MUTABLE KEYWORD

You can also make variables that are captured *by value* changeable:

`[` *capture-list* `]` `(` *parameters* `)` **`mutable`** `->` *result* `{` *body* `}`

- The mutable lets the body change the new variables that are copies
- (C++ makes the **`operator()`** method **`const`** otherwise.)
- This demonstrates its effect:

```
int startAt = 100;
std::function<int(void)> dbl =
  [startAt](void) mutable -> int {
     startAt *= 2; return startAt;
  };
std::cout << dbl() << " " << startAt << std::endl;
std::cout << dbl() << " " << startAt << std::endl;
std::cout << dbl() << " " << startAt << std::endl;
```

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std::cout << dbl() << " " << startAt << std::endl;
std::cout << dbl() << " " << startAt << std::endl;
```

This outputs:

```
200 100
400 100
800 100
```

MUTABLE KEYWORD

You can also make variables that are captured *by value* changeable:

[*capture-list*] (*parameters*) **mutable** -> *result* { *body* }

- The mutable lets the body change the new variables that are copies
- (C++ makes the **operator()** method **const** otherwise.)
- This demonstrates its effect:

```
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std::function<int(void)> dbl =
  [startAt](void) mutable -> int {
     startAt *= 2; return startAt;
  };
std::cout << dbl() << " " << startAt << std::endl;
std::cout << dbl() << " " << startAt << std::endl;
std::cout << dbl() << " " << startAt << std::endl;
```

This outputs:

```
200 100
400 100
800 100
```

- The captured copy of the variable makes the lambda (internally) *stateful*.

SMART POINTERS

LECTURE 11-3

JIM FIX, REED COLLEGE CS2-S20

SOME WAYS OF HAVING POINTER-BASED CODE BREAK

- You use **&** on a stack variable/object in a function and that pointer gets exported outside a function. You try to access the component referenced by that pointer outside that function.
- You forget to initialize a pointer component. You try to access that component.
- You try to access a component referenced by a null pointer.
- Two data structures share a pointer, one calls a delete on it. You try to access it through the other data structure. Or maybe you try to delete again it there.
- You don't call delete on a pointer to a component no longer used by a data structure.
  - ➡ A lot of these problems arise because of "by hand" memory management

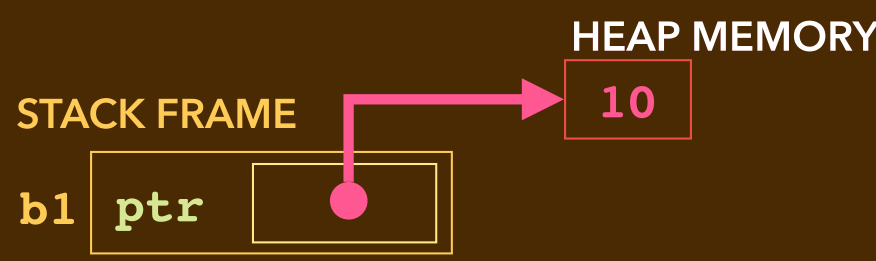
BUGS BUGS BUGS

- These kinds of bugs are so rampant in C++ code.
- Many of them go unnoticed
- Practictioners and researchers are heavily devoted to finding and preventing these bugs.
  - ➡Programming disciplines/idioms developed
  - ➡Programming libraries developed
  - ➡Programming languages developed
  - ➡Program analysis tools developed
  - ➡Runtime instruments developed
  - ➡Testing strategies developed.

A BUGGY BOX

```
class Box {
public:
  int* ptr;
  Box(int value) : {new int[value]} { }
  Box(const Box& b) : {b.ptr} { }
  Box& operator=(const Box& b) { ptr = b.ptr; return *this; }
 ~Box(void) { delete ptr; }
};

int main(void) {
  Box b1 { 10 };
  Box b2 { b1 };
  Box b3 { 11 };
  b3 = b2;
}
```



A BUGGY BOX

```
class Box {
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  int* ptr;
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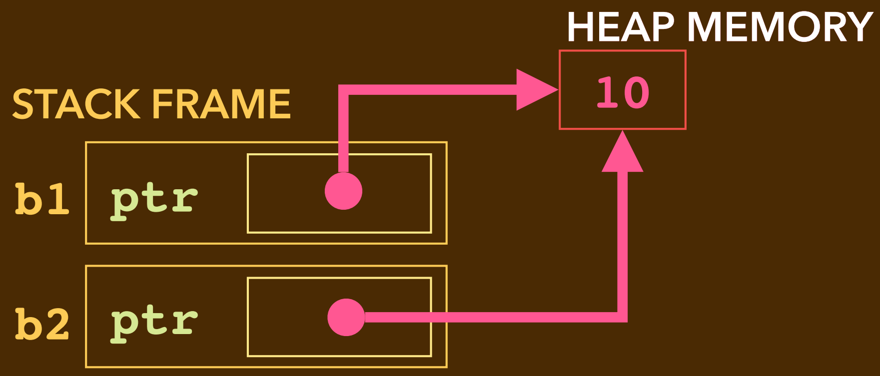
  Box(const Box& b) : {b.ptr} { }
  Box& operator=(const Box& b) { ptr = b.ptr; return *this; }
 ~Box(void) { delete ptr; }
};

int main(void) {
  Box b1 { 10 };
  Box b2 { b1 };
  Box b3 { 11 };
  b3 = b2;
}
```



A BUGGY BOX

