CS24: Introduction to Computing Systems

Spring 2015

Lecture 10

PREVIOUSLY: ARRAY ACCESS

- C doesn't provide a very safe programming environment
- Previous example: array bounds checking

```
int a;
int r[4];
int b;
...
r[4] = 12345;       /* Compiles!      */
r[-1] = 67890;      /* Also compiles! */
```

- Depending on variable placement, could affect:
  - `a` and/or `b`
  - Caller's `ebp`, return address on stack, etc.
- Or, perhaps nothing at all!

CHECKED ARRAY INDEXING

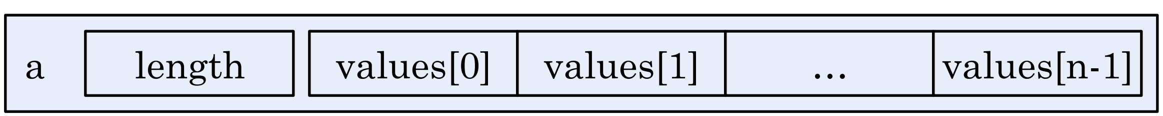
- Could add metadata to arrays

```
struct array_t {
    int length;  /* Number of elements */
    struct value_t values[];
};
```

  - Arrays include length information in their run-time representation
  - Last member of a struct can be an array with no size
- To initialize a new array:

```
array_t *a = (array_t *)
  malloc(sizeof(array_t) + n*sizeof(value_t));
a->length = n;
```

  - **`values`** is a pointer to start of variable-size array



Array Bounds-Checking (2)

- Arrays are now a more intelligent data type:

```
for (int i = 0; i < a.length; i++) {
    compute(a[i]);
}
```

  - A composite type containing multiple related values
  - Ideally, **`length`** would be read-only, and every indexing operation would be verified against **`length`**

- If only our type could also expose specific behaviors…
  - Operations that can be performed on these values
  - e.g. expose length via a function, or check indexes in an access function

Object Oriented Programming

- Idea:
  - Group together related data values into a single unit
  - Provide functions that operate on these data values
  - This state and its associated behavior is an object
- A class is a definition or blueprint of what appears within objects of that type
- Encapsulation:
  - Disallow direct access to the state values of an object
  - Provide accessors and mutators that control *when* and *how* state is modified
- Abstraction:
  - Class provides simplified representation of what it models
  - Compose simpler objects together to represent assemblies
    - e.g. a Car has an Engine, a Transmission, Pedals, a SteeringWheel, Instruments, etc.

Object Oriented Programming (2)

- Idea:
  - Object oriented programming paradigm makes it easier to create large software systems
  - Promotes modularity and encapsulation of state
  - Provides sophisticated modeling and abstraction capabilities for programs to use
- (Not everyone believes that OOP is best way to provide these features…)
- Many different object-oriented languages now!
  - C++, Java, C#, Scala, Python, Ruby, JavaScript, Perl, PHP, …
- Today: focus on some OO features found in Java

Object Oriented Programming: Java

- Java presents a specific object-oriented programming model
- Includes some kinds of variables we recognize:
  - Global variables
  - Function arguments
  - Local variables
- Object-oriented model also introduces:
  - Class variables
  - Instance variables

```
public class RGBColor {
  public static RGBColor RED =
    new RGBColor(1.0, 0.0, 0.0);

  private float red, green, blue;

  public RGBColor(...) { ... }

  public void setRed(float v) {
    red = v;
  }
  ...

  public void fromHSV(float h,
                      float s,
                      float v) {
    float p = v * (1.0 - s);
    ...
  }
}
```

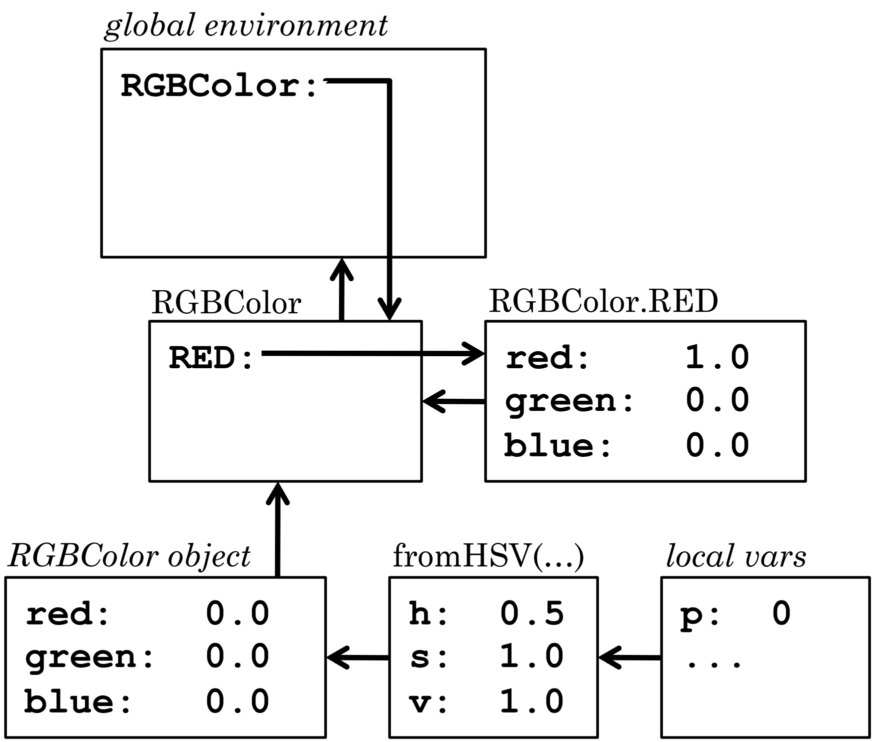
Java Types and Abstractions (2)

