18. Dynamic Data Structures I

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

Recap: `vector<`T`>`

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v[i] = e;          // Set element
l = v.size();      // Get size
v.push_front(e);   // Prepend element
v.push_back(e);    // Append element
...
```

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```

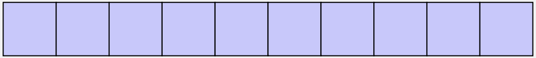
- A vector is a *dynamic data structure*, whose size may change at runtime

Our Own Vector!

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

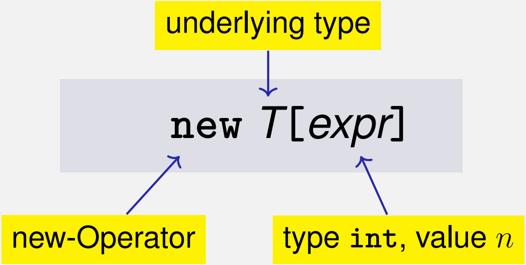
Vectors in Memory

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



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

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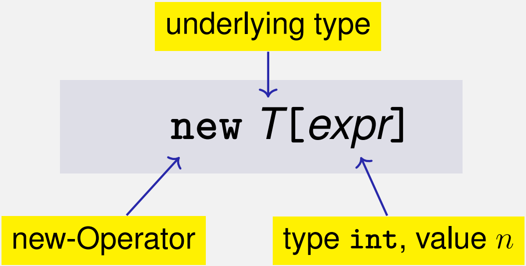

- **Effect**: new contiguous chunk of memory n elements of type *T* is allocated

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

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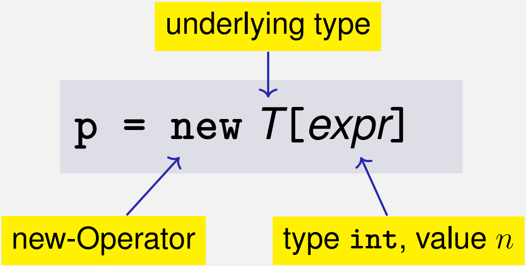
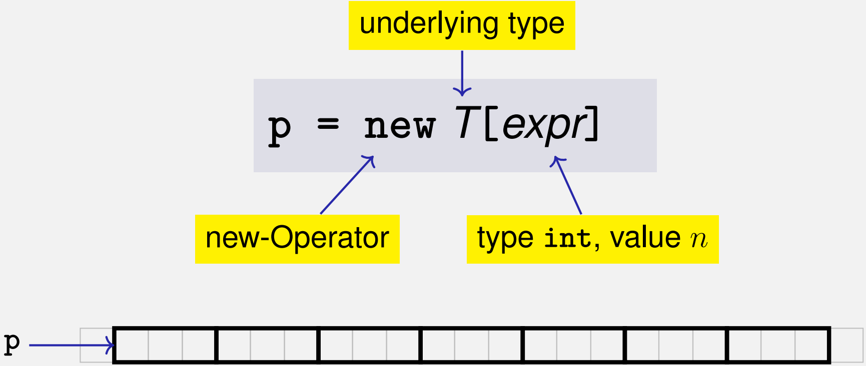


- **Type**: A pointer $T*$ (more soon)

`new` for Arrays



- **Type**: A pointer $T*$ (more soon)
- **Value**: the starting address of the memory chunk

Outlook: `new` and `delete`

new *T*[*expr*]

- So far: memory (local variables, function arguments) "lives" only inside a function call

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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)

underlying type

