# Data Structures Fundamentals: Dynamic Arrays and Amortized Analysis

Neil Rhodes

Department of Computer Science and Engineering
University of California, San Diego

Data Structures Fundamentals

# Outline

Problem: static arrays are static!

```
int my_array[100];
```

Problem: static arrays are static!

```
int my_array[100];
```

Semi-solution: dynamically-allocated arrays:

```
int *my_array = new int[size];
```

Problem: might not know max size when allocating an array

Problem: might not know max size when allocating an array

> *All problems in computer science can be solved by another level of indirection.*

Problem: might not know max size when allocating an array

> *All problems in computer science can be solved by another level of indirection.*

Solution: *dynamic arrays* (also known as *resizable arrays*)

Idea: store a pointer to a dynamically allocated array, and replace it with a newly-allocated array as needed.

## Definition

### Dynamic Array:

Abstract data type with the following operations (at a minimum):

---

*must be constant time

## Definition

### Dynamic Array:

Abstract data type with the following operations (at a minimum):

- `Get`($i$): returns element at location $i$*

*must be constant time

## Definition

### Dynamic Array:

Abstract data type with the following operations (at a minimum):

- `Get`($i$): returns element at location $i$*
- `Set`($i, val$): Sets element $i$ to $val$*

---

*must be constant time

## Definition

### Dynamic Array:

Abstract data type with the following operations (at a minimum):

- `Get`($i$): returns element at location $i$*
- `Set`($i, val$): Sets element $i$ to $val$*
- PushBack($val$): Adds $val$ to the end

*must be constant time

## Definition

### Dynamic Array:

Abstract data type with the following operations (at a minimum):

- `Get`($i$): returns element at location $i$*
- `Set`($i, val$): Sets element $i$ to $val$*
- PushBack($val$): Adds $val$ to the end
- `Remove`($i$): Removes element at location $i$

*must be constant time

## Definition

### Dynamic Array:

Abstract data type with the following operations (at a minimum):

- `Get`($i$): returns element at location $i$*
- `Set`($i$, *val*): Sets element $i$ to *val**
- PushBack(*val*): Adds *val* to the end
- `Remove`($i$): Removes element at location $i$
- `Size`(): the number of elements

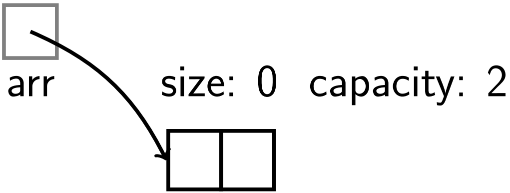
*must be constant time

# Implementation

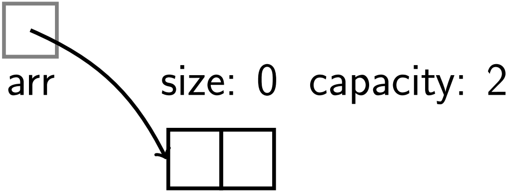
Store:

- `arr`: dynamically-allocated array
- `capacity`: size of the dynamically-allocated array
- `size`: number of elements currently in the array

