Programming in C++

Session 10 – When things go wrong: Exceptions and Resource management

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(based on slides originally produced by Dr Ross Paterson)

Outline

- Exceptions in C++
- ***Resource acquisition is initialization (RAII)***
  - A **fundamental** C++ technique **C++'s GC !**
  - Ensures that resources are freed, even in the presence of exceptions, without writing lots of exception-handling code.
    (Java's `try`-with-resources on steroids)
- RAII: a special case of the *smart pointer* and *proxy* patterns
- Plus Revision!

Part I

Exceptions

Failures (revision)

- Method cannot meet its specification?
  $\Rightarrow$ Communicate this to its caller!
- May cause the caller to fail, and so on
  But sometimes the caller can work around the failure
- Might be necessary to clean up in the event of failure
- Traditional (C) approach – an `if` on a status variable – is very cumbersome (and often left out)
- Disciplined use of *exceptions* makes error-handling clearer and more robust

Throwing an exception in C++

- Any object can be thrown (even basic types)

```
class my_exception { ... };
```

- `throw` statements typically take TEMPORARY OBJECTS

```
throw my_exception("Bad date");
```

- Exceptions should be caught BY REFERENCE
  - This is the "best practice"
  - Can also be caught by value
    But avoid it, since catch-by-value:
    - Slices derived exceptions
    - Requires copying (so extra memory)

Catching an exception in C++

- C++ has `try`/`catch` statement (as in Java)

```
try {
        // do something that might fail
} catch (my_exception &e) { // or derived
        // deal with the exception
} catch (AnotherException &ae) { // or derived
        // deal with the exception
}
```

- Like Java, exceptions may form hierarchies
  - A `catch` clause also handles any derived classes
- C++ has no `finally` clause

(we don't need no filthy finally clauses!)

The C++ treatment of exceptions

- If (inside a `try` block
  `&&` there's a matching `catch` clause)
  Then execute the first matching `catch` clause

  "matching" = the exception type or some base type of it
- Otherwise
  - Exit from the current block or function
    Destroying any locally allocated variables in the process, and
  - Continue searching for a matching `try` block
- If the `main` function is exited in this way
  Halt the program with an error message.

This is called ***unwinding the stack***

Exception – What do? QUICK QUIZ!!!

At a family party: cousin Jim starts to choke on a piece of meat!

1. Catch exception & ignore it
   Hide Jim in a closet & pretend nothing's happened
2. Catch exception & log it
   "Dear diary, Jim ruined the party once again. . . " (& into a closet)
3. Catch exception & fix the problem
   Help Jim spit what is choking him
4. Not catch the exception – propagate it to your caller, who might know how to fix it
   Call 999 and let 'em know someone's choking; they'll deal with it (if they can)

HINT: One should do neither #1 nor #2 . . .

Clean up and rethrow

Often exception handlers are used to free resources on failure:

```
// acquire resource
try {
        // do something that might fail
        // free resource
} catch (...) {     // any exception
        // free resource
        throw;      // rethrow the exception
}
```

This can often be avoided, using the ***RAII*** technique
"Resource Acquisition Is Initialization"

Note on syntax:

- Catch any exception: ***`catch (...)`***
- Rethrow an exception: ***`throw;`***

Resource management

- Programs acquire resources
  Allocate memory, open files, create windows, acquire locks, etc.
- These resources should be released
  Even if there are exceptions!
- Some resources are freed when a program terminates
  `:-)`
- But some are not, *e.g.*, some kinds of lock
  `:-(`
- Releasing resources properly is tricky & easy to get wrong

A typical pattern of resource use

Resources must often be released in the opposite order to acquisition:

```
// acquire resource 1
// ...
// acquire resource n

// use resources

// release resource n
// ...
// release resource 1
```

Wait – that's just like locally allocated data!

