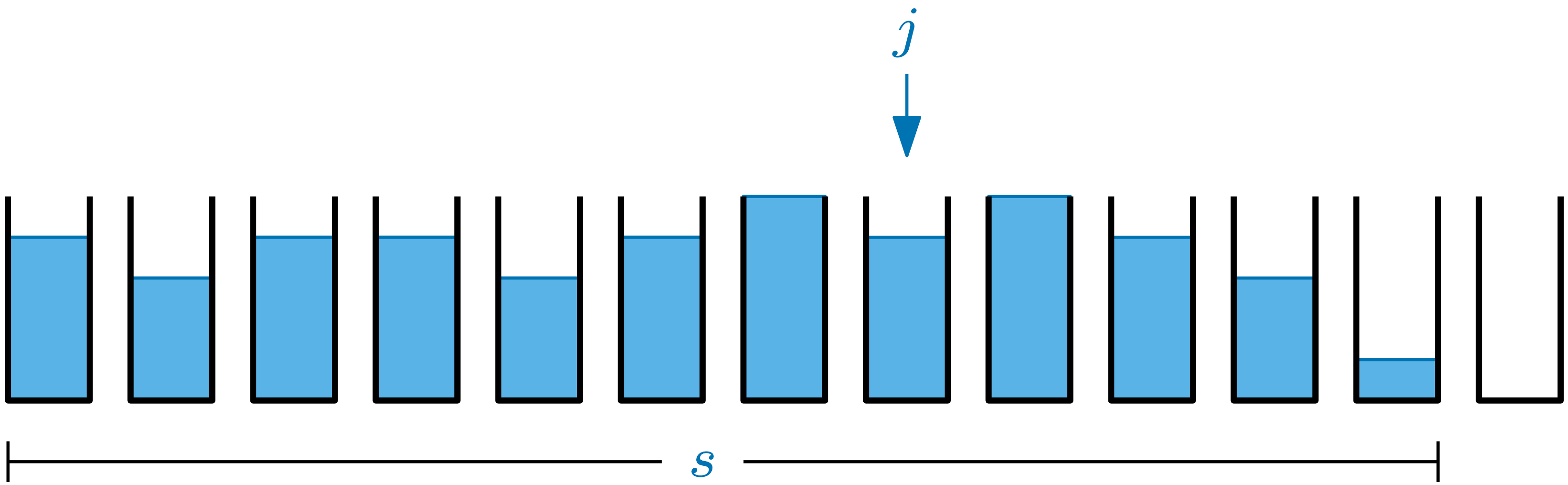

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we have that $\lceil 2s/3 \rceil - 1 < \mathrm{Opt}$

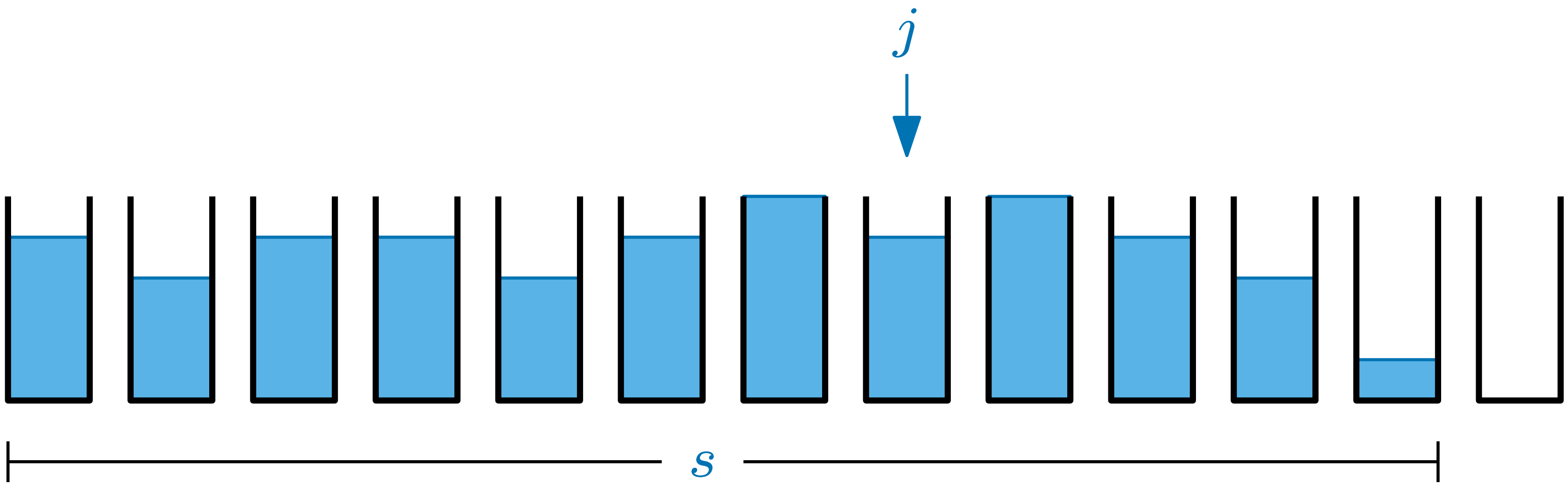
. . . but both sides are integers. . .