```
class Box {
public:
  int* ptr;
  Box(int value) : {new int[value]} { }
  Box(const Box& b) : {b.ptr} { }
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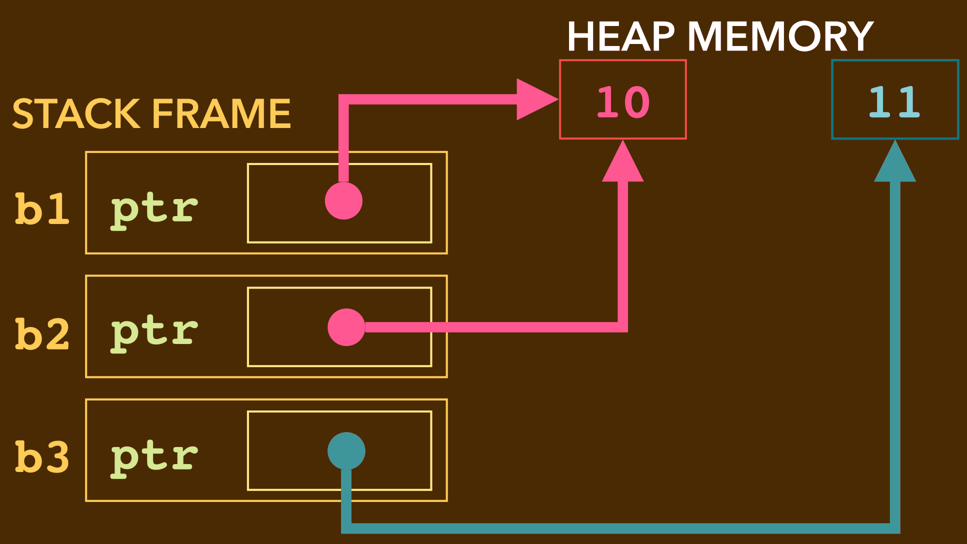
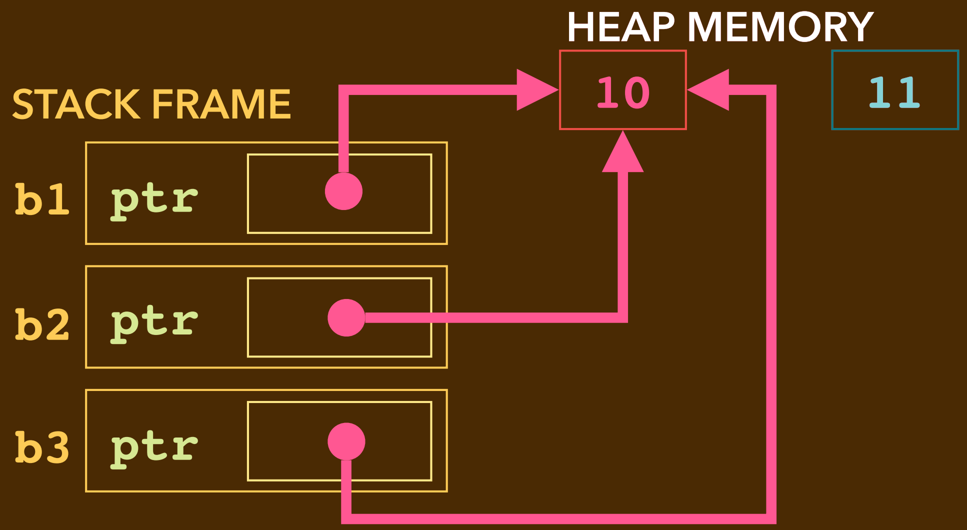


A BUGGY BOX

```
class Box {
public:
  int* ptr;
  Box(int value) : {new int[value]} { }
  Box(const Box& b) : {b.ptr} { }
  Box& operator=(const Box& b) { ptr = b.ptr; return *this; }
 ~Box(void) { delete ptr; }
};

int main(void) {
  Box b1 { 10 };
  Box b2 { b1 };
  Box b3 { 11 };
  b3 = b2;
}
```



Changed reference in b3.

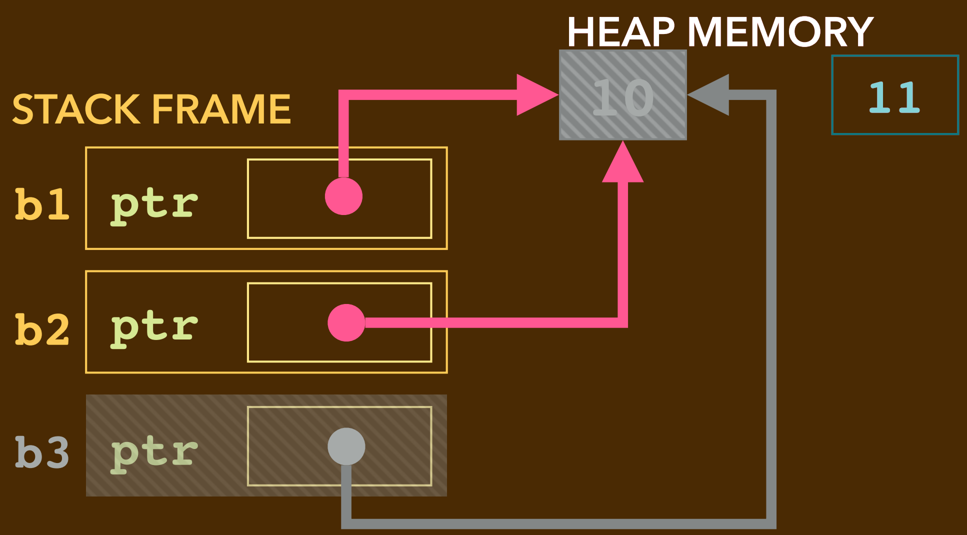
This is a "memory leak" error.

