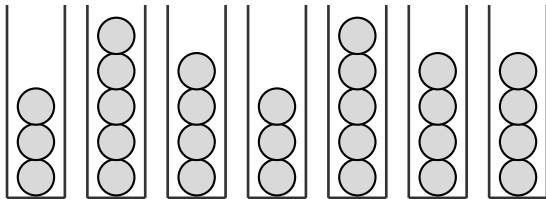


History-Independent Load Balancing



Michael A. Bender

Stony Brook University

William Kuszmaul

CMU

Elaine Shi

CMU

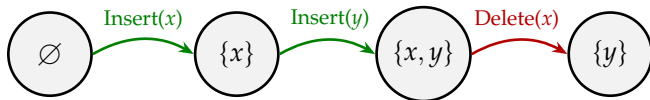
Rose Silver

CMU

HISTORY-INDEPENDENT DATA STRUCTURES

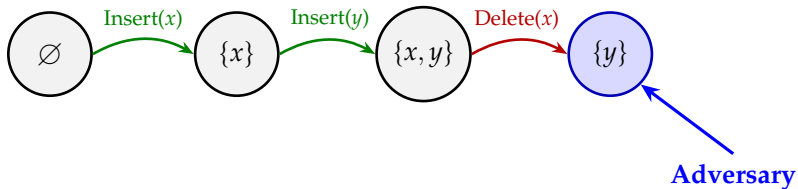
HISTORY-INDEPENDENT DATA STRUCTURES

History 1:

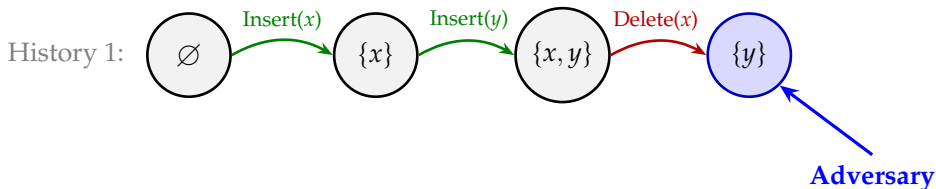


HISTORY-INDEPENDENT DATA STRUCTURES

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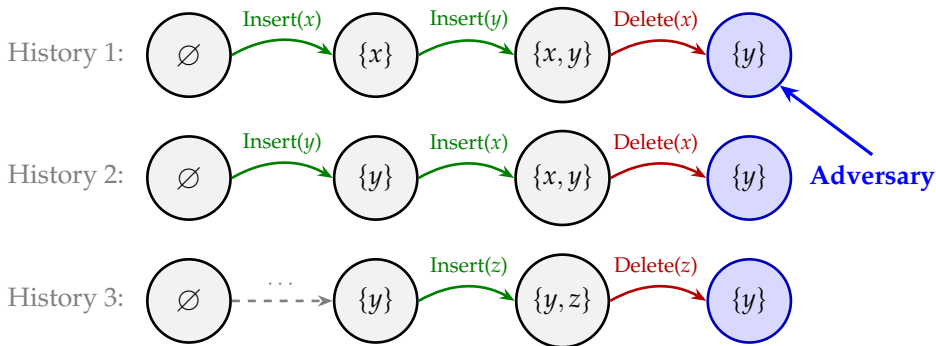
HISTORY-INDEPENDENT DATA STRUCTURES



History Independence (Micciancio '97, Naor & Teague '01)

- ▶ The state reveals only the current elements—**not the history of operations.**

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HISTORY INDEPENDENT DATA STRUCTURES

A History of Applications

Hash tables, trees, memory allocation, PMAs, graph algorithms, cache-oblivious data structures, and more.

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Yet some basic questions remain open.

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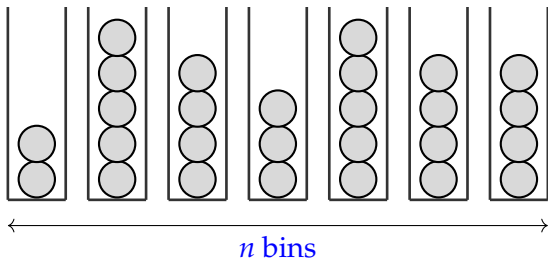
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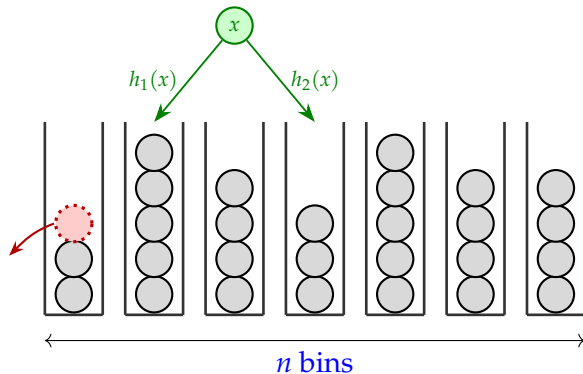
Yet some basic questions remain open.

This work: History-Independent Load Balancing

TWO-CHOICE LOAD BALANCING

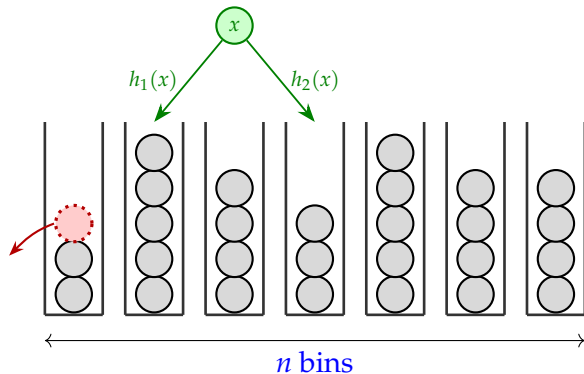


TWO-CHOICE LOAD BALANCING



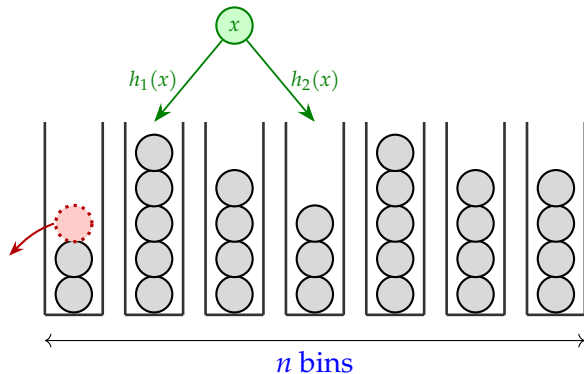
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TWO-CHOICE LOAD BALANCING



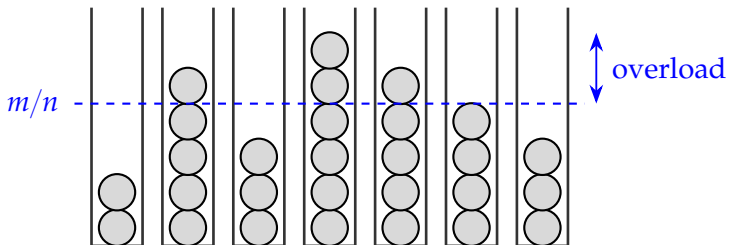
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TWO-CHOICE LOAD BALANCING



- ▶ Balls are **inserted**/**deleted**, with up to m present at a time.
- ▶ Each ball has two random bins where it can go.
- ▶ We must maintain a valid assignment of balls to bins.

