

Algorithms and Datastructures

Runtime analysis Minsort / Heapsort, Induction

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Algorithms and Datastructures, October 2017

Structure

Runtime Example

Minsort

Basic Operations

Runtime analysis

Minsort

Heapsort

Introduction to Induction

Logarithms

Structure

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Runtime analysis

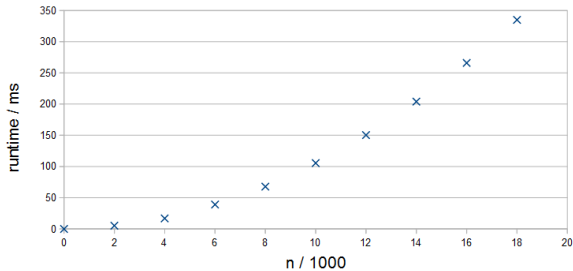
Minsort

Heapsort

Introduction to Induction

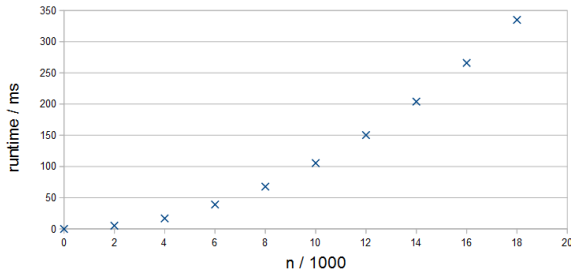
Logarithms

Runtime analysis - Minsort



How long does the program run?

Runtime analysis - Minsort



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- ▶ In the last lecture we had a schematic
- ▶ **Observation:** It is going to be “disproportionally” slower the more numbers are being sorted

Runtime analysis - Minsort



How long does the program run?

- ▶ In the last lecture we had a schematic
- ▶ **Observation:** It is going to be “disproportionally” slower the more numbers are being sorted
- ▶ How can we say more precisely what is happening?

Runtime analysis - Minsort

How can we analyze the runtime?

- ▶ Ideally we have a formula which provides the runtime of the program for an specific input

Runtime analysis - Minsort

How can we analyze the runtime?

- ▶ Ideally we have a formula which provides the runtime of the program for an specific input
- ▶ **Problem:** The runtime is also depending on many other influences, especially:
 - ▶ Which kind of computer is the code executed on
 - ▶ What is running in the background
 - ▶ Which compiler is used to compile the code

Runtime analysis - Minsort

How can we analyze the runtime?

- ▶ Ideally we have a formula which provides the runtime of the program for an specific input
- ▶ **Problem:** The runtime is also depending on many other influences, especially:
 - ▶ Which kind of computer is the code executed on
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 - ▶ Which compiler is used to compile the code
- ▶ **Abstraction 1:** Analyze the number of basic operations, rather than analyzing the runtime

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Basic Operations

Incomplete list of basic operations:

- ▶ Arithmetic operation, for example: $a + b$
- ▶ Assignment of variables, for example: $x = y$
- ▶ Function call, for example: *minsort(lst)*

Basic Operations

Intuitive:

lines of code

Better:

lines of machine
code

Best:

process cycles

Important:

The actual runtime has to be roughly proportional to the number of operations.

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How many operations does *Minsort* need?

- ▶ **Abstraction 2:** We calculate the upper (lower) bound, rather than counting the operations exactly

Reason: Runtime is approximated by number of basic operations, but we can still infer:

- ▶ Upper bound
- ▶ Lower bound

Runtime analysis - Minsort

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Reason: Runtime is approximated by number of basic operations, but we can still infer:

- ▶ Upper bound
 - ▶ Lower bound
-
- ▶ **Basic Assumption:**
 - ▶ n is size of the input data (i.e. array)
 - ▶ $T(n)$ number of operations for input n

Runtime analysis - Minsort

How many operations does *Minsort* need?

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Runtime analysis - Minsort

How many operations does *Minsort* need?

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- ▶ **Claim:** There are constants C_1 and C_2 such that:

$$C_1 \cdot n^2 \leq T(n) \leq C_2 \cdot n^2$$

Runtime analysis - Minsort

How many operations does *Minsort* need?

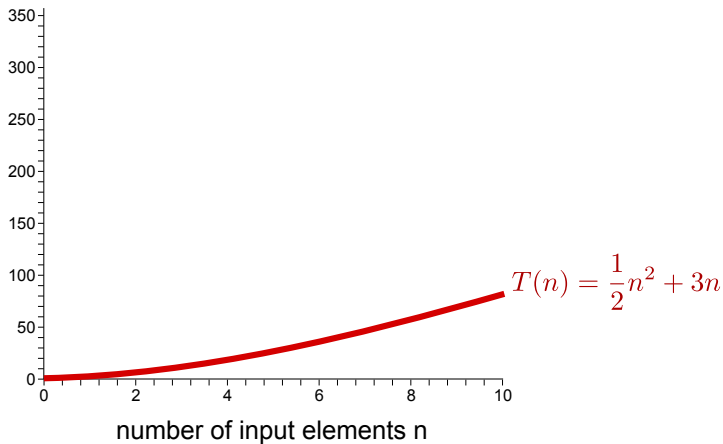
- ▶ **Observation:** The number of operations depends only on the size n of the array and not on the content!
- ▶ **Claim:** There are constants C_1 and C_2 such that:

$$C_1 \cdot n^2 \leq T(n) \leq C_2 \cdot n^2$$

- ▶ This is called “quadratic runtime” (due to n^2)

