6.096 Lecture 8: Memory Management

Clean up after your pet program

Geza Kovacs

Review: Constructors

- Method that is called when an instance is created

```
class Integer {
public:
  int val;
  Integer() {
    val = 0; cout << "default constructor" << endl;
  }
};

int main() {
  Integer i;
}
```

Output:
default constructor

- When making an array of objects, default constructor is invoked on each

```
class Integer {
public:
  int val;
  Integer() {
    val = 0; cout << "default constructor" << endl;
  }
};

int main() {
  Integer arr[3];
}
```

Output:
default constructor
default constructor
default constructor

- When making a class instance, the default constructor of its fields are invoked

```
class Integer {
public:
  int val;
  Integer() {
    val = 0; cout << "Integer default constructor" << endl;
  }
};
class IntegerWrapper {
public:
  Integer val;
  IntegerWrapper() {
    cout << "IntegerWrapper default constructor" << endl;
  }
};

int main() {
  IntegerWrapper q;
}
```

Output:
Integer default constructor
IntegerWrapper default constructor

- Constructors can accept parameters

```
class Integer {
public:
  int val;
  Integer(int v) {
    val = v; cout << "constructor with arg " << v << endl;
  }
};

int main() {
  Integer i(3);
}
```

Output:
constructor with arg 3

- Constructors can accept parameters
  - Can invoke single-parameter constructor via assignment to the appropriate type

```
class Integer {
public:
  int val;
  Integer(int v) {
    val = v; cout << "constructor with arg " << v << endl;
  }
};

int main() {
  Integer i(3);
  Integer j = 5;
}
```

Output:
constructor with arg 3
constructor with arg 5

- If a constructor with parameters is defined, the default constructor is no longer available

```cpp
class Integer {
public:
  int val;
  Integer(int v) {
    val = v;
  }
};

int main() {
  Integer i(3); // ok
  Integer j;
}
```

Error: No default constructor available for Integer

- If a constructor with parameters is defined, the default constructor is no longer available
  - Without a default constructor, can't declare arrays without initializing

```
class Integer {
public:
  int val;
  Integer(int v) {
    val = v;
  }
};

int main() {
  Integer a[] = { Integer(2), Integer(5) }; // ok
  Integer b[2];
}
```

Error: No default constructor available for Integer

- If a constructor with parameters is defined, the default constructor is no longer available
  - Can create a separate 0-argument constructor

```
class Integer {
public:
  int val;
  Integer() {
    val = 0;
  }
  Integer(int v) {
    val = v;
  }
};

int main() {
  Integer i; // ok
  Integer j(3); // ok
}
```

- If a constructor with parameters is defined, the default constructor is no longer available
  - Can create a separate 0-argument constructor
  - Or, use default arguments

```
class Integer {
public:
  int val;
  Integer(int v = 0) {
    val = v;
  }
};

int main() {
  Integer i; // ok
  Integer j(3); // ok
}
```

- How do I refer to a field when a method argument has the same name?
- **this**: a pointer to the current instance

```
class Integer {
public:
  int val;
  Integer(int val = 0) {
    this->val = val;
  }
};
```

this->val is a shorthand for (*this).val

- How do I refer to a field when a method argument has the same name?
- **this**: a pointer to the current instance

```
class Integer {
public:
  int val;
  Integer(int val = 0) {
    this->val = val;
  }
  void setVal(int val) {
    this->val = val;
  }
};
```

Scoping and Memory

- Whenever we declare a new variable (int x), memory is allocated
- When can this memory be freed up (so it can be used to store other variables)?
  - When the variable goes out of scope

Scoping and Memory

- When a variable goes out of scope, that memory is no longer guaranteed to store the variable's value

```
int main() {
  if (true) {
    int x = 5;
  }
  // x now out of scope, memory it used to occupy can be reused
}
```

Scoping and Memory

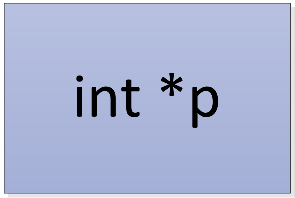
- When a variable goes out of scope, that memory is no longer guaranteed to store the variable's value

```
int main() {
  int *p;
  if (true) {
    int x = 5;
    p = &x;
  }
  cout << *p << endl; // ???
}
```

Scoping and Memory

- When a variable goes out of scope, that memory is no longer guaranteed to store the variable's value

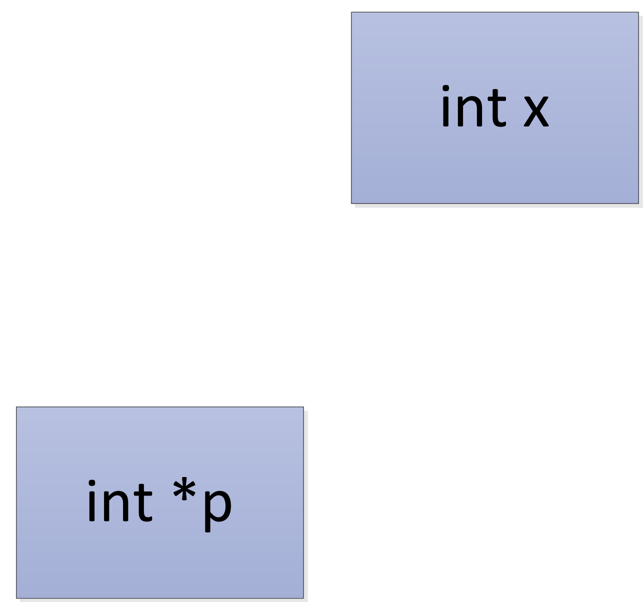
```
int main() {
  int *p;
  if (true) {
    int x = 5;
    p = &x;
  }
  cout << *p << endl; // ???
}
```



Scoping and Memory

- When a variable goes out of scope, that memory is no longer guaranteed to store the variable's value

```
int main() {
  int *p;
  if (true) {
    int x = 5;
    p = &x;
  }
  cout << *p << endl; // ???
}
```

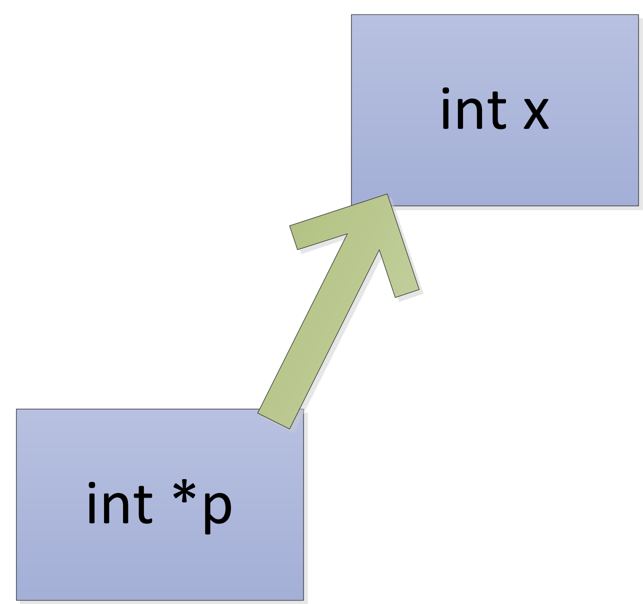


Scoping and Memory

- When a variable goes out of scope, that memory is no longer guaranteed to store the variable's value

```
int main() {
  int *p;
  if (true) {
    int x = 5;
    p = &x;
  }
  cout << *p << endl; // ???
}
```

