20. Dynamic Data Structures I

Dynamic Memory, Addresses and Pointers, Const-Pointer Arrays,
Array-based Vectors

Recap: `vector<`T`>`

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v.push_front(e);   // Prepend element
v.push_back(e);    // Append element
...
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```

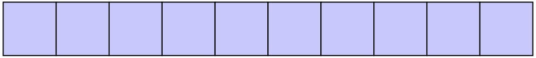
- A vector is a *dynamic data structure*, whose size may change at runtime

Our Own Vector!

- Today, we'll implement our own vector: **`vec`**
- Step 1: **`vec<int>`** (today)
- Step 2: **`vec<T>`** (later, only superficially)

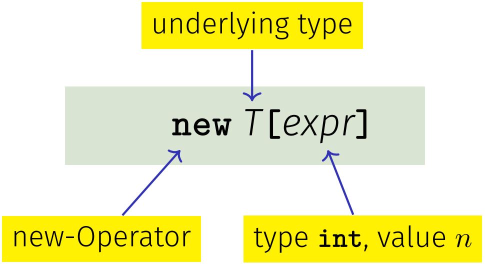
Vectors in Memory

Already known: A vector has a *contiguous* memory layout

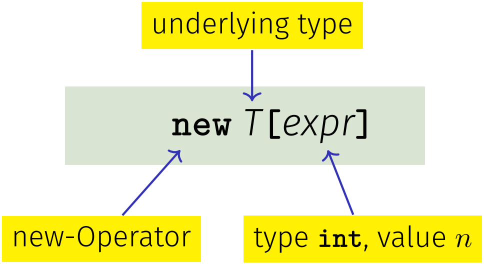


Question: How to *allocate* a chunk of memory of *arbitrary* size during runtime, i.e. *dynamically*?

new for Arrays



`new` for Arrays



- **Effect**: new contiguous chunk of memory n elements of type *T* is allocated

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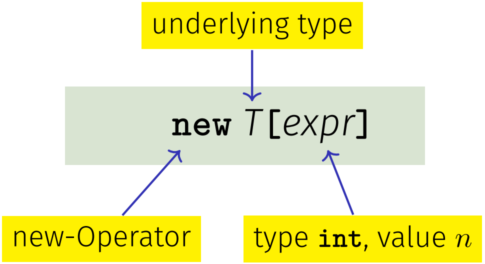


- **Effect**: new contiguous chunk of memory n elements of type *T* is allocated

- This chunk of memory is called an *array* (of length n)

`new` for Arrays

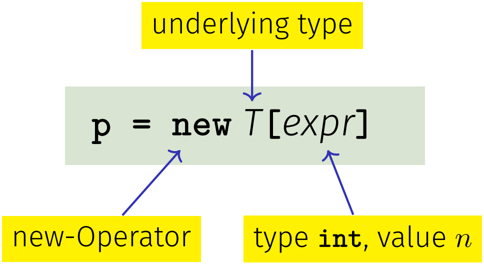
underlying type

`p = new` *T*`[`*expr*`]`

new-Operator

type **`int`**, value n

`new` for Arrays



- **Value**: the starting address of the memory chunk

- **Type**: A pointer $T*$ (more soon)

Outlook: `new` and `delete`

`new` *T*`[`*expr*`]`

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Outlook: `new` and `delete`

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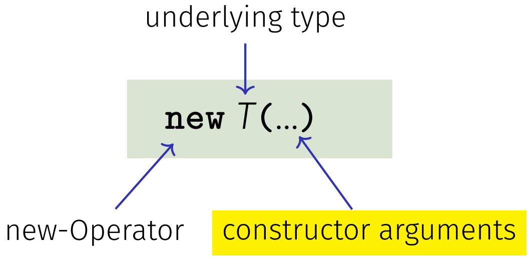
- So far: memory (local variables, function arguments) “lives” only inside a function call
- But now: memory chunk inside vector must not “die” before the vector itself
- Memory allocated with **`new`** is *not* automatically *deallocated* (= released)
- Every **`new`** must have a matching **`delete`** that releases the memory explicitly → **in two weeks**

`new` (Without Arrays)



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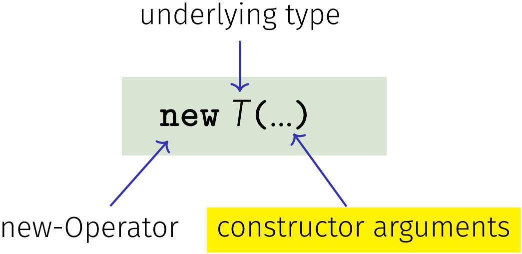
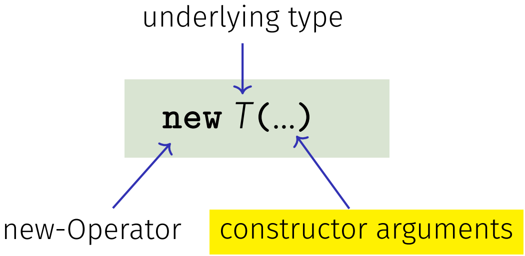


- **Effect**: memory for a new object of type T is allocated …

`new` (Without Arrays)



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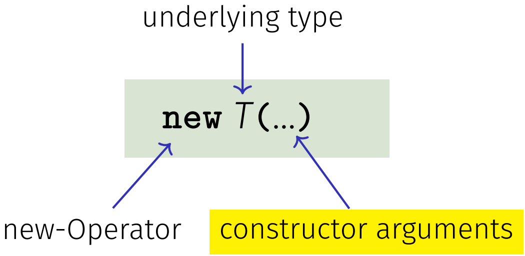

