20. Dynamic Data Structures I

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

Recap: `vector<`T`>`

- Can be initialised with arbitrary size `n`
- Supports various operations:

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

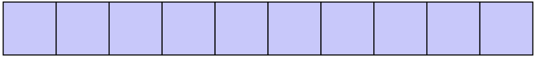
- A vector is a *dynamic data structure*, whose size may change at runtime

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

underlying type

`new` *T*[*expr*]

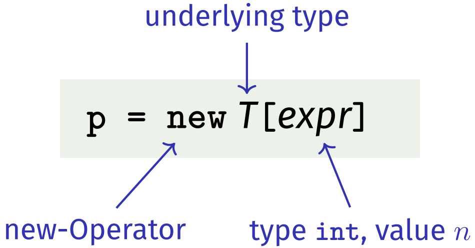
new-Operator

type `int`, value n

- 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



- Value: the starting address of the memory chunk

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

Outlook I: `new` and `delete`

`new` $T[expr]$

- 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

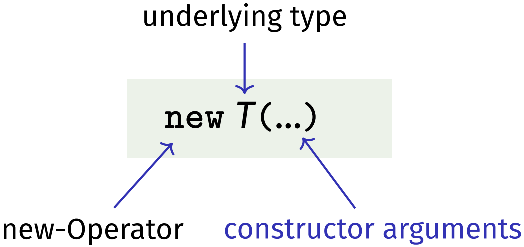
Outlook II: Today's Lecture

- Goal: understanding pointers and dynamic memory/dynamically allocated objects
- Running example: own vector
- Outline:

  1. *individual* dynamically allocated objects
     $\rightarrow$ introduce pointers, explain basics
  2. *array* of dynamically allocated objects
     $\rightarrow$ introduce pointer arithmetic, explain random and sequential access
  3. develop *vector class*, based on a dynamic array
     $\rightarrow$ application of pointers in a nontrivial example; class design

- 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)



