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Efficient Sorting – The Power of Divide & Conquer

13 October 2023

Sebastian Wild

Learning Outcomes

1. Know principles and implementation of *mergesort* and *quicksort*.
2. Know properties and *performance characteristics* of mergesort and quicksort.
3. Know the comparison model and understand the corresponding *lower bound*.
4. Understand *counting sort* and how it circumvents the comparison lower bound.
5. Know ways how to exploit *presorted* inputs.

Unit 3: *Efficient Sorting*



Outline

3 Efficient Sorting

- 3.1 Mergesort
- 3.2 Quicksort
- 3.3 Comparison-Based Lower Bound
- 3.4 Integer Sorting
- 3.5 Adaptive Sorting
- 3.6 Python's list sort
- 3.7 Order Statistics
- 3.8 Further D&C Algorithms

Why study sorting?

- ▶ fundamental problem of computer science that is still not solved
 - ▶ building brick of many more advanced algorithms
 - ▶ for preprocessing
 - ▶ as subroutine
 - ▶ playground of manageable complexity to practice algorithmic techniques
- Algorithm with optimal #comparisons in worst case?

Here:

- ▶ “classic” fast sorting method
- ▶ exploit **partially sorted** inputs
- ▶ **parallel** sorting

Part I

The Basics

Rules of the game

► **Given:**

► array $A[0..n) = A[0..n - 1]$ of n objects

► a total order relation \leq among $A[0], \dots, A[n - 1]$

(a comparison function)

Python: elements support `<=` operator (`__le__()`)

Java: `Comparable` class (`x.compareTo(y) <= 0`)

► **Goal:** rearrange (i. e., permute) elements within A ,
so that A is *sorted*, i. e., $A[0] \leq A[1] \leq \dots \leq A[n - 1]$

► for now: A stored in main memory (*internal sorting*)
single processor (*sequential sorting*)

Clicker Question



What is the complexity of sorting? Type your answer, e.g., as
"Theta(sqrt(n))"

$\Theta(n \log n)$ \leftarrow $O(n \log n)$ & $\Omega(n \log n)$
algorithm lower bound

of that cost impossible to do better



[→ sli.do/comp526](https://sli.do/comp526)

3.1 Mergesort

Clicker Question



How does mergesort work?

- ☐ **A** Split elements around median, then recurse on small / large elements.
- ☐ **B** Recurse on left / right half, then combine sorted halves.
- ☐ **C** Grow sorted part on left, repeatedly add next element to sorted range.
- ☐ **D** Repeatedly choose 2 elements and swap them if they are out of order.
- ☐ **E** Don't know.



→ *sli.do/comp526*

Clicker Question

How does mergesort work?



- ☐ A ~~Split elements around median, then recurse on small / large elements.~~
- ☒ B Recurse on left / right half, then combine sorted halves. ✓
- ☐ C ~~Crow sorted part on left, repeatedly add next element to sorted range.~~
- ☐ D ~~Repeatedly choose 2 elements and swap them if they are out of order.~~
- ☐ E ~~Don't know.~~

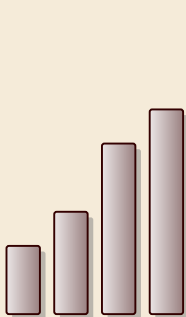


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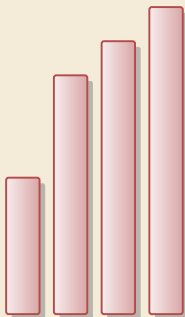
Merging sorted lists



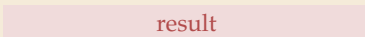
Merging sorted lists



run1



run2

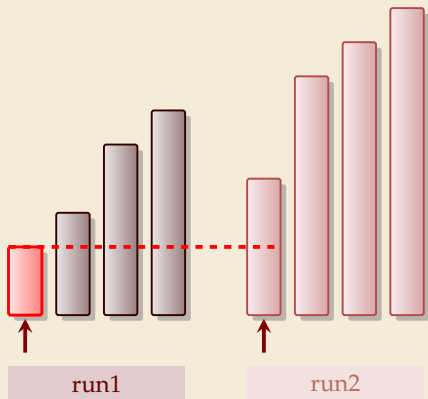


result

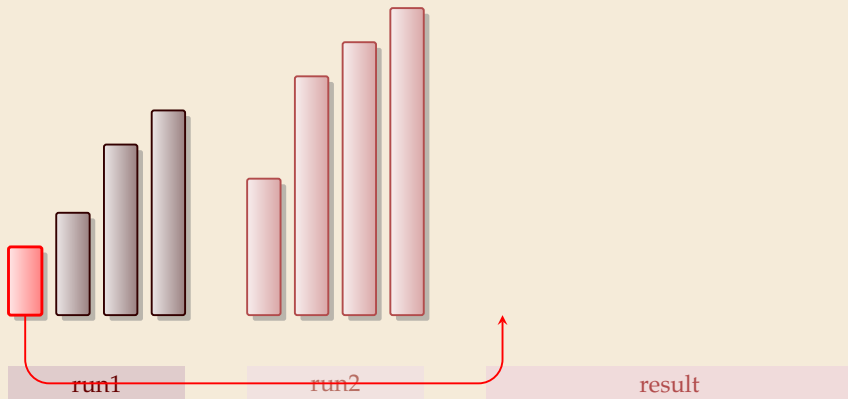
Merging sorted lists



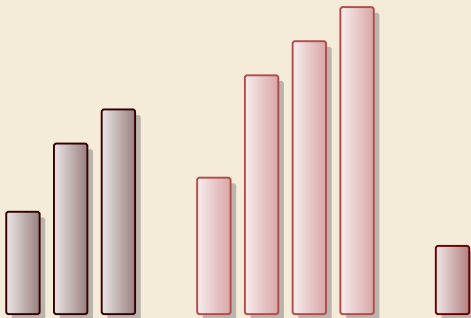
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Merging sorted lists



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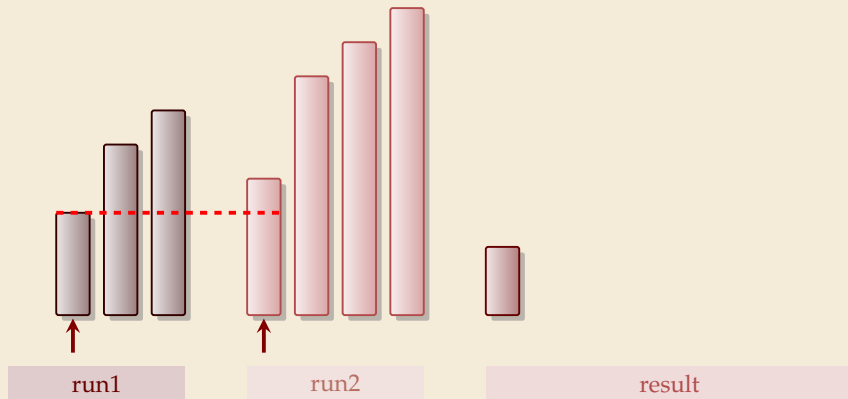


run1

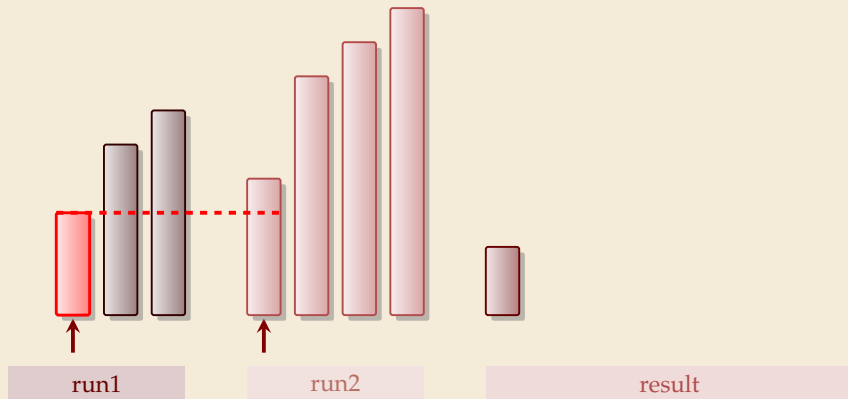
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result

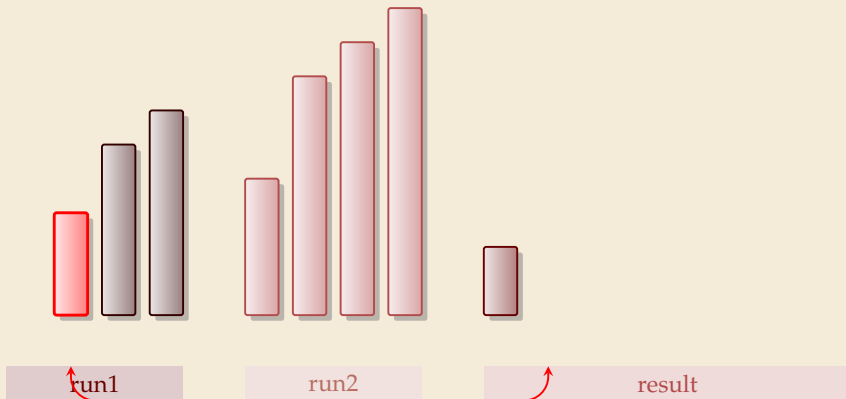
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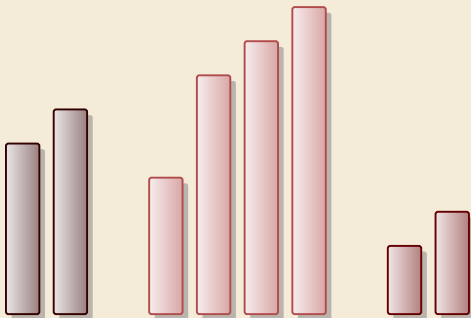
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Merging sorted lists

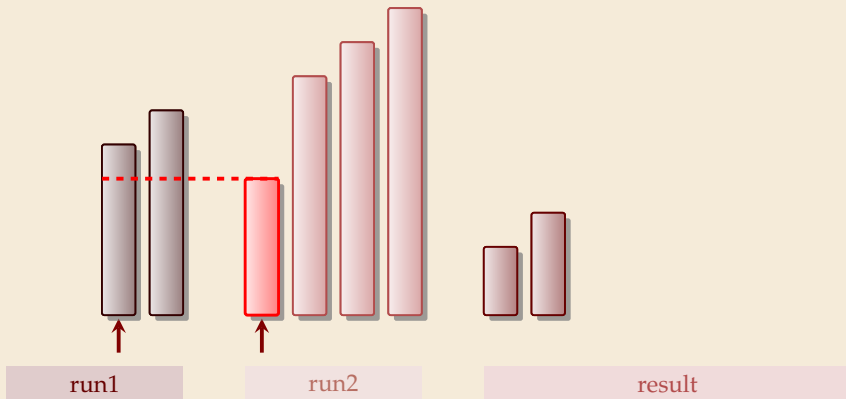


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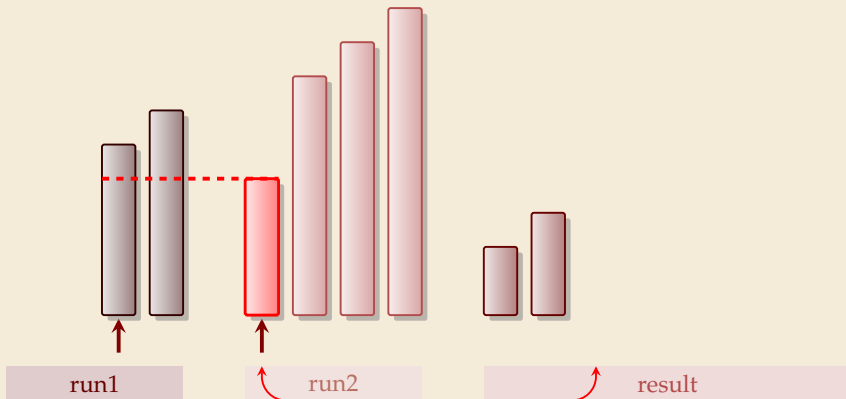
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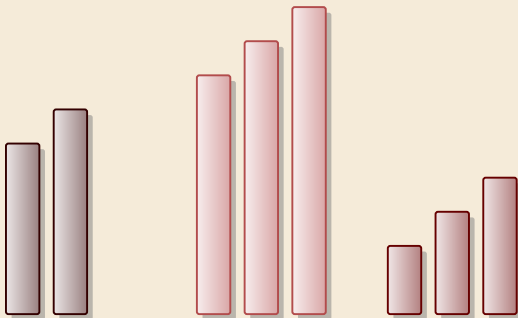
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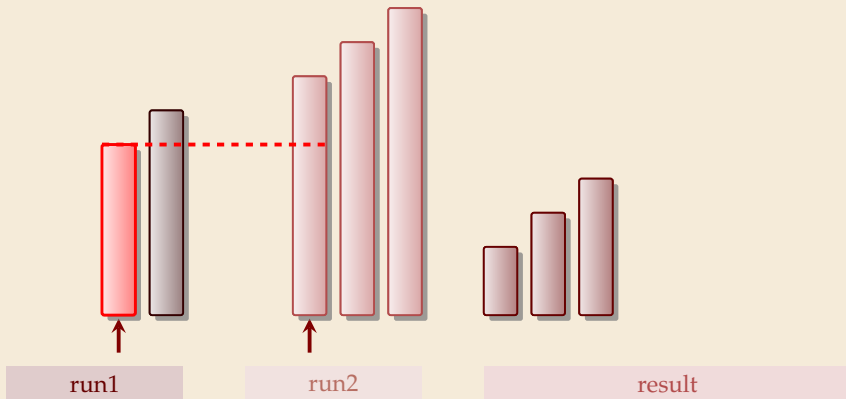


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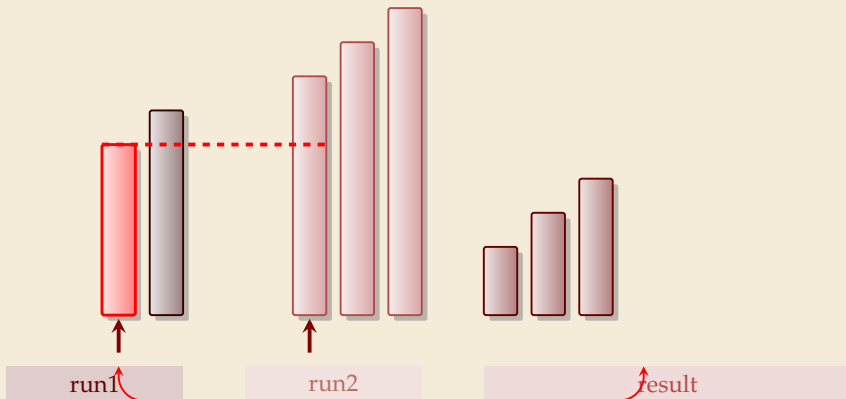
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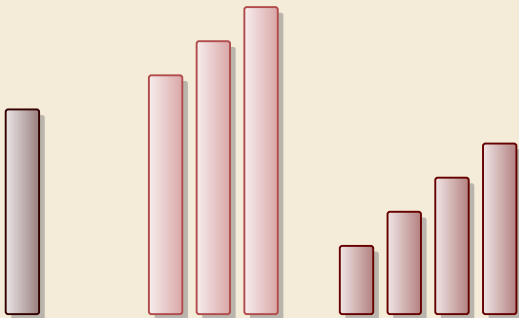
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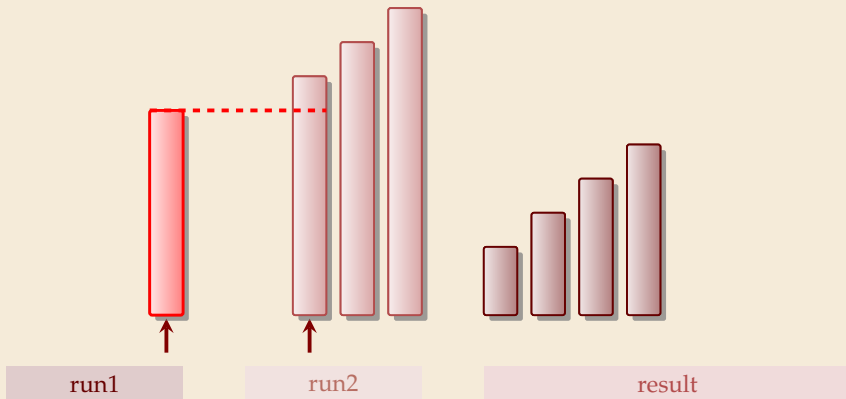


run1

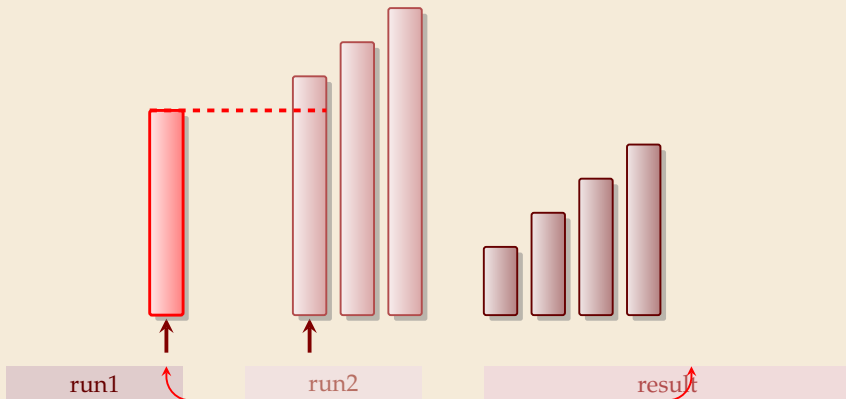
run2

result

Merging sorted lists



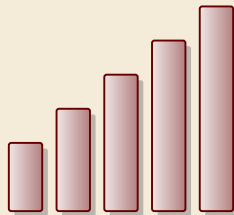
Merging sorted lists



Merging sorted lists



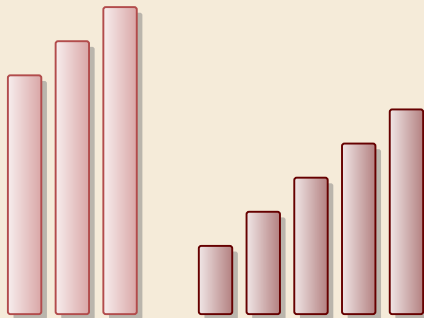
run1



run2

result

Merging sorted lists

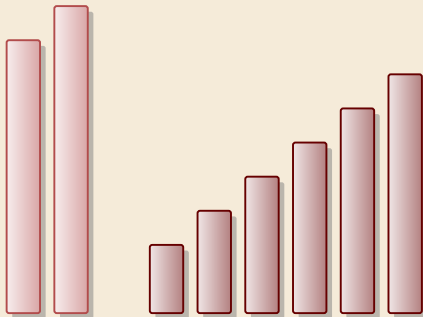


run1

run2

result

Merging sorted lists

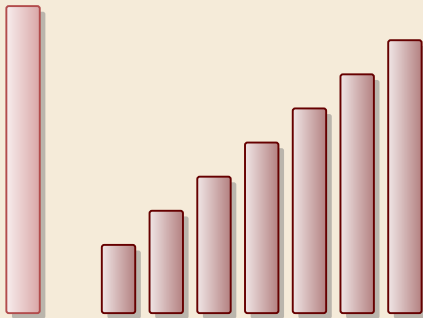


run1

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Merging sorted lists

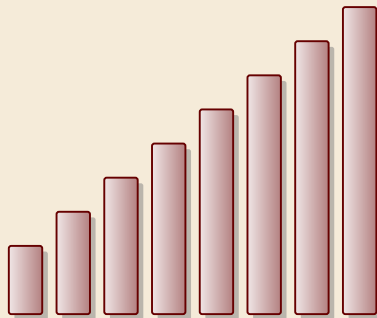


run1

run2

result

Merging sorted lists



run1

run2

result

Clicker Question

What is the worst-case running time of mergesort?