A BUGGY BOX

```
class Box {
public:
  int* ptr;
  Box(int value) : {new int[value]} { }
  Box(const Box& b) : {b.ptr} { }
  Box& operator=(const Box& b) { ptr = b.ptr; return *this; }
 ~Box(void) { delete ptr; }
};

int main(void) {
  Box b1 { 10 };
  Box b2 { b1 };
  Box b3 { 11 };
  b3 = b2;
}
```

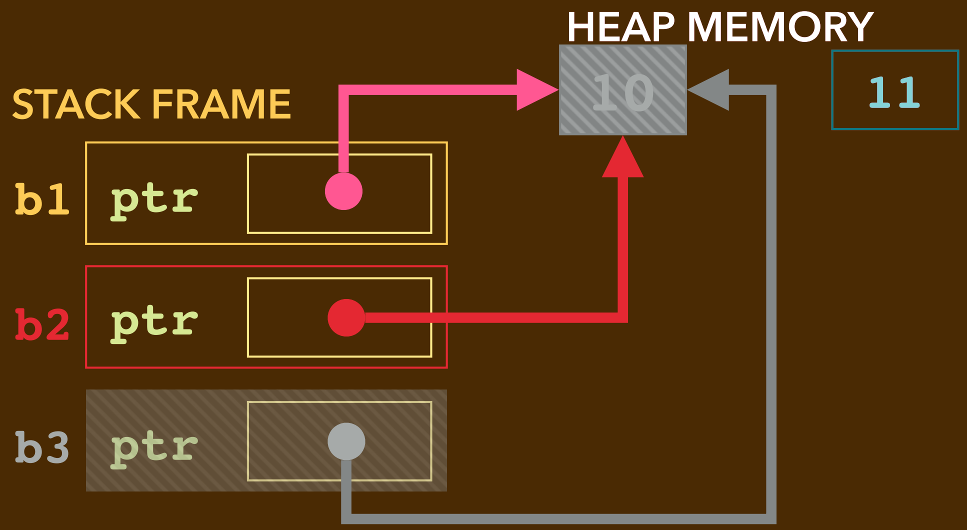
Destructor called on b3, b3.ptr deleted.



A BUGGY BOX

```
class Box {
public:
   int* ptr;
   Box(int value) : {new int[value]} { }
   Box(const Box& b) : {b.ptr} { }
   Box& operator=(const Box& b) { ptr = b.ptr; return *this; }
  ~Box(void) { delete ptr; }
};

int main(void) {
   Box b1 { 10 };
   Box b2 { b1 };
   Box b3 { 11 };
   b3 = b2;
}
```



Destructor called on b3, b3.ptr deleted.

Destructor called on b2, b2.ptr delete.

This is a "double delete" error.

RESOURCE MANAGEMENT VIEWPOINT

- An object's memory storage is a *resource*
  - It might be shared amongst several parts of the program
    - ➡ If so, treat it specially. Can't delete if shared.
  - It might not be shared. Maybe only one part of the program is *using* it.
    - ➡ When that part of the program is done with it, it should delete it.
- Some languages and language libraries work to make this explicit
    - ➡ They help your code manage *ownership*
- **E.g.** the **Rust** programming language
    - ➡ has a notion of *borrowing* an object; and transfer of single ownership
    - ➡ compiler has a *borrow checker*; based on *linear* types

AUTOMATIC GARBAGE COLLECTION

- Some problems can be prevented/solved with automatic garbage collection.
  - ➡ A runtime component checks whether any part of the code can access an object.
  - ➡ If not, it reclaims that object's storage.
- **Question:** How does it do that?
- **Answers:** There are several ways.
  - **E.g.** a "stop-the-world mark-and-sweep" garbage collector halts the program, briefly, then scans through the program's stack frames and marks what objects are reachable by links. Unreachable objects are reclaimed,
  - **E.g.** in a "reference count" scheme, every object has a count of how many things point to it. When that count goes to 0, its storage is reclaimed.

REFERENCE COUNT DIAGRAM

REFERENCE COUNT WITH CYCLES

SMART POINTERS IN THE C++ STL

- The C++ STL provides three template types (`#include <memory>`)
  - **`std::unique_ptr<T>`**: used to reference an object owned by one code component (i.e. one variable). It cannot be *copied*. It can be *moved*.
  - **`std::shared_ptr<T>`**: used to reference an object shared by several code components. It maintains a count of these. *Copying* a shared pointer increments this count. If a **`shared_ptr`** variable loses scope or if an object with a **`shared_ptr`** component is **`delete`**d, it is decremented.
  - **`std::weak_ptr<T>`**: only constructable from a **`shared_ptr`** without incrementing its count. Used many ways, including in cyclic structures.