- How do environments fit together to provide these kinds of state?
  - Global variables
  - Function arguments
  - Local variables
  - Class variables
  - Instance variables

```
public class RGBColor {
  public static RGBColor RED =
    new RGBColor(1.0, 0.0, 0.0);

  private float red, green, blue;

  public RGBColor(...) { ... }

  public void setRed(float v) {
    red = v;
  }
  ...

  public void fromHSV(float h,
                      float s,
                      float v) {
    float p = v * (1.0 - s);
    ...
  }
}
```

Java Types and Abstractions (3)

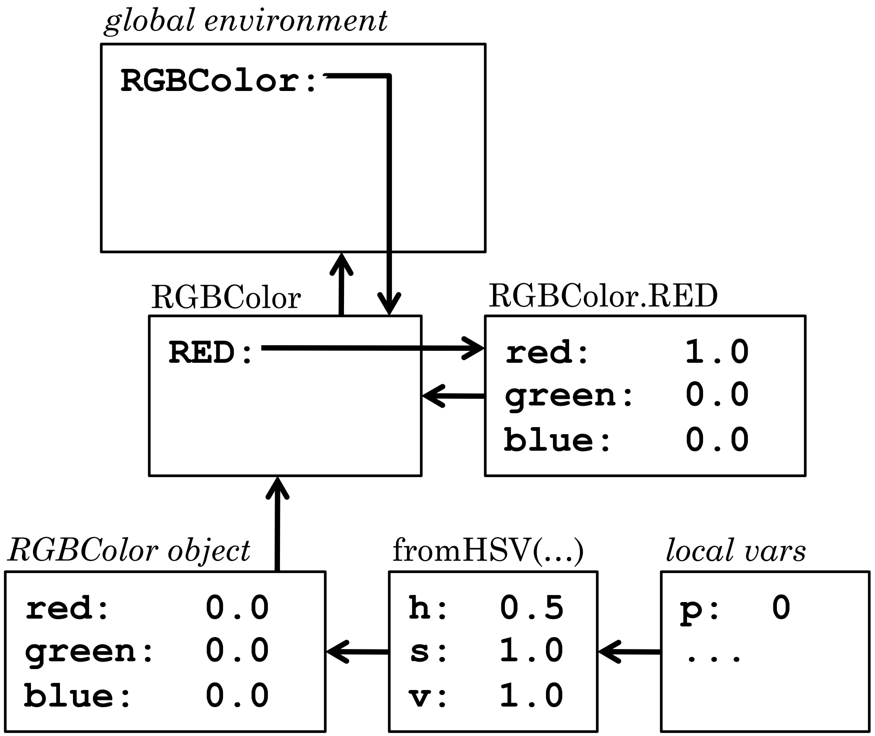
- Example environment structure:




```java
public class RGBColor {
  public static RGBColor RED =
    new RGBColor(1.0, 0.0, 0.0);

  private float red, green, blue;

  public RGBColor(...) { ... }

  public void setRed(float v) {
    red = v;
  }
  ...

  public void fromHSV(float h,
                      float s,
                      float v) {
    float p = v * (1.0 - s);
    ...
  }
}
```

Java Types and Abstractions (4)

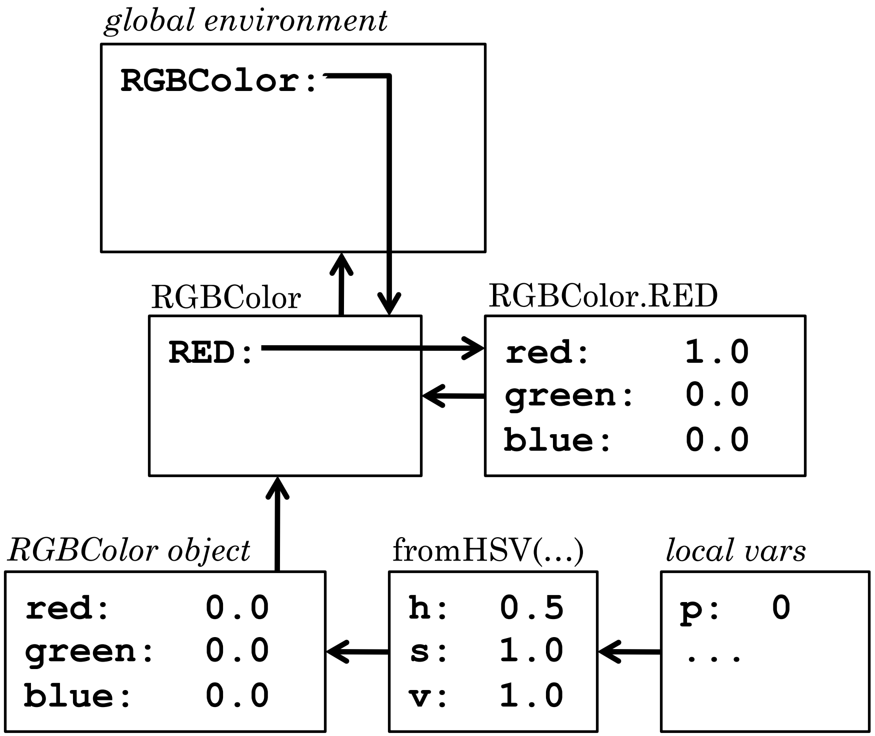
- Example environment structure:



- To support objects:
  - Need to introduce new frames to represent classes
  - Also need frames to represent specific instances of a class

Java Types and Abstractions (5)

- Example environment structure:



- Can use memory heap to implement these frames
- By controlling what programs can do with references, can also provide precise garbage collection for frames
  - Clean up objects when no longer referenced by any frame
  - Can even remove class definitions when not referenced by any object (used by Java application servers for code-reloading)

IMPLEMENTING OOP IN C

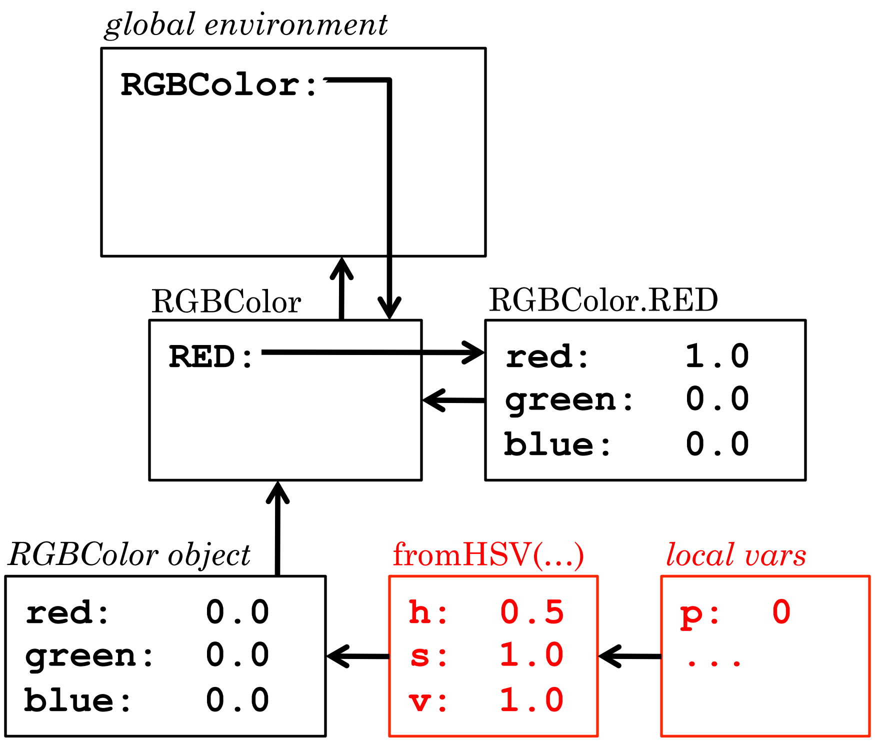
- How might we implement this object-oriented programming model in C?
- A *very* rich topic… Definitely won't cover it all

- Start with basic object-oriented concepts
  - See how these translate into C-style concepts
- Build up the model until it includes most Java OOP capabilities

- Discussion will necessarily be at a high level
  - Many implementation details left out!!

Implementing OOP in C (2)

- Can already implement some aspects of this model
  - Function calls, local variables
  - Implement these with a stack




```
public class RGBColor {
  public static RGBColor RED =
    new RGBColor(1.0, 0.0, 0.0);

  private float red, green, blue;

  public RGBColor(...) { ... }

  public void setRed(float v) {
    red = v;
  }
  ...

  public void fromHSV(float h,
                      float s,
                      float v) {
    float p = v * (1.0 - s);
    ...
  }
}
```

Implementing OOP in C (3)

- How to store object data in C?

```
public class RGBColor {
  private float red, green, blue;
  ...
}
```

- C provides composite data types using **`struct`**
- Can use this to represent the data in our objects

```
struct RGBColor_Data {
  float red;
  float green;
  float blue;
};
```

  - This **`struct`** loosely corresponds to a class declaration
  - Variables of this type will represent individual objects
- Each **`RGBColor`** object will have its own frame for its state variables

Implementing OOP in C (4)

- C representation of our object:

```
struct RGBColor_Data {
  float red;
  float green;
  float blue;
};
```

- Need a way to provide methods as well:

```
public class RGBColor {
  ...
  public float getRed() {
    return red;
  }
  public void setRed(float v) {
    red = v;
  }
}
```

  - No explicit argument representing the object

```
c.setRed(0.5);
```

Methods and `this`

- Need to introduce an implicit parameter into methods
  - **`this`**: a reference to the object the method is called on
- Object-oriented code:

```
public class RGBColor {
  ...
  public void setRed(float v) {
    red = v;
  }
  ...
}
```

- Translate into this equivalent C code:

```
RGBColor_setRed(RGBColor_Data *this, float v) {
  this->red = v;
}
```

METHODS AND **`this`** (2)

- Instance methods include an implicit parameter **`this`**
  - Allows the object's code to refer to its own fields
- When a program calls a method on an object:
  - The underlying implementation transparently passes a reference to the called object, to the method code
- A common feature across all OO languages
  - Some languages explicitly specify this parameter
  - e.g. Python:

```
class RGBColor:
    def __init__(self, red, green, blue):
        self.red = red
        self.green = green
        self.blue = blue

    def get_red(self):
        return self.red
    ...
```

