

# Algorithmns and Datastructures

## Static Arrays, Dynamic Arrays, Amortized Analysis

Albert-Ludwigs-Universität Freiburg



UNI  
FREIBURG

Prof. Dr. Rolf Backofen

Bioinformatics Group / Department of Computer Science  
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- Static arrays exist in nearly every programming language
- They are initialized with a fixed size  $n$
- **Problem:** The needed size is not always clear at compile time

Table: Static array with size  $n = 5$

Index	0	1	2	3	4
Value	"a"	"b"	"c"	"d"	"e"

### Python:

- We have dynamic sized lists
- Python does automatic resizing when needed

```
# Creates a list of "0"s with init. size 10
numbers = [0] * 10
```

```
# Prints number at index 7 ("0")
print("%d" % numbers[7])
```

```
# Saves number 42 at index 8
numbers[8] = 42
```

```
# Prints the number at index 8 ("42")
print("%d" % numbers[8])
```

- The name “static array” has nothing to do with the keyword **static** from Java / C++
- Nor is the array allocated before the program starts
- The **size** of the array is static and can not be changed after creation
- The name “fixed-size array” would be more appropriate

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### Dynamic arrays:

- The array is created with an initial size
- The size can be dynamically modified
- **Problem:** We need a dynamic structure to store the data

### Python:

```
greetings = ["Good morning", "ohai"]

greetings.append("Guten morgen")
greetings.append("bonjour")

# Prints text at index 2 ("Guten morgen")
print("%s" % greetings[2])

# Removes all elements
greetings.clear();
```

- We store the data in a fixed-size array with the needed size
- **Append:**
  - Create fixed-size array with the needed size
  - Copy elements from the old to the new array
- **Remove:**
  - Create fixed-size array with the needed size
  - Copy elements from the old to the new array

First implementation:

- We resize the array before each append
- We choose the size exactly as needed

```
class DynamicArray:

    def __init__(self):
        self.size = 0
        self.elements = []

    def capacity(self):
        return len(self.elements)

    ...
```

```
class DynamicArray:
    ...

    def append(self, item):
        newElements = [0] * (self.size + 1)

        for i in range(0, self.size):
            newElements[i] = self.elements[i]

        self.elements = newElements

        newElements[self.size] = item
        self.size += 1
```

- Why is the runtime quadratic?

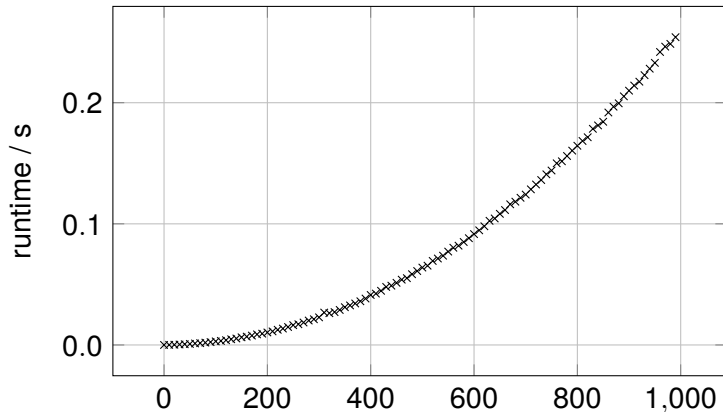



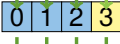

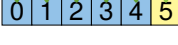


Figure: Runtime of *DynamicArray*

### Runtime:

	$O(1)$	write 1 element
	$O(1 + 1)$	write 1 element, copy 1 element
	$O(1 + 2)$	write 1 element, copy 2 elements
	$O(1 + 3)$	write 1 element, copy 3 elements
	$O(1 + 4)$	write 1 element, copy 4 elements
	$O(1 + 5)$	write 1 element, copy 5 elements
...	...	...