SMART POINTERS IN THE C++ STL

- The C++ STL provides three template types (`#include <memory>`)
  - `std::unique_ptr<T>`: used to reference an object owned by one code component (i.e. one variable). It cannot be *copied*. It can be *moved*.
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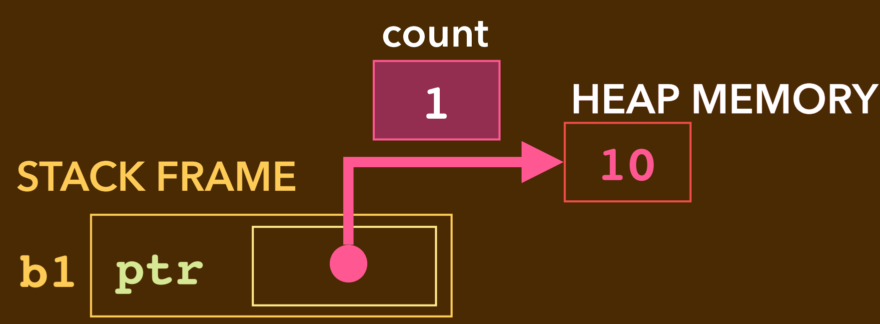
  - `std::weak_ptr<T>`: only constructable from a `shared_ptr` without incrementing its count. Used many ways, including in cyclic structures.

- We'll look at use of `shared_ptr` in a linked list implementation.

A SHARED_PTR BOX

```
#include <memory>
class Box {
public:
  std::shared_ptr<int> ptr;
  Box(int value) : {new int[value]} { }
  Box(const Box& b) : {b.ptr} { }
  Box& operator=(const Box& b) { ptr = b.ptr; return *this; }
 ~Box(void) { delete ptr; }
};

int main(void) {
  Box b1 { 10 };
  Box b2 { b1 };
  Box b3 { 11 };
  b3 = b2;
}
```



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  Box b2 { b1 };
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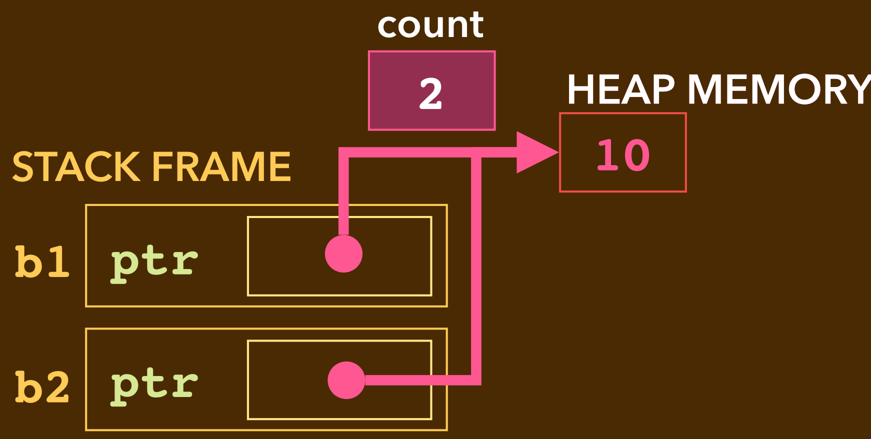
  b3 = b2;
}
```



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   Box b3 { 11 };
   b3 = b2;
}
```