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- **Value**: address of the new T object, **Type**: Pointer T*

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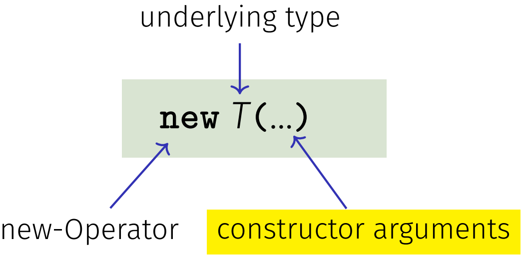

- **Effect**: memory for a new object of type *T* is allocated . . .
- . . . and initialized by means of the matching constructor
- **Value**: address of the new T object, **Type**: Pointer T`*`
- Also true here: object “lives” until deleted explicitly (usefulness will become clearer later)

Pointer Types

`T*` Pointer type for base type **`T`**

An expression of type **`T*`** is called *pointer (to `T`)*

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```
int* p; // Pointer to an int
std::string* q; // Pointer to a std::string
```

Pointer Types

`T*` Pointer type for base type **`T`**

A T`*` must actually point to a T

```
int* p = ...;
std::string* q = p; // compiler error!
```

Pointer Types

Value of a pointer to `T` is the *address* of an object of type `T`

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Value of a pointer to **T** is the *address* of an object of type **T**

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int* p = ...;
std::cout << p; // e.g. 0x7ffd89d5f7cc
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Pointer Types

Value of a pointer to **`T`** is the *address* of an object of type **`T`**

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int* p = ...;
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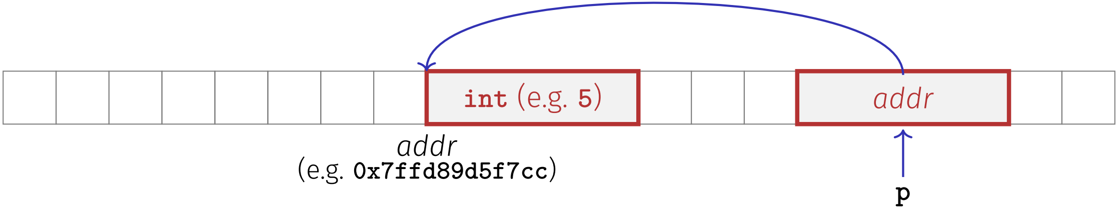

Address Operator

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$$\&expr$$

expr: l-value of type T

- **Value** of the expression: the *address* of object (l-value) *expr*

Address Operator

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1. Directly, when creating a new object via **`new`**

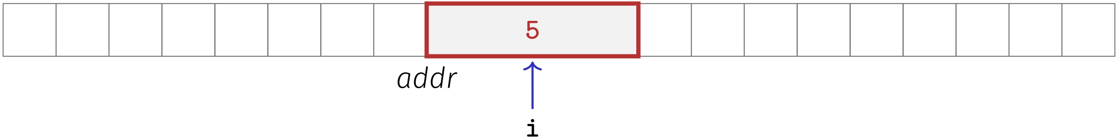
2. For existing objects: via the *address operator* **`&`**

$\&expr$ ← expr: l-value of type T

- **Value** of the expression: the *address* of object (l-value) *expr*
- **Type** of the expression: A pointer $T*$ (of type T)

Address Operator

```
int i = 5; // i initialised with 5
```



Address Operator

```
int i = 5; // i initialised with 5
int* p = &i; // p initialised with address of i
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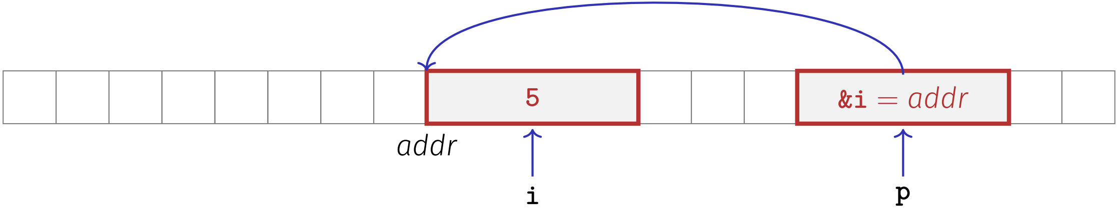

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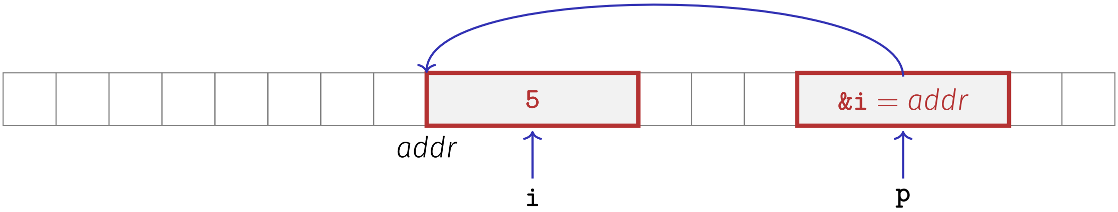

Next question: How to “follow” a pointer?