### Analysis:

- Let  $T(n)$  be the runtime of  $n$  sequential append operations
- Let  $T_i$  be the runtime of each  $i$ -th operation
  - Then  $T_i = A \cdot i$  for a constant  $A$
  - We have to copy  $i - 1$  element

$$\begin{aligned} T(n) &= \sum_{i=1}^n T_i = \sum_{i=1}^n (A \cdot i) = A \cdot \sum_{i=1}^n i = A \cdot \frac{n^2 + n}{2} \\ &= O(n^2) \end{aligned}$$

### Idea:

- Better resize strategy
- We allocate more space than needed
- We over-allocate a constant amount of elements
  - Amount:  $C = 3$  or  $C = 100$

```
def append(self, item):  
    if self.size >= len(self.elements):  
        newElements = [0] * (self.size + 100)  
  
        for i in range(0, self.size - 1):  
            newElements[i] = self.elements[i]  
  
        self.elements = newElements  
  
    self.elements[self.size] = item  
    self.size += 1
```

- Why is the runtime still quadratic?

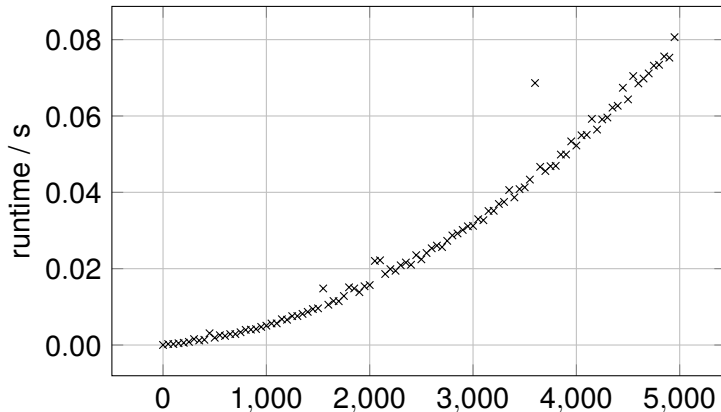


Figure: Runtime of *DynamicArray*

### Runtime for $C = 3$ :

	$O(1)$	write 1 element
	$O(1)$	write 1 element
	$O(1)$	write 1 element
	$O(1 + 3)$	write 1 element, copy 3 elements
	$O(1)$	write 1 element
	$O(1)$	write 1 element
	$O(1 + 6)$	write 1 element, copy 6 elements
...	...	...

### Analysis:

- Most of the append operations now just cost  $O(1)$
- Every  $C$  steps the costs for copying are added:  
 $C, 2 \cdot C, 3 \cdot C, \dots$  this means:

$$\begin{aligned}T(n) &= \sum_{i=1}^n A \cdot 1 + \sum_{i=1}^{n/C} A \cdot i \cdot C \\&= A \cdot n + A \cdot C \cdot \sum_{i=1}^{n/C} i \\&= A \cdot n + A \cdot C \cdot \frac{\frac{n^2}{C^2} + \frac{n}{C}}{2} \\&= A \cdot n + \frac{A}{2 \cdot C} \cdot n^2 + \frac{A}{2} \cdot n = O(n^2)\end{aligned}$$

- The factor of  $n^2$  is getting smaller

### Idea:

- Double the size of the array

```
def append(self, item):  
    if self.size >= len(self.elements):  
        newElements = [0] \  
            * max(1, 2 * self.size)  
  
        for i in range(0, self.size):  
            newElements[i] = self.elements[i]  
  
        self.elements = newElements  
  
    self.elements[self.size] = item  
    self.size += 1
```

- Now the runtime is linear with some bumps. Why?

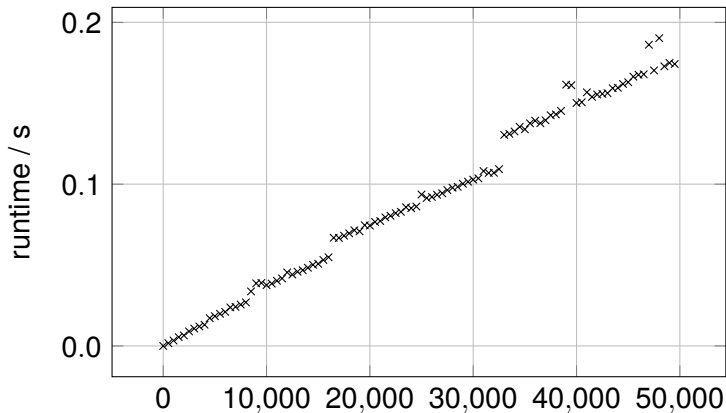



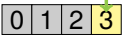

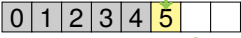
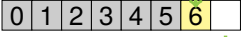
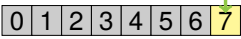



