EDAF50 – C++ Programming

2. Types and variables.

Sven Gestegård Robertz
Computer Science, LTH

2023

Outline

Data types and variables
C++ is a strictly typed language

- Every name and every expression has a type
- some concepts:
  - a *declaration* introduces a *name* (and gives it a *type*)
  - a *type* defines the set of possible values and operations (for an *object*)
  - an *object* is a place in memory that holds a *value*
  - a *value* is a bit pattern interpreted according to a *type*.
  - a *variable* is a named *object*

An object has

- a *value* and
- a *representation*
- a type cast can change the *value* of an object by changing its *type*

Unnamed objects

Unnamed objects include

- temporary values
- objects on the heap (allocated with **new**)

Data types
Primitive types

- Integral types: **char**, **short**, **int**, **long**, **long long**
  - **signed** (as in Java)
  - **unsigned** (*modulo* 2^N "non-negative" numbers, not in Java)
- Floting point types: **float**, **double**, **long double**
- **bool** (boolean in Java)
  - integer values are implicitly converted to **bool**
  - zero is **false**, non-zero is **true**
- The type **char** is "the natural size to hold a character" on a given machine (often 8 bits). Its size (in C/C++) is called "a byte" regardless of the number of bits.
- **sizeof**(**char**) $\equiv 1$ (1 byte)
- The sizes of all other data types are multiples of **sizeof**(**char**).
  - sizes are *implementation defined*
  - **sizeof**(**int**) is commonly 4.

Variables
Declaration and initialization

Declaration without initialization (avoid)

```
int x;          // x has an undefined value (if local)
                // (as local variables in Java)
```

Declaration and initialization

```
int a{7};     // list initialization (recommended for most types)
int b(17);    // "constructor call"
int y = {7}; // list initialization with extra = (copy)
int z = 7;    // C style

vector<int> v{1,2,3,4,5};
```

C style: Beware of implicit type conversion

```
int x = 7.8;  // x == 7. No warning
int y {7.8};  // Gives a warning (or error with -pedantic-errors)
```

Data types
Pointers, Arrays and References

- References
- Pointers (similar to Java references)
- Arrays ("built-in arrays"). Similar to Java arrays of primitive types

Pointers

Similar to references in Java, but

- a pointer is the *memory address of an object*
- a pointer *is an object* (a C++ reference is not)
  - can be assigned and copied
  - has an address
  - can be declared without initialization, but then it gets an *undefined value* , as do other variables
- four possible states
  1. point to an object
  2. point to the address immediately past the end of an object
  3. point to nothing: `nullptr`. Before C++11: `NULL`
  4. invalid
- can be used as an iteger value
  - arithmetic, comparisons, etc.

Be very careful!

Pointers
Syntax, operatorers * and &

- In a *declaration*:
  - prefix *: "pointer to"

    `int *p;` : p is *a pointer to an int*

    `void swap(int*, int*);` : *function taking two pointers*
  - prefix &: "reference to"

    `int &r;` : r is *a reference to an* **int**

- In an *expression*:
  - prefix *: dereference, "contents of" (*pointer → object*)

    `*p = 17;` *the object that p points to* is assigned 17
  - prefix &: "address of", "pointer to" (*object → pointer*)

```
int x = 17;
int y = 42;

swap(&x, &y);
```

Call swap(**int***, **int***) with *pointers to* x *and* y

Pointers
Be careful with declarations

Advice: One declaration per line

```
int *a;       // pointer to int
int* b;       // pointer to int
int c;        // int

int* d, e;    // d is a pointer, e is an int
int* f, *g;   // f and g are both pointers
```

Choose a style, either `int *a` *or* `int* b`*, and be consistent.*

References

References are similar to pointers, but

- A reference is *an alias to* a variable
  - must be initialized
  - cannot be changed (*reseated* to refer to another variable)
  - is not an object (has no address)

  - Dereferencing does not use the operator *
    - Using a reference *is* to use the referenced object.

Use a reference if you don't have (a good reason) to use a pointer.

- E.g., if it may have the value `nullptr` (*"no object"*)
- or if you need to change("reseat") the pointer
- More on this later.

