Binomial Heaps

Outline for this Week

- ***Binomial Heaps (Today)***
  - A simple, flexible, and versatile priority queue.
- ***Lazy Binomial Heaps (Today)***
  - A powerful building block for designing advanced data structures.
- ***Fibonacci Heaps (Thursday)***
  - A heavyweight and theoretically excellent priority queue.

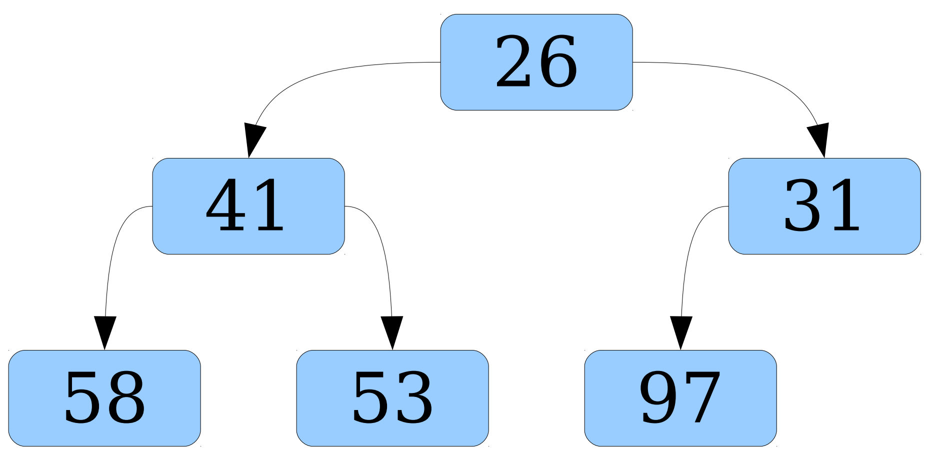
Review: Priority Queues

Priority Queues

- A ***priority queue*** is a data structure that stores a set of elements annotated with totally-ordered *keys* and allows efficient extraction of the element with the least key.
- More concretely, supports these operations:
  - *pq*.***enqueue***(*v*, *k*), which enqueues element *v* with key *k*;
  - *pq*.***find-min***(), which returns the element with the least key; and
  - *pq*.***extract-min***(), which removes and returns the element with the least key,

Binary Heaps

- Priority queues are frequently implemented as ***binary heaps***.
- ***enqueue*** and ***extract-min*** run in time O(log *n*); ***find-min*** runs in time O(1).
- We're not going to cover binary heaps this quarter; I assume you've seen them before.



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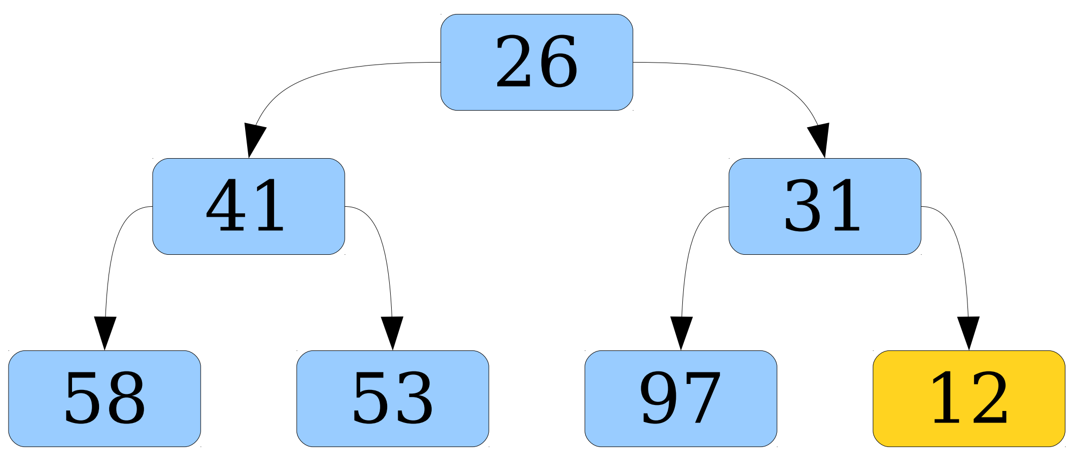

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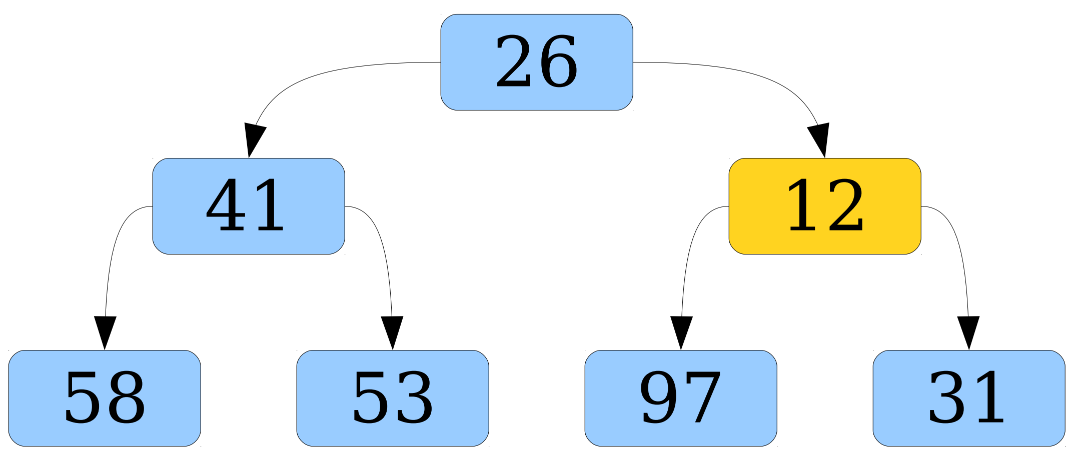

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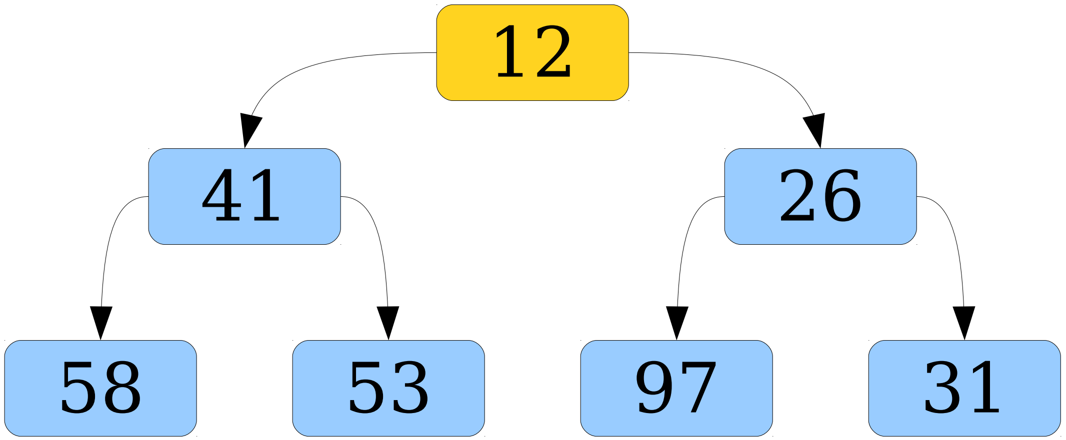

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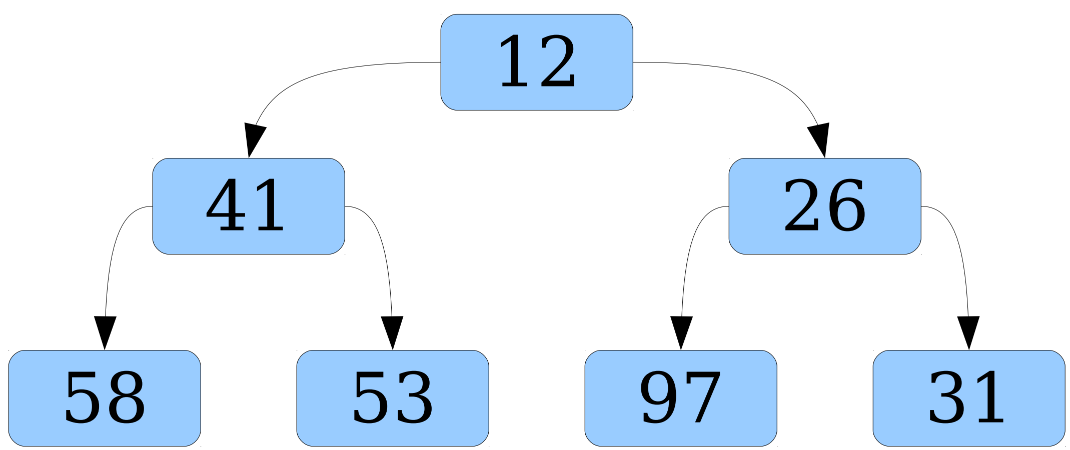

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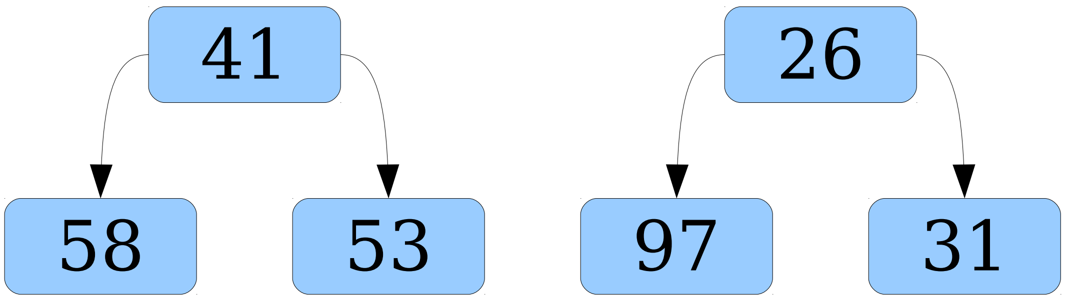

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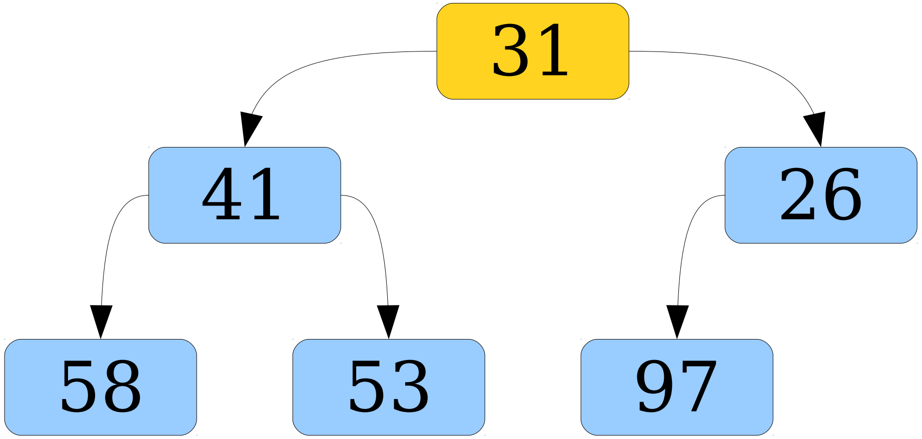

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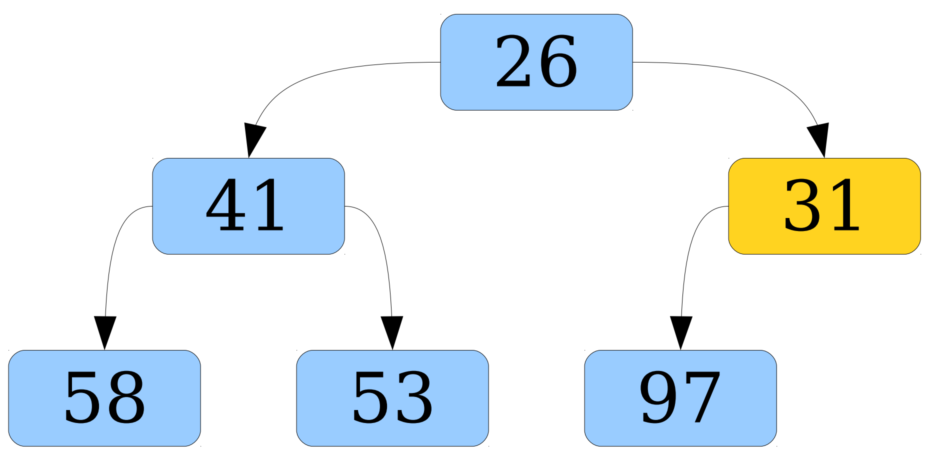

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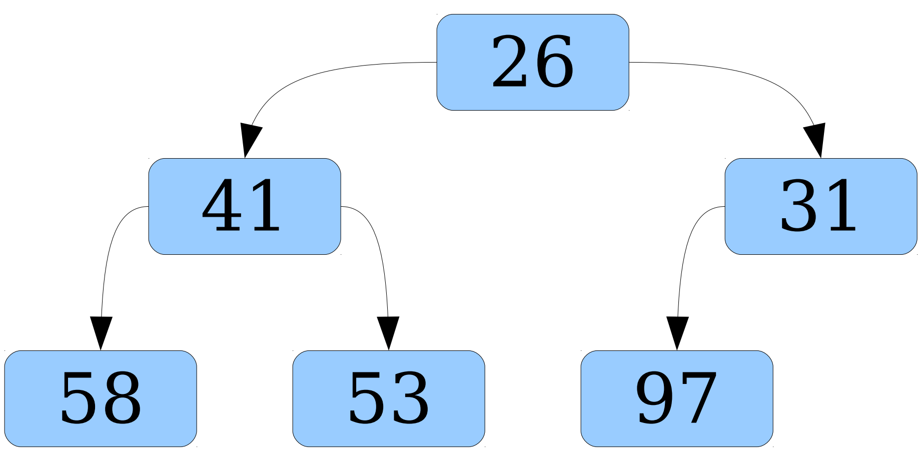
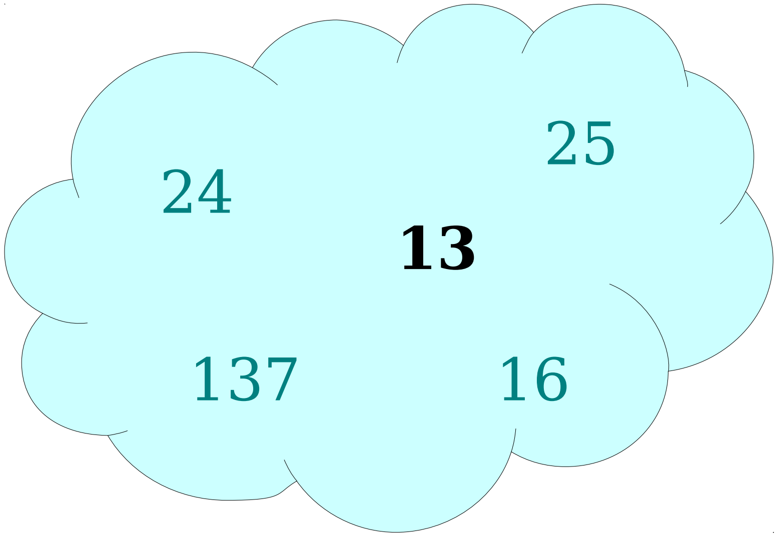


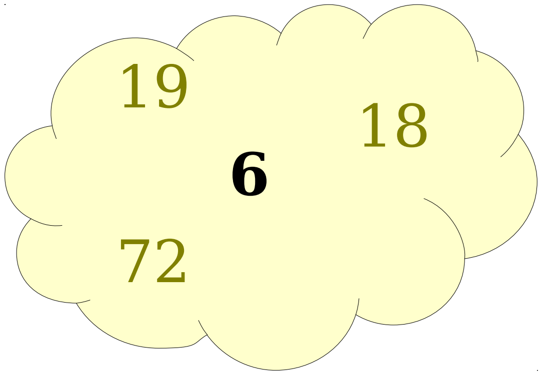
Priority Queues in Practice

- Many graph algorithms directly rely priority queues supporting extra operations:
  - ***meld***(pq_1, pq_2): Destroy pq_1 and pq_2 and combine their elements into a single priority queue.
  - *pq*.***decrease-key***(v, k'): Given a pointer to element v already in the queue, lower its key to have new value k'.
  - *pq*.***add-to-all***(Δk): Add Δk to the keys of each element in the priority queue (typically used with ***meld***).
- In lecture, we'll cover binomial heaps to efficiently support ***meld*** and Fibonacci heaps to efficiently support ***meld*** and ***decrease-key***.
- You'll design a priority queue supporting efficient ***meld*** and ***add-to-all*** on the problem set.

Meldable Priority Queues

- A priority queue supporting the ***meld*** operation is called a ***meldable priority queue***.
- ***meld***(pq_1, pq_2) destructively modifies pq_1 and pq_2 and produces a new priority queue containing all elements of pq_1 and pq_2.





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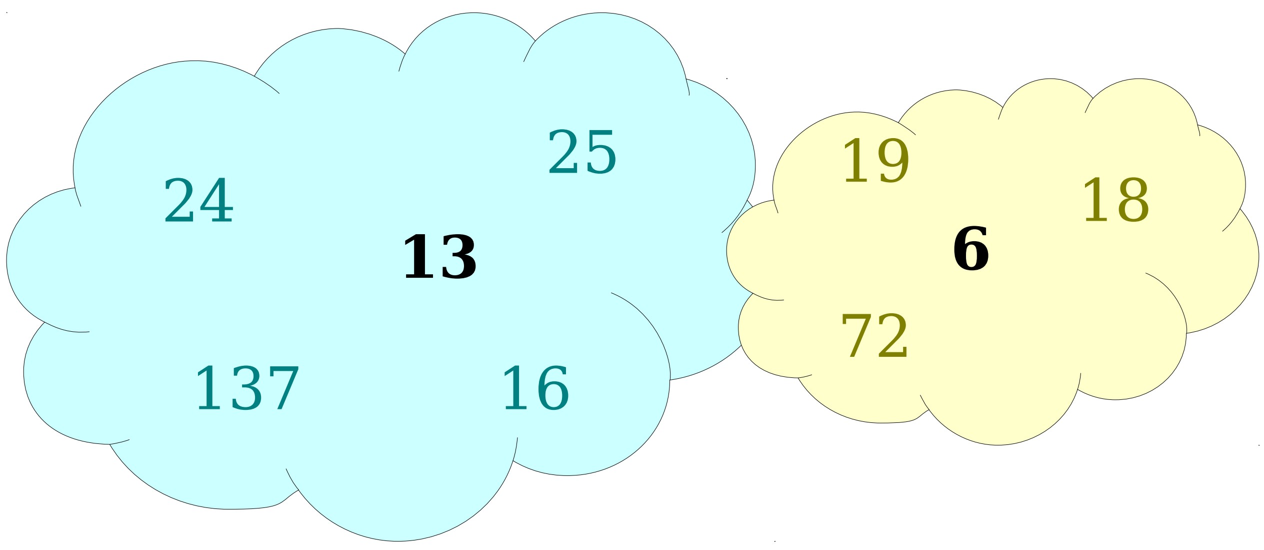

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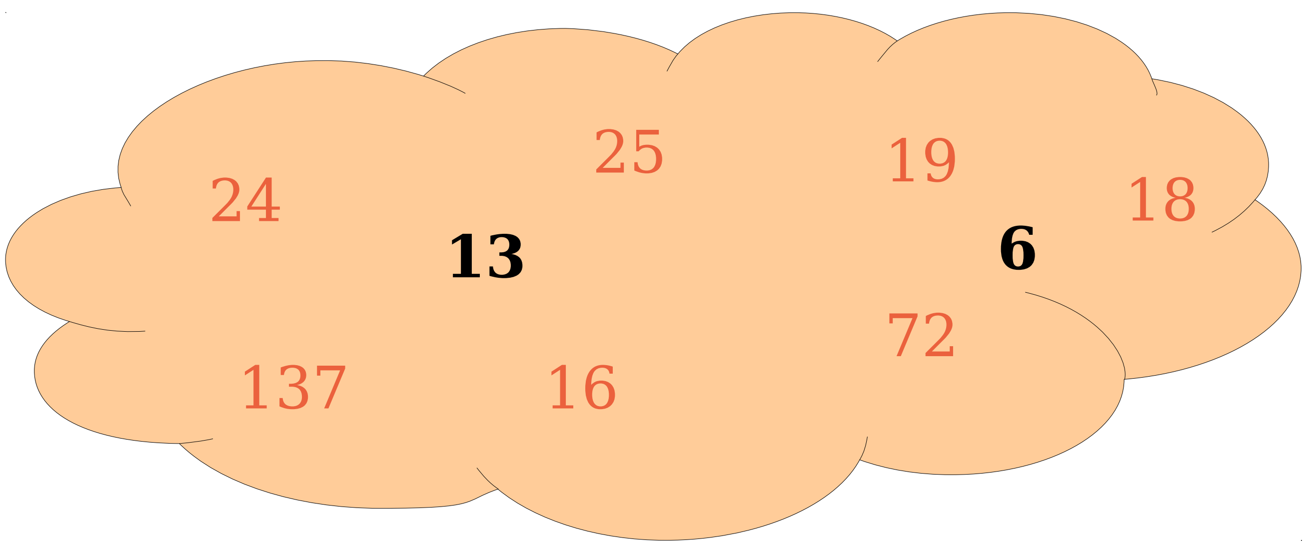

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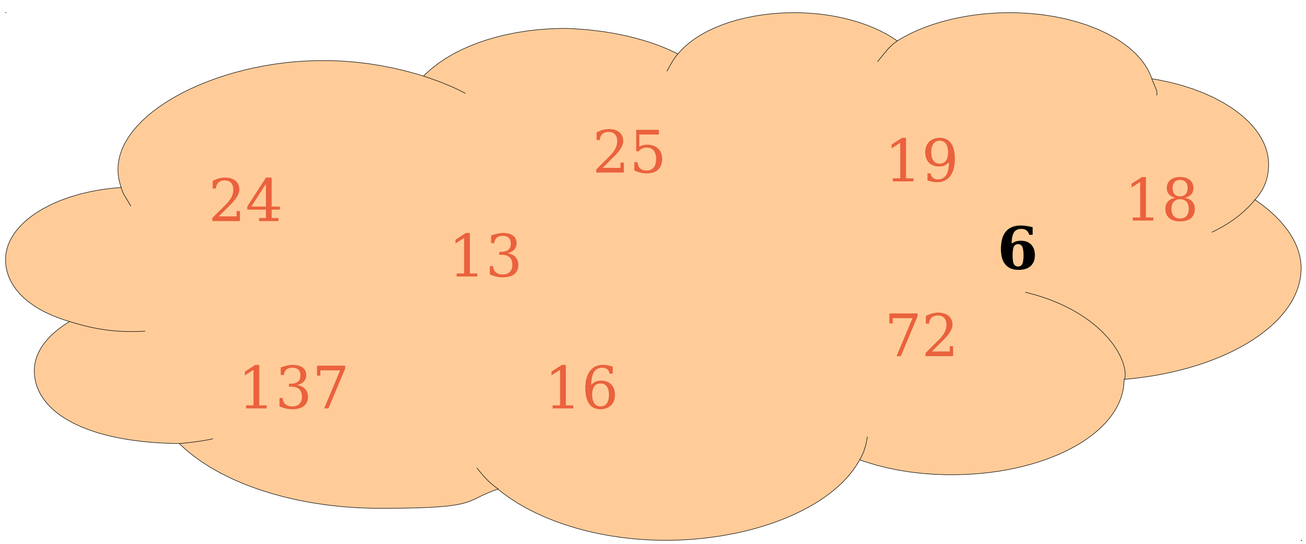
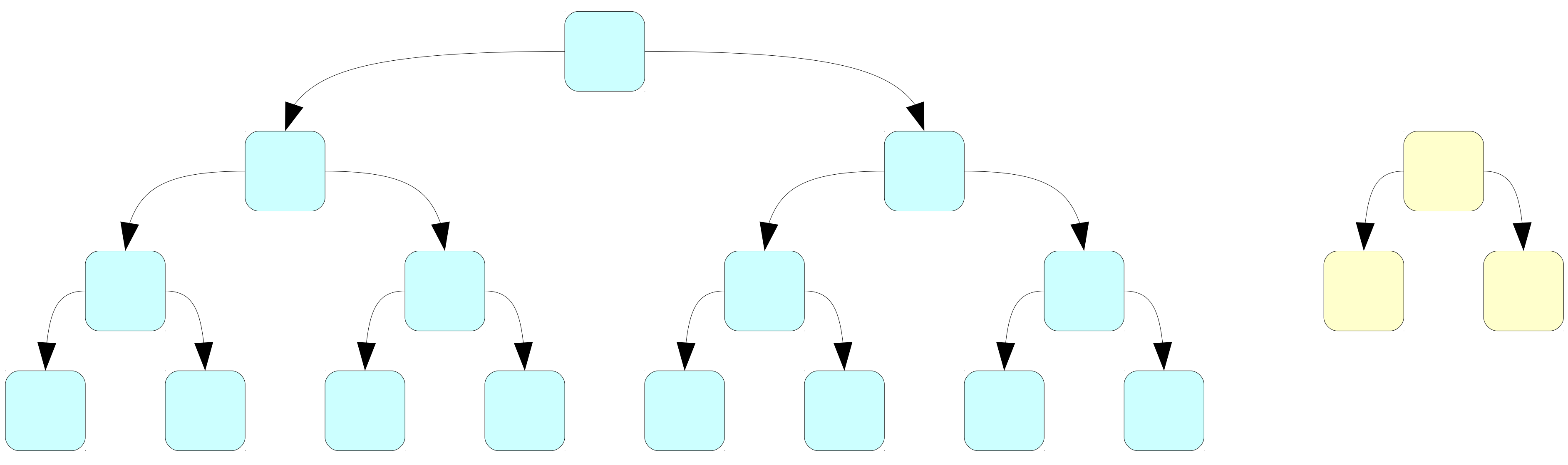


Efficiently Meldable Queues

- Standard binary heaps do not efficiently support ***meld***.
- ***Intuition***: Binary heaps are complete binary trees, and two complete binary trees cannot easily be linked to one another.



Binomial Heaps

- The ***binomial heap*** is an priority queue data structure that supports efficient melding.
- We'll study binomial heaps for several reasons:
  - Implementation and intuition is totally different than binary heaps.
  - Used as a building block in other data structures (Fibonacci heaps, soft heaps, etc.)
  - Has a beautiful intuition; similar ideas can be used to produce other data structures.

The Intuition: ***Binary Arithmetic***

Adding Binary Numbers

- Given the binary representations of two numbers n and m, we can add those numbers in time $\Theta(\max\{\log m, \log n\})$.

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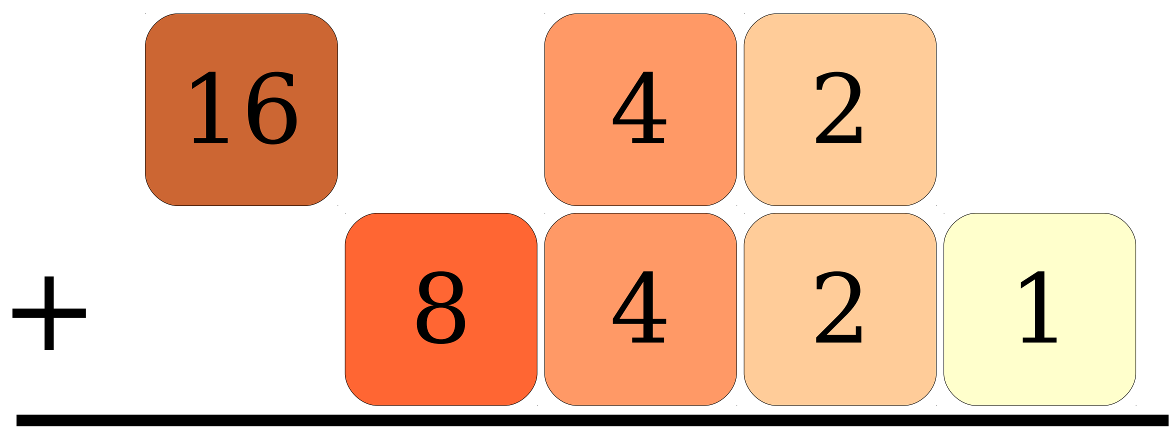

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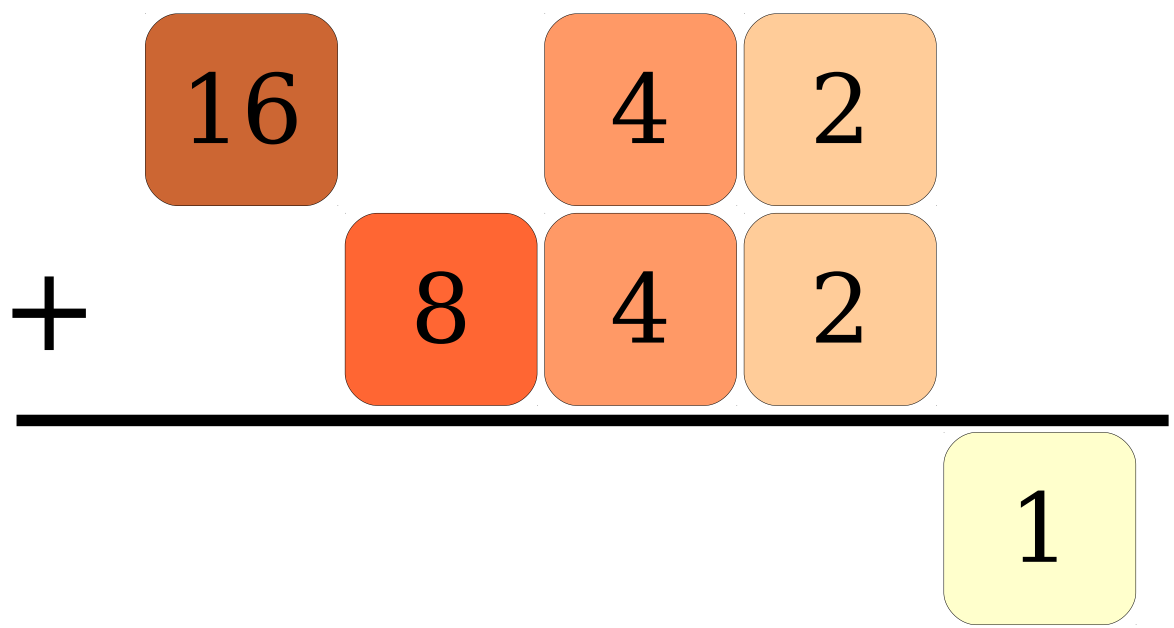

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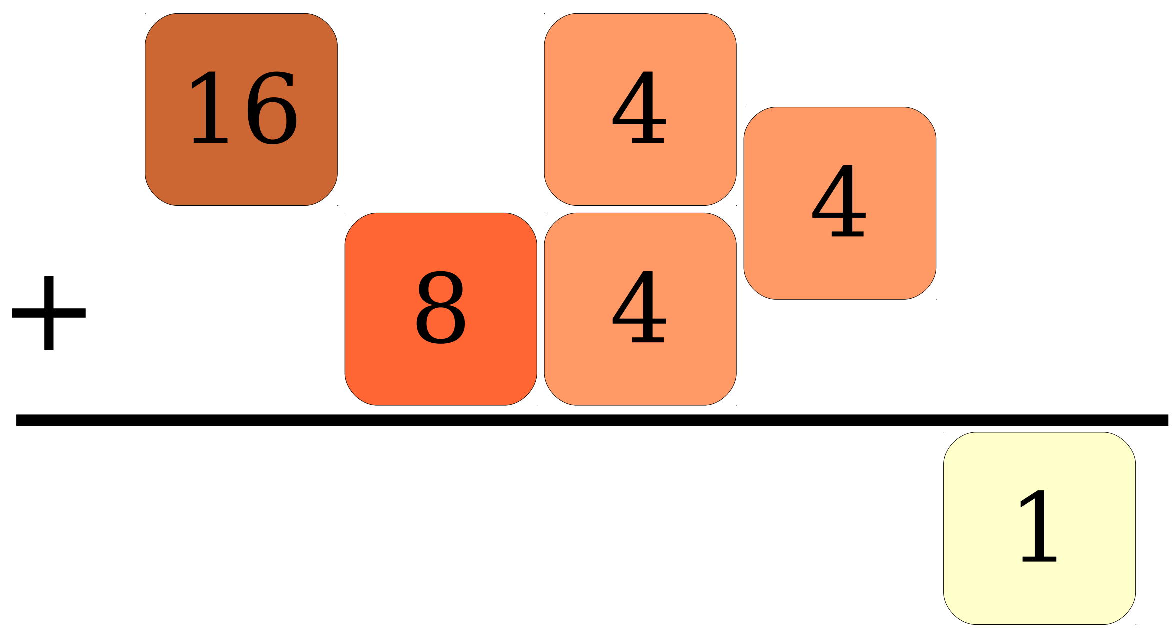

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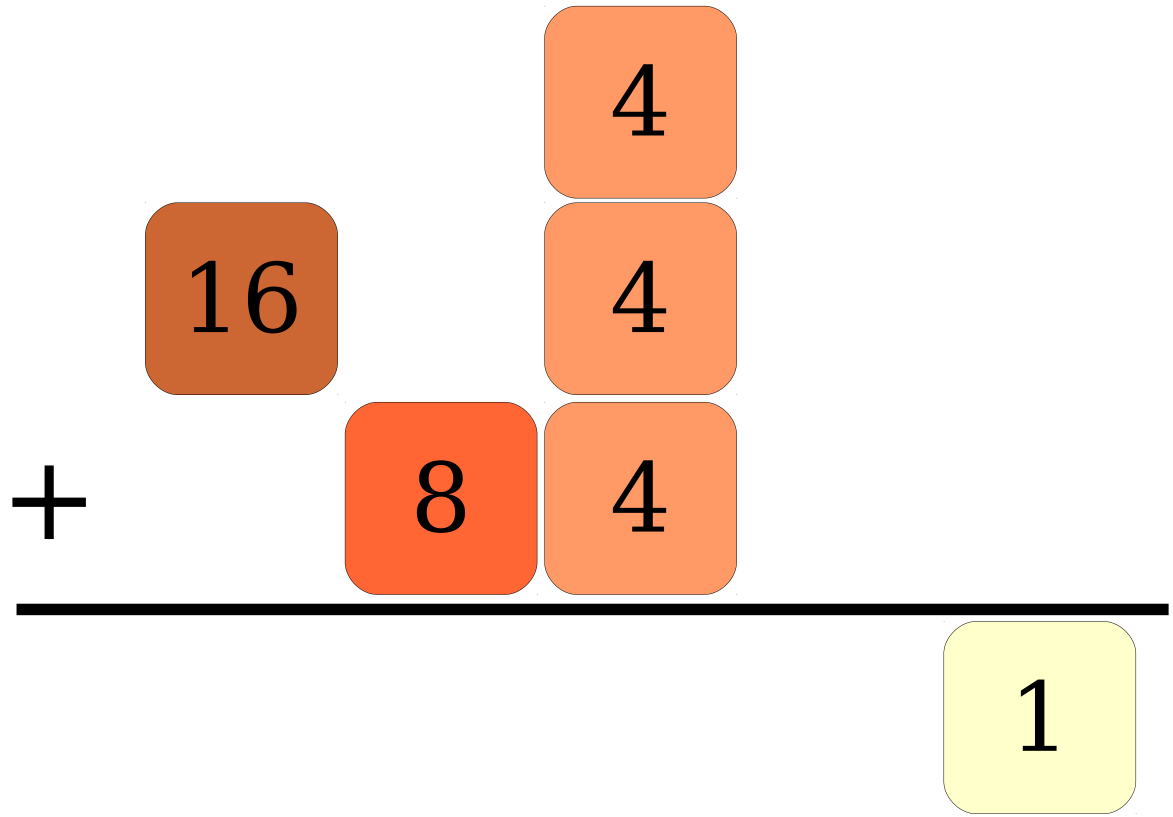

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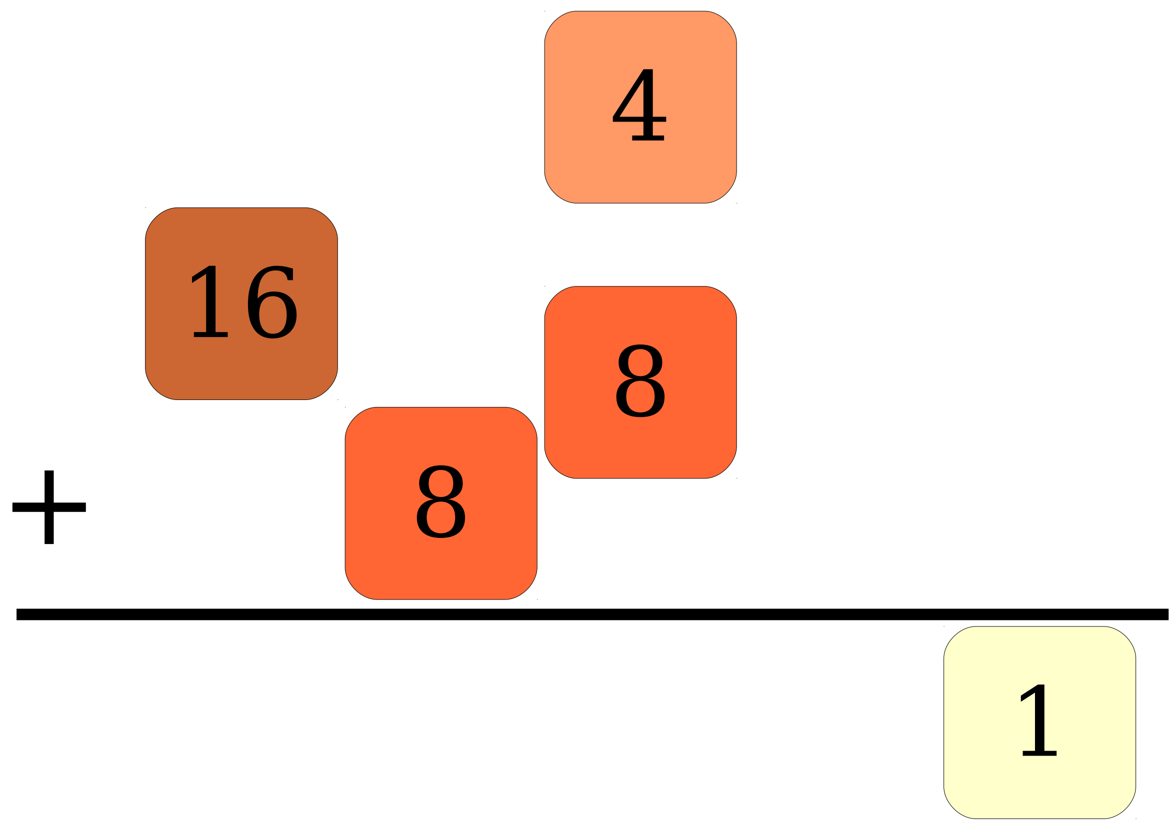

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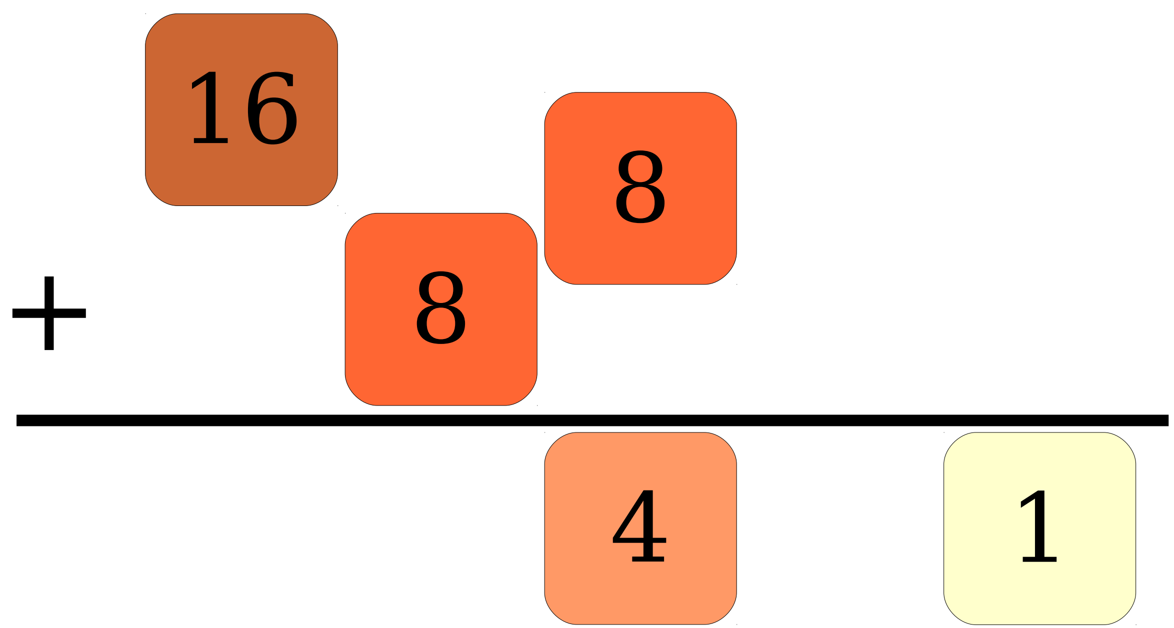

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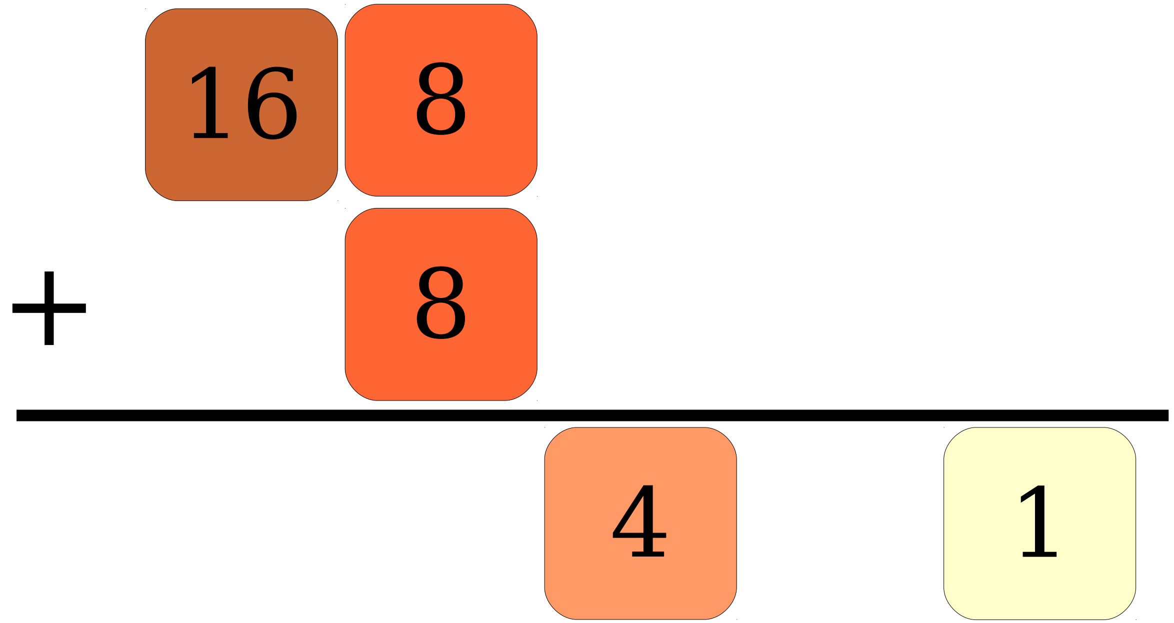