A $\Theta(1)$

B $\Theta(\log n)$

C $\Theta(\log \log n)$

D $\Theta(\sqrt{n})$

E $\Theta(n)$

F $\Theta(n \log \log n)$

G $\Theta(n \log n)$

H $\Theta(n \log^2 n)$

I $\Theta(n^{1+\epsilon})$

J $\Theta(n^2)$

K $\Theta(n^3)$

L $\Theta(2^n)$



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Clicker Question



What is the worst-case running time of mergesort?

☐ A ~~$\Theta(1)$~~

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☐ E ~~$\Theta(n)$~~

☐ F ~~$\Theta(n \log \log n)$~~

☒ G $\Theta(n \log n)$ ✓

☐ H ~~$\Theta(n \log^2 n)$~~

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☐ L ~~$\Theta(2^n)$~~



→ sli.do/comp526

Mergesort

```
1 procedure mergesort( $A[l..r]$ )
```

```
2    $n := r - l$ 
```

```
3   if  $n \leq 1$  return
```

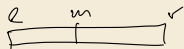
```
4    $m := l + \lfloor \frac{n}{2} \rfloor$ 
```

```
5   mergesort( $A[l..m]$ )
```

```
6   mergesort( $A[m..r]$ )
```

```
7   merge( $A[l..m]$ ,  $A[m..r]$ ,  $buf$ )
```

```
8   copy  $buf$  to  $A[l..r]$ 
```



$mergesort(A[0..n])$

► recursive procedure

► merging needs

- temporary storage *buf* for result
(of same size as merged runs)
- to read and write each element twice
(once for merging, once for copying back)

Mergesort

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1 procedure mergesort( $A[l..r]$ )  
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```

- recursive procedure
- merging needs
 - temporary storage *buf* for result (of same size as merged runs)
 - to read and write each element twice (once for merging, once for copying back)

Analysis: count “*element visits*” (read and/or write)

$$C(n) = \begin{cases} 0 & n \leq 1 \\ C(\lfloor n/2 \rfloor) + C(\lceil n/2 \rceil) + 2n & n \geq 2 \end{cases}$$

comps between $\frac{n}{2}$ and n

Simplification

$$n = 2^k$$

same for best and worst case!

$$C(2^k) = \begin{cases} 0 & k \leq 0 \\ 2 \cdot C(2^{k-1}) + 2 \cdot 2^k & k \geq 1 \end{cases} = \underline{2 \cdot 2^k} + \underline{2^2 \cdot 2^{k-1}} + 2^3 \cdot 2^{k-2} + \dots + 2^k \cdot 2^1 = 2k \cdot 2^k$$

$$C(n) = 2n \lg(n) = \Theta(n \log n) \quad (\text{arbitrary } n: C(n) \leq C(\text{next larger power of } 2) \leq 4n \lg(n) + 2n = \Theta(n \log n))$$

Mergesort

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- ▶ recursive procedure
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$$\left(\begin{array}{l} \text{precisely(!) solvable without assumption } n = 2^k: \\ C(n) = \underbrace{2n \lg(n)} + (2 - \{\lg(n)\} - 2^{1-\{\lg(n)\}}) \underline{2n} \\ \text{with } \{x\} := x - \lfloor x \rfloor \end{array} \right)$$

Simplification $n = 2^k$

same for best and worst case!

$$C(2^k) = \begin{cases} 0 & k \leq 0 \\ 2 \cdot C(2^{k-1}) + 2 \cdot 2^k & k \geq 1 \end{cases} = 2 \cdot 2^k + 2^2 \cdot 2^{k-1} + 2^3 \cdot 2^{k-2} + \dots + 2^k \cdot 2^1 = 2k \cdot 2^k$$

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Mergesort – Discussion

- 👍 optimal time complexity of $\Theta(n \log n)$ in the worst case
- 👍 *stable* sorting method i. e., retains relative order of equal-key items
- 👍 memory access is sequential (scans over arrays)
- 👎 requires $\Theta(n)$ extra space
 - there are in-place merging methods,
but they are substantially more complicated
and not (widely) used

3.2 Quicksort

Clicker Question



How does quicksort work?

- A** split elements around median, then recurse on small / large elements.
- B** recurse on left / right half, then combine sorted halves.
- C** grow sorted part on left, repeatedly add next element to sorted range.
- D** repeatedly choose 2 elements and swap them if they are out of order.
- E** Don't know.



→ *sli.do/comp526*

Clicker Question

How does quicksort work?



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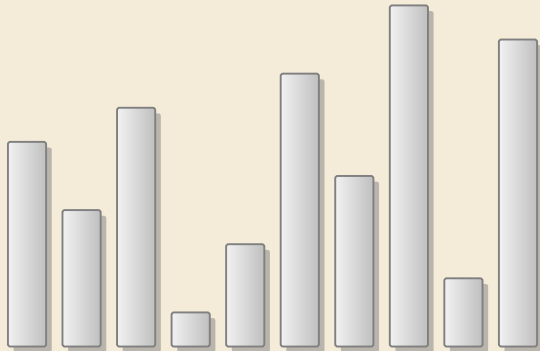


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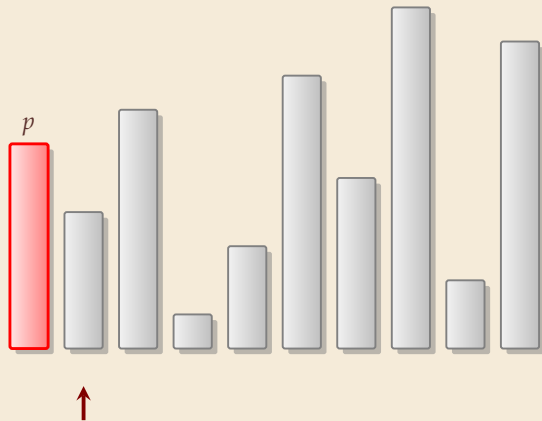
Partitioning around a pivot