- 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`

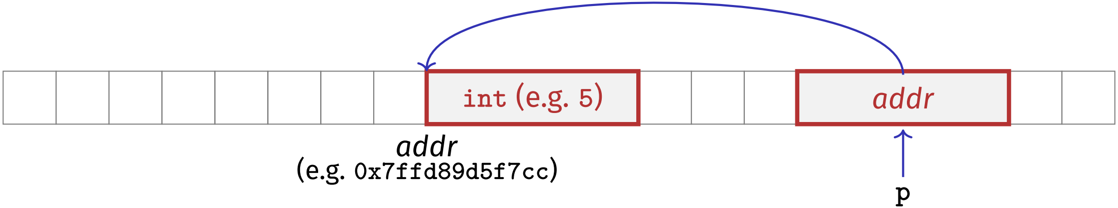
A $T*$ must actually point to a T

```
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`

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



Address Operator

Question: How to obtain an object's address?

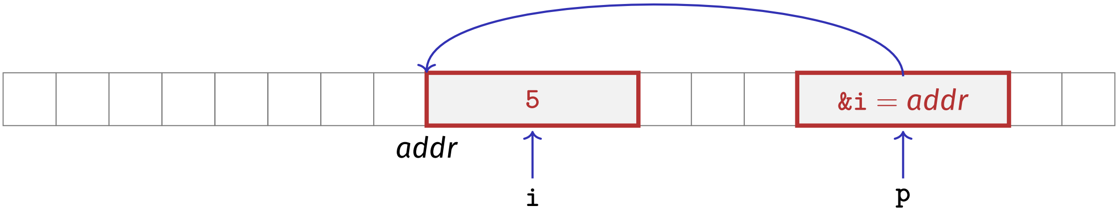
1. Directly, when creating a new object via **`new`**
2. For existing objects: via the *address operator* **`&`**

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



Next question: How to “follow” a pointer?

Dereference Operator

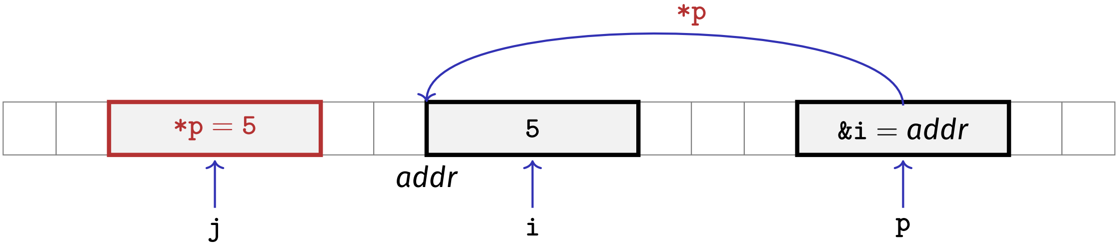
Answer: by using the *dereference operator* *

$$*expr \longleftarrow \text{expr: r-value of type } T*$$

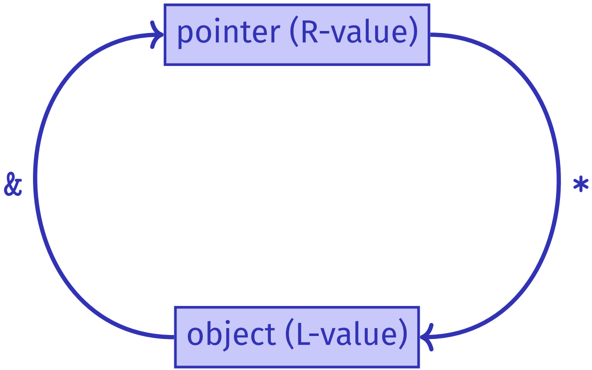
- Value of the expression: the *value* of the object located at the address denoted by *expr*
- Type of the expression: T

Dereference Operator

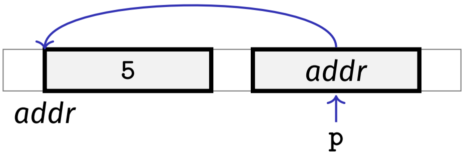
```
int i = 5;
int* p = &i; // p = address of i
int j = *p; // j = 5
```



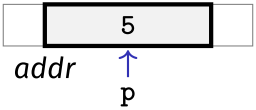
Address and Dereference Operator



Pointer Visualisations



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



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

Mnenmonic Trick

The declaration

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

can be read as

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

Although this is legal, we do not write it like this!

Null-Pointer

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

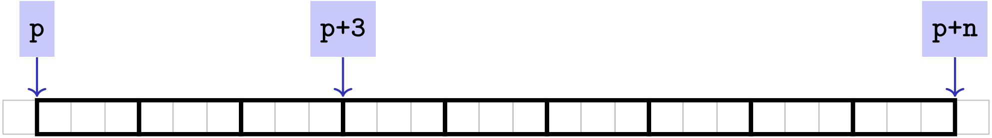
```
int* p = nullptr;
```

- 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
```

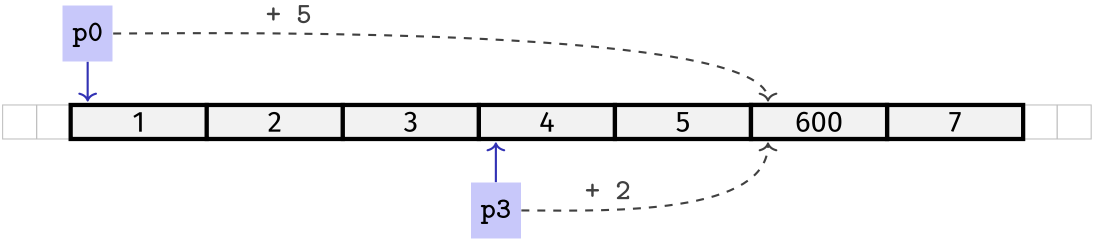


Question: How to point to rear elements? $\rightarrow$ via *Pointer arithmetic*:

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



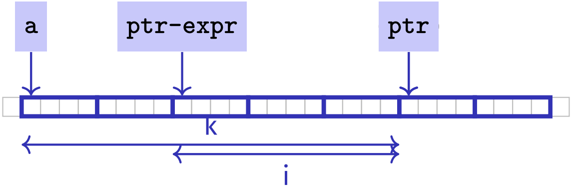
Pointer Arithmetic: Pointer minus `int`

- If *ptr* is a pointer to the element with index k in an array a with length n
- and the value of *expr* is an integer i, $0 \leq k - i \leq n$,

then the expression

ptr - expr

provides a pointer to an element of a with index $k - i$.