Runtime Example

Number of Steps
(runtime [s])



Runtime Example

Number of Steps
(runtime [s])



Runtime Example

Number of Steps
(runtime [s])



$C_2 = 7/2$ could have
been larger or small
(exact value not
relevant)

$$T(n) = \frac{1}{2}n^2 + 3n$$

$$\frac{1}{2} \cdot n^2$$

$C_1 = 1/2$ could have been
chosen smaller (not
relevant), but not larger

number of input elements n

Runtime analysis - Minsort

We declare:

- ▶ Runtime of operations: $T(n)$
- ▶ Number of Elements: n
- ▶ Constants: C_1 (lower bound), C_2 (upper bound)
$$C_1 \cdot n^2 \leq T(n) \leq C_2 \cdot n^2$$
- ▶ Number of operations in round i : T_i



Figure: *Minsort* at the iteration $i = 4$. We have to check $n - 3$ elements

Runtime analysis - Minsort

Compares at each iteration:

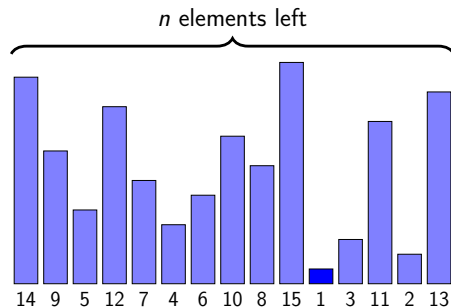


Figure: *Minsort* with start data

Runtime analysis - Minsort

Compares at each iteration:

$$T_1 \leq C'_2 \cdot (n - 0)$$



Figure: *Minsort* at iteration $i = 1$

Runtime analysis - Minsort

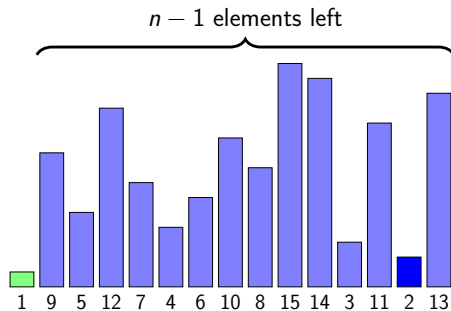


Figure: *Minsort* at iteration $i = 2$

Compares at each iteration:

$$T_1 \leq C'_2 \cdot (n - 0)$$

$$T_2 \leq C'_2 \cdot (n - 1)$$

Runtime analysis - Minsort

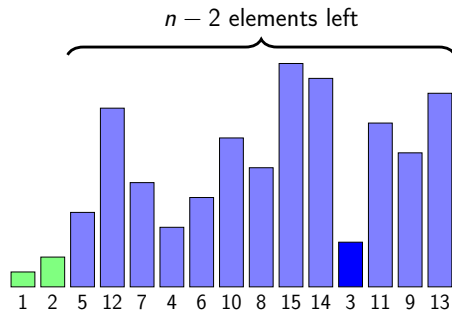


Figure: *Minsort* at iteration $i = 3$

Compares at each iteration:

$$T_1 \leq C'_2 \cdot (n - 0)$$

$$T_2 \leq C'_2 \cdot (n - 1)$$

$$T_3 \leq C'_2 \cdot (n - 2)$$

Runtime analysis - Minsort

Compares at each iteration:

$$T_1 \leq C'_2 \cdot (n - 0)$$

$$T_2 \leq C'_2 \cdot (n - 1)$$

$$T_3 \leq C'_2 \cdot (n - 2)$$

$$T_4 \leq C'_2 \cdot (n - 3)$$

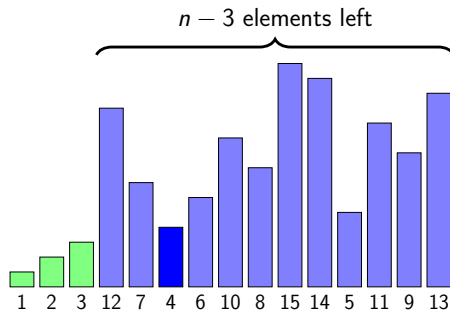


Figure: *Minsort* at iteration $i = 4$

Runtime analysis - Minsort

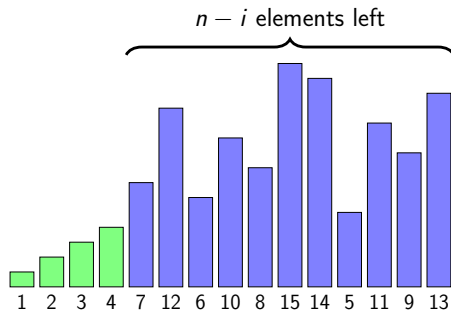


Figure: Minsort at iteration i

Compares at each iteration:

$$T_1 \leq C'_2 \cdot (n - 0)$$

$$T_2 \leq C'_2 \cdot (n - 1)$$

$$T_3 \leq C'_2 \cdot (n - 2)$$

$$T_4 \leq C'_2 \cdot (n - 3)$$

\vdots

$$T_{n-1} \leq C'_2 \cdot 2$$

$$T_n \leq C'_2 \cdot 1$$

Runtime analysis - Minsort

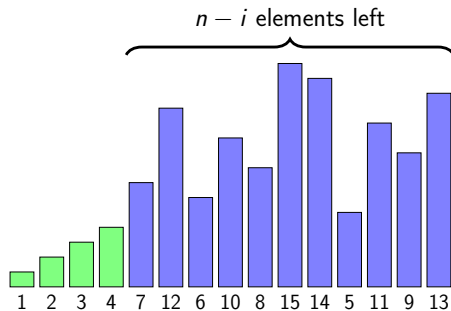


Figure: Minsort at iteration

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$$T(n) = C'_2 \cdot (T_1 + \dots + T_n) \leq \sum_{i=1}^n (C'_2 \cdot i)$$

Runtime analysis - Minsort

Alternative: Analyse the Code:

```
def minsort(elements):  
    for i in range(0, len(elements)-1):  
        minimum = i  
  
        for j in range(i+1, len(elements)):  
            if elements[j] < elements[minimum]:  
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        if minimum != i:  
            elements[i], elements[minimum] = \  
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        } const.  
        } runtime  
  
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$$T(n) \leq \sum_{i=0}^{n-2} \sum_{j=i+1}^{n-1} C_2'$$

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$$T(n) \leq \sum_{i=0}^{n-2} \sum_{j=i+1}^{n-1} C'_2 = \sum_{i=0}^{n-2} (n-i-1) \cdot C'_2$$

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Remark: C'_2 is cost of comparison \Rightarrow assumed constant

Runtime analysis - Minsort

Proof of upper bound: $T(n) \leq C_2 \cdot n^2$

$$T(n) \leq \sum_{i=1}^n C'_2 \cdot i$$

Runtime analysis - Minsort

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Runtime analysis - Minsort

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$$\begin{aligned} T(n) &\leq \sum_{i=1}^n C'_2 \cdot i \\ &= C'_2 \cdot \sum_{i=1}^n i \\ &\quad \downarrow \text{Small Gauss sum} \\ &= C'_2 \cdot \frac{n(n+1)}{2} \end{aligned}$$

Runtime analysis - Minsort

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Excursion - Small Gauss Formula

Runtime analysis - Minsort

Proof of lower bound: $C_1 \cdot n^2 \leq T(n)$

Like for the upper boundary there exists a C_1 . Summation analysis is the same

$$T(n) \geq \sum_{i=1}^{n-1} C'_1 \cdot (n - i)$$

Runtime analysis - Minsort

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Runtime analysis - Minsort

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Runtime analysis - Minsort

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How do we get to n^2 ?

Runtime analysis - Minsort

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Runtime analysis - Minsort

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Runtime analysis - Minsort

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Runtime analysis - Minsort

Runtime Analysis:

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Runtime analysis - Minsort

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Runtime analysis - Minsort

Runtime Analysis:

- ▶ Upper bound: $T(n) \leq C'_2 \cdot n^2$
- ▶ Lower bound: $\frac{C'_1}{4} \cdot n^2 \leq T(n)$

Summarized:

$$\frac{C'_1}{4} \cdot n^2 \leq T(n) \leq C'_2 \cdot n^2$$

Quadratic runtime proven:

$$C_1 \cdot n^2 \leq T(n) \leq C_2 \cdot n^2$$

Runtime Example

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 - ▶ $n = 10^6$ (1 million numbers = 4 MB with 4 B/number)
 - ▶ $C \cdot n^2 = 10^{-9} \text{ s} \cdot 10^{12} = 10^3 \text{ s} = 16.7 \text{ min}$

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- ▶ Let constants C_1 and C_2 for which $C_1 \cdot n^2 \leq T(n) \leq C_2 \cdot n^2$
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 - ▶ $n = 10^9$ (1 billion numbers = 4 GB)
 - ▶ $C \cdot n^2 = 10^{-9} \text{ s} \cdot 10^{18} = 10^9 \text{ s} = 31.7 \text{ years}$
- ▶ **Quadratic runtime = “big” problems unsolvable**

Structure