Methods Calling Methods

- Methods frequently call other methods

```
public float getGrayScale() {
  return 0.30 * getRed() +
         0.59 * getGreen() +
         0.11 * getBlue();
}
```

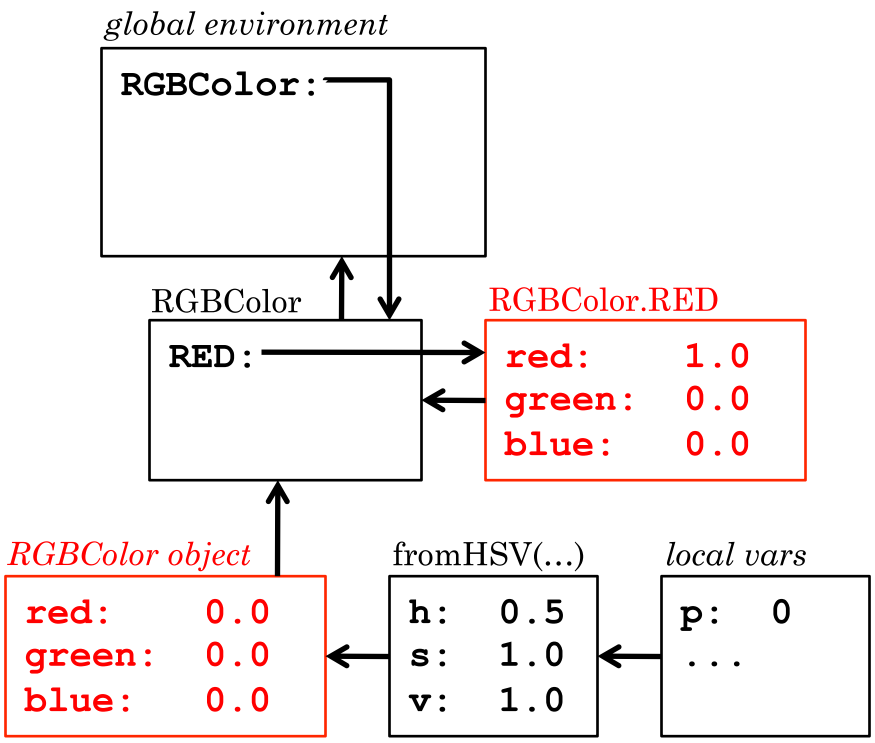
  - Calls other methods on the same object
- Must pass the **`this`** reference to called methods

```
float RGBColor_getGrayScale(RGBColor_Data *this) {
  return 0.30 * RGBColor_getRed(this) +
         0.59 * RGBColor_getGreen(this) +
         0.11 * RGBColor_getBlue(this);
}
```

  - Again, straightforward translation to support this

OBJECT FRAMES

- This approach allows us to implement our object frames
  - Programs can manipulate independent objects of a class




```
public class RGBColor {
  public static RGBColor RED =
    new RGBColor(1.0, 0.0, 0.0);

  private float red, green, blue;

  public RGBColor(...) { ... }

  public void setRed(float v) {
    red = v;
  }
  ...

  public void fromHSV(float h,
                      float s,
                      float v) {
    float p = v * (1.0 - s);
    ...
  }
}
```

Frames for Classes?

- Our example also has a class-level constant:

```
public class RGBColor {
  public static RGBColor RED =
    new RGBColor(1.0, 0.0, 0.0);
  ...
}
```

  - Many OO languages call these <u>static members</u>
  - Member isn't associated with a specific object
  - Refer to member using the class name:

```
g.setColor(RGBColor.RED);
```

- Clearly requires a frame at the class-level for such constants
- Object frames should also reference their class' frame
  - Specifies object's type, allow easy use of static members

RGBColor Class Frame

- Simple frame for our **RGBColor** class:

```
struct RGBColor_Class {
  RGBColor_Data *RED;     /* static member */
};
```

- Update definition of **RGBColor_Data**:

```
struct RGBColor_Data {
  RGBColor_Class *class;  /* type info */
  float red;
  float green;
  float blue;
};
```

- A new problem: how to initialize the static members?
- Classes define constructors to set up new objects…
- Similarly, init class info first time type is referenced

RGBColor Class Frame

- Mechanism to initialize **RGBColor** class frame:

```
RGBColor_class_init(RGBColor_Class *class) {
  /* Initialize static member RED. */
  class->RED = malloc(sizeof(RGBColor_Data));
  RGBColor_init(class, class->RED, 1.0, 0.0, 0.0);
}
```