# Dynamic Array Resizing

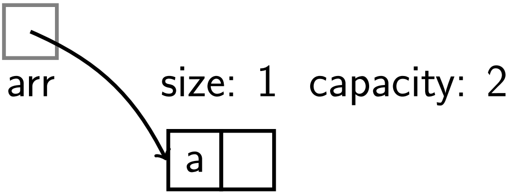


# Dynamic Array Resizing



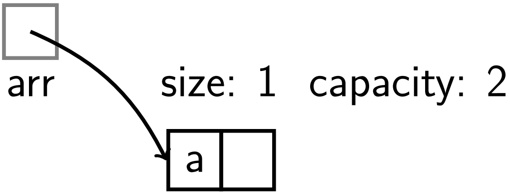

`PushBack(a)`

# Dynamic Array Resizing

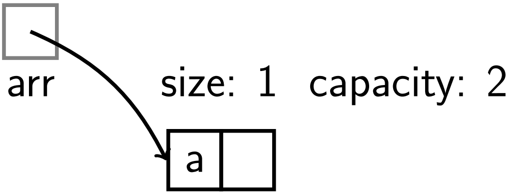



`PushBack(a)`

# Dynamic Array Resizing

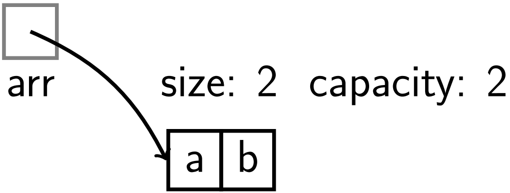


# Dynamic Array Resizing



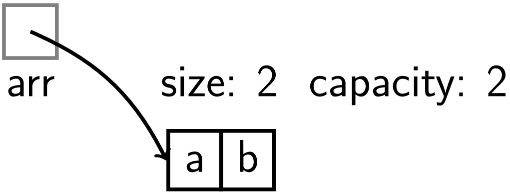

`PushBack(b)`

# Dynamic Array Resizing

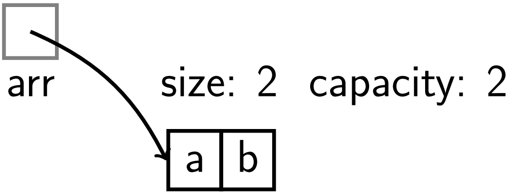



`PushBack(b)`

# Dynamic Array Resizing

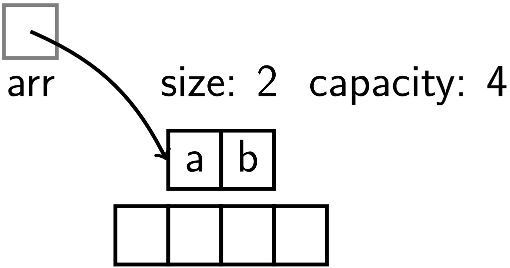


# Dynamic Array Resizing



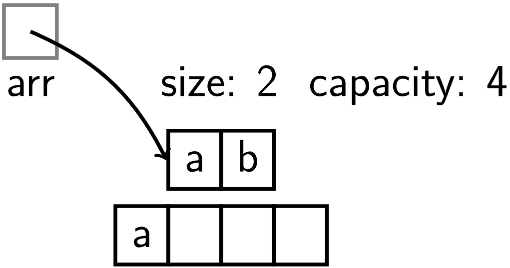

`PushBack(c)`

# Dynamic Array Resizing



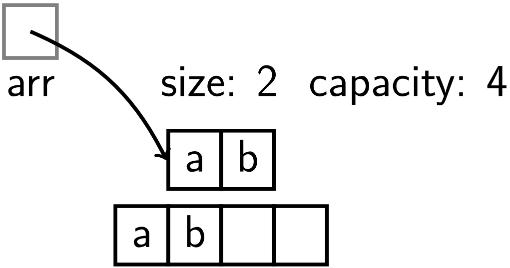

`PushBack(c)`

# Dynamic Array Resizing



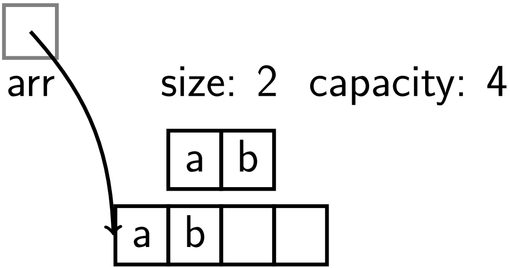

`PushBack(c)`

# Dynamic Array Resizing



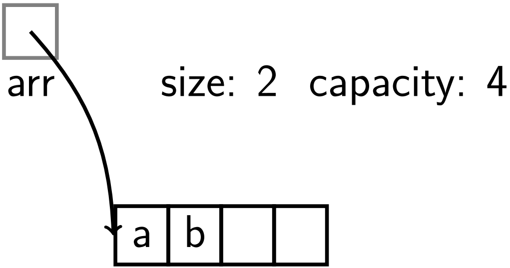

`PushBack(c)`

# Dynamic Array Resizing



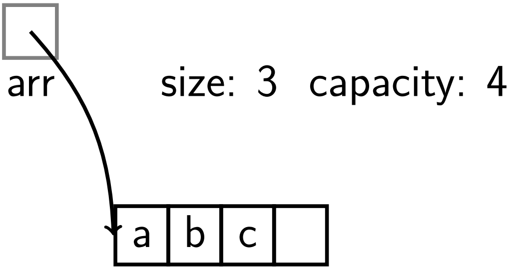

`PushBack(c)`

# Dynamic Array Resizing



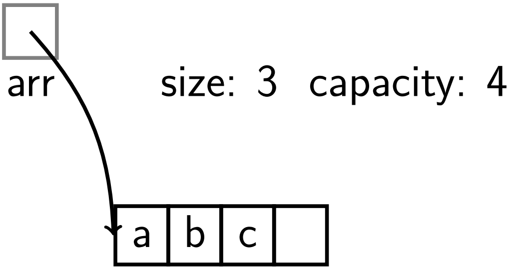

`PushBack(c)`

# Dynamic Array Resizing

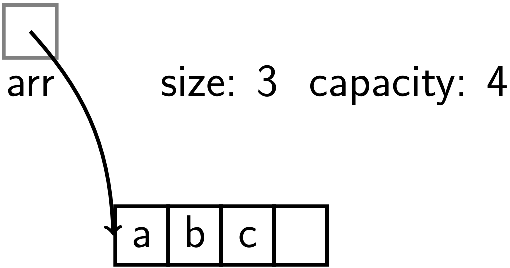



`PushBack(c)`

# Dynamic Array Resizing

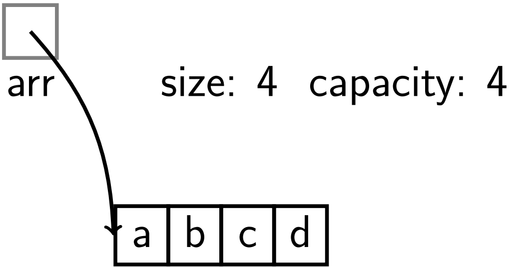


# Dynamic Array Resizing



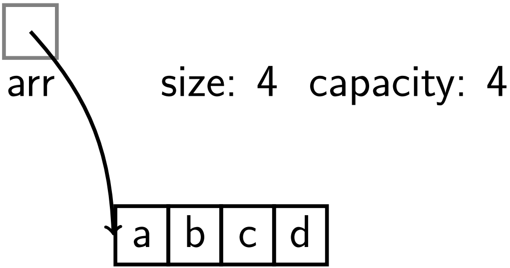

`PushBack(d)`

# Dynamic Array Resizing

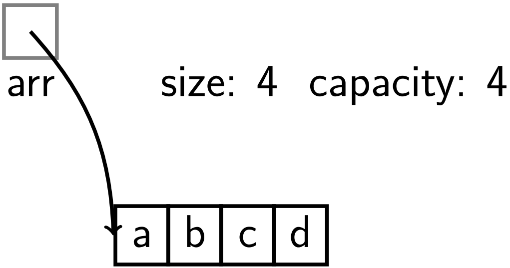



`PushBack(d)`

# Dynamic Array Resizing

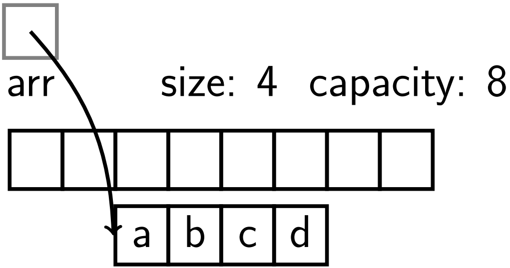


# Dynamic Array Resizing



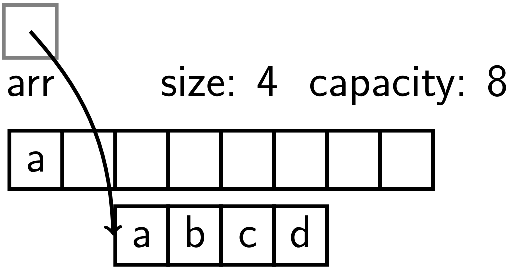

`PushBack(e)`

# Dynamic Array Resizing



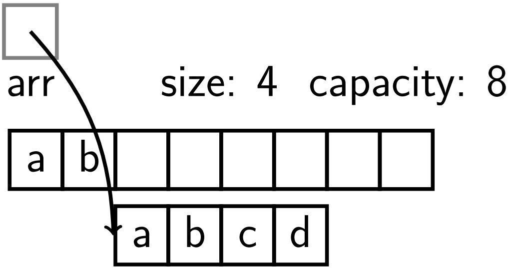

`PushBack(e)`

# Dynamic Array Resizing



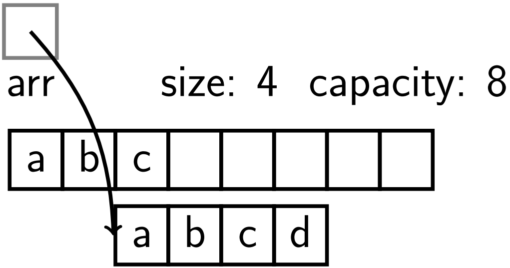

`PushBack(e)`

# Dynamic Array Resizing



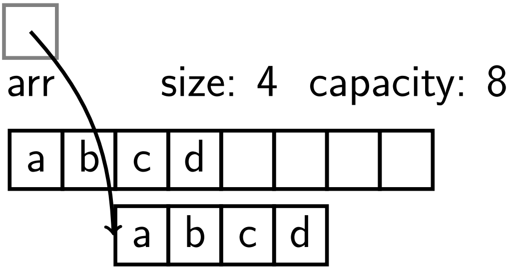

`PushBack(e)`

# Dynamic Array Resizing



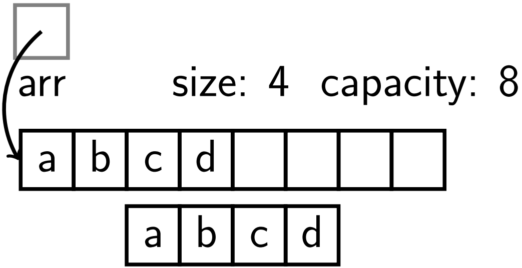

`PushBack(e)`

# Dynamic Array Resizing



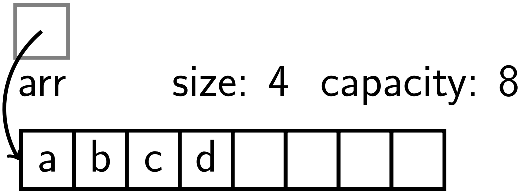

`PushBack(e)`

# Dynamic Array Resizing



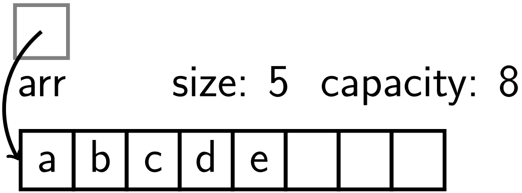

`PushBack(e)`

# Dynamic Array Resizing




`PushBack(e)`

# Dynamic Array Resizing




`PushBack(e)`

```
Get(i)

if i < 0 or i ≥ size:
  ERROR: index out of range
return arr[i]
```

