Smart Pointers

ITP 435 – Spring 2016
Week 4, Lecture 2
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Memory Leaks 101

- Forgetting to deallocate memory is a very common mistake in C/C++ code

```
int main()
{
    Square* mySquare = new Square();

    // OOPS!
    return 0;
}
```

Memory Leaks 102

- Sometimes the leaks can be caused by exceptions:

```
bool badStuff = false;
Square* mySquare = new Square();

if (badStuff)
{
   throw std::exception();
}

// Deallocate, but what happens if there's a throw?
delete mySquare;
```

Memory Leaks 201

- Worse is when there's confusion between who should delete what:

```
void doStuff(Shape* shape) {
   // Do stuff...
   // Done with shape, so delete it!
   delete shape;
}

int main() {
   Square* mySquare = new Square();
   doStuff(mySquare);
   delete mySquare;

   return 0;
}
```

Uh-oh…

Smart Pointer

- A ***smart pointer*** is an object that encapsulates dynamically allocated data

- There are several variations of smart pointers, some providing more general usage than others

Scoped Pointer

- We'll define a ***scoped pointer*** as a smart pointer that encapsulates dynamic data for the single scope in which it's used

- This will solve the basic Memory Leaks 101/102 problems:
  - Forgetting to deallocate
  - Exception bypassing a delete statement

ScopedPtr – Minimal Declaration


```
template <typename T>
class ScopedPtr {
public:
   // Construct based on pointer to dynamic object
   explicit ScopedPtr(T* obj);

   // Destructor (clean up memory)
   ~ScopedPtr();

   // Overload dereferencing * and ->
   T& operator*();
   T* operator->();
private:
   // Disallow assignment/copy
   ScopedPtr(const ScopedPtr& other);
   ScopedPtr& operator=(const ScopedPtr& other);

   // Track the dynamically allocated object
   T* mObj;
};
```

ScopedPtr – Constructor/Destructor


```
// Construct based on pointer to dynamic object
template <typename T>
ScopedPtr<T>::ScopedPtr(T* obj)
: mObj(obj)
{
}

// Destructor (clean up memory)
template <typename T>
ScopedPtr<T>::~ScopedPtr()
{
   // Delete dynamically allocated object
   delete mObj;
}
```

ScopedPtr – Operators


```
// Overloaded dereferencing
template <typename T>
T& ScopedPtr<T>::operator*()
{
   return *mObj;
}

template <typename T>
T* ScopedPtr<T>::operator->()
{
   return mObj;
}
```

ScopedPtr in Action


```
int main() {
   // Construct a scoped pointer to a newly-allocated object
   ScopedPtr<Square> mySquare(new Square());

   // Can call functions just like a regular pointer!
   mySquare->Draw();

   // No delete necessary
   return 0;
}
```

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When mySquare is destructed, the underlying dynamic data will automatically be deleted. Keep in mind the destructor will automatically be called in the event of an exception

Reference Counting Pointer

- ***Reference counting*** is a method in which the number of references to a dynamically allocated object is tracked
- When the references hit zero, the object will be automatically deallocated
- **Important!!!** – This is different from garbage collection (in a language such as Java) because there is a well-defined and consistent point where it will deallocate

This should fix the memory leaks 201 problem

Control Block

- A reference counting pointer needs a ***control block*** – another dynamically allocated object which tracks the number of references

- All instances of `RefCountPtr` that point to the same object will also point to the same control block

RefCountPtr – Minimal Declaration


```
// Declare the control block
struct ControlBlock {
   unsigned mRefCount;
};

template <typename T>
class RefCountPtr {
public:
   // Construct based on pointer to dynamic object
   explicit RefCountPtr(T* obj);
   // Allow copy constructor
   RefCountPtr(const RefCountPtr& other);
   // Destructor (reduce ref count)
   ~RefCountPtr();
   // Overload dereferencing * and ->
   T& operator*();
   T* operator->();
private:
   // Disallow assignment (for simplicity)
   RefCountPtr& operator=(const RefCountPtr& other);
   // Pointer to dynamically allocated object
   T* mObj;
   // Pointer to control block
   ControlBlock* mBlock;
};
```