Dereference Operator

Answer: by using the *dereference operator* $*$

$*$*expr* ← expr: r-value of type $T*$

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Dereference Operator

Answer: by using the *dereference operator* $*$

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- **Value** of the expression: the *value* of the object located at the address denoted by *expr*
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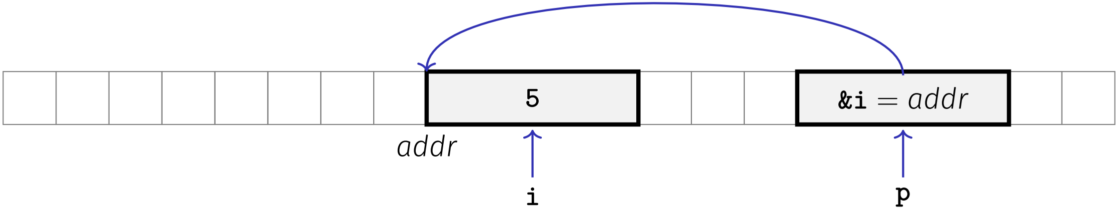

Dereference Operator

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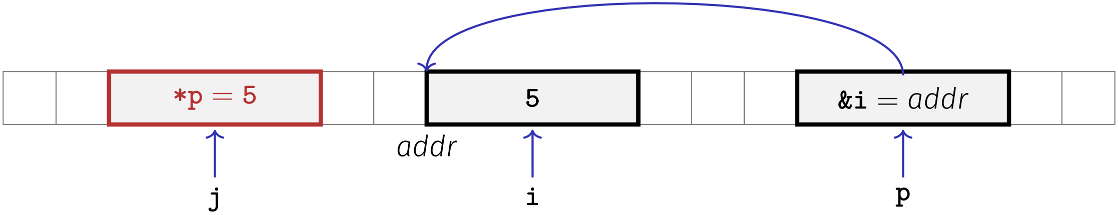
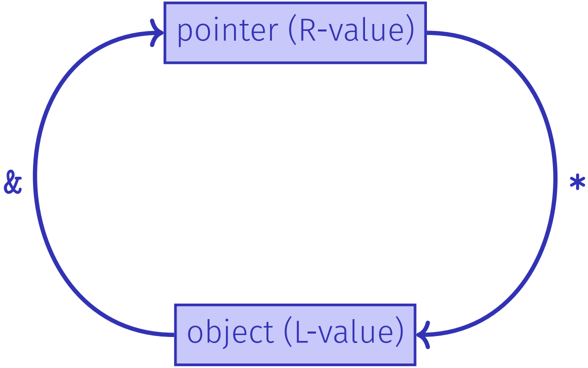
int i = 5;
int* p = &i; // p = address of i
int j = *p; // j = 5
```



Address and Dereference Operator



Mnenmonic Trick

The declaration

```
T* p;        // p is of the type “pointer to T”
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```

can be read as

```
T *p;       // *p is of type T
```

Null-Pointer

- Special pointer value that signals that no object is pointed to
- represented b the literal **`nullptr`** (convertible to **`T*`**)

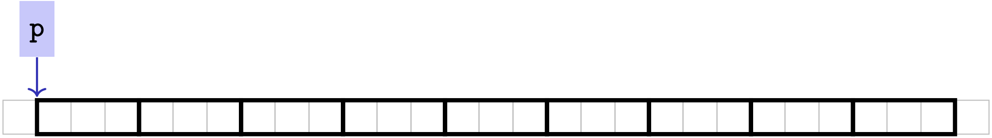
```
int* p = nullptr;
```

- Cannot be dereferenced (runtime error)
- Exists to avoid undefined behaviour

```
int* p; // Accessing p is undefined behaviour
int* q = nullptr; // q explicitly points nowhere
```

Pointer Arithmetic: Pointer plus `int`

```
T* p = new T[n]; // p points to first array element
```



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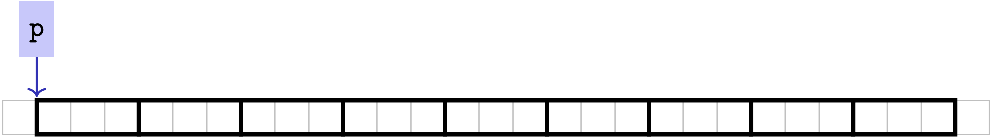

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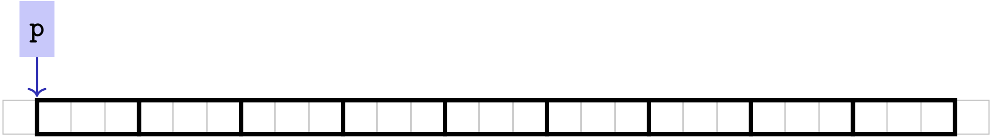

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- `p` yields the *value* of the *first* array element, `*p` its *value*

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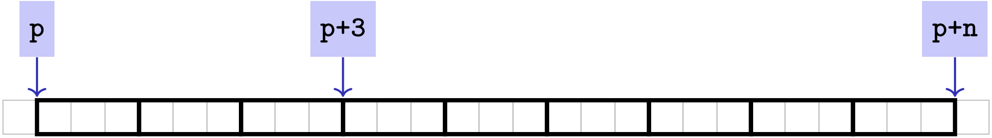

Question: How to point to rear elements? → via *Pointer arithmetic*:

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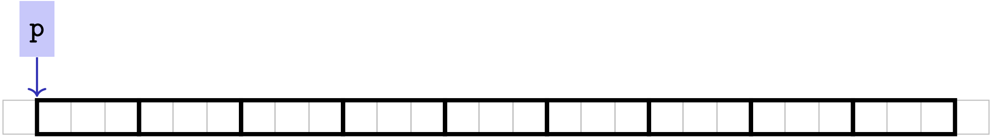

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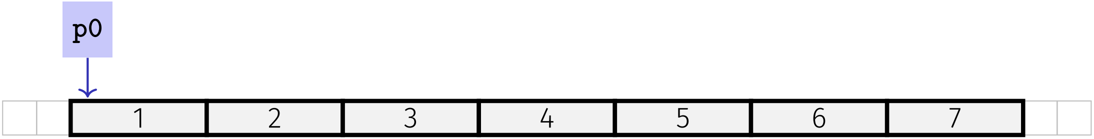
- `*p` is equivalent to `*(p + 0)`

Pointer Arithmetic: Pointer plus `int`

```
int* p0 = new int[7]{1,2,3,4,5,6,7}; // p0 points to 1st element
```



Pointer Arithmetic: Pointer plus `int`

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int* p0 = new int[7]{1,2,3,4,5,6,7}; // p0 points to 1st element
int* p3 = p0 + 3; // p3 points to 4th element
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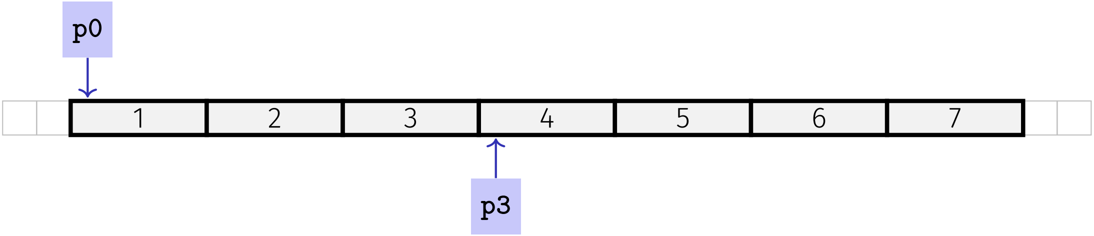

Pointer Arithmetic: Pointer plus `int`

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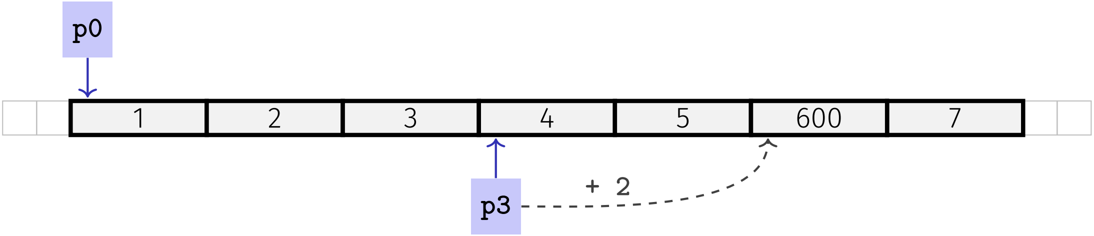
int* p3 = p0 + 3; // p3 points to 4th element
*(p3 + 2) = 600; // set value of 6th element to 600
std::cout << *(p0 + 5);
```



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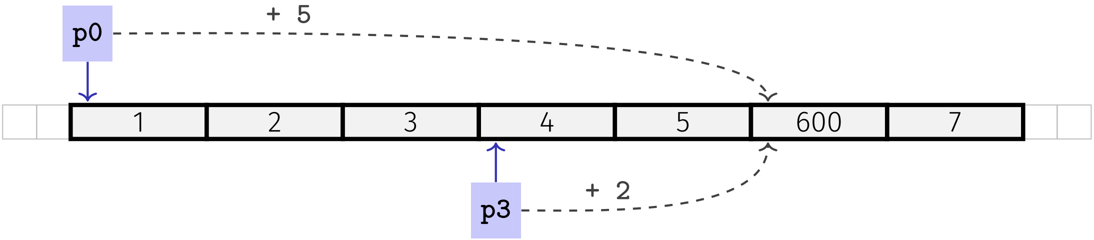
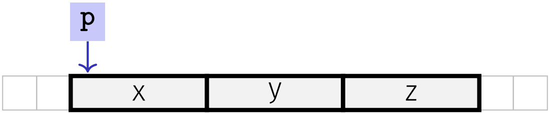
std::cout << *(p0 + 5); // output 6th element's value (i.e. 600)
```



Sequential Pointer Iteration

```
char* p = new char[3]{'x', 'y', 'z'};
```



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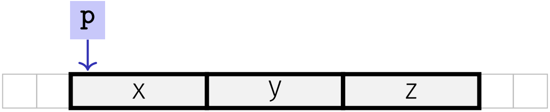


```
  for (char* it = p;
         it != p + 3;
         ++it) {

    std::cout << *it << ' ';
  }
```

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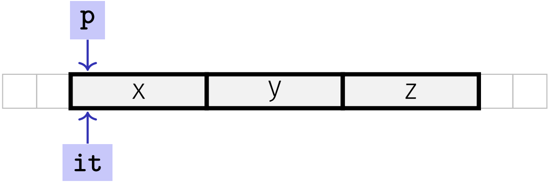


