EDAF30 – Programming in C++

6. Resource management

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Outline

1. Resource management
   - Memory allocation
   - Stack allocation
   - Heap allocation: `new` and `delete`
2. Smart pointers
3. Classes, resource management
   - Rule of three
   - copy assignment
4. Function calls

Resource management

A *resource* is

- something that must be *allocated*
- and later *released*

Example:

- memory
- file handles
- sockets
- locks
- . . .

Resource handles

Organize resource management with classes that *own* resources

- allocates resources in the constructor
- releases resources in the destructor
- *RAII* User-defined types that behave like built-in types

Memory Allocation

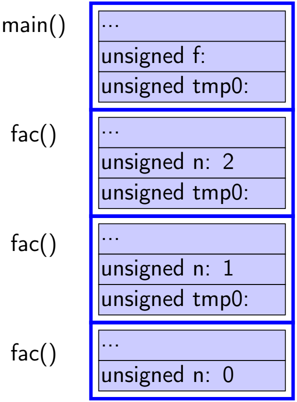
Two kinds of memory allocation:

- on the *stack* - *automatic* variables. Are destroyed when the program exits the *block* where they are declared.
- on the *heap* - *dynamically allocated* objects. Live until explicitly destroyed.

Memory allocation
stack allocation

```
unsigned fac(unsigned n)
{
  if(n == 0)
    return 1;
  else return n * fac(n-1);
}

int main()
{
  unsigned f = fac(2);
  cout << f;
  return 0;
}
```


main()

...
unsigned f:
unsigned tmp0:

fac()

...
unsigned n: 2
unsigned tmp0:

fac()

...
unsigned n: 1
unsigned tmp0:

fac()

...
unsigned n: 0

Memory allocation

Dynamic memory, allocation “on the *heap*”, or “*free store*”

Dynamically allocated memory

- is allocated on the *heap*, with **`new`** (like in Java)
  - does not belong to a *scope*
  - unnamed object: access through pointer or reference
  - **`new`** returns a pointer
- remains in memory until deallocated with **`delete`** (difference from Java)
- Objects allocated in dynamic memory can *outlive the scope they were allocated in*

Memory Allocation

Dynamic memory, allocation “on the *heap*”, or “*free store*”

Space for dynamic objects is allocated with `new`

```
double* pd = new double;                // allocate a double
*pd = 3.141592654;                      // assign a value
float* px;                              // uninitialized pointers
float* py;                              //   (avoid when possible)
px = new float[20];                     // allocate an array
py = new float[20] {1.1, 2.2, 3.3};     // allocate and initialize
```

Memory is released with `delete`

```
delete pd;
delete[] px; // [] is required for an array
delete[] py;
```

Memory Allocation
Warning! be careful with parentheses

Allocating an array: `char[80]`

```
char* c = new char[80];
```

Almost the same...

```
char* c = new char(80);
```

Almost the same...

```
char* c = new char{80};
```

The latter two allocate *one byte*

and *initializes* it with the value 80 (`'P'`).

```
char* c = new char('P');
```

Memory Allocation

Mistake: not allocating memory

```
char name[80];

*name = 'Z'; // OK, name allocated on the stack. name[0]='Z'



char *p;      // Uninitialized  pointer
              // No compiler warning

*p = 'Z';     // Error! 'Z' written to an undefined memory address

cin.getline(p, 80); //(almost) certain error during execution
                    //("Segmentation fault") or memory corruption
```

modern C++: **auto** is safer

```
auto q = new char[80];  // auto --> cannot be uninitialized
```

Memory Allocation

Example: failed `read_line` function

```
constexpr auto bufsz = 80;
char* read_line() {
   char temp[bufsz];
   cin.getline(temp, bufsz);
   return temp;
}

void exempel () {
  cout << "Enter your name: ";
  char* name = read_line();

  cout << "Enter your town: ";
  char* town = read_line();

  cout << "Hello " << name << " from " << town << endl;
}
```

"Dangling pointer": pointer to object that no longer exists

Memory Allocation

Partially corrected version of `read_line`

```
constexpr auto bufsz = 80;
char* read_line() {
   char temp[bufsz];
   cin.getline(temp, bufsz);
   size_t len=strnlen(temp,bufsz);
   char *res = new char[len+1];
   strncpy(res, temp, len+1);
   return res; // dynamically allocated: survives
}
void exempel () {
   cout << "Enter your name";
   char* name = read_line();
   cout << "Enter your town";
   char* town = read_line();
   cout << "Hello " << name << " from " << town << endl;
}
```