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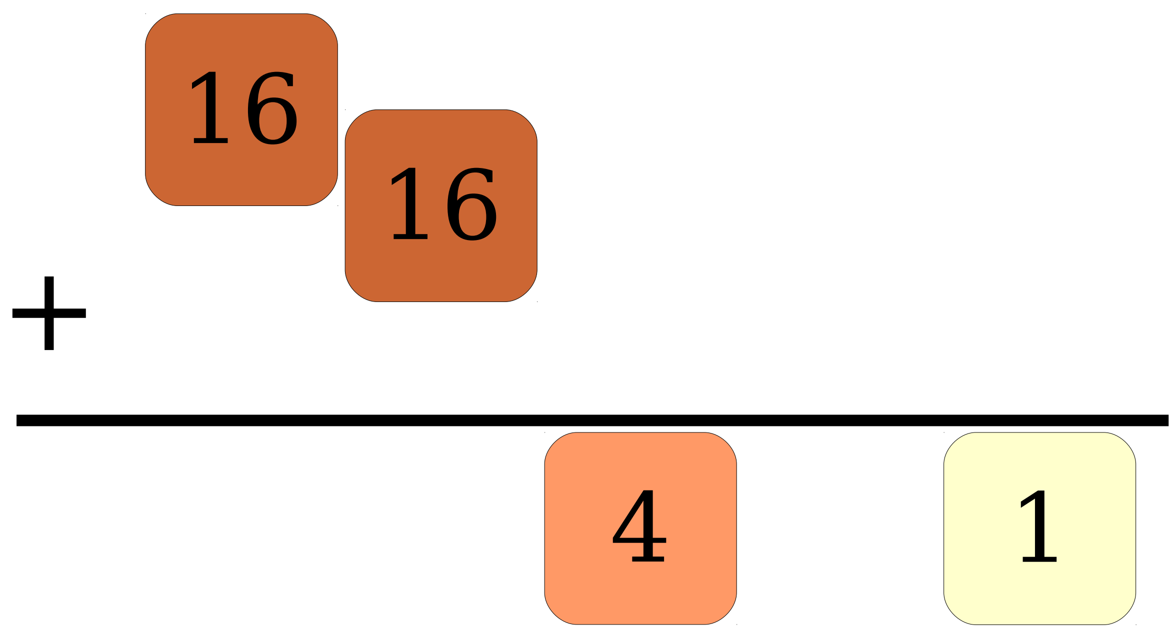

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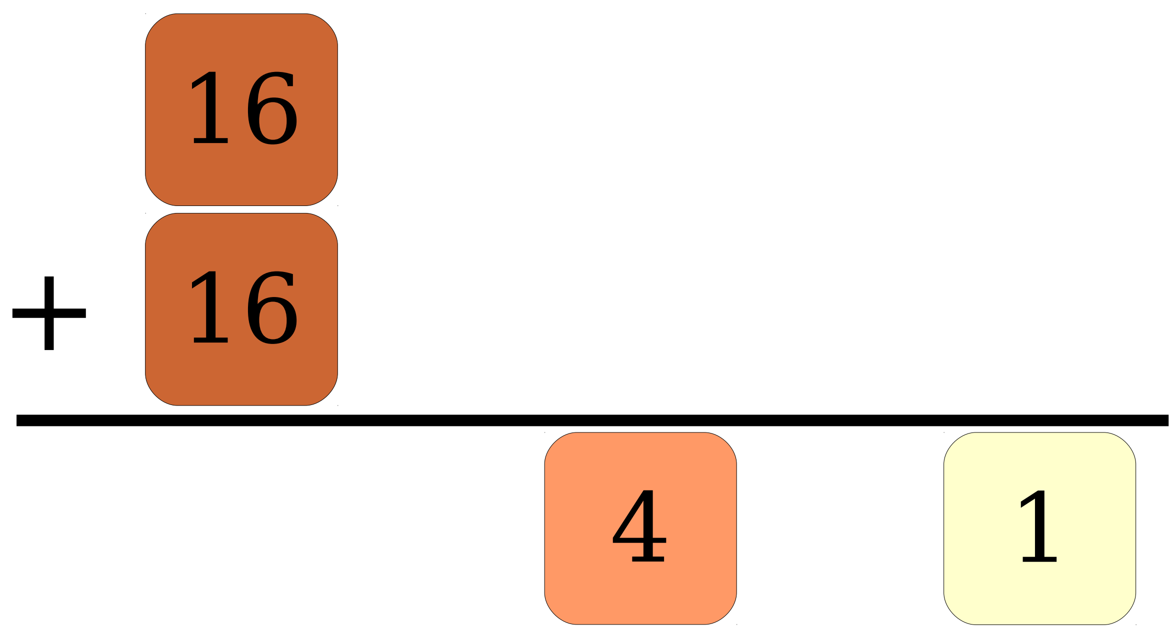

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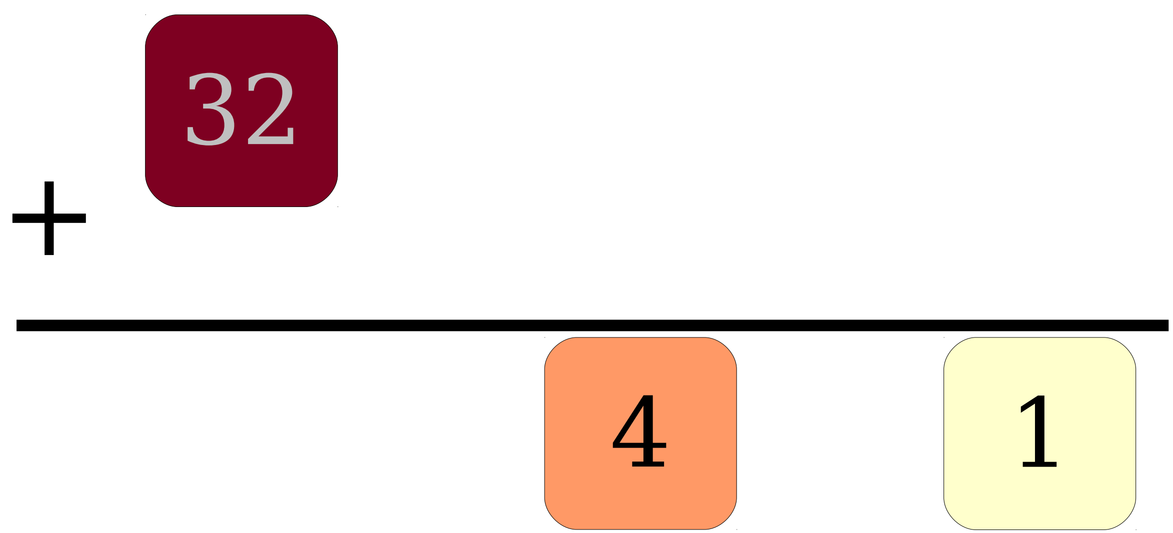

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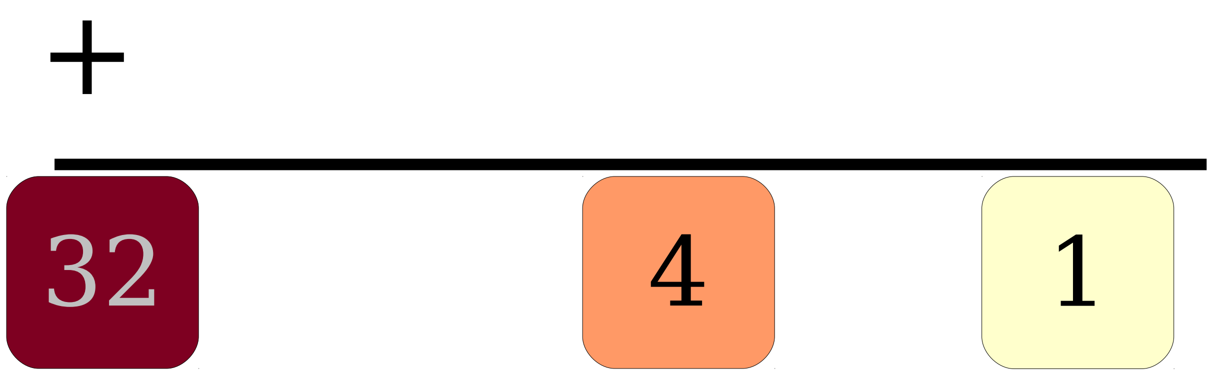

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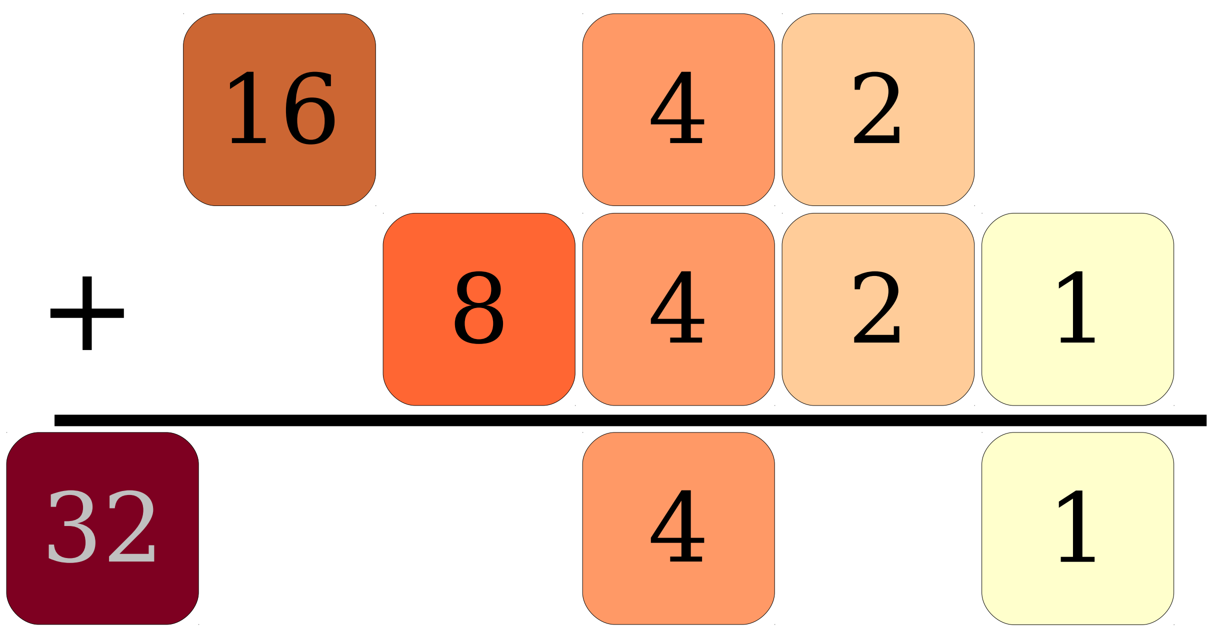
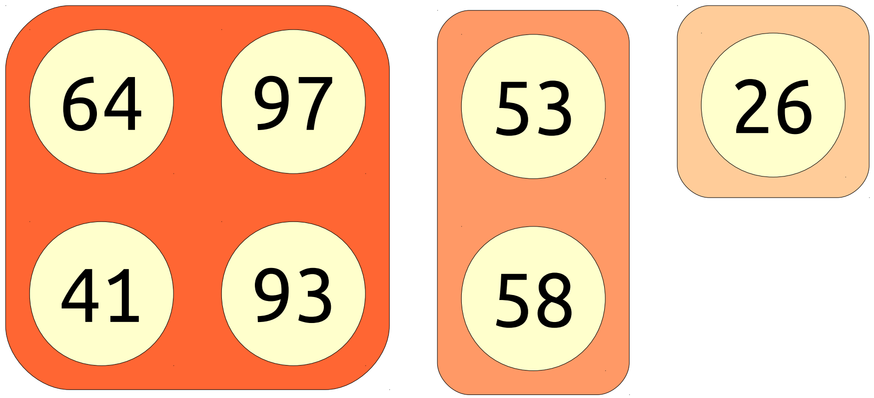


Why This Works

- In order for this arithmetic procedure to work efficiently, the packets must obey the following properties:
  - The packets must be stored in ascending/descending order of size.
  - The packets must be stored such that there are no two packets of the same size.
  - Two packets of the same size must be efficiently “fusable” into a single packet.

Building a Priority Queue

- ***Idea:*** Adapt this approach to build a priority queue.
- Store elements in the priority queue in “packets” whose sizes are powers of two.
- Store packets in ascending size order.
- We'll choose a representation of a packet so that two packets of the same size can easily be fused together.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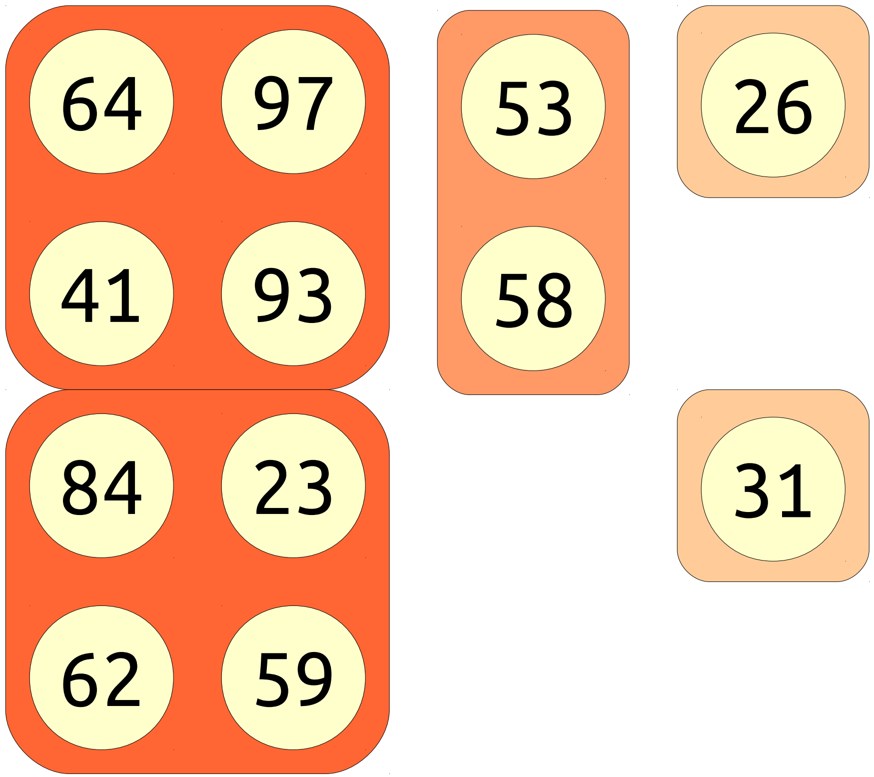
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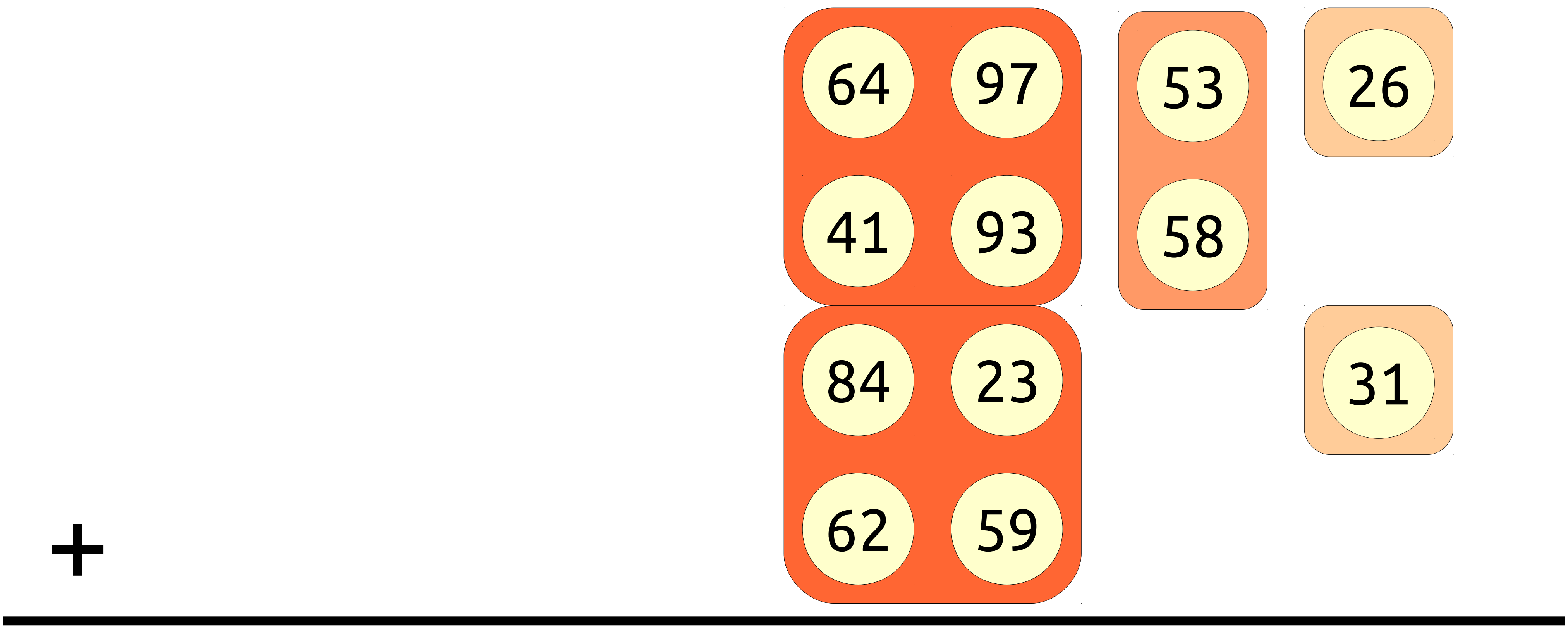
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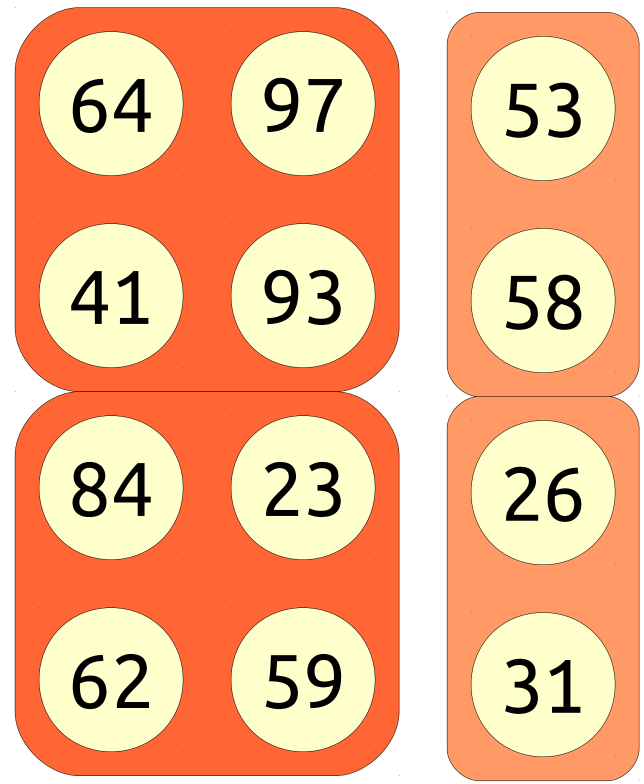
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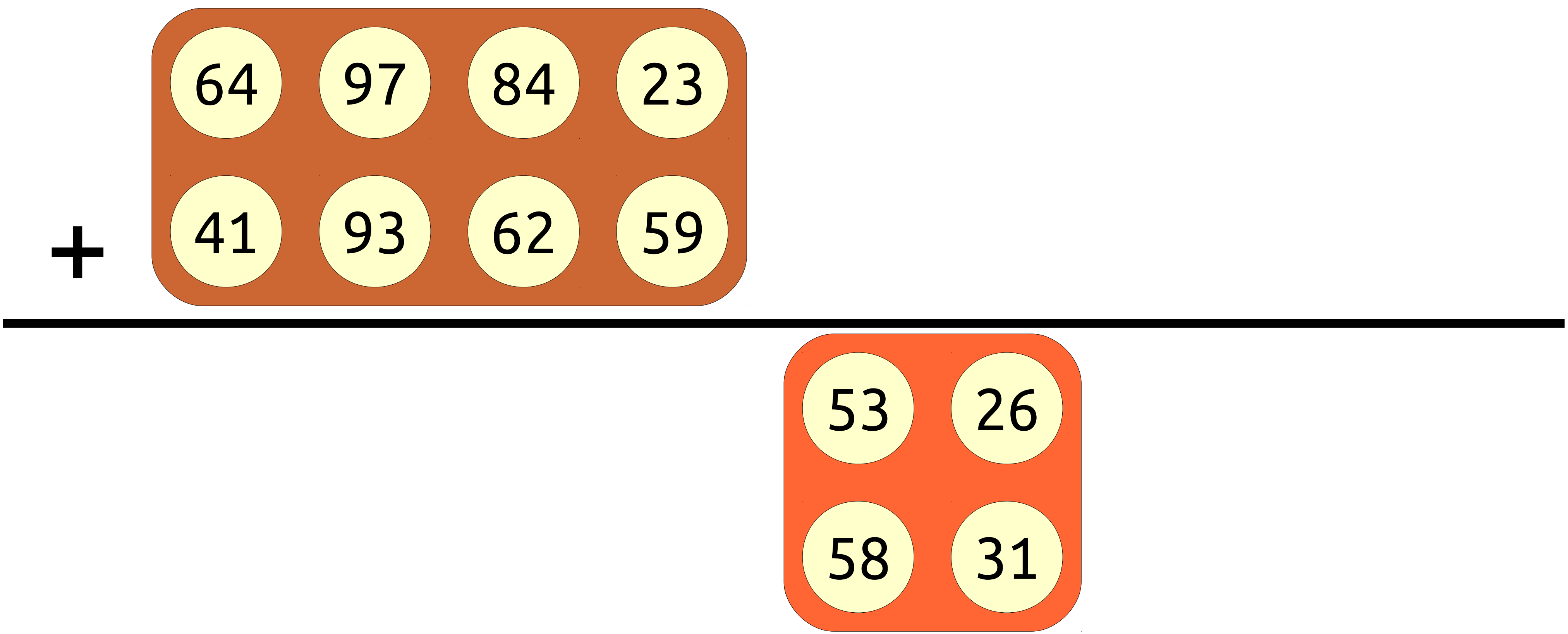
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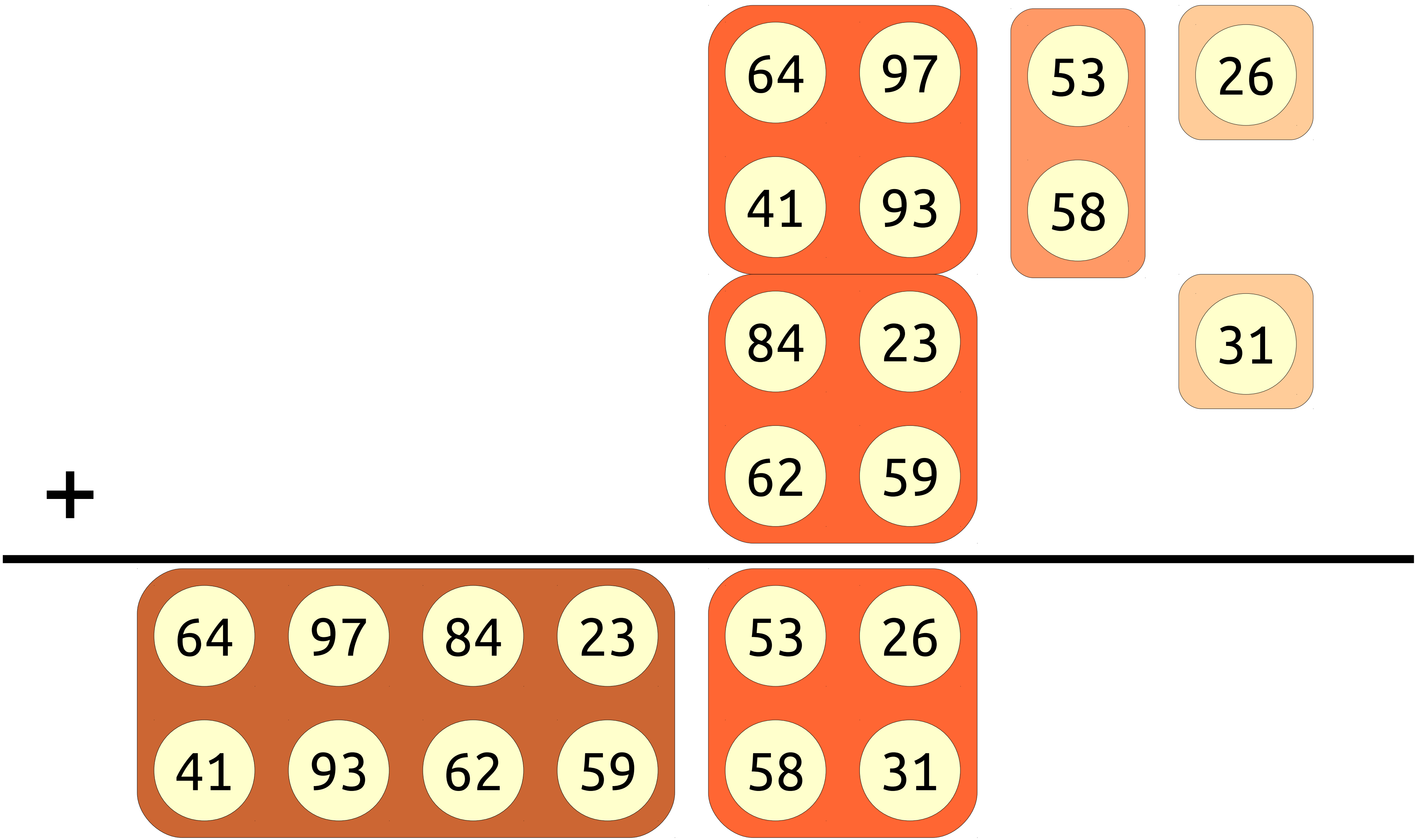
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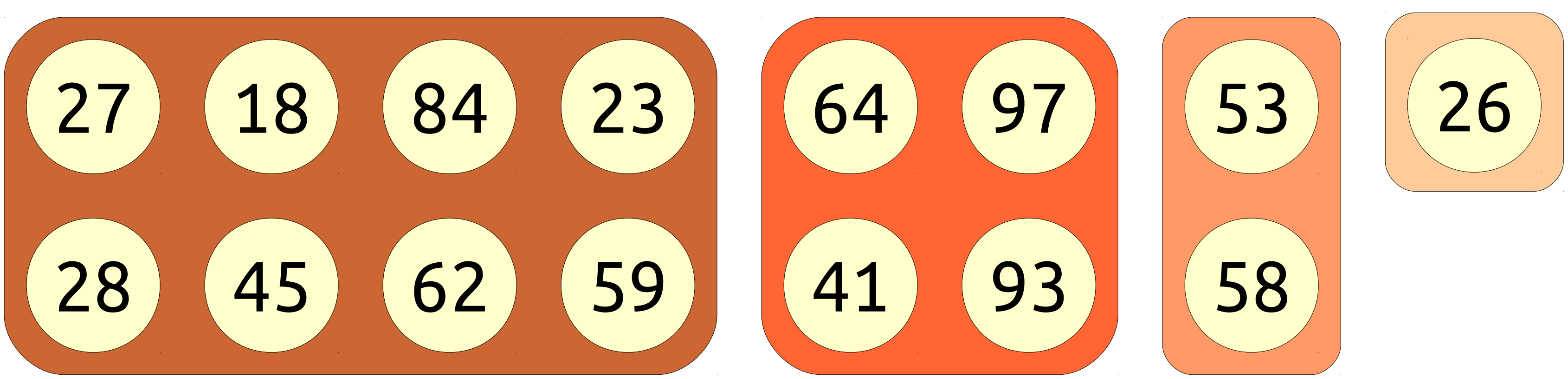

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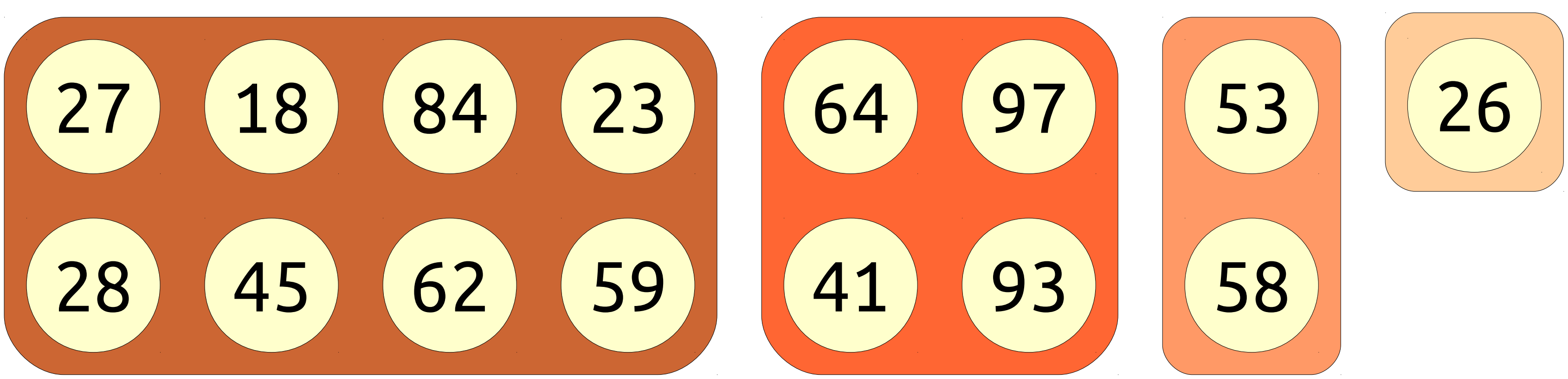

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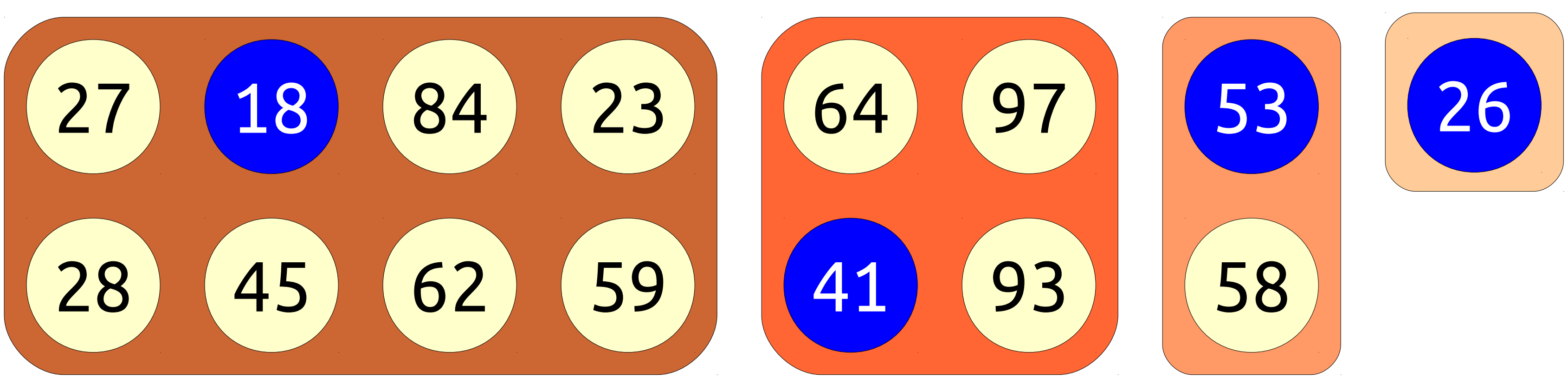

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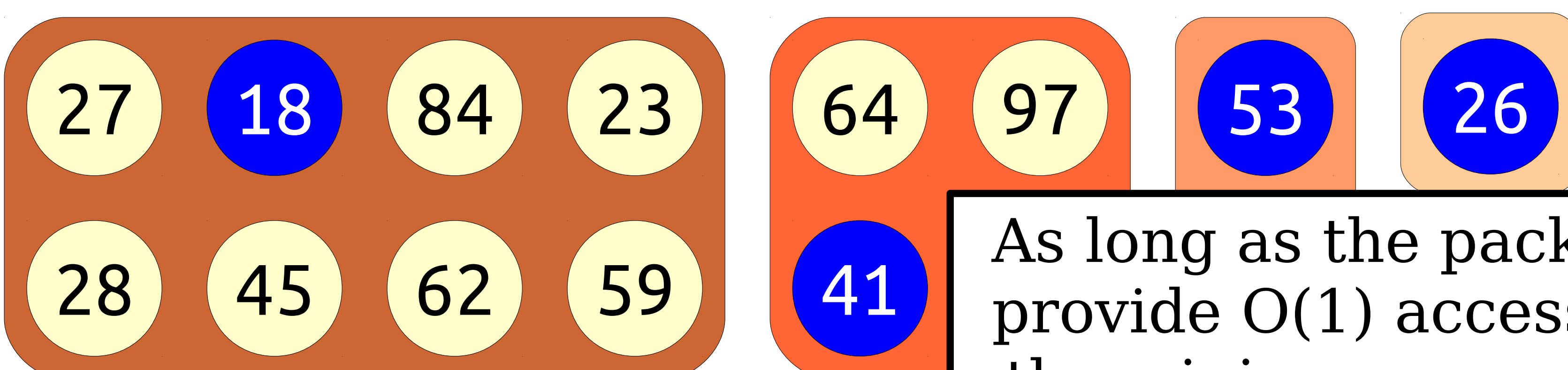

As long as the packets provide O(1) access to the minimum, we can execute ***find-min*** in time O(log *n*).

Building a Priority Queue

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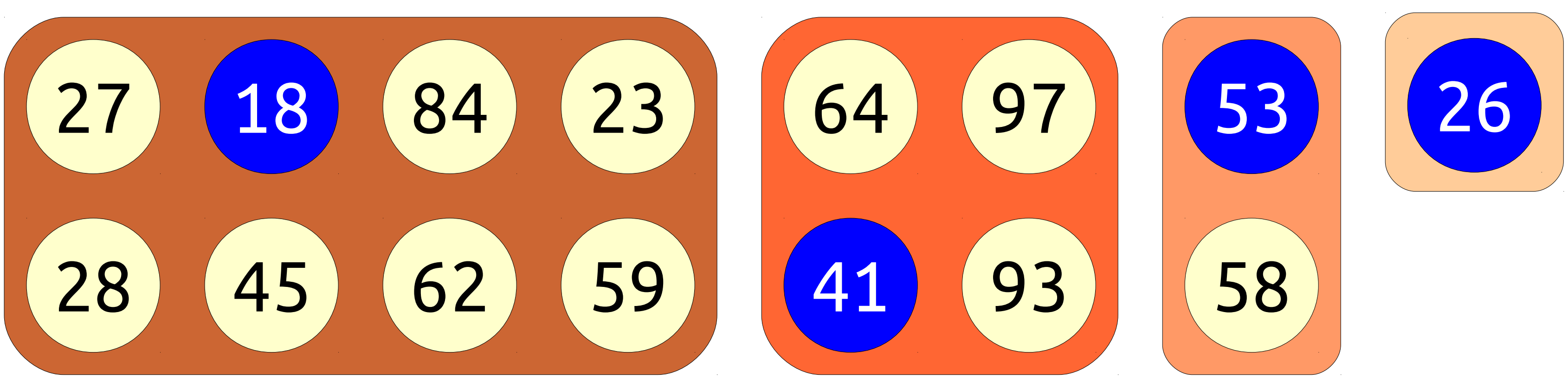

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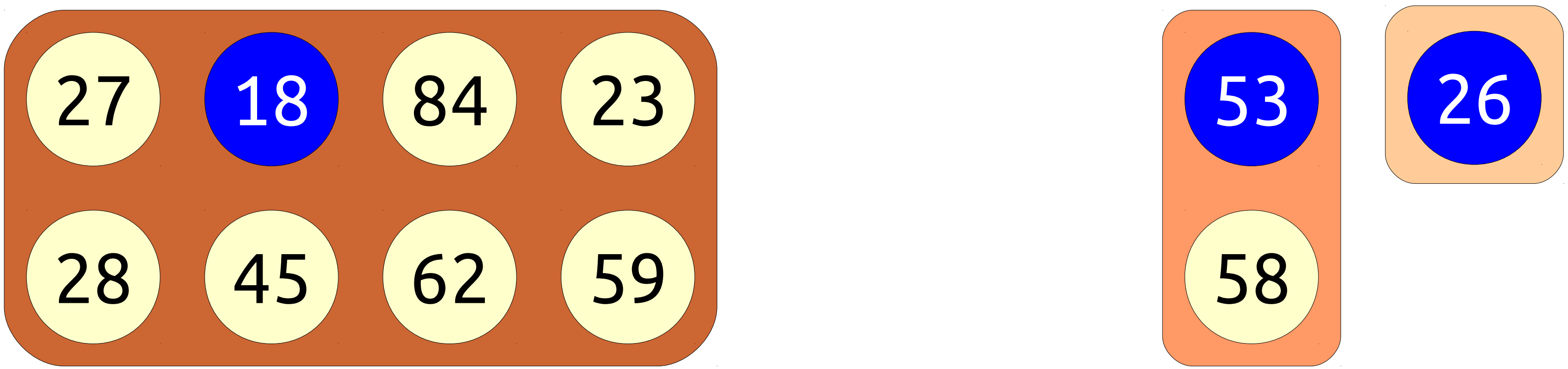

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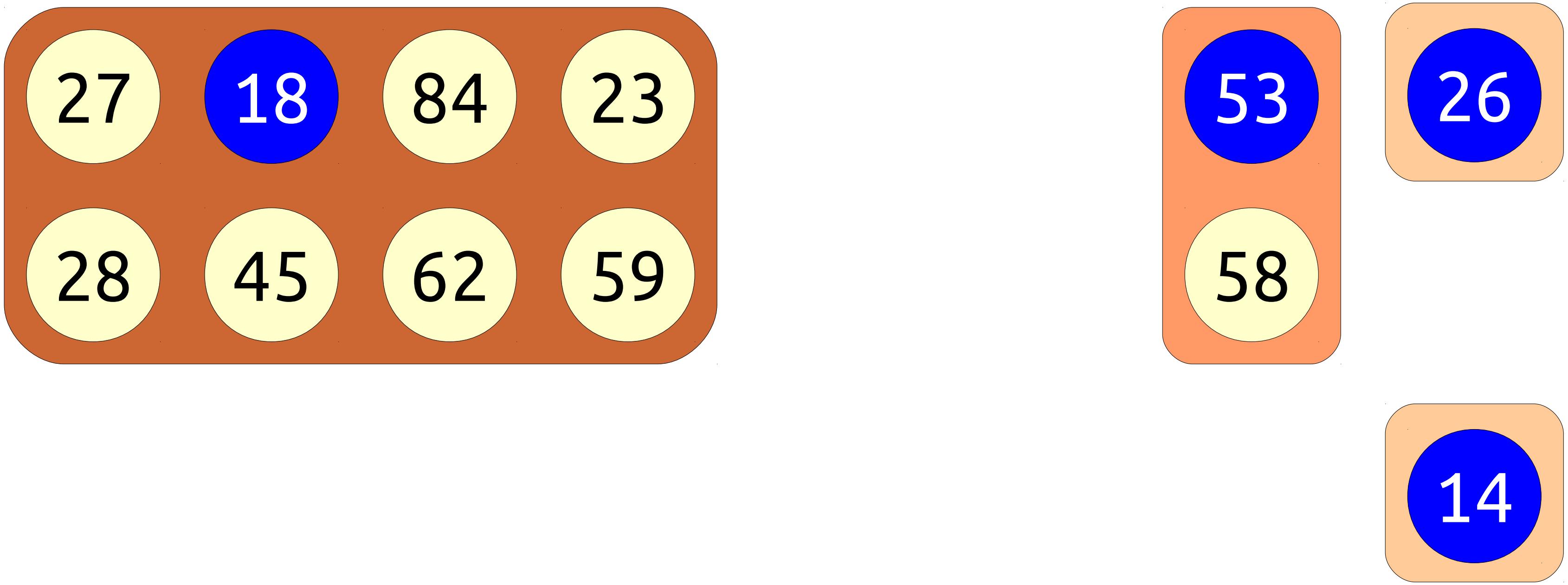

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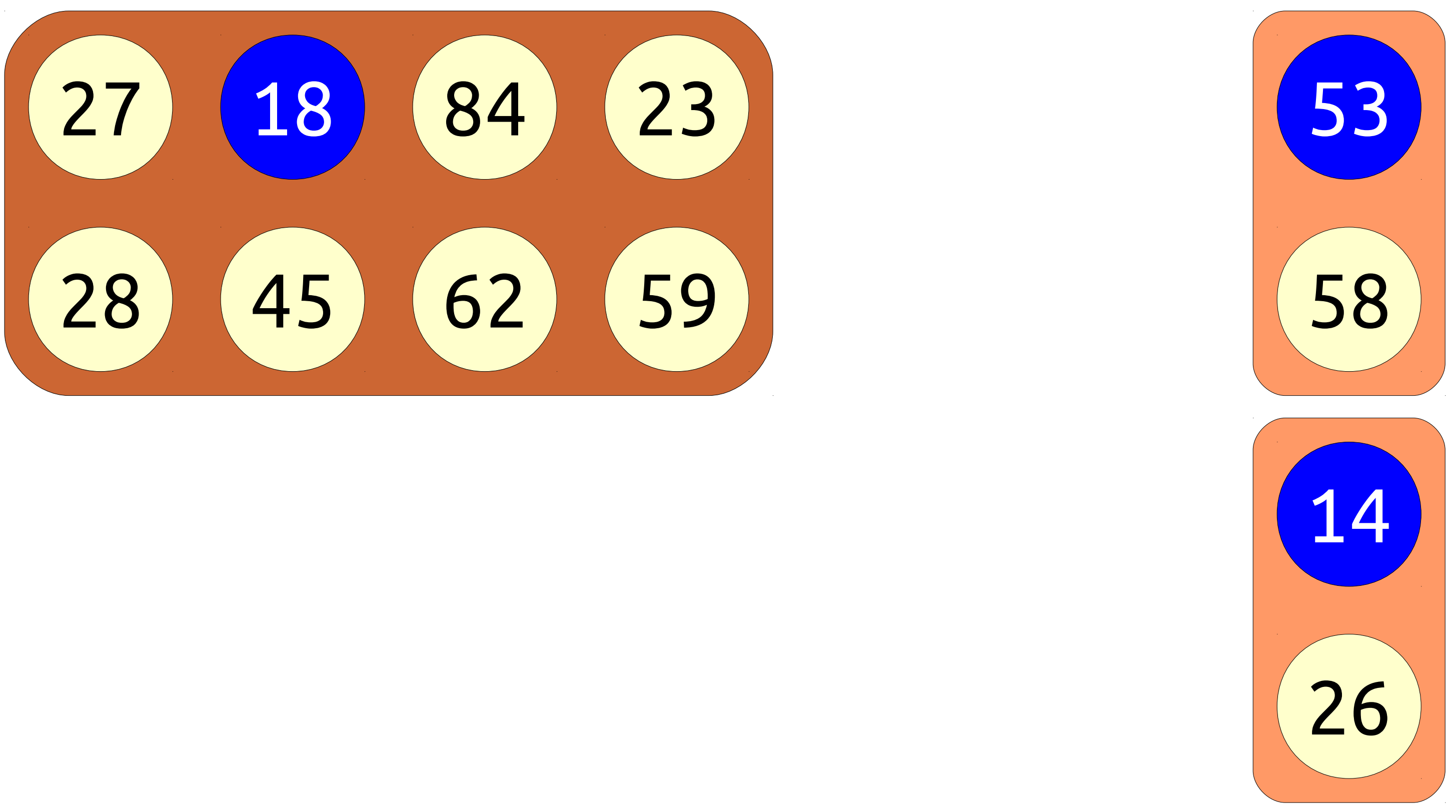

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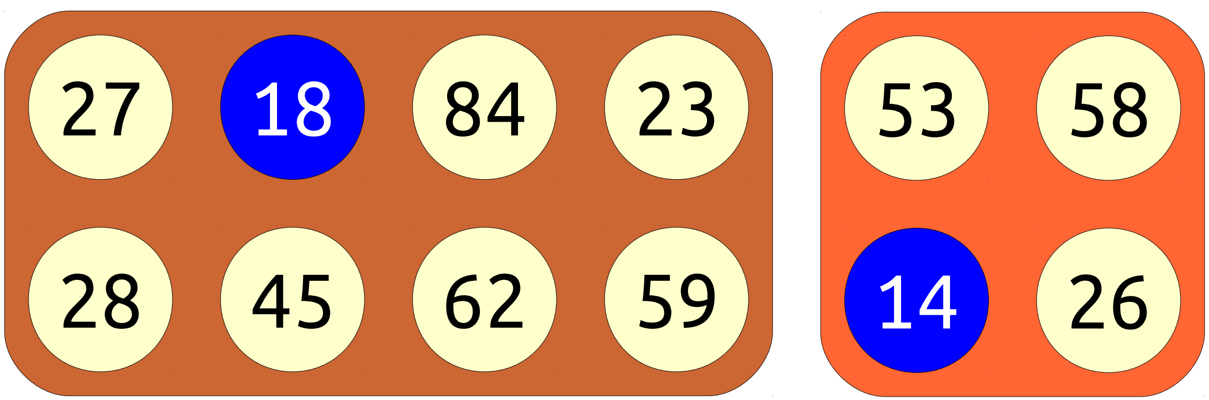

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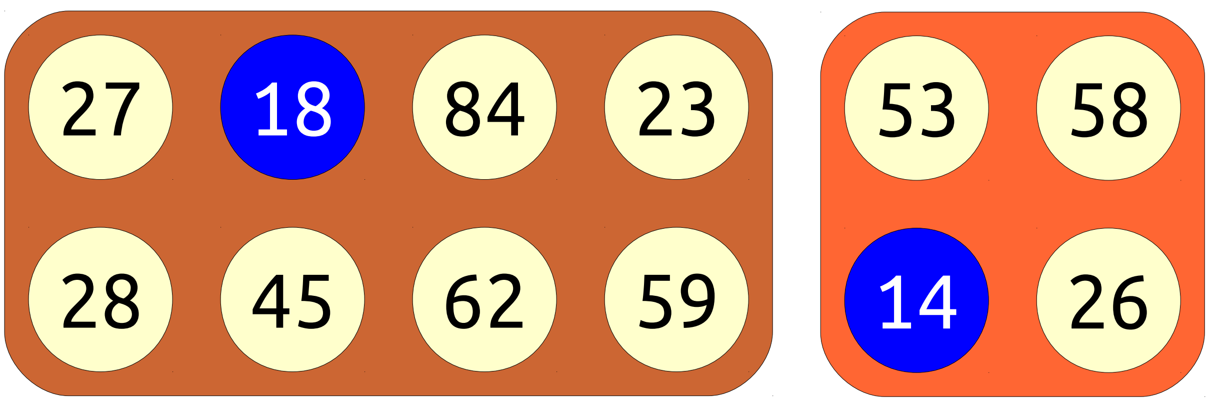

Time required:
O(log n) fuses.