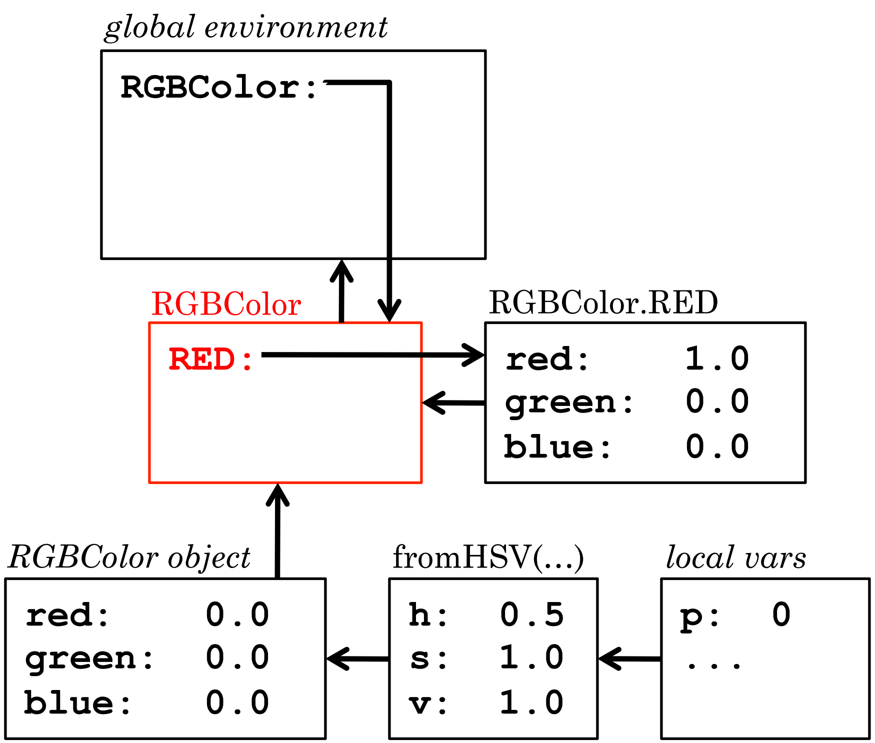
  - *Global environment manages class frames, somehow…* ☺

- Simple **RGBColor** constructor translated to C:

```
RGBColor_init(RGBColor_Class *class,
              RGBColor_Data *this, float red,
              float green, float blue) {
  this->class = class;
  this->red   = red;
  this->green = green;
  this->blue  = blue;
}
```

RGBColor Class Frame (2)

- Now we can do everything in our simplified object-oriented programming model!




```
public class RGBColor {
  public static RGBColor RED =
    new RGBColor(1.0, 0.0, 0.0);

  private float red, green, blue;

  public RGBColor(...) { ... }

  public void setRed(float v) {
    red = v;
  }
  ...

  public void fromHSV(float h,
                      float s,
                      float v) {
    float p = v * (1.0 - s);
    ...
  }
}
```

More Advanced OOP Concepts

- Object-oriented programming languages also support class inheritance and polymorphism
- Class inheritance:
  - Can construct hierarchies of classes
  - Parent classes represent more general-purpose types
  - Child classes are specializations of parent classes
    - Can extend functionality of parent classes with new fields and methods
    - Can override parent-class methods with specialized features
- Polymorphism:
  - Parent class specifies a common interface
  - Subclasses provide specialized implementations
  - Code written against the parent class behaves differently, depending on which subclass it is given

Class Inheritance and Polymorphism

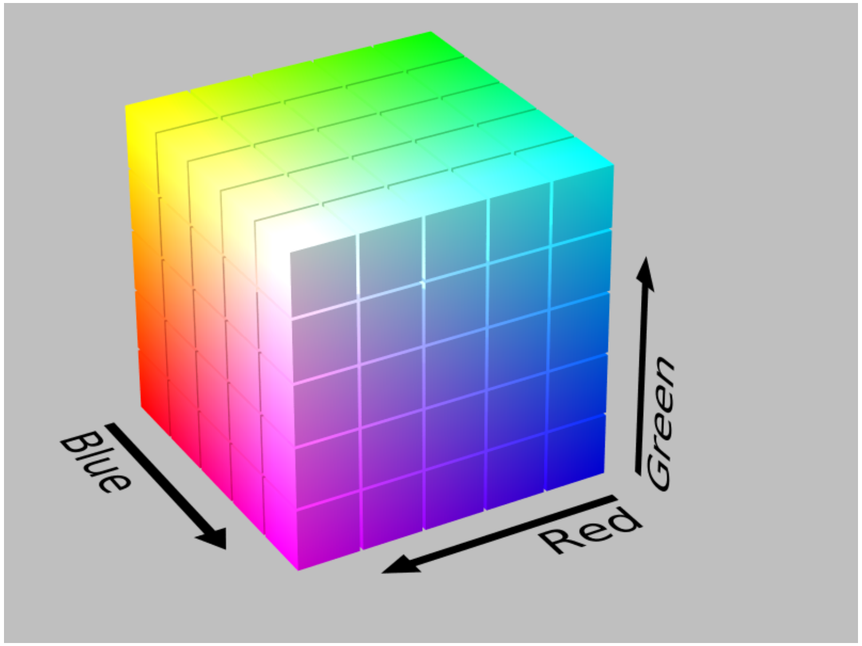
- Instead of a simple **`RGBColor`** class, provide a color class hierarchy
  - Parent class specifies methods that all subclasses will provide
  - **`toRGB()`** produces an integer value usable by the graphics hardware
    - Bits 16-23 are red value
    - Bits 8-15 are green value
    - Bits 0-7 are blue value
- Implement two subclasses
  - **`RGBColor`** subclass, using RGB color space
    - Red, green, blue color components
  - **`HSVColor`** subclass, using HSV color space
    - Hue, saturation, value; effectively implements a color wheel