Pointers and references
Call by pointer

In some cases, a *pointer* is used instead of a *reference* to "call by reference:

Example: swap two integers

```
void swap2(int* a, int* b)
{
  if(a != nullptr && b != nullptr) {
    int tmp=*a;
    *a = *b;
    *b = tmp;
  }
}  ...  and use:                int x, y;
                                ...
                                swap2(&x, &y);
```

NB!:

- a pointer can be `nullptr` or uninitialized
- dereferencing such a pointer gives *undefined behaviour*

Pointers and references

Pointer and reference versions of swap

```
// References
void swap(int& a, int& b)
{

   int tmp = a;
   a = b;
   b = tmp;
}
```

```
// Pointers
void swap(int* pa, int* pb)
{
  if(pa != nullptr && pb != nullptr) {
     int tmp = *pa;
     *pa = *pb;
     *pb = tmp;
  }
}
```

```
int m=3, n=4;
swap(m,n);    Reference version is called

swap(&m,&n); Pointer version is called
```

NB! Pointers are *called by value*: *the address* is copied

Arrays ("C-arrays", "*built-in arrays*")

- A sequence of values of the same type (homogeneous sequence)
- Similar to Java for primitive types
  - but *no safety net* – difference from Java
  - an array does not know its size – the programmer's responsibility
- *Can contain elements of any type*
  - Java arrays *can only contain references* (or primitive types)
- Can be a local (or member) variable (Difference from Java)
- Is declared `T a[size];` (Difference from Java)
  - The size must be *a (compile-time) constant*.
    (Different from C99 which has VLAs)

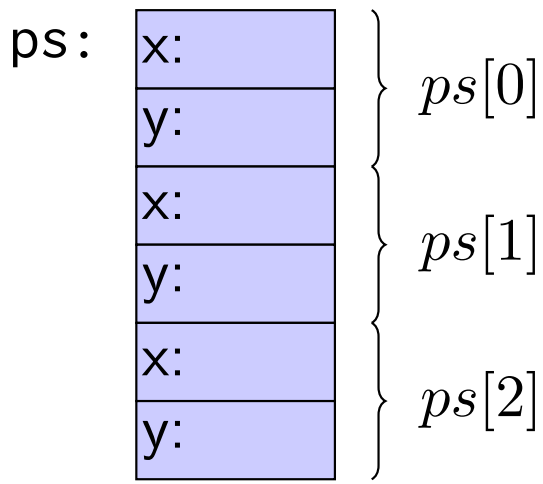
Arrays
Representation in memory

The elements of an array can be of any type

- Java: only primitive types or a reference to an object
- C++: an object or a pointer

Example: array of `Point`

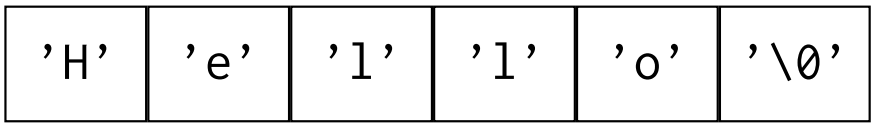
```
class Point{
    signed char x;
    signed char y;
};

Point ps[3];
```



Important difference from Java: no fundamental difference between built-in and user defined types.

Data types
C strings

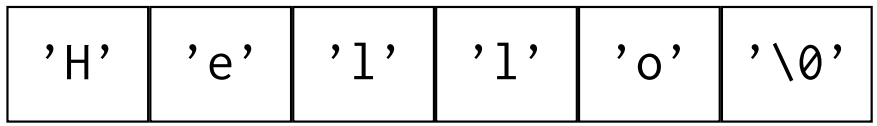
- C strings are `char[]` that are *null terminated*.
  Example: `char s[6] = "Hello";`



NB! A *string literal* is a C-style string (not a `std::string`)
The type of `"Hello"` is `const char[6]`.