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Minsort

Basic Operations

Runtime analysis

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Heapsort

Introduction to Induction

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Runtime - Heapsort

Intuitive to extract minimum:

- ▶ **Minsort:** To determine the minimum value we have to iterate through all the unsorted elements.

Runtime - Heapsort

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Formal:

Runtime - Heapsort

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Formal:

- ▶ Let $T(n)$ be the runtime for the *Heapsort* algorithm with n elements

Runtime - Heapsort

Intuitive to extract minimum:

- ▶ **Minsort:** To determine the minimum value we have to iterate through all the unsorted elements.
- ▶ **Heapsort:** The root node is always the smallest (minheap). We only need to repair a part of the full tree after delete operation.

Formal:

- ▶ Let $T(n)$ be the runtime for the *Heapsort* algorithm with n elements
- ▶ On the next pages we will proof $T(n) \leq C \cdot n \log_2 n$

Runtime - Heapsort

Depth of a binary tree:

- ▶ **Depth d :** longest path through the tree
- ▶ Complete binary tree has $n = 2^d - 1$ nodes
- ▶ Example: $d = 4$
 $\Rightarrow n = 2^4 - 1 = 15$



Figure: Binary tree with 15 nodes

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Induction

Basics:

Induction

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- ▶ You want to show assumption $A(n)$ is valid $\forall n \in \mathbb{N}$

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Induction

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 1. **Induction basis:** we show that our assumption is valid at one point (for example: $n = 1, A(1)$).
 2. **Induction step:** we show that the assumption is valid for all n (normally one step forward: $n = n + 1, A(1), \dots, A(n)$).

Induction

Basics:

- ▶ You want to show assumption $A(n)$ is valid $\forall n \in \mathbb{N}$
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- ▶ If both has been proven, then $A(n)$ holds for all natural numbers n by **induction**

Induction - Example 1

Claim:

A **complete** binary tree of depth d has $n(d) = 2^d - 1$ nodes

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Root



$$n(1) = 2^1 - 1 = 1$$

Figure: Tree of depth 1 has 1 node

Induction - Example 1

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A **complete** binary tree of depth d has $n(d) = 2^d - 1$ nodes

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\Rightarrow correct ✓

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Induction - Example 1

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Figure: Binary tree with subtrees

Induction - Example 1

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$$n(d+1) = 2 \cdot n(d) + 1$$

Figure: Binary tree with subtrees

Induction - Example 1

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Figure: Binary tree with subtrees

$$\begin{aligned}n(d+1) &= 2 \cdot n(d) + 1 \\&= 2 \cdot (2^d - 1) + 1\end{aligned}$$

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Figure: Binary tree with subtrees

$$\begin{aligned}n(d+1) &= 2 \cdot n(d) + 1 \\&= 2 \cdot (2^d - 1) + 1 \\&= 2^{d+1} - 2 + 1\end{aligned}$$

Induction - Example 1

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Figure: Binary tree with subtrees

$$\begin{aligned}n(d+1) &= 2 \cdot n(d) + 1 \\&= 2 \cdot (2^d - 1) + 1 \\&= 2^{d+1} - 2 + 1 \\&= 2^{d+1} - 1 \quad \checkmark\end{aligned}$$

Induction - Example 1

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- ▶ **Induction assumption:** $n(d) = 2^d - 1$
