TDDD38/726G82:
Adv. Programming in C++
Advanced Constructs I

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1. Forwarding references
2. Smart pointers
3. `std::unique_ptr`
4. `std::shared_ptr`

1. Forwarding references
2. Smart pointers
3. `std::unique_ptr`
4. `std::shared_ptr`

Forwarding references

Opportunity for optimization

```
1 template <typename T>
2 void add(vector<T>& v,
3           T value)
4 {
5   v.push_back(value);
6 }
```

```
1 vector<string> w;
2 add(w, "hello"s);
3
4 string s { "bye" };
5 add(w, s);
```

Forwarding references

Opportunity for optimization

```
1 template <typename T>
2 void add(vector<T>& v,
3           T value)
4 {
5   v.push_back(value);
6 }
```

```
1 vector<string> w;
2 add(w, "hello"s);
3
4 string s { "bye" };
5 add(w, s);
```

create!

Forwarding references

Opportunity for optimization

```
1  template <typename T>
2  void add(vector<T>& v,
3      copy! T value)
4  {
5    v.push_back(value);
6  }
```

```
1  vector<string> w;
2  add(w, "hello"s);
3
4  string s { "bye" };
5  add(w, s);
```

create!

Forwarding references

Opportunity for optimization

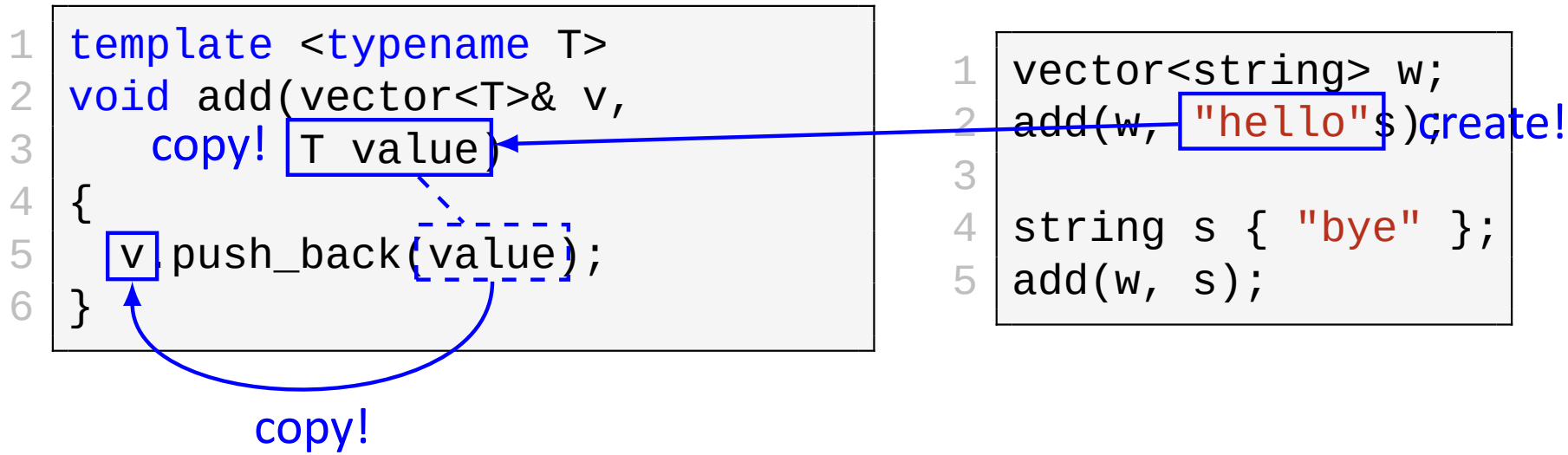
```
1  template <typename T>
2  void add(vector<T>& v,
3      copy! T value)
4  {
5    v.push_back(value);
6  }
```

```
1  vector<string> w;
2  add(w, "hello"s);
3
4  string s { "bye" };
5  add(w, s);
```

create!

Forwarding references

Opportunity for optimization



Forwarding references

Opportunity for optimization

```
1 template <typename T>
2 void add(vector<T>& v,
3           T value)
4 {
5   v.push_back(value);
6 }
```

```
1 vector<string> w;
2 add(w, "hello"s);
3
4 string s { "bye" };
5 add(w, s);
```

rvalue $\Rightarrow$ 3 created

Forwarding references

Opportunity for optimization

```
1 template <typename T>
2 void add(vector<T>& v,
3   destroy T value)
4 {
5   v.push_back(value);
6 }
```

```
1 vector<string> w;
2 add(w, "hello"s);
3
4 string s { "bye" };
5 add(w, s);
```

rvalue $\Rightarrow$ 3 created

Forwarding references

Opportunity for optimization

```
1 template <typename T>
2 void add(vector<T>& v,
3   destroy T value)
4 {
5   v.push_back(value);
6 }
```

```
1 vector<string> w;
2 add(w, "hello"s);
3
4 string s { "bye" };
5 add(w, s);
```

destroy

rvalue $\Rightarrow$ 3 created

Forwarding references

Opportunity for optimization

```
1 template <typename T>
2 void add(vector<T>& v,
3           T value)
4 {
5   v.push_back(value);
6 }
```

```
1 vector<string> w;
2 add(w, "hello"s);
3
4 string s { "bye" };
5 add(w, s);
```

rvalue $\Rightarrow$ 3 created, 2 destroyed

Forwarding references

Opportunity for optimization

```
1 template <typename T>
2 void add(vector<T>& v,
3           T value)
4 {
5   v.push_back(value);
6 }
```

```
1 vector<string> w;
2 add(w, "hello"s);
3                create!
4 string s { "bye" };
5 add(w, s);
```

rvalue $\Rightarrow$ 3 created, 2 destroyed

Forwarding references

Opportunity for optimization

```
1  template <typename T>
2  void add(vector<T>& v,
3           T value)
4  {
5    v.push_back(value);
6  }
```

```
1  vector<string> w;
2  add(w, "hello"s);
3
4  string s { "bye" };
5  add(w, s);
```

create!

rvalue $\Rightarrow$ 3 created, 2 destroyed

Forwarding references

Opportunity for optimization

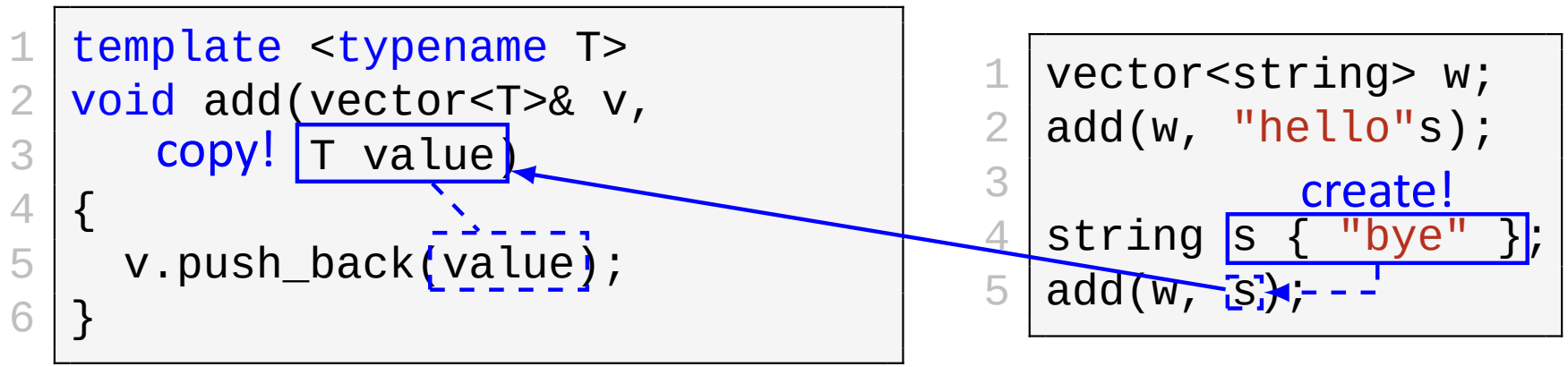
```
1 template <typename T>
2 void add(vector<T>& v,
3     copy! T value)
4 {
5   v.push_back(value);
6 }
```

```
1 vector<string> w;
2 add(w, "hello"s);
3             create!
4 string s { "bye" };
5 add(w, s);  ---
```

rvalue $\Rightarrow$ 3 created, 2 destroyed

Forwarding references

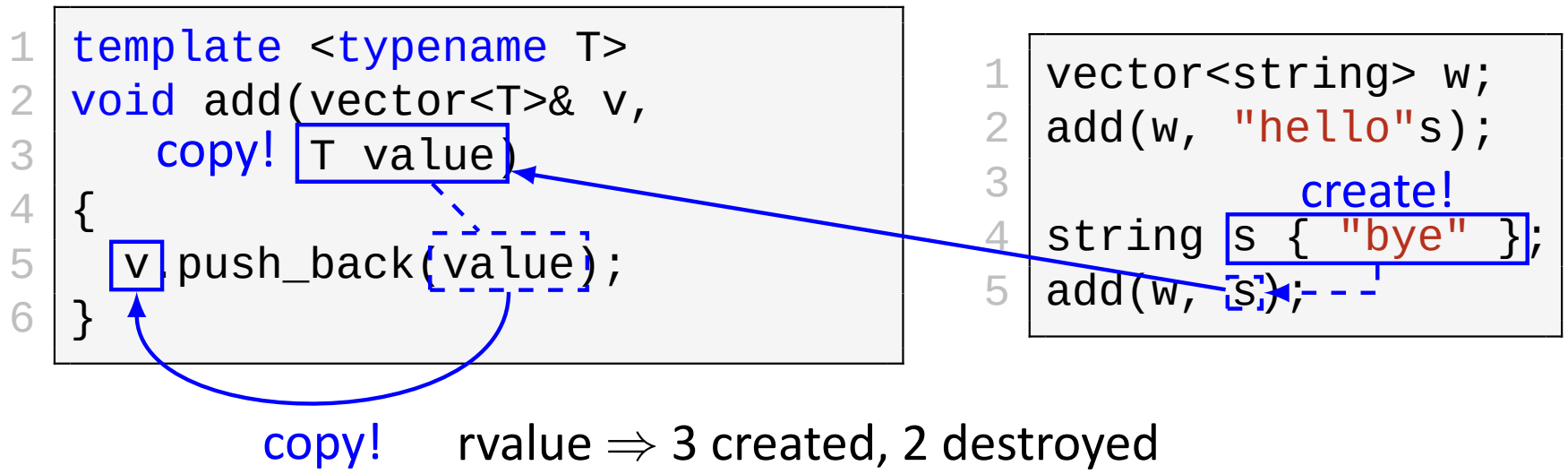
Opportunity for optimization



rvalue ⇒ 3 created, 2 destroyed

Forwarding references

Opportunity for optimization



copy! rvalue ⇒ 3 created, 2 destroyed

Forwarding references

Opportunity for optimization

```
1 template <typename T>
2 void add(vector<T>& v,
3           T value)
4 {
5   v.push_back(value);
6 }
```

```
1 vector<string> w;
2 add(w, "hello"s);
3
4 string s { "bye" };
5 add(w, s);
```