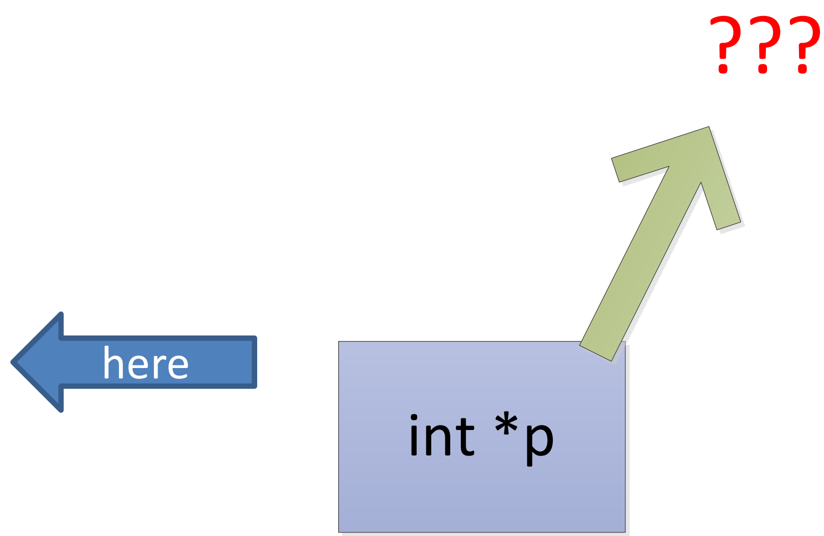
here



Scoping and Memory

- When a variable goes out of scope, that memory is no longer guaranteed to store the variable's value
  - Here, p has become a **dangling pointer** (points to memory whose contents are undefined)

```
int main() {
  int *p;
  if (true) {
    int x = 5;
    p = &x;
  }
  cout << *p << endl; // ???
}
```



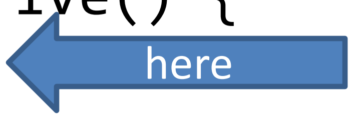
A Problematic Task

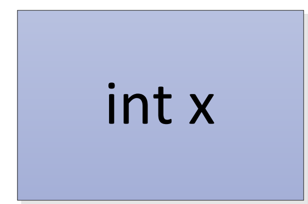
- Implement a function which returns a pointer to some memory containing the integer 5
- Incorrect implementation:

```
int* getPtrToFive() {
  int x = 5;
  return &v;
}
```

- Implement a function which returns a pointer to some memory containing the integer 5
- Incorrect implementation:
  - x is declared in the function scope

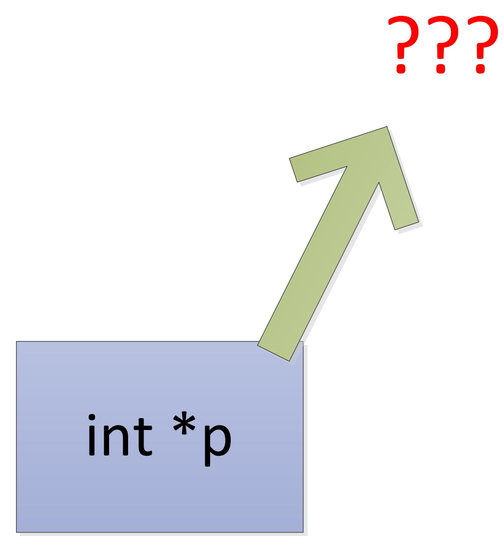
```
int* getPtrToFive() {
  int x = 5;
  return &x;
}

int main() {
  int *p = getPtrToFive();
  cout << *p << endl; // ???
}
```





- Implement a function which returns a pointer to some memory containing the integer 5
- Incorrect implementation:
  - x is declared in the function scope
  - As getPtrToFive() returns, x goes out of scope. So a dangling pointer is returned

```
int* getPtrToFive() {
  int x = 5;
  return &x;
}

int main() {
  int *p = getPtrToFive();
  cout << *p << endl; // ???
}
```



The **new** operator

- Another way to allocate memory, where the memory will remain allocated until you manually de-allocate it
- Returns a pointer to the newly allocated memory

```
int *x = new int;
```

The **new** operator

- Another way to allocate memory, where the memory will remain allocated until you manually de-allocate it
- Returns a pointer to the newly allocated memory

```
int *x = new int;
```

Type parameter needed to determine how much memory to allocate

The **new** operator

- Another way to allocate memory, where the memory will remain allocated until you manually de-allocate it
- Returns a pointer to the newly allocated memory
- Terminology note:
  - If using **int x;** the allocation occurs on a region of memory called **the stack**
  - If using **new int;** the allocation occurs on a region of memory called **the heap**

The **delete** operator

- De-allocates memory that was previously allocated using **new**
- Takes a pointer to the memory location

```
int *x = new int;
// use memory allocated by new
delete x;
```

- Implement a function which returns a pointer to some memory containing the integer 5
  - Allocate memory using **new** to ensure it remains allocated

```
int *getPtrToFive() {
  int *x = new int;
  *x = 5;
  return x;
}
```

- Implement a function which returns a pointer to some memory containing the integer 5
  - Allocate memory using **new** to ensure it remains allocated.
  - When done, de-allocate the memory using **delete**

```
int *getPtrToFive() {
  int *x = new int;
  *x = 5;
  return x;
}

int main() {
  int *p = getPtrToFive();
  cout << *p << endl; // 5
  delete p;
}
```

Delete Memory When Done Using It

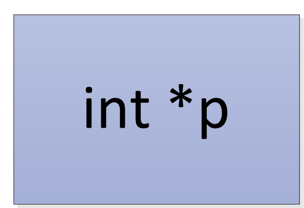
- If you don't use de-allocate memory using **delete**, your application will waste memory

```
int *getPtrToFive() {
  int *x = new int;
  *x = 5;
  return x;
}

int main() {
  int *p;
  for (int i = 0; i < 3; ++i) {
    p = getPtrToFive();
    cout << *p << endl;
  }
}
```

incorrect

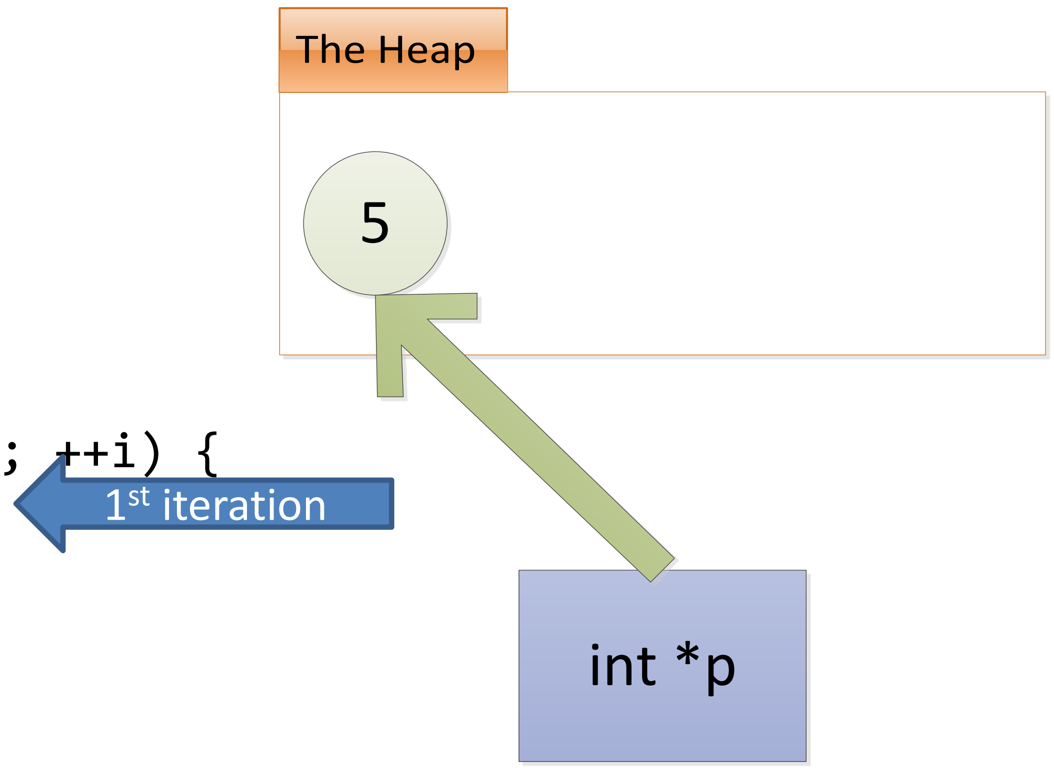
- If you don’t use de-allocate memory using **delete**, your application will waste memory

```
int *getPtrToFive() {
  int *x = new int;
  *x = 5;
  return x;
}

int main() {
  int *p;
  for (int i = 0; i < 3; ++i) {
    p = getPtrToFive();
    cout << *p << endl;
  }
}
```



