Functional Programming with Haskell

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The University of Arizona
William H. Mitchell
whm@cs

Paradigms

Paradigms

Thomas Kuhn's *The Structure of Scientific Revolutions* (1962) describes a *paradigm* as a scientific achievement that is...

- "...sufficiently unprecedented to attract an enduring group of adherents away from competing modes of scientific activity."

- "...sufficiently open-ended to leave all sorts of problems for the redefined group of practitioners to resolve."

Examples of works that documented paradigms:

- Newton's *Principia*
- Lavoisier's *Chemistry*
- Lyell's *Geology*

Paradigms, continued

Kuhn says a paradigm has:

- A world view
- A vocabulary
- A set of techniques for solving problems

A paradigm provides a conceptual framework for understanding and solving problems.

Kuhn equates a paradigm shift with a scientific revolution.

The imperative programming paradigm

Imperative programming is a very early paradigm that's still used.

Originated with machine-level programming:

- Instructions change memory locations or registers
- Branching instructions alter the flow of control

Examples of areas of study for those interested in the paradigm:

- Data types
- Operators
- Branching mechanisms and (later) control structures

Imperative programming fits well with the human mind's ability to describe and understand processes as a series of steps.

The imperative paradigm, continued

Language-wise, imperative programming requires:

- "Variables"—data objects whose values can change
- Expressions to compute values
- Support for iteration—a “while” control structure, for example.

Support for imperative programming is very common.

- Java
- C
- C++
- Python
- and hundreds more
- but not Haskell

Code inside a Java method or C function is likely imperative.

The procedural programming paradigm

An outgrowth of imperative programming was *procedural programming*:

- Programs are composed of bodies of code (procedures) that manipulate individual data elements or structures.
- Procedures encapsulate complexity.

Examples of areas of study:

- How to decompose a computation into procedures and calls
- Parameter-passing mechanisms in languages
- Scoping of variables and nesting of procedures
- Visualization of procedural structure

What does a language need to provide to support procedural programming?

The procedural paradigm, continued

Support for procedural programming is very common.

- C
- Python
- Ruby
- and hundreds more

The procedural and imperative paradigms can be combined:

- Procedural programming: the set of procedures
- Imperative programming: the contents of procedures

Devising the set of functions for a C program is an example of procedural programming.

Procedural programming is possible but clumsy in Java.

– Classes devolve into collections of static methods and data

The object-oriented programming paradigm

The essence of the object-oriented programming paradigm:

Programs are a system of interacting objects.

Dan Ingalls said,

"*Instead of a bit-grinding processor plundering data structures, we have a universe of well-behaved objects that courteously ask each other to carry out their various desires.*"

Examples of areas of study:

- How to model systems as interacting objects
- Managing dependencies between classes
- Costs and benefits of multiple inheritance
- Documentation of object-oriented designs

What does a language need to support OO programming?

The object-oriented paradigm, continued

Brief history of the rise of the object-oriented paradigm:

- Simula 67 recognized as first language to support objects
- Smalltalk created broad awareness of OO programming
  (see https://archive.org/details/byte-magazine-1981-08)
- C++ started a massive shift to OO programming
- Java broadened the audience even further

Object-oriented programming fits Kuhn's paradigm definition well:

World view:

Systems are interacting objects

Vocabulary:

Methods, inheritance, superclass, instances

Techniques:

Model with classes, work out responsibilities and collaborators, don't have public data, etc.

The object-oriented paradigm, continued

Language support for OOP has grown since mid-1980s.

Many languages support OO programming but don't force it.

- C++
- Python
- Ruby

Java forces at least a veneer of OO programming.

The OO and imperative paradigms can be combined:

- OO: the set of classes and their methods
- Imperative: the code inside methods

Multiple paradigms(?)

Paradigms in a field of science are often incompatible.

Example: geocentric vs. heliocentric model of the universe

Imperative programming is used both with procedural and object-oriented programming.

Is imperative programming really a paradigm?

Wikipedia's **Programming_paradigm** has this:

Programming paradigms are a way to classify programming languages based on their features. Languages can be classified into multiple paradigms.

Are "programming paradigms" really paradigms by Kuhn's definition or are they just characteristics?

The level of a paradigm

Programming paradigms can apply at different levels:

- Making a choice between procedural and object-oriented programming fundamentally determines the nature of the high-level structure of a program.

- The imperative paradigm is focused more on the small aspects of programming—how code looks at the line-by-line level.

The procedural and object-oriented paradigms apply to *programming in the large*.

The imperative paradigm applies to *programming in the small*.

Do co-existing paradigms imply they're solving fundamentally different types of problems?

The influence of paradigms

The programming paradigms we know affect how we approach problems.

- If we use the procedural paradigm, we'll first think about breaking down a computation into a series of steps.

- If we use the object-oriented paradigm, we'll first think about modeling the problem with a set of objects and then consider their interactions.

- If we know only imperative programming, code inside methods and functions will be imperative.

Imperative programming revisited

Recall these language requirements for imperative programming:

- "Variables"—data objects whose values can change
- Expressions to compute values
- Support for iteration—a “while” control structure, for example.

Another:

- Statements are sequentially executed

Imperative summation

Here's an imperative solution in Java to sum the integers in an array:

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

    return sum;
}
```

How does it exemplify imperative programming?

- The values of **sum** and **i** change over time.
- An iterative control structure is at the heart of the computation.

Imperative summation, continued

With Java's "enhanced **for**", also known as a for-each loop, we can avoid array indexing.

```
int sum(int a[])
{
    int sum = 0;
    for (int val: a)
        sum += val;

    return sum;
}
```

Is this an improvement? If so, why?

Can we write **sum** in a non-imperative way?

Non-imperative summation

We can use recursion to get rid of loops and assignments, but...ouch!

```
int sum(int a[])
{
   return sum(a, 0);
}

int sum(int a[], int i)
{
   if (i == a.length)
      return 0;
   else
      return a[i] + sum(a, i+1);
}
```

Which of the three versions is the easiest to believe it is correct?

Background:
Value, type, side effect

Value, type, and side effect

An *expression* is a sequence of symbols that can be evaluated to produce a value.

Here are some Java expressions:

```
'x'
i + j * k
f(args.length * 2) + n
```

Three questions to consider about an expression:

- What value does the expression produce?
- What's the type of that value?
- Does the expression have any side effects?

Mnemonic aid for the three: Imagine you're wearing a vest that's reversed.
"vest" reversed is "t-se-v": type/side-effect/value.

Value, type, and side effect, continued

What is the value of the following Java expressions?

```
3 + 4

1 < 2

"abc".charAt(1)

s = 3 + 4 + "5"

"a,bb,c3".split(",")

"a,bb,c3".split(",")[2]

"a,bb,c3".split(",")[2].charAt(0) == 'X'
```

Value, type, and side effect, continued

What is the type of each of the following Java expressions?

```
3 + 4

1 < 2

"abc".charAt(1)

s = 3 + 4 + "5"

"a,bb,c3".split(",")

"a,bb,c3".split(",")[2]

"a,bb,c3".split(",")[2].charAt(0) == 'X'
```

> When we ask,
> "What's the type of this expression?"
>
> we're actually asking this:
> "What's the type of the value produced by this expression?"

Value, type, and side effect, continued

A "side effect" is a change to the program's observable data or to the state of the environment in which the program runs.

Which of these Java expressions have a side effect?

```
x + 3 * y
```

```
x += 3 * y
```

```
s.length() > 2 || s.charAt(1) == '#'
```

Value, type, and side effect, continued

More expressions to consider wrt. side effects:

"testing".toUpperCase()

L.add("x"), where L is an ArrayList

System.out.println("Hello!")

window.checkSize()

The hallmark of imperative programming

Side effects are the hallmark of imperative programing.

Code written in an imperative style is essentially an orchestration of side effects.

Recall:

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

Can we program without side effects?

The Functional Paradigm

The functional programming paradigm

A key characteristic of the functional paradigm is writing functions that are like pure mathematical functions.

Pure mathematical functions:

- Always produce the same value for given input(s)
- Have no side effects
- Can be easily combined to produce more powerful functions
- Are often specified with cases and expressions

Functional programming, continued

Other characteristics of the functional paradigm:

- Values are <u>never</u> changed but lots of new values are created.

- Recursion is used in place of iteration.

- <u>Functions are values</u>. Functions are put into data structures, passed to functions, and returned from functions. Lots of temporary functions are created.

Based on the above, how well would the following languages support functional programming?

- Java?
- Python?
- C?

Haskell basics

What is Haskell?

Haskell is a pure functional programming language; it has no imperative features.

Designed by a committee with the goal of creating a standard language for research into functional programming.

First version appeared in 1990. Latest version is known as Haskell 2010.

Is said to be *non-strict*—it supports *lazy evaluation*.

Is not object-oriented in any way.

Haskell resources

Website: **haskell.org**

All sorts of resources!

Books: (all on Safari Books Online)

Learn You a Haskell for Great Good!, by Miran Lipovača

http://learnyouahaskell.com (Known as LYAH.)

Programming in Haskell, by Graham Hutton

Note: See appendix B for mapping of non-ASCII chars!

Thinking Functionally with Haskell by Richard Bird

Real World Haskell, by O'Sullivan, Stewart, and Goerzen

http://book.realworldhaskell.org (I'll call it RWH.)

Haskell 2010 Report (I'll call it H10.)

http://haskell.org/definition/haskell2010.pdf

Getting Haskell

Windows

1. https://www.haskell.org/platform/windows.html
2. Download Core (64 bit)
3. Install it!
   - Under "Choose Components", deselect "Stack"

macOS

1. https://www.haskell.org/platform/mac.html
2. Download Core (64 bit)
3. Install it!

The latest version is 8.2.2. Lectura is running 8.0.1 but there should be no significant differences for our purposes.

Interacting with Haskell

On macOS and Linux machines like lectura we can interact with Haskell by running ghci:

```
% ghci
GHCi, version 8.0.1:  ...  :? for help
Loaded GHCi configuration from /p1/hw/whm/.ghci

Prelude> 3 + 4
7

Prelude> 1 > 2
False
```

With no arguments, ghci starts a read-eval-print loop (REPL):
Expressions typed at the prompt (Prelude>) are evaluated and the result is printed.

Interacting with Haskell, continued

On Windows there's a choice between **ghci**:

And WinGHCi:

Suggested WinGHCi options: (File > Options)

Prompt: Just a >

Uncheck Print type after evaluation (for now)

The ~/.ghci file

When **ghci** starts up on macOS or Linux it looks for the file **~/.ghci** – a **.ghci** file in the user's home directory.

I have these two lines in my **~/.ghci** file on both my Mac and on lectura:

```
:set prompt "> "
import Text.Show.Functions
```

The first line simply sets the prompt to just "**>** ".

The second line is very important:

- It loads a module that lets functions be printed.
- Prints **<function>** for function values.
- <u>Without it, lots of examples in these slides won't work!</u>

~/.ghci, continued

Goofy fact: ~/.ghci must not be group- or world-writable!

If you see something like this,