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- After losing an element, the packet will not necessarily hold a number of elements that is a power of two.

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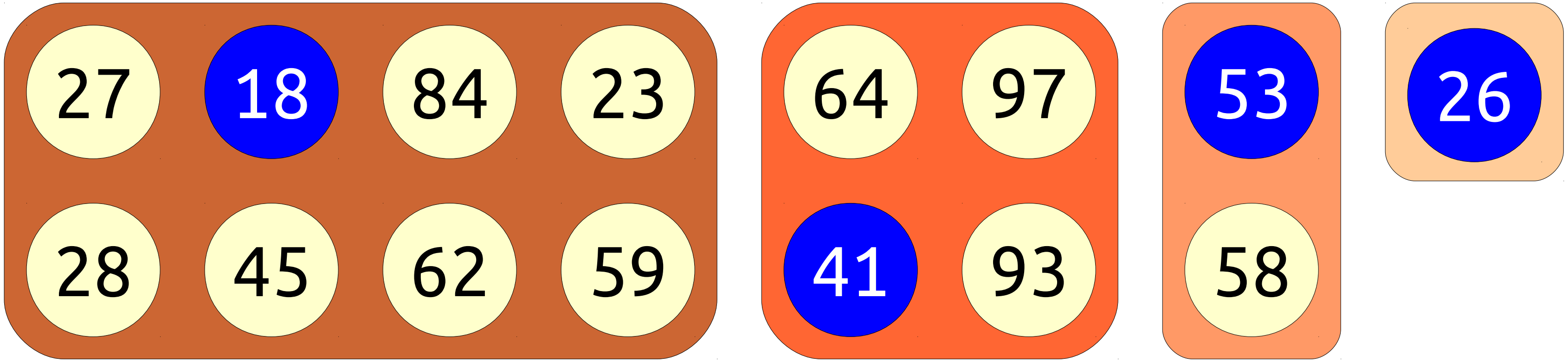

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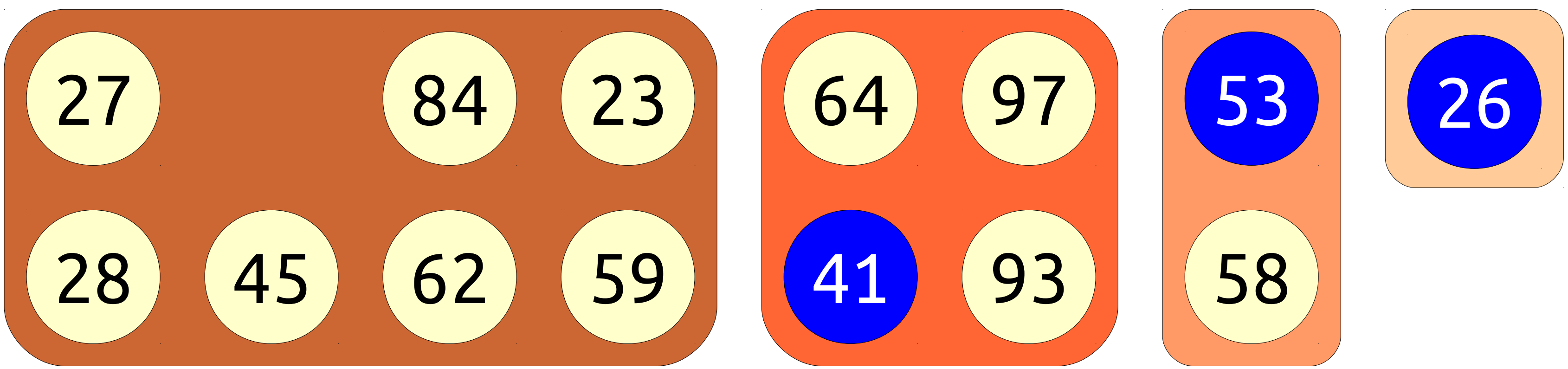
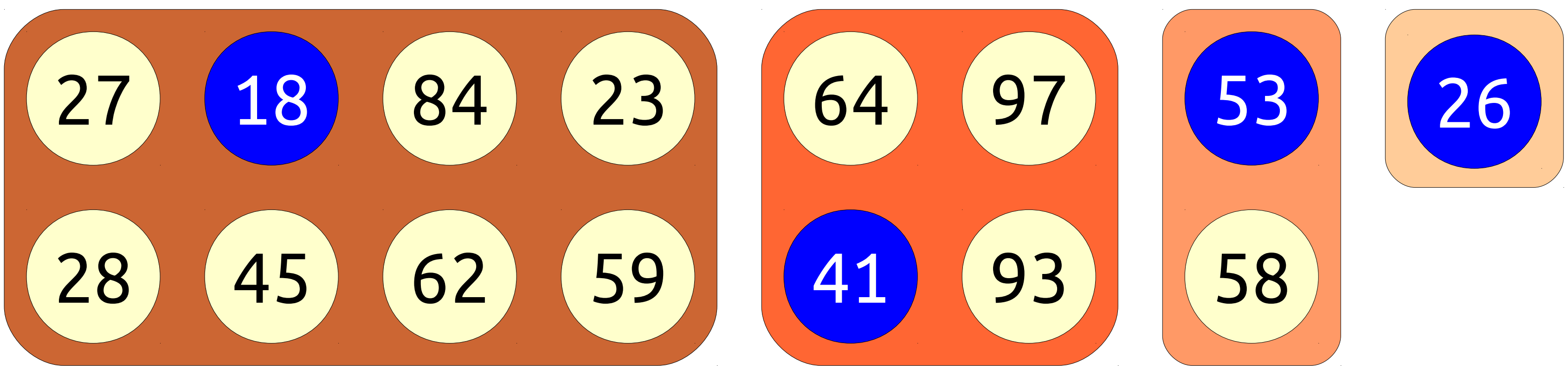


Fracturing Packets

- If we have a packet with 2^k elements in it and remove a single element, we are left with $2^k - 1$ remaining elements.
- ***Fun fact***: $2^k - 1 = 1 + 2 + 4 + \ldots + 2^{k-1}$.
- ***Idea***: "Fracture" the packet into $k - 1$ smaller packets, then add them back in.

Fracturing Packets

- We can ***extract-min*** by fracturing the packet containing the minimum and adding the fragments back in.



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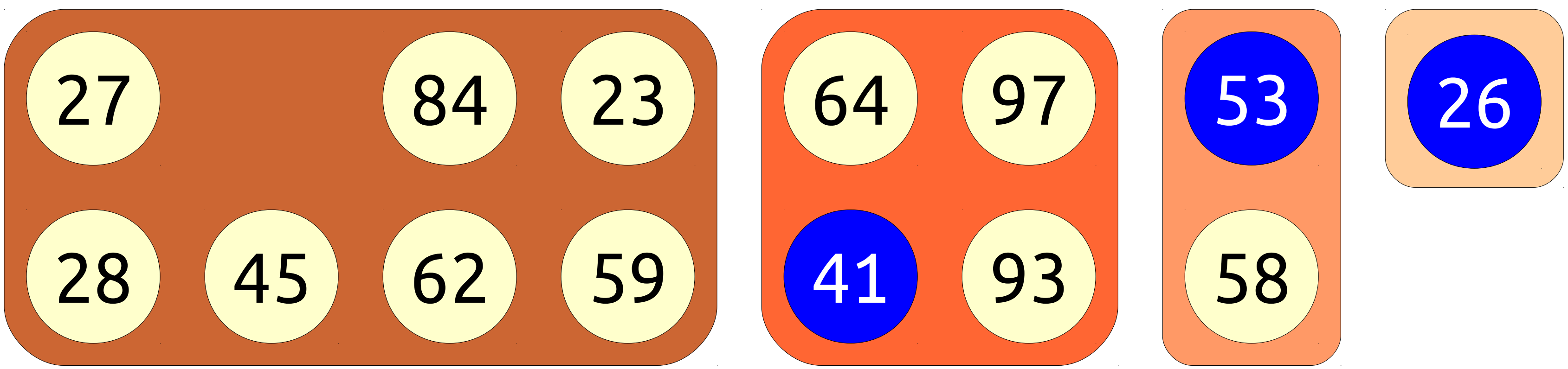

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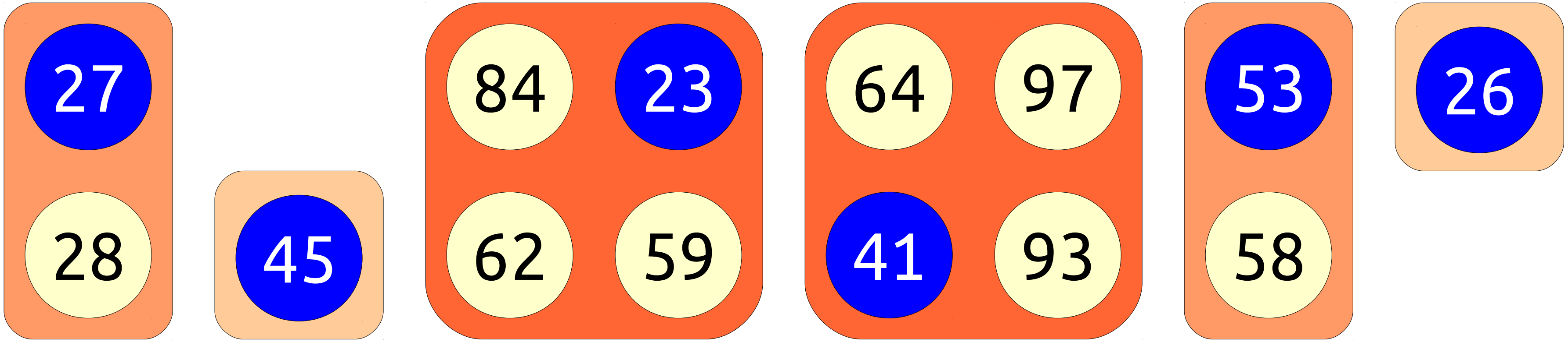

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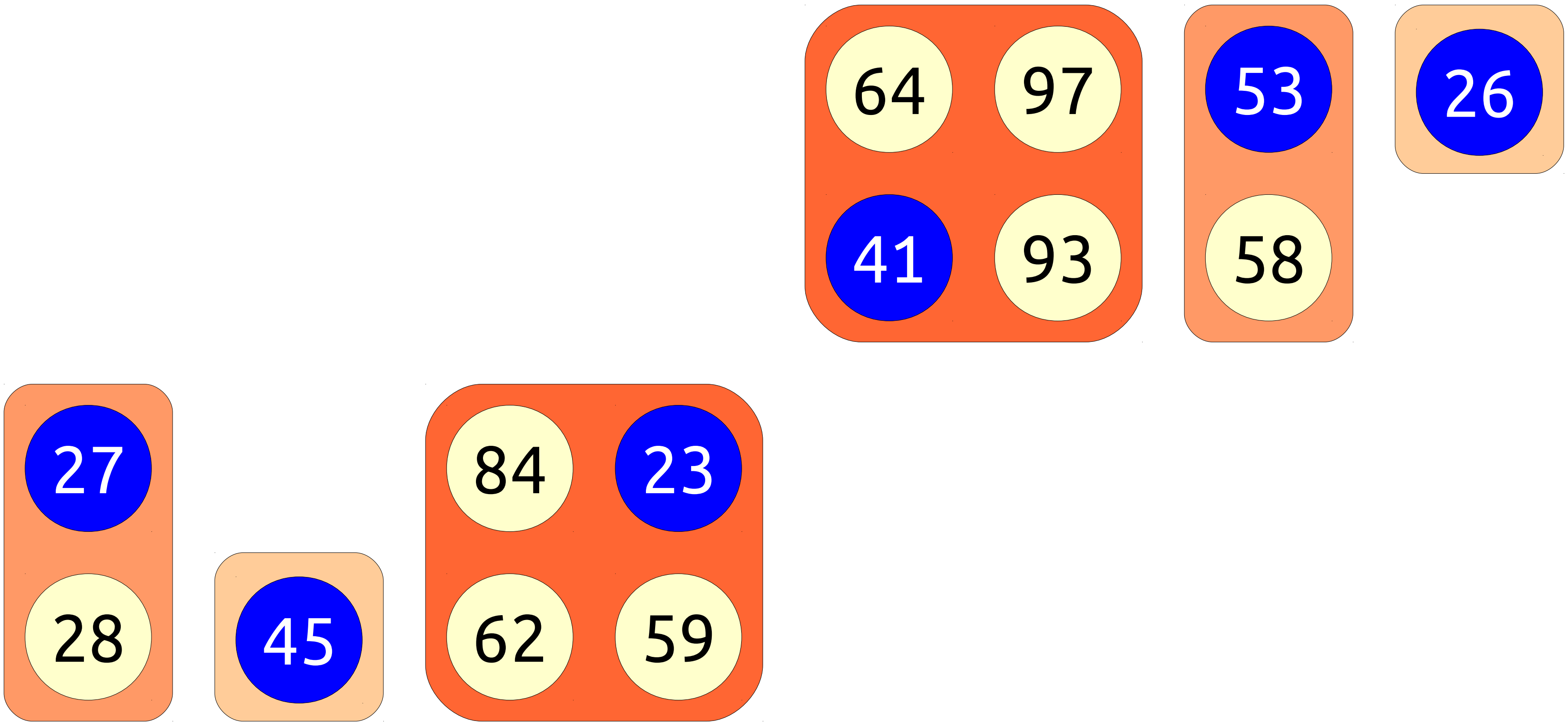

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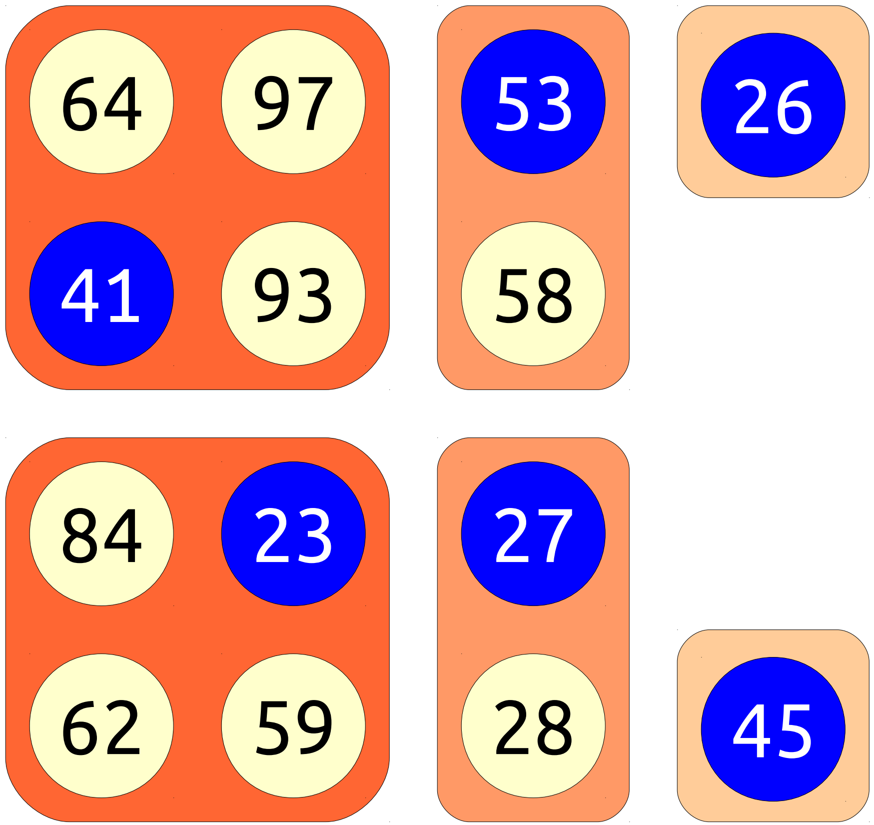

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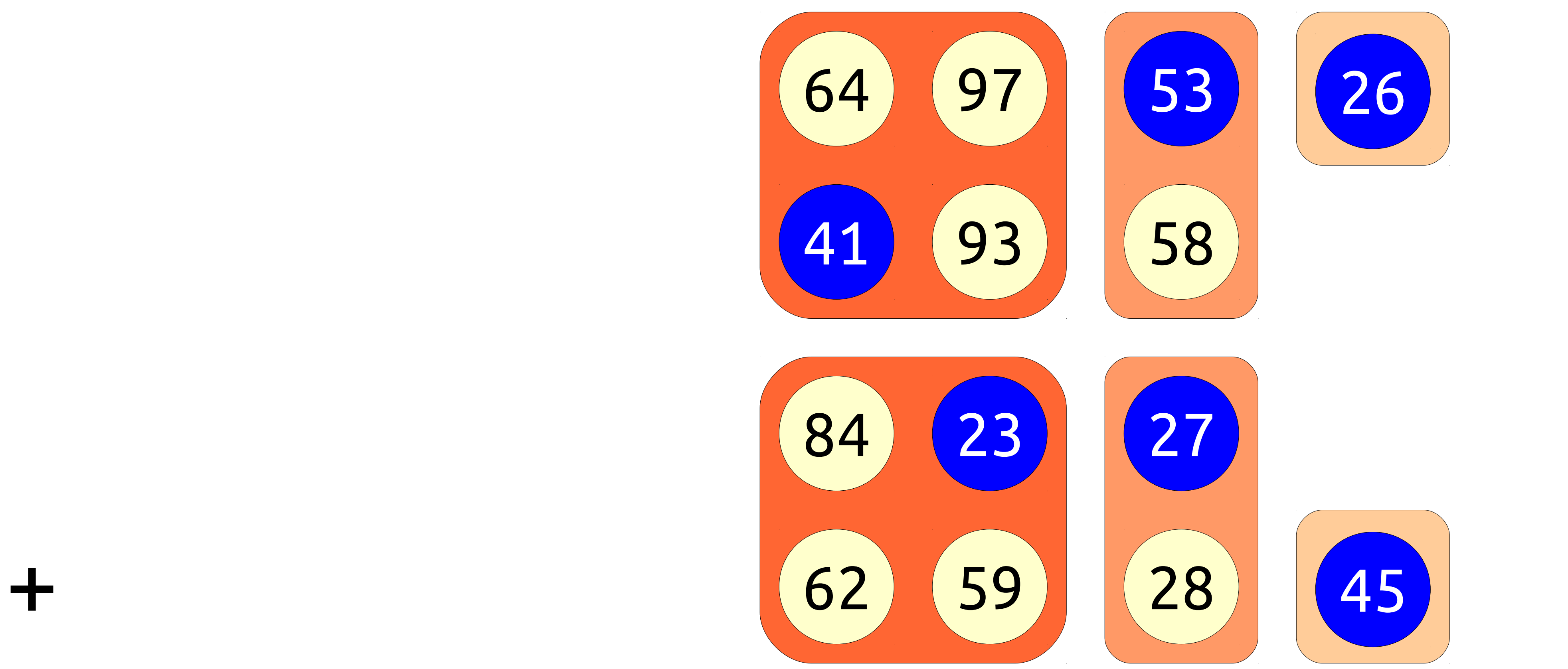
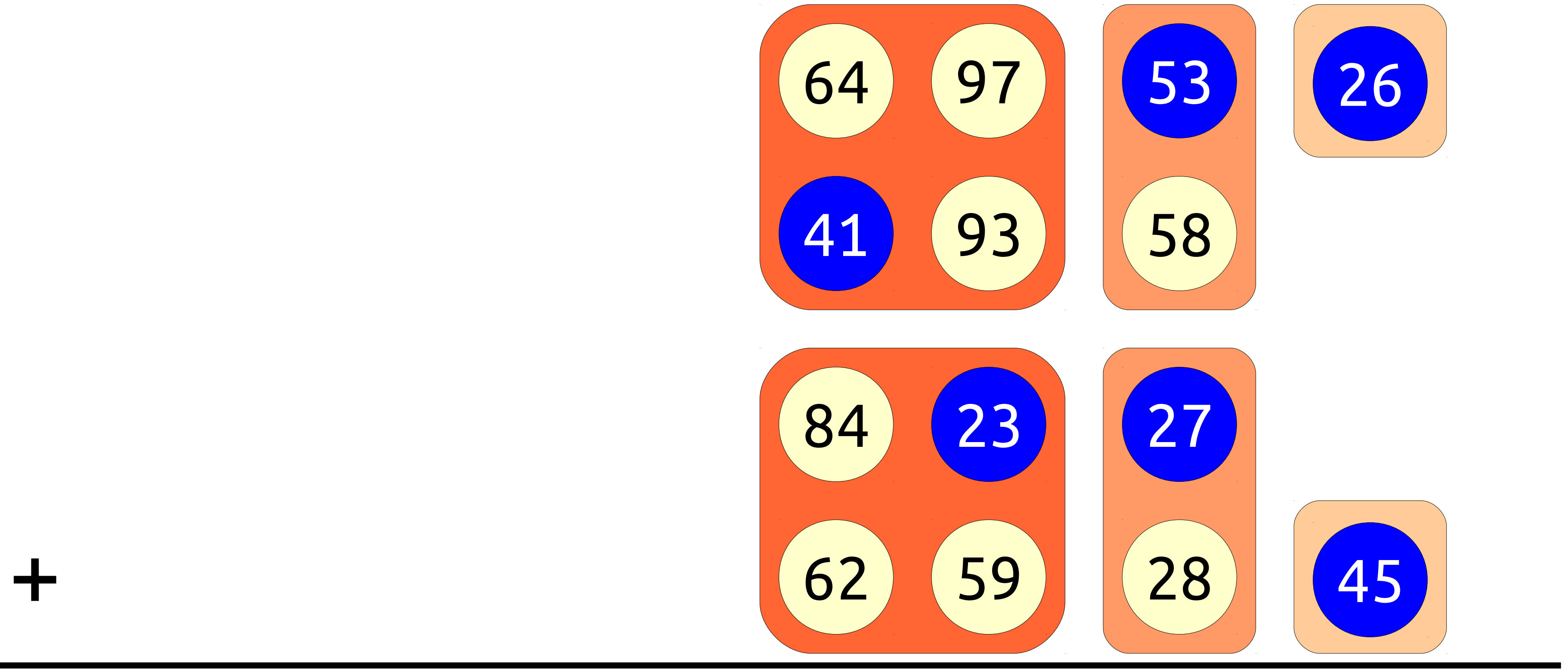


Fracturing Packets

- We can ***extract-min*** by fracturing the packet containing the minimum and adding the fragments back in.
- Runtime is O(log n) fuses in ***meld***, plus fragment cost.



Building a Priority Queue

- What properties must our packets have?
  - Size must be a power of two.
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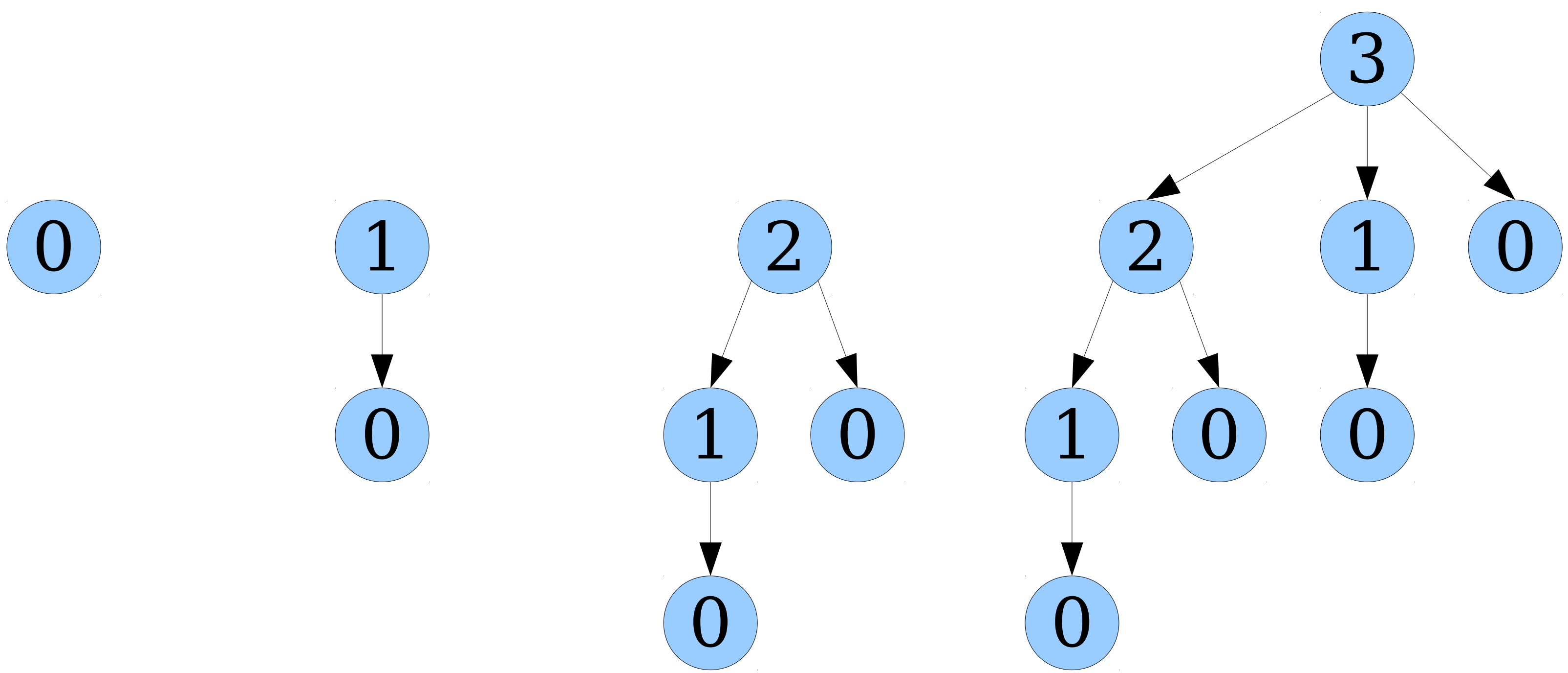
  - Can efficiently find the minimum element of each packet.
  - Can efficiently “fracture” a packet of 2^k nodes into packets of 1, 2, 4, 8, …, 2^{k-1} nodes.
- What representation of packets will give us these properties?

Binomial Trees

- A ***binomial tree of order k*** is a type of tree recursively defined as follows:

  A binomial tree of order *k* is a single node whose children are binomial trees of order 0, 1, 2, …, *k* – 1.

- Here are the first few binomial trees:



Binomial Trees

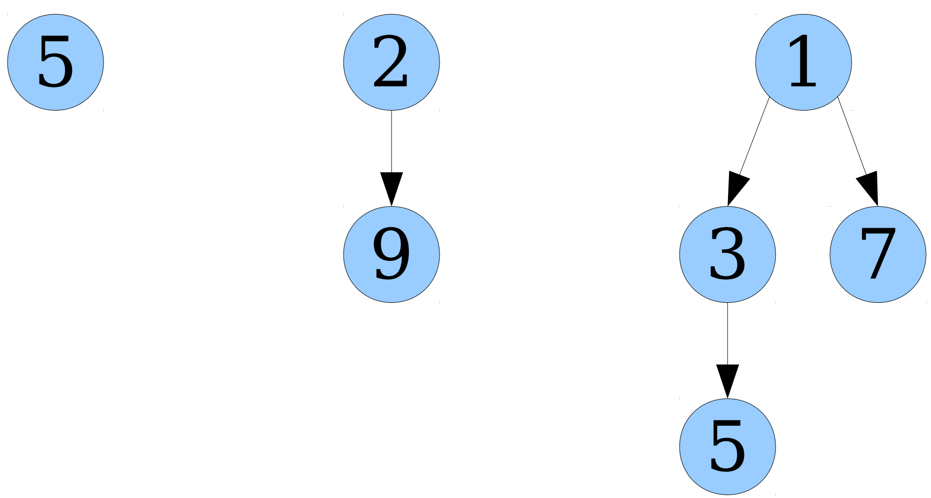
- ***Theorem:*** A binomial tree of order k has exactly 2^k nodes.
- ***Proof:*** Induction on k. Assuming that binomial trees of orders 0, 1, 2, …, k – 1 have $2^0, 2^1, 2^2, \ldots, 2^{k-1}$ nodes, then then number of nodes in an order-k binomial tree is

$$2^0 + 2^1 + \ldots + 2^{k-1} + 1 = 2^k - 1 + 1 = 2^k$$

So the claim holds for k as well. ■

Binomial Trees

- A ***heap-ordered binomial tree*** is a binomial tree whose nodes obey the heap property: all nodes are less than or equal to their descendants.
- We will use heap-ordered binomial trees to implement our “packets.”



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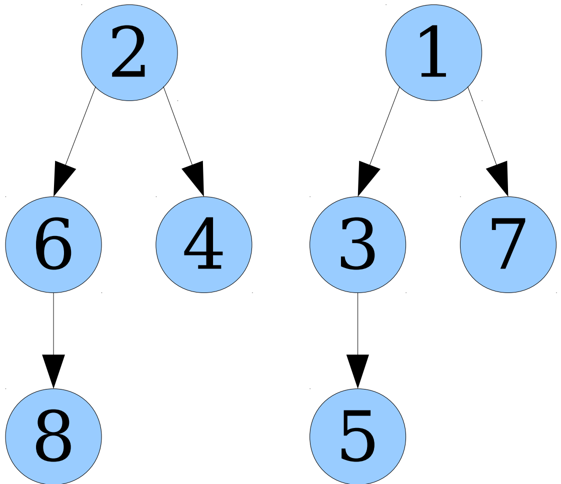

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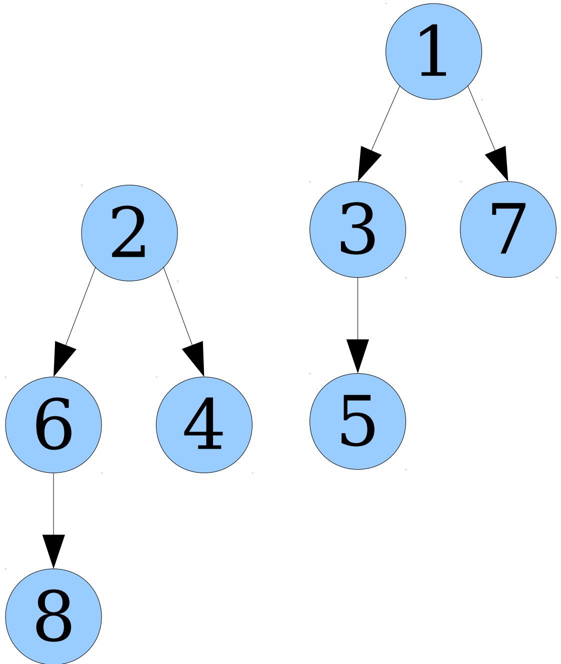

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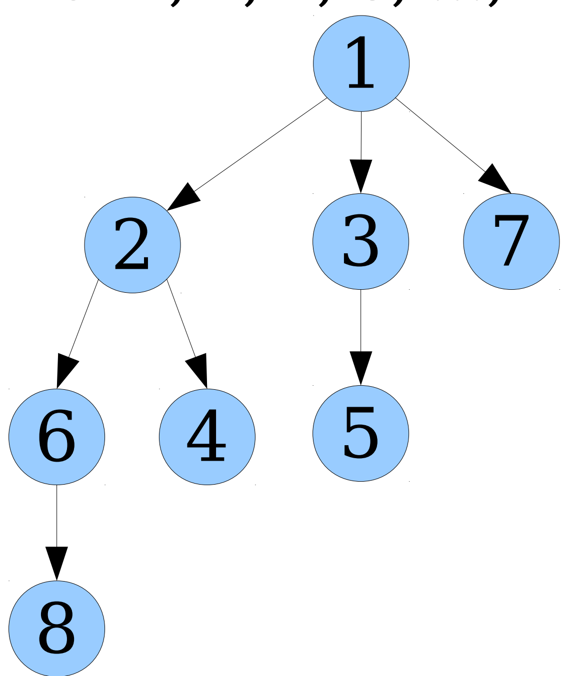

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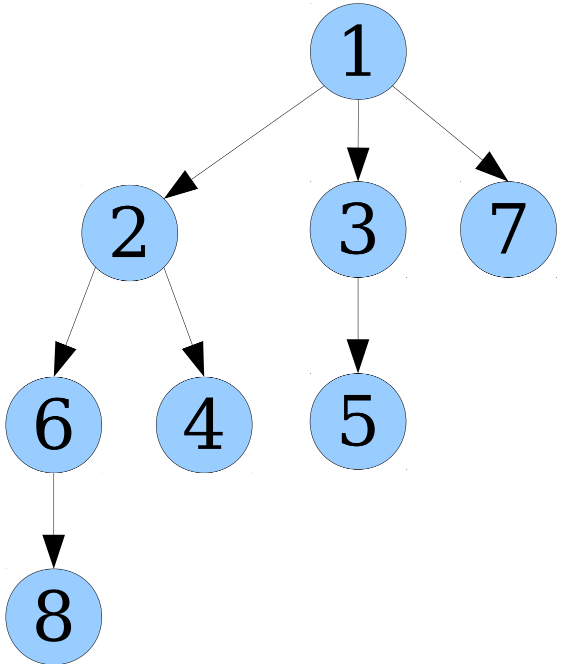

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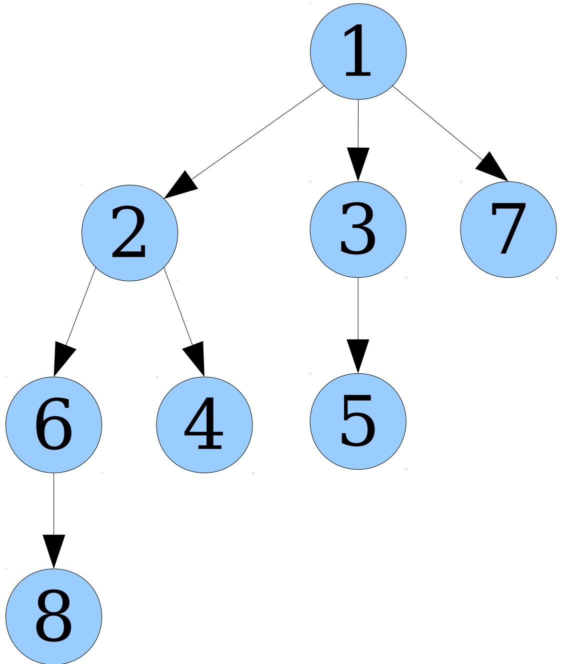

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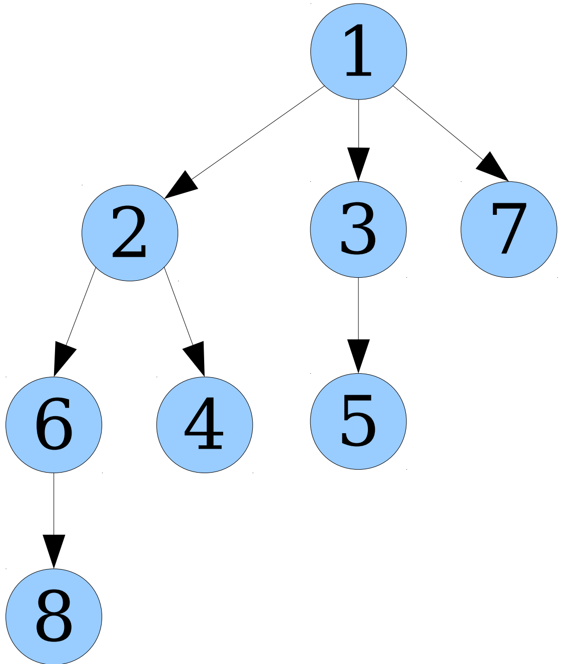

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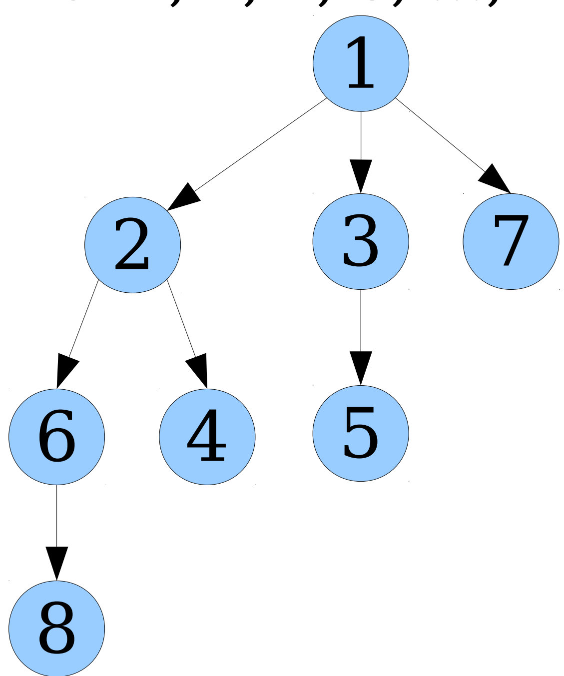