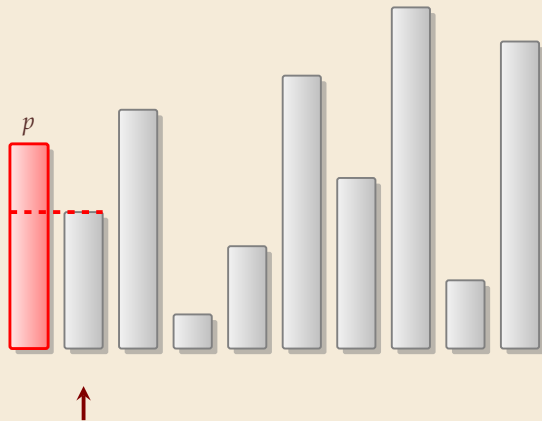
Partitioning around a pivot



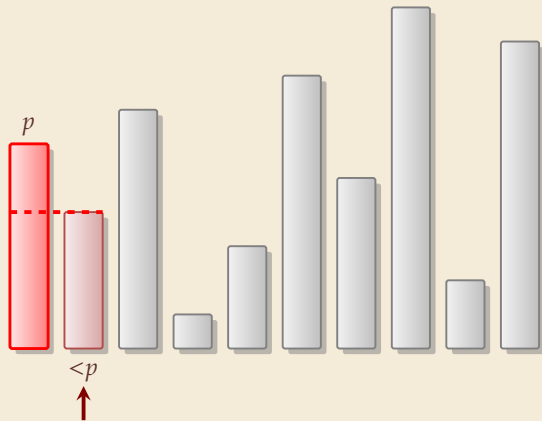
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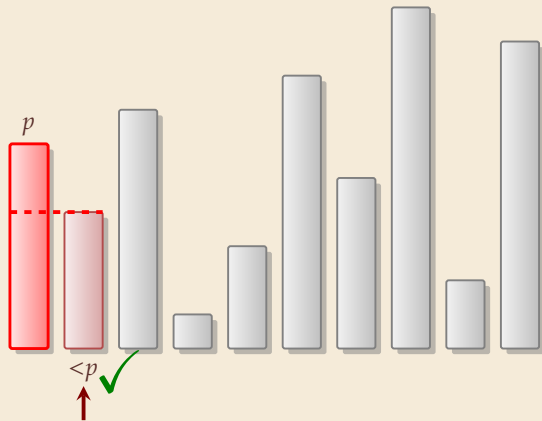
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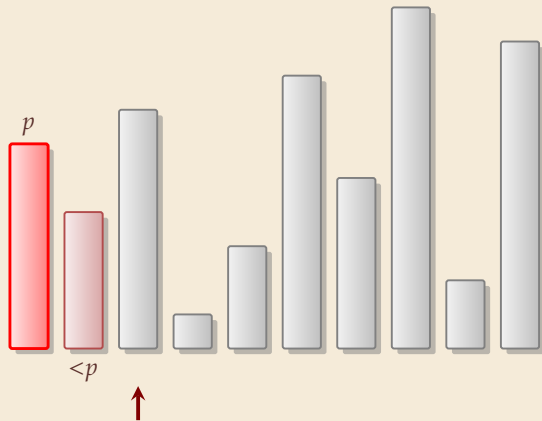
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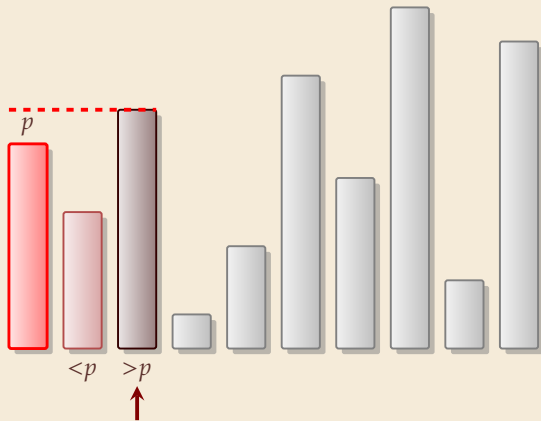
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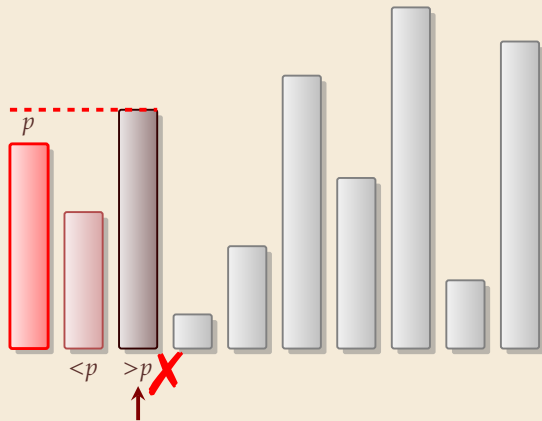
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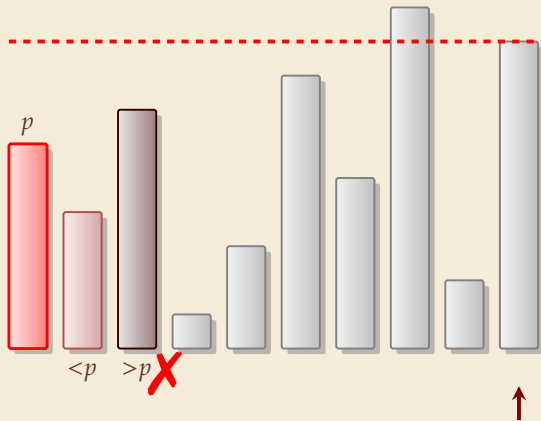
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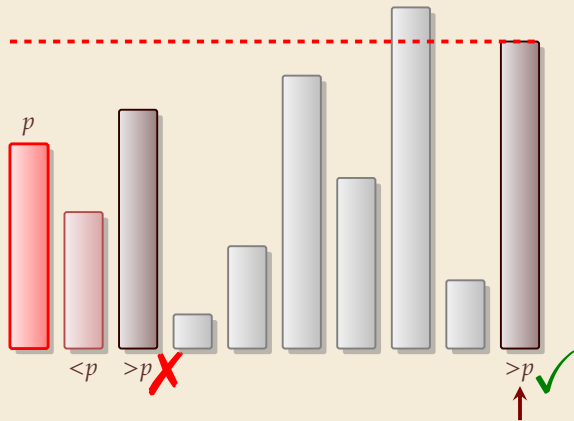
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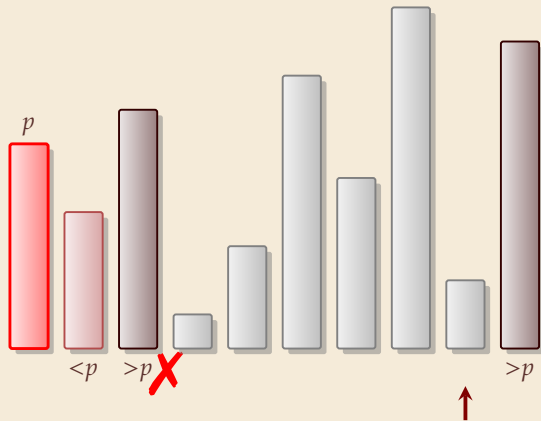
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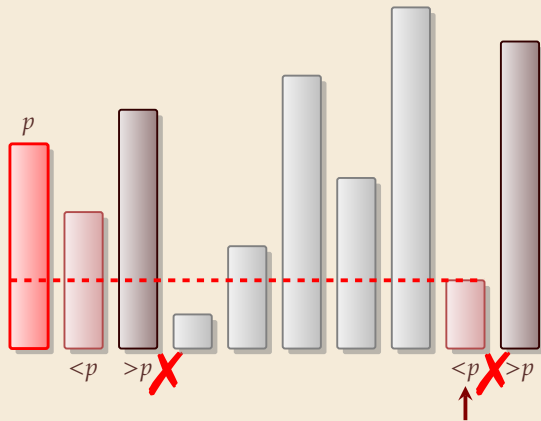
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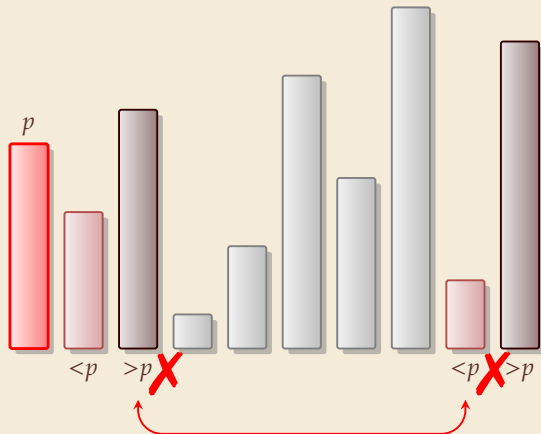
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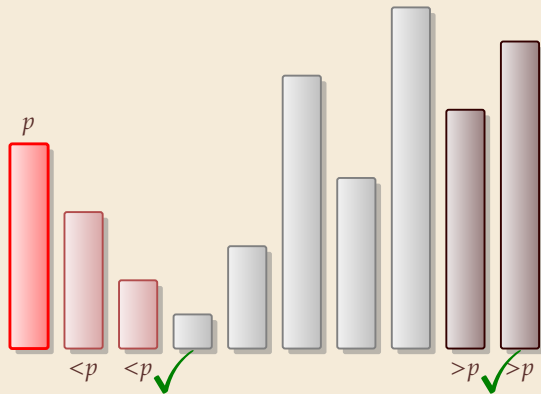
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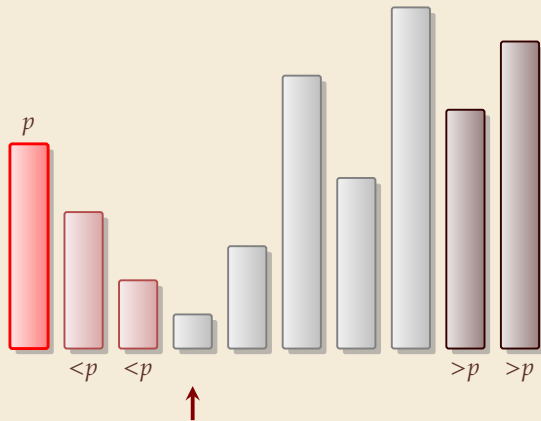
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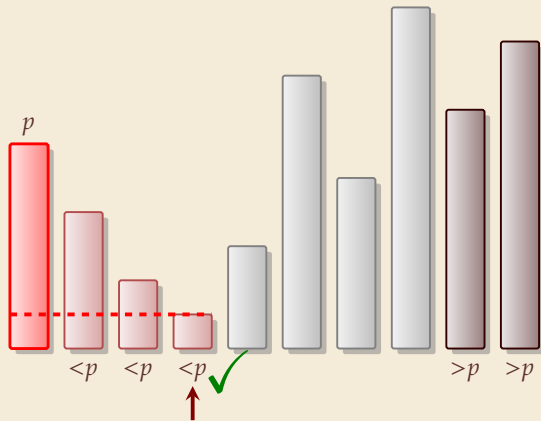
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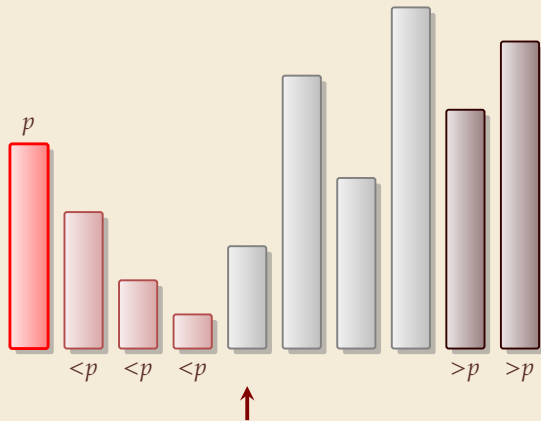
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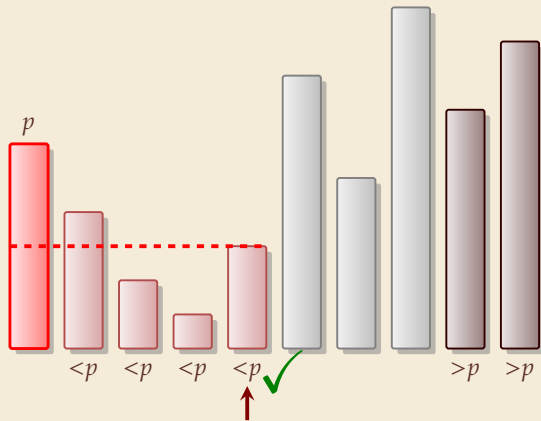
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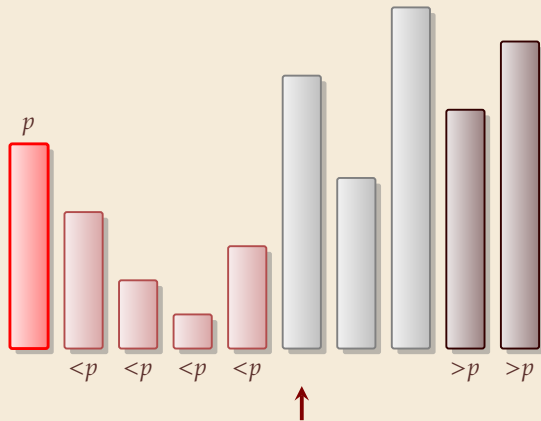
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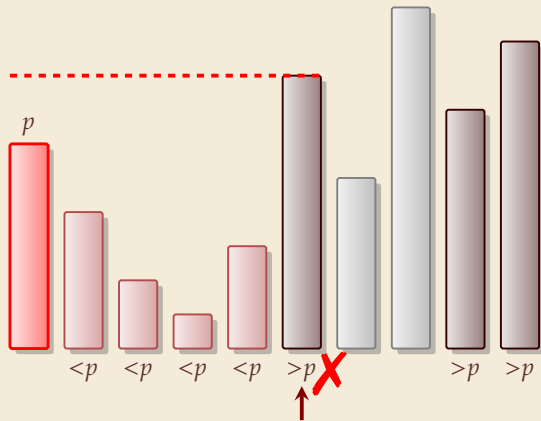
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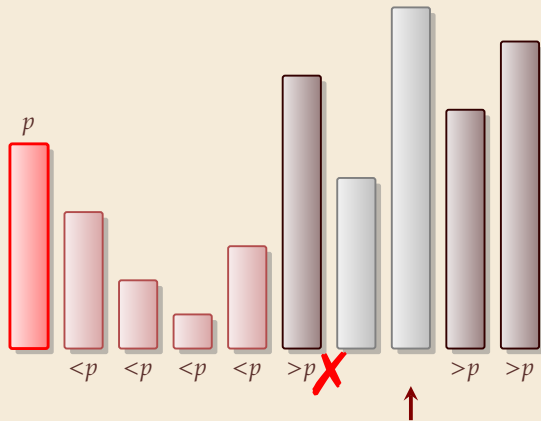
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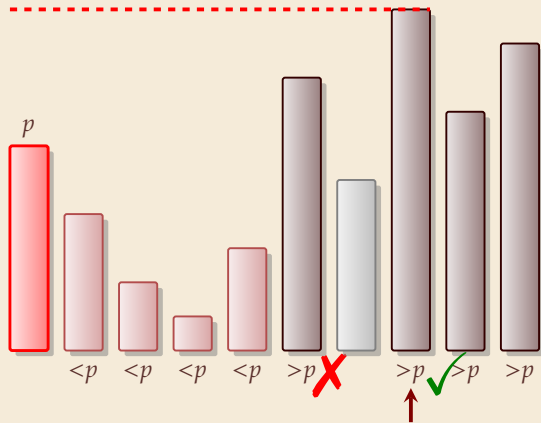
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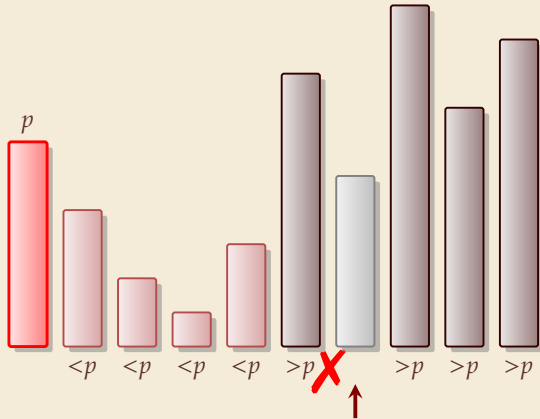
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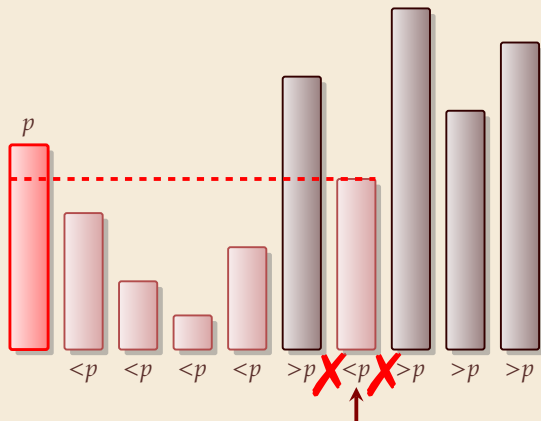
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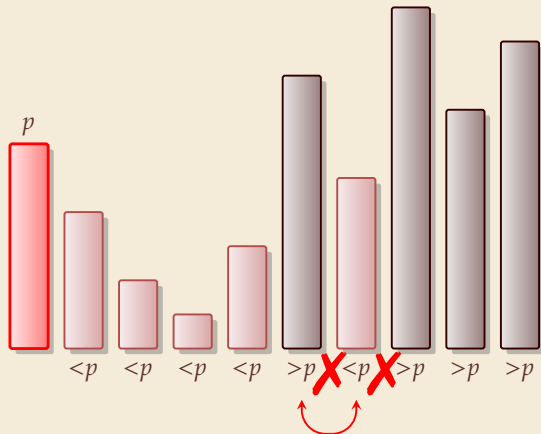
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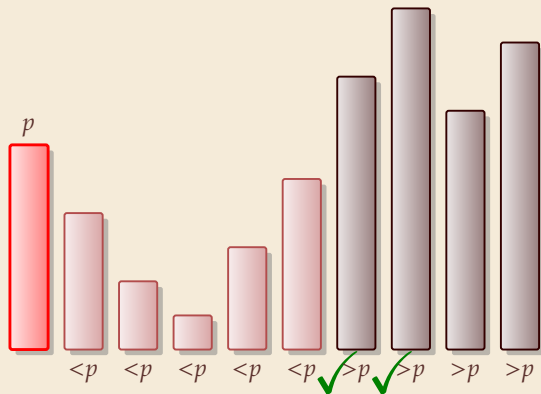
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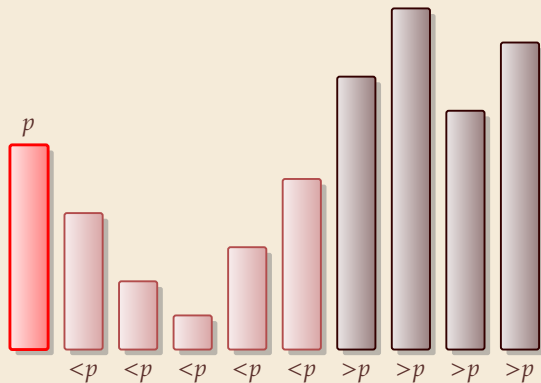
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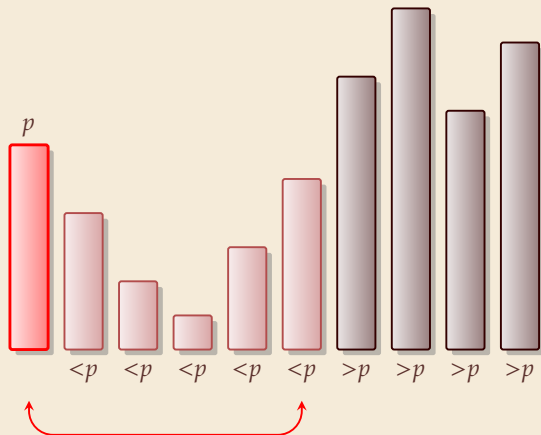
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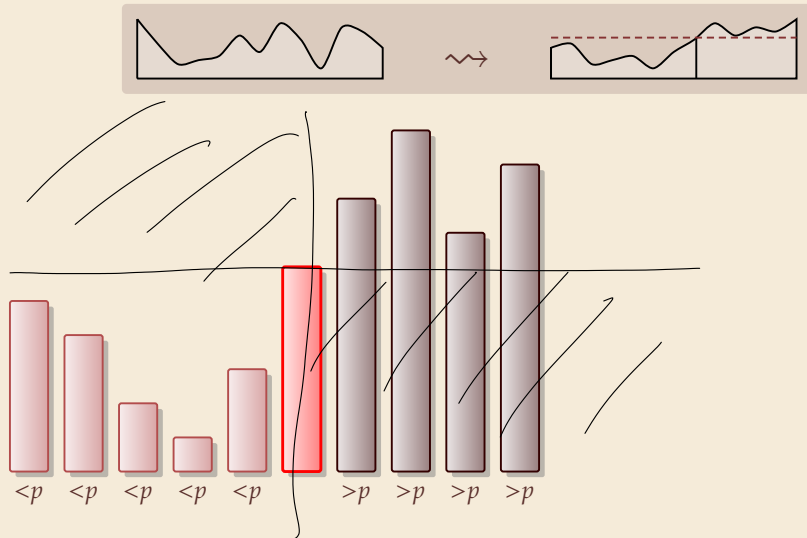
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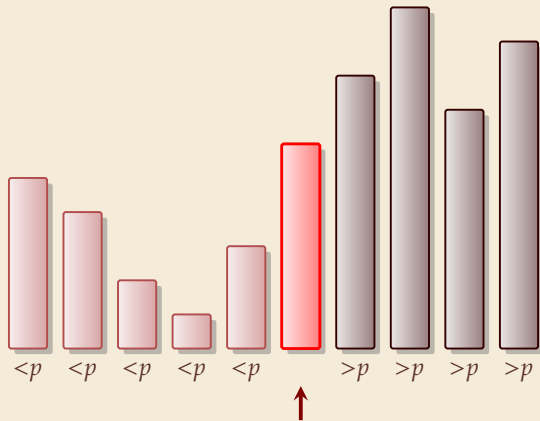
Partitioning around a pivot



Partitioning around a pivot



Partitioning around a pivot



- ▶ no extra space needed
- ▶ visits each element once
- ▶ returns rank/position of pivot

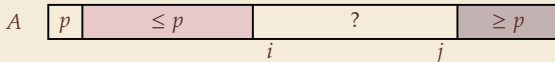
Partitioning – Detailed code

Beware: details easy to get wrong; use this code!

(if you ever have to)

```
1 procedure partition( $A, b$ )
2   // input: array  $A[0..n)$ , position of pivot  $b \in [0..n)$ 
3   swap( $A[0], A[b]$ )
4    $i := 0, j := n$ 
5   while true do
6     do  $i := i + 1$  while  $i < n$  and  $A[i] < A[0]$ 
7     do  $j := j - 1$  while  $j \geq 1$  and  $A[j] > A[0]$ 
8     if  $i \geq j$  then break (goto 11)
9     else swap( $A[i], A[j]$ )
10  end while
11  swap( $A[0], A[j]$ )
12  return  $j$ 
```

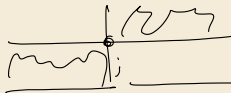
Loop invariant (5–10):



Quicksort

initial call
 $\text{quicksort}(A[0..n])$

```
1 procedure quicksort( $A[l..r]$ )  
2   if  $r - l \leq 1$  then return  
3    $b := \text{choosePivot}(A[l..r])$   
4    $j := \text{partition}(A[l..r], b)$   
5   quicksort( $A[l..j]$ )  
6   quicksort( $A[j + 1..r]$ )
```



- ▶ recursive procedure
- ▶ choice of pivot can be
 - ▶ fixed position \rightsquigarrow dangerous!
 - ▶ random
 - ▶ more sophisticated, e. g., median of 3

Clicker Question

What is the worst-case running time of quicksort?