```
*** WARNING: /home/whm/.ghci is writable by
someone else, IGNORING!
Suggested fix: execute
    'chmod go-w /home/whm/.ghci'
```

the suggested fix should work.

Details on .ghci and lots more can be found in
downloads.haskell.org/~ghc/latest/docs/users_guide.pdf

~/.ghci, continued

On Windows, **ghci** and WinGHCi use a different initialization file:

    %APPDATA%\ghc\ghci.conf

(Note: the file is named **ghci.conf**, not **.ghci**!)

%APPDATA% represents the location of your **Application Data** directory. You can find that path by typing **set appdata** in a command window, like this:

```
C:\>set appdata
APPDATA=C:\Users\whm\AppData\Roaming
```

Combing the two, the full path to the file <u>for me</u> would be

    C:\Users\whm\AppData\Roaming\ghc\ghci.conf

Extra Credit Assignment 1

For two assignment points of extra credit:

1. Run **ghci** (or WinGHCi) somewhere and try ten Haskell expressions with some degree of variety. (Not just ten additions, for example!)

2. Demonstrate that you've got **import Text.Show.Functions** in your **~/.ghci** or **ghc.conf** file, as described on slides 35-37, by showing that typing **negate** produces **<function>,** like this:

   ```
   Prelude> negate
   <function>
   ```

3. Capture the interaction (both expressions and results) and put it in a plain text file, eca1.txt. No need for your name, NetID, etc. in the file. No need to edit out errors.

4. On lectura, turn in eca1.txt with the following command:

   ```
   % turnin 372-eca1 eca1.txt
   ```

Due: At the start of the next lecture after we hit this slide.

Collaborative Learning Exercise

Haskell by Observation

cs.arizona.edu/classes/cs372/spring18/cle-haskell-obs.html

Functions and function types

Calling functions

In Haskell, *juxtaposition* indicates a function call:

```
> negate 3
-3

> even 5
False

> pred 'C'
'B'

> signum 2
1
```

Note: These functions and many more are defined in the Haskell "Prelude", which is loaded by default when **ghci** starts up.

Calling functions, continued

Function call with juxtaposition is left-associative.

signum negate 2 means (signum negate) 2

```
> signum negate 2
<interactive>:11:1: error:
    • Non type-variable argument ...
    ...
```

We add parentheses to call negate 2 first:

```
> signum (negate 2)
-1
```

Calling functions, continued

Function call has higher precedence than any operator.

```
> negate 3+4
```

`negate 3 + 4` means `(negate 3) + 4.` Use parens to force `+` first:

```
> negate (3 + 4)
-7

> signum (negate (3 + 4))
-1
```

The **Data.Char** module

Haskell's **Data.Char** module has functions for working with characters. We'll use it to start learning about function types.

```
> import Data.Char
```
(import the Data.Char module)

```
> isLower 'b'

> toUpper 'a'

> ord 'A'

> chr 66

> Data.Char.ord 'G'
```
(uses a *qualified* name)

Function types, continued

We can use **ghci**'s **:type** command to see what the type of a function is:

```
> :type isLower
isLower :: Char -> Bool
```

The type **Char -> Bool** says that **isLower** is a function that

1. Takes an argument of type **Char**
2. Produces a result of type **Bool**

The text

```
isLower :: Char -> Bool
```

is read as "**isLower** <u>has type</u> **Char** <u>to</u> **Bool**"

Function types, continued

Recall:

```
> toUpper 'a'
'A'
> ord 'A'
65
> chr 66
'B'
```

What are the types of those three functions?

```
> :t toUpper



> :t ord



> :t chr
```

Sidebar: Contrast with Java

What is the type of the following Java methods?

```
jshell> Character.isLetter('4')
$1==> false

jshell> Character.toUpperCase('a')
$2 ==> 'A'
```

```
% javap java.lang.Character | grep "isLetter(\|toUpperCase("
  public static boolean isLetter(char);
  public static boolean isLetter(int);
  public static char toUpperCase(char);
  public static int toUpperCase(int);
```

Important:

- Java: common to think of a method's return type as the method's type
- Haskell: function's type has both type of argument(s) and return type

Type consistency

Like most languages, Haskell requires that expressions be *type-consistent* (or *well-typed*).

Here is an example of an inconsistency:

```
> chr 'x'
<interactive>:1:5: error:
   • Couldn't match expected type ‘Int’ with actual type ‘Char’
   • In the first argument of ‘chr’, namely ‘'x'’

> :t chr
chr :: Int -> Char

> :t 'x'
'x' :: Char
```

chr requires its argument to be an **Int** but we gave it a **Char**. We can say that **chr 'x'** is *ill-typed*.

Type consistency, continued

State whether each expression is well-typed and if so, its type.

```
'a'
isUpper
isUpper 'a'
not (isUpper 'a')
not not (isUpper 'a')
toUpper (ord 97)
isUpper (toUpper (chr 'a'))
isUpper (intToDigit 100)
```

```
'a' :: Char
chr :: Int -> Char
digitToInt :: Char -> Int
intToDigit :: Int -> Char
isUpper :: Char -> Bool
not :: Bool -> Bool
ord :: Char -> Int
toUpper :: Char -> Char
```

Sidebar: Key bindings in ghci

ghci uses the **haskeline** package to provide line-editing.

A few handy bindings:

TAB	completes identifiers
^A	Start of line
^E	End of line
^R	Incremental search through previously typed lines

More:

https://github.com/judah/haskeline/wiki/KeyBindings

Windows: Use **Home** and **End** for start- and end-of-line

Sidebar: Using a REPL to help learn a language

ghci provides a REPL (read-eval-print loop) for Haskell.

How does a REPL help us learn a language?

Is there a REPL for Java?

What are some other languages that have a REPL available?

What characteristics does a language need to support a REPL?

If there's no REPL for a language, how hard is it to write one?

Type classes

What's the type of `negate`?

Recall the `negate` function:

```
> negate 5
-5

> negate 5.0
-5.0
```

Speculate: What's the type of `negate`?

Type classes

"A type is a collection of related values." —Hutton

Bool, **Char**, and **Int** are examples of Haskell types.

Haskell also has *type classes*.

Type class:

A collection of types that support a specified set of of operations.

Num is one of the many type classes defined in the Prelude.

Haskell's type classes are unrelated to classes in the OO sense.

Important:

The names of types and type classes are always capitalized.

The **Num** type class

```
> :info Num
class Num a where
  (+) :: a -> a -> a
  (-) :: a -> a -> a
  (*) :: a -> a -> a
  negate :: a -> a
  abs :: a -> a
  signum :: a -> a
  fromInteger :: Integer -> a
```

A type must support all of these operations to be an instance of **Num**

```
instance Num Word
instance Num Integer
instance Num Int
instance Num Float
instance Num Double
```

The Prelude defines these types as instances of **Num**

Type classes, continued

Here's the type of **negate:**

```
> :type negate
negate :: Num a => a -> a
```

The type of **negate** is specified using a *type variable*, **a**.

The portion **a -> a** specifies that **negate** returns a value having the same type as its argument.

*"If you give me an **X**, I'll give you back an **X**."*

The portion **Num a =>** is a *class constraint*. It specifies that the type **a** must be an instance of the type class **Num**.

How can we state the type of **negate** in English?

Type classes, continued

What type do integer literals have?

```
> :type 3
3 :: Num p => p

> :type (-27)              -- Note: Parens needed!
(-27) :: Num p => p
```

Why are integer literals typed with a class constraint rather than just `Int` or `Integer`?

Type classes, continued

What's the type of a decimal fraction?

```
> :type 3.4
3.4 :: Fractional a => a
```

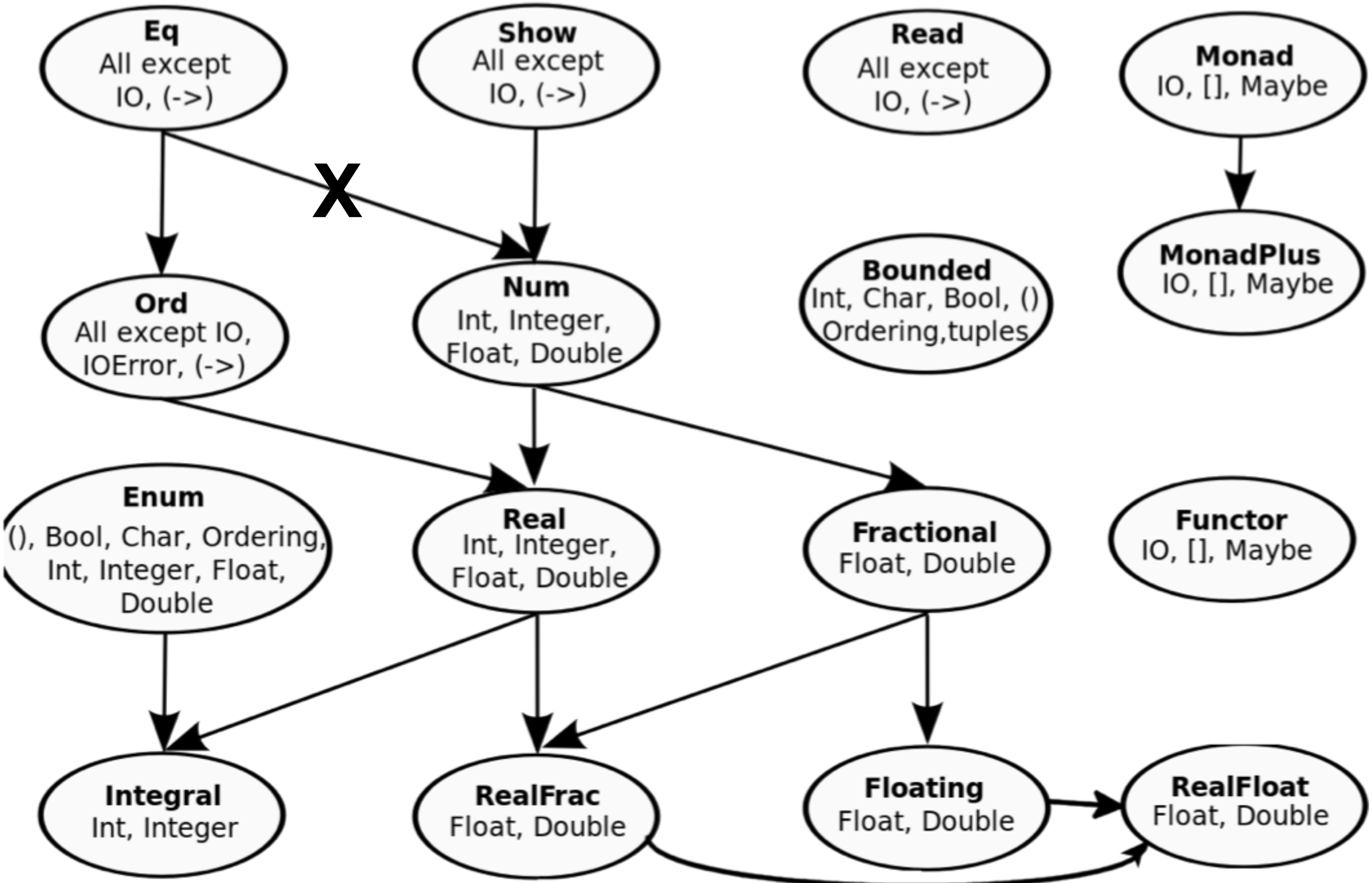
Will **negate 3.4** work?