Data types
C strings

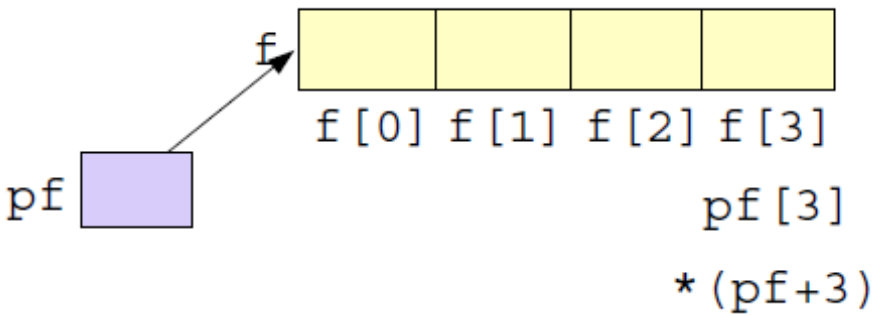
- C strings are `char[]` that are *null terminated*.
  Example: `char s[6] = "Hello";`



Pointers and arrays

Arrays are accessed through pointers

```
float f[4];          // 4 floats
float* pf;           // pointer to float

pf = f;              // same as = &f[0]
float x = *(pf+3); // Alt. x = pf[3];
x = pf[3];           // Alt. x = *(pf+3);
```



Pointers and arrays
What does array indexing really mean?

The expression `a[b]` is equivalent to `*(a + b)` (and, thus, to `b[a]`)

Definition

For a pointer, `T* p`, and an integer `i`, the expression `p + i` is defined as `p + i * sizeof(T)`

That is,

- `p+1` points to the address after the object pointed to by `p`
- `p+i` is an address *i objects of type* `T` *after* `p`.

Example: confusing code (Don't do this)

```
int a[] {1,4,5,7,9};

cout << a[2] << " == "<< 2[a] << endl;
```

```
  5 == 5
```

Pointers and arrays
Function calls

Function for zeroing an array

```
void zero(int* x, size_t n) {
   for (int* p=x; p != x+n; ++p)
      *p = 0;
}

   ...
   int a[5];

   zero(a,5);
```

- *The name of an array variable* in an expression is interpreted as *"a pointer to the first element"*: *array decay*
- a ⇔ &a[0]
- arrays cannot be copied (passed by value)

Array subscripting

```
void zero(int x[], size_t n) {
  for (size_t i=0; i < n; ++i)
    x[i] = 0;
}
```

- In function parameters T a[] *is equivalent to* T* a. (Syntactic sugar)
- T* is more common

- An array is passed as *a pointer and a size*.

Pointers and references

Pointer and reference versions of swap

```
// References
void swap(int& a, int& b)
{

   int tmp = a;
   a = b;
   b = tmp;
}
```

```
// Pointers
void swap(int* pa, int* pb)
{
  if(pa != nullptr && pb != nullptr) {
     int tmp = *pa;
     *pa = *pb;
     *pb = tmp;
  }
}
```

```
int m=3, n=4;
swap(m,n);   Reference version is called

swap(&m,&n); Pointer version is called
```

NB! Pointers are *called by value*: *the address* is copied

Declarations
Scope

A declaration introduces a *name* in a *scope*

Local scope: A name declared in a function is visible

- From the declaration
- To the end of the block (delimited by `{ }`)
- Parameters to functions are local names

Class scope: A name is called a *member* if it is declared *in a class**. It is visible in the entire class.

Namespace scope: A named is called a *namespace member* if it is defined *in a namespace**. E.g, `std::cout`.

A name declared outside of the above is called a *global name* and is in *the global namespace*.

* outside a function, class or *enum class*.

Declarations
lifetimes

- The lifetime of an object is determined by its *scope*:
- An object
  - must be initialized (constructed) before it can be used
  - is destroyed *at the end of its scope*.
- a *local variable* only exists until the function returns
- *class members* are destroyed when the object is destroyed
- *namespace objects* are destroyed when the program terminates
- an *object allocated with* `new` lives until destroyed with `delete`. (different from Java)
  - Manual memory management
  - **new** is not used as in Java
  - Avoid **new** except in special cases
  - more on this later

