

Lazy Data Structures

"Average" analysis of algorithms

↑
(without sacrificing worst-case robustness)

① Amortized analysis ("average" in hindsight)

② Randomized algorithms ("average" over random bits)

Both are very practical, different perspectives

Incrementing Binary Counters

`i++;` `//increment i`

In bits: 0, 1, 10, 11, 100, 101, ~

Running time of `i++`?

Incrementing Binary Counters

 $i++;$

```
//increment i
```

In bits: 0, 1, 10, 11, 100, 101, ...

Two bits Slipped!

[illegible]

1

k bits $\Rightarrow k$ flips (not constant time!)

from $i=1$ to n , how many total flips?

	how often	total
• 1st bit (least significant)	every time	n
• 2nd bit	every 2 times	$\lfloor n/2 \rfloor$
• 3rd bit	every 4 times	$\lfloor n/4 \rfloor$

⋮

• kth bit	every 2^{k-1} times	$\lfloor n/2^{k-1} \rfloor$
-----------	-----------------------	-----------------------------

$2n$

[illegible]

	how often	total
• 1st bit	every time	n
• 2nd bit	every 2 times	$\lfloor n/2 \rfloor$
• 3rd bit	every 4 times	$\lfloor n/4 \rfloor$
⚡		
• kth bit	every 2^{k-1} times	$\lfloor n/2^{k-1} \rfloor$

n increments $\Rightarrow O(n)$ total time

each increment takes $O(1)$ on average

" $O(1)$ amortized time"

Amortized Analysis

	how often	total
• 1st bit (least significant)	every time	n
• 2nd bit	every 2 times	$\lfloor n/2 \rfloor$
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"T amortized time"

$\Rightarrow$ n operations take $O(nT)$ time

Extends to multiple operations $OP_1, \dots, OP_k$

" OP_1 takes T_1 amortized time, OP_2 takes $\dots$,

OP_k takes T_k amortized time"

Ways to do amortized analysis

- direct analysis (like above)
- credit schemes ("banker's method")
- potential function

	how often	total
• 1st bit	every time	n
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Credit schemes

Idea:

Buy credits ahead of time to pay for work later

$$(\text{running time}) + \underbrace{\alpha(1) \cdot (\Delta \text{ credit})}_{(\text{net increase})} \leq \text{amortized time}$$

Credit schemes Idea: Buy credits ahead of time to pay for work later

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eg. for binary counters, when incrementing:

ideas

0, 1, 10, 11, 100, 101, ...
1111111111111111111111111111111111
1000000000000000000000000000000000

	how often	total
• ^(least significant) 1st bit	every time	n
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[illegible]

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put: 1 credit on first bit
 $\frac{1}{2}$ credit on 2nd bit
 $\frac{1}{4}$ credit on 3rd bit
 $\vdots$
 $+$ $\frac{1}{2^{i-1}}$ credits on i th bit

2 credits total

whenever we need to flip bit i , we have already saved 1 credit to pay for it.

Credit schemes

Idea:

Buy credits ahead of time to pay for work later

$$(\text{running time}) + \underbrace{\alpha(i) \cdot (\Delta \text{ credit})}_{(\text{net increase})} \leq \text{amortized time}$$

Main rule:

only spend credits that
you already saved

e.g. for binary counters, when incrementing:

[illegible]

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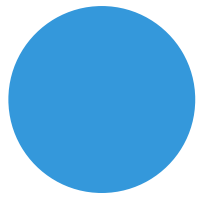
put: 1 credit on first bit
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$+ \frac{1}{2}i-1$ credits on i th bit

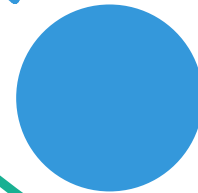
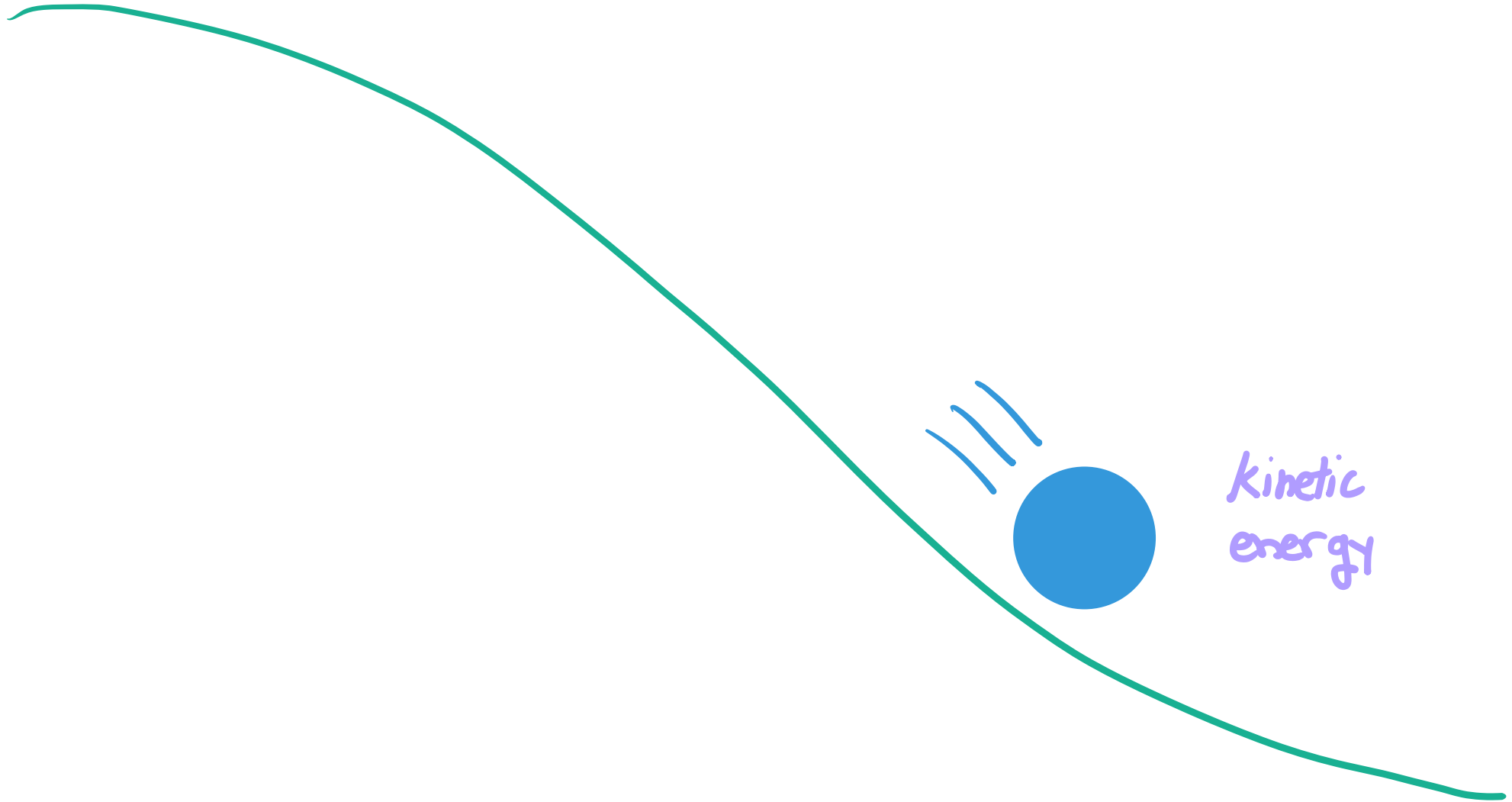
2 credits total

whenever we need to flip bit i , we have already saved 1 credit to pay for it.

Potential method



potential
energy



kinetic
energy

Potential method
Invent "potential Φ "



Amortized cost of operation:

$$(\text{real time}) + \Delta \Phi$$

(change in potential)

Potential method

Amortized cost of operation:

(real time) + $\Delta \Phi$
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e.g. binary counter

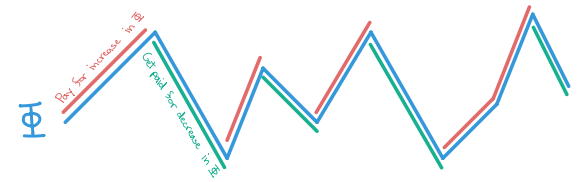
$\Phi = \# \text{ bits set to } 1$

then for each increment,

$$(\text{real time}) + \Delta\Phi \leq O(1)$$

each bit reset to 0 paid by $\Delta \Phi$)

"potential Φ "



$0, 1, 10, 11, 100, 101, \dots$

$\underbrace{11111111111111111111111111}_{\text{10 ones}}$

$\underbrace{10000000000000000000000000}_{\text{16 zeros}}$

	how often	total
• 1st [*] bit	every time	n
• 2nd bit	every 2 times	$\lfloor \frac{n}{2} \rfloor$
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+ $\frac{1}{2^{i-1}}$ credits on i th bit

2 credits total

- potential function method

$\Phi = \# \text{ bits set to } 1$

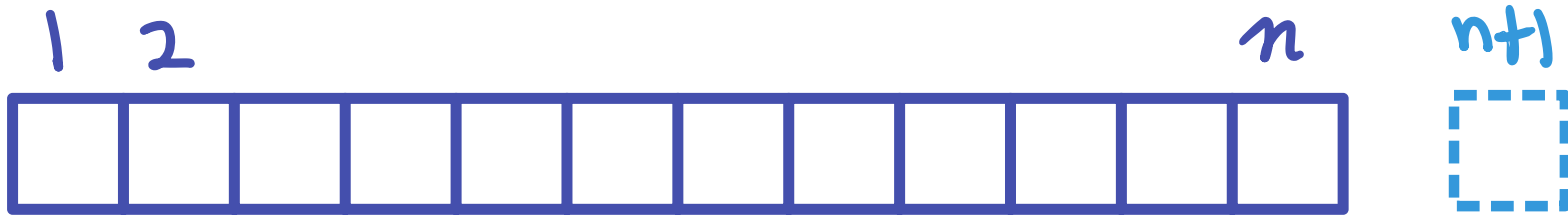
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"T amortized time"
 $\Rightarrow n$ operations take $O(nT)$ time