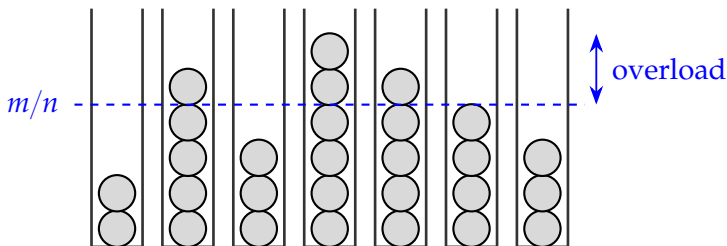
TWO GOALS



Minimize Overload:

- ▶ i.e., the amount by which the fullest bin exceeds m/n .

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Minimize Overload:

- ▶ i.e., the amount by which the fullest bin exceeds m/n .

Minimize Recourse:

- ▶ i.e., the number of balls moved around on any given insertion/deletion.

PUTTING IT ALL TOGETHER

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History-Independent Load Balancing:

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- ▶ For all sets S of balls: If the current set is S , then the assignment is always A_S .

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Question: Does there exist a **history-independent** solution with small **recourse** and small **overload**?

PUTTING IT ALL TOGETHER

History-Independent Load Balancing:

- ▶ For all sets S of balls: If the current set is S , then the assignment is always A_S .

Question: Does there exist a **history-independent** solution with small **recourse** and small **overload**?

Our Main Result: There exists a **history-independent** solution with:

- ▶ High probability **overload** $O(1)$
- ▶ Expected **recourse** $O(\log \log(m/n))$

PAST WORK (NOT HISTORY INDEPENDENT)

Overload	Recourse	Reference	Caveats
$O(\log \log n)$	0	[ABKU '94] [BCSV '00]	insertion-only
$O(1)$	$O(\log(m/n))$	[Dietzfelbinger, Weidling '07]	insertion-only
$\tilde{O}(\sqrt{m/n})$	$O(1)$	[Frieze, Petti '18]	insertion-only
$O(\log(m/n))$	0	[Bansal, Kuszmaul '22]	no reinsertions
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If we want overload $O(1)$, our result is a new state of the art!

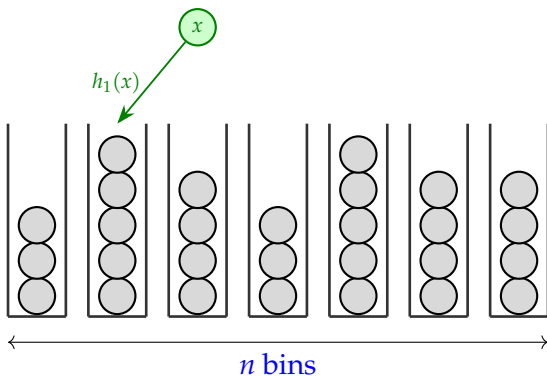
REST OF TALK: A SIMPLE WARMUP

Theorem: There exists a history-independent solution with:

- ▶ High-probability overload $\Theta(1)$ $O(\log \log n)$.
- ▶ Expected recourse $\Theta(\log \log(m/n))$ $O(m/n)$.

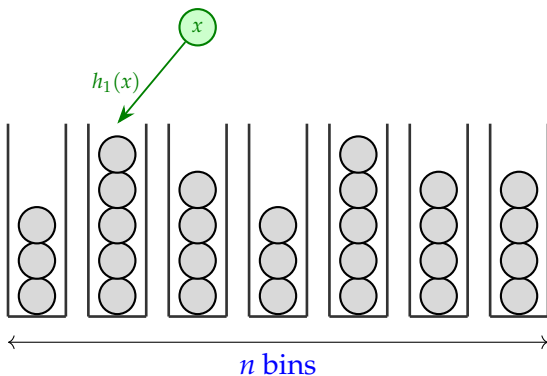
BASLINE 1: THE SINGLE-CHOICE STRATEGY

To insert a ball x , just put it in bin $h_1(x)$:



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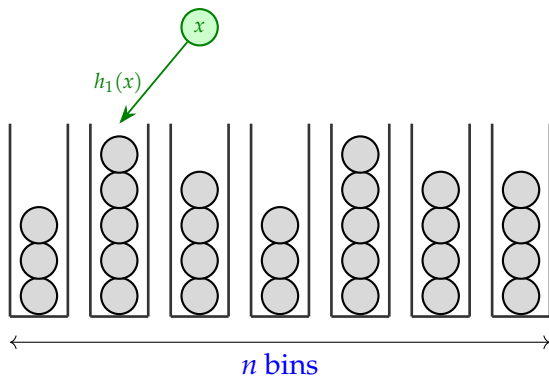
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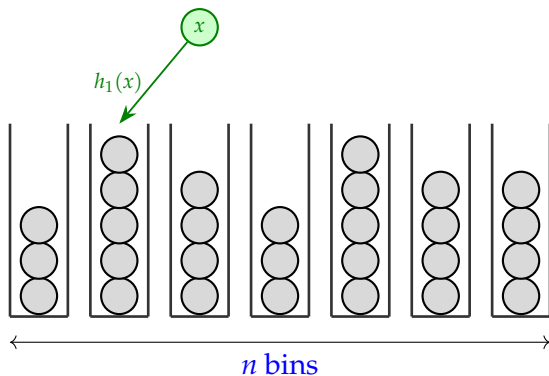
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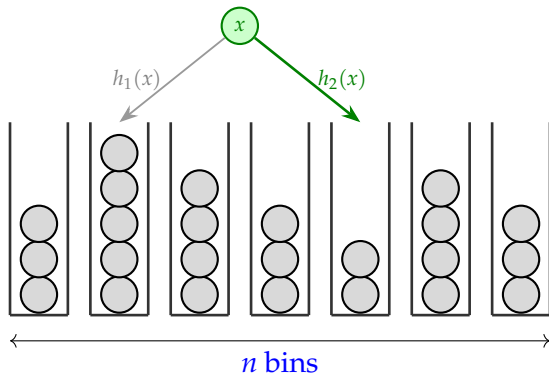
To insert a ball x , just put it in bin $h_1(x)$:



- ▶ This is history-independent ✓
- ▶ The recourse is 0 ✓
- ▶ But... the overload is huge, roughly $\sqrt{m/n}$ ✗