RefCountPtr – Basic Constructor


```
// Construct based on pointer to dynamic object
template <typename T>
RefCountPtr<T>::RefCountPtr(T* obj)
   : mObj(obj)
{
   // Dynamically allocate a new control block
   mBlock = new ControlBlock;
   // Initially, one reference (self)
   mBlock->mRefCount = 1;
}
```

RefCountPtr – Copy Constructor


```
// Copy constructor
template <typename T>
RefCountPtr<T>::RefCountPtr(const RefCountPtr<T>& other)
{
    // Grab object and control block from other
    mObj = other.mObj;
    mBlock = other.mBlock;

    // Increment ref count
    mBlock->mRefCount += 1;
}
```

RefCountPtr – Destructor


```
// Destructor (reduce ref count)
template <typename T>
RefCountPtr<T>::~RefCountPtr()
{
   // Decrement ref count
   mBlock->mRefCount -= 1;

   // If there are zero references, delete the object
   // and the control block
   if (mBlock->mRefCount == 0) {
      delete mObj;
      delete mBlock;
   }
}
```

RefCountPtr in Action


```
int main() {
   // Construct a RefCountPtr to a newly-allocated object
   RefCountPtr<Square> mySquare(new Square());

   mySquare->Draw();

   {
      RefCountPtr<Square> mySquareTwo(mySquare);

      // This will call Draw on the same underlying square
      mySquareTwo->Draw();
   }

   return 0;
}
```

RefCountPtr in Action


```
int main() {
   // Construct a RefCountPtr to a newly-allocated object
   RefCountPtr<Square> mySquare(new Square());

   mySquare->Draw();

   {
      RefCountPtr<Square> mySquareTwo(mySquare);

      // This will call Draw on the same underlying square
      mySquareTwo->Draw();
   }

   return 0;
}
```

Construct, set ref count to 1

RefCountPtr in Action


```
int main() {
   // Construct a RefCountPtr to a newly-allocated object
   RefCountPtr<Square> mySquare(new Square());

   mySquare->Draw();

   {
      RefCountPtr<Square> mySquareTwo(mySquare);

      // This will call Draw on the same underlying square
      mySquareTwo->Draw();
   }

   return 0;
}
```

Construct as copy, increment ref count (now 2)

RefCountPtr in Action


```
int main() {
   // Construct a RefCountPtr to a newly-allocated object
   RefCountPtr<Square> mySquare(new Square());

   mySquare->Draw();

   {
      RefCountPtr<Square> mySquareTwo(mySquare);

      // This will call Draw on the same underlying square
      mySquareTwo->Draw();
   }

   return 0;
}
```

mySquareTwo destructed, decrement ref count (now 1)

RefCountPtr in Action


```
int main() {
   // Construct a RefCountPtr to a newly-allocated object
   RefCountPtr<Square> mySquare(new Square());

   mySquare->Draw();

   {
      RefCountPtr<Square> mySquareTwo(mySquare);

      // This will call Draw on the same underlying square
      mySquareTwo->Draw();
   }

   return 0;
}
```

mySquare destructed, decrement ref count (now 0), so delete underlying object

Using RefCountPtr w/ Functions


```
// Smart pointers should almost always be passed by value
void doStuff(RefCountPtr<Shape> shape) {
    shape->Draw();
}

int main() {
    // Construct a scoped pointer to a newly-allocated object
    RefCountPtr<Shape> myShape(new Square());

    doStuff(myShape);

    return 0;
}
```

Problems w/ RefCountPtr

- **Q:** What if class A has a RefCountPtr to class B, and class B has a RefCountPtr to class A?
- **A:** Circular references means neither will ever be deleted
- **Q:** What if you want to have an "observer" that can observe the RefCountPtr but not affect the number of references?
- **A:** It's currently not possible

Weak Pointer

- A ***weak pointer*** is a pointer that keeps a weak reference to a reference counter pointer

- A ***weak reference*** does not affect the lifetime of the object, because it uses a separate count (this is in contrast to the references we had before, which were ***strong references***)

Adding Weak References

- First, add a weak reference count to `ControlBlock`:

```
// Declare the control block
struct ControlBlock {
   unsigned mRefCount;
   unsigned mWeakRefCount;
};
```