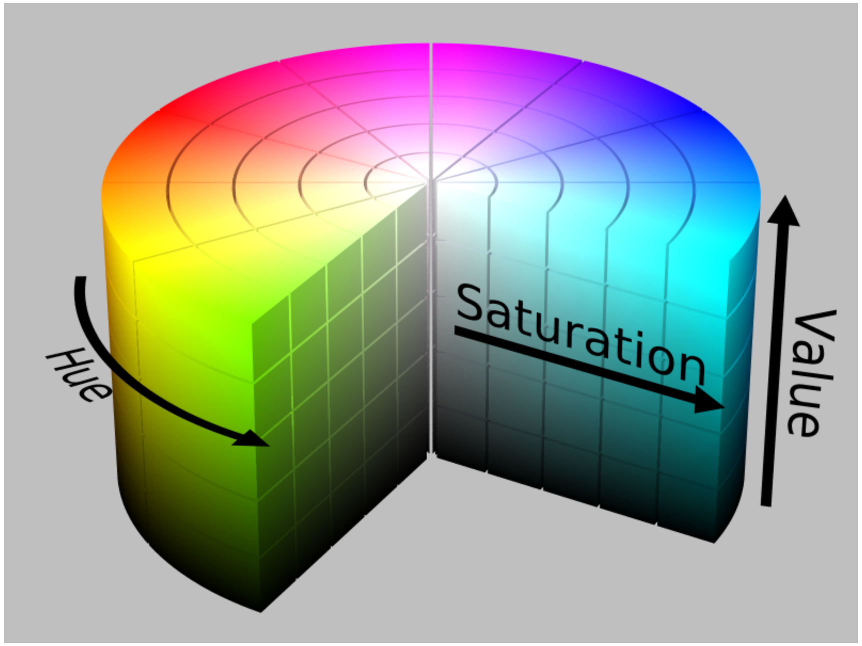
```
Color
-----------------------
int toRGB()
float getGrayScale()
```

Bits:	31 24	23 16	15 8	7 0
		R	G	B

Color Spaces

- RGB and HSV are different *color spaces*
  - Different ways of representing colors
- RGB mixes red, green, and blue components
  - Used by virtually all graphics hardware
- HSV combines hue, saturation, and value
  - Frequently used for color-choosers in UIs
  - Also used frequently in computer vision



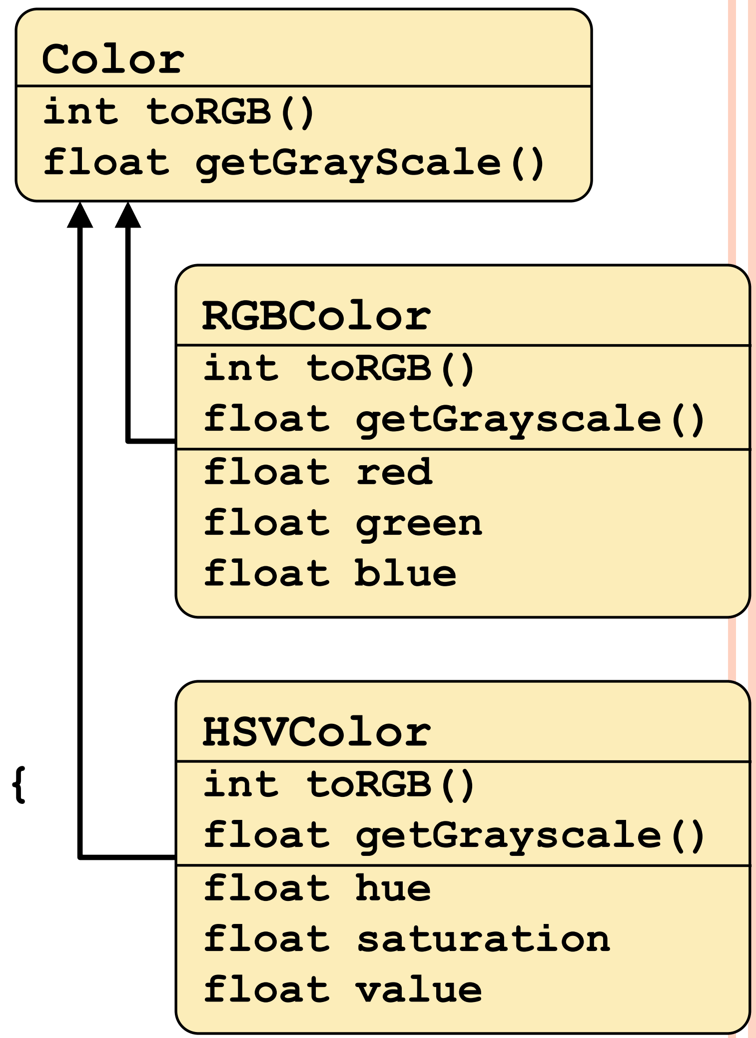


Images from Wikimedia Commons

Color Class Hierarchy

- Now, can implement functions that use the abstract base-class
  - **`Shape.setColor(Color)`**
  - **`Graphics.setColor(Color)`**
  - etc.
- Programs can use the type of color that makes sense for them
- Graphics code can use **`toRGB()`** method to set up for drawing:

```
public class Graphics {
   ...
   public void setColor(Color c) {
      device.setRGB(c.toRGB());
   }
}
```