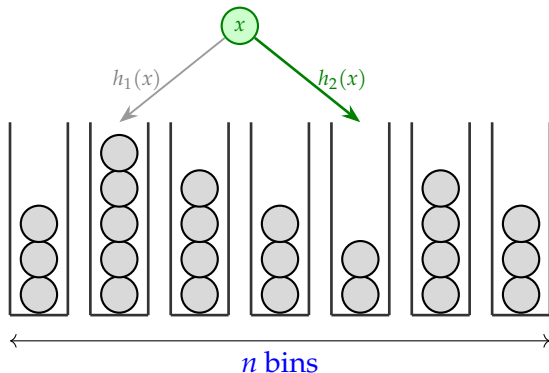
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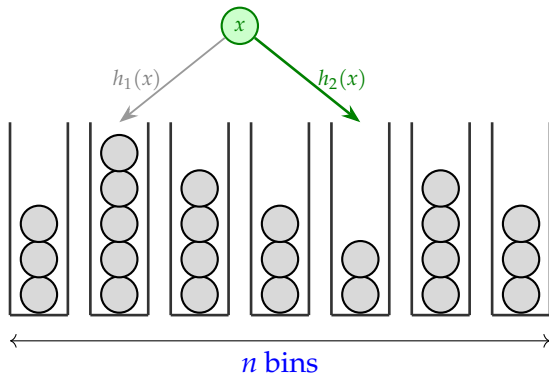
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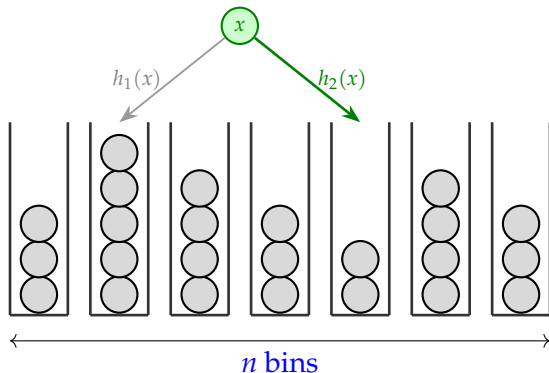
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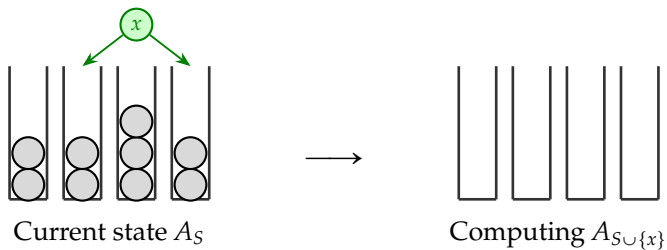
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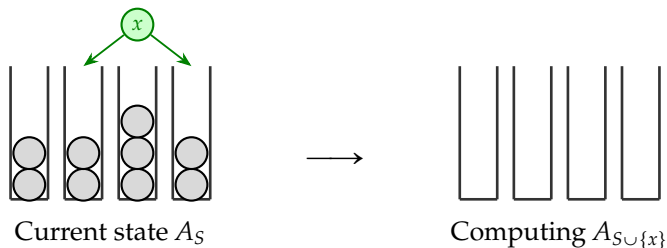
- ▶ This is **not** history-independent ✗
 - ▶ The recourse is 0 ✓
 - ▶ In the insertion-only case, the overload is $O(\log \log n)$ ✓
- [Berenbrink, Czumaj, Steger, and Vöcking '00]

WARMUP: HISTORY-INDEPENDENT GREEDY

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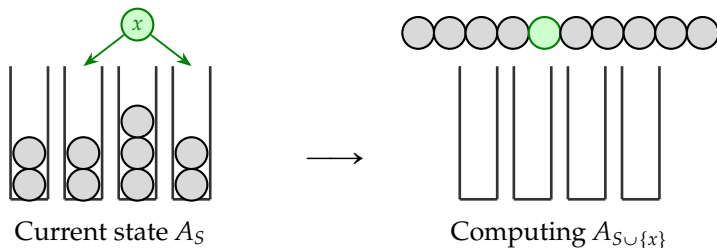
WARMUP: HISTORY-INDEPENDENT GREEDY



To compute $A_{S \cup \{x\}}$:

1. Empty out the bins.
2. Sort the balls in $S \cup \{x\}$ to get x_1, x_2, \dots
3. Insert the balls in sorted order using greedy.

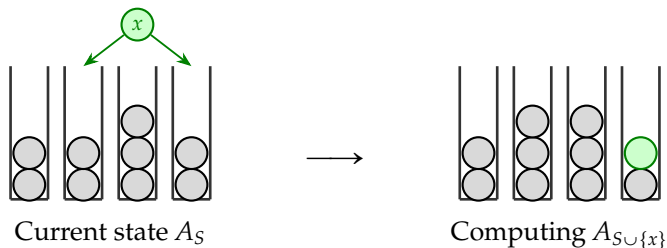
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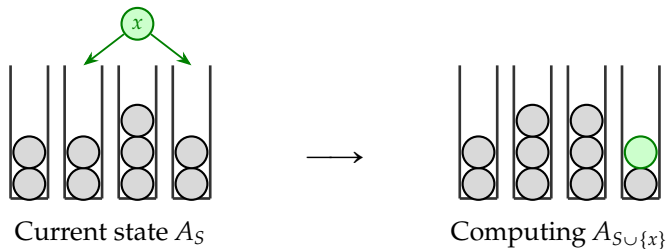
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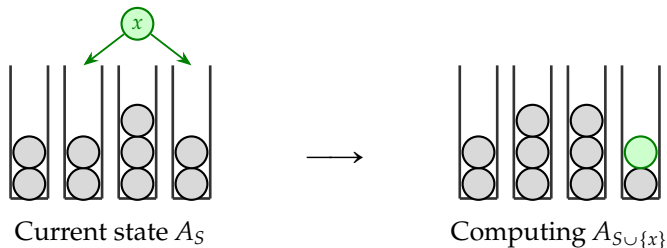
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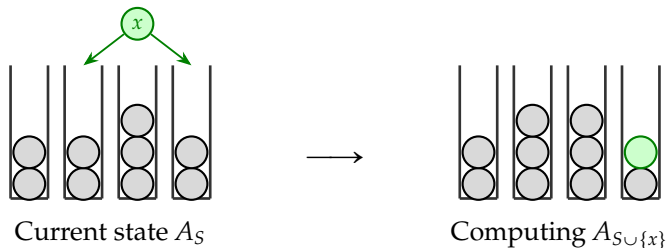


ANALYZING HISTORY-INDEPENDENT GREEDY



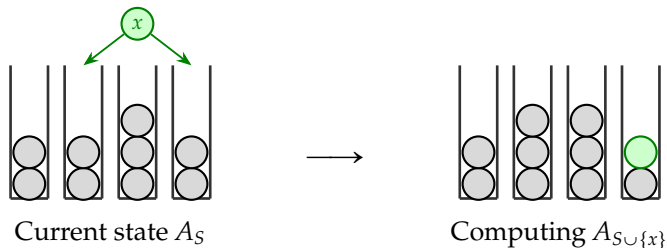
- The algorithm is history independent ✓

ANALYZING HISTORY-INDEPENDENT GREEDY



- ▶ The algorithm is history independent ✓
- ▶ The overload is $O(\log \log n)$ ✓

ANALYZING HISTORY-INDEPENDENT GREEDY



- ▶ The algorithm is history independent ✓
- ▶ The overload is $O(\log \log n)$ ✓
- ▶ What is the recourse?