A $\Theta(1)$

B $\Theta(\log n)$

C $\Theta(\log \log n)$

D $\Theta(\sqrt{n})$

E $\Theta(n)$

F $\Theta(n \log \log n)$

G $\Theta(n \log n)$

H $\Theta(n \log^2 n)$

I $\Theta(n^{1+\epsilon})$

J $\Theta(n^2)$

K $\Theta(n^3)$

L $\Theta(2^n)$



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G ~~$\Theta(n \log n)$~~

H ~~$\Theta(n \log^2 n)$~~

I ~~$\Theta(n^{1+\epsilon})$~~

J $\Theta(n^2)$ ✓

K ~~$\Theta(n^3)$~~

L ~~$\Theta(2^n)$~~



→ sli.do/comp526

Quicksort & Binary Search Trees

Quicksort

7	4	2	9	1	3	8	5	6
---	---	---	---	---	---	---	---	---

Quicksort & Binary Search Trees

Quicksort

7	4	2	9	1	3	8	5	6
---	---	---	---	---	---	---	---	---

Quicksort & Binary Search Trees

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7	4	2	9	1	3	8	5	6
---	---	---	---	---	---	---	---	---

4	2	1	3	5	6
---	---	---	---	---	---

9	8
---	---

Quicksort & Binary Search Trees

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7	4	2	9	1	3	8	5	6
---	---	---	---	---	---	---	---	---

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---	---	---	---	---	---

7

9	8
---	---

Quicksort & Binary Search Trees

Quicksort

7	4	2	9	1	3	8	5	6
---	---	---	---	---	---	---	---	---

4	2	1	3	5	6	7	9	8
---	---	---	---	---	---	---	---	---

Quicksort & Binary Search Trees

Quicksort

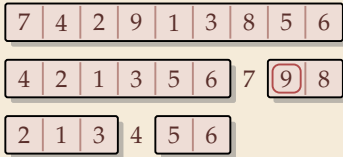
7	4	2	9	1	3	8	5	6
---	---	---	---	---	---	---	---	---

4	2	1	3	5	6	7	9	8
---	---	---	---	---	---	---	---	---

2	1	3	4	5	6
---	---	---	---	---	---

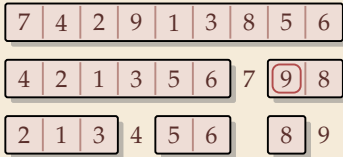
Quicksort & Binary Search Trees

Quicksort



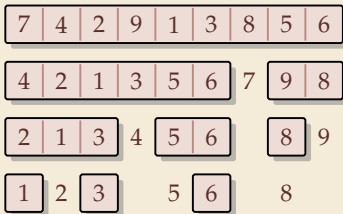
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Quicksort & Binary Search Trees

Quicksort

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---	---	---	---	---	---	---	---	---

4	2	1	3	5	6
---	---	---	---	---	---

 7

9	8
---	---

2	1	3
---	---	---

 4

5	6
---	---

8

 9

1

 2

3

 5

6

 8

1

3

6

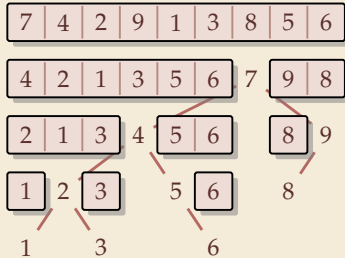
Quicksort & Binary Search Trees

Quicksort



Quicksort & Binary Search Trees

Quicksort

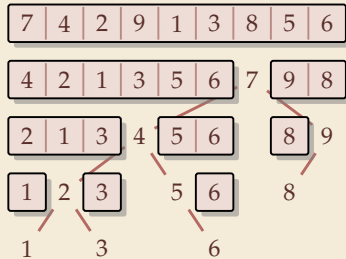


Binary Search Tree (BST)

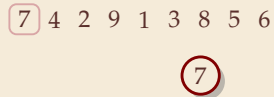
7 4 2 9 1 3 8 5 6

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Quicksort



Binary Search Tree (BST)



Quicksort & Binary Search Trees

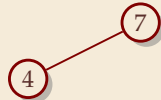
Quicksort



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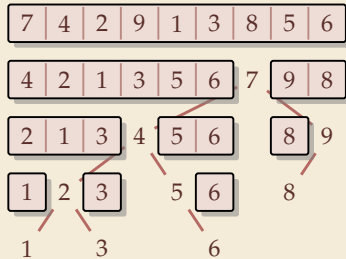
4

 2 9 1 3 8 5 6

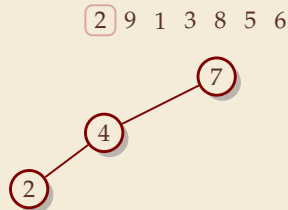


Quicksort & Binary Search Trees

Quicksort



Binary Search Tree (BST)

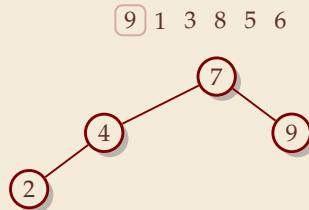


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Quicksort

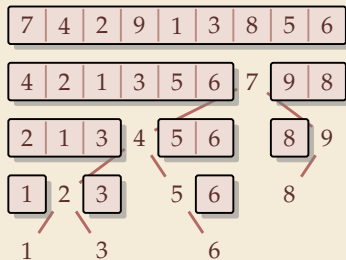


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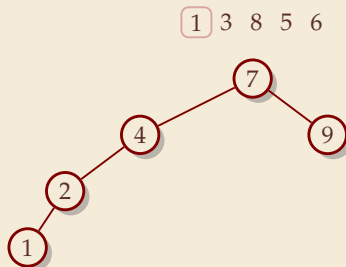


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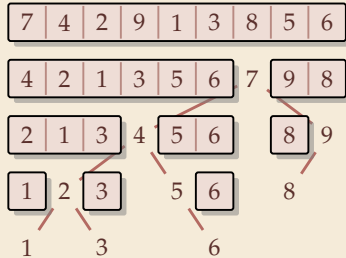


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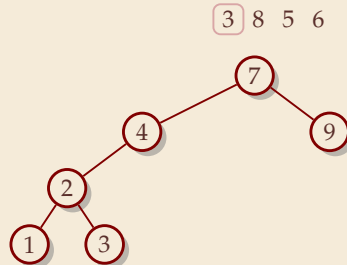


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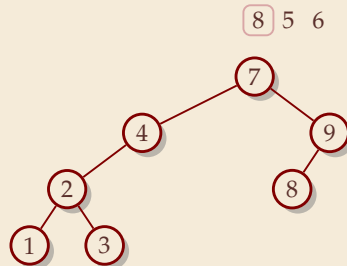


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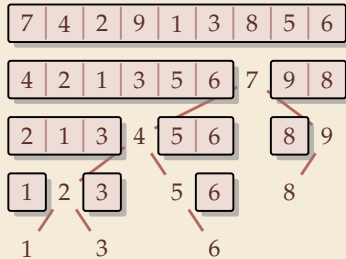


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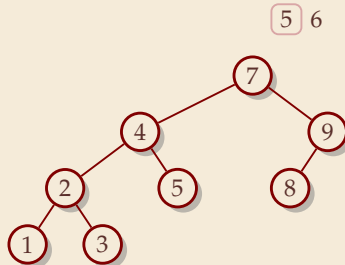


Quicksort & Binary Search Trees

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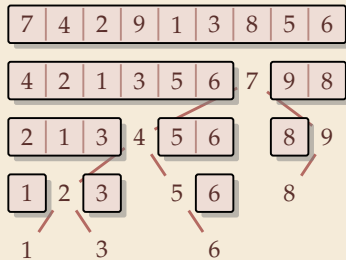


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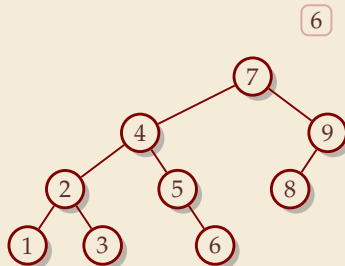


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Quicksort

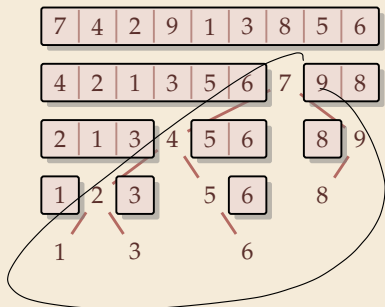


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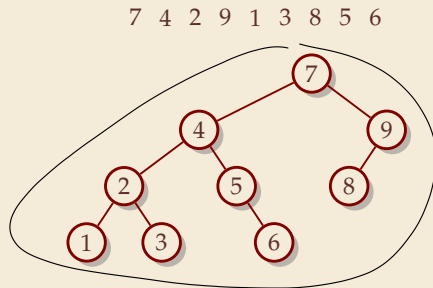


Quicksort & Binary Search Trees

Quicksort



Binary Search Tree (BST)



► recursion tree of quicksort = binary search tree from successive insertion

► comparisons in quicksort = comparisons to build BST

(► comparisons in quicksort \approx comparisons to search each element in BST)

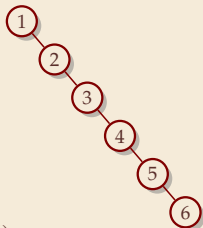
Quicksort – Worst Case

► Problem: BSTs can degenerate

► Cost to search for k is $k - 1$

~> Total cost $\underbrace{\sum_{k=1}^n (k - 1)} = \frac{n(n - 1)}{2} \sim \frac{1}{2}n^2$

~> quicksort worst-case running time is in $\Theta(n^2)$
terribly slow!



But, we can fix this:

Randomized quicksort:

► choose a *random pivot* in each step

~> same as randomly *shuffling* input before sorting

Randomized Quicksort – Analysis

- ▶ $C(n)$ = element visits (as for mergesort)

↪ quicksort needs $\sim 2 \ln(2) \cdot n \lg n \approx \underline{1.39n \lg n}$ *in expectation*

- ▶ also: very unlikely to be much worse:
e. g., one can prove: $\Pr[\text{cost} > 10n \lg n] = O(n^{-2.5})$
distribution of costs is “concentrated around mean”
- ▶ intuition: have to be *constantly* unlucky with pivot choice



Quicksort – Discussion

- 👍 fastest general-purpose method
- 👍 $\Theta(n \log n)$ average case
- 👍 works *in-place* (no extra space required)
- 👍 memory access is sequential (scans over arrays)
- 👎 $\Theta(n^2)$ worst case (although extremely unlikely)
- 👎 not a *stable* sorting method

Open problem: Simple algorithm that is fast, stable and in-place.

3.3 Comparison-Based Lower Bound

Lower Bounds

- ▶ **Lower bound:** mathematical proof that *no algorithm* can do better.
 - ▶ very powerful concept: bulletproof *impossibility* result
 - ≈ *conservation of energy* in physics
 - ▶ **(unique?) feature of computer science:**
for many problems, solutions are known that (asymptotically) **achieve the lower bound**
- ≈⇒ can speak of “optimal algorithms”

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 - ▶ **(unique?) feature of computer science:**
for many problems, solutions are known that (asymptotically) **achieve the lower bound**
~> can speak of “*optimal* algorithms”
- ▶ To prove a statement about *all algorithms*, we must precisely define what that is!
- ▶ already know one option: the word-RAM model
- ▶ Here: use a simpler, more restricted model.


The Comparison Model

- ▶ In the *comparison model* data can only be accessed in two ways:
 - ▶ comparing two elements
 - ▶ moving elements around (e. g. copying, swapping)
 - ▶ Cost: number of these operations.

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- ▶ Mergesort and Quicksort work in the comparison model.

That's good!
Keeps algorithms general!



The Comparison Model

- ▶ In the *comparison model* data can only be accessed in two ways:

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That's good!
Keeps algorithms general!

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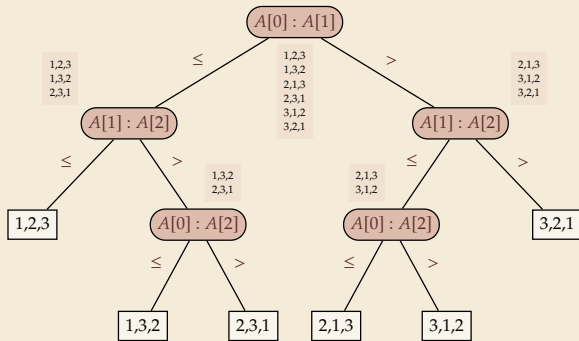


Every comparison-based sorting algorithm corresponds to a *decision tree*.

- ▶ only model comparisons \rightsquigarrow ignore data movement
- ▶ nodes = comparisons the algorithm does
- ▶ next comparisons can depend on outcomes \rightsquigarrow different subtrees
- ▶ child links = outcomes of comparison
- ▶ leaf = unique initial input permutation compatible with comparison outcomes

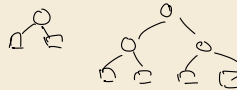
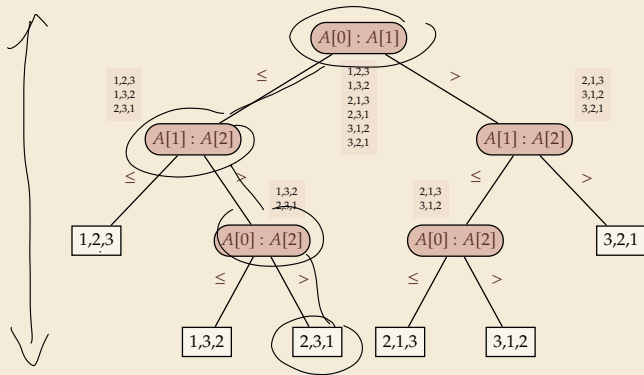
Comparison Lower Bound

Example: Comparison tree for a sorting method for $A[0..2]$:



Comparison Lower Bound

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► Execution = follow a path in comparison tree.

~ height of comparison tree = worst-case # comparisons

► comparison trees are *binary* trees

~ ℓ leaves ~ height $\geq \lceil \lg(\ell) \rceil$

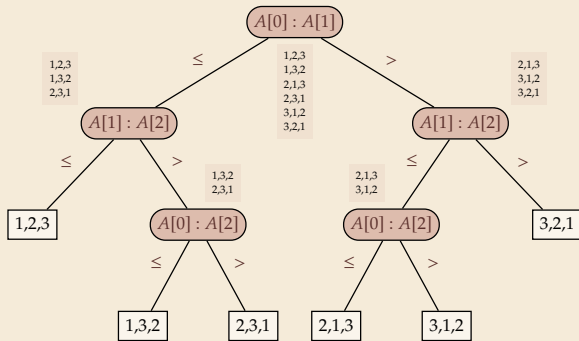
► comparison trees for sorting method must have $\geq n!$ leaves

~ height $\geq \lg(n!) \sim n \lg n$

more precisely: $\lg(n!) = n \lg n - \lg(e)n + O(\log n)$

Comparison Lower Bound

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↪ height $\geq \lg(n!) \sim \underline{n \lg n}$

more precisely: $\lg(n!) = n \lg n - \lg(e)n + O(\log n)$

► Mergesort achieves $\sim n \lg n$ comparisons ↪ asymptotically comparison-optimal!

► Open (theory) problem: Sorting algorithm with $n \lg n - \lg(e)n + o(n)$ comparisons?

≈ 1.4427

Clicker Question



Does the comparison-tree from the previous slide correspond to a worst-case optimal sorting method?

A Yes

B No



→ *sli.do/comp526*

Clicker Question



Does the comparison-tree from the previous slide correspond to a worst-case optimal sorting method?

A Yes ✓

B ~~No~~



→ *sl.i.do/comp526*

Clicker Question



Select all **correct formulations** of our lower bound from §3.3.

- ☐ **A** Any sorting algorithm requires $O(n \log n)$ running time in the worst case. {
- ☐ **B** Every comparison-based sorting algorithm requires $\Omega(n \log n)$ running time in worst case for sorting n elements. ✓
- ☐ **C** Every comparison-based sorting algorithm requires $\Omega(n \log n)$ comparisons in worst case for sorting n elements. ✓
- ☐ **D** Every sorting algorithm requires $\Omega(n \log n)$ comparisons in worst case for sorting n elements.
- ☐ **E** The complexity of sorting n elements in the comparison-model is $\Theta(n \log n)$. }
- ☐ **F** The complexity of sorting n elements in the comparison-model is $\Omega(n \log n)$.



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Clicker Question



Select all **correct formulations** of our **lower bound** from §3.3.

- ☐ A ~~Any sorting algorithm requires $O(n \log n)$ running time in the worst case.~~
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- ☒ C Every comparison-based sorting algorithm requires $\Omega(n \log n)$ comparisons in worst case for sorting n elements. ✓
- ☐ D ~~Every sorting algorithm requires $\Omega(n \log n)$ comparisons in worst case for sorting n elements.~~
- ☐ E ~~The complexity of sorting n elements in the comparison model is $O(n \log n)$.~~
- ☐ F The complexity of sorting n elements in the comparison-model is $\Omega(n \log n)$. ✓



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3.4 Integer Sorting

How to beat a lower bound

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 - ↪ Lower bounds show where to *change* the model!
- ▶ Here: sort *n* integers
 - ▶ can do *a lot* with integers: add them up, compute averages, ... (full power of word-RAM)
 - ↪ we are **not** working in the comparison model
 - ↪ *above lower bound does not apply!*

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 - ▶ can do *a lot* with integers: add them up, compute averages, ... (full power of word-RAM)
 - ~> we are **not** working in the comparison model
 - ~> *above lower bound does not apply!*
 - ▶ but: a priori unclear how much arithmetic helps for sorting ...

Counting sort

- ▶ Important parameter: size/range of numbers
 - ▶ numbers in range $[0..U) = \{0, \dots, U-1\}$ typically $U = 2^b \rightsquigarrow$ b -bit binary numbers

Counting sort

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 - ▶ numbers in range $[0..U) = \{0, \dots, U-1\}$ typically $U = 2^b \rightsquigarrow b$ -bit binary numbers
- ▶ We can sort n integers in $\Theta(n + U)$ time and $\Theta(U)$ space when $b \leq w$:

word size

Counting sort

```
1 procedure countingSort( $A[0..n)$ )
2   //  $A$  contains integers in range  $[0..U)$ .
3    $C[0..U) :=$  new integer array, initialized to 0 |  $O(U)$ 
4   // Count occurrences
5   for  $i := 0, \dots, n-1$ 
6      $C[A[i]] := C[A[i]] + 1$   $O(1)$  }  $O(n)$ 
7    $i := 0$  // Produce sorted list
8   for  $k := 0, \dots, U-1$ 
9     for  $j := 1, \dots, C[k]$ 
10       $A[i] := k; i := i + 1$   $O(1)$  }  $C[k]$  times
```

▶ count how often each possible value occurs

▶ produce sorted result directly from counts

▶ circumvents lower bound by using integers as array index / pointer offset

$$\sum_{k=0}^{U-1} (C[k] \cdot O(1) + O(1)) = O(n+U)$$

\rightsquigarrow Can sort n integers in range $[0..U)$ with $U = O(n)$ in time and space $\Theta(n)$.

$$\sum C[k] = n$$

Integer Sorting – State of the art

- ▶ $O(n)$ time sorting also possible for numbers in range $U = O(n^c)$ for constant c .
 - ▶ *radix sort* with radix 2^w
- ▶ **Algorithm theory**
 - ▶ suppose $U = 2^w$, but w can be an arbitrary function of n
 - ▶ how fast can we sort n such w -bit integers on a w -bit word-RAM?
 - ▶ for $w = O(\log n)$: linear time (*radix/counting sort*)
 - ▶ for $w = \Omega(\log^{2+\varepsilon} n)$: linear time (*signature sort*)
 - ▶ for w in between: can do $O(n\sqrt{\lg \lg n})$ (very complicated algorithm)
don't know if that is best possible!