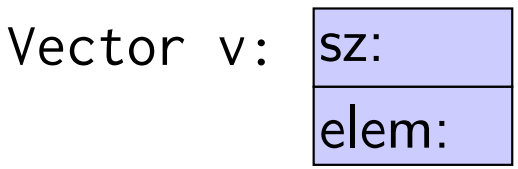
User defined types

- Built-in types (e.g., **`char`**, **`int`**, **`double`**, pointers, . . .) and operations
  - Rich, but deliberately low-level
  - Directly and efficiently reflect the capabilites of conventional computer hardware
- User-defined types
  - Built using the built-in types and abstraction mechanisms
  - **`struct`**, **`class`** (cf. **`class`** i Java)
  - Examples from the standard library
    - `std::string` (cf. `java.lang.String`)
    - `std::vector`, `std::list` . . . (cf. corresponding class in `java.util`)
  - **`enum class`**: enumeration (cf. **`enum`** in Java)
- A *concrete type* can behave "just like a built-in type".

Structures

The first step in building a new type is to organize the elements it needs into a data structure, a *struct*.
Example: a vector of doubles

```
struct Vector {
  int sz;
  double* elem;

};
```



A variable of the type `Vector` can be created with

```
Vector v;
```

but now v.sz and the pointer `v.elem` are uninitialized.

To be useful, we must give `elem` som elements to point to.

Structures
Initialization

A function for initializing a `Vector`:

```
void vector_init(Vector& v, int s)
{
  v.elem = new double[s];
  v.sz = s;
}
```

A variable of type `Vector`, with size 10, can be created with

```
Vector vec;
vector_init(vec, 10); //call-by-reference: vec is changed
```

- the operator **new** allocates an object on *the heap* ("the free store")
- objects on the heap live until removed using **delete**
- more on (better alternatives to) this later

Structures
Representation

```
struct Vector {
  int sz;
  double* elem;
};
void vector_init(Vector& v, int s)
{
  v.elem = new double[s];
  v.sz = s;
}

void test()
{
   Vector vec;
   vector_init(vec, 5);
   vec.elem[2] = 7;
}
```

Structures
Use

Now we can use our `Vector`:

```
#include <iostream>
double read_and_sum(int s)
{
    Vector v;                   // create Vector object
    vector_init(v,s);           // initialize v with size s
    for(int i=0; i!=s; ++i) {
        std::cin >> v.elem[i];
    }

    double sum{0};
    for(int i=0; i!=s; ++i) {
        sum += v.elem[i];
    }

    return sum;
}
```

- `>>` is *the input operator*
- the standard library `<iostream>`
- `std::cin` is *standard input*

Structures
Access of **struct** members

```
Vector v;

Vector& rv = v;

Vector* pv = &v;

...

int i = v.sz;      // direct access (with name of variable)

int j = rv.sz;     // access via reference (alias for name)

int k = pv->sz;    // access via pointer
```

Access of members through pointers
The operator ->

For a pointer p, we can express
"The member x in the object p points to in two ways:

- `(*p).x`
- `p->x`

Classes

- Make a user-defined type behave like “a real type”
- Tight coupling between operations and the data representation
- Often: make the representation inaccessible to users

A class can have

- data members (“attributes”)
- member functions (“methods”)
- type members
- members can be
  - **`public`**
  - **`private`**
  - **`protected`**
  - like in Java

Classes
Example

```
class Vector{
public:
    Vector(int s) :elem{new double[s]}, sz{s} {}  // constructor
    double& operator[](int i) {return elem[i];}   // subscripting
    int size() {return sz;}
private:
    double* elem;
    int sz;
};
```

- *constructor*, like in Java
  - Creates an object and *initializes members*
  - the statements `Vector vec;` `vector_init(vec, 5);` become `Vector vec(5);`
- *operators* can be overloaded, e.g. **`operator[](int)`**
  - `vec.elem[2]` becomes `vec[2]`
  - The representation is not accessible (`elem` is **`private`**)
  - NB! Returns a *reference* so that `vec[i]` *can be changed (assigned)*

Classes
Example

```
double read_and_sum(int s)
{
    Vector v(s);  // Create and initialize a Vector of size s
    for(int i=0; i!=v.size(); ++i) {
        std::cin >> v[i];
    }

    double sum{0};
    for(int i=0; i!=v.size(); ++i) {
        sum += v[i];
    }

    return sum;
}
```

