

20. Dynamic Data Structures I

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

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v.push_front(e);  // Prepend element
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...
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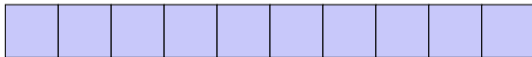
- A vector is a *dynamic data structure*, whose size may change at runtime

Our Own Vector!

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

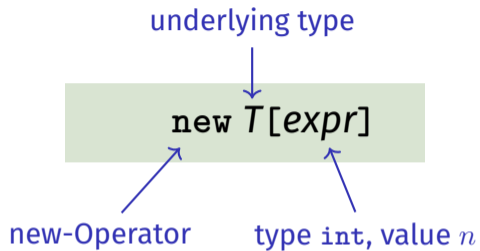
Vectors in Memory

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

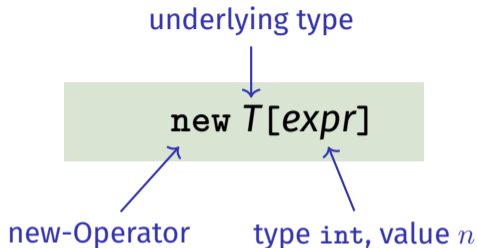


Question: How to *allocate* a chunk of memory of *arbitrary* size during runtime, i.e. *dynamically*?

new for Arrays



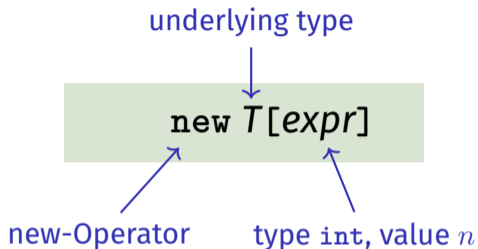
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- **Effect:** new contiguous chunk of memory n elements of type T is allocated



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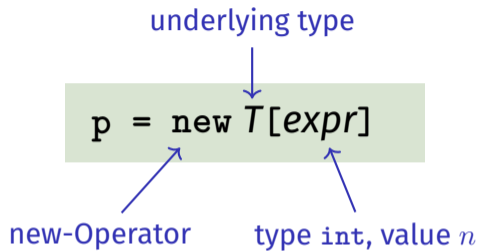


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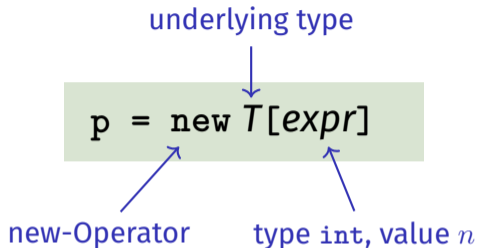


- This chunk of memory is called an *array* (of length n)

new for Arrays



new for Arrays



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



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

Outlook I: `new` and `delete`

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new T[expr]
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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

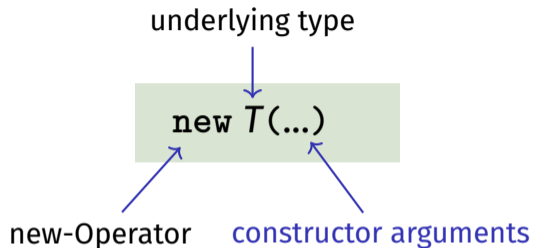
Outlook II: Today's Lecture

- Goal: understanding pointers and dynamic memory/dynamically allocated objects
- Running example: own vector
- Outline:
 1. *individual* dynamically allocated objects
→ introduce pointers, explain basics
 2. *array* of dynamically allocated objects
→ introduce pointer arithmetic, explain random and sequential access
 3. develop *vector class*, based on a dynamic array
→ application of pointers in a nontrivial example; class design

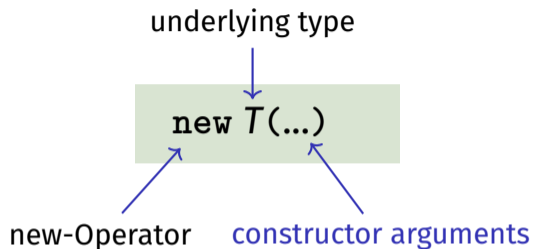
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- Course website: Experiment with the example code (e.g. Tiny Pointer Example 1/2), have a look at the slides on references vs. pointers (Additional Pointer Slides)

new (Without Arrays)