```
> :type negate
negate :: Num a => a -> a

> negate 3.4
```

Type classes, continued

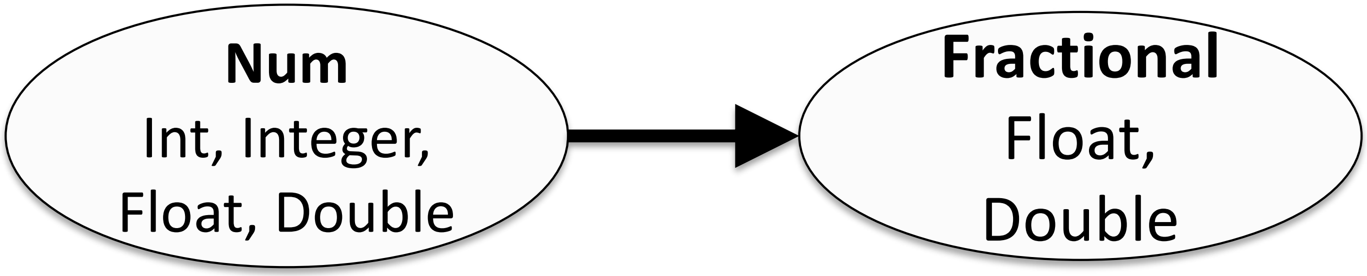
Haskell type classes form a hierarchy. The Prelude has these:



Adapted from http://en.wikibooks.org/wiki/Haskell/Classes_and_types

Type classes, continued

Excerpt:



The arrow from **Num** to **Fractional** means that a **Fractional** can be used as a **Num**.

Given

```
negate :: Num a => a -> a
```

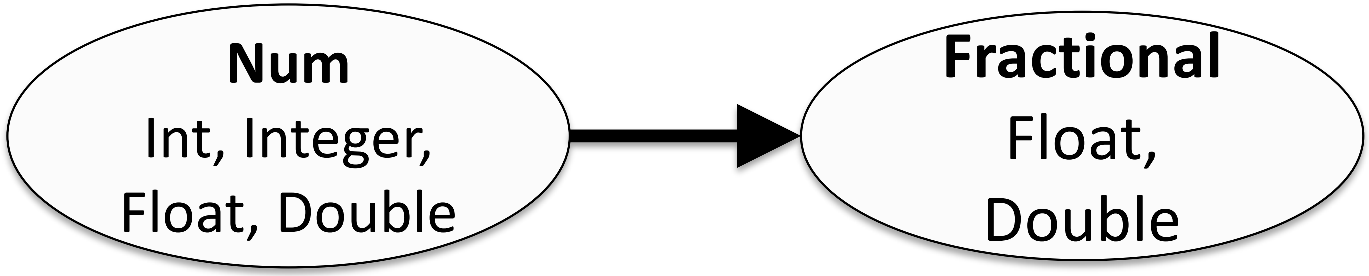
and

```
5.0 :: Fractional a => a
```

then

negate 5.0 is valid.

Type classes, continued

Excerpt: 

What does the diagram show us other than the relationship between **Num** and **Fractional**?

Type classes, continued

The Prelude has a **truncate** function:

```
> truncate 3.4
3
```

What does the type of **truncate** tell us?

```
truncate :: (Integral b, RealFrac a) => a -> b
```

Explore the **Integral** and **RealFrac** type classes with **:info**.

Type classes, continued

:info *Type* shows the classes that ***Type*** is an instance of.

```
> :info Int
data Int = GHC.Types.I# GHC.Prim.Int#
instance Eq Int
instance Ord Int
instance Show Int
instance Read Int
instance Enum Int
instance Num Int
instance Real Int
instance Bounded Int
instance Integral Int
```

Try **:info** for each of the classes.

Type classes, continued

In LYAH, Type Classes 101 has a good description of the Prelude's type classes.

Note:

> Type classes are not required for functional programming but because Haskell makes extensive use of them, we must learn about them.

Remember:

> Haskell's type classes are unrelated to classes in the OO sense.

negate is *polymorphic*

In essence, **negate :: Num a => a -> a** describes many functions:

negate :: Integer -> Integer
negate :: Int -> Int
negate :: Float -> Float
negate :: Double -> Double
...*and more*...

negate is a *polymorphic function*. It handles values of many forms.

If a function's type has any type variables, it is a polymorphic function.

Does Java have polymorphic methods? Does C? Python?

A mystery

Consider this excerpt from **Bounded**:

```
> :info Bounded
class Bounded a where
  minBound :: a
  maxBound :: a
  ...
```

What sort of things are **minBound** and **maxBound**?

How can we use them?

Polymorphic values

The construct ***::type*** is an *expression type signature*.

A usage of it:

```
> minBound::Char


> maxBound::Int


> maxBound::Bool


> maxBound::Integer
```

:set +t

We can use **:set +t** to direct **ghci** to automatically show types:

```
> :set +t

> 3
3
it :: Num p => p

> 3 + 4.5
7.5
it :: Fractional a => a

> abs
<function>
it :: Num a => a -> a
```

Use **:unset +t** to turn off display of types.

Sidebar: LHtLaL—introspective tools

:type, **:info** and **:set +t** are three introspective tools that we can use to help learn Haskell.

<u>When learning a language, look for such tools early on.</u>

Some type-related tools in other languages:

Python: **type(*expr*)** and **repr(*expr*)**

JavaScript: **typeof(expr)**

PHP: **var_dump(*expr1*, *expr2*, ...)**

C: **sizeof(*expr*)**

Java: **getClass()**; **/var** in **jshell**.

What's a difference between **ghci**'s **:type** and Java's **getClass()**?

Sidebar, continued

Here's a Java program that makes use of the "boxing" mechanism to show the type of values, albeit with wrapper types for primitives.

```
public class exprtype {
   public static void main(String args[]) {
      showtype(3 + 'a');
      showtype(3 + 4.0);
      showtype("(2<F".toCharArray());
      showtype("a,b,c".split(","));
      showtype(new HashMap());
   }
   private static void showtype(Object o) {
      System.out.println(o.getClass());
   }}
```

Output:

```
class java.lang.Integer
class java.lang.Double
class [C
class [Ljava.lang.String;
class java.util.HashMap
```

(Note: no String *or* Integer*—type erasure!)*

More on functions

Writing simple functions

A function can be defined at the REPL prompt. Example:

```
> double x = x * 2
double :: Num a => a -> a        (:set +t is in effect)

> double 5
10
it :: Num a => a

> double 2.7
5.4
it :: Fractional a => a
```

General form of a function definition for the moment:

function-name parameter = expression

Function and parameter names must begin with a lowercase letter or an underscore.

Simple functions, continued

Two more functions:

```
> neg x = -x
neg :: Num a => a -> a
```

(:set +t is in effect)

```
> toCelsius temp = (temp - 32) * 5/9
toCelsius :: Fractional a => a -> a
```

The determination of types based on the operations performed is known as *type inferencing*. (More on it later!)

Problem: Write **isPositive x** which returns **True** iff **x** is positive.

Simple functions, continued

We can use :: *type* to constrain a function's type:

```
> neg x = -x :: Int
neg :: Int -> Int

> toCelsius temp = (temp - 32) * 5/9 :: Double
toCelsius :: Double -> Double
```

:: *type* has low precedence; parentheses are required for this:

```
> isPositive x = x > (0::Int)
isPositive :: Int -> Bool
```

Note that :: *type* applies to an expression, not a function.

We'll use :: *type* to simplify some following examples.

Sidebar: loading functions from a file

We can put function definitions in a file.

The file **simple.hs** has four function definitions:

```
% cat simple.hs
double x = x * 2 :: Int
neg x = -x :: Int
isPositive x = x > (0::Int)
toCelsius temp = (temp - 32) * 5/(9::Double)
```

We'll use the extension **.hs** for Haskell source files.

Generally, code from the slides will be (poorly organized) here:

https://www2.cs.arizona.edu/classes/cs372/spring18/haskell/
/cs/www/classes/cs372/spring18/haskell (on lectura)

Sidebar, continued

Assuming **simple.hs** is in the current directory, we can load it with **:load** and see what we got with **:browse**.

```
% ghci
> :load simple                (assumes .hs suffix)
[1 of 1] Compiling Main ...
Ok, one module loaded.

> :browse
double :: Int -> Int
neg :: Int -> Int
isPositive :: Int -> Bool
toCelsius :: Double -> Double
```

Sidebar: My usual edit-run cycle

ghci is clumsy to type! I've got an **hs** alias in my **~/.bashrc**:

```
alias hs=ghci
```

I specify the file I'm working with as an argument to **hs**.

```
% hs simple
[1 of 1] Compiling Main             ( simple.hs, interpreted )
Ok, one module loaded.
> ... experiment ...
```

After editing in a different window, I use **:r** to reload the file.

```
> :r
[1 of 1] Compiling Main             ( simple.hs, interpreted )
Ok, one module loaded.
> ...experiment some more...
```

Lather, rinse, repeat.

Functions with multiple arguments

Functions with multiple arguments

Here's a function that produces the sum of its two arguments:

```
> add x y = x + y :: Int
```

Here's how we call it: (no commas or parentheses!)

```
> add 3 5
8
```

Here is its type:

```
> :type add
add :: Int -> Int -> Int
```

The operator -> is right-associative, so the above means this:

```
add :: Int -> (Int -> Int)
```

But what does that mean?

Multiple arguments, continued

Recall our negate function:

```
> neg x = -x :: Int
neg :: Int -> Int
```

Here's **add** again, with parentheses added to show precedence:

```
> add x y = x + y :: Int
add :: Int -> (Int -> Int)
```

add is a function that takes an integer as an argument and produces a function as its result!

add 3 5 means **(add 3) 5**

Call **add** with the value 3, producing a nameless function.
Call that nameless function with the value 5.

REPLACEMENTS! Discard 81+ in the old set

Exercise

Consider the following expression:

```
r = f a b + g c b(a)
```

1. Fully parenthesize it to show the order of operations

2. Write some code to precede it such that `r` gets bound to `3`.

Collaborative Learning Exercise

Haskell Functions

http://cs.arizona.edu/classes/cs372/spring18/cle-3-functions.html

Partial applications

Partial application

When we give a function fewer arguments than it requires, the resulting value is a *partial application*. It is a function.

We can bind a name to a partial application like this:

```
> plusThree = add 3
plusThree :: Int -> Int
```

The name **plusThree** now references a function that takes an **Int** and returns an **Int**.

What will **plusThree 5** produce?