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it points to first element

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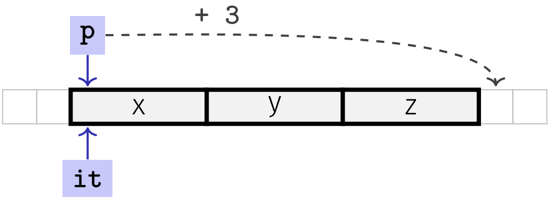


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  std::cout << *it << ' ';
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```

Abort if end reached

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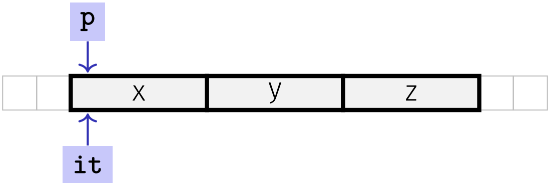


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```

Output current element: 'x'

Sequential Pointer Iteration

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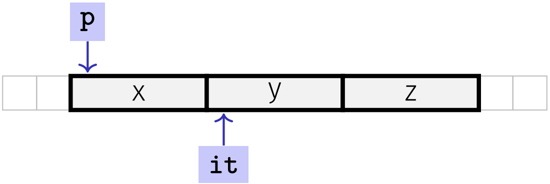


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```

Advance pointer element-wise

Sequential Pointer Iteration

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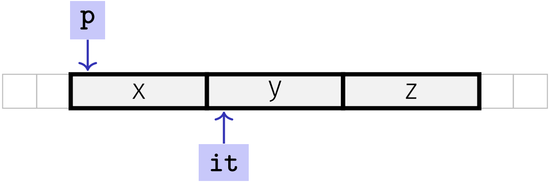


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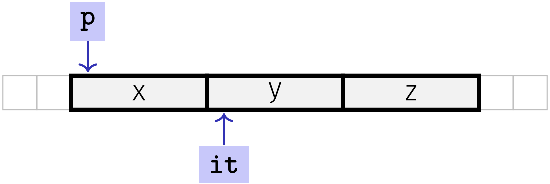


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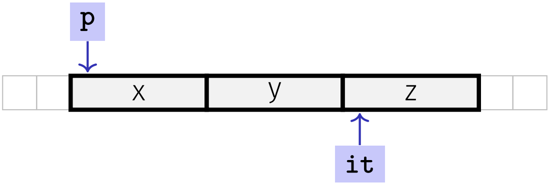


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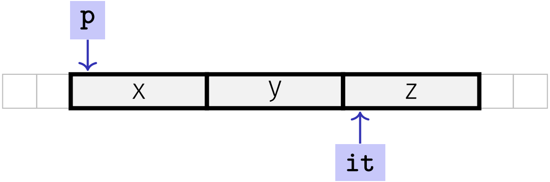


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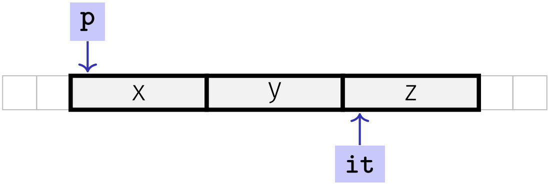


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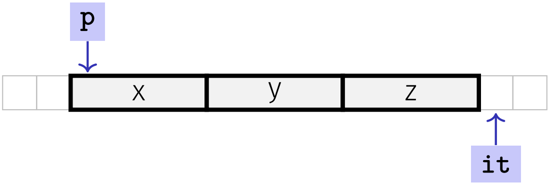


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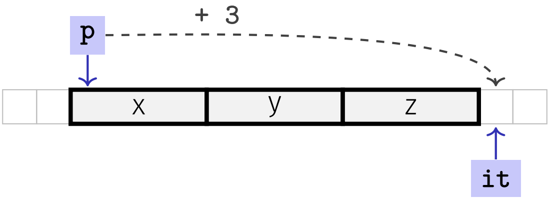



```
for (char* it = p;
     it != p + 3;
     ++it) {

  std::cout << *it << ' ';  // x y z
}
```

Random Access to Arrays

```
char* p = new char[3]{'x', 'y', 'z'};
```

- The expression `*(p + i)`
- can also be written as `p[i]`

Random Access to Arrays

```
char* p = new char[3]{'x', 'y', 'z'};
```

- The expression `*(p + i)`
- can also be written as `p[i]`
- E.g. `p[1] == *(p + 1) == 'y'`

Random Access to Arrays

iteration over an array via indices and *random access*:

```
char* p = new char[3]{'x', 'y', 'z'};

for (int i = 0; i < 3; ++i)
  std::cout << p[i] << ' ';
```

Random Access to Arrays

iteration over an array via indices and *random access*:

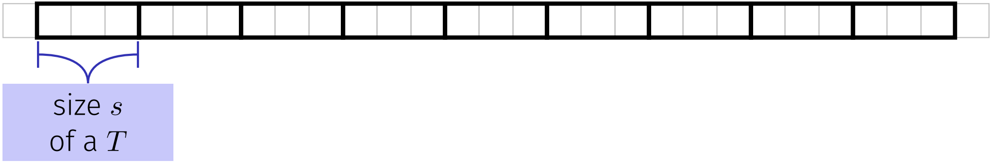
```
char* p = new char[3]{'x', 'y', 'z'};

for (int i = 0; i < 3; ++i)
  std::cout << p[i] << ' ';
```

But: this is less *efficient* than the previously shown *sequential* access via pointer iteration