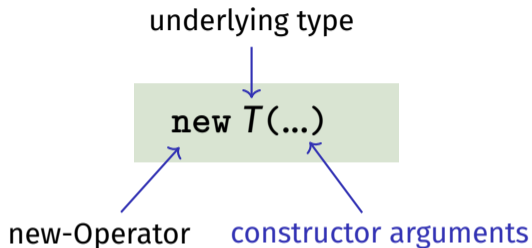


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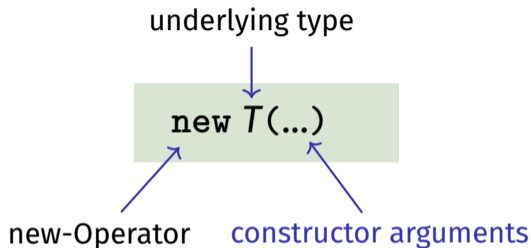
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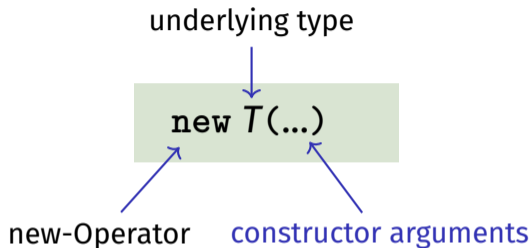
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new (Without Arrays)



