MODERN C++ DESIGN PATTERNS

Smart Pointers

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Plan for Today

- `std::unique_ptr<T>`
- `std::unique_ptr<T[]>`
- `std::shared_ptr<T>`

Raw Pointers: Usage (1/4)

- Non-copying view of object owned by caller ["*in*" parameter]
- For callee to modify object owned by caller ["*in/out*" parameter]
- One-half of pointer/length pair for passing arrays ["*in*" or "*in/out*" parameter]
- Express "*no value*" in parameter or return value
- To manage heap memory

Raw Pointers: Usage (2/4)

- Non-copying view of object owned by caller [“*in*” parameter]
  - Replaced with native references [such as `X const&`]
- For callee to modify object owned by caller [“*in/out*” parameter]
  - Replaced with native references [such as `X&`]

Raw Pointers: Usage (3/4)

- One-half of pointer/length pair for passing arrays ["*in*" or "*in/out*" parameter]
  - Replaced with standard library containers such as `std::string`, `std::array<>`, `std::deque<>`, and `std::vector<>`

Raw Pointers: Usage (4/4)

- Express "*no value*" in parameter or return value
  - C++17 provides vocabulary type `std::optional<>` to simulate use of `nullptr` by raw pointers to express having no value
- To manage heap memory
  - C++11 provides smart pointers

Why Not Raw Pointers To Manage Heap? (1/2)

- Declaration doesn't indicate whether it is pointer to single object or array
- Declaration doesn't indicate whether pointer owns thing it points to
- If you want to destroy what pointer points to, there's no way to tell how
  - If `delete` is way to go, can't say whether to use `delete` or `delete[]`
- Difficult to ensure memory is released exactly once along every path in your code
- No way to tell if pointer dangles

Why Not Raw Pointers To Manage Heap? (2/2)

- Memory leaks
  - You might allocate object on heap and accidentally forget to write code that frees it
  - You might have written freeing code, but due to early return or exception being thrown, that code never runs and memory remains unfreed
- Use-after-free
  - You make copy of a pointer to heap object, and then free that object thro' original pointer; holder of copied pointer doesn't realize their pointer is no longer valid
- Heap corruption via pointer arithmetic
  - You allocate array on heap starting at address A; using raw pointer you do pointer arithmetic; you accidentally free pointer to address $A+k$ where $k \neq 0$

Zombie Objects


```cpp
// memory that can never be recovered ...
size_t make_a_wish(std::string owner, int id) {
  Wish *wish = new Wish(wishes[id], owner);
  return wish->size();
}
```

```cpp
// possible problems: memory leak
// pre-mature deletion, double deletion
Wish* make_a_wish(std::string owner, int id) {
  Wish *wish = new Wish(wishes[id], owner);
  return wish;
}
```

What are Smart Pointers? (1/2)

- Class wrappers around raw pointers so that heap resource is managed using RAII idiom
  - Behaves syntactically just like a pointer
  - Special member functions [ctors, dtors, copy/move] have additional bookkeeping to ensure certain constraints

What are Smart Pointers? (2/2)

- Fundamental property: overload operator *
- Overload special member functions to preserve its class invariants, whatever those are:
  - Pointer's dtor also free its pointee
  - Maybe pointer cannot be copied
  - Or, maybe pointer can be copied, but it knows how many copies exist and won't free pointee until last pointer to it has been destroyed
  - Or maybe pointer can be copied, and you can free pointee, but if you do, all other pointers to it magically become null
  - Or, maybe pointer has no built-in operator +
  - Or, maybe you're allowed to adjust pointer's value arithmetically, but arithmetic "what object is pointed-to"is managed separately from identity of "what object is to be freed"

Smart Pointers: <memory>

Name	Description
`std::unique_ptr`	*Exclusively owns resources* Can't be copied Uses RAII to automatically delete resource when owner goes out-of-scope
`std::shared_ptr`	Uses *reference counter* to keep track of users of resource Deletes resource when reference counter is 0
`std::weak_ptr`	Doesn't own resources Merely observes objects being shared by `shared_ptr`s

`std::unique_ptr<T>`

- Embodies *exclusive ownership* semantics
- Can neither implicitly nor explicitly copy such a pointer – you can only *move* it
- Automatically releases resource when it goes out of scope
- No pointer arithmetic is defined
- Equally sized and equally fast as raw pointers

`std::unique_ptr<>` Methods

Name	Description
`get`	Returns pointer to resource
`get_deleter`	Returns `delete` function
`release`	Returns pointer to resource and releases it
`reset`	Resets resource
`swap`	Swaps resource