- ▶ **Induction basis:** $n(1) = 2^1 - 1 = 2^1 - 1 = 1$ ✓
- ▶ **Induction step:** to show for $d := d + 1$



Figure: Binary tree with subtrees

⇒ **By induction:**

$$\begin{aligned}n(d+1) &= 2 \cdot n(d) + 1 \\&= 2 \cdot (2^d - 1) + 1 \\&= 2^{d+1} - 2 + 1 \\&= 2^{d+1} - 1 \quad \checkmark\end{aligned}$$

$$n(d) = 2^d - 1 \quad \forall n \in \mathbb{N} \quad \square$$

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Runtime - Heapsort

Heapsort has the following steps:

- ▶ **Initially:** heapify list of n elements

Runtime - Heapsort

Heapsort has the following steps:

- ▶ **Initially:** heapify list of n elements
- ▶ **Then:** until all n elements are sorted

Runtime - Heapsort

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Runtime - Heapsort

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 - ▶ Move last leaf to root position

Runtime - Heapsort

Heapsort has the following steps:

- ▶ **Initially:** heapify list of n elements
- ▶ **Then:** until all n elements are sorted
 - ▶ Remove root as minimal element
 - ▶ Move last leaf to root position
 - ▶ Repair heap by sifting

Runtime - Heapsort

Heapify

Runtime of heapify depends on depth d :



Runtime - Heapsort

Heapify

Runtime of heapify depends on depth d :



Runtime of heapify with depth of d :

- No costs at depth d with 2^{d-1} (or less) nodes

Runtime - Heapsort

Heapify

Runtime of heapify depends on depth d :



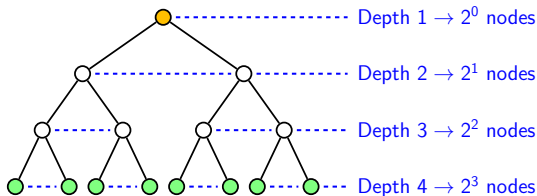
Runtime of heapify with depth of d :

- ▶ No costs at depth d with 2^{d-1} (or less) nodes
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Runtime - Heapsort

Heapify

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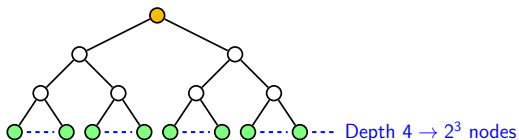
Runtime of heapify with depth of d :

- ▶ No costs at depth d with 2^{d-1} (or less) nodes
- ▶ The cost for sifting with depth 1 is at most $1C$ per node
- ▶ In general: Sifting costs are linear with path length **and** number of nodes

Runtime - Heapsort

Heapify

Heapify total runtime:



Depth	Nodes	Path length	Costs per node
d	2^{d-1}	0	$\leq C \cdot 0$

Runtime - Heapsort

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d	2^{d-1}	0	$\leq C \cdot 0$
$d - 1$	2^{d-2}	1	$\leq C \cdot 1$

Runtime - Heapsort

Heapify

Heapify total runtime:



Depth	Nodes	Path length	Costs per node
d	2^{d-1}	0	$\leq C \cdot 0$
$d - 1$	2^{d-2}	1	$\leq C \cdot 1$
$d - 2$	2^{d-3}	2	$\leq C \cdot 2$

Runtime - Heapsort

Heapify

Heapify total runtime:



Generally: Depth $d \rightarrow 2^{d-1}$ nodes

Depth	Nodes	Path length	Costs per node	
d	2^{d-1}	0	$\leq C \cdot 0$	
$d - 1$	2^{d-2}	1	$\leq C \cdot 1$	
$d - 2$	2^{d-3}	2	$\leq C \cdot 2$	
$d - 3$	2^{d-4}	3	$\leq C \cdot 3$	

Runtime - Heapsort

Heapify

Heapify total runtime:



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Depth	Nodes	Path length	Costs per node	
d	2^{d-1}	0	$\leq C \cdot 0$	
$d-1$	2^{d-2}	1	$\leq C \cdot 1$	
$d-2$	2^{d-3}	2	$\leq C \cdot 2$	
$d-3$	2^{d-4}	3	$\leq C \cdot 3$	

In total:
$$T(d) \leq \sum_{i=1}^d \left(C \cdot (i-1) \cdot 2^{d-i} \right)$$

Runtime - Heapsort

Heapify

Heapify total runtime:



Generally: Depth $d \rightarrow 2^{d-1}$ nodes

Depth	Nodes	Path length	Costs per node	Upper bound
d	2^{d-1}	0	$\leq C \cdot 0$	Standard Equation
$d-1$	2^{d-2}	1	$\leq C \cdot 1$	
$d-2$	2^{d-3}	2	$\leq C \cdot 2$	
$d-3$	2^{d-4}	3	$\leq C \cdot 3$	

In total:
$$T(d) \leq \sum_{i=1}^d \left(C \cdot (i-1) \cdot 2^{d-i} \right) \leq \sum_{i=1}^d \left(C \cdot i \cdot 2^{d-i} \right)$$

Runtime - Heapsort

Heapify

Heapify total runtime:



Generally: Depth $d \rightarrow 2^{d-1}$ nodes

Depth	Nodes	Path length	Costs per node	Upper bound
d	2^{d-1}	0	$\leq C \cdot 0$	$\leq C \cdot 1$