Multiple operations $OP_1, \dots, OP_k$

" OP_1 takes T_1 amortized time, OP_2 takes $\dots$
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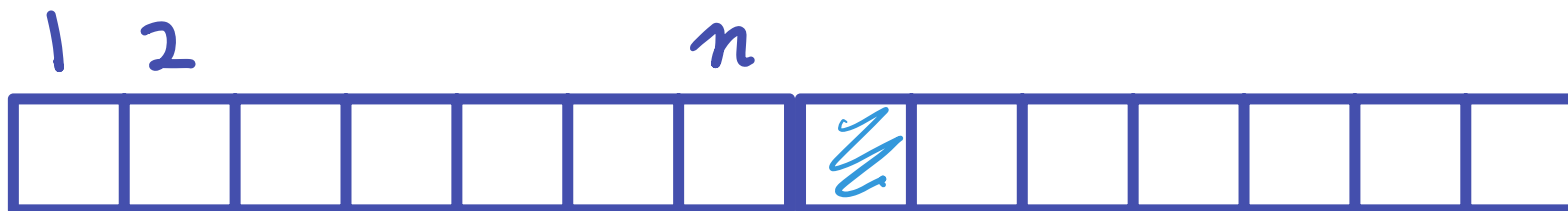
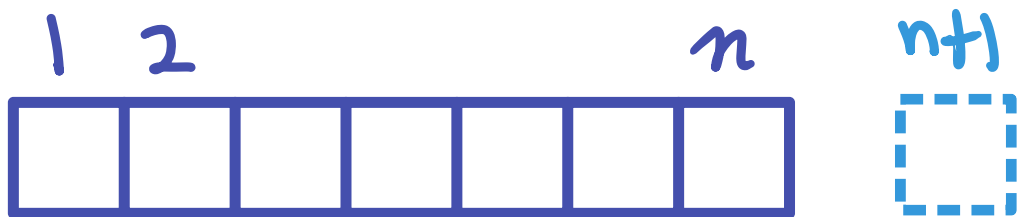
Array-backed lists



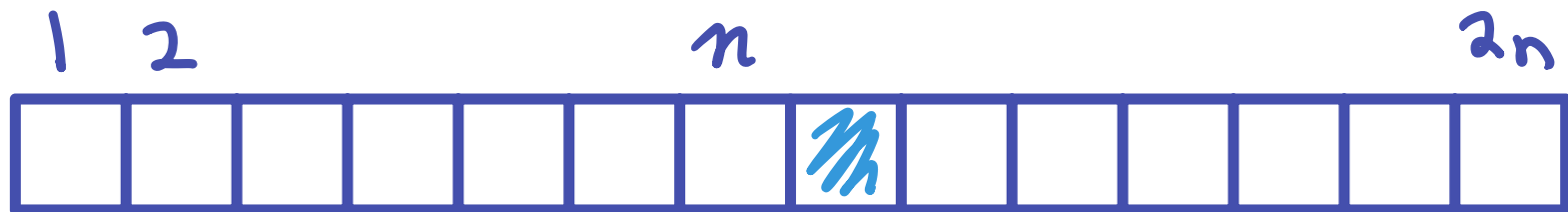
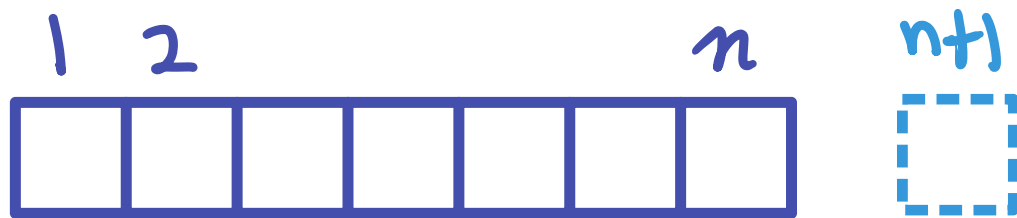
Good: $O(1)$ access by index

Bad: $O(n)$ append

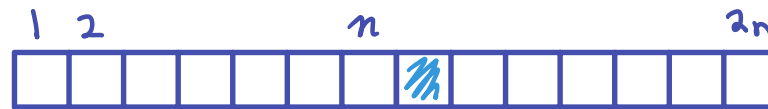
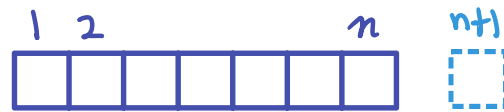
Doubling Trick



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Theorem w/ doubling trick, arraylist has

- lookup in $O(1)$
- append in $O(1)$ amortized

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$\Phi = \text{empty slots in array}$

Proof

$$\Phi = \left(\frac{\text{\# elements in array}}{\text{capacity}} \right) n$$

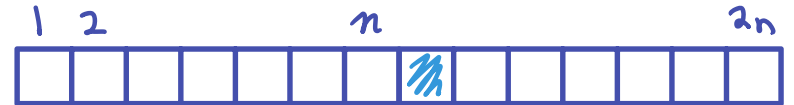
Append: $\leftarrow \Phi = n$

Allocate 2x space

Copy n elements $O(n)$

$\Phi = \text{elements in array} - \text{empty slots}$

Doubling Trick



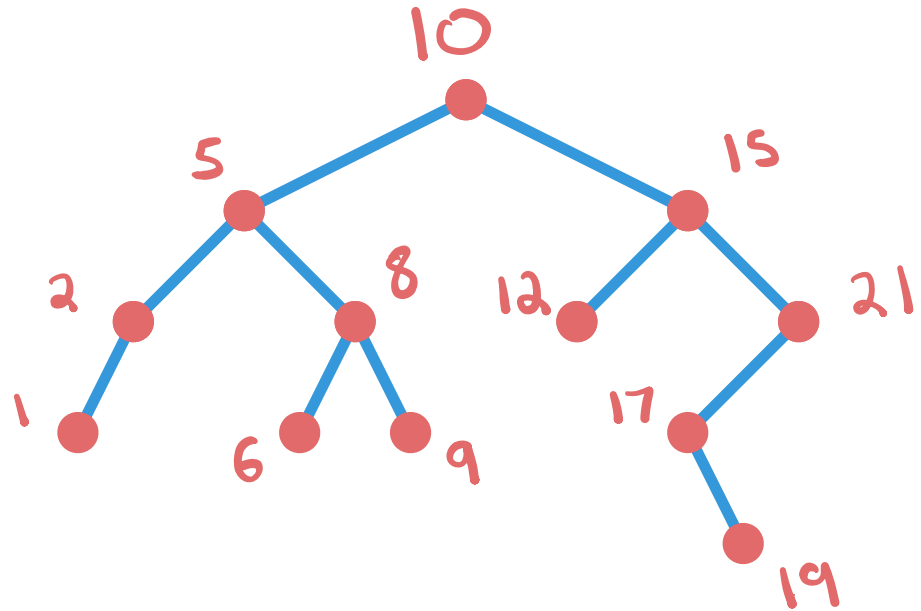
Search trees

Organizes keys
in a tree

Invariant:

a node's # is

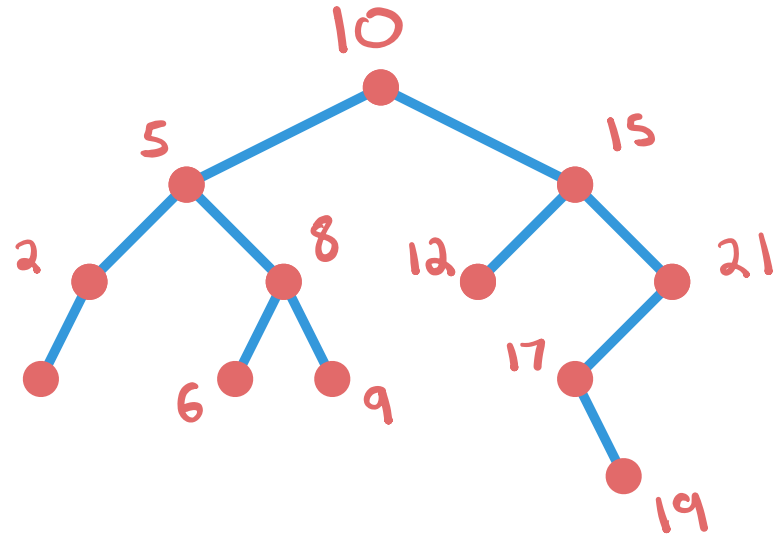
- $\geq$ any # in left subtree
- $\leq$ any # in right subtree



Invariant:

a node's # is

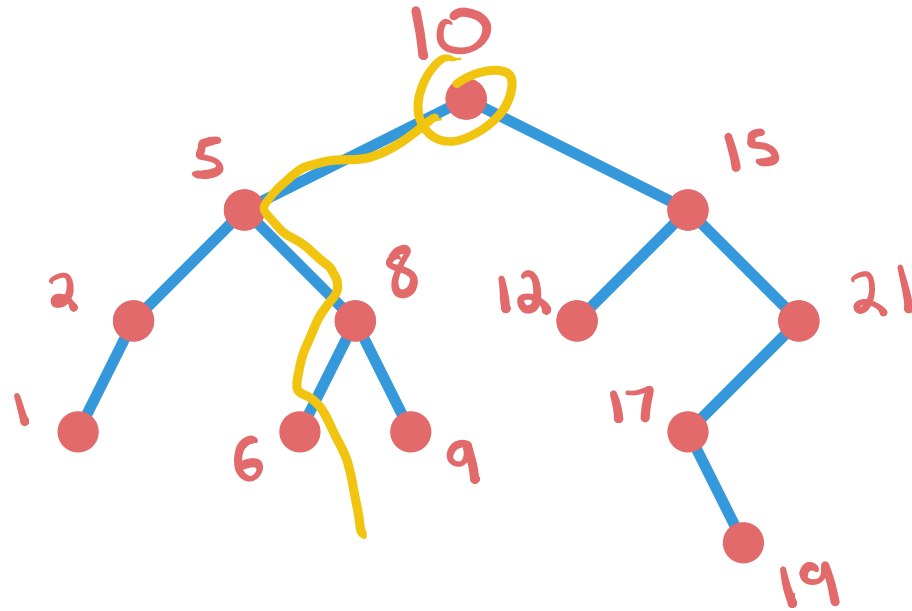
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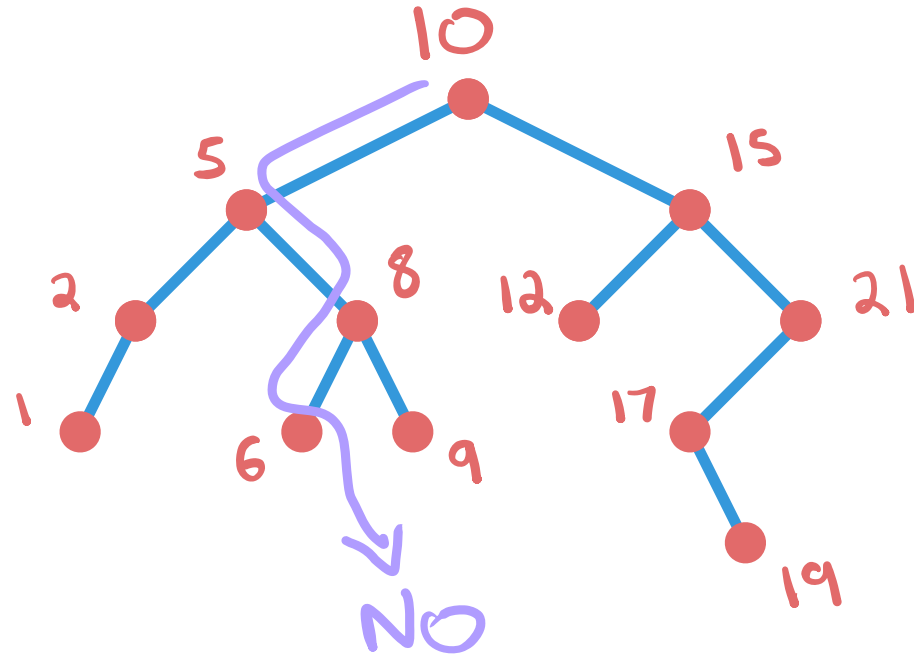
Leads to operations like:

- is a given key in the set?
- what is the first key $\geq x$
- list all keys between x and y
- how many keys are between x and y ?

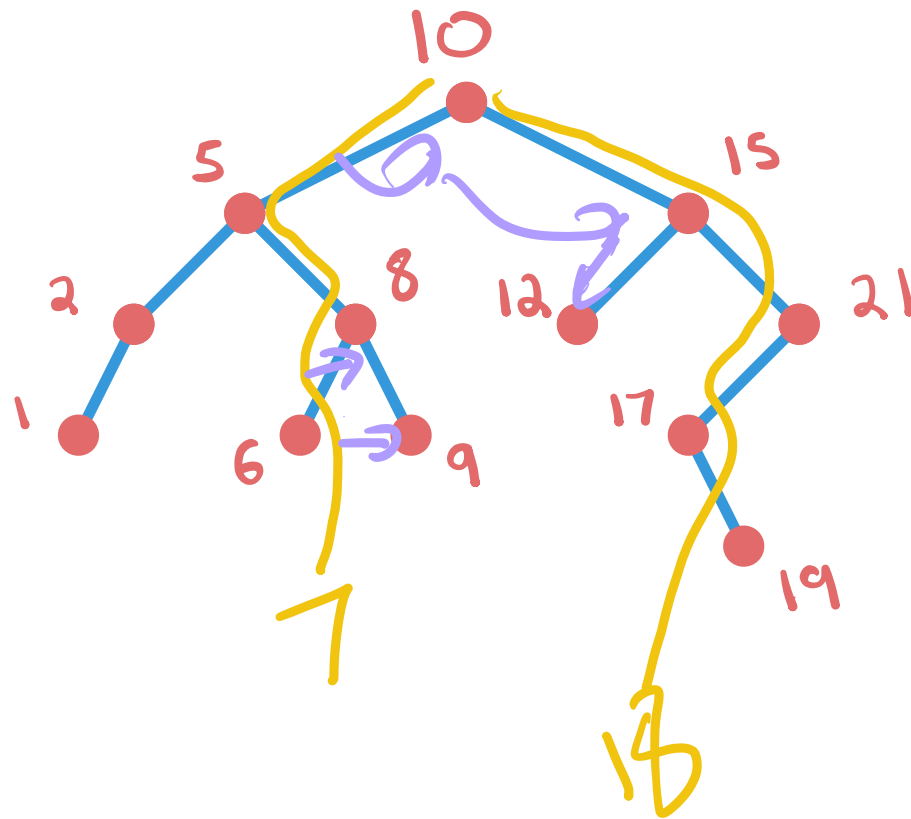
does the tree contain 7?



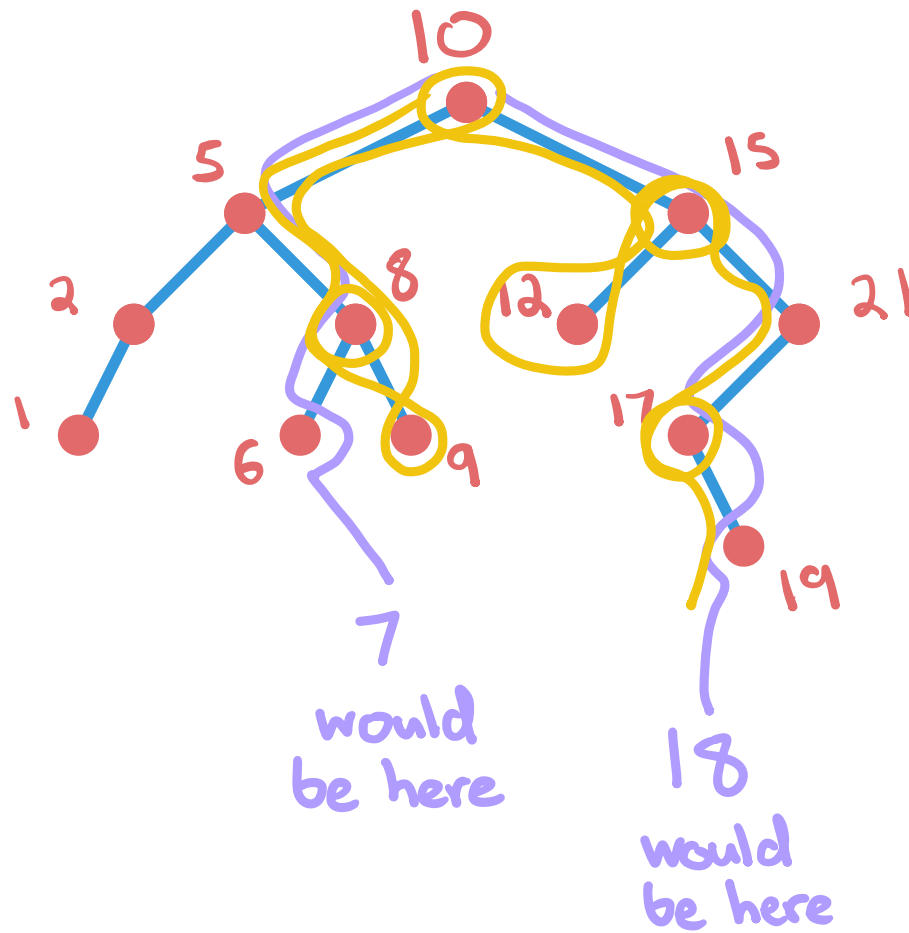
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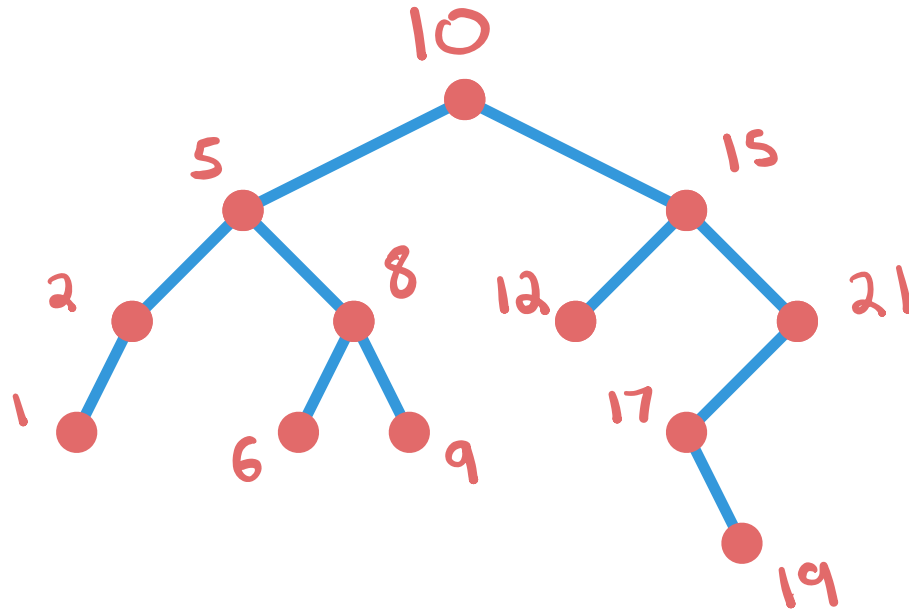
list all keys between 7 and 18



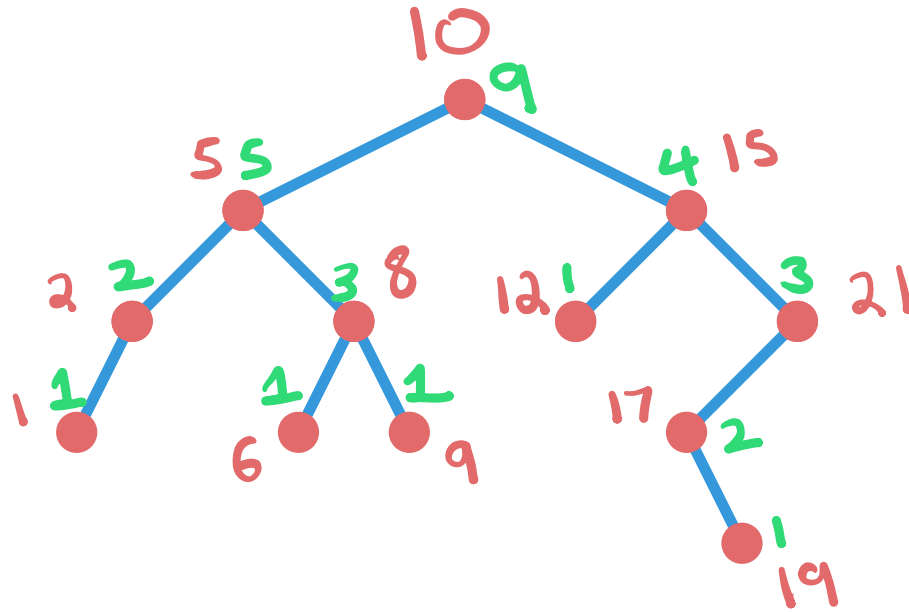
list all keys between 7 and 18



How many keys are between 5 and 25?