Using std::unique_ptr<T> (1/3)

- Same interface as ordinary pointer
  - Operator * dereferences object to which it points
  - Operator -> provides access to member if object is class or structure

```
std::unique_ptr<std::string> up{new std::string{"hlp3"}};
(*up)[0] = 'H';              // replace first character
up->append("good");          // append some characters
std::unique_ptr<int> up2 = new int; // error
std::unique_ptr<int> up3(new int);  // ok
std::unique_ptr<std::string> up4;   // ok: empty
up.reset(); // up = nullptr;
std::unique_ptr<std::string> up4{new std::string{"hlp3"}};
std::string *ps = up4.release(); // up4 loses ownership
```

Using std::unique_ptr<T> (2/3)


```
std::unique_ptr<std::string> up{new std::string{"hlp3"}};
if (up) { // call operator bool()
  std::cout << *up << '\n';
}

if (up != nullptr) { // if up is not empty
  std::cout << *up << '\n';
}

if (up.get() != nullptr) { // if up is not empty
  std::cout << *up << '\n';
}
```

Using std::unique_ptr<T> (3/3)

- See *using_up.cpp*

```
std::unique_ptr<int> up1 {new int {10}};
// make code exception-safe
std::unique_ptr<int> up2 {std::make_unique<int>(10)};
std::unique_ptr<int> up3 = up2; // error: no copies
std::unique_ptr<int> up4 = std::move(up1); // ok
```

```
template<typename T, typename... Args>
std::unique_ptr<T> make_unique( Args&&... args ) {
    return std::unique_ptr<T>(
      new T( std::forward<Args>(args)... ) );
}
```

std::unique_ptr<T> Clone (1/6)


```
template <typename T>
class ToyPtr {
public:
  ToyPtr() noexcept = default;
  ToyPtr(T *rhs) noexcept : m_ptr{rhs} {}
  ToyPtr(ToyPtr const& rhs) = delete;

  ToyPtr& operator=(ToyPtr const& rhs) = delete;

  T* get() const noexcept { return m_ptr; }
  operator bool() const noexcept { return bool(get()); }
  T& operator*() const noexcept { return *get(); }
  T* operator->() const noexcept { return get(); }
private:
  T *m_ptr{nullptr};
};
```

SIDENOTE: Dereferencing (1/2)

- Dereferencing operator -> can be defined as unary postfix operator:

```
struct X { int m; };

struct Ptr {
  // ...
  X *x;
  X* operator->() { return x; }
};
```

```
void f(Ptr p) {
  p->m = 7; // (p.operator())->m = 7
}
```

- Objects of type Ptr can be used to access members of X similar to way pointers are used

SIDENOTE: Dereferencing (2/2)

- If used, return type of operator -> must be pointer or object of class to which you can apply ->

```
struct A { int a; };

struct BA {
  A *p;
  A* operator->()  { return p; }
};

struct CBA {
  BA *p;
  BA& operator->()  { return *p; }
};
```

```
A   a{2};
BA  ba{&a};
CBA cba{&ba};

std::cout << a.a
          << (ba.operator->())->a
          << cba->a
          << '\n';
```

std::unique_ptr<T> Clone (2/6)


```
template <typename T>
class ToyPtr {
public:
  // ...
  void reset(T *p = nullptr) noexcept;
private:
  T *m_ptr{nullptr};
};

// p.reset(q) frees current contents of p, and
// then puts raw pointer q in its place:
template <typename T>
void ToyPtr<T>::reset(T *p) noexcept {
  T *old_ptr = std::exchange(m_ptr, p);
  delete old_ptr;
}
```

std::unique_ptr<T> Clone (3/6)


```cpp
template <typename T>
class ToyPtr {
public:
  // ...
  T* release() noexcept;
private:
  T *m_ptr{nullptr};
};

// p.release is just like p.get, but in addition to returning a
// copy of original raw pointer, it nulls out contents of p without
// freeing original pointer, because presumably caller wants to
// take ownership of pointer
template <typename T>
T* ToyPtr<T>::release() noexcept {
  return std::exchange(m_ptr, nullptr);
}
```

std::unique_ptr<T> Clone (4/6)