rvalue $\Rightarrow$ 3 created, 2 destroyed

lvalue $\Rightarrow$ 3 created

Forwarding references

Opportunity for optimization

```
1 template <typename T>
2 void add(vector<T>& v,
3   destroy T value)
4 {
5   v.push_back(value);
6 }
```

```
1 vector<string> w;
2 add(w, "hello"s);
3
4 string s { "bye" };
5 add(w, s);
```

rvalue $\Rightarrow$ 3 created, 2 destroyed

lvalue $\Rightarrow$ 3 created

Forwarding references

Opportunity for optimization

```
1 template <typename T>
2 void add(vector<T>& v,
3   destroy T value)
4 {
5   v.push_back(value);
6 }
```

```
1 vector<string> w;
2 add(w, "hello"s);
3
4 string s { "bye" };
5 add(w, s);
```

rvalue $\Rightarrow$ 3 created, 2 destroyed

lvalue $\Rightarrow$ 3 created

Forwarding references

Opportunity for optimization

```
1 template <typename T>
2 void add(vector<T>& v,
3   destroy T value)
4 {
5   v.push_back(value);
6 }
```

```
1 vector<string> w;
2 add(w, "hello"s);
3             destroy
4 string s { "bye" };
5 add(w, s);
```

rvalue ⇒ 3 created, 2 destroyed

lvalue ⇒ 3 created

Forwarding references

Opportunity for optimization

```
1 template <typename T>
2 void add(vector<T>& v,
3           T value)
4 {
5   v.push_back(value);
6 }
```

```
1 vector<string> w;
2 add(w, "hello"s);
3
4 string s { "bye" };
5 add(w, s);
```

rvalue $\Rightarrow$ 3 created, 2 destroyed

lvalue $\Rightarrow$ 3 created, 2 destoyed

Forwarding references

Opportunity for optimization

```
1  template <typename T>
2  void add(vector<T>& v,
3           T value)
4  {
5    v.push_back(value);
6  }
```

```
1  vector<string> w;
2  add(w, "hello"s);
3
4  string s { "bye" };
5  add(w, s);
```

rvalue $\Rightarrow$ 3 created, 2 destroyed

lvalue $\Rightarrow$ 3 created, 2 destoyed

Must be possible to reduce!

Forwarding references

Attempt #1

```
1  template <typename T>
2  void add(vector<T>& v,
3           T const& value)
4  {
5    v.push_back(value);
6  }
```

```
1  vector<string> w;
2  add(w, "hello"s);
3
4  string s { "bye" };
5  add(w, s);
```

Forwarding references

Attempt #1

```
1  template <typename T>
2  void add(vector<T>& v,
3           T const& value)
4  {
5    v.push_back(value);
6  }
```

```
1  vector<string> w;
2  add(w, "hello"s);
3
4  string s { "bye" };
5  add(w, s);
```

create!

Forwarding references

Attempt #1

```
1  template <typename T>
2  void add(vector<T>& v,
3           T const& value)
4  {
5    v.push_back(value);
6  }
```

```
1  vector<string> w;
2  add(w, "hello"s);
3
4  string s { "bye" };
5  add(w, s);
```

create!

Forwarding references

Attempt #1

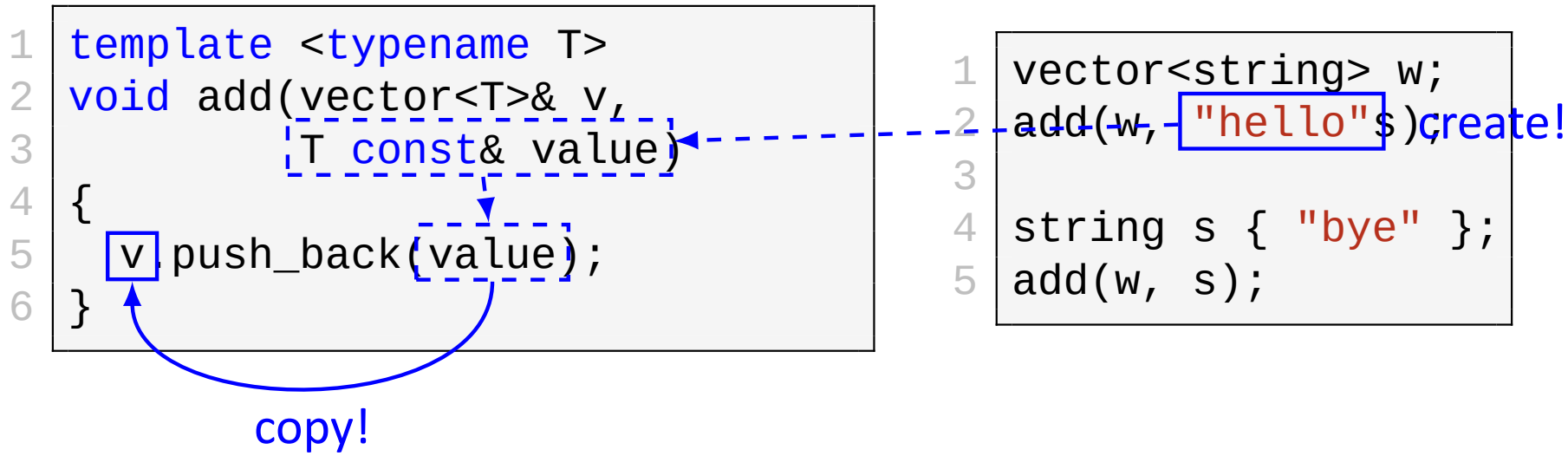
```
1  template <typename T>
2  void add(vector<T>& v,
3           T const& value)
4  {
5    v.push_back(value);
6  }
```

```
1  vector<string> w;
2  add(w, "hello"s);
3
4  string s { "bye" };
5  add(w, s);
```

create!

Forwarding references

Attempt #1



Forwarding references

Attempt #1

```
1 template <typename T>
2 void add(vector<T>& v,
3           T const& value)
4 {
5   v.push_back(value);
6 }
```

```
1 vector<string> w;
2 add(w, "hello"s);
3
4 string s { "bye" };
5 add(w, s);
```

rvalue $\Rightarrow$ 2 created

Forwarding references

Attempt #1

```
1  template <typename T>
2  void add(vector<T>& v,
3           T const& value)
4  {
5    v.push_back(value);
6  }
```

```
1  vector<string> w;
2  add(w, "hello"s);
3
4  string s { "bye" };
5  add(w, s);
```

rvalue $\Rightarrow$ 2 created

Forwarding references

Attempt #1

```
1  template <typename T>
2  void add(vector<T>& v,
3           T const& value)
4  {
5    v.push_back(value);
6  }
```

```
1  vector<string> w;
2  add(w, "hello"s);
3
4  string s { "bye" };
5  add(w, s);
```

rvalue $\Rightarrow$ 2 created

Forwarding references

Attempt #1

```
1 template <typename T>
2 void add(vector<T>& v,
3           T const& value)
4 {
5   v.push_back(value);
6 }
```

```
1 vector<string> w;
2 add(w, "hello"s);
3
4 string s { "bye" };
5 add(w, s);
```

rvalue $\Rightarrow$ 2 created, 1 destroyed

Forwarding references

Attempt #1

```
1  template <typename T>
2  void add(vector<T>& v,
3           T const& value)
4  {
5    v.push_back(value);
6  }
```

```
1  vector<string> w;
2  add(w, "hello"s);
3                create!
4  string s { "bye" };
5  add(w, s);
```

rvalue $\Rightarrow$ 2 created, 1 destroyed

Forwarding references

Attempt #1

```
1  template <typename T>
2  void add(vector<T>& v,
3           T const& value)
4  {
5    v.push_back(value);
6  }
```

```
1  vector<string> w;
2  add(w, "hello"s);
3
4  string s { "bye" };
5  add(w, s);
```

create!

rvalue $\Rightarrow$ 2 created, 1 destroyed

Forwarding references

Attempt #1

```
1  template <typename T>
2  void add(vector<T>& v,
3           T const& value)
4  {
5    v.push_back(value);
6  }
```

```
1  vector<string> w;
2  add(w, "hello"s);
3                create!
4  string s { "bye" };
5  add(w, s);
```

rvalue $\Rightarrow$ 2 created, 1 destroyed

Forwarding references

Attempt #1

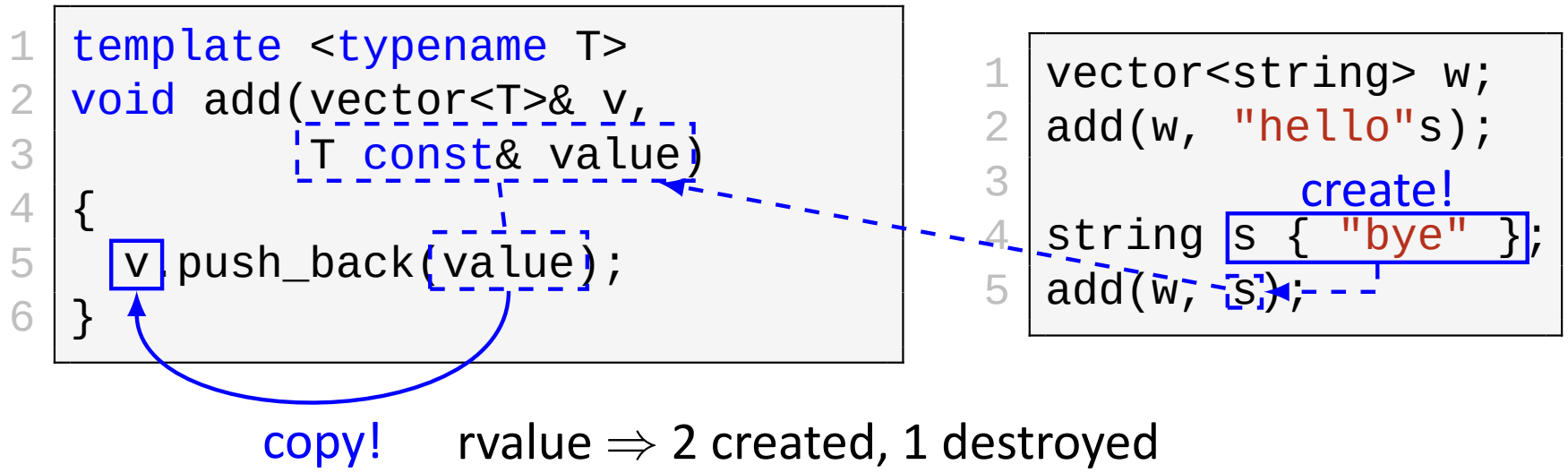
```
1  template <typename T>
2  void add(vector<T>& v,
3           T const& value)
4  {
5    v.push_back(value);
6  }
```

```
1  vector<string> w;
2  add(w, "hello"s);
3              create!
4  string s { "bye" };
5  add(w, s);
```