$d-1$	2^{d-2}	1	$\leq C \cdot 1$	$\leq C \cdot 2$
$d-2$	2^{d-3}	2	$\leq C \cdot 2$	$\leq C \cdot 3$
$d-3$	2^{d-4}	3	$\leq C \cdot 3$	$\leq C \cdot 4$

In total:
$$T(d) \leq \sum_{i=1}^d \left(C \cdot (i-1) \cdot 2^{d-i} \right) \leq \sum_{i=1}^d \left(C \cdot i \cdot 2^{d-i} \right)$$

Runtime - Heapsort

Heapify

Heapify total runtime:

$$T(d) \leq C \cdot \sum_{i=1}^d \left(i \cdot 2^{d-i} \right) \leq C \cdot 2^{d+1}$$

Runtime - Heapsort

Heapify

Heapify total runtime:

$$T(d) \leq C \cdot \sum_{i=1}^d \left(i \cdot 2^{d-i} \right) \leq C \cdot 2^{d+1}$$

- **Hence:** Resulting costs for heapify:

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Runtime - Heapsort

Heapify

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$$T(d) \leq C \cdot \sum_{i=1}^d \left(i \cdot 2^{d-i} \right) \leq C \cdot 2^{d+1}$$

- **Hence:** Resulting costs for heapify:

$$T(d) \leq C \cdot 2^{d+1}$$

- **However:** We want costs in relation to n

Runtime - Heapsort

Heapify

Heapify total runtime:

$$T(d) \leq C \cdot 2^{d+1}$$

Runtime - Heapsort

Heapify

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- ▶ A binary tree of depth d has $2^{d+1} - 1 \leq n$ nodes

Runtime - Heapsort

Heapify

Heapify total runtime:

$$T(d) \leq C \cdot 2^{d+1}$$

- ▶ A binary tree of depth d has $2^{d+1} - 1 \leq n$ nodes Why?

Runtime - Heapsort

Heapify

Heapify total runtime:

$$T(d) \leq C \cdot 2^{d+1}$$

- ▶ A binary tree of depth d has $2^{d-1} \leq n$ nodes **Why?**



Figure: Partial binary tree

Runtime - Heapsort

Heapify

Heapify total runtime:

$$T(d) \leq C \cdot 2^{d+1}$$

- ▶ A binary tree of depth d has $2^{d-1} \leq n$ nodes **Why?**
- ▶ $2^{d-1} - 1$ nodes in full tree
till layer $d - 1$



Figure: Partial binary tree

Runtime - Heapsort

Heapify

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$$T(d) \leq C \cdot 2^{d+1}$$

- ▶ A binary tree of depth d has $2^{d+1} - 1$ nodes **Why?**
- ▶ $2^{d-1} - 1$ nodes in full tree till layer $d - 1$
- ▶ At least 1 node in layer d



Figure: Partial binary tree

Runtime - Heapsort

Heapify

Heapify total runtime:

$$T(d) \leq C \cdot 2^{d+1}$$

- ▶ A binary tree of depth d has $2^{d-1} \leq n$ nodes **Why?**
- ▶ $2^{d-1} - 1$ nodes in full tree till layer $d - 1$
- ▶ At least 1 node in layer d
- ▶ Equation multiplied by 2^2
 $\Rightarrow 2^{d-1} \cdot 2^2 \leq 2^2 \cdot n$

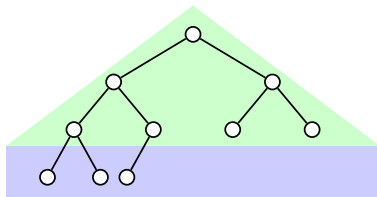


Figure: Partial binary tree

Runtime - Heapsort

Heapify

Heapify total runtime:

$$T(d) \leq C \cdot 2^{d+1}$$

- ▶ A binary tree of depth d has $2^{d-1} \leq n$ nodes **Why?**
- ▶ $2^{d-1} - 1$ nodes in full tree till layer $d - 1$
- ▶ At least 1 node in layer d
- ▶ Equation multiplied by 2^2
 $\Rightarrow 2^{d-1} \cdot 2^2 \leq 2^2 \cdot n$
- ▶ Cost for heapify:
 $\Rightarrow T(n) \leq C \cdot 4 \cdot n$



Figure: Partial binary tree

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Induction - Example 2

- ▶ We want to proof (induction assumption):

$$\underbrace{\sum_{i=1}^d \left(i \cdot 2^{d-i} \right)}_{A(d)} \leq \underbrace{2^{d+1}}_{B(d)}$$

- ▶ We denote the left side with A , the right side with B

Induction - Example 2

- **Induction basis:** $d := 1$:

$$A(d) \leq B(d)$$

Induction - Example 2

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$$\sum_{i=1}^d \left(i \cdot 2^{d-i} \right) \leq 2^{d+1}$$

Induction - Example 2

- **Induction basis:** $d := 1$:

$$A(d) \leq B(d)$$

$$\sum_{i=1}^d (i \cdot 2^{d-i}) \leq 2^{d+1}$$

$$\sum_{i=1}^1 (i \cdot 2^{1-i}) \leq 2^{1+1}$$

Induction - Example 2

- **Induction basis:** $d := 1$:

$$A(d) \leq B(d)$$

$$\sum_{i=1}^d (i \cdot 2^{d-i}) \leq 2^{d+1}$$