- Need to implement special member functions of `unique_ptr<>` so as to preserve invariant:
  - *Once raw pointer is acquired by `unique_ptr` object, it will remain valid as long as the `unique_ptr` object has same value, and when that's no longer true – when the `unique_ptr` is adjusted to point elsewhere, or destroyed – the raw pointer will be freed correctly*

std::unique_ptr<T> Clone (5/6)


```
template <typename T>
class ToyPtr {
public:
  // ...
  ToyPtr(ToyPtr&& rhs) noexcept;
  ~ToyPtr();
  ToyPtr& operator=(ToyPtr&& rhs) noexcept;
private:
  T *m_ptr{nullptr};
};

template <typename T>
ToyPtr<T>::ToyPtr(ToyPtr&& rhs) noexcept {
  this->reset(rhs.release());
}

template <typename T>
ToyPtr<T>& ToyPtr<T>::operator=(ToyPtr&& rhs) noexcept {
  this->reset(rhs.release());
  return *this;
}
```

```
template <typename T>
ToyPtr<T>::~ToyPtr() { reset(); }
```

std::unique_ptr<T> Clone (6/6)

- Need helper function make_toyptr so as to
  - Never touch raw pointers with our hands
  - Make code using ToyPtr exception safe

```
template<typename T, typename... Args>
ToyPtr<T> make_toyptr( Args&&... args ) {
    return ToyPtr<T>(
      new T( std::forward<Args>(args)... ) );
}
```

std::unique_ptrs As Members

- By using unique_ptrs within a class, you avoid …
  - Resource leaks caused by exceptions thrown during initialization of an object [see following slides labeled Exception-Safe Function Calls]
  - Defining a destructor

Rules For Function Call Evaluation

- Function arguments may generally be evaluated in any order including being interleaved
- All functions arguments must be completely evaluated before function is called
- Execution of callee and called functions cannot be interleaved
  - Once called function begins execution, no expressions from calling function may begin or continue to be evaluated until called function's execution is completed

Exception-Safe Function Calls: Example 1 (1/2)

- Assuming `expr1` and `expr2` don't contain function calls, what can you say about following function call? `f(expr1, expr2)`
  - All we can say is that `expr1` and `expr2` must be fully evaluated before `f` is called
  - Compiler may choose to evaluate `expr1` before, after, or interleaved with evaluation of `expr2`

Exception-Safe Function Calls: Example 1 (2/2)

- Assuming `expr1` and `expr2` don't contain function calls, what can you say about following function call?

```
f(g(expr1), h(expr2))
```

- Functions and expressions may be evaluated in any order as long as following rules are respected:
  - `expr1` must be fully evaluated before `g` is called
  - `expr2` must be fully evaluated before `h` is called
  - Both `g` and `h` must complete execution before `f` is called
  - Evaluations of `expr1` and `expr2` may be interleaved with each other, but nothing may be interleaved with any of function calls

Exception-Safe Function Calls: Example 2 (1/3)

- What do you think about following function call?

```
void f(T1*, T2*); // function declaration

f(new T1, new T2); // function call
```

SIDEBAR: What Does `new` Expression Do?

- What does `new` expression do?
  1. Call `operator new` function to allocate memory
  2. Call new object's ctor to initialize object in that memory
  3. Free allocated memory if construction fails because of exception

Exception-Safe Function Calls: Example 2 (2/3)

- What do you think about following function call?

```
void f(T1*, T2*); // function declaration
f(new T1, new T2); // function call
```

1. Allocate memory for T1 object
2. Construct T1 object
3. Allocate memory for T2 object
4. Construct T2 object
5. Call f

Possible evaluation order of arguments

Memory leak occurs if either step 3 or step 4 fails due to exception. C++ standard doesn't require T1 object be destroyed and its memory deallocated.

Exception-Safe Function Calls: Example 2 (3/3)

- Another possible sequence of calls:

```
void f(T1*, T2*); // function declaration
f(new T1, new T2); // function call
```

1. Allocate memory for T1 object
2. Allocate memory for T2 object
3. Construct T1 object
4. Construct T2 object
5. Call f

If step 3 fails, C++ standard requires memory for T1 object be automatically deallocated but memory allocated for T2 object is leaked.
If step 4 fails, memory allocated for T2 object is freed but standard doesn't require fully constructed T1 object be destroyed and its memory deallocated.

Exception-Safe Function Calls: Example 3 (1/2)

- Does the following function call offer improvements?

```
// declaration of non-template function
void f(std::unique_ptr<T1>, std::unique_ptr<T2>);

// call in some source file
f(std::unique_ptr<T1>{new T1}, std::unique_ptr<T2>{new T2});
```

Each resource is safe if they're captured by their `unique_ptr`, but same problems in Example 2 occur before `unique_ptr` objects are created. Therefore, nothing has changed!!!
This is not a problem with `unique_ptr`; it's just being used the wrong way!!!