so $\lceil 2s/3 \rceil \leqslant \mathrm{Opt}$

finally . . . $2s/3 \leqslant \lceil 2s/3 \rceil \leqslant \mathrm{Opt}$

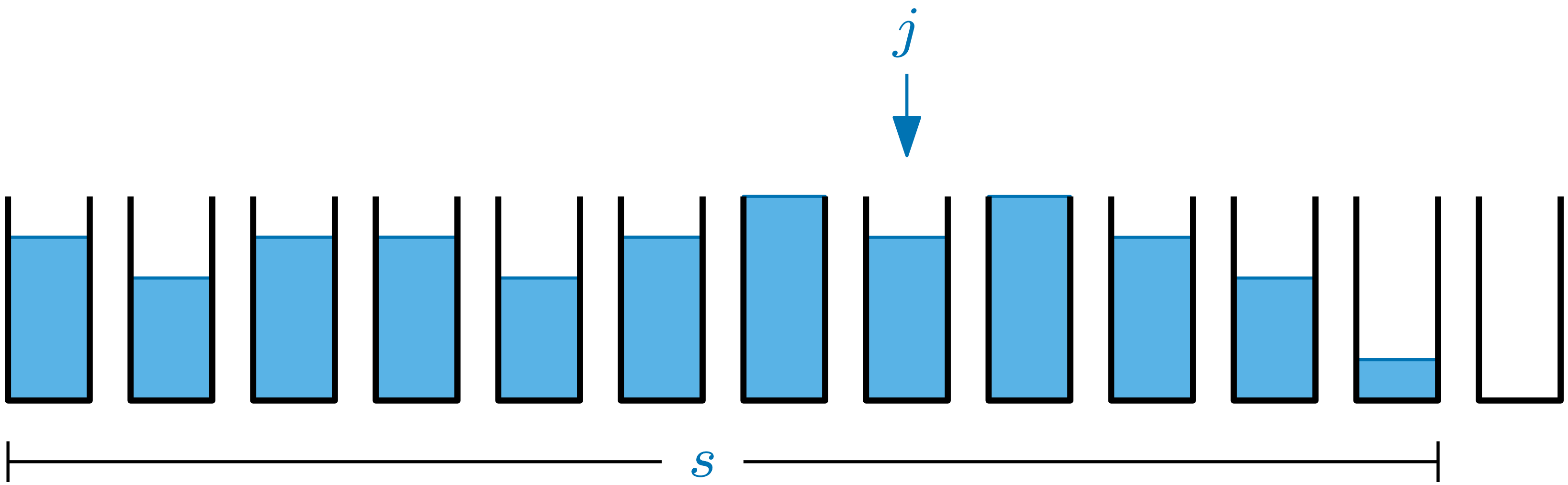
or $s \leqslant (3/2)\mathrm{Opt}$

First fit decreasing (FFD)



Consider bin $j = \left\lceil \frac{2s}{3} \right\rceil$ (s is the number of bins FFD uses on this input)

First fit decreasing (FFD)



