RAII and Smart Pointers

CS 106L Spring 2020 – Avery Wang and Anna Zeng

Game Plan

- Brief Recap of Exceptions
- RAII
- Examples
- Smart Pointers

Without any extra information, how many potential code paths are in this function?

```
string EvaluateSalaryAndReturnName( Employee e ) {

  if ( e.Title() == "CEO" || e.Salary() > 100000 ) {
    cout << e.First() << " "
         << e.Last() << " is overpaid" << endl;
  }
  return e.First() + " " + e.Last();

}
```

Code path 1

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Code path 2

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Code path 3 (short-circuiting)

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  }
  return e.First() + " " + e.Last();

}
```

Are there any more code paths?

```
string EvaluateSalaryAndReturnName( Employee e ) {

  if ( e.Title() == "CEO" || e.Salary() > 100000 ) {
    cout << e.First() << " "
         << e.Last() << " is overpaid" << endl;
  }
  return e.First() + " " + e.Last();

}
```

Hidden Code Paths

There are (at least) 23 code paths in the code before!

- 1 – Copy constructor of Employee parameter, may throw.
- 5 – Constructor of temp string/ints, may throw.
- 6 – Call to Title, Salary, First (2), Last (2), may throw.
- 10 – Operators may be user-overloaded, may throw.
- 1 – Copy constructor of string for return value, may throw.

A Brief Review of Exceptions

Example

A Brief Review of Exceptions

Aside: Exceptions

Exceptions are a way to transfer control and information to a (potential) exception handler.

```
try {
    // code associated with exception handler
} catch ( [exception type] e ) {
    // exception handler
} catch ( [exception type] e )  {
    // exception handler
} // etc.
```

Aside: Exceptions

Exceptions are a way to transfer control and information to a (potential) exception handler.

We won’t cover in depth how to use exceptions (you’ve used them, kinda, in 106B, and they’re easy to figure out).

However, the idea of exception safety is extremely important in object-oriented programming!

Aside: Enforcing exception safety

Functions can have four levels of exception safety:

- Nothrow exception guarantee
  - absolutely does not throw exceptions: destructors, swaps, move constructors, etc.
- Strong exception guarantee
  - rolled back to the state before function call
- Basic exception guarantee
  - program is in valid state after exception
- No exception guarantee
  - resource leaks, memory corruption, bad…

Aside: Enforcing exception safety

Functions can have four levels of exception safety:

- Nothrow exception guarantee
- Strong exception guarantee
- Basic exception guarantee
- No exception guarantee

All of these guarantees are just promises!

noexcept is just a promise that a function won't throw any errors, but not a compile-time check!

Aside: Enforcing exception safety

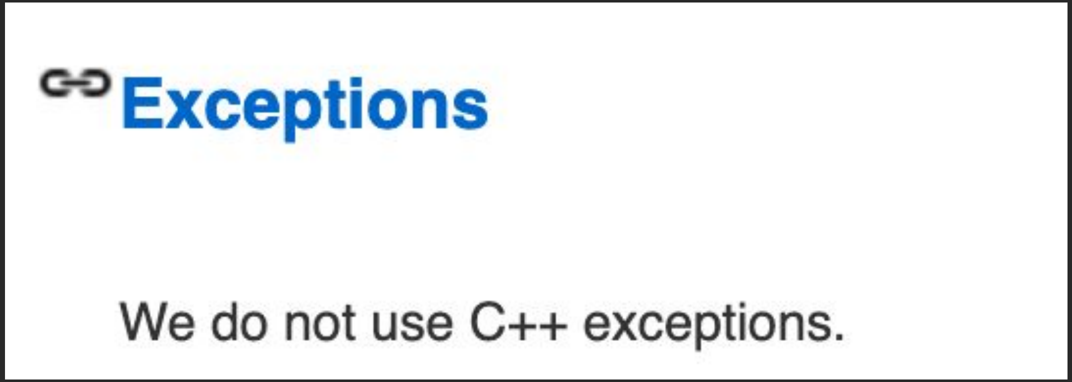
Is it worth it to enforce exception safety?

“Exceptions happen. They just do. The standard library emits them. The language emits them. We have to code for them… It does require adopting a few habits, however, and following them diligently -- but then so did learning to program with error codes” (or just learning to program).

- Herb Sutter, current C++ overlord

*i.e. head of the ISO C++ Committee

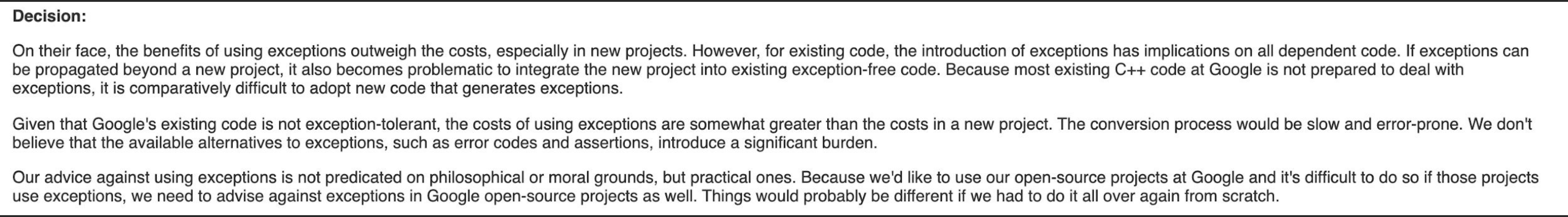
Aside: avoiding exceptions entirely


Exceptions

We do not use C++ exceptions.

Source: https://google.github.io/styleguide/cppguide.html#Exceptions

Aside: avoiding exceptions entirely



Decision:

On their face, the benefits of using exceptions outweigh the costs, especially in new projects. However, for existing code, the introduction of exceptions has implications on all dependent code. If exceptions can be propagated beyond a new project, it also becomes problematic to integrate the new project into existing exception-free code. Because most existing C++ code at Google is not prepared to deal with exceptions, it is comparatively difficult to adopt new code that generates exceptions.

Given that Google's existing code is not exception-tolerant, the costs of using exceptions are somewhat greater than the costs in a new project. The conversion process would be slow and error-prone. We don't believe that the available alternatives to exceptions, such as error codes and assertions, introduce a significant burden.

Our advice against using exceptions is not predicated on philosophical or moral grounds, but practical ones. Because we'd like to use our open-source projects at Google and it's difficult to do so if those projects use exceptions, we need to advise against exceptions in Google open-source projects as well. Things would probably be different if we had to do it all over again from scratch.

Source: https://google.github.io/styleguide/cppguide.html#Exceptions

tl;dr We forgot to do it initially, so let’s not bother getting started.

So let’s go back to our 23+ code paths…