Random Access to Arrays

T`* p = new `T`[n];`



Random Access to Arrays

```
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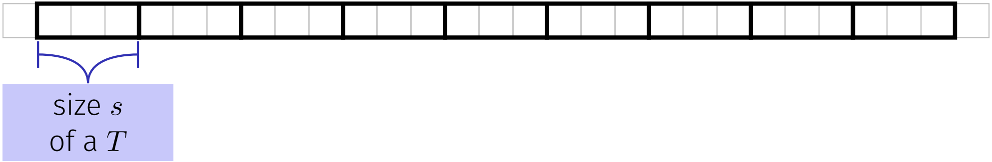

- Access **p[i]**, i.e. ***(p + i)**, "costs" computation $p + i \cdot s$

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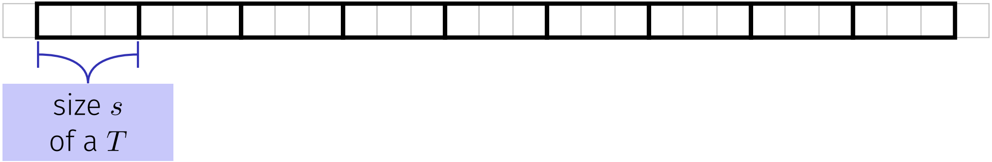

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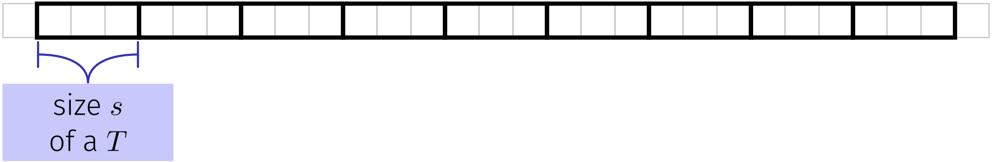

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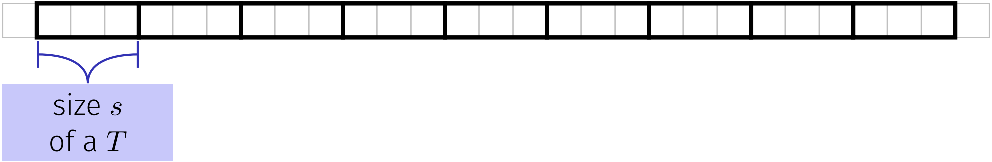

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- Iteration via *random access* (**p[0]**, **p[1]**, ...) costs one addition and one multiplication per access
- Iteration via *sequentiall access* (**++p**, **++p**, ...) costs only one addition per access
- Sequential access is thus to be preferred for iterations

Reading a book …with random access

Random Access

- open book on page 1
- close book
- open book on pages 2-3
- close book
- open book on pages 4-5
- close book
- ....

Reading a book …with sequential access

Random Access

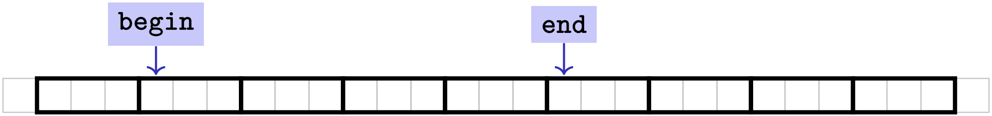
- open book on page 1
- close book
- open book on pages 2-3
- close book
- open book on pages 4-5
- close book
- ....

Sequential Access

- open book on page 1
- turn the page
- turn the page
- turn the page
- turn the page
- turn the page
- ...

Arrays in Functions

C++*covention*: arrays (or a segment of it) are passed using two pointers



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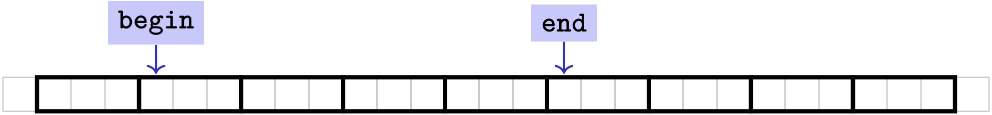

- `begin`: Pointer to the first element
- `end`: Pointer *past* the last element

Arrays in Functions

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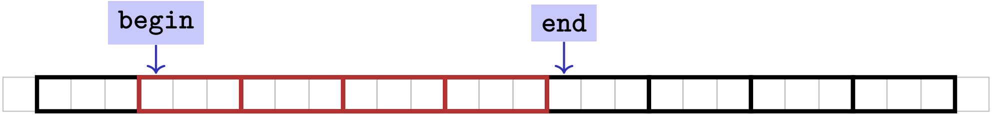

- **`begin`**: Pointer to the first element
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- **`[begin, end)`** Designates the elements of the segment of the array

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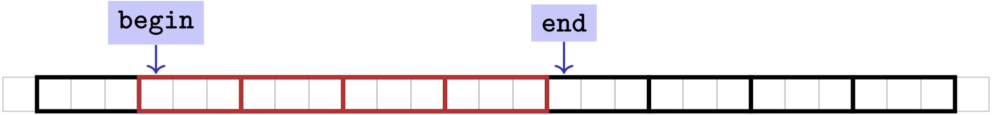

- **begin**: Pointer to the first element
- **end**: Pointer *past* the last element
- **[begin, end)** Designates the elements of the segment of the array
- **[begin, end)** is empty if **begin == end**
- **[begin, end)** must be a *valid range*, i.e. a (pot. empty) array segment

Arrays in (mutating) Functions: `fill`