✱ exam

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don't know if that is best possible!

* * *

- ▶ for the rest of this unit: back to the comparisons model!

Clicker Question

Which statements are correct? Select all that apply.

My computer has 64-bit words, so an int has 64 bits. Hence I can sort any `int[]` of length n ...



- ☐ A in constant time.
- ☐ B in $O(\log n)$ time.
- ☐ C in $O(n)$ time.
- ☐ D in $O(n \log n)$ time.
- ☐ E some time, but not possible to say from given information.



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☐ E some time, but not possible to say from given information. ✓

in theory counting sort ✓



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Part II

Exploiting presortedness

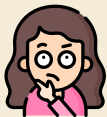
3.5 Adaptive Sorting

Adaptive sorting

- ▶ Comparison lower bound also holds for the *average case* $\rightsquigarrow \sim n \lg n$ [lg(n!)] cmps necessary
- ▶ Mergesort and Quicksort from above use $\sim n \lg n$ cmps even in best case

Adaptive sorting

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Can we do better if the input is already “almost sorted”?

Scenarios where this may arise naturally:

- ▶ Append new data as it arrives, regularly sort entire list (e. g., log files, database tables)
- ▶ Compute summary statistics of time series of measurements that change slowly over time (e. g., weather data)
- ▶ Merging locally sorted data from different servers (e. g., map-reduce frameworks)

\rightsquigarrow Ideally, algorithms should *adapt* to input: *the more sorted the input, the faster the algorithm*
... but how to do that!?

Warmup: check for sorted inputs

- ▶ Any method could first check if input already completely in order!



Best case becomes $\Theta(n)$ with $n - 1$ comparisons!



Usually $n - 1$ extra comparisons and pass over data “wasted”



Only catches a single, extremely special case . . .

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Potentially exploits partial sortedness!



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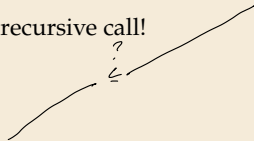
usually adds $\Omega(n \log n)$ extra comparisons



For Mergesort, can instead check before merge with a **single** comparison

- ▶ If last element of first run \leq first element of second run, skip merge

How effective is this idea?

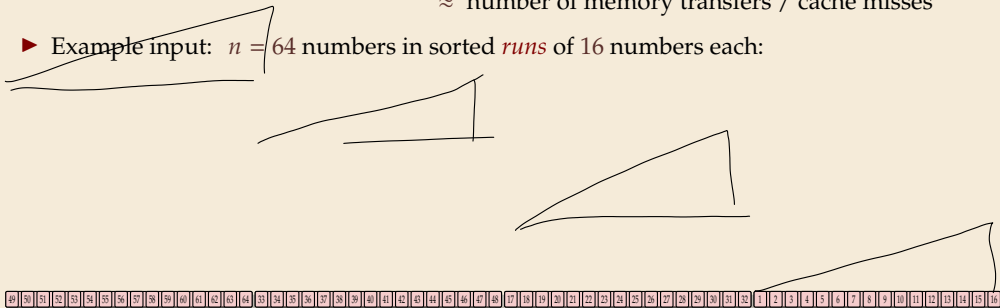


```
1 procedure mergesortCheck(A[l..r])
2   n := r - l
3   if n ≤ 1 return
4   m := l + ⌊ $\frac{n}{2}$ ⌋
5   mergesortCheck(A[l..m])
6   mergesortCheck(A[m..r])
7   if A[m - 1] > A[m]
8     merge(A[l..m], A[m..r], buf)
9   copy buf to A[l..r]
```

Mergesort with sorted check – Analysis

- ▶ Simplified cost measure: *merge cost* = size of output of merges
 \approx number of comparisons
 \approx number of memory transfers / cache misses

- ▶ Example input: $n = 64$ numbers in sorted *runs* of 16 numbers each:



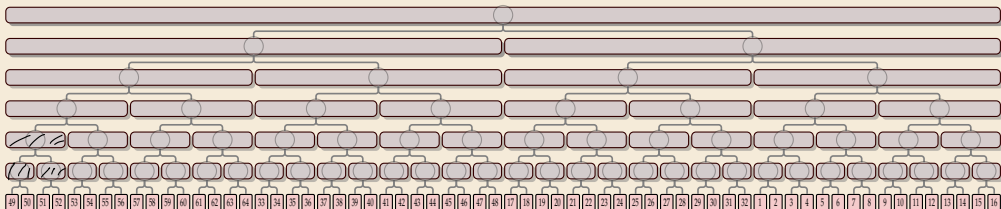
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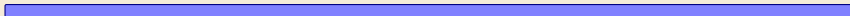
49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	---	---	---	---	---	---	---	---	---	----	----	----	----	----	----	----

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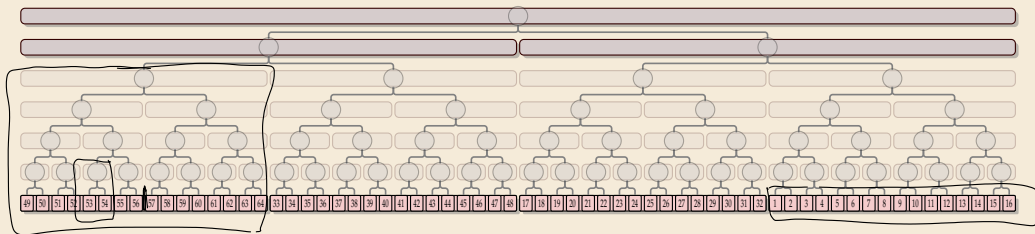
Merge costs:



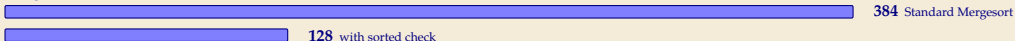
384 Standard Mergesort

Mergesort with sorted check – Analysis

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 \approx number of memory transfers / cache misses
- Example input: $n = 64$ numbers in sorted *runs* of 16 numbers each:



Merge costs:



Sorted check can help a lot!

Alignment issues

- In previous example, each run of length ℓ saved us $\ell \lg(\ell)$ in merge cost.

= exactly the cost of *creating* this run in mergesort had it not already existed

\rightsquigarrow best savings we can hope for!

\rightsquigarrow Are overall merge costs $\mathcal{H}(\ell_1, \dots, \ell_r) := \underbrace{n \lg(n)}_{\text{mergesort}} - \underbrace{\sum_{i=1}^r \ell_i \lg(\ell_i)}_{\text{savings from runs}} ?$

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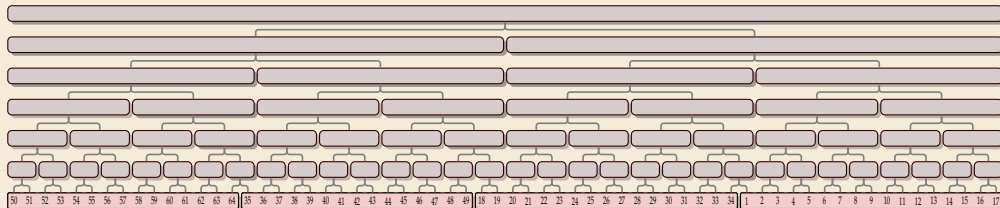
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Unfortunately, not quite:



Merge costs:



384 Standard Mergesort



127.8 $\mathcal{H}(15, 15, 17, 17)$

128

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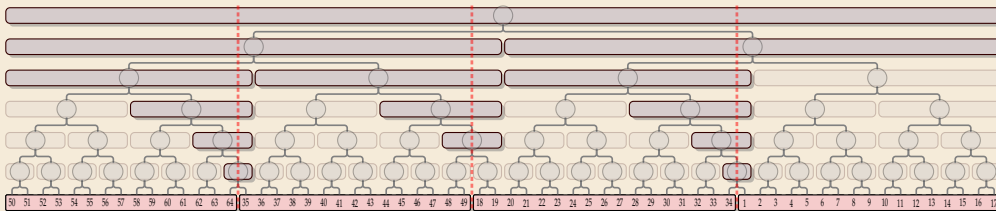
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384 Standard Mergesort



216 with sorted check

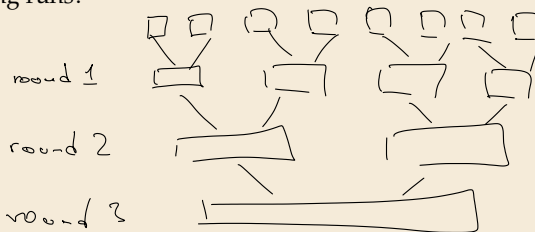


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Bottom-Up Mergesort

- Can we do better by explicitly detecting runs?

```
1 procedure bottomUpMergesort( $A[0..n]$ )
2    $Q := \text{new Queue}$  // runs to merge
3   // Phase 1: Enqueue singleton runs
4   for  $i = 0, \dots, n - 1$  do
5      $Q.\text{enqueue}((i, i + 1))$ 
6   // Phase 2: Merge runs level-wise
7   while  $Q.\text{size}() \geq 2$ 
8      $Q' := \text{new Queue}$ 
9     while  $Q.\text{size}() \geq 2$ 
10       $(i_1, j_1) := Q.\text{dequeue}()$ 
11       $(i_2, j_2) := Q.\text{dequeue}()$ 
12       $\text{merge}(A[i_1..j_1], A[i_2..j_2], \text{buf})$ 
13       $\text{copy buf to } A[i_1..j_2]$ 
14       $Q'.\text{enqueue}((i_1, j_2))$ 
15     if  $\neg Q.\text{isEmpty}()$  // lonely run
16        $Q'.\text{enqueue}(Q.\text{dequeue}())$ 
17    $Q := Q'$ 
```



Bottom-Up Mergesort

- Can we do better by explicitly detecting runs?

$$A[n] = -\infty$$

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16       $Q'.\text{enqueue}(Q.\text{dequeue}())$ 
17     $Q := Q'$ 
```

```
1 procedure naturalMergesort( $A[0..n]$ )
2    $Q := \text{new Queue}; i := 0$  find run  $A[i..j]$ 
3   while  $i < n$  starting at  $i$ 
4      $j := i + 1$ 
5     while  $A[j] \geq A[j - 1]$  do  $j := j + 1$ 
6      $Q.\text{enqueue}((i, j)); i := j$ 
7   while  $Q.\text{size}() \geq 2$ 
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Clicker Question

Suppose we have an input with the 5 elements a, b, c, d, e and we sort them with **bottomUpMergesort**. What sequence of merges are executed?



A Policy 1

a	b	c	d	e
a	b	c	d	e
a	b	c	d	e
a	b	c	d	e

Policy 1

B Policy 2

a	b	c	d	e
a	b	c	d	e
a	b	c	d	e
a	b	c	d	e

Policy 2

C Policy 3

a	b	c	d	e
a	b	c	d	e
a	b	c	d	e
a	b	c	d	e

Policy 3



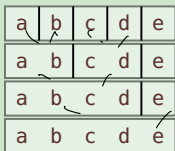
→ sli.do/comp526

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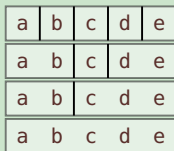


A Policy 1 ✓



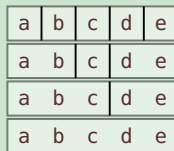
Policy 1

B ~~Policy 2~~



Policy 2

C ~~Policy 3~~



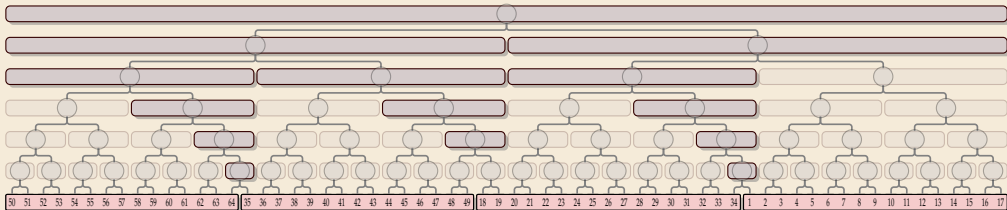
Policy 3



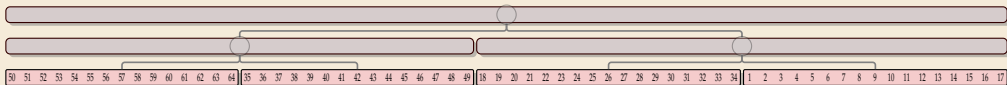
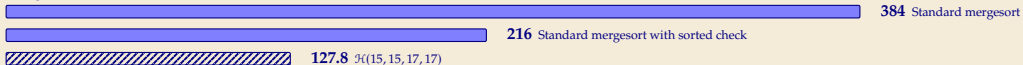
→ sli.do/comp526

Natural Bottom-Up Mergesort – Analysis

- Works well runs of roughly equal size, regardless of alignment ...



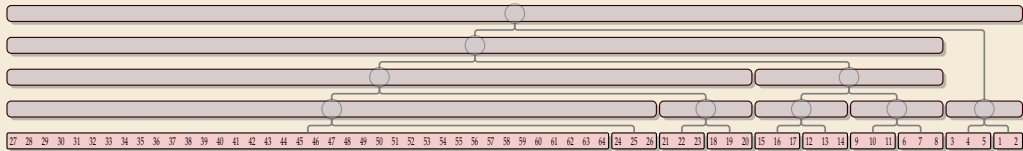
Merge costs:



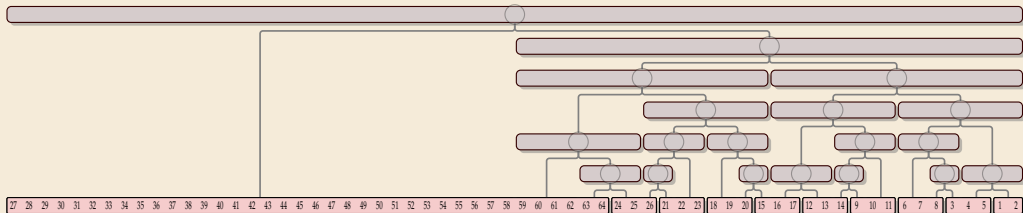
128 Natural bottom-up mergesort

Natural Bottom-Up Mergesort – Analysis [2]

- ... but less so for uneven run lengths



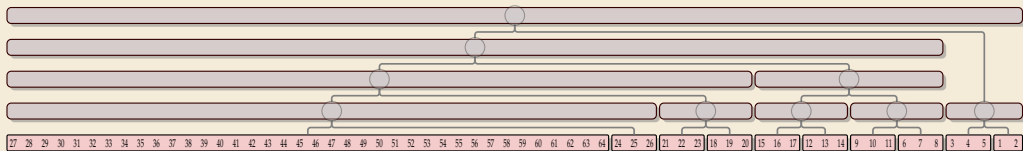
246 Natural bottom-up mergesort



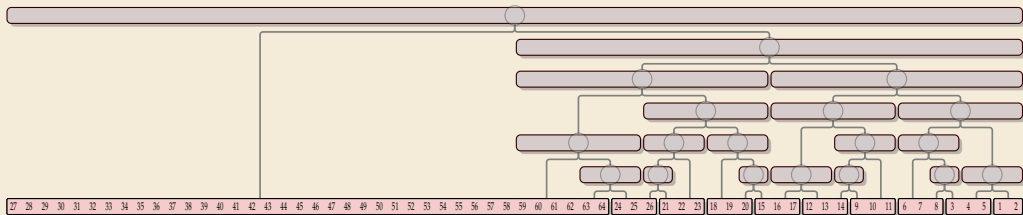
196 Standard mergesort with sorted check

Natural Bottom-Up Mergesort – Analysis [2]

- ... but less so for uneven run lengths



246 Natural bottom-up mergesort



196 Standard mergesort with sorted check

... can't we have both at the same time?!

Good merge orders

◀◀ *Let's take a step back and breathe.*

Good merge orders

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► Conceptually, there are two tasks:

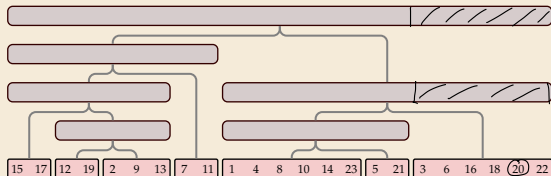
1. Detect and use existing runs in the input $\rightsquigarrow \ell_1, \dots, \ell_r$ (easy)
2. Determine a favorable *order of merges* of runs (“automatic” in top-down mergesort)

Good merge orders

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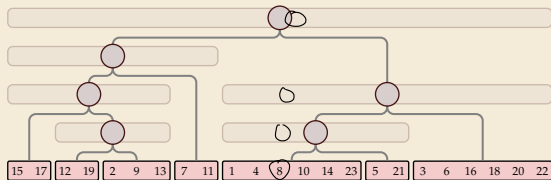
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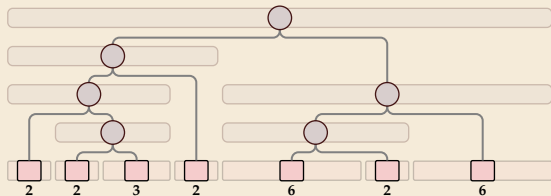
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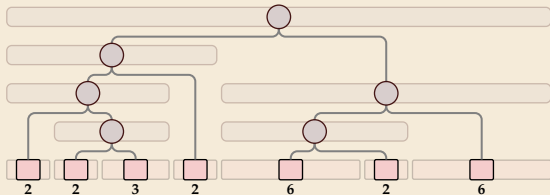
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well-understood problem
with known algorithms

\rightsquigarrow *optimal* merge tree
= optimal *binary search tree*
for leaf weights ℓ_1, \dots, ℓ_r
(optimal expected search cost)

Nearly-Optimal Mergesort

Nearly-Optimal Mergesorts:

Fast, Practical Sorting Methods That Optimally Adapt to Existing Runs

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Abstract

We present two stable mergesort variants, “peeksort” and “powersort”, that exploit existing runs and find nearly-optimal merging orders with negligible overhead. Previous methods either require substantial effort for determining the merging order (Takaoka 2009; Barbay & Navarro 2013) or do not have an optimal worst-case guarantee (Peters 2002; Auger, Nicaud & Pivert 2015; Buss & Knap 2016). We demonstrate that our methods are competitive in terms of running time with state-of-the-art implementations of stable sorting methods.