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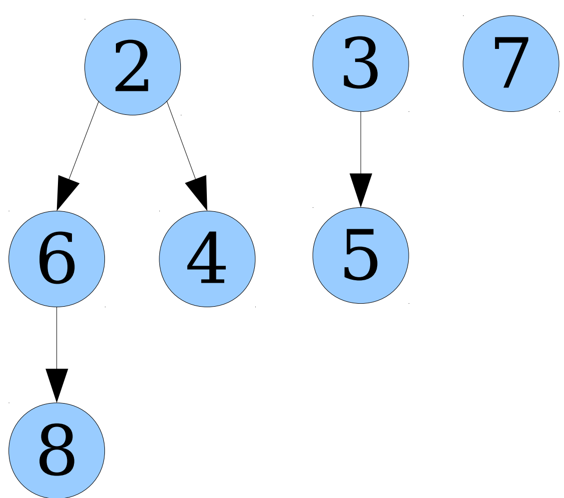

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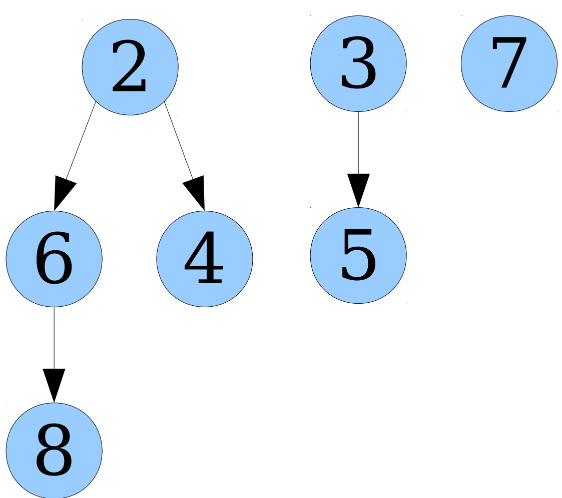
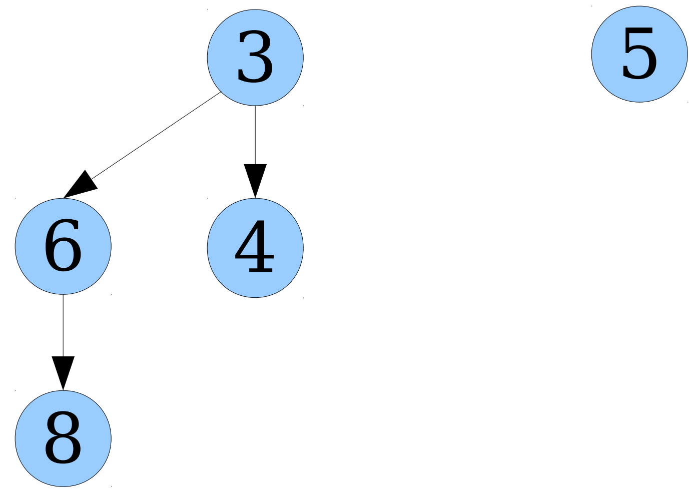


The Binomial Heap

- A ***binomial heap*** is a collection of heap-ordered binomial trees stored in ascending order of size.
- Operations defined as follows:
  - ***meld***(pq_1, pq_2): Use addition to combine all the trees.
    - Fuses O(log n) trees. Total time: O(log n).
  - pq.***enqueue***(v, k): Meld pq and a singleton heap of (v, k).
    - Total time: O(log n).
  - pq.***find-min***(): Find the minimum of all tree roots.
    - Total time: O(log n).
  - pq.***extract-min***(): Find the min, delete the tree root, then meld together the queue and the exposed children.
    - Total time: O(log n).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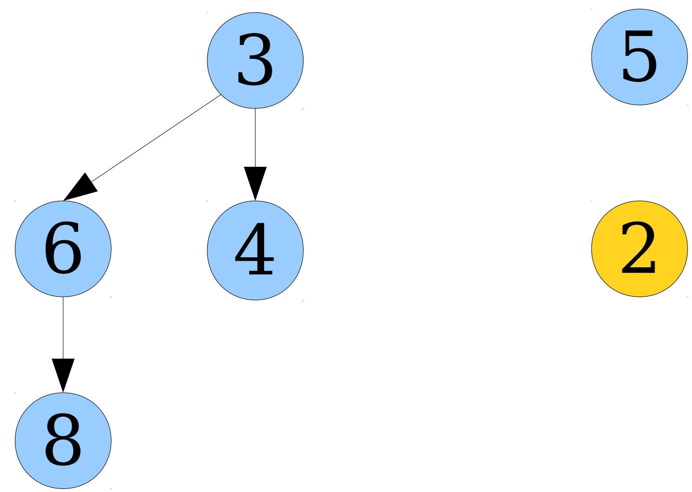
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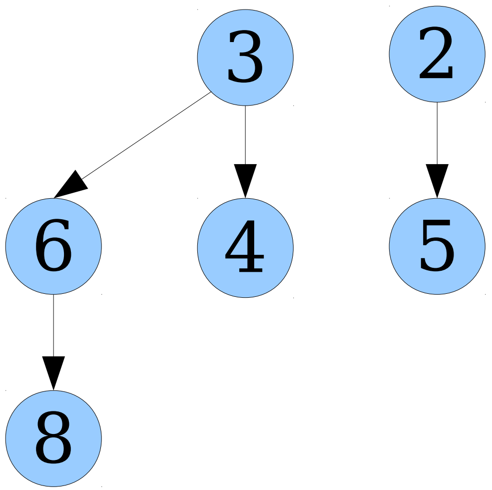
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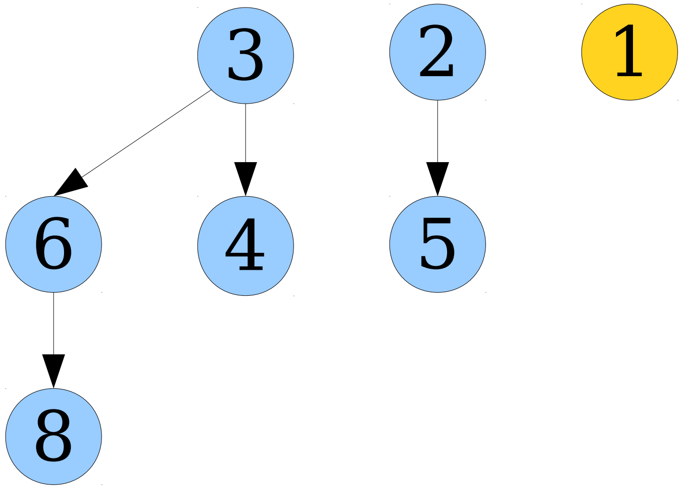
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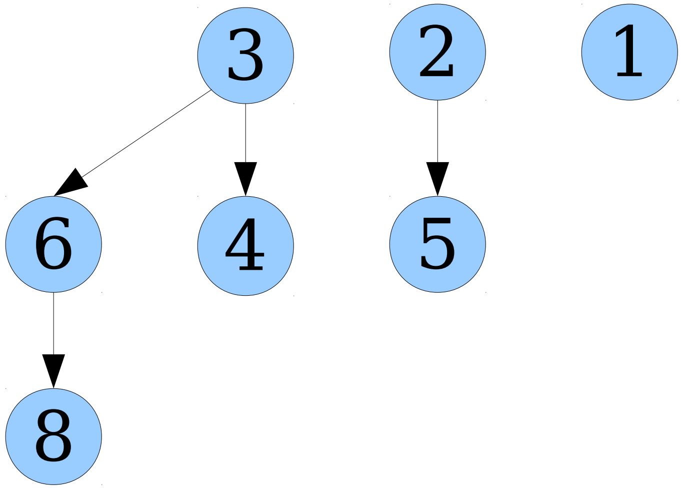
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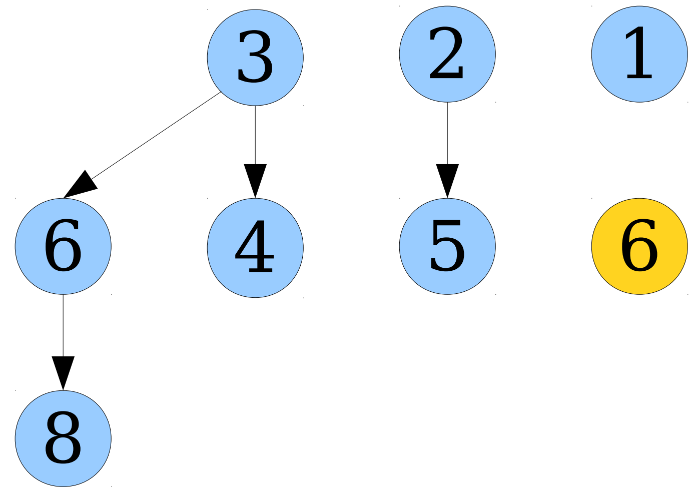
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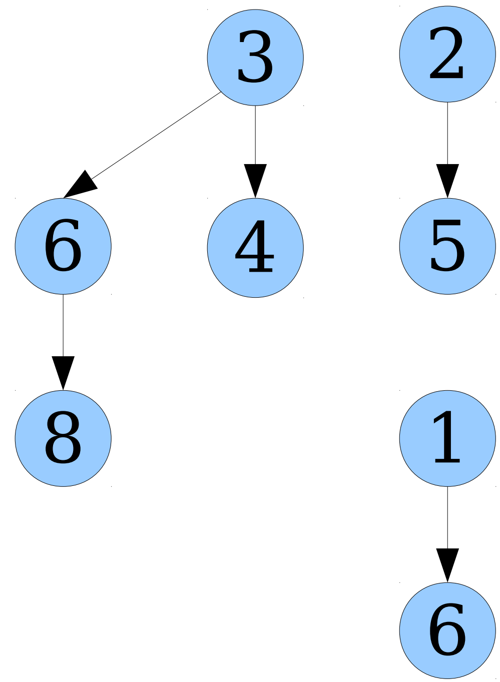
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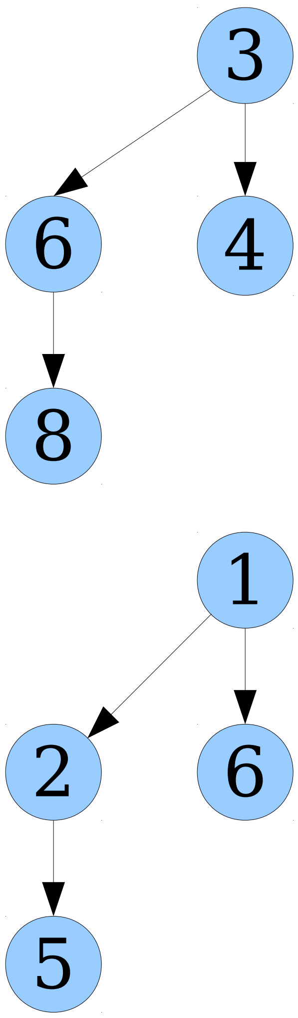
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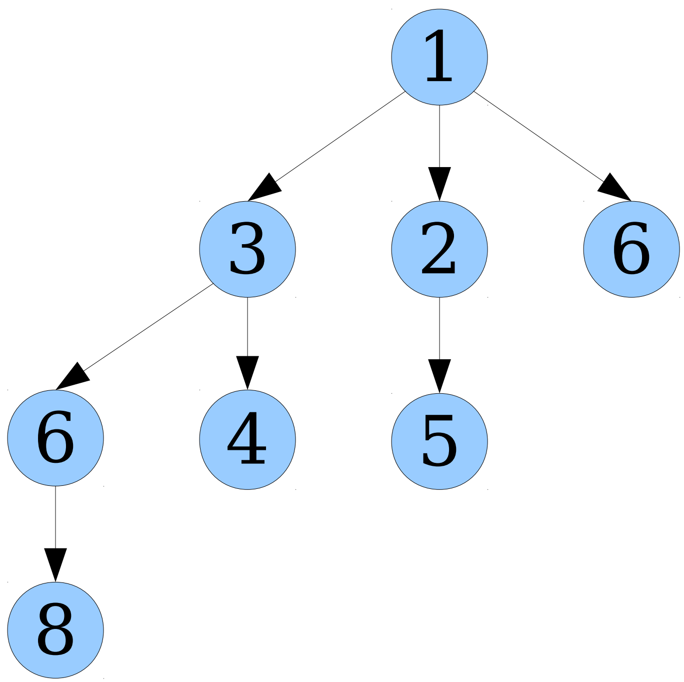
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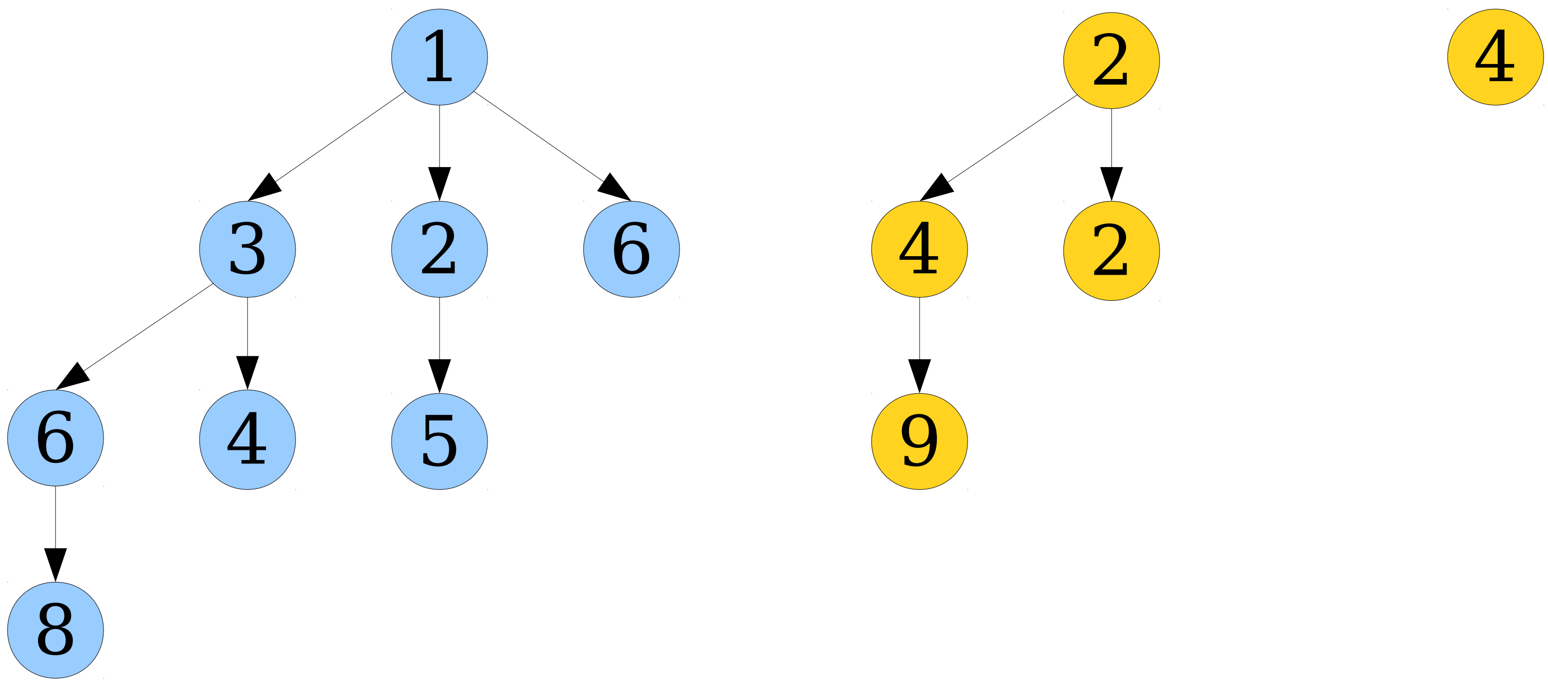
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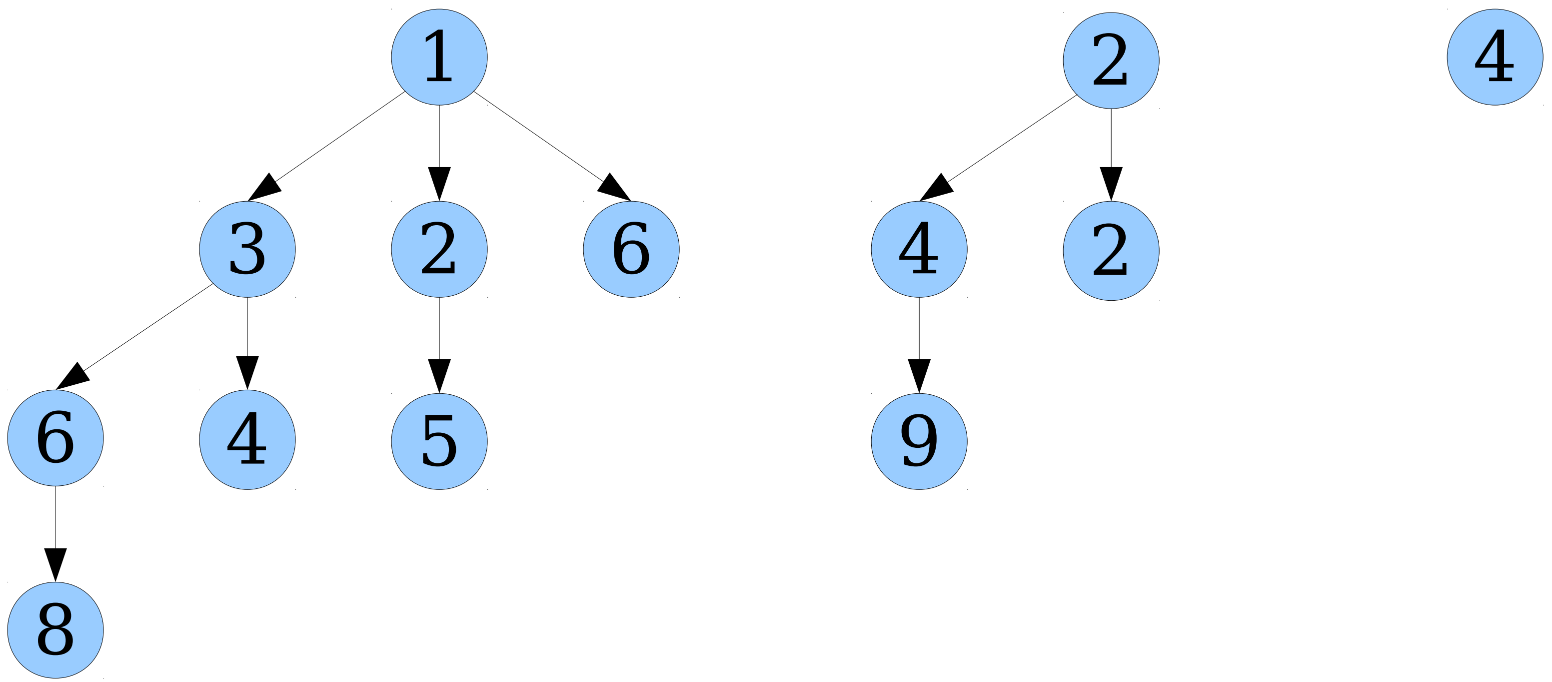
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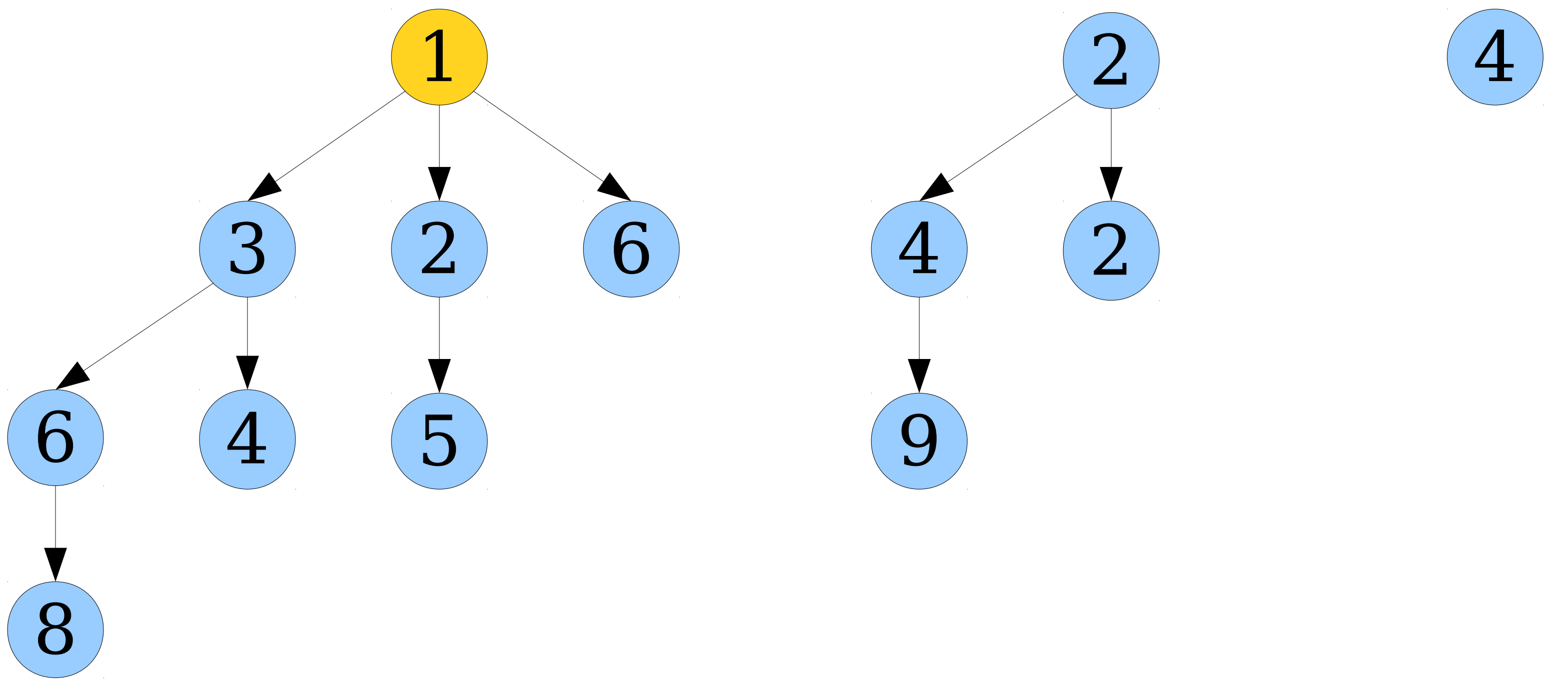
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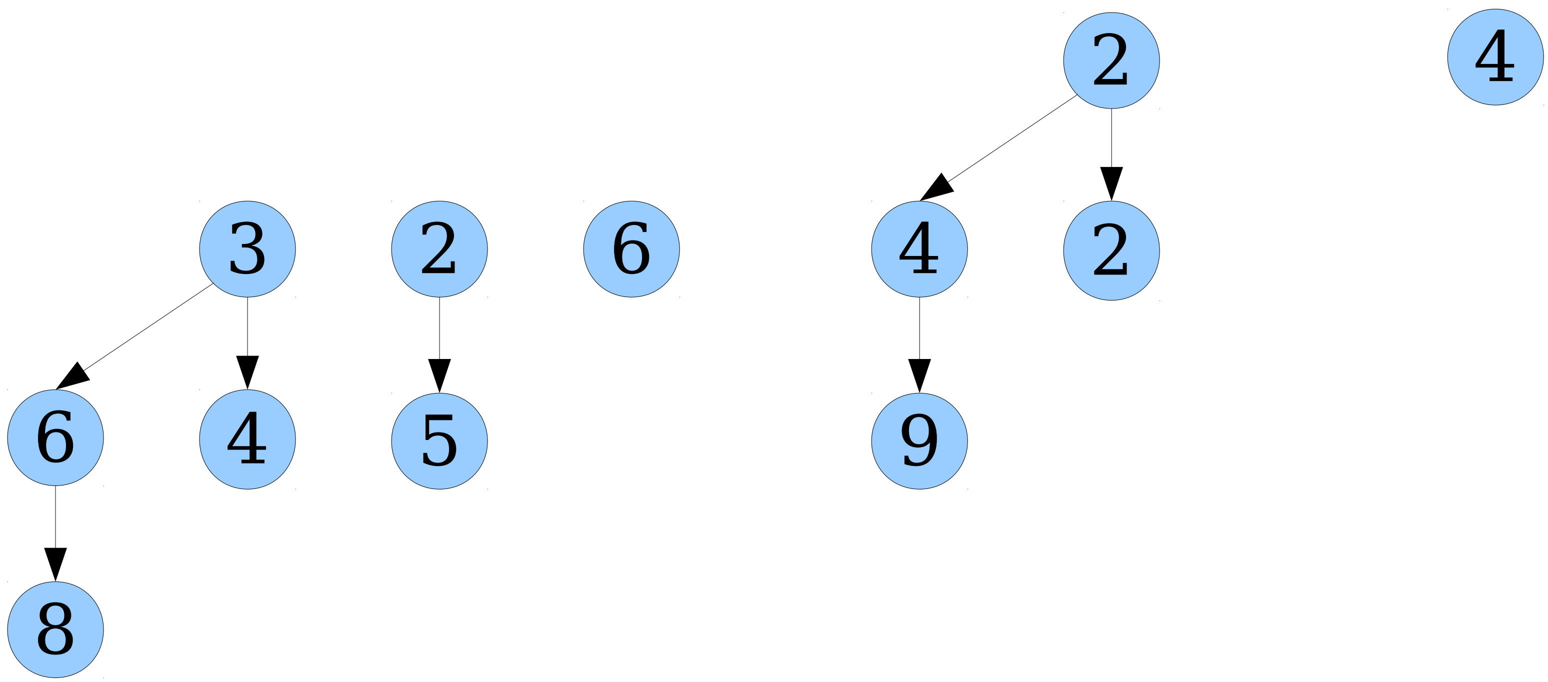
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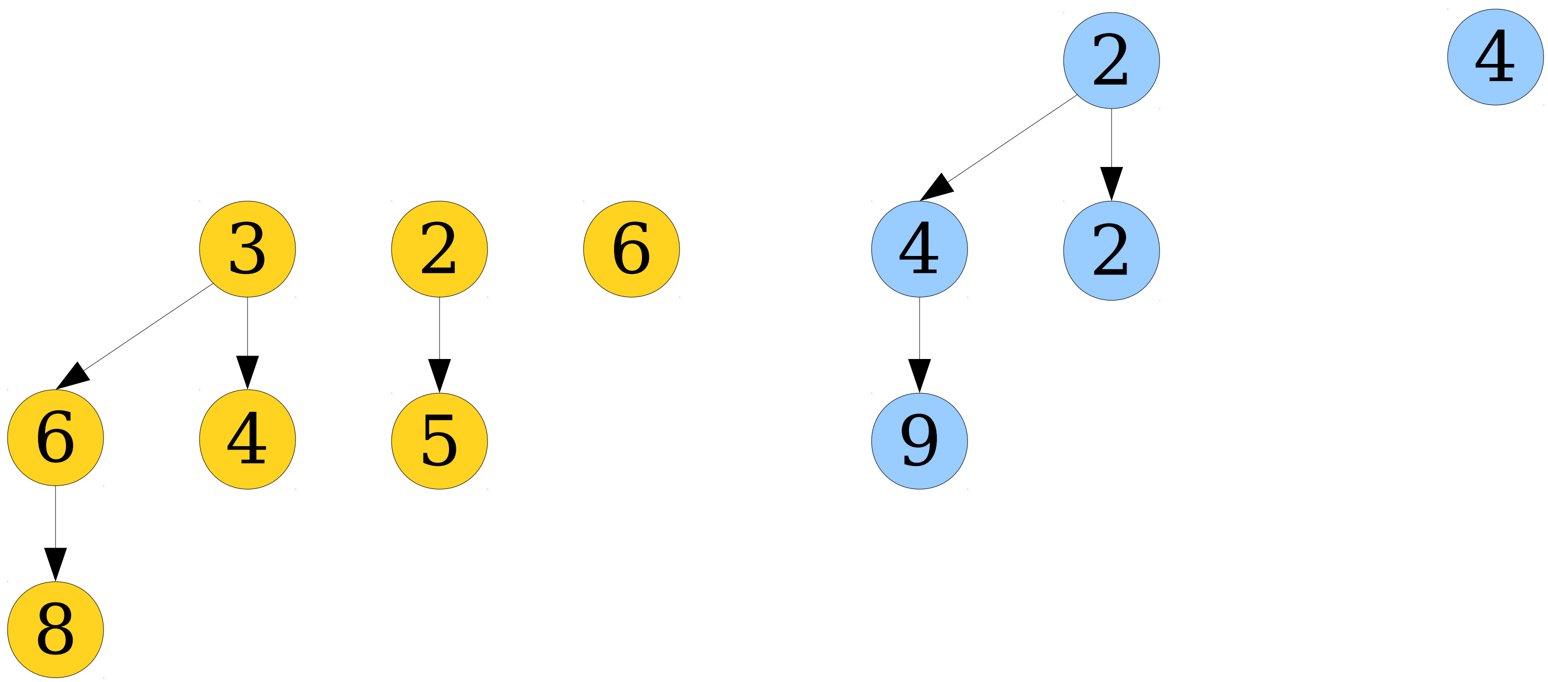
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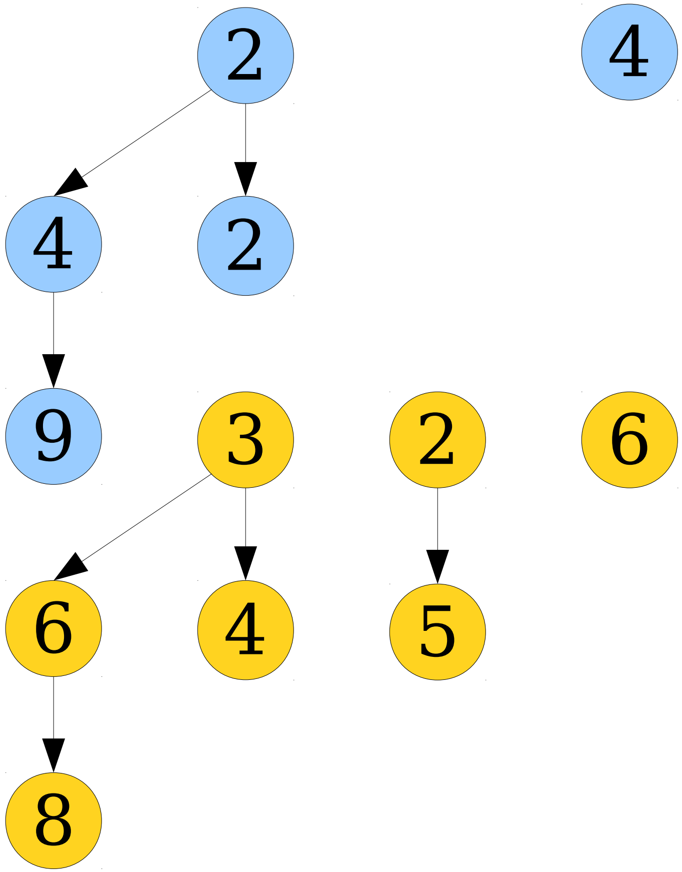
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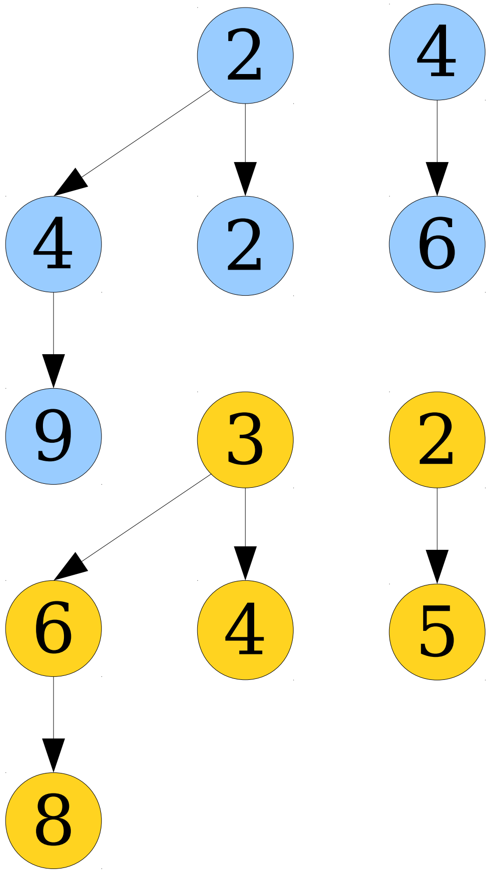
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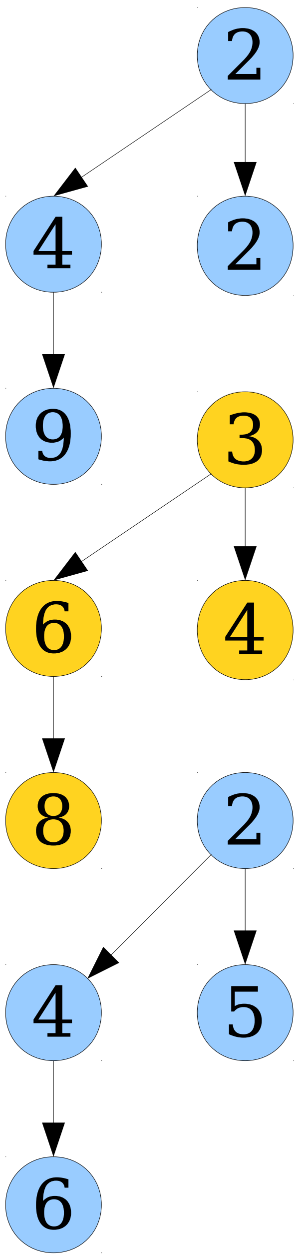
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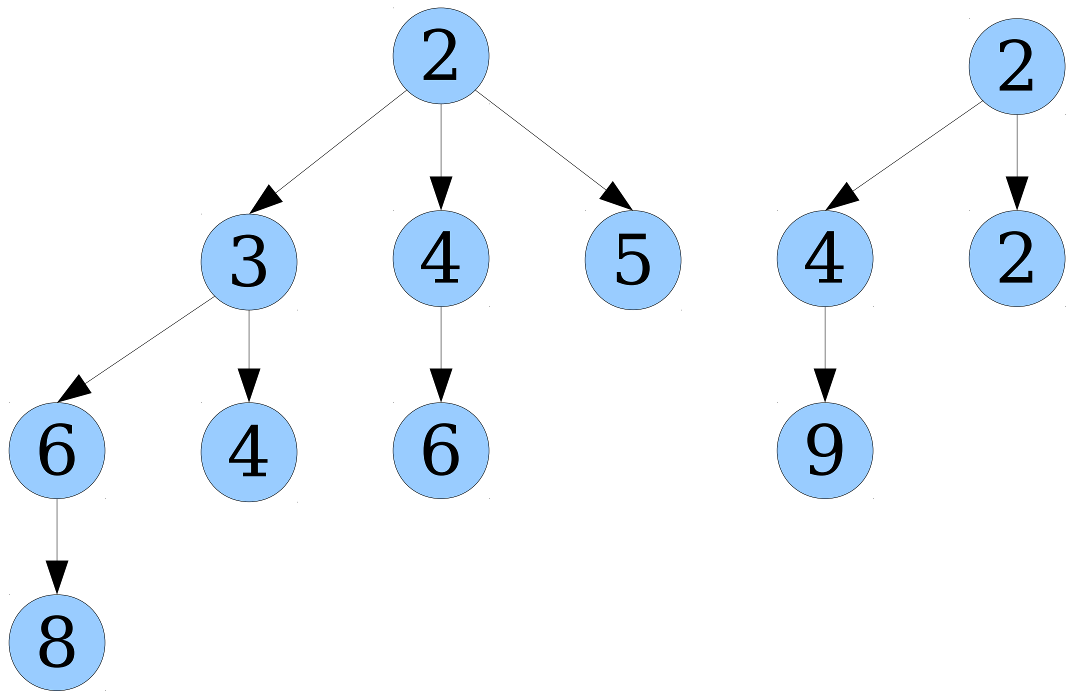
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Time-Out for Announcements!

Problem Sets

- Problem Set Two has been graded. Check GradeScope for details!
- Problem Set Three is due on Thursday of this week.
  - Have questions? Stop by office hours or ask on Piazza!

COMBATTING INEQUITY IN EDUCATION

A CRITICAL CONVERSATION ABOUT THE PATH TOWARD EDUCATION EQUITY IN AMERICA

APRIL 27, 7PM PAUL BREST HALL

PLEASE RSVP HERE: BIT.LY/INEQUITYEDU

WHY IS THE ACHIEVEMENT GAP STILL SO DEEP? WHAT ROLES DO POVERTY AND RACE PLAY IN CREATING AND SUSTAINING THAT GAP? AND HOW DO WE ADDRESS THE ROOT CAUSES OF INEQUITY? JOIN STANFORD PRESIDENT JOHN HENNESSY AS HE MODERATES AN URGENT DISCUSSION ABOUT PERVASIVE INEQUITY IN THE AMERICAN EDUCATION SYSTEM WITH THREE OF THE NATION'S MOST FORWARD-LOOKING EDUCATION THOUGHT LEADERS.

MODERATOR
JOHN L. HENNESSY
PRESIDENT,
STANFORD UNIVERSITY

PANELIST
LINDA DARLING-HAMMOND
FACULTY DIRECTOR,
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FOR OPPORTUNITY AND
POLICY IN EDUCATION

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FOUNDER AND CEO,
KHAN ACADEMY;
GLOBAL EDUCATOR,
ENTREPRENEUR

PANELIST
SEAN F. REARDON
PROFESSOR OF POVERTY
AND INEQUALITY
IN EDUCATION;
STANFORD UNIVERSITY

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Open Xchange

Back to CS166!

Analyzing Insertions

- Each ***enqueue*** into a binomial heap takes time O(log n), since we have to meld the new node into the rest of the trees.
- However, it turns out that the amortized cost of an insertion is lower in the case where we do a series of n insertions.

Adding One

- Suppose we want to execute n++ on the binary representation of n.
- Do the following:
  - Find the longest span of 1's at the right side of n.
  - Flip those 1's to 0's.
  - Set the preceding bit to 1.

1 0 1 1 0

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$$1 \quad 1 \quad 0 \quad 0 \quad 0$$

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- Do the following:
  - Find the longest span of 1's at the right side of n.
  - Flip those 1's to 0's.
  - Set the preceding bit to 1.
- Runtime: $\Theta(b)$, where b is the number of bits flipped.

An Amortized Analysis

- ***Claim:*** Starting at zero, the amortized cost of adding one to the total is O(1).
- ***Idea:*** Use as a potential function the number of 1's in the number.

$\boxed{\Phi = 0}$ 0 0 0 0 0

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$\Phi = 1$ 0 0 0 0 1

Actual cost: 1
$\Delta\Phi$: +1

Amortized cost: **2**

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$\Phi = 1$ 0 0 0 1 0

Actual cost: 2
$\Delta\Phi$: 0

Amortized cost: **2**

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$\boxed{\Phi = 2}$ 0 0 0 1 1

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$\Phi = 2$ 0 0 0 1 1

Actual cost: 1
$\Delta\Phi$: 1

Amortized cost: **2**

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0	0	1	0	0

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$\Phi = 1$

0 0 1 0 0

Actual cost: 3

$\Delta\Phi$: -1

Amortized cost: **2**

Properties of Binomial Heaps

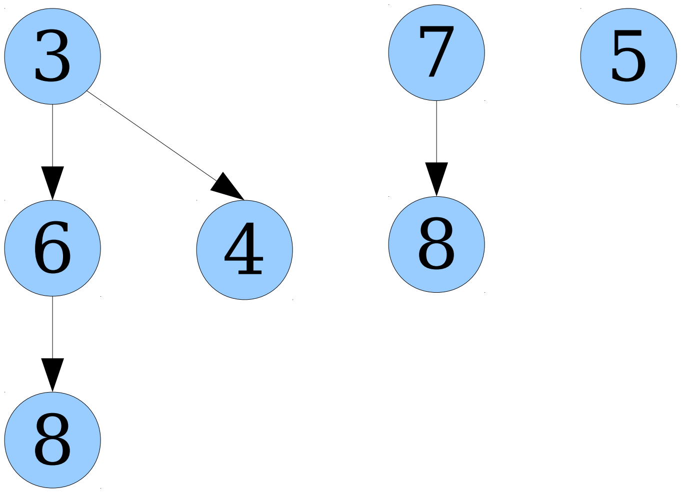
- Starting with an empty binomial heap, the amortized cost of each insertion into the heap is O(1), assuming there are no deletions.
- ***Rationale:*** Binomial heap operations are isomorphic to integer arithmetic.
- Since the amortized cost of incrementing a binary counter starting at zero is O(1), the amortized cost of enqueuing into an initially empty binomial heap is O(1).

Binomial vs Binary Heaps

- Interesting comparison:
  - The cost of inserting n elements into a binary heap, one after the other, is $\Theta(n \log n)$ in the worst-case.
  - If n is known in advance, a binary heap can be constructed out of n elements in time $\Theta(n)$.
  - The cost of inserting n elements into a binomial heap, one after the other, is $\Theta(n)$, even if n is not known in advance!

A Catch

- This amortized time bound does not hold if ***enqueue*** and ***extract-min*** are intermixed.
- ***Intuition:*** Can force expensive insertions to happen repeatedly.



