

Algorithms and Datastructures

Runtime analysis Minsort / Heapsort, Induction

Albert-Ludwigs-Universität Freiburg



**UNI
FREIBURG**

Prof. Dr. Rolf Backofen

Bioinformatics Group / Department of Computer Science
Algorithms and Datastructures, October 2018

Algorithms and Datastructures

- Structure

- Links

- Organisation

 - Daphne

 - Forum

 - Checkstyle

 - Unit Tests

 - Version management

 - Jenkins

Sorting

- Minsort

- Heapsort

Topics of the Lecture:

- Algorithms and Data Structures
- **Algorithm** $\hat{=}$ Solving of complex computational problems
- **Datastructure** $\hat{=}$ Representation of data on computer

Topics of the Lecture:

- Algorithms and Data Structures
Efficient data handling and processing
... for problems that occur in practical **any** larger program / project
- **Algorithm** $\hat{=}$ Solving of complex computational problems
- **Datastructure** $\hat{=}$ Representation of data on computer

Example 1: Sorting

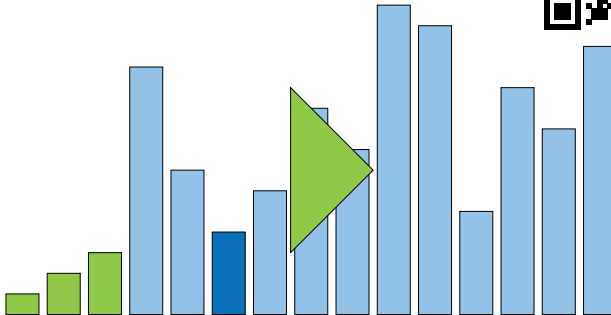


Figure: Sorting with *Minsort*

Example 2: Navigation

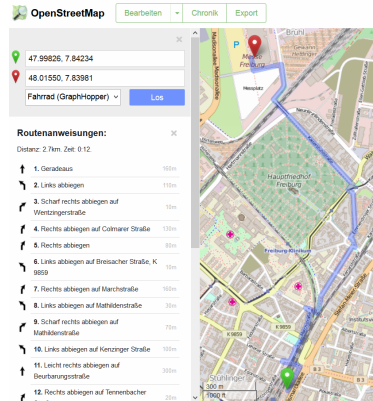


Figure: Navigationplan
© OpenStreetMap

Example 2: Navigation

- **Datastructures:** How to represent the map as data?



Figure: Navigationplan
© OpenStreetMap

Example 2: Navigation

- **Datastructures:** How to represent the map as data?
- **Algorithms:** How to find the shortest / fastest way?



Figure: Navigationplan
© OpenStreetMap

Algorithms and Datastructures

Structure

Links

Organisation

Daphne

Forum

Checkstyle

Unit Tests

Version management

Jenkins

Sorting

Minsort

Heapsort

General:

- Most of you had a lecture on basic programming ...
performance was not an issue

General:

- Most of you had a lecture on basic programming ...
performance was not an issue
- Here it is going to be:

General:

- Most of you had a lecture on basic programming ...
performance was not an issue
- Here it is going to be:
 - 1 How fast is our program?

General:

- Most of you had a lecture on basic programming ...
performance was not an issue
- Here it is going to be:
 - 1 How fast is our program?
 - 2 How can we make it faster?

General:

- Most of you had a lecture on basic programming ...
performance was not an issue
- Here it is going to be:
 - 1 How fast is our program?
 - 2 How can we make it faster?
 - 3 How can we proof that it will always be that fast?

General:

- Most of you had a lecture on basic programming ...
performance was not an issue
- Here it is going to be:
 - 1 How fast is our program?
 - 2 How can we make it faster?
 - 3 How can we proof that it will always be that fast?
- **Important** issues:
 - Most of the time: application runtime
 - Sometimes also: resource / space consumption



Algorithms:

Algorithms:

- Sorting
- Dynamic Arrays
- Associative Arrays
- Hashing
- Edit distance
- Priority Queue
- Linked Lists
- Pathfinding / Dijkstra Algorithm
- Search Trees

Algorithms:

- Sorting
- Dynamic Arrays
- Associative Arrays
- Hashing
- Edit distance
- Priority Queue
- Linked Lists
- Pathfinding / Dijkstra Algorithm
- Search Trees

Mathematics:

Algorithms:

- Sorting
- Dynamic Arrays
- Associative Arrays
- Hashing
- Edit distance
- Priority Queue
- Linked Lists
- Pathfinding / Dijkstra Algorithm
- Search Trees

Mathematics:

- Runtime analysis
- Proof of correctness
- \mathcal{O} -Notation

After the lecture ...