```
string EvaluateSalaryAndReturnName( Employee e ) {

  if ( e.Title() == "CEO" || e.Salary() > 100000 ) {
    cout << e.First() << " "
         << e.Last() << " is overpaid" << endl;
  }
  return e.First() + " " + e.Last();

}
```

Follow-up example: what might go wrong?

```
string EvaluateSalaryAndReturnName(int idNumber) {
  Employee* e = new Employee(idNumber);

  if ( e.Title() == "CEO" || e.Salary() > 100000 ) {
    cout << e.First() << " "
         << e.Last() << " is overpaid" << endl;
  }
  auto result = e.First() + " " + e.Last();

  delete e;
  return result;
}
```

Can you guarantee this function will not have a memory leak?

```
string EvaluateSalaryAndReturnName(int idNumber) {
  Employee* e = new Employee(idNumber);

  if ( e.Title() == "CEO" || e.Salary() > 100000 ) {
    cout << e.First() << " "
         << e.Last() << " is overpaid" << endl;
  }
  auto result = e.First() + " " + e.Last();

  delete e;
  return result;
}
```

We can’t guarantee the ‘delete’ call is called if an exception is thrown!

```
string EvaluateSalaryAndReturnName(int idNumber) {
  Employee* e = new Employee(idNumber);

  if ( e.Title() == "CEO" || e.Salary() > 100000 ) {
    cout << e.First() << " "
         << e.Last() << " is overpaid" << endl;
  }
  auto result = e.First() + " " + e.Last();

  delete e;
  return result;
}
```

More general concern:
resources that need to be released.

Resources that need to be returned.

	Acquire	Release
• Heap memory	new	delete

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	Acquire	Release
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• Files	open	close

More general concern: resources that need to be released.

Resources that need to be returned.

	Acquire	Release
• Heap memory	new	delete
• Files	open	close
• Locks	try_lock	unlock
• Sockets	socket	close

How do we guarantee classes release their resources?

Regardless of exceptions!

RAII

Resource Acquisition Is Initialization

RAII

"The best example of why I shouldn't be in marketing"

"I didn't have a good day when I named that”

-- Bjarne Stroustrup

SBRM

Scope Based Memory Management

CADRE

Constructor Acquires, Destructor Releases

PIMPL

Pointer to Implementation.

(this is not another name for RAII. just wanted to bring it up since we are talking about bad C++acronyms).

What is RAII?

All resources should be acquired in the constructor.

All resources should be released in the destructor.

What is the rationale?

There should never be a ”half-valid” state of the object. Object useable after its creation.

The destructor is always called (even with exceptions), so the resource is always freed.

You learned this in CS 106B.
Is it RAII Complaint?