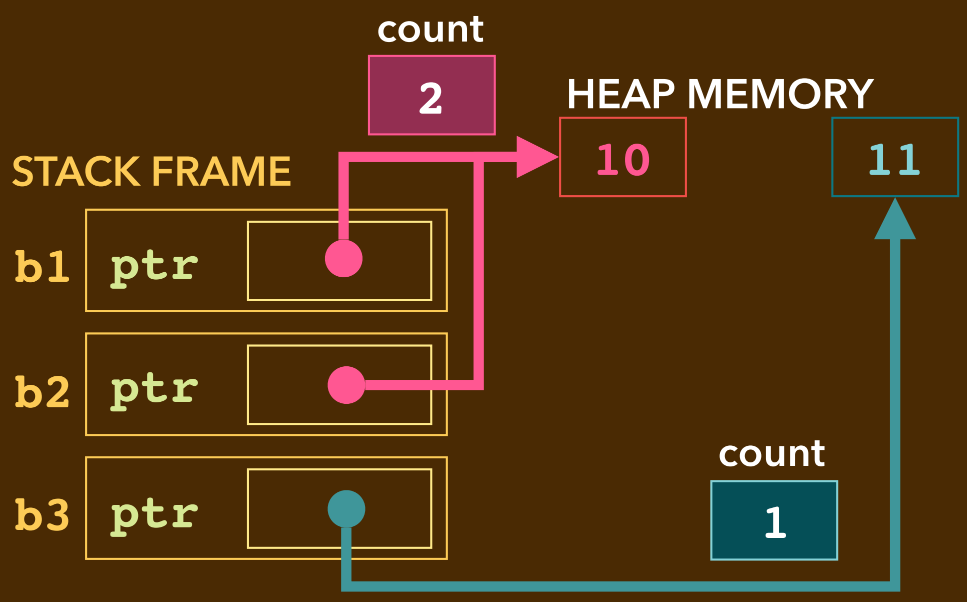

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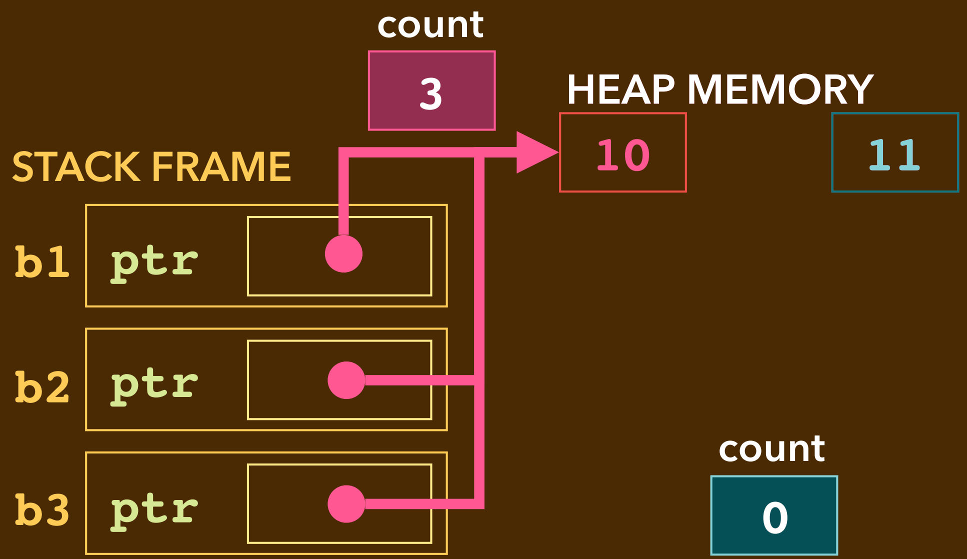

b1.ptr count increments to 3

old b3.ptr decrements to 0

A SHARED_PTR BOX

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class Box {
public:
   std::shared_ptr<int> ptr;
   Box(int value) : {new int[value]} { }
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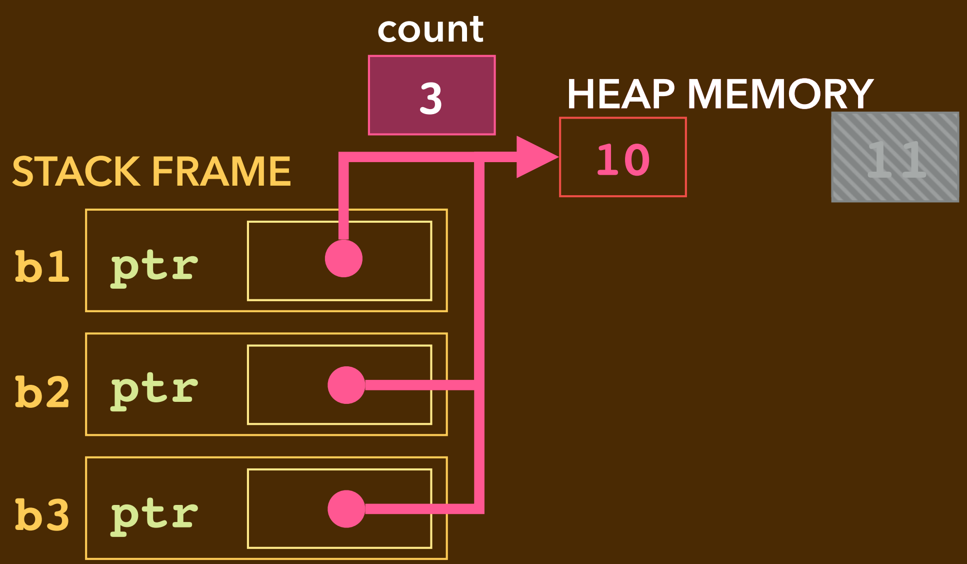