- Also make WeakRefPtr a friend of RefCountPtr

Adding Weak References, Cont'd

- Update constructor for RefCountPtr:

```
// Construct based on pointer to dynamic object
template <typename T>
RefCountPtr<T>::RefCountPtr(T* obj)
    : mObj(obj)
{
    // Dynamically allocate a new control block
    mBlock = new ControlBlock;
    // Initially, one reference (self)
    mBlock->mRefCount = 1;
    // No weak references to start
    mBlock->mWeakRefCount = 0;
}
```

Adding Weak References, Cont'd

- The destructor should now only delete the control block if both regular and weak references are 0:

```
// Destructor (reduce ref count)
template <typename T>
RefCountPtr<T>::~RefCountPtr()
{
   // Decrement ref count
   mBlock->mRefCount -= 1;

   // If there are zero references, delete the object
   // and the control block
   if (mBlock->mRefCount == 0) {
      delete mObj;
      if (mBlock->mWeakRefCount == 0) {
         delete mBlock;
      }
   }
}
```

Declaration of WeakRefPtr


```
template <typename T>
class WeakRefPtr {
public:
   // Constructor accepts RefCountPtr
   explicit WeakRefPtr(RefCountPtr<T>& refPtr);
   // Allow copy constructor
   WeakRefPtr(const WeakRefPtr& other);
   // Destructor
   ~WeakRefPtr();
   // Overload dereferencing * and ->
   T& operator*();
   T* operator->();
   // Determines whether or not the object is alive
   bool isAlive();
private:
   // Disallow assignment (for simplicity)
   WeakRefPtr& operator=(const WeakRefPtr& other);
   // Pointer to dynamically allocated object
   T* mObj;
   // Pointer to control block
   ControlBlock* mBlock;
};
```

WeakRefPtr – Constructor


```
// Constructor accepts RefCountPtr
template <typename T>
WeakRefPtr<T>::WeakRefPtr(RefCountPtr<T>& refPtr)
{
    // Copy object/block from RefCountPtr
    mObj = refPtr.mObj;
    mBlock = refPtr.mBlock;

    // Increment weak reference count
    mBlock->mWeakRefCount += 1;
}
```

WeakRefPtr – Copy Constructor


```
// Copy constructor
template <typename T>
WeakRefPtr<T>::WeakRefPtr(const WeakRefPtr<T>& other)
{
    mObj = other.mObj;
    mBlock = other.mBlock;

    // Increment weak reference count
    mBlock->mWeakRefCount += 1;
}
```

WeakRefPtr – Destructor


```
// Destructor
template <typename T>
WeakRefPtr<T>::~WeakRefPtr()
{
   // Decrement weak reference count
   mBlock->mWeakRefCount -= 1;

   // If both strong and weak references are 0,
   // delete control block
   if (mBlock->mRefCount == 0 &&
       mBlock->mWeakRefCount == 0) {
      delete mBlock;
   }
}
```

WeakRefPtr – isAlive


```
template <typename T>
bool WeakRefPtr<T>::isAlive()
{
   // Only alive if strong ref count is not 0
   // (Because if it hits 0, object is destroyed)
   return (mBlock->mRefCount != 0);
}
```

WeakRefPtr – Dereferencing


```
template <typename T>
T& WeakRefPtr<T>::operator*()
{
   if (!isAlive()) {
      throw std::exception();
   }
   return *mObj;
}

template <typename T>
T* WeakRefPtr<T>::operator->()
{
   if (!isAlive()) {
      throw std::exception();
   }
   return mObj;
}
```

WeakRefPtr in Action


```
WeakRefPtr<Shape> makeShapeWeak() {
   // Construct a RefCountPtr
   RefCountPtr<Shape> myShape(new Square());

   WeakRefPtr<Shape> weakShape(myShape);

   weakShape->Draw();

   // Return a WeakRefPtr to the shape
   return weakShape;
}

int main() {
   WeakRefPtr<Shape> weakPtr(makeShapeWeak());

   // Try to access weak reference here
   weakPtr->Draw();

   return 0;
}
```


The weakPtr dereference inside main will throw an exception, because the strong ref count hit 0

A Question…

- So if you want to use smart pointers, do you have to declare your own?