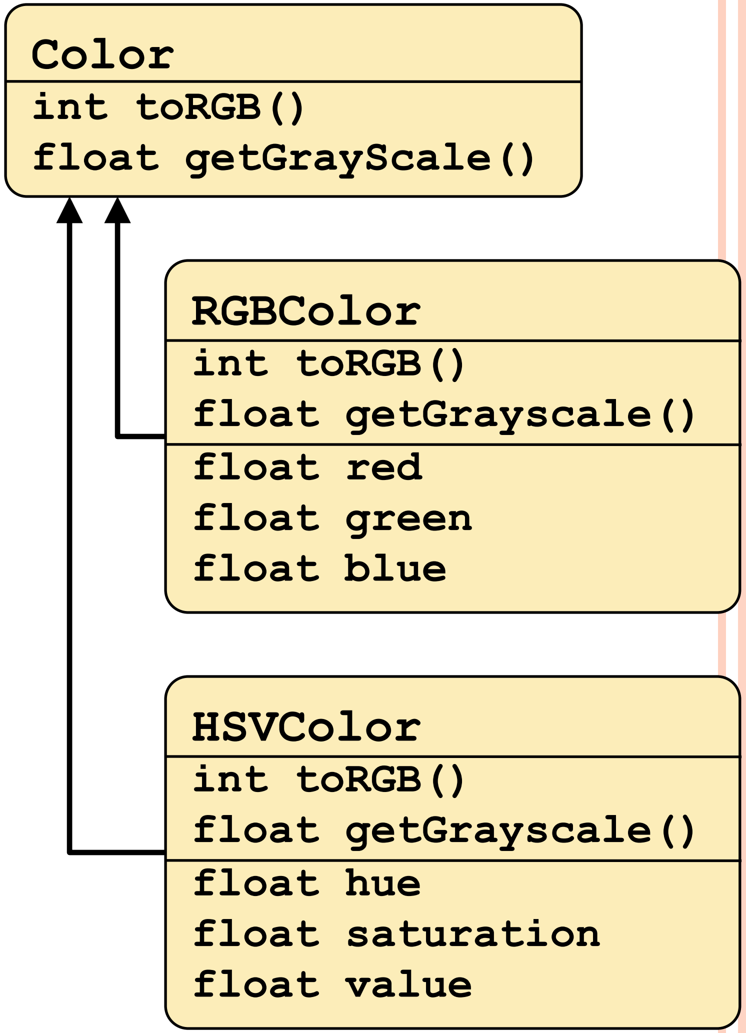


Color Class Hierarchy (2)

- Graphics code:

```
public class Graphics {
  ...
  public void setColor(Color c) {
    device.setRGB(c.toRGB());
  }
}
```

- **`RGBColor`** and **`HSVColor`** provide different versions of this function!
  - **`RGBColor`** can simply pack up the RGB components into an **`int`**
  - **`HSVColor`** must convert to RGB before returning the result
- **`Graphics.setColor()`** needs to call proper version of **`toRGB()`**, depending on type of argument!

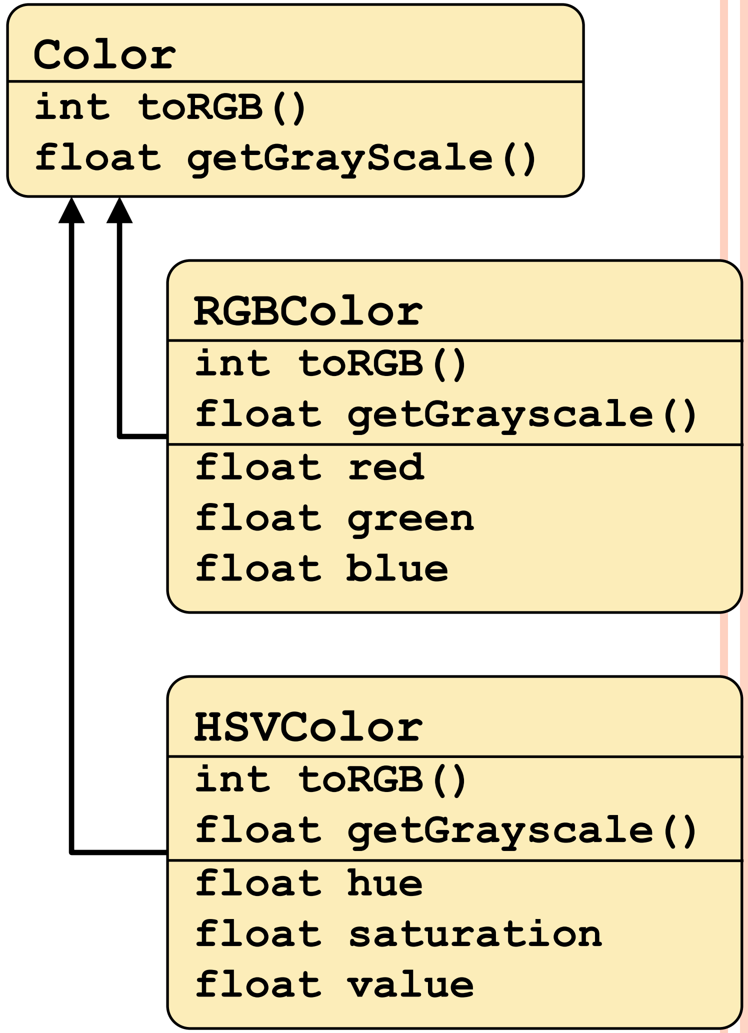


VIRTUAL FUNCTIONS

- **`toRGB()`** and **`getGrayScale()`** are called <u>virtual functions</u>
- Subclasses have provided their own implementations…
- Code written against base-class must call appropriate version when passed a subclass object

```
public class Graphics {
  ...
  public void setColor(Color c) {
    device.setRGB(c.toRGB());
  }
}
```