Figure: Runtime of *DynamicArray*



### Runtime for $C = 2$ (Double the size):

	$O(1)$	write 1
	$O(1 + 1)$	write 1, copy 1 element
	$O(1 + 2)$	write 1, copy 2 elements
	$O(1)$	write 1
	$O(1 + 4)$	write 1, copy 4 elements
	$O(1)$	write 1
	$O(1)$	write 1
	$O(1)$	write 1
 ...	$O(1 + 8)$	write 1, copy 8 elements
...	...	...

### Analysis:

- Now all appends cost  $O(1)$
- Every  $2^i$  steps we have to add the cost  $A \cdot 2^i$  (for  $i = 0, 1, 2, \dots, k$  with  $k = \text{floor}(\log_2(n-1))$ )
- In total that accounts to:

$$\begin{aligned} T(n) &= n \cdot A + A \cdot \sum_{i=0}^k 2^i = n \cdot A + A(2^{k+1} - 1) \\ &\leq n \cdot A + A \cdot 2^{(k+1)} \\ &= n \cdot A + 2 \cdot A \cdot 2^{(k)} \\ &\leq n \cdot A + 2 \cdot A \cdot n \\ &= 3 \cdot A \cdot n \\ &= O(n) \end{aligned}$$

### How do we shrink the array?

- Like for the extension of the array, we can shrink the array by half, if it is half-full
- If we *append* directly after *shrinking* we have to extend the array again
  - We only shrink the array to 75%

### Analysis:

- **Difficult:** We have a random number of *append* / *remove* operations
- We can not exactly predict when resizing is happening

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Figure: Static array with capacity  $c_i$

### Notation:

- We have  $n$  instructions  $O = \{O_1, \dots, O_n\}$
- The **size** after operation  $i$  is  $s_i$ , with  $s_0 := 0$
- The **capacity** after operation  $i$  is  $c_i$ , with  $c_0 := 0$
- The **cost** of operation  $i$  is  $\text{cost}(O_i)$  (previously named  $T_i$ )

Reallocation:  $\text{cost}(O_i) \leq A \cdot s_i$ ,

Insert / Delete (Update):  $\text{cost}(O_i) \leq A$ ,

# Dynamic Arrays

## Amortized Analysis - Example



Operation			Size $s_i$	Capacity $c_i$	Costs $\text{cost}(O_i)$
$O_1$	append	realloc.	$s_1 = 1$	$c_1 = 3$	$A \cdot s_1$
$O_2$	append		$s_2 = 2$	$c_2 = c_1$	$A$
$O_3$	append		$s_3 = 3$	$c_3 = c_1$	$A$
$O_4$	remove		$s_4 = 2$	$c_4 = c_1$	$A$
$O_5$	remove	realloc.	$s_5 = 1$	$c_5 = \frac{2}{3}c_1 = 2$	$A \cdot s_5$
$O_6$	append		$s_6 = 2$	$c_6 = c_5$	$A$
$O_7$	remove		$s_7 = 1$	$c_7 = c_5$	$A$
$O_8$	append		$s_8 = 2$	$c_8 = c_5$	$A$
$O_9$	append	realloc.	$s_9 = 3$	$c_9 = 3 \cdot c_5 = 6$	$A \cdot s_9$
...	...		...	...	...
$O_n$	append		$s_n$	$c_n$	$A$

### Implementation:

- If  $O_i$  is an *append* operation and  $s_{i-1} = c_{i-1}$ :
  - $\Rightarrow$  Resize array to  $c_i = \left\lfloor \frac{3}{2} s_i \right\rfloor$
  - $\Rightarrow \text{cost}(O_i) = A \cdot s_i$