Exception-Safe Function Calls: Example 3 (2/2)

- Possible sequence of calls would be:

```
void f(std::unique_ptr<T1>, std::unique_ptr<T2>);
f(std::unique_ptr<T1>{new T1}, std::unique_ptr<T2>{new T2});
```

1. Allocate memory for `T1` object
2. Construct `T1` object
3. Allocate memory for `T2` object
4. Construct `T2` object
5. Construct `unique_ptr<T1>` object
6. Construct `unique_ptr<T2>` object
7. Call `f`

Same problems are present if either step 3 or step 4 throws.

Exception-Safe Function Calls: Solution (1/2)

- We want single function that does work of memory allocation, construction of object, and construction of `unique_ptr` object
  - Such a function will be used to build `unique_ptr` object for each argument
  - Since execution of functions cannot be interleaved, each argument of `f` will execute to completion
  - Or not if exception is thrown in which case allocated memory is returned to free store

Exception-Safe Function Calls: Solution (2/2)

- Standard library provides necessary function:

Function is template because it should work for any type

Function template is variadic because ctors of various types will have different parameters

```
template<typename T, typename... Args>
std::unique_ptr<T> make_unique(Args&&... args) {
    return std::unique_ptr<T>(
      new T(std::forward<Args>(args)...));
}
```

Because caller will want to pass ctor parameters from outside `make_unique`, perfect forwarding is necessary to pass not only values but also value categories

`std::unique_ptr`s As Members (1/3)

- By using `unique_ptr`s within a class, you avoid …
  - Resource leaks caused by exceptions thrown during initialization of an object [see preceding slides labeled Exception-Safe Function Calls]
  - Defining a destructor

std::unique_ptrs As Members (2/3)


```
// possible resource leaks when using raw pointers ...
class A {
private:
  B *pb;
  C *pc;
public:
  // might cause leak if second new throws ...
  A(int i1, int i2) : pb{new B{i1}}, pc{new C{i2}} {}
  // might cause leaks if second new throws ...
  A(A const& rhs) : pb{new B{*rhs.pb}}, pc{new C{*rhs.pc}} {}
  A const& operator=(A const& rhs) {
    *pb = *rhs.pb;
    *pc = *rhs.pc;
    return *this;
  }
  ~A() { delete pb; delete pc; }
};
```

std::unique_ptrs As Members (3/3)


```
// to avoid possible resource leaks, you can use unique_ptrs ...
class A {
private:
  std::unique_ptr<B> pb;
  std::unique_ptr<C> pc;
public:
  // no resource leak possible anymore ...
  A(int i1, int i2) : pb{std::make_unique<B>(i1)},
                      pc{ std::make_unique<C>(i2)} {}
  A(A const& rhs) : pb{std::make_unique<B>(*rhs.pb)},
         pc{std::make_unique<C>(*rhs.pc)} { return *this; }
  A const& operator=(A const& rhs) {
    pb.reset(std::make_unique<B>(*rhs.pb));
    pc.reset(std::make_unique<C>(*rhs.pc));
    return *this;
  }
  // default dtor lets pb and pc delete their objects]
};
```

Containers of `std::unique_ptr`s

- Should a large number of non-trivial objects [of same type] be stored in a container [such as `std::vector`] by value, or by pointer, or by `unique_ptr`s?
- See *uptr-cont.cpp* for an answer …

Deletion Callback (1/2)


```
template <typename T, typename... Types>
unique_ptr<T> make_unique(Types&&... params) {
  return unique_ptr<T>(new T(std::forward<Types>(params)...));
}
```

make_unique uses new operator to allocate and initialize memory

```
unique_ptr<double> ud {make_unique<double>(1.9)};
```

dtor of class unique_ptr will use delete operator to return memory pointed to by raw pointer [encapsulated by ud] back to free store

Deletion Callback (2/2)

- In some cases, memory provided to `unique_ptr` cannot be released using `delete`
- `std::unique_ptr<T,D>` has 2nd template type parameter: a *deletion callback type*
  - Parameter `D` defaults to `std::default_delete<T>` which uses `delete` to deallocate memory
- See *fred-deleter.cpp* and *file-deleter.cpp*

std::unique_ptr<T[]> Specialization for Arrays (1/2)


```
// value initializes 3 ints to 0
// i.e., new T[3]{}
std::unique_ptr<int[]>
upi{std::make_unique<int[]>(3)};

// partial specialization doesn't overload
// operators * and ->
// operator[] is provided to access
// one of the elements inside the array

upi[0] = 11; upi[1] = 12; upi[2] = 13;
```

std::unique_ptr<T[]> Specialization for Arrays (2/2)

- Better to use `vector<>` container because it is more flexible and powerful than smart pointer

Conclusion (1/4)