```
new T(...)
```

new-Operator

constructor arguments

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- **Effect**: memory for a new object of type *T* is allocated . . .
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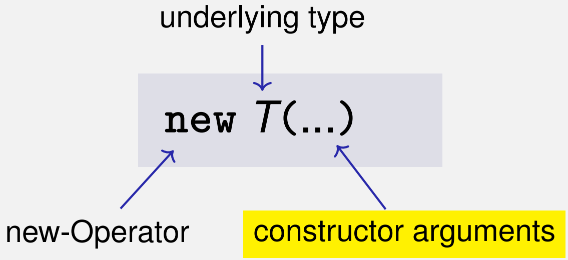
- **Value**: address of the new T object, **Type**: Pointer $T*$

`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`

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

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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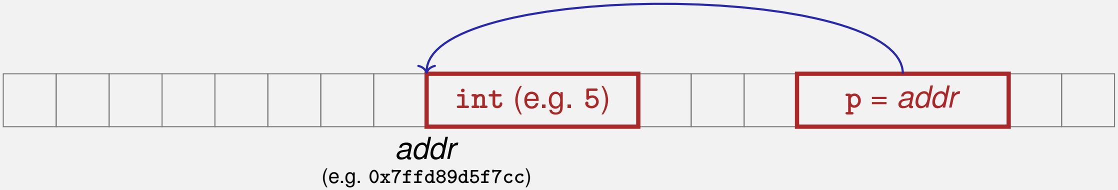

Address Operator

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

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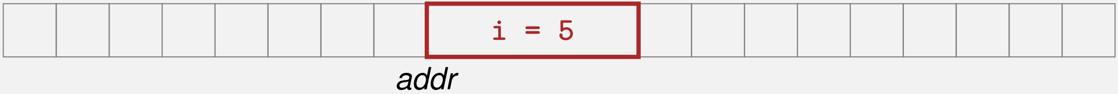
2. For existing objects: via the *address operator* &

&*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)

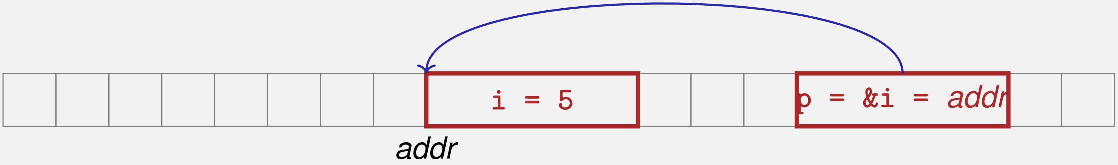
Address Operator

```
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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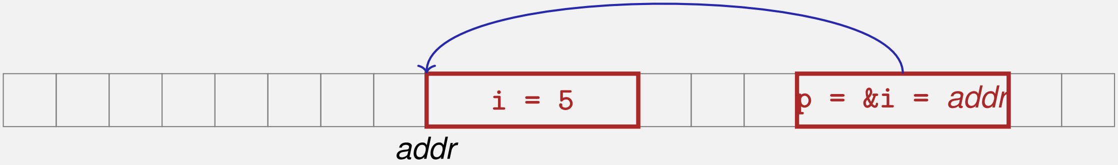

Next question: How to “follow” a pointer?

Dereference Operator

Answer: by using the *dereference operator* ∗

∗*expr* ← r-value of type T*

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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Answer: by using the *dereference operator* ∗

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Dereference Operator

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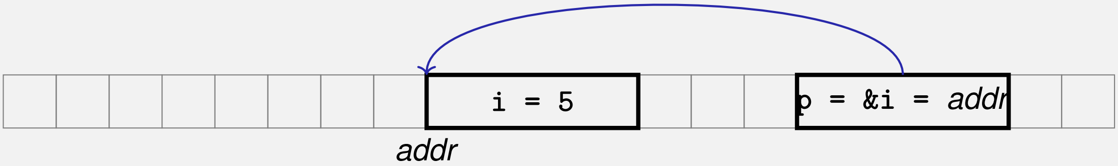

Dereference Operator

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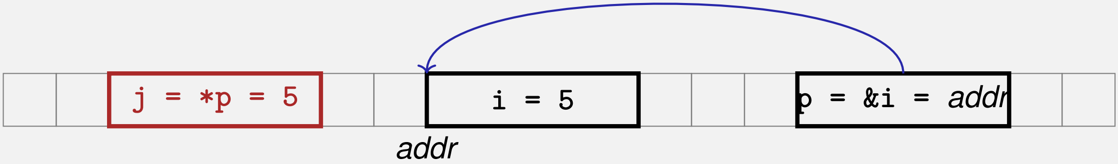
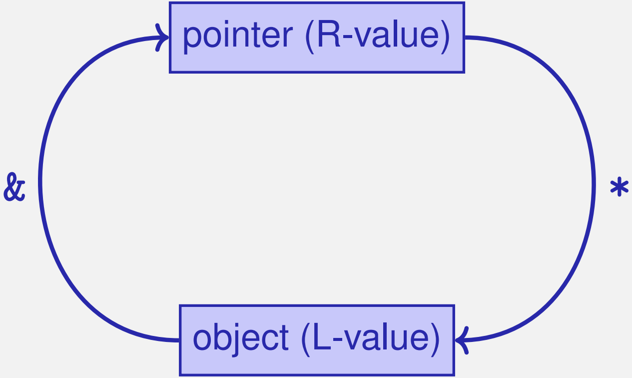
int* p = &i; // p = address of i
int j = *p; // j = 5
```



Address and Dereference Operator



Pointer Types

A T* must actually point to a T