2012 ACM Subject Classification Theory of computation → Sorting and searching

Keywords and phrases adaptive sorting, nearly-optimal binary search tree, Timsort

Digital Object Identifier 10.4230/LIPIcs.ESA.2018.03

Related Version arXiv: 1805.04154 (extended version with appendices)

Supplement Material zenodo: 1241162 (code to reproduce running time study)

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1 Introduction

Sorting is a fundamental building block for numerous tasks and ubiquitous in both the theory and practice of computing. While practical and theoretically (close-to) optimal comparison-based sorting methods are known, *instance-optimal sorting*, i.e., methods that adapt to the actual input and exploit specific structural properties if present, is still an area of active research. We survey some recent developments in Section 1.1.

Many different structural properties have been investigated in theory. Two of them have also found wide adoption in practice, e.g., in Oracle’s Java runtime library: adapting to the presence of duplicate keys and using existing sorted segments, called *runs*. The former is achieved by a so-called *fast-pivot* partitioning variant of quicksort [8], which is also used in the OpenBSD implementation of *qsort* from the C standard library. It is an unstable sorting method, though, i.e., the relative order of elements with equal keys might be destroyed in the process. It is hence used in Java solely for primitive-type arrays.

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2018, Annual European Symposium on Algorithms (ESA 2018).
Revised: Victor Arlitt, Benjamin Bredt, and Gregoire Berthou, Article No. 03, pp. 03:1–03:15
Leibniz International Proceedings in Informatics
LIPIcs, Schloss Dagstuhl – Leibniz-Zentrum für Informatik, Dagstuhl Publishing, Germany

- ▶ In 2018, with Ian Munro, I combined research on nearly-optimal BSTs with mergesort

→ 2 new algorithms: *Peeksort* and *Powersort*

- ▶ both adapt provably optimally to existing runs even in worst case:
 $\text{mergcost} \leq \mathcal{H}(\ell_1, \dots, \ell_r) + 2n$
- ▶ both are lightweight extensions of existing methods with negligible overhead
- ▶ both fast in practice

Peeksort

- ▶ based on top-down mergesort

- ▶ “peek” at middle of array
& find closest run boundary



- ~> split there and recurse
(instead of at midpoint)



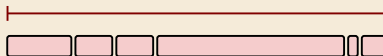
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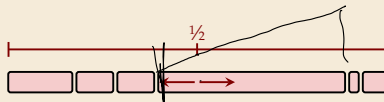
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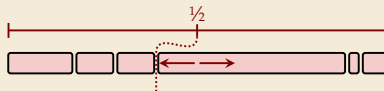
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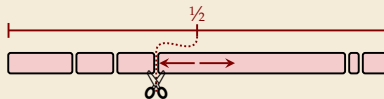
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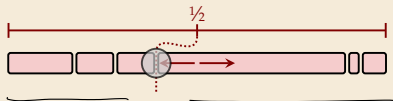
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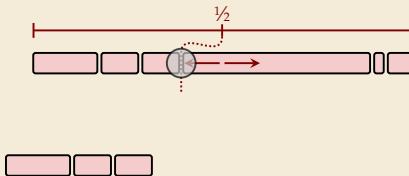
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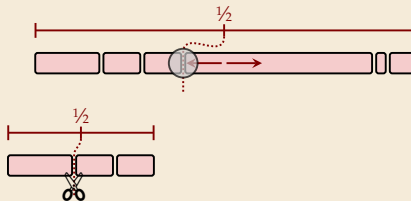
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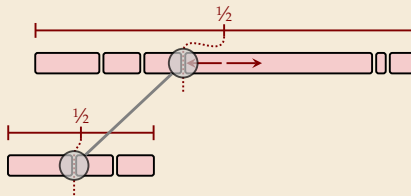
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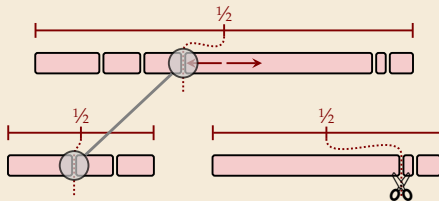
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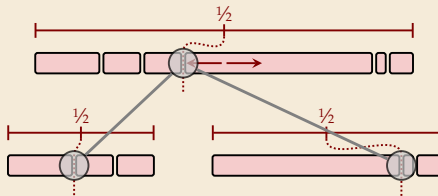
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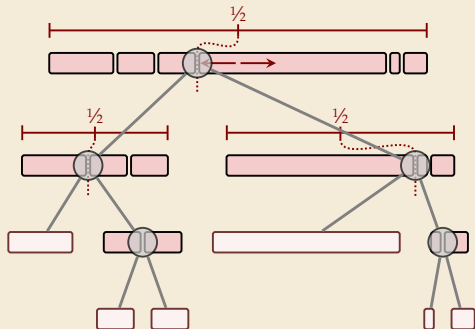
Peeksort

► based on top-down mergesort

► “peek” at middle of array
& find closest run boundary



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Peeksort

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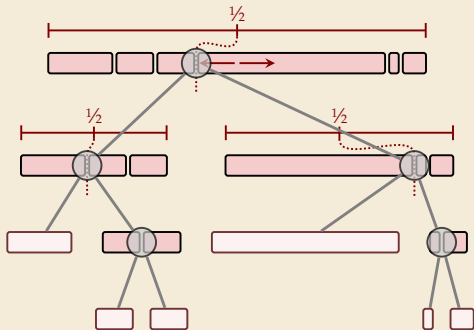


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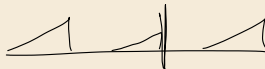
- ▶ can avoid scanning runs repeatedly:
 - ▶ find full run straddling midpoint
 - ▶ remember length of known runs at boundaries



~> with clever recursion, scan each run only once.

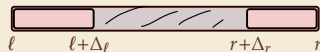


Peeksort – Code



```
1 procedure peeksort( $A[\ell..r]$ ,  $\Delta_\ell$ ,  $\Delta_r$ )
2   if  $r - \ell \leq 1$  then return
3   if  $\ell + \Delta_\ell == r \vee \ell == r + \Delta_r$  then return
4    $m := \ell + \lfloor (r - \ell)/2 \rfloor$ 
5    $i := \begin{cases} \ell + \Delta_\ell & \text{if } \ell + \Delta_\ell \geq m \\ \text{extendRunLeft}(A, m) & \text{else} \end{cases}$ 
6    $j := \begin{cases} r + \Delta_r \leq m & \text{if } r + \Delta_r \leq m \leq m \\ \text{extendRunRight}(A, m) & \text{else} \end{cases}$ 
7    $g := \begin{cases} i & \text{if } m - i < j - m \\ j & \text{else} \end{cases}$ 
8    $\Delta_g := \begin{cases} j - i & \text{if } m - i < j - m \\ i - j & \text{else} \end{cases}$ 
9   peeksort( $A[\ell..g]$ ,  $\Delta_\ell$ ,  $\Delta_g$ )
10  peeksort( $A[g..r]$ ,  $\Delta_g$ ,  $\Delta_r$ )
11  merge( $A[\ell, g]$ ,  $A[g..r]$ , buf)
12  copy buf to  $A[\ell..r]$ 
```

► Parameters:



► initial call:

peeksort($A[0..n]$, Δ_0 , Δ_n) with
 $\Delta_0 = \text{extendRunRight}(A, 0)$
 $\Delta_n = n - \text{extendRunLeft}(A, n)$

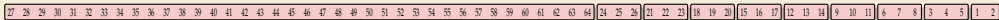
► helper procedure

```
1 procedure extendRunRight( $A[0..n]$ ,  $i$ )
2    $j := i + 1$ 
3   while  $j < n \wedge A[j - 1] \leq A[j]$ 
4      $j := j + 1$ 
5   return  $j$ 
```

(extendRunLeft similar)

Peeksort – Analysis

- Consider tricky input from before again:



144.5 $\mathcal{H}(38, 3, 3, 3, 3, 3, 3, 3, 3, 2)$



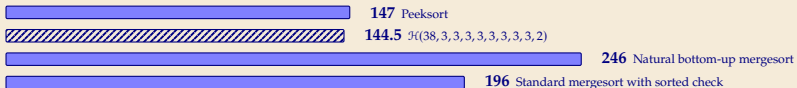
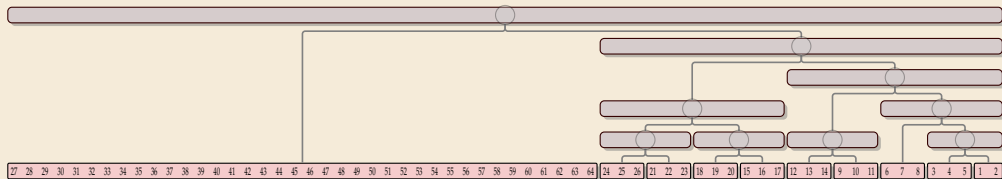
246 Natural bottom-up mergesort



196 Standard mergesort with sorted check

Peeksort – Analysis

- Consider tricky input from before again:



- One can prove: Merge cost always $\leq \mathcal{H}(\ell_1, \dots, \ell_r) + 2n$

$$0 \leq \mathcal{H} \leq n \lg n$$

~> We can have the best of both worlds!

3.6 Python's list sort

Sorting in Python

- ▶ *CPython*
 - ▶ *Python* is only a specification of a programming language
 - ▶ The Python Foundation maintains *CPython* as the official reference implementation of the Python programming language
 - ▶ If you don't specifically install something else, python will be CPython
- ▶ part of Python are `list.sort` resp. `sorted` built-in functions
 - ▶ implemented in C
 - ▶ use *Timsort*,
custom Mergesort variant by Tim Peters

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Sept 2021: **Python uses Powersort!**
since CPython 3.11 and PyPy 7.3.6

msg400864 - (view) Author: Tim Peters (tim.peters) * 🌐 Date: 2021-09-01 19:43

I created a PR that implements the powersort merge strategy:
<https://github.com/python/cpython/pull/28108>

Across all the time this issue report has been open, that strategy continues to be the top contender. Enough already ;-) It's indeed a more difficult change to make to the code, but that's in relative terms. In absolute terms, it's not at all a hard change.

Laurent, if you find that some variant of ShiversSort actually runs faster than that, let us know here! I'm a big fan of Vincent's innovations too, but powersort seems to do somewhat better "on average" than even his length-adaptive ShiversSort (and implementing that too would require changing code outside of `merge_collapse()`).

Timsort (original version)

```

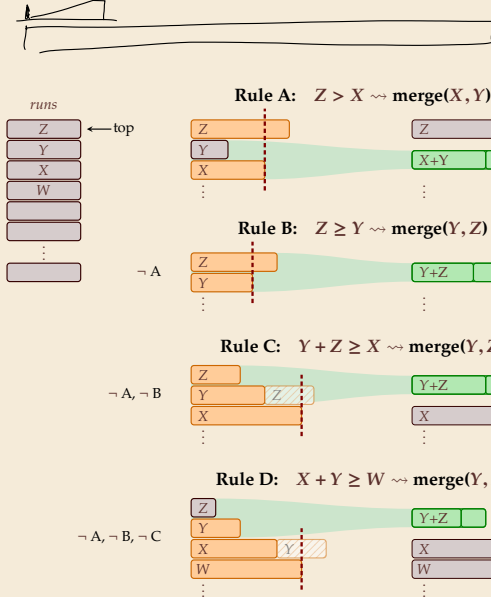
1 procedure Timsort( $A[0..n]$ )
2    $i := 0$ ;  $runs := \text{new Stack}()$ 
3   while  $i < n$ 
4      $j := \text{ExtendRunRight}(A, i)$ 
5      $runs.push(i, j)$ ;  $i := j$ 
6     while rule A/B/C/D applicable
7       merge corresponding runs
8   while  $runs.size() \geq 2$ 
9     merge topmost 2 runs
  
```

- ▶ above shows the core algorithm;
many more algorithm engineering tricks

Advantages:

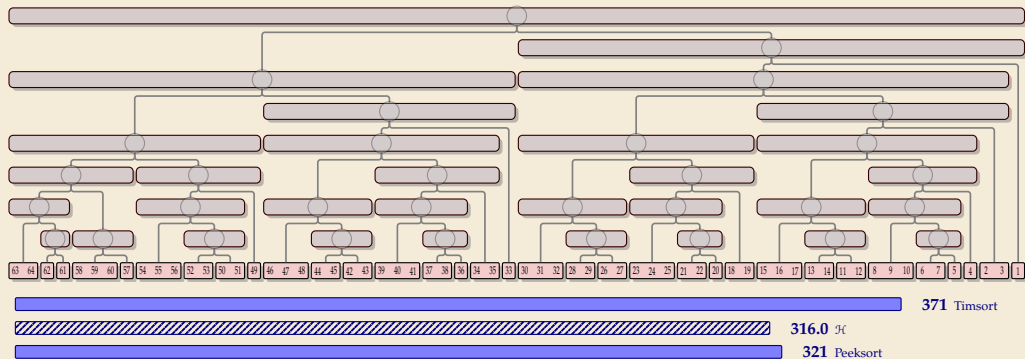
- ▶ profits from existing runs
- ▶ *locality of reference* for merges

- ▶ **But: *not* optimally adaptive!** (next slide)
Reason: Rules A–D (Why exactly these?!)



Timsort bad case

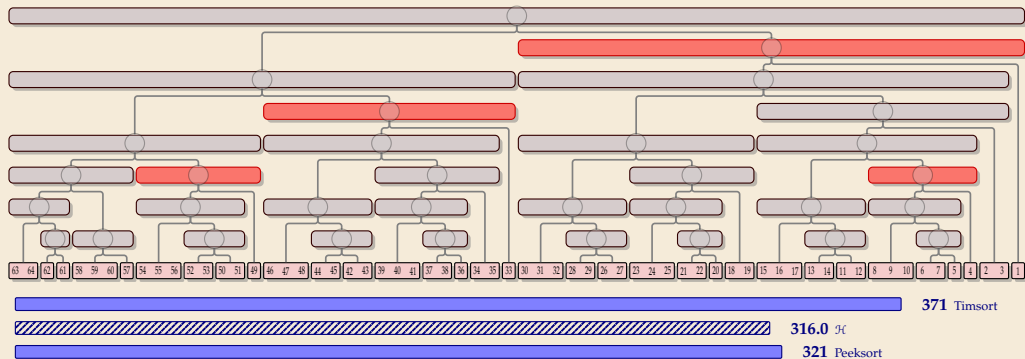
- On certain inputs, Timsort's merge rules don't work well:



- As n increases, Timsort's cost approach $1.5 \cdot \mathcal{H}$, i.e., 50% more merge costs than necessary

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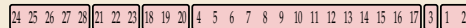
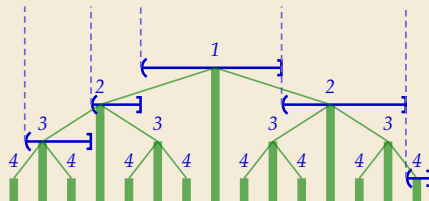


- ▶ As n increases, Timsort's cost approach $1.5 \cdot \mathcal{H}$, i.e., 50% more merge costs than necessary
 - ▶ intuitive problem: regularly very unbalanced merges

Powersort

→ Timsort's *merge rules* aren't great, but overall algorithm has appeal ... can we keep that?