- **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)*

```
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

Pointer Types

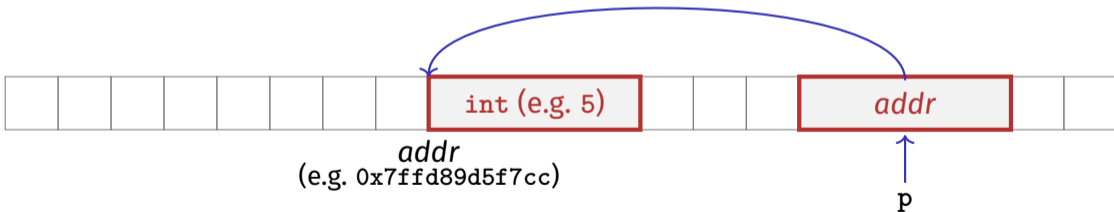
Value of a pointer to T is the *address* of an object of type T

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int* p = ...;  
std::cout << p; // e.g. 0x7ffd89d5f7cc
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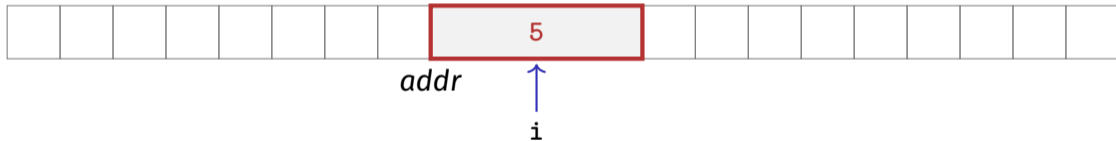
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- **Value** of the expression: the *address* of object (l-value) `expr`
- **Type** of the expression: A pointer `T*` (of type `T`)

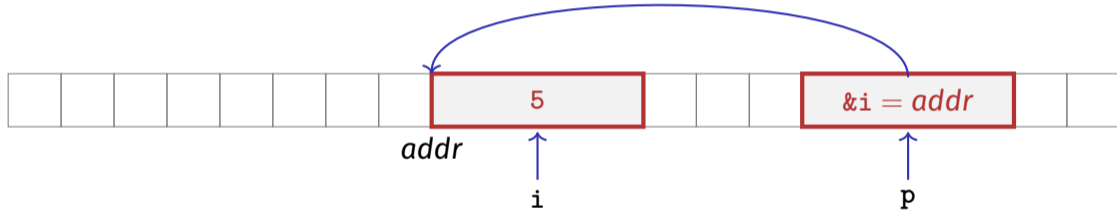
Address Operator

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



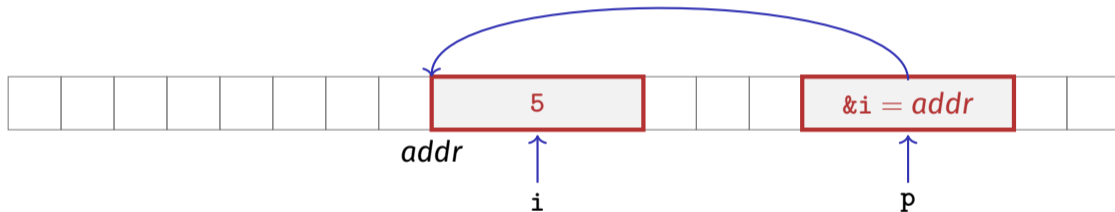
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int* p = &i; // p initialised with address of i
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Next question: How to “follow” a pointer?

Dereference Operator

Answer: by using the *dereference operator* *

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Dereference Operator

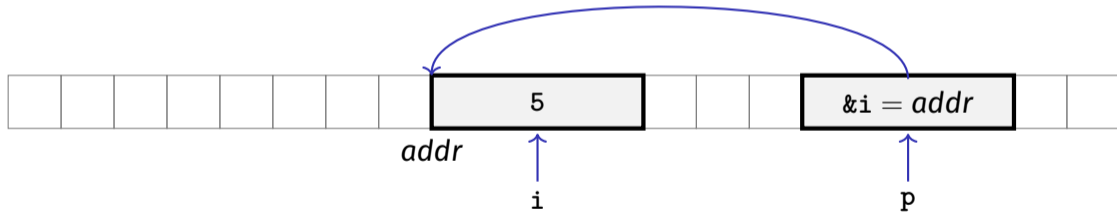
Answer: by using the *dereference operator* *

`*expr` ← *expr*: r-value of type T^*

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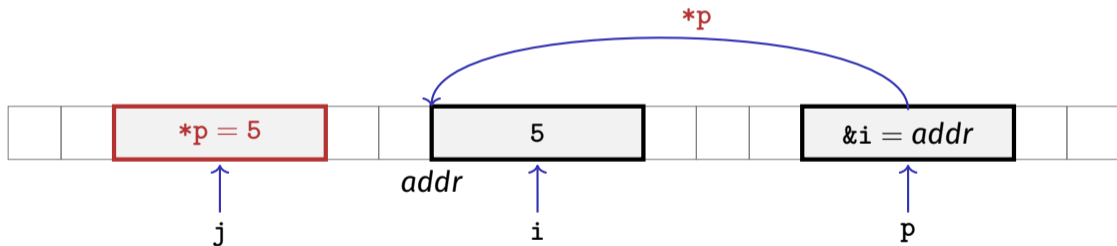
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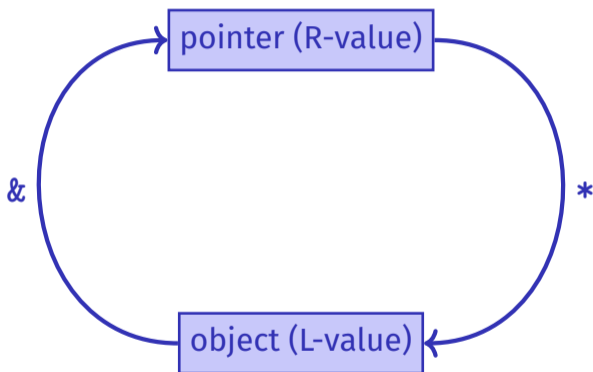


Dereference Operator

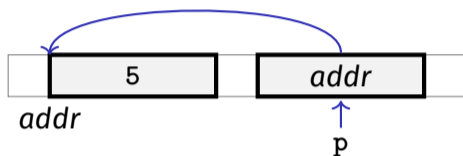
```
int i = 5;  
int* p = &i; // p = address of i  
int j = *p; // j = 5
```



Address and Dereference Operator

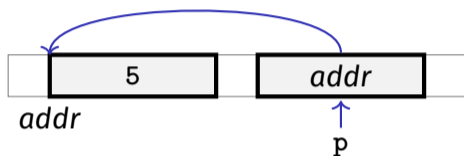


Pointer Visualisations

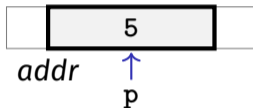


- So far: technically precise visualisation *with indirection*
- `p` holds an address, only `*p` yields the value/object that `p` conceptually points to

Pointer Visualisations



- So far: technically precise visualisation *with indirection*
- `p` holds an address, only `*p` yields the value/object that `p` conceptually points to



- New: simplified visualisation *without indirection*
- Address is only a “technical mean”; relevant is what `p` conceptually points to

Mnemonic Trick

The declaration

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

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 by 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
```



Question: How to point to rear elements?