```
int* p = ...;  // p points to an int
double* q = p; // but q to a double → compiler error!
```

Mnenmonic 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"
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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*`)

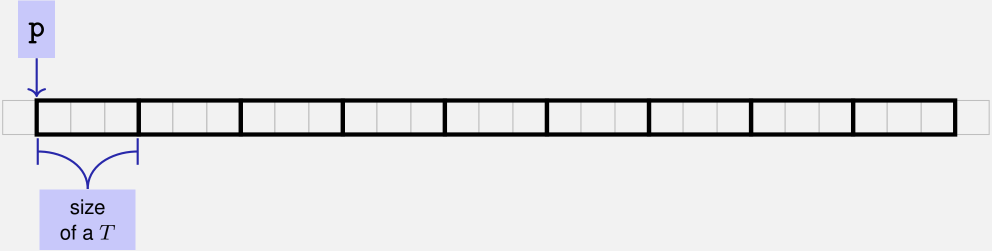
```
int* p = nullptr;
```

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

```
int* p; // p could point to anything
int* q = nullptr; // q explicitly points nowhere
```

Pointer Arithmetic: Pointer plus `int`

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



How to point to rear elements?

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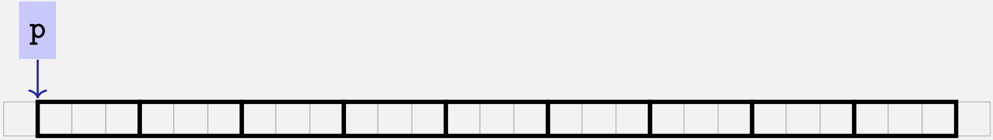

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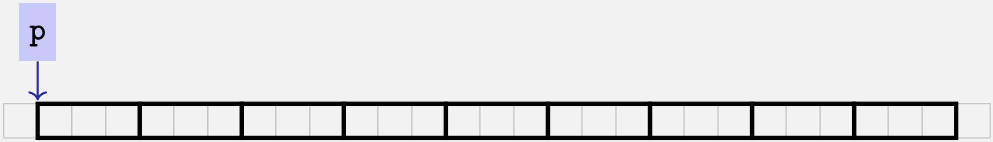

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- `p` yields the *value* of the *first* array element, `*p` its *value*

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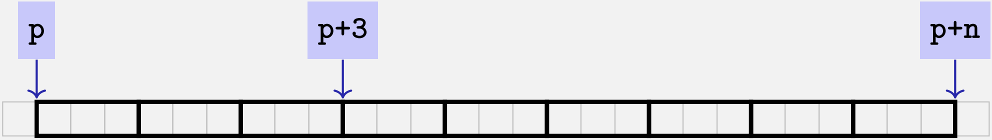

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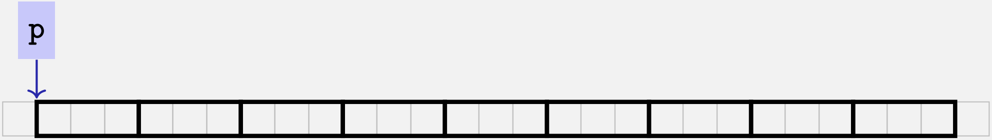

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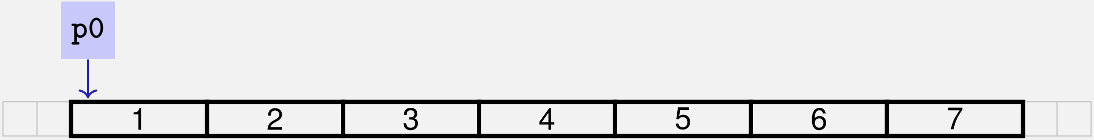
- `p` yields the *value* of the *first* array element, `*p` its *value*
- `*(p + i)` yields the value of the `i`*th* array element, for $0 \leq$ `i` $<$ `n`
- `*p` is equivalent to `*(p + 0)`

Pointer Arithmetic: Pointer plus `int`

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



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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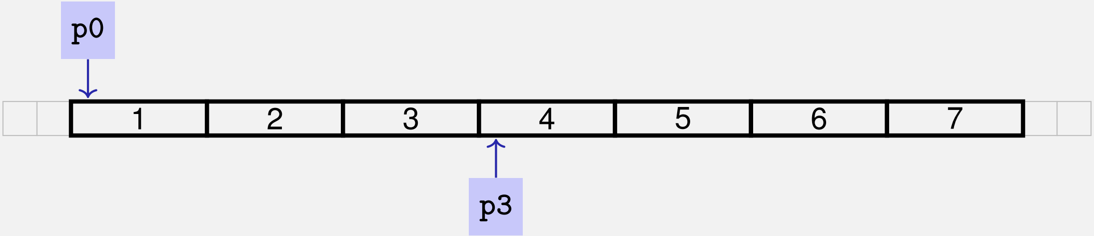

Pointer Arithmetic: Pointer plus `int`

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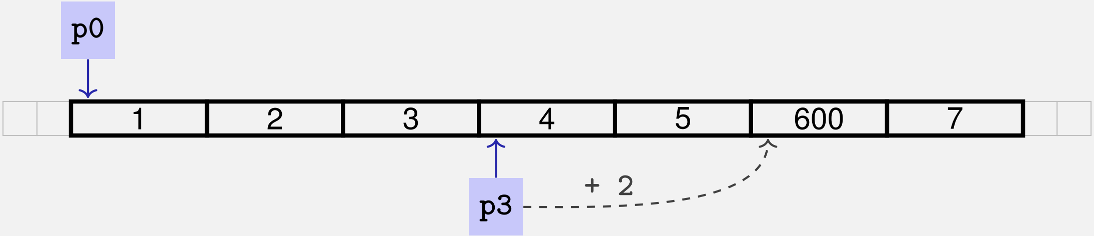
int* p0 = new int[7]{1,2,3,4,5,6,7}; // p0 points to 1st element
int* p3 = p0 + 3; // p3 points to 4th element
*(p3 + 2) = 600; // set value of 6th element to 600
std::cout << *(p0 + 5);
```



