Designing Programs with Class

Version 0.1

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1 Object = structure + functions

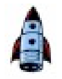
1.1 Functional rocket

Here's a review of the first program we wrote last semester. It's the program to launch a rocket, written in the Beginner Student Language:

```
(require 2htdp/image)
(require 2htdp/universe)

; Use the rocket key to insert the rocket here.
(define ROCKET (bitmap class0/rocket.png))

(define WIDTH 100)
(define HEIGHT 300)
(define MT-SCENE (empty-scene WIDTH HEIGHT))

; A World is a Number.
; Interp: distance from the ground in AU.

; render : World -> Scene
(check-expect (render 0)
              (place-image ROCKET (/ WIDTH 2) HEIGHT MT-SCENE))
(define (render h)
  (place-image ROCKET
               (/ WIDTH 2)
               (- HEIGHT h)
               MT-SCENE))

; next : World -> World
(check-expect (next 0) 7)
(define (next h)
  (+ h 7))

(big-bang 0
          (on-tick next)
          (to-draw render))
```

It's a shortcoming of our documentation system that we can't define ROCKET to be the rocket image directly, but as you can see this did the right thing:

```
> ROCKET
```



You can use the same trick, or you can copy this rocket image and paste it directly into DrRacket.

1.2 Object-oriented rocket

You'll notice that there are two significant components to this program. There is the data, which in this case is a number representing the height of the rocket, and the functions that operate over that class of data, in this case `next` and `render`.

This should be old-hat programming by now. But in this class, we are going to explore a new programming paradigm that is based on objects. Objects are an old programming concept that first appeared in the 1950s just across the Charles river. As a first approximation, you can think of an object as the coupling together of the two significant components of our program (data and functions) into a single entity: an object.

Since we are learning a new programming language, you will no longer be using BSL and friends. Instead, select Language|Choose Language... in DrRacket, then select the "Use the language declared in the source" option and add the following to the top of your program:

```
#lang class0
```

The way to define a class is with **define-class**:

```
(define-class world%
  (fields height))
```

This declares a new class of values, namely `world%` objects. (By convention, we will use the `%` suffix for the name of classes.) For the moment, `world%` objects consist only of data: they have one field, the `height` of the rocket.

Like a structure definition, this class definition defines a new kind of data, but it does not make any particular instance of that data. To make an new instance of a particular class, you use the **new** syntax, which takes a class name and expressions that produce a value for each field of the new object. Since a `world%` has one field, **new** takes the shape:

```
> (new world% 7)
(object:world% 7)
```

This creates a world% representing a rocket with height 7.

In order to access the data, we can invoke the height accessor method. Methods are like functions for objects and they are called (or invoked) by using the **send** form like so:

```
> (send (new world% 7) height)
7
```

This suggests that we can now re-write the data definition for Worlds:

```
; A World is a (new world% Number).
; Interp: height represents distance from the ground in AU.
```

To add functionality to our class, we define methods using the **define/public** form. In this case, we want to add two methods **on-tick** and **to-draw**:

```
; A World is a (new world% Number).
; Interp: height represents distance from the ground in AU.
(define-class world%
  (fields height)

  ; on-tick : ...
  (define/public (on-tick ...) ...)

  ; to-draw : ...
  (define/public (to-draw ...) ...))
```

We will return to the contracts and code, but now that we've seen how to define methods, let's look at how to invoke them in order to actually compute something. To call a defined method, we again use the **send** form, which takes an object, a method name, and any inputs to the method:

```
(send (new world% 7) on-tick ...)
```

This will call the **on-tick** method of the object created with (**new** world% 7). This is analogous to calling the next function on the world 7. The ellided code (...) is where we would write additional inputs to the method, but it's not clear what further inputs are needed, so now let's turn to the contract and method signatures for **on-tick** and **to-draw**.

When we designed the functional analogues of these methods, the functions took as input the world on which they operated, i.e. they had contracts like:

```
; tick : World -> World
; render : World -> Scene
```

But in an object, the data and functions are packaged together. Consequently, the method does not need to take the world input; that data is already a part of the object and the values of the fields are accessible using the **field** form.

That leads us to the following method signatures:

```
; A World is a (new world% Number).
; Interp: height represents distance from the ground in AU.
(define-class world%
  (fields height)

  ; on-tick : -> World
  (define/public (on-tick) ...)

  ; to-draw : -> Scene
  (define/public (to-draw) ...))
```

Since we have contracts and have seen how to invoke methods, we can now formulate test cases:

```
(check-expect (send (new world% 7) on-tick)
              (new world% 8))
(check-expect (send (new world% 7) to-draw)
              (place-image ROCKET
                           (/ WIDTH 2)
                           (- HEIGHT 7)
                           MT-SCENE))
```

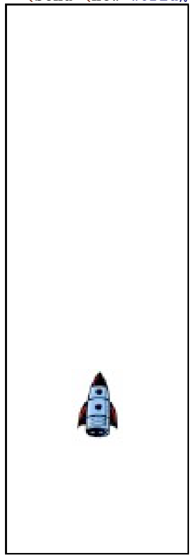
Finally, we can write the code from our methods:

```
; A World is a (new world% Number).
; Interp: height represents distance from the ground in AU.
(define-class world%
  (fields height)

  ; on-tick : -> World
  (define/public (on-tick)
    (new world% (add1 (field height))))

  ; to-draw : -> Scene
  (define/public (to-draw)
    (place-image ROCKET
                 (/ WIDTH 2)
                 (- HEIGHT (field height))
                 MT-SCENE)))
```

At this point, we can construct world% objects and invoke methods.

Examples:

```
> (new world% 7)
(object:world% 7)
> (send (new world% 7) on-tick)
(object:world% 8)
> (send (new world% 80) to-draw)
```



But if we want to see an animation, we need to have our program interact with the big-bang system. Since we are now writing programs in an object-oriented style, we have a new big-bang system that uses an interface more suited to objects. To import this OO-style big-bang, add the following to the top of your program:

```
(require class0/universe)
```

In the functional setting, we had to explicitly give a piece of data representing the state of the initial world and list which functions should be used for each event in the system. In other words, we had to give both data and functions to the big-bang system. In an object-oriented system, the data and functions are already packaged together, and thus the big-bang form takes a single argument: an object that both represents the initial world and implements the methods needed to handle system events such as to-draw and on-tick. (Our choice of method names was important;

had we used the names render and next, for example, big-bang would not have known how to make the animation work.)

So to launch our rocket, we simply do the following:

```
(big-bang (new world% 0))
```

Our complete program is:

```
#lang class0
(require 2htdp/image)
(require class0/universe)

; Use the rocket key to insert the rocket here.
(define ROCKET (bitmap class0/rocket.png))

(define WIDTH 100)
(define HEIGHT 300)
(define MT-SCENE (empty-scene WIDTH HEIGHT))

; A World is a (new world% Number).
; Interp: height represents distance from the ground in AU.
(define-class world%
  (fields height)

  ; on-tick : -> World
  (define/public (on-tick)
    (new world% (add1 (field height))))

  ; to-draw : -> Scene
  (define/public (to-draw)
    (place-image ROCKET
                 (/ WIDTH 2)
                 (- HEIGHT (field height))
                 MT-SCENE)))

(check-expect (send (new world% 7) on-tick)
              (new world% 8))
(check-expect (send (new world% 7) to-draw)
              (place-image ROCKET
                           (/ WIDTH 2)
                           (- HEIGHT 7)
                           MT-SCENE))

; Run, program, run!
(big-bang (new world% 0))
```

1.3 Landing and taking off

Let's now revise our program so that the rocket first descends toward the ground, lands, then lifts off again. Our current representation of a world is insufficient since it's ambiguous whether we are going up or down. For example, if the rocket is at 42, are we landing or taking off? There's no way to know. We can revise our data definition to included a representation of this missing information. A simple solution is to add a number representing the velocity of the rocket. When it's negative, we are moving toward the ground. When positive, we are taking off.

In the functional approach, this new design criterion motivated the use of compound data, which are represented with structures. With objects, atomic and compound data are represented the same way; all that changes are the number of fields contained in each object.

Our revised class definition is then:

```
(define-class world%
  (fields height velocity)
  ...)
```

When constructing `world%` objects now give two arguments in addition to the class name:

```
> (new world% 7 -1)
(object:world% 7 -1)
```

Both components can be accessed through the accessor methods:

```
> (send (new world% 7 -1) height)
7
> (send (new world% 7 -1) velocity)
-1
```

And within method definitions, we can refer to the values of fields using the **`field`** form. The signatures for our methods don't change, and rockets should render just the same as before, however we need a new behavior for **`on-tick`**. When a world ticks, we want its new height to be calculated based on its current height and velocity, and its new velocity is the same as the old velocity, unless the rocket has landed, in which case we want to flip the direction of the velocity.

First, let's make some test cases for the new **`on-tick`**:

```
(check-expect (send (new world% 0 1) on-tick)
              (new world% 1 1))
(check-expect (send (new world% 10 -2) on-tick)
              (new world% 8 -2))
```

```
(check-expect (send (new world% 0 -1) on-tick)
              (new world% -1 1))
```

Based on this specification, we revise the **`on-tick`** method definition as follows:

```
(define-class world%
  ...

  (define/public (on-tick)
    (new world%
         (+ (field velocity) (field height))
         (cond [(<= (field height) 0) (abs (field velocity))]
               [else (field velocity)])))
  ...)
```

Giving us an overall program of:

```
#lang class0
(require 2htdp/image)
(require class0/universe)

(define ROCKET (bitmap class0/rocket.png))

(define WIDTH 100)
(define HEIGHT 300)
(define MT-SCENE (empty-scene WIDTH HEIGHT))

; A World is a (new world% Number Number).
; Interp: height represents the height of the rocket in AU,
; velocity represents the speed of the rocket in AU/seconds.
(define-class world%
  (fields height velocity)

  ; on-tick : -> World
  (define/public (on-tick)
    (new world%
         (+ (field velocity) (field height))
         (cond [(<= (field height) 0) (abs (field velocity))]
               [else (field velocity)])))

  ; to-draw : -> Scene
  (define/public (to-draw)
    (place-image ROCKET
                 (/ WIDTH 2)
                 (- HEIGHT (field height))
                 (empty-scene WIDTH HEIGHT))))
```

```
(check-expect (send (new world% 0 1) to-draw)
              (place-image ROCKET
                           (/ WIDTH 2)
                           HEIGHT
                           MT-SCENE))

(check-expect (send (new world% 0 1) on-tick)
              (new world% 1 1))
(check-expect (send (new world% 10 -2) on-tick)
              (new world% 8 -2))
(check-expect (send (new world% 0 -1) on-tick)
              (new world% -1 1))

(big-bang (new world% HEIGHT -1))
```

1.4 Adding a moon

Adding more components is straightforward.

Here is a complete program that includes an orbiting moon:

```
#lang class0
(require 2htdp/image)
(require class0/universe)

(define ROCKET (bitmap class0/rocket.png))
(define MOON (circle 20 "solid" "blue"))

(define WIDTH 300)
(define HEIGHT 300)
(define MT-SCENE (empty-scene WIDTH HEIGHT))

; A World is a (new world% Number Number Number).
; Interp: height represents distance from the ground in AU.
; velocity represents the speed of the rocket in AU/sec.
; moon-height represents the height of the moon.
(define-class world%
  (fields height velocity moon-height)

  ; on-tick : -> World
  (define/public (on-tick)
    (new world%
         (+ (field velocity) (field height))
```

```
         (cond [(= (field height) 0) (abs (field velocity))]
               [else (field velocity)])
         (modulo (+ 5 (field moon-height)) 200)))

  ; to-draw : -> Scene
  (define/public (to-draw)
    (place-image MOON
                 (/ WIDTH 3)
                 (field moon-height)
                 (place-image ROCKET
                              (/ WIDTH 2) (- HEIGHT (field height))
                              MT-SCENE))))

(check-expect (send (new world% 0 1 100) to-draw)
              (place-image MOON
                           (/ WIDTH 3) 100
                           (place-image ROCKET (/ WIDTH 2) HEIGHT MT-
SCENE)))

(check-expect (send (new world% 0 1 100) on-tick)
              (new world% 1 1 105))
(check-expect (send (send (new world% 10 -2 100) on-
tick) height) 8)

(big-bang (new world% HEIGHT -1 100))
```

2 Designing classes

2.1 Designing Classes

One of the most important lessons of How to Design Programs is that the structure of code follows the structure of the data it operates on, which means that the structure of your code can be derived systematically from your data definitions. In this lecture, we see how to apply the design recipe to design data represented using classes as well as operations implemented as methods in these classes.

2.1.1 Atomic and Compound Data

We saw already in section 1 and in section ??? how to design classes that contain multiple pieces of data. Given a class defined as follows:

```
; A Posn is (new posn% Number Number)
(define-class posn%
  (fields x y)

  ...)
```

the template for a posn% method is:

```
; -> ???
(define (posn%-method)
  ... (field x) ... (field y) ...)
```

Here we see that our template lists the available parts of the posn% object, in particular the two fields x and y.

2.1.2 Enumerations

An enumeration is a data definition for a finite set of possibilities. For example, we can represent a traffic light like the ones on Huntington Avenue with a finite set of symbols, as we did in Fundies I:

```
;; A Light is one of:
;; - 'Red
;; - 'Green
;; - 'Yellow
```

Following the design recipe, we can construct the template for functions on Lights:

```
; Light -> ???
(define (light-temp l)
  (cond [(symbol=? 'Red l) ...]
        [(symbol=? 'Green l) ...]
        [(symbol=? 'Yellow l) ...]))
```

Finally, we can define functions over Lights, following the template.

```
; next : Light -> Light
; switch to the next light in the cycle
(define (next l)
  (cond [(symbol=? 'Red l) 'Green]
        [(symbol=? 'Green l) 'Yellow]
        [(symbol=? 'Yellow l) 'Red]))
(check-expect (next 'Green) 'Yellow)
(check-expect (next 'Red) 'Green)
(check-expect (next 'Yellow) 'Red)
```

That's all well and good for a function-oriented design, but we want to design this using classes, methods, and objects.

There are two obvious possibilities. First, we could create a light% class, with a field holding a Light. However, this fails to use classes and objects to their full potential. Instead, we will design a class for each state the traffic light can be in. Each of the three classes will have their own implementation of the next method, producing the appropriate Light.

```
#lang class0
; A Light is one of:
; - (new red%)
; - (new green%)
; - (new yellow%)

(define-class red%
  ; -> Light
  ; Produce the next traffic light
  (define/public (next)
    (new green%)))

(define-class green%
  ; -> Light
  ; Produce the next traffic light
  (define/public (next)
    (new yellow%)))

(define-class yellow%
  ; -> Light
  ; Produce the next traffic light
  (define/public (next)
    (new red%)))

(check-expect (send (new red%) next) (new green%))
(check-expect (send (new green%) next) (new yellow%))
(check-expect (send (new yellow%) next) (new red%))
```

If you have a `Light` `L`, how do you get the next light?

```
(send L next)
```

Note that there is no use of `cond` in this program, although the previous design using functions needed a `cond`. Instead, the `cond` is happening behind your back, because the object system picks the appropriate `next` method to call.

2.2 Unions and Recursive Unions

Unions are a generalization of enumerations to represent infinite families of data. One example is binary trees, which can contain arbitrary other data as elements. We'll now look at how to model binary trees of numbers, such as:

```
7         6              8
         / \            / \
        8   4          2   1
           / \
          3   2
```

How would we represent this with classes and objects?

```
#lang class0
; A BT is one of:
; - (new leaf% Number)
; - (new node% Number BT BT)
(define-class leaf%
  (fields number))

(define-class node%
  (fields number left right))

(define ex1 (new leaf% 7))
(define ex2 (new node% 6
                 (new leaf% 8)
                 (new node% 4
```

```
                          (new leaf% 3)
                          (new leaf% 2))))
(define ex3 (new node% 8
                 (new leaf% 2)
                 (new leaf% 1)))
```

We then want to design a method `count` which produces the number of numbers stored in a `BT`.

Here are our examples:

```
(check-expect (send ex1 count) 1)
(check-expect (send ex2 count) 5)
(check-expect (send ex3 count) 3)
```

Next, we write down the templates for methods of our two classes.

The template for `leaf%`:

```
; -> Number
; count the number of numbers in this leaf
(define/public (count)
 ... (field number) ...)
```

The template for `node%`:

```
; -> Number
; count the number of numbers in this node
(define/public (count)
 ... (field number) ...
 (send (field left) count) ...
 (send (field right) count) ...)
```

Now we provide a definition of the `count` method for each of our classes.

For `leaf%`:

```
; -> Number
; count the number of numbers in this leaf
(define/public (count)
  1)
```

For `node%`:

```
; -> Number
; count the number of numbers in this node
(define/public (count)
  (+ 1
      (send (field left) count)
      (send (field right) count)))
```

Next, we want to write the double function, which takes a number and produces two copies of the BT with the given number at the top. Here is a straightforward implementation for leaf%:

```
; Number -> BT
; double the leaf and put the number on top
(define/public (double n)
  (new node%
       n
       (new leaf% (field number))
       (new leaf% (field number))))
```

Note that (new leaf% (field number)) is just constructing a new leaf% object just like the one we started with. Fortunately, we have a way of referring to ourselves, using the identifier this. We can thus write the method as:

```
; Number -> BT
; double the leaf and put the number on top
(define/public (double n)
  (new node% n this this))
```

For node%, the method is very similar:

Since these two methods are so similar, you may wonder if they can be abstracted to avoid duplication. We will see how to do this in a subsequent class.

```
; Number -> BT
; double the node and put the number on top
(define/public (double n)
  (new node% n this this))
```

The full BT code is now:

```
#lang class0
; A BT is one of:
; - (new leaf% Number)
; - (new node% Number BT BT)

(define-class leaf%
  (fields number)
  ; -> Number
  ; count the number of numbers in this leaf
  (define/public (count)
  1)
  ; Number -> BT
  ; double the leaf and put the number on top
  (define/public (double n)
```

```
    (new node% n this this)))

(define-class node%
  (fields number left right)
  ; -> Number
  ; count the number of numbers in this node
  (define/public (count)
    (+ 1
       (send (field left) count)
       (send (field right) count)))
  ; Number -> BT
  ; double the node and put the number on top
  (define/public (double n)
    (new node% n this this)))

(define ex1 (new leaf% 7))
(define ex2 (new node% 6
                 (new leaf% 8)
                 (new node% 4
                      (new leaf% 3)
                      (new leaf% 2))))
(define ex3 (new node% 8
                 (new leaf% 2)
                 (new leaf% 1)))

(check-expect (send ex1 count) 1)
(check-expect (send ex2 count) 5)
(check-expect (send ex3 count) 3)

(check-expect (send ex1 double 5)
              (new node% 5 ex1 ex1))
(check-expect (send ex3 double 0)
              (new node% 0 ex3 ex3))
```

3 Inheritance and interfaces

3.1 Discussion of assignment 2

3.1.1 Lists

On the subject of the list finger exercises, we got email like this:

> We are not allowed to use `class0` lists; are we allowed to use `null` (aka `empty`), or must we create our own version of that too?

and:

> Should my functions also apply for empty lists (i.e. have empty lists be represented as objects), or could we simply use the built-in `empty` datatype (on which none of my methods would work)?