Resource acquisition is initialization (RAII)

Introduce a resource management class with

- A constructor to acquire the resource (or just to record it)
- A destructor to release the resource
- Possibly an access method

Locally allocate an object of this class when acquiring the resource, and the resource will be ***automatically*** released!
Moreover, resources will be released in the correct order!

```
// Without RAII :-(
// acquire resource
try {
  // this might fail
  // now free resource
}catch (...) {//any exception
  // free resource
  throw; //rethrow exception
}
```

```
// With RAII :-) :-)
 {
   // acquire resource
   try {
     // this might fail
   }
 } // resource freed here!

//Single try in main is enough!
```

Example: file streams

- `ifstream`/`ofstream`'s constructors open streams

  ```
  ifstream in("file.txt");
  ```

- Their destructors close the streams
  (though one can do it earlier if required)
- Hence code safely like this:

  ```
  {
    ifstream inp("file.txt");
    // read and process file
  } // inp is destroyed here (IF inside a try{}!!!)
  ```

  Whether control leaves the block normally or due to an exception, the file stream will be closed.

  (must have a surrounding `try` somewhere!)

Example: storage management

This class manages the deletion of dynamically allocated `point` objects

```
class point_manager {
   point *ptr;

public:
   point_manager(point *p) : ptr(p) {}

   ~point_manager() { delete ptr; }
   point_manager(const point_manager &) = delete;
   point_manager &operator=(const point_manager &)
     = delete;
};
```


Using the `point_manager`

Whenever a `point` that is only required for this block is dynamically allocated, make a local `point_manager` to manage it:

```
point *p1 = new point(20,30);
point_manager m1(p1);

point *p2 = window->get_middle();
point_manager m2(p2);
```

On leaving the block (normally, via `return`, or by an exception), then `m2` will be destroyed, which will `delete p2`, and then `m1`, which will `delete p1`.

Generic storage management

The standard header `<memory>` ***provided [*]*** a class `auto_ptr`. Here is a simplified version:

```
template <typename T> class auto_ptr {
    T *_ptr;

public:
    auto_ptr(T *ptr) : _ptr(ptr) {}

    ~auto_ptr() { delete _ptr; }
};
```

(more to come later)

[*] Until C++11 – deprecated since!!!

Using `auto_ptr` – The promise

IT'S A LIE!!!

- To ensure that dynamically allocated storage is reclaimed, create a local `auto_ptr` to manage it:

```
point *p = new point(20,30);
auto_ptr<point> p_ptr(p);
```

- On leaving the block, `p` is automatically deleted.
- One can also use `auto_ptr` as a subobject
  No need to write our own destructors!
- Since all methods are inline, there is very little overhead.

IT'S A LIE!!!

More convenience

We add the following operator definitions to the `auto_ptr` class:

```
T & operator*() { return *_ptr; }
T * operator->() { return _ptr; }
```

Then we can use the `auto_ptr` as a *proxy* for the pointer:

```
auto_ptr<int> ip(new int);
*ip = 3;

auto_ptr<point> pp(new point(20,30));
pp->x = 4;
pp->y = 5;
```


Completing `auto_ptr`

Gang of Three!

- Since `auto_ptr` has a non-trivial destructor, it requires
  - A copy constructor; and
  - An assignment operator
- ***Only one of the copies of an `auto_ptr` should call `delete`.***
- Might as well add a default constructor too.

Let's do it!

```
template <typename T>
auto_ptr( ) :  _ptr(nullptr) {}

template <typename T>
auto_ptr(auto_ptr<T> &other){// *** NOT const & !!!
   _ptr = other._ptr;
   other._ptr = nullptr; // *** other loses pointer!
}
```


Completing `auto_ptr` – II

```
template <typename T>
auto_ptr<T> &
operator=(auto_ptr<T> &other){// *** NOT const & !!!
  if (this != &other) {
   delete _ptr;
   _ptr = other._ptr;
   other._ptr = nullptr; // *** other loses pointer!
  }
  return *this;
}
```