- In C++98, the answer was yes ☹ (more or less)

- But in C++11 the answer is ***no!***

Smart Pointers in C++ 11

`std::unique_ptr` (similar to `ScopedPtr`)

- A pointer that allows only a single reference at a time
- When it's out of scope, delete the dynamically allocated object
- Should create with `std::make_unique`

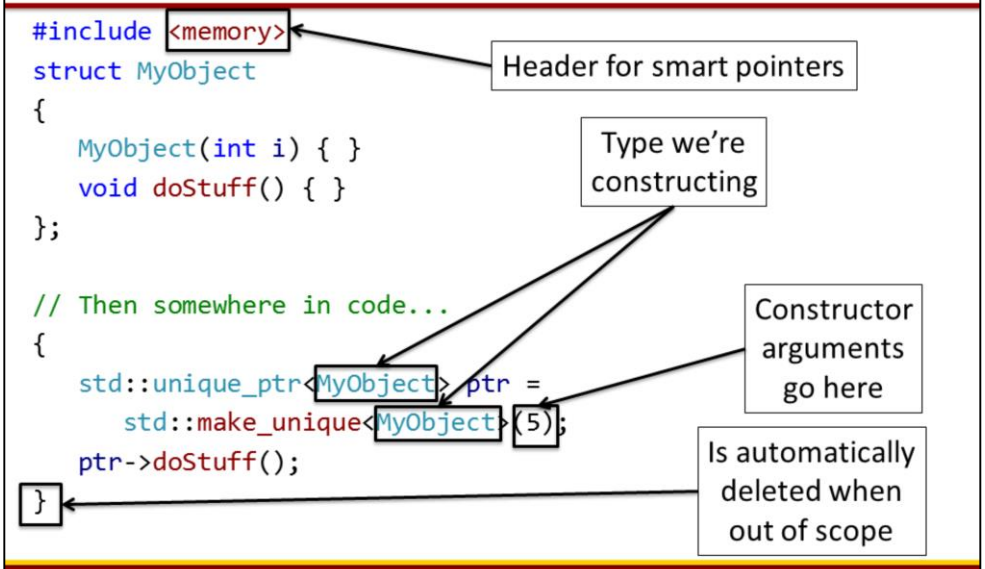
`std::shared_ptr` (similar to `RefCountPtr`)

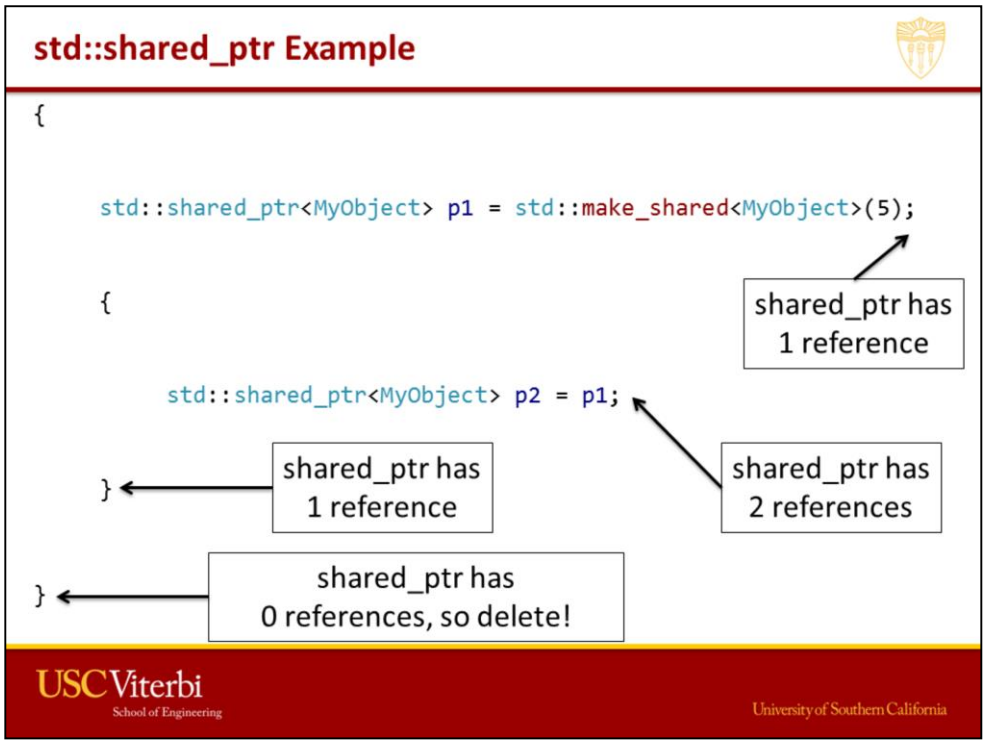
- Allows multiple references at once
- When it goes out of scope, decrement the reference
- If references hit 0, delete the dynamically allocated object
- Should create with `std::make_shared`