Class definitions
Member functions: declarations and definitions

Member functions ($\Leftrightarrow$ "methods" in Java)

Definition of class

```
class Foo {
public:
    int fun(int, int);       // Declaration of member function
    int get_x() {return x;} // ... incl definition (inline)
    ...
private:
    int x;
};
```

NB! Semicolon after class definition

Definition of member function (outside the class)

```
int Foo::fun(int x, int y) {
    // ...
}
```

No semicolon after function definition

Classes
Resource management

- *RAII Resource Acquisition Is Initialization*
- An object is initialized by a *constructor*
  - Allocates the needed resources
- When an object is destroyed, its *destructor* is executed
  - Free resources owned by the object
  - In the `Vector` example: the array pointed to by `elem`

```
class Vector{
  public:
  Vector(int s) :elem{new double[s]}, sz{s} {}  // constructor
  ~Vector() {delete[] elem;}   // destructor, delete the array
  ...
};
```

Manual memory management

- Objects allocated with **`new`** must be freed with **`delete`**
- Objects allocated with **`new[]`** must be freed with **`delete[]`**
- otherwise, the program has a *memory leak*
- (much) more on this later

Two types from the standard library
Alternatives to C-style arrays

Do not use built-in arrays unless you have (a strong reason) to.
Instead of

- **char**`[]` – Strings – use `std::string`
- `T[]` – Sequences – use `std::vector<T>`

More like in Java:

- more functionality – *"behaves like a built-in type"*
- safety net

Strings: `std::string`

`std::string` has operations for

- assigning
- copying
- concatenation
- comparison
- input and output (<< >>)

and

- knows its size

Similar to `java.lang.String` *but is mutable*.

Sequences: `std::vector<T>`

A `std::vector<T>` is

- an ordered collection of objects (of the same type, `T`)
- every element has an index

which, in contrast to a built-in array

- knows its size
  - `vector<T>::operator[]` does no bounds checking
  - `vector<T>::at(size_type)` throws `out_of_range`
- can grow (and shrink)
- can be assigned, compared, etc.

Similar to `java.util.ArrayList`

Is a *class template*

Example: std::string

```
#include <iostream>
#include <string>
using std::string;
using std::cout;
using std::endl;

string make_email(string fname,
                  string lname,
                  const string& domain)
{
    fname[0] = toupper(fname[0]);
    lname[0] = toupper(lname[0]);
    return fname + '.' + lname + '@' + domain;
}

void test_string()
{
    string sr = make_email("sven", "robertz", "cs.lth.se");

    cout << sr << endl;
}
```

Sven.Robertz@cs.lth.se

Example: std::vector<int> initialisation

```
void print_vec(const std::string& s, const std::vector<int>& v)
{
    std::cout << s << " : " ;
    for(int e : v) {
        std::cout << e << " ";
    }
    std::cout << std::endl;
}
void test_vector_init()
{
    std::vector<int> x(7);
    print_vec("x", x);

    std::vector<int> y(7,5);
    print_vec("y", y);

    std::vector<int> z{1,2,3};
    print_vec("z", z);
}
```

```
x: 0 0 0 0 0 0 0
y: 5 5 5 5 5 5 5
z: 1 2 3
```

Example: `std::vector<int>` assignment

```
void test_vector_assign()
{
    std::vector<int> x {1,2,3,4,5};
    print_vec("x", x);
    std::vector<int> y {10,20,30,40,50};
    print_vec("y", y);
    std::vector<int> z;
    print_vec("z", z);
    z = {1,2,3,4,5,6,7,8,9};
    print_vec("z", z);
    z = x;
    print_vec("z", z);
}
```

```
x : 1 2 3 4 5
y : 10 20 30 40 50
z :
z : 1 2 3 4 5 6 7 8 9
z : 1 2 3 4 5
```

Example: `std::vector<int>` insertion and comparison

```
void test_vector_eq()
{
    std::vector<int> x {1,2,3};
    std::vector<int> y;
    y.push_back(1);
    y.push_back(2);
    y.push_back(3);

    if(x == y) {
        std::cout << "equal" << std::endl;
    } else {
        std::cout << "not equal" << std::endl;
    }
}
```

```
equal
```