```
// PRE: [begin, end) is a valid range
// POST: Every element within [begin, end) was set to value
void fill(int* begin, int* end, int value) {
  for (int* p = begin; p != end; ++p)
    *p = value;
}
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void fill(int* begin, int* end, int value) {
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    *p = value;
}
```

```
int* p = new int[5];
fill(p, p+5, 1); // Array at p becomes {1, 1, 1, 1, 1}
```

Functions with/without Effect

- Pointers can (like references) be used for functions with effect. Example: `fill`

Functions with/without Effect

- Pointers can (like references) be used for functions with effect. Example: **`fill`**
- But many functions don't have an effect, they only read the data
- $\Rightarrow$ Use of **`const`**

Functions with/without Effect

- Pointers can (like references) be used for functions with effect. Example: **`fill`**
- But many functions don't have an effect, they only read the data
- $\Rightarrow$ Use of **`const`**
- So far, for example:

```
const int zero = 0;
const int& nil = zero;
```

Positioning of Const

`const` T is equivalent to T **`const`** (and can be written like this):

```
const int zero = ...    ⟺   int const zero = ...
const int& nil = ...    ⟺   int const& nil = ...
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const int zero = ...   ⟺   int const zero = ...
const int& nil = ...   ⟺   int const& nil = ...
```

Both keyword orders are used in praxis

Const and Pointers

Read the declaration from right to left

`int const p;`	**p** is a constant integer

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Non-mutating Functions: `print`

```
// PRE: [begin, end) is a valid range
// POST: The values in [begin, end) were printed
void print(
    int const* const begin,
    const int* const end) {

  for (int const* p = begin; p != end; ++p)
    std::cout << *p << ' ';
}
```

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Likewise (but different keyword order)

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Pointer, *not const*, to const int

Arrays, `new`, Pointer: Conclusion

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- Memory allocated by **`new`** is *not* automatically released (more on this soon)
- Pointers and references are related, both “link” to objects in memory. See also additional the slides **`pointers.pdf`**)

Array-based Vector

- Vectors …that somehow rings a bell

Unser eigener Vektor!

- Wir implementieren unseren eigenen Vektor: `vec`
- Schritt 1: `vec<int>` (heute)
- Schritt 2: `vec<`T`>` (später, nur kurz angeschnitten)

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Array-based Vector

- Vectors ...that somehow rings a bell 🤔
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- ...we can implement a vector, based on such a chunk of memory
- **`avec`** – an array-based vector of **`int`** elements

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Array-based Vector `avec`: Class Signature

```
class avec {
  // Private (internal) state:
  int* elements;
  unsigned int count;






}
```

Pointer to first element

Array-based Vector avec: Class Signature

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class avec {
  // Private (internal) state:
  int* elements; // Pointer to first element
  unsigned int count;







}
```

Number of elements

Array-based Vector `avec`: Class Signature

```
class avec {
  // Private (internal) state:
  int* elements; // Pointer to first element
  unsigned int count; // Number of elements

public: // Public interface:
  avec(unsigned int size);
  unsigned int size() const;
  int& operator[](int i);
  void print(std::ostream& sink) const;
}
```

Constructor

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```

← Size of vector

Array-based Vector avec: Class Signature

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public: // Public interface:
  avec(unsigned int size); // Constructor
  unsigned int size() const; // Size of vector
  int& operator[](int i);
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}
```

Access an element

Array-based Vector avec: Class Signature

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  unsigned int count; // Number of elements

public: // Public interface:
  avec(unsigned int size); // Constructor
  unsigned int size() const; // Size of vector
  int& operator[](int i); // Access an element
  void print(std::ostream& sink) const;
}
```

Output elements

Array-based Vector avec: Class Signature

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  unsigned int count; // Number of elements

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  avec(unsigned int size); // Constructor
  unsigned int size() const; // Size of vector
  int& operator[](int i); // Access an element
  void print(std::ostream& sink) const; // Output elems.
}
```

Constructor `avec::avec()`

```
avec::avec(unsigned int size)
        : count(size)  {

  elements = new int[size];
}
```

Save size

Constructor `avec::avec()`

```
avec::avec(unsigned int size)
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  elements = new int[size];
}
```

← Allocate memory

Constructor `avec::avec()`

```
avec::avec(unsigned int size)
        : count(size)  {

  elements = new int[size];
}
```

Side remark: vector is not initialised with a default value

Excursion: Accessing Member Variables

```
avec::avec(unsigned int size): count(size) {
  elements = new int[size];
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```

- **`elements`** is a member variable of our **`avec`** instance

Excursion: Accessing Member Variables

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Excursion: Accessing Member Variables

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avec::avec(unsigned int size): count(size) {
  (*this).elements = new int[size];
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```

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- **`elements`** is a shorthand for **`(*this).elements`**

Excursion: Accessing Member Variables

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avec::avec(unsigned int size): count(size) {
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- Equivalent, but shorter: **`this->elements`**
- Mnemonic trick: “Follow the pointer to the member variable”

Function `avec::size()`

```
int avec::size() const  {
  return this->count;
}
```

Doesn't modify the vector

Function `avec::size()`

```
int avec::size() const  {
  return this->count;
}
```

Return size

Usage example:

```
avec v = avec(7);
assert(v.size() == 7); // ok
```

Function `avec::operator[]`

```
int& avec::operator[](int i) {
  return this->elements[i];
}
```

← Return `i`th element

Function avec::operator[]

```
int& avec::operator[](int i) {
  return this->elements[i];
}
```