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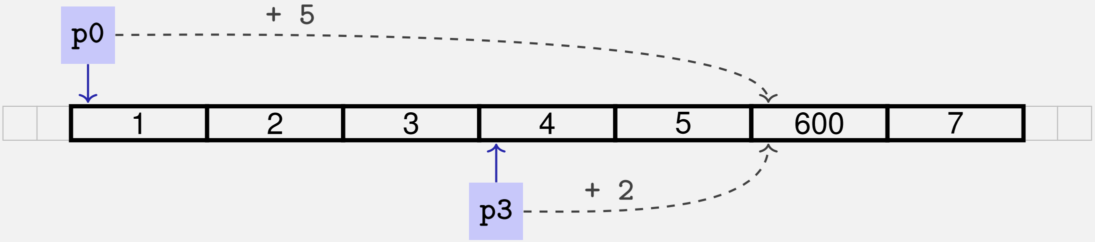
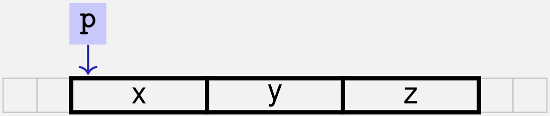
std::cout << *(p0 + 5); // output 6th element's value (i.e. 600)
```



Sequential Pointer Iteration

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



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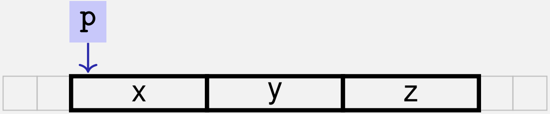


```
for (char* it = p;
        it != p + 3;
        ++it) {

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

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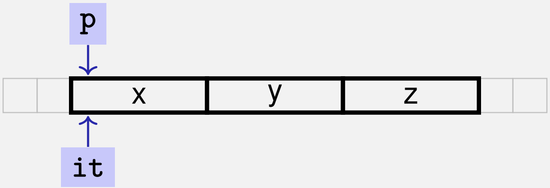