There are two things worth noting, one is important and one is not:

1. The `empty` value is a list and the assignment specifically prohibited using lists; so even if you could use `empty` to represent the empty list, this wouldn't live up to the specification of the problem.
2. You won't be able to represent the empty list with a value that is not an object. The problem asks you to implement methods that can be invoked on lists; the requirement to have methods dictates that lists are represented as objects since only an object can understand method sends. If the empty list were represented with `empty`, then `(send empty length)` would blow-up when it should instead produce `0`. Moreover, if the empty list were not represented as an object, the design of a `cons%` class will break too since the template for a method in the `cons%` class is something along the lines of:

   ```
   (define-class cons%
     (fields first rest)
     (define/public (method-template ...)
       (field first) ...
       (send (field rest) method-template ...)))
   ```

   Notice that the method is sent to the rest of this list. If the rest of the list is empty, then this will break unless the empty list is an object, and moreover, an object that understands `method-template`.

3.1.2 Zombie

On the subject of the zombie game, we got a bunch of emails like this:

> My partner and I have come upon a dilemma in Homework 2 in Honors Fundies 2 because we have not learned inheritance yet. We can have two separate classes Player and Zombie and tie them together in a union called Being, but that'll result in some significant copy-and-paste code. The alternative is to make one class called Being and in the *single* function that differs between players and zombies, use a `cond` based on a field (`'zombie` or `'player`). We were told not to do this, but we were also told copy-and-pasting code is bad...hence the dilemma.

and:

> My partner and I have been working through the current assignment and with our representation of zombies and players there is a lot of reused code. I was wondering if there is some form of inheritance in the `class0` language that has not been covered. I think that inheritance would make our current code much cleaner by solving the problem of reused code. Is there a way to implement inheritance in the `class0` language currently?

One of the subjects of today's lecture is inheritance, however let's step back and ask ourselves if this dilemma is really as inescapable as described.

First, let's consider the information that needs to be represented in a game. When you look at the game, you see several things: live zombies, dead zombies, a player, and a mouse. That might lead you to a representation of each of these things as a separate class, in which case you may later find many of the methods in these classes are largely identical. You would like to abstract to avoid the code duplication, but thus far, we haven't seen any class-based abstraction mechanisms. So there are at least two solutions to this problem:

1. Re-consider your data definitions.

   Program design is an iterative process; you are continually revising your data definitions, which induces program changes, which may cause you to redesign your data definitions, and so on. So when you find yourself wanting to copy and paste lots of code, you might want to reconsider how you're representing information in your program. In the case of zombie, you might step back and see that although the game consists of a player, dead zombies, live zombies, and a mouse, these things have much in common. What changes over time about each of them is their position. Otherwise, what makes them different is how they are rendered visually. But it's important to note that way any of these things are rendered does not change over the course of the game—a dead zombie is always drawn as a gray dot; a live zombie is always drawn as a green dot; etc. Taking this view, we can represent the position of each entity uniformly using a single class. This avoids duplicating method definitions since there is only a single class to represent each of these entities.

2. Abstract using the functional abstraction recipe of last semester.

   Just because we are in a new semester and studying a new paradigm of programming, we should not throw out the lessons and techniques we've previously learned. In particular, since we are writing programs in a multi-pararadigm language—one that accomodates both structural and functional programming and object-oriented programming—we can mix and match as our designs necessitate. In this case, we can apply the recipe for functional abstraction to the design of identical or similar methods, i.e. two methods with similar implementations can be abstracted to a single point of control by writing a helper function that encapsulates the common code. The method can then call the helper function, supplying as arguments values that encapsulate the differences of the original methods.

That said, one of the subjects of today's lecture will be an object-oriented abstraction mechanism that provides a third alternative to resolving this issue.

3.2 Inheritance

3.2.1 Method inheritance with binary trees

Last time, we developed classes for representing binary trees and wrote a couple methods for binary trees. The code we ended with was:

```
#lang class0
; A BT is one of:
; - (new leaf% Number)
; - (new node% Number BT BT)

(define-class leaf%
  (fields number)
  ; -> Number
  ; count the number of numbers in this leaf
  (define/public (count)
    1)
  ; Number -> BT
  ; double the leaf and put the number on top
  (define/public (double n)
    (new node% n this this)))
```

```
(define-class node%
  (fields number left right)
  ; -> Number
  ; count the number of numbers in this node
  (define/public (count)
    (+ 1
       (send (field left) count)
       (send (field right) count)))
  ; Number -> BT
  ; double the node and put the number on top
  (define/public (double n)
    (new node% n this this)))

(define ex1 (new leaf% 7))
(define ex2 (new node% 6
                 (new leaf% 8)
                 (new node% 4
                      (new leaf% 3)
                      (new leaf% 2))))
(define ex3 (new node% 8
                 (new leaf% 2)
                 (new leaf% 1)))

(check-expect (send ex1 count) 1)
(check-expect (send ex2 count) 5)
(check-expect (send ex3 count) 3)

(check-expect (send ex1 double 5)
              (new node% 5 ex1 ex1))
(check-expect (send ex3 double 0)
              (new node% 0 ex3 ex3))
```

One of the troublesome aspects of this code is the fact that the two implementations of `double` are identical. If we think by analogy to the structural version of this code, we have something like this:

```
#lang class0
; A BT is one of:
; - (make-leaf Number)
; - (make-node Number BT BT)
(define-struct leaf (number))
(define-struct node (number left right))

; BT Number -> BT
; Double the given tree and put the number on top.
```

```
(define (double bt n)
  (cond [(leaf? bt) (make-node n bt bt)]
        [(node? bt) (make-node n bt bt)]))
```

We would arrive at this code by developing the double function according to the design recipe; in particular, this code properly instantiates the template for binary trees. However, after noticing the duplicated code, it is straightforward to rewrite this structure-oriented function into an equivalent one that duplicates no code. All cases of the cond clause produce the same result, hence the cond can be eliminated, replaced by a single occurrence of the duplicated answer expressions:

```
; BT Number -> BT
; Double the given tree and put the number on top.
(define (double bt n)
  (make-node n bt bt))
```

But switching back to the object-oriented version of this code, it is not so simple to ”eliminate the cond”—there is no cond! The solution, in this context, is to abstract the identical method defintions to a common super class. That is, we define a third class that contains the method shared among leaf% and node%:

```
(define-class bt%
  ; -> BT
  ; Double this tree and put the number on top.
  (define/public (double n)
    (new node% n this this)))
```

The double method can be removed from the leaf% and node% classes and instead these class can rely on the bt% definition of double, but to do this we must establish a relationship between leaf%, node% and bt%: we declare that leaf% and node% are subclasses of bt%, and therefore they inherit the double method; it is as if the code were duplicated without actually writing it twice:

```
(define-class leaf%
  (super bt%)
  (fields number)
  ; -> Number
  ; count the number of numbers in this leaf
  (define/public (count)
    1))

(define-class node%
  (super bt%)
  (fields number left right)
  ; -> Number
  ; count the number of numbers in this node
  (define/public (count)
```

```
    (+ 1
       (send (field left) count)
       (send (field right) count))))
```

To accomodate this new feature—inheritance—we need to adjust our programming language. We’ll now program in class1, which is a superset of class0—all class0 programs are class1 programs, but not vice versa. The key difference is the addition of the (super *class-name*) form.

At this point we can construct binary trees just as before, and all binary trees understand the double method even though it is only defined in bt%:

```
> (new leaf% 7)
(object:leaf% 7)
> (send (new leaf% 7) double 8)
(object:node% 8 (object:leaf% 7) (object:leaf% 7))
> (send (send (new leaf% 7) double 8) double 9)
(object:node% 9 (object:node% 8 (object:leaf% 7) (object:leaf% 7))
(object:node% 8 (object:leaf% 7) (object:leaf% 7)))
```

3.2.2 ”Abstract” classes

At this point, it is worth considering the question: what does a bt% value represent? We have arrived at the bt% class as a means of abstracting identical methods in leaf% and node%, but if I say (new bt%), as I surely can, what does that mean? The answer is: nothing.

Going back to our data definition for BTs, it’s clear that the value (new bt%) is not a BT since a BT is either a (new leaf% Number) or a (new node% Number BT BT). In other words, a (new bt%) makes no more sense as a representation of a binary tree than does (new node% "Hello Fred" 'y-is-not-a-number add1). With that in mind, it doesn’t make sense for our program to ever construct bt% objects—they exist purely as an abstraction mechanism. Some languages, such as Java, allow you to enforce this property by declaring a class as ”abstract”; a class that is declared abstract cannot be constructed. Our language will not enforce this property, much as it does not enforce contracts. Again we rely on data definitions to make sense of data, and (new bt%) doesn’t make sense.

3.2.3 Data inheritance with binary trees

Inheritance allows us to share methods amongst classes, but it also possible to share data. Just as we observed that double was the same in both leaf% and node%, we can also observe that there are data similarities between leaf% and node%. In particular, both leaf% and node% contain a number field. This field can be abstracted just like double was—we can lift the field to the bt% super class and elimate the duplicated field in the subclasses:

```
(define-class bt%
  (fields number)
  ; -> BT
  ; Double this tree and put the number on top.
  (define/public (double n)
    (new node% n this this)))

(define-class leaf%
  (super bt%)
  ; -> Number
  ; count the number of numbers in this leaf
  (define/public (count)
    1))

(define-class node%
  (super bt%)
  (fields left right)
  ; -> Number
  ; count the number of numbers in this node
  (define/public (count)
    (+ 1
       (send (field left) count)
       (send (field right) count))))
```

The leaf% and node% class now inherit both the number field and the double method from bt%. This has a consequence for the class constructors. Previously it was straightforward to construct an object: you write down **new**, the class name, and as many expressions as there are fields in the class. But now that a class may inherit fields, you must write down as many expressions as there are fields in the class definition itself and in all of the super classes. What's more, the order of arguments is important. The fields defined in the class come first, followed by the fields in the immediate super class, followed by the super class's super classes, and so on. Hence, we still construct leaf%s as before, but the arguments to the node% constructor are changed: it takes the left subtree, the right subtree, and then the number at that node:

It's an unfortunate consequence of our documentation tool that the value is not printed in the same order it is constructed. For now, we hope you can just see through the confusion.

```
; A BT is one of:
; - (new leaf% Number)
; - (new node% BT BT Number)

> (new leaf% 7)
(object:leaf% 7)
> (new node% (new leaf% 7) (new leaf% 13) 8)
```

```
(object:node% 8 (object:leaf% 7) (object:leaf% 13))
```

Although none of our method so far have needed to access the number field, it is possible to access number in leaf% and node% (and bt%) methods as if they had their own number field. Let's write a sum method to make it clear:

Notice that the double method swapped the order of arguments when constructing a new node% to reflect the fact that the node constructor now takes values for its fields first, then values for its inherited fields.

```
(define-class bt%
  (fields number)
  ; -> BT
  ; Double this tree and put the number on top.
  (define/public (double n)
    (new node% this this n)))

(define-class leaf%
  (super bt%)
  ; -> Number
  ; count the number of numbers in this leaf
  (define/public (count)
    1)

  ; -> Number
  ; sum all the numbers in this leaf
  (define/public (sum)
    (field number)))

(define-class node%
  (super bt%)
  (fields left right)
  ; -> Number
  ; count the number of numbers in this node
  (define/public (count)
    (+ 1
       (send (field left) count)
       (send (field right) count)))

  ; -> Number
  ; sum all the numbers in this node
  (define/public (sum)
    (+ (field number)
       (send (field left) sum)
       (send (field right) sum))))
```

As you can see, both of the sum methods refer to the number field, which is inherited from bt%.

3.2.4 Inheritance with shapes

Let's consider another example and see how data and method inheritance manifests. This example will raise some interesting issues for how super classes can invoke the methods of its subclasses. Suppose we are writing a program that deals with shapes that have position. To keep the example succint, we'll consider two kinds of shapes: circles and rectangles. This leads us to a union data definition (and class definitions) of the following form:

We are using `+Real` to be really precise about the kinds of numbers that are allowable to make for a sensible notion of a shape. A circle with radius `-5` or `3+2i` doesn't make a whole lot of sense.

```
; A Shape is one of:
; - (new circ% +Real Real Real)
; - (new rect% +Real +Real Real Real)
; A +Real is a positive, real number.
(define-class circ%
  (fields radius x y))
(define-class rect%
  (fields width height x y))
```

Already we can see an opportunity for data abstraction since `circ%`s and `rect%`s both have `x` and `y` fields. Let's define a super class and inherit these fields:

```
; A Shape is one of:
; - (new circ% +Real Real Real)
; - (new rect% +Real +Real Real Real)
; A +Real is a positive, real number.
(define-class shape%
  (fields x y))
(define-class circ%
  (super shape%)
  (fields radius))
(define-class rect%
  (super shape%)
  (fields width height))
```

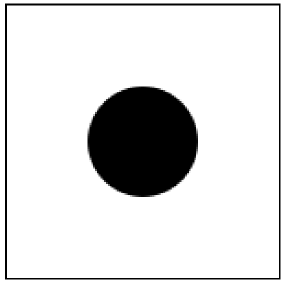
Now let's add a couple methods: `area` will compute the area of the shape, and `draw-on` will take a scene and draw the shape on the scene at the appropriate position:

```
(define-class circ%
  (super shape%)
  (fields radius)

  ; -> +Real
  (define/public (area)
    (* pi (sqr (field radius))))

  ; Scene -> Scene
```

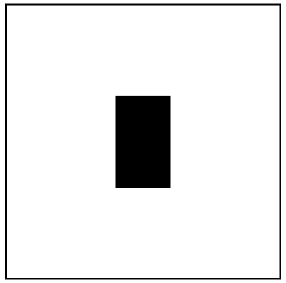
```
  ; Draw this circle on the scene.
  (define/public (draw-on scn)
    (place-image (circle (field radius) "solid" "black")
                 (field x)
                 (field y)
                 scn)))

(define-class rect%
  (super shape%)
  (fields width height)

  ; -> +Real
  ; Compute the area of this rectangle.
  (define/public (area)
    (* (field width)
       (field height)))

  ; Scene -> Scene
  ; Draw this rectangle on the scene.
  (define/public (draw-on scn)
    (place-image (rectangle (field width) (field height) "solid" "black")
                 (field x)
                 (field y)
                 scn)))
```

Examples:

```
> (send (new circ% 30 75 75) area)
2827.4333882308138
> (send (new circ% 30 75 75) draw-on (empty-scene 150 150))
```



```
> (send (new rect% 30 50 75 75) area)
1500
> (send (new rect% 30 50 75 75) draw-on (empty-scene 150 150))
```



The area method is truly different in both variants of the shape union, so we shouldn't attempt to abstract it by moving it to the super class. However, the two definitions of the draw-on method are largely the same. If they were identical, it would be easy to abstract the method, but until the two methods are identical, we cannot lift the definition to the super class. One way forward is to rewrite the methods by pulling out the parts that differ and making them seperate methods. What differs between these two methods is the expression constructing the image of the shape, which suggests defining a new method img that constructs the image. The draw-on method can now call img and rewriting it this way makes both draw-on methods identical; the method can now be lifted to the super class:

```
(define-class shape%
  (fields x y)

  ; Scene -> Scene
  ; Draw this shape on the scene.
  (define/public (draw-on scn)
    (place-image (img)
                 (field x)
                 (field y)
                 scn)))
```

But there is a problem with this code. While this code makes sense when it occurrs inside of rect% and circ%, it doesn't make sense inside of shape%. In particular, what does img mean here? The img method is a method of rect% and circ%, but not of shape%, and therefore the name img is unbound in this context.

On the other hand, observe that all shapes are either rect%s or circ%s. We therefore know that the object invoking the draw-on method understands the img message, since both rect% and circ% implement the img method. Therefore we can use **send** to invoke the img method on **this** object and thanks to our data definitions for shapes, it's guaranteed to succeed. (The message send would fail if **this** referred to

a shape%, but remember that shape%s don't make sense as objects in their own right and should never be constructed).

We arrive at the folllowing final code:

```
#lang class1
(require 2htdp/image)

; A Shape is one of:
; - (new circ% +Real Real Real)
; - (new rect% +Real +Real Real Real)
; A +Real is a positive, real number.
(define-class shape%
  (fields x y)

  ; Scene -> Scene
  ; Draw this shape on the scene.
  (define/public (draw-on scn)
    (place-image (send this img)
                 (field x)
                 (field y)
                 scn)))

(define-class circ%
  (super shape%)
  (fields radius)

  ; -> +Real
  ; Compute the area of this circle.
  (define/public (area)
    (* pi (sqr (field radius))))

  ; -> Image
  ; Render this circle as an image.
  (define/public (img)
    (circle (field radius) "solid" "black")))

(define-class rect%
  (super shape%)
  (fields width height)

  ; -> +Real
  ; Compute the area of this rectangle.
  (define/public (area)
    (* (field width)
       (field height)))
    ; -> Image
    ; Render this rectangle as an image.
    (define/public (img)
      (rectangle (field width) (field height) "solid" "black")))

  (check-expect (send (new rect% 10 20 0 0) area)
                200)
  (check-within (send (new circ% 10 0 0) area)
                (* pi 100)
                0.0001)
  (check-expect (send (new rect% 5 10 10 20) draw-on
                      (empty-scene 40 40))
                (place-image (rectangle 5 10 "solid" "black")
                             10 20
                             (empty-scene 40 40)))
  (check-expect (send (new circ% 4 10 20) draw-on
                      (empty-scene 40 40))
                (place-image (circle 4 "solid" "black")
                             10 20
                             (empty-scene 40 40)))
```

3.3 Interfaces

[This section is still under construction and will be posted soon. Please check back later.]

3.3.1 Lights, redux

- a look back at light
- add a draw method
- make it a world program that cycles through the lights
- what does it mean to be a light? next and draw
- alternative design of light class
- Q: what changes in world? A: nothing.
- add interface to light design. both alternatives implement it, and the world will work with anything that implements it

4 Larger system design: Snakes on a plane

4.1 Questions and answers

- Q: I've designed a single interface `being<%>` that subsumes both `zombie<%>` and `player<%>` in the current assignment. Do I still have to design a `zombie<%>` and `player<%>` interface?

  A: Yes. There are a couple reasons for this. One is that there really are some differences between the operations that should be supported by a player versus a zombie. For example, zombies eat brains; players don't. Another is that, as you are probably noticing, much of this course is about interface specification and implementation. As we build larger and larger programs, interfaces become a much more important engineering tool. An interface can be viewed as a contract—an agreement on the terms of engagement—between the implementor and the consumer of a software component. In this assignment, even though you are acting simultaneously as both of these parties, we are asking you to write down the agreement you are making between the world program that uses zombies and players and the classes that implement zombies and players. Part of our agreement with you, is that you'll write separate specifications; so that's what you need to do.