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

- p yields the *value* of the *first* array element, $*p$ its *value*
- $*(p + i)$ yields the value of the *i*th array element, for $0 \leq i < n$
- $*p$ is equivalent to $*(p + 0)$

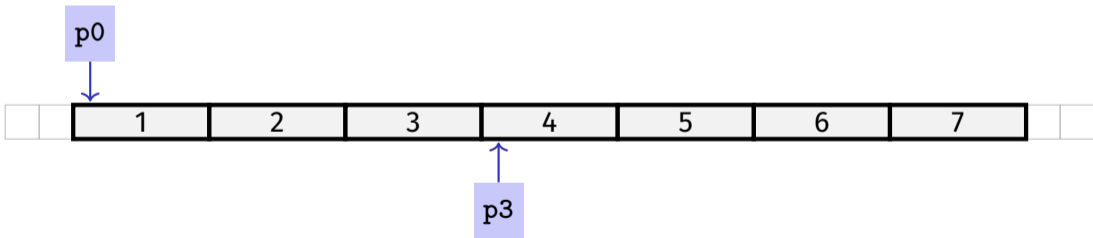
Pointer Arithmetic: Pointer plus int

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



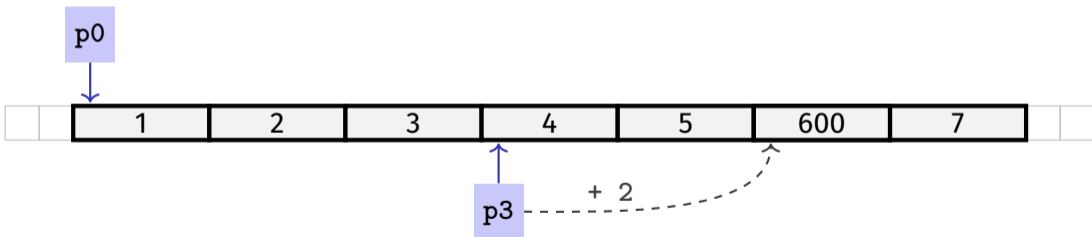
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int* p3 = p0 + 3; // p3 points to 4th element
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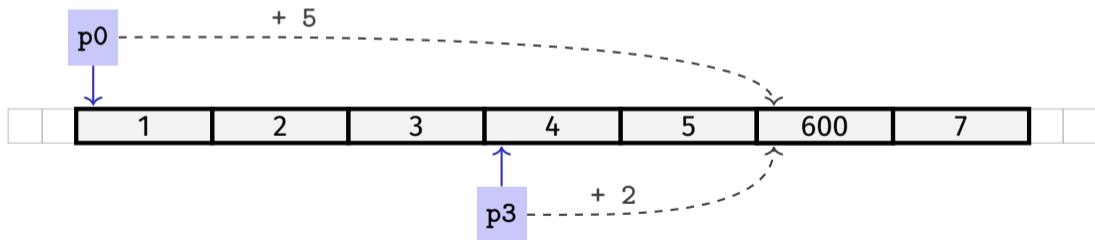
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int* p0 = new int[7]{1,2,3,4,5,6,7}; // p0 points to 1st element
int* p3 = p0 + 3; // p3 points to 4th element
*(p3 + 2) = 600; // set value of 6th element to 600
std::cout << *(p0 + 5);
```



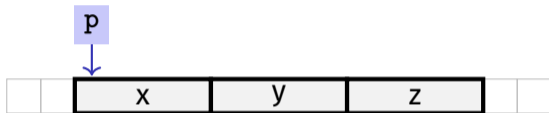
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std::cout << *(p0 + 5); // output 6th element's value (i.e. 600)
```