### $\texttt{Set}(i, val)$

```
if i < 0 or i ≥ size:
  ERROR: index out of range
arr[i] = val
```

## PushBack($val$)

```
if size = capacity:
    allocate new_arr[2 × capacity]
    for i from 0 to size − 1:
        new_arr[i] ← arr[i]
    free arr
    arr ← new_arr; capacity ← 2 × capacity
arr[size] ← val
size ← size + 1
```

## Remove($i$)

```
if i < 0 or i ≥ size:
  ERROR: index out of range
for j from i to size − 2:
  arr[j] ← arr[j + 1]
size ← size − 1
```

## `Size()`

`return` *size*

# Common Implementations

- **C++**: `vector`
- **Java**: `ArrayList`
- **Python**: `list` (the only kind of array)

# Runtimes

| | |
|---|---|
| Get($i$) | $O(1)$ |

# Runtimes

| | |
|---|---|
| $\texttt{Get}(i)$ | $O(1)$ |
| $\texttt{Set}(i, val)$ | $O(1)$ |

# Runtimes

| | |
|---|---|
| $\texttt{Get}(i)$ | $O(1)$ |
| $\texttt{Set}(i, val)$ | $O(1)$ |
| $\texttt{PushBack}(val)$ | $O(n)$ |

# Runtimes

| | |
|---|---|
| Get($i$) | $O(1)$ |
| Set($i$, $val$) | $O(1)$ |
| PushBack($val$) | $O(n)$ |
| Remove($i$) | $O(n)$ |

# Runtimes

| | |
|---|---|
| $\texttt{Get}(i)$ | $O(1)$ |
| $\texttt{Set}(i, val)$ | $O(1)$ |
| $\texttt{PushBack}(val)$ | $O(n)$ |
| $\texttt{Remove}(i)$ | $O(n)$ |
| $\texttt{Size}()$ | $O(1)$ |

# Summary

- Unlike static arrays, dynamic arrays can be resized.

# Summary

- Unlike static arrays, dynamic arrays can be resized.
- Appending a new element to a dynamic array is often constant time, but can take $O(n)$.

# Summary

- Unlike static arrays, dynamic arrays can be resized.
- Appending a new element to a dynamic array is often constant time, but can take $O(n)$.
- Some space is wasted

# Summary

- Unlike static arrays, dynamic arrays can be resized.
- Appending a new element to a dynamic array is often constant time, but can take $O(n)$.
- Some space is wasted

# Summary

- Unlike static arrays, dynamic arrays can be resized.
- Appending a new element to a dynamic array is often constant time, but can take $O(n)$.
- Some space is wasted—at most half.

# Outline

1. Dynamic Arrays
2. Amortized Analysis—Aggregate Method
3. Amortized Analysis—Banker's Method
4. Amortized Analysis—Physicist's Method

Sometimes, looking at the individual worst-case may be too severe. We may want to know the total worst-case cost for a sequence of operations.

## Dynamic Array

We only resize every so often.

Many $O(1)$ operations are followed by an $O(n)$ operations.

What is the total cost of inserting many elements?

## Definition

Amortized cost: Given a sequence of $n$ operations, the amortized cost is:

$$\frac{\text{Cost}(n \text{ operations})}{n}$$

# Aggregate Method

Dynamic array: $n$ calls to `PushBack`

# Aggregate Method

Dynamic array: $n$ calls to `PushBack`

Let $c_i =$ cost of $i$'th insertion.

# Aggregate Method

Dynamic array: $n$ calls to PushBack

Let $c_i =$ cost of $i$'th insertion.

$$c_i = 1 + \begin{cases} \\ \\ \end{cases}$$

# Aggregate Method

Dynamic array: $n$ calls to $\texttt{PushBack}$

Let $c_i =$ cost of $i$'th insertion.

$$c_i = 1 + \begin{cases} i-1 & \text{if } i-1 \text{ is a power of 2} \\ & \end{cases}$$

# Aggregate Method

Dynamic array: $n$ calls to $\texttt{PushBack}$

Let $c_i$ = cost of $i$'th insertion.

$$c_i = 1 + \begin{cases} i-1 & \text{if } i-1 \text{ is a power of 2} \\ 0 & \text{otherwise} \end{cases}$$

# Aggregate Method

Dynamic array: $n$ calls to PushBack

Let $c_i =$ cost of $i$'th insertion.

$$c_i = 1 + \begin{cases} i-1 & \text{if } i-1 \text{ is a power of 2} \\ 0 & \text{otherwise} \end{cases}$$

$$\frac{\sum_{i=1}^{n} c_i}{n}$$

# Aggregate Method

Dynamic array: $n$ calls to PushBack

Let $c_i$ = cost of $i$'th insertion.

$$c_i = 1 + \begin{cases} i-1 & \text{if } i-1 \text{ is a power of } 2 \\ 0 & \text{otherwise} \end{cases}$$

$$\frac{\sum_{i=1}^{n} c_i}{n} = \frac{n + \sum_{j=1}^{\lfloor \log_2(n-1) \rfloor} 2^j}{n}$$

# Aggregate Method

Dynamic array: $n$ calls to PushBack

Let $c_i$ = cost of $i$'th insertion.

$$c_i = 1 + \begin{cases} i-1 & \text{if } i-1 \text{ is a power of 2} \\ 0 & \text{otherwise} \end{cases}$$

$$\frac{\sum_{i=1}^{n} c_i}{n} = \frac{n + \sum_{j=1}^{\lfloor \log_2(n-1) \rfloor} 2^j}{n} = \frac{O(n)}{n}$$

# Aggregate Method

Dynamic array: $n$ calls to PushBack

Let $c_i$ = cost of $i$'th insertion.

$$c_i = 1 + \begin{cases} i-1 & \text{if } i-1 \text{ is a power of } 2 \\ 0 & \text{otherwise} \end{cases}$$

$$\frac{\sum_{i=1}^{n} c_i}{n} = \frac{n + \sum_{j=1}^{\lfloor \log_2(n-1) \rfloor} 2^j}{n} = \frac{O(n)}{n} = O(1)$$

# Outline

1. Dynamic Arrays
2. Amortized Analysis—Aggregate Method
3. Amortized Analysis—Banker's Method
4. Amortized Analysis—Physicist's Method

# Banker's Method

- Charge extra for each cheap operation.

# Banker's Method

- Charge extra for each cheap operation.
- Save the extra charge as tokens in your data structure (conceptually).