Memory Allocation

Further corrected version of `read_line`

```
constexpr auto bufsz = 80;
char* read_line() {
    char temp[bufsz];
    cin.getline(temp, bufsz);
    size_t len=strnlen(temp,bufsz);
    char *res = new char[len+1];
    strncpy(res, temp, len+1);
    return res;  Dynamically allocated: survives
}
void exempel () {
    cout << "Enter your name: ";
    char* name = read_line();   NB! calling function takes ownership
    cout << "Enter your town ";
    char* town = read_line();
    cout << "Hello " << name << " from " << town << endl;

    delete[] name;        Deallocate strings
    delete[] town;
}
```

Use `std::string`

Simpler and safer with `std::string`

```cpp
#include <iostream>
#include <string>

using std::cin;
using std::cout;
using std::string;

string read_line()
{
  string res;
  getline(cin, res);
  return res;
}
```

```cpp
void example()
{
    cout << "Name:";
    string name = read_line();
    cout << "Town:";
    string town = read_line();

    cout << "Hello, " << name <<
    " from " << town << endl;
}
```

- `std::string` is a *resource handle*
- *RAII*
- Dynamic memory is rarely needed (in user code)

Memory Allocation
ownership of resources

For dynamically allocated objects, *ownership* is important

- An object or a function can *own* a resource
- *The owner* is responsible for deallocating the resource
- If you have a pointer, you must know *who owns the object it points to*
- Ownership *can be transferred* by a function call
    - but is often not
    - be clear about owning semantics

Every time you write **`new`** you are responsible for that someone will do a **`delete`** *when the object is no longer in use*.

Classes

RAII

- *RAII Resource Acquisition Is Initialization*
- An object is initialized by a *constructor*
  - Allocates the resources needed (*"resource handle"*)
- When an object is destroyed, its *destructor* is executed
  - Free the resources owned by the object
  - Example: `Vector`: delete the array `elem` points to

```
class Vector{
private:
  double elem*;  // pointer to an array
  int sz;        // the size of the array
public:
  Vector(int s) :elem{new double[s]}, sz{s} {}  // ctor
  ~Vector() {delete[] elem;}   // dtor, delete the array
};
```

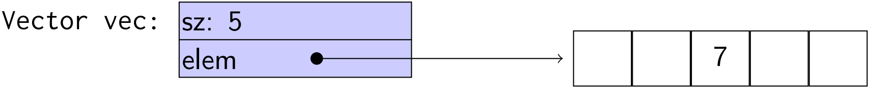
Manual memory management

- Objects allocated with **`new`** must be dellocated with **`delete`**
- Objects allocated with **`new`**`[]` must be dellocated with **`delete`**`[]`
- otherwise the program will *leak memory*

Classes
Resource management, representation

```
struct Vector {
  Vector(int s) :sz{s},elem{new double(sz)} {}
  ~Vector() {delete[] elem;}
  double& operator[](int i) {return elem[i];}
  int sz;
  double* elem;
};

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



- *Resource handle* – Vector owns its **double**[]
- the object: pointer + size, the array is on the heap

Dynamic memory, example

Error handling

```
void f(int i, int j)
{
    X* p=new X;             // allocate new X
    //...
    if(i<99) throw E{};     // may throw an exception
    if(j<77) return;        // may return "early"
    //
    p->do_something();      // may throw
    //
    delete p;
}
```

Will leak memory if `delete p` is not called

Memory allocation
C++: Smart pointers

The standard library `<memory>` has two "smart" pointer types (C++11):

- `std::unique_ptr<T>` – *a single owner*
- `std::shared_ptr<T>` – *shared ownership*

that are *resource handles*:

- their destructor deallocates the object they point to.

- Other examples of *resource handles*:
  - `std::vector<T>`
  - `std::string`

`shared_ptr` contains a *reference counter*: when *the last* `shared_ptr` to an object is destroyed, the object is destroyed. Cf. *garbage collection* in Java.

Smart pointer, example

```
void f(int i, int j)
{
    unique_ptr<X> p{new X};// allocate new X and give to unique_ptr
    //...
    if(i<99) throw E{};     // may throw an exception
    if(j<77) return;        // may return "early"
    //
    p->do_something();      // may throw
}
```

The destructor of `p` is always executed: no leak

Smart pointer, example

Dynamic memory is rarely needed

```
void f(int i, int j)
{
  X x{};

  if(i<99) throw E{};       // may throw an exception
  if(j<77) return;          // may return "early"

  x.do_something();        // may throw
}
```

Use local variables when possible

`read_line` with `unique_ptr`