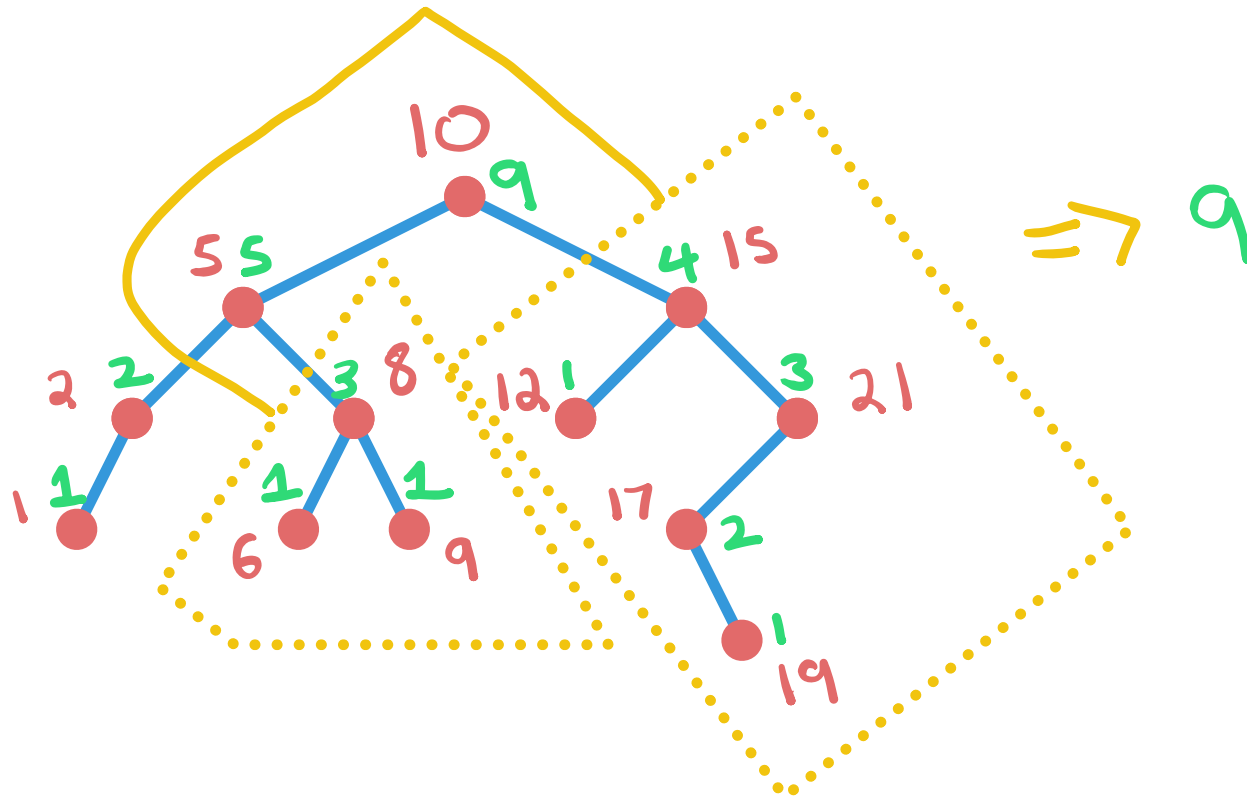


How many keys are between 5 and 25?

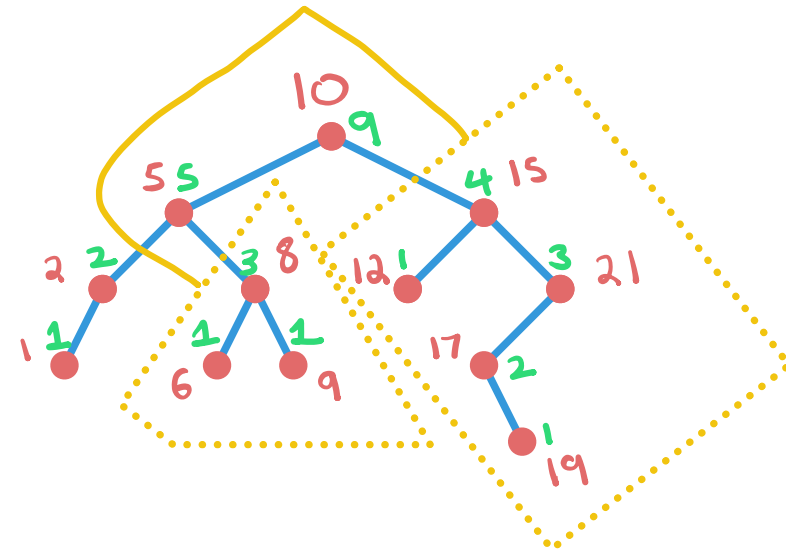
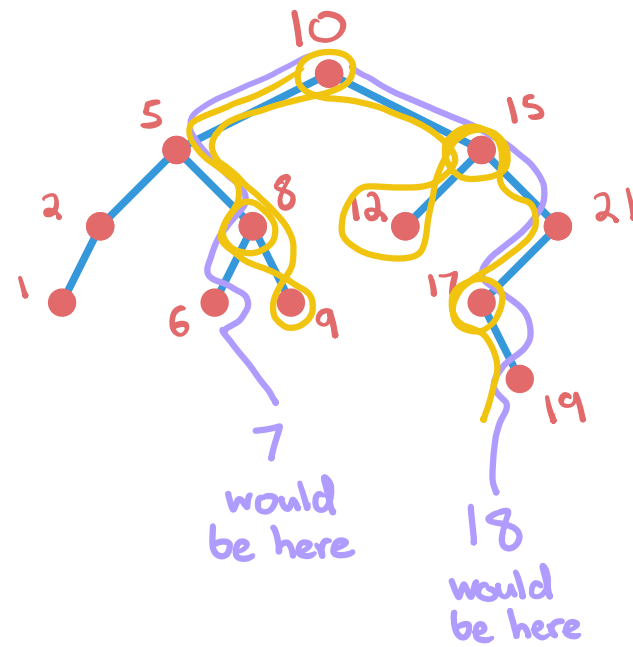
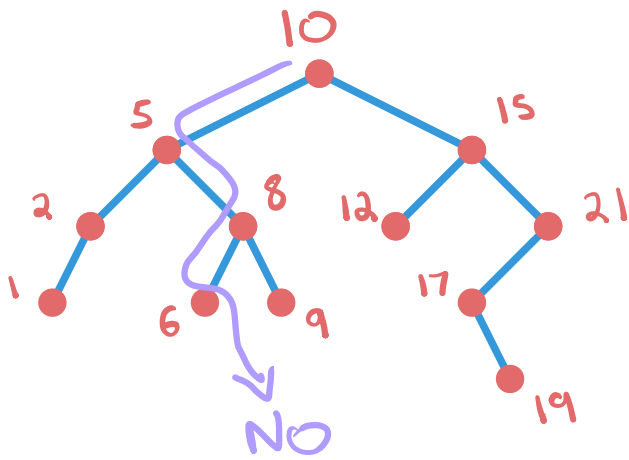


Record # nodes in each subtree

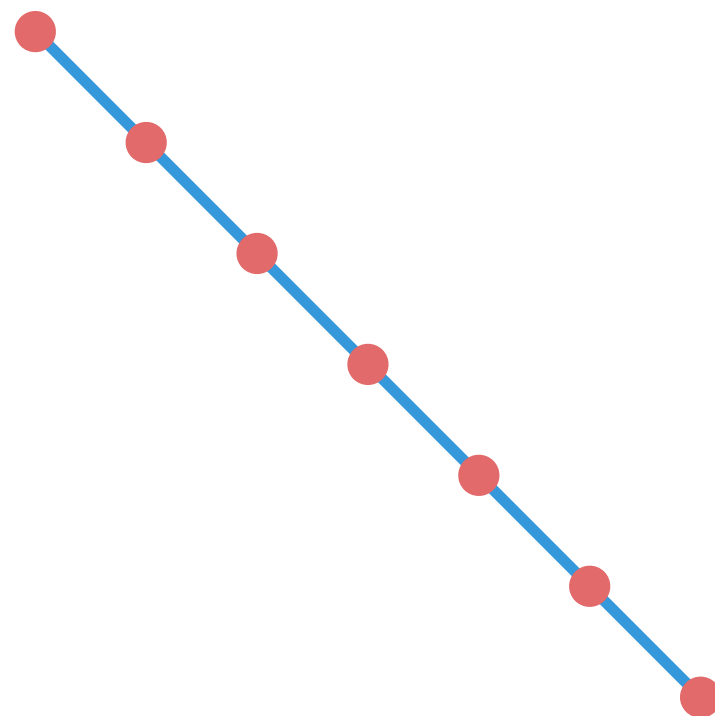
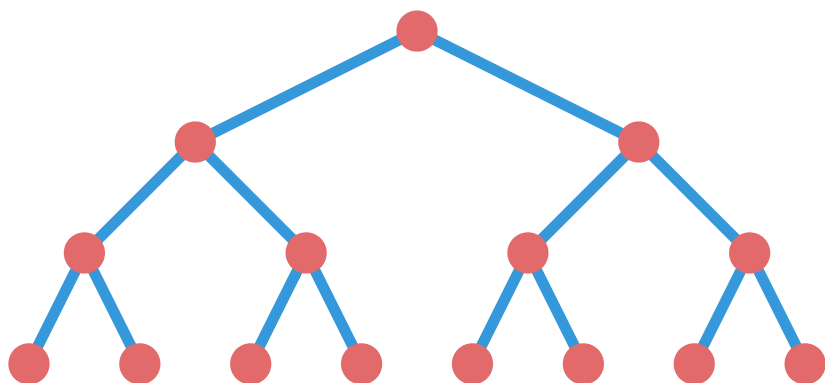
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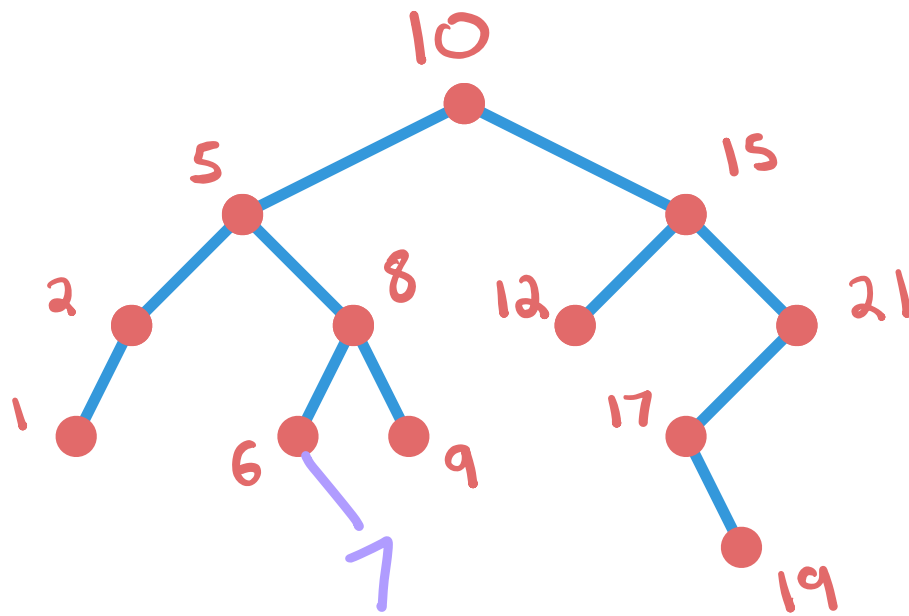