rvalue $\Rightarrow$ 2 created, 1 destroyed

Forwarding references

Attempt #1



rvalue $\Rightarrow$ 2 created, 1 destroyed

Forwarding references

Attempt #1

```
1 template <typename T>
2 void add(vector<T>& v,
3           T const& value)
4 {
5   v.push_back(value);
6 }
```

```
1 vector<string> w;
2 add(w, "hello"s);
3
4 string s { "bye" };
5 add(w, s);
```

rvalue $\Rightarrow$ 2 created, 1 destroyed

lvalue $\Rightarrow$ 2 created

Forwarding references

Attempt #1

```
1  template <typename T>
2  void add(vector<T>& v,
3           T const& value)
4  {
5    v.push_back(value);
6  }
```

```
1  vector<string> w;
2  add(w, "hello"s);
3
4  string s { "bye" };
5  add(w, s);
```

rvalue $\Rightarrow$ 2 created, 1 destroyed

lvalue $\Rightarrow$ 2 created

Forwarding references

Attempt #1

```
1  template <typename T>
2  void add(vector<T>& v,
3           T const& value)
4  {
5    v.push_back(value);
6  }
```

```
1  vector<string> w;
2  add(w, "hello"s);
3
4  string s { "bye" };
5  add(w, s);
```

rvalue ⇒ 2 created, 1 destroyed

lvalue ⇒ 2 created

Forwarding references

Attempt #1

```
1  template <typename T>
2  void add(vector<T>& v,
3           T const& value)
4  {
5    v.push_back(value);
6  }
```

```
1  vector<string> w;
2  add(w, "hello"s);
3                destroy
4  string s { "bye" };
5  add(w, s);
```

rvalue ⇒ 2 created, 1 destroyed

lvalue ⇒ 2 created

Forwarding references

Attempt #1

```
1  template <typename T>
2  void add(vector<T>& v,
3           T const& value)
4  {
5    v.push_back(value);
6  }
```

```
1  vector<string> w;
2  add(w, "hello"s);
3
4  string s { "bye" };
5  add(w, s);
```

rvalue $\Rightarrow$ 2 created, 1 destroyed

lvalue $\Rightarrow$ 2 created, 1 destoyed

Forwarding references

Attempt #1

```
1 template <typename T>
2 void add(vector<T>& v,
3           T const& value)
4 {
5   v.push_back(value);
6 }
```

```
1 vector<string> w;
2 add(w, "hello"s);
3
4 string s { "bye" };
5 add(w, s);
```

rvalue $\Rightarrow$ 2 created, 1 destroyed

lvalue $\Rightarrow$ 2 created, 1 destoyed

The rvalue case should probably use move!

Forwarding references

Attempt #2

```
1  template <typename T>
2  void add(vector<T>& v, T const& value) // #1
3  {
4    v.push_back(value);
5  }
6
7  template <typename T>
8  void add(vector<T>& v, T&& value) // #2
9  {
10   v.push_back(std::move(value));
11 }
```

```
1  vector<string> w;
2  string s { "bye" };
3
4
5  add(w, "hello"s);
6
7
8  add(w, s);
```

Forwarding references

Attempt #2

```
1  template <typename T>
2  void add(vector<T>& v, T const& value) // #1
3  {
4    v.push_back(value);
5  }
6
7  template <typename T>
8  void add(vector<T>& v, T&& value) // #2
9  {
10   v.push_back(std::move(value));
11 }
```

```
1  vector<string> w;
2  string s { "bye" };
3
4  // chooses #2!
5  add(w, "hello"s);
6
7
8  add(w, s);
```

Forwarding references

Attempt #2

```
1  template <typename T>
2  void add(vector<T>& v, T const& value) // #1
3  {
4    v.push_back(value);
5  }
6
7  template <typename T>
8  void add(vector<T>& v, T&& value) // #2
9  {
10   v.push_back(std::move(value));
11 }
```

```
1  vector<string> w;
2  string s { "bye" };
3
4  // chooses #2!
5  add(w, "hello"s);
6
7  // chooses #1!
8  add(w, s);
```

Forwarding references

Attempt #2

```cpp
template <typename T>
void add(vector<T>& v, T const& value) // #1
{
  v.push_back(value);
}

template <typename T>
void add(vector<T>& v, T&& value) // #2
{
  v.push_back(std::move(value));
}
```

```cpp
vector<string> w;
string s { "bye" };

// chooses #2!
add(w, "hello"s);

// chooses #1!
add(w, s);
```

Cool!

Forwarding references

Attempt #2

```
1  template <typename T>
2  void add(vector<T>& v, T const& value) // #1
3  {
4    v.push_back(value);
5  }
6
7  template <typename T>
8  void add(vector<T>& v, T&& value) // #2
9  {
10   v.push_back(std::move(value));
11 }
```

```
1  vector<string> w;
2  string s { "bye" };
3
4  // chooses #2!
5  add(w, "hello"s);
6
7  // chooses #1!
8  add(w, s);
```

Cool!

But what about the duplication?

Forwarding references

Attempt #3

```
1  template <typename T, typename U>
2  void add(vector<T>& v, U&& value)
3  {
4    v.push_back(std::move(value));
5  }
```

```
1  vector<string> w;
2  string s { "bye" };
3
4
5  add(w, "hello"s);
6
7
8  add(w, s);
```

Forwarding references

Attempt #3

```
1  template <typename T, typename U>
2  void add(vector<T>& v, U&& value)
3  {
4    v.push_back(std::move(value));
5  }
```

```
1  vector<string> w;
2  string s { "bye" };
3
4  // Works (as expected)!
5  add(w, "hello"s);
6
7
8  add(w, s);
```

Forwarding references

Attempt #3

```
1  template <typename T, typename U>
2  void add(vector<T>& v, U&& value)
3  {
4    v.push_back(std::move(value));
5  }
```

```
1  vector<string> w;
2  string s { "bye" };
3
4  // Works (as expected)!
5  add(w, "hello"s);
6
7  // Also works?!
8  add(w, s);
```

Forwarding references

Attempt #3

```
1  template <typename T, typename U>
2  void add(vector<T>& v, U&& value)
3  {
4    v.push_back(std::move(value));
5  }
```

```
1  vector<string> w;
2  string s { "bye" };
3
4  // Works (as expected)!
5  add(w, "hello"s);
6
7  // But s is now empty?!
8  add(w, s);
```

Forwarding references

What is going on?

```
1  vector<string> w;
2  string s { "bye" };
3
4
5  add(w, "hello"s);
6
7
8  add(w, s);
```

```
1  template <typename T, typename U>
2  void add(vector<T>& v, U&& value);
3
4
5
6
7
8
```

Forwarding references

What is going on?

```
1  vector<string> w;
2  string s { "bye" };
3
4  // T = string
5  add(w, "hello"s);
6
7
8  add(w, s);
```

```
1  template <typename T, typename U>
2  void add(vector<T>& v, U&& value);
3
4
5
6
7
8
```

Forwarding references

What is going on?

```
1  vector<string> w;
2  string s { "bye" };
3
4  // T = string, U = string
5  add(w, "hello"s);
6
7
8  add(w, s);
```

```
1  template <typename T, typename U>
2  void add(vector<T>& v, U&& value);
3
4
5
6
7
8
```

Forwarding references

What is going on?

```
1  vector<string> w;
2  string s { "bye" };
3
4  // T = string, U = string
5  add(w, "hello"s);
6
7
8  add(w, s);
```

```
1  template <typename T, typename U>
2  void add(vector<T>& v, U&& value);
3
4  void add(vector<string>& v,
5           string&& value);
6
7
8
```

Forwarding references

What is going on?

```
1  vector<string> w;
2  string s { "bye" };
3
4  // T = string, U = string
5  add(w, "hello"s);
6
7  // T = string
8  add(w, s);
```

```
1  template <typename T, typename U>
2  void add(vector<T>& v, U&& value);
3
4  void add(vector<string>& v,
5           string&& value);
6
7
8
```

Forwarding references

What is going on?

```
1  vector<string> w;
2  string s { "bye" };
3
4  // T = string, U = string
5  add(w, "hello"s);
6
7  // T = string, U = string& (???)
8  add(w, s);
```

```
1  template <typename T, typename U>
2  void add(vector<T>& v, U&& value);
3
4  void add(vector<string>& v,
5           string&& value);
6
7
8
```

Forwarding references

What is going on?

```
1  vector<string> w;
2  string s { "bye" };
3
4  // T = string, U = string
5  add(w, "hello"s);
6
7  // T = string, U = string& (???)
8  add(w, s);
```

```
1  template <typename T, typename U>
2  void add(vector<T>& v, U&& value);
3
4  void add(vector<string>& v,
5           string&& value);
6
7  void add(vector<string>& v,
8           string&&& value); // ???
```

Forwarding references

What is going on?

- Why did it choose `U = string&` in the second case?
- Well, if the compiler would have picked `U = string`, then the second parameter of `add()` would end up being an rvalue-reference, which wouldn't have compiled (since `s` is an lvalue)
- However, the compiler knows of something called *reference collapsing* which has the consequence that whenever `U = V&` then U&& "collapses" into V&, which means that deducing `U = string&` results in the second parameter collapsing into a `string` lvalue-reference.

Forwarding references

Reference collapsing

- Suppose we have a function parameter T& and T = `int`&, then what should happen?
- `int`&& would make no sense since that represents an *rvalue* reference.
- We have to think about the *intention* behind these decisions.
- If the parameter is T& then the author of the function intends to take an *lvalue* by-reference.
- If T = `int`& then the function caller also intends for the parameter to be passed as an lvalue reference.
- So both the function and the caller are in agreement, therefore the resulting parameter should be `int`&.
- This implies that some form of simplification happens with T& when T = `int`&. This simplification is part of a larger rule called *reference collapsing*.
- Let us investigate this further, taking both lvalue- and rvalue-references into account.