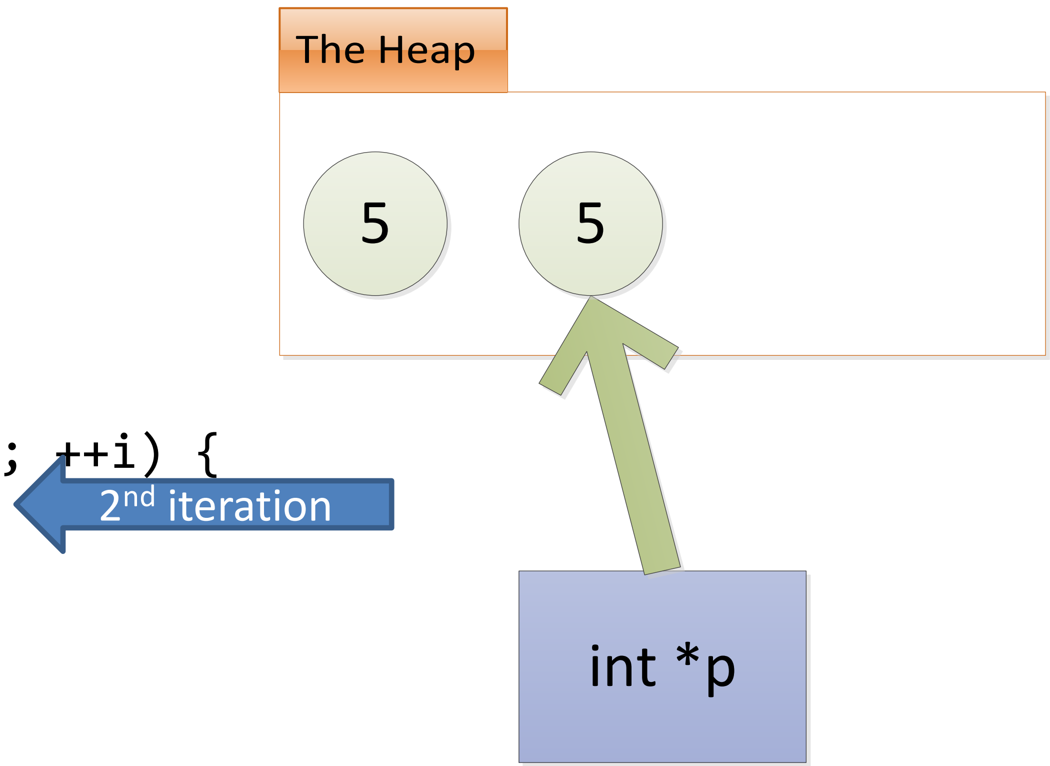
- If you don't use de-allocate memory using **delete**, your application will waste memory

```
int *getPtrToFive() {
  int *x = new int;
  *x = 5;
  return x;
}

int main() {
  int *p;
  for (int i = 0; i < 3; ++i) {
    p = getPtrToFive();
    cout << *p << endl;
  }
}
```



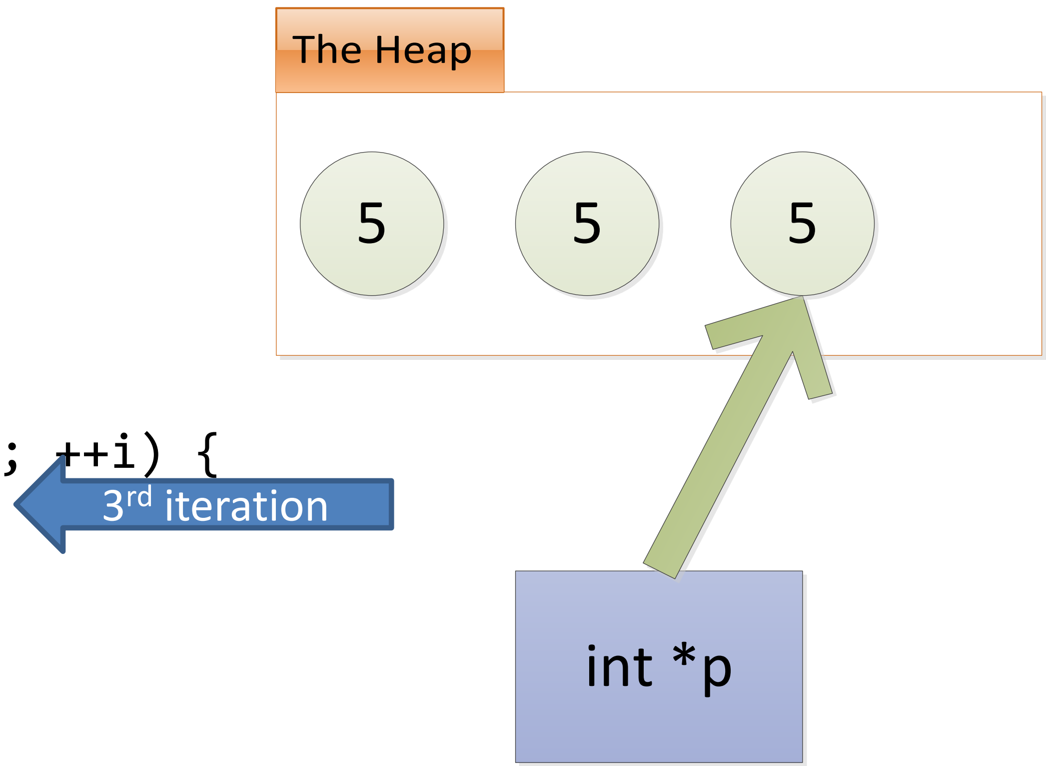
- If you don’t use de-allocate memory using **delete**, your application will waste memory

```
int *getPtrToFive() {
  int *x = new int;
  *x = 5;
  return x;
}

int main() {
  int *p;
  for (int i = 0; i < 3; ++i) {
    p = getPtrToFive();
    cout << *p << endl;
  }
}
```



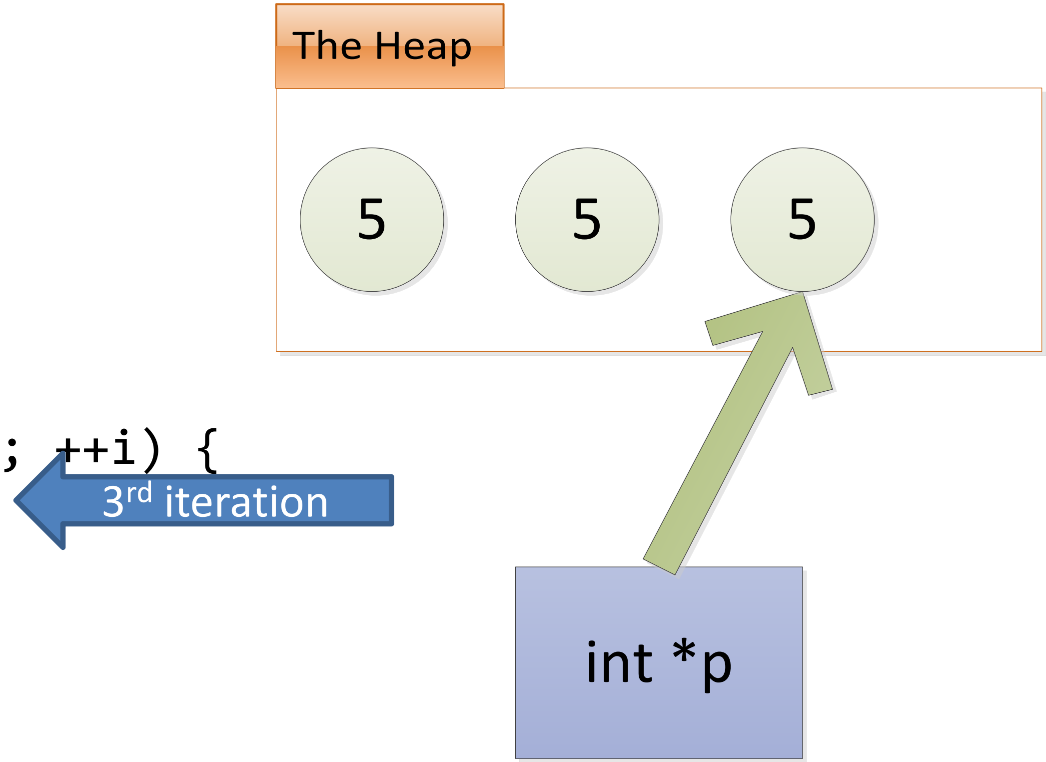
- If you don’t use de-allocate memory using **delete**, your application will waste memory
- When your program allocates memory but is unable to de-allocate it, this is a **memory leak**

```
int *getPtrToFive() {
  int *x = new int;
  *x = 5;
  return x;
}

int main() {
  int *p;
  for (int i = 0; i < 3; ++i) {
    p = getPtrToFive();
    cout << *p << endl;
  }
}
```