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for (char* it = p;
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```

it points to first element

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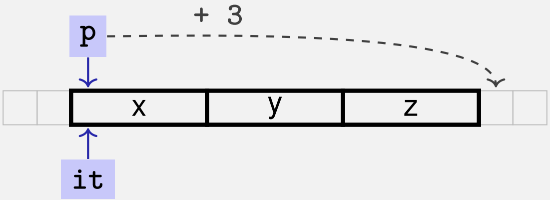


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```

Abort if end reached

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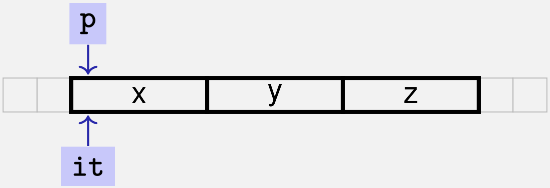


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for (char* it = p;
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    std::cout << *it << ' ';
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```

Output current element: 'x'

Sequential Pointer Iteration

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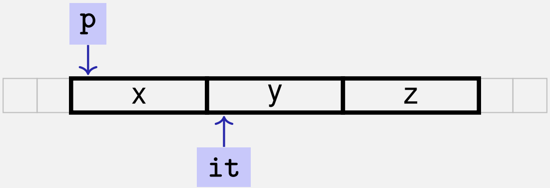


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    std::cout << *it << ' ';  // x
}
```

Advance pointer element-wise

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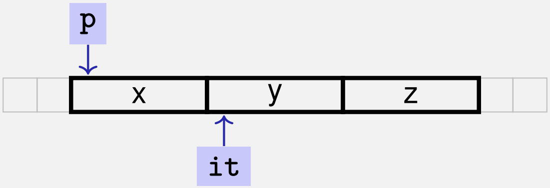


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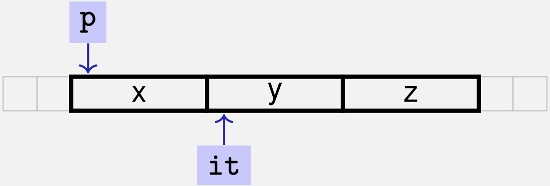


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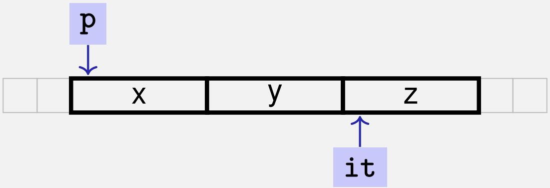


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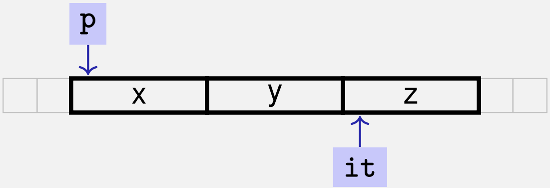


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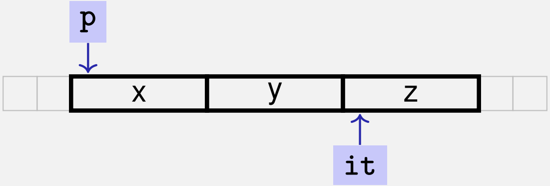


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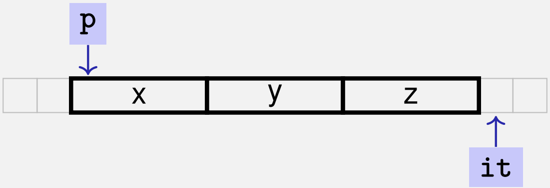


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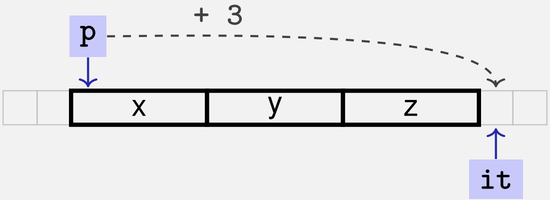


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Random Access to Arrays

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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*:

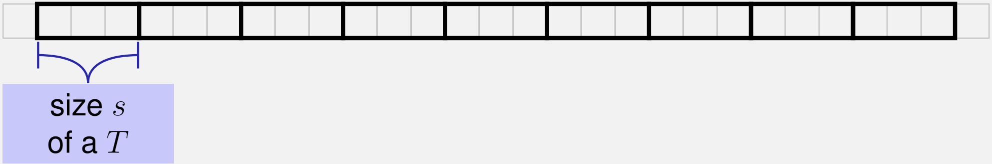
```
char* p = new char[3]{'x', 'y', 'z'};