`std::weak_ptr` (similar to `WeakPtr`)

- Allows for weak references to shared pointers

std::unique_ptr Example





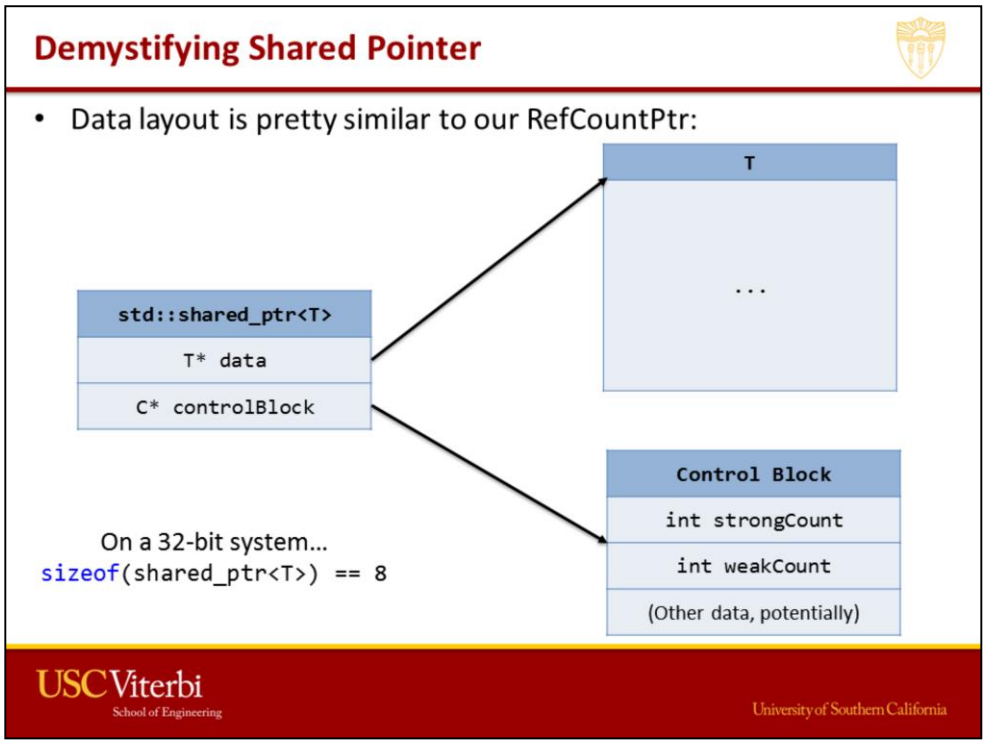
So for shared_ptrs, we use make_shared

A more complex shared_ptr example


```
struct A
{ };
struct B
{
B(std::shared_ptr<A> ptr)
   : mPtr(ptr)
   { }
private:
   std::shared_ptr<A> mPtr;
};

// Then...
std::shared_ptr<B> ptrB;
{
   std::shared_ptr<A> ptrA = std::make_shared<A>();
   ptrB = std::make_shared<B>(ptrA);
}
```

What happens here?



In most implementations, a smart pointer is sizeof(void*) x 2.

make_shared

- Technically, you don't ***have*** to use make_shared (or make_unique).

- Eg:

```
std::shared_ptr<MyObject> ptr(new MyObject(5));
```

- Problems:
  - This requires ***two*** heap allocations (one for MyObject and one for the shared_ptr)
  - What if there is an exception?