```
> plusThree 5
```

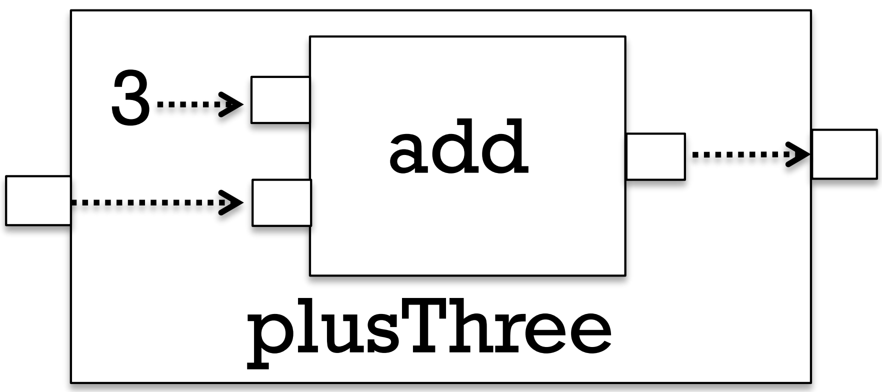
Partial application, continued

At hand:

```
> add x y = x + y :: Int
add :: Int -> (Int -> Int)  -- parens added

> plusThree = add 3
plusThree :: Int -> Int
```

Imagine **add** and **plusThree** as machines with inputs and outputs:



Analogy: **plusThree** is like a calculator where you've clicked 3, then **+**, and handed it to somebody.

Partial application, continued

At hand:

```
> add x y = x + y :: Int
add :: Int -> (Int -> Int)  -- parens added
```

Another: *(with parentheses added to type to aid understanding)*

```
> add3 x y z = x + y + z :: Int
add3 :: Int -> (Int -> (Int -> Int))
```

These functions are said to be defined in *curried* form, which allows partial application of arguments.

LYAH nails it:

> *... functions in Haskell are curried by default, which means that a function that seems to take several parameters actually takes just one parameter and returns a function that takes the next parameter and so on.*

Partial application, continued

A little history:

- The idea of a partially applicable function was first described by Moses Schönfinkel.
- It was further developed by Haskell B. Curry.
- Both worked with David Hilbert in the 1920s.

What prior use have you made of partially applied functions?

Another model of partial application

When an argument is provided to a function...

- The next parameter is dropped
- The argument's value is "wired" into the expression
- The result is a new function with one less parameter

```
> f x y = (y * x + x)::Int          -- f :: Int -> Int -> Int

> g = f 3
g :: Int -> Int
                    -- as if we'd done this:  g y = y * 3 + 3

> g 5
18

> f 3 5
18
```

Everybody: Try it!

Another model, continued

Consider this function:

```
f x y z = x + y + y * z
```

```
f1 = f 3
```

is equivalent to

```
f1 y z = 3 + y + y * z
```

```
f2 = f1 5
```

is equivalent to

```
f2 z = 3 + 5 + 5 * z
```

```
val = f2 7
```

is equivalent to

```
val = f 3 5 7
```

and

```
val = f1 5 7
```

When an argument is provided to a function...

- A parameter is dropped
- The argument's value is "wired" into the expression
- The result is a new function with one less parameter

Some key points about functions

- The *general form* of a function definition (for now):

  name param1 param2 ... paramN = expression

- A function with a type like **Int -> Char -> Char** takes two arguments, an **Int** and a **Char**. It produces a **Char**.

- Remember that **->** is a right-associative type operator.

  Int -> Char -> Char means **Int -> (Char -> Char)**

- A function call like

  f x y z

  means

  ((f x) y) z

  and (conceptually) causes two temporary, unnamed functions to be created.

Key points, continued

- Calling a function with fewer arguments than it requires creates a *partial application*, a function value.

- There's really nothing special about a partial application—it's just another function.

Functions are values

A fundamental characteristic of a functional language: functions are values that can be used as flexibly as values of other types.

The following creates a function and binds the name **add** to it.

```
> add x y = x + y
```

add, plus

...code...

The following binds the name **plus** to the expression **add**.

```
> plus = add
```

Either name can be used to reference the function value:

```
> add 3 4
7
> plus 5 6
11
```

Functions as values, continued

What does the following suggest to you?

```
> :info add
add :: Num a => a -> a -> a

> :info +
class Num a where
  (+) :: a -> a -> a
  ...
infixl 6 +
```

<u>Operators in Haskell are simply functions that have a symbolic name bound to them.</u>

infixl 6 + shows that the symbol **+** can be used as a infix operator that is <u>l</u>eft associative and has precedence level 6.

Use **:info** to explore these operators: **==**, **>**, **+**, *****, **||**, **^**, **^^** and ******.

Function/operator equivalence

To use an operator like a function, enclose it in parentheses:

```
> (+) 3 4
7
```

Conversely, we can use a <u>function</u> like an <u>operator</u> by enclosing it in backquotes:

```
> 3 `add` 4
7

> 11 `rem` 3
2
```

Speculate: do **`add`** and **`rem`** have precedence and associativity?

Sidebar: Custom operators

Haskell lets us define custom operators.

```
% cat plusper.hs
infixl 6 +%
x +% percentage = x + x * percentage / 100
```

Usage:

```
> 100 +% 1

> 12 +% 25
```

The characters ! # $ % & * + . / < = > ? @ \ ^ | - ~ : and others can be used in custom operators.

Haskell's standard modules define LOTS of custom operators.

Reference: Operators from the Prelude

<table>
<tr><th>Precedence</th><th>Left associative operators</th><th>Non associative operators</th><th>Right associative operators</th></tr>
<tr><td>9</td><td>!!</td><td></td><td>.</td></tr>
<tr><td>8</td><td></td><td></td><td>^, ^^, **</td></tr>
<tr><td>7</td><td>*, /, `div`, `mod`, `rem`, `quot`</td><td></td><td></td></tr>
<tr><td>6</td><td>+, -</td><td></td><td></td></tr>
<tr><td>5</td><td></td><td></td><td>:, ++</td></tr>
<tr><td>4</td><td></td><td>==, /=, <, <=, >, >=, `elem`, `notElem`</td><td></td></tr>
<tr><td>3</td><td></td><td></td><td>&&</td></tr>
<tr><td>2</td><td></td><td></td><td>||</td></tr>
<tr><td>1</td><td>>>, >>=</td><td></td><td></td></tr>
<tr><td>0</td><td></td><td></td><td>$, $!, `seq`</td></tr>
</table>

Note: From page 51 in Haskell 2010 report

Squeezed in for flip, to avoid adding a slide.

```
> :set +t
> add x y = x + y
add :: Num a => a -> a -> a
```

What has Haskell inferred (figured out)?

- Both arguments must have same type.
- That type must be an instance of the ***Num*** class.
- A value of that same type is returned.

Type Inferencing

Type inferencing

Haskell does type inferencing:

- The types of values are inferred based on the operations performed on the values.
- Inferences based on assumption that there are no errors.

Example:

```
> isCapital c = c >= 'A' && c <= 'Z'
isCapital :: Char -> Bool
```

Process:

1. `c` is being compared to `'A'` and `'Z'`
2. `'A'` and `'Z'` are of type `Char`
3. `c` must be a `Char`
4. The result of `&&`, of type `Bool`, is returned

Type inferencing, continued

Recall **ord** in the **Data.Char** module:

```
> :t ord
ord :: Char -> Int
```

What type will be inferred for **f**?

```
f x y = ord x == y
```

Type inferencing, continued

Recall this example:

```
> isPositive x = x > 0
isPositive :: (Num a, Ord a) => a -> Bool
```

:info shows that **>** operates on types that are instances of **Ord**:

```
> :info >
class Eq a => Ord a where
  (>) :: a -> a -> Bool
  ...
```

1. Because **x** is an operand of **>**, Haskell infers that the type of **x** must be a member of the **Ord** type class.

2. Because **x** is being compared to **0**, Haskell also infers that the type of **x** must be an instance of the **Num** type class.

Type inferencing, continued

If a contradiction is reached during type inferencing, it's an error.

The function below uses **x** as both a **Num** and a **Char**.

```
> g x y = x > 0 && x > '0'
<interactive>:1:13: error:
    • No instance for (Num Char) arising from the literal ‘0’
    • In the second argument of ‘(>)’, namely ‘0’
      In the first argument of ‘(&&)’, namely ‘x > 0’
      In the expression: x > 0 && x > '0'
```

What does the error "**No instance for (Num Char)**" mean?

Type Specifications

Type specifications for functions

Even though Haskell has type inferencing, a common practice is to specify the types of functions.

Here's a file with several functions, each preceded by its type:

```
% cat typespecs.hs
min3::Ord a => a -> a -> a -> a
min3 x y z = min x (min y z)

isCapital :: Char -> Bool
isCapital c = c >= 'A' && c <= 'Z'

isPositive :: (Num a, Ord a) => a -> Bool
isPositive x = x > 0
```

Type specifications, continued

Sometimes type specifications can backfire.

What's a ramification of the difference between the types of `add1` and `add2`?

```
add1::Num a => a -> a -> a
add1 x y = x + y

add2::Integer -> Integer -> Integer
add2 x y = x + y
```

Challenge: Without using ::*type*, show an expression that works with `add1` but fails with `add2`.

Type specification for functions, continued

Two pitfalls related to type specifications for functions:

- Specifying a type, such as `Integer`, rather than a type class, such as `Num`, may make a function's type needlessly specific, like `add2` on the previous slide.

- In some cases the type can be plain wrong without the mistake being obvious, leading to a baffling problem. (An "Ishihara".)

Recommendation:

Try writing functions without a type specification and see what type gets inferred. If the type looks reasonable, and the function works as expected, add a specification for that type.

Type specifications can prevent Haskell's type inferencing mechanism from making a series of bad inferences that lead one far away from the actual source of an error.

Indentation

Continuation with indentation

A Haskell source file is a series of *declarations*. Here's a file with two declarations:

```
% cat indent1.hs
add::Integer -> Integer -> Integer
add x y = x + y
```

<u>Rule</u>: A declaration can be continued across multiple lines by indenting subsequent lines more than the first line of the declaration.

These weaving declarations are poor style but are valid:

```
add
      ::
  Integer-> Integer-> Integer
add x y
     =
           x
               +            y
```

Indentation, continued

Rule: A line that starts in the same column as did the previous declaration ends that previous declaration and starts a new one.

```
% cat indent2.hs
add::Integer -> Integer -> Integer
add x y =
x + y

% ghci indent2
...
indent2.hs:3:1: error:
    parse error (possibly incorrect indentation ...)
  |
3 | x + y
  | ^
```

Note that **3:1** indicates line 3, column 1.

Guards

Guards

Recall this characteristic of mathematical functions:

"Are often specified with cases and expressions."

This function definition uses *guards* to specify three cases:

```
sign x | x < 0 = -1
       | x == 0 = 0
       | otherwise = 1
```

Notes:

- This definition would be found in a file, not typed in **ghci.**
- **sign x** appears just once. First guard might be on next line.
- The guards appear between **|** and **=**, and produce **Bool**s.
- What is **otherwise**?

Guards, continued

Problem: Using guards, define a function **smaller**, like **min**:

```
> smaller 7 10
7

> smaller 'z' 'a'
'a'
```

Guards, continued

Problem: Write a function **weather** that classifies a given temperature as hot if 80+, else nice if 70+, and cold otherwise.