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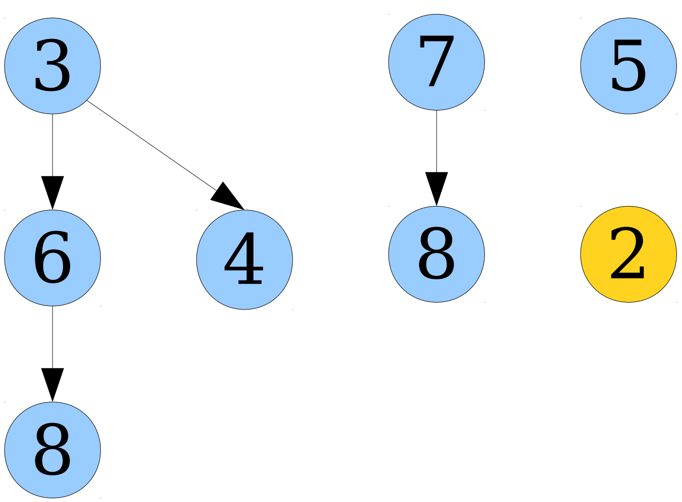

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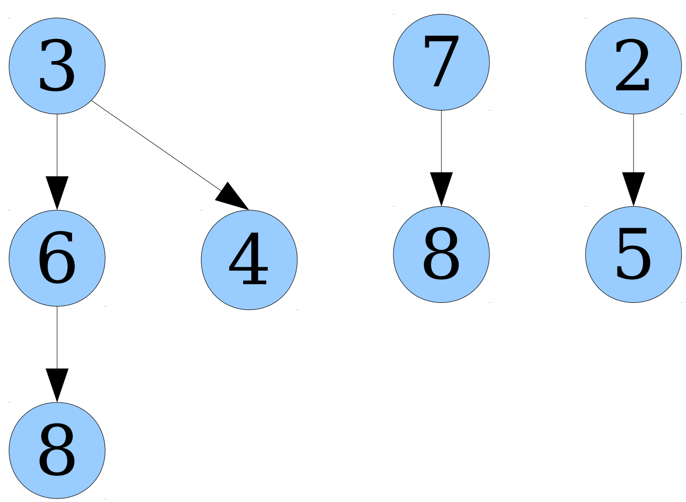

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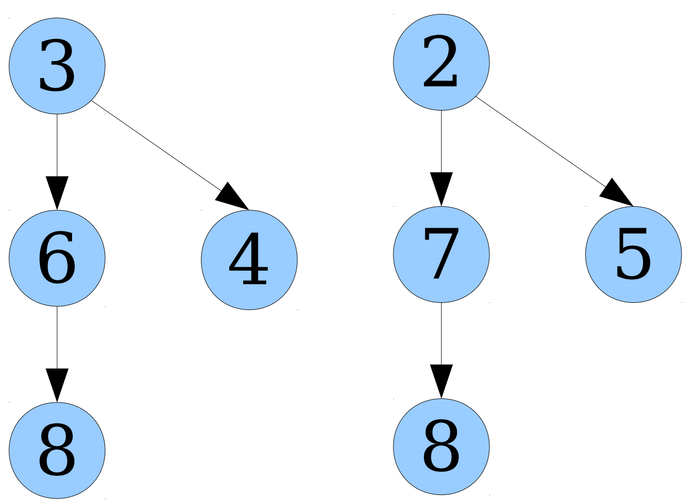

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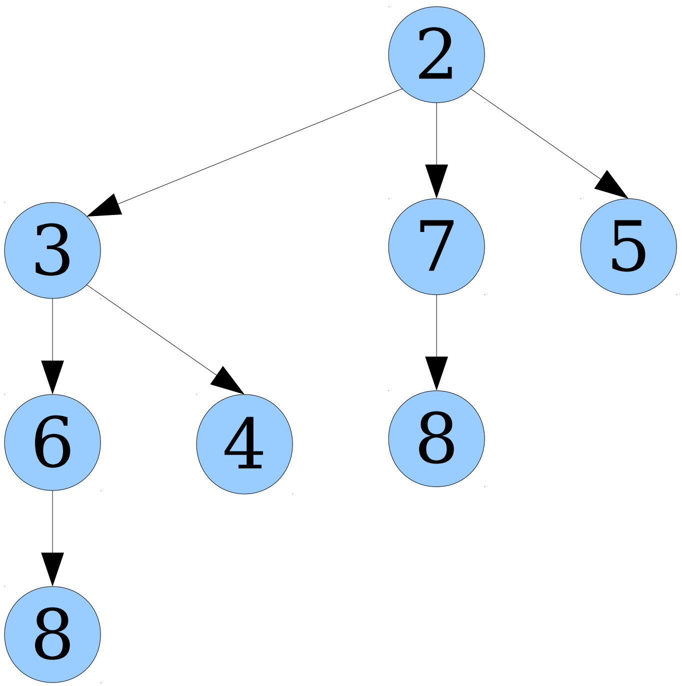

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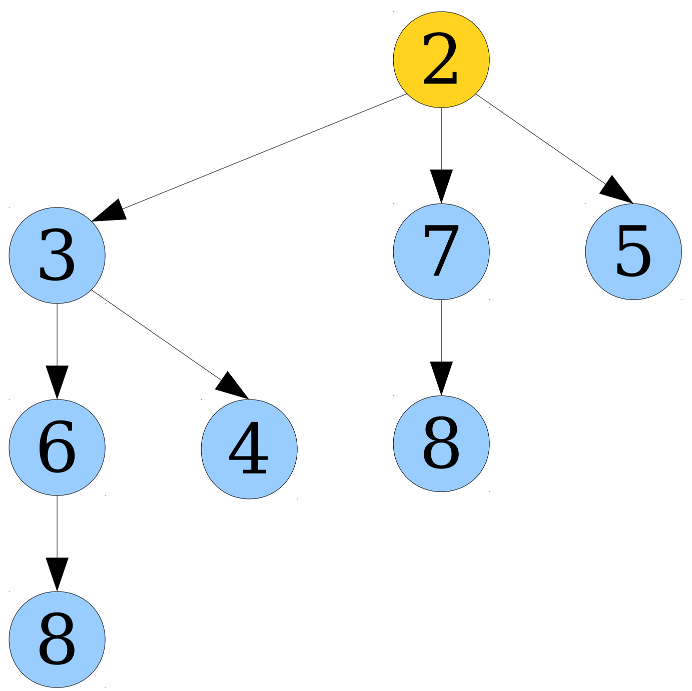

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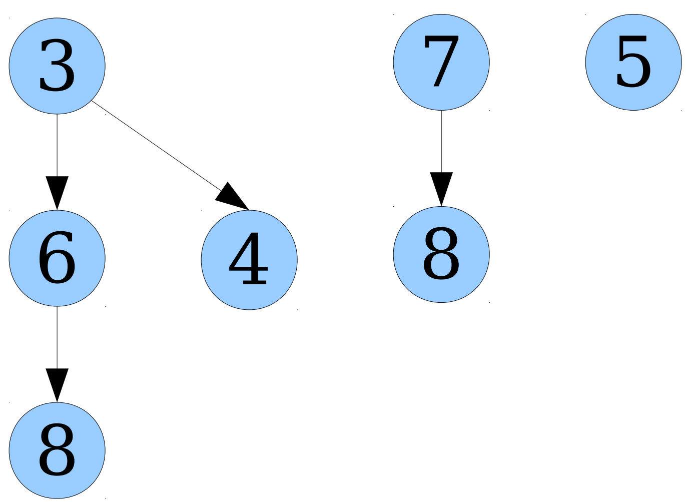

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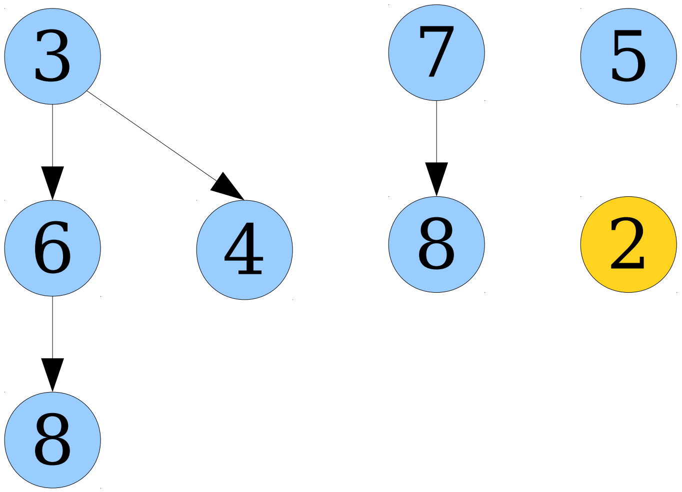

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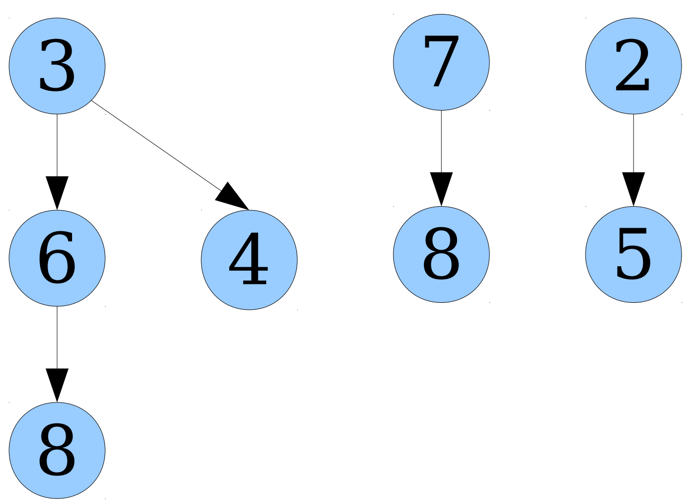

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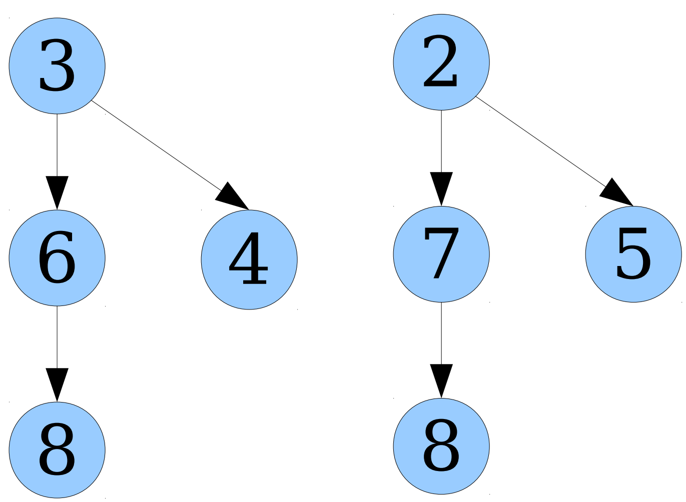

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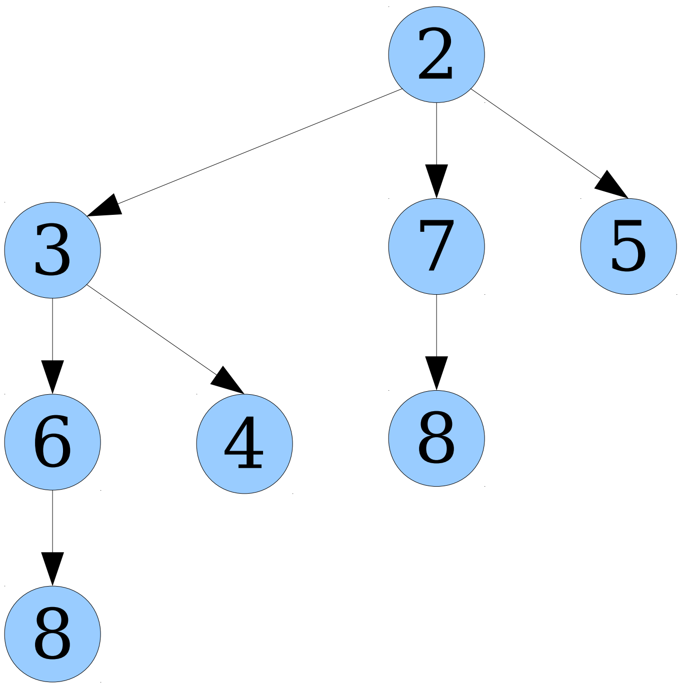

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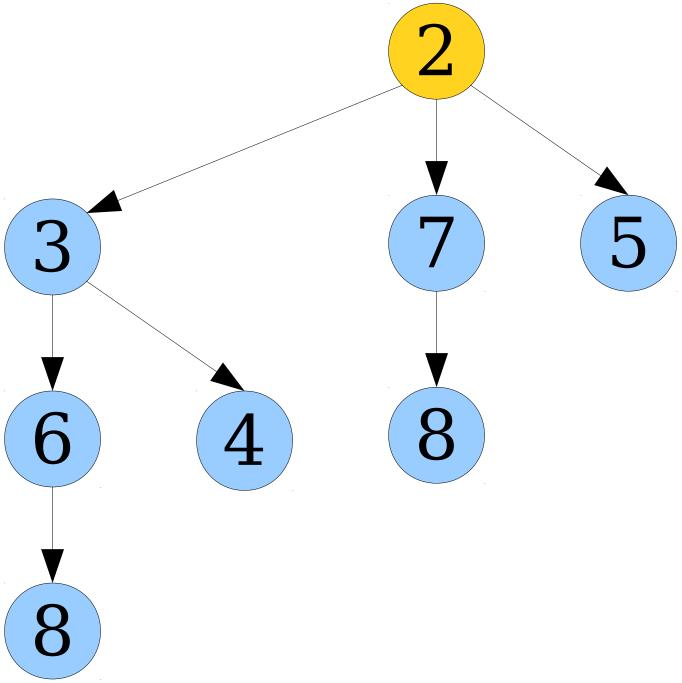

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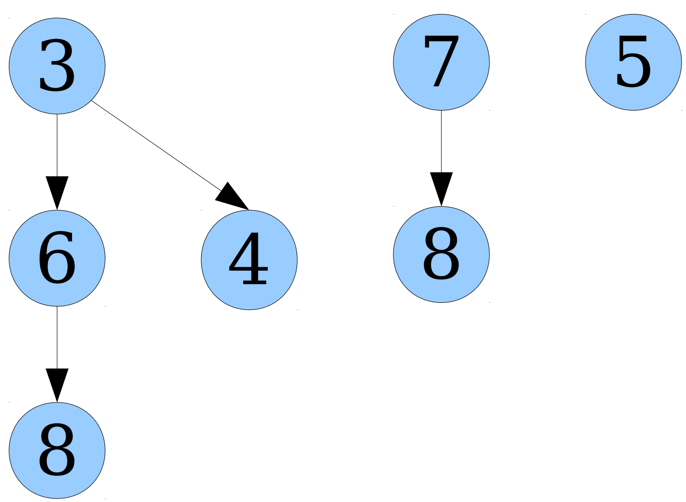


Question: Can we make insertions amortized O(1), regardless of whether we do deletions?

Where's the Cost?

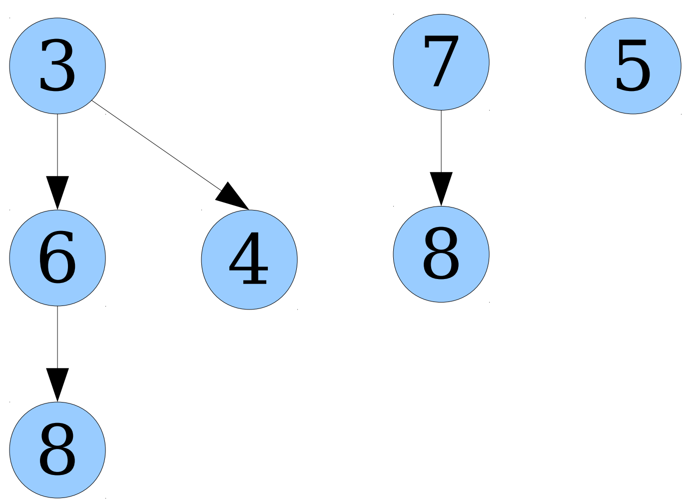
- Why does ***enqueue*** take time O(log *n*)?
- ***Answer***: May have to combine together O(log *n*) different binomial trees together into a single tree.
- ***New Question***: What happens if we don't combine trees together?
- That is, what if we just add a new singleton tree to the list?

Lazy Melding

- More generally, consider the following lazy melding approach:

  To meld together two binomial heaps, just combine the two sets of trees together.

- If we assume the trees are stored in doubly-linked lists, this can be done in time O(1).



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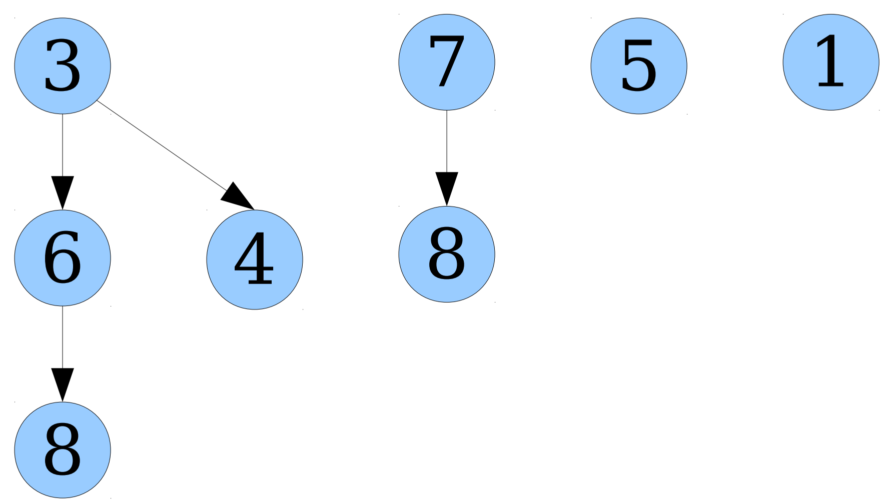

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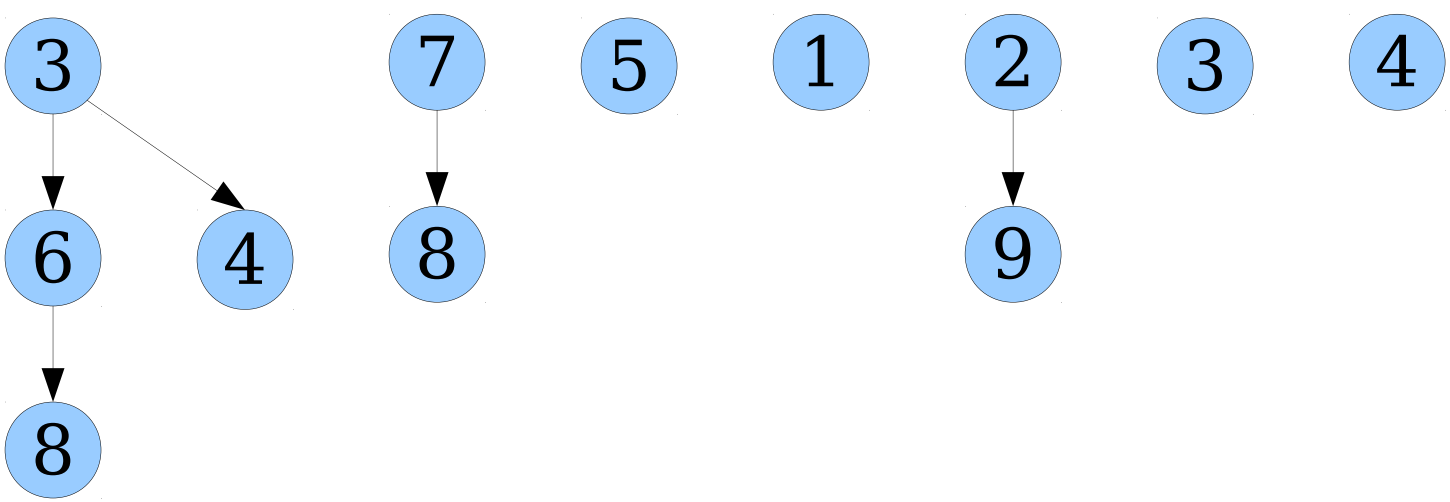
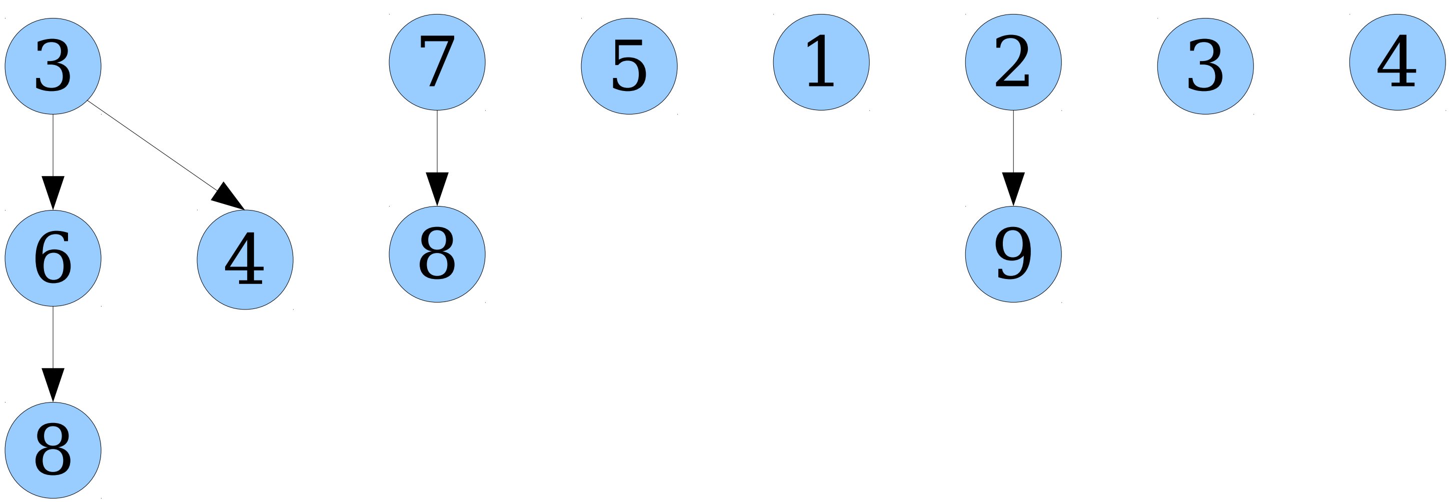


The Catch: Part One

- When we use eager melding, the number of trees is O(log n).
- Therefore, ***find-min*** runs in time O(log n).
- ***Problem:*** ***find-min*** no longer runs in time O(log n) because there can be Θ(n) trees.



A Solution

- Have the binomial heap store a pointer to the minimum element.
- Can be updated in time O(1) after doing a meld by comparing the minima of the two heaps.

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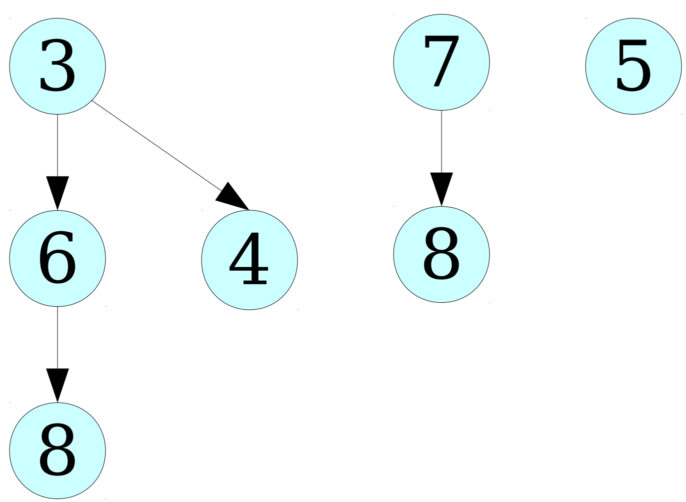

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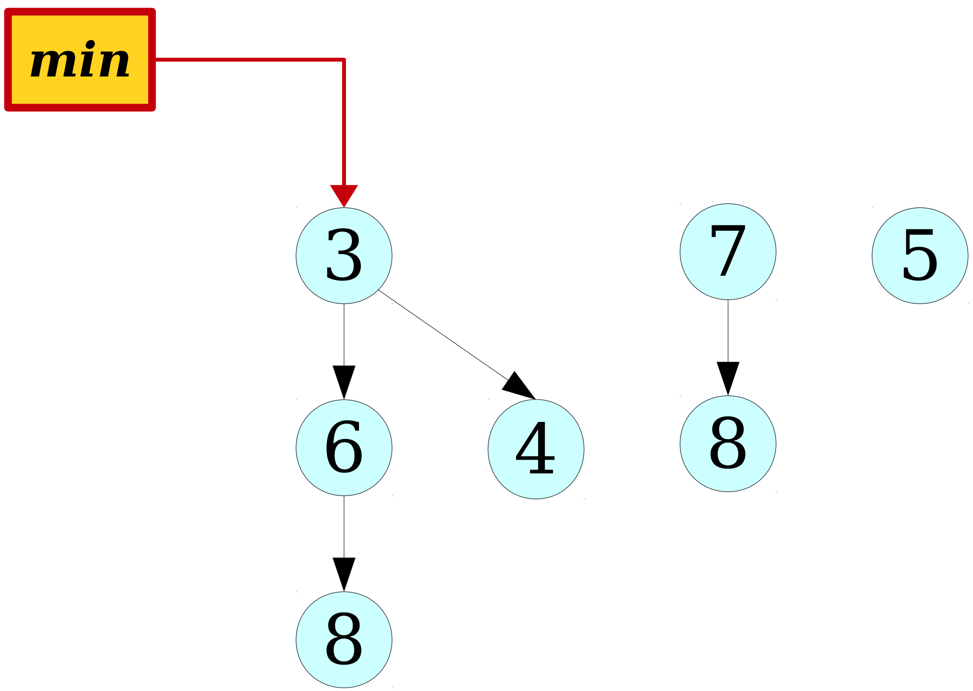

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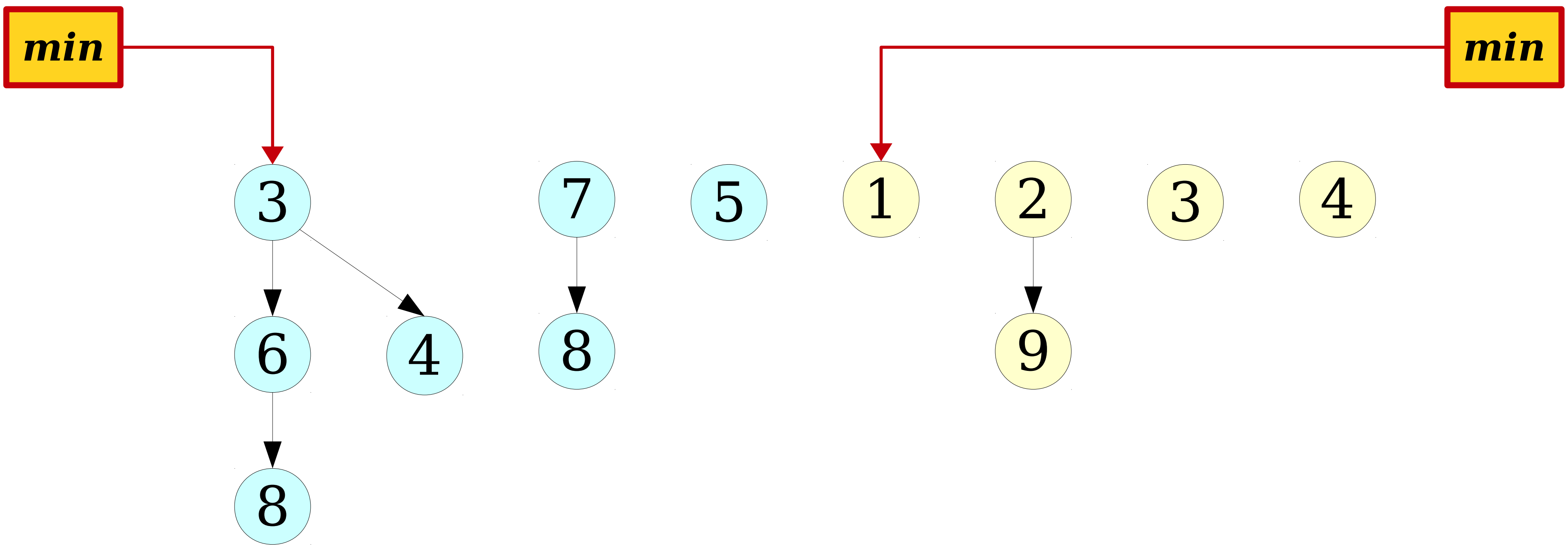

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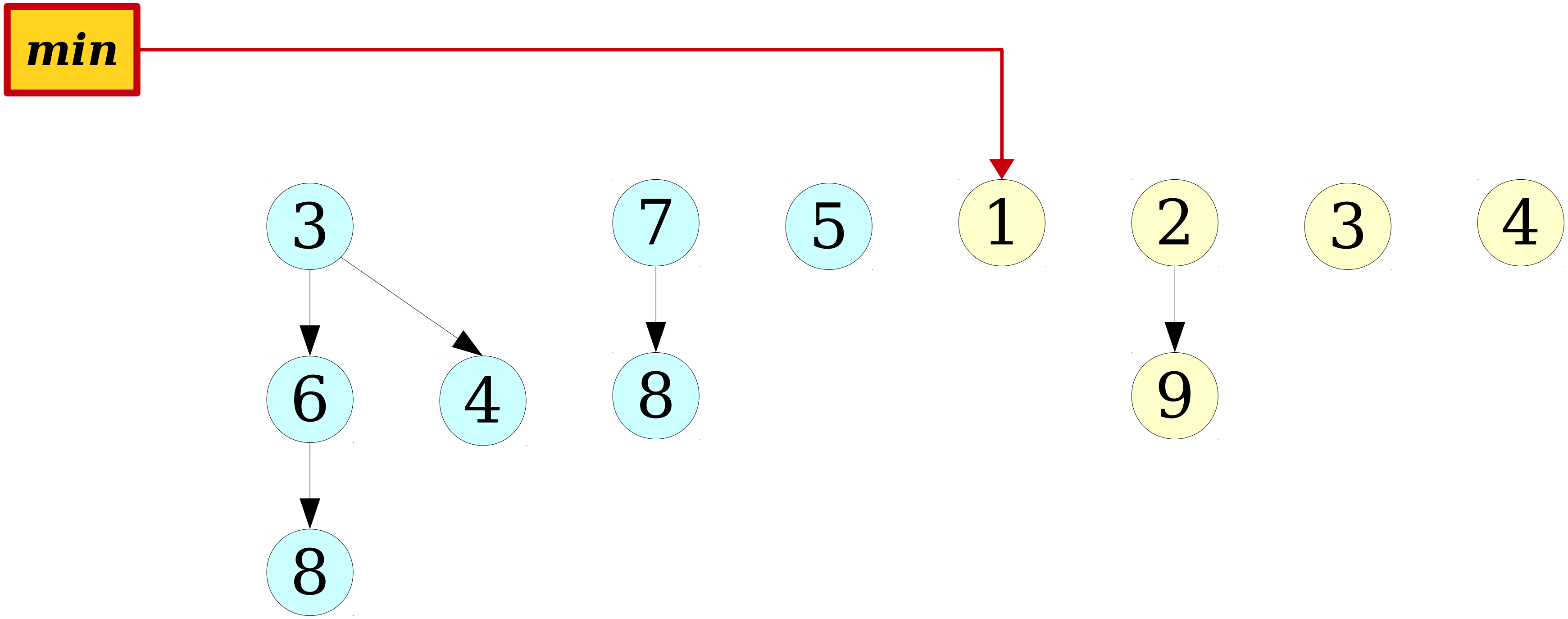

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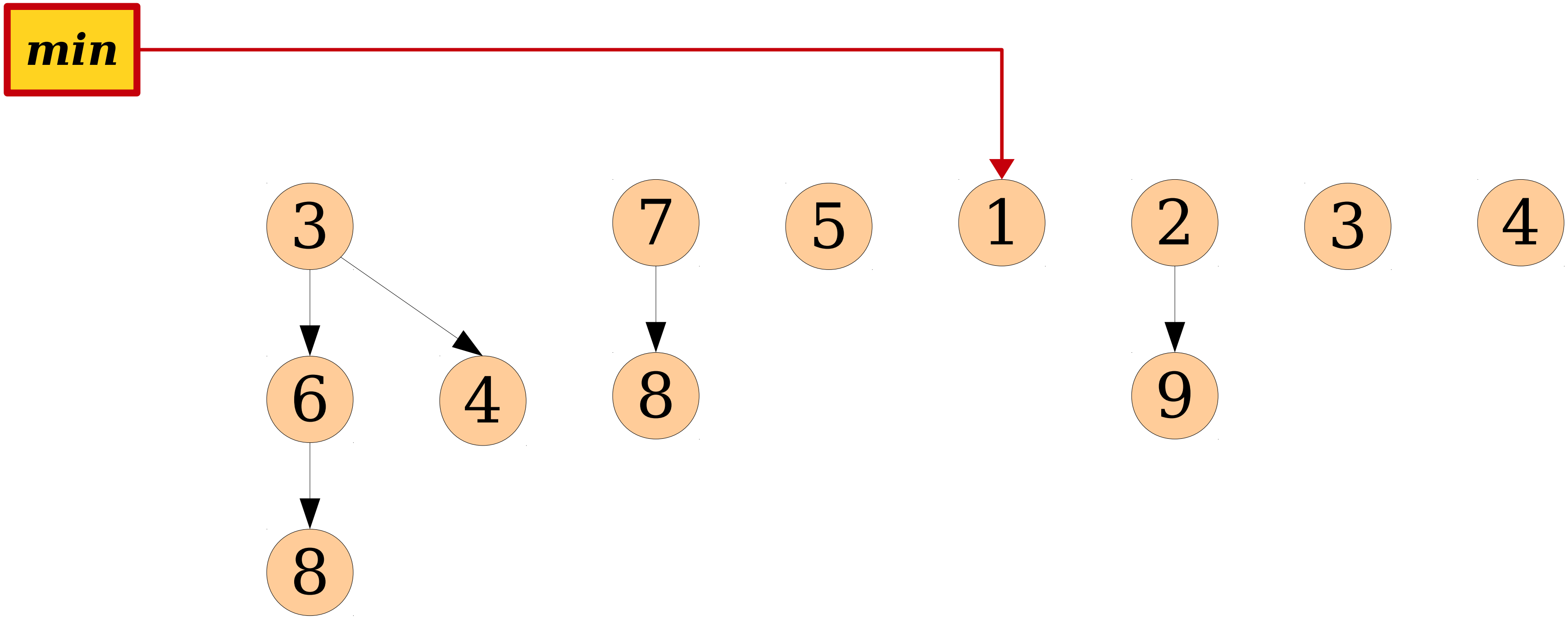
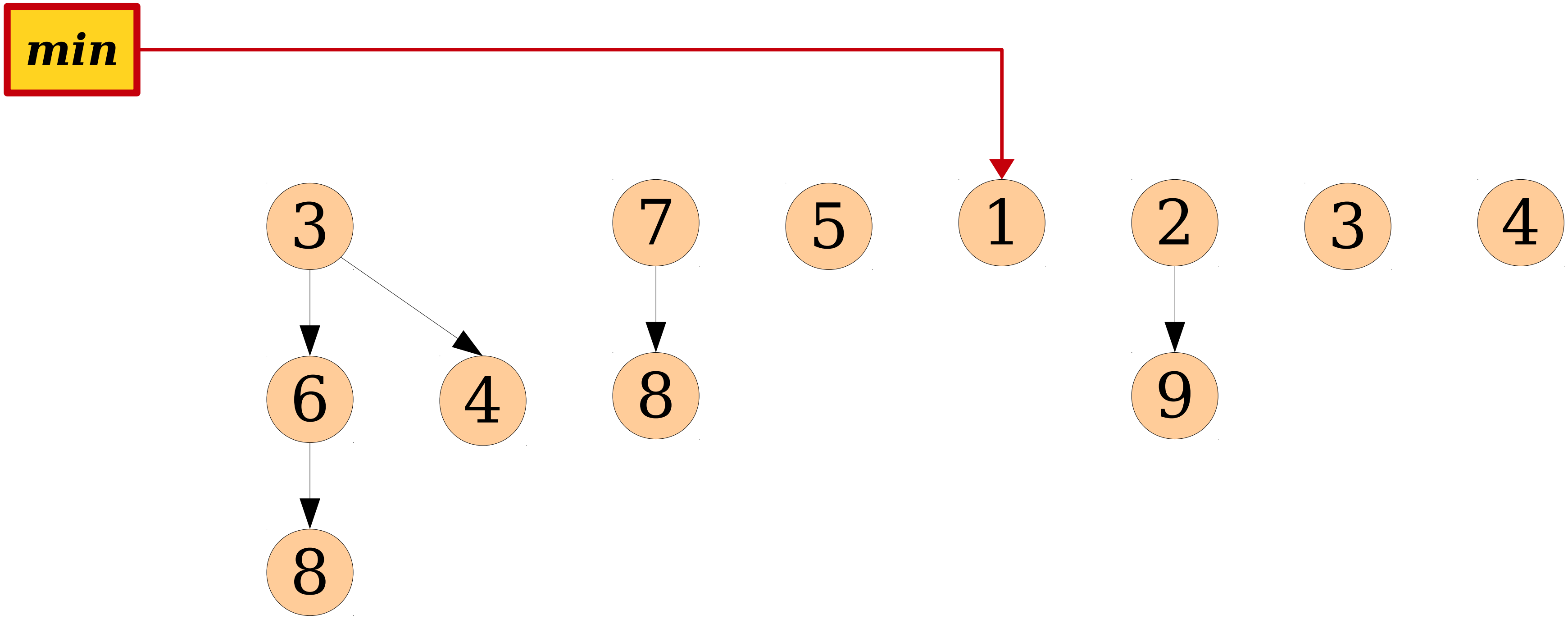


The Catch: Part Two

- Even with a pointer to the minimum, deletions might now run in time $\Theta(n)$.
- ***Rationale:*** Need to update the pointer to the minimum.