  That said, if really believe that there should be a single uniform interface that all zombies and players should adhere to, you can write a `being<%>` interface. You still need to write down the `zombie<%>` and `player<%>` interfaces, but if you're careful, you may be able to arrange things so that your classes that implement zombies and players declare to implement the `being<%>` interface which implies they also implement the `zombie<%>` and `player<%>` interface, respectively. We will cover this topic in more depth next Monday.

- Q: Interfaces often have overlapping sets of behaviors. For example, zombies and players share much of the same functionality. Is there a way to do abstraction at the interface level?

  A: In `class1`, there is currently no way to express this kind of abstraction. We will consider adding this feature and covering it in future lectures.

- Q: Which is considered a better design: a union with two variants, or a single variant with a Boolean field that indicates "which part of the union this data belongs to"? For example, is it better to have a `live-zombie%` and `dead-zombie%` class or a single `zombie%` class with a `dead?` field.

  A: One of the themes of this and last semester is that once you have settled on choice for the representation of information in your program, the structure of your program follows the structure of that data. We've trained you to systematically derive code structure from data structure; there's a recipe—you don't even have to think. That's great because it frees up significant quantities of the most precious and limited resource in computing: your brain. But unfortunately, that recipe kicks in only after you've chosen how information will be represented, i.e. after you've written down data definitions. Much of the hard work in writing programs, and where your creative energy and brain power is really needed, is going from information to representation. There is no recipe for this part of program design. You need to develop the ability to analyze problems, take an account of what knowledge needs to be represented to solve a problem, and practice making decisions about how that knowledge can be represented computationally. The good news is you don't have to be struck by divine inspiration to manage this step. Program design is a process of iterative refinement: make some choices, follow the recipe. You will discover ways to improve your initial choices, so go back and revise, then carry out the changes in code structure those design decision entail. Rinse and repeat.

This is a long winded way of saying: there is no universal "right" answer to this question. It will depend on the larger context. That said, there are some important things to take into account for this particular question. It is much easier to add new variants to a union than it is to create Boolean values other than `true` and `false`. Good program design is often based on anticipating future requirements. If you think it's possible that there might be some other kind of zombie down the road, the union design will be less painful to extend and maintain.

- Q: The **`define-interface`** mechanism is a way of enforcing that a class implements a certain set of method names, but is there a way of enforcing things like the number of arguments one of these methods must accept?

  A: There are no linguistic mechanisms, but there are meta-linguistic mechanisms. This is no different than our approach last semester to enforcing things like the number of arguments a function accepts. Our approach has been to write down contracts and purpose statements, which specify these things, and unit tests, which check that we've followed the specification. Our language does not enforce these specifications, but that is really just a detail of the particulars of the languages we've been using. Even though contracts are not a language feature (in the languages we've used so far), they are an important concept for organizing software components.

  It is important to keep in mind that an interface is more than a set of method names. Think of this analogously to structures: `define-struct` gives you a mechanism for defining structures, but a structure does not a data definition make. We now have **`define-interface`**, but an interface is more than a set of method names; it is a set of method names with contracts and purpose statements. Only the method name part is enforced, but the concept of an interface is what's important. It is a useful tool for organizing and developing software components. Even if we didn't have ***`define-interface`***, interfaces would be a useful conceptual tool for writing programs.

4.2 Information in the Snake Game

In the previous lecture, we introduced a lot of important new concepts such as interfaces and data and method inheritance for class-based abstraction. Today we are going to see these concepts being applied in the context of a larger program design that we will develop together. It's a game you've all seen and designed before; we're going to develop a class-based version of the Snake Game.

Our first task in designing the Snake Game is to take an account of the information that our program will need to represent. This includes:

- a system of coordinates
- a snake, which has
  - direction
  - segments
- food
- a world

4.3 The world

Let's start by designing a minimal `world%` class. We will iteratively refine it later to add more an more features. For now, let's just have the snake move.

```
; A World is a (new world% Snake Food).
(define-class world%
  (fields snake food)

  (define/public (on-tick)
    (new world%
         (send (field snake) move)
         (field food)))

  (define/public (tick-rate) 1/8)

  (define/public (to-draw)
    (send (field food) draw
          (send (field snake) draw MT-SCENE))))
```

4.4 Coordinate interface

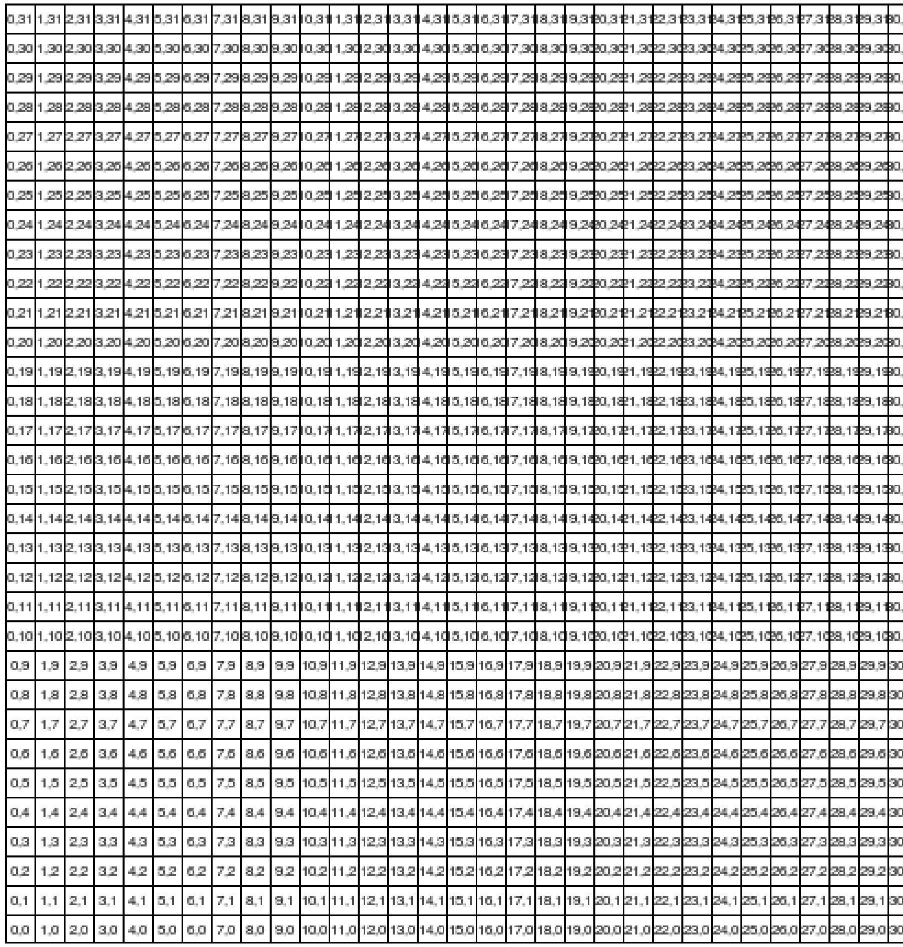
Let's focus on the system of coordinates. There are really two coordinate systems we will need to represent; one is necessitated by the animation system we are using, the other by the logic of the Snake Game. We are consumers of the `big-bang` animation system, which uses a pixel-based, graphics-coordinate system (meaning the origin is at the Northwest corner). This is part of `big-bang`'s interface, which we don't have the power to change, and therefore we have to communicate to `big-bang` using pixels in graphics-coordinates. In general, when we design programs, the interfaces of libraries we use impose obligations on our code.

On the other hand, using pixel-based graphics-coordinates is probably not the best representation choice for the information of the Snake Game. We'll be better off if we design our own representation and have our program translate between representations at the communication boundaries between our code and `big-bang`. Let's use a grid-based coordinate system where the origin is the Southwest corner. We can define a mapping between the coordinate systems by defining some constants such as the grid size and the size of the screen:

```
#lang class1
(define WIDTH  32) ; in grid units
(define HEIGHT 32) ; in grid units
(define SIZE   16) ; in pixels / grid unit
(define WIDTH-PX  (* SIZE WIDTH))  ; in pixels
(define HEIGHT-PX (* SIZE HEIGHT)) ; in pixels
```

This defines that our game is logically played on a 32x32 grid, which we will render visually as a 512x512 pixel image. This are the values we cooked up in class, which results in the following grid for our game:

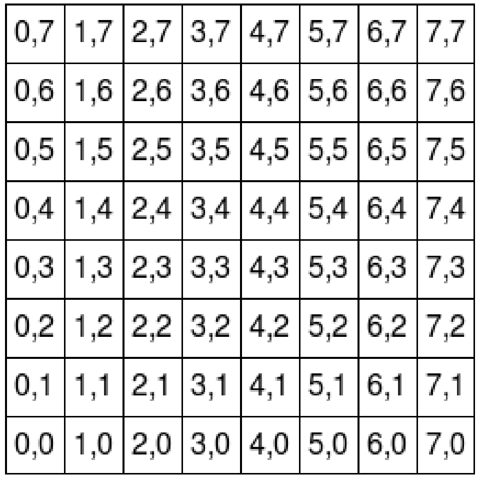
As an exercise, try to write an expression that produces this image.



But for the sake of our notes, let's develop the game for a much smaller grid that is rendered on a larger scale. It will be easy to change our definitions at the end in order to recover the original design. If done properly, all of test cases will remain unaffected by the change.

```
(define WIDTH   8) ; in grid units
(define HEIGHT  8) ; in grid units
(define SIZE   32) ; in pixels / grid unit
```

This defines that our game is logically played on a 8x8 grid, which we will render visually as a 256x256 pixel image. The grid for our game now looks like:



0,7	1,7	2,7	3,7	4,7	5,7	6,7	7,7
0,6	1,6	2,6	3,6	4,6	5,6	6,6	7,6
0,5	1,5	2,5	3,5	4,5	5,5	6,5	7,5
0,4	1,4	2,4	3,4	4,4	5,4	6,4	7,4
0,3	1,3	2,3	3,3	4,3	5,3	6,3	7,3
0,2	1,2	2,2	3,2	4,2	5,2	6,2	7,2
0,1	1,1	2,1	3,1	4,1	5,1	6,1	7,1
0,0	1,0	2,0	3,0	4,0	5,0	6,0	7,0

Now we need to consider the interface for coordinates (henceforth, the term "coordinate" refers to our representation of coordinates in the Snake Game, not the graphics-coordinates of big-bang). What do we need to do with coordinates? Here's a coarse first approximation:

- Compare two coordinates for equality.
- Draw something at a coordinate on to a scene.
- Move a coordinate.
- Check that a coordinate is on the board.

This list suggest the following interface for coordinates:

```
; A Coord implements coord<%>.
(define-interface coord<%>
  [; Coord -> Boolean
   ; Is this coordinate at the same position as the given one?
   compare
   ; Scene -> Scene
   ; Draw this coordinate on the scene.
   draw
   ; -> Coord
   ; Move this coordinate.
   move
   ; -> Boolean
   ; Is this coordinate on the board?
   check])
```

This is a good place to start, but as we start thinking about what these methods should do and how we might write them, some issues should come to mind. For example, in thinking about the what: what should be drawn when the draw method is invoked? Perhaps we want the coordinate "to just know" what should be drawn, which suggests that when we implement coordinates they should contain data representing what to draw. Perhaps we want to tell the draw method what to draw, which suggests we should revise the contract to include an argument or arguments that represent what to draw. For the time-being, let's decide that the coordinate will know what to draw.

In the thinking about the how: how do you imagine the draw coordinate will be written? Assuming we know what to draw, the next question is how will the method know where to draw it? We have a coordinate, which is a grid coordinate, but will need to use place-image to actually draw that image on the given scene. But place-image works in the pixel-based graphics-coordinate system. We need to be able to convert a coordinate to a pixel-based graphics-coordinate in order to write the draw method, but there is nothing in the interface that gives us that capability, and the interface is all we will have to work with. This suggests we should revise the interface to include this needed behavior.

Similarly, if we consider how to write the compare method, we will want to compare the x- and y-components of the given coordinate with the x- and y-components of this coordinate. Again, there is nothing in the interface as given that allows this, so we need to revise.

Now consider the move method. How can we write it? What do we expect to happen? There's not enough information to know—should the coordinate move up? Down? Right three and down seven? Hard to say. While we might expect a coordinate to know how to draw itself, we cannot expect a coordinate to know which way to move itself. This suggests we need to add inputs to the method that represent this needed information. For the purposes of our game, a position needs to be able to move one grid unit in one of four directions. Let's design the representation of a direction and a directional input to the move method.

Finally, the names check and compare are less informative than they could be. The compare method answers the question "are two coordinates at the same position?", so let's instead call it same-pos?. The check method answers the question "is this coordinate on the board?", so let's instead call it on-board?.

Interface design is incredibly important, especially when, unlike in our current situation, it is not easy to revise in the future. Modern computer systems are littered with detritus of past interface design choices because interfaces are difficult and expensive, if not impossible, to change. As an example, the developers of the UNIX operating system, which was developed in the 1970s and is now the basis of both Linux and Mac OS, made the choice to save characters and call the operation that creates a file "CREAT". Forty years later, I'm writing these notes on a portable computer while flying from Boston to Houston. My machine, which weighs far less than any computer that ran UNIX in the 70's, has not one, but two 2.66 GHz processors and 8 gigs of RAM: unimaginable computing resources in the 70s. And yet, when my OS wants to make a new file, it calls the "CREAT" function—not because that missing "E" is a computational extravangance I cannot afford, far from it, but because it is simply too difficult a task to realize a redesign of the interface between my computer and its operating system. The unforunate thing about interfaces is that when they change, all parties that have agreed to that interface must change as well. Too many people, programs, and devices have agreed to the UNIX interface to make changing "CREAT" to "CREATE" worthwhile.

You won't be able to make the perfect interface on the first try, but the closer you get, the better your life will be in the future.

Revising our interface as described above, we arrive at the following:

```
; A Coord implements coord<%>.
(define-interface coord<%>
  [; Coord -> Boolean
   ; Is this coordinate at the same position as the given one?
   same-pos?
   ; Scene -> Scene
   ; Draw this coordinate on the scene.
   draw
   ; Dir -> Coord
   ; Move this coordinate in the given direction.
   move
   ; -> Boolean
   ; Is this coordinate on the board?
   on-board?
   ; -> Nat
```

```
   ; The {x,y}-component of grid-coordinate.
   x y
   ; -> Nat
   ; The {x,y}-component of pixel-graphics-coordinate.
   x-px y-px])
```

We haven't designed Dir data definition for representing direction; let's take care of that quickly. In our game, a direction is one of four possibilities, i.e. it is an enumeration. We could use a class-based enumeration, but for the sake of simplicity, let's just use strings and say that:

```
; A Dir is one of:
; - "left"
; - "right"
; - "up"
; - "down"
```

This representation has the nice property of being a subset of big-bang's KeyEvent representation, so we can rely on the coincidence and handle the "up" key event by moving in the "up" direction without need to convert between representations.

4.5 An implementation of coordinates: segments

At this point, we've flushed out enough of the initial design of the coordinate interface we can now start working on an implementation of it. There are two components that will implement the coordinate interface: segments and food. Let's start with segments.

```
; A Segment is a (new seg% Int Int)
; Interp: represents a segment grid-coordinate.
(define-class seg%
  (implements coord<%>)
  (fields x y)
  ...)
```

Our template for seg% methods is:

```
; ? ... -> ?
(define/public (seg-template ...)
  (field x) ... (field y) ...)
```

We've now made a data definition for segments and committed ourselves to implementing the interface. This obligates us to implement all of the methods in coord%. We've decided to implement the coord% using a class with an x and y field. This satisfies part of our implementation right off the bat: we get an x and y method by definition. Let's now do same-pos?:

```
(check-expect (send (new seg% 0 0) same-pos? (new seg% 0 0)) true)
(check-expect (send (new seg% 0 0) same-pos? (new seg% 1 0)) false)
```

```
                                                          "seg%"
  (define/public (same-pos? c)
    (and (= (field x) (send c x))
         (= (field y) (send c y))))
```

And now draw:

```
(check-expect (send (new seg% 0 0) draw MT-SCENE)
              (place-image (square SIZE "solid" "red")
                           (* 1/2 SIZE)
                           (- HEIGHT-PX (* 1/2 SIZE))
                           MT-SCENE))
```

```
                                                          "seg%"
  (define/public (draw scn)
    (place-image (square SIZE "solid" "red")
                 (x-px)
                 (y-px)
                 scn))
```

And now move:

```
(check-expect (send (new seg% 0 0) move "up")    (new seg%  0  1))
(check-expect (send (new seg% 0 0) move "down")  (new seg%  0 -1))
(check-expect (send (new seg% 0 0) move "left")  (new seg% -1  0))
(check-expect (send (new seg% 0 0) move "right") (new seg%  1  0))
```

```
                                                          "seg%"
  (define/public (move d)
    (cond [(string=? d "up")
           (new seg% (field x) (add1 (field y)))]
          [(string=? d "down")
           (new seg% (field x) (sub1 (field y)))]
          [(string=? d "left")
           (new seg% (sub1 (field x)) (field y))]
          [(string=? d "right")
           (new seg% (add1 (field x)) (field y))]))
```

And now on-board?:

```
(check-expect (send (new seg% 0  0) on-board?) true)
```

```
(check-expect (send (new seg% 0 -1) on-board?) false)
(check-expect (send (new seg% 0 (sub1 HEIGHT)) on-board?) true)
(check-expect (send (new seg% 0 HEIGHT) on-board?) false)
```

```
                                                          "seg%"
  (define/public (on-board?)
    (and (<= 0 (field x) (sub1 WIDTH))
         (<= 0 (field y) (sub1 HEIGHT))))
```

And finally, the x-px and y-px methods:

```
(check-expect (send (new seg% 0 0) x-px) (* 1/2 SIZE))
(check-expect (send (new seg% 0 0) y-px) (- HEIGHT-
PX (* 1/2 SIZE)))
```

```
                                                          "seg%"
  (define/public (x-px)
    (* (+ 1/2 (field x)) SIZE))
  (define/public (y-px)
    (- HEIGHT-PX (* (+ 1/2 (field y)) SIZE)))
```

That completes all of the obligations of the seg% interface.