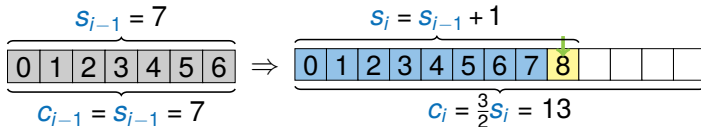


Figure: *Append* operation with reallocation



### Implementation:

- If  $O_i$  is an *remove* operation and  $s_{i-1} \leq \frac{1}{3}c_{i-1}$ :
  - $\Rightarrow$  Resize array to  $c_i = \left\lfloor \frac{3}{2}s_i \right\rfloor$
  - $\Rightarrow \text{cost}(O_i) = A \cdot s_i$

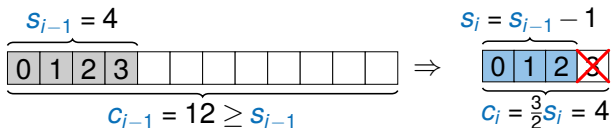


Figure: Remove operation with reallocation

### Idea for prove:

- Expansive are only those operations, where reallocations are necessary.
- If we just reallocated, it takes some time until the next reallocation is required.
- After a costly *reallocation* of size  $X$  we have at least  $X$  operations of runtime  $O(1)$
- Total cost of  $n$  operations is maximally  $2 \cdot n$

Table: Dynamic Array with  $C_{\text{ext}} = \frac{3}{2}$

Operation (append)		Size $s_i$	Capacity $c_i$	Costs $\text{cost}(O_i)$	
$O_1$	realloc.	$s_1 = 1$	$c_1 = 4$	$C_1 \cdot s_1$	$\left. \begin{array}{c} \\ \\ \\ \end{array} \right\} \text{distance}$ $4 \geq \left\lfloor \frac{s_1}{2} \right\rfloor$
$O_2$		$s_2 = 2$	$c_2 = c_1$	$C_2$	
$O_3$		$s_3 = 3$	$c_3 = c_1$	$C_2$	
$O_4$		$s_4 = 4$	$c_4 = c_1$	$C_2$	
$O_5$	realloc.	$s_5 = 5$	$c_5 = \frac{3}{2}s_5 = 7$	$C_1 \cdot s_5$	$\left. \begin{array}{c} \\ \\ \end{array} \right\} \text{distance}$ $3 \geq \left\lfloor \frac{s_5}{2} \right\rfloor$
$O_6$		$s_6 = 6$	$c_6 = c_5$	$C_2$	
$O_7$		$s_7 = 7$	$c_7 = c_5$	$C_2$	
$O_8$	realloc.	$s_8 = 8$	$c_8 = \frac{3}{2}s_8 = 12$	$C_1 \cdot s_8$	
...	...	...	...	...	

### To show:

- **Lemma:** If a *reallocation* occurs at  $O_i$  the nearest *reallocation* is at  $O_j$  with  $j - i > \frac{s_i}{2}$
- **Corollary:**  $\text{cost}(O_1) + \dots + \text{cost}(O_n) \leq 4A \cdot n$

Table: Case 1:  $\frac{1}{2}s_j$  appends

Array

Costs

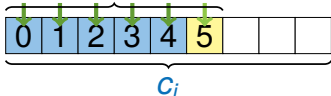
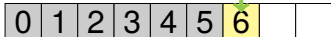

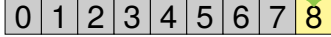

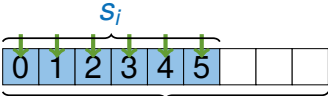



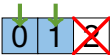
$O_i$ : 	reallocation $A \cdot s_j$ (linear)
$O_{i+1}$ : 	$A$ (constant)
$O_{i+2}$ : 	$A$ (constant)
$O_{i+3}$ : 	$A$ (constant)
$O_j$ : 	reallocation $A \cdot s_j$ (earliest reallocation)