```
> weather 95
"Hot!"
> weather 32
"Cold!"
> weather 75
"Nice"
```

Hint: guards are tried in turn.

if-else

Haskell's **if-else**

Here's an example of Haskell's **if-else**:

```
> if 1 < 2 then 3 else 4
3
```

How does it compare to Java's **if-else**?

Sidebar: Java's **if-else**

Java's **if-else** is a statement. It cannot be used where a value is required. **System.out.println(if 1 < 2 then 3 else 4);**

Does Java have an analog to Haskell's **if-else**?

Java's **if-else** statement has an **else**-less form but Haskell's **if-else** does not. Why doesn't Haskell allow it?

Java's **if-else** vs. Java's conditional operator provides a good example of a *statement* vs. an *expression*.

Pythonistas: Is there an **if-else** expression in Python?

An Original Thought

"A statement changes the *state* of the program while an expression wants to *express* itself. "

— Victor Nguyen, CSC 372, Spring 2014

Guards vs. **if-else**

Which of the versions of **sign** below is better?

```
sign x
    | x < 0 = -1
    | x == 0 = 0
    | otherwise = 1
```

```
sign x = if x < 0 then -1
                   else if x == 0 then 0
                                  else 1
```

- We'll later see that *patterns* add a third possibility for expressing cases.
- For now, prefer guards over **if-else**.

A Little Recursion

Recursion

A recursive function is a function that calls itself either directly or indirectly.

Computing the factorial of a integer (N!) is a classic example of recursion.

```
> factorial 40
```

Write factorial in Haskell. (p.s. `0!` is 1)

What is the type of `factorial`?

Recursion, continued

One way to manually trace through a recursive computation is to underline a call, then rewrite the call with a textual expansion.

```
factorial n
    | n == 0 = 1
    | otherwise = n * factorial (n – 1)
```

<u>factorial 4</u>

4 * <u>factorial 3</u>

4 * 3 * <u>factorial 2</u>

4 * 3 * 2 * <u>factorial 1</u>

4 * 3 * 2 * 1 * <u>factorial 0</u>

4 * 3 * 2 * 1 * 1

Lists

List basics

In Haskell, a list is a sequence of values of the same type.

Here's one way to make a list.

```
> [7, 3, 8]
[7,3,8]
it :: Num a => [a]

> ['x', 10]
```

It is said that lists in Haskell are homogeneous.

List basics, continued

The function **length** returns the number of elements in a list:

```
> length [3,4,5]
```

```
> length []
```

What's the type of **length**?

```
> :type length
```

With no class constraint specified, **[a]** indicates that **length** operates on lists containing elements of any type.

List basics, continued

The **head** function returns the first element of a list.

```
> head [3,4,5]
```

What's the type of **head**?

Here's what **tail** does. How would you describe it?

```
> tail [3,4,5]
[4,5]
```

What's the type of **tail**?

Important: **head** and **tail** are good for learning about lists but we'll almost always use *patterns* to access list elements!

List basics, continued

The ++ operator concatenates two lists, producing a new list.

```
> [3,4] ++ [10,20,30]
```

```
> it ++ reverse(it)
```

What are the types of ++ and **reverse**?

```
> :type (++)
```

```
> :type reverse
```

List basics, continued

Haskell has an *arithmetic sequence notation*:

```
>[1..20]

it :: (Enum a, Num a) => [a]

> [-5,-3..20]


> [10..5]
```

List basics, continue

Here are ***drop*** and ***take***:

> drop 3 [1..10]

> take 5 [1.0,1.2..2]

Problem: **halves**

Problem:

Write **halves lst** that returns a list with the two halves of **lst**, a list. If **lst**'s length is odd, the second "half" is longer.

```
> halves([1..10])
[[1,2,3,4,5],[6,7,8,9,10]]

> halves([1])
[[],[1]]
```

halves will be a little repetitious because we don't have the *where clause* in our toolbox yet.

Solution: **halves**

Solution:

List basics, continued

The !! operator produces a list's Nth element, zero-based:

```
> [10,20..100] !! 3
```

```
> :type (!!)
```

Speculate: do negative indexes work?

```
> [10,20..100] !! (-2)
```

Important:

Much use of !! might indicate you're writing a Java program in Haskell!

Comparing lists

Haskell lists are <u>values</u> and can be compared as values:

```
> [3,4] == [1+2, 2*2]
```

```
> [3] ++ [] ++ [4] == [3,4]
```

```
> tail (tail [3,4,5,6]) == [last [4,5]] ++ [6]
```

Conceptually, how many lists are created by each of the above?

In Haskell we'll write complex expressions using lists (and more) as freely as a Java programmer might write

```
f(x) * a == g(a,b) + c.
```

Comparing lists, continued

Lists are compared *lexicographically*:

- Corresponding elements are compared until an inequality is found.
- The inequality determines the result of the comparison.

Example:

```
> [1,2,3] < [1,2,4]
```

Lists of Lists

We can make lists of lists.

```
> x = [[1], [2,3,4], [5,6]]
x :: Num a => [[a]]
```

Note the type: `x` is a list of `Num a => [a]` lists.

What's the length of `x`?

```
> length x
```

Lists of lists, continued

More examples:

```
> x = [[1], [2,3,4], [5,6]]

> head x

> tail x

> x !! 1 !! 2

> head (head (tail (tail x)))
```

I lied!

Earlier I showed you this:

length :: [a] -> Int

Around version 7.10 **length** was generalized to this:

length :: Foldable t => t a -> Int

<u>We're going to think of **Foldable t => t a** as meaning **[a]**</u>.

Instead of	**sum :: (Num a, Foldable t) => t a -> a**
Pretend this	**sum :: Num a => [a] -> a**

Instead of	**minimum :: (Ord a, Foldable t) => t a -> a**
Pretend this	**minimum :: Ord a => [a] -> a**

Strings are [Char]

Strings in Haskell are simply lists of characters.

```
> "testing"
"testing"
it :: [Char]

> ['a'..'z']



> ["just", "a", "test"]
["just","a","test"]
```

What's the beauty of this?

Strings, continued

All list functions work on strings, too!

```
> asciiLets = ['A'..'Z'] ++ ['a'..'z']


> length asciiLets


> reverse (drop 26 asciiLets)


> :type elem
elem :: Eq a => a -> [a] -> Bool

> isAsciiLet c = c `elem` asciiLets
```

Strings, continued

The Prelude defines **String** as **[Char]** (a *type synonym*).

```
> :info String
type String = [Char]
```

A number of functions operate on **String**s. Here are two:

```
> :type words
words :: String -> [String]

> :type unwords
unwords :: [String] -> String
```

What's the following doing?

```
> unwords (tail (words "Just some words!"))
```

"cons" lists

Like most functional languages, Haskell's lists are "cons" lists.

A "cons" list has two parts:

    head: a value
    tail: a list of values (possibly empty)

The **:** ("cons") operator creates a list from a value and a list of values of that same type (or an empty list).

```
> 5 : [10, 20,30]
[5,10,20,30]
```

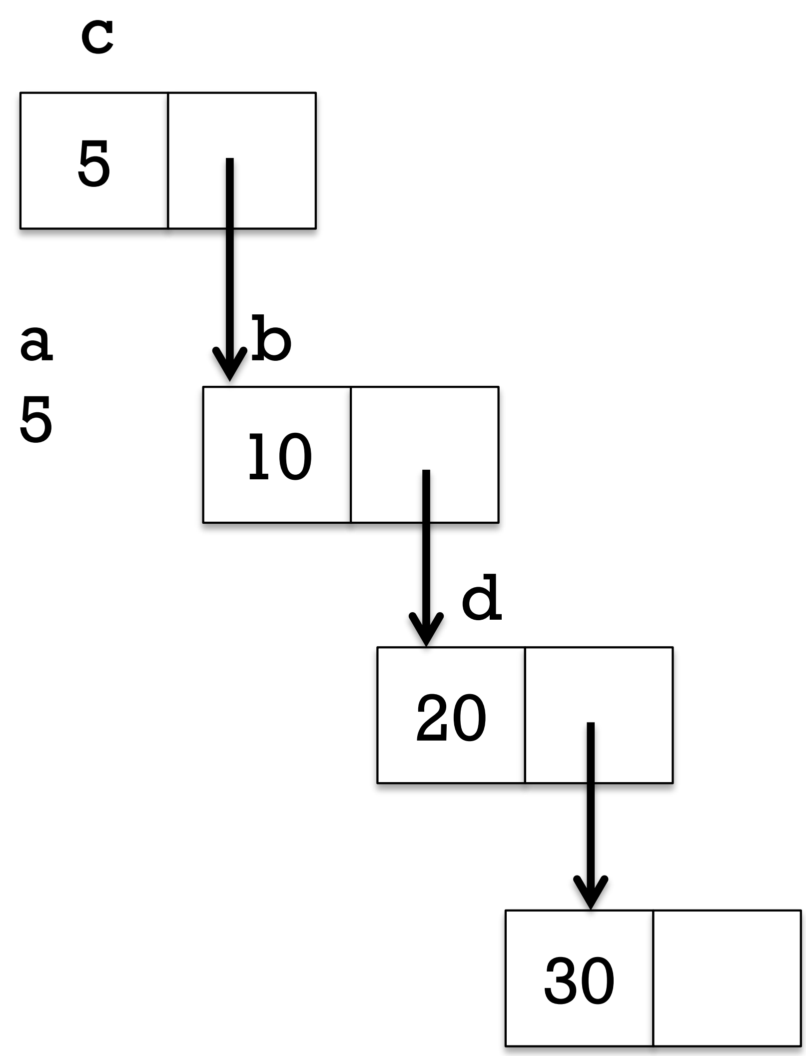
What's the type of the cons operator?

```
> :type (:)
```

"cons" lists, continued

The cons (:) operation forms a new list from a value and a list.