```
void printFile () {
  ifstream input();
  input.open(“hamlet.txt”);

  string line;
  while (getline(input, line)) {
    cout << line << endl;
  }

  input.close();
}
```

Resource not acquired in the constructor or released in the destructor.

```
void printFile () {
  ifstream input();
  input.open("hamlet.txt");

  string line;
  while (getline(input, line)) {
    cout << line << endl;
  }

  input.close();
}
```

Resource not acquired in the constructor or released in the destructor.

```
void printFile () {
  ifstream input(“hamlet.txt”);


  string line;
  while (getline(input, line)) { // might throw exception
    cout << line << endl;
  }

  // no close call needed!
} // stream destructor, releases access to file
```

Resource not acquired in the constructor or released in the destructor.

```
void cleanDatabase (mutex& databaseLock,
         map<int, int>& database) {

  databaseLock.lock();

  // other threads will not modify database
  // modify the database
  // if exception thrown, mutex never unlocked!

  databaseLock.unlock();
}
```

The fix: an object whose sole job is to release the resource when it goes out of scope.

```
void cleanDatabase (mutex& databaseLock,
         map<int, int>& database) {

  lock_guard<mutex> lock(databaseLock);

  // other threads will not modify database
  // modify the database
  // if exception thrown, that’s fine!

  // no release call needed
} // lock always unlocked when function exits.
```

How do you think lock_guard is implemented?

Here’s a non-template version.