Table: Case 2:  $\frac{1}{2}s_j$  removes

Array	Costs
$O_i$ : 	reallocation $A \cdot s_j$ (linear)
$O_{i+1}$ : 	$A$ (constant)
$O_{i+2}$ : 	$A$ (constant)
$O_{i+3}$ : 	$C_2$ (constant)
$O_j$ : 	reallocation $A \cdot s_j$ (earliest reallocation)

$\left. \begin{array}{l} A \text{ (constant)} \\ A \text{ (constant)} \\ C_2 \text{ (constant)} \end{array} \right\} \frac{s_j}{2} \text{ times}$

### Proof of lemma:

- If a reallocation happens at  $O_i$  and then again at  $O_j$ , then  $j - i \geq s_i/2$
- After operation  $O_i$  the capacity is

$$c_i = \text{floor} \left( \frac{3}{2} \cdot s_i \right)$$

- Lets consider a operation  $O_k$  to  $O_i$  with  $k - i \leq \frac{s_i}{2}$ :
  - Case 1: Since the *reallocation* we have inserted at maximum  $\text{floor} \left( \frac{1}{2} \cdot s_i \right)$  elements

$$s_k \leq s_i + \left\lfloor \frac{s_i}{2} \right\rfloor = \left\lfloor \frac{3}{2} s_i \right\rfloor = c_i \quad \text{no reallocation needed}$$

### Proof of lemma - continued:

- Case 2: Since the *reallocation* we have removed at maximum  $\left\lfloor \frac{1}{2} \cdot s_i \right\rfloor$  elements

$$s_k \geq s_i - \left\lfloor \frac{s_i}{2} \right\rfloor = \left\lceil \frac{1}{2} s_i \right\rceil$$

no reallocation needed

$$\Rightarrow 3 \cdot s_k \geq \left\lceil \frac{3}{2} s_i \right\rceil \geq \left\lfloor \frac{3}{2} s_i \right\rfloor = c_i$$



### Corollary:

$$\text{cost}(O_1) + \dots + \text{cost}(O_n) \leq 4A \cdot n$$

- Let the *reallocations* be at operations  $\text{cost}(O_{i_1}), \dots, \text{cost}(O_{i_\ell})$
- The **cost** of all *reallocations* are  $A \cdot (s_{i_1} + \dots + s_{i_\ell})$
- With the lemma we know:

$$i_2 - i_1 > \frac{s_{i_1}}{2}, \quad i_3 - i_2 > \frac{s_{i_2}}{2}, \quad \dots, \quad i_\ell - i_{\ell-1} > \frac{s_{i_{\ell-1}}}{2}$$

- We can conclude that:

$$i_2 - i_1 > \frac{s_{i_1}}{2} \quad \Rightarrow \quad s_{i_1} < 2(i_2 - i_1)$$

$$i_3 - i_2 > \frac{s_{i_2}}{2} \quad \Rightarrow \quad s_{i_2} < 2(i_3 - i_2)$$

$$\vdots$$

$$i_\ell - i_{\ell-1} > \frac{s_{i_{\ell-1}}}{2} \quad \Rightarrow \quad s_{i_{\ell-1}} < 2(i_\ell - i_{\ell-1})$$

$$s_{i_\ell} \leq n \quad (\text{trivial})$$

- The **costs** of all reallocations are:

$$\begin{aligned}\text{cost}(\text{realloc.}) &= A \cdot (s_{i_1} + \dots + s_{i_\ell}) \\ &< A \cdot (2(i_2 - i_1) + 2(i_3 - i_2) + \dots + 2(i_\ell - i_{\ell-1}) + n) \\ &= A \cdot (2(i_\ell - i_1) + n) \\ &\leq A \cdot (2n + n) = 3A \cdot n\end{aligned}$$

- Additionally we have to consider the respective constant costs for a normal append or remove:  $\leq A \cdot n$  therefore in total  $\leq 4 \cdot A \cdot n$