```
> a = 5
> b = [10,20,30]
> c = a:b
```




```
5

[10,20,30]

> d = tail (tail c)

[20,30]
```

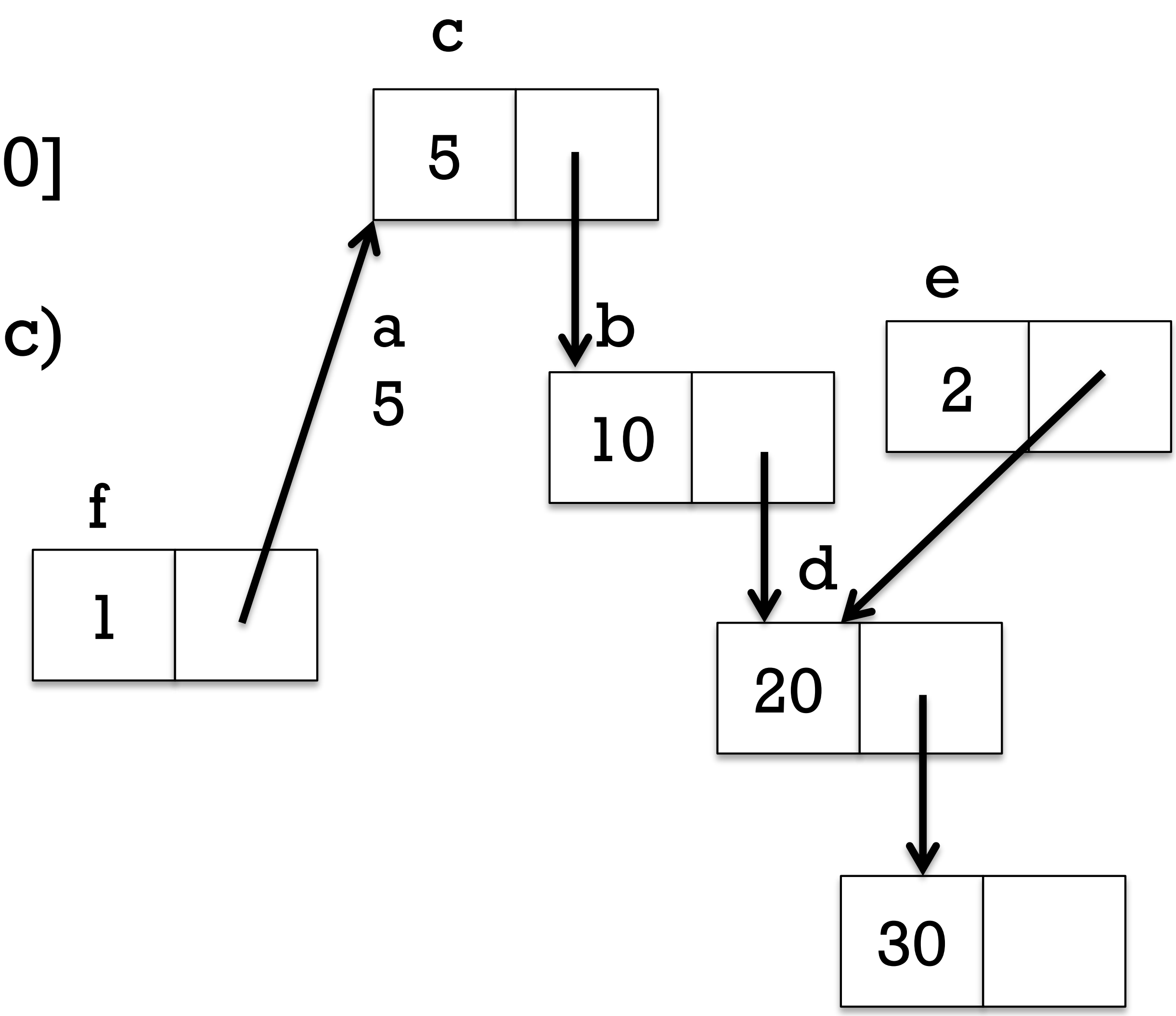
"cons" lists, continued

A cons node can be referenced by multiple cons nodes.

> a = 5
> b = [10,20,30]
> c = a:b
> d = tail (tail c)

> e=2:d

> f=1:c



"cons" lists, continued

What are the values of the following expressions?

```
> 1:[2,3]

> 1:2

> chr 97:chr 98:chr 99:[]

> []:[]

> [1,2]:[]

> []:[1]
```

cons is right associative

```
chr 97:(chr 98:(chr 99:[]))
```

head and **tail** visually

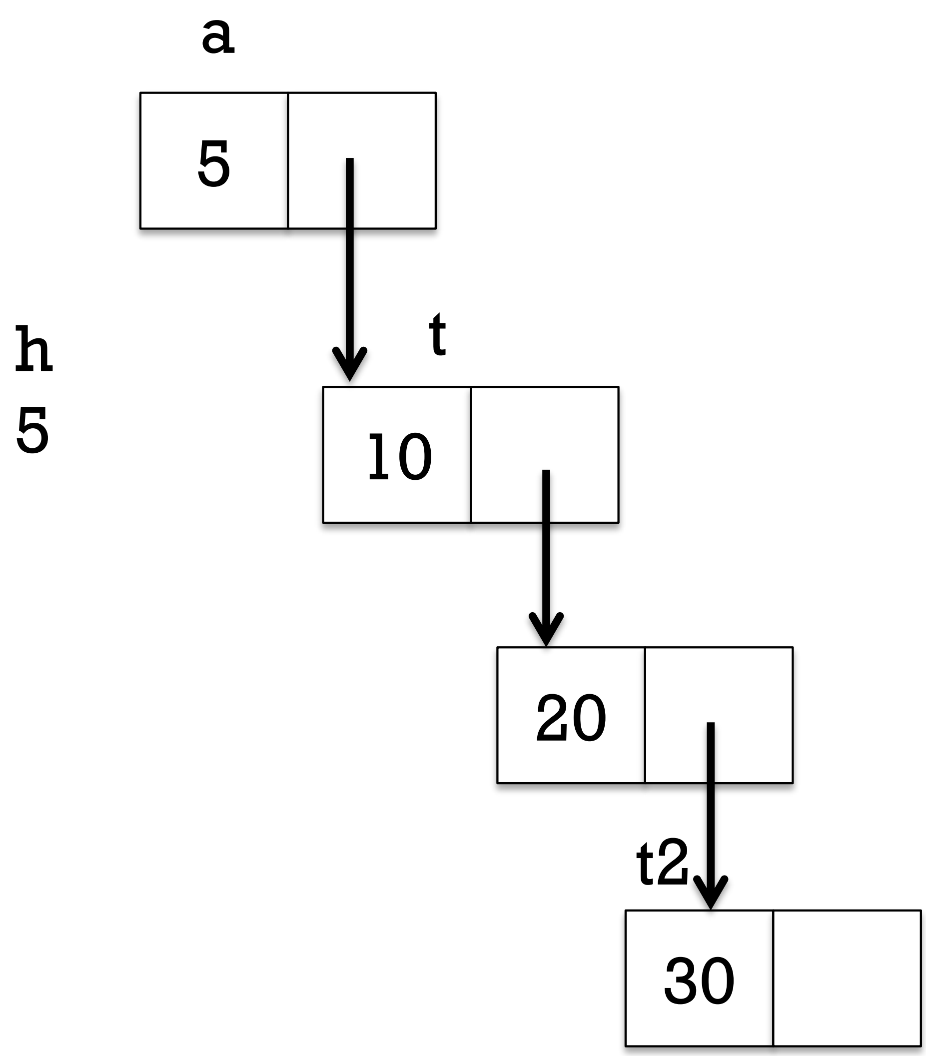
It's important to understand that <u>**tail** does not create a new list</u>. Instead it simply returns an existing cons node.

```
> a = [5,10,20,30]

> h = head a
> h
5

> t = tail a
> t
[10,20,30]

> t2 = tail (tail t)
> t2
[30]
```



A little on performance

What operations are likely fast with cons lists?

-
-
-

What operations are likely slower?

-
-

With cons lists, what does list concatenation involve?

```
> m=[1..10000000]
> length (m++[0])
10000001
```

True or false?

The head of a list is a one-element list.

The tail of a list is a list.

The tail of an empty list is an empty list.

`length (tail (tail x)) == (length x) – 2`

A cons list is essentially a singly-linked list.

A doubly-linked list might help performance in some cases.

Changing an element in a list might affect the value of many lists.

fromTo

Here's a function that produces a list with a range of integers:

```
> fromTo first last = [first..last]

> fromTo 10 15
[10,11,12,13,14,15]
```

Problem:

Write a recursive version of **fromTo** that uses the cons operator to build up its result.

fromTo, continued

One solution:

Evaluation of **fromTo 1 3** via substitution and rewriting:

```
fromTo 1 3
1 : fromTo (1+1) 3
1 : fromTo 2 3
1 : 2 : fromTo (2+1) 3
1 : 2 : fromTo 3  3
1 : 2 : 3 : fromTo (3+1) 3
1 : 2 : 3 : fromTo 4 3
1 : 2 : 3 : []
```

The **Enum** type class has **enumFromTo** and more.

fromTo, continued

Do **:set +s** to get timing and memory information, and make some lists. Try these:

```
fromTo 1 10
f = fromTo          -- So we can type f instead of fromTo
f 1 1000
f = fromTo 1        -- Note partial application
f 1000
x = f 1000000
length x
take 5 (f 1000000)
```

List comprehensions

Here's a simple example of a *list comprehension*:

```
> [x^2 | x <- [1..10]]
[1,4,9,16,25,36,49,64,81,100]
```

In English:

Make a list of the squares of **`x`** where **`x`** takes on each of the values from 1 through 10.

List comprehensions are very powerful but in the interest of time and staying focused on the core concepts of functional programming, we're not going to cover them.

Chapter 5 in Hutton has some very interesting examples of practical computations with list comprehensions.

What are other languages with list comprehensions?

REPLACEMENTS! Discard 150+ in the old set

A little output

Handy: the **show** function

What can you tell me about **show**?

```
show :: Show a => a -> String
```

show produces a string representation of a value.

```
> show 10
```

```
> show [10,20]
```

```
> show show
```

Important: **show** does not produce output!

What's the Python analog for **show**?

Challenge: Write a Java analog for **show**.

A little output

The **putStr** function outputs a string:

```
> putStr "just\ntesting\n"
just
testing
```

Type:

```
putStr :: String -> IO ()
```

- **IO ()**, the type returned by **putStr**, is an *action*.
- An action is an interaction with the outside world.
- An interaction with the outside world is a side effect.
- An action can hold/produce a value. (simplistic)
- The construct () is read as "unit".
- The unit type has a single value, unit.
- Both the type and the value are written as ().
- Contrast: **getChar :: IO Char**

Our approach

For the time being, we'll use this approach for functions that produce output:

- A helper function produces a ready-to-print string that represents all the output to be produced by the function.
  - We'll often use **show** to create pieces of the string.
  - The string will often have embedded newlines.

- The top-level function calls the helper function to get a string.

- The top-level function uses **putStr** to print that string returned by the helper.

Our approach, continued

A Java analog to our approach for functions that produce output:

```
public class output {
   public static void main(String args[]) {
      System.out.print(computeOutput(args));
      }
   ...
   }
```

Why **print** instead of **println**?

printN

Let's write a function to print the integers from 1 to N:

```
> printN 3
1
2
3
```

First, write a helper, **printN'**:

```
> printN' 3
"1\n2\n3\n"
```

Solution: (does appear on next slide)

printN, continued

At hand:

```
printN'::Integer -> String  -- Covered in flip!
printN' n
    | n == 0 = ""
    | otherwise = printN' (n-1) ++ show n ++ "\n"
```

Usage:

```
> printN' 10
"1\n2\n3\n4\n5\n6\n7\n8\n9\n10\n"
```

Let's write the top-level function:

```
printN::Integer -> IO ()
printN n = putStr (printN' n)
```

printN, continued

All together in a file:

```
% cat printN.hs
printN::Integer -> IO ()
printN n = putStr (printN' n)

printN'::Integer -> String
printN' n
    | n == 0 = ""
    | otherwise = printN' (n-1) ++ show n ++ "\n"

% ghci printN
...
> printN 3
1
2
3
```

charbox

Let's write **charbox**:

```
> charbox 5 3 '*'
*****
*****
*****

> :t charbox
charbox :: Int -> Int -> Char -> IO ()
```

How can we approach it?

charbox, continued

Let's work out a sequence of computations with ghci:

```
> replicate 5 '*'


> it ++ "\n"


> replicate 2 it


> :t concat
concat :: [[a]] -> [a]

> concat it


> putStr it
*****
*****
```

charbox, continued

Let's write **charbox'**:

```
charbox'::Int -> Int -> Char -> String
```

Test:

```
> charbox' 3 2 '*'
"***\n***\n"
```

Now we're ready for the top-level function:

```
charbox::Int -> Int -> Char -> IO ()
```

- Should we have used a helper function **charrow rowLen char**?
- How does this approach contrast with how we'd write it in Java?

Patterns

Motivation: Summing list elements

Imagine a function that computes the sum of a list's elements.