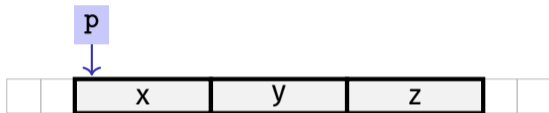
Sequential Pointer Iteration

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

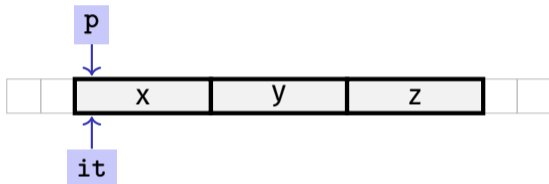
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char* p = new char[3]{'x', 'y', 'z'};
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```
for (char* it = p;  
     it != p + 3;  
     ++it) {  
  
    std::cout << *it << ' ';  
}
```


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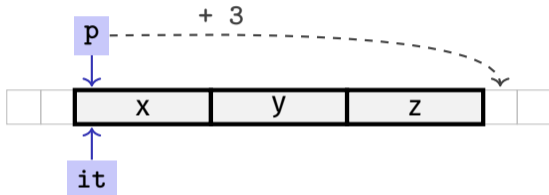


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Sequential Pointer Iteration

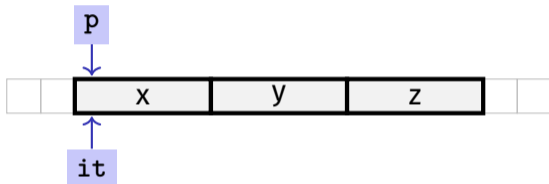
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```



```
for (char* it = p;  
    it != p + 3; Abort if end reached  
    ++it) {  
  
    std::cout << *it << ' ';  
}
```

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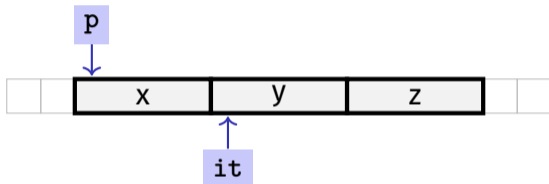
```
    std::cout << *it << ' ';
```

← Output current element: 'x'