Record # nodes in each subtree



Running time $\approx$ height of tree

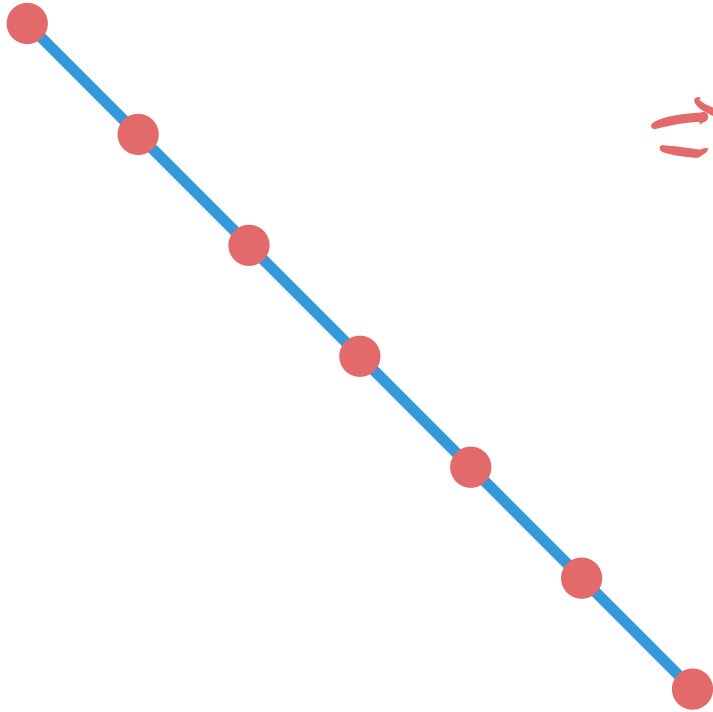


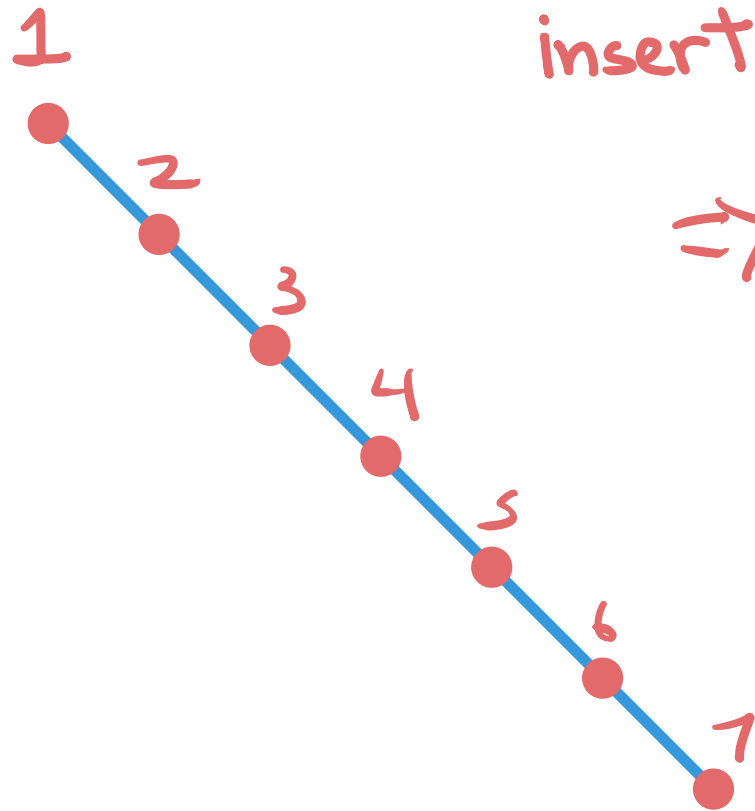


Most natural method for insertion is as leaves
(search for where the key would be, and put it there)

insert 1, 2, 3, 4, 5, 6, 7

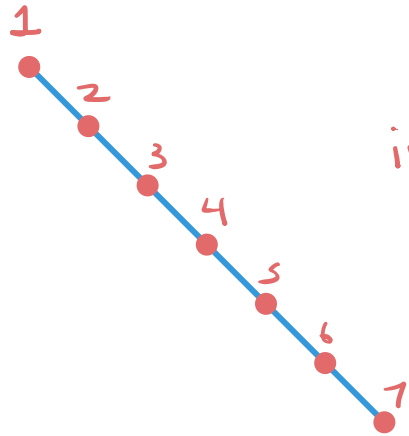
$\Rightarrow$ imbalanced





insert 1, 2, 3, 4, 5, 6, 7

$\Rightarrow$ imbalanced



insert 1, 2, 3, 4, 5, 6, 7
 $\Rightarrow$ imbalanced

Red black trees
B-tree

splay trees
AVL trees
Scapegoat
2-3 trees

How to keep trees balanced?