```
class lock_guard {
public:
  lock_guard(mutex& lock) : acquired_lock(lock) {
    acquired_lock.lock()
  }
  ~lock_guard() {
    acquired_lock.unlock();
  }
private:
  mutex& acquired_lock;
}
```

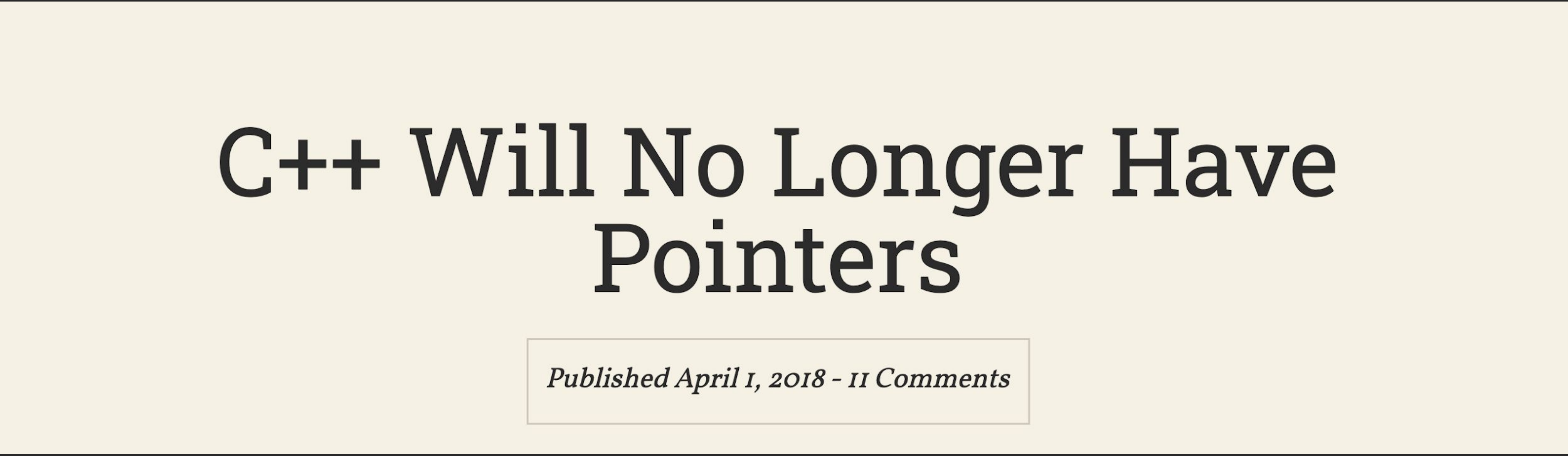
Summary for RAII

Acquire resources in the constructor,
release in the destructor.

Clients of your class won’t have to worry about
mismanaged resources.

RAII for Memory!

This is what we are approaching (kinda)!

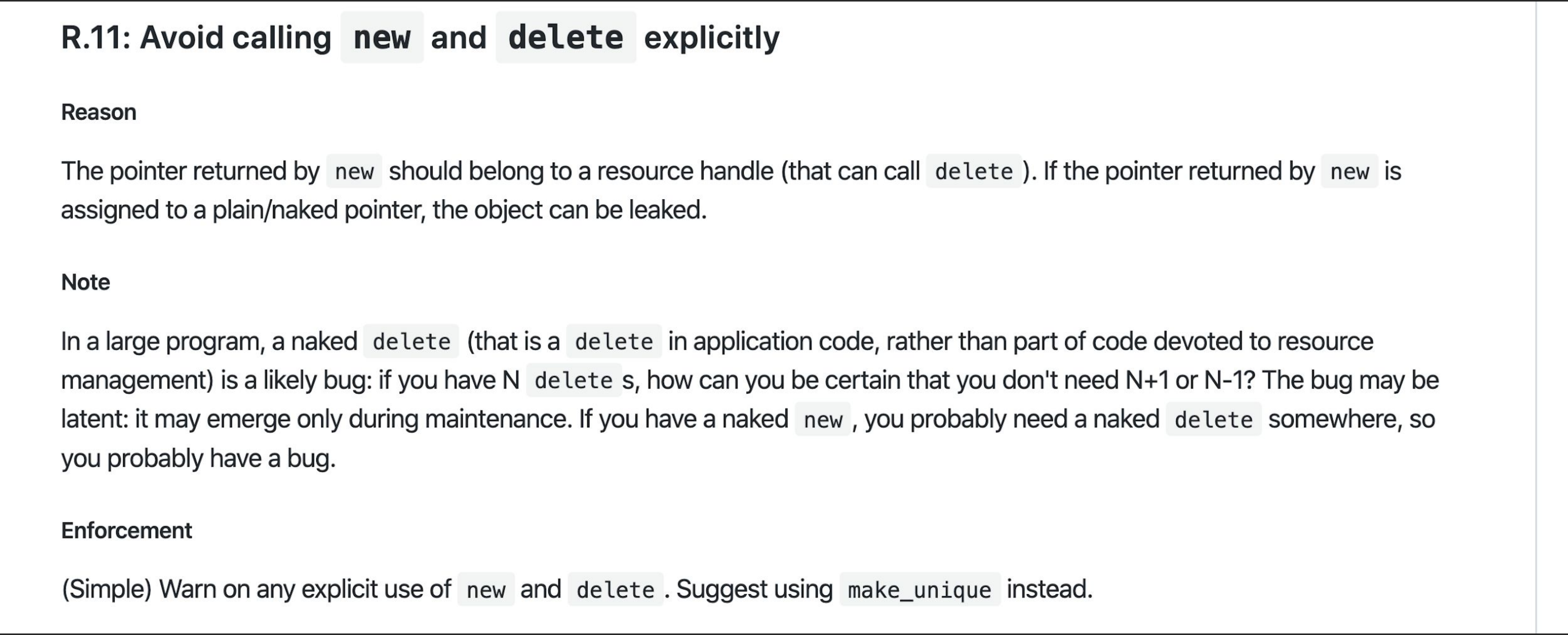


C++ Will No Longer Have Pointers

Published April 1, 2018 - 11 Comments

(note: this is an April Fools joke by a C++ blog, even if it has some truth, please do not take this as a truth!). Do not blindly believe this.

More accurately…



R.11: Avoid calling `new` and `delete` explicitly

Reason

The pointer returned by `new` should belong to a resource handle (that can call `delete`). If the pointer returned by `new` is assigned to a plain/naked pointer, the object can be leaked.

Note

In a large program, a naked `delete` (that is a `delete` in application code, rather than part of code devoted to resource management) is a likely bug: if you have N `delete`s, how can you be certain that you don't need N+1 or N-1? The bug may be latent: it may emerge only during maintenance. If you have a naked `new`, you probably need a naked `delete` somewhere, so you probably have a bug.

Enforcement

(Simple) Warn on any explicit use of `new` and `delete`. Suggest using `make_unique` instead.

Bad Dad Joke of the Day 1:

- What do you call two bass players standing perpendicular to each in their band?
- ...A set of orthogonal bassists!

Creds: Jack

Bad Dad Joke of the Day 2:

- How do you define recursion?
- You first define recursion.

Creds: Paul

2-min stretch break!

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- How do you define recursion?
- You first define recursion.

Creds: Paul

2-min stretch break!

Bad Dad Joke of the Day 3:

- What do you call a hippie's wife?
- A Mississippi!

Creds: Claire

Bad Dad Joke of the Day 4:

- What do you call the child of a guy from Holland and a girl from the Philippines?
- ... A JALEPAÑO. Thank you y'all, I'm here all week via Zoom.

Creds: Neetish

Smart Pointers

We just saw how file reading and locks can be non-RAII compliant...

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  while (getline(input, line)) {
    cout << line << endl;
  }
  input.close();
}
```

```
void cleanDatabase (mutex& databaseLock,
                    map<int, int>& database) {
  databaseLock.lock();
  // other threads will not modify
database
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}
```