# Banker's Method

- Charge extra for each cheap operation.
- Save the extra charge as tokens in your data structure (conceptually).
- Use the tokens to pay for expensive operations.

# Banker's Method

- Charge extra for each cheap operation.
- Save the extra charge as tokens in your data structure (conceptually).
- Use the tokens to pay for expensive operations.

Like an amortizing loan.

# Banker's Method

Dynamic array: $n$ calls to `PushBack`

# Banker's Method

Dynamic array: $n$ calls to `PushBack`

Charge 3 for each insertion: 1 token is the raw cost for insertion.

# Banker's Method

Dynamic array: $n$ calls to `PushBack`

Charge 3 for each insertion: 1 token is the raw cost for insertion.

- Resize needed: To pay for moving the elements, use the token that's present on each element that needs to move.

# Banker's Method

Dynamic array: $n$ calls to `PushBack`

Charge 3 for each insertion: 1 token is the raw cost for insertion.

- Resize needed: To pay for moving the elements, use the token that's present on each element that needs to move.
- Place one token on the newly-inserted element, and one token $\frac{capacity}{2}$ elements prior.

# Dynamic Array Resizing

arr

size: 0 capacity: 0

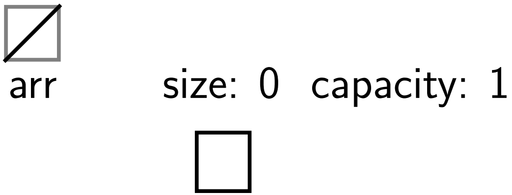
# Dynamic Array Resizing

arr

size: 0 capacity: 0

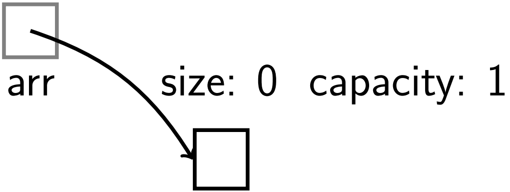
PushBack(a)

# Dynamic Array Resizing



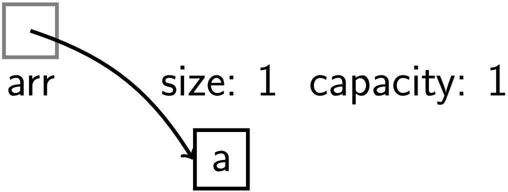

PushBack(a)

# Dynamic Array Resizing



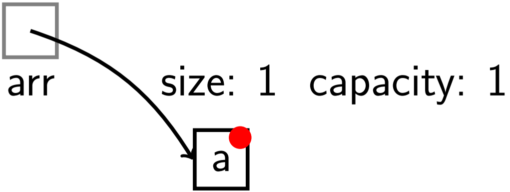

PushBack(a)

# Dynamic Array Resizing



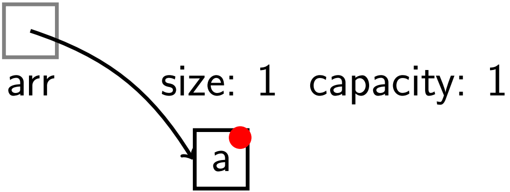

PushBack(a)

# Dynamic Array Resizing

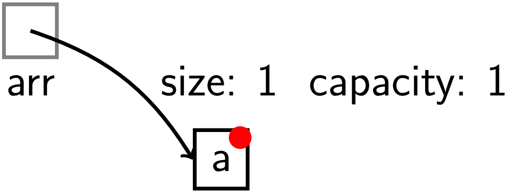



PushBack(a)

# Dynamic Array Resizing

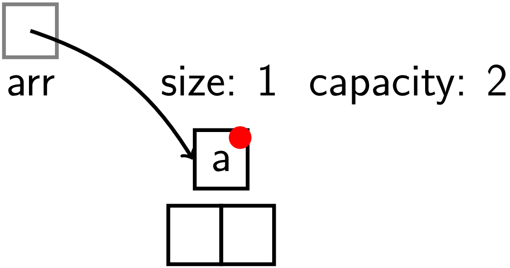


# Dynamic Array Resizing



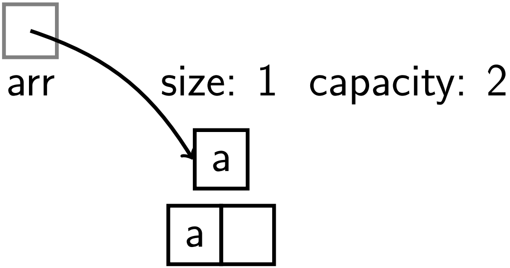

PushBack(b)

# Dynamic Array Resizing



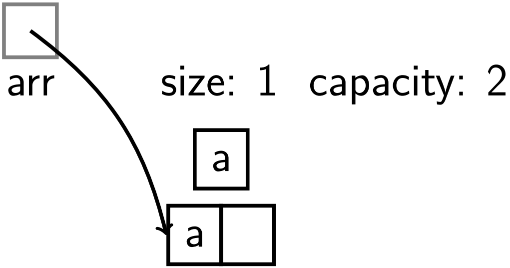

PushBack(b)

# Dynamic Array Resizing



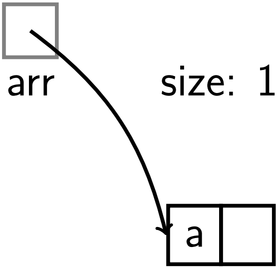

PushBack(b)

# Dynamic Array Resizing




PushBack(b)

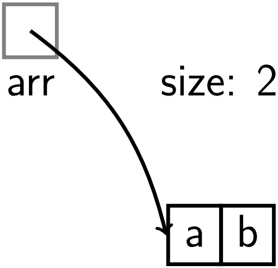
# Dynamic Array Resizing




size: 1 capacity: 2

PushBack(b)

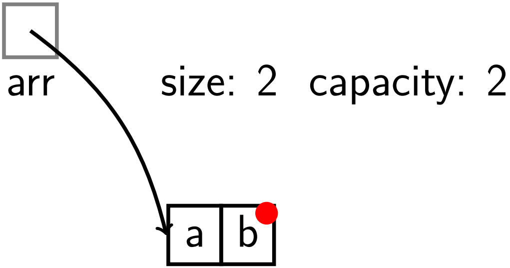
# Dynamic Array Resizing




size: 2 capacity: 2

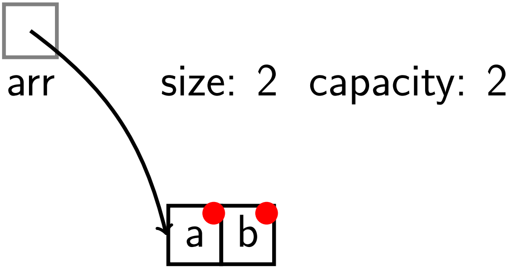
PushBack(b)

# Dynamic Array Resizing



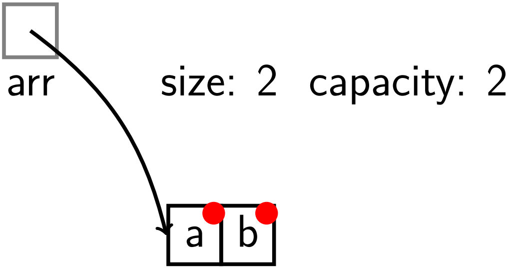

PushBack(b)