- ... you should be able to understand the joke



Figure: Comic © [xkcd/835](https://xkcd.com/835/)

After the lecture ...

- ... you should be able to understand the joke

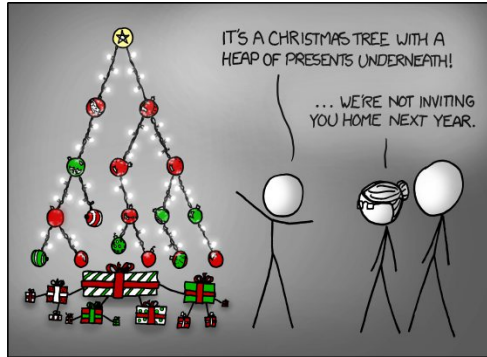


Figure: Comic © [xkcd/835](https://xkcd.com/835/)

- Hopefully your parents will still invite you

Algorithms and Datastructures

Structure

Links

Organisation

Daphne

Forum

Checkstyle

Unit Tests

Version management

Jenkins

Sorting

Minsort

Heapsort



Homepage:

- Exercise sheets
- Lectures
- Materials

Link to [Homepage](#)

Algorithms and Datastructures

Structure

Links

Organisation

Daphne

Forum

Checkstyle

Unit Tests

Version management

Jenkins

Sorting

Minsort

Heapsort

Lecture:

- Tuesday, 12:00 - 14:00, HS 00 006, Build. 082
- Recordings of the lecture will be uploaded to the webpage

Exercises:

- One exercise sheet per week
- Submission / Correction / Assistance online
- Tutorial: (if needed)
Wednesday, 13:00-14:00 - HS 00 006, Build. 082

Exam:

- Planned: Sa. 23th March 2019, 10:00-12:00, Build. 101,
Lec. theater 026 & 036

Exercises:

- 80% practical, 20% theoretical

Exercises:

- 80% practical, 20% theoretical
- We expect **everyone** to solve **every** exercise sheet

Exercises:

- 80% practical, 20% theoretical
- We expect **everyone** to solve **every** exercise sheet

Exam:

Exercises:

- 80% practical, 20% theoretical
- We expect **everyone** to solve **every** exercise sheet

Exam:

- 50% of all points from the exercise sheets are needed

Exercises:

- 80% practical, 20% theoretical
- We expect **everyone** to solve **every** exercise sheet

Exam:

- 50% of all points from the exercise sheets are needed
- Content of exam: whole lecture **and all exercises**



Exercises:

- Tutors: [Tim Maffenbeier](#), [Till Steinmann](#), [Tobias Faller](#)

Exercises:

- Tutors: [Tim Maffenbeier](#), [Till Steinmann](#), [Tobias Faller](#)
- Coordinators: [Michael Uhl](#), [Florian Eggenhofer](#) and [Björn Grüning](#)

Exercises:

- Tutors: [Tim Maffenbeier](#), [Till Steinmann](#), [Tobias Faller](#)
- Coordinators: [Michael Uhl](#), [Florian Eggenhofer](#) and [Björn Grüning](#)
- Deadline: ESE: [1 week](#), IEMS: [none](#)

Exercises:

- Post questions into the forum (link later)

Exercises:

- Post questions into the forum (link later)
- Submission via “commit” through `svn` and Daphne

Exercises:

- Post questions into the forum (link later)
- Submission via “commit” through `svn` and Daphne
- Feedback one week after deadline through “update” (`svn`)

Exercises:

- Post questions into the forum (link later)
- Submission via “commit” through `svn` and Daphne
- Feedback one week after deadline through “update” (`svn`)
- Unit test / checkstyle via Jenkins

Exercises - Points:

- Practical:
 - 60% functionality
 - 20% tests
 - 20% documentation, Checkstyle, etc.
 - Program is not running \Rightarrow 0 points

Exercises - Points:

- Practical:
 - 60% functionality
 - 20% tests
 - 20% documentation, Checkstyle, etc.
 - Program is not running \Rightarrow 0 points
- Theoretical (mathematical proof):
 - 40% general idea / approach
 - 60% clean / complete

Effort:

- 4 ECTS (ESE), 6 ECTS (IEMS)
- 120 / 180 working hours per semester
- 14 Lectures each 6h / 8h + exam
- 4h / 6h per exercise sheet (one per week)

Algorithms and Datastructures

Structure

Links

Organisation

Daphne

Forum

Checkstyle

Unit Tests

Version management

Jenkins

Sorting

Minsort

Heapsort

Daphne:

- Provides the following information:
 - Name / contact information of your tutor
 - Download of / info needed for exercise sheets
 - Collected points of all exercise sheets
 - Links to:
 - 1 Coding standards
 - 2 Build system
 - 3 The other systems
- Link: [Daphne](#)

Forum:

- Please don't hesitate to ask if something is unclear
- Ask in the forum and not separate. Others might also be interested in the answer
- The [tutors](#) or the [coordinators](#) will reply as soon as possible
- Link: [Forum](#)

Checkstyle / Linting (flake8):

- Installation: **python3** -m pip install flake8
- Check file: **python3** -m flake8 path/to/files/*.py
- Link: [flake8](#)

Why unit tests?

- 1 A non-trivial method without a unit test is probably wrong

Why unit tests?

- 1 A non-trivial method without a unit test is probably wrong
- 2 Simplifies debugging

Why unit tests?

- 1 A non-trivial method without a unit test is probably wrong
- 2 Simplifies debugging
- 3 We and you can automatically check correctness of code

Why unit tests?

- 1 A non-trivial method without a unit test is probably wrong
- 2 Simplifies debugging
- 3 We and you can automatically check correctness of code

What is a good unit test?

Why unit tests?

- 1 A non-trivial method without a unit test is probably wrong
- 2 Simplifies debugging
- 3 We and you can automatically check correctness of code

What is a good unit test?

- Unit test checks desired output for a given input

Why unit tests?

- 1 A non-trivial method without a unit test is probably wrong
- 2 Simplifies debugging
- 3 We and you can automatically check correctness of code

What is a good unit test?

- Unit test checks desired output for a given input
- At least one **typical** input

Why unit tests?

- 1 A non-trivial method without a unit test is probably wrong
- 2 Simplifies debugging
- 3 We and you can automatically check correctness of code

What is a good unit test?

- Unit test checks desired output for a given input
- At least one **typical** input
- At least one **critical** case
E.g. double occurrence of a value in sorting

Testing (doctest):

```
def subtract_one(n):  
    """Subtracts 1 from n
```

- Tests are contained in docstrings

```
>>> subtract_one(5)  
4
```

```
>>> subtract_one(3)  
2  
"""
```

```
return n-1
```

```
if __name__ == "__main__":  
    print("2 - 1 = %d" % subtract_one(2))
```

Testing (doctest):

```
def subtract_one(n):  
    """Subtracts 1 from n
```

```
>>> subtract_one(5)  
4
```

```
>>> subtract_one(3)  
2  
"""
```

```
return n-1
```

```
if __name__ == "__main__":  
    print("2 - 1 = %d" % subtract_one(2))
```

- Tests are contained in docstrings
- Module doctest runs them

Testing (doctest):

```
def subtract_one(n):  
    """Subtracts 1 from n
```

```
>>> subtract_one(5)  
4
```

```
>>> subtract_one(3)  
2  
"""
```

```
return n-1
```

```
if __name__ == "__main__":  
    print("2 - 1 = %d" % subtract_one(2))
```

- Tests are contained in docstrings
- Module doctest runs them
- Run check with:
python3 -m doctest
path/to/files/*.py -v

Version management (subversion):

- Keeps a history of code changes
- Initialize / update directory: **svn** checkout <URL>
- Add files / folders: **svn** add <file> --all
- Create snapshot: **svn** commit -m "<Your Message>"
Data is uploaded to Jenkins automatically
- Link: [Subversion](#)