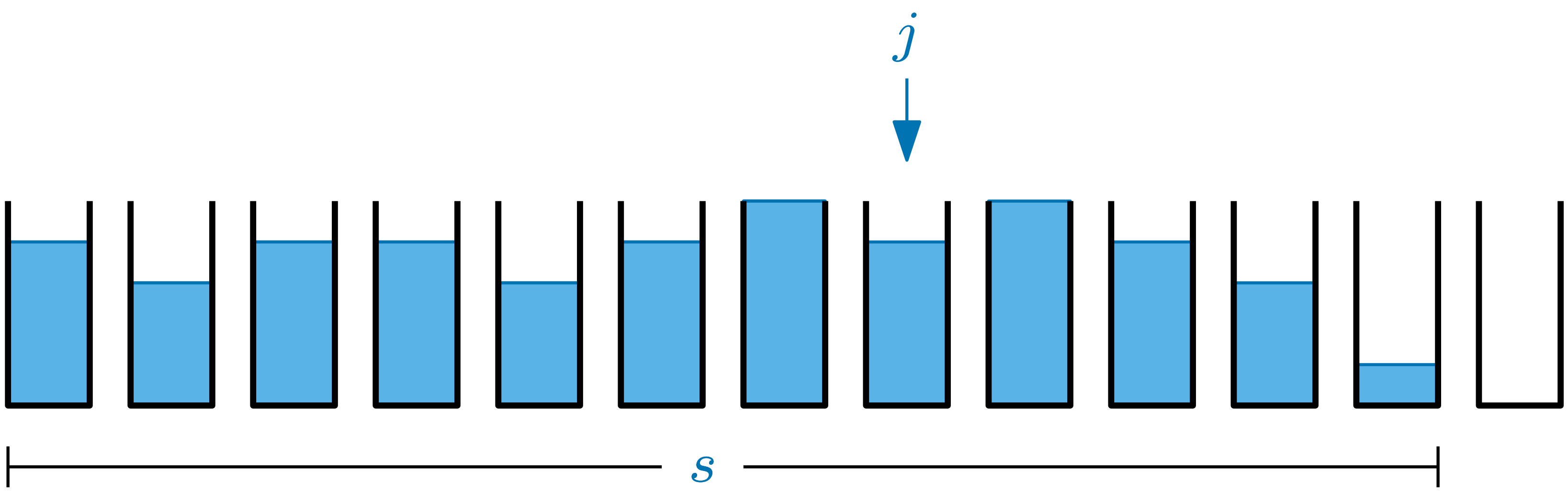
Consider bin $j = \left\lceil \frac{2s}{3} \right\rceil$ (s is the number of bins FFD uses on this input)

Case 1: Bin j contains an item of size $> 1/2$

Case 2: Bin j contains only items of size $\leqslant 1/2$

in both cases... $s \leqslant \dfrac{3\mathrm{Opt}}{2}$

First fit decreasing (FFD)



Consider bin $j = \left\lceil \frac{2s}{3} \right\rceil$ (s is the number of bins FFD uses on this input)

Case 1: Bin j contains an item of size $> 1/2$

Case 2: Bin j contains only items of size $\leqslant 1/2$

in both cases... $s \leqslant \dfrac{3\mathrm{Opt}}{2}$

So FFD is a $3/2$-approximation algorithm for BINPACKING

Approximation Algorithms Summary

An algorithm A is an α-approximation algorithm for problem P if,

- A runs in polynomial time
- A always outputs a solution with value s within an α factor of Opt

Here P is an optimisation problem with optimal solution of value Opt

If P is a *maximisation* problem, $\frac{\mathrm{Opt}}{\alpha} \leqslant s \leqslant \mathrm{Opt}$

If P is a *minimisation* problem (like BINPACKING), $\mathrm{Opt} \leqslant s \leqslant \alpha \cdot \mathrm{Opt}$

We have seen Next Fit which is a 2-approximation algorithm for BINPACKING

which runs in $O(n)$ time

and First Fit Decreasing which is a $3/2$-approximation algorithm for BINPACKING

which runs in $O(n^2)$ time

Bin Packing is NP-hard so solving it exactly in polynomial time would prove that $\mathrm{P} = \mathrm{NP}$