- What can you say about semantics by looking at following function signatures?

```
void foo(std::unique_ptr<Widget> p);

std::unique_ptr<Widget> boo();

void coo(Widget *p);
```

Conclusion (2/4)

- `foo` is a *consumer* of widgets
- When we call `foo`, we must have unique ownership of a `Widget` that was allocated with `new`, and which is safe to `delete`!

```
void foo(std::unique_ptr<Widget>);
```

Conclusion (3/4)

- boo is a *producer* of widgets
- When we call boo, we get unique ownership of a Widget that was allocated with new, and which is safe to delete!

```
std::unique_ptr<Widget> boo();
```

Conclusion (4/4)

- `coo` expresses *ambiguity*
- `unique_ptr<T>` is a *vocabulary type* for expressing ownership transfer, whereas `T*` is C++'s equivalent of nonsense word that no two people will necessarily agree on what it means

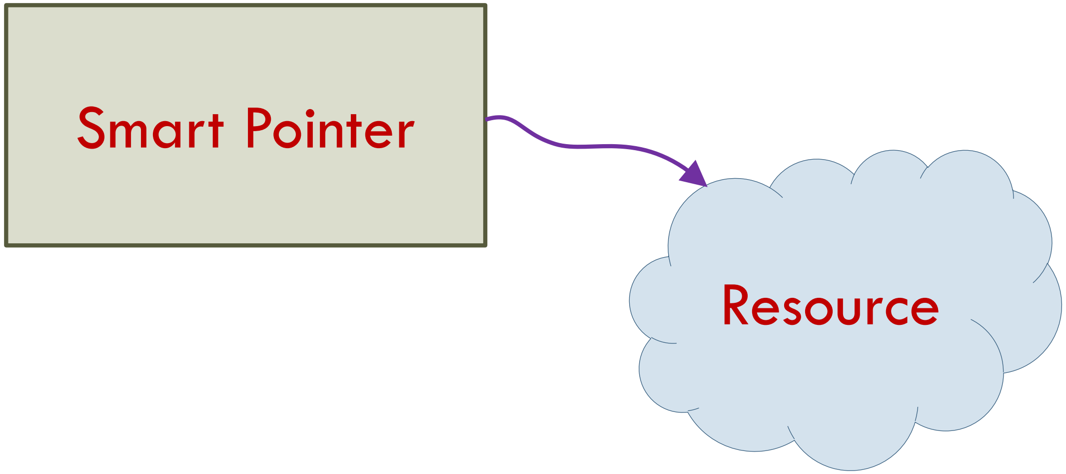
```
void coo(Widget *p);
```

std::shared_ptr<T>

- Unique pointers embody *exclusive ownership* semantics
- Shared pointers embody *unclear ownership* of resource using technique called *reference counting*

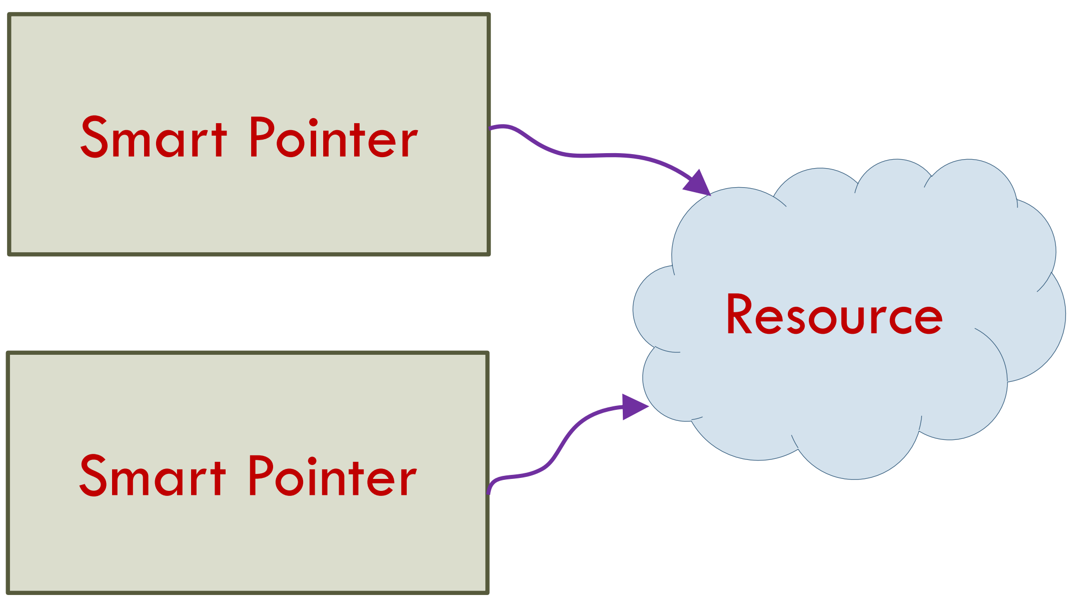
Reference Counting: Idea

- Consider smart pointer class that stores pointer to resource
- Dtor can then delete resource automatically, so clients of smart pointer never need to explicitly clean up any resources