Jenkins:

- Provides our build system
- You can check if your uploaded code runs
 - Especially whether all **unit test** pass
 - And if **checkstyle** (`flake8`) is statisfied
- Will be shown in the first exercise
- Link: [Jenkins](#)

Algorithms and Datastructures

Structure

Links

Organisation

Daphne

Forum

Checkstyle

Unit Tests

Version management

Jenkins

Sorting

Minsort

Heapsort

Problem:

- Input: n elements x_1, \dots, x_n
- Transitive operator “ $<$ ” which returns **true** if the left value is smaller than the right one
 - Transitivity: $x < y, y < z \rightarrow x < z$
- Output: x_1, \dots, x_n sorted with operator

Problem:

- Input: n elements x_1, \dots, x_n
- Transitive operator “ $<$ ” which returns **true** if the left value is smaller than the right one
 - Transitivity: $x < y, y < z \rightarrow x < z$
- Output: x_1, \dots, x_n sorted with operator

Example

Input: 14, 4, 32, 19, 8, 44, 65

Output:

Why do we need sorting?

- Nearly **every** program needs a sorting algorithm
- **Examples:**
 - Index of a search engine
 - Listing filesystem in explorer / finder
 - (Music) library
 - Highscore list

Algorithms and Datastructures

Structure

Links

Organisation

Daphne

Forum

Checkstyle

Unit Tests

Version management

Jenkins

Sorting

Minsort

Heapsort

Informal description:

- Find the minimum and switch the value with the **first** position
- Find the minimum and switch the value with the **second** position
- ...



Figure: Minsort

Informal description:

- Find the minimum and switch the value with the **first** position
- Find the minimum and switch the value with the **second** position
- ...



Figure: Minsort

Informal description:

- Find the minimum and switch the value with the **first** position
- Find the minimum and switch the value with the **second** position
- ...



Figure: Minsort

Informal description:

- Find the minimum and switch the value with the **first** position
- Find the minimum and switch the value with the **second** position
- ...



Figure: Minsort

Informal description:

- Find the minimum and switch the value with the **first** position
- Find the minimum and switch the value with the **second** position
- ...



Figure: Minsort

Informal description:

- Find the minimum and switch the value with the **first** position
- Find the minimum and switch the value with the **second** position
- ...



Figure: Minsort

Informal description:

- Find the minimum and switch the value with the **first** position
- Find the minimum and switch the value with the **second** position
- ...



Figure: Minsort

Informal description:

- Find the minimum and switch the value with the **first** position
- Find the minimum and switch the value with the **second** position
- ...



Figure: Minsort

Informal description:

- Find the minimum and switch the value with the **first** position
- Find the minimum and switch the value with the **second** position
- ...



Figure: Minsort

Informal description:

- Find the minimum and switch the value with the **first** position
- Find the minimum and switch the value with the **second** position
- ...



Figure: Minsort

Informal description:

- Find the minimum and switch the value with the **first** position
- Find the minimum and switch the value with the **second** position
- ...



Figure: Minsort

Minsort in Python:

```
def minsort(lst):  
    for i in range(0, len(lst)-1):  
        minimum = i  
  
        for j in range(i+1, len(lst)):  
            if lst[j] < lst[minimum]:  
                minimum = j  
  
        if minimum != i:  
            lst[i], lst[minimum] = \  
                lst[minimum], lst[i]  
  
    return lst
```

How long does our program run?

- We test it for different input sizes

How long does our program run?

Table: Runtime for *Minsort*

- We test it for different input sizes

n	Runtime / ms
2×10^3	5.24
4×10^3	16.92
6×10^3	39.11
8×10^3	67.80
10×10^3	105.50
12×10^3	150.38
14×10^3	204.00
16×10^3	265.98
18×10^3	334.94

How long does our program run?

Table: Runtime for *Minsort*

- We test it for different input sizes

- **Observation:**

It is going to be “disproportionately” slower the more numbers are being sorted

n	Runtime / ms
2×10^3	5.24
4×10^3	16.92
6×10^3	39.11
8×10^3	67.80
10×10^3	105.50
12×10^3	150.38
14×10^3	204.00
16×10^3	265.98
18×10^3	334.94

How long does our program run?