# Dynamic Array Resizing

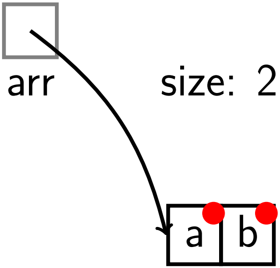



PushBack(b)

# Dynamic Array Resizing



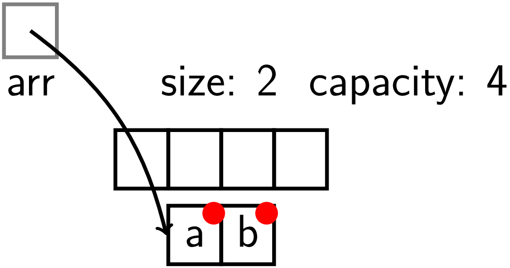
# Dynamic Array Resizing




size: 2 capacity: 2

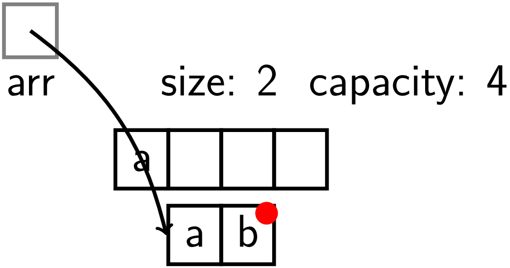
PushBack(c)

# Dynamic Array Resizing



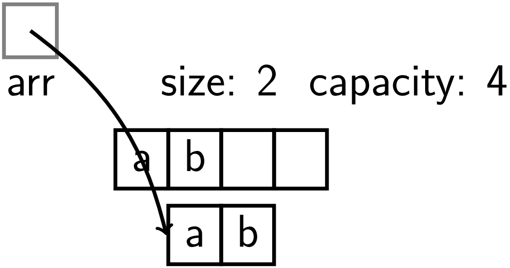

PushBack(c)

# Dynamic Array Resizing



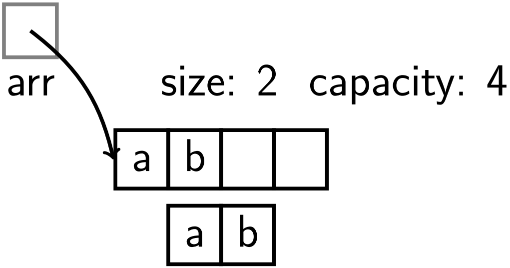

PushBack(c)

# Dynamic Array Resizing



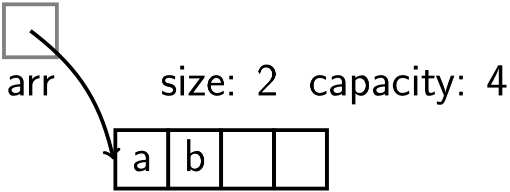

PushBack(c)

# Dynamic Array Resizing



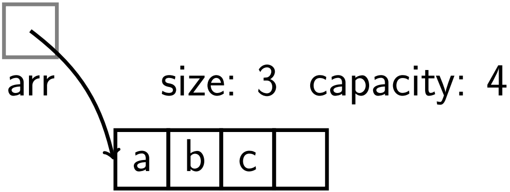

PushBack(c)

# Dynamic Array Resizing



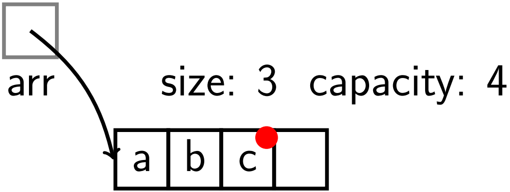

PushBack(c)

# Dynamic Array Resizing



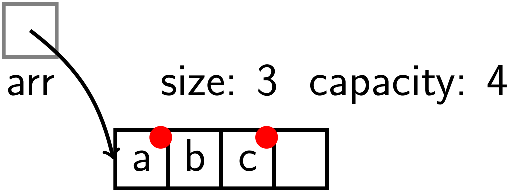

PushBack(c)

# Dynamic Array Resizing



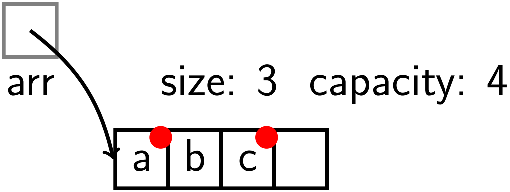

PushBack(c)

# Dynamic Array Resizing

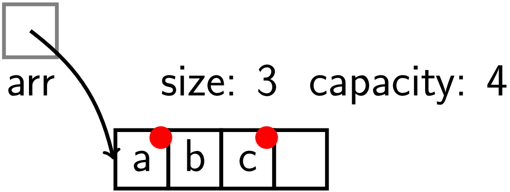



PushBack(c)

# Dynamic Array Resizing

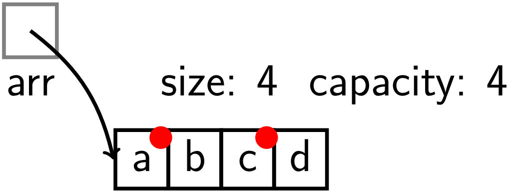


# Dynamic Array Resizing



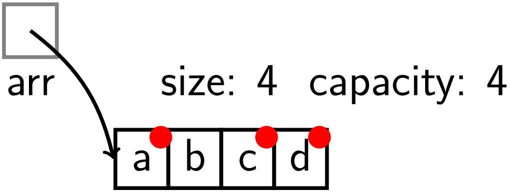

PushBack(d)

# Dynamic Array Resizing



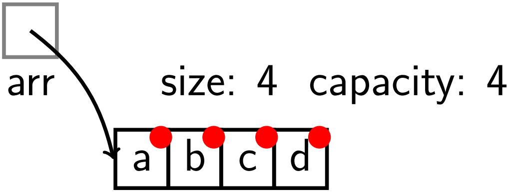

PushBack(d)

# Dynamic Array Resizing



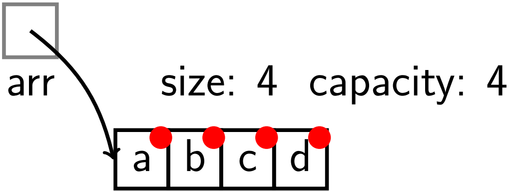

PushBack(d)

# Dynamic Array Resizing

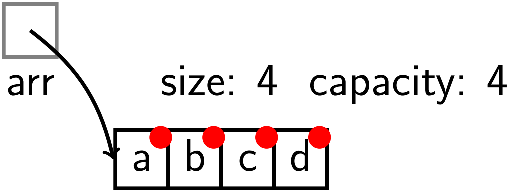



PushBack(d)