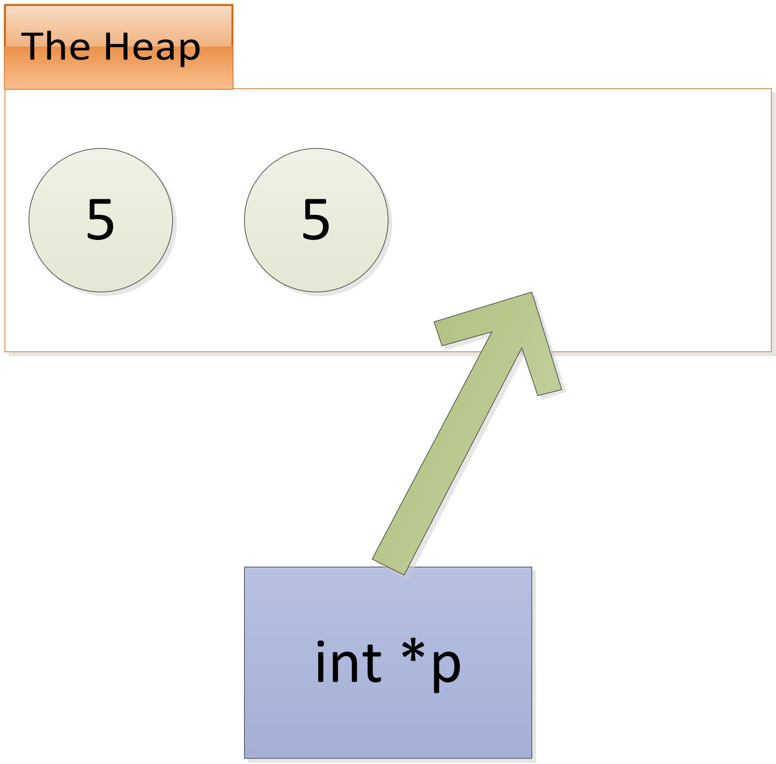
- Does adding a delete after the loop fix this memory leak?

```
int *getPtrToFive() {
  int *x = new int;
  *x = 5;
  return x;
}

int main() {
  int *p;
  for (int i = 0; i < 3; ++i) {
    p = getPtrToFive();
    cout << *p << endl;
  }
  delete p;
}
```



- Does adding a delete after the loop fix this memory leak?
  - No; only the memory that was allocated on the last iteration gets de-allocated

```
int *getPtrToFive() {
  int *x = new int;
  *x = 5;
  return x;
}

int main() {
  int *p;
  for (int i = 0; i < 3; ++i) {
    p = getPtrToFive();
    cout << *p << endl;
  }
  delete p;
}
```

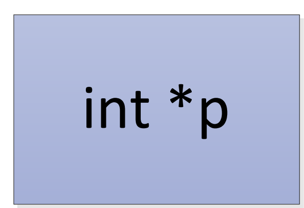


- To fix the memory leak, de-allocate memory within the loop

```
int *getPtrToFive() {
  int *x = new int;
  *x = 5;
  return x;
}

int main() {
  int *p;
  for (int i = 0; i < 3; ++i) {
    p = getPtrToFive();
    cout << *p << endl;
    delete p;
  }
}
```

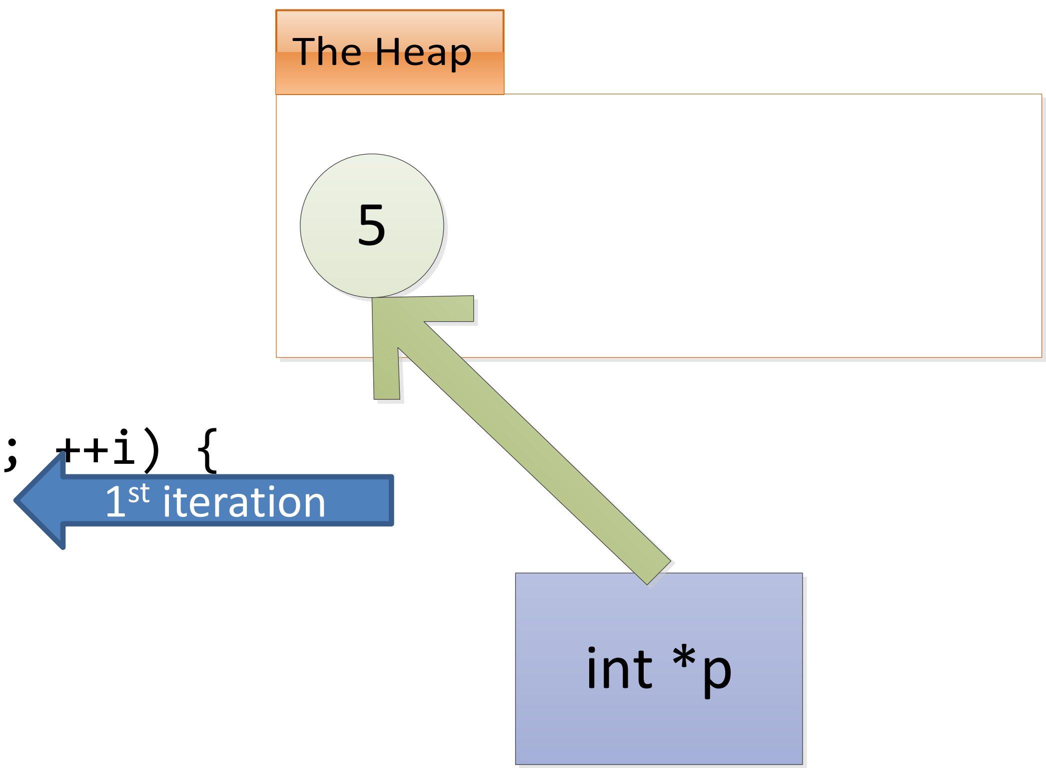
- To fix the memory leak, de-allocate memory within the loop

```
int *getPtrToFive() {
  int *x = new int;
  *x = 5;
  return x;
}

int main() {
  int *p;
  for (int i = 0; i < 3; ++i) {
    p = getPtrToFive();
    cout << *p << endl;
    delete p;
  }
}
```



- To fix the memory leak, de-allocate memory within the loop

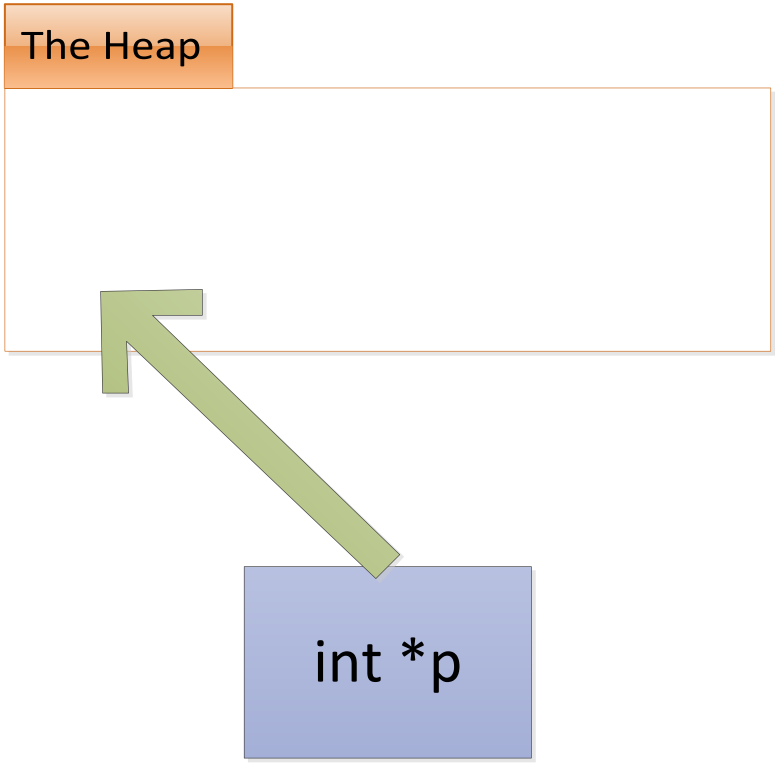
```
int *getPtrToFive() {
  int *x = new int;
  *x = 5;
  return x;
}

int main() {
  int *p;
  for (int i = 0; i < 3; ++i) {
    p = getPtrToFive();
    cout << *p << endl;
    delete p;
  }
}
```