```
unique_ptr<char[]> read_line()
{
  char temp[80];
  cin.getline(temp, 80);
  int size = strlen(temp)+1;
  char* res = new char[size];
  strncpy(res, temp, size);
  return unique_ptr<char[]>{res};
}

void example()
{
  cout << "Enter name: ";
  unique_ptr<char[]> name = read_line();
  cout << "Enter town: ";
  unique_ptr<char[]> town = read_line();
  cout << "Hello " << name.get() << " from " << town.get() << endl;
}
```

- To get a **char**∗ we call `unique_ptr<`**`char`**`[]>::get()`.
- Needed here to get right overload for **operator**<<

`read_line` with `unique_ptr` with no explicit **`new`** and **`delete`** (c++14)

```
unique_ptr<char[]> read_line()
{
    char temp[80];
    cin.getline(temp, 80);
    int size = strlen(temp)+1;
    auto res = std::make_unique<char[]> (size);
    strncpy(res.get(), temp, size);
    return res;
}
```

Smart pointers

`Vector` from previous examples

```
class Vector{
public:
    Vector(int s) :elem{new double[s]}, sz{s} {}
    double& operator[](int i) {return elem[i];}
    int size() {return sz;}
private:
    std::unique_ptr<double[]> elem;
    int sz;
};
```

- All member variables are of RAII types
- The default *destructor* works
- The object cannot be copied (no default functions generated)
    - A `unique_ptr` cannot be copied – it is *unique*

Smart pointers
Vector from previous examples

```
class Vector{
public:
    Vector(int s) :elem{new double[s]}, sz{s} {}
    double& operator[](int i) {return elem[i];}
    int size() {return sz;}
private:
    std::unique_ptr<double[]> elem;
    int sz;
};
```

- To make the type possible to copy
  - Define a copy constructor
  - Define a copy assignment operator

Memory allocation
C++: Smart pointers

Rules of thumb for pointer parameters to functions:

if ownership *is not* transferred

- Use "raw" pointers
- Use `std::unique_ptr<T> const &`

if ownership *is transferred*

.

- Use *by-value* `std::unique_ptr<T>`
  (then `std::move()` must be used)

- This is an orientation about smart pointers.
- "Raw" pointers are common; you must master them.

C++: Smart pointers
Coarse summary

“Raw” (“naked”) pointers:

- The programmer takes all responsibility
- Risk of memory leaks
- Risk of *dangling pointers*

Smart pointers:

- No (less) risk of memory leaks
- (minor) Risk of *dangling pointers* if used incorrectly (e.g., more than one `unique_ptr` to the same object)

Common pitfall
Default copying

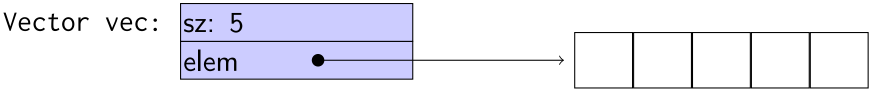
For classes containing *owning pointers*,
the default copying does not work.

Example: `Vector`

- call by value
- copying pointer values
  (both objects point to the same resource)
- the destructor is executed on **`return`**
- *dangling pointer*
- *double delete*

Classes
Example: Copying the Vector class

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



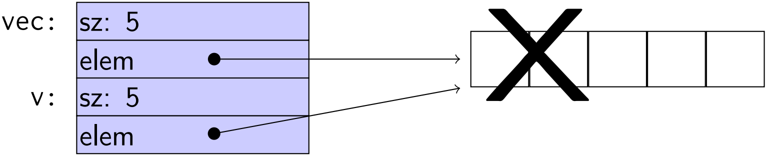
No copy constructor defined ⇒ default generated.

Classes

Default copy construction: shallow copy