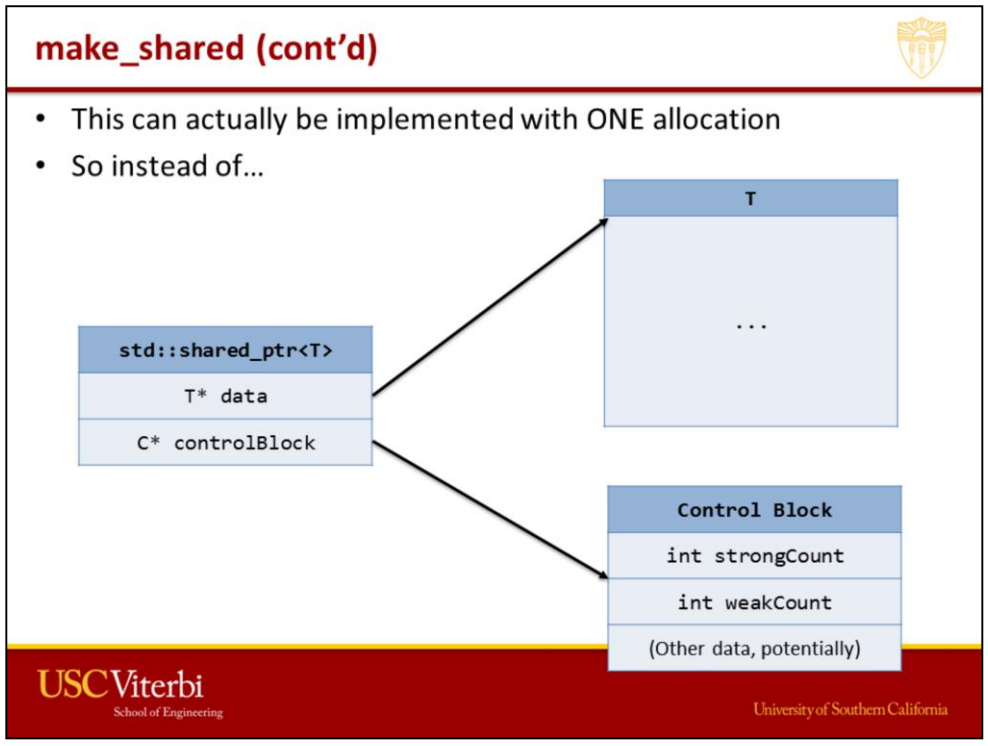
Note: You can't use make_shared in instances where the constructor is protected/private (looking at you Gdiplus::Pen!!)

Other advantage of make_shared/unique

- If you initialize a smart pointer std::make_shared/unique, you can declare your pointer as an auto and its type will be deduced correctly:

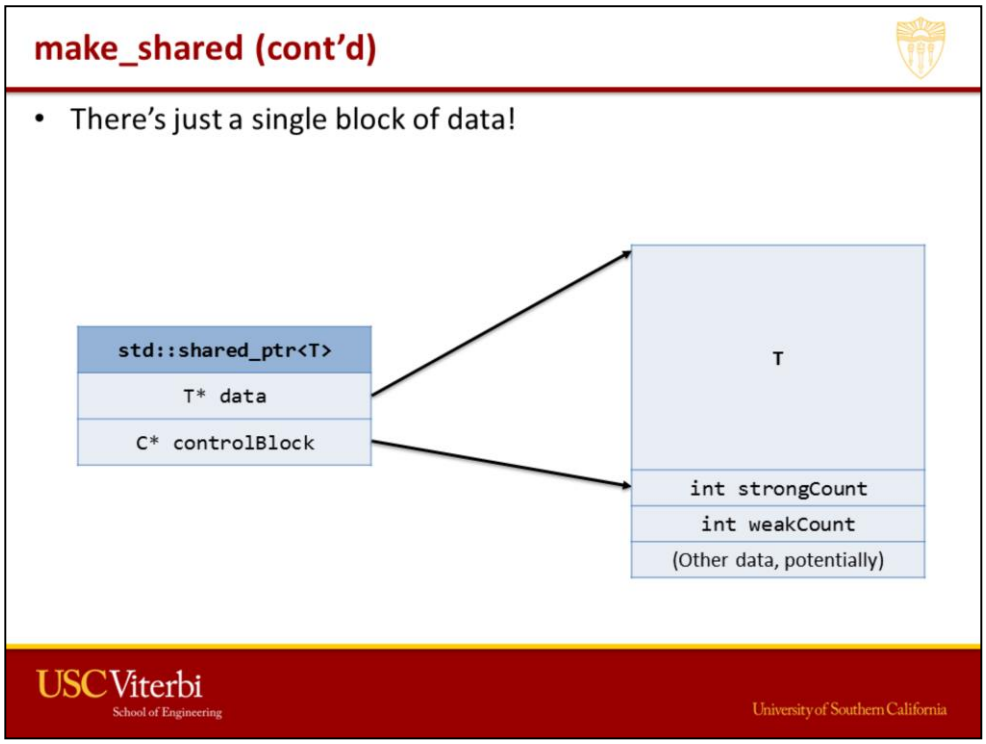
```
// auto will automatically be a std::shared_ptr<A>
auto ptrA = std::make_shared<A>();
```