- We test it for different input sizes
- **Observation:**
It is going to be “disproportionately” slower the more numbers are being sorted



Figure: Runtime of *Minsort*

Runtime analysis:

- *Minsort* runtime depicted in a diagram
 - That is what you should do in the first exercise sheet

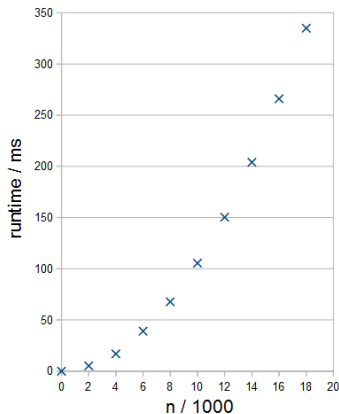


Figure: Runtime of *Minsort*

Runtime analysis:

- *Minsort* runtime depicted in a diagram
 - That is what you should do in the first exercise sheet
- **We observe:**
 - The runtime **grows faster than linear**
 - With double the input size we need four times the time

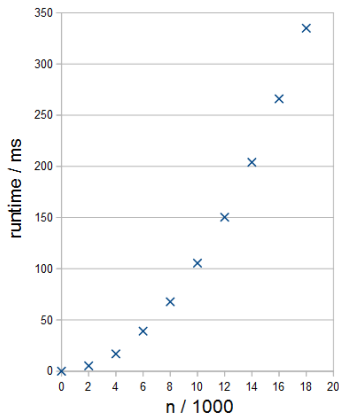


Figure: Runtime of *Minsort*

Runtime analysis:

- *Minsort* runtime depicted in a diagram
 - That is what you should do in the first exercise sheet
- **We observe:**
 - The runtime **grows faster than linear**
 - With double the input size we need four times the time



Figure: Runtime of *Minsort*

Algorithms and Datastructures

Structure

Links

Organisation

Daphne

Forum

Checkstyle

Unit Tests

Version management

Jenkins

Sorting

Minsort

Heapsort

Heapsort:

- The principle stays the same
- Better structure for finding the smallest element quicker

Heapsort:

- The principle stays the same
- Better structure for finding the smallest element quicker

Binary heap:

- Preferably a complete binary tree
- **Heap property:** Each child is **smaller** (larger) than the parent element

Min heap:

- **Heap property:** Each child is **smaller** (larger) than the parent element

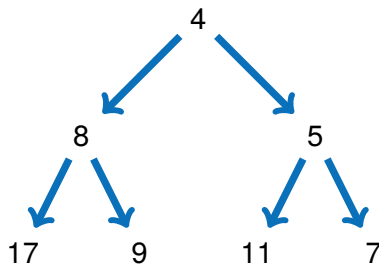


Figure: Valid min heap

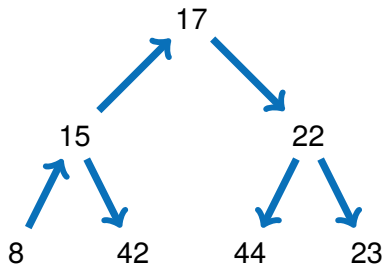


Figure: Invalid min heap

Min heap:

- **Heap property:** Each child is **smaller** (larger) than the parent element
- A valid heap fulfills the property at each node



Figure: Valid min heap



Figure: Invalid min heap

How to save the heap?

- We number all nodes from top to bottom and left to right starting at 0
 - The children of node i are $2i+1$ and $2i+2$
 - The parent node of node i is $\text{floor}\left(\frac{i-1}{2}\right)$



Table: Elements can be stored in array



How to save the heap?

- We number all nodes from top to bottom and left to right starting at 0
 - The children of node i are $2i+1$ and $2i+2$
 - The parent node of node i is $\text{floor}\left(\frac{i-1}{2}\right)$



Table: Elements can be stored in array

0						
4						

How to save the heap?

- We number all nodes from top to bottom and left to right starting at 0
 - The children of node i are $2i+1$ and $2i+2$
 - The parent node of node i is $\text{floor}\left(\frac{i-1}{2}\right)$



Table: Elements can be stored in array

0	1					
4	8					

How to save the heap?