Forwarding references

Reference collapsing

T	T = U	⇒ U
T&	T = U	⇒ U&
T&&	T = U	⇒ U&&
T	T = U&	⇒ U&
T&	T = U&	⇒ U&
T&&	T = U&	⇒ U&
T	T = U&&	⇒ U&&
T&	T = U&&	⇒ U&
T&&	T = U&&	⇒ U&&

Forwarding references

Reference collapsing

T	T = U	⇒ U
T&	T = U	⇒ U&
T&&	T = U	⇒ U&&
T	T = U&	⇒ U&
T&	T = U&	⇒ U&
T&&	T = U&	⇒ U&
T	T = U&&	⇒ U&&
T&	T = U&&	⇒ U&
T&&	T = U&&	⇒ U&&

function & caller agrees

Forwarding references

Reference collapsing

T	T = U	⇒ U	function & caller agrees
T&	T = U	⇒ U&	function wins
T&&	T = U	⇒ U&&	
T	T = U&	⇒ U&	
T&	T = U&	⇒ U&	
T&&	T = U&	⇒ U&	
T	T = U&&	⇒ U&&	
T&	T = U&&	⇒ U&	
T&&	T = U&&	⇒ U&&	

Forwarding references

Reference collapsing

T	T = U	⇒ U	function & caller agrees
T&	T = U	⇒ U&	function wins
T&&	T = U	⇒ U&&	function wins
T	T = U&	⇒ U&	
T&	T = U&	⇒ U&	
T&&	T = U&	⇒ U&	
T	T = U&&	⇒ U&&	
T&	T = U&&	⇒ U&	
T&&	T = U&&	⇒ U&&	

Forwarding references

Reference collapsing

T	T = U	⇒ U	function & caller agrees
T&	T = U	⇒ U&	function wins
T&&	T = U	⇒ U&&	function wins
T	T = U&	⇒ U&	caller wins
T&	T = U&	⇒ U&	
T&&	T = U&	⇒ U&	
T	T = U&&	⇒ U&&	
T&	T = U&&	⇒ U&	
T&&	T = U&&	⇒ U&&	

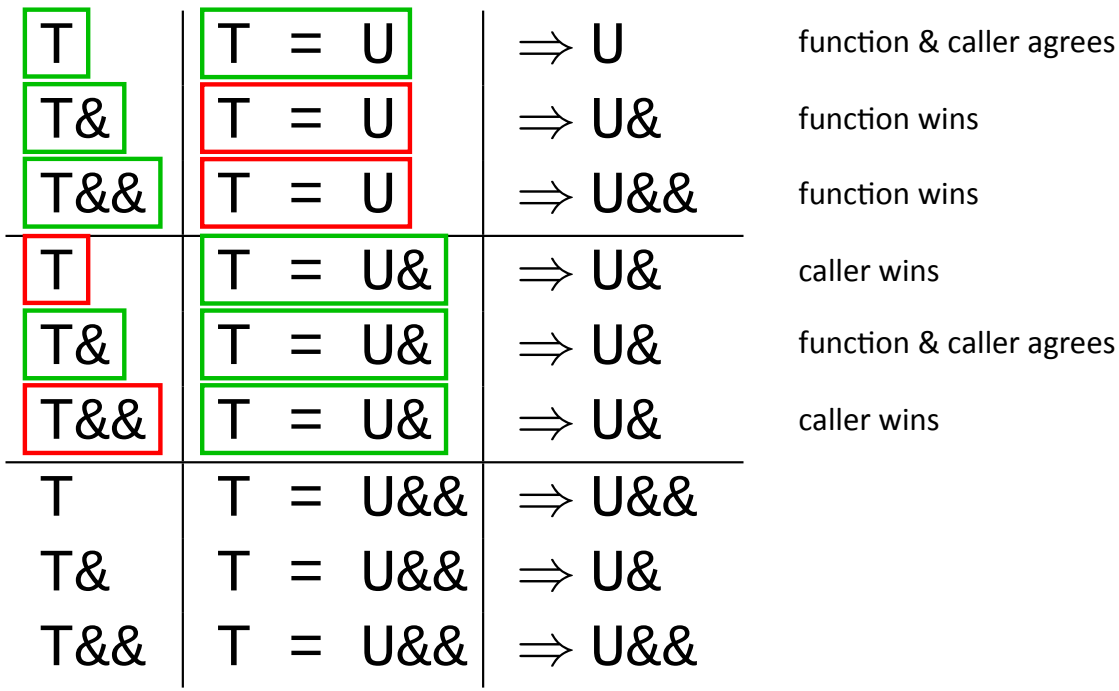
Forwarding references

Reference collapsing

T	T = U	⇒ U	function & caller agrees
T&	T = U	⇒ U&	function wins
T&&	T = U	⇒ U&&	function wins
T	T = U&	⇒ U&	caller wins
T&	T = U&	⇒ U&	function & caller agrees
T&&	T = U&	⇒ U&	
T	T = U&&	⇒ U&&	
T&	T = U&&	⇒ U&	
T&&	T = U&&	⇒ U&&	