4.6 Another implementation of coordinates: food

Food is another implementation of the coord<%> interface, and it is largely similar to the seg% class, which suggests that seg% and food% may be good candidates for abstraction, but that's something to worry about later. For now, let's implement food%. Since we've already been through the design of seg%, we'll do food% quickly:

```
; A Food is a (new food% Nat Nat).
(define-class food%
  (implements coord<%>)
  (fields x y)

  (define/public (same-pos? c)
    (and (= (field x) (send c x))
         (= (field y) (send c y))))

  (define/public (draw scn)
    (place-image (square SIZE "solid" "green")
                 (x-px)
                 (y-px)
                 scn))
(define/public (move d)
  (cond [(string=? d "up")
         (new food% (field x) (add1 (field y)))]
        [(string=? d "down")
         (new food% (field x) (sub1 (field y)))]
        [(string=? d "left")
         (new food% (sub1 (field x)) (field y))]
        [(string=? d "right")
         (new food% (add1 (field x)) (field y))]))

(define/public (on-board?)
  (and (<= 0 (field x) (sub1 WIDTH))
       (<= 0 (field y) (sub1 HEIGHT))))

(define/public (x-px)
  (* (+ 1/2 (field x)) SIZE))
(define/public (y-px)
  (- HEIGHT-PX (* (+ 1/2 (field y)) SIZE))))
```

You'll notice that this class definition is nearly identical to the definition of `seg%`. The key differences are in `move` and `draw`. We'll hold off on abstracting for now.

4.7 Representing the snake

What information needs to be represented in a snake?

- Direction
- Segments

What are the operations we need to perform on snakes?

```
(define-interface snake<%>
  [; -> Snake
   ; Move this snake in its current direction.
   move
   ; -> Snake
   ; Grow this snake in its current direction.
   grow
   ; Dir -> Snake
   ; Turn this snake in the given direction.
   turn
   ; Scene -> Scene
   ; Draw this snake on the scene.
```

```
   draw])
```

Here's a possible data definition:

```
; A Snake is a (new snake% Dir [Listof Seg])
(define-class snake%
  (fields dir segs))
```

But after a moment of reflection, you will notice that a snake with no segments doesn't make sense—a snake should always have at least one segment. Moreover, we need to settle on an interpretion of the order of the list; either the front of the list is interpreted as the front of the snake or the rear of the list is interpreted as the front of the snake. Together, non-emptiness and order let us determine which element is the head of the snake.

Here's our revised data definition:

```
; A Snake is a (new snake% Dir (cons Seg [Listof Seg]))
(define-class snake%
  (fields dir segs)
  (implements snake<%>)
  ...)
```

An alternative data definition that might be worth considering is:

```
; A Snake is a (new snake% Dir Seg [Listof Seg])
(define-class snake%
  (fields dir head segs))
```

But for the time being let's stick with the former one.

Now let's implement the interface. Here's the template:

```
; ? ... -> ?
(define/public (snake-template ...)
  (field dir) ... (field segs) ...)
```

The `move` method works by moving the head of the snake and dropping the last element of the list of segments:

```
(check-expect (send (new snake% "right" (list (new seg% 0 0))) move)
              (new snake% "right" (list (new seg% 1 0))))
```

"snake%"

```
(define/public (move)
  (new snake%
       (field dir)
       (cons (send (first (field segs)) move (field dir))
                (all-but-last (field segs)))))
```

This relies on a helper function, `all-but-last`, which is straightforward to write (recall that `segs` is a non-empty list):

```
  (check-expect (all-but-last (list "x")) empty)
  (check-expect (all-but-last (list "y" "x")) (list "y"))

  ; (cons X [Listof X]) -> [Listof X]
  ; Drop the last element of the given list.
  (define (all-but-last ls)
    (cond [(empty? (rest ls)) empty]
          [else (cons (first ls)
                      (all-but-last (rest ls)))]))
```

The `grow` method is much like `move`, except that no element is dropped from the segments list:

```
  (check-expect (send (new snake% "right" (list (new seg% 0 0))) grow)
                (new snake% "right" (list (new seg% 1 0)
                                          (new seg% 0 0))))

                                                       "snake%"
    (define/public (grow)
      (new snake%
           (field dir)
           (cons (send (first (field segs)) move (field dir))
                 (field segs))))
```

Now let's write the `turn` method:

```
  (check-expect (send (new snake% "left" (list (new seg% 0 0))) turn "up")
                (new snake% "up" (list (new seg% 0 0))))

                                                       "snake%"
    (define/public (turn d)
      (new snake% d (field segs)))
```

And finally, `draw`:

```
  (check-expect (send (new snake% "left" (list (new seg% 0 0))) draw MT-
SCENE)
                (send (new seg% 0 0) draw MT-SCENE))

                                                       "snake%"
    (define/public (draw scn)
      (foldl (λ (s scn) (send s draw scn))
```

```
             scn
             (field segs)))
```

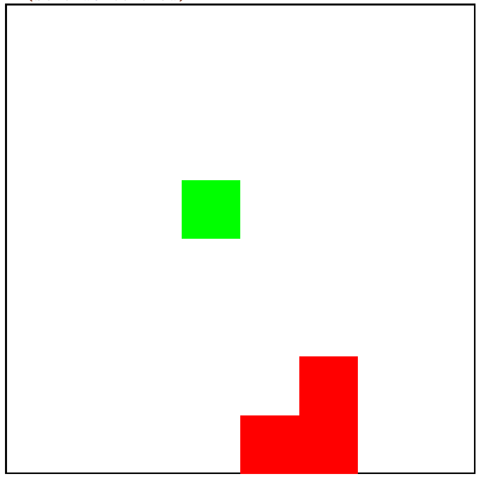
As this method shows, functions and methods can co-exist nicely in a single language.

4.8 Seeing the world

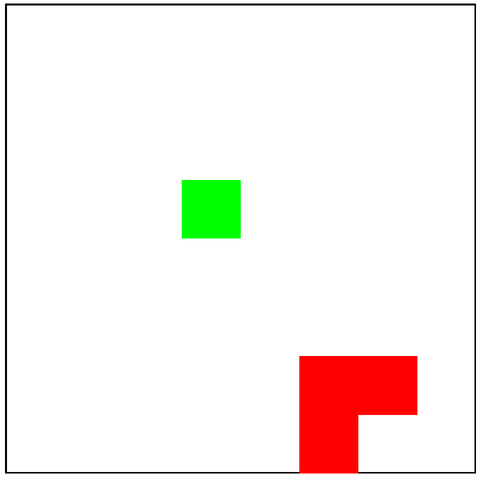
At this point we have a working but incomplete system and we can interact with it in the interactions window:

Examples:

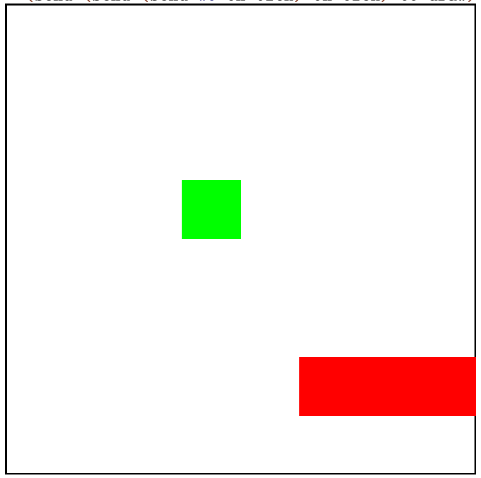
```
  > (define w0 (new world%
                    (new snake%
                         "right"
                         (list (new seg% 5 1)
                               (new seg% 5 0)
                               (new seg% 4 0)))
                    (new food% 3 4)))
  > (send w0 to-draw)
```



```
  > (send (send w0 on-tick) to-draw)
```



```
> (send (send (send w0 on-tick) on-tick) to-draw)
```



We'll leave it at this point and further the refine the program in the future.

4.9 The whole ball of wax

```
#lang class1
(require 2htdp/image)
(require class1/universe)

(define WIDTH   8) ; in grid units
(define HEIGHT  8) ; in grid units
(define SIZE   32) ; in pixels / grid unit
(define WIDTH-PX  (* SIZE WIDTH))  ; in pixels
(define HEIGHT-PX (* SIZE HEIGHT)) ; in pixels
(define MT-SCENE (empty-scene WIDTH-PX HEIGHT-PX))

; A World is a (new world% Snake Food).
(define-class world%
  (fields snake food)

  (define/public (on-tick)
    (new world%
         (send (field snake) move)
         (field food)))

  (define/public (tick-rate) 1/8)

  (define/public (to-draw)
    (send (field food) draw
          (send (field snake) draw MT-SCENE))))


; A Coord implements coord<%>.
(define-interface coord<%>
  [; Coord -> Boolean
   ; Is this coordinate at the same position as the given one?
   same-pos?
   ; Scene -> Scene
   ; Draw this coordinate on the scene.
   draw
   ; Dir -> Coord
   ; Move this coordinate in the given direction.
   move
   ; -> Boolean
   ; Is this coordinate on the board?
   on-board?
   ; -> Nat
   ; The {x,y}-component of grid-coordinate.
   x y
   ; -> Nat
   ; The {x,y}-component of pixel-graphics-coordinate.
   x-px y-px])

; A Dir is one of:
; - "left"
; - "right"
; - "up"
; - "down"

; A Segment is a (new seg% Int Int)
; Interp: represents a segment grid-coordinate.
(define-class seg%
  (implements coord<%>)
  (fields x y)
  (define/public (same-pos? c)
    (and (= (field x) (send c x))
         (= (field y) (send c y))))
  (define/public (draw scn)
    (place-image (square SIZE "solid" "red")
                 (x-px)
                 (y-px)
                 scn))
  (define/public (move d)
    (cond [(string=? d "up")
           (new seg% (field x) (add1 (field y)))]
          [(string=? d "down")
           (new seg% (field x) (sub1 (field y)))]
          [(string=? d "left")
           (new seg% (sub1 (field x)) (field y))]
          [(string=? d "right")
           (new seg% (add1 (field x)) (field y))]))
  (define/public (on-board?)
    (and (<= 0 (field x) (sub1 WIDTH))
         (<= 0 (field y) (sub1 HEIGHT))))
  (define/public (x-px)
    (* (+ 1/2 (field x)) SIZE))
  (define/public (y-px)
    (- HEIGHT-PX (* (+ 1/2 (field y)) SIZE))))

(check-expect (send (new seg% 0 0) same-pos? (new seg% 0 0)) true)
(check-expect (send (new seg% 0 0) same-pos? (new seg% 1 0)) false)
```

```
  (check-expect (send (new seg% 0 0) draw MT-SCENE)
                (place-image (square SIZE "solid" "red")
                             (* 1/2 SIZE)
                             (- HEIGHT-PX (* 1/2 SIZE))
                             MT-SCENE))
  (check-expect (send (new seg% 0 0) move "up")    (new seg%  0  1))
  (check-expect (send (new seg% 0 0) move "down")  (new seg%  0 -1))
  (check-expect (send (new seg% 0 0) move "left")  (new seg% -1  0))
  (check-expect (send (new seg% 0 0) move "right") (new seg%  1  0))
  (check-expect (send (new seg% 0  0) on-board?) true)
  (check-expect (send (new seg% 0 -1) on-board?) false)
  (check-expect (send (new seg% 0 (sub1 HEIGHT)) on-board?) true)
  (check-expect (send (new seg% 0 HEIGHT) on-board?) false)
  (check-expect (send (new seg% 0 0) x-px) (* 1/2 SIZE))
  (check-expect (send (new seg% 0 0) y-px) (- HEIGHT-
PX (* 1/2 SIZE)))

  ; A Food is a (new food% Nat Nat).
  (define-class food%
    (implements coord<%>)
    (fields x y)

    (define/public (same-pos? c)
      (and (= (field x) (send c x))
           (= (field y) (send c y))))

    (define/public (draw scn)
      (place-image (square SIZE "solid" "green")
                   (x-px)
                   (y-px)
                   scn))

    (define/public (move d)
      (cond [(string=? d "up")
             (new food% (field x) (add1 (field y)))]
            [(string=? d "down")
             (new food% (field x) (sub1 (field y)))]
            [(string=? d "left")
             (new food% (sub1 (field x)) (field y))]
            [(string=? d "right")
             (new food% (add1 (field x)) (field y))]))

    (define/public (on-board?)
      (and (<= 0 (field x) (sub1 WIDTH))
           (<= 0 (field y) (sub1 HEIGHT))))
  (define/public (x-px)
    (* (+ 1/2 (field x)) SIZE))
  (define/public (y-px)
    (- HEIGHT-PX (* (+ 1/2 (field y)) SIZE))))

(define-interface snake<%>
  [; -> Snake
   ; Move this snake in its current direction.
   move
   ; -> Snake
   ; Grow this snake in its current direction.
   grow
   ; Dir -> Snake
   ; Turn this snake in the given direction.
   turn
   ; Scene -> Scene
   ; Draw this snake on the scene.
   draw])

; A Snake is a (new snake% Dir Seg [Listof Seg])
(define-class snake%
  (fields dir segs)
  (define/public (move)
    (new snake%
         (field dir)
         (cons (send (first (field segs)) move (field dir))
               (all-but-last (field segs)))))

  (define/public (grow)
    (new snake%
         (field dir)
         (cons (send (first (field segs)) move (field dir))
               (field segs))))

  (define/public (turn d)
    (new snake% d (field segs)))

  (define/public (draw scn)
    (foldl (λ (s scn) (send s draw scn))
           scn
           (field segs))))

(check-expect (send (new snake% "right" (list (new seg% 0 0))) move)
              (new snake% "right" (list (new seg% 1 0))))
(check-expect (send (new snake% "right" (list (new seg% 0 0))) grow)
              (new snake% "right" (list (new seg% 1 0)
```

```
                                                (new seg% 0 0))))
  (check-expect (send (new snake% "left" (list (new seg% 0 0))) turn "up")
                (new snake% "up" (list (new seg% 0 0))))
  (check-expect (send (new snake% "left" (list (new seg% 0 0))) draw MT-
SCENE)
                (send (new seg% 0 0) draw MT-SCENE))

  (check-expect (all-but-last (list "x")) empty)
  (check-expect (all-but-last (list "y" "x")) (list "y"))

  ; (cons X [Listof X]) -> [Listof X]
  ; Drop the last element of the given list.
  (define (all-but-last ls)
    (cond [(empty? (rest ls)) empty]
          [else (cons (first ls)
                      (all-but-last (rest ls)))]))

  (big-bang (new world%
                 (new snake%
                      "right"
                      (list (new seg% 5 1)
                            (new seg% 5 0)
                            (new seg% 4 0)))
                 (new food% 3 4)))
```

5 Universe

5.1 A look at the Universe API

Today we're going to start looking at the design of multiple, concurrently running programs that communicate we each other. We will use the `universe` system as our library for communicating programs.

The basic universe concept is that there is a "universe" program that is the administrator of a set of world programs. The universe and the world programs can communicate with each other by sending messages, which are represented as S-Expressions.

So far we have focused on the design of single programs; we are now going to start looking at the design of communicating systems of programs.

In addition to these notes, be sure to read the documentation on section ???.

5.2 Messages

A message is represented as an S-Expression. Here is there is their data definition:

An S-expression is roughly a nested list of basic data; to be precise an S-expression is one of:

- a string,
- a symbol,
- a number,
- a boolean,
- a char, or
- a list of S-expressions.

The way that a world program sends a message to the universe is by constructing a package:

```
; A Package is a (make-package World SExp).
```

The world component is the new world just like the event handler's produced for single world programs. The s-expression component is a message that is sent to the universe.

5.3 Simple universe example

As a simple example, let's look at a world program that counts up and sends messages to a universe server as it counts. In this simple example there is only one world that communicates with the server, and the server does nothing but receive the count message (it sends no messages back to the world).

Let's start with the counting world program:

```
#lang class1
(require class1/universe)
(require 2htdp/image)

(define-class counter-world%
  (fields n)

  (define/public (on-tick)
    (new counter-world% (add1 (field n))))

  (define/public (tick-rate)
    1)

  (define/public (to-draw)
    (overlay (text (number->string (field n))
                   40
                   "red")
             (empty-scene 300 100))))

(big-bang (new counter-world% 0))
```

When you run this program, you see the world counting up from zero.

Now to register this program with a universe server, we need to implement a `register` method that produces a string that is the IP address of the server. (Since we're going to run the universe and world on the same computer, we will use `LOCALHOST` which is bound to the address of our computer.)

```
                                                  "world%"
  (define/public (register) LOCALHOST)
```

Now when you run this program you will see the world program try to connect to the universe, but since we have not written—much less run—the server, it cannot find the universe. After a few tries, it gives up and continues running without communicating with the universe.

Now let's write a seperate simple universe server. To do this, you want to open a new tab or window.

A universe program, much like a world program, consists of a current state of the universe and is event-driven, invoking methods to produce new universe states.

We'll be working with the OO-style universe, but you should read the documentation for 2htdp/universe and translate over the concepts to our setting as you've done for big-bang.

At a minimum, the universe must handle the events of:

1. a world registering with this universe, and
2. a registered world sending a message to the universe.

The first is handled by the on-new method and the second by the on-msg:

```
#lang class1
(require class1/universe)

(define-class universe%
  ; IWorld -> Bundle
  (define/public (on-new iw) ...)

  ; IWorld S-Expr -> Bundle
  (define/public (on-msg iw m) ...))
```

When a world registers, the on-new method is called with an IWorld value. An IWorld value opaquely represents a world, that is you do not have the ability to examine the contents of the value, but you can compare it for equality with other IWorld values using iworld=?.

When a world sends message, the on-msg method is called with the IWorld representing the world that sent the message and the S-Exp message that was sent.

In both cases, the method must produce a bundle:

```
; A Bundle is a (make-bundle Universe [Listof Mail] [Listof IWorld]).
```

The universe component is the new state of the universe; the list of mail is a list of messages that will be sent back to the worlds (more on this in a moment), and the list of worlds are worlds that the server has chosen to disconnect from.

For the purposes of our example, the universe maintains no state (the class has no data). When a new world registers, we do nothing, and when a world sends a message, we also do nothing, send nothing in response, and disconnect no worlds:

```
#lang class1
```

```
(require class1/universe)

(define-class universe%
  ; IWorld -> Bundle
  (define/public (on-new iw)
    (make-bundle this empty empty))

  ; IWorld S-Expr -> Bundle
  (define/public (on-msg iw m)
    (make-bundle this empty empty)))

(universe (new universe%))
```

Running this program launches the universe server, making it ready to receive registrations from worlds. After starting the universe server, if we switch back to the world program tab and run it, we'll see that it successfully registers with the universe and the universe console reports that the world signed up with it.

Thrilling.

At this point, the world registers, but never sends any message to the server. Now let's modify the world program to notify the server when it ticks by sending it's current count as a message.

That requires changing our on-tick method from:

```
                                                    "world%"
  (define/public (on-tick)
    (new counter-world% (add1 (field n))))
```

to one that constructs a package:

```
                                                    "world%"
  (define/public (on-tick)
    (make-package (new counter-world% (add1 (field n)))
                  (add1 (field n))))
```

Now let's re-run the world program. Notice that messages are being received by the server in the console.