- We number all nodes from top to bottom and left to right starting at 0
 - The children of node i are $2i+1$ and $2i+2$
 - The parent node of node i is $\text{floor}\left(\frac{i-1}{2}\right)$

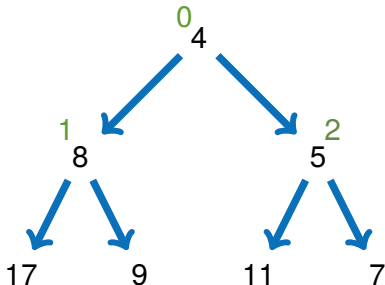


Table: Elements can be stored in array

0	1	2				
4	8	5				

How to save the heap?

- We number all nodes from top to bottom and left to right starting at 0
 - The children of node i are $2i+1$ and $2i+2$
 - The parent node of node i is $\text{floor}\left(\frac{i-1}{2}\right)$



Table: Elements can be stored in array

0	1	2	3			
4	8	5	17			

How to save the heap?

- We number all nodes from top to bottom and left to right starting at 0
 - The children of node i are $2i+1$ and $2i+2$
 - The parent node of node i is $\text{floor}\left(\frac{i-1}{2}\right)$



Table: Elements can be stored in array

0	1	2	3	4		
4	8	5	17	9		

How to save the heap?

- We number all nodes from top to bottom and left to right starting at 0
 - The children of node i are $2i+1$ and $2i+2$
 - The parent node of node i is $\text{floor}\left(\frac{i-1}{2}\right)$



Table: Elements can be stored in array

0	1	2	3	4	5	
4	8	5	17	9	11	

How to save the heap?

- We number all nodes from top to bottom and left to right starting at 0
 - The children of node i are $2i+1$ and $2i+2$
 - The parent node of node i is $\text{floor}\left(\frac{i-1}{2}\right)$



Table: Elements can be stored in array

0	1	2	3	4	5	6
4	8	5	17	9	11	7

Repairing after taking the smallest element: `heap.pop()`

Repairing after taking the smallest element: `heap.pop()`

- Remove the smallest element (root node)

Repairing after taking the smallest element: `heap.pop()`

- Remove the smallest element (root node)
- Replace the root with the last node

Repairing after taking the smallest element: `heap.pop()`

- Remove the smallest element (root node)
- Replace the root with the last node
- **Sift** the new root node down until the **heap property** is satisfied

Repairing after taking the smallest element: `heap.pop()`

- Remove the smallest element (root node)
- Replace the root with the last node
- **Sift** the new root node down until the **heap property** is satisfied

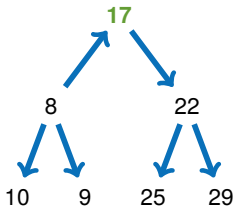


Figure: Repairing a min heap

Repairing after taking the smallest element: `heap.pop()`

- Remove the smallest element (root node)
- Replace the root with the last node
- Sift the new root node down until the **heap property** is satisfied



Figure: Repairing a min heap

Repairing after taking the smallest element: `heap.pop()`

- Remove the smallest element (root node)
- Replace the root with the last node
- Sift the new root node down until the **heap property** is satisfied



Figure: Repairing a min heap

Repairing after taking the smallest element: `heap.pop()`

- Remove the smallest element (root node)
- Replace the root with the last node
- Sift the new root node down until the **heap property** is satisfied



Figure: Repairing a min heap

Repairing after taking the smallest element: `heap.pop()`

- Remove the smallest element (root node)
- Replace the root with the last node
- Sift the new root node down until the **heap property** is satisfied



Figure: Repairing a min heap

Heapsort:

- Organize the n elements as heap
- While the heap still contains elements
 - Take the smallest element
 - Move the last node to the root
 - Repair the heap as described

Heapsort:

- Organize the n elements as heap
- While the heap still contains elements
 - Take the smallest element
 - Move the last node to the root
 - Repair the heap as described
- Output: 4



Figure: One iteration of Heapsort

Heapsort:

- Organize the n elements as heap
- While the heap still contains elements
 - Take the smallest element
 - Move the last node to the root
 - Repair the heap as described
- Output: 4