$$\sum_{i=1}^1 (i \cdot 2^{1-i}) \leq 2^{1+1}$$

$$2^0 \leq 2^2 \quad \checkmark$$

Induction - Example 2

Induction step: ($d := d + 1$):

- ▶ **Idea:** Write down right hand formula and try to get $A(d)$ and $B(d)$ out of it

$$A(d) \leq B(d) \quad \Rightarrow \quad A(d+1) \leq B(d+1)$$

Induction - Example 2

Induction step: ($d := d + 1$):

- **Idea:** Write down right hand formula and try to get $A(d)$ and $B(d)$ out of it

$$A(d) \leq B(d) \quad \Rightarrow \quad A(d+1) \leq B(d+1)$$

$$\sum_{i=1}^{d+1} \left(i \cdot 2^{d+1-i} \right) \leq 2^{d+1+1}$$

Induction - Example 2

Induction step: ($d := d + 1$):

- **Idea:** Write down right hand formula and try to get $A(d)$ and $B(d)$ out of it

$$A(d) \leq B(d) \quad \Rightarrow \quad A(d+1) \leq B(d+1)$$

$$\sum_{i=1}^{d+1} \left(i \cdot 2^{d+1-i} \right) \leq 2^{d+1+1}$$
$$2 \cdot \sum_{i=1}^{d+1} \left(i \cdot 2^{d-i} \right) \leq 2 \cdot 2^{d+1}$$

\vdots

Induction - Example 2

Induction step: ($d := d + 1$):

\vdots

$$2 \cdot \sum_{i=1}^{d+1} \left(i \cdot 2^{d-i} \right) \leq 2 \cdot 2^{d+1}$$

Induction - Example 2

Induction step: ($d := d + 1$):

\vdots

$$2 \cdot \sum_{i=1}^{d+1} (i \cdot 2^{d-i}) \leq 2 \cdot 2^{d+1}$$

$$2 \cdot \sum_{i=1}^{d+1} (i \cdot 2^{d-i}) \leq 2 \cdot B(d)$$

Induction - Example 2

Induction step: ($d := d + 1$):

\vdots

$$2 \cdot \sum_{i=1}^{d+1} (i \cdot 2^{d-i}) \leq 2 \cdot 2^{d+1}$$

$$2 \cdot \sum_{i=1}^{d+1} (i \cdot 2^{d-i}) \leq 2 \cdot B(d)$$

$$2 \cdot \sum_{i=1}^d (i \cdot 2^{d-i}) + 2 \cdot (d+1) \cdot 2^{d-(d+1)} \leq 2 \cdot B(d)$$

Induction - Example 2

Induction step: ($d := d + 1$):

\vdots

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$$2 \cdot A(d) + (d+1) \leq 2 \cdot B(d)$$

Induction - Example 2

Induction step: ($d := d + 1$):

\vdots

$$2 \cdot \sum_{i=1}^{d+1} (i \cdot 2^{d-i}) \leq 2 \cdot 2^{d+1}$$

$$2 \cdot \sum_{i=1}^{d+1} (i \cdot 2^{d-i}) \leq 2 \cdot B(d)$$

$$2 \cdot \sum_{i=1}^d (i \cdot 2^{d-i}) + 2 \cdot (d+1) \cdot 2^{d-(d+1)} \leq 2 \cdot B(d)$$

$$2 \cdot A(d) + (d+1) \leq 2 \cdot B(d)$$

► **Problem:** Does not work but claim still holds

Induction - Example 2

Working proof:

- Show a little bit stronger claim

$$\sum_{i=1}^d \left(i \cdot 2^{d-i} \right) \leq 2^{d+1} - d - 2 \leq 2^{d+1}$$

Induction - Example 2

Working proof:

- ▶ Show a **little bit stronger** claim

$$\sum_{i=1}^d \left(i \cdot 2^{d-i} \right) \leq 2^{d+1} - d - 2 \leq 2^{d+1}$$

- ▶ **Advantage:** Results in a stronger induction assumption
 \Rightarrow **exercise**

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Runtime of the other operations:

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- ▶ Constant costs for taking out $n \times$ maximum

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- ▶ Maximum of d steps repairing the heap n times

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- ▶ Constant costs for taking out $n \times$ maximum
- ▶ Maximum of d steps repairing the heap n times
- ▶ Depth of heap at the start is $d \leq 1 + \log_2 n$ Why?

$$2^{d-1} \leq n \Rightarrow d - 1 \leq \log_2 n \Rightarrow d \leq 1 + \log_2 n$$

Runtime of the other operations:

- ▶ Constant costs for taking out $n \times$ maximum
- ▶ Maximum of d steps repairing the heap n times
- ▶ Depth of heap at the start is $d \leq 1 + \log_2 n$ Why?

$$2^{d-1} \leq n \Rightarrow d - 1 \leq \log_2 n \Rightarrow d \leq 1 + \log_2 n$$

- ▶ **Recall:** The depth and number of elements is decreasing

Runtime of the other operations:

- ▶ Constant costs for taking out $n \times$ maximum
- ▶ Maximum of d steps repairing the heap n times
- ▶ Depth of heap at the start is $d \leq 1 + \log_2 n$ Why?