5.4 Migrating computation from client to server

Now let's change the system so that "work" of adding is done on the server side. When the world ticks it sends its current count to the server; when the server receives the count, it responds by sending a message back to the world that is the count plus one. On the world side, that means we must now add the ability to receive messages by implementing the on-receive method, which will update the world state appropriately and the **on-tick** method will do no computation, but only communication:

```
                                                    "world%"
  (define/public (on-tick)
    (make-package this (field n)))

  (define/public (on-receive m)
    (new counter-world% m))
```

On the server side, we now need to send a message back to the world, so we need to consider the data definition for mail:

```
; A Mail is a (make-mail IWorld S-Exp).
```

This constructs a message that will be sent to the world represented by the IWorld value consisting of the S-Exp value.

```
                                                 "universe%"
  (define/public (on-msg iw m)
    (make-bundle this
                 (list (make-mail iw (add1 m)))
                 empty))
```

If we restart the universe and world, you'll notice that the universe console is now showing messages going in both directions.

Now let's see an example of multiple world programs communicating with a single server.

If we were to just write this:

```
(big-bang (new counter-world% 0))
(big-bang (new counter-world% 50))
```

the program would wait for the first big-bang expression to finish evaluating before moving on the second one. To make it possible to run many worlds at the same time, the universe library provides the launch-many-worlds form that will evaluate all of its subexpressions in parallel:

```
(launch-many-worlds
  (big-bang (new counter-world% 0))
  (big-bang (new counter-world% 50)))
```

Notice that both worlds count independently.

5.5 Guess my number

Now let's a more interesting game. We'll start by considering the guess my number game.

In this game, the server is thinking of a number and you have to guess it.

Here's the server:

```
#lang class1
(require class1/universe)

(define-class universe%
  (fields the-number)

  (define/public (on-new iw)
    (make-bundle this empty empty))

  (define/public (on-msg iw m)
    (make-bundle this
                 (list (make-mail iw (respond m (field the-
number))))
                 empty)))

; Number Number -> String
(define (respond guess number)
  (cond [(< guess number) "too small"]
        [(> guess number) "too big"]
        [else "just right"]))

; the universe is thinking of 2.
(universe (new universe% 2))
```

The universe now has a single peice of data, which is the number it is thinking of. It responds to guesses by sending back a string indicating whether the guess is just right, too big, or too small.

Here is the client:

```
#lang class1
(require class1/universe)
(require 2htdp/image)

(define-class guess-world%
  (fields status)
  (define/public (on-receive m)
    (new guess-world% m))

  (define/public (to-draw)
    (overlay (text (field status)
                   40
                   "red")
             (empty-scene 300 100)))

  (define/public (on-key k)
    (local [(define n (string->number k))]
      (if (number? n)
          (make-package this n)
          this)))

  (define/public (register) LOCALHOST))

(big-bang (new guess-world% "guess a number"))
```

The client has a single peice of data, which represents the status of its guess. It responds to numeric key events by sending the guess to the server and ignores all other key events.

The string->number function is being used to test for numeric key events—it works by producing false when given a string that cannot be converted to a number, otherwise it converts the string to a number.

5.6 Two player guess my number

Now let's write a 2-player version of the game where one player thinks of a number and the other player guesses.

Here is the server:

```
#lang class1
(require class1/universe)

; A Universe is a (new universe% [U #f Number] [U #f IWorld] [U #f
IWorld]).
(define-class universe%
  (fields number
          picker
          guesser)

  ; is the given world the picker?
```

```
  (define/public (picker? iw)
    (and (iworld? (field picker))
         (iworld=? iw (field picker))))

  ; is the given world the guesser?
  (define/public (guesser? iw)
    (and (iworld? (field guesser))
         (iworld=? iw (field guesser))))

  (define/public (on-new iw)
    (cond [(false? (field picker))
           (make-bundle
            (new universe% false iw false)
            (list (make-mail iw "pick a number"))
            empty)]
          [(false? (field guesser))
           (make-bundle
            (new universe% (field number) (field picker) iw)
            empty
            empty)]
          [else
           (make-bundle this empty (list iw))]))

  (define/public (on-msg iw m)
    (cond [(and (picker? iw)
                (false? (field number)))
           (make-bundle
            (new universe% m (field picker) (field guesser))
            empty
            empty)]
          [(picker? iw) ; already picked a number
           (make-bundle this empty empty)]
          [(and (guesser? iw)
                (number? (field number)))
           (make-bundle this
                        (list (make-mail iw (respond m (field number))))
                        empty)]
          [(guesser? iw)
           (make-bundle this
                        (list (make-mail iw "no number"))
                        empty)])))

; Number Number -> String
(define (respond guess number)
  (cond [(< guess number) "too small"]
        [(> guess number) "too big"]
        [else "just right"]))

(universe (new universe% false false false))
```

The client stays the same! You can launch the two players with:

```
(launch-many-worlds
 (big-bang (new guess-world% "guess a number"))
 (big-bang (new guess-world% "guess a number")))
```

6 Delegation

6.1 New language features

6.1.1 Interface inheritance

Interfaces can now inherit from other interfaces. In this example, the `foo%` class promises to implement the methods specified in `bar<%>`, but also the methods listed in the super-interfaces `baz<%>` and `foo<%>`.

```
#lang class1
(define-interface baz<%> (blah))
(define-interface foo<%> (blah))
(define-interface bar<%>
  (super foo<%>)
  (super baz<%>)
  (x y))

(define-class foo%
  (implements bar<%>)
  (fields x y z blah))
```

6.1.2 Dot notation

To make programming with objects more convenient, we've added new syntax to `class1` to support method calls. In particular, the following now sends method `x` to object `o` with argument `arg`:

```
(x . o arg)
```

This is equivalent to

```
(send x o arg)
```

We can chain method calls like this:

```
(x . o arg . m arg*)
```

This sends the `m` method to the result of the previous expression. This is equivalent to

```
(send (send x o arg) m arg*)
```

Although in lecture this didn't work in the interactions window, it now works everywhere that you use class1.

6.2 Constructor design issue in modulo zombie (Assignment 3, Problem 3)

Course staff solution for regular zombie game:

"world%"

```
(define/public (teleport)
  (new world%
       (new player%
            (random WIDTH)
            (random HEIGHT))
       (field zombies)
       (field mouse)))
```

This has a significant bug: it always produces a plain player%, not a modulo-player%.

Bug (pair0MN):

"modulo-player%"

```
(define/public (teleport)
  (new player%
       (* -1 (random WORLD-SIZE))
       (* -1 (random WORLD-SIZE))))
```

This has a similar bug: it always produces a plain player%, not a modulo-player%. However, it's in the the modulo-player% file, so there's an easy fix.

Lack of abstraction (pair0PQ):

"modulo-player%"

```
; warp : Real Real -> ModuloPlayer
; change the location of this player to the given location
(define/public (warp x y)
  (new modulo-player%
       (field dest-x)
       (field dest-y)
       x y))
```

"player%"

```
; warp : Real Real -> Player
; change the location of this player to the given location
(define/public (warp x y)
```

```
  (new player%
       (field dest-x)
       (field dest-y)
       x y))
```

This works correctly (this is the fix for the bug in Pair0MN's solution), but it duplicates code.

We want to fix these bugs without duplicating code.

Possible solutions (suggested in class):

- Parameterize the teleport method with a class name. Unfortunately, this doesn't work because the class name in **new** is not an expression.
- Use **this** as the class name. This doesn't work because **this** is an instance, not a class.

The solution is to add a new method to the interface, which constructs a new method of the appropriate class. So, we add this method to the player% class:

```
(define/public (move x y)
  (new player% x y))
```

And this method to the modulo-player% class:

```
(define/public (move x y)
  (new modulo-player% x y))
```

Here's an example of the technique in full. We start with these classes:

```
#lang class1
(define-class s%
  (fields x y))

;; A Foo is one of:
;; - (new c% Number Number)
;; - (new d% Number Number)

(define-class c%
  (super s%)
  (define/public (make x y) (new c% x y))
  (define/public (origin) (new c% 0 0)))
(define-class d%
  (super s%)
  (define/public (make x y) (new d% x y))
  (define/public (origin) (new d% 0 0)))
```

Now we abstract the `origin` method to use `make`, and we can abstract `origin` to the superclass `s%`, since it becomes identical in both classes, avoiding the code duplication.

```
#lang class1
(define-class s%
  (fields x y)
  (send this make 0 0))

;; A Foo is one of:
;; - (new c% Number Number)
;; - (new d% Number Number)

(define-class c%
  (super s%)
  (define/public (make x y)
    (new c% x y)))
(define-class d%
  (super s%)
  (define/public (make x y)
    (new d% x y)))

(new c% 50 100)
(send (new c% 50 100) origin)
```

6.3 Abstracting list methods with different representations

Here is the list interface from the last homework assignment:

```
; ==========================================================
; Parametric lists

; A [Listof X] implements list<%>.
(define-interface list<%>
  [; X -> [Listof X]
   ; Add the given element to the front of the list.
   cons
   ; -> [Listof X]
   ; Produce the empty list.
   empty
   ; -> Nat
   ; Count the number of elements in this list.
   length
   ; [Listof X] -> [Listof X]
```

```
   ; Append the given list to the end of this list.
   append
   ; -> [Listof X]
   ; Reverse the order of elements in this list.
   reverse
   ; [X -> Y] -> [Listof Y]
   ; Construct the list of results of applying the function
   ; to elements of this list.
   map
   ; [X -> Boolean] -> [Listof X]
   ; Construct the list of elements in this list that
   ; satisfy the predicate.
   filter
   ; [X Y -> Y] Y -> Y
   ; For elements x_0...x_n, (f x_0 ... (f x_n b)).
   foldr
   ; [X Y -> Y] Y -> Y
   ; For elements x_0...x_n, (f x_n ... (f x_0 b)).
   foldl])
```

Here's the usual implementation of a small subset of this interface, first for the recursive union implementation:

```
(define-class cons%
  (fields first rest)

  (define/public (cons x)
    (new cons% x this))

  (define/public (empty)
    (new empty%))

  (define/public (length)
    (add1 (send (field rest) length)))

  (define/public (foldr c b)
    (c (field first)
       (send (field rest) foldr c b))))

(define-class empty%

  (define/public (cons x)
    (new cons% x this))

  (define/public (empty)
    this)
  (define/public (length)
    0)

  (define/public (foldr c b)
    b))
```

And for the wrapper list implementation:

```
(define-class wlist%
  (fields ls)

  (define/public (cons x)
    (new wlist% (ls:cons x (field ls))))

  (define/public (empty)
    (new wlist% ls:empty))

  (define/public (length)
    (ls:length (field ls)))

  (define/public (foldr c b)
    (ls:foldr c b (field ls))))
```

None of these look the same, so how can we abstract? Our abstraction design recipe for using inheritance requires that methods look identical in order to abstract them into a common super class. But, for example, the `length` method looks like this for `wlist%`:

```
(define/public (length)
  (ls:length (field ls)))
```

Like this for `empty%`:

```
(define/public (length)
  0)
```

And like this for `cons%`:

```
(define/public (length)
  (add1 (send (field rest) length)))
```

In fact, all of them—but that's a topic for another day.

Before we can abstract this method, we must make them all look the same. Fortunately, many list operations can be expressed using just a few simple operations, of which the most important is `foldr`. Here's an implementation of `length` which just uses `foldr` and simple arithmetic.

```
(define/public (length)
  (send this foldr (λ (a b) (add1 b)) 0))
```

Note that this isn't specific to any one implementation of lists—in fact, we can use it for any of them. This means that we can now abstract the method, creating a new `list%` class to share all of our common code:

```
(define-class list%
   (define/public (length)
     (send this foldr (λ (a b) (add1 b)) 0))
   ; other methods here)
```

The only methods that need to be implemented differently for different list versions are `empty` and `cons`, because they construct new lists, and `foldr`, because it's the fundamental operation we use to build the other operations out of. It's also helpful to implementat `foldl`, since it's fairly complex to factor out.

6.4 Solidifying what we've done

So far in this class, we've seen a number of different ways of specifying the creation and behavior of the data we work with. At this point, it's valuable to take a step back and consider all of the concepts we've seen, and how they differ from what we had in Fundies 1.

6.4.1 Data Definitions

Data defintions describe how data is constructed. For example, primitive classes of data such as `Number` and `String` are examples, of data defintions, as is `(make-posn Number Number)`. We can also describe enumerations and unions, just as we did previously.

In this class, we've introduced a new way of writing data defintions, referring to classes. For example:

```
; A [WList X] is (new wlist% [Listof X])
```

We can combine this style of data defintion with other data definition forms, such as unions. However, classes also need to describe one other important aspect—their interface. So we will add the following to the above data defintion:

```
; A [WList X] is (new wlist% [Listof X])
;  and implements the [IList X] interface
```

6.4.2 Interface Definitions

An interface defintion lists the operations that something that implements the interface will support. Just as we have a convention that data defintions start with a capital letter, interface defintions start with a capital letter "I". The interface defintion for `[IList X]` is:

```
;; An [IList X] implements

;; empty : -> [IList X]
;; Produce an empty list
;; cons : X -> [IList X]
;; Produce a list with the given element at the front.
;; empty? : -> Boolean
;; Determine if this list is empty.
;; length : -> Number
;; Count the elements in this list

;; ... and other methods ...
```

There are several important aspects of this interface defintion to note. First, it lists all of the methods that can be used on an `[IList X]`, along with their contracts and purpose statements. Mere method names are not enough—with just a method name you have no idea how to use a method, or what to use it for. Second, interface defintions can have parameters (here `X`), just like data defintions. Third, there is no description of how to construct an `[IList X]`. That's the job of data defintions that implement this interface.

Of course, just like data defintions don't have to be named, interface defintions don't have to be named either. If you need to describe an interface just once, it's fine to write the interface right there where you need it.

6.4.3 Contracts

Contracts describe the appropriate inputs and outputs of functions and methods. In the past, we've seen many contracts that refer to data defintions. In this class, we've also seen contracts that refer to interface defintions, like so:

```
; [IList Number] -> [IList Number]
```

When describing the contract of a function or method, it's almost always preferable to refer to an interface definition instead of a data defintion that commits to a specific representation.

6.4.4 Design Recipe

Interfaces change the design recipe in one important way. In the Template step, we take an inventory of what is available in the body of a function or method. When designing a method, we have the following available to us:

- The fields of this object, accessed with **`field`**,
- The methods of this object, accessed by calling them,
- And the operations of the arguments, which are given by their interfaces.

For example, if a method takes an input `a-list` which is specified in the contract to be an `IList`, then we know that `(send a-list empty?)`, `(send a-list length)`, and so on.

6.5 Delegation

So far, we've seen multiple ways to abstract repeated code. First, in Fundies 1, we saw functional abstraction, where we take parts of functions that differ and make them parameters to the abstracted function. Second, in this class we've seen abstraction by using inheritance, where if methods in two related classes are identical, they can be lifted into one method in a common superclass.

However, can we still abstract common code without either of these mechanisms? Yes.

Consider the `class0`, without helper functions. We can write a binary tree class like this:

```
#lang class0
; A BT is one of:
; - (new leaf% Number)
; - (new node% Number BT BT)

; double : Number -> BT
; Double this tree and put the number on top.

(define-class leaf%
  (fields number)

  (define/public (double n)
    (new node% n this this)))
```

```
(define-class node%
  (fields number left right)

  (define/public (double n)
    (new node% n this this)))
```

Unfortunately, the `double` method is identical in both the `leaf%` and `node%` classes. How can we abstract this without using inheritance or a helper function?

One solution is to create a new class, and delegate the responsibility of doing the doubling to it. Below is an example of this:

```
(define-class helper%
  ; Number BT -> BT
  ; Double the given tree and puts the number on top.
  (define/public (double-helper number bt)
    (new node% number bt bt)))
(define tutor (new helper%))

(define-class leaf%
  (fields number)

  (define/public (double n)
    (send tutor double-helper n this)))

(define-class node%
  (fields number left right)

  (define/public (double n)
    (send tutor double-helper n this)))
```

The `helper%` class has just one method, although we could add as many as we wanted. We also need only one instance of `helper%`, called `tutor`, although we could create new instances when we needed them as well. Now the body of `double-helper` contains all of the doubling logic in our program, which might become much larger without needing duplicate code.

7 Abstraction, Invariants, Testing

7.1 New language features: `check-expect` in new places

It's now possible to use `check-expect` in several places that didn't work before. First, it now works inside functions. The test is run every time the function is called. Second, it works inside class definitions. Tests in classes are lifted out of the class, so they cannot refer to fields, or directly call methods, or refer to **`this`**.

For example:

```
#lang class1
(define-class c%
  (fields x y z)

  ;; works
  (check-expect ((new c% 1 2 3) . m) 1)
  ;; doesn't work
  (check-expect ((new c% 1 2 3) . m) (field x))
  (define/public (m) 1))

(define (f x)
  (check-expect 1 1))
(f 5)
```

When used in an expression, as in a function, `check-expect` does not produce any value, and should not be combined with any other expressions that do computation.

7.2 Invariants of Data Structures

Here's an interface for a sorted list of numbers.

```
#lang class1
;; An ISorted implements
;; insert : Number -> Sorted
;; contains? : Number -> Boolean
;; ->list : -> [Listof Number]
;; empty? : -> Boolean

;; Invariant: The list is sorted in ascending order.

;; Precondition: the list must not be empty
;; max : -> Number
;; min : -> Number
```

How would we implement this interface?

We can simply adopt the recursive union style that we've already seen for implementing lists. Here we see the basic defintion as well as the implementation of the contains? method.

```
#lang class1
;; A Sorted is one of
;; - (new smt%)
;; - (new scons% Number Sorted)
(define-class smt%
  (check-expect ((new smt%) . contains? 5) false)
  (define/public (contains? n)
    false))

(define-class scons%
  (fields first rest)
  (check-expect ((new scons% 5 (new smt%)) . contains? 5) true)
  (check-expect ((new scons% 5 (new smt%)) . contains? 7) false)
  (check-expect ((new scons% 5 (new scons% 7 (new smt%))) . contains? 3)
                false)
  (check-expect ((new scons% 5 (new scons% 7 (new smt%))) . contains? 9)
                false)
  (define/public (contains? n)
    (or (= n (field first))
        ((field rest) . contains? n))))
```

However, we can write a new implementation that uses our invariant to avoid checking the rest of the list when it isn't necessary.

```
(define/public (contains? n)
  (cond [(= n (field first)) true]
        [(< n (field first)) false]
        [else ((field rest) . contains? n)]))
```

Because the list is always sorted in ascending order, if n is less than the first element, it must be less than every other element, and therefore can't possibly be equal to any element in the list.

Now we can implement the remaining methods from the interface. First, insert

```
                                                       "smt%"
(check-expect ((new smt%) . insert 5)
              (new scons% 5 (new smt%)))
(define/public (insert n)
```

```
  (new scons% n (new smt%)))
```

```
                                                       "scons%"
(check-expect ((new scons% 5 (new smt%)) . insert 7)
              (new scons% 5 (new scons% 7 (new smt%))))
(check-expect ((new scons% 7 (new smt%)) . insert 5)
              (new scons% 5 (new scons% 7 (new smt%))))
(define/public (insert n)
  (cond [(< n (field first))
         (new scons% n this)]
        [else
         (new scons%
              (field first)
              ((field rest) . insert n))]))
```

Note that we don't have to look at the whole list to insert the elements. This is again a benefit of programming using the invariant that we have a sorted list.