…where the fix was to wrap it in a special object that always releases the resource…

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```
void printFile () {
  ifstream input("hamlet.txt");
  string line;
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    cout << line << endl;
  }
  // no close call needed!
}
// stream destructor
// releases access to file
```

```
void cleanDatabase (mutex& databaseLock,
           map<int, int>& database) {
  lock_guard<mutex>(databaseLock);
  // other threads will not modify
database
  // modify the database
  // if exception thrown, that's fine!
  // no release call needed
}
// lock_guard destructor
// releases lock
```

…so let’s do it again!

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You learned this in CS 106B. Is it RAII Complaint?

```
void rawPtrFn () {

  Node* n = new Node;

  // do some stuff with n…

  delete n;

}
```

…so let’s do it again!

You learned this in CS 106B. Is it RAII Complaint?

```cpp
void rawPtrFn () {

  Node* n = new Node;

  // do some stuff with n…
  // if exception thrown, n never deleted!
  delete n;

}
```

❌

C++ has built-in “smart” (i.e. RAII-compliant) pointers:

```
std::unique_ptr
std::shared_ptr
std::weak_ptr
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boost::intrusive_ptr
...
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...
```

Aside: `std::auto_ptr` is deprecated!

`std::unique_ptr`

Uniquely owns its resource and deletes it when the object is destroyed.

Cannot be copied (but can be moved, if non-const)!

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```
void rawPtrFn () {
  Node* n = new Node;
  // do stuff with n…
  delete n;
}
```

```
void rawPtrFn () {
  std::unique_ptr<Node> n(new Node);
  // do some stuff with n

} // Freed!
```

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  // do stuff with n…
  delete n;
}
```

```
void rawPtrFn () {
  std::unique_ptr<Node> n(new Node);
  // do some stuff with n

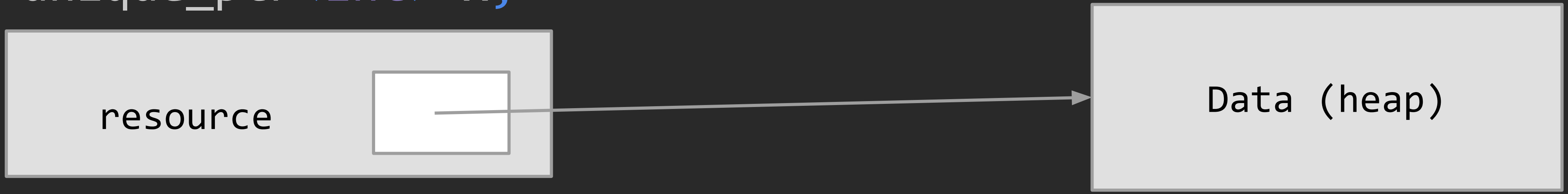
} // Freed!
```

What happens if we try to copy a unique_ptr?

Let’s try it!

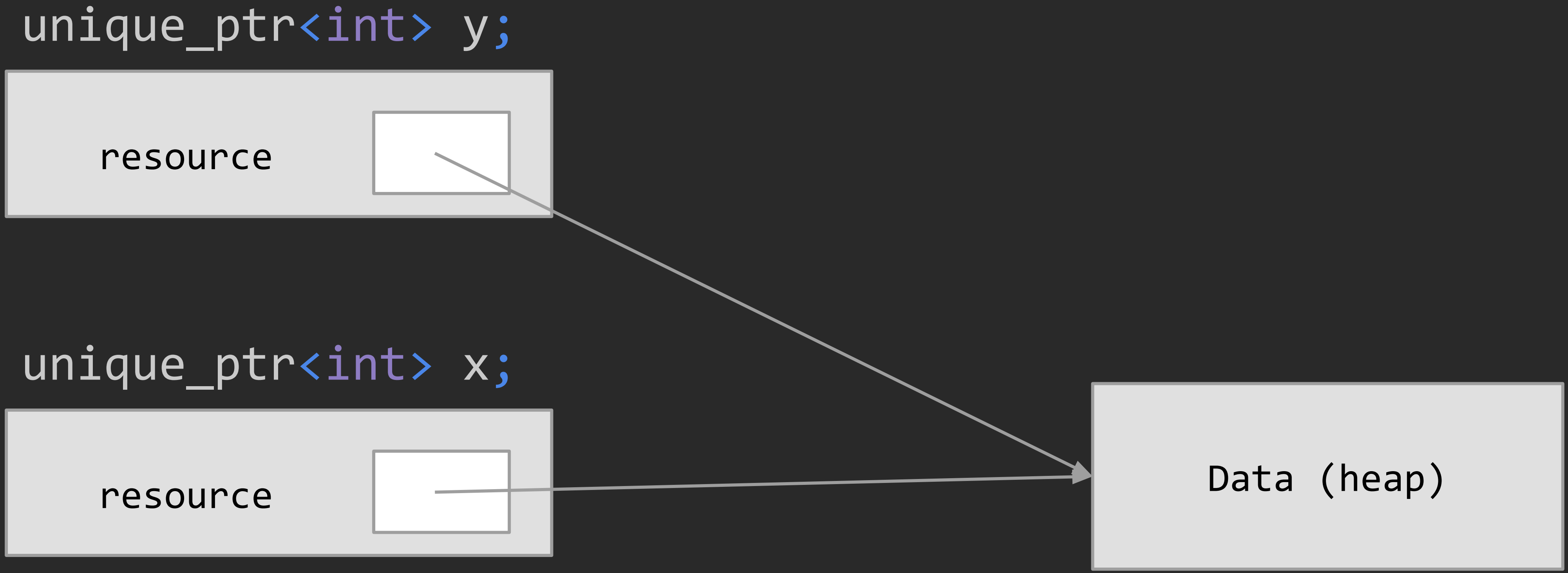
First we make a `unique_ptr`