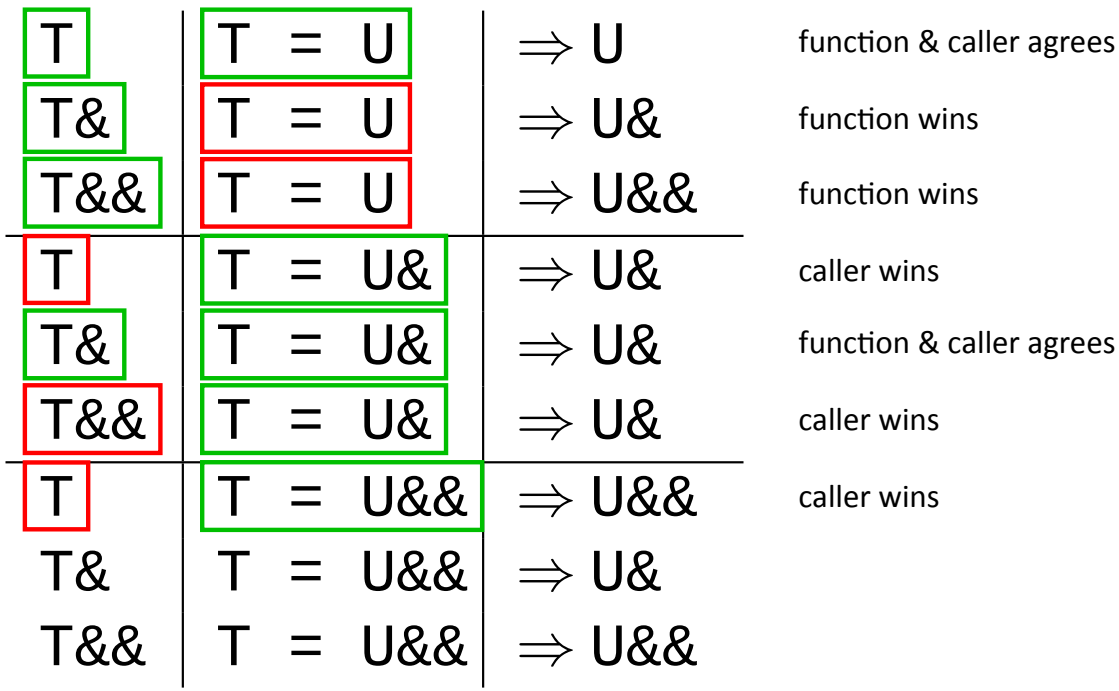
Forwarding references

Reference collapsing



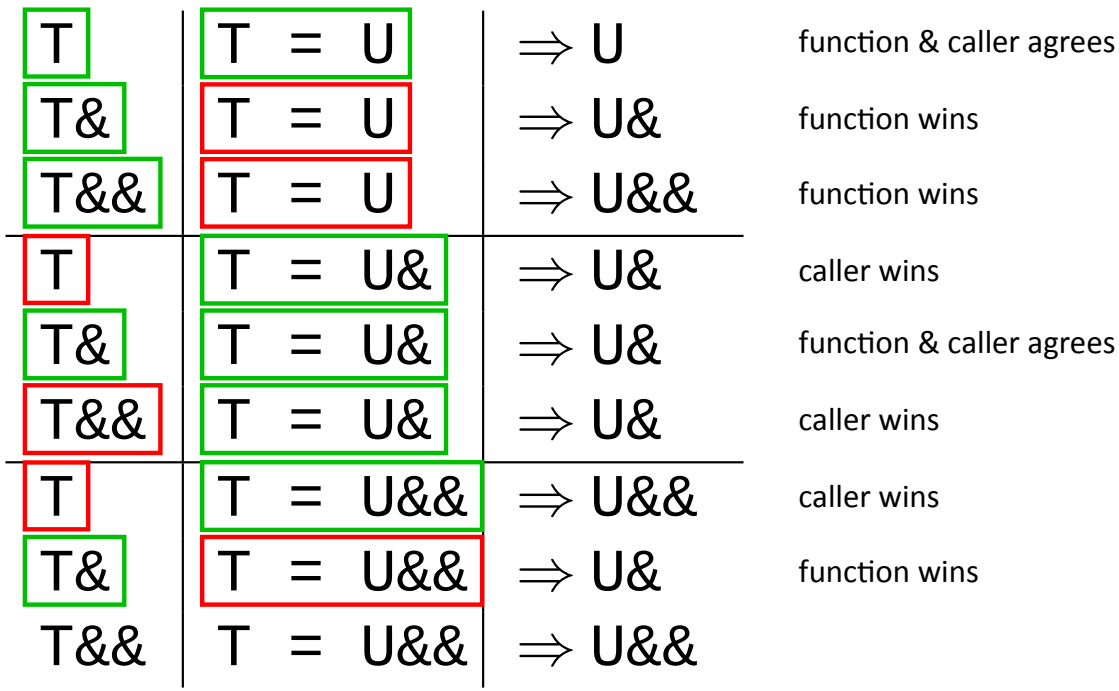
Forwarding references

Reference collapsing



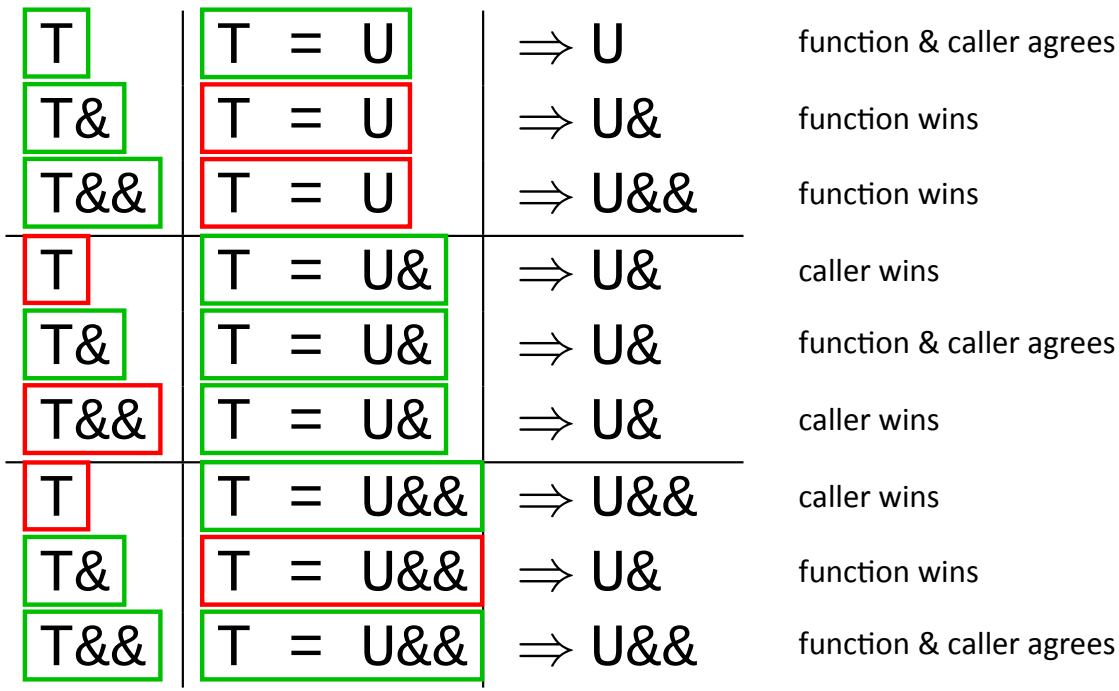
Forwarding references

Reference collapsing



Forwarding references

Reference collapsing



Forwarding references

Reference collapsing

- Whoever (function or caller) picks lvalue reference always takes priority
- If noone picks lvalue reference, than whoever pick rvalue reference takes priority
- Finally, if both the function and the caller agrees on not having a reference, then and only then does the parameter collapses into a pass by-copy parameter

Forwarding references

Reference collapsing

- The intuition behind these rules is primarily based around the idea of *copy* and *move* semantics.
- Whenever a function takes an rvalue reference it is because the function intends for the object to be *moved* to someplace else within the function.
- It is also important to recall that moving an object is *destructive*, while *copying* is not, so if there is any disagreement what-so-ever whether an object should be moved or copied, the safe option is to *copy*.
- So if the function and the caller is in disagreement wheter the object should be an rvalue reference (moved) or an lvalue reference (copied), then the lvalue reference (copied) should take priority.
- The compiler should only allow rvalue references if the function and the caller agrees that moving is the better option.
- If either the function or caller doesn't specify any reference what-so-ever, then they are not considered during the decision.

Forwarding references

Reference collapsing

Rule of thumb: & > && > no reference

Forwarding references

Problem

```
1  template <typename T, typename U>
2  void add(vector<int>& v, U&& value)
3  {
4    v.push_back(std::move(value));
5  }
```

Forwarding references

Problem

```
1  template <typename T, typename U>
2  void add(vector<int>& v, U&& value)
3  {
4    v.push_back(std::move(value));
5  }
```

Forwarding references

Problem

```
1  template <typename T, typename U>
2  void add(vector<int>& v, U&& value)
3  {
4    v.push_back(std::move(value));
5  }
```

← will **always** move

Forwarding references

Fix by duplication

```
1  template <typename T, typename U>
2  void add(vector<int>& v, U&& value)
3  {
4    if (std::is_lvalue_reference_v<U>)
5      v.push_back(value);
6    else
7      v.push_back(std::move(value));
8  }
```

Forwarding references

Fix by duplication

```
1  template <typename T, typename U>
2  void add(vector<int>& v, U&& value)
3  {
4    if (std::is_lvalue_reference_v<U>)
5      v.push_back(value);
6    else
7      v.push_back(std::move(value));
8  }
```

Forwarding references

Fix by duplication

```
1  template <typename T, typename U>
2  void add(vector<int>& v, U&& value)
3  {
4    if (std::is_lvalue_reference_v<U>)
5      v.push_back(value);
6    else
7      v.push_back(std::move(value));
8  }
```

value is lvalue ⇒ copy!

Forwarding references

Fix by duplication

```
1  template <typename T, typename U>
2  void add(vector<int>& v, U&& value)
3  {
4    if (std::is_lvalue_reference_v<U>)
5      v.push_back(value);
6    else
7      v.push_back(std::move(value));
8  }
```

value is lvalue ⇒ copy!

Forwarding references

Fix by duplication

```
1  template <typename T, typename U>
2  void add(vector<int>& v, U&& value)
3  {
4    if (std::is_lvalue_reference_v<U>)
5      v.push_back(value);
6    else
7      v.push_back(std::move(value));
8  }
```

value is lvalue ⇒ copy!

value is rvalue ⇒ move!

Forwarding references

Better fix!

```
1  template <typename T, typename U>
2  void add(vector<int>& v, U&& value)
3  {
4    v.push_back(std::forward<U>(value));
5  }
```

Forwarding references

`std::forward`

- `std::forward<U>(value)` is an expression that performs `std::move(value)` *if and only if* `U` is **NOT** an lvalue-reference
- If `U` is an lvalue-reference then `std::forward<U>(value)` is equivalent to the expression `value`

Forwarding references

Forwarding references

T&& is called a *forwarding reference* **if**:

1. T is an arbitrary type (template parameter or `auto`)
2. T is *deduced* by the compiler

Forwarding references

Examples: Is there a forwarding reference in this example?

```
1  template <typename T>
2  struct X
3  {
4    static void fun(T&&);
5  };
```

Forwarding references

Examples: Is there a forwarding reference in this example?

```
1  template <typename T>
2  struct X
3  {
4    static void fun(T&&);
5  };
```

No!

Forwarding references

Examples: Is there a forwarding reference in this example?

```
1 template <typename T>
2 void fun(T&&);
3
4
5
```

Forwarding references

Examples: Is there a forwarding reference in this example?

```
1 template <typename T>
2 void fun(T&&);
3
4 int x { 5 };
5 fun(x); // yes!
```

Forwarding references

Examples: Is there a forwarding reference in this example?

```
1 template <typename T>
2 void fun(T&&);
3
4 int x { 5 };
5 fun<int>(x); // no...
```

Forwarding references

Examples: Is there a forwarding reference in this example?

```
1 template <typename T>
2 void fun(T&&);
3
4 int x { 5 };
5 fun<int>(x); // no...
```

Yes, if T is not specified

Forwarding references

Examples: Is there a forwarding reference in this example?

```
1 template <typename T>
2 void fun(vector<T>&& v);
3
4
5
```

Forwarding references

Examples: Is there a forwarding reference in this example?

```
1 template <typename T>
2 void fun(vector<T>&& v);
3
4
5
```

No!

Forwarding references

Examples: Is there a forwarding reference in this example?

```
1 auto&& var = 5;
2
3
4
5
```

Forwarding references

Examples: Is there a forwarding reference in this example?

```
1 auto&& var = 5;
2
3
4
5
```

Yes!

Forwarding references

Rule of thumb

Use forwarding references if:

Forwarding references

Rule of thumb

Use forwarding references if:

- a templated parameter is passed to another function

Forwarding references

Rule of thumb

Use forwarding references if:

- a templated parameter is passed to another function, or
- you are writing generic code

Forwarding references

Rule of thumb

Use forwarding references if:

- a templated parameter is passed to another function, or
- you are writing generic code, e.g.: `for (auto&& v : c)`

1. Forwarding references
2. Smart pointers
3. `std::unique_ptr`
4. `std::shared_ptr`

Smart pointers

Can we get memory problems here?

```
1  class My_Class
2  {
3  public:
4    My_Class(int x, int y);
5    ~My_Class()
6    {
7      delete p1;
8      delete p2;
9    }
10 private:
11   int* p1;
12   int* p2;
13 };
```

Smart pointers

Can we get memory problems here?

```
1  static int* create(int n)
2  {
3    if (n >= 0)
4    {
5      return new int{n};
6    }
7    throw domain_error{"Negative"};
8  }
9
10 My_Class::My_Class(int x, int y)
11   : p1{create(x)}, p2{create(y)}
12 { }
```

Smart pointers

Yes, there are problems!

```
1  int main()
2  {
3    My_Class c{0, -1};
4  }
```

Smart pointers

Why?

- When the constructor is aborted the object will be removed without running the destructor
- All data that were allocated before the crash will therefore not be deallocated
- How can we solve this?

Smart pointers

Solution?

```
1  My_Class::My_Class(int x, int y) try
2    : p1{create(x)}, p2{create(y)}
3  { }
4  catch (domain_errror& e)
5  {
6    delete p1;
7  }
8  int main()
9  {
10   My_Class c{-1, 0};
11 }
```

Smart pointers

Solution?

```
1  My_Class::My_Class(int x, int y) try
2    : p1{create(x)}, p2{create(y)}
3  { }
4  catch (domain_errror& e)
5  {
6    delete p1;
7  }
8  int main()
9  {
10   My_Class c{-1, 0};
11 }
```

Segmentation Fault

Smart pointers

Why?

- Now `p1` will throw an exception
- In the catch-block we are trying to `delete` it, but it has not been allocated
- This gives us a segmentation fault

Smart pointers

Solution?

```
1  My_Class::My_Class(int x, int y)
2    : p1{create(x)}, p2{}
3  {
4    try
5    {
6      p2 = create(y);
7    }
8    catch (domain_error& e)
9    {
10     delete p1;
11     throw;
12   }
13 }
```

Smart pointers

Solution?

```
1  My_Class::My_Class(int x, int y)
2    : p1{create(x)}, p2{}
3  {
4    try
5    {
6      p2 = create(y);
7    }
8    catch (domain_error& e)
9    {
10     delete p1;
11     throw;
12   }
13 }
```

Works...

Smart pointers

Solution?

