601.220 Intermediate Programming

Rule of 3

An Image class

Image has resources managed by the constructor & destructor:

```
// image.h:
class Image {
  public:
      Image(const char *orig, int r, int c) : nrow(r), ncol(c) {
          image = new char[r*c];
          for(int i = 0; i < nrow * ncol; i++) {
              image[i] = orig[i];
          }
      }

      ~Image() { delete[] image; }

      const char *get_image() const { return image; }
      int get_nrow() const { return nrow; }
      int get_ncol() const { return ncol; }

      void set_pixel(char pix, int row, int col) {
          image[row * ncol + col] = pix;
      }
  private:
      char *image;     // image data
      int nrow, ncol; // # rows and columns
};

std::ostream& operator<<(std::ostream&, const Image&);
```

image.cpp

```cpp
// image.cpp:
#include <iostream>
#include "image.h"

using std::endl;
using std::ostream;

ostream& operator<<(ostream& os, const Image& image) {
    for(int i = 0; i < image.get_nrow(); i++) {
        for(int j = 0; j < image.get_ncol(); j++) {
            os << image.get_image()[i*image.get_ncol()+j] << ' ';
        }
        os << endl;
    }
    return os;
}
```

image_main.cpp

```
// image_main.cpp:
#include <iostream>
#include "image.h"
using std::cout;  using std::endl;

int main() {
    Image x_wins("X-O-XO--X", 3, 3);
    cout << x_wins << "** X wins! **" << endl;
    return 0;
}
```

```
$ g++ -o image_main image_main.cpp image.cpp
$ ./image_main
X - O
- X O
- - X
** X wins! **
```

image_main2.cpp

```cpp
// image_main.cpp:
#include <iostream>
#include "image.h"

using std::cout;  using std::endl;

int main() {
    Image x_wins("X-O-XO--X", 3, 3);
    Image o_wins = x_wins;
    o_wins.set_pixel('O', 2, 2); // set bottom right to 'O'
    cout << x_wins << "** X wins! **" << endl << endl;
    cout << o_wins << "** O wins! **" << endl;
    return 0;
}
```

image_main2.cpp

```
$ g++ -o image_main image_main.cpp image.cpp
$ ./image_main
X - O
- X O
- - O
** X wins! **

X - O
- X O
- - O
** O wins! **
free(): double free detected in tcache 2
Aborted
```

Oops, both have `O` in bottom right corner

`o_wins.set_pixel(...)` affected both `x_wins` & `o_wins`!

image_main2.cpp

Also: destructor `delete[]`s the same pointer twice

```
$ valgrind ./image_main > /dev/null
==3635== Memcheck, a memory error detector
==3635== Copyright (C) 2002-2017, and GNU GPL'd, by Julian Seward et al.
==3635== Using Valgrind-3.13.0 and LibVEX; rerun with -h for copyright info
==3635== Command: ./image_main
==3635==
==3635== Invalid free() / delete / delete[] / realloc()
==3635==    at 0x4C3373B: operator delete[](void*) (in /usr/lib/valgrind/vgpreload_memcheck-amd64-linux.so
==3635==    by 0x400C1C: Image::~Image() (in /d/Study/PhDCS(JHU)/JHU2021/2021-06-09(Summer) - Intermediate
==3635==    by 0x400ACF: main (in /d/Study/PhDCS(JHU)/JHU2021/2021-06-09(Summer) - Intermediate Programmin
==3635==  Address 0x5bdac80 is 0 bytes inside a block of size 9 free'd
==3635==    at 0x4C3373B: operator delete[](void*) (in /usr/lib/valgrind/vgpreload_memcheck-amd64-linux.so
==3635==    by 0x400C1C: Image::~Image() (in /d/Study/PhDCS(JHU)/JHU2021/2021-06-09(Summer) - Intermediate
==3635==    by 0x400AC3: main (in /d/Study/PhDCS(JHU)/JHU2021/2021-06-09(Summer) - Intermediate Programmin
==3635==  Block was alloc'd at
==3635==    at 0x4C3289F: operator new[](unsigned long) (in /usr/lib/valgrind/vgpreload_memcheck-amd64-lin
==3635==    by 0x400BA2: Image::Image(char const*, int, int) (in /d/Study/PhDCS(JHU)/JHU2021/2021-06-09(Su
==3635==    by 0x400A24: main (in /d/Study/PhDCS(JHU)/JHU2021/2021-06-09(Summer) - Intermediate Programmin
==3635==
==3635==
==3635== HEAP SUMMARY:
==3635==     in use at exit: 0 bytes in 0 blocks
==3635==   total heap usage: 3 allocs, 4 frees, 76,809 bytes allocated
==3635==
==3635== All heap blocks were freed -- no leaks are possible
==3635==
==3635== For counts of detected and suppressed errors, rerun with: -v
```