```
> sumElems  [1..10]
55

> :type sumElems
```

Implementation:

```
sumElems list
    | list == [] = 0
    | otherwise = head list + sumElems (tail list)
```

- It works but it's not idiomatic Haskell.
- We should use *patterns* instead!

Patterns

In Haskell we can use *patterns* to bind names to elements of data structures.

```
> [x,y] = [10,20]
> x

> y

> [inner] = [[2,3]]
> inner
```

Speculate: Given a list like `[10,20,30]` how could we use a pattern to bind names to the head and tail of the list?

Patterns, continued

We can use the cons operator in a pattern.

> *h:t = [10,20,30]*

> *h*

> *t*

What values get bound by the following pattern?

> *a:b:c:d = [10,20,30]*

> *[c,b,a]* -- *Why in a list?*

> *d*

-- *Why did I do* **[c,b,a]** *instead of* **[d,c,b,a]**?

Patterns, continued

If some part of a structure is not of interest, we indicate that with an underscore, known as the *wildcard pattern*.

```
> _ :( a :[b] ) :c = [ [1], [2, 3], [4] ]
> a

> b

> c
```

No binding is done for the wildcard pattern.

The pattern mechanism is completely general—patterns can be arbitrarily complex.

Patterns, continued

A name can only appear once in a pattern.

```
> a:a:[] = [3,3]
<interactive>: error: Multiple declarations of ‘a’
```

A failed pattern isn't manifested until we try to see what's bound to a name.

```
> a:b:[] = [1]
> a
**** Exception: Irrefutable pattern failed for pattern
a : b : []
```

Practice

Describe in English what must be on the right hand side for a successful match.

```
let (a:b:c) = ...
```

Does `[[10,20]]` match?
`[20,30]` ?
`"abc"` ?

```
let [x:xs] = ...
```

Does `words "a test"` match?
`[words "a test"]` ?
`[[]]` ?
`[[[]]]` ?

Patterns in function definitions

Recall our non-idiomatic **sumElems**:

```
sumElems list
    | list == [] = 0
    | otherwise = head list + sumElems (tail list)
```

How could we redo it using patterns?

```
sumElems [] = 0
sumElems (h:t) = h + sumElems t
```

Note that **sumElems** appears on both lines and that there are no guards. **sumElems** has two *clauses*. (H10 4.4.3.1)

The parentheses in (h:t) are required!!

Do the types of the two versions differ?

Patterns in functions, continued

Here's a buggy version of **sumElems**:

```
buggySum [x] = x
buggySum (h:t) = h + buggySum t
```

What's the bug?

```
> buggySum [1..100]
5050
```

Patterns in functions, continued

At hand:

```
buggySum [x] = x
buggySum (h:t) = h + buggySum t
```

If we use the **-fwarn-incomplete-patterns** option of **ghci**, we'll get a warning when loading:

```
% ghci -fwarn-incomplete-patterns buggySum.hs
buggySum.hs:1:1: Warning:
    Pattern match(es) are non-exhaustive
    In an equation for ‘buggySum’: Patterns not matched: []
    >
```

Suggestion: add a bash alias! (See us if you don't know how to.)

```
alias ghci="ghci -fwarn-incomplete-patterns"
```

Todo: Find a Windows analog.

Patterns in functions, continued

What's a little silly about the following list-summing function?

```
sillySum [] = 0
sillySum [x] = x
sillySum (h:t) = h + sillySum t
```

An "as pattern"

Consider a function that duplicates the head of a list:

```
> duphead [10,20,30]
[10,10,20,30]
```

Here's one way to write it, but it's repetitious:

```
duphead (x:xs) = x:x:xs
```

We can use an "as pattern" to bind a name to the list as a whole:

```
duphead all@(x:xs) = x:all
```

Can it be improved?

The term "as pattern" perhaps comes from Standard ML, which uses an "as" keyword for the same purpose.

Patterns, then guards, then **if-else**

Good coding style in Haskell:
Prefer patterns over guards
Prefer guards over **if-else**

Patterns—first choice!

```
sumElems [] = 0
sumElems (h:t) = h + sumElems t
```

Guards—second choice...

```
sumElems list
    | list == [] = 0
    | otherwise = head list + sumElems (tail list)
```

And, these comparisons imply that **list**'s type must be an **Eq**!

if-else—third choice...

```
sumElems list =
    if list == [] then 0
    else head list + sumElems (tail list)
```

A student wrote...

"Throughout the assignment I tried to keep in mind that I should use patterns first then guards if patterns didn't work.

"However, as I was doing the assignment, I realized that sometimes I couldn't see the patterns until I had written them as guards, so I would go back and change them.

"As I continued with the assignment, this happened less because the more code I wrote the more I was able to see patterns before I had them written as guards."

—Kelsey McCabe, Spring 2016, `a3/observations.txt`

Patterns, then guards, then if-else

Recall this example of guards:

```
weather temp | temp >= 80 = "Hot!"
             | temp >= 70 = "Nice"
             | otherwise = "Cold!"
```

Can we rewrite **weather** to have three clauses with patterns?

Design question: should patterns and guards be unified?

Revision: the general form of a function

An earlier *general form* of a function definition:

name param1 param2 ... paramN = expression

Revision: A function may have one or more clauses, of this form:

function-name pattern1 pattern2 ... patternN

$\left\{ \mid \textit{guard-expression1} \right\} = \textit{result-expression1}$

...

$\left\{ \mid \textit{guard-expressionN} \right\} = \textit{result-expressionN}$

The set of clauses for a given name is the *binding* for that name. (See 4.4.3 in H10.)

If values in a call match the pattern(s) for a clause and a guard is true, the corresponding expression is evaluated.

Revision, continued

At hand, a more general form for functions:

function-name pattern1 pattern2 ... patternN

$\{$ | *guard-expression1* $\}$ = *result-expression1*

...

$\{$ | *guard-expressionN* $\}$ = *result-expressionN*

How does

`add x y = x + y`

conform to the above specification?

-
-

Pattern/guard interaction

If the patterns of a clause match but all guards fail, the next clause is tried. Here's a contrived example:

```
f (h:_) | h < 0 = "negative head"
f list | length list > 3 = "too long"
f (_:_) = "ok"
f [] = "empty"
```

Usage:

```
> f [-1,2,3]

> f []

> f [1..10]
```

How many clauses does **f** have?

What if 2nd and 3rd clauses swapped?

What if 4th clause is removed?

REPLACEMENTS! Discard 179+ in the old set

Recursive functions on lists

Simple recursive list processing functions

Problem: Write ***len x***, which returns the length of list ***x***.

```
> len []
0

> len "testing"
7
```

Solution:

Simple list functions, continued

Problem: Write **odds x**, which returns a list having only the odd numbers from the list **x**.

```
> odds [1..10]
[1,3,5,7,9]

> take 10 (odds [1,4..100])
[1,7,13,19,25,31,37,43,49,55]
```

Handy: `odd :: Integral a => a -> Bool`

Solution:

Simple list functions, continued

Problem: write **isElem x vals**, like **elem** in the Prelude.

```
> isElem 5 [4,3,7]
False

> isElem 'n' "Bingo!"
True

> "quiz" `isElem` words "No quiz today!"
True
```

Solution:

Simple list functions, continued

Problem: Write a function that returns a list's maximum value.

```
> maxVal "maximum"
'x'

> maxVal [3,7,2]
7

> maxVal (words "i luv this stuff")
"this"
```

Recall that the Prelude has `max :: Ord a => a -> a -> a`

One solution:

Sidebar: C and Python challenges

C programmers:

- Write **strlen** in C in a functional style. (No loops or assignments.)
- Do **strcmp** and **strchr**, too!
- Mail us!

Python programmers:

- In a functional style write **size(x)**, which returns the number of elements in the string, list, or range **x**.

  Restriction: You may not use **type()** or **len()**.
- Mail us!

Tuples

Tuples

A Haskell *tuple* is an ordered aggregation of two or more values of possibly differing types.

```
> (1, "two", 3.0)
(1,"two",3.0)
it :: (Num a, Fractional c) => (a, [Char], c)

> (3 < 4, it)
(True,(1,"two",3.0))
it :: (Num a, Fractional c) => (Bool, (a, [Char], c))

> (head, tail, [words], putStr)
```

Tuples, continued

A function can return a tuple:

```
pair x y = (x,y)
```

What's the type of `pair`?

Usage:

```
> pair 3 4
```

```
> pair (3,4)
```

```
> it 5
```

Tuples, continued

The Prelude has two functions that operate on 2-tuples.

```
> p = pair 30 "forty"

> p
(30,"forty")

> fst p


> snd p
```

Tuples, continued

Recall: patterns used to bind names to list elements have the same syntax as expressions to create lists.

Patterns for tuples have the same syntax as expressions to create tuples.

Problem: Write **middle**, to extract a 3-tuple's second element.

```
> middle ("372", "ILC 119", "Mitchell")
"ILC 119"

> middle (1, [2], True)
[2]
```

(Solution on next slide. Don't peek! This means **<u>you</u>**!)

Tuples, continued

At hand:

```
> middle (1, [2], True)
[2]
```

Solution:

```
middle (_, m, _) = m
```

What's the type of **middle?**

Wil the following call work?

```
> middle(1,[(2,3)],4)
```

Tuples, continued

Problem: Write a function **swap** that behaves like this:

```
> swap ('a',False)
(False,'a')

> swap (1,(2,3))
((2,3),1)
```

Solution:

What is the type of **swap**?

Tuples, continued

Here's the type of **zip** from the Prelude:

```
zip :: [a] -> [b] -> [(a, b)]
```

Speculate: What does **zip** do? *(Pythonistas: Silence please!)*

```
> zip ["one","two","three"] [10,20,30]
[("one",10),("two",20),("three",30)]

> zip ['a'..'z'] [1..]
```

What's especially interesting about the second example?

Tuples, continued

Problem: Write **elemPos**, which returns the zero-based position of a value in a list, or -1 if not found.

```
> elemPos 'm' ['a'..'z']
12
```

Hint: Have a helper function do most of the work.

Solution:

What's wrong?

What's wrong below?