ANALYZING THE RECOURSE

Recourse = 0



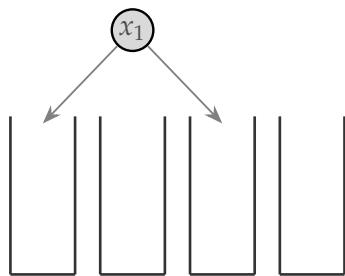
Computing A_S



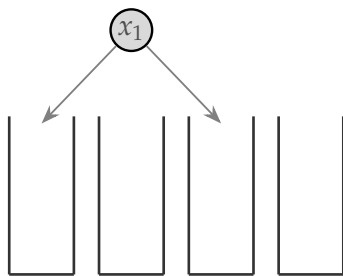
Computing $A_{S \cup \{x\}}$

How many balls change assignments between A_S and $A_{S \cup \{x\}}$?

ANALYZING THE RECOURSE



Computing A_S



Computing $A_{S \cup \{x\}}$

Recourse = 0

ANALYZING THE RECOURSE

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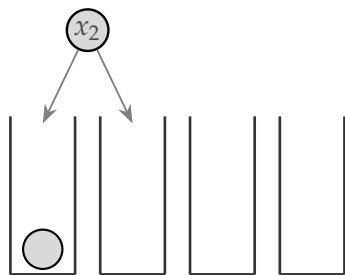


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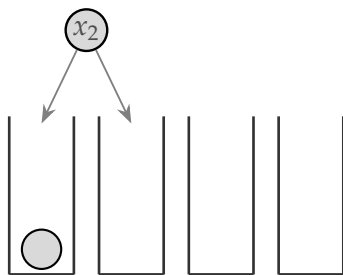


Computing $A_{S \cup \{x\}}$

ANALYZING THE RECOURSE



Computing A_S

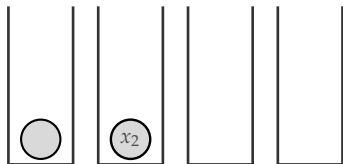


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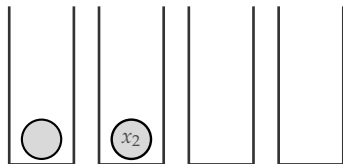
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ANALYZING THE RECOURSE

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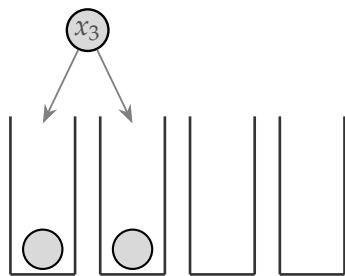


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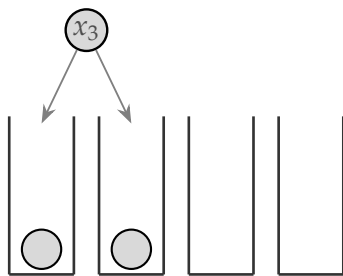


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ANALYZING THE RECOURSE



Computing A_S

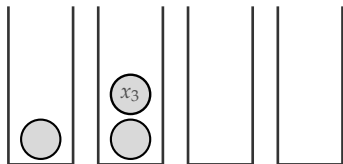


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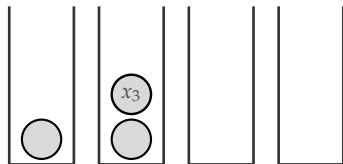
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ANALYZING THE RECOURSE

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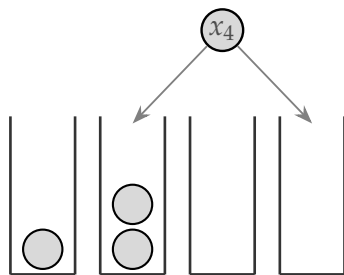


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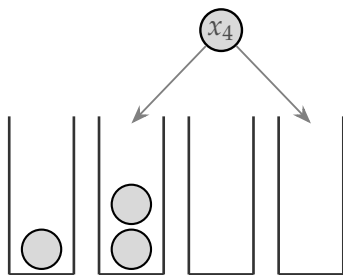


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ANALYZING THE RECOURSE



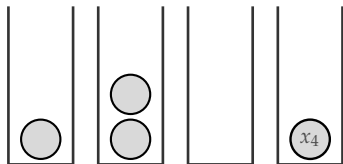
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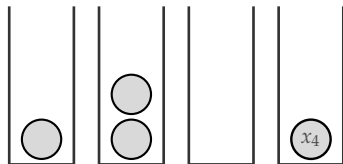
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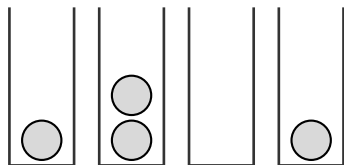


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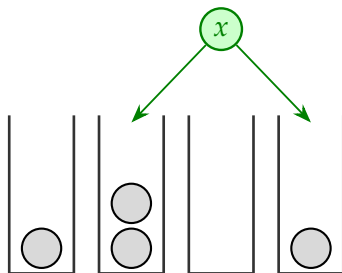


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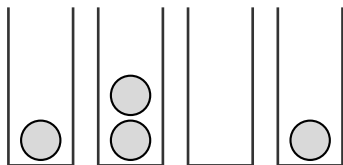


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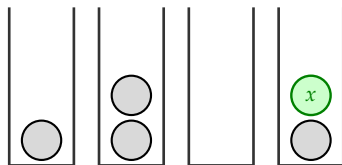
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ANALYZING THE RECOURSE

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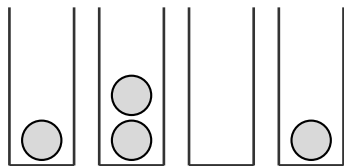
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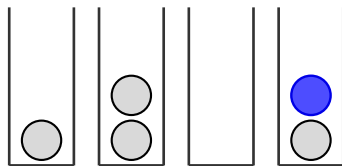
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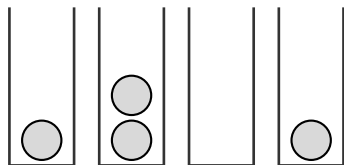


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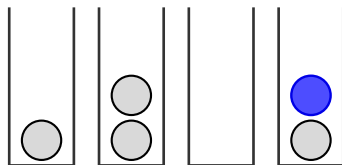
Subsequent balls will experience either:

ANALYZING THE RECOURSE

Recourse = 0



Computing A_S

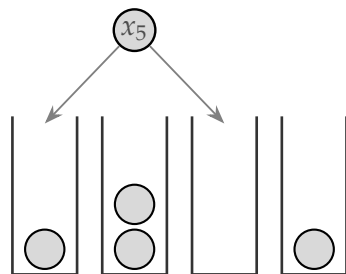


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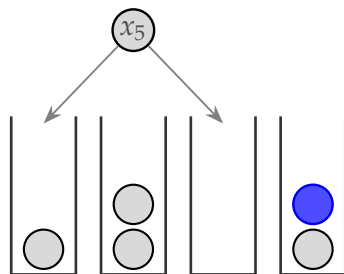
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1. No recourse

ANALYZING THE RECOURSE



Computing A_S



Recourse = 0

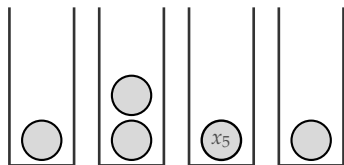
Computing $A_{S \cup \{x\}}$

Future insertions will experience either:

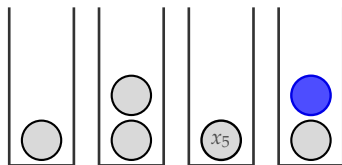
1. No recourse

ANALYZING THE RECOURSE

Recourse = 0



Computing A_S

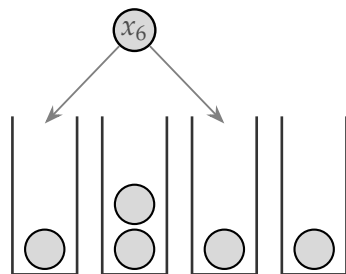


Computing $A_{S \cup \{x\}}$

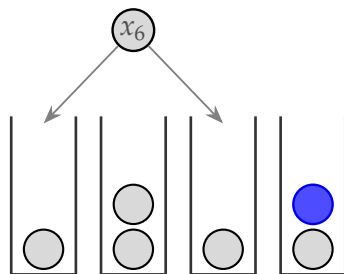
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ANALYZING THE RECOURSE



Computing A_S



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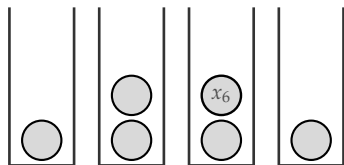
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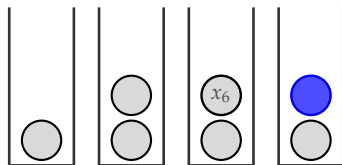
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ANALYZING THE RECOURSE

Recourse = 0



Computing A_S

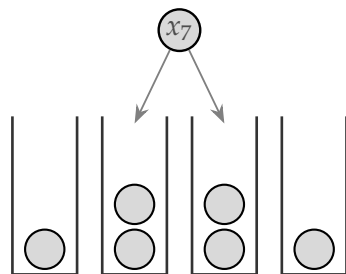


Computing $A_{S \cup \{x\}}$

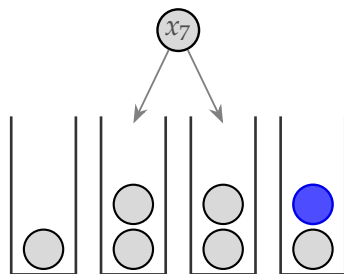
Subsequent balls will experience either:

1. No recourse

ANALYZING THE RECOURSE



Computing A_S



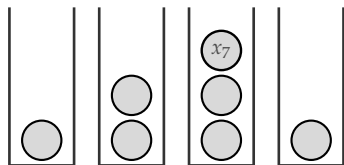
Computing $A_{S \cup \{x\}}$

Subsequent balls will experience either:

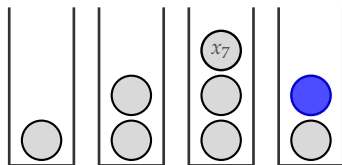
1. No recourse

ANALYZING THE RECOURSE

Recourse = 0



Computing A_S



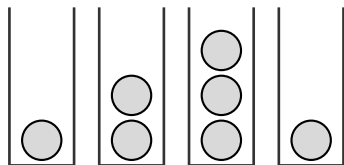
Computing $A_{S \cup \{x\}}$

Subsequent balls will experience either:

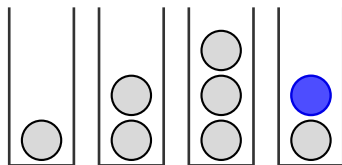
1. No recourse

ANALYZING THE RECOURSE

Recourse = 0



Computing A_S

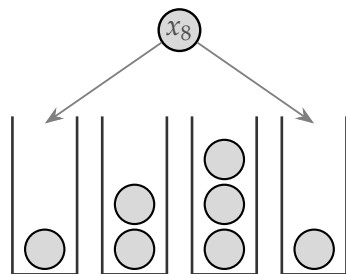


Computing $A_{S \cup \{x\}}$

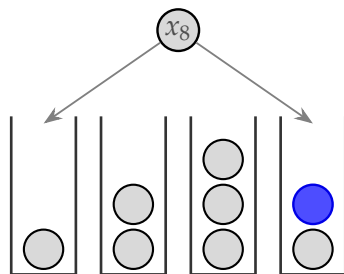
Subsequent balls will experience either:

1. No recourse
2. Recourse

ANALYZING THE RECOURSE



Computing A_S



Recourse = 0

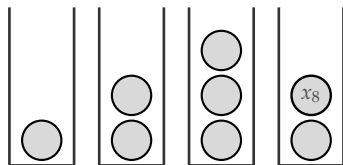
Computing $A_{S \cup \{x\}}$

Subsequent balls will experience either:

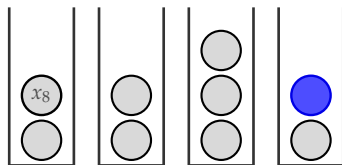
1. No recourse
2. Recourse

ANALYZING THE RECOURSE

Recourse = 1



Computing A_S



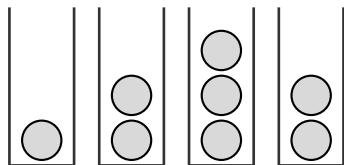
Computing $A_{S \cup \{x\}}$

Subsequent balls will experience either:

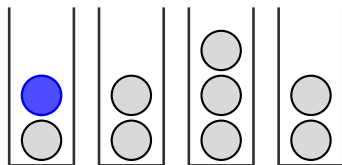
1. No recourse
2. Recourse

ANALYZING THE RECOURSE

Recourse = 1



Computing A_S

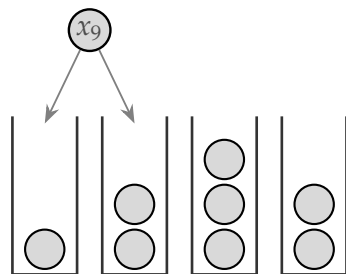


Computing $A_{S \cup \{x\}}$

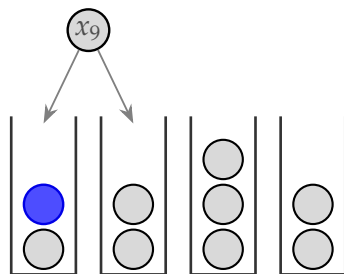
Subsequent balls will experience either:

1. No recourse
2. Recourse

ANALYZING THE RECOURSE



Computing A_S



Recourse = 1

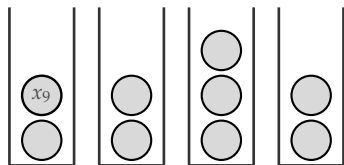
Computing $A_{S \cup \{x\}}$

Subsequent balls will experience either:

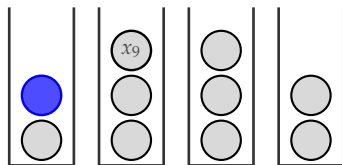
1. No recourse
2. Recourse

ANALYZING THE RECOURSE

Recourse = 2



Computing A_S



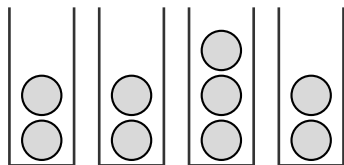
Computing $A_{S \cup \{x\}}$

Subsequent balls will experience either:

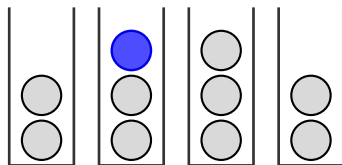
1. No recourse
2. Recourse

ANALYZING THE RECOURSE

Recourse = 2



Computing A_S



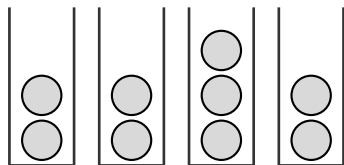
Computing $A_{S \cup \{x\}}$

Subsequent balls will experience either:

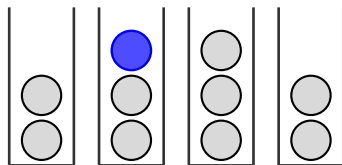
1. No recourse
2. Recourse

ANALYZING THE RECOURSE

Recourse = 2



Computing A_S

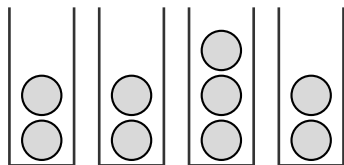


Computing $A_{S \cup \{x\}}$

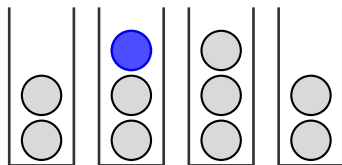
Two key observations:

ANALYZING THE RECOURSE

Recourse = 2



Computing A_S



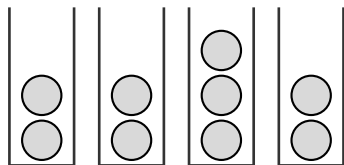
Computing $A_{S \cup \{x\}}$

Two key observations:

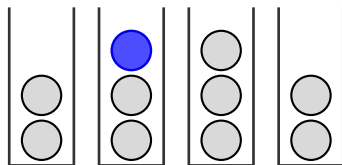
1. There's always one special bin with an extra ball

ANALYZING THE RECOURSE

Recourse = 2



Computing A_S



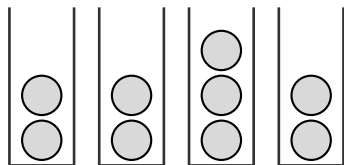
Computing $A_{S \cup \{x\}}$

Two key observations:

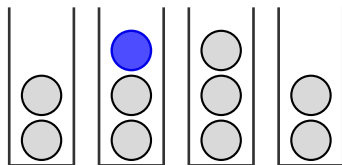
1. There's always one special bin with an extra ball
2. If a ball incurs recourse, one of its choices is the special bin

ANALYZING THE RECOURSE

Recourse = 2



Computing A_S

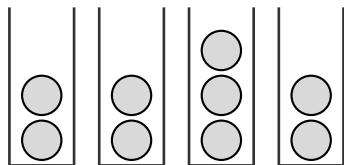


Computing $A_{S \cup \{x\}}$

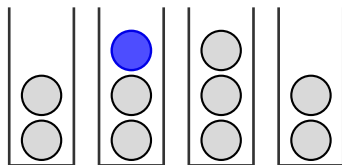
$$\Pr[\text{ball } x_i \text{ incurs recourse}] = O(1/n)$$

ANALYZING THE RECOURSE

Recourse = 2



Computing A_S



Computing $A_{S \cup \{x\}}$

$$\Pr[\text{ball } x_i \text{ incurs recourse}] = O(1/n)$$

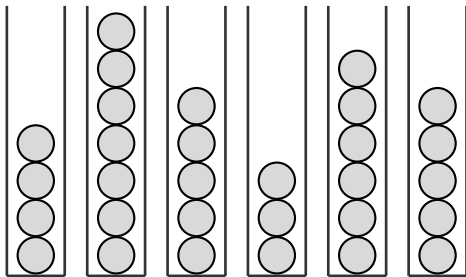
$$\implies \mathbb{E}[\text{total recourse}] = \sum_i \Pr[\text{ball } x_i \text{ incurs recourse}] = O(m/n)$$

A SIMPLE WARMUP

Theorem: There exists a history-independent solution with:

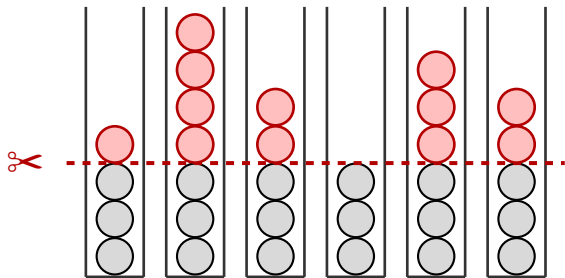
- ▶ High-probability overload $\Theta(1)$ $O(\log \log n)$.
- ▶ Expected recourse $\Theta(\log \log(m/n))$ $O(m/n)$.