Element access with index check:

```
int& avec::at(int i) const {
  assert(0 <= i && i < this->count);

  return this->elements[i];
}
```

Function avec::operator[]

```
int& avec::operator[](int i) {
  return this->elements[i];
}
```

Usage example:

```
avec v = avec(7);
std::cout << v[6]; // Outputs a "random" value
v[6] = 0;
std::cout << v[6]; // Outputs 0
```

Function `avec::print()`

Output elements using sequential access:

```
void avec::print(std::ostream& sink) const {
  for (int* p = this->elements;
       p != this->elements + this->count;
       ++p)
  {
    sink << *p << ' ';
  }
}
```

← Pointer to first element

Function avec::print()

Output elements using sequential access:

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void avec::print(std::ostream& sink) const {
  for (int* p = this->elements;
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  {
    sink << *p << ' ';
  }
}
```

Abort iteration if past last element

Function `avec::print()`

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  for (int* p = this->elements;
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```

Advance pointer element-wise

Function `avec::print()`

Output elements using sequential access:

```
void avec::print(std::ostream& sink) const {
  for (int* p = this->elements;
       p != this->elements + this->count;
       ++p)
  {
    sink << *p << ' ';
  }
}
```

Output current element

Function `avec::print()`

Finally: overload output operator:

```
______________ operator<<(______________ sink,
                          ______________ vec) {
  vec.print(sink);
  return ______________;
}
```

Function `avec::print()`

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std::ostream& operator<<(std::ostream& sink,
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Observations:

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- But not to **`sink`**: Outputing elements equals change

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Finally: overload output operator:

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std::ostream& operator<<(std::ostream& sink,
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  vec.print(sink);
  return sink;
}
```

Observations:

- Constant reference to **`vec`**, since unchanged
- But not to **`sink`**: Outputing elements equals change
- **`sink`** is returned to enable output chaining, e.g.
  `std::cout << v << '\n'`

Further Functions?

```
class avec {
  ...
  void push_front(int e)        // Prepend e to vector
  void push_back(int e)         // Append e to vector
  void remove(unsigned int i)   // Cut out ith element
  ...
}
```

Further Functions?

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class avec {
  ...
  void push_front(int e)       // Prepend e to vector
  void push_back(int e)        // Append e to vector
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  ...
}
```

Commonalities: such operations need to change the vector's *size*

Resizing arrays

An allocated block of memory (e.g. `new int[3]`) cannot be resized later on

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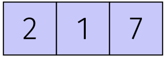

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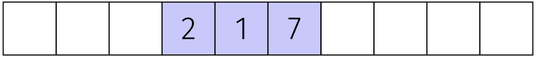
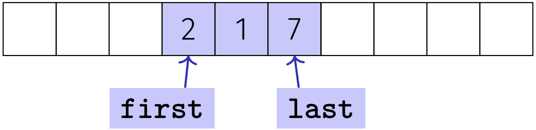


Possibility:

- Allocate more memory than initially necessary

Resizing arrays

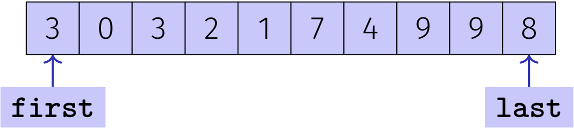
An allocated block of memory (e.g. **`new int[3]`**) cannot be resized later on



Possibility:

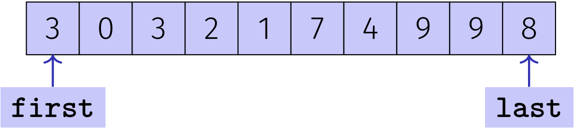
- Allocate more memory than initially necessary
- Fill from inside out, with pointers to first and last element

Resizing arrays



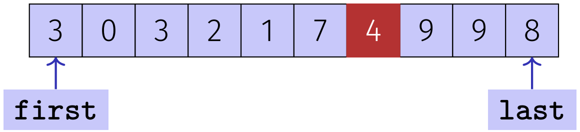
- But eventually, all slots will be in use

Resizing arrays



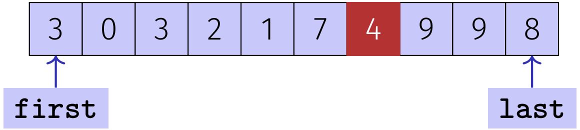
- But eventually, all slots will be in use
- Then unavoidable: Allocate larger memory block and copy data over

Resizing arrays

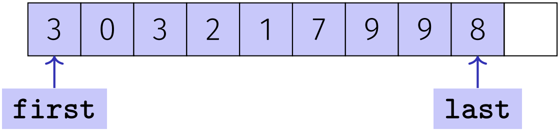


Deleting elements requires shifting (by copying) all preceding or following elements

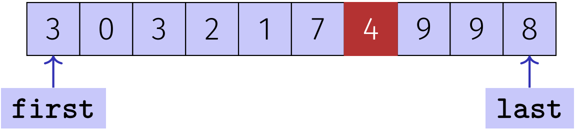
Resizing arrays



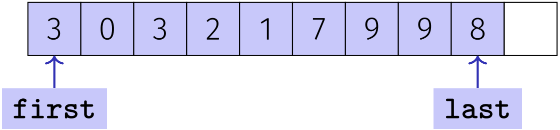
Deleting elements requires shifting (by copying) all preceding or following elements



Resizing arrays



Deleting elements requires shifting (by copying) all preceding or following elements



Similar: inserting at arbitrary position