make_shared (cont'd)



- This can actually be implemented with ONE allocation
- So instead of…

make_shared (cont'd)



- There's just a single block of data!

std::weak_ptr in Action


```
std::shared_ptr<Shape> myShape = std::make_shared<Square>();

{
   // Make a weak ptr to this
   std::weak_ptr<Shape> myWeakPtr(myShape);

   // expired is roughly the equivalent of isAlive
   if (!myWeakPtr.expired()) {
      // lock will create a shared_ptr that references the object
      // (this can be used to temporarily "acquire" the object)
      std::shared_ptr<Shape> ptrB = myWeakPtr.lock();
   }
}
```

std::weak_ptr in Action


```
std::shared_ptr<Shape> myShape = std::make_shared<Square>();

{
   // Make a weak ptr to this
   std::weak_ptr<Shape> myWeakPtr(myShape);

   // expired is roughly the equivalent of isAlive
   if (!myWeakPtr.expired()) {
      // lock will create a shared_ptr that references the object
      // (this can be used to temporarily "acquire" the object)
      std::shared_ptr<Shape> ptrB = myWeakPtr.lock();
   }
}
```

Strong Count = 1
Weak Count = 0

std::weak_ptr in Action


```
std::shared_ptr<Shape> myShape = std::make_shared<Square>();

{
   // Make a weak ptr to this
   std::weak_ptr<Shape> myWeakPtr(myShape);

   // expired is roughly the equivalent of isAlive
   if (!myWeakPtr.expired()) {
      // lock will create a shared_ptr that references the object
      // (this can be used to temporarily "acquire" the object)
      std::shared_ptr<Shape> ptrB = myWeakPtr.lock();
   }
}
```

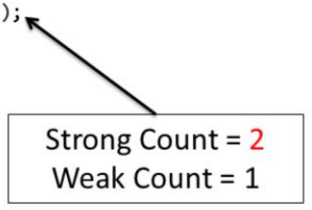
Strong Count = 1
Weak Count = 1

std::weak_ptr in Action


```
std::shared_ptr<Shape> myShape = std::make_shared<Square>();

{
   // Make a weak ptr to this
   std::weak_ptr<Shape> myWeakPtr(myShape);

   // expired is roughly the equivalent of isAlive
   if (!myWeakPtr.expired()) {
      // lock will create a shared_ptr that references the object
      // (this can be used to temporarily "acquire" the object)
      std::shared_ptr<Shape> ptrB = myWeakPtr.lock();
   }
}
```



std::weak_ptr in Action


```
std::shared_ptr<Shape> myShape = std::make_shared<Square>();

{
   // Make a weak ptr to this
   std::weak_ptr<Shape> myWeakPtr(myShape);

   // expired is roughly the equivalent of isAlive
   if (!myWeakPtr.expired()) {
      // lock will create a shared_ptr that references the object
      // (this can be used to temporarily "acquire" the object)
      std::shared_ptr<Shape> ptrB = myWeakPtr.lock();
   }
}
```

Strong Count = 1
Weak Count = 1

std::weak_ptr in Action


```
std::shared_ptr<Shape> myShape = std::make_shared<Square>();

{
   // Make a weak ptr to this
   std::weak_ptr<Shape> myWeakPtr(myShape);

   // expired is roughly the equivalent of isAlive
   if (!myWeakPtr.expired()) {
      // lock will create a shared_ptr that references the object
      // (this can be used to temporarily "acquire" the object)
      std::shared_ptr<Shape> ptrB = myWeakPtr.lock();
   }
}
```