- Somehow, objects must indicate which version of **`toRGB()`** to use



Classes and Function Pointers

- Each object already has a reference to its class info…
- Simple solution:
  - Add details of which methods go with each type, into the class information
  - Can look up which method to call, using object's class-info
- The C language supports *function pointers*
  - Instead of a pointer to data, points to a function
  - A function-pointer **`fp`**, which points to a function that takes a **`double`** and returns a **`double`**:

    ```
    double (*fp)(double);
    ```
  - Set **`fp`** to point to the **`sin()`** function:

    ```
    fp = sin;   /* Note:  NO parentheses!! */
    ```
  - Call the **`sin()`** function through **`fp`**:

    ```
    result = fp(x);
    ```

Color Class Details

- Base class representation:

```
struct Color_Class {
  int   (*toRGB)(Color_Data *this);
  float (*getGrayScale)(Color_Data *this);
};
```

  - Two function pointers, one for each virtual function
- Subclass type information is identical
  - (These subclasses don't have static members…)

```
struct RGBColor_Class {
  int   (*toRGB)(RGBColor_Data *this);
  float (*getGrayScale)(RGBColor_Data *this);
};

struct HSVColor_Class { ... /* same idea */ };
```

Color Class Details (2)

- Can model basic class-inheritance with C structs
- Declare "base-type" struct with certain members

```
struct Color_Data {
  Color_Class *class;
};
```

- "Sub-type" structs can add other members if needed, but <u>must</u> have same types of members at the start!

```
struct RGBColor_Data {
  RGBColor_Class *class;
  float red;
  float green;
  float blue;
};
```

- Then, can cast a base-type pointer to subtype pointer
  - The common members are at same offsets in both structs

Color Class Initialization

- Now our class-initialization code becomes:

```
RGBColor_class_init(RGBColor_Class *class) {
  /* Initialize function pointers */
  class->toRGB        = RGBColor_toRGB;
  class->getGrayScale = RGBColor_getGrayScale;
}

HSVColor_class_init(HSVColor_Class *class) {
  /* Initialize function pointers */
  class->toRGB        = HSVColor_toRGB;
  class->getGrayScale = HSVColor_getGrayScale;
}
```

- Objects of each type can easily invoke the proper version of **`Color.toRGB()`** now

Color-Object Data Types

- **`RGBColor_Data`** definition is same as before:

```
struct RGBColor_Data {
  RGBColor_Class *class;  /* type info */
  float red;
  float green;
  float blue;
};
```

- **`HSVColor_Data`** definition:

```
struct HSVColor_Data {
  HSVColor_Class *class;  /* type info */
  float hue;
  float saturation;
  float value;
};
```

Graphics Code Translation

- Our Graphics code from before:

```
public class Graphics {
  ...
  public void setColor(Color c) {
    device.setRGB(c.toRGB());
  }
}
```

- Translate into C code:

```
void Graphics_setColor(Graphics_Data *this,
                       Color_Data *c) {
  Device_setRGB(this->device, c->class->toRGB(c));
}
```

- If **`RGBColor`** passed in, **`RGBColor_toRGB()`** is used
- If **`HSVColor`** passed in, **`HSVColor_toRGB()`** is used

GRAPHICS CODE TRANSLATION (2)

- Note the two different calling patterns:

```
void Graphics_setColor(Graphics_Data *this,
                       Color_Data *c) {
  Device_setRGB(this->device, c->class->toRGB(c));
}
```

non-virtual method invocation *virtual method invocation*

- Non-virtual methods do not support polymorphism
  - The method is chosen at compile-time, and cannot change
    - Also called static dispatch
  - Doesn't require an extra lookup, so it's faster
- Virtual methods do support polymorphism:
  - Method is determined at run-time, from the object itself
    - Also called dynamic dispatch
  - *Essential* when methods are overridden by subclasses!
  - Slightly slower, due to the extra lookup

Object Oriented Programming Model

- Our simple example now supports simple class hierarchies and polymorphism
- Conceptually straightforward to implement in C
  - Structs to represent data for objects and classes
  - Implement virtual functions by storing function-pointers in the class descriptions
  - Look up which virtual function to call at run-time, *directly from the object itself*
- Note 1: almost all Java methods are virtual
  - …unlike C++, where member functions must explicitly be declared virtual

OOP Model (2)

- Note 2:
  - Many OOP languages represent virtual function pointers with a *virtual-function pointer table* (a.k.a. vtable)
- Our representation:

```
struct color_class {
  int   (*toRGB)(Color_Data *this);
  float (*getGrayScale)(Color_Data *this);
};
```

  - Our simple example includes more type information
- Frequently:
  - Class information contains an array of virtual function pointers (or references)
  - Individual functions are often referred to by slot-index
    - e.g. slot 0 = **`toRGB()`**, slot1 = **`getGrayScale()`**
- Some languages (like Java) refer to functions by name

OOP Model (3)

- Note 3: Our example is distinctly hard-coded…
  - Mapped our example classes to C structs and code
  - Doesn't support the same ability to dynamically load and run code that the Java VM provides!
- Java virtual machine uses sophisticated data structures to represent class information
  - …including fields, method signatures, method definitions, class hierarchy information…
- Allows Java VM to dynamically load class definitions and execute them
  - Even allows Java programs to generate new classes on the fly, then load and run them!