# Dynamic Arrays

## Amortized Analysis - Alternate Proof of Corollary

Table: Case 1:  $\frac{1}{2}s_j$  appends

Array

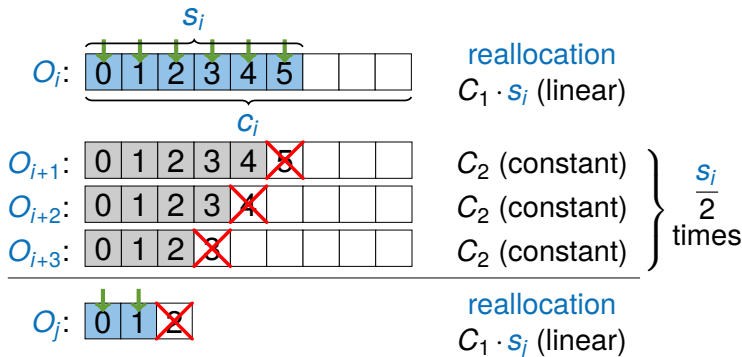
Costs

$O_i$ :		reallocation $C_1 \cdot s_j$ (linear)
$O_{i+1}$ :		$C_2$ (constant)
$O_{i+2}$ :		$C_2$ (constant)
$O_{i+3}$ :		$C_2$ (constant)
$O_j$ :		reallocation $C_1 \cdot s_j$ (earliest reallocation)

- Total costs of  $A \cdot \frac{3}{2} \cdot s_i$  for  $\frac{s_i}{2} + 1$  operations
- Cost per operation:

$$\frac{\frac{3}{2}A \cdot s_i}{\frac{1}{2}s_i + 1} \leq \frac{\frac{3}{2}A \cdot s_i}{\frac{1}{2}s_i} = 3 \cdot A = \text{const.}$$

- Runtime analysis for local worst-case sequence
- | Array | Costs |
|-------|-------|
|-------|-------|



- Same total cost as previous slide

### Bank account paradigm:

- **Idea:** “Save first, spend later”
- For each operation we deposit some coins on an “bank account”  
We still have constant costs.
- When we have a linear (reallocation) operation we pay with the coins from our “bank account”
- For the Duplication strategy we have to pay two coins per operation.

# Dynamic Arrays

## Amortized Analysis - Yet Another Proof of Corollary



### Double the size:

	$\text{cost}(O_i)$	deposit / withdraw	account value
	$O(1)$	+2	2
	$O(1 + 1)$	+2 -1	3
	$O(1 + 2)$	+2 -2	3
	$O(1)$	+2	5
	$O(1 + 4)$	+2 -4	3
	$O(1)$	+2	5
	$O(1)$	+2	7
	$\%_0(1)$	+2	9
...	$O(1 + 8)$	+2 -8	3
...	...	...	...



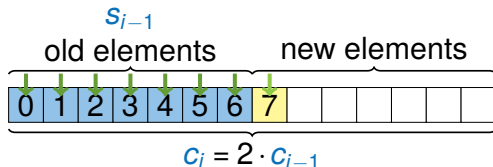


Figure: Array after realloc. (insert) operation

### Why do we need to deposit 2 coins per operation?

- 1 Each newly inserted element has to be copied later (first coin)
- 2 Due to the factor of two there is for each new element also an old one in the array that also has to be copied (second coin)

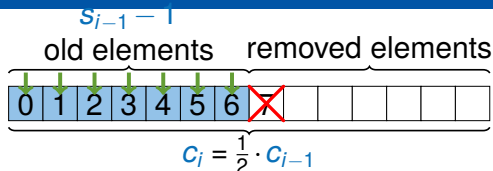


Figure: Array after realloc. (remove) operation

### Shrinking strategy: if array 1/4 full shrink by half

- How many coins do we need per *remove* operation?
- **Worst case:** The previous remove operation triggered a *reallocation*
  - ⇒ Array is half full
- The nearest *reallocation* is after removing  $\frac{1}{4}C_i$  elements
- We have to copy  $\frac{1}{4}C_i$  elements
  - ⇒ 1 coin per operation is enough

## ■ General

- [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>.

## ■ Amortized Analysis

[Wik] [Amortized analysis](https://en.wikipedia.org/wiki/Amortized_analysis)

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`//en.wikipedia.org/wiki/Amortized_analysis`