- To fix the memory leak, de-allocate memory within the loop

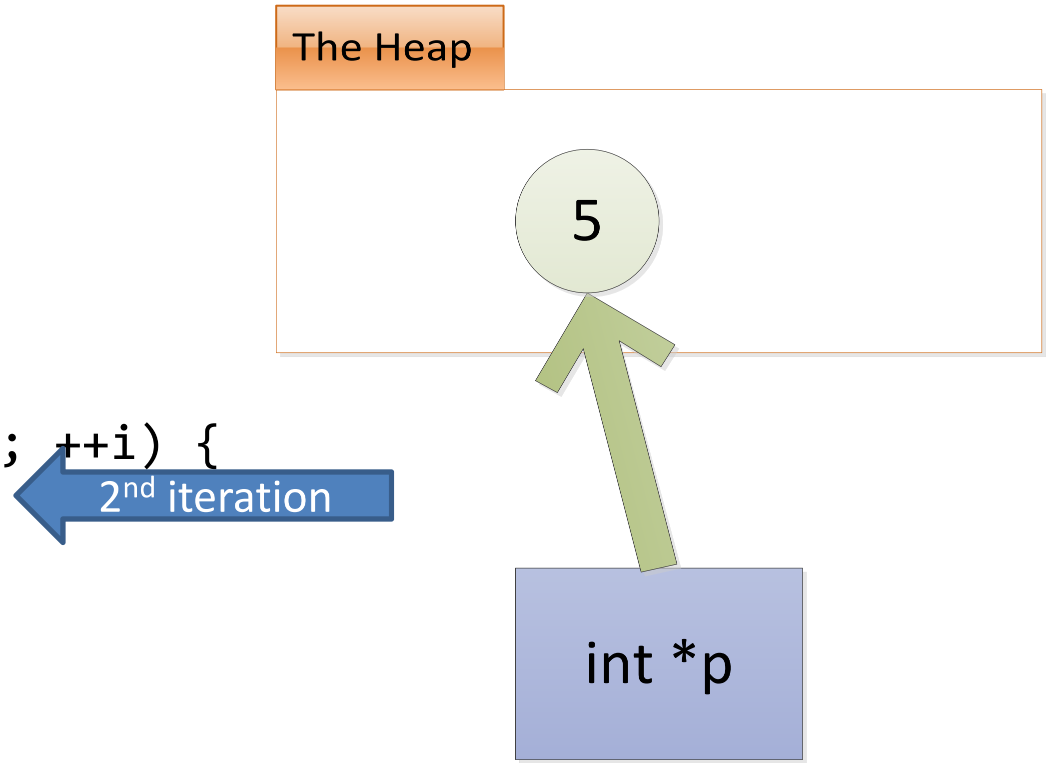
```
int *getPtrToFive() {
  int *x = new int;
  *x = 5;
  return x;
}

int main() {
  int *p;
  for (int i = 0; i < 3; ++i) {
    p = getPtrToFive();
    cout << *p << endl;
    delete p;
  }
}
```

1st iteration



- To fix the memory leak, de-allocate memory within the loop

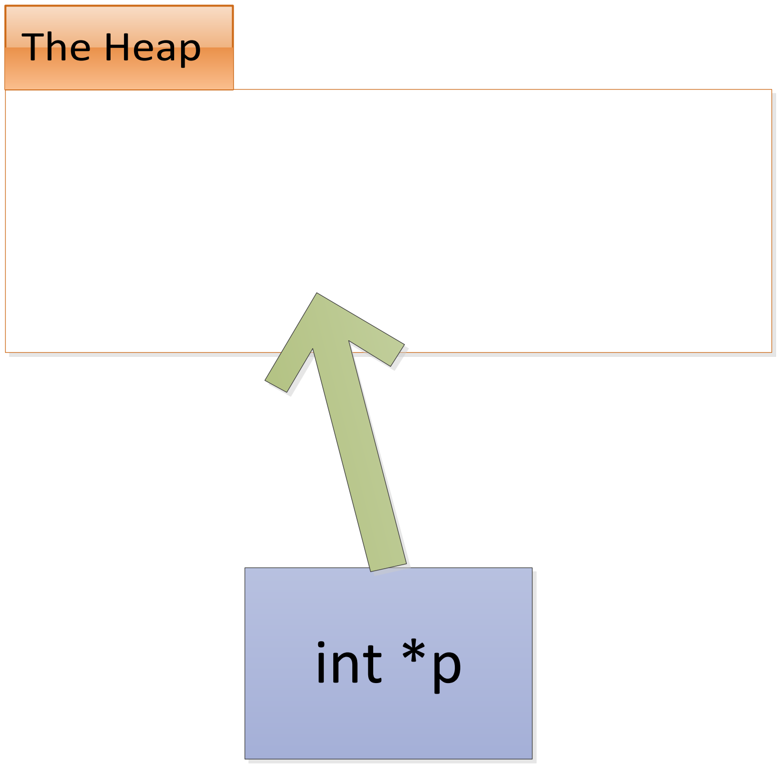
```
int *getPtrToFive() {
  int *x = new int;
  *x = 5;
  return x;
}

int main() {
  int *p;
  for (int i = 0; i < 3; ++i) {
    p = getPtrToFive();
    cout << *p << endl;
    delete p;
  }
}
```



- To fix the memory leak, de-allocate memory within the loop

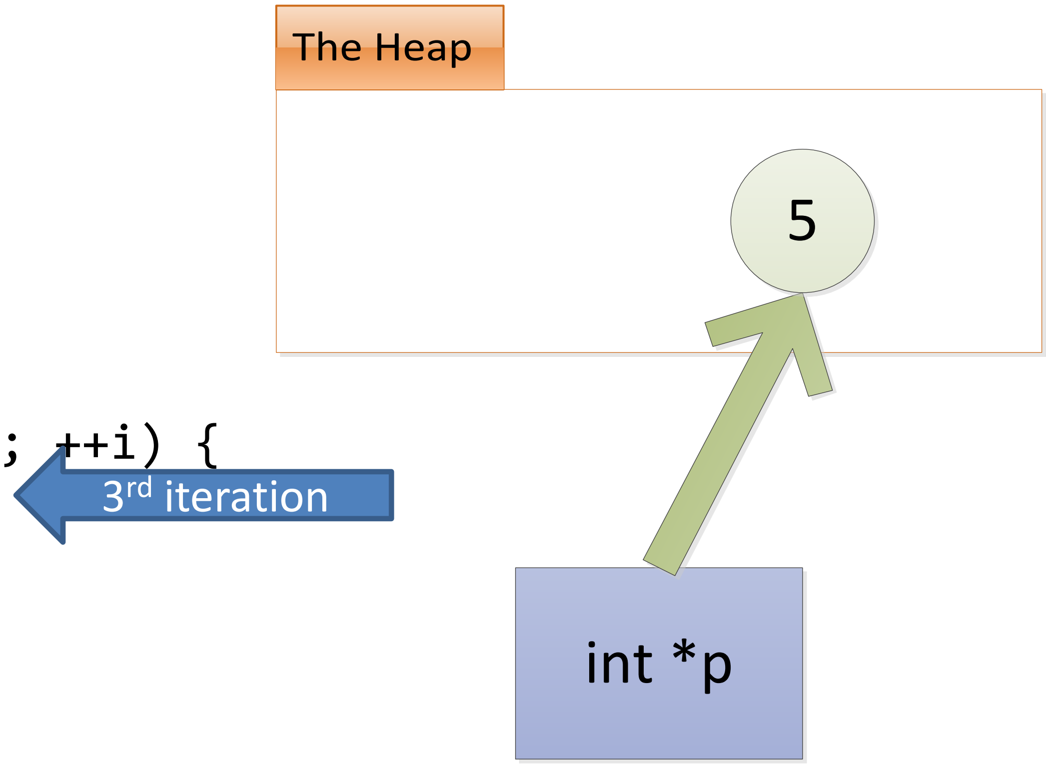
```
int *getPtrToFive() {
  int *x = new int;
  *x = 5;
  return x;
}

int main() {
  int *p;
  for (int i = 0; i < 3; ++i) {
    p = getPtrToFive();
    cout << *p << endl;
    delete p;
  }
}
```