```
}
```

Sequential Pointer Iteration

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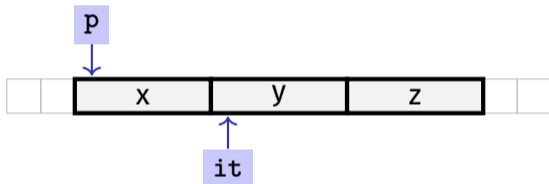
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```

Advance pointer element-wise

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

Sequential Pointer Iteration

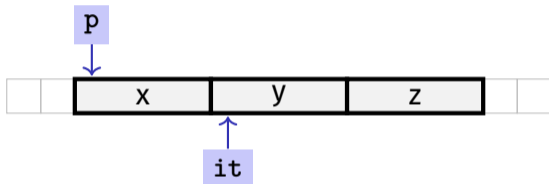
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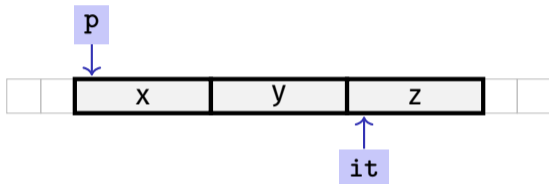
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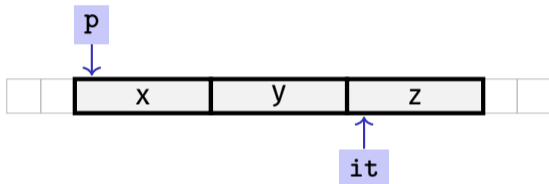
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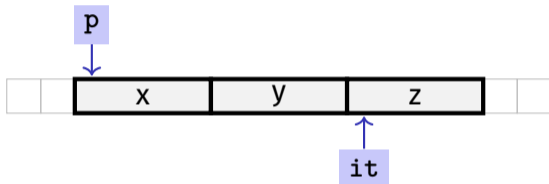
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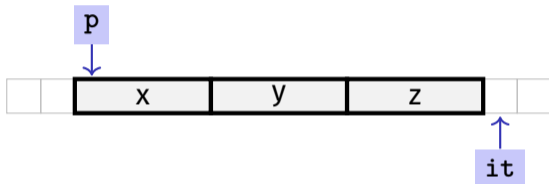
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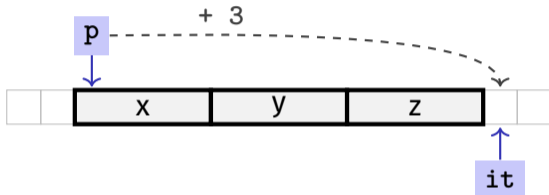
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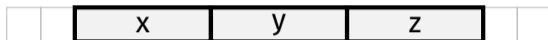
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Random Access to Arrays

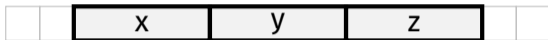
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Random Access to Arrays

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- 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

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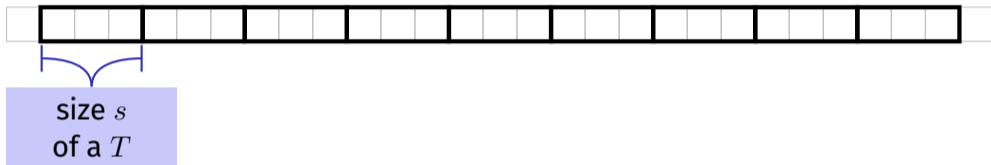
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for (int i = 0; i < 3; ++i)
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```

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

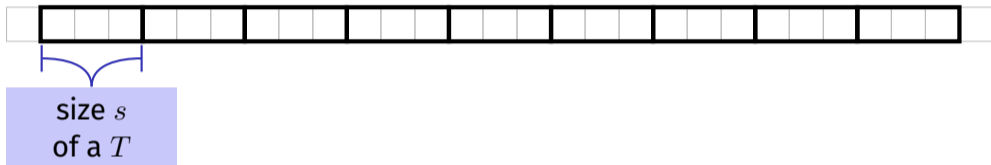
Random Access to Arrays

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



Random Access to Arrays

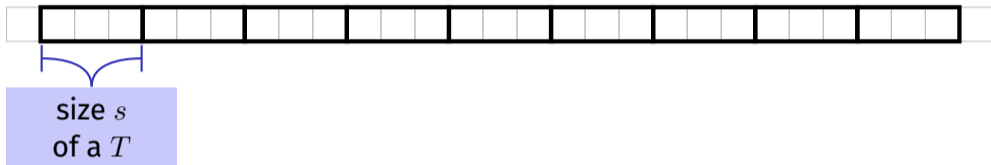
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- Access $p[i]$, i.e. $*(p + i)$, “costs” computation $p + i \cdot s$

Random Access to Arrays

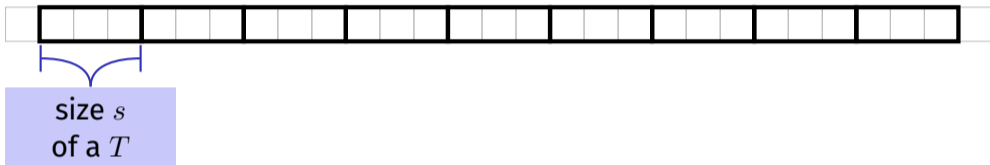
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- Access $p[i]$, i.e. $*(p + i)$, “costs” computation $p + i \cdot s$
- Iteration via *random access* ($p[0], p[1], \dots$) costs one addition and one multiplication per access

Random Access to Arrays

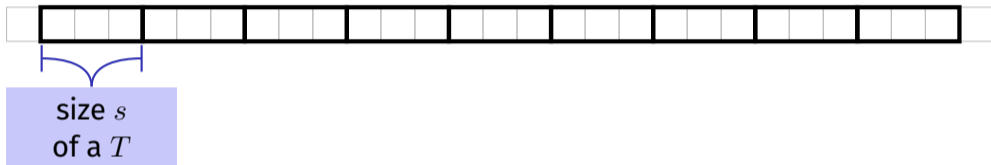
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- Iteration via *random access* ($p[0], p[1], \dots$) costs one addition and one multiplication per access
- Iteration via *sequential access* ($++p, ++p, \dots$) costs only one addition per access

Random Access to Arrays

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



- Access $p[i]$, i.e. $*(p + i)$, “costs” computation $p + i \cdot s$
- Iteration via *random access* ($p[0], p[1], \dots$) costs one addition and one multiplication per access
- Iteration via *sequential access* ($++p, ++p, \dots$) 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
-

Random Access

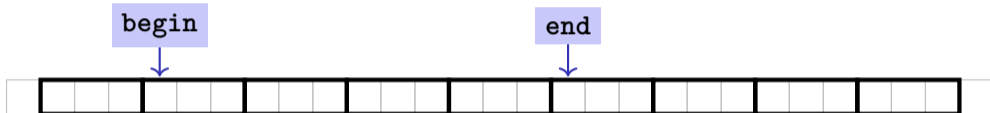
- open book on page 1
- close book
- open book on pages 2-3
- close book
- open book on pages 4-5
- close book
-

Sequential Access

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

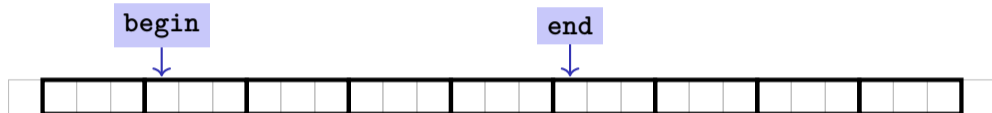
Arrays in Functions

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



Arrays in Functions

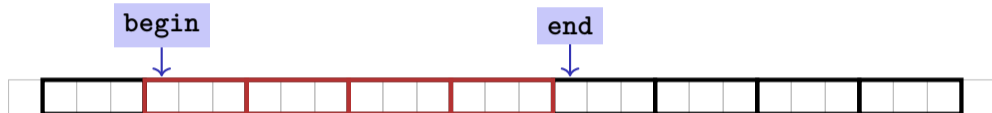
C++ *covention*: arrays (or a segment of it) are passed using two pointers



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

Arrays in Functions

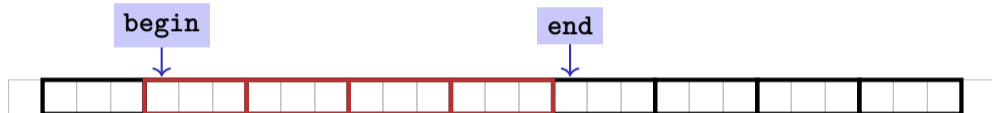
C++ *covention*: arrays (or a segment of it) are passed using two pointers



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- **[begin, end)** Designates the elements of the segment of the array

Arrays in Functions

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



- **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;
}
```