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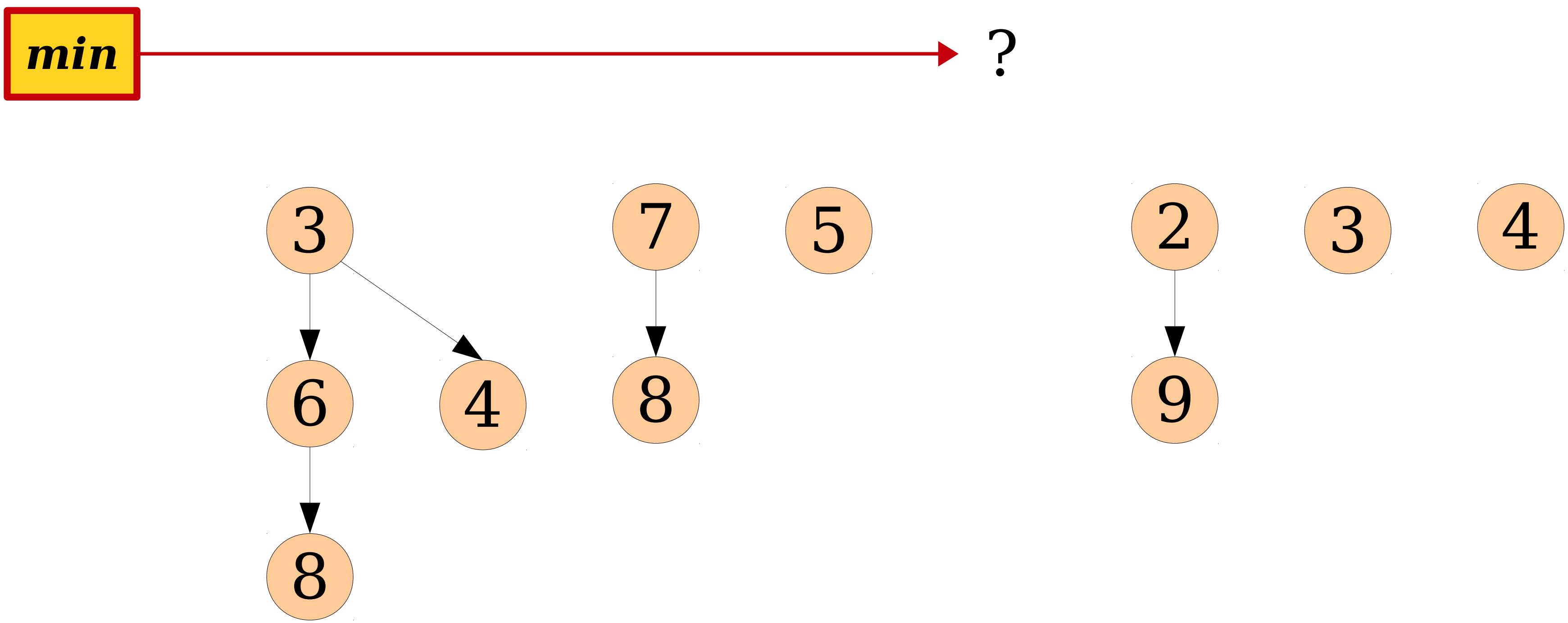

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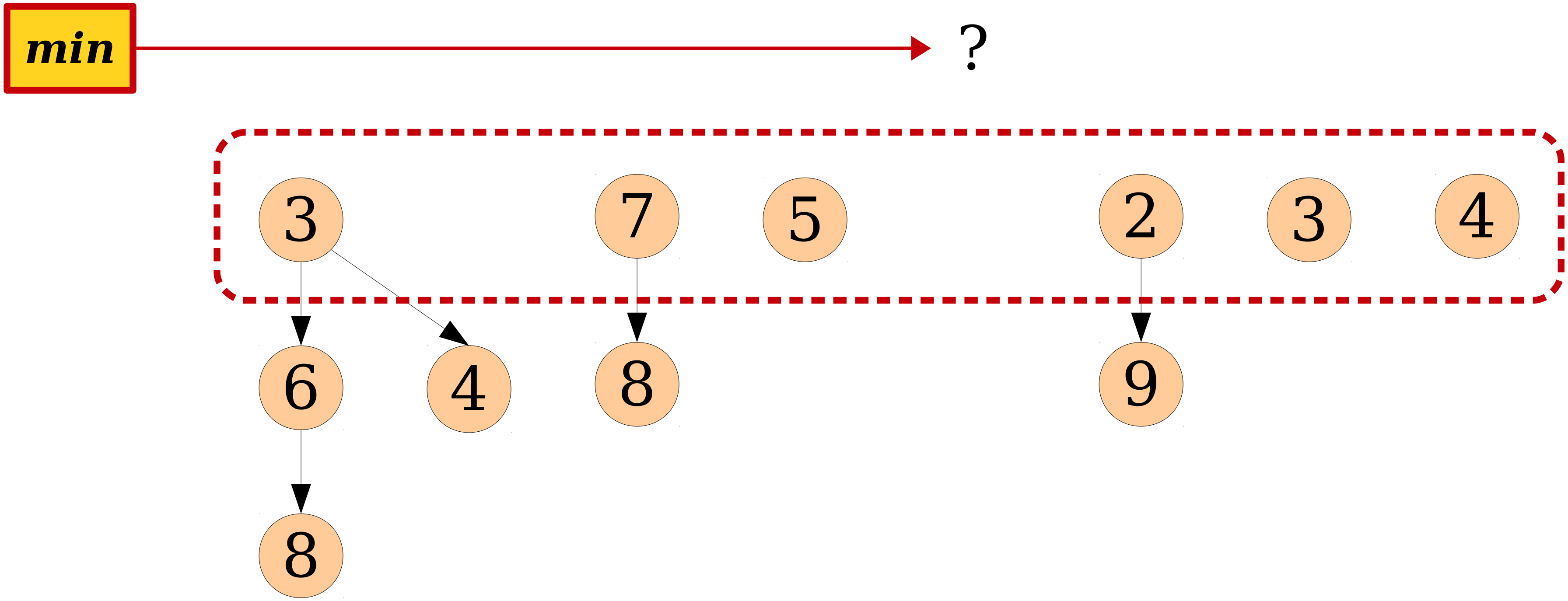

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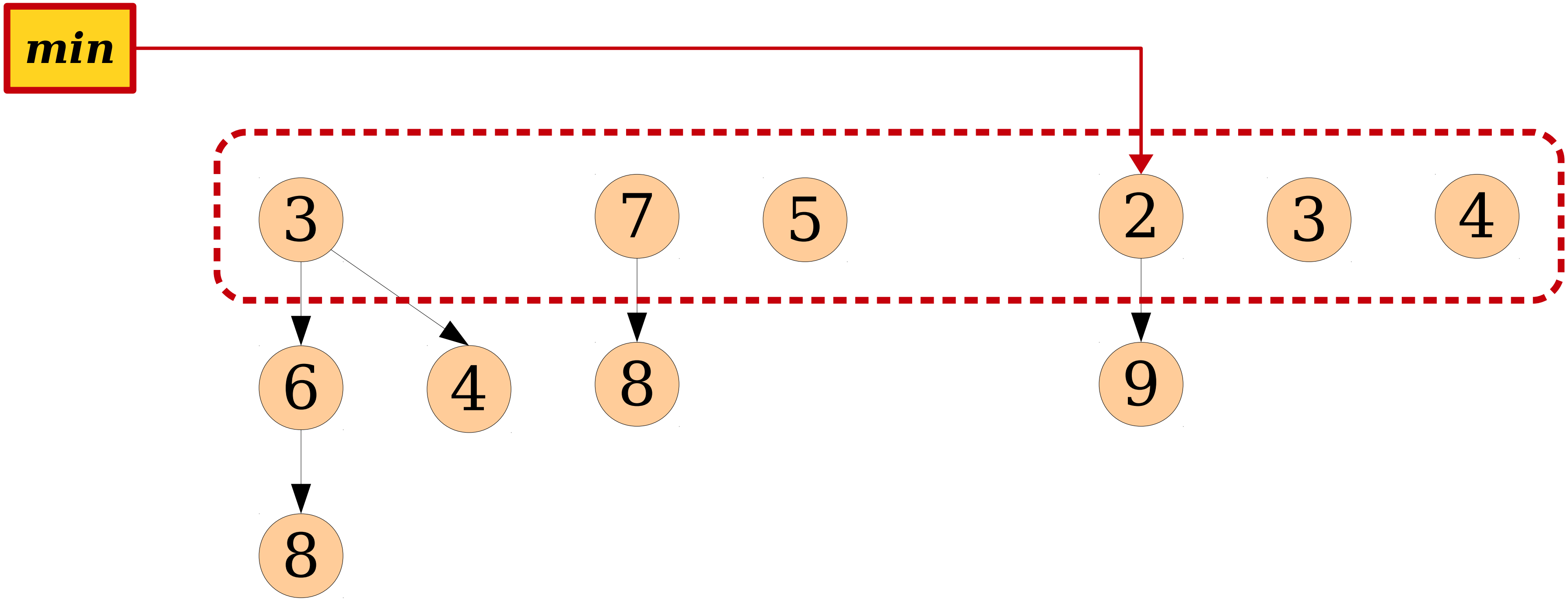

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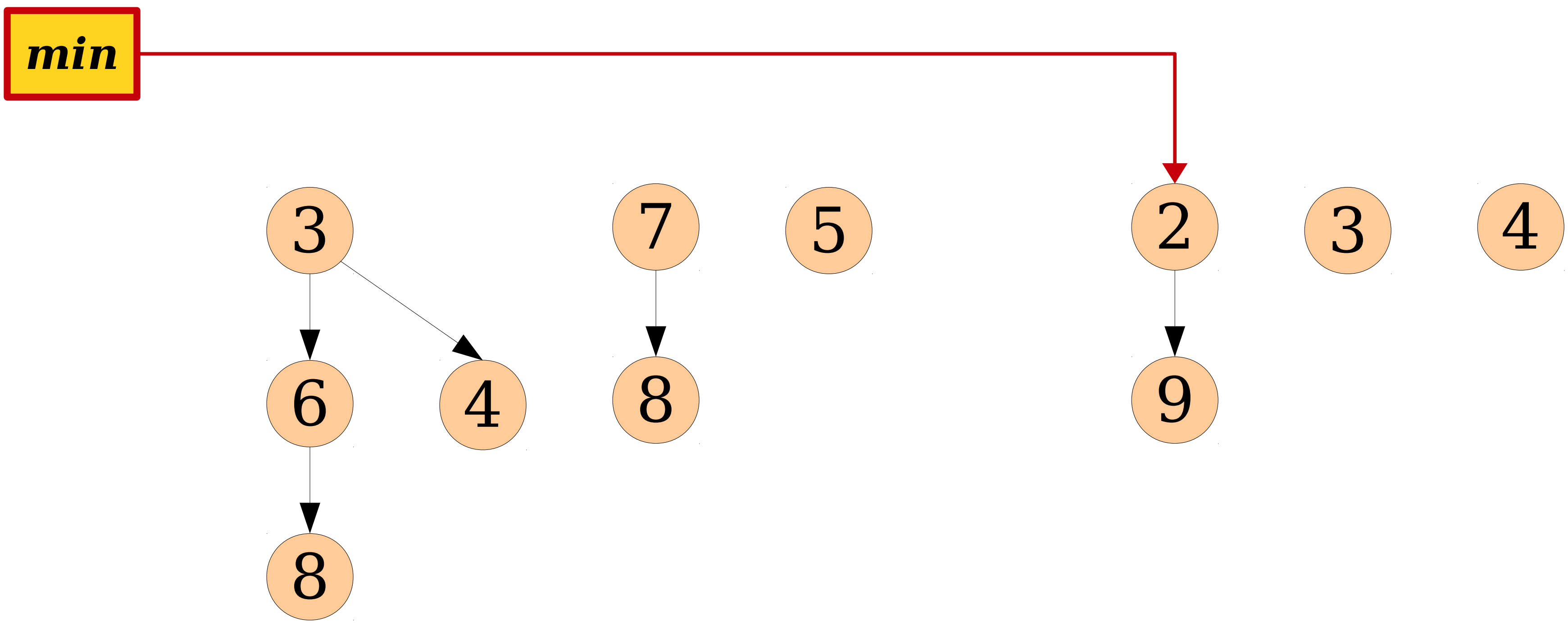
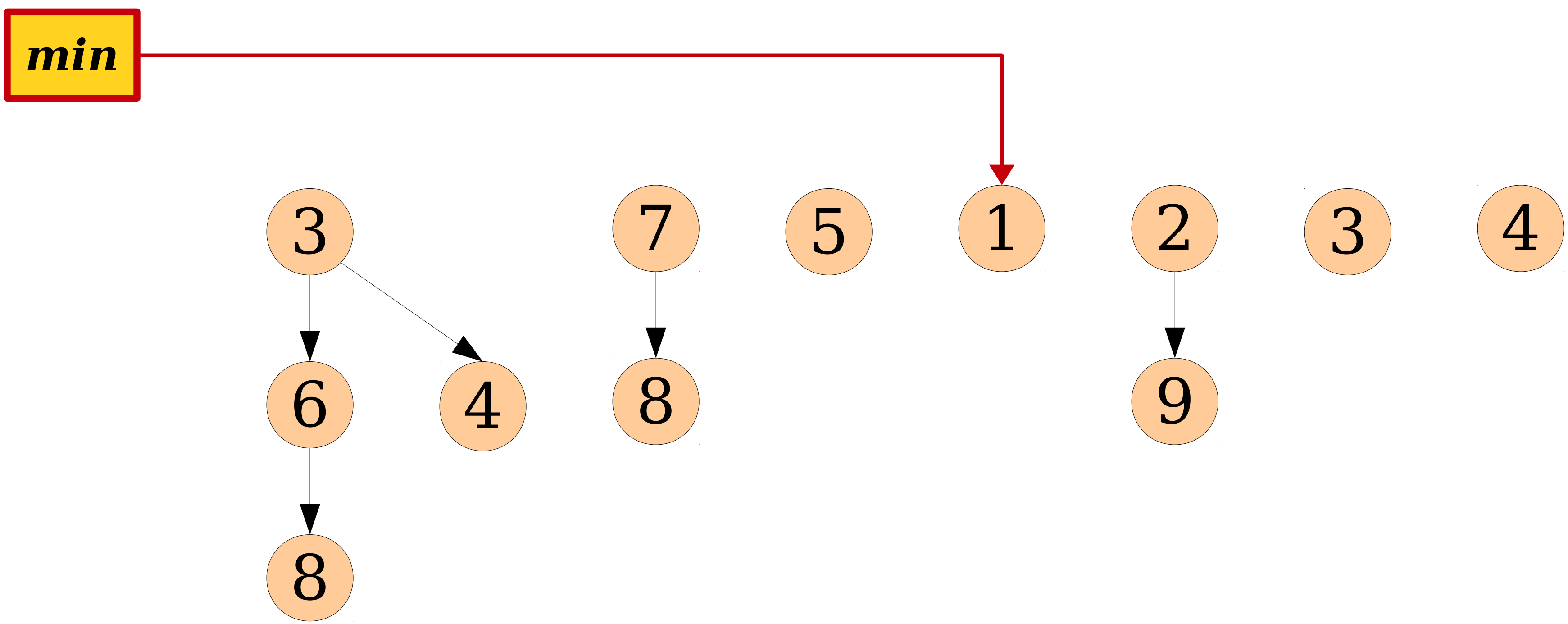


Resolving the Issue

- ***Idea:*** When doing an ***extract-min***, coalesce all of the trees so that there's at most one tree of each order.
- Intuitively:
  - The number of trees in a heap grows slowly (only during an insert or meld).
  - The number of trees in a heap drops rapidly after coalescing (down to O(log n)).
  - Can backcharge the work done during an ***extract-min*** to ***enqueue*** or ***meld***.

Coalescing Trees

- Our eager melding algorithm assumes that
  - there is either zero or one tree of each order, and that
  - the trees are stored in ascending order.
- ***Challenge:*** When coalescing trees in this case, neither of these properties necessarily hold.



Wonky Arithmetic

- Let's turn back to arithmetic to get an intuition for how to solve this problem.

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Sum: **19**
Bits Needed: **5**

4	2	8	2	1	1	1

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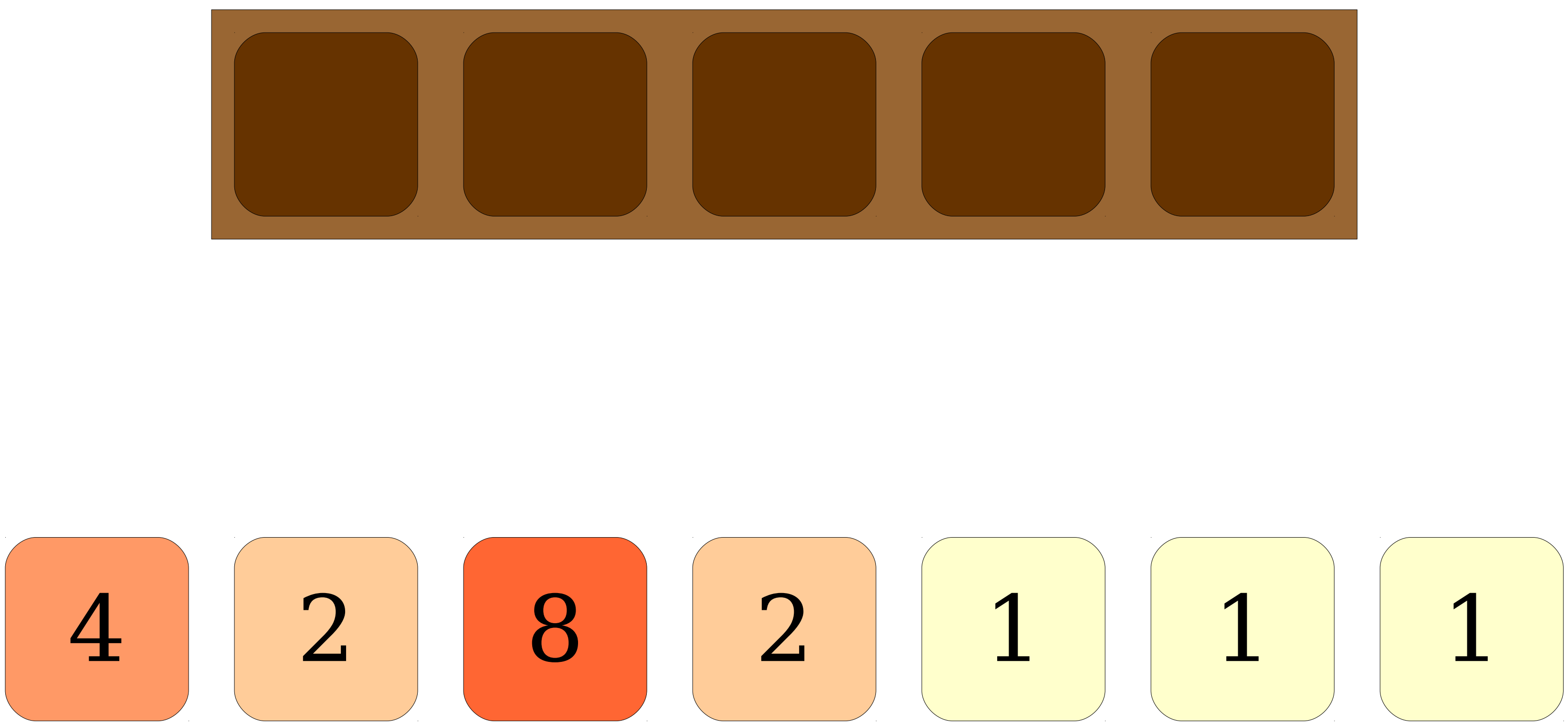

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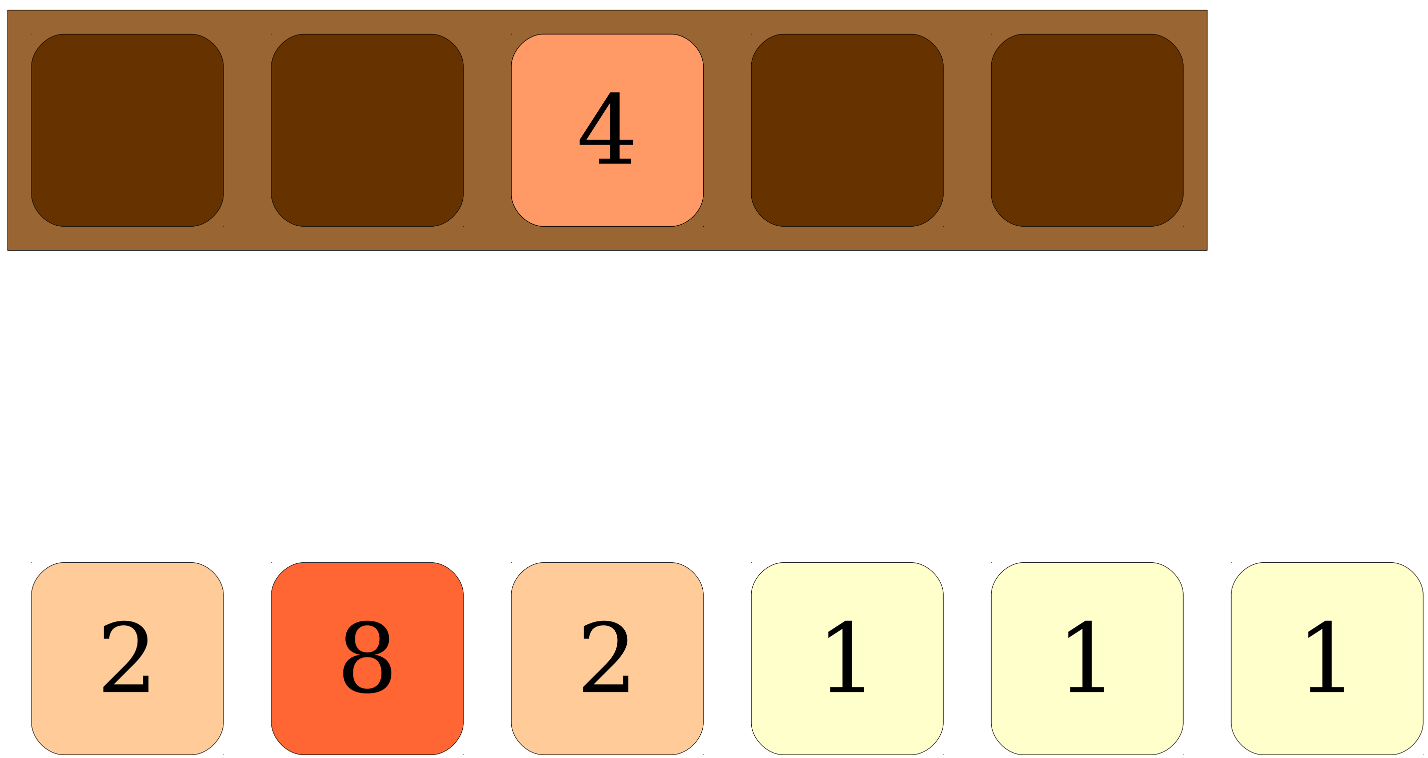

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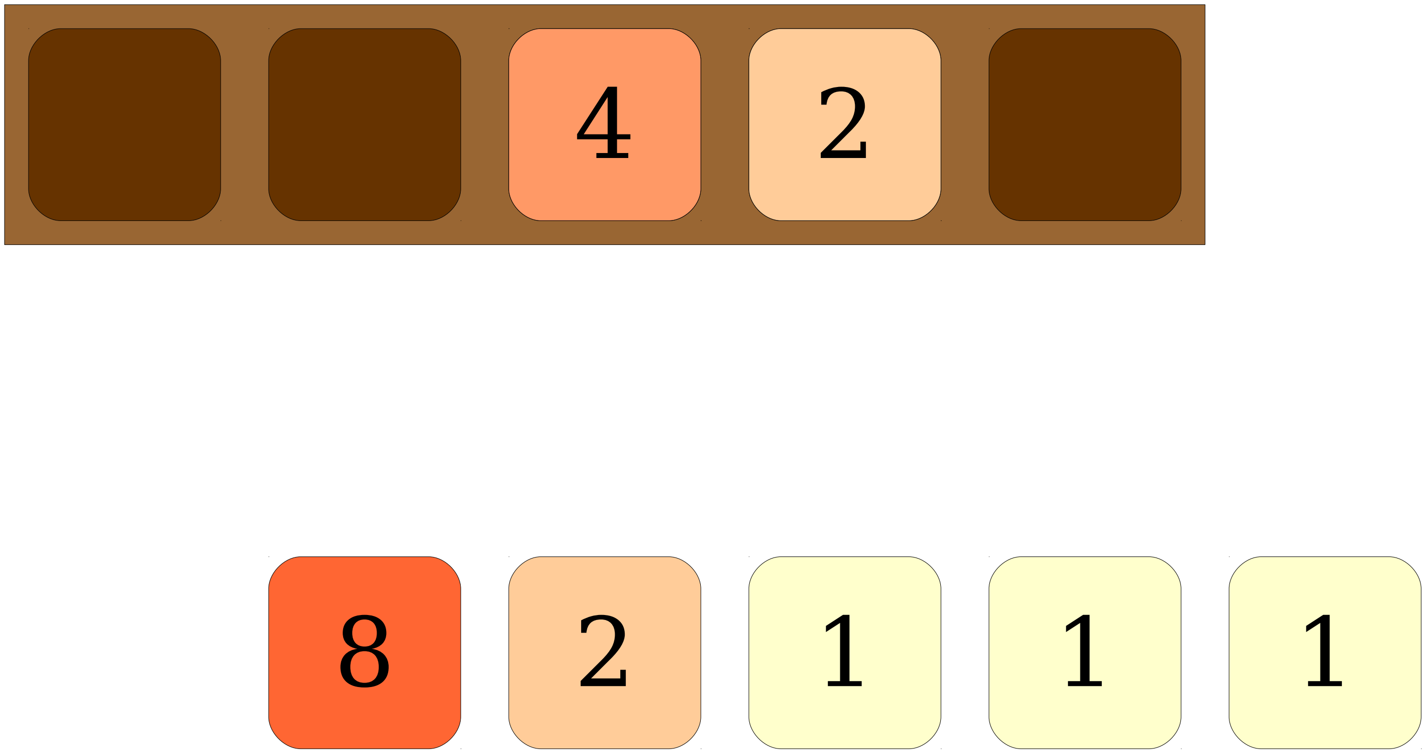

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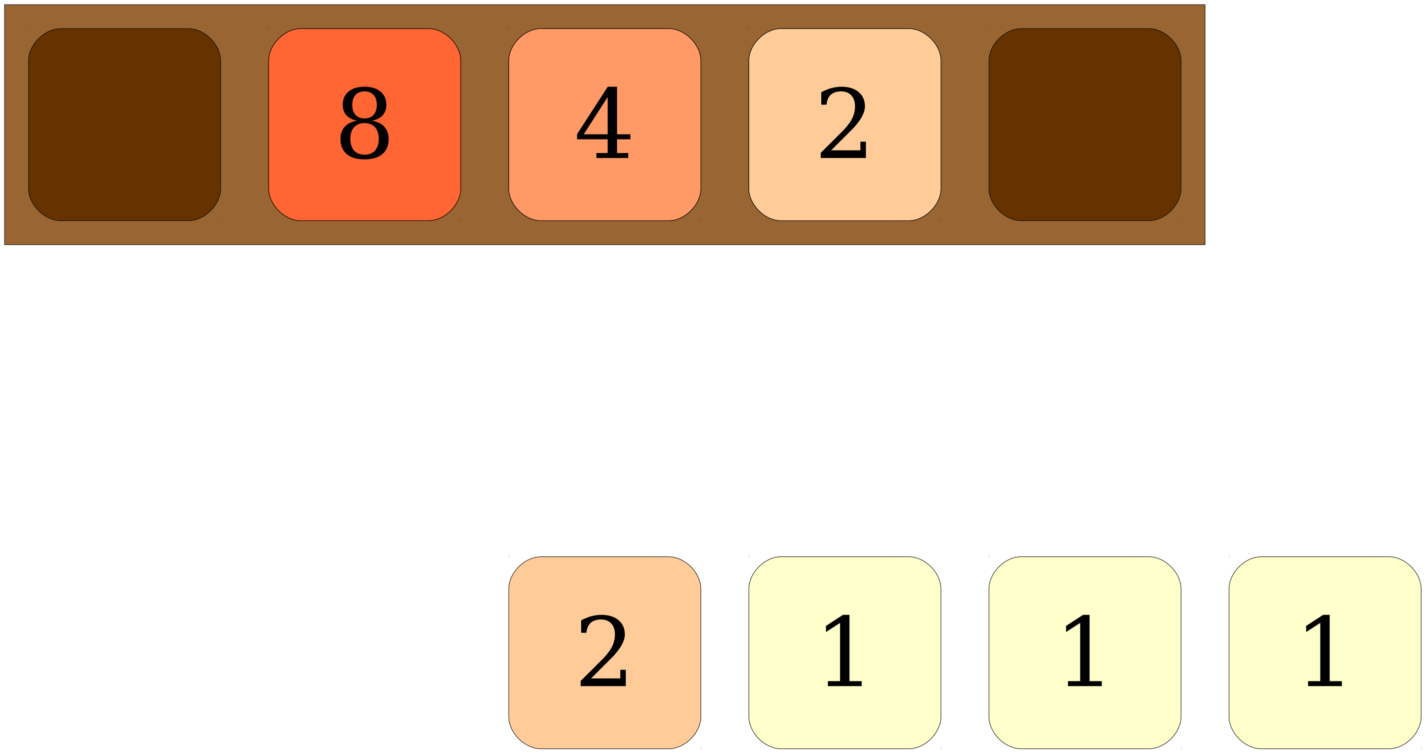

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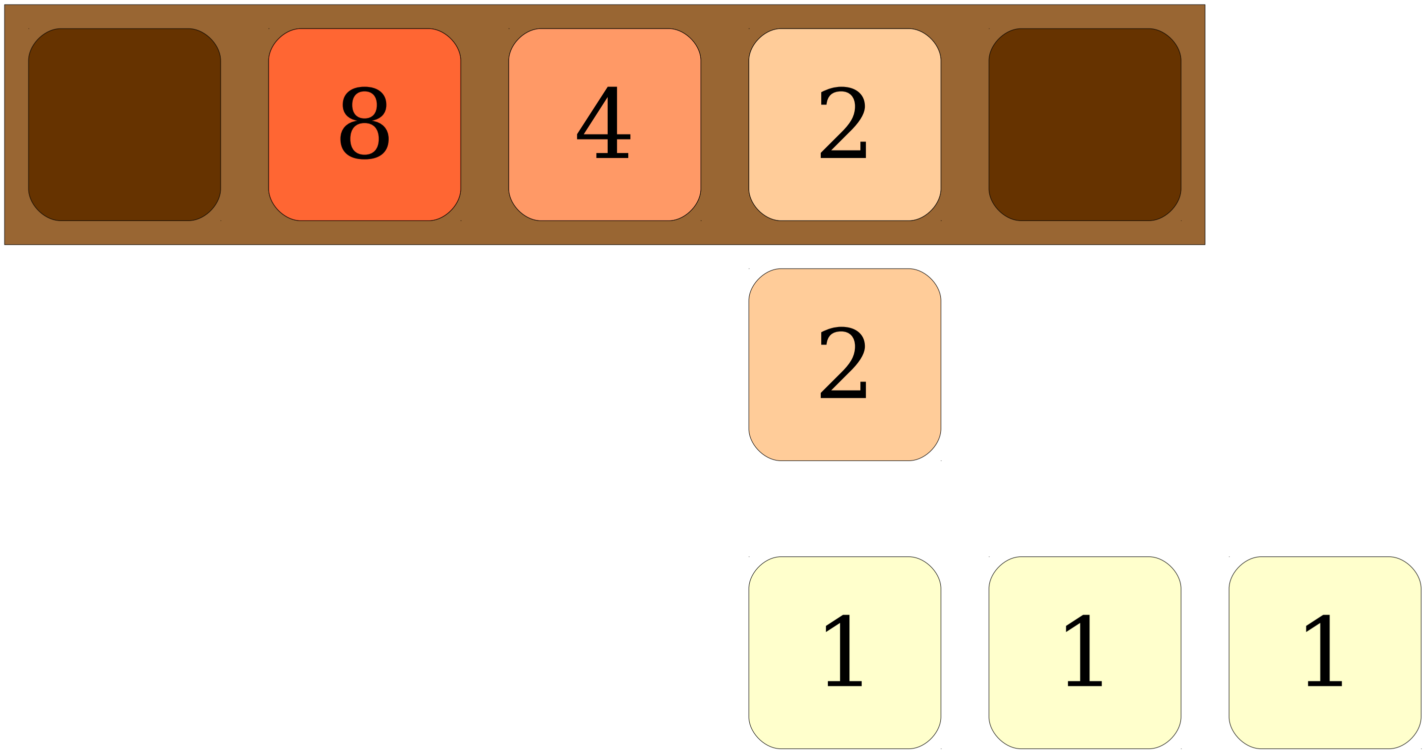

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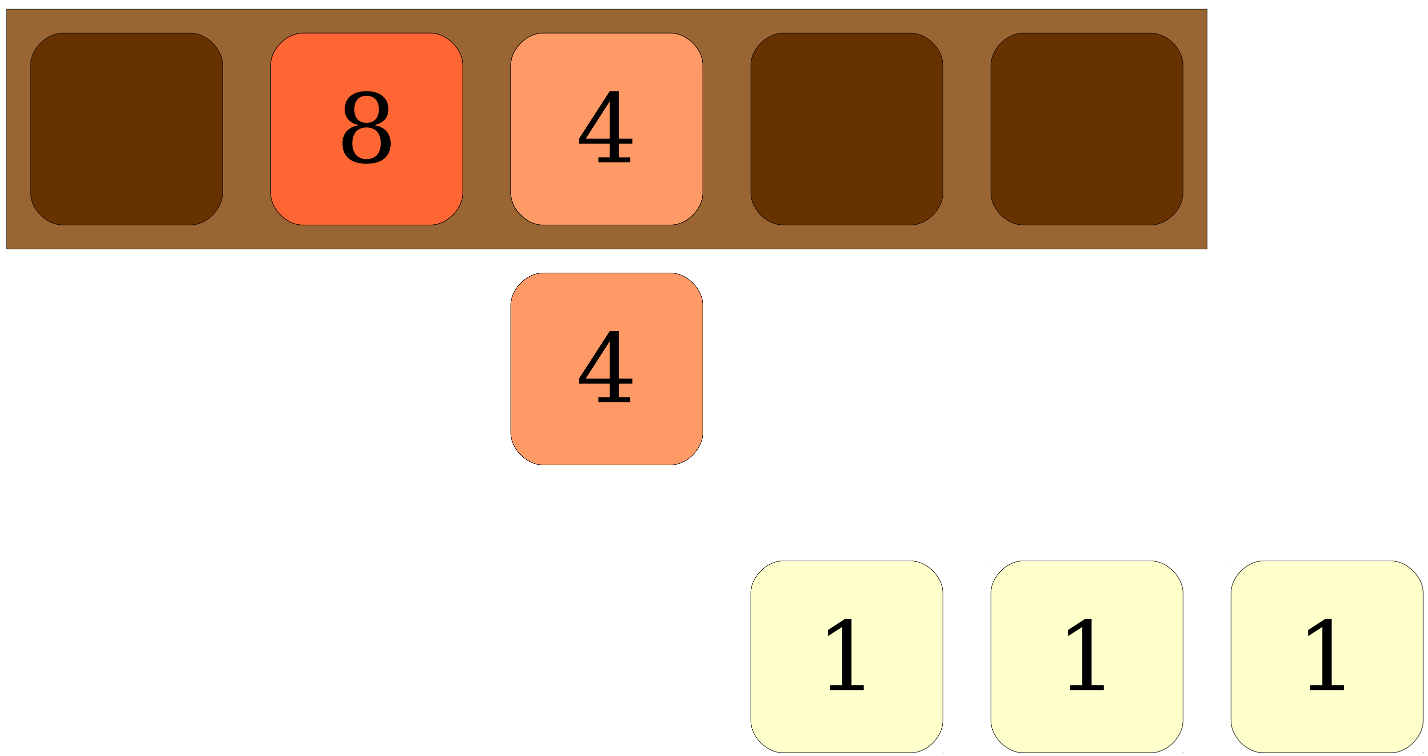

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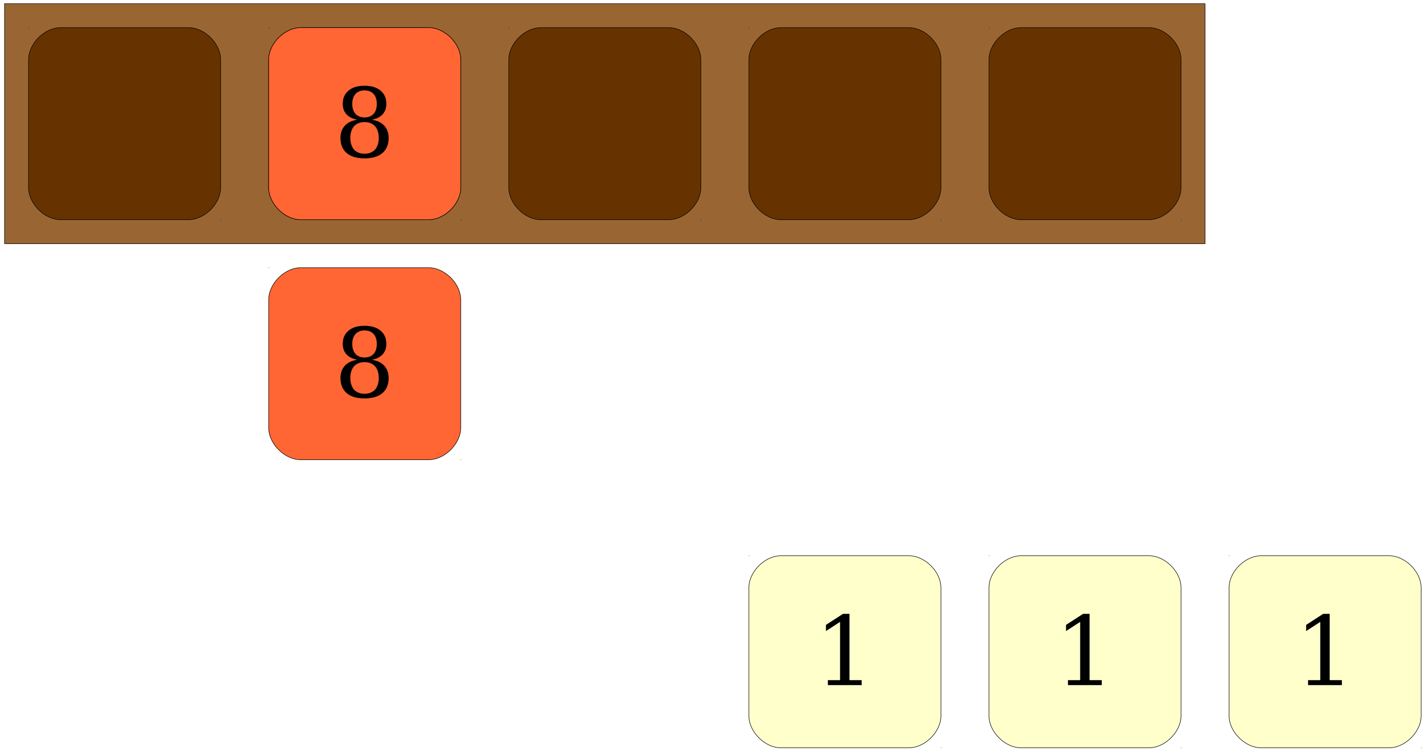

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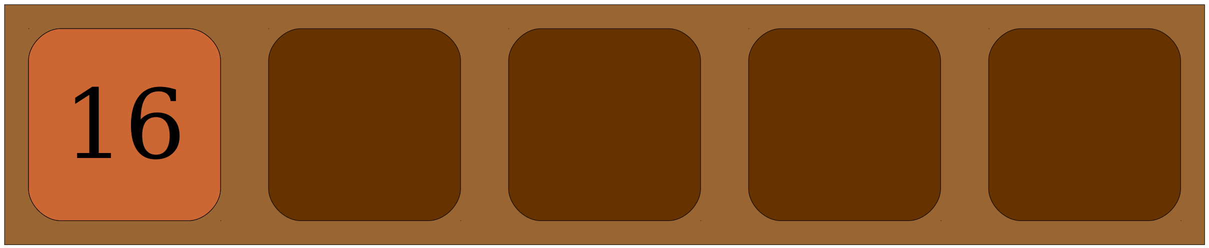

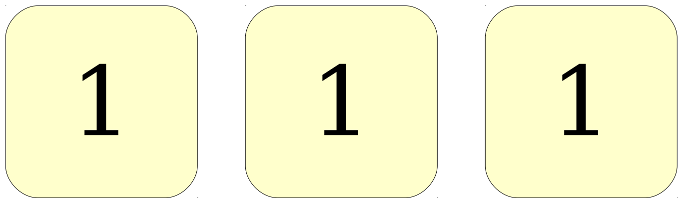

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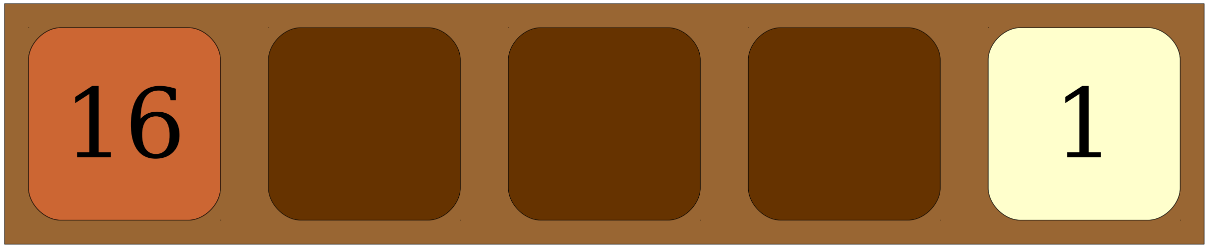

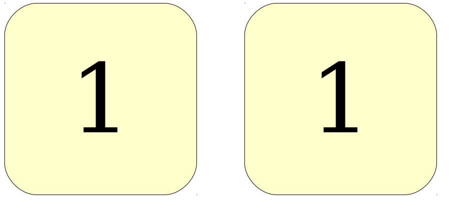

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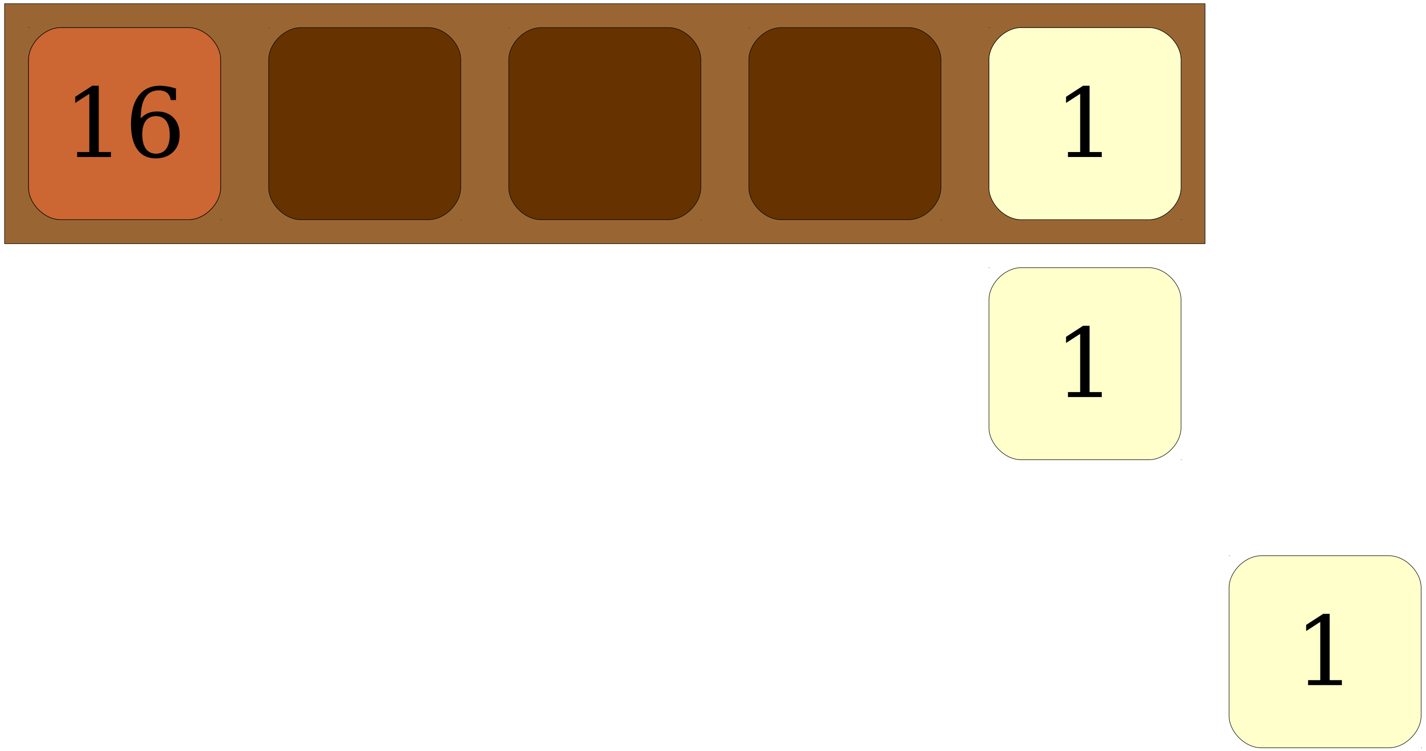

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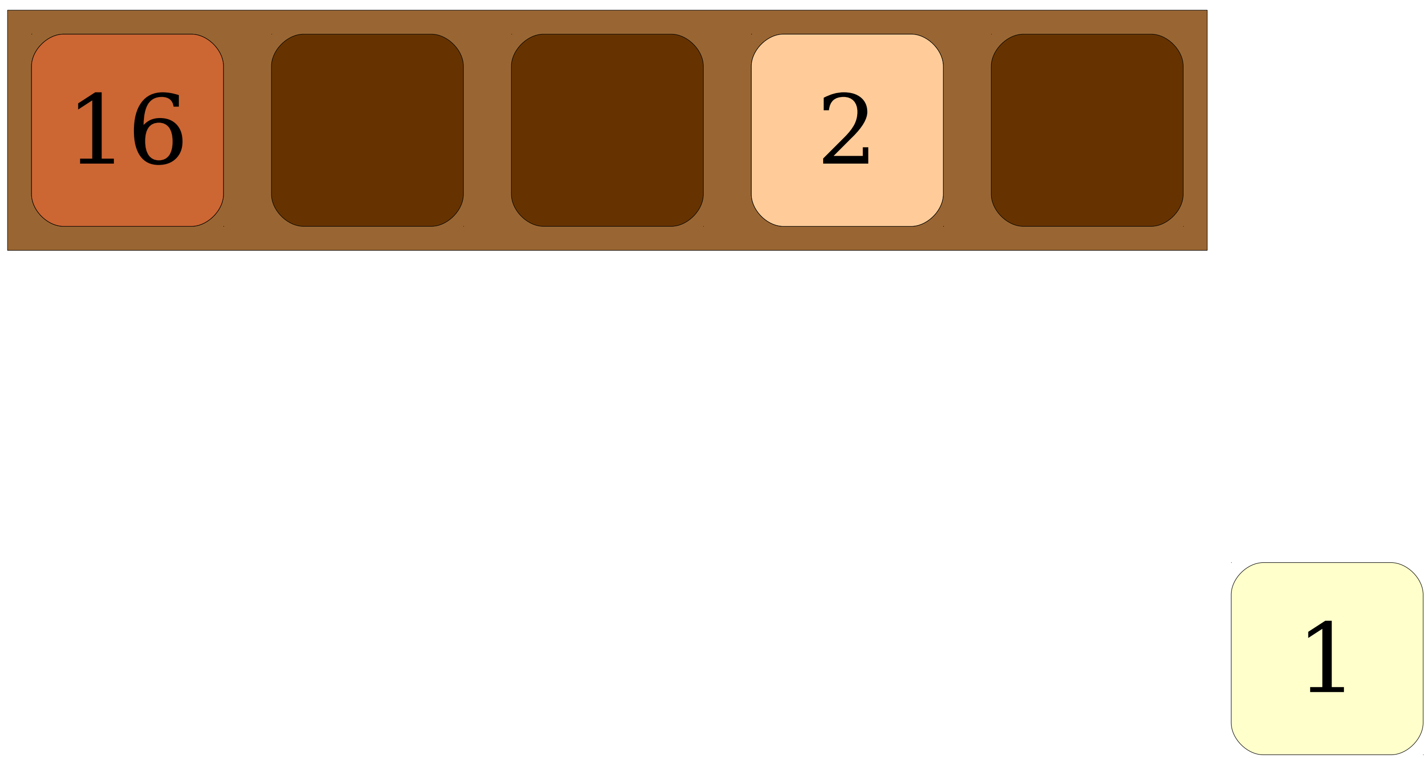

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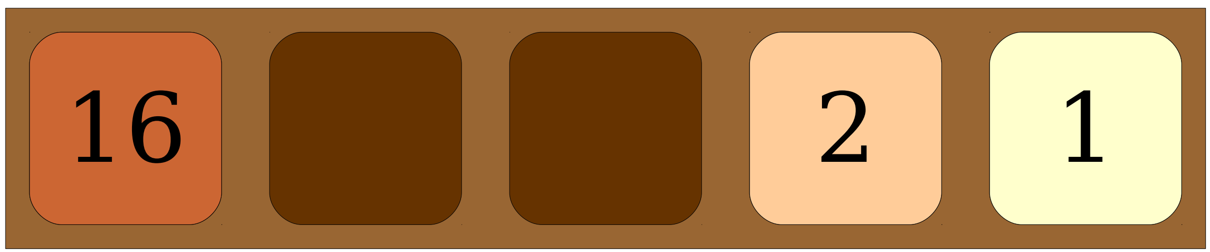


Wonky Arithmetic

- Let's turn back to arithmetic to get an intuition for how to solve this problem.