# Dynamic Array Resizing

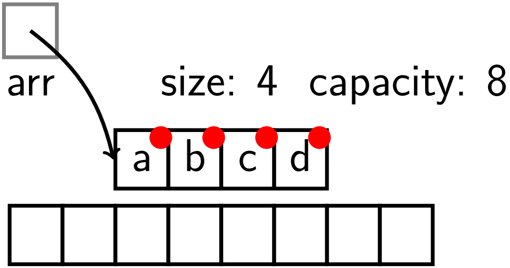


# Dynamic Array Resizing



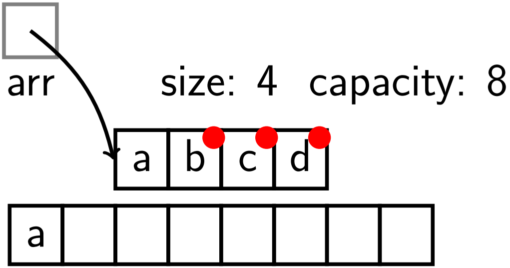

PushBack(e)

# Dynamic Array Resizing



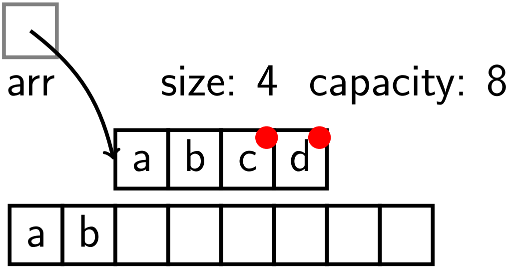

PushBack(e)

# Dynamic Array Resizing



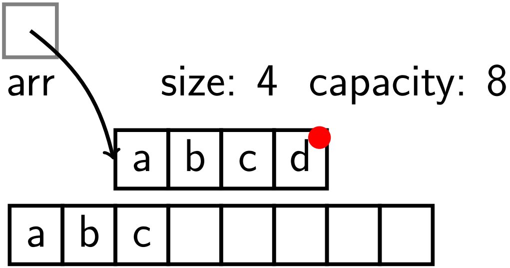

PushBack(e)

# Dynamic Array Resizing



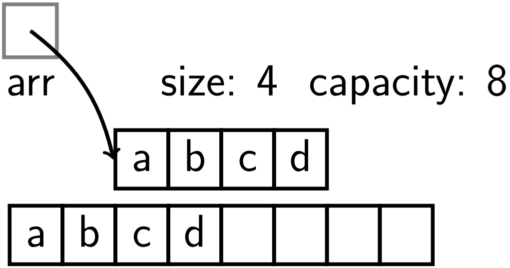

PushBack(e)

# Dynamic Array Resizing



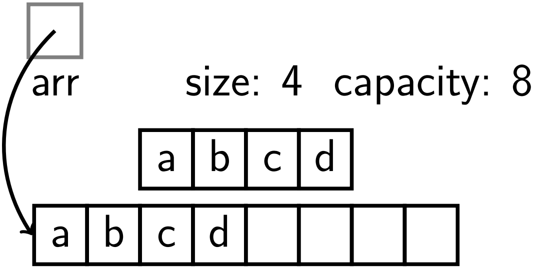

PushBack(e)

# Dynamic Array Resizing



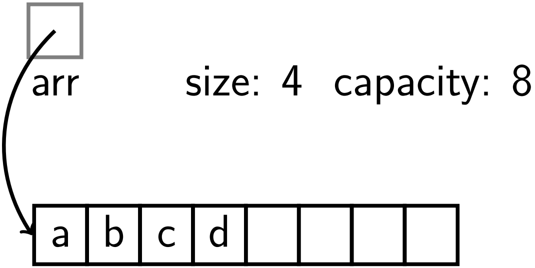

PushBack(e)

# Dynamic Array Resizing



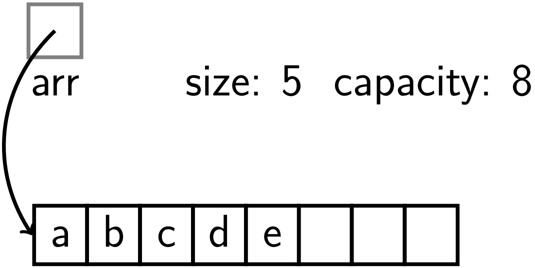

PushBack(e)

# Dynamic Array Resizing



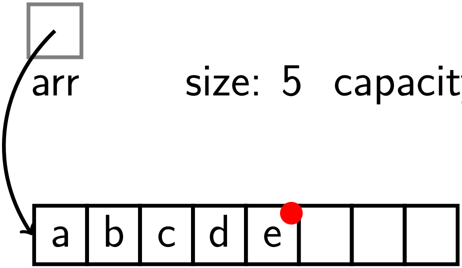

PushBack(e)

# Dynamic Array Resizing




PushBack(e)

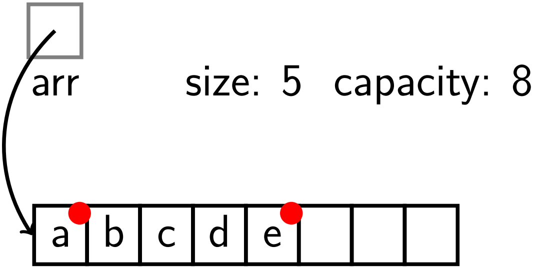
# Dynamic Array Resizing




size: 5 capacity: 8

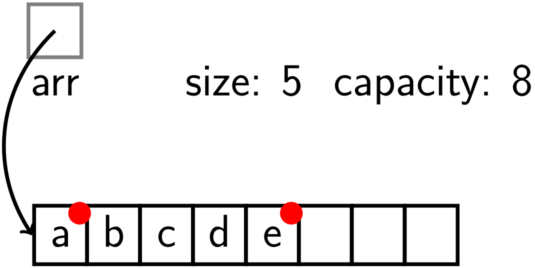
PushBack(e)

# Dynamic Array Resizing

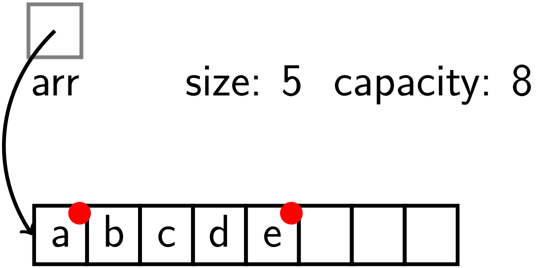



PushBack(e)

# Dynamic Array Resizing



# Dynamic Array Resizing




$O(1)$ amortized cost for each `PushBack`

# Banker's Method

Dynamic array: $n$ calls to `PushBack`

Charge 3 for each insertion. 1 coin is the raw cost for insertion.

- Resize needed: To pay for moving the elements, use the coin that's present on each element that needs to move.
- Place one coin on the newly-inserted element, and one coin $\frac{capacity}{2}$ elements prior.

