EDAF50 – C++ Programming

5. 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
   - copy assignment
4. type casts

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

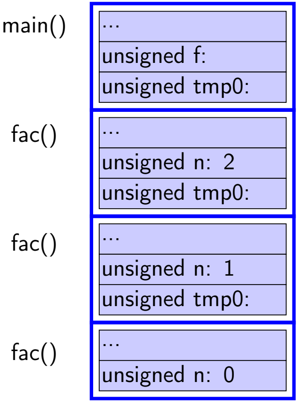
Two kinds of memory allocation:

- 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;
}
```



- local variables are allocated on the stack in an activation record
- objects are destroyed when exiting their scope

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

```
char* read_line() {
   char temp[80];
   cin.getline(temp, 80);
   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`

```
char* read_line() {
   char temp[80];
   cin.getline(temp, 80);
   size_t len=strnlen(temp,80);
   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;
}
```

Works, but memory leak !

Memory Allocation

Further corrected version of `read_line`

```
char* read_line() {
   char temp[80];
   cin.getline(temp, 80);
   size_t len=strnlen(temp,80);
   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

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

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

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

```
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
};
```

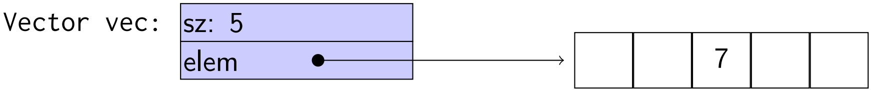
Manual memory management

- 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, exempel

```
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 exempel()
{
  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*

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_pointer<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.

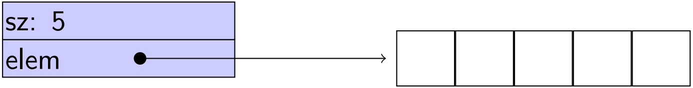
Example: `Vector`

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

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;
};
```

Vector vec:

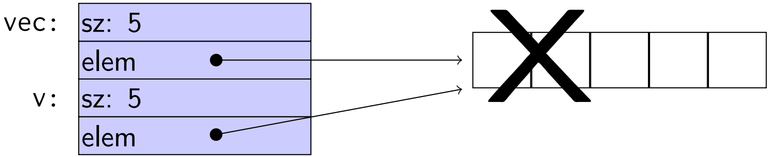


No copy constructor defined ⇒ default generated.

Default copy construction: shallow copy

```
void f(Vector v);

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

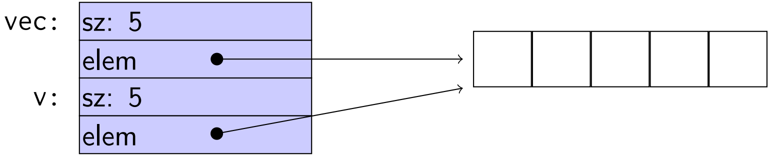


- The parameter v is default copy constructed: the value of each member variable is copied
- When `f()` returns, the destructor of v is executed: (`delete[] elem;`)
- The array pointed to *by both copies* is deleted. Disaster!

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];
      for (int i=0; i<v.sz; i++)
          tmp[i] = v.elem[i];
      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.*

Type casts
Implicit conversions

Automatic conversions

- Expressions of the type $x \odot y$, for some binary operator $\odot$
  E.g.: **`double + int ==> double`**

  `float + long + char ==> float`
- Assignments and initialization: The value of the right-hand-side is converted to the type of the left-hand-side
- Conversion of an argument to the type of the (formal) parameter
- Expresions in **`if`** statements, etc. $\Rightarrow$ **`bool`**
- built-in array $\Rightarrow$ pointer (*array decay*)
- `0` $\Rightarrow$ `nullptr` (empty pointer in C++11, previously the constant `NULL` was defined)

type casts
Named casts (C++-11)

Example

```
char c;                // 1 byte
int *p = (int*) &c;    // pointer to int: 4 bytes

*p = 5; // undefined behaviour, stack corruption

int *q = static_cast<int*> (&c); // compiler error
```

- `static_cast<new_type> (expr)`
  - convert between compatible types (*does not do range check*)
  - "the inverse of a standard implicit conversion sequence"
- `reinterpret_cast<new_type> (expr)`
  - no safety net, same as C-style cast
- `const_cast<new_type> (expr)` - remove **const**
- `dynamic_cast<new_type> (expr)` - use for pointers to objects in class hierarchies. Uses *run-time type info*, like `instanceof` in Java.

Type casting
C style casts

Syntax in C and in C++, like in Java

`(type) expression` , e.g. `(float) 10`

- Greater risk of mistakes - use named casts
  - makes the code clearer, e.g., **`const_cast`** can only change **`const`**
  - easy to search for: casts are among the first to look for when debugging
- Warning in GCC: `-Wold-style-casts`
- Common in older code

Alternative syntax in C++

```
type(expression)
```

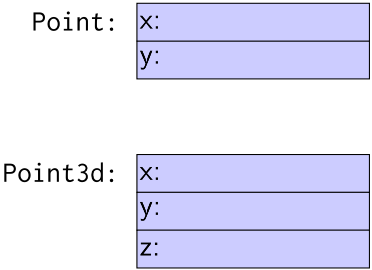
`type` must be *a single word*,

`int *(...)` eller i.e., `unsigned long(...)` is not OK.

Type casts
Warning example

```
struct Point{
    int x;
    int y;
};

struct Point3d {
    int x;
    int y;
    int z;
};
```



Data types and variables

- some concepts:
  - 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 set of bits interpreted according to a *type*.

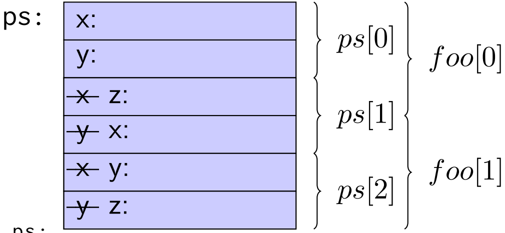
A typecast changes the ***value*** *of a particurlar memory location by changing how* ***it should be interpreted****.*

Type casts
Warning example

```
struct Point{
    int x;
    int y;
};

Point ps[3];

struct Point3d{
     int x;
     int y;
     int z;
};
Point3d* foo = (Point3d*) ps;
```



With *named casts*, this requires a `reinterpret_cast<Point3d*>`

With `static_cast<Point3d*>` the compiler gives the error
`invalid static_cast from type 'Point[3] to type 'Point3d*'`

special case: **void** pointer

A **void*** can point to an object of any type

In C
: a **void*** is implicitly converted to/from any pointer type.

In C++
: a T* is implicitly converted to **void***. The other direction requires an explicit *type cast*.

Next lecture: Algorithms

References to sections in Lippman

Function templates	16.1.1
Algorithms	10 – 10.3.1, 10.5
Iterators	10.4
Function objects	14.8
Random numbers	17.4.1

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

Type casts 4.11