Next, the max method. We don't have to do anything for the empty list, because we have a precondition that we can only call max when the list is non-empty.

```
                                                       "scons%"
(define real-max max)
(check-expect ((new scons% 5 (new smt%)) . max) 5)
(check-expect ((new scons% 5 (new scons% 7 (new smt%))) . max) 7)
(define/public (max)
  (cond [((field rest) . empty?) (field first)]
        [else ((field rest) . max)]))
```

Again, this implementation relies on our data structure invariant. To make this work, though, we need to implement empty?.

```
                                                       "smt%"
(check-expect ((new smt%) . empty?) true)
(define/public (empty?) true)
```

```
                                                       "scons%"
(check-expect ((new scons% 1 (new smt%)) . empty?) false)
(define/public (empty?) false)
```

The final two methods are similar. Again, we don't implement min in smt%, because of the precondition in the interface.

```
                                                       "smt%"
; no min method
(define/public (->list) empty)
```

"scons%"

```
  (define/public (min) (field first))
  (define/public (->list)
    (cons (field first) ((field rest) . ->list)))
```

7.3 Properties of Programs and Randomized Testing

A property is a claim about the behavior of a program. Unit tests check particular, very specific properties, but often there are more general properties that we can state and check about programs.

Here's a property about our sorted list library, which we would like to be true:

`∀ sls : ISorted . ∀ n : Number . ((sls . insert n) . contains? n)`

How would we check this? We can check a few instances with unit tests, but this property makes a very strong claim. If we were working in ACL2, as in the Logic and Computation class, we could provide a machine-checked proof of the property, verifying that it is true for every single `Sorted` and `Number`.

For something in between these two extremes, we can use randomized testing. This allows us to gain confidence that our property is true, with just a bit of programming effort.

First, we want to write a program that asks the question associated with this property.

```
  ; Property: forall sorted lists and numbers, this predicate holds
  ; insert-contains? : ISorted Number -> Boolean
  (define (insert-contains? sls n)
    ((sls . insert n) . contains? n))
```

Now we make lots of randomly generated tests, and see if the predicate holds. First, let's build a random sorted list generator.

```
  ; build-sorted : Nat (Nat -> Number) -> Sorted
  (define (build-sorted)
    (cond [(zero? i) (new smt%)]
          [else
           (new scons%
                (f i)
                (build-sorted (sub1 i) f))]))
  (build-sorted 5 (lambda (x) x))
```

Oh no! We broke the invariant. The `scons%` constructor allows you to break the invariant, and now all of our methods don't work. Fortunately, we can implement a

fixed version that uses the `insert` method to maintain the sorted list invariant:

```
  ; build-sorted : Nat (Nat -> Number) -> Sorted
  (define (build-sorted)
    (cond [(zero? i) (new smt%)]
          [else
           ((build-sorted (sub1 i) f) . insert (f i))]))
  (check-expect (build-sorted 3 (lambda (x) x))
                (new scons% 1 (new scons% 2 (new scons% 3 (new smt%)))))
```

Now `build-sorted` produces the correct answer, which we can easily verify at the Interactions window.

Using `build-sorted`, we can develop `random-sorted`, which generates a sorted list of random numbers.:

```
  ; Nat -> Sorted
  (define (random-sorted i)
    (build-sorted i (lambda (_) (random 100))))
```

Given these building blocks, we can write a test that checks our property.

```
  (check-expect (insert-contains? (random-sorted 30) (random 50))
                true)
```

Every time we hit the **Run** button, we generate a random sorted list of numbers, and check if a particular random integer behaves appropriately when `insert`ed into it. But if we could repeatedly check this property hundreds or thousands of times, it would be even more unlikely that our program violates the property. After all, we could have just gotten lucky.

First, we write a function to perform some action many times:

```
  ; Nat (Any -> Any) -> 'done
  ; run the function f i times
  (define (do i f)
    (cond [(zero? i) 'done]
          [else (f (do (sub1 i) f))]))
```

Then we can run our test many times:

```
  (do 1000
      (lambda (_)
        (check-expect (insert-contains? (random-
sorted 30) (random 50))
                      true)))
```

When this says that we've passed 1000 tests, we'll be more sure that we've gotten our function right.

What if we change our property to this untrue statement?

```
; Property: forall sorted lists and numbers, this predicate holds
; insert-contains? : ISorted Number -> Boolean
(define (insert-contains? sls n)
  (sls . contains? n))
```

Now we get lots of test failures, but the problem is not in our implementation of sorted lists, it's in our property definition. If we had instead had a bug in our implementation, we would have similarly seen many failures. Thus, it isn't always possible to tell from a test failure, or even many failures, whether it's the code or the specification is wrong—you have to look at the test failure to check.

This is why it's extremely important to get your specifications (like contracts, data definitions, and interface definitions) correct. Your program can only be correct if they are.

7.4 Abstraction Barriers and Modules

Recall that in our original version of `build-sorted`, we saw that the `scons%` constructor allowed us to violate the invariant—it didn't check that the value provided for `first` was at least as small as the elements of `rest`. We would like to prevent clients of our sorted list implementation from having access to this capability, so that we can be sure that our invariant is maintained.

To address this, we set up an abstraction barrier, preventing other people from seeing the `scons%` constructor. To create these barriers, we use a module system. We will consider our implementation of sorted lists to be one module, and we can add a simple specification to allow other modules to see parts of the implementation (but not all of it).

Modules in our languages are very simple—you've already written them. They start with `#lang classN` and cover a whole file.

Here's the module implementing our sorted list, which we save in a file called `"sorted-list.rkt"`.

"sorted-list.rkt"

```
#lang class1

;; ... all of the rest of the code ...

(define smt (new smt%))

(provide smt)
```

We've added two new pieces to this file. First, we define `smt` to be an instance of the empty sorted list. Then, we use `provide` to make `smt`, but not any other definition from our module, available to other modules.

Therefore, the only part of our code that the rest of the world can see is the `smt` value. To add new elements, the rest of the world has to use the `insert` method.

```
#lang class1
(require "sorted-list.rkt")

(smt . insert 4)
```

Here, we've used **`require`**, which we've used to refer to libraries that come with DrRacket. However, we can specify the name of a file, and we get everything that the module in that file `provide`s, which here is just the `smt` definition. Everything else, such as the dangerous `scons%` constructor, is hidden, and our implementation of sorted lists can rely on its invariant.

8 Constructors

8.1 Canonical forms

Today we're going to look more at the concept of invariants. Invariants often let us write code that takes advantage of the fact that we know some property, the invariant, of our data. We saw this last class using sorted lists of numbers. Today we're going to examine a new example: fractions.

A fraction can be represented as a compound data that consists of two numbers representing the numerator and denominator:

```
;; A Fraction is a (new fraction% Integer Integer).
(define-class fraction%
  (fields numerator denominator))
```

The problem here is that we'd like to consider the fractions:

```
(new fraction% 1 2)
(new fraction% 2 4)
```

as representing the same number, namely `1/2`, but these are different representations of the same information. The issue with fractions is a recurring issue we've seen with information that allows for multiple representations (sets are another example).

There are a couple approaches to solving this issue:

1. Represents information is some canonical way.
2. Codify the interpretation of data as a program.

The first approach basically eliminates the problem of multiple representations by picking a unique representation for any given piece of information. For example, with fractions, we might choose to represent all fractions in lowest terms. This means any fraction admits only a single representation and therefore any fractions which are interpreted as ”the same” have exactly the same structure. (This approach is not always possible or feasible.)

The second approach requires us to write a program (a function, a method, etc.) that determines when two pieces of data are interpreted as representing the same information. For example, we could write a method that converts fractions to numbers and compares them for numerical equality; or we simplify the fraction to lowest terms and compare them structurally.

Along the lines of the second approach, let's consider adding the following method:

```
"fraction%"
; to-number : -> Number
; Convert this fraction to a number.
(define/public (to-number)
  (/ (field numerator)
     (field denominator)))
```

This method essentially embodies our interpretation of the `fraction%` class of data. It doesn't help with this issues:

```
(check-expect (new fraction% 1 2)
              (new fraction% 2 4))
```

But of course now we can write our tests to rely on this interpretation function:

```
(check-expect ((new fraction% 1 2) . to-number)
              ((new fraction% 2 4) . to-number))
```

But what if we wanted to go down the second route? We could define a method that computes a fraction in lowest terms:

```
"fraction%"
; simplify : -> Fraction
; Simplify a fraction to lowest terms.
(check-expect ((new fraction% 3 6) . simplify)
              (new fraction% 1 2))
```

We can use the `gcd` function to compute the greatest common denominator of the terms:

```
"fraction%"
(define/public (simplify)
  (new fraction%
       (/ (field numerator)
          (gcd (field numerator)
               (field denominator)))
       (/ (field denominator)
          (gcd (field numerator)
               (field denominator)))))
```

This allows us to structurally compare two fractions that have been simplified to lowest terms:

```
(check-expect ((new fraction% 3 6) . simplify)
              ((new fraction% 1 2) . simplify))
```

But it does not prevent us from constructing fractions that are not in lowest terms, which is what we were aiming for — we want it to be an invariant of fraction% objects that they are in their simplest form. One possibility is to define a constructor function that consumes a numerator and denominator and constructs a fraction% object in lowest terms:

```
;; fract-constructor : Number Number -> Fraction
;; construct a fraction in lowest terms.
(define (fract-constructor n d)
  (new fraction%
       (/ n (gcd n d))
       (/ d (gcd n d))))
```

So we are able to write a new function with the behavior we want and it establishes our invariant. That's good, but there are still some inconveniences:

- We have to write a function.
- We have to remember to use it everywhere in place of the constructor.
- We still have the fraction% constructor around, which allows users, including ourselves, to violate the invariant.

If we want to have a stronger guarantee that we maintain the lowest term invariant, we need a stronger mechanism for enforcing our discipline at construction-time. The idea is to allow arbitrary computation to occur between the call to a constructor and the initialization of an object. To enable this mechanism, we need to bump the language level up to class2.

All class1 programs continue to work in class2. The main difference is that we now the ability to write constructors.

```
                                                   "fraction%"
  (constructor (n d)
    ;;...some expression that uses the fields form to return values
    ;;   for all of the fields...
    ...)
```

The constructor form can take any number of arguments and must use the **fields** to initialize each of the fields. If you leave off the constructor form, a default constructor is generated as:

```
(constructor (n d)
  (fields n d))
```

And in general if you have n fields, the defaults constructor looks like:

```
(constructor (field1 field2 ... fieldn)
  (fields field1 field2 ... fieldn))
```

But by writing our own constructor, we can insert computation to convert arguments in a canonical form. For our fraction% class, we can use the following code:

```
;; Number Number -> Fraction
(constructor (n d)
  (fields (/ n (gcd n d))
          (/ d (gcd n d))))
```

This code is used every time we have a (**new** fraction% Number Number) expression. Since this is the only way to construct a fraction, we know that all fractions are represented in lowest terms. It is simply impossible, through both error or malice, to construct an object that does not have this property.

Returning to our simplify method; we don't really need it any longer. (We could, if need be, re-write the code to take advantage of the invariant and give a correct implementation of simplify as (**define/public** (simplify) **this**), since all fractions are already simplified.) Likewise, we no longer need the fract-constructor function.

Finally, we get to the point we wanted:

```
(check-expect (new fraction% 1 2)
              (new fraction% 2 4))
```

Q: Can you have multiple constructor?

A: No. We've been thinking about multiple constructors, but we don't have a strong story for them yet. Remember: you can always write functions and you can think of these as alternative constructors.

That brings up another feature in the class2 language — constructors and functions are treated more uniformly now: you may leave off the **new** keyword when constructing objects.

Examples:

```
> (define-class posn%
    (fields x y))
> (new posn% 2 3)
(object:posn% 2 3)
> (posn% 4 5)
(object:posn% 4 5)
```

Q: Can you have a different number of arguments to the constructor than to the number of fields?

A: Yes. There's no relation between the number of arguments to your constructor and the number of fields in the object being constructed.

One thing to note is that printing values has changed. You'll notice that `fraction%` values no longer print as `(new fraction% Number Number)`, but instead as `(object:fraction% Number Number)`. This is because by adding arbitrary computation at construction-time, there's no longer a close relationship between a call to a constructor and the contents of an object. So in printing values we have a choice to make: either print the constructor call, which doesn't tell us about the contents of the object, or print the contents of the object, which doesn't tell us about the call to the constructor. We chose the latter.

Q: Can you call methods on the object being constructed?

A: No. What would they do? Suppose you invoked a method that referred to fields of **this** object — those things just don't exist yet.

Some languages allow this. Java for example, will let you invoke methods from within constructors and should those methods reference fields that are not initialized, bad things happen. (This is just poor language design, and descends from Sir Tony Hoare's "Billion Dollar Mistake": the null reference.)

8.2 Integrity checking

Beyond computing canonical forms, constructors are also useful for checking the integrity of data given to a constructor. For example, suppose we are writing a class to represent dates in terms of their year, month, and day of the month. Now, what if we're given the 67th day of March in the year -17? What should that data represent? Maybe it should be March 40 (because as we heard in class, `(= 40 (- 67 17))`; maybe it should be May 6th, 17 B.C., maybe it should May 6th, 17 years before the UNIX epoch of 1970; maybe it should be March 5, 17 A.D., which we arrive at by mod'ing 67 by the number of days in March and making the year positive; or maybe... this data is just bogus and we should raise an error and refuse to continue computing.

Let's see how we can implement a simple form of integrity checking in a constructor. We will implement a class to represent dates and raise an error in case of a situation like the above.

```
;; A Date is (date% Number Number Number).
;; Interp: Year Month Day.
;; Year must be positive.
;; Month must be in [1,12].
;; Day must be in [1,31].
(define-class date%
  (fields year month day))
```

We can still construct meaningless dates, so what we would like to do is check the inputs to a constructor make some sense. This let's us establish the integrity of all `date%` objects — if you have your hands on a `date%` object, you can safely assume it satisfies the specification we've given in the data definition.

The simplest way to satisfy the specification is with this constructor:

```
                                                    "date%"
(constructor (y m d)
  (error "I didn't like this date!"))
```

This is known as a "sound" solution in the program verification community. Notice: if you have your hands on a `date%` object, you can safely assume it satisfies the specification we've given in the data definition. Why? Because you cannot construct a `date%` object.

We'd like to do better by accepting more legitimate dates. Here is one that accepts all the things deemed acceptable in our specification (this is both "sound" and "complete"):

```
                                                    "date%"
(constructor (y m d)
  (cond [(<= y 0) (error "year was negative or zero")]
        [(or (> m 12) (< m 1)) (error "month too big or too small")]
        [(or (> d 31) (< d 1)) (error "day too big or too small")]
        [else (fields y m d)]))
```

Example:

```
> (date% 2011 3 67)
day too big or too small
```

Thus we can establish invariants with computation, or we can reject inputs that don't have the invariant we want to maintain. And we can combine these approaches. (You may want to compute fractions in lowest terms and reject 0 as a denominator in `fraction%`, for example.)

It is still possible to construct meaningless dates, such as February 31, 2011. However, more stringent validation is just some more code away, and since we are more concerned with the concept of integrity checking than in a robust date library, we won't go into the details.

8.3 Ordered binary trees

Now we want to look at a slightly larger program and how we use constructors to enforce important invariants. In this section, we want to develop a representation of sorted lists of numbers, which is what we did in the last lecture, but this time we're going to represent a sorted list of numbers as an ordered binary tree.

An ordered binary tree looks like this:

```
    *
   / \
  *   3
 / \
1   2
```

Notice that there is data only at the leaves of the tree and that if you traverse the leaves in left-to-right order, you recover the sorted list of numbers. Thus there is an important invariant about this data structure: whenever we have an ordered binary tree node, the left sub-tree is sorted and the right sub-tree is sorted and and numbers in the left sub-tree are smaller than or equal to all the numbers in the right sub-tree.

Here is our data and class definition for ordered binary trees:

```
;; A OBT is one of:
;; - (node% OBT OBT)
;; - (leaf% Number)
(define-class leaf%
  (fields number))
(define-class node%
  (fields left right))
```

Some examples:

```
(leaf% 7)
(node% (leaf% 1) (leaf% 2))
```

Now, is this an example?

```
(node% (leaf% 7) (leaf% 2))
```

This example points out that we are currently missing the specification of our invariant in the data definition:

```
;; A OBT is one of:
;; - (node% OBT OBT)
;; - (leaf% Number)
;; Invariant: numbers are in ascending order from left to right.
```

What happens if we try to construct something that violates our invariant? Nothing – we just construct bogus things. Now how could enforce this ascending order invariant?

Well, let's first think about the `leaf%` case. We are given a number and we need to construct an ordered binary tree, meaning all the numbers in the tree are in ascending order. Since we are constructing a tree with only one number in it, it's trivial to enforce this invariant—it's always true!

Now consider the `node%` case. We are given two ordered binary trees. What does that mean? It means the numbers of each tree are in ascending order. But wait—isn't that the property we are trying to enforce? Yes. Notice that if we assume this of the inputs and guarantee this of the constructed value, then it must be true of all *OBT*s; i.e. the assumption was valid. If this reasoning seems circular to you, keep in mind this is not unlike "the magic of recursion", which is not magic at all, but seems to be since it lets you assume the very function you are writing works in recursive calls on structurally smaller inputs. If you do the right thing in the base case, and if on that assumption of the recursive call, you can construct the correct result, then that assumption about the recursive call was valid and your program is correct for all inputs.

OK, so the challenge at hand is not in verifying that the input `OBT`s posses the invariant, but in guaranteeing that the result of the constructor possesses it. If we can do that, than we know the given `OBT`s must have the property.

But now this assumption is not sufficient to guarantee that the default constructor works:

"node%"

```
;; OBT OBT -> OBT
(constructor (a b)
  (fields a b))
```

Why? Although we know that the left and right sub-tree are `OBT`s, we know nothing about the relationship between the left and right sub-tree, which was an important part of the invariant. Consider for example, the `OBT`s:

```
(node% (leaf% 4) (leaf% 5))
(node% (leaf% 2) (leaf% 3))
```

Independently considered, these are definitely `OBT`s. However, if we construct a `node%` out of these two trees, we get:

```
(node% (node% (leaf% 4) (leaf% 5))
       (node% (leaf% 2) (leaf% 3)))
```

which is definitely not an `OBT`. (Thus we have broken the stated contract on the constructor.)