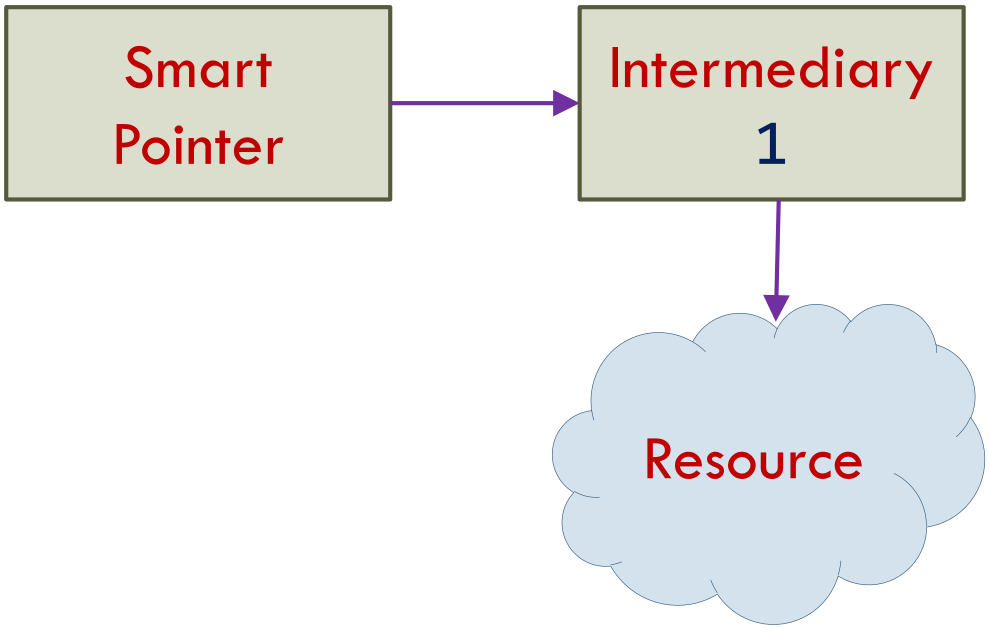
Reference Counting: Idea

- We hit a snag when several smart pointers point to same resource



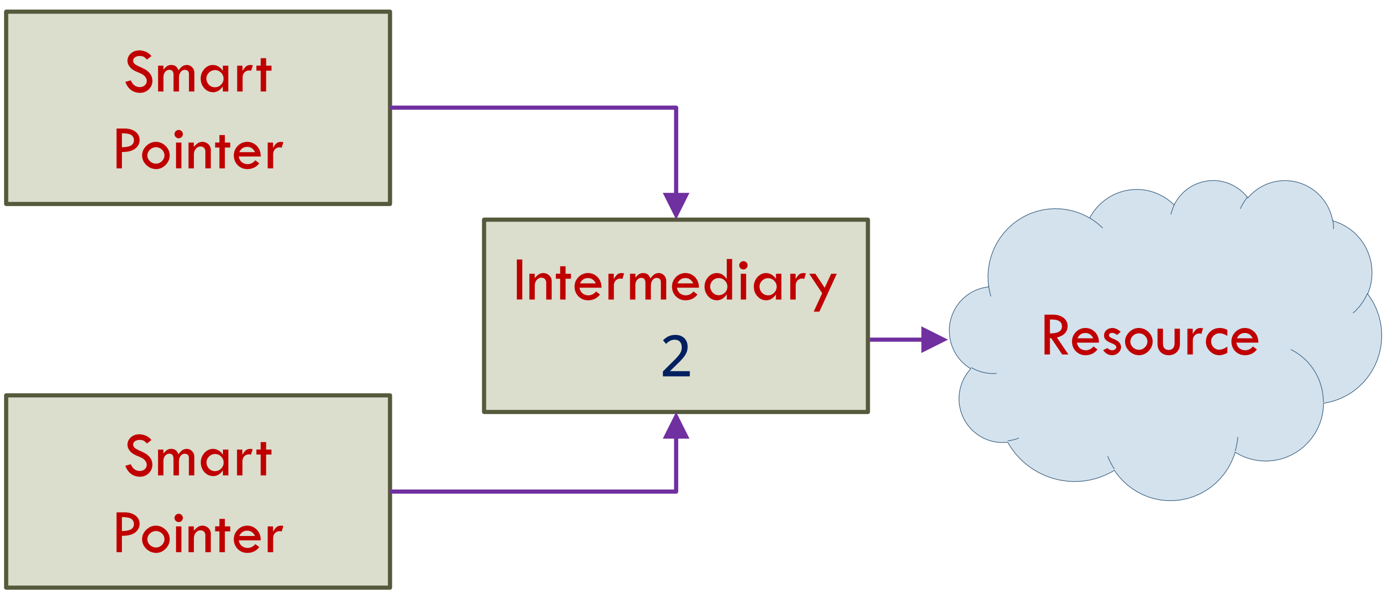
Reference Counting: Idea

- Reference counting keeps track of number of pointers to dynamically-allocated resource