SLICE AND SPREAD



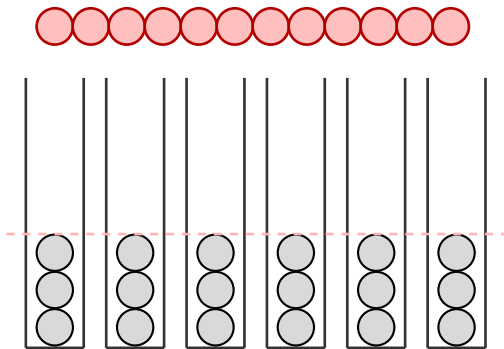
1. **Slice** off the jagged surface

SLICE AND SPREAD



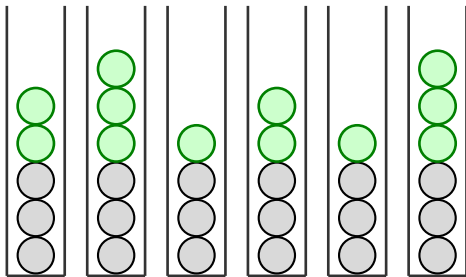
1. **Slice** off the jagged surface

SLICE AND SPREAD



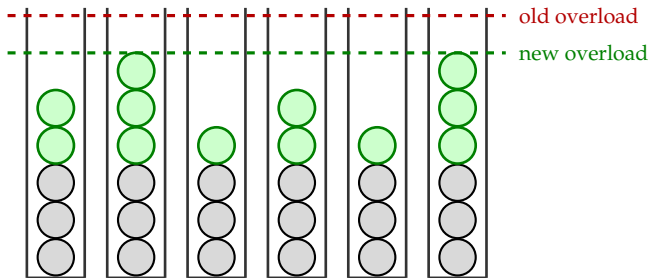
1. **Slice** off the jagged surface
2. **Spread** balls to their second-choice bins

SLICE AND SPREAD



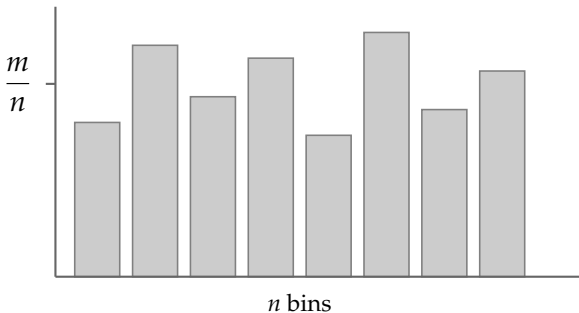
1. **Slice** off the jagged surface
2. **Spread** balls to their second-choice bins

SLICE AND SPREAD

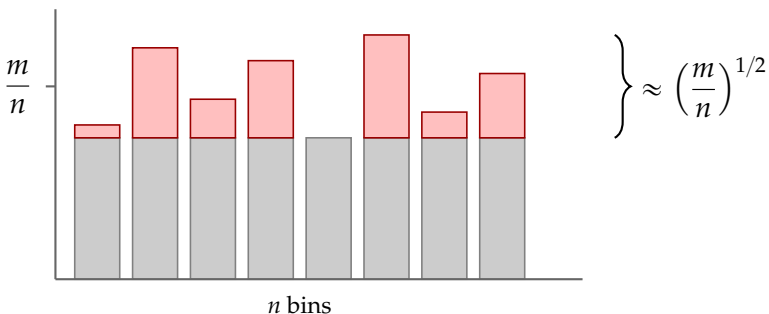


1. **Slice** off the jagged surface
2. **Spread** balls to their second-choice bins

SLICE AND SPREAD REDUCES OVERLOAD



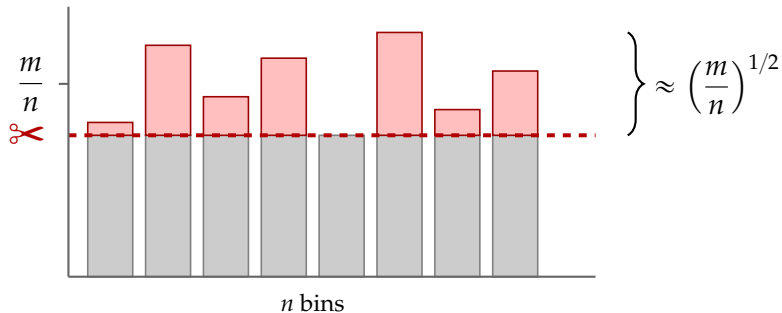
SLICE AND SPREAD REDUCES OVERLOAD



Key Fact

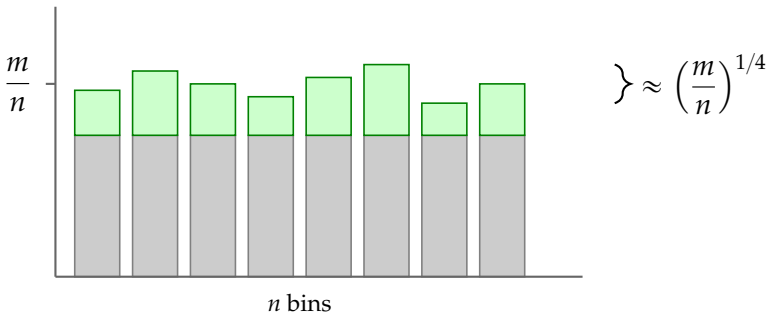
After throwing $m \gg n$ balls uniformly at random into n bins, the bin loads are within roughly $\approx \sqrt{m/n}$ with high probability in n .

SLICE AND SPREAD REDUCES OVERLOAD



- Balls above dotted line $\approx (mn)^{1/2}$

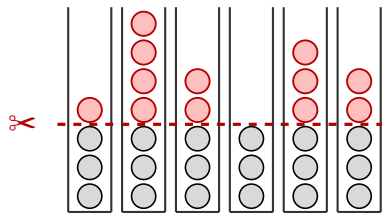
SLICE AND SPREAD REDUCES OVERLOAD



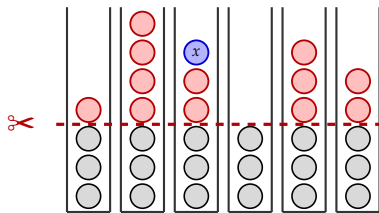
- ▶ Balls above dotted line $\approx (mn)^{1/2}$
- ▶ By Key Fact, bin loads within $\approx (m/n)^{1/4}$

WHAT'S THE RECOURSE?

WHAT'S THE RECOURSE?

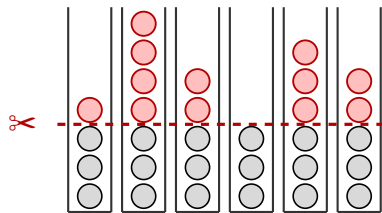


Computing A_S

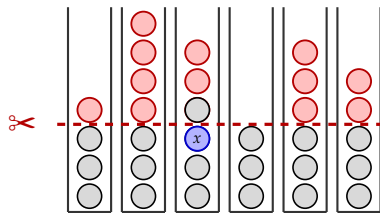


Computing $A_{S \cup \{x\}}$

WHAT'S THE RECOURSE?

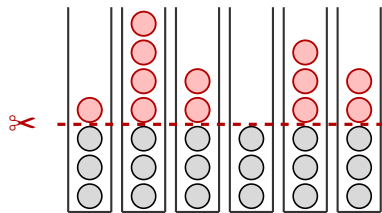


Computing A_S

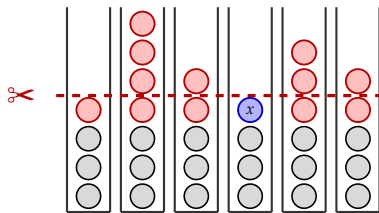


Computing $A_{S \cup \{x\}}$

WHAT'S THE RECOURSE?