2nd iteration



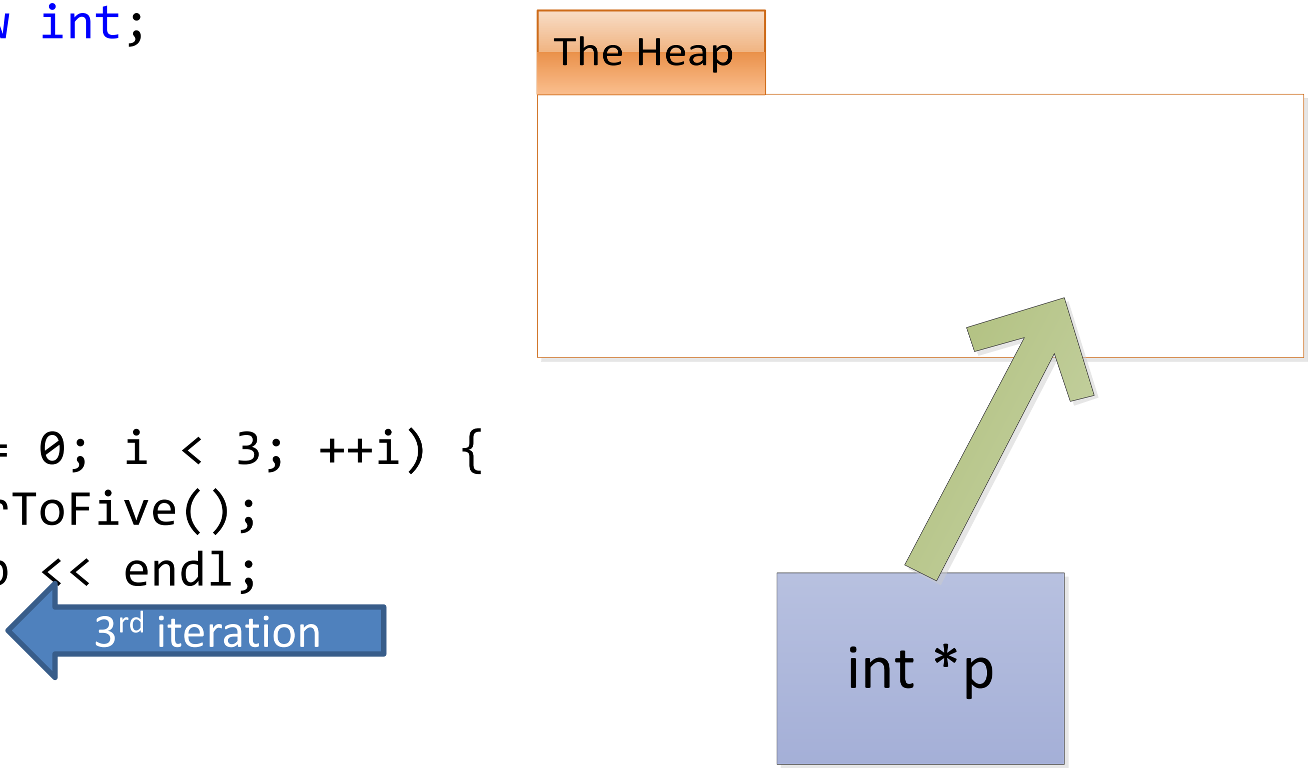
- To fix the memory leak, de-allocate memory within the loop

```
int *getPtrToFive() {
  int *x = new int;
  *x = 5;
  return x;
}

int main() {
  int *p;
  for (int i = 0; i < 3; ++i) {
    p = getPtrToFive();
    cout << *p << endl;
    delete p;
  }
}
```



- To fix the memory leak, de-allocate memory within the loop

```
int *getPtrToFive() {
  int *x = new int;
  *x = 5;
  return x;
}

int main() {
  int *p;
  for (int i = 0; i < 3; ++i) {
    p = getPtrToFive();
    cout << *p << endl;
    delete p;
  }
}
```



Don’t Use Memory After Deletion

incorrect

```
int *getPtrToFive() {
  int *x = new int;
  *x = 5;
  return x;
}

int main() {
  int *x = getPtrToFive();
  delete x;
  cout << *x << endl; // ???
}
```

Don’t Use Memory After Deletion

incorrect

```
int *getPtrToFive() {
  int *x = new int;
  *x = 5;
  return x;
}

int main() {
  int *x = getPtrToFive();
  delete x;
  cout << *x << endl; // ???
}
```

correct

```
int *getPtrToFive() {
  int *x = new int;
  *x = 5;
  return x;
}

int main() {
  int *x = getPtrToFive();
  cout << *x << endl; // 5
  delete x;
}
```

Don’t delete memory twice

incorrect

```
int *getPtrToFive() {
  int *x = new int;
  *x = 5;
  return x;
}

int main() {
  int *x = getPtrToFive();
  cout << *x << endl; // 5
  delete x;
  delete x;
}
```

Don’t delete memory twice

incorrect

```
int *getPtrToFive() {
  int *x = new int;
  *x = 5;
  return x;
}

int main() {
  int *x = getPtrToFive();
  cout << *x << endl; // 5
  delete x;
  delete x;
}
```

correct

```
int *getPtrToFive() {
  int *x = new int;
  *x = 5;
  return x;
}

int main() {
  int *x = getPtrToFive();
  cout << *x << endl; // 5
  delete x;
}
```

Only **delete** if memory was allocated by **new**

incorrect

```
int main() {
  int x = 5;
  int *xPtr = &x;
  cout << *xPtr << endl;
  delete xPtr;
}
```

Only **delete** if memory was allocated by **new**

incorrect

```
int main() {
  int x = 5;
  int *xPtr = &x;
  cout << *xPtr << endl;
  delete xPtr;
}
```

correct

```
int main() {
  int x = 5;
  int *xPtr = &x;
  cout << *xPtr << endl;
}
```

Allocating Arrays

- When allocating arrays on the stack (using “int arr[SIZE]”), size must be a constant

```
int numItems;
cout << "how many items?";
cin >> numItems;
int arr[numItems]; // not allowed
```

Allocating Arrays

- If we use **new[]** to allocate arrays, they can have variable size

```
int numItems;
cout << "how many items?";
cin >> numItems;
int *arr = new int[numItems];
```

Type of items in array

Allocating Arrays

- If we use **new[]** to allocate arrays, they can have variable size

```
int numItems;
cout << "how many items?";
cin >> numItems;
int *arr = new int[numItems];
```

Number of items to allocate

Allocating Arrays

- If we use **new[]** to allocate arrays, they can have variable size
- De-allocate arrays with **delete[]**

```
int numItems;
cout << "how many items?";
cin >> numItems;
int *arr = new int[numItems];
delete[] arr;
```

Ex: Storing values input by the user

```
int main() {
  int numItems;
  cout << "how many items? ";
  cin >> numItems;
  int *arr = new int[numItems];
  for (int i = 0; i < numItems; ++i) {
    cout << "enter item " << i << ": ";
    cin >> arr[i];
  }
  for (int i = 0; i < numItems; ++i) {
    cout << arr[i] << endl;
  }
  delete[] arr;
}
```

```
how many items? 3
enter item 0: 7
enter item 1: 4
enter item 2: 9
7
4
9
```

Allocating Class Instances using **new**

- **new** can also be used to allocate a class instance

```
class Point {
public:
  int x, y;
};

int main() {
  Point *p = new Point;
  delete p;
}
```

Allocating Class Instances using **new**

- **new** can also be used to allocate a class instance
- The appropriate constructor will be invoked

```
class Point {
public:
  int x, y;
  Point() {
    x = 0; y = 0; cout << "default constructor" << endl;
  }
};

int main() {
  Point *p = new Point;
  delete p;
}
```