Pointer Subtraction

- If *p1* and *p2* point to elements of the same array `a` with length n
- and $0 \leq k_1, k_2 \leq n$ are the indices corresponding to *p1* and *p2*, then

p1 - *p2* has value k_1 - k_2

↑

Only valid if *p1* and p2 point into the same array.

- The pointer difference describes how far apart the elements are from each other in memory

Pointer Operators

Description	Op	Arity	Precedence	Associativity	Assignment
Subscript	`[]`	2	17	left	R-value $\to$ L-value
Dereference	`*`	1	16	right	R-Wert $\to$ L-Wert
Address	`&`	1	16	rechts	L-value $\to$ R-value

Precedences and associativities of +, −, ++ (etc.) as in Chapter 2

Pointers are not Integers!

- Addresses can be interpreted as house numbers of the memory, that is, integers
- But integer and pointer arithmetic behave differently.

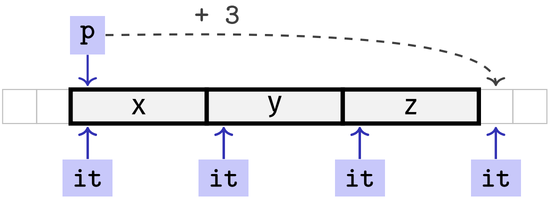
`ptr + 1` is not the next house number but the s-next, where s is the memory requirement of an object of the type behind the pointer `ptr`.

- Integers and pointers are not compatible

```
int* ptr = 5; // error: invalid conversion from int to int*
int a = ptr;  // error: invalid conversion from int* to int
```

Sequential Pointer Iteration

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




```
for (char* it = p;       // it points to first element
     it != p + 3;        // Abort if end reached
     ++it){              // Advance pointer element-wise

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

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*:

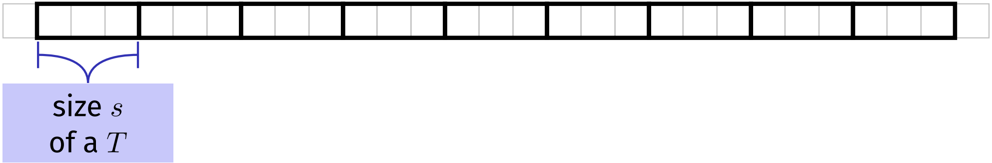
```
char* p = new char[3]{'x', 'y', 'z'};

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

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

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]`, ...) 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

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

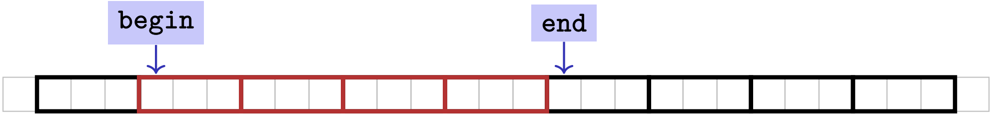
- open book on page 1
- turn the page
- turn the page
- turn the page
- turn the page
- turn the page
- ...

Static Arrays

- `int* p = new int[`$expr$`]` creates a dynamic array of size $expr$
- C++has inherited *static* arrays from its predecessor language C:
  `int a[`$cexpr$`]`
- Static arrays have, among others, the disadvantage that their size $cexpr$ must be a constant. I.e. $cexpr$ can, e.g. be `5` or `4*3+2`, but kein von der Tastatur eingelesener Wert `n`.
- A static array variable `a` can be used just like a pointer
- Rule of thumb: Vectors are better than dynamic arrays, which are better than static arrays

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;
}
```

```
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[6]. 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;
```

[6] on the data specified by the pointer(intervals)

Positioning of Const

Where does the `const`-modifier belong to?
`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 = ...
```

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
`int const* p2;`	`p2` is a pointer to a constant integer
`int* const p3;`	`p3` is a constant pointer to an integer
`int const* const p4;`	`p4` is a constant pointer to a constant integer

Non-mutating Functions: `print`

There are also *non*-mutating functions that access elements of an array only in a read-only fashion

```
// 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 << ' ';
}
```

Const pointer to const int

Likewise (but different keyword order)

Pointer, *not const*, to const int

Pointer `p` may itself not be `const` since it is mutated (`++p`)

`const` is not absolute

- The value at an address can change even if a `const`-pointer stores this address.