# Outline

1. Dynamic Arrays
2. Amortized Analysis—Aggregate Method
3. Amortized Analysis—Banker's Method
4. Amortized Analysis—Physicist's Method

# Physicist's Method

- Define a *potential function*, $\Phi$ which maps states of the data structure to integers:

# Physicist's Method

- Define a *potential function*, $\Phi$ which maps states of the data structure to integers:
  - $\Phi(h_0) = 0$

# Physicist's Method

- Define a *potential function*, $\Phi$ which maps states of the data structure to integers:
  - $\Phi(h_0) = 0$
  - $\Phi(h_t) \geq 0$

# Physicist's Method

- Define a *potential function*, $\Phi$ which maps states of the data structure to integers:
    - $\Phi(h_0) = 0$
    - $\Phi(h_t) \geq 0$
- amortized cost for operation t:

  $c_t + \Phi(h_t) - \Phi(h_{t-1})$

# Physicist's Method

- Define a *potential function*, $\Phi$ which maps states of the data structure to integers:
  - $\Phi(h_0) = 0$
  - $\Phi(h_t) \geq 0$
- amortized cost for operation t:

  $c_t + \Phi(h_t) - \Phi(h_{t-1})$

Choose $\Phi$ so that:

# Physicist's Method

- Define a *potential function*, $\Phi$ which maps states of the data structure to integers:
  - $\Phi(h_0) = 0$
  - $\Phi(h_t) \geq 0$
- amortized cost for operation t:

  $c_t + \Phi(h_t) - \Phi(h_{t-1})$

Choose $\Phi$ so that:

- if $c_t$ is small, the potential increases

# Physicist's Method

- Define a *potential function*, $\Phi$ which maps states of the data structure to integers:
  - $\Phi(h_0) = 0$
  - $\Phi(h_t) \geq 0$
- amortized cost for operation t:

  $c_t + \Phi(h_t) - \Phi(h_{t-1})$

Choose $\Phi$ so that:

- if $c_t$ is small, the potential increases
- if $c_t$ is large, the potential decreases by the same scale

# Physicist's Method

- The cost of $n$ operations is: $\sum_{i=1}^{n} c_i$

# Physicist's Method

- The cost of $n$ operations is: $\sum_{i=1}^{n} c_i$
- The sum of the amortized costs is:

$$\sum_{i=1}^{n}(c_i + \Phi(h_i) - \Phi(h_{i-1}))$$

# Physicist's Method

- The cost of $n$ operations is: $\sum_{i=1}^{n} c_i$
- The sum of the amortized costs is:

$$\sum_{i=1}^{n}(c_i + \Phi(h_i) - \Phi(h_{i-1}))$$

$$\begin{aligned} = & c_1 + \Phi(h_1) - \Phi(h_0) + \\ & c_2 + \Phi(h_2) - \Phi(h_1) \cdots + \\ & c_n + \Phi(h_n) - \Phi(h_{n-1}) \end{aligned}$$

# Physicist's Method

- The cost of $n$ operations is: $\sum_{i=1}^{n} c_i$
- The sum of the amortized costs is:

$$
\begin{aligned}
&\sum_{i=1}^{n}(c_i + \Phi(h_i) - \Phi(h_{i-1})) \\
=& c_1 + \Phi(h_1) - \Phi(h_0) + \\
& c_2 + \Phi(h_2) - \Phi(h_1) \cdots + \\
& c_n + \Phi(h_n) - \Phi(h_{n-1}) \\
=& \Phi(h_n) - \Phi(h_0) + \sum_{i=1}^{n} c_i
\end{aligned}
$$

# Physicist's Method

- The cost of $n$ operations is: $\sum_{i=1}^{n} c_i$
- The sum of the amortized costs is:

$$
\begin{aligned}
&\sum_{i=1}^{n}(c_i + \Phi(h_i) - \Phi(h_{i-1})) \\
=&c_1 + \Phi(h_1) - \Phi(h_0) + \\
&c_2 + \Phi(h_2) - \Phi(h_1) \cdots + \\
&c_n + \Phi(h_n) - \Phi(h_{n-1}) \\
=&\Phi(h_n) - \Phi(h_0) + \sum_{i=1}^{n} c_i \geq \quad \sum_{i=1}^{n} c_i
\end{aligned}
$$

# Physicist's Method

Dynamic array: $n$ calls to `PushBack`

# Physicist's Method

Dynamic array: $n$ calls to `PushBack`

Let $\Phi(h) = 2 \times \mathit{size} - \mathit{capacity}$

# Physicist's Method

Dynamic array: $n$ calls to $\texttt{PushBack}$

Let $\Phi(h) = 2 \times \mathit{size} - \mathit{capacity}$

- $\Phi(h_0) = 2 \times 0 - 0 = 0$

# Physicist's Method

Dynamic array: $n$ calls to `PushBack`

Let $\Phi(h) = 2 \times size - capacity$

- $\Phi(h_0) = 2 \times 0 - 0 = 0$
- $\Phi(h_i) = 2 \times size - capacity > 0$ (since $size > \frac{capacity}{2}$)

# Dynamic Array Resizing

Without resize when adding element $i$

Amortized cost of adding element $i$:

# Dynamic Array Resizing

Without resize when adding element $i$

Amortized cost of adding element $i$:

# Dynamic Array Resizing

Without resize when adding element $i$

Amortized cost of adding element $i$:

$$c_i + \Phi(h_i) - \Phi(h_{i-1})$$

# Dynamic Array Resizing

Without resize when adding element $i$

Amortized cost of adding element $i$:

$$c_i + \Phi(h_i) - \Phi(h_{i-1})$$

$$= 1 + 2 \times size_i - cap_i - (2 \times size_{i-1} - cap_{i-1})$$

# Dynamic Array Resizing

Without resize when adding element $i$

Amortized cost of adding element $i$:

$$
\begin{aligned}
& c_i + \Phi(h_i) - \Phi(h_{i-1}) \\
=& 1 + 2 \times \mathit{size}_i - \mathit{cap}_i - (2 \times \mathit{size}_{i-1} - \mathit{cap}_{i-1}) \\
=& 1 + 2 \times (\mathit{size}_i - \mathit{size}_{i-1})
\end{aligned}
$$

# Dynamic Array Resizing

Without resize when adding element $i$

Amortized cost of adding element $i$:

$$
\begin{aligned}
& c_i + \Phi(h_i) - \Phi(h_{i-1}) \\
=& 1 + 2 \times size_i - cap_i - (2 \times size_{i-1} - cap_{i-1}) \\
=& 1 + 2 \times (size_i - size_{i-1}) \\
=& 3
\end{aligned}
$$

# Dynamic Array Resizing

With resize when adding element $i$

# Dynamic Array Resizing

With resize when adding element $i$

Let $k = size_{i-1} = cap_{i-1}$

# Dynamic Array Resizing

With resize when adding element $i$

Let $k = size_{i-1} = cap_{i-1}$

Then:

$\Phi(h_{i-1}) = 2size_{i-1} - cap_{i-1} = 2k - k = k$

# Dynamic Array Resizing

With resize when adding element $i$

Let $k = size_{i-1} = cap_{i-1}$

Then:

$\Phi(h_{i-1}) = 2size_{i-1} - cap_{i-1} = 2k - k = k$

$\Phi(h_i) = 2size_i - cap_i = 2(k+1) - 2k = 2$

# Dynamic Array Resizing

With resize when adding element $i$

Let $k = size_{i-1} = cap_{i-1}$

Then:

$\Phi(h_{i-1}) = 2size_{i-1} - cap_{i-1} = 2k - k = k$

$\Phi(h_i) = 2size_i - cap_i = 2(k+1) - 2k = 2$

Amortized cost of adding element $i$:

# Dynamic Array Resizing

With resize when adding element $i$

Let $k = size_{i-1} = cap_{i-1}$

Then:

$\Phi(h_{i-1}) = 2size_{i-1} - cap_{i-1} = 2k - k = k$

$\Phi(h_i) = 2size_i - cap_i = 2(k+1) - 2k = 2$

Amortized cost of adding element $i$:

$$c_i + \Phi(h_i) - \Phi(h_{i-1})$$

# Dynamic Array Resizing

With resize when adding element $i$

Let $k = size_{i-1} = cap_{i-1}$

Then:

$\Phi(h_{i-1}) = 2size_{i-1} - cap_{i-1} = 2k - k = k$

$\Phi(h_i) = 2size_i - cap_i = 2(k+1) - 2k = 2$

Amortized cost of adding element $i$:

$$
\begin{aligned}
& c_i + \Phi(h_i) - \Phi(h_{i-1}) \\
=& (size_i) + 2 - k
\end{aligned}
$$

# Dynamic Array Resizing

With resize when adding element $i$

Let $k = size_{i-1} = cap_{i-1}$

Then:

$\Phi(h_{i-1}) = 2size_{i-1} - cap_{i-1} = 2k - k = k$

$\Phi(h_i) = 2size_i - cap_i = 2(k+1) - 2k = 2$

Amortized cost of adding element $i$:

$$
\begin{aligned}
& c_i + \Phi(h_i) - \Phi(h_{i-1}) \\
=& (size_i) + 2 - k \\
=& (k+1) + 2 - k
\end{aligned}
$$

# Dynamic Array Resizing

With resize when adding element $i$

Let $k = size_{i-1} = cap_{i-1}$

Then:

$\Phi(h_{i-1}) = 2size_{i-1} - cap_{i-1} = 2k - k = k$

$\Phi(h_i) = 2size_i - cap_i = 2(k+1) - 2k = 2$

Amortized cost of adding element $i$:

$$
\begin{aligned}
& c_i + \Phi(h_i) - \Phi(h_{i-1}) \\
=& (size_i) + 2 - k \\
=& (k+1) + 2 - k \\
=& 3
\end{aligned}
$$

# Alternatives to Doubling the Array Size

We could use some different growth factor (1.5, 2.5, etc.).
Could we use a constant amount?

# Cannot Use Constant Amount

If we expand by 10 each time, then:

Let $c_i =$ cost of $i$'th insertion.

# Cannot Use Constant Amount

If we expand by 10 each time, then:

Let $c_i$ = cost of $i$'th insertion.

# Cannot Use Constant Amount

If we expand by 10 each time, then:

Let $c_i$ = cost of $i$'th insertion.

$$c_i = 1 + \begin{cases} \\ \end{cases}$$

# Cannot Use Constant Amount

If we expand by 10 each time, then:

Let $c_i$ = cost of $i$'th insertion.

$$c_i = 1 + \begin{cases} i - 1 & \text{if } i - 1 \text{ is a multiple of } 10 \\ & \end{cases}$$

# Cannot Use Constant Amount

If we expand by 10 each time, then:

Let $c_i =$ cost of $i$'th insertion.

$$c_i = 1 + \begin{cases} i - 1 & \text{if } i - 1 \text{ is a multiple of } 10 \\ 0 & \text{otherwise} \end{cases}$$

# Cannot Use Constant Amount

If we expand by 10 each time, then:

Let $c_i$ = cost of $i$'th insertion.

$$c_i = 1 + \begin{cases} i-1 & \text{if } i-1 \text{ is a multiple of } 10 \\ 0 & \text{otherwise} \end{cases}$$

$$\frac{\sum_{i=1}^{n} c_i}{n}$$

# Cannot Use Constant Amount

If we expand by 10 each time, then:

Let $c_i$ = cost of $i$'th insertion.

$$c_i = 1 + \begin{cases} i - 1 & \text{if } i - 1 \text{ is a multiple of } 10 \\ 0 & \text{otherwise} \end{cases}$$

$$\frac{\sum_{i=1}^{n} c_i}{n} = \frac{n + \sum_{j=1}^{(n-1)/10} 10j}{n}$$

# Cannot Use Constant Amount

If we expand by 10 each time, then:

Let $c_i$ = cost of $i$'th insertion.

$$c_i = 1 + \begin{cases} i-1 & \text{if } i-1 \text{ is a multiple of } 10 \\ 0 & \text{otherwise} \end{cases}$$

$$\frac{\sum_{i=1}^{n} c_i}{n} = \frac{n + \sum_{j=1}^{(n-1)/10} 10j}{n} = \frac{n + 10 \sum_{j=1}^{(n-1)/10} j}{n}$$

# Cannot Use Constant Amount

If we expand by 10 each time, then:

Let $c_i =$ cost of $i$'th insertion.

$$c_i = 1 + \begin{cases} i - 1 & \text{if } i - 1 \text{ is a multiple of } 10 \\ 0 & \text{otherwise} \end{cases}$$

$$\frac{\sum_{i=1}^{n} c_i}{n} = \frac{n + \sum_{j=1}^{(n-1)/10} 10j}{n} = \frac{n + 10 \sum_{j=1}^{(n-1)/10} j}{n}$$

$$= \frac{n + 10\,O(n^2)}{n}$$

# Cannot Use Constant Amount

If we expand by 10 each time, then:

Let $c_i$ = cost of $i$'th insertion.

$$c_i = 1 + \begin{cases} i-1 & \text{if } i-1 \text{ is a multiple of } 10 \\ 0 & \text{otherwise} \end{cases}$$

$$\frac{\sum_{i=1}^{n} c_i}{n} = \frac{n + \sum_{j=1}^{(n-1)/10} 10j}{n} = \frac{n + 10 \sum_{j=1}^{(n-1)/10} j}{n}$$

$$= \frac{n + 10\,O(n^2)}{n} = \frac{O(n^2)}{n}$$

# Cannot Use Constant Amount

If we expand by 10 each time, then:

Let $c_i =$ cost of $i$'th insertion.

$$c_i = 1 + \begin{cases} i-1 & \text{if } i-1 \text{ is a multiple of } 10 \\ 0 & \text{otherwise} \end{cases}$$

$$\frac{\sum_{i=1}^{n} c_i}{n} = \frac{n + \sum_{j=1}^{(n-1)/10} 10j}{n} = \frac{n + 10 \sum_{j=1}^{(n-1)/10} j}{n}$$

$$= \frac{n + 10\,O(n^2)}{n} = \frac{O(n^2)}{n} = O(n)$$

# Summary

- Calculate amortized cost of an operation in the context of a sequence of operations.

# Summary

- Calculate amortized cost of an operation in the context of a sequence of operations.
- Three ways to do analysis:

# Summary

- Calculate amortized cost of an operation in the context of a sequence of operations.
- Three ways to do analysis:
    - Aggregate method (brute-force sum)

# Summary

- Calculate amortized cost of an operation in the context of a sequence of operations.
- Three ways to do analysis:
  - Aggregate method (brute-force sum)
  - Banker's method (tokens)

# Summary

- Calculate amortized cost of an operation in the context of a sequence of operations.
- Three ways to do analysis:
  - Aggregate method (brute-force sum)
  - Banker's method (tokens)
  - Physicist's method (potential function, $\Phi$)

# Summary

- Calculate amortized cost of an operation in the context of a sequence of operations.
- Three ways to do analysis:
  - Aggregate method (brute-force sum)
  - Banker's method (tokens)
  - Physicist's method (potential function, $\Phi$)
- Nothing changes in the code: runtime analysis only.