```
void f(Vector v);

void test()
{
   Vector vec(5);
   f(vec); // call by value -> copy
   // ... other uses of vec
}
```

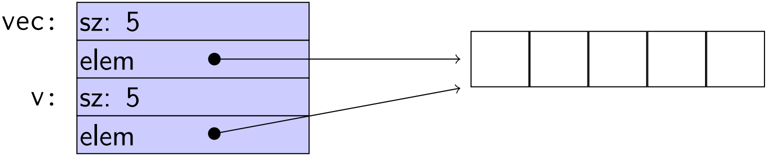


- The parameter v is default copy constructed: the value of each member variable is copied
- When `f()` returns, the destructor of v is executed: (`delete[] elem;`)
- The array pointed to *by both copies* is deleted. Disaster!

Copying objects
the *copy assignment* operator: `operator=`

The *copy assignment operator* is implicitly defined

- with the type `T& T::operator=(const T&)`
- if no `operator=` is declared for the type
- if all member variables can be copied
  - i.e., define a copy-assignment operator
- If all members are of built-in (and RAII) types the default variant works (same problems as with copy ctor).



- For *owning pointers*, the copy member functions must be implemented

“Rule of three”
Canonical construction idiom

IF a class owns a resource, it shall implement a

1. Destructor
2. Copy constructor
3. Copy assignment operator

in order not to leak memory. E.g. the class `Vector`

Rule:

If you define *any* of these, you should define *all*.

Copy control
Example: Vector

Copy constructor

```
Vector::Vector(const Vector& v) :elem{new double[v.sz]}, sz{v.sz}
{
    for(int i=0; i < sz; ++i) {
        elem[i] = v[i];
    }
}
```

Or, use the standard library:

```
std::copy(v.elem, v.elem+v.sz, elem);
```

Copy control

Example: Vector

Copy assignment

```
Vector& Vector::operator=(const Vector& v) {
  if (this != &v) {
      auto tmp = new double[v.sz];
      std::copy(v.elem, v.elem+v.sz,
                tmp);
      sz = v.sz;
      delete[] elem;
      elem = tmp;
  }
  return *this;
}
```

1. check “self assignment”
2. allocate new resources
3. copy values
4. free old resources

Only **`delete`** *if allocation succeeded.*

Function calls and results

Returning objects by value

- A function cannot return references to local variables
    - the object is destroyed at **`return`** – *dangling reference*
- How (in)efficient is it to return objects by value (a copy)?

return value optimization (RVO)

The compiler may optimize away copies of objects on `return` from functions

- *return by value* often efficient, also for larger objects
- RVO allowed *even if the copy-constructor or destructor has side effects*
- avoid such side effects to make code portable

Rules of thumb for function parameters

- Return by value more often
- Do not over-use call-by-value

“reasonable defaults”

	cheap to copy	moderately cheap to copy	expensive to copy
In	`f(X)`	`f(const X&)`	
In/Out	`f(X&)`		
Out	`X f()`		`f(X&)`

For results, if the cost of copying is

- small, or moderate ($< 1k$, contiguous): return by value (modern copilers do RVO: return value optimization)
- large : call by reference as *out parameter*
  - or maybe allocate with **`new`** and return pointer

Call by reference or by value?
Rules of thumb

For passing an object to a function when

- you may want *to change the value* of the object
  - reference: `void f(T&);` or
  - pointer: `void f(T*);`
- you *will not* change it, it is *large* (or impossible to copy)
  - constant reference: `void f(const T&);`
- otherwise, *call by value*
  - `void f(T);`

reference or pointer?

- required parameter: pass reference
- optional parameter: pass pointer (can be `nullptr`)

```
void f(widget& w)
{
    use(w); //required parameter
}

void g(widget* w)
{
    if(w) use(w); //optional parameter
}
```

Call by reference or by value?

- How big is “large”?
  - more than a few *words*
- When to use out parameters?
  - prefer code that is obvious

    Example: two functions:

    ```
    void incr1(int& x)
    {
       ++x;
    }

    int incr2(int x)
    {
      return x + 1;
    }
    ```

    Use:

    ```
    int v = 0;
    ...

    incr1(v);


    ...

    v = incr2(v);
    ```

    Here it is much clearer that `v = incr2(v)` changes `v`

  - For multiple output values, consider returning a **`struct`**, a `std::pair` or a `std::tuple`

Rules of thumb for function parameters

- Return by value more often
- Do not over-use call-by-value

“reasonable defaults”

	cheap to copy	moderately cheap to copy	expensive to copy
In	`f(X)`	`f(const X&)`	
In/Out	`f(X&)`		
Out	`X f()`		`f(X&)`

Next lecture: Error handling

References to sections in Lippman

Error handling, exceptions	(5.6, 18.1.1)
Namespaces	18.2
static assert	*not in Lippman*
assert	6.5.3
Type casts	4.11
const_cast and const overloading	6.2 (p 232–233)
Multi-dimensional arrays	3.6

Suggested reading

References to sections in Lippman

Dynamic memory and smart pointers 12.1

Dynamically allocated arrays 12.2.1

Classes, resource management 13.1, 13.2