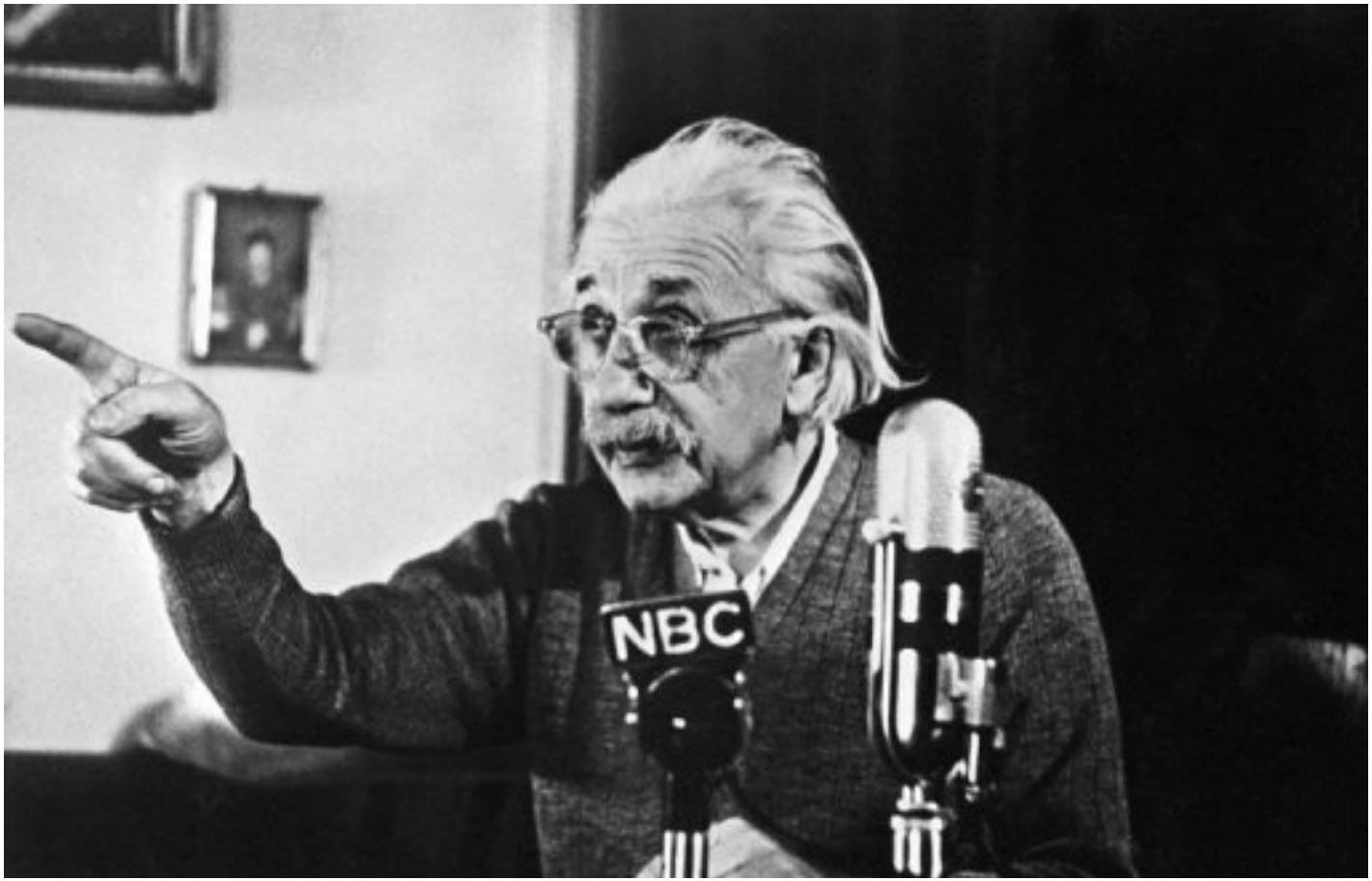
```
1  My_Class::My_Class(int x, int y)
2    : p1{create(x)}, p2{}
3  {
4    try
5    {
6      p2 = create(y);
7    }
8    catch (domain_error& e)
9    {
10     delete p1;
11     throw;
12   }
13 }
```

At what cost?

Smart pointers

It would be nice if pointers could deallocate themselves...

Smart pointers



Smart pointers

Let's use RAII!

```
1  template <typename T>
2  struct Smart_Pointer
3  {
4    T* data; // the data
5
6    // automatically delete (and null)
7    ~Smart_Pointer()
8    {
9      delete data;
10     data = nullptr;
11   }
12
13   // access by casting to T*
14   operator T*()
15   {
16     return data;
17   }
18 };
```

Disclaimer: This class has many problems, don't use it

Smart pointers

Better solution!

```
1  class My_Class
2  {
3  public:
4    My_Class(int x, int y);
5    ~My_Class() = default;
6  private:
7    Smart_Pointer<int> p1;
8    Smart_Pointer<int> p2;
9  };
```

Smart pointers

Better solution!

```
1 My_Class::My_Class(int x, int y)
2   : p1{create(x)}, p2{create(y)}
3 { }
```

Smart pointers

Let’s see another motivating example

Smart pointers

Do you see any issues here?

```
1  struct Image  {
2    Color data[250000000]; // 1 GB
3  };
4  Image load_image(string const& file);
5
6  struct Sprite {
7    // ...
8
9    Image image;
10 };
11 Sprite create_sprite(string const& file) {
12   return Sprite { load_image(file) };
13 }
14
15 void run() {
16
17   auto s1 = create_sprite("image.png");
18   auto s2 = create_sprite("image.png");
19   // use s1 and s2
20 }
```

Smart pointers

Do you see any issues here?

```
1  struct Image  {
2    Color data[250000000]; // 1 GB
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4  Image load_image(string const& file);
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14
15 void run() {
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17   auto s1 = create_sprite("image.png");
18   auto s2 = create_sprite("image.png");
19   // use s1 and s2
20 }
```

Segmentation fault!

Smart pointers

Some issues

- Each image is 1 GB large
- Whenever we create a sprite, we first load the image and then we *move* it into the sprite, making each sprite *at least* 1 GB large as well
- Note however, that *moving* doesn't help us *at all* here, since the pixel data is stored directly in the object.
- During the call to `create_sprite()` we are therefore actively using *at least* 2 GB of data, because we are holding two images at the same time in memory
- A second issue is that we are storing the sprites, and therefore the images, on the stack. The stack is typically in the range of *megabytes* not *gigabytes*, so we immediately write outside the designated memory area.
- We can solve these issues by putting the images on the heap and then just storing pointers.

Smart pointers

Do you see any issues now?

```
1  struct Image  {
2    Color data[250000000]; // 1 GB
3  };
4  Image* load_image(string const& file);
5
6  struct Sprite {
7    // ...
8
9    Image* image;
10 };
11 Sprite create_sprite(string const& file) {
12   return Sprite { load_image(file) };
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15 void run() {
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17   auto s1 = create_sprite("image.png");
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```

Smart pointers

Do you see any issues now?

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15 void run() {
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17   auto s1 = create_sprite("image.png");
18   auto s2 = create_sprite("image.png");
19   // use s1 and s2
20 }
```

Memory leaks!

Smart pointers

Another issue

- Now we can run the program fine
- However, each time we execute the `run()` function, our memory usage jumps up by 2 GB since we never deallocate the memory
- Who should be responsible for deallocating the memory?
- Probably `Sprite`…?

Smart pointers

How about **now**?

```
1  struct Image  {
2    Color data[250000000]; // 1 GB
3  };
4  Image* load_image(string const& file);
5
6  struct Sprite {
7    // ...
8    ~Sprite() { delete image; }
9    Image* image;
10 };
11 Sprite create_sprite(string const& file) {
12   return Sprite { load_image(file) };
13 }
14
15 void run() {
16
17   auto s1 = create_sprite("image.png");
18   auto s2 = create_sprite("image.png");
19   // use s1 and s2
20 }
```

Smart pointers

How about **now**?

```
1  struct Image  {
2    Color data[250000000]; // 1 GB
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5
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8    ~Sprite() { delete image; }
9    Image* image;
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13 }
14
15 void run() {
16
17   auto s1 = create_sprite("image.png");
18   auto s2 = create_sprite("image.png");
19   // use s1 and s2
20 }
```

Smart pointers

Wasted memory

- Now the memory is handled properly
- However, we are strictly speaking using more memory than needed since `s1` and `s2` *always* uses the same image.
- Maybe we can make them share the same image?

Smart pointers

How about **now**?

```
1  struct Image  {
2    Color data[250000000]; // 1 GB
3  };
4  Image* load_image(string const& file);
5
6  struct Sprite {
7    // ...
8    ~Sprite() { delete image; }
9    Image* image;
10 };
11 Sprite create_sprite(Image* image) {
12   return Sprite { image };
13 }
14
15 void run() {
16   Image* image = load_image("image.png");
17   auto s1 = create_sprite(image);
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```

Smart pointers

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15 void run() {
16   Image* image = load_image("image.png");
17   auto s1 = create_sprite(image);
18   auto s2 = create_sprite(image);
19   // use s1 and s2
20 }
```

Double free error!

Smart pointers

Double free error

- Now that the sprites are sharing the same image we are getting a double free error
- This is because the destructor of `s2` deletes it, and then `s1` tries to delete it as well.
- How do we solve this? If we think about it, what part of the code actually is responsible for deallocating the image?

Smart pointers

Two solutions

This problem can be solved in two ways:

- *unique ownership*
- *shared ownership*

Depending on your perspective

Smart pointers

Important model: Ownership

Whoever is responsible for deallocating a resource is the *owner* of said resource

Smart pointers

Important model: Ownership

Whoever is responsible for deallocating a resource is the *owner* of said resource

If done correctly *ownership* can be enforced by the compiler

Smart pointers

Important model: Ownership

Whoever is responsible for deallocating a resource is the *owner* of said resource

If done correctly *ownership* can be enforced by the compiler

In C++ this is done through *smart pointers*

Smart pointers

Different kinds of smart pointers

- Ownership is unique – `std::unique_ptr`
- Ownership is shared – `std::shared_ptr`

Smart pointers

Shared properties of all smart pointers

A smart pointer:

Smart pointers

Shared properties of all smart pointers

A smart pointer:

- Is used like a “normal” pointer

Smart pointers

Shared properties of all smart pointers

A smart pointer:

- Is used like a “normal” pointer
- Deletes the memory when no owner remains

Smart pointers

Shared properties of all smart pointers

A smart pointer:

- Is used like a “normal” pointer
- Deletes the memory when no owner remains
- Sets itself to `nullptr` once it is deleted

1 Forwarding references
2 Smart pointers
3 `std::unique_ptr`
4 `std::shared_ptr`

`std::unique_ptr`

Unique ownership

- The key aspect of *unique ownership* is that there can only ever be one owner of a resource at any given point in time
- If the unique owner is destroyed or it deems the resource no longer needed, then the resource is deallocated
- However, unique ownership is not *static*, meaning ownership can be *transfered* (or *moved*) between objects

std::unique_ptr

Identifying the *owner*

```
1  struct Image  {
2    Color data[250000000]; // 1 GB
3  };
4  Image* load_image(string const& file);
5
6  struct Sprite {
7    // ...
8    ~Sprite() { delete image; } // Sprite owns it
9    Image* image;
10 };
11 Sprite create_sprite(Image* image) {
12   return Sprite { image };
13 }
14
15 void run() {
16   Image* image = load_image("image.png");
17   auto s1 = create_sprite(image);
18   auto s2 = create_sprite(image);
19   // use s1 and s2
20 }
```

std::unique_ptr

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13
14 void run() {
15   Image* image = load_image("image.png");
16   auto s1 = create_sprite(image);
17   auto s2 = create_sprite(image);
18   // use s1 and s2
19   delete image; // run() owns it
20 }
```

`std::unique_ptr`

Identifying ownership

- There is no right or wrong answer on the question of *who* owns the memory
- However it can be quite confusing who is responsible since the compiler doesn't really stop us from mixing the two

std::unique_ptr

Incorrect solution

```
1  struct Image  {
2    Color data[250000000]; // 1 GB
3  };
4  Image* load_image(string const& file);
5
6  struct Sprite {
7    // ...
8    ~Sprite() { delete image; } // sprite owns it
9    Image* image;
10 };
11 Sprite create_sprite(Image* image) {
12   return Sprite { image };
13 }
14
15 void run() {
16   Image* image = load_image("image.png");
17   auto s1 = create_sprite(image);
18   auto s2 = create_sprite(image);
19   // use s1 and s2
20   delete image; // run() owns it
21 }
```

std::unique_ptr

Incorrect solution

```
1  struct Image  {
2    Color data[250000000]; // 1 GB
3  };
4  Image* load_image(string const& file);
5
6  struct Sprite {
7    // ...
8    ~Sprite() { delete image; } // sprite owns it
9    Image* image;
10 };
11 Sprite create_sprite(Image* image) {
12   return Sprite { image };
13 }
14
15 void run() {
16   Image* image = load_image("image.png");
17   auto s1 = create_sprite(image);
18   auto s2 = create_sprite(image);
19   // use s1 and s2
20   delete image; // run() owns it
21 }
```

conflicting ownership!

std::unique_ptr

Who owns the memory?