Arrays in (mutating) Functions: fill

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void fill(int* begin, int* end, int value) {
    for (int* p = begin; p != end; ++p)
        *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 effect⁶. Example:
`fill`

⁶on the data specified by the pointer(intervals)

Functions with/without Effect

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- But many functions don't modify but only read the data
- \Rightarrow Use of `const`

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Functions with/without Effect

- Pointers can (like references) be used for functions with effect⁶. Example: `fill`
- But many functions don't modify but only read the data
- \Rightarrow Use of `const`
- So far, for example:

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

⁶on the data specified by the pointer(intervals)

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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```

Both keyword orders are used in praxis

Const and Pointers

Read the declaration from right to left

```
int const p1;
```

p1 is a constant integer

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p2 is a pointer to a constant integer

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Read the declaration from right to left

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int const p1;
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p1 is a constant integer

```
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```

p2 is a pointer to a constant integer

```
int* const p3;
```

p3 is a constant pointer to an integer

Const and Pointers

Read the declaration from right to left

<code>int const p1;</code>	p1 is a constant integer
<code>int const* p2;</code>	p2 is a pointer to a constant integer
<code>int* const p3;</code>	p3 is a constant pointer to an integer
<code>int const* const p4;</code>	p4 is a constant pointer to a constant integer

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 << ' ';
}
```

Non-mutating Functions: print

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```
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```

Const pointer to const int

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

Likewise (but different keyword order)

```
}
```

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Likewise (but different keyword order)

Pointer, *not const*, to const int

Arrays, new, Pointer: Conclusion

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- Pointers can point to something (not) `const`, and they can be (not) `const` themselves
- 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 🤔
- Now we know how to allocate memory chunks of arbitrary size ...
- ...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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public: // Public interface:  
    avec(unsigned int size); // Constructor  
    unsigned int size() const; ← Size of vector  
    int& operator[](int i);  
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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;  
}
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Output elements