old b3.ptr 's raw pointer is deleted

A SHARED_PTR BOX

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class Box {
public:
   std::shared_ptr<int> ptr;
   Box(int value) : {new int[value]} { }
   Box(const Box& b) : {b.ptr} { }
   Box& operator=(const Box& b) { ptr = b.ptr; return *this; }
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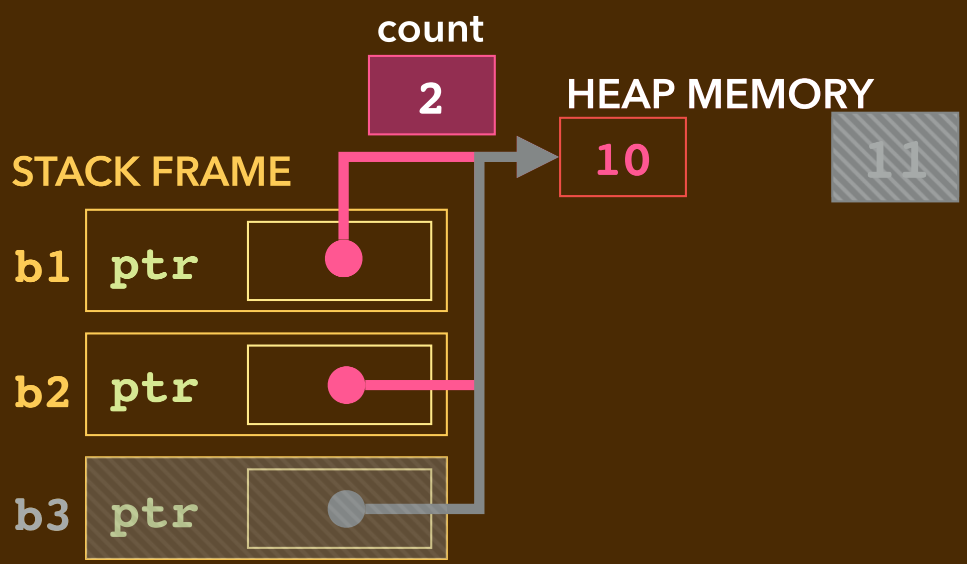
};

int main(void) {
   Box b1 { 10 };
   Box b2 { b1 };
   Box b3 { 11 };
   b3 = b2;
}
```

Destructor called on b3; decrement.



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};

int main(void) {
  Box b1 { 10 };
  Box b2 { b1 };
  Box b3 { 11 };
  b3 = b2;
}
```
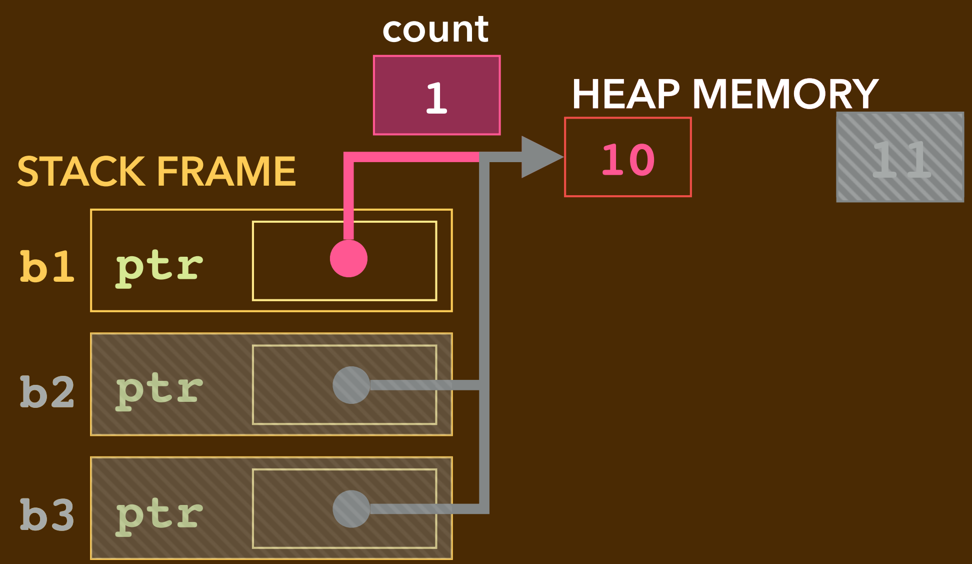

Destructor called on b3; decrement.

Destructor called on b2; decrement.



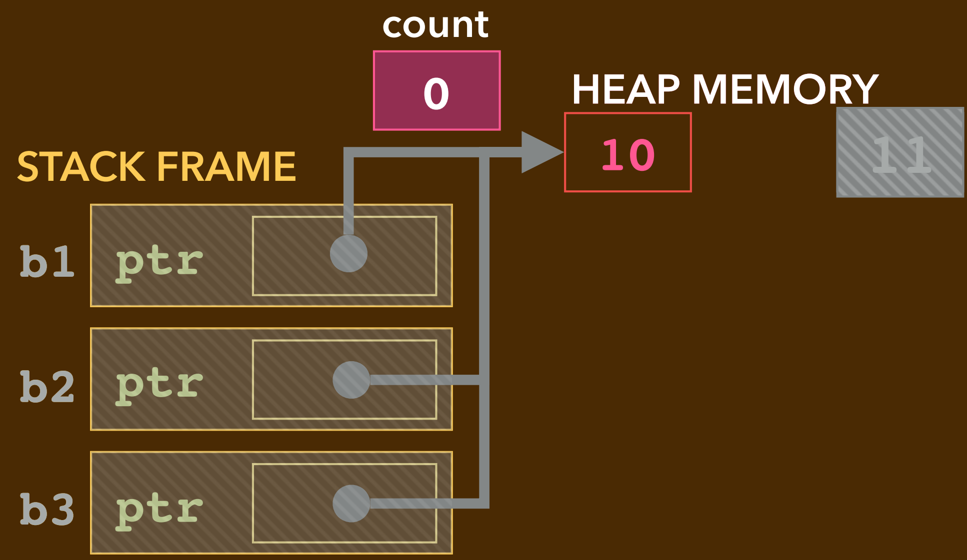
A SHARED_PTR BOX

```
#include <memory>
class Box {
public:
  std::shared_ptr<int> ptr;
  Box(int value) : {new int[value]} { }
  Box(const Box& b) : {b.ptr} { }
  Box& operator=(const Box& b) { ptr = b.ptr; return *this; }
 ~Box(void) { delete ptr; }
};

int main(void) {
  Box b1 { 10 };
  Box b2 { b1 };
  Box b3 { 11 };
  b3 = b2;
}
```

Destructor called on b3; decrement.