16

2 1

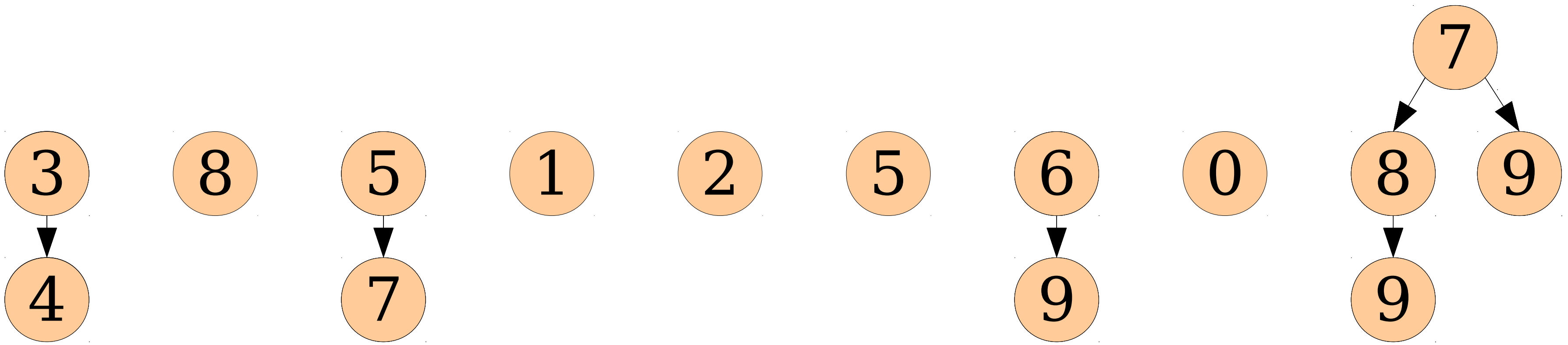
Wonky Arithmetic

- Compute the number of bits necessary to hold the sum.
  - Only O(log n) bits are needed.
- Create an array of that size, initially empty.
- For each packet:
  - If there is no packet of that size, place the packet in the array at that spot.
  - If there is a packet of that size:
    - – Fuse the two packets together.
    - – Recursively add the new packet back into the array.

Now With Trees!

- Compute the number of *trees* necessary to hold the *nodes*.
  - Only O(log n) *trees* are needed.
- Create an array of that size, initially empty.
- For each *tree*:
  - If there is no *tree* of that size, place the *tree* in the array at that spot.
  - If there is a *tree* of that size:
    - Fuse the two *trees* together.
    - Recursively add the new *tree* back into the array.

Coalescing Trees

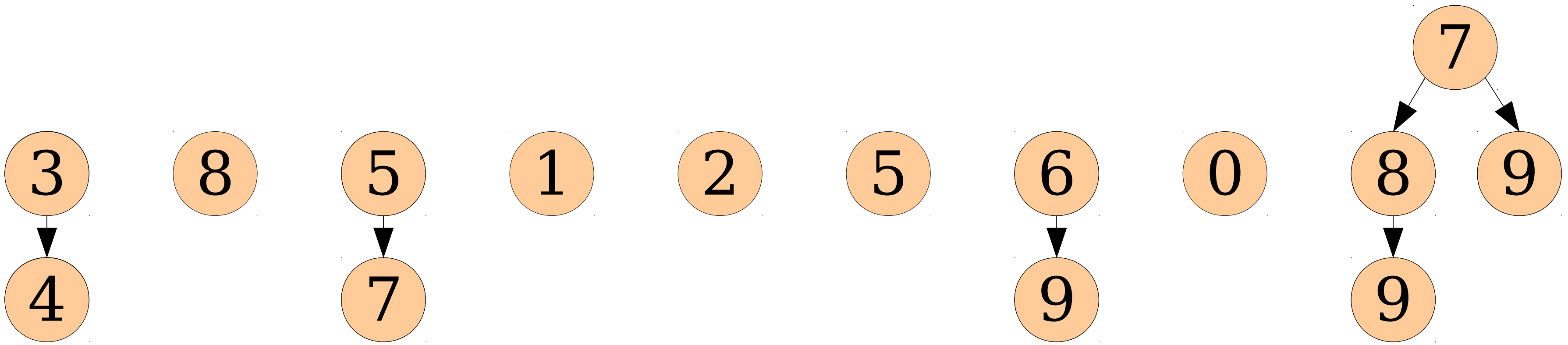


Coalescing Trees

Total number of nodes: **15**

(Can compute in time $\Theta(T)$, where T is the number of trees, if each tree is tagged with its order)

Bits needed: **4**



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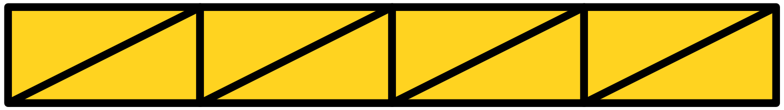

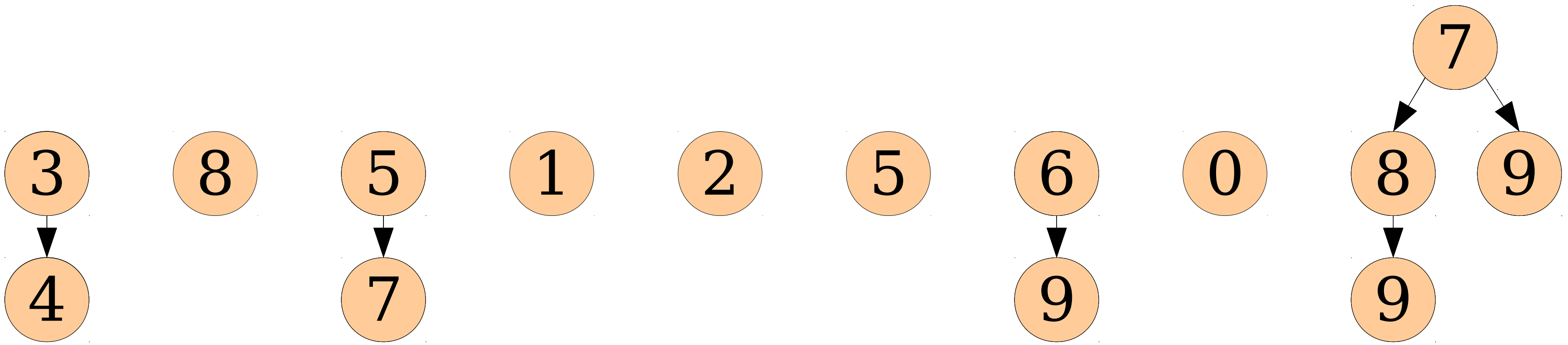

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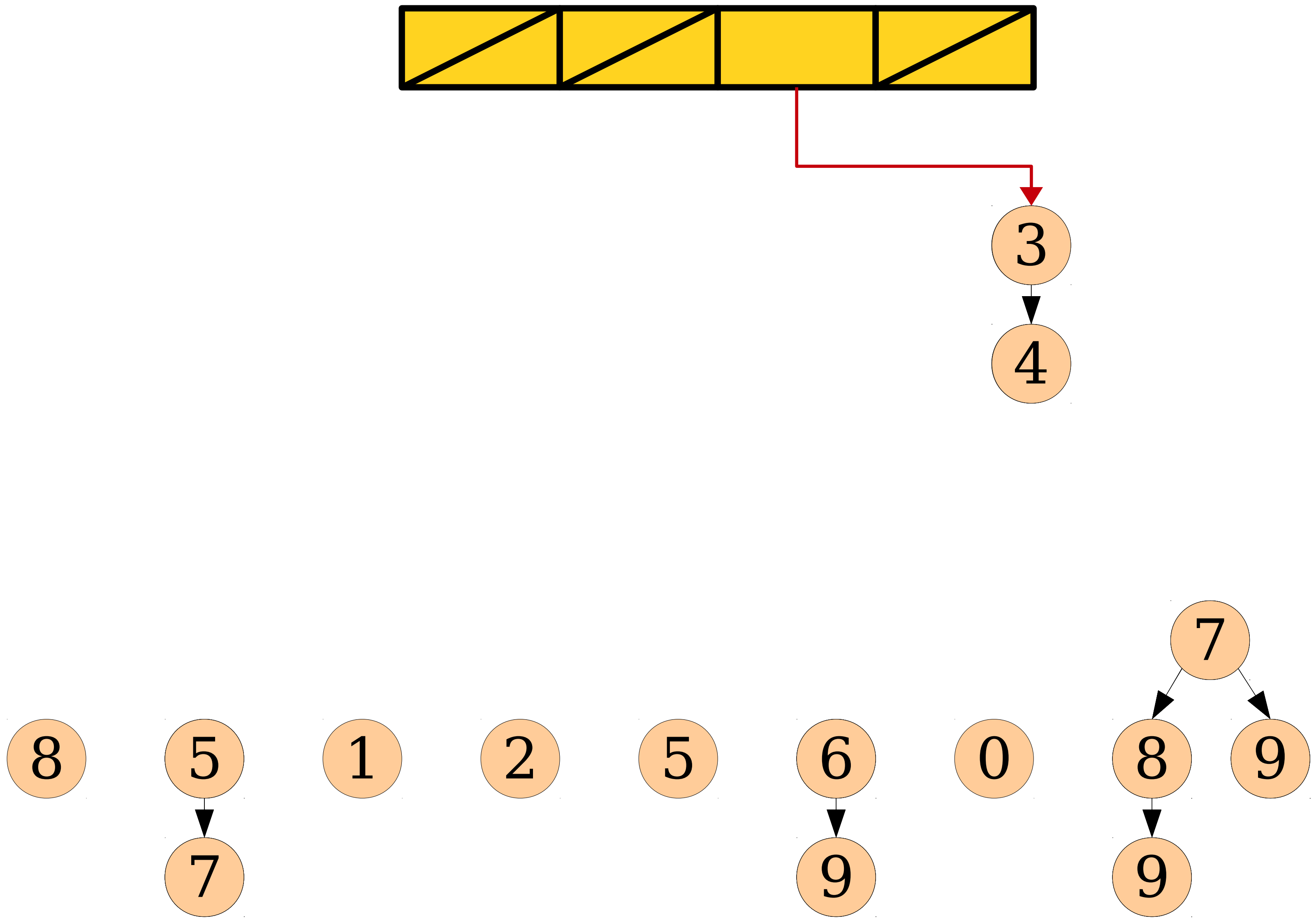

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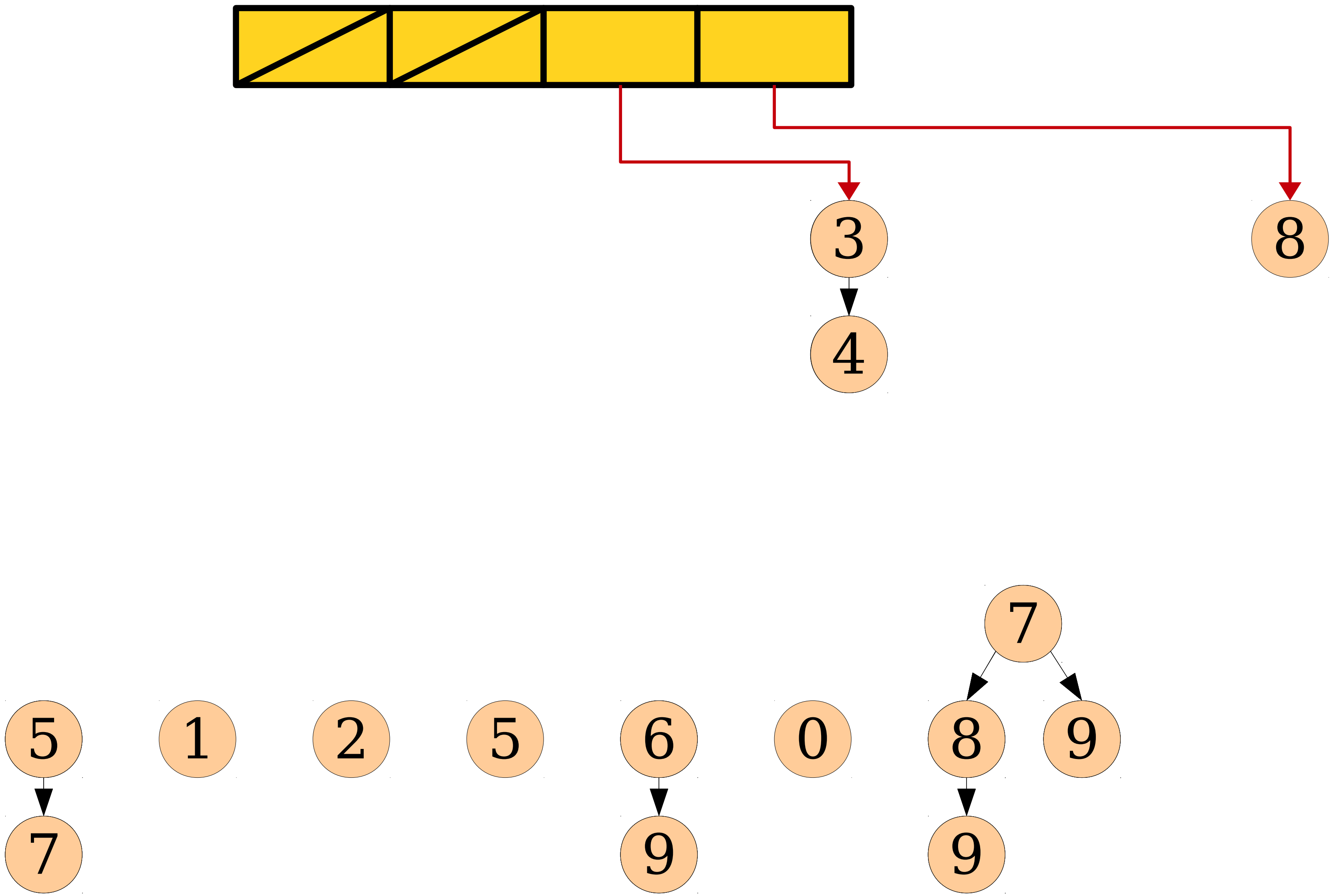

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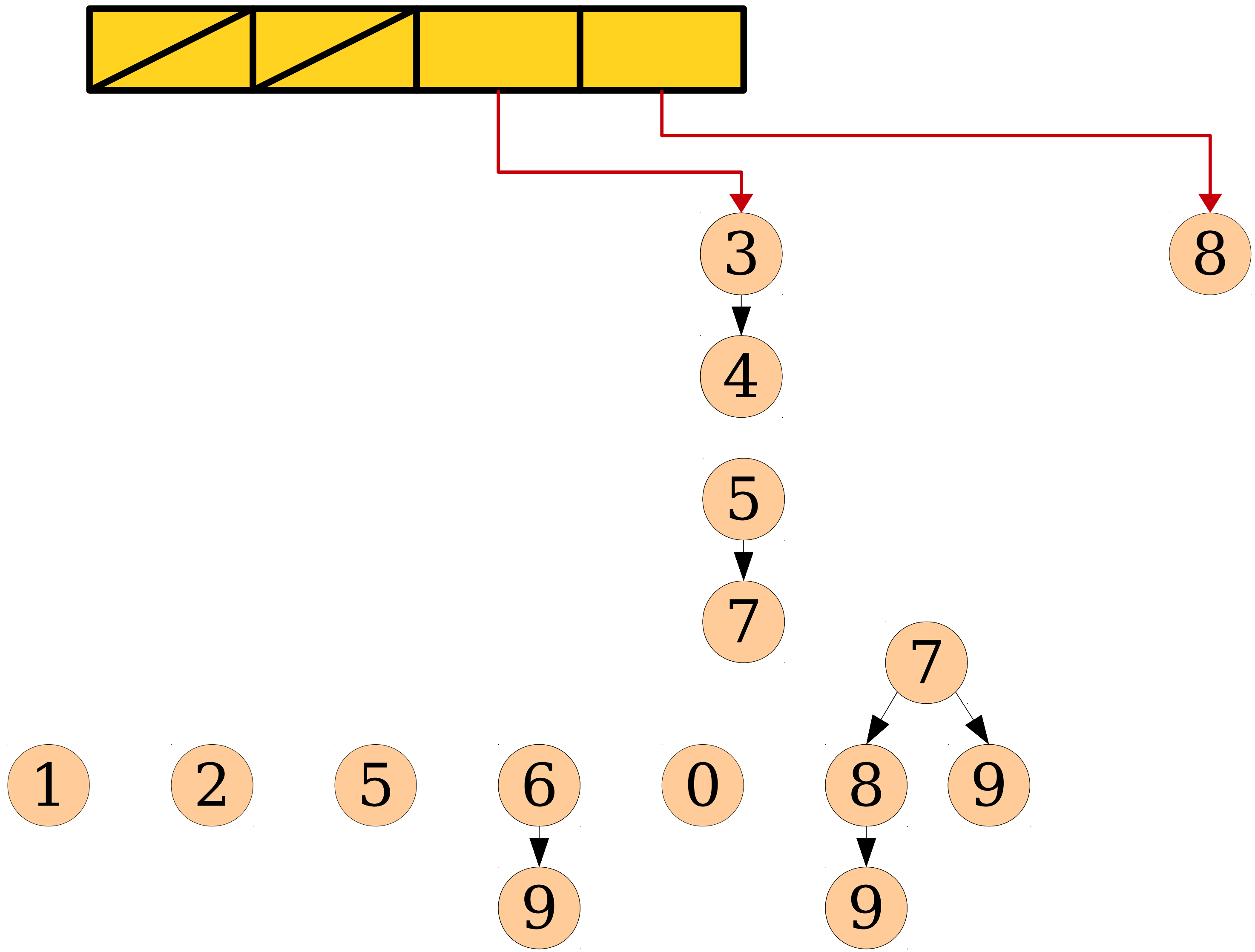

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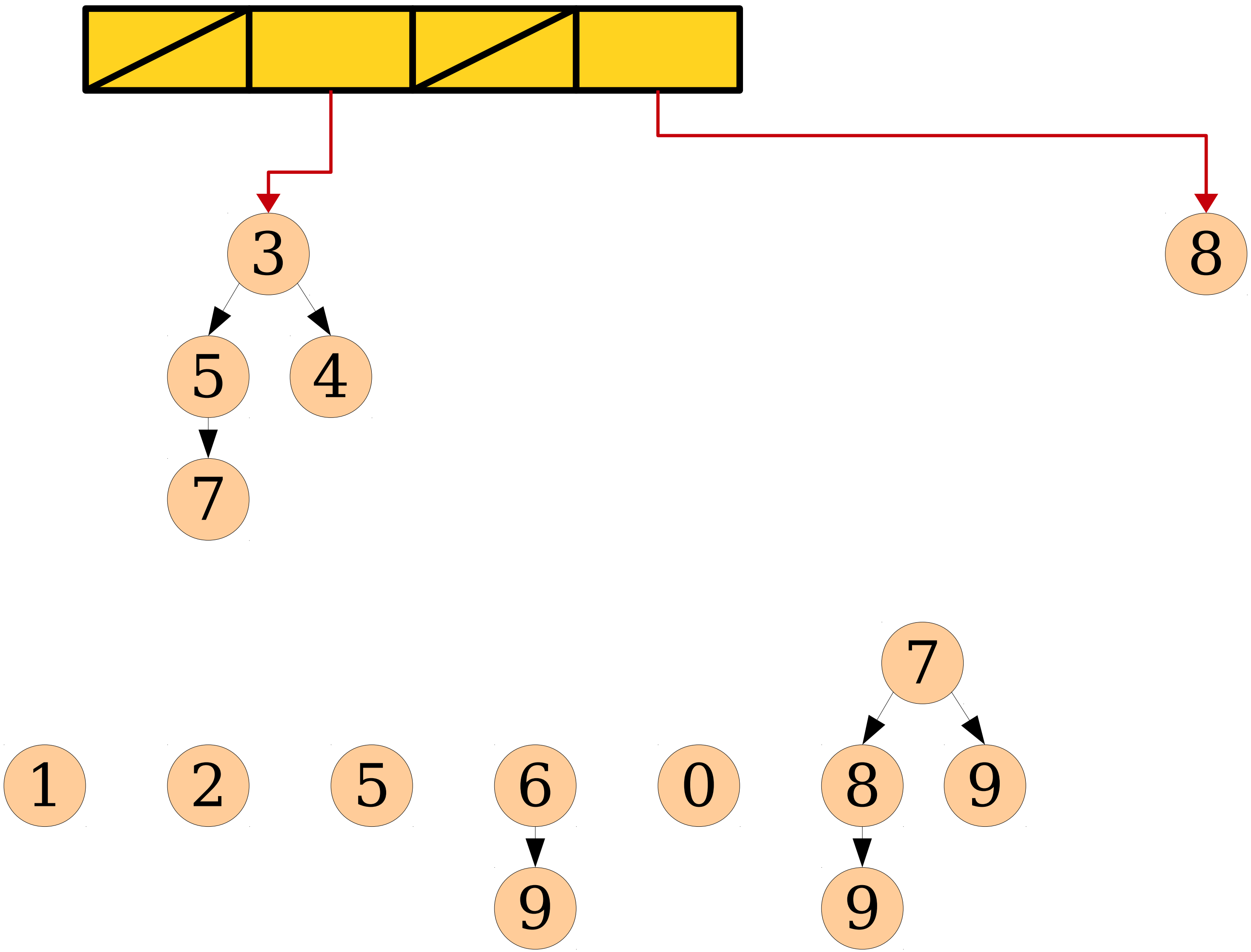

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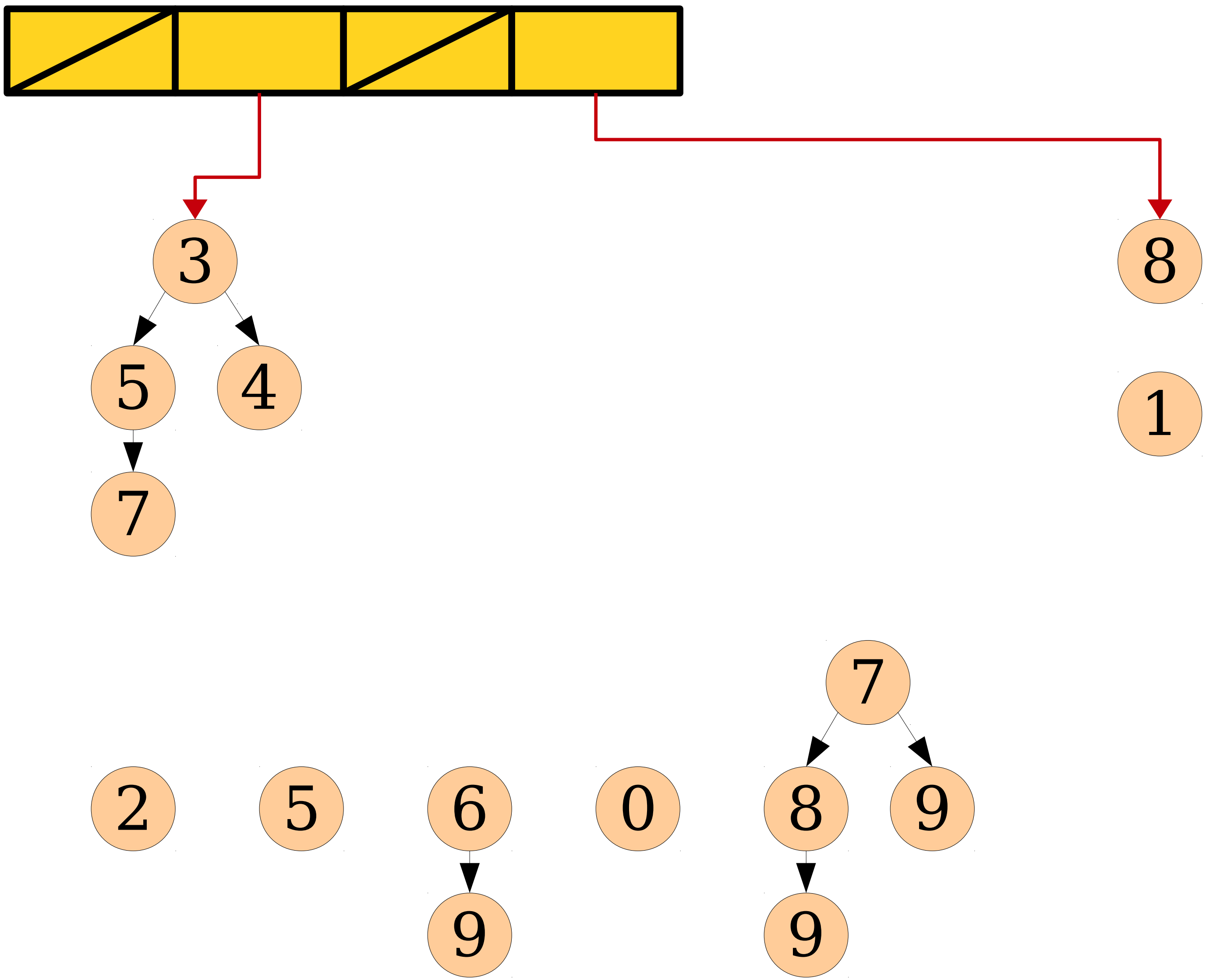

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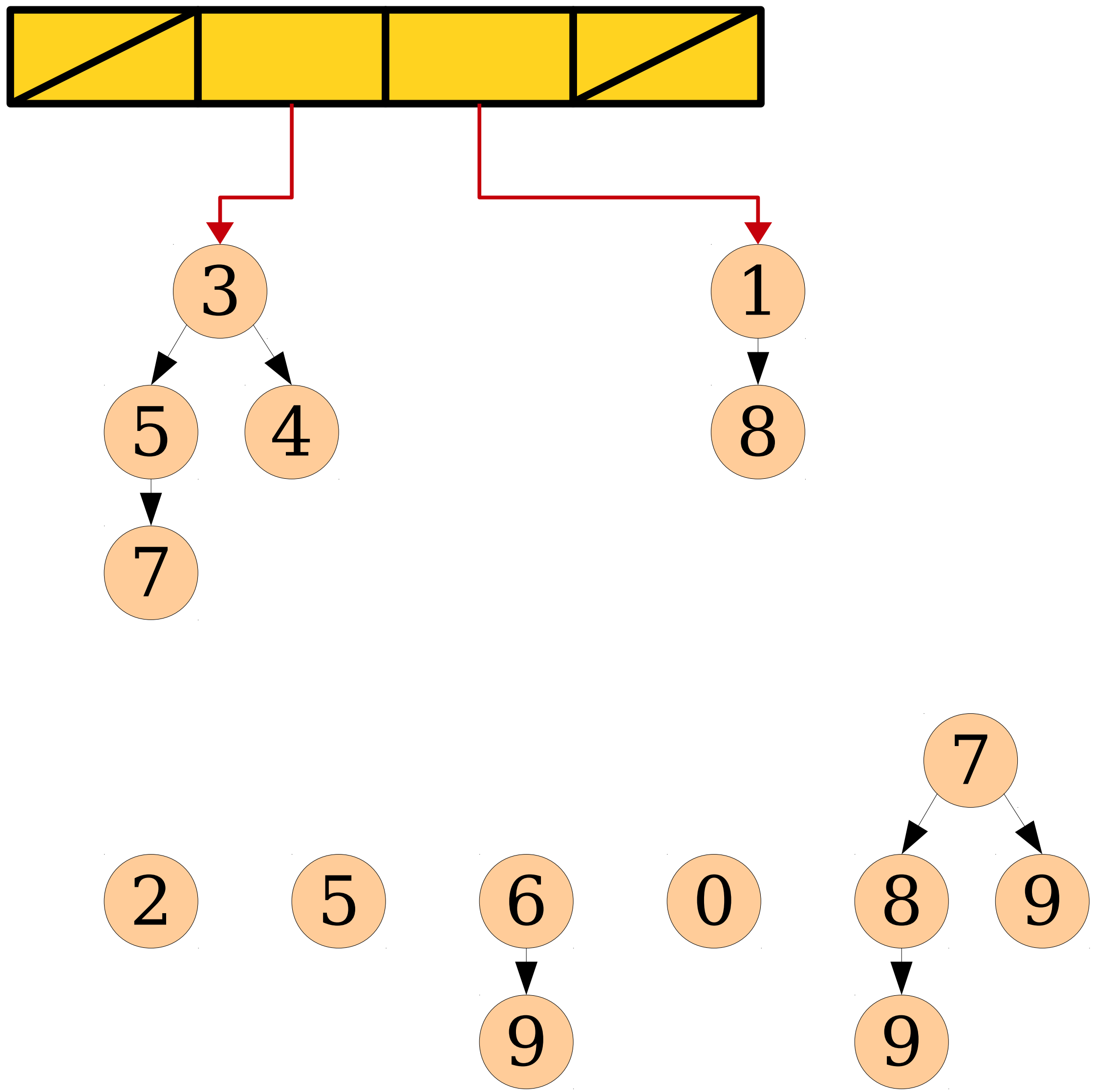

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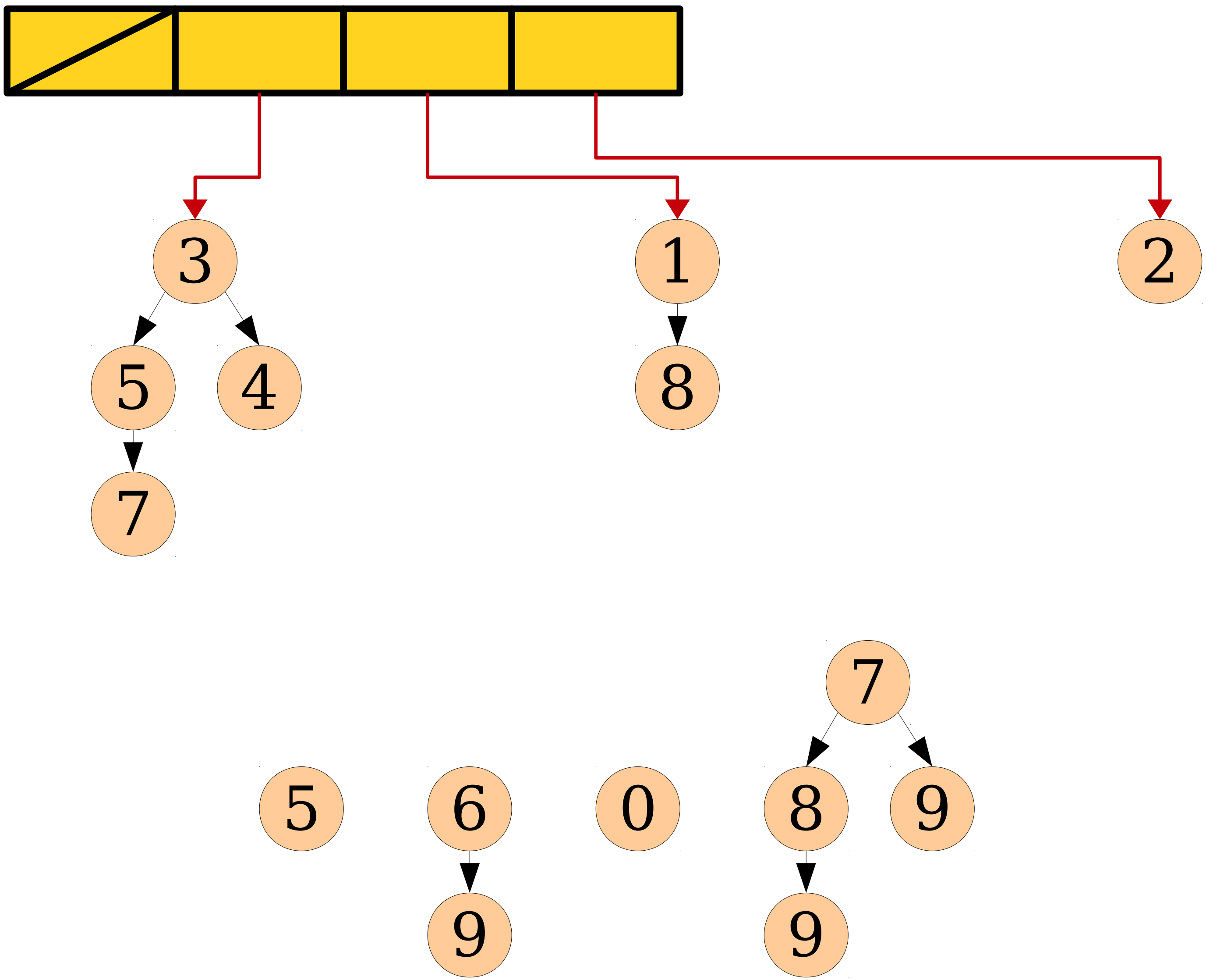

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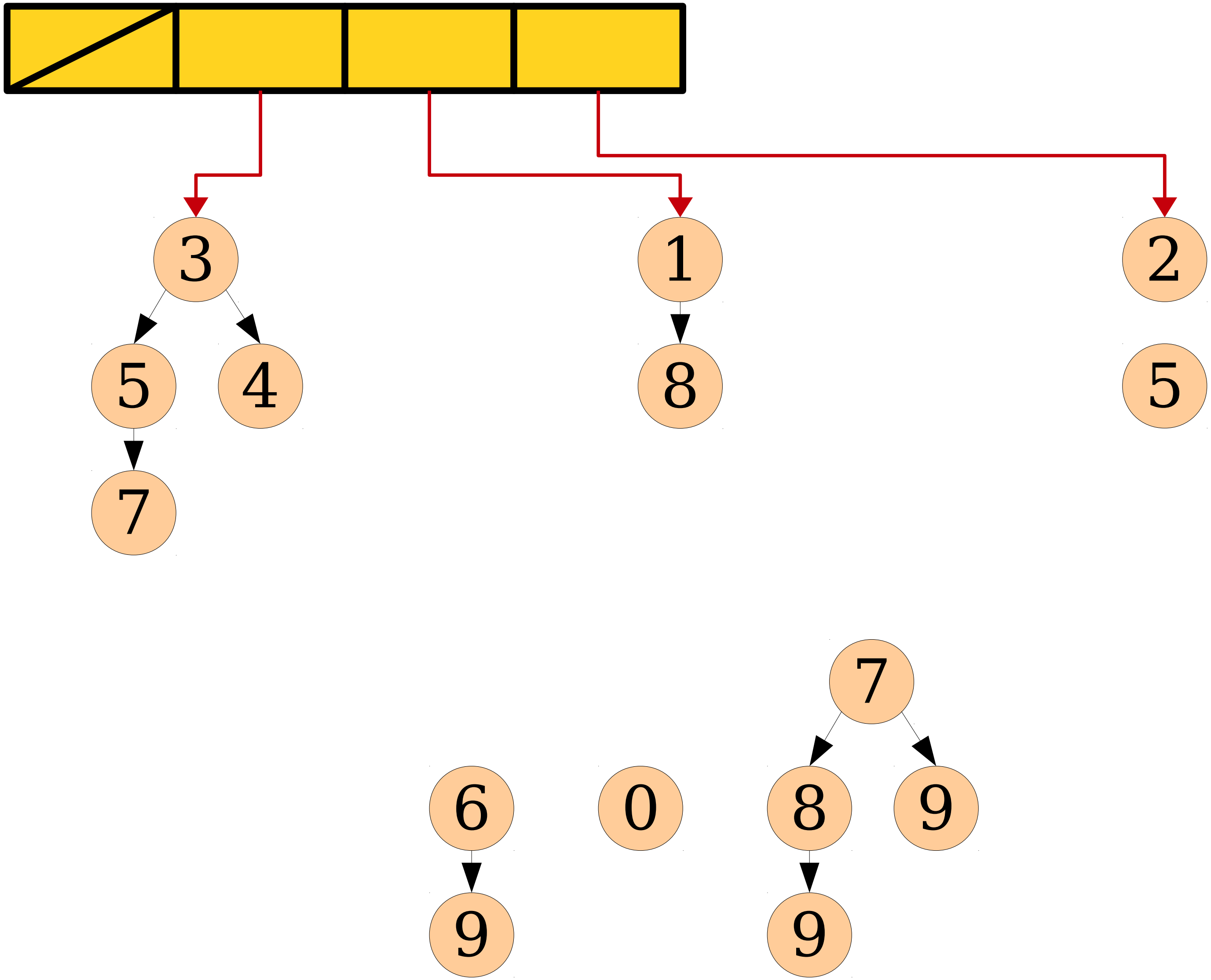

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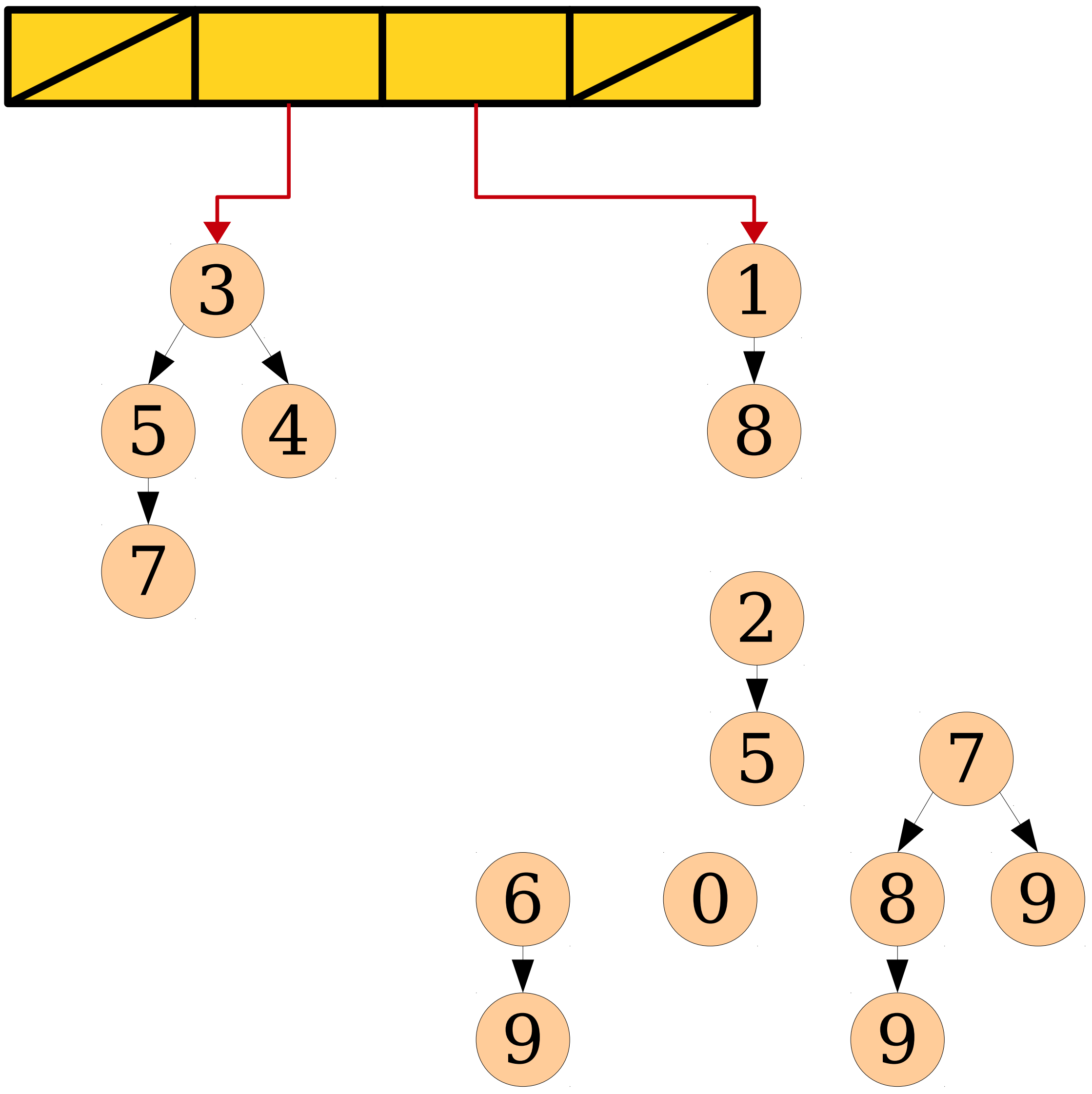