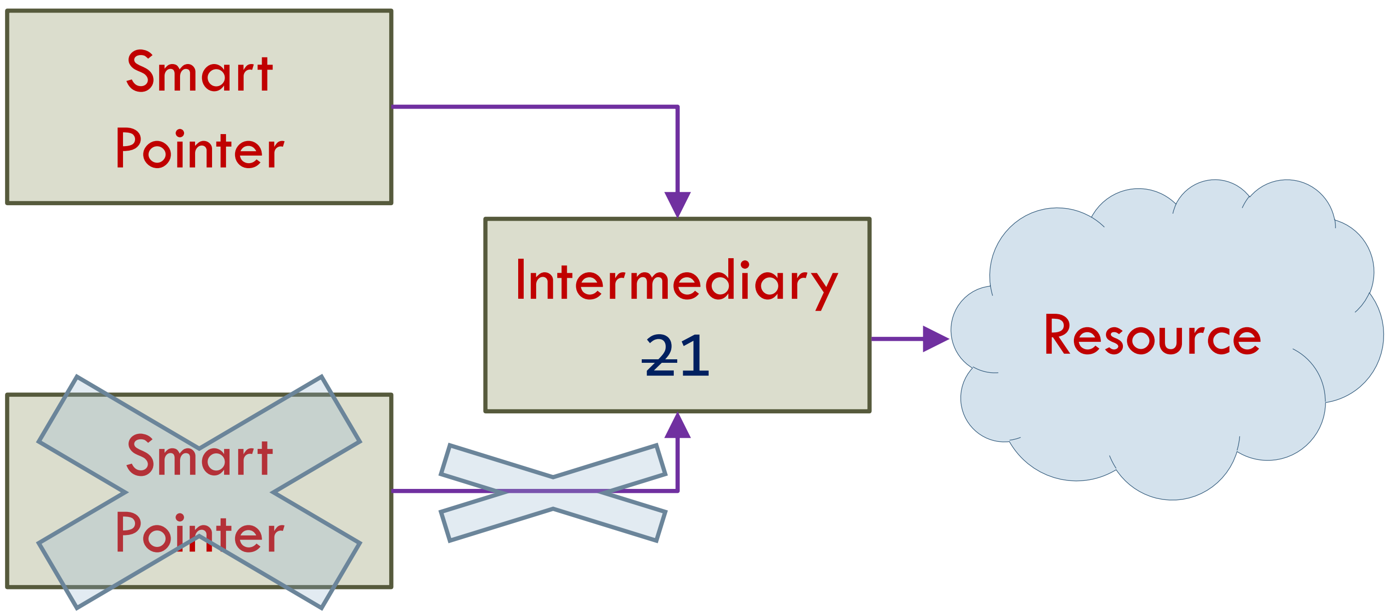
Reference Counting: Idea

- Suppose we want to share the resource with another smart pointer



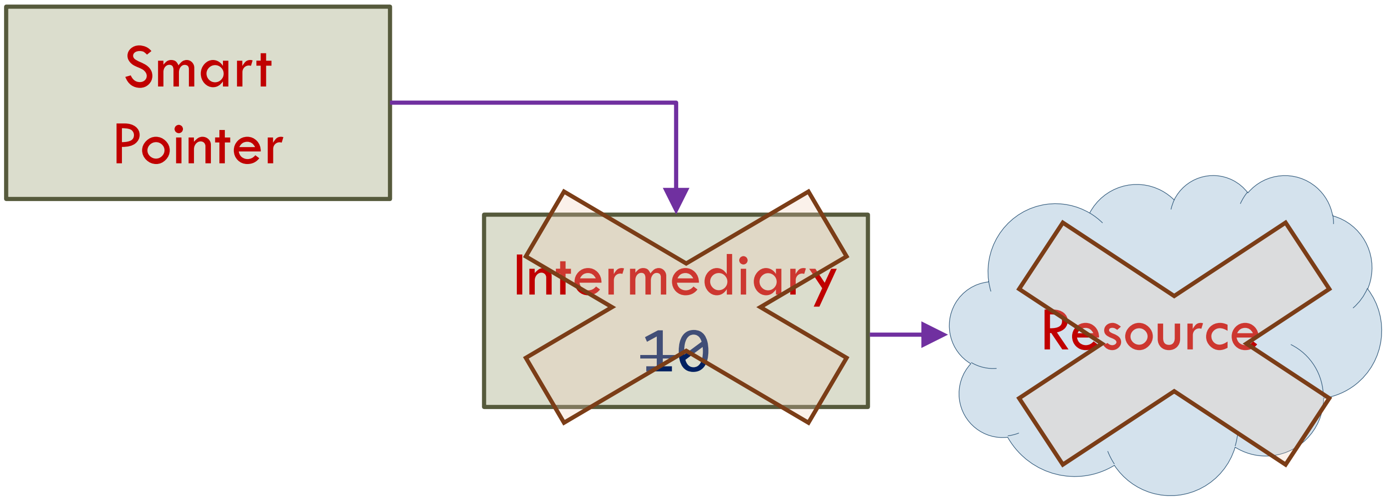
Reference Counting: Idea

- Now, suppose one smart pointer needs to stop pointing to the resource:



Reference Counting: Idea

- Finally, suppose last smart pointer needs to stop pointing to the resource:



Reference Counting: Summary

- When creating a smart pointer to manage newly allocated memory, 1^{st} create intermediary object and make the intermediary object point to resource; then attach smart pointer to intermediary and set reference count to one
- To make new smart pointer point to same resource as existing one, make new smart pointer point to old smart pointer's intermediary object; then increment intermediary's reference count
- To remove smart pointer from resource, decrement intermediary object's reference count; if count reaches zero, deallocate resource and intermediary object

Reference Counting: Summary


```
template <typename T> class smart_ptr {
public:
  explicit smart_ptr(T *memory);
  smart_ptr(smart_ptr const&);
  smart_ptr(smart_ptr &&);
  smart_ptr& operator=(smart_ptr const&);
  smart_ptr& operator=(smart_ptr &&);
  ~smart_ptr();

  T& operator* () const;
  T* operator->() const;

  T* get() const;
  size_t get_ref_count() const;
  void reset(T *new_resource);
```

```
private:
  struct Intermediary {
    T* resource;
    size_t ref_cnt;
  };
  Intermediary *data;

  void detach();
  void attach(Intermediary *other);
};
```

Using `std::shared_ptr<T>` (1)

- See *using_shared.cpp* and *sharedptr-cont.cpp*

Using `std::shared_ptr<T>` (1)

- See *using_shared.cpp* and *sharedptr-cont.cpp*

What is RAII Idiom?

