EDAF50 – C++ Programming

5. Resource management

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Outline

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

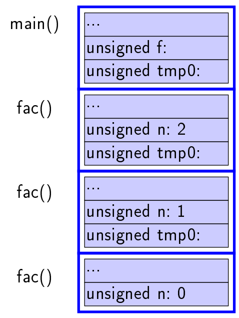
Memory Allocation

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*
  - remains in memory until deallocated with **delete** (difference from Java)

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;
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
};
```

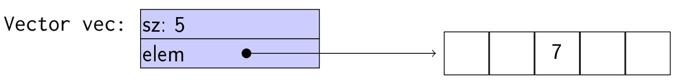
Manual memory management

- 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().

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)

"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*.

Warning example
Default copying

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

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

Example: `Vector`

Move semantics

- Copying is unnecessary if the source will not be used again e.g. if
  - it is a *temporary value* ,e.g.
    - a + b
    - (implicitly) converted function arguments
    - function return values
  - the programmer explicitly specifies it
    `std::move()` is a *type cast* to *rvalue-reference* (T&&)
- Better to "steal" the contents
- Makes *resource handles* even more efficient
- Some objects may/can not be copied
  - e.g., std::unique_ptr
  - use std::move

rule-of-thumb: "if it has a name, it is an lvalue"

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];
    }
}
```

Move constructor (C++-11)

```
Vector::Vector(Vector&& v) : elem{v.elem}, sz{v.sz}
{
    v.elem = nullptr;
    v.sz = 0;          // v has no elements
}
```

Copy control
Example: Vector

Copy assignment

```
Vector& Vector::operator=(const Vector& v) {
  if (this != &v) {
      auto tmp = new int[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.*

Copy control: (Move semantics – C++11)
Example: Vector

Move assignment

```
Vector& Vector::operator=(Vector&& v) {
    if(this != &v) {
        delete[] elem;      // delete current array
        elem = v.elem;      // "move" the array from v
        v.elem = nullptr;   // mark v as an "empty hulk"
        sz = v.sz;
        v.sz = 0;
    }
    return *this;
}
```


"Rule of ~~three~~ five"
Canonical construction idiom, in C++11

If a class owns a resource, it should implement

1. Destructor
2. Copy constructor
3. Copy assignment operator
4. *Move* constructor
5. *Move* assignment operator

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. ⇒ **bool**
- built-in array ⇒ pointer (*array decay*)
- `0` ⇒ nullptr (empty pointer in C++11, previously the constant NULL was defined)

type casts
Explicit, named type casts (C++-11)

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

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
```


Type casting
Explicit type casts, C style

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++

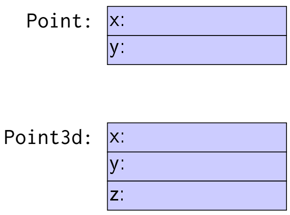
```
type(expression)
```

`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*.

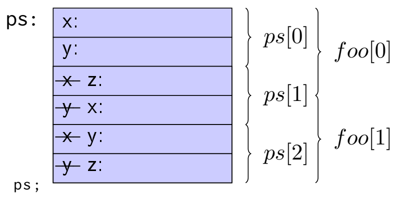
A typecast changes the ***value*** *of a particurlar memory location by changing how* ***it should be interpreted****.*

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

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