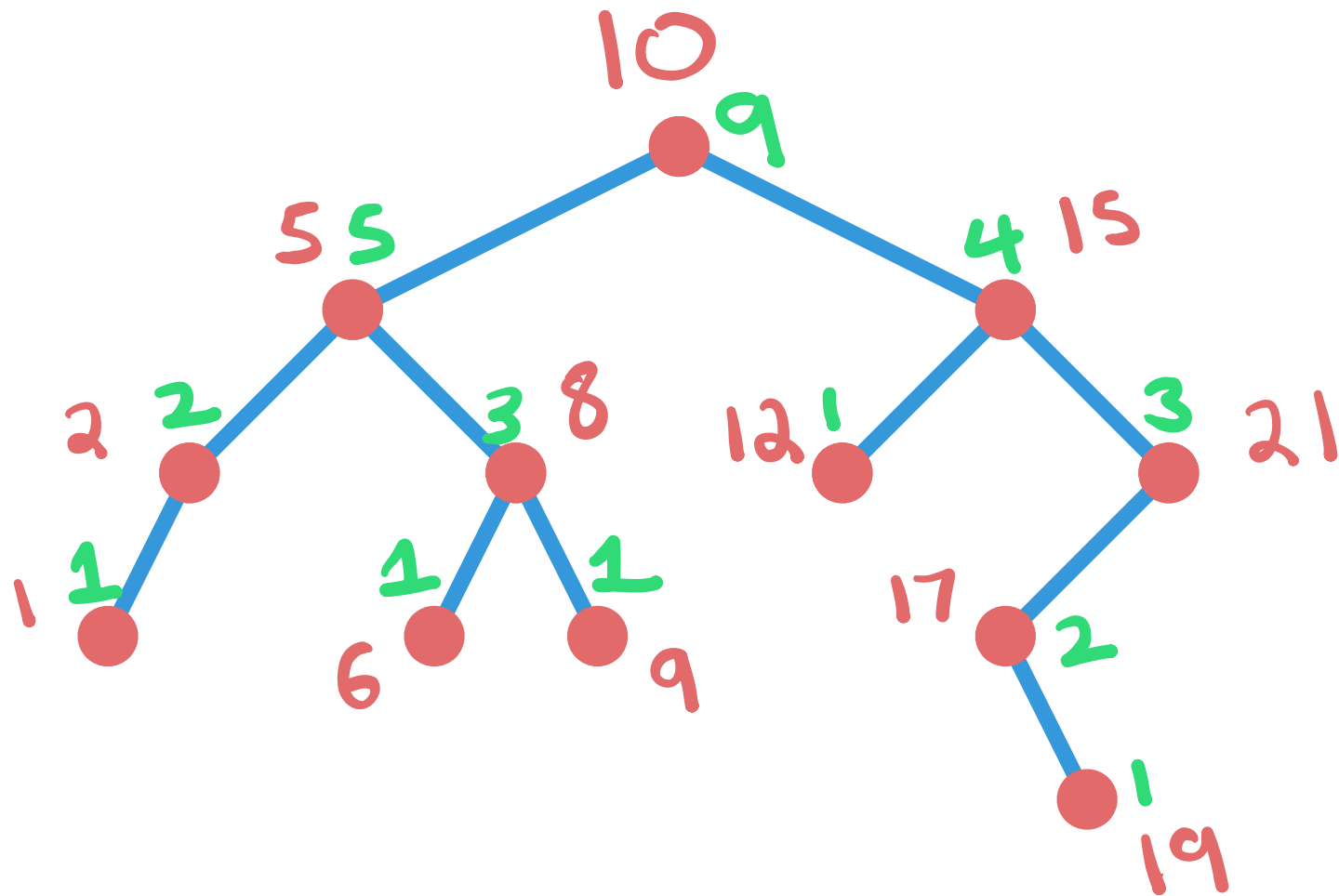
AVL trees

Red-black trees

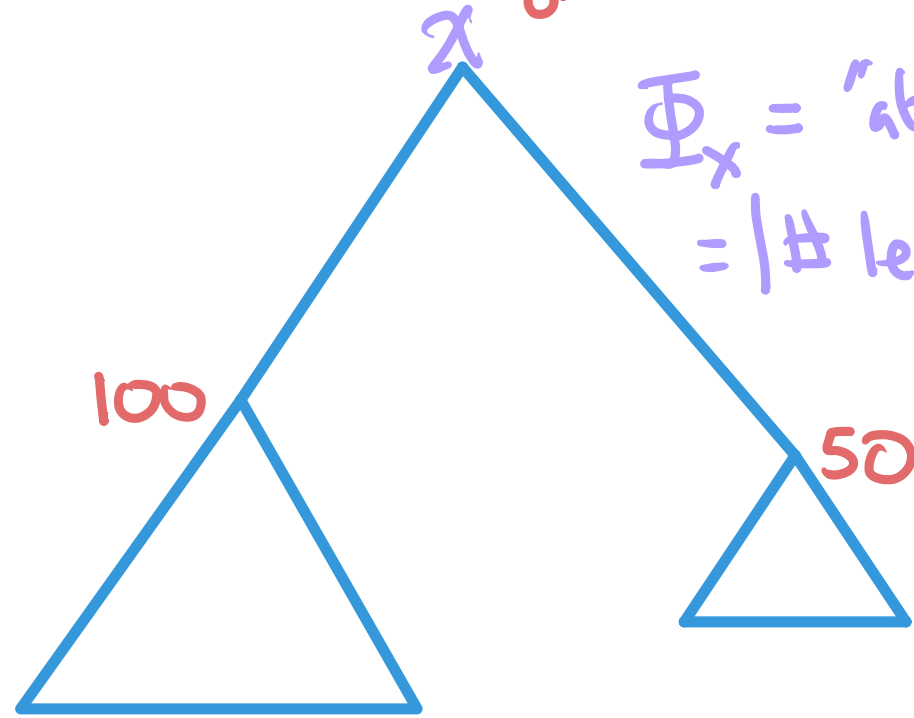
typically covered in
UG data structures

Today we will be very lazy

Record # nodes in each subtree



If we detect big imbalance:



$$\Phi_x = \text{"absolute imbalance"} \\ = |\# \text{ left} - \# \text{ right}|$$

$$(\# \text{ in one subtree}) > 2 \times (\# \text{ in other subtree})$$

rebuild entire subtree optimally

(choose median to be root of subtree, recurse) (linear time)

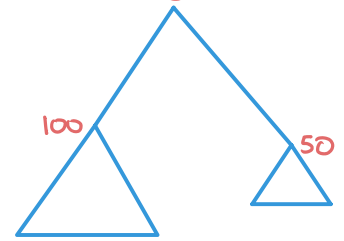
Lemma: height is $O(\log n)$
(always)

Theorem Insertion takes $O(\log n)$
amortized time

$$\Phi_x = |\# \text{left}_x - \# \text{right}_x|$$

$$\Phi = \sum_x \Phi_x + \# \text{deleted}$$

If we detect big imbalance:



$(\# \text{ in one subtree}) > 2 \times (\# \text{ in other subtree})$

rebuild entire subtree optimally

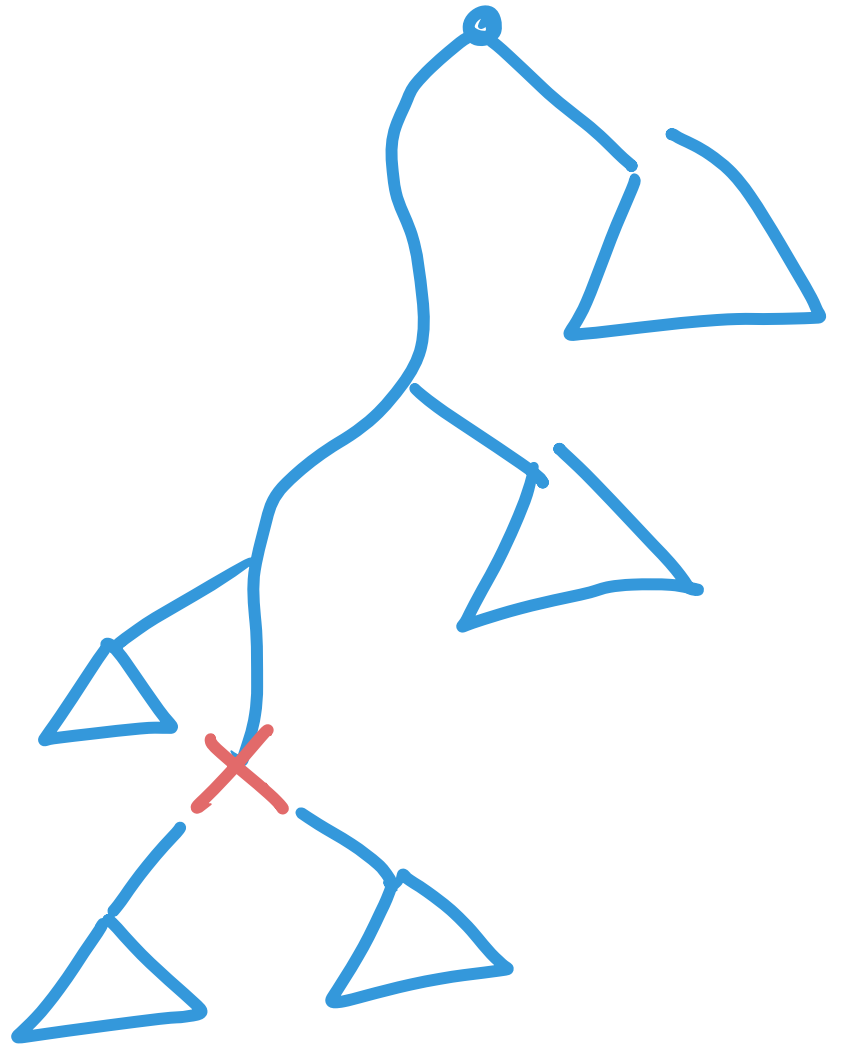
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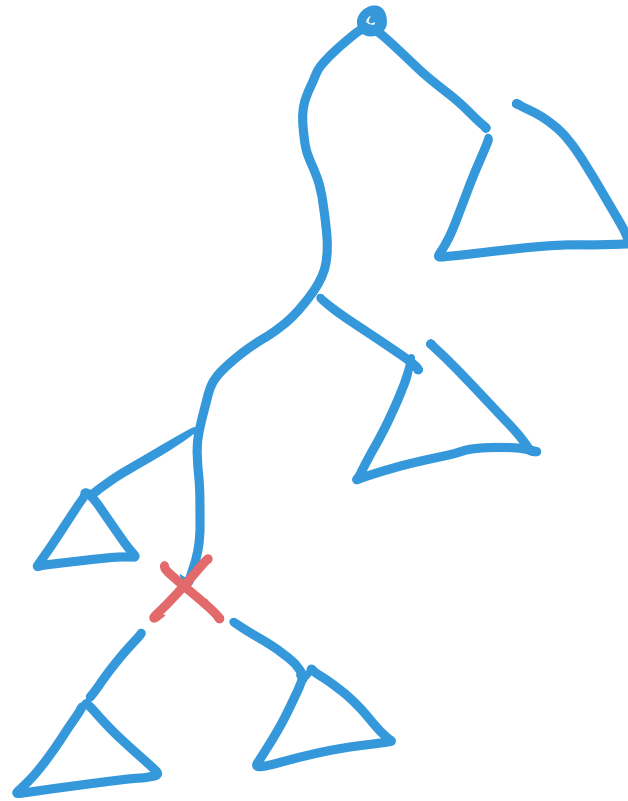
Deletions (remove key from BST)

Old-fashioned way:

① search for key

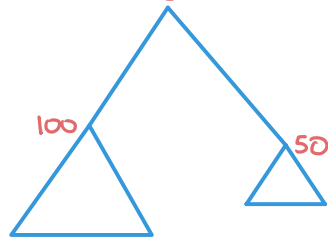
② If key is not a leaf:
chaos





Lazy idea: mark node as deleted

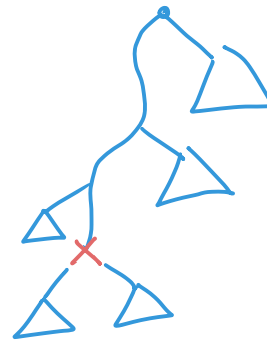
IS we detect big imbalance:



$(\# \text{ in one subtree}) > 2 \times (\# \text{ in other subtree})$

rebuild entire subtree tree optimally

(choose median to be root of subtree, recurse) (linear time)



Lazy idea: mark node as deleted

if $\geq 50\%$ marked for deletion,

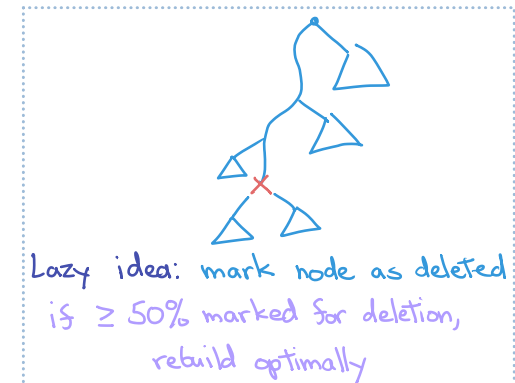
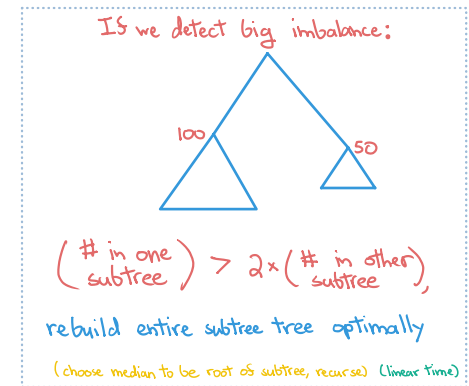
rebuild optimally

Theorem: lazy insertion and lazy deletion take

$O(\log n)$ amortized time

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Proof



Immutable data structures

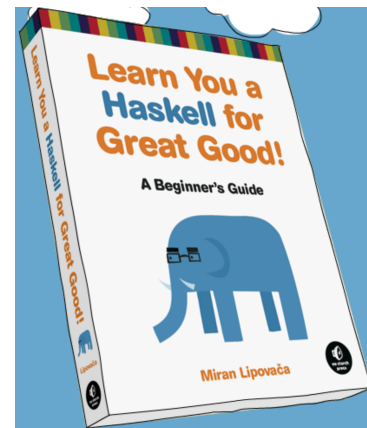
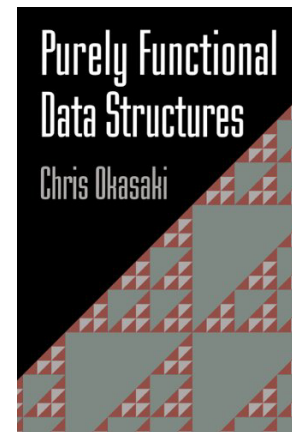
Once something is written, never changes