Initialization & assignment

`Image o_wins = x_wins;` does *shallow copy*

- Copies `x_wins.image` pointer directly into `o_wins.image`, so both are using same heap array
- Instead, we want *deep copy*; `o_wins` should be a new buffer, with contents of `x_wins` copied over
- Want this both for initialization and for assignment

```
Image x_wins("X-O-XO--X", 3, 3);
Image o_wins = x_wins;
```

Rule of 3

`Image` is an example of a class that manages resources, and therefore has a *non-trivial destructor*

Rule of 3: If you have to manage how an object is destroyed, you should also manage how it's copied

Rule of 3 (technical version): If you have a non-trivial destructor, you should also define a *copy constructor* and *`operator=`*

Case in point: `Image` should be deep copied

Rule of 3

Copy constructor initializes a `class` variable as a copy of another

`operator=` is called when one object is assigned to another

```
Complex c = {3.0, 2.0}; // non-default constructor
Complex c2 = c;         // copy constructor
c = Complex(4.0, 5.0);  // non-default ctor for right-hand side
                        // operator= to copy into left-hand side
```

Copy constructor

Copy constructor is called when:

- Initializing:
  - `Image o_wins = x_wins;`
  - `Image o_wins(x_wins);` (same meaning as above)
- Passing by value
- Returning by value

Copy constructor

Copy constructor for Image:

```
Image(const Image& o) : nrow(o.nrow), ncol(o.ncol) {
    // Do a *deep copy*, similarly to the
    // non-default constructor
    image = new char[nrow * ncol];
    for(int i = 0; i < nrow * ncol; i++) {
        image[i] = o.image[i];
    }
}
```

operator=

`operator=` is called when assigning one `class` variable to another

- Except for initialization; copy constructor handles that

```
Image& operator=(const Image& o) {
    delete[] image;  // deallocate previous image memory
    nrow = o.nrow;
    ncol = o.ncol;
    image = new char[nrow * ncol];
    for(int i = 0; i < nrow * ncol; i++) {
        image[i] = o.image[i];
    }
    return *this; // for chaining
}
```

It's a normal member function, not a constructor, so we can't use initializer list syntax

Rule of 3

If you don't specify copy constructor or `operator=`, compiler adds *implicit* version that *shallow copies*

- Simply the contents of the fields
- `class` fields will have their corresponding copy constructors or `operator=` functions called
- Pointers to heap memory will simply be copied, without the heap memory itself being copied

Another way of stating the Rule of 3: if your class has a non-trivial destructor, you probably *don't* want shallow copying

Rule of 3

When we add the copy constructor and `operator=` defined above, we get the expected behavior:

Rule of 3

```cpp
// image_fixed.cpp:
#include <iostream>
#include "image_fixed.h"
using std::cout;  using std::endl;
int main() {
    Image x_wins("X-O-XO--X", 3, 3);
    Image o_wins = x_wins;
    o_wins.set_pixel('O', 2, 2); // set bottom right to 'O'
    cout << x_wins << "** X wins! **" << endl << endl;
    cout << o_wins << "** O wins! **" << endl;
    return 0;
}
```

```
$ g++ -o image_fixed image_fixed.cpp image.cpp
$ ./image_fixed
X - O
- X O
- - X
** X wins! **

X - O
- X O
- - O
** O wins! **
```

Rule of 3

And no complaints from `valgrind`:

```
$ valgrind ./image_fixed > /dev/null
==3649== Memcheck, a memory error detector
==3649== Copyright (C) 2002-2017, and GNU GPL'd, by Julian Seward et al.
==3649== Using Valgrind-3.13.0 and LibVEX; rerun with -h for copyright info
==3649== Command: ./image_fixed
==3649==
==3649==
==3649== HEAP SUMMARY:
==3649==     in use at exit: 0 bytes in 0 blocks
==3649==   total heap usage: 4 allocs, 4 frees, 76,818 bytes allocated
==3649==
==3649== All heap blocks were freed -- no leaks are possible
==3649==
==3649== For counts of detected and suppressed errors, rerun with: -v
==3649== ERROR SUMMARY: 0 errors from 0 contexts (suppressed: 0 from 0)
```