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

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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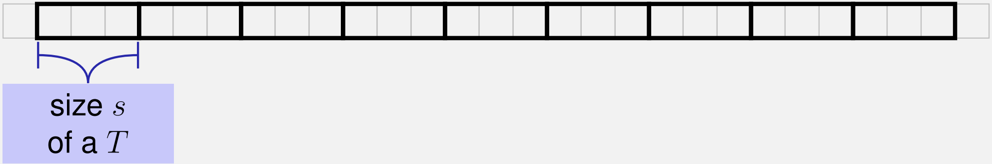

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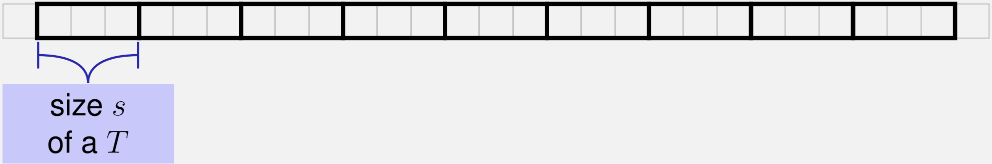

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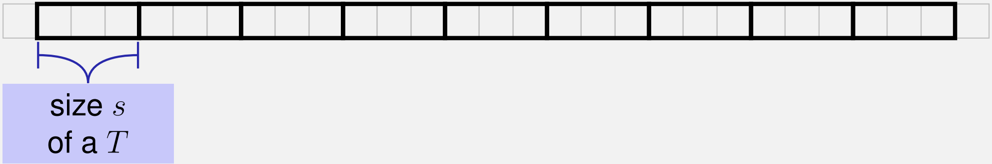

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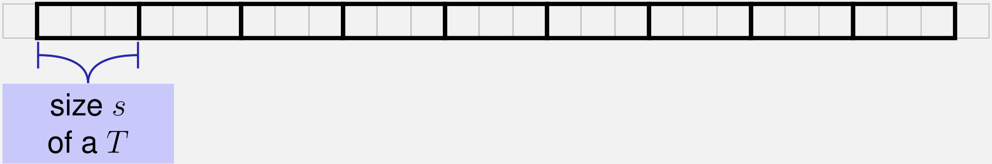

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- Iteration via *sequentiall access* (`++p`, `++p`, ...) costs only one addition per access
- Sequential access is thus to be preferred for iterations

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

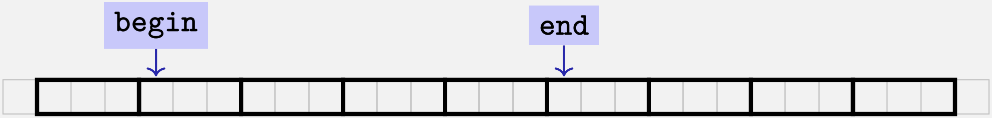
- open book on page 1
- close book
- open book on pages 2-3
- close book
- open book on pages 4-5
- close book
- ....

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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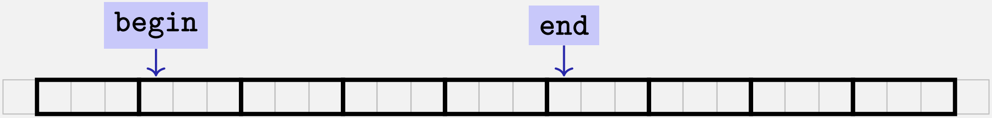

- `begin`: Pointer to the first element
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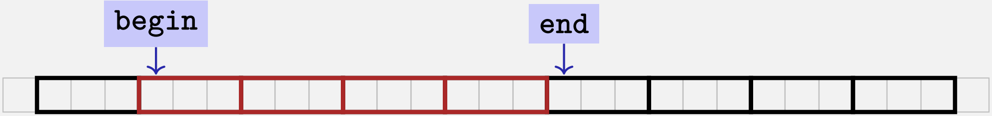