$$2^{d-1} \leq n \Rightarrow d - 1 \leq \log_2 n \Rightarrow d \leq 1 + \log_2 n$$

- ▶ **Recall:** The depth and number of elements is decreasing
 - ▶ **Hence:** $T(n) \leq n \cdot (1 + \log_2 n) \cdot C$

Runtime of the other operations:

- ▶ Constant costs for taking out $n \times$ maximum
- ▶ Maximum of d steps repairing the heap n times
- ▶ Depth of heap at the start is $d \leq 1 + \log_2 n$ Why?

$$2^{d-1} \leq n \Rightarrow d - 1 \leq \log_2 n \Rightarrow d \leq 1 + \log_2 n$$

- ▶ **Recall:** The depth and number of elements is decreasing
 - ▶ **Hence:** $T(n) \leq n \cdot (1 + \log_2 n) \cdot C$
 - ▶ We can reduce this to:

$$T(n) \leq 2 \cdot n \log_2 n \cdot C \quad (\text{holds for } n > 2)$$

Runtime - Heapsort

Runtime costs:

- ▶ Heapify: $T(n) \leq 4 \cdot n \cdot C$

Runtime - Heapsort

Runtime costs:

- ▶ Heapify: $T(n) \leq 4 \cdot n \cdot C$
- ▶ Remove: $T(n) \leq 2 \cdot n \log_2 n \cdot C$

Runtime - Heapsort

Runtime costs:

- ▶ Heapify: $T(n) \leq 4 \cdot n \cdot C$
- ▶ Remove: $T(n) \leq 2 \cdot n \log_2 n \cdot C$
- ▶ Total runtime: $T(n) \leq 6 \cdot n \log_2 n \cdot C$

Runtime - Heapsort

Runtime costs:

- ▶ Heapify: $T(n) \leq 4 \cdot n \cdot C$
- ▶ Remove: $T(n) \leq 2 \cdot n \log_2 n \cdot C$
- ▶ Total runtime: $T(n) \leq 6 \cdot n \log_2 n \cdot C$
- ▶ Constraints:
 - ▶ **Upper bound:** $C_2 \cdot n \log_2 n \geq T(n)$ (for $n \geq 2$)
 - ▶ **Lower bound:** $C_1 \cdot n \log_2 n \leq T(n)$ (for $n \geq 2$)

Runtime - Heapsort

Runtime costs:

- ▶ Heapify: $T(n) \leq 4 \cdot n \cdot C$
- ▶ Remove: $T(n) \leq 2 \cdot n \log_2 n \cdot C$
- ▶ Total runtime: $T(n) \leq 6 \cdot n \log_2 n \cdot C$
- ▶ Constraints:
 - ▶ **Upper bound:** $C_2 \cdot n \log_2 n \geq T(n)$ (for $n \geq 2$)
 - ▶ **Lower bound:** $C_1 \cdot n \log_2 n \leq T(n)$ (for $n \geq 2$)
 - ▶ $\Rightarrow C_1$ and C_2 are constant

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Base of Logarithms

Logarithm to different bases:

$$\log_a n = \frac{\log_b n}{\log_b a} = \log_b n \cdot \frac{1}{\log_b a}$$

The only difference is a constant coefficient $\frac{1}{\log_b a}$

Examples:

- ▶ $\log_2 4 = \log_{10} 4 \cdot \frac{1}{\log_2 10} = 0.602 \dots \cdot 3.322 \dots = 2$ ✓
- ▶ $\log_{10} 1000 = \log_e 1000 \cdot \frac{1}{\log_e 10} = \ln 1000 \cdot \frac{1}{\ln 10} = 3$ ✓

Runtime Example

Runtime of $n \log_2 n$:

- ▶ Assume we have constants C_1 and C_2 with

$$C_1 \cdot n \cdot \log_2 n \leq T(n) \leq C_2 \cdot n \cdot \log_2 n \quad \text{for } n \geq 2$$

Runtime Example

Runtime of $n \log_2 n$:

- ▶ Assume we have constants C_1 and C_2 with

$$C_1 \cdot n \cdot \log_2 n \leq T(n) \leq C_2 \cdot n \cdot \log_2 n \quad \text{for } n \geq 2$$

- ▶ $2 \times$ elements \Rightarrow only slightly larger than $2 \times$ runtime

Runtime Example

Runtime of $n \log_2 n$:

- ▶ Assume we have constants C_1 and C_2 with

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 - ▶ $C = 1 \text{ ns}$ (1 simple instruction $\approx 1 \text{ ns}$)

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- ▶ **Runtime $n \log_2 n$ is nearly as good as linear!**

Further Literature

► General for this Lecture

[CRL01] Thomas H. Cormen, Ronald L. Rivest, and Charles E. Leiserson.

Introduction to Algorithms.

MIT Press, Cambridge, Mass, 2001.

[MS08] Kurt Mehlhorn and Peter Sanders.

Algorithms and data structures, 2008.

<https://people.mpi-inf.mpg.de/~mehlhorn/ftp/Mehlhorn-Sanders-Toolbox.pdf>.

Further Literature

- ▶ **Mathematical Induction**

[Wik] [Mathematical induction](https://en.wikipedia.org/wiki/Mathematical_induction)

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induction`