Destructor called on b2; decrement.

Destructor called on b1; decrement.



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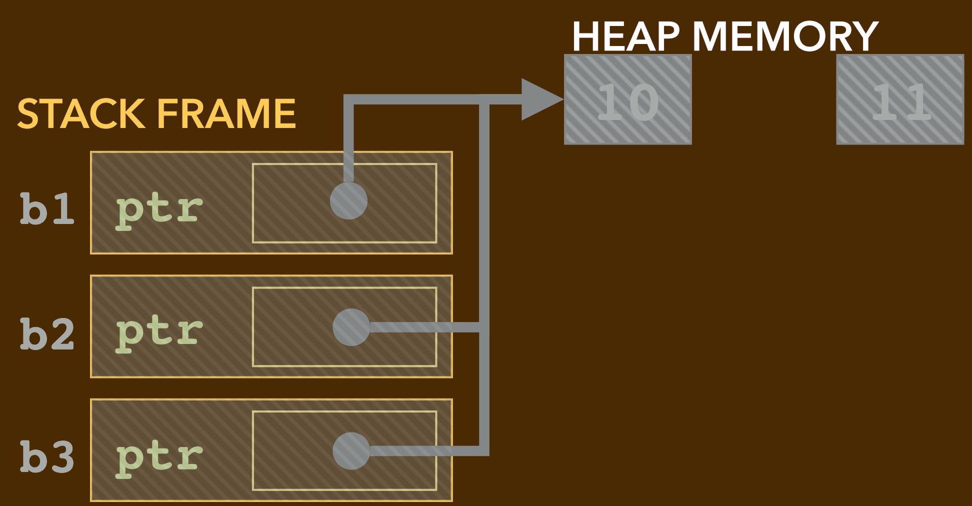
int main(void) {
  Box b1 { 10 };
  Box b2 { b1 };
  Box b3 { 11 };
  b3 = b2;
}
```



Destructor called on b3; decrement.

Destructor called on b2; decrement.

Destructor called on b1; decrement. The raw pointer of b1.ptr is deleted.

A SINGLY LINKED LIST WITH RAW POINTERS

```
#include <memory>

class node {
public:
  int data;
  node* next;
  node(int value) : data {value}, next {nullptr} { }
 ~node(void) { }
};

class llist {
private:
  node* first;
  node* last;
public:
  llist(void) : first {nullptr}, last {nullptr} { }
 ~llist(void) { ... // traversal with delete of each    }
  void prepend(int value) { ... // new node as first    }
  void append(int value)  { ... // new node as last     }
  void remove(int value)  { ... // extract; delete node }
};
```

A SINGLY LINKED LIST WITH RAW POINTERS

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#include <memory>

class node {
public:
  int data;
  node* next;
  node(int value) : data {value}, next {nullptr} { }
 ~node(void) { }
};

class llist {
private:
  node* first;
  node* last;
public:
  llist(void) : first {nullptr}, last {nullptr} { }
 ~llist(void) { ... // traversal with delete of each    }
  void prepend(int value) { ... // new node as first    }
  void append(int value)  { ... // new node as last     }
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};
```

A SINGLY LINKED LIST WITH RAW POINTERS

```
#include <memory>

class node {
public:
  int data;
  node* next;
  node(int value) : data {value}, next {nullptr} { }
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};

class llist {
private:
  node* first;
  node* last;
public:
  llist(void) : first {nullptr}, last {nullptr} { }
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  void prepend(int value) { ... // new node as first    }
  void append(int value)  { ... // new node as last     }
  void remove(int value)  { ... // extract; delete node }
};
```

A SHARED_PTR SINGLY LINKED LIST

```
#include <memory>

class node {
public:
  int data;
  std::shared_ptr<node> next;
  node(int value) : data {value}, next {nullptr} { }
 ~node(void) { }
};

class llist {
private:
  std::shared_ptr<node> first;
  std::shared_ptr<node> last;
public:
  llist(void) : first {nullptr}, last {nullptr} { }
 ~llist(void) { // NOTHING HERE!! }
  void prepend(int value);
  void append(int value);
  void remove(int value);
};
```

A SHARED_PTR SINGLY LINKED LIST

```
#include <memory>

class node {
public:
  int data;
  std::shared_ptr<node> next;
  node(int value) : data {value}, next {nullptr} { }
 ~node(void) { }
};

class llist {
private:
  std::shared_ptr<node> first;
  std::shared_ptr<node> last;
public:
  llist(void) : first {nullptr}, last {nullptr} { }
 ~llist(void) { // NOTHING HERE!! }
  void prepend(int value);
  void append(int value);
  void remove(int value);
};
```

LINKED LIST SHARED_PTR USE

```
void llist::prepend(int value) {
  std::shared_ptr<node> newNode {new node {value}};
  newNode->next = first;
  first = newNode;
  if (last == nullptr) {
    last = first;
  }
}

void llist::append(int value) {
  std::shared_ptr<node> newNode {new node {value}};
  if (first == nullptr) {
    first = newNode;
  } else {
    last->next = newNode;
  }
  last = newNode;
}
```