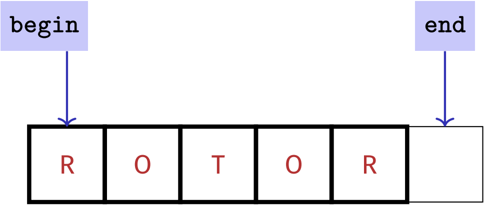
Beispiel

```
int a[5];
const int* begin1 = a;
int*       begin2 = a;
*begin1 = 1;     // error *begin1 is const
*begin2 = 1;     // ok, although *begin will be modified
```

- `const` is a promise from the point of view of the `const`-pointer, not an absolute guarantee

Wow – Palindromes!

```
// PRE: [begin end) is a valid range of characters
// POST: returns true if the range forms a palindrome
bool is_palindrome (const char* begin, const char* end) {
  while (begin < end)
    if (*(begin++) != *(--end)) return false;
  return true;
}
```



Arrays, `new`, Pointer: Conclusion

- Arrays are contiguous chunks of memory of statically unknown size
- `new` T`[`n`]` allocates a T-array of size n
- T`* p = new` T`[`n`]`: pointer `p` points to the first array element
- Pointer arithmetic enables accessing rear array elements
- Sequentially iterating over arrays via pointers is more efficient than random access
- `new` T allocates memory for (and initialises) a single T-object, and yields a pointer to it
- 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
- 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

Unser eigener Vektor!

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

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); // 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];
}
```


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

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();
```

- 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

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::operator[]` is needed twice

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

- The first member function is *not const* and returns a *non-const* reference

```
avec v = ...; // A non-const vector
std::cout << v.get[0]; // Reading elements is allowed
v.get[0] = 123; // Modifying elements is allowed
```

- It is called on non-const vectors

Function `avec::operator[]` is needed twice

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

- The second member function *is const* and returns a *const* reference

```
const avec v = ...; // A const vector
std::cout << v.get[0]; // Reading elements is allowed
v.get[0] = 123; // Compiler error: modifications are not allowed
```

- It is called on const vectors

Also see the example getters_and_const.cpp attached to this PDF

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

Advance pointer element-

Abort iteration if past last element

Output current element

Function `avec::print()`

Finally: overload output operator:

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

```
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

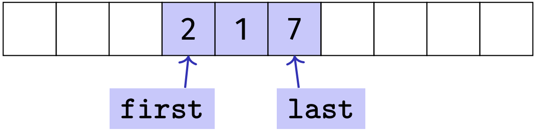
Further Functions?

```
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
  ...
}
```

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

Resizing arrays

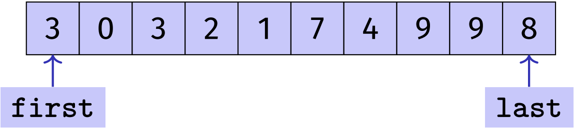
An allocated block of memory (e.g. `new int[3]`) cannot be resized later on



Possibility:

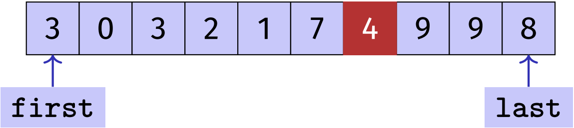
- Allocate more memory than initially necessary
- Fill from inside out, with pointers to first and last element

Resizing arrays

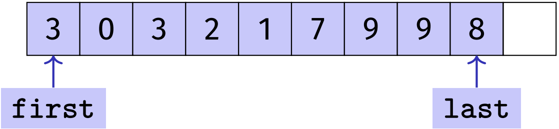


- But eventually, all slots will be in use
- Then unavoidable: Allocate larger memory block and copy data over

Resizing arrays



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



Similar: inserting at arbitrary position