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1 procedure Powersort( $A[0..n]$ )
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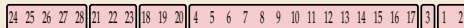
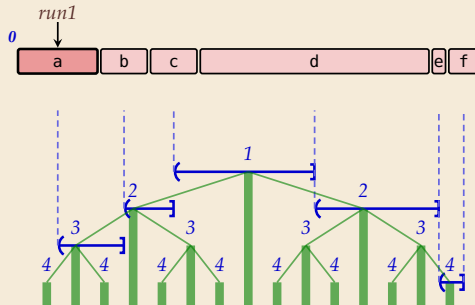
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a - 0
run stack



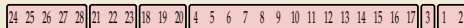
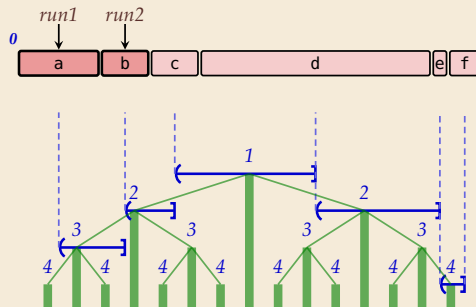
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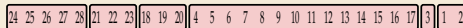
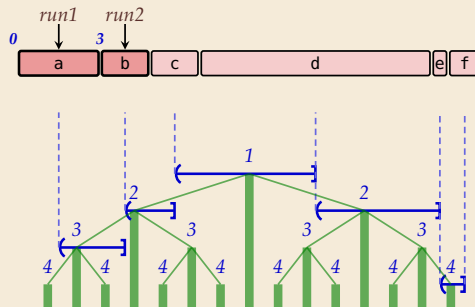
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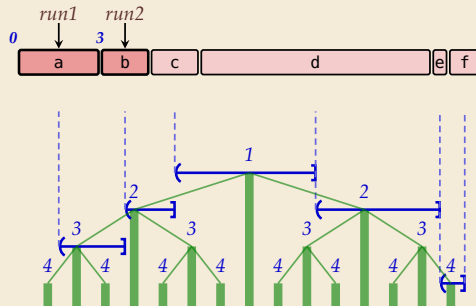
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12    merge topmost 2 runs

```

b - 3
a - 0

run stack



24 25 26 27 28	21 22 23	18 19 20	4 5 6 7 8 9 10 11 12 13 14 15 16 17	3	1	2
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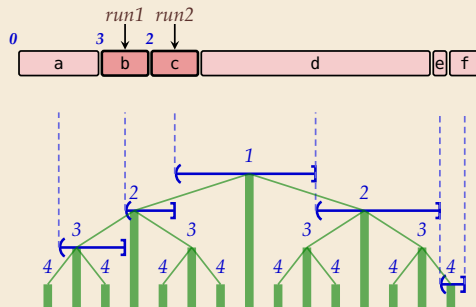
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b - 3
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run stack



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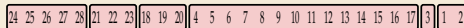
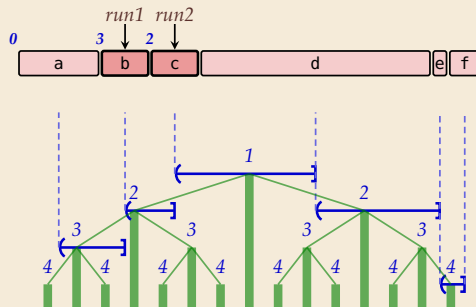
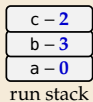
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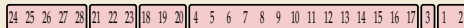
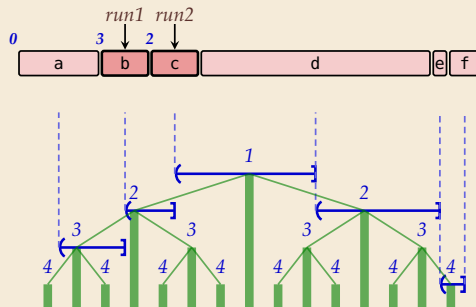
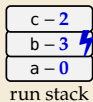


Powersort

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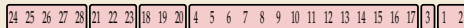
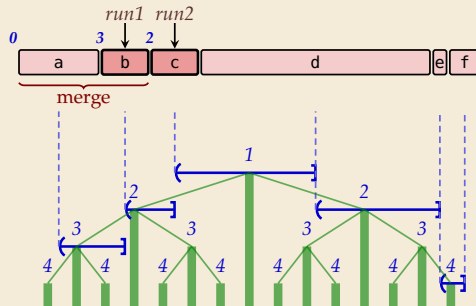
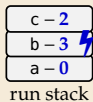
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Powersort

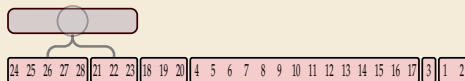
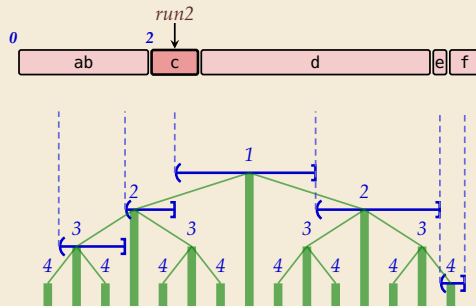
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```

c - 2
ab - 0

run stack



Powersort

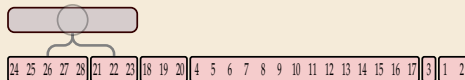
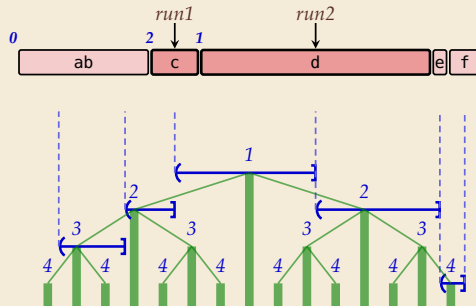
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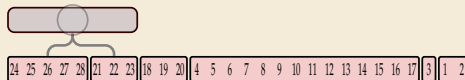
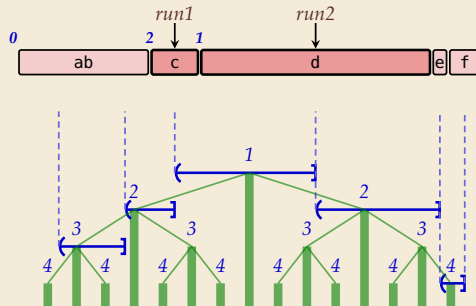
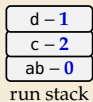


Powersort

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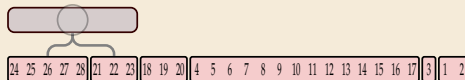
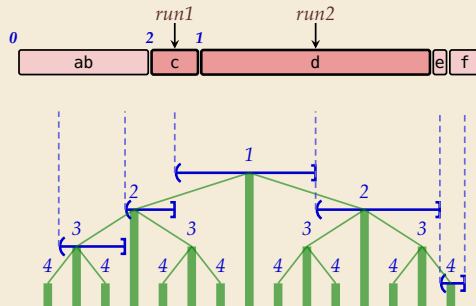
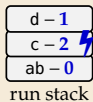


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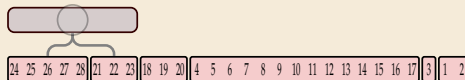
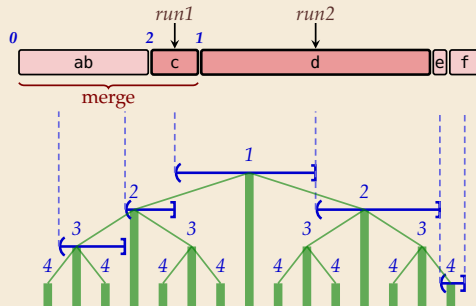
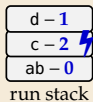
Powersort

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Powersort

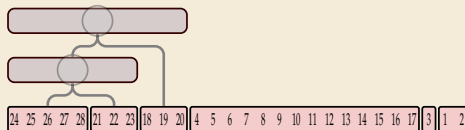
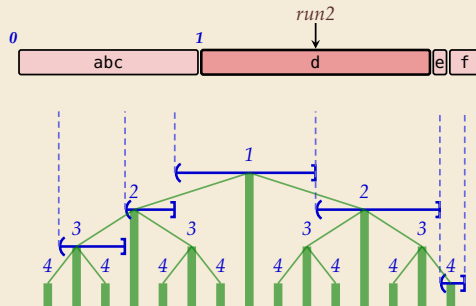
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d - 1
abc - 0

run stack



Powersort

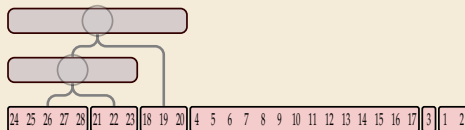
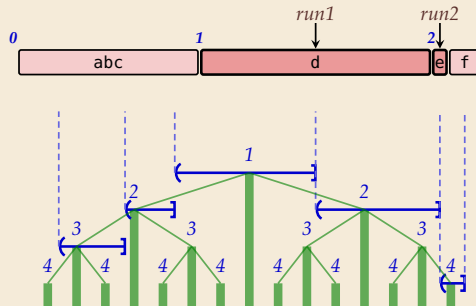
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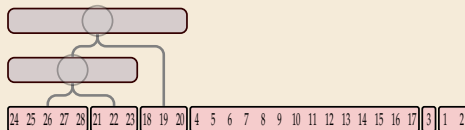
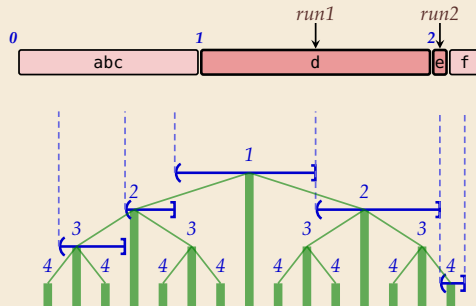
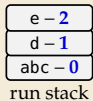


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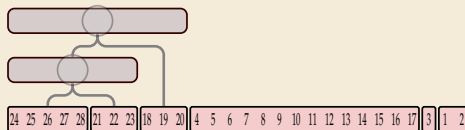
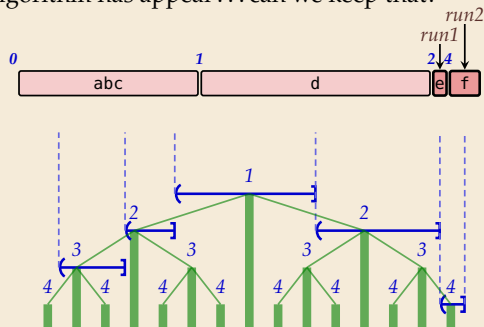
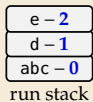


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Powersort

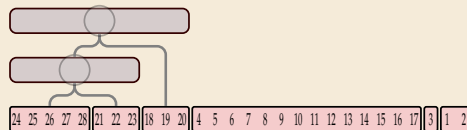
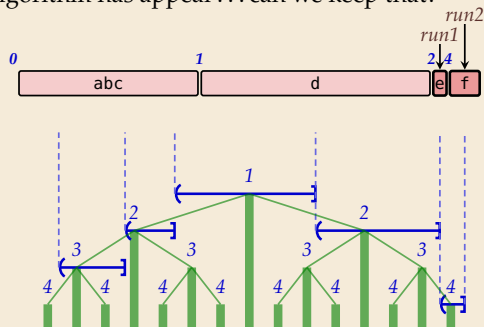
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f - 4
e - 2
d - 1
abc - 0

run stack



Powersort

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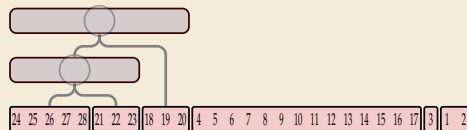
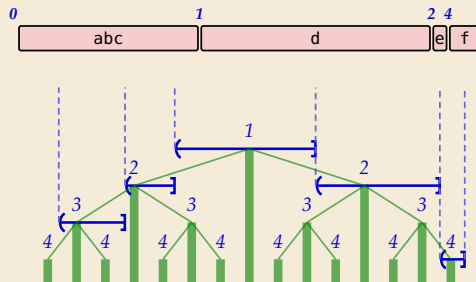
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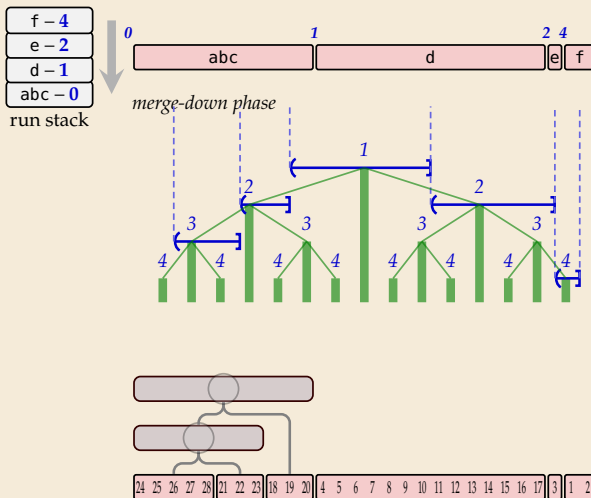


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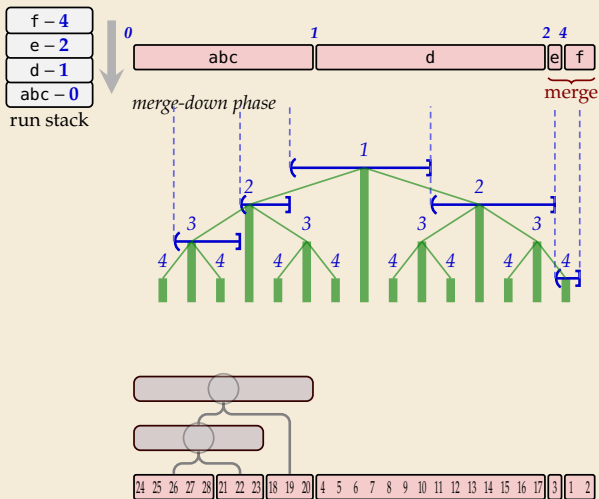


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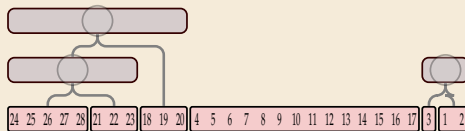
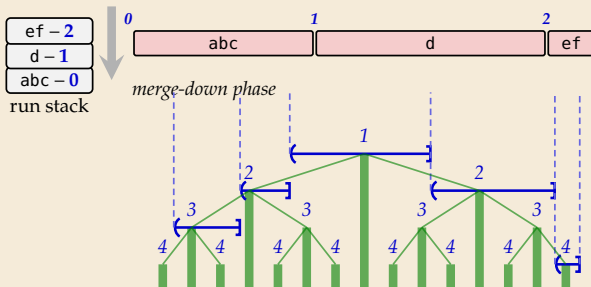


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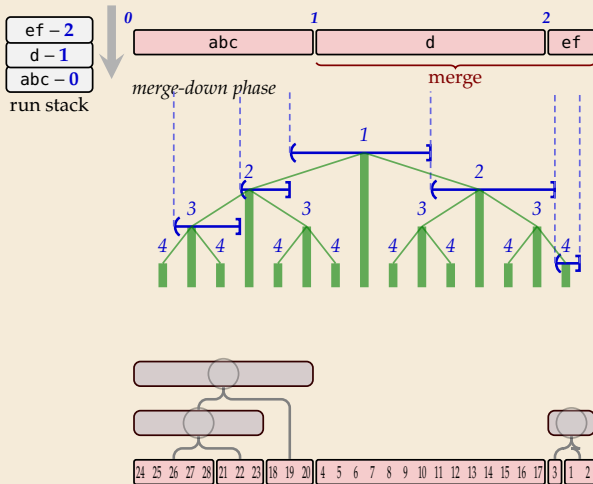


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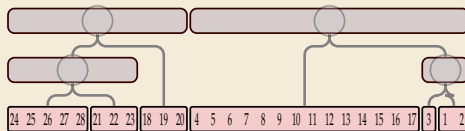
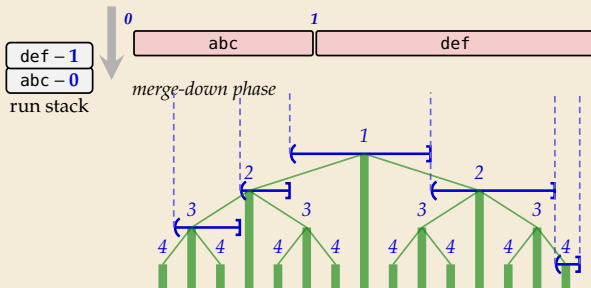
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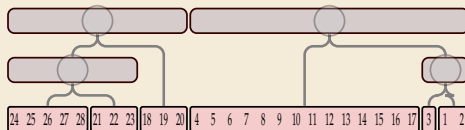