Output:
default constructor

Allocating Class Instances using **new**

- **new** can also be used to allocate a class instance
- The appropriate constructor will be invoked

```
class Point {
public:
  int x, y;
  Point(int nx, int ny) {
    x = ny; x = ny; cout << "2-arg constructor" << endl;
  }
};

int main() {
  Point *p = new Point(2, 4);
  delete p;
}
```

Output:
2-arg constructor

Destructor

- Destructor is called when the class instance gets de-allocated

```
class Point {
public:
  int x, y;
  Point() {
    cout << "constructor invoked" << endl;
  }
  ~Point() {
    cout << "destructor invoked" << endl;
  }
}
```

- Destructor is called when the class instance gets de-allocated
  - If allocated with **new**, when **delete** is called

```
class Point {
public:
  int x, y;
  Point() {
    cout << "constructor invoked" << endl;
  }
  ~Point() {
    cout << "destructor invoked" << endl;
  }
};
int main() {
  Point *p = new Point;
  delete p;
}
```

Output:
constructor invoked
destructor invoked

- Destructor is called when the class instance gets de-allocated
  - If allocated with **new**, when **delete** is called
  - If stack-allocated, when it goes out of scope

```
class Point {
public:
  int x, y;
  Point() {
    cout << "constructor invoked" << endl;
  }
  ~Point() {
    cout << "destructor invoked" << endl;
  }
};
int main() {
  if (true) {
    Point p;
  }
  cout << "p out of scope" << endl;
}
```

Output:
constructor invoked
destructor invoked
p out of scope

Representing an Array of Integers

- When representing an array, often pass around both the pointer to the first element and the number of elements
  - Let's make them fields in a class

```
class IntegerArray {
public:
  int *data;
  int size;
};
```

Pointer to the first element

Representing an Array of Integers

- When representing an array, often pass around both the pointer to the first element and the number of elements
  - Let's make them fields in a class

```
class IntegerArray {
public:
  int *data;
  int size;
};
```

Number of elements in the array

```cpp
class IntegerArray {
public:
  int *data;
  int size;
};

int main() {
  IntegerArray arr;
  arr.size = 2;
  arr.data = new int[arr.size];
  arr.data[0] = 4; arr.data[1] = 5;
  delete[] a.data;
}
```

```
class IntegerArray {
public:
  int *data;
  int size;
};

int main() {
  IntegerArray arr;
  arr.size = 2;
  arr.data = new int[arr.size];
  arr.data[0] = 4; arr.data[1] = 5;
  delete[] a.data;
}
```

Can move this into a constructor

```
class IntegerArray {
public:
  int *data;
  int size;
  IntegerArray(int size) {
    data = new int[size];
    this->size = size;
  }
};

int main() {
  IntegerArray arr(2);
  arr.data[0] = 4; arr.data[1] = 5;
  delete[] arr.data;
}
```

```cpp
class IntegerArray {
public:
  int *data;
  int size;
  IntegerArray(int size) {
    data = new int[size];
    this->size = size;
  }
};

int main() {
  IntegerArray arr(2);
  arr.data[0] = 4; arr.data[1] = 5;
  delete[] arr.data;
}
```

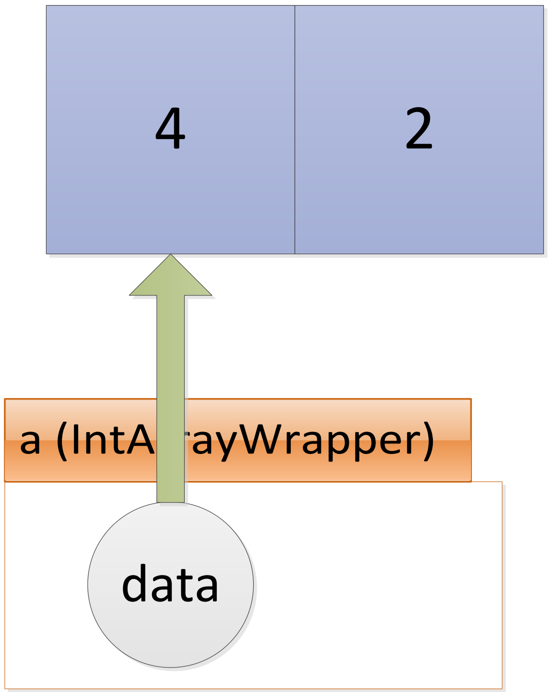
Can move this into a destructor

```
class IntegerArray {
public:
  int *data;
  int size;
  IntegerArray(int size) {
    data = new int[size];
    this->size = size;
  }
  ~IntegerArray () {
    delete[] data;
  }
};

int main() {
  IntegerArray arr(2);
  arr.data[0] = 4; arr.data[1] = 5;
}
```

De-allocate memory used by fields in destructor incorrect

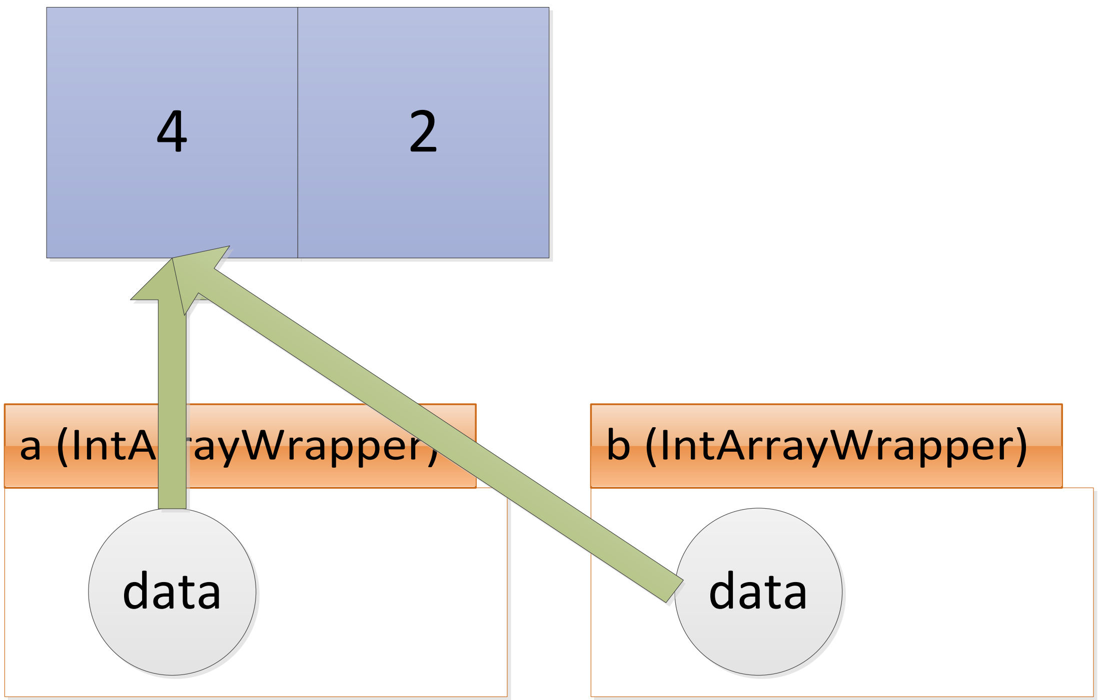
```
class IntegerArray {
public:
  int *data;
  int size;
  IntegerArray(int size) {
    data = new int[size];
    this->size = size;
  }
  ~IntegerArray() {
    delete[] data;
  }
};

int main() {
  IntegerArray a(2);
  a.data[0] = 4; a.data[1] = 2;
  if (true) {
    IntegerArray b = a;
  }
  cout << a.data[0] << endl; // not 4!
}
```

```
class IntegerArray {
public:
  int *data;
  int size;
  IntegerArray(int size) {
    data = new int[size];
    this->size = size;
  }
  ~IntegerArray() {
    delete[] data;
  }
};

int main() {
  IntegerArray a(2);
  a.data[0] = 4; a.data[1] = 2;
  if (true) {
    IntegerArray b = a;
  }
  cout << a.data[0] << endl; // not 4!
}
```