Strong Count = 1
Weak Count = 0

One Complexity – Custom Deleters

- By default, shared_ptrs just use the basic delete

- What if you want a shared_ptr to a dynamically allocated array?

```
{
   std::shared_ptr<int> sharedArray(new int[10]);
}
```

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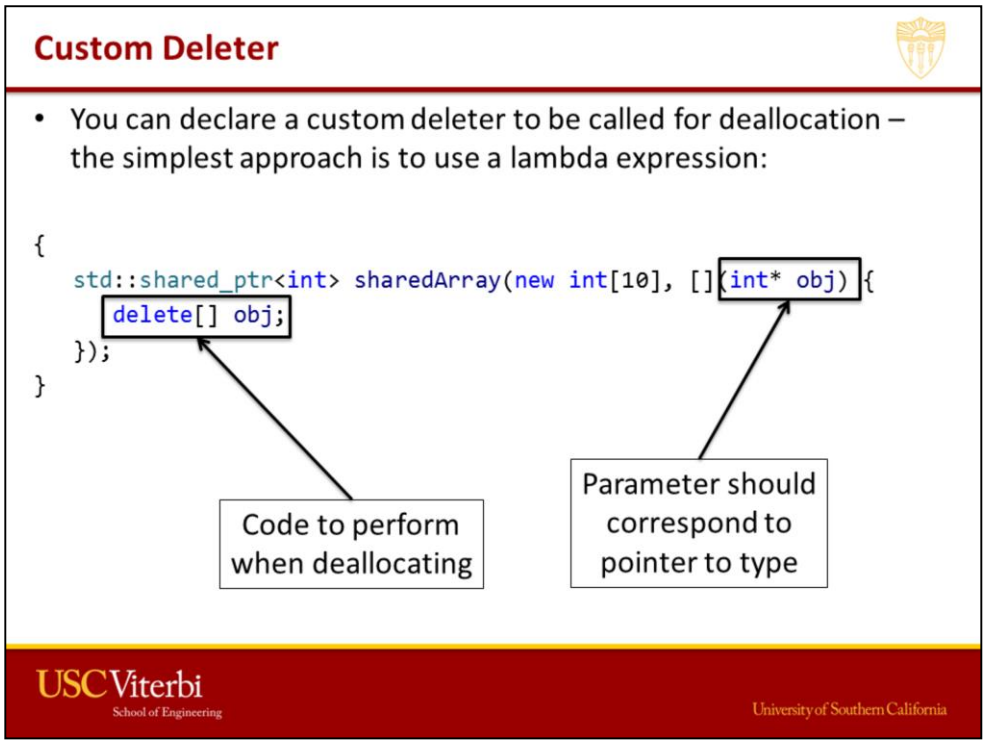
This is a problem, because it'll only call delete and not delete[]

Custom Deleter



- You can declare a custom deleter to be called for deallocation – the simplest approach is to use a lambda expression:

```
{
   std::shared_ptr<int> sharedArray(new int[10], [](int* obj) {
      delete[] obj;
   });
}
```

Code to perform when deallocating

Parameter should correspond to pointer to type

This won't leak memory anymore

Custom Deleters, Cont'd

- When you use a custom deleter, you ***can't*** use make_shared
- In the prior example, as opposed to using a shared_ptr to an array, it may be better to just use an STL data structure
- However, custom deleters can be useful in the instance where there's some very specific deinitialization you must perform

When to Use Smart Pointers?

- Unless the code is ***really*** low level and you ***really*** need the highest possible performance you should probably use smart pointers!

- The additional cost of using a smart pointer, especially if you stick to make_unique and make_shared, is not terribly high

Which Smart Pointer?

- If there's only one owner, ever, use std::unique_ptr
- If there's multiple possible owners, use std::shared_ptr
- Usage of std::weak_ptr is more rare

- For more information on when to pick which one, you can read the following in *Effective Modern C++*:
  - Item 18: Use std::unique_ptr for exclusive-ownership resource management
  - Item 19: Use std::shared_ptr for shared-ownership resource management
  - Item 20: Use std::weak_ptr for std::shared_ptr-like pointers that can dangle