LINKED LIST SHARED_PTR NODE ALLOCATION

```
void llist::prepend(int value) {
  std::shared_ptr<node> newNode {new node {value}};
  newNode->next = first;
  first = newNode;
  if (last == nullptr) {
    last = first;
  }
}

void llist::append(int value) {
  std::shared_ptr<node> newNode {new node {value}};
  if (first == nullptr) {
    first = newNode;
  } else {
    last->next = newNode;
  }
  last = newNode;
}
```

These each initialize their `shared_ptr` *count to 1.*

LINKED LIST SHARED_PTR SHARING

```
void llist::prepend(int value) {
  std::shared_ptr<node> newNode {new node {value}};
  newNode->next = first;
  first = newNode;
  if (last == nullptr) {
    last = first;
  }
}

void llist::append(int value) {
  std::shared_ptr<node> newNode {new node {value}};
  if (first == nullptr) {
    first = newNode;
  } else {
    last->next = newNode;
  }
  last = newNode;
}
```

These each initialize their `shared_ptr` *count to 1.*

These ***copy assignments*** *each increment their* `shared_ptr` *count.*

LINKED LIST SHARED_PTR REMOVE METHOD

```
void llist::remove(int value) {
  std::shared_ptr<node> follow {nullptr};
  std::shared_ptr<node> current {first};
  while (current != nullptr && current->data != value) {
    follow = current;
    current = current->next;
  }
  if (current != nullptr) {
    if (follow == nullptr) {
      first = current->next;
      if (current->next == nullptr) {
        last = first;
      }
    } else {
      follow->next = current->next;
      if (current->next == nullptr) {
        last = follow;
      }
    }
  }
}
```

LINKED LIST SHARED_PTR REMOVE METHOD

```
void llist::remove(int value) {
  std::shared_ptr<node> follow {nullptr};
  std::shared_ptr<node> current {first};
  while (current != nullptr && current->data != value) {
    follow = current;
    current = current->next;
  }
  if (current != nullptr) {
    if (follow == nullptr) {
      first = current->next;
      if (current->next == nullptr) {
        last = first;
      }
    } else {
      follow->next = current->next;
      if (current->next == nullptr) {
        last = follow;
      }
    }
  }
}
```

Unlinking `current` decreases its shared_ptr's reference count.

LINKED LIST SHARED_PTR REMOVE METHOD

```
void llist::remove(int value) {
  std::shared_ptr<node> follow {nullptr};
  std::shared_ptr<node> current {first};
  while (current != nullptr && current->data != value) {
    follow = current;
    current = current->next;
  }
  if (current != nullptr) {
    if (follow == nullptr) {
      first = current->next;
      if (current->next == nullptr) {
        last = first;
      }
    } else {
      follow->next = current->next;
      if (current->next == nullptr) {
        last = follow;
      }
    }
  }
}
```

Unlinking **`current`** decreases its shared_ptr's reference count.

E.g. *This copy assignment takes* **`current`***'s shared_ptr out of* **`follow->next`**.

LINKED LIST SHARED_PTR REMOVE METHOD

```
void llist::remove(int value) {
  std::shared_ptr<node> follow {nullptr};
  std::shared_ptr<node> current {first};
  while (current != nullptr && current->data != value) {
    follow = current;
    current = current->next;
  }
  if (current != nullptr) {
    if (follow == nullptr) {
      first = current->next;
      if (current->next == nullptr) {
        last = first;
      }
    } else {
      follow->next = current->next;
      if (current->next == nullptr) {
        last = follow;
      }
    }
  }
}
```

Here `current` goes out of scope; count goes to 0; node is reclaimed

A SHARED_PTR SINGLY LINKED LIST SUMMARY

- By using shared_ptr, every reference to a node is counted.
- When a new node is made, a shared_ptr is invented with a count of 1.
  - It has an underlying raw pointer obtained from **`new`**.
- When a relink happens:
  - ➡ A non-null reference's count decrements.
  - ➡ Another reference's count increments.
- When a reference count goes to 0:
  - ➡ The underlying raw pointer is **`delete`**d.
  - ➡ If non-null, its **`next`** reference's count is decremented.
- The *code never explictly calls* **`delete`**.

CHECK OUT MY SAMPLE CODE

- I have four versions of linked lists that use **`shared_ptr`** in samples:
  - **llist.cc:** what I just showed you with test code
  - **dbllist_*.cc**: three doubly-linked lists, each with test code
    - **_bad.cc**: because of circular paths in the data structure, *memory leak*
    - **_better.cc**: detaches **`prev`** links in **`~dbllist()`** to break cycles
    - **_best.cc**: uses **`weak_ptr`** for **`prev`** to break **`shared_ptr`** cycles
- In the last, **`weak_ptr`** back references aren't counted... one typical use.

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  - We'll look at the Berkeley **`socket`** library.
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  - It's written so that it can run on *multiple processor cores*.
  - We'll look at the POSIX **`pthread`** library.
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- ***We'll have a last homework assignment.***
- ***We'll have a comprehensive final exam.***