Restrictions bring benefits:

no side effects

simplifies concurrency

helps compiler



Immutable data structures

Once something is written, never changes

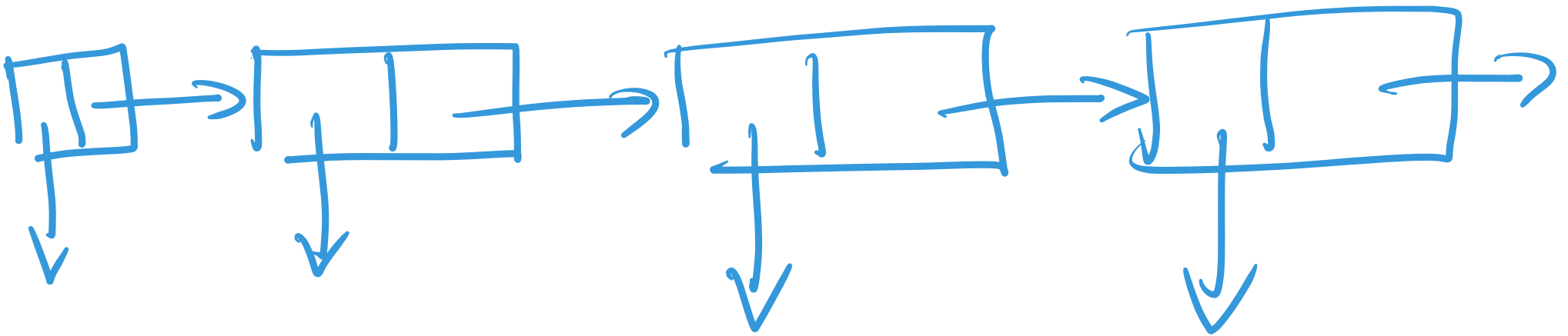
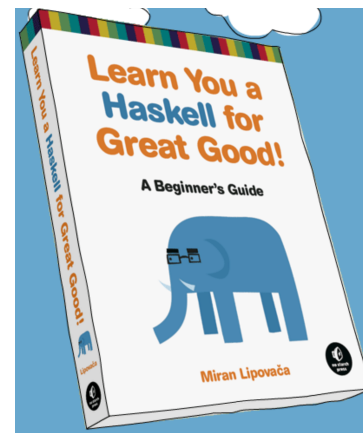
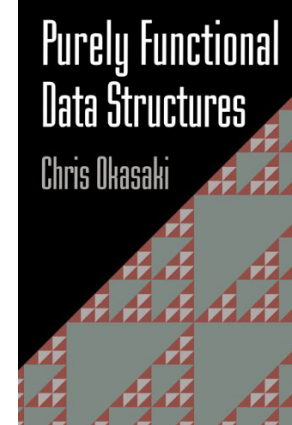
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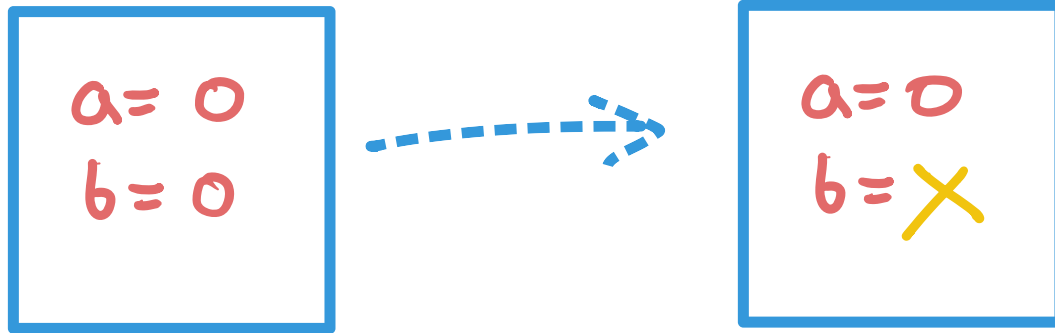
helps compiler

e.g. linked list

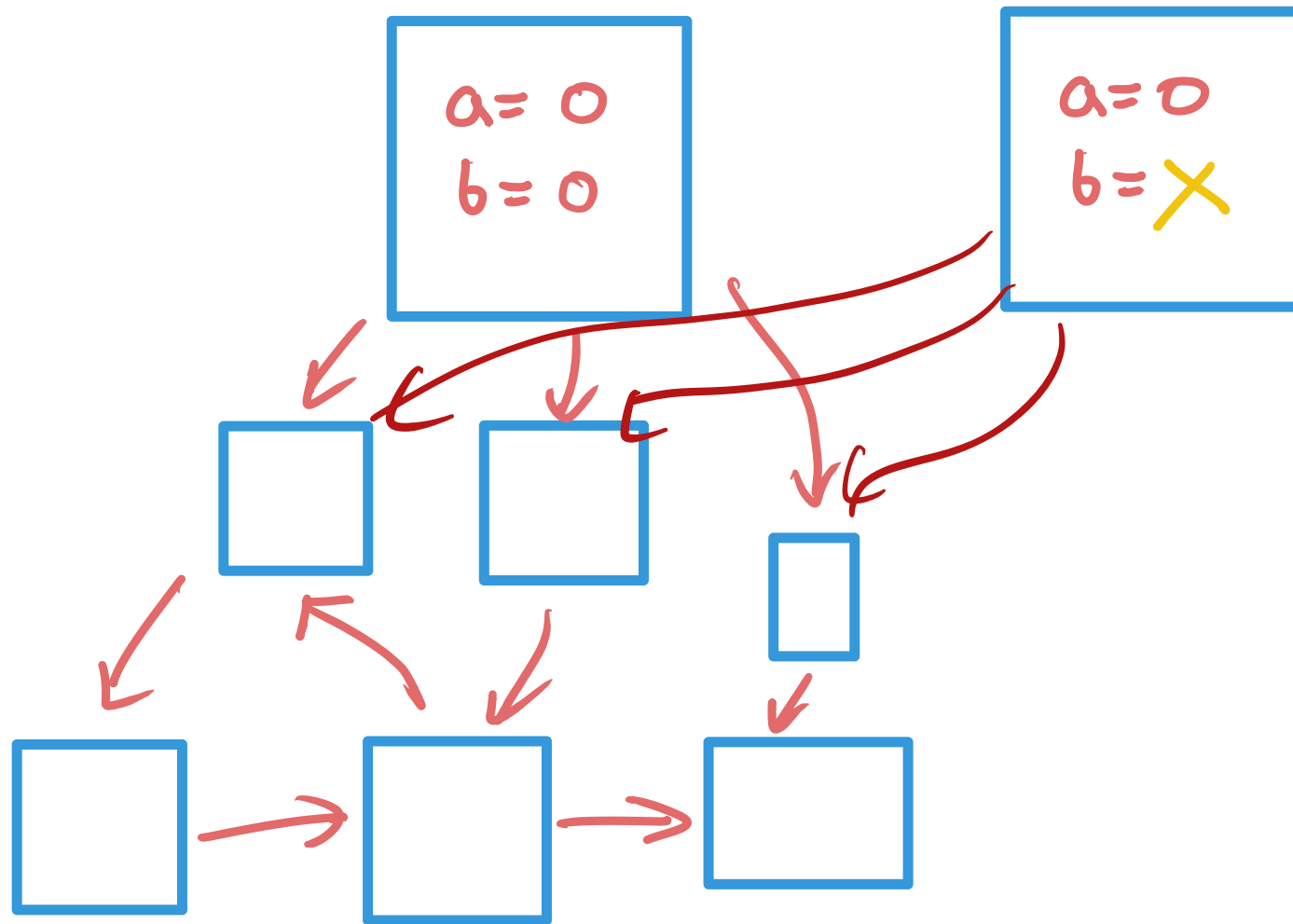


Editing objects by copying

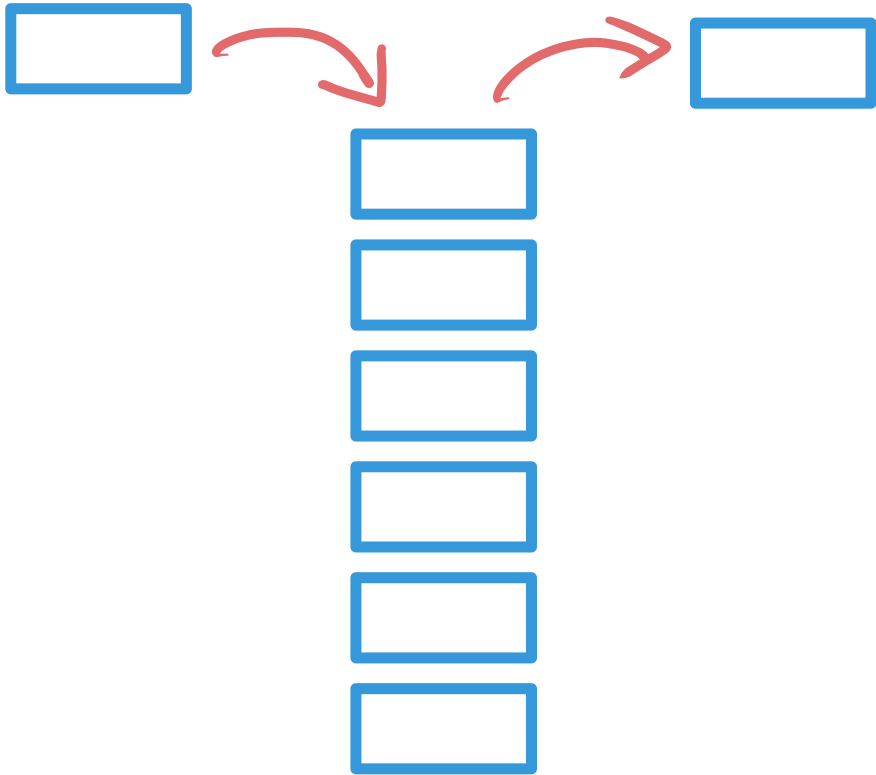
small change $\Rightarrow$ copy whole object