```
1  Data* get_data();
2
3  int main()
4  {
5    auto data = get_data();
6
7    // who is the owner?
8
9  }
```

std::unique_ptr

Who owns the memory?

```
1  Data* get_data();
2
3  int main()
4  {
5    auto data = get_data();
6
7    // who is the owner?
8
9  }
```

```
1  Data* get_data()
2  {
3    static Data data { ... };
4    return &data;
5  }
```

std::unique_ptr

Who owns the memory?

```
1  Data* get_data();
2
3  int main()
4  {
5    auto data = get_data();
6
7    // who is the owner?
8    // get_data()!
9  }
```

```
1  Data* get_data()
2  {
3    static Data data { ... };
4    return &data;
5  }
```

std::unique_ptr

Who owns the memory?

```
1  Data* get_data();
2
3  int main()
4  {
5    auto data = get_data();
6
7    // who is the owner?
8
9  }
```

```
1  Data* get_data()
2  {
3    return new Data { ... };
4  }
```

std::unique_ptr

Who owns the memory?

```
1  Data* get_data();
2
3  int main()
4  {
5    auto data = get_data();
6
7    // who is the owner?
8    // main()!
9  }
```

```
1  Data* get_data()
2  {
3    return new Data { ... };
4  }
```

std::unique_ptr

Who owns the memory?

```
1  Data* get_data();
2
3  int main()
4  {
5    auto data = get_data();
6
7    // who is the owner?
8    // main()!
9  }
```

```
1  Data* get_data()
2  {
3    return new Data { ... };
4  }
```

How can we communicate this?

std::unique_ptr

Enter std::unique_ptr!

```
1  // raw pointer => you are NOT the owner
2  Data* get_data()
3  {
4    static Data data { ... };
5    return &data;
6  }
```

```
1  Data* get_data();
2
3  int main()
4  {
5    // I am not owner...
6    auto data = get_data();
7
8    // ... So I don't delete it
9  }
```

std::unique_ptr

Enter `std::unique_ptr`!

```
1  // smart pointer => you ARE the owner
2  std::unique_ptr<Data> get_data()
3  {
4
5    return new Data { ... };
6  }
```

```
1  std::unique_ptr<Data> get_data();
2
3  int main()
4  {
5    // I am the owner...
6    auto data = get_data();
7    // ... So it dies when I do
8    // => no need to delete!
9  }
```

std::unique_ptr

A big gotcha with std::unique_ptr

```
1  int* memory { new int { 5 } };
2  {
3    std::unique_ptr<int> ptr1 { memory };
4    {
5      std::unique_ptr<int> ptr2 { memory };
6    }
7  }
```

std::unique_ptr

A big gotcha with std::unique_ptr

```
1  int* memory { new int { 5 } };
2  {
3    std::unique_ptr<int> ptr1 { memory };
4    {
5      std::unique_ptr<int> ptr2 { memory };
6    }
7  }
```

Double free error!

std::unique_ptr

A big gotcha with std::unique_ptr

```
1  int* memory { new int { 5 } };
2  {
3    std::unique_ptr<int> ptr1 { memory };
4    {
5      std::unique_ptr<int> ptr2 { memory };
6    } // ptr2 deletes the memory
7  }
```

Double free error!

std::unique_ptr

A big gotcha with std::unique_ptr

```
1  int* memory { new int { 5 } };
2  {
3    std::unique_ptr<int> ptr1 { memory };
4    {
5      std::unique_ptr<int> ptr2 { memory };
6    } // ptr2 deletes the memory
7  } // ptr1 TRIES to delete the same memory
```

Double free error!

`std::unique_ptr`

Rule of thumb: Don’t manually allocate the memory

std::unique_ptr

Solution

```
1 {
2   auto ptr1 = std::make_unique<int>(5);
3   {
4     std::unique_ptr<int> ptr2 { ptr1 };
5   }
6 }
```

std::unique_ptr

Solution

```
1  {
2    auto ptr1 = std::make_unique<int>(5);
3    {
4      std::unique_ptr<int> ptr2 { ptr1 };
5    }
6  }
```

Compile error!

`std::unique_ptr`

Solution

- When allocating memory and then passing it to a `std::unique_ptr` we are explicitly *handing over* the ownership of said memory to the smart pointer
- However, doing so doesn't explicitly *stop* us from trying to pass it to another `std::unique_ptr`, thus breaking the *uniqueness* assumption of the ownership
- Because of this, it better to never even manually handle the memory at all (because then we cannot accidentally do anything incorrectly)
- Instead we use the `std::make_unique<T>()` function which acts similar to `new`, but it instead produces a `std::unique_ptr<T>`.

`std::unique_ptr`

Why did it not compile?

`std::unique_ptr<T>`:

- Represents *unique* ownership

`std::unique_ptr`

Why did it not compile?

`std::unique_ptr<T>`:

- Represents *unique* ownership
- The ownership can not be *shared*

`std::unique_ptr`

Why did it not compile?

`std::unique_ptr<T>`:

- Represents *unique* ownership
- The ownership can not be *shared*
- $\Rightarrow$ you are not allowed to copy it

`std::unique_ptr`

Why did it not compile?

`std::unique_ptr<T>`:

- Represents *unique* ownership
- The ownership can not be *shared*
- $\Rightarrow$ you are not allowed to copy it
- You can however *move* the ownership

std::unique_ptr

Solution

```
1  {
2    auto ptr1 = std::make_unique<int>(5);
3    {
4      std::unique_ptr<int> ptr2 { std::move(ptr1) };
5      assert( *ptr2 == 5 );
6    }
7    assert( ptr1 == nullptr );
8  }
```

std::unique_ptr

Solution

```
1  {
2    auto ptr1 = std::make_unique<int>(5);
3    {
4      std::unique_ptr<int> ptr2 { std::move(ptr1) };
5      assert( *ptr2 == 5 );
6    }
7    assert( ptr1 == nullptr );
8  }
```

Works!

std::unique_ptr

Solving our example

```
1  struct Image  {
2    Color data[250000000]; // 1 GB
3  };
4  unique_ptr<Image> load_image(string const& file);
5
6  struct Sprite {
7    // ...
8    Image const& image;
9  };
10 Sprite create_sprite(Image const& image) {
11   return Sprite { image };
12 }
13
14 void run() {
15   // run() is the owner of the image
16   auto image = load_image("image.png");
17   auto s1 = create_sprite(*image);
18   auto s2 = create_sprite(*image);
19   // use s1 and s2
20 }
```

`std::unique_ptr`

Solving our example

- If we are using `std::unique_ptr` then we need a *unique* owner
- The most appropriate owner in that instance (if our wish is to not duplicate the image) is to pass the ownership of the image to whomever owns the sprites
- In this instance that owner is the `run()` function
- But how is it solved with *shared* ownership?

1. Forwarding references
2. Smart pointers
3. `std::unique_ptr`
4. `std::shared_ptr`

`std::shared_ptr`

Shared ownership

- *Shared ownership* means that there can be many owners of the same resource, and the amount of owners can vary over time
- Once *all* owners have decided that they don't need the resource anymore, then, and only then, is the resource deallocated
- In this model ownership *can* be *copied* and *moved* between objects
- `std::shared_ptr` represents shared ownership in C++

std::shared_ptr

Solving our example with *shared* ownership

```
1  struct Image  {
2    Color data[250000000]; // 1 GB
3  };
4  shared_ptr<Image> load_image(string const& file);
5
6  struct Sprite {
7    // ...
8    shared_ptr<Image> image;
9  };
10 Sprite create_sprite(shared_ptr<Image> image) {
11   return Sprite { image };
12 }
13
14 void run() {
15   // run() is owner #1 of the image
16   auto image = load_image("image.png");
17   auto s1 = create_sprite(image); // owner #2
18   auto s2 = create_sprite(image); // owner #3
19   // use s1 and s2
20 } // once *all* owners are destroyed, the memory is deallocated
```

`std::shared_ptr`

Notes on `std::shared_ptr`

- using `std::shared_ptr` $\neq$ a garbage collector
- `std::shared_ptr` cannot handle cycles
- it is *only* used for independent sharing of ownership

std::shared_ptr

Cycles

```
1  struct Node {
2    // make_shared requires a constructor
3    Node(int v, shared_ptr<Node> n = nullptr)
4      : value { v }, next { n } { }
5
6    int value;
7    shared_ptr<Node> next { };
8  };
9
10 int main() {
11   auto root = make_shared<Node>(0);
12   auto next = make_shared<Node>(1);
13
14   next->next = root;
15   root->next = std::move(next);
16   // next is no longer an owner
17 }
```

std::shared_ptr

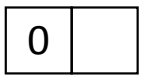
Cycles

```
1  struct Node {
2    // make_shared requires a constructor
3    Node(int v, shared_ptr<Node> n = nullptr)
4      : value { v }, next { n } { }
5
6    int value;
7    shared_ptr<Node> next { };
8  };
9
10 int main() {
11   auto root = make_shared<Node>(0);
12   auto next = make_shared<Node>(1);
13
14   next->next = root;
15   root->next = std::move(next);
16   // next is no longer an owner
17 }
```

std::shared_ptr

Cycles

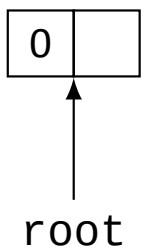
```
1  struct Node {
2    // make_shared requires a constructor
3    Node(int v, shared_ptr<Node> n = nullptr)
4      : value { v }, next { n } { }
5
6    int value;
7    shared_ptr<Node> next { };
8  };
9
10 int main() {
11   auto root = make_shared<Node>(0);
12   auto next = make_shared<Node>(1);
13
14   next->next = root;
15   root->next = std::move(next);
16   // next is no longer an owner
17 }
```



std::shared_ptr

Cycles