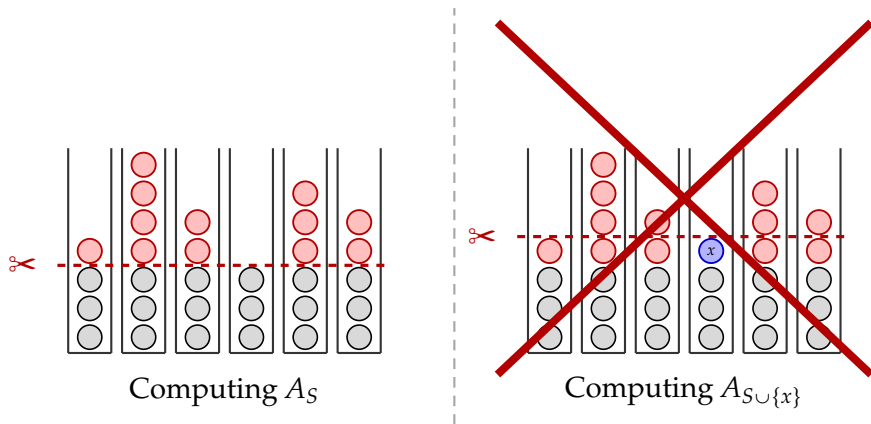


Computing A_S



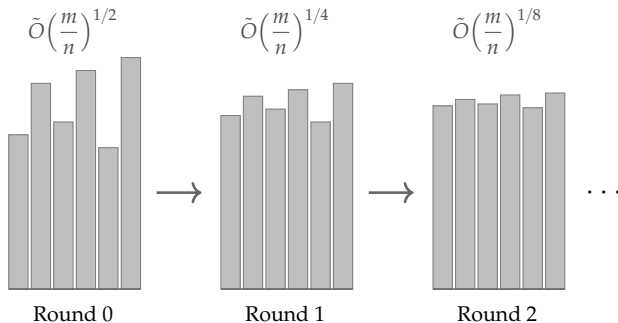
Computing $A_{S \cup \{x\}}$

WHAT'S THE RECOURSE?

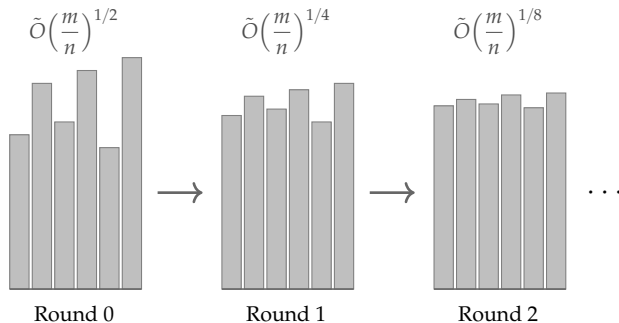


To keep recourse low, fix the slicing line (as a function of the maximum number of balls in the system).

REPEATEDLY SLICING AND SPREADING



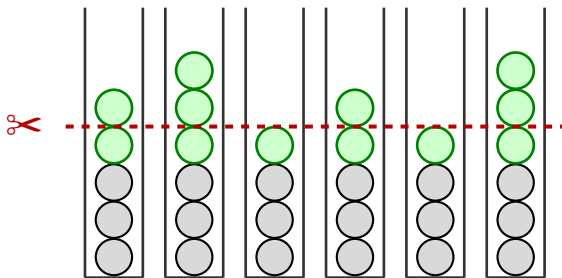
REPEATEDLY SLICING AND SPREADING



Proposition

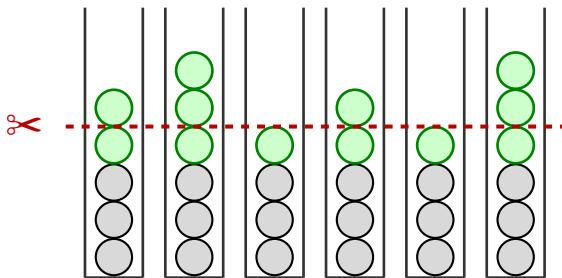
After $O(\log \log(m/n))$ rounds of slice-and-spread, the cumulative overload is $O(n)$ with high probability in n . The expected recourse is $O(\log \log(m/n))$.

ALGORITHMIC QUESTION



Question: Which balls do we slice in each round?

ALGORITHMIC QUESTION

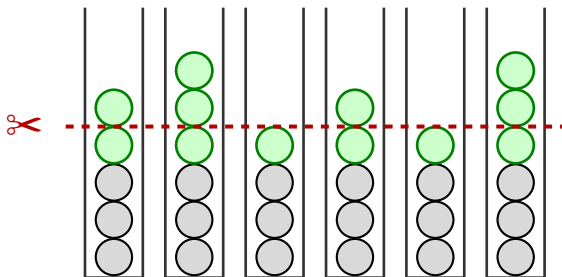


Question: Which balls do we slice in each round?

► **Option 1:** Scrape off the top

✗ Reuses stale randomness

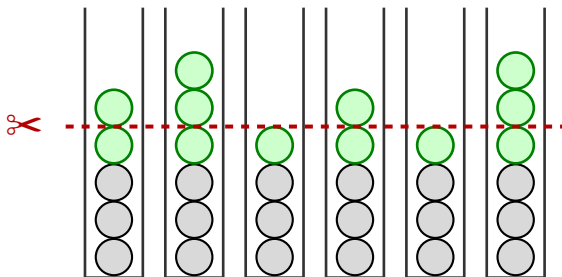
ALGORITHMIC QUESTION



Question: Which balls do we slice in each round?

- ▶ **Option 1:** Scrape off the top ✗ Reuses stale randomness
- ▶ **Option 2:** Priority queue per bin ✗ Exploding recourse

ALGORITHMIC QUESTION



Question: Which balls do we slice in each round?

- ▶ **Option 1:** Scrape off the top ✗ Reuses stale randomness
- ▶ **Option 2:** Priority queue per bin ✗ Exploding recourse
- ▶ **Our approach:** Option 2 + Assign every ball a **round number**

CHALLENGE 1: SLICING FAILURES

Challenge: There may not be enough fresh randomness in each bin. Not enough balls assigned to that round in that bin.

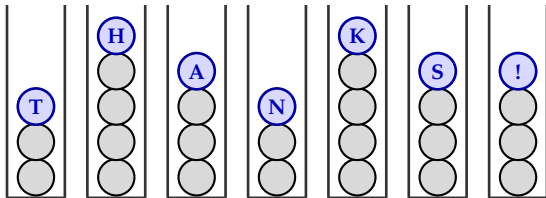
Result: We won't be able to slice off enough balls, and so the jaggedness will remain.

CHALLENGE 2: SPREADING FAILURES

Challenge: Spreading step got unlucky and didn't spread very evenly. There's more jaggedness than we want

Result: Either we have to slice more balls than we want and may not get the overload down, or we have to slice less balls than we want and may not get the jaggedness down.

History-Independent Load Balancing



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Stony Brook University

William Kuszmaul

CMU

Elaine Shi

CMU

Rose Silver

CMU