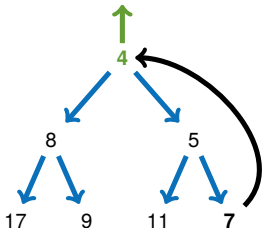


Figure: One iteration of Heapsort

Heapsort:

- Organize the n elements as heap
- While the heap still contains elements
 - Take the smallest element
 - Move the last node to the root
 - Repair the heap as described
- Output: 4



Figure: One iteration of Heapsort

Heapsort:

- Organize the n elements as heap
- While the heap still contains elements
 - Take the smallest element
 - Move the last node to the root
 - Repair the heap as described
- Output: 4



Figure: One iteration of Heapsort

Heapsort:

- Organize the n elements as heap
- While the heap still contains elements
 - Take the smallest element
 - Move the last node to the root
 - Repair the heap as described
- Output: 4, 5, ...



Figure: One iteration of Heapsort

Heapsort:

- Organize the n elements as heap
- While the heap still contains elements
 - Take the smallest element
 - Move the last node to the root
 - Repair the heap as described
- Output: 4, 5, ...

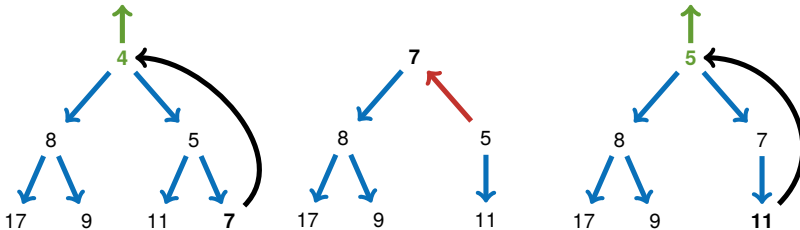


Figure: One iteration of Heapsort

Creating a heap:

- This operation is called **heapify**

Creating a heap:

- This operation is called **heapify**
- The n elements are already stored in an array

Creating a heap:

- This operation is called **heapify**
- The n elements are already stored in an array
- Interpret the array as binary heap where the **heap property** is not yet satisfied

Creating a heap:

- This operation is called **heapify**
- The n elements are already stored in an array
- Interpret the array as binary heap where the **heap property** is not yet satisfied
- We repair the heap from bottom up (in layers) with **sift**

Heapsort - Algorithm 7 / 10

Table: Input in array

0	1	2	3	4	5	6
11	7	8	3	2	5	4



Figure: Heapify lower layer

Heapsort - Algorithm 7 / 10

Table: Input in array

0	1	2	3	4	5	6
11	7	8	3	2	5	4



Figure: Heapify lower layer

Heapsort - Algorithm 8 / 10



Figure: Heapify upper layer

Heapsort - Algorithm 8 / 10



Figure: Heapify upper layer



Figure: Resulting heap

Finding the minimum is intuitive:

- **Minsort:** Iterate through all non-sorted elements
- **Heapsort:** Finding the minimum is trivial (concept)

Just take the root of the heap

Finding the minimum is intuitive:

- **Minsort:** Iterate through all non-sorted elements
- **Heapsort:** Finding the minimum is trivial (concept)

Just take the root of the heap

Removing the minimum in Heapsort:

- Repair the heap and restore the **heap property**
 - We don't have to repair the whole heap
- More of this in the next lecture

■ Course literature

[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.

Springer, Berlin, 2008.

[https://people.mpi-inf.mpg.de/~mehlhorn/
ftp/Mehlhorn-Sanders-Toolbox.pdf](https://people.mpi-inf.mpg.de/~mehlhorn/ftp/Mehlhorn-Sanders-Toolbox.pdf).

■ Sorting

[Wika] [Wikipedia - Heapsort](https://en.wikipedia.org/wiki/Heapsort)

<https://en.wikipedia.org/wiki/Heapsort>

[Wikb] [Wikipedia - Selectionsort](https://de.wikipedia.org/wiki/Selectionsort)

<https://de.wikipedia.org/wiki/Selectionsort>

■ Subversion

[Apa] [Apache Subversion](https://subversion.apache.org/)

`https://subversion.apache.org/`