Data types
Two kinds of constants

- A variable declared **`const`** must not be changed(`final` in Java)
  - Roughly:"I promise not to change this variable."
  - Is checked by the compiler
  - Use when specifying function interfaces
    - A function that does not change its (reference) argument
    - A member function ("method") that does not change the state of the object.
  - Important for function overloading
    - T and **`const`** T are different types
    - One can overload **`int`** `f(T&)` and **`int`** `f(`**`const`** `T&)` (for some type T)
- A variable declared **`constexpr`** must have a value that can be computed at compile time.
  - Use to specify constants
  - Functions can be **`constexpr`**
  - Introduced in C++-11

`char[]`, `char*` och `const char*`
`const` is important for C-strings

A *string literal* (e.g., `"I am a string literal"`) is **`const`**.

- Can be stored in read-only memory
- **`char*`** `str1 = "Hello";` — *deprecated* in C++ – gives a warning
- **`const char*`** `str2 = "Hello";` — OK, the string is **`const`**
- **`char`** `str3[] = "Hello";` — `str3` can be modified

`const` and pointers

const modifies everything to the left (exception: if **const** is first, it modifies what is directly after)

Example

```
      int* ptr;
const int* ptrToConst;  //NB! (const int) *
int const* ptrToConst,  // equivalent, clearer?

int* const  constPtr;   // the pointer is constant

const int* const constPtrToConst; // Both pointer and object
int const* const constPtrToConst; // equivalent, clearer?
```

Be careful when reading:

```
char *strcpy(char *dest, const char *src);
```

(const char)*, not const (char*)

`const` and pointers
Example:

```
void Exempel( int* ptr,
              int const * ptrToConst,
              int* const constPtr,
              int const * const constPtrToConst )
{
    *ptr = 0;                       // OK: changes the value of the object
    ptr  = nullptr;                 // OK: changes the pointer

    *ptrToConst = 0;                // Error! cannot change the value
    ptrToConst  = nullptr;          // OK: changes the pointer

    *constPtr = 0;                  // OK: changes the value
    constPtr  = nullptr;            // Error! cannot change the pointer

    *constPtrToConst = 0;           // Error! cannot change the value
    constPtrToConst  = nullptr; // Error! cannot change the pointer
}
```

Pointers

Pointers to constant and constant pointer

```
int k;              // int that can be modified
int const c = 100;// constant int
int const * pc;    // pointer to constant int
int *pi;           // pointer to modifiable int

pc = &c;    // OK
pc = &k;    // OK, but k cannot be changed through *pc
pi = &c;    // Error! pi may not point to a constant
*pc = 0;    // Error! pc is a pointer to const int

int* const cp = &k; // Constant pointer
cp = nullptr;       // Error! The pointer cannot be reseated
*cp = 123;          // OK! Changes k to 123
```

Variables
Automatic type inference

auto: The compiler deduces the type from the initialization.

Declaration and initialization

```
auto x = 7;                    // int x
auto c = 'c';                  // char c
auto b = true;                 // bool b
auto d = 7.8;                  // double d

std::vector<int> v;
auto it = v.begin();           // std::vector<int>::iterator it

double calc_epsilon();
auto ep = static_cast<float>(calc_epsilon());  // float ep
```

In `float ep = calc_epsilon();` *the narrowing is not obvious* NB!

with **auto** there is no risk of narrowing type conversion, so using = is safe.

Suggested reading

References to sections in Lippman

Types, variables	2.1,2.2,2.5.2 (p 31–37, 41–47, 69)
Type aliases	2.5.1
Type deduction (auto)	2.5.2
Pointers and references	2.3
Scope and lifetimes	2.2.4, 6.1.1
const, constexpr	2.4
Arrays and pointers	3.5
Classes	2.6, 7.1.4, 7.1.5, 13.1.3
std::string	3.2
std::vector	3.3
enumeration types	19.3

Next lecture
Modularity

References to sections in Lippman

Exceptions	5.6, 18.1.1
Namespaces	18.2
I/O	1.2, 8.1–8.2, 17.5.2