(Smart pointers

`auto_ptr` is a so-called *"smart pointer"*
It looks like a pointer, but does something extra
Some other examples:

- **reference counting** proxy counts references to a dynamically allocated object, and deletes it when count reaches zero
- **persistent data** proxy reads data from a file on first use, and saves it in the file on destruction
- **virtual/lazy object** proxy delays creating a complex object until it is used (and if the object is never used, avoids creating it)

The Proxy pattern)

More generally, a *proxy* is any object that is interposed between the client and some other object. Some other uses:

- **wrapper** proxy provides consistent access to foreign language data
- **protection** proxy provides more limited access to the object, for greater security
- **handle** proxy represents an object in a different address space, *e.g.*, an operating system object, a graphical system object, or an object on another machine

. . .

May you live
in interesting times. . . :−(

(2019: This 2011 statement did not age well at all!)

C++11

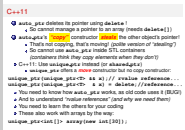
1. `auto_ptr` deletes its pointer using `delete` !
   - So cannot manage a pointer to an array (needs `delete[]`)
2. `auto_ptr`'s ***"copy"*** constructor ***steals*** the other object's pointer!
   - That's not copying, that's moving! *(polite version of "stealing")*
   - So cannot use `auto_ptr` inside STL containers
     (containers think they copy elements when they don't)

- C++11: Use `unique_ptr` instead (or `shared_ptr`)
  - `unique_ptr` offers a ***move*** constructor but no copy constructor:

```
unique_ptr(unique_ptr<T> && x);// rvalue reference...
unique_ptr(unique_ptr<T>  & x) = delete;//reference...
```

- You need to know how `auto_ptr` works, as old code uses it (BUG!)
- And to understand *"rvalue references" (and why we need them)*
- You need to learn the others for your coding
- These also work with arrays by the way:

```
unique_ptr<int[]> array(new int[30]);
```



C++11 – II

Advanced – not assessed (neither is **`unique_ptr`** nor rvalue references/move constructors).

- **`shared_ptr`**:
  "It's complicated" (see stackoverflow **`t.ly/lXveD`***)*
  And the class documentation:
  `https://en.cppreference.com/w/cpp/memory/shared_ptr`
  Especially the constructors:
  `https://en.cppreference.com/w/cpp/memory/shared_ptr/shared_ptr`
- ***!!!** Avoid temporary smart pointers.*
  Why? See Boost **`t.ly/MfyGQ`**
- Or BETTER YET use **`make_shared`**
  See stackoverflow **`t.ly/bN-lL`**

Further reading

- Exceptions: Stroustrup 14, Meyer 12.
- Resource acquisition is initialization (RAII): Stroustrup 14.4.
- Smart pointers: Stroustrup 14.4.2, 11.10.

Part II

Revision

Major Differences between Java and C++

C++ allows direct access to objects!!!

- ***[*]*** call-by-value & call-by-reference (session 1 and since)
- operator overloading (session 3)
- genericity or template classes (sessions 4–6)
- ***[*]*** slicing of derived objects on copying (session 6)
- memory management
  - local allocation of objects (sessions 1–2 and since, esp. 9–10)
  - pointers (sessions 5 and 6)
  - dynamic allocation (sessions 8–9) ***[*]*** No GC
- multiple inheritance (session 7)
- ***[*]*** gang of three (session 8)
- ***[*]*** Rvalue references (& call-by-rvalue-reference – session 10)

[*] Because C++ allows direct access to objects...

Things you should be able to do

- Write simple C++ classes/functions
- Use STL containers/iterators to write compact (& correct!) code
- Understand how call-by-value & call-by-reference differ
- The various meanings of **`const`** & know when to use it
- Read programs using overloaded operators; identify which methods/independent functions are called
- Overload operators for new types
  - As member functions
  - As independent functions

(continued)

More things you should be able to do

- Distinguish between objects & pointers (& how each behaves)
- Know how to use static, local, dynamic and temporary allocation, appreciating their properties and distinctive features
- Understand the properties of subobjects (= fields of other objects)
- Use inheritance, method redefinition and abstract classes in C++
  - Know the order of initialisation (parents [*], fields [*], constructor) and destruction (opposite)
    [*] IN THE ORDER OF DECLARATION!!!