- Resource Acquisition Is Allocation
- Resource acquisition and release are bound to lifetime of an object
- Resource is allocated in ctor and deallocated in dtor
- Works because dtor is called when stack-based object goes out of scope

RAII Classes: Rule of Three

- If your class manages a resource, you'll ***need to write*** three special member functions:
  - Destructor to release the resource
  - Copy constructor to clone the resource
  - Copy assignment operator to release current resource and acquire cloned resource
- Caveat: You'll need to define swap function to implement copy assignment operator using copy-swap idiom

Rule of Five

- C++11 introduced move operations, transforming ROT into ROF
  - ROF because move operations were implicitly generated under certain circumstances
- Lots of rules for implicit move operations but generalized like this:
  - You get default move ctor or move assignment operator if and only if none of other four are defined/defaulted by class
  - Compiler will enforce this rule

Rule of Five


```
class P {
public:
  P(int x) : i{x} {}
  ~P() {}
  P(P&& rhs) : i{rhs.i} {}
  int I() const { return i; }
  void I(int x) { i = x; }
private:
  int i;
};

int main() {
  P a1{10}, a2{20};
  a2 = a1; // compiler error!!!
}
```

Rule of Zero

- Rule of Five transitions into Rule of Zero

Write your classes in a way so that you don’t need to declare/define neither destructor, nor copy/move constructor, nor copy/move assignment operator

Use smart pointers & standard library classes for managing resources

Exceptions to ROZ Guideline

- Two cases where users generally bypass compiler and write their own declarations:
  - Managing resources
  - Polymorphic deletion and/or virtual functions