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    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)
    : count(size) {

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

Allocate memory



Constructor avec::avec()

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

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

Attention: vector has not been initialised (with some default value, e.g. 0)

Function avec::size()

```
int avec::size() const ←  
    return count;  
}
```

Doesn't modify the vector

Function avec::size()

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



Return size

Usage example:

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

Excursion: Accessing Member Variables

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

```
avec v1 = ...;  
avec v2 = ...;  
std::cout << v1.size();
```

Excursion: Accessing Member Variables

```
int avec::size() const {  
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avec v1 = ...;  
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std::cout << v1.size();
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- Call `v1.size()`: `size()` returns value of the member variable `count` of `v1`

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- Question: how can member function `size()` refer to *receiver object* `v1`?

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- Call `v1.size()`: `size()` returns value of the member variable `count` of `v1`
- Question: how can member function `size()` refer to *receiver object* `v1`?
- Via the special `this` pointer (briefly introduced last week)
- Three possibilities:
 - `return (*this).count` Explicit, but cumbersome syntax
 - `return this->count` Explicit, nicer syntax
 - `return count` Implicit
- Mnemonic trick: “Follow the pointer to the member variable”

Function avec::operator []

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

Return ith 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);  
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;  Pointer to first element  
        p != this->elements + this->count;  
        ++p)  
    {  
        sink << *p << ' ' ;  
    }  
}
```

Function avec::print()

Output elements using sequential access:

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```



Abort iteration if
past last element

Function avec::print()

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← Advance pointer element-wise

Function avec::print()

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    {  
        sink << *p << ' '; ←  
    }  
}
```

Output current element

Function avec ::print()

Finally: overload output operator:

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

Function `avec::print()`

Finally: overload output operator:

```
std::ostream& operator<<(std::ostream& sink,  
                        const avec& vec) {  
    vec.print(sink);  
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Function `avec::print()`

Finally: overload output operator:

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Observations:

- Constant reference to `vec`, since unchanged

Function `avec::print()`

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- Constant reference to `vec`, since unchanged
- But not to `sink`: Outputting elements equals change

Function `avec::print()`

Finally: overload output operator:

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

Observations:

- Constant reference to `vec`, since unchanged
- But not to `sink`: Outputting 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?

```
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

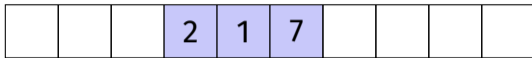
Resizing arrays

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2	1	7
---	---	---

Resizing arrays

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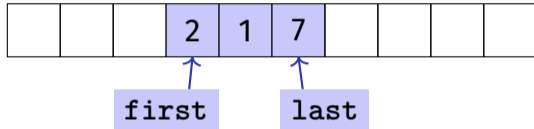


Possibility:

- Allocate more memory than initially necessary

Resizing arrays

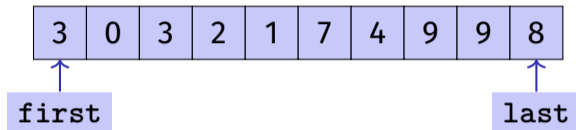
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Possibility:

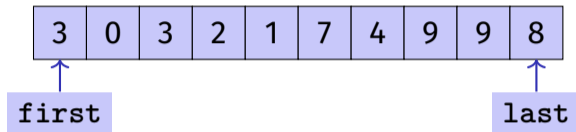
- Allocate more memory than initially necessary
- Fill from inside out, with pointers to first and last element

Resizing arrays



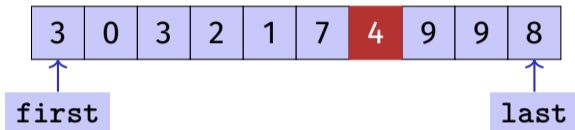
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Resizing arrays



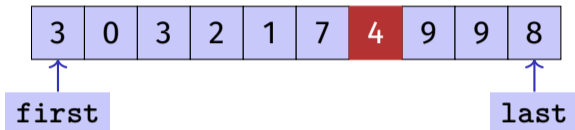
- But eventually, all slots will be in use
- Then unavoidable: Allocate larger memory block and copy data over

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