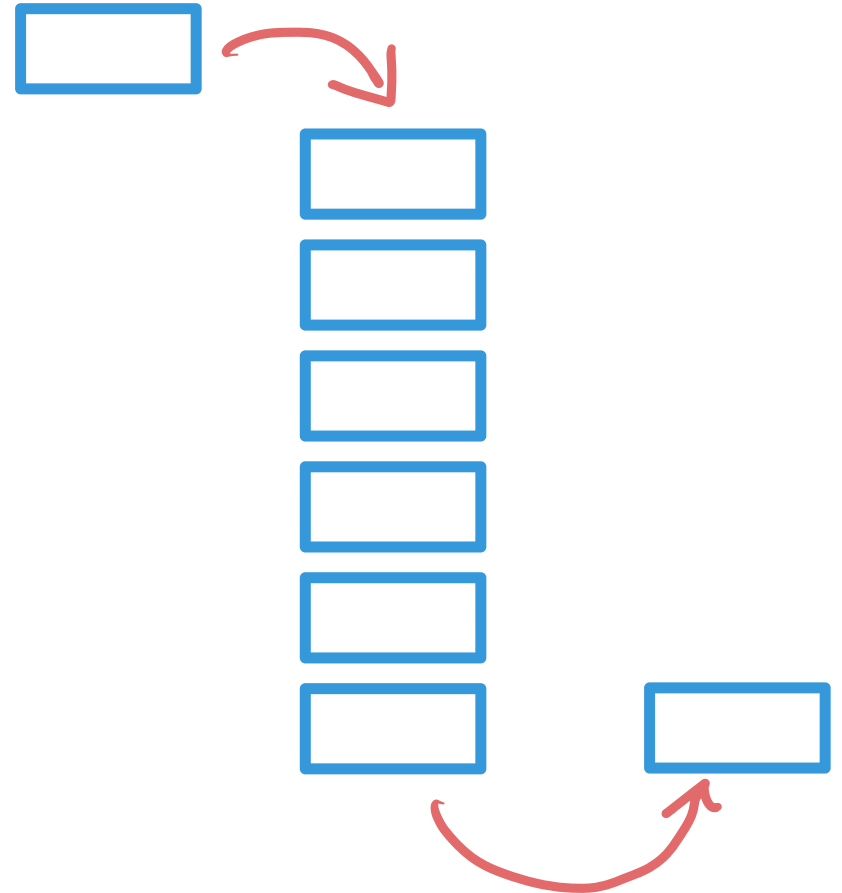
what about "deep" objects?



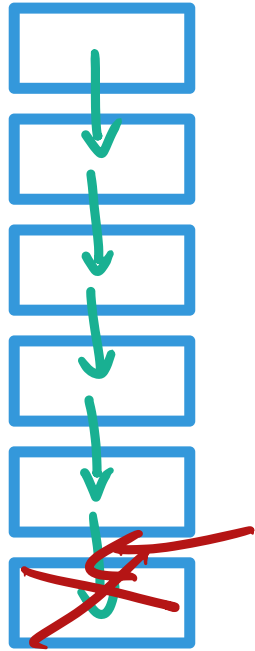
Stacks



Queues



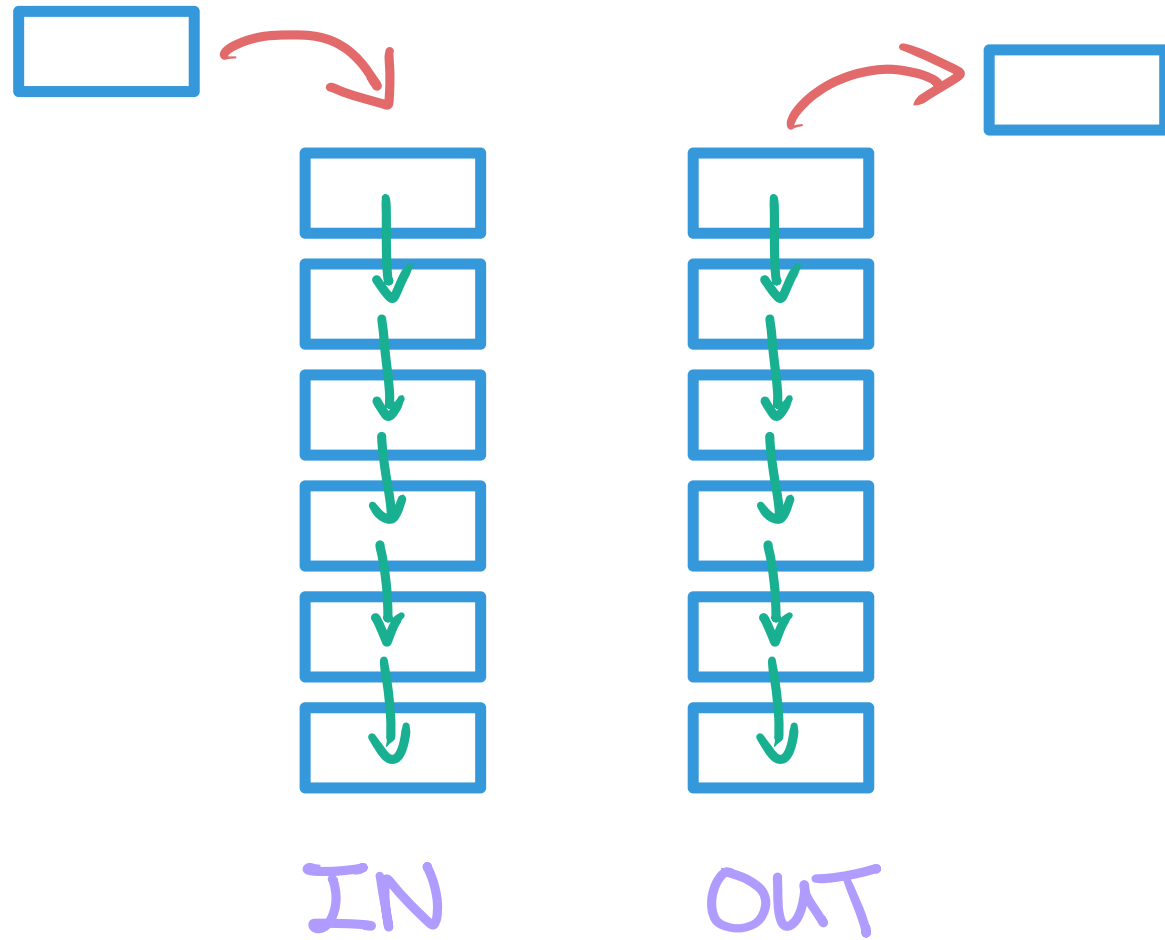
Immutable stacks

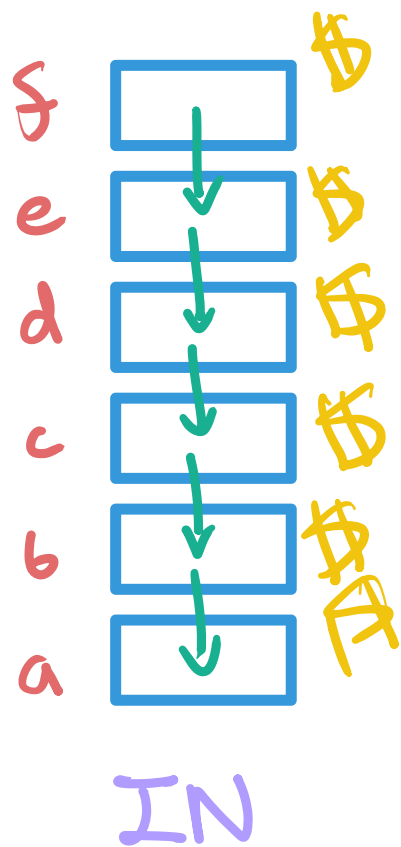


(just a linked list)

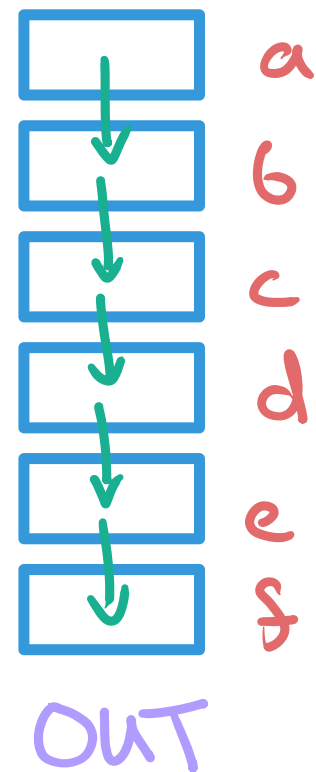
Immutable queues

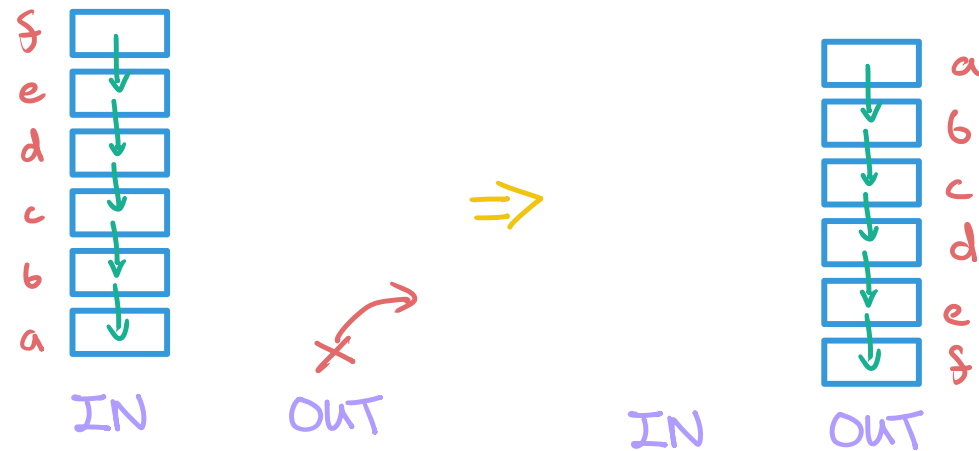
Immutable queues





IN





Theorem: insertion/deletion take $O(1)$ amortized