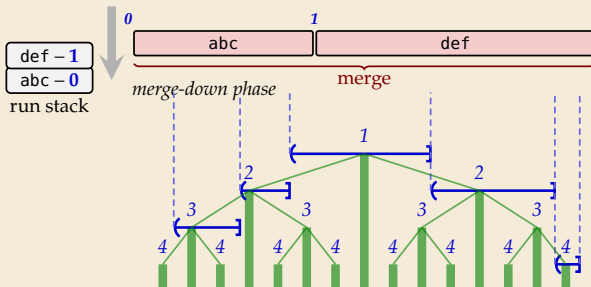


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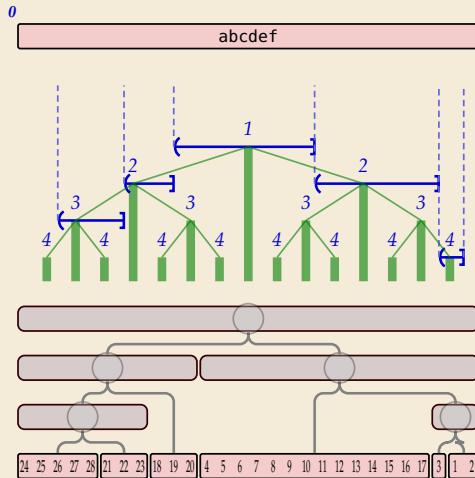


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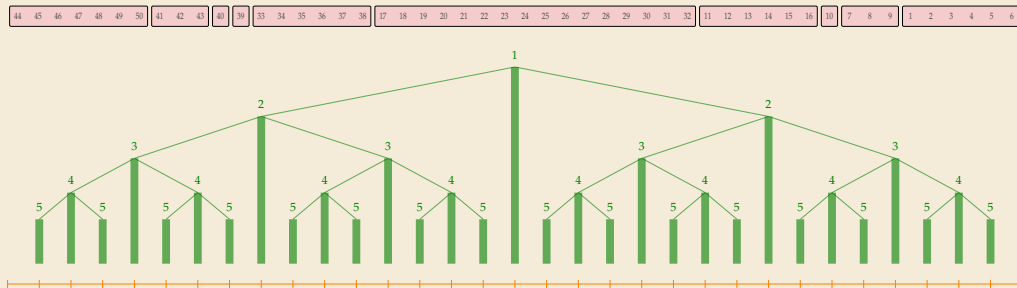
abcdef - 0
run stack



Powersort – Run-Boundary Powers

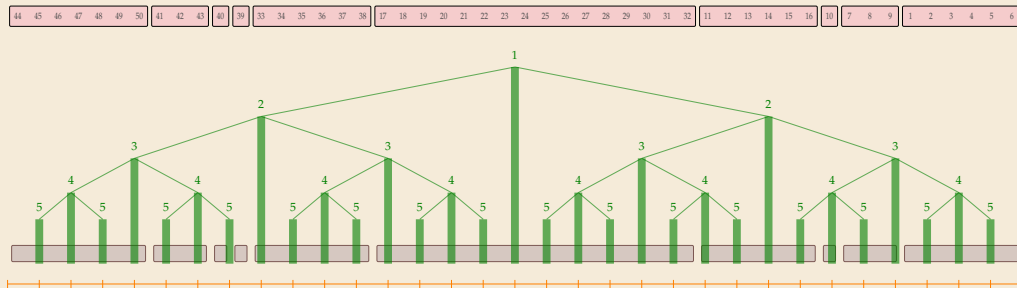
44	45	46	47	48	49	50	41	42	43	40	39	33	34	35	36	37	38	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	11	12	13	14	15	16	10	7	8	9	1	2	3	4	5	6
----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	---	---	---	---	---	---	---	---	---

Powersort – Run-Boundary Powers



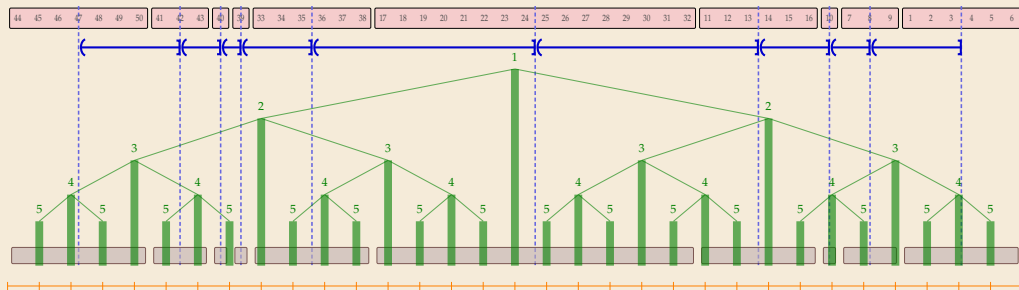
► (virtual) perfect balanced binary tree

Powersort – Run-Boundary Powers



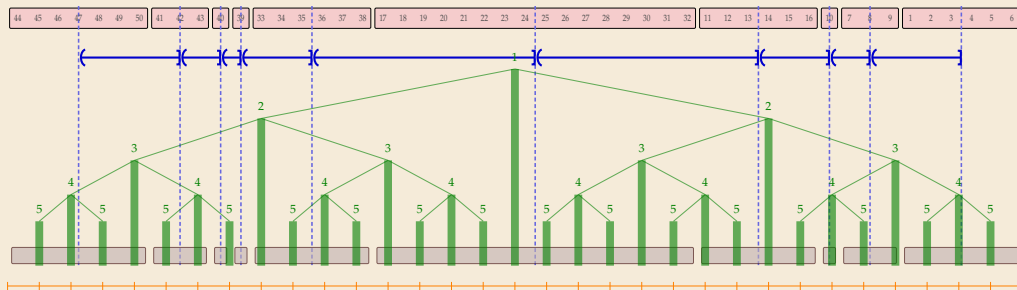
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Powersort – Run-Boundary Powers



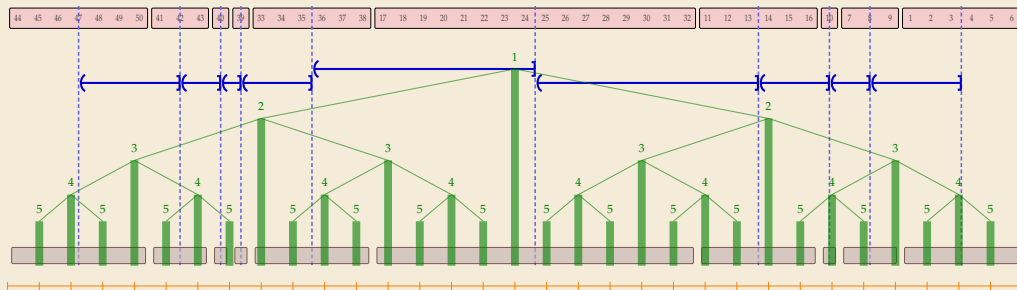
- (virtual) perfect balanced binary tree
- midpoint intervals “snap” to closest virtual tree node

Powersort – Run-Boundary Powers



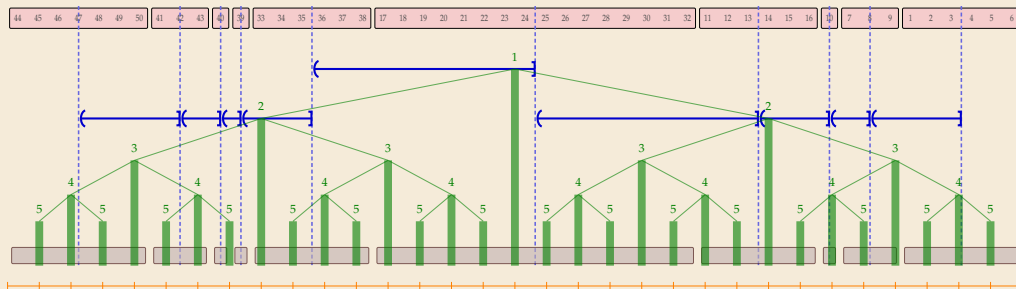
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Powersort – Run-Boundary Powers



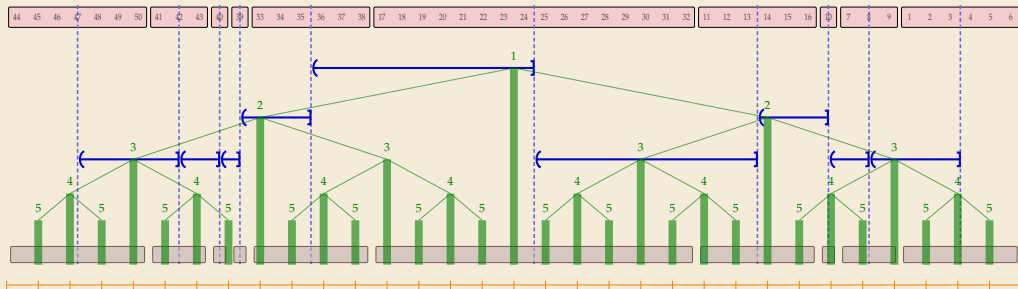
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Powersort – Run-Boundary Powers



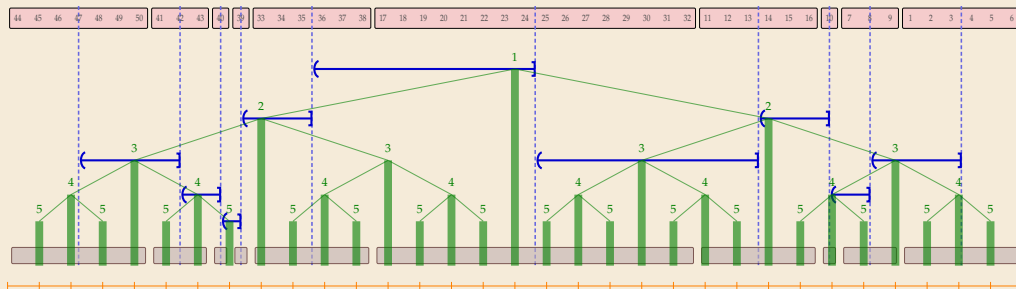
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Powersort – Run-Boundary Powers



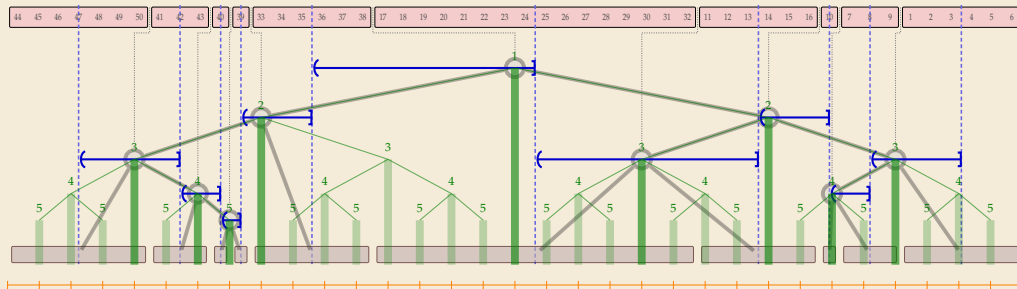
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Powersort – Run-Boundary Powers



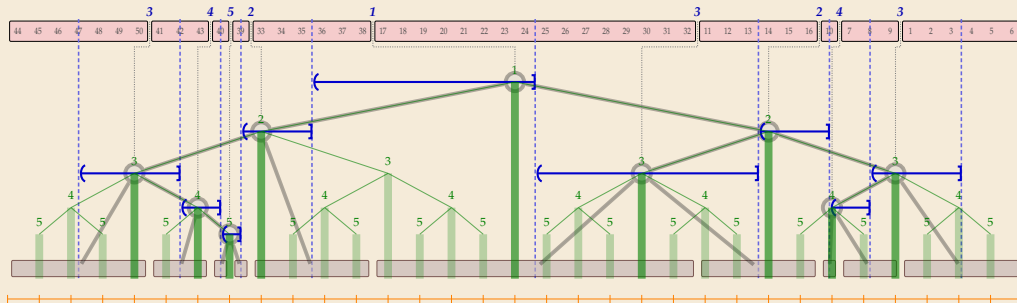
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Powersort – Run-Boundary Powers



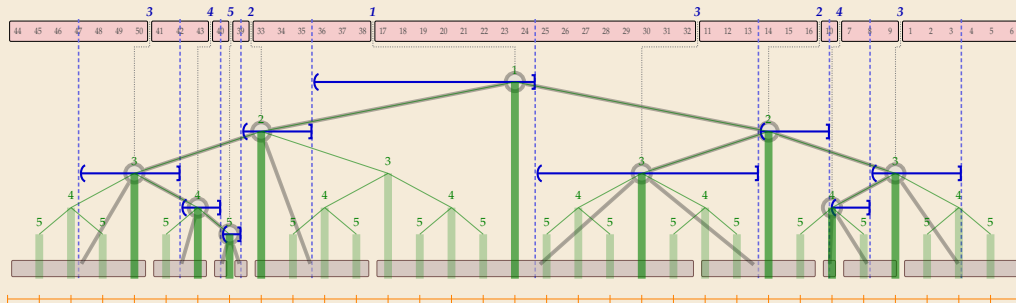
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Powersort – Run-Boundary Powers



- (virtual) perfect balanced binary tree
- midpoint intervals “snap” to closest virtual tree node
 - ↪ assigns each run boundary a depth

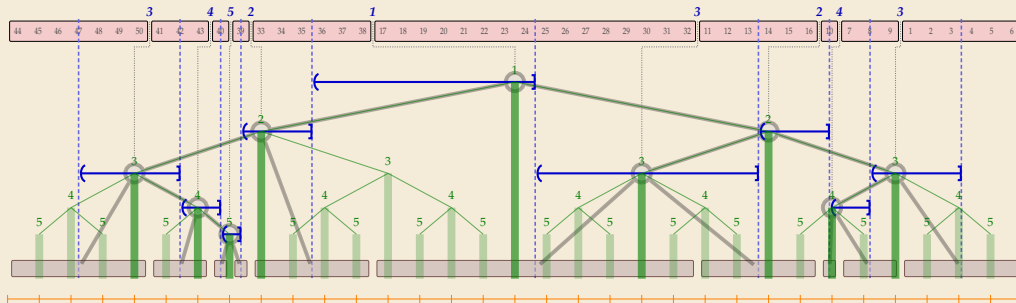
Powersort – Run-Boundary Powers



- ▶ (virtual) perfect balanced binary tree
- ▶ midpoint intervals “snap” to closest virtual tree node
 \rightsquigarrow assigns each run boundary a depth = its *power*



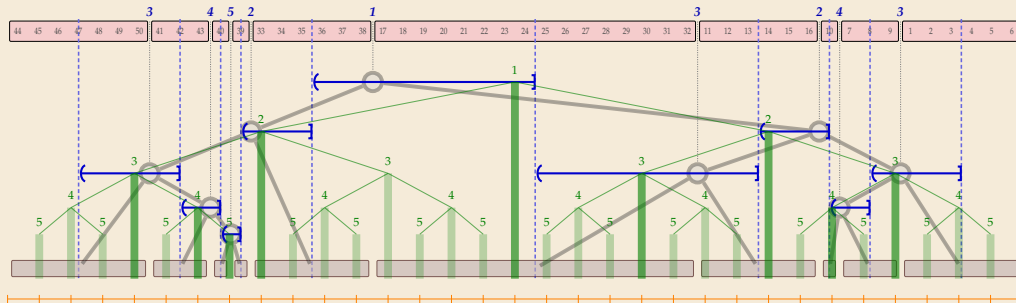
Powersort – Run-Boundary Powers



- ▶ (virtual) perfect balanced binary tree
- ▶ midpoint intervals “snap” to closest virtual tree node
 - ~> assigns each run boundary a depth = its *power*
- ~> merge tree follows **virtual tree**



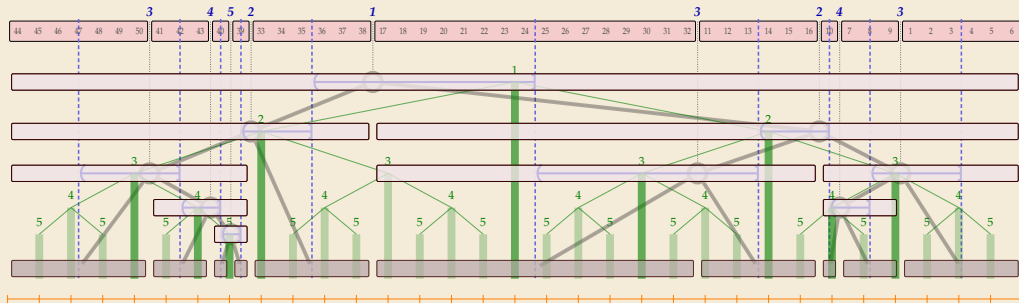
Powersort – Run-Boundary Powers



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- ~> merge tree follows **virtual tree**



Powersort – Run-Boundary Powers



- ▶ (virtual) perfect balanced binary tree
- ▶ midpoint intervals “snap” to closest virtual tree node
 - ~> assigns each run boundary a depth = its *power*
- ~> merge tree follows *virtual tree*



Powersort – Run-Boundary Powers are Local



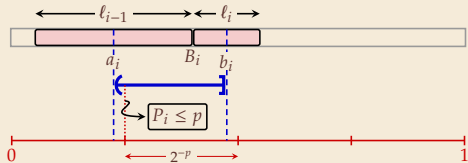
Computation of powers only depends on two adjacent runs.

Powersort – Computing powers

- ▶ Computing the power of
(run boundary between) two runs

- ▶ $\llbracket \cdot \rrbracket$ = normalized midpoint interval

- ▶ power = min ℓ s.t. $\llbracket \cdot \rrbracket$
contains $c \cdot 2^{-\ell}$

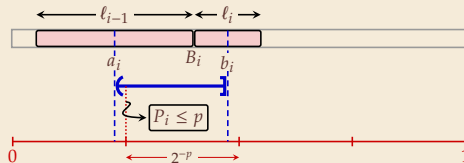


Powersort – Computing powers

- Computing the power of (run boundary between) two runs

- $\llbracket \cdot \rrbracket$ = normalized midpoint interval

- power = $\min \ell$ s.t. $\llbracket \cdot \rrbracket$ contains $c \cdot 2^{-\ell}$

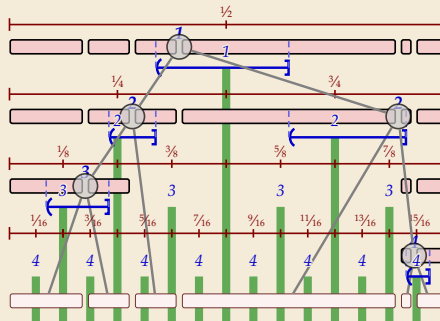


```

1 procedure power((i_1, j_1), (i_2, j_2), n)
2   n_1 := j_1 - i_1
3   n_2 := j_2 - i_2
4   a := (i_1 + \frac{1}{2}n_1 - 1) / n
5   b := (i_2 + \frac{1}{2}n_2 - 1) / n // interval (a, b]
6   \ell := 0
7   while \lfloor a \cdot 2^\ell \rfloor \neq \lfloor b \cdot 2^\ell \rfloor
8     \ell := \ell + 1
9   return \ell

```

- with bitwise trickery $O(1)$ time possible



Powersort – Discussion



Retains all advantages of Timsort

- ▶ good locality in memory accesses
- ▶ no recursion
- ▶ all the tricks in Timsort



optimally adapts to existing runs



minimal overhead for finding merge order