    BE CAREFUL WITH FIELD INITIALISATION!!!
- Write generic C++ classes/functions
- Use the standard generic algorithms!!!

(continued)

Even more things you should be able to do

- Multiple inheritance – both replicated & virtual inheritance
- Explain — Gang of Three
  1. What the automatically generated constructors, destructors & assignment operators do
  2. When they are inadequate, and if so
  3. How they should be replaced
- Use the exception syntax of C++ (**`try`**, **`catch`**, **`throw`**, **`rethrow`**)
- **Use RAII** (“resource acquisition is initialization”)
  to safely release resources,
  even in the presence of exceptions
  - Use **`unique_ptr`** (and less often **`shared_ptr`** [*]) to automatically manage your pointers
    ([*] sharing makes it harder to parallelise)

Empty On Purpose

Even more things you should be able to do
- Multiple inheritance – both replicated & virtual inheritance
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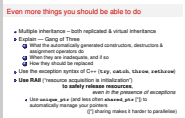
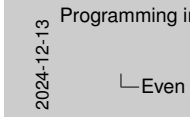
  1. What the automatically generated constructors, destructors & assignment operators do
  2. When they are inadequate, and if so
  3. How they should be replaced
- Use the exception syntax of C++ (try, catch, throw, rethrow)
- Use RAII (“resource acquisition is initialization”)
  to safely release resources,
  even in the presence of exceptions
  - Use unique_ptr (and less often shared_ptr [*]) to automatically manage your pointers
    ([*] sharing makes it harder to parallelise)



Final Notes – I

- Java has **`Exception`** (or some such) from which all exceptions MUST derive.
- C++ doesn't impose such a constraint (though it does have **`std::exception`** that you could derive from)
  - So you can throw/catch an object of ANY class in C++ (even basic types – but avoid this).
- **Good practice:** throw a TEMPORARY object!
  `throw my_exception("Not your lucky day!");`
- How can I catch it?
  The same way I can receive a parameter – EITHER BY VALUE (exception is *COPIED* and *SLICED* – BAD!) or BY REFERENCE (GOOD!)

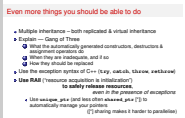
```
try {
  // dangerous stuff
} catch (problem1 p1) { // catch BY VALUE - BAD! BAD!  >:-(
  // exception object COPIED and POTENTIALLY SLICED
  // treat p1
} catch (problem2 & p2) { // catch BY REFERENCE - GOOD! :-)
  // exception object NOT COPIED
  // treat p2
}
```

Final Notes – II

- A **`catch`** clause catches all exceptions of derived classes too – be careful to place clauses for these classes before the clauses of their superclasses.
- If no **`catch`** clause matches, then the function is terminated, destroying all its local stack-allocated variables, and the system looks for a matching catch clause in its caller.
- As exceptions can belong to ANY class (even basic types. . .), we cannot write **`catch (Exception &e)`** to catch any kind of exception. Instead we need to use the ellipsis notation in C++
  `catch (...)` matches any exception
- In order to state that we want to re-throw the same exception we simply write: **`throw;`** (EVEN when we have a name for the exception – it makes explicit that we're re-throwing)

- Resource allocation very often uses a pattern similar to stack-based allocation (acquire, use, release), thus the pattern:
  "Resource Acquisition Is Initialization (RAII)"
  Introduce a local manager object for the resource that releases the resource in its destructor.
  In this way it is released whether the code block is terminated normally or through an exception, avoiding boiler-plate code with try/catch clauses.
- Simple example of that: **`point_manager`** (slides 14–15)