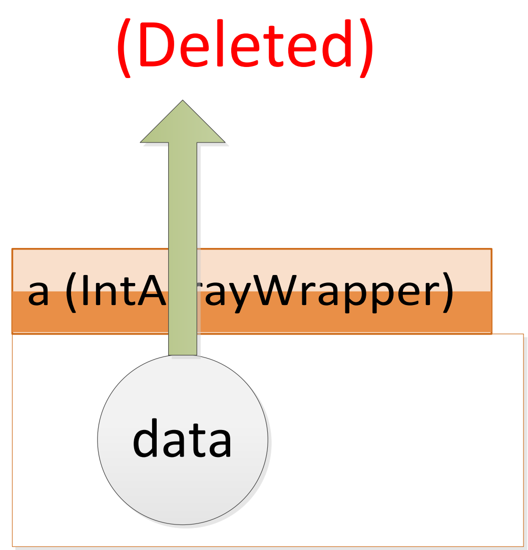
- Default copy constructor copies fields

```
class IntegerArray {
public:
  int *data;
  int size;
  IntegerArray(int size) {
    data = new int[size];
    this->size = size;
  }
  ~IntegerArray() {
    delete[] data;
  }
};

int main() {
  IntegerArray a(2);
  a.data[0] = 4; a.data[1] = 2;
  if (true) {
    IntegerArray b = a;
  }
  cout << a.data[0] << endl; // not 4!
}
```



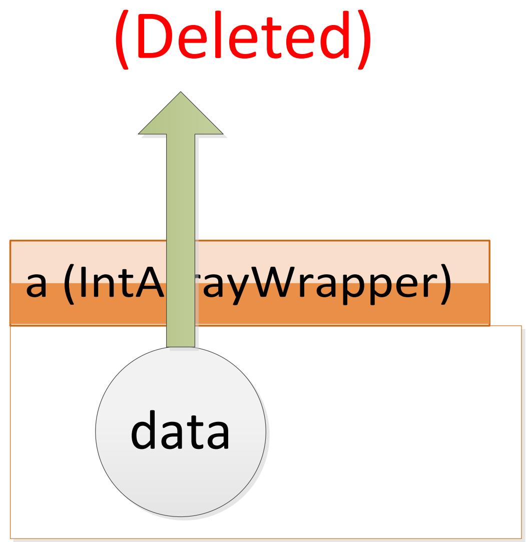
- When b goes out of scope, destructor is called (de-allocates array), a.data now a dangling pointer

```
class IntegerArray {
public:
  int *data;
  int size;
  IntegerArray(int size) {
    data = new int[size];
    this->size = size;
  }
  ~IntegerArray() {
    delete[] data;
  }
};

int main() {
  IntegerArray a(2);
  a.data[0] = 4; a.data[1] = 2;
  if (true) {
    IntegerArray b = a;
  }
  cout << a.data[0] << endl; // not 4!
}
```



- 2nd bug: when a goes out of scope, its destructor tries to delete the (already-deleted) array

```
class IntegerArray {
public:
  int *data;
  int size;
  IntegerArray(int size) {
    data = new int[size];
    this->size = size;
  }
  ~IntegerArray() {
    delete[] data;
  }
};

int main() {
  IntegerArray a(2);
  a.data[0] = 4; a.data[1] = 2;
  if (true) {
    IntegerArray b = a;
  }
  cout << a.data[0] << endl; // not 4!
}
```

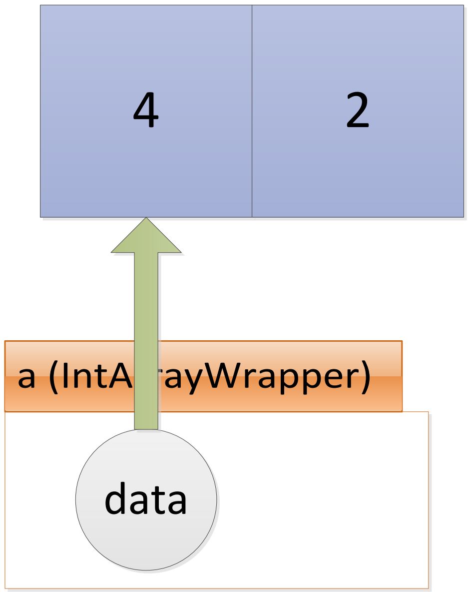


Program crashes as it terminates

- Write your own a copy constructor to fix these bugs

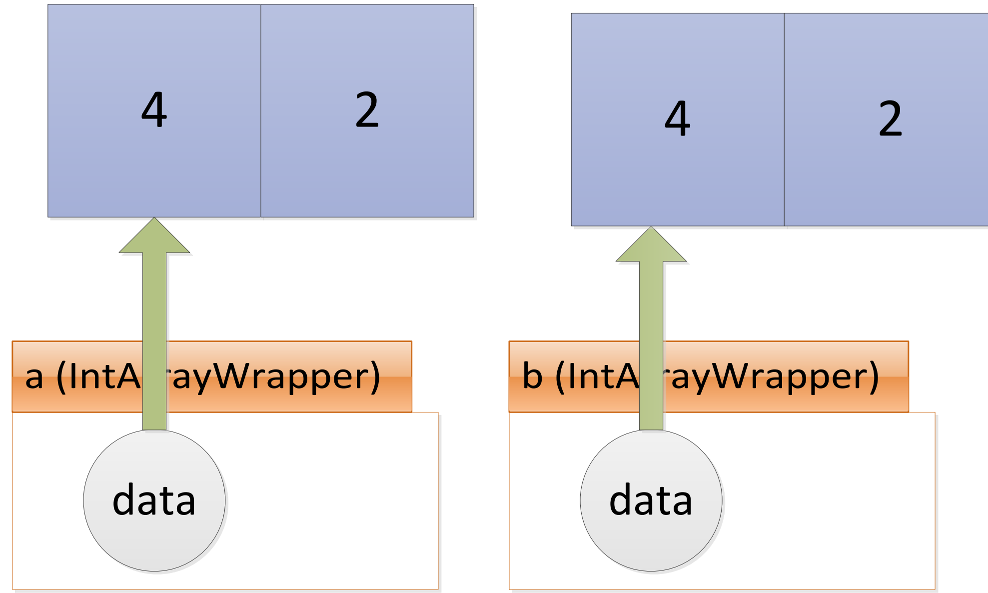
```
class IntegerArray {
public:
  int *data;
  int size;
  IntegerArray(int size) {
    data = new int[size];
    this->size = size;
  }
  IntegerArray(IntegerArray &o) {
    data = new int[o.size];
    size = o.size;
    for (int i = 0; i < size; ++i)
      data[i] = o.data[i];
  }
  ~IntegerArray() {
    delete[] data;
  }
};
```

```
class IntegerArray {
public:
  int *data; int size;
  IntegerArray(int size) {
    data = new int[size];
    this->size = size;
  }
  IntegerArray(IntegerArray &o) {
    data = new int[o.size];
    size = o.size;
    for (int i = 0; i < size; ++i)
      data[i] = o.data[i];
  }
  ~IntegerArray() {
    delete[] data;
  }
};
int main() {
  IntegerArray a(2);
  a.data[0] = 4; a.data[1] = 2;
  if (true) {
    IntegerArray b = a;
  }
  cout << a.data[0] << endl; // 4
}
```



here

```
class IntegerArray {
public:
  int *data; int size;
  IntegerArray(int size) {
    data = new int[size];
    this->size = size;
  }
  IntegerArray(IntegerArray &o) {
    data = new int[o.size];
    size = o.size;
    for (int i = 0; i < size; ++i)
      data[i] = o.data[i];
  }
  ~IntegerArray() {
    delete[] data;
  }
};
int main() {
  IntegerArray a(2);
  a.data[0] = 4; a.data[1] = 2;
  if (true) {
    IntegerArray b = a;
  }
  cout << a.data[0] << endl; // 4
}
```



Copy constructor invoked

```
class IntegerArray {
public:
  int *data; int size;
  IntegerArray(int size) {
    data = new int[size];
    this->size = size;
  }
  IntegerArray(IntegerArray &o) {
    data = new int[o.size];
    size = o.size;
    for (int i = 0; i < size; ++i)
      data[i] = o.data[i];
  }
  ~IntegerArray() {
    delete[] data;
  }
};
int main() {
  IntegerArray a(2);
  a.data[0] = 4; a.data[1] = 2;
  if (true) {
    IntegerArray b = a;
  }
  cout << a.data[0] << endl; // 4
}
```