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Arrays in Functions

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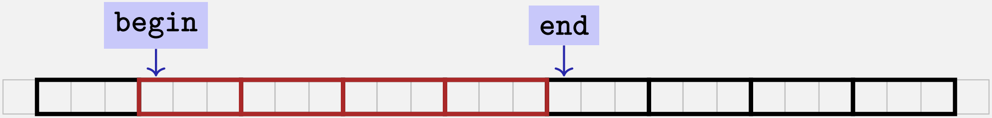

- `begin`: Pointer to the first element
- `end`: Pointer *past* the last element
- `[begin, end)` Designates the elements of the segment of the array
- `[begin, end)` is empty if `begin == end`
- `[begin, end)` must be a *valid range*, i.e. a (pot. empty) array segment

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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}


...
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`

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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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```

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

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// PRE: [begin, end) is a valid range
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void print(
    int const* const begin,
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Pointer, *not const*, to const int

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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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- `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 {
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  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

Array-based Vector `avec`: Class Signature

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Size of vector

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Access an element

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  int& operator[](int i); // Access an element
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Output 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)
        : count(size)  {

  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

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avec::avec(unsigned int size): count(size) {
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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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- `elements` is a shorthand for `(*this).elements`

Excursion: Accessing Member Variables

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avec::avec(unsigned int size): count(size) {
  this->elements = new int[size];
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- `elements` is a shorthand for `(*this).elements`
- 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 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);
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()`

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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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  }
}
```

Output current element

Function `avec::print()`

Finally: overload output operator:

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

Function `avec::print()`

Finally: overload output operator:

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Function `avec::print()`

Finally: overload output operator:

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                         const avec& vec) {
  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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```

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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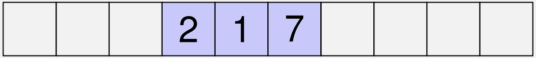

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- Allocate more memory than initially necessary

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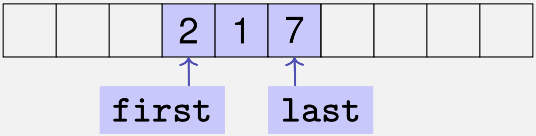
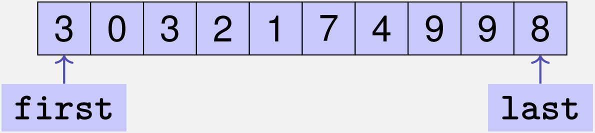


Possibility:

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

Resizing arrays



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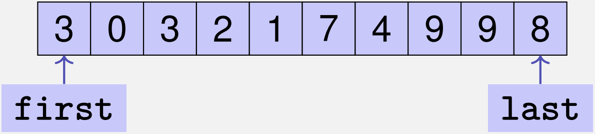
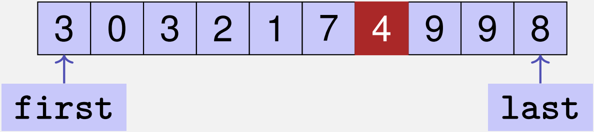
Resizing arrays



- 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

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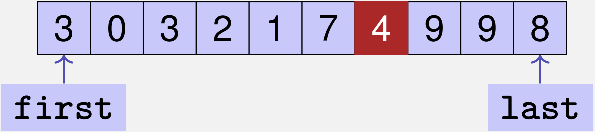
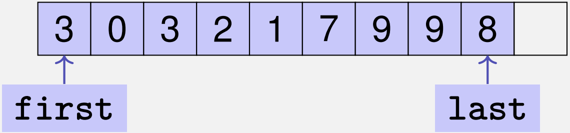
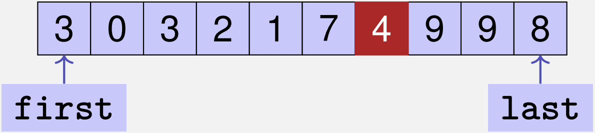


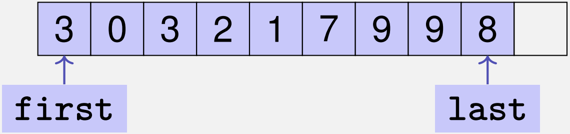
Deleting elements requires shifting (by copying) all preceding or following elements



Resizing arrays



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



Similar: inserting at arbitrary position