```
1  struct Node {
2    // make_shared requires a constructor
3    Node(int v, shared_ptr<Node> n = nullptr)
4      : value { v }, next { n } { }
5
6    int value;
7    shared_ptr<Node> next { };
8  };
9
10 int main() {
11   auto root = make_shared<Node>(0);
12   auto next = make_shared<Node>(1);
13
14   next->next = root;
15   root->next = std::move(next);
16   // next is no longer an owner
17 }
```



std::shared_ptr

Cycles

```
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3    Node(int v, shared_ptr<Node> n = nullptr)
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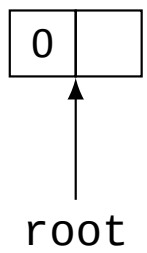
16   // next is no longer an owner
17 }
```



std::shared_ptr

Cycles

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1  struct Node {
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14   next->next = root;
15   root->next = std::move(next);
16   // next is no longer an owner
17 }
```
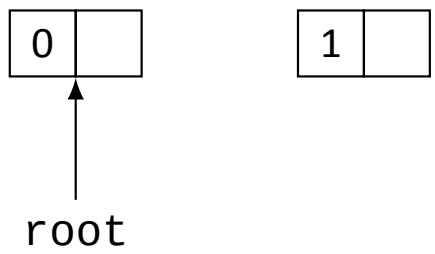
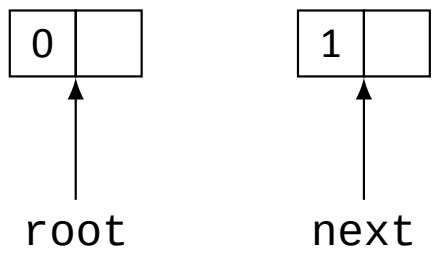



std::shared_ptr

Cycles

```
1  struct Node {
2    // make_shared requires a constructor
3    Node(int v, shared_ptr<Node> n = nullptr)
4      : value { v }, next { n } { }
5
6    int value;
7    shared_ptr<Node> next { };
8  };
9
10 int main() {
11   auto root = make_shared<Node>(0);
12   auto next = make_shared<Node>(1);
13
14   next->next = root;
15   root->next = std::move(next);
16   // next is no longer an owner
17 }
```



std::shared_ptr

Cycles

```
1  struct Node {
2    // make_shared requires a constructor
3    Node(int v, shared_ptr<Node> n = nullptr)
4      : value { v }, next { n } { }
5
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7    shared_ptr<Node> next { };
8  };
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10 int main() {
11   auto root = make_shared<Node>(0);
12   auto next = make_shared<Node>(1);
13
14   next->next = root;
15   root->next = std::move(next);
16   // next is no longer an owner
17 }
```
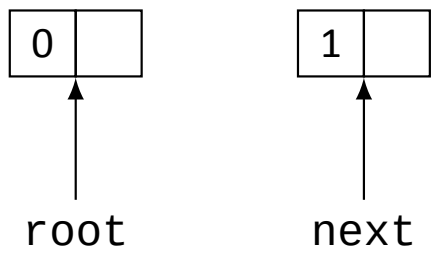
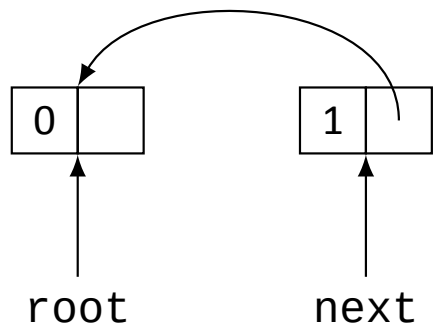



std::shared_ptr

Cycles

```
1  struct Node {
2    // make_shared requires a constructor
3    Node(int v, shared_ptr<Node> n = nullptr)
4      : value { v }, next { n } { }
5
6    int value;
7    shared_ptr<Node> next { };
8  };
9
10 int main() {
11   auto root = make_shared<Node>(0);
12   auto next = make_shared<Node>(1);
13
14   next->next = root;
15   root->next = std::move(next);
16   // next is no longer an owner
17 }
```



std::shared_ptr

Cycles

```
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3    Node(int v, shared_ptr<Node> n = nullptr)
4      : value { v }, next { n } { }
5
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14   next->next = root;
15   root->next = std::move(next);
16   // next is no longer an owner
17 }
```

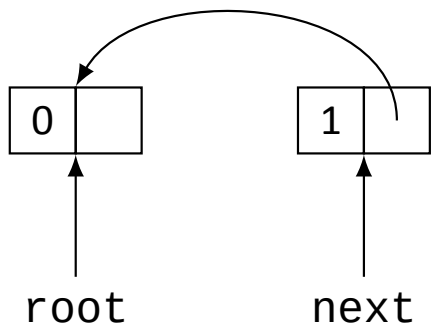

std::shared_ptr

Cycles

```
1  struct Node {
2    // make_shared requires a constructor
3    Node(int v, shared_ptr<Node> n = nullptr)
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5
6    int value;
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10 int main() {
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14   next->next = root;
15   root->next = std::move(next);
16   // next is no longer an owner
17 }
```

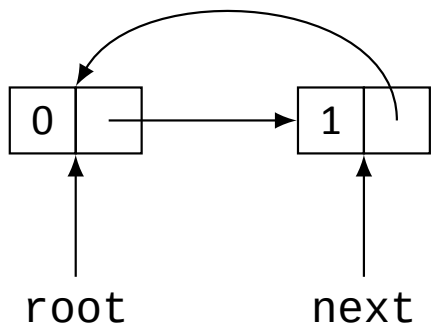

std::shared_ptr

Cycles

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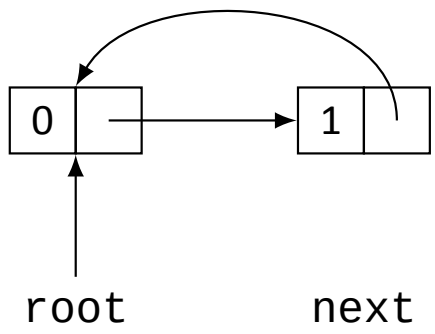
17 }
```



std::shared_ptr

Cycles

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17 }
```

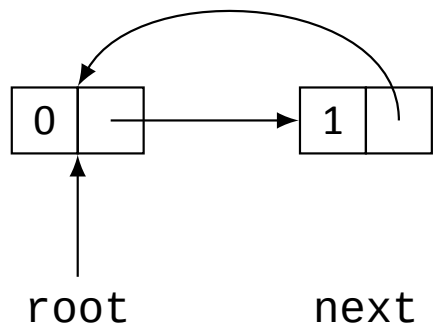

std::shared_ptr

Cycles

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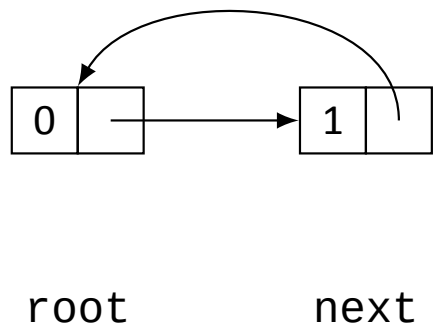

std::shared_ptr

Cycles

```
1  struct Node {
2    // make_shared requires a constructor
3    Node(int v, shared_ptr<Node> n = nullptr)
4      : value { v }, next { n } { }
5
6    int value;
7    shared_ptr<Node> next { };
8  };
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10 int main() {
11   auto root = make_shared<Node>(0);
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17 }
```

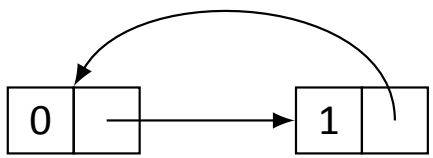

std::shared_ptr

Cycles

```
1  struct Node {
2    // make_shared requires a constructor
3    Node(int v, shared_ptr<Node> n = nullptr)
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5
6    int value;
7    shared_ptr<Node> next { };
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9
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11   auto root = make_shared<Node>(0);
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13
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```
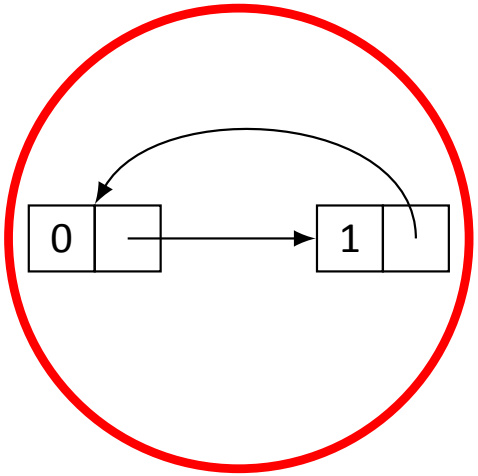
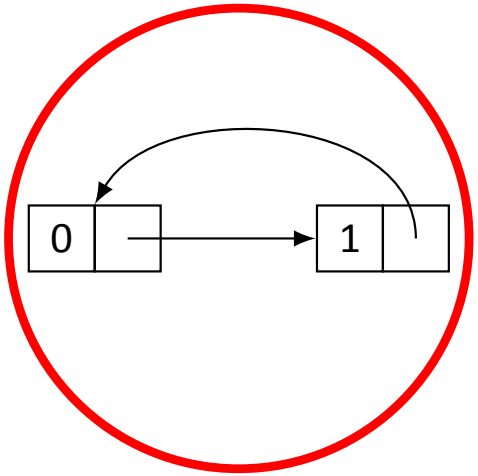



std::shared_ptr

Cycles

```
1  struct Node {
2    // make_shared requires a constructor
3    Node(int v, shared_ptr<Node> n = nullptr)
4      : value { v }, next { n } { }
5
6    int value;
7    shared_ptr<Node> next { };
8  };
9
10 int main() {
11   auto root = make_shared<Node>(0);
12   auto next = make_shared<Node>(1);
13
14   next->next = root;
15   root->next = std::move(next);
16   // next is no longer an owner
17 }
```



Keeping each other alive!

`std::shared_ptr`

Cycles

- `std::unique_ptr` is not magic
- It is implemented with a reference counter
- When that counter reaches zero, the memory is deallocated
- So when a `std::shared_ptr` points to an object that implicitly is a shared owner of the same memory, then the reference counter will never reach zero...
- So we get memory leaks.

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