```
unique_ptr<int> x;
```



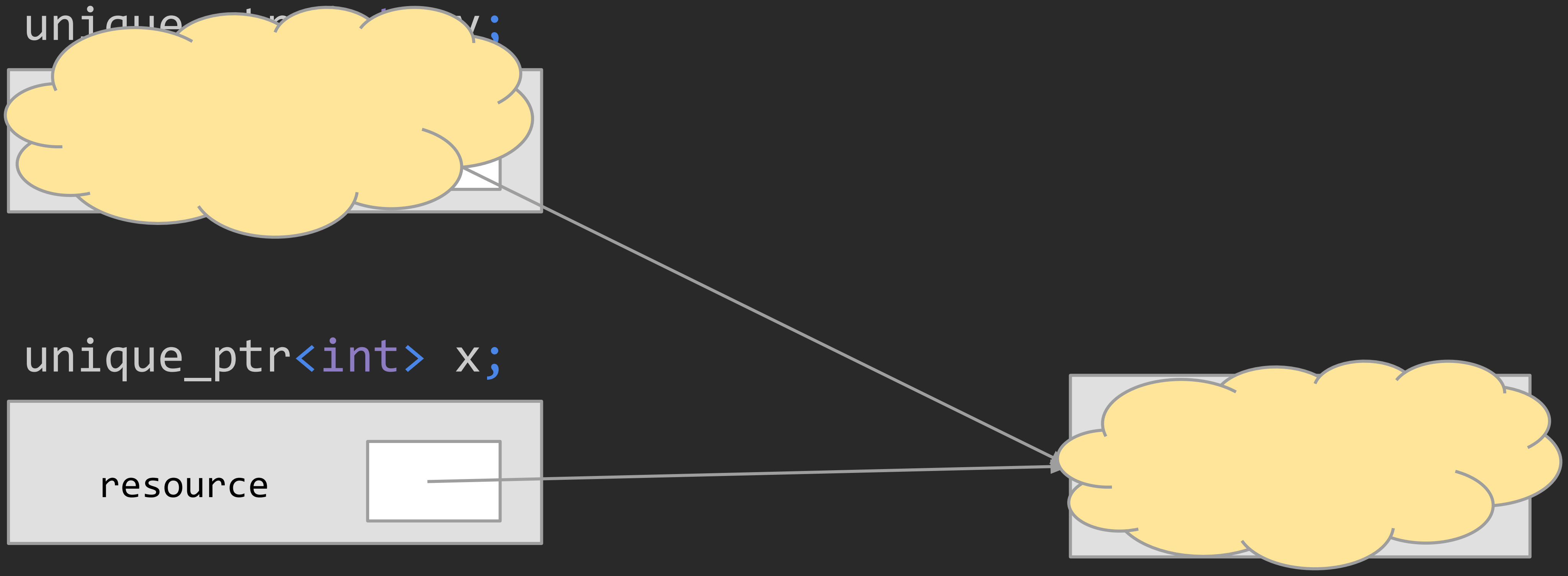
Let’s try it!

We then make a copy of our `unique_ptr`



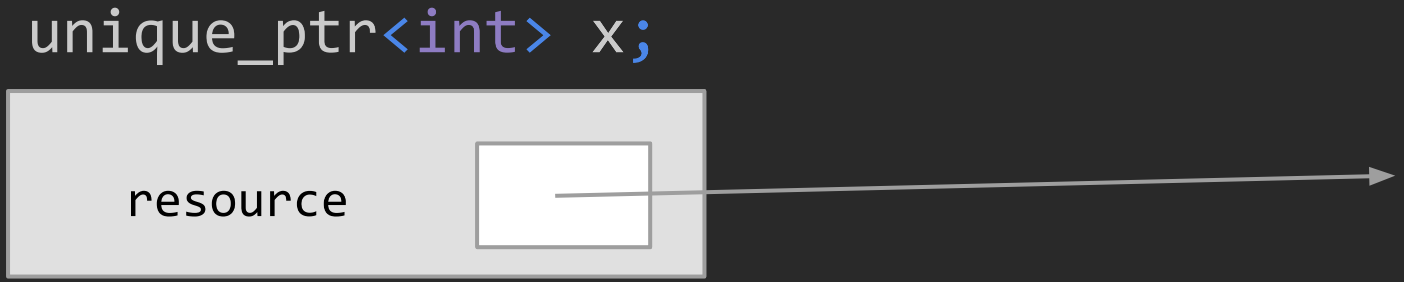
Let's try it!

When y goes out of scope, it deletes the heap data



Let’s try it!

This leaves x pointing at deallocated data



Let’s try it!

If we dereference x or its destructor calls delete, we crash

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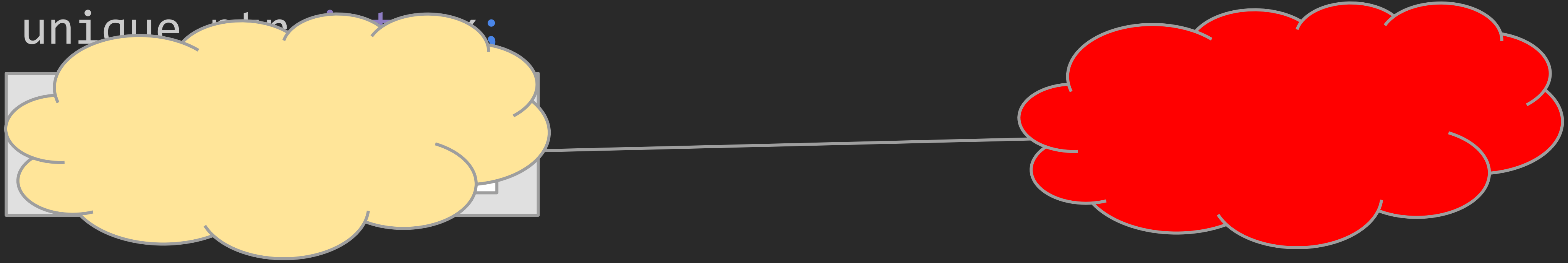