We could correctly compute an `OBT` by determining that, in this example, the first given tree needs to be the right sub-tree and the second given tree needs to be the left sub-tree. We can make such a determination based on the maximum and minimum numbers in each of the given trees, and that suggest the following constructor:

"node%"

```
;; OBT OBT -> OBT
```

```
(constructor (a b)
  (cond [(<= (b . max) (a . min))
         (fields b a)]
        [(<= (a . max) (b . min))
         (fields a b)]
        [else
         ...]))
```

The max and min methods are easily dismissed from our wish list:

```
                                                      "leaf%"
(define/public (min)
  (field n))
(define/public (max)
  (field n))
```

```
                                                      "node%"
(define/public (min)
  ((field left) . min))
(define/public (max)
  ((field right) . max))
```

At this point, our constructor does the right thing when given two OBTs that do not overlap, as in the example we considered, but a troubling pair of examples to ponder over is:

```
(node% (leaf% 2) (leaf% 4))
(node% (leaf% 3) (leaf% 5))
```

Again, considered independently, these are definitely OBTs, but there's no way to construct an ordered binary tree with one of these as the left and the other as the right; either order you pick will be wrong. This case is the else clause of our constructor. What should we do? One solution is just to reject this case and raise and error:

```
                                                      "node%"
;; OBT OBT -> OBT
(constructor (a b)
  (cond [(<= (b . max) (a . min))
         (fields b a)]
        [(<= (a . max) (b . min))
         (fields a b)]
        [else
         (error "trees overlap")]))
```

But really this again fails to live up to the stated contract since we should be able to take any two OBTs and construct an OBT out of them. We know that if the trees

overlap, we can't simple make a node with them as sub-trees; we have to do something more sophisticated. Here's an idea: insert all of the elements of one into the other. So long as we make this insertion do the right thing, our constructor will succeed in maintaining the invariant properly.

So if we indulge in some wishful thinking and suppose we have a insert-tree in our interface:

```
;; insert-tree : OBT -> OBT
;; Insert all elements of this tree into the given one.
```

then we can write the constructor as follows:

```
                                                      "node%"
(constructor (a b)
  (cond [(<= (b . max) (a . min))
         (fields b a)]
        [(<= (a . max) (b . min))
         (fields a b)]
        [else
         (local [(define t (a . insert-tree b))]
           (fields (t . left) (t . right)))]))
```

That leaves insert-tree to be written. First let's consider the case of inserting a leaf% into a tree. If we again rely on some wishful thinking and relegate the work to another method that inserts a number into a list, we can easily write insert-tree for the leaf% case:

```
                                                      "leaf%"
(define/public (insert-tree other)
  (send other insert (field number)))
```

In the node% case, if we first consider the template (the inventory of what we have available to use), we have:

```
                                                      "node%"
(define/public (insert-tree other)
  ((field left) . insert-tree other) ...
  ((field right) . insert-tree other) ...)
```

But here we don't really want to insert the left tree into the other and the right into the other. We want to insert the right tree into the other, then insert the left tree into that one (other permutations of the order of insertions would work, too). That leads us to:

```
                                                      "node%"
(define/public (insert-tree other)
    ((field left) . insert-tree ((field right) . insert-
tree other)))
```

We have only a single item remaining on our wish list—we need to implement the `insert` method for inserting a single number into a tree.

First let's consider the case of inserting a number into a `leaf%`. If we have a leaf and we insert a number into it, we know we get a node with two leaves. But where should the inserted number go? One solution is to compare the inserted number against the existing number to determine which side the number should go to:

"leaf%"

```
(define/public (insert m)
  (node% (leaf% (the-real-min n m))
         (leaf% (the-real-max n m))))
```

In the case of inserting a number into a node, we compare the number against the maximum of the left sub-tree to determine if the number should be inserted in the left or right:

"node%"

```
(define/public (insert n)
  (cond [(> n ((field left) . max))
         (node% (field left)
                ((field right) . insert n))]
        [else
         (node% ((field left) . insert n)
                (field right))]))
```

9 Lab Notes

9.1 Classes and objects

Classes and objects

Here is an example class in Racket to represent balls that we can ask geometric questions of and draw to the screen.

```
; A Ball is a (new ball% Number Number Number Color)
(define-class ball%
  (fields x y radius color)

  ; -> Number
  ; The Ball's area
  (define/public (area)
    (* pi (sqr (field radius))))

  ; Ball -> Boolean
  ; Do the Balls have the same radius?
  (define/public (same-radius? b)
    (equal? (field radius)    ; (How to access our own field)
            (send b radius))) ; (How to access someone else's field)

  ; Ball -> Boolean
  ; Do the Balls have the same area?
  (define/public (same-area? b)
    (equal? (area)            ; (How to call our own method)
            (send b area)))   ; (How to call someone else's method)

  ; -> Image
  ; The image representing the Ball
  (define/public (draw)
    (circle (field radius) "solid" (field color))))
```

We can create and use Ball objects as follows:

```
> (define b (new ball% 50 25 10 "red"))
> b
(object:ball% 50 25 10 "red")
> (send b x)
50
> (send b radius)
10
> (send b area)
```

```
314.1592653589793
> (send b same-radius? (new ball% 10 20 3 "red"))
#f
> (send b same-area? (new ball% 10 20 3 "red"))
#f
> (send b draw)
```

We can add new Ball behaviors by adding methods to the `ball%` class.

Exercise 1. Write a `circumference` method for the class `ball%` that calculates the Ball's circumference.

Exercise 2. Write a `distance-to` method for the class `ball%` that takes another Ball and returns the distance between the centers of the two Balls.

Exercise 3. Write an `overlaps?` method for the class `ball%` that takes another Ball and determines whether the two Balls overlap.

Let's construct another class to represent rectangles.

Exercise 4. Write a `block%` class to represent rectangular blocks on the screen. Include `x` and `y` fields to record its position, `width` and `height` fields to record its size, and a `color` field. Construct some examples of Blocks.

Exercise 5. Write a `diagonal` method for `block%` that calculates the length of the rectangle's diagonal.

Exercise 6. Write a `draw` method for `block%` that returns an image representing the Block.

The World as an object

Recall how we used `big-bang` last semester:

```
; A World is a (make-world ...)
(define-struct world (...))

; tick : World -> World
(define (tick w)
  ...)

; draw : World -> Image
(define (draw w)
  ...)
```

```
(big-bang (make-world ...)
          (on-tick tick)
          (on-draw draw))
```

We would define functions to implement the various behaviors of the World and then pass each of them off to `big-bang`, along with an initial World value. In other words, `big-bang` needed a combination of structure—the initial World—and functions—the various behaviors. But we know that

structure + functions = object

So here's how we will use our new version of `big-bang` that expects just a single object:

```
; A World is a (new world% ...)
(define-class world%
  (fields ...)

  ; -> World
  (define/public (on-tick)
    ...)

  ; -> Image
  (define/public (to-draw)
    ...))

(big-bang (new world% ...))
```

`big-bang` is now a function that takes an object (here, `(new world% ...)`) which must respond to the `to-draw` method, and may respond to a handful of others, including `on-tick`, `on-mouse`, and `on-key`—see the `big-bang` docs for the full list. To create such an object, we define a class with the desired methods. Here we use the name `world%`, but you can call it anything you like.

Exercise 7. Using `big-bang`, create an animation where the user clicks to place Balls on the screen. Each click adds a Ball to the screen at the location of the mouse. For now, all the Balls can be the same color and size.

To use `big-bang`, you'll need to construct an object, and to construct an object, you'll need to write a class. Which fields and methods should you include?

Let's add some variety by randomly selecting various aspects of what we put on the screen. Here are a few useful functions for choosing things randomly:

```
; random-between : Integer Integer -> Integer
; Randomly choose a number between a and b (inclusive)
```

```
(define (random-between a b)
  (+ a (random (+ 1 (- b a)))))

; choose : [Listof X] -> X
; Randomly choose an element from the list
(define (choose xs)
  (list-ref xs (random (length xs))))

; random-color : -> Color
; Randomly choose a color from a set of common colors
(define (random-color)
  (choose (list "red" "blue" "green" "yellow" "orange" "purple" "black")))
```

Exercise 8. Extend your animation so that when the user creates a Ball, its size and color of the Ball is chosen randomly.

Exercise 9. Modify your animation to use Blocks instead of Balls. Which methods need to change?

Exercise 10. Extend your animation to use Blocks and Balls—let's call them, collectively, Creatures:

```
; A Creature is one of:
;  - Ball
;  - Block
```

When the user clicks, first randomly choose whether to create a Block or a Ball, and then randomly choose its parameters.

So far our animation isn't very animate. Let's teach our Creatures how to change over time.

Exercise 11. Add a `step` method to both Balls and Blocks. Sending `step` to a Ball should return a new Ball that has been moved or resized in some way, and sending `step` to a Block should return a new Block that has been moved or resized in some other way.

Exercise 12. Add an `on-tick` method to your class of Worlds that `step`s all of its creatures.

Now we have a basic framework for animating various kinds of Creatures. Unless you've done something strange, any objects that understand the `x`, `y`, `draw`, and `step` methods should slot in with minimal changes.

Exercise 13. (Open ended) Create new kinds of Creatures with new kinds of movement. Try some of these ideas:

- speeding up over time
- changing direction over time
- moving randomly
- moving randomly with a bias
- gravitating toward a fixed point
- gravitating toward each other
- moving in circles
- moving in spirals

If large numbers of off-screen or invisible Creatures are slowing down your animation, detect when they disappear and remove them.

9.2 Interfaces and inheritance

Invaders

Let me start you with a basic animation in need of abstraction. A `World` consists of `Invaders`, each of which has a location (`x`, `y`), can `draw` itself, and can `step` itself through an animation. An `Invader`, for now, is either a `Ball` or a `Block`.

```
#lang class1
(require 2htdp/image)
(require class1/universe)

(define WIDTH  500)
(define HEIGHT 500)

; A World is a (new world% [Listof Invader])
(define-class world%
  (fields invaders)

  ; -> World
  ; Advance the World
  (define/public (on-tick)
    (new world% (map (λ (c) (send c step)) (field invaders))))

  ; -> Image
  ; Draw the World
  (define/public (to-draw)
    (foldr (λ (c scn) (place-image (send c draw)
                                    (send c x)
                                    (send c y)
                                    scn))
                (empty-scene WIDTH HEIGHT)
                (field invaders))))

  ; An Invader is one of:
  ;  - Ball
  ;  - Block

  ; A Location is a Complex where (x,y) is represented as the complex
number x+yi
```

—complex numbers? We're going to use a trick for working with 2D geometry: represent the location (x,y) with the complex number x+yi. Common geometric transformations can now be done simply with addition and subtraction.

For instance, if you're at location (2,5) and want to translate by (-1,2)—1 step left and 2 steps down, in screen coordinates—to get to location (1,7), then you can add your location 2+5i to the translation -1+2i to get your new location 1+7i.

Or consider the opposite situation: if you're at (2,5) and want to know what you must translate by to get to (1,7), you can subtract 1+7i - 2+5i = -1+2i to find out that (-1,2) is the translation from (2,5) to (1,7).

There's much more to say about the relationship between 2D geometry and complex arithmetic, but we can get a long way with just the basics. Now where were we?

```
  ; A Non-Negative is a non-negative Number
  ; A Color is a String

  ; A Ball is a (new ball% Location Non-Negative Color)
  (define-class ball%
    (fields radius color location)

    ; -> Number
    ; The x-coordinate of the Ball
    (define/public (x)
      (real-part (field location)))

    ; -> Number
    ; The y-coordinate of the Ball
    (define/public (y)
      (imag-part (field location)))

    ; -> Image
```

```
  ; The image representing the Ball
  (define/public (draw)
    (circle (field radius) "solid" (field color)))

  ; -> Ball
  ; The next Ball in the animation sequence
  (define/public (step)
    (new ball%
         (field radius)
         (field color)
         (+ 0+1i (field location)))))

(check-expect (send (new ball% 5 "red" 50+10i) x) 50)
(check-expect (send (new ball% 5 "red" 50-10i) x) 50)
(check-expect (send (new ball% 5 "red" 50+10i) y) 10)
(check-expect (send (new ball% 5 "red" 50-10i) y) -10)
(check-expect (send (new ball% 5 "red" 50+10i) draw)
              (circle 5 "solid" "red"))
(check-expect (send (new ball% 5 "red" 50+10i) step)
              (new ball% 5 "red" 50+11i))
(check-expect (send (new ball% 5 "red" 50-10i) step)
              (new ball% 5 "red" 50-9i))

; A Block is a (new block% Location Non-Negative Non-Negative Color)
(define-class block%
  (fields width height color location)

  ; -> Number
  ; The x-coordinate of the Block
  (define/public (x)
    (real-part (field location)))

  ; -> Number
  ; The y-coordinate of the Block
  (define/public (y)
    (imag-part (field location)))

  ; -> Image
  ; The image representing the Block
  (define/public (draw)
    (rectangle (field width) (field height) "solid" (field color)))

  ; -> Block
  ; The next Block in the animation sequence
  (define/public (step)
    (new block%
          (field width)
          (field height)
          (field color)
          (+ 0+1i (field location)))))

(check-expect (send (new block% 10 20 "blue"  50+60i) x) 50)
(check-expect (send (new block% 10 20 "blue" -50+60i) x) -50)
(check-expect (send (new block% 10 20 "blue"  50+60i) y) 60)
(check-expect (send (new block% 10 20 "blue" -50+60i) y) 60)
(check-expect (send (new block% 10 20 "blue" -50+60i) draw)
              (rectangle 10 20 "solid" "blue"))
(check-expect (send (new block% 10 20 "blue" 50+60i) step)
              (new block% 10 20 "blue" 50+61i))
(check-expect (send (new block% 10 20 "blue" -50+60i) step)
              (new block% 10 20 "blue" -50+61i))

(big-bang (new world% (list (new ball%   5    "red"   50+10i)
                            (new ball%  10    "red"  150+10i)
                            (new ball%  20    "red"  250+10i)
                            (new ball%  10    "red"  350+10i)
                            (new ball%   5    "red"  450+10i)
                            (new block% 30 20 "blue"  50+60i)
                            (new block% 15 10 "blue" 150+60i)
                            (new block%  5  5 "blue" 250+60i)
                            (new block% 15 10 "blue" 350+60i)
                            (new block% 30 20 "blue" 450+60i))))
```

When you run this, you should see balls and blocks falling. (Simple beginnings...)

As we said above, an Invader is something that has a `location` along with convenience methods for its `x` and `y` coordinates, can `draw` itself, and can `step` itself through an animation.

Exercise 1. Introduce an `invader<%>` interface for the behaviors common to both `ball%` and `block%`.

The convenience methods `x` and `y` are useful in the World's `to-draw` method where it needs to use the x- and y-coordinates separately, but notice that the methods are implemented in the same way for Balls and Blocks. Also notice that both classes have a `location` field.

Exercise 2. Use inheritance to abstract the `location` field and the `x` and `y` methods into a common superclass, `invader%`.

Also, the two `step` methods for Balls and Blocks are trying to do the same thing—move the Invader down by 1—but they aren't expressed in a way that we can abstract.

Exercise 3. Refactor the `step` methods. In each of `ball%` and `block%`, define a `move` method that takes a location `dz` and updates the Ball's (or Block's) `location` by translating by `dz`.

This way, the `ball% move` method will know how to say `(new ball% ...)` and the `block% move` method will know how to say `(new block% ...)`, and `step` can remain oblivious to which kind of object it's working on.

Abstract `step` into the superclass.

(Aside: the letter z is typically used for complex numbers, just as x and y are typically used for real numbers.)

Invasion

Exercise 4. End the game when any Invader successfully invades. Use an `invaded?` method on Invaders to test whether the Invader has reached the bottom of the screen, and end the game when any has done so.

When an Invader reaches the bottom of the screen, you lose—but for this to be any fun, we need a way to win! Next we will add a spaceship to the bottom of the screen to defend against the invaders:

The ship won't do much: it just updates its position to the horizontal position of the mouse. It's vertical position stays fixed.

Exercise 5. Add a Ship to the game. Fix its vertical position near the bottom of the screen and keep its horizontal position aligned with the position of the mouse.

Suggestion: Define a `ship%` class that understands `location`, `x`, `y`, and `draw`. (They can be either methods or fields.)

How much did you have to change your `to-draw` method in `world%`? If your answer isn't "very little", then pause and reconsider your Ship design.

A Ship isn't an Invader since it doesn't `step` and never needs to answer `invaded?`, but it does `draw` and have an `x`, `y`, and `location`. Moreover, `to-draw` in `world%` only relies on these last four behaviors—but we currently lack an interface to codify it.

Exercise 6. Split the `invader<%>` interface into two: a `drawable<%>` interface to support the needs of `to-draw`, and a simpler `invader<%>` interface that just includes step and invaded?.

Of your classes, which should implement which interfaces?—note that a class can implement multiple interfaces (even though it can only have one superclass).

Now compare your ship% class with your invader% class: invader% has a location field with x and y methods reading from it, and the ship% class you just defined should look very similar.

Exercise 7. Abstract the location field and the x and y methods out of ship% and invader% and into a common superclass, drawable%.

Exercise 8. Now you have a variety of interfaces, classes, and inheritance relationships. Take a moment to sanity check each of them. Which classes should implement which interfaces? Which superclasses exist only to be inherited from?

Surviving invasion

To survive the invasion, the Ship must shoot some kind of projectile at the Invaders: bullets, lasers, bananas—your choice.

Exercise 9. Define a class for your projectile. For the sake of concreteness, I'll assume you chose Banana. Bananas must (1) have a location, (2) know how to draw themselves, and (3) step upward over time.

Which of the superclasses can you inherit from to save yourself work? Which aren't appropriate to inherit from?

Which interfaces do Bananas implement?

Exercise 10. Add a list of Bananas to the World. Draw them when the World draws, and step them when the World ticks.

But whence Bananas?

Exercise 11. Add a shoot method to ship% that creates a new Banana at the Ship's location. Also add a shoot method to world% that asks the Ship to shoot and begins tracking its newly fired Banana.

Fire Bananas when the user clicks the mouse.

Too many Bananas!

Exercise 12. Remove Bananas from the World after they leave the screen. Add an on-screen? method to banana%, and remove off-screen Bananas on each World tick.

If a Banana falls in a forest...

Exercise 13. Add a contains? method to the invader<%> interface that takes a Location and computes whether the location is within the spatial extent of the Invader.

Implement contains? appropriately for each of ball% and block%. Note that circles and rectangles occupy different parts of space...

Exercise 14. Add a zapped? method to invader<%> and invader% that takes a list of Bananas as input and tests whether the Invader has been hit by any of them. Each tick, remove all Invaders from the World that are being zapped by a Banana.

For the purposes of detecting a collision, just test to see if the center of the Banana is contained in the Invader. (For added realism, try drawing your Bananas as very small dots. Or if you really want to try proper shape intersection, try something shaped not like a banana.)

Go, banana

Exercise 15. (Open ended) Now that we've laid the groundwork for our new hit iPhone game, all that's left is a few splashes of creativity. Below are a few ideas—and remember: a little randomness can substitute for a lot of complexity.