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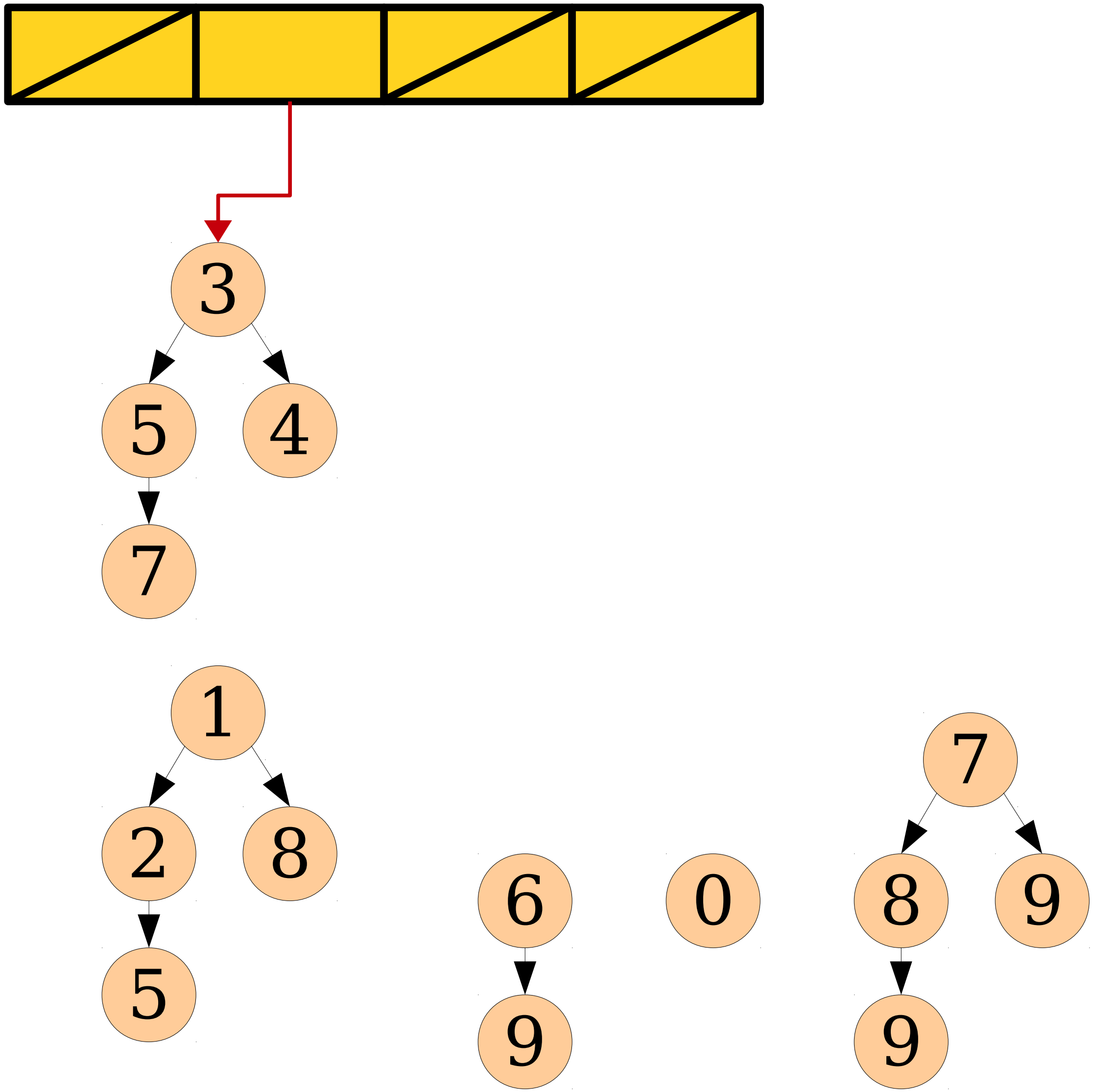

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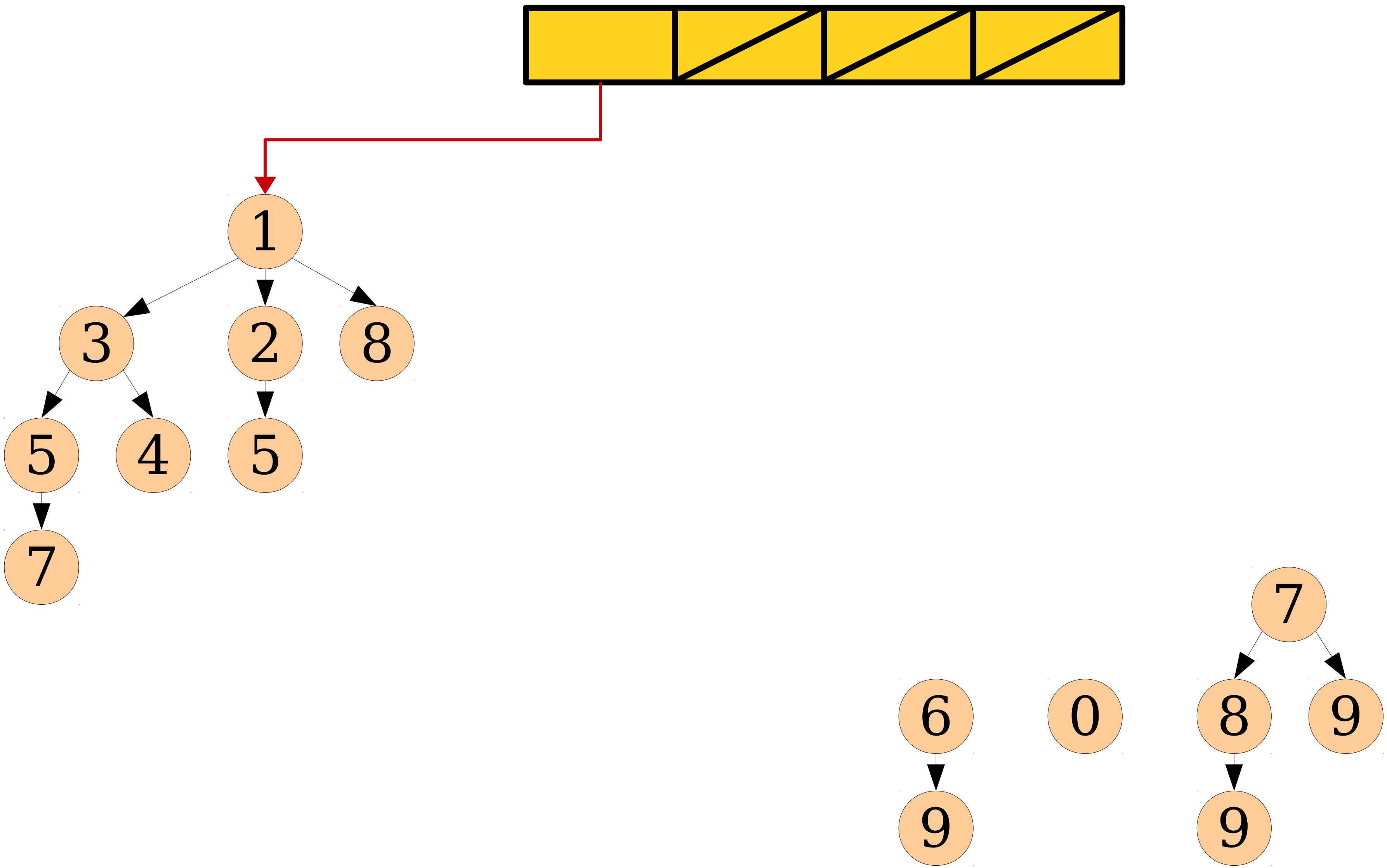

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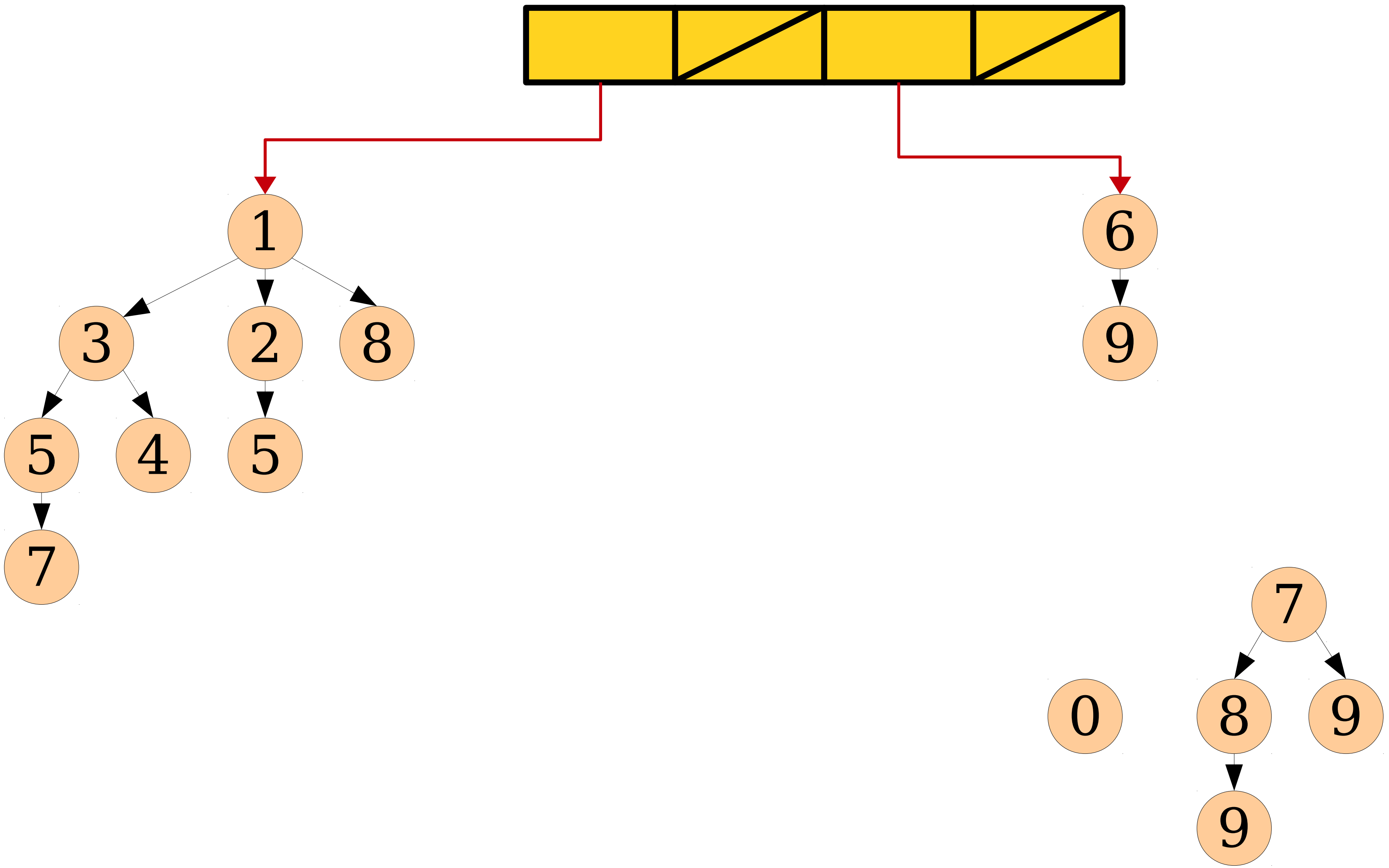

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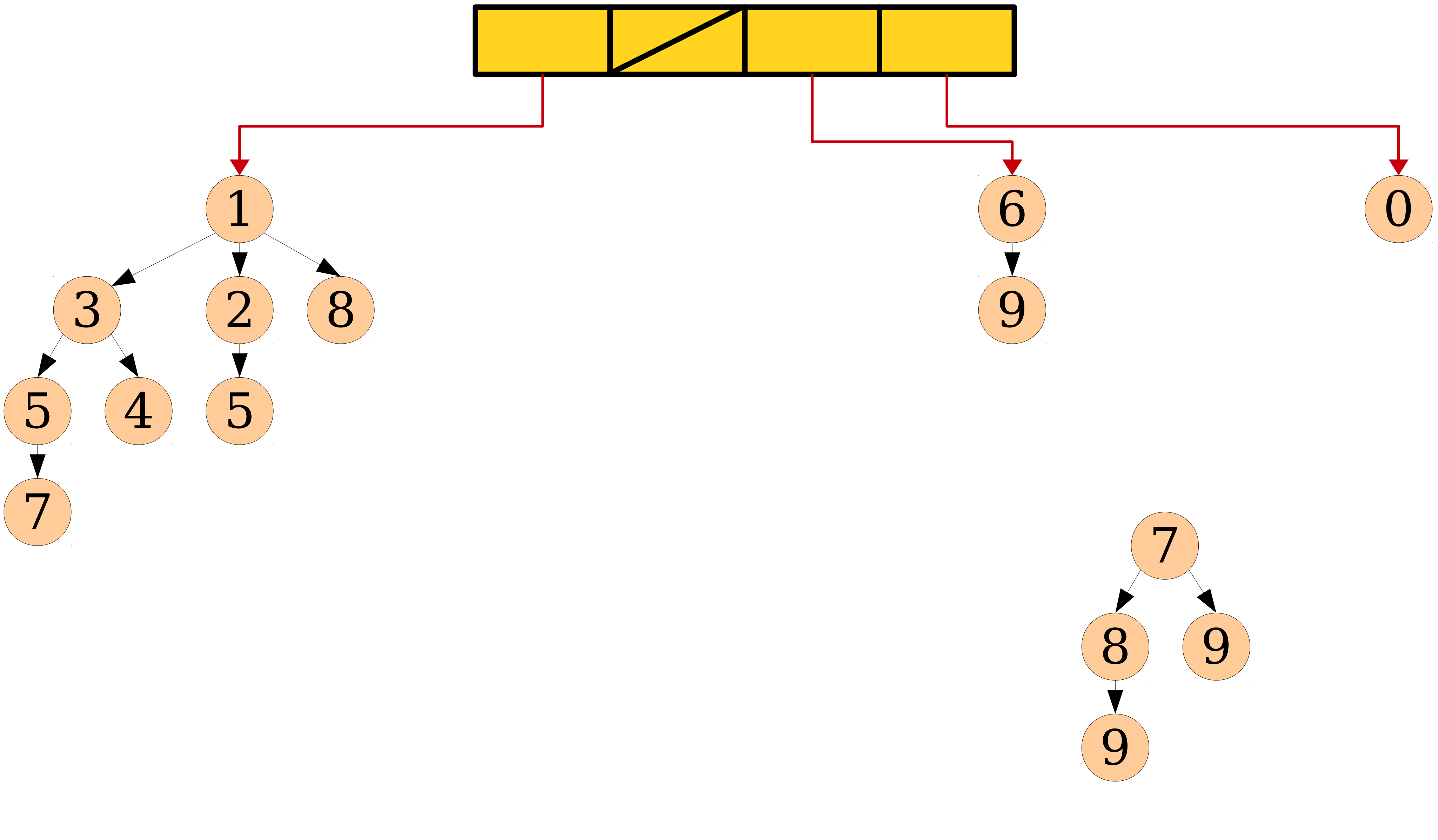

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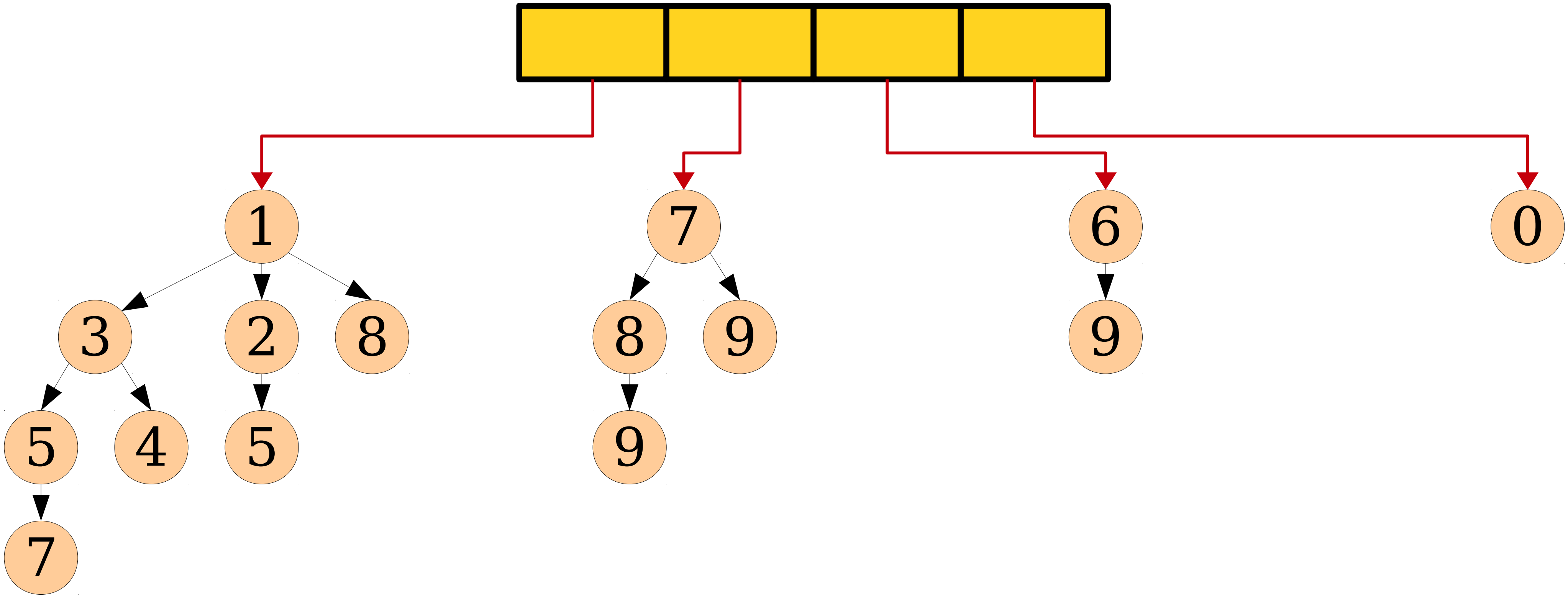


Analyzing Coalesce

- Suppose there are T trees.
- We spend $\Theta(T)$ work iterating across the main list of trees twice:
  - Pass one: Count up number of nodes (if each tree stores its order, this takes time $\Theta(T)$).
  - Pass two: Place each node into the array.
- Each merge takes time O(1).
- The number of merges is $O(T)$.
- Total work done: $\boldsymbol{\Theta(T)}$.
- In the worst case, this is $O(n)$.

The Story So Far

- A binomial heap with lazy melding has these worst-case time bounds:
  - ***enqueue***: O(1)
  - ***meld***: O(1)
  - ***find-min***: O(1)
  - ***extract-min***: O(n).
- These are *worst-case* time bounds. What about an *amortized* time bounds?

An Observation

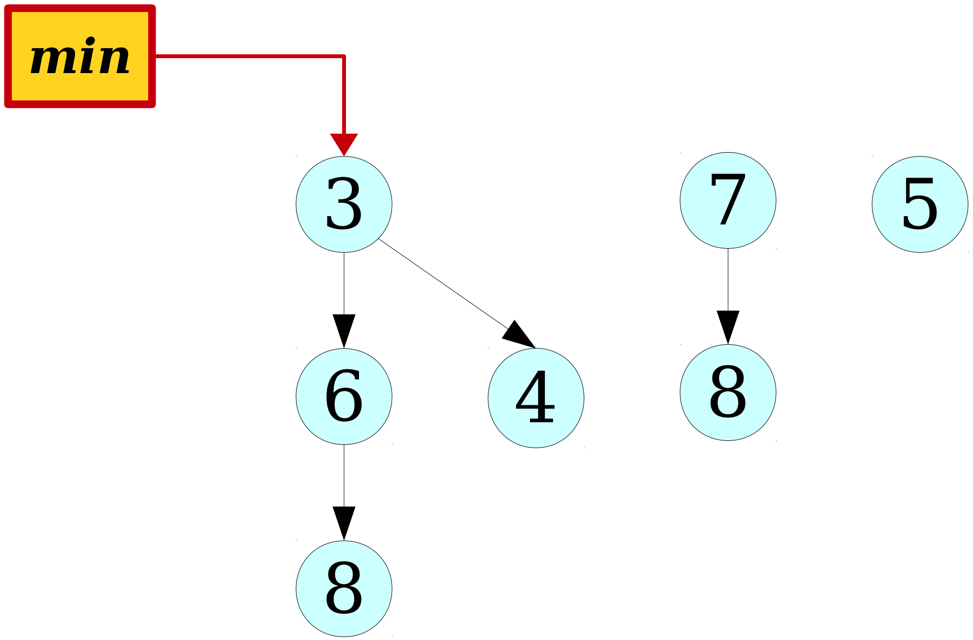
- The expensive step here is ***extract-min***, which runs in time proportional to the number of trees.
- Each tree can be traced back to one of three sources:
  - An ***enqueue***.
  - A ***meld*** with another heap.
  - A tree exposed by an ***extract-min***.
- Let's use an amortized analysis to shift the blame for the ***extract-min*** performance to other operations.

The Potential Method

- We will use the potential method in this analysis.
- When analyzing insertions with eager merges, we set $\Phi(D)$ to be the number of trees in D.
- Let's see what happens if we use this Φ here.

Analyzing an Insertion

- To ***enqueue*** a key, we add a new binomial tree to the forest and possibly update the *min* pointer.



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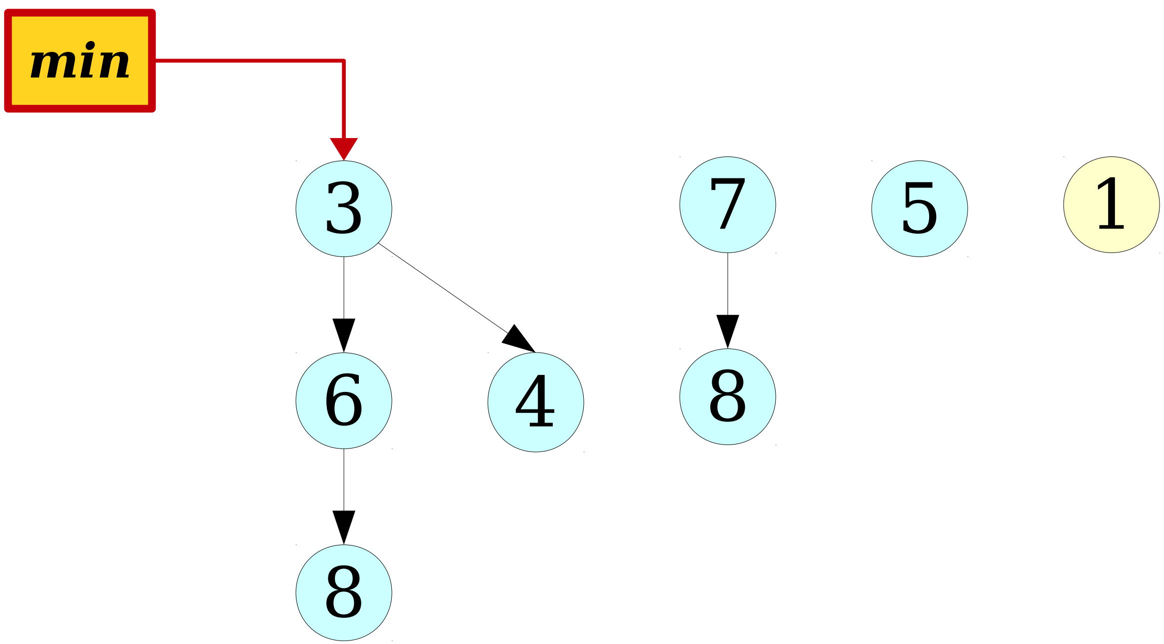

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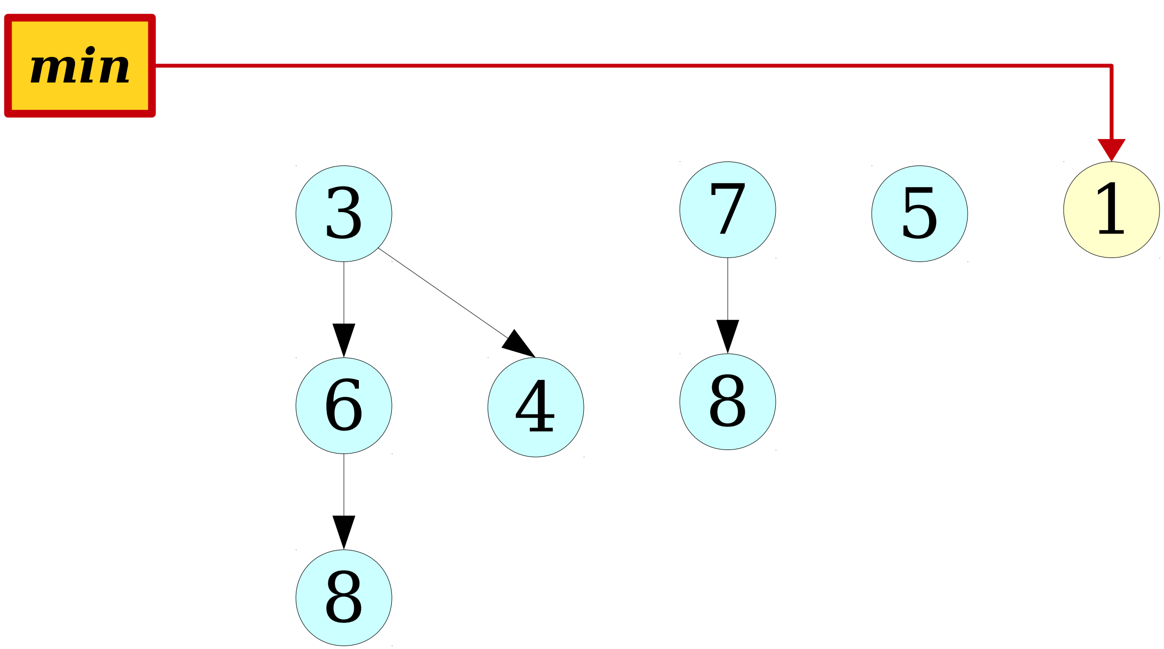
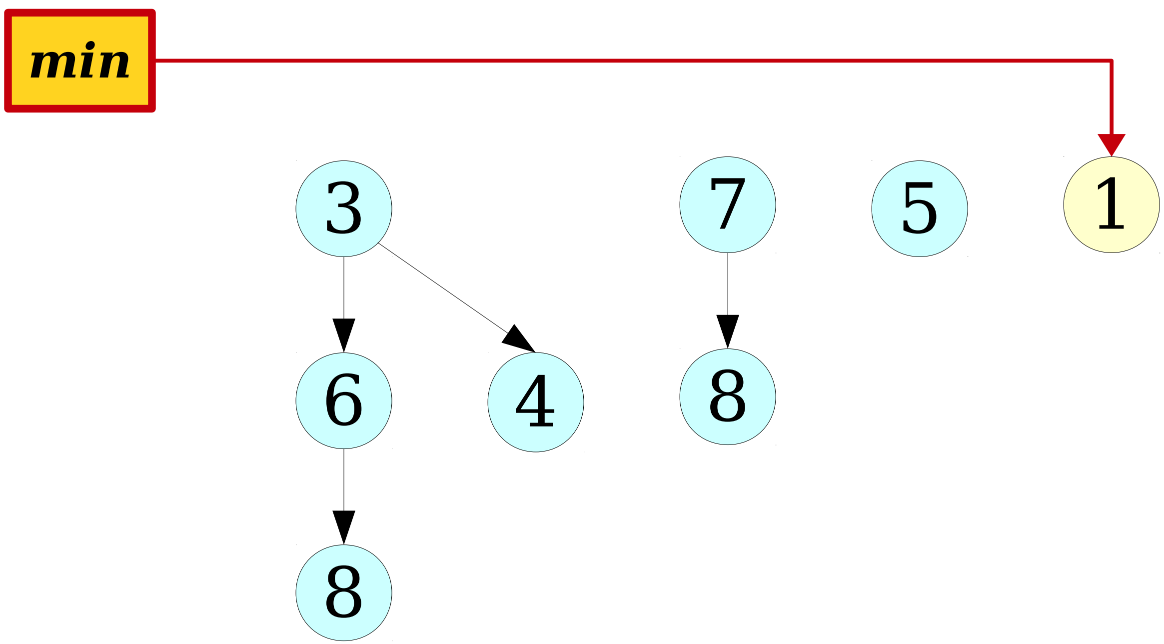


Analyzing an Insertion

- To ***enqueue*** a key, we add a new binomial tree to the forest and possibly update the *min* pointer.

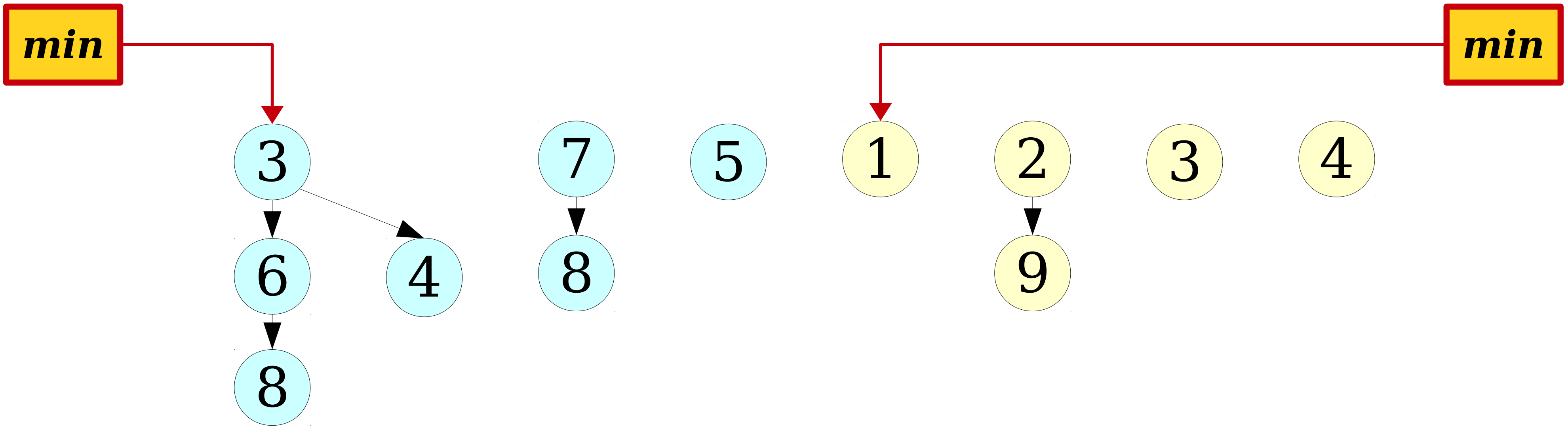
  Actual time: O(1). ΔΦ: +1

  Amortized time: **O(1)**.



Analyzing a Meld

- Suppose that we ***meld*** two lazy binomial heaps B_1 and B_2. Actual cost: O(1).



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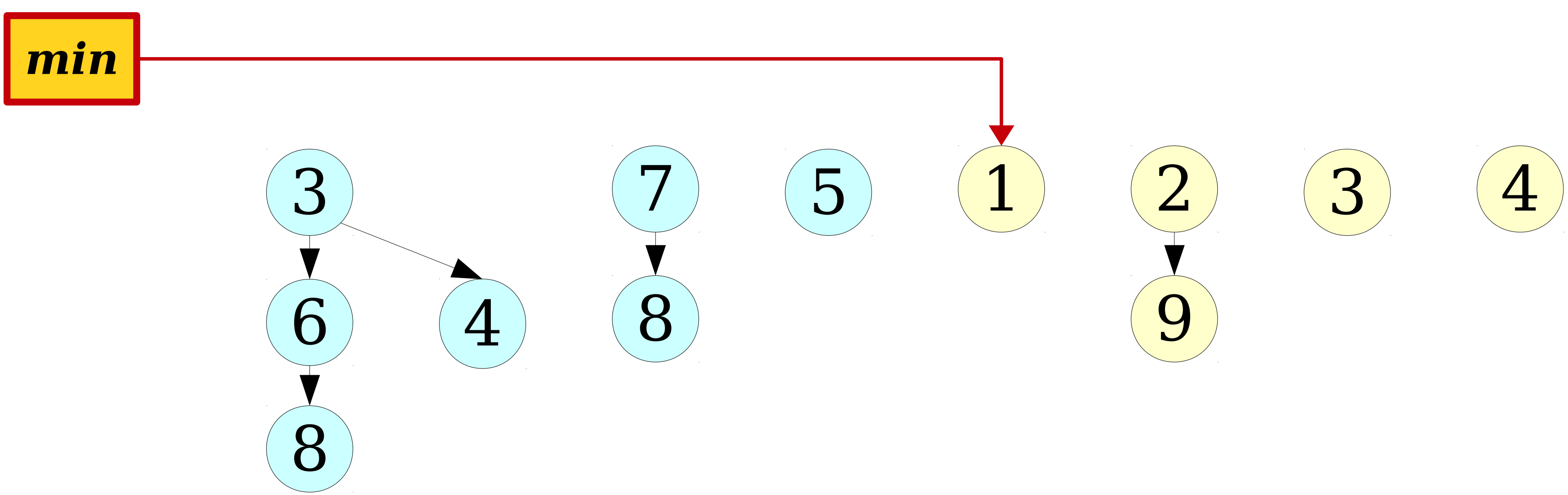

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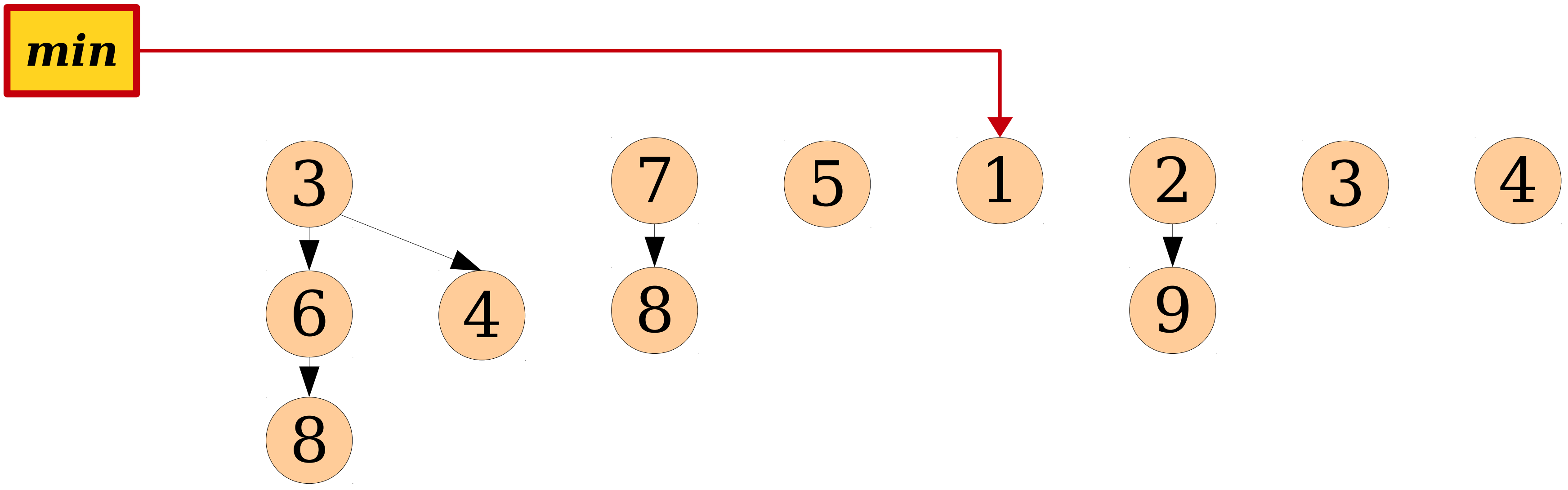
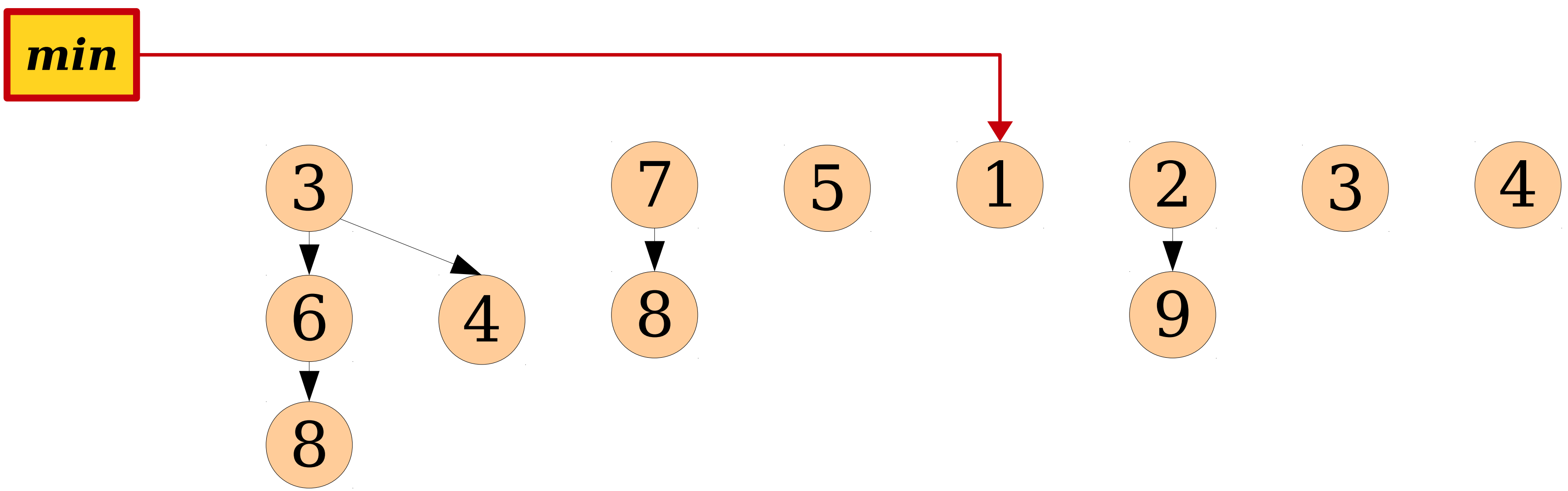


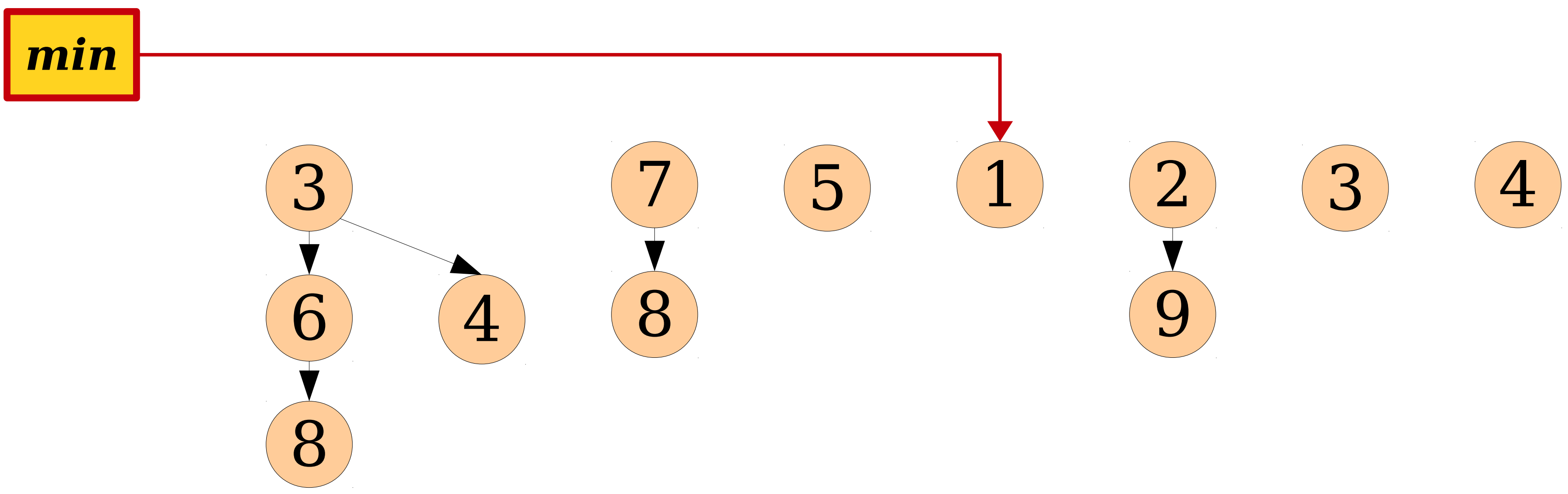
Analyzing a Meld

- Suppose that we ***meld*** two lazy binomial heaps B_1 and B_2. Actual cost: O(1).
- Let Φ_{B_1} and Φ_{B_2} be the initial potentials of B_1 and B_2.
- The new heap B has potential $\Phi_{B_1} + \Phi_{B_2}$ and B_1 and B_2 have potential 0.
- $\Delta\Phi$ is zero.
- Amortized cost: **O(1)**.



Analyzing a Find-Min

- Each ***find-min*** does O(1) work and does not add or remove trees.
- Amortized cost: **O(1)**.



Analyzing Extract-Min

- Initially, we expose the children of the minimum element. This takes time O(log n).
- Suppose that at this point there are T trees. As we saw earlier, the runtime for the coalesce is $\Theta(T)$.
- When we're done merging, there will be O(log n) trees remaining, so $\Delta\Phi = -T + O(\log n)$.
- Amortized cost is

$$
\begin{aligned}
& O(\log n) + \Theta(T) + O(1) \cdot (-T + O(\log n)) \\
= \; & O(\log n) + \Theta(T) - O(1) \cdot T + O(1) \cdot O(\log n) \\
= \; & \mathbf{O(\log n)}.
\end{aligned}
$$

The Overall Analysis

- The *amortized* costs of the operations on a lazy binomial heap are as follows:
  - ***enqueue***: O(1)
  - ***meld***: O(1)
  - ***find-min***: O(1)
  - ***extract-min***: O(log n)
- Any series of e ***enqueues*** mixed with d ***extract-min***s will take time O($e + d \log e$).

Why This Matters

- Lazy binomial heaps are a powerful building block used in many other data structures.
- We'll see one of them, the *Fibonacci heap,* when we come back on Thursday.
- You'll see another (supporting ***add-to-all***) on the problem set.

Next Time

- ***The Need for decrease-key***
  - A powerful and versatile operation on priority queues.
- ***Fibonacci Heaps***
  - A variation on lazy binomial heaps with efficient decrease-key.
- ***Implementing Fibonacci Heaps***
  - … is harder than it looks!