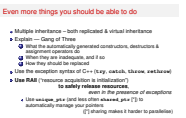
Final Notes – III

- Standard manager class: **`auto_ptr`** (slides16–20)
  An example of a "**smart pointer**" (which are examples of the "**proxy**" pattern)
- **`auto_ptr`** copy constructor:

```
template <typename T>
auto_ptr<T>::auto_ptr(/*NO const!*/ auto_ptr<T> & other )
  : _ptr(other._ptr) { other._ptr = nullptr; }
```

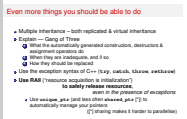
- **`auto_ptr`** assignment operator:

```
template <typename T>
auto_ptr<T> &
auto_ptr<T>::operator=(/*NO const!*/ auto_ptr<T> & other )
{
  if (&other != this) {
      delete _ptr;
      _ptr = other._ptr;      // MOVE (STEAL) THE POINTER
      other._ptr = nullptr;
  }
  return *this;
}
```

Final Notes – IV

- **`auto_ptr`** is badly broken. . .
  1. It calls **`delete`**, so cannot handle arrays of objects (these need **`delete []`**)
     (OK, can always have a pointer to a vector)
  2. It says it has a copy constructor but it doesn't copy, it ***moves*** the value from the other object into itself – major breakage!
     Cannot use them in standard containers!!!
- In C++11 **`auto_ptr`** has been deprecated and replaced by **`unique_ptr`**
- You still need to learn how to implement **`auto_ptr`** and understand it and its problems
  Only then you'll understand why we need rvalue references

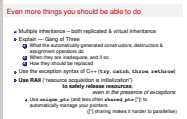


Final Notes – V

- What to do when you receive an exception?
  You're at a family party and cousin Jim starts to choke on a piece of meat!
  1. Catch the exception and ignore it – hide Jim in a closet and pretend nothing's happened.
  2. Catch the exception and log it – "Dear diary, Jim once again ruined the party. . . " (after having hidden Jim in a closet).
  3. Catch the exception and fix the problem – Help Jim spit the piece of meat that is choking him.
  4. Not catch the exception but let it propagate instead to your caller (or catch/rethrow), who might know how to fix it – Call 999 and let them know there's someone choking; they'll deal with it (if they can).

  HINT: It's neither #1 nor #2 that you should be doing. . .

2024-12-13
Programming in C++
└Even more things you should be able to do



Final Notes – VI

Further pointers:

- "What should I throw?"
  A temporary object.
  https://isocpp.org/wiki/faq/exceptions#what-to-throw
- "What should I catch?"
  Catch by reference if given the choice (avoids copying).
  https://isocpp.org/wiki/faq/exceptions#what-to-catch
- "But MFC seems to encourage the use of catch-by-pointer; should I do the same?" (aka When in Rome. . .)
  When working with MFC yes, otherwise no as it's not clear who's responsible for deleting the pointed-to object.
  https://isocpp.org/wiki/faq/exceptions#catch-by-ptr-in-mfc
- "What does throw; (without an exception object after the throw keyword) mean? Where would I use it?"
  Re-throw.
  https://isocpp.org/wiki/faq/exceptions#throw-without-an-object
- "How do I throw polymorphically?"
  To catch derived exceptions instead of base exceptions, make sure you're throwing derived exception objects! Use virtual functions.
  https://isocpp.org/wiki/faq/exceptions#throwing-polymorphically
- "When I throw this object, how many times will it be copied?"
  Nobody knows (zero up to some N) but the exception object must have a copy-constructor (even if the compiler will never copy it).
  https://isocpp.org/wiki/faq/exceptions#num-copies-of-exception

- Check out on StackOverflow the iterator proxy I created for implementing **`copy_if_and_transform`**
  https://stackoverflow.com/questions/23579832/why-is-there-no-transform-if-in-the-c-standard-library/74288551#74288551
  or **`t.ly/1LCtT`**
  (it tries to make **`*from`** *behave differently, depending on the context)*