- Add new shapes of Invaders
- Give Invaders more complicated movement
- Let Invaders shoot back
- Increase the difficulty by using keyboard instead of mouse control
- Spawn new Invaders over time

9.3 Universe

Universe with objects

```
#lang class1
(require class1/universe)
(require 2htdp/image)

(define WIDTH  500)
(define HEIGHT 500)
```

Exercise 1. Create a World that connects to the Universe using the register method. The IP of the Universe machine is written on the board.

You must include a to-draw method—for now just have it create an empty scene with the dimensions above.

If you don't include an on-receive method then the Universe will disconnect you immediately, after it tries to send you a message and you fail to receive it. To get started, just create one that returns the World unchanged.

The Universe consists of circular rocks flying through space. You are one of these rocks, and if you collide with another you will be destroyed and the Universe will disconnect you.

The Universe keeps track of all the rocks. Your job is to build a World to give you a visual display of what's going on in the Universe and give you control over your rock so that you can navigate it away from danger.

The Universe communicates to you by sending you the list of all the rocks every 1/10th of a second. Each rock is sent over the wire as RockData:

```
; A  RockData is a (list Location Velocity Acceleration Radius Color)

; A  Location is a Complex
; A  Velocity is a Complex
; An Acceleration is a Complex
; A  Radius is a non-negative Real
; A  Color is a String
```

We will again use complex numbers for 2D geometry like we did in lab 3.

Exercise 2. Define a Rock class. It should have fields for all the data in RockData, and it should know how to draw itself.

The Universe sends you RockData by calling your on-receive method. The input SExp is a list of RockData.

Exercise 3. Elaborate on-recieve and to-draw to display the current state of all the Rocks in the Universe.

You can only control yourself by sending messages back to the Universe. In fact, all you can control is your acceleration. The Package you may send to the Universe consists of one value: your new Acceleration.

Exercise 4. Add simple keyboard controls to your World so that you can control your acceleration.

Notice that your acceleration stays constant until you send a new one...

Exercise 5. (Open ended) Using either the mouse or the keyboard, design a control scheme that gives you precise control over your Rock. Consider how you can both (1) control the angle of your acceleration, and (2) modulate the magnitude of your acceleration.

Exercise 6. (Open ended) The Universe gives you the location (and velocity) of every Rock in play, and yours is always the first in the list. Design an automated control scheme that avoids other Rocks.

Here's a basic approach to get you started: assign a repulsive acceleration to each rock, weighted by its distance from you, and sum them all together to find the direction of least "immediate" danger. (This strategy will need a bit of refinement...)

9.4 Dictionaries

A dictionary is a commonly used data structure that maps keys to values. Like an actual dictionary on your bookshelf, the central operation is to lookup a value given its key, just like you would lookup a definition given a word. Dictionaries also provide operations to add, remove, and update their key-value mappings. Here's an example interaction with the kinds of dictionaries we will build in this lab:

```
> (define d (empty-dict . set 1 "one" . set 2 "two" . set 3 "three"))
> (d . lookup 1)
"one"
> (d . lookup 2)
"two"
> (d . set 1 "uno" . lookup 1)
"uno"
> (d . set 1 "uno" . lookup 2)
"two"
> (d . has-key? 4)
#f
> (d . has-value? "two")
#t
```

An interface for dictionaries

Before we build anything, we should first specify what a dictionary is.

```
; A Key is a Nat

; An [IDict V] implements:
(define-interface dict<%>
  [; Key -> Boolean
   ; Does the given key exist?
   has-key?

   ; Key -> V
   ; The value mapped to by the given key
   ; Assumption: the key exists
```

```
    lookup

    ; Key V -> [IDict V]
    ; Set the given key-value mapping
    set])
```

Notice that a dictionary `[IDict V]` is parameterized by the type of its values, `V`. This enables us to give precise contracts to the methods.

Dictionaries as lists of pairs

Like most structures we encounter in programming, dictionaries can be implemented in many different ways. Let's begin with a simple representation: a list of key-value pairs.

```
  ; A [ListDict V] is one of:
  ;  - (ld-empty%)
  ;  - (ld-cons% Key V [ListDict V])
```

Exercise 1. Define the classes `ld-empty%` and `ld-cons%`.

Exercise 2. Define the method `has-key?` for `ListDict`s.

Exercise 3. Define the method `lookup` for `ListDict`s.

Exercise 4. Define the method `set` for `ListDict`s.

How good are your tests?—make sure you pass this one:

```
  (check-expect ((ld-empty%) . set 1 "one"
                             . set 2 "two"
                             . set 1 "uno"
                             . lookup 1)
                "uno")
```

Exercise 5. Here's an interesting property relating the `set` and `has-key?` methods: for all dictionaries `d`, keys `k`, and values `v`, if you ask `has-key? k` after setting the mapping `k` → `v`, then you should always get `true`.

Write this property down as a function that takes an `[IDict V]`, a `Key`, a `V`, and returns `true` if the property is satisfied by the particular inputs given. (If it ever returns `false`, then the property is invalid!)

Exercise 6. As above, write a property relating `set` and `lookup`.

To randomly test these properties we need a way to randomly generate dictionaries.

Exercise 7. Define a function `random-list-dict` that takes a number `n` and builds a `[ListDict Key Nat]` of size `n` with random key-value mappings. (It's not important that the size is exactly `n`.)

Exercise 8. Randomly test your properties: for each property, call `check-expect` a large number of times, testing the property on random inputs each time.

Dictionaries as sorted lists of pairs

What `ListDict` do you get back if you set the same key twice?

```
  ((ld-empty%) . set 1 "one" . set 1 "uno")
```

Does your `set` method hunt through the list and remove old mappings for the key `1`, or do you tolerate multiple occurrences of the same key by ignoring all but the first? Either way works fine, but the question suggests we use a less ambiguous representation to avoid the issue in the first place.

```
  ; A [SortedListDict V] is one of:
  ;  - (sld-empty%)
  ;  - (sld-cons Key V [SortedListDict V])
  ;
  ; Invariant: The keys are sorted (increasing).
```

Exercise 9. Define the classes `sld-empty%` and `sld-cons%`.

Exercise 10. Define the methods `has-key?`, `lookup`, and `set` for `SortedListDict`s. Pay attention to the invariant!

How about randomized testing? The properties we wrote above are generic over any `IList`s, so we can reuse them to test our `SortedListDict`s.

Exercise 11. Define a function `random-sorted-list-dict`, similar to `random-list-dict` above.

Identify and abstract out their common behavior.

Exercise 12. Randomly test your `IList` properties on random `SortedListDict`s.

The methods you wrote for `SortedListDict` should preserve its sorting invariant, but nothing prevents client code from combining `sld-empty%` and `sld-cons%` in ways that violate it. Modules enable us to hide our implementation details and prevent clients from violating our internal invariants.

And while we're thinking about module boundaries, let's take a moment to organize the rest of our code, too.

Exercise 13. Split your code into separate modules:

- "dict.rkt" contains and **provide**s the IDict interface
- "list-dict.rkt" **require**s "dict.rkt", contains the ListDict implementation, and **provide**s only an empty ListDict
- "sorted-list-dict.rkt" **require**s "dict.rkt", contains the SortedList-Dict implementation, and **provide**s only an empty SortedListDict
- "random-tests.rkt" **require**s all the other modules, and specifies and randomly tests properties for the various kinds of dictionaries

The IDict interface stands alone, ready for other modules to implement or use it. The ListDict implementation follows the IDict interface and tests its individual methods. The SortedListDict implementation does the same. And the randomized testing code acts as our “client”: it lives outside the module boundaries of each implementation and thus can only interact with them in approved ways—for example, it has no way to violate the sorting invariant in SortedListDict.

Dictionaries as binary search trees

Oh snap!—I just thought of an even better way to represent dictionaries. Searching through a binary search tree (BST) is way faster than searching through a list, even a sorted one, so let’s use that to build a better kind of dictionary.

```
; A [TreeDict V] is one of:
;  - (td-leaf%)
;  - (td-node% Key V [TreeDict V] [TreeDict V])
;
; Invariant: The keys form a BST.
```

So each key-value mapping is stored at the node of a BST ordered by the keys, which means that if I’m a node, then my key is bigger than all the keys to my left and smaller than all the keys to my right. This ordered structure enables us to find a given key—and thus its value—in O(log n) time.

Two points to be careful about:

- Only keys follow the BST ordering; values are just along for the ride.
- This is different than what we saw in class today.

Exercise 14. Define the classes td-leaf% and td-node% in a new module "tree-dict.rkt".

Exercise 15. Define IDict methods on TreeDicts. Know your invariant!—make sure you both preserve and exploit it.

Exercise 16. Define a function random-tree-dict, similar to random-list and random-sorted-list. (If you abstracted things properly before, this should be a one-liner.)

Exercise 17. Randomly test your IList properties on random TreeDicts.

More useful dictionaries

Dictionaries tend to have many more behaviors than the three we’ve been playing with so far.

Exercise 18. Add a method has-value? to IDicts that tests whether a given value is present. (Invariants won’t help you here!)

Specify and randomly test a property relating set and has-value?.

Exercise 19. Add a method update to IDicts that takes a key k and an update function f : V -> V, and updates k’s value by applying f to it. The method should assume that the key k already exists in the dictionary.

Specify and randomly test a property relating update and lookup.

Exercise 20. Add a method extend to IDicts that takes another IDict (who knows which kind!) and combines all of its mappings with this’ mappings. What if the mappings from the two dictionaries overlap?—pick an easy-to-understand policy and document it in your contract/purpose.

Specify and randomly test a property relating extend and has-key?.

Specify and randomly test a property relating extend and lookup.

10 Class 0

```
#lang class0
```

```
(require module-name ...)
```

Imports all the modules named *module-name*s.

```
(define-class class-name
  fields-spec
  method-spec ...)

fields-spec =
            | (fields field-name ...)

method-spec = (define/public (method-name arg ...)
                body)
            | (define/private (method-name arg ...)
                body)
```

Defines a new class named *class-name* with fields *field-name*s and methods *method-name*s. The class has one additional method for each field name *field-name*, which access the field values.

Methods defined with **define/public** are accessible both inside and outside of the class definition, while methods defined with **define/private** are only accessible within the class definition.

To refer to a field within the class definition, use `(field field-name)`.

Methods may be invoked within the class definition using the function call syntax `(method-name arg ...)`, but must be invoked with **send** from oustide the class definition as in `(send object method-name arg ...)`.

The name **this** is implicitly bound to the current object, i.e. the object whose method was called.

To construct an instance of *class-name*, use `(new class-name arg ...)` with as many arguments as there are fields in the class.

```
this
(fields id ...)
(define/public (method-name id ...) body)
(define/private (method-name id ...) body)
```

See **define-class**.

```
(new class-name arg ...)
```

Creates an object which is an instance of *class-name* with *arg*s as the values for the fields.

```
(field field-name)
```

References the value of the field named *field-name*.

```
(send object message arg ...)
```

Send *object* the message *message* with arguments *arg*s, that is, invoke *object*'s *message* method with the given arguments, *arg*s.

10.1 Object-oriented Universe

10.1.1 Big bang

```
(require class0/universe)
```

```
(big-bang obj) → World
  obj : World
```

An object-oriented version of `2htdp:big-bang`.

The given world object should provide some of the methods descibed below. For any methods that are not provided, DrRacket will use a default behavior. The world must at least provide a **to-draw** method.

Here is an example world program that counts up from zero:

```
#lang class0
(require class0/universe)
(require 2htdp/image)

(define-class counter-world%
  (fields n)

  (define/public (on-tick)
    (new counter-world% (add1 (field n))))
    (define/public (tick-rate)
      1)

    (define/public (to-draw)
      (overlay (text (number->string (field n))
                     40
                     "red")
               (empty-scene 300 100))))

  (big-bang (new counter-world% 0))
```

`(send a-world name)`

Produces the name of the world.

`(send a-world on-tick)`

Tick this world, producing a world.

`(send a-world on-key key)`

`key : key-event?`

Handle the keystroke `key`, producing a world.

`(send a-world on-release key)`

`key : key-event?`

Handle the key release `key`, producing a world.

`(send a-world on-mouse x y m)`

`x : integer?`
`y : integer?`
`m : mouse-event?`

Handle the mouse event `m` at location (`x`,`y`), producing a world.

`(send a-world to-draw)`

Draw this world, producing an image.

`(send a-world tick-rate)`

Produce the rate at which the clock should tick for this world.

`(send a-world stop-when)`

If this method produces `true`, the world program is shut down.

`(send a-world check-with)`

If this method produces `true`, the world is considered a valid world; otherwise the world program signals an error.

`(send a-world record?)`

If this method produces `true` for the initial world, DrRacket enables a visual replay of the interaction.

`(send a-world state)`

If this method produces `true` for the initial world, DrRacket displays a seperate window in which the current state is rendered.

10.1.2 Universe

`(universe obj) → Universe`
`  obj : Universe`

An object-oriented version of `2htdp:universe`.

The given universe object should provide some of the methods descibed below. For any methods that are not provided, DrRacket will use a default behavior. The universe must at least provide a `on-new` and `on-msg` method.

`(send a-universe on-new iw)`

`iw : iworld?`

Signal that the given new world has joined the universe, producing a bundle.

```
(send a-universe on-msg iw msg)

  iw : iworld?
  msg : sexp?
```

Signal that the given world has sent the given message to the universe, producing a bundle.

```
(send a-universe on-tick)
```

Tick this universe, producing a bundle.

```
(send a-universe tick-rate)
```

Produce the rate at which the clock should tick for this universe.

```
(send a-universe on-disconnect iw)

  iw : iworld?
```

Signal that the given world has left the universe, producing a bundle.

```
(send a-universe check-with)
```

If this method produces `true`, the universe is considered a valid universe; otherwise the universe program signals an error.

```
(send a-universe to-string)
```

Produce a string representation of the universe.

```
(send a-universe state)
```

If this method produces `true` for the initial universe, DrRacket displays a seperate window in which the current state is rendered.

11 Class 1

```
#lang class1
```

```
(require module-name ...)
```

Imports all the modules named *module-name*s.

```
(define-class class-name
  super-spec
  implements-spec
  fields-spec
  method-spec ...)

     super-spec =
                | (super super-name)

implements-spec =
                | (implements interface-name ...)

    fields-spec =
                | (fields field-name ...)

    method-spec = (define/public (method-name arg ...)
                    body)
                | (define/private (method-name arg ...)
                    body)
```

Defines a new class named *class-name*, much like as with `class0`, however a class may declare *super-name* as a super class of *class-name* by using `(super super-name)`. A class may also declare to implement a number of interfaces using `(implements interface-name ...)`.

When a class definition declares a super class, it inherits all of the super class's fields and methods. The constructor for the class takes values for its fields followed by values for the fields of the super class.

```
> (define-class c%
    (fields x)
    (define/public (m) 'm!))
> (define-class d%
    (super c%)
    (fields y)
    (define/public (n) 'n!))
```

```
> (define d (new d% 'y! 'x!))
> (send d m)
'm!
> (send d n)
'n!
> (send d x)
'x!
> (send d y)
'y!
```

When a class definition declares to implement any interfaces, it must define all the methods of the interfaces, otherwise an error is signalled.

```
(super class-or-interface-name)
(implements interface-name ...)
```

See **define-class** and **define-interface**.

```
this
(fields id ...)
(define/public (method-name id ...) body)
(define/private (method-name id ...) body)
(new class-name arg ...)
(field field-name)
(send object message arg ...)
```

These have the same meaning as in `class0`.

```
(define-interface interface-name
  (super super-interface) ...
  (method-name ...))
```

Defines a new interface named *interface-name*. Classes declaring to implement *interface-name* must provide methods implementing each of the *method-name*s, as well as all methods declared in any of the *super-interface*s. The *super-interface*s must name previously defined interfaces.

11.1 Object-oriented Universe (class 1)

```
(require class1/universe)
```

```
(big-bang obj) → World
  obj : World
(universe obj) → Universe
  obj : Universe
```

These have the same meaning as in `class0/universe`.

12 Class 2

```
#lang class2
```

```
(require module-name ...)
```

Imports all the modules named *module-name*s.

```
(provide id ...)
```

Makes all of the *id*s available to other modules.

```
(define-class class-name
  super-spec
  implements-spec
  fields-spec
  constructor-spec
  method-spec ...)

      super-spec =
                 | (super super-name)

 implements-spec =
                 | (implements interface-name ...)

     fields-spec =
                 | (fields field-name ...)

constructor-spec =
                 | (constructor (arg ...) body ...)

     method-spec = (define/public (method-name arg ...)
                     body)
                 | (define/private (method-name arg ...)
                     body)
```

Defines a new class named *class-name*, much like as with `class0`, however a class may declare *super-name* as a super class of *class-name* by using `(super super-name)`. A class may also declare to implement a number of interfaces using `(implements interface-name ...)`.

When a class definition declares a super class, it inherits all of the super class's fields and methods.

If no *constructor-spec* is provided, the default constructor simply accepts as many arguments as the class has fields, and initializes them in positional order, with subclass arguments before superclass arguments.

If a *constructor-spec* is provided, then constructing the object takes as many arguments as the *constructor-spec* has `args`. The provided values are bound to the `args`, and the *body* of the constructor is run. The constructor must use the `fields` form to produce values to use to initialize the fields of the object.

The constructor for the class takes values for its fields followed by values for the fields of the super class.

```
> (define-class c%
    (fields x)
    (define/public (m) 'm!))
> (define-class d%
    (super c%)
    (fields y)
    (define/public (n) 'n!))
> (define d (new d% 'y! 'x!))
> (send d m)
'm!
> (send d n)
'n!
> (send d x)
'x!
> (send d y)
'y!

> (define-class mul%
    (fields a b prod)
    (constructor (x y)
      (fields x y (* x y))))
> (new mul% 5 7)
(object:mul% 5 7 35)
```

When a class definition declares to implement any interfaces, it must define all the methods of the interfaces, otherwise an error is signalled.

```
(super class-or-interface-name)
(implements interface-name ...)
(constructor (args ...) body)
```

See `define-class` and `define-interface`.

```
this
(fields id ...)
(define/public (method-name id ...) body)
(define/private (method-name id ...) body)
(new class-name arg ...)
(field field-name)
(send object message arg ...)
```

These have the same meaning as in `class0`.

```
(define-interface interface-name
  (super super-interface) ...
  (method-name ...))
```

Defines a new interface named *`interface-name`*. Classes declaring to implement *`interface-name`* must provide methods implementing each of the *`method-name`*s, as well as all methods declared in any of the *`super-interface`*s. The *`super-interface`*s must name previously defined interfaces.

12.1 Object-oriented Universe (class 2)

```
(require class2/universe)
```

```
(big-bang obj) → World
  obj : World
(universe obj) → Universe
  obj : Universe
```

These have the same meaning as in `class0/universe`.