```
unique_ptr<int> x;
```

`std::unique_ptr`

The unique_ptr class hence disallows copying.

Recall: How can you tell a class to disallow copying?

std::unique_ptr

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Recall: How can you tell a class to disallow copying?

```
// Delete the copy constructor and assignment!
unique_ptr(unique_ptr& u) = delete;
unique_ptr& operator=(unique_ptr& r) = delete;
```

std::unique_ptr

The unique_ptr class hence disallows copying.

Recall: How can you tell a class to disallow copying?

```
// Delete the copy constructor and assignment!
unique_ptr(unique_ptr& u) = delete;
unique_ptr& operator=(unique_ptr& r) = delete;
```

What if we want to have multiple pointers to the same object?

`std::shared_ptr`

Resource can be stored by any number of `shared_ptr`s.

Deleted when none of them point to it.

std::shared_ptr

Resource can be stored by any number of `shared_ptr`s.

Deleted when none of them point to it.

```
{
    std::shared_ptr<int> p1(new int);
    // Use p1
    {
        std::shared_ptr<int> p2 = p1;
        // Use p1 and p2
    }
    // Use p1
}
// Object is freed!
```

std::shared_ptr

Resource can be stored by any number of shared_ptrs.

Deleted when none of them point to it.

```
{
    std::shared_ptr<int> p1(new int);
    // Use p1
    {
        std::shared_ptr<int> p2 = p1;
        // Use p1 and p2
    }
    // Use p1
}
// Object is freed!
```

Important: this only works if new shared_ptrs are made though copy, not the raw pointer!

`std::shared_ptr`

How are these implemented?

`std::shared_ptr`

How are these implemented? Reference counting!

- Idea: Store int that tracks how many shared_ptrs currently reference that data
    - Increment in copy constructor/copy assignment
    - Decrement in destructor or when overwritten with copy assignment
- Frees the resource when reference count hits 0

std::shared_ptr

Notice that our previous example still works!

```
void rawPtrFn () {
  Node* n = new Node;
  // do stuff with n…
  delete n;
}
```

```
void rawPtrFn () {
  std::unique_ptr<Node> n(new Node);
  // do some stuff with n

} // Freed!
```

std::shared_ptr

Notice that our previous example still works!

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void rawPtrFn () {
  Node* n = new Node;
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```
void rawPtrFn () {
  Node* n = new Node;
  // do stuff with n…
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}
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```
void rawPtrFn () {
  std::shared_ptr<Node> n(new Node);
  // do some stuff with n

} // Freed!
```

Why?

And finally, std::weak_ptr

Similar to shared_ptr, but doesn’t contribute to the reference count.

To access the referenced data, must convert to shared_ptr:

```
std::shared_ptr<T> tempSharedPtr = weakPtr.lock();
```

And finally, `std::weak_ptr`

Similar to shared_ptr, but doesn't contribute to the reference count.

To access the referenced data, must convert to shared_ptr:

```
std::shared_ptr<T> tempSharedPtr = weakPtr.lock();
```

Use to observe a resource without influencing its lifetime, or to break shared_ptr cycles!

Smart Pointers: RAII wrapper for pointers

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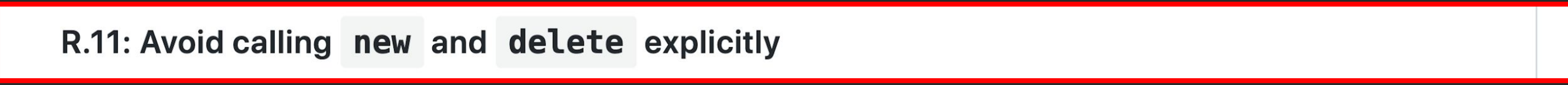
```
std::unique_ptr<T> up{new T};


std::shared_ptr<T> sp{new T};


std::weak_ptr<T> wp = sp;
```

But wait… aren’t we still using new?

```cpp
std::unique_ptr<T> up{new T};


std::shared_ptr<T> sp{new T};


std::weak_ptr<T> wp = sp;
```



R.11: Avoid calling `new` and `delete` explicitly

C++ has built-in Smart Pointer constructors!

```
std::unique_ptr<T> up{new T};


std::shared_ptr<T> sp{new T};


std::weak_ptr<T> wp = sp;
```

C++ has built-in Smart Pointer constructors!

```
std::unique_ptr<T> up{new T};
std::unique_ptr<T> up = std::make_unique<T>();

std::shared_ptr<T> sp{new T};


std::weak_ptr<T> wp = sp;
```

C++ has built-in Smart Pointer constructors!

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std::unique_ptr<T> up{new T};
std::unique_ptr<T> up = std::make_unique<T>();

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std::weak_ptr<T> wp = sp;
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std::unique_ptr<T> up{new T};
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//can only be copy/move constructed (or empty)!
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C++ has built-in Smart Pointer constructors!

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std::unique_ptr<T> up{new T};
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std::weak_ptr<T> wp = sp;
//can only be copy/move constructed (or empty)!
```

Which way is better?

```
std::unique_ptr<T> up{new T};
std::unique_ptr<T> up = std::make_unique<T>();
```

Which way is better?

```
std::unique_ptr<T> up{new T};
std::unique_ptr<T> up = std::make_unique<T>();
```

Answer:

Always use `std::make_unique<T>()`!

We'll see why at the beginning of next lecture.

So, coming full circle...

R.11: Avoid calling `new` and `delete` explicitly

In modern C++, we almost never see `new` and `delete`!

Example

RAII in our Template-Vector class!

Next time

Multithreading