```
> x = ((1,2),(3,4,5))
> fst x
(1,2)

> snd x
(3,4,5)

> fst (snd x)
<interactive> error: Couldn't match expected type '(a, b0)'
              with actual type '(Integer, Integer, Integer)'
```

What's wrong with **fst (snd x)**?

- We can write a function that handles a list of arbitrary length.
- We can't write a function that operates on a tuple of arbitrary "arity".*

The **Eq** type class and tuples

:info Eq shows many lines like this:

```
...
instance (Eq a, Eq b, Eq c, Eq d, Eq e) => Eq (a, b, c, d, e)
instance (Eq a, Eq b, Eq c, Eq d) => Eq (a, b, c, d)
instance (Eq a, Eq b, Eq c) => Eq (a, b, c)
instance (Eq a, Eq b) => Eq (a, b)
```

Speculate: What's being specified by the above?

One of them:

```
instance (Eq a, Eq b, Eq c) => Eq (a, b, c)
```

The **Ord** and **Bounded** type classes have similar instance declarations.

Lists vs. tuples

Type-wise, lists are homogeneous; tuples are heterogeneous.

Using a tuple lets type-checking ensure that an exact number of values is being aggregated, even if all values have the same type.

> Example: A 3D point could be represented with a 3-element list but using a 3-tuple guarantees points have three coordinates.

In our Haskell we can't write functions that operate on tuples of arbitrary arity.

If there were *Head First Haskell*, it would no doubt have an interview with List and Tuple, each arguing their own merit.

Sidebar: To curry or not to curry?

Consider these two functions:

```
> add_c x y = x + y     -- _c for curried arguments
add_c :: Num a => a -> a -> a

> add_t (x,y) = x + y    -- _t for tuple argument
add_t :: Num a => (a, a) -> a
```

Usage:

```
> add_c 3 4
7

> add_t (3,4)
7
```

Important: Note the difference in types!

Which is better, add_c or add_t?

The **where** clause

The **where** clause

Intermediate values and/or helper functions can be defined using an optional ***where** clause* for a function.

Here's a declaration that shows the syntax; the computation is not meaningful.

```
f x
    | x < 0 = g a + g b
    | a > b = g b
    | otherwise = c + 10
  where {
    a = x * 5;
    b = a * 2 + x;
    g t = log t + a;
    c = a * 3;
    }
```

The ***where** clause* specifies bindings that may be needed when evaluating the guards and their associated expressions.

Like variables defined in a method or block in Java, **a**, **b**, **c** and **g** are not visible outside the the function **f**.

The **where** clause, continued

A Computer Science Tapestry by Owen Astrachan shows an interesting way to raise a number to a power:

```
power base expo
    | expo == 0 = 1.0
    | even expo = semi * semi
    | otherwise = base * semi * semi
   where {
      semi = power base (expo `div` 2)
      }
```

Binding **semi** in a **where** clause avoids lots of repetition.

Exercise for the mathematically inclined: Figure out how it works.

Problem: **halves**

Recall:

```
> halves ['a'..'z']
("abcdefghijklm","nopqrstuvwxyz")

halves lst =
  [take (length lst `div` 2) lst, drop (length lst `div` 2) lst]
```

Problem: Rewrite **halves** to be less repetitious. Also, have it return a tuple instead of a list.

Solution:

The *layout rule*

The *layout rule* for **where** (and more)

This is a valid declaration with a **where** clause:

```
f x = a + b + g a where { a = 1; b = 2; g x = -x }
```

The **where** clause has three declarations enclosed in braces and separated by semicolons.

We can take advantage of Haskell's *layout rule* and write it like this instead:

```
f x = a + b + g a
    where
        a = 1
        b = 2
        g x =
              -x
```

Besides whitespace what's different about the second version?

The layout rule, continued

At hand:

```
f x = a + b + g a
    where
      a = 1
      b = 2
      g x =
            -x
```

Another example:

```
f x = a + b + g a where a = 1
                        b = 2
                        g x =
                          -x
```

The <u>absence of a brace</u> after **where** activates the layout rule.

The column position of the <u>first token after **where**</u> establishes the column in which declarations in the **where** must start.

Note that the declaration of **g** is continued onto a second line; if the minus sign were at or left of the line, it would be an error.

The layout rule, continued

Don't confuse the layout rule with indentation-based continuation of declarations! (See slides 106-108.)

The layout rule allows omission of braces and semicolons in **where**, **do**, **let**, and **of** blocks. (We'll see **do** and **let** later.)

Indentation-based continuation applies

1. outside of **where/do/let/of** blocks
2. inside **where/do/let/of** blocks when the layout rule is triggered by the absence of an opening brace.

The layout rule is also called the "off-side rule".

TAB characters are assumed to have a width of 8.

What other languages have rules of a similar nature?

Literals in patterns

Literals in patterns

Literal values can be part or all of a pattern. Here's a 3-clause binding for **f**:

```
f 1 = 10
f 2 = 20
f n = n
```

For contrast, with guards:

```
f n
  | n == 1 = 10
  | n == 2 = 20
  | otherwise = n
```

Usage:

```
> f 1
10

> f 3
3
```

Remember: Patterns are tried in the order specified.

Literals in patterns, continued

Here's a function that classifies characters as parentheses (or not):

```
parens c
    | c == '(' = "left"
    | c == ')' = "right"
    | otherwise = "neither"
```

Could we improve it by using patterns instead of guards?

Which is better?

Remember: Patterns, then guards, then **if-else**.

Literals in patterns, continued

not is a function:

```
> :type not
not :: Bool -> Bool

> not True
False
```

Problem: Using literals in patterns, define **not**.

Solution:

```
not True = False
not _ = True           -- Using wildcard avoids comparison
```

Pattern construction

A pattern can be:

- A literal value such as 1, '`x`', or `True`
- An identifier (bound to a value if there's a match)
- An underscore (the wildcard pattern)
- A tuple composed of patterns
- A list of patterns in square brackets (fixed size list)
- A list of patterns constructed with `:` operators
- Other things we haven't seen yet

Note the recursion.

Patterns can be arbitrarily complex.

3.17.1 in H10 shows the full syntax for patterns.

Larger examples

countEO

Imagine a function that counts occurrences of even and odd numbers in a list.

```
> countEO [3,4,5]
(1,2)                    -- one even, two odds
```

Code:

```
countEO [] = (0,0)       -- no odds or evens in []
countEO (x:xs)
    | odd x = (evens, odds+1)
    | otherwise = (evens+1, odds)
  where
    (evens, odds) = countEO xs    -- do counts for tail first!
```

countEO, continued

At hand:

```
countEO [] = (0,0)
countEO (x:xs)
    | odd x = (evens, odds + 1)
    | otherwise = (1+ evens, odds)
  where (evens, odds) = countEO xs
```

Here's one way to picture this recursion:

countEO [10,20,25] returns (2,1) (result of (1 + 1,1))

countEO [20,25] returns (1,1) (result of (1 + 0,1))

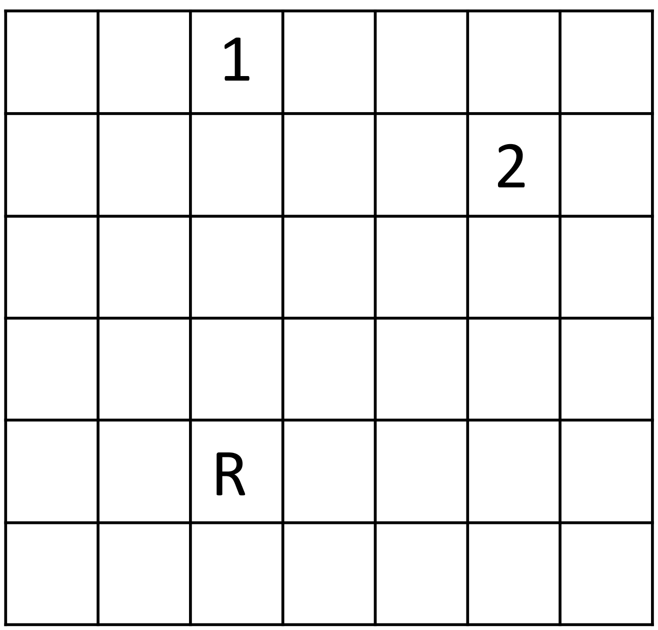
countEO [25] returns (0,1) (result of (0,0 + 1))

countEO [] returns (0,0)

travel

Imagine a robot that travels on an infinite grid of cells. Movement is directed by a series of one character commands: **n**, **e**, **s**, and **w**.

Let's write a function **travel** that moves the robot about the grid and determines if the robot ends up where it started (i.e., it got home) or elsewhere (it got lost).



If the robot starts in square R the command string **nnnn** leaves the robot in the square marked 1.

The string **nenene** leaves the robot in the square marked 2.

nnessw and **news** move the robot in a round-trip that returns it to square R.

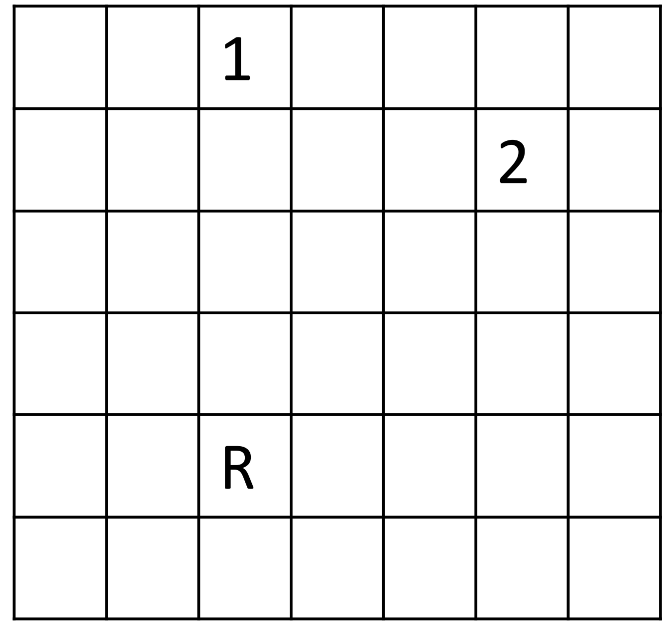
travel, continued

Usage:

```
> travel "nnnn"        -- ends at 1
"Got lost; 4 from home"

> travel "nenene"      -- ends at 2
"Got lost; 6 from home"

> travel "nnessw"
"Got home"
```



How can we approach this problem?

travel, continued

One approach:

1. Map letters into integer 2-tuples representing X and Y displacements on a Cartesian plane.
2. Sum the X and Y displacements to yield a net displacement.

Example:

Argument value: "**nnee**"

Mapped to tuples: (0,1) (0,1) (1,0) (1,0)

Sum of tuples: (2,2)

Another:

Argument value: "**nnessw**"

Mapped to tuples: (0,1) (0,1) (1,0) (0,-1) (0,-1) (-1,0)

Sum of tuples: (0,0)

travel, continued

First, let's write a helper function to turn a direction into an **(x,y)** displacement:

```
mapMove :: Char -> (Int, Int)
mapMove 'n' = (0,1)
mapMove 's' = (0,-1)
mapMove 'e' = (1,0)
mapMove 'w' = (-1,0)
mapMove c = error ("Unknown direction: " ++ [c])
```

Usage:

```
> mapMove 'n'
(0,1)

> mapMove 'w'
(-1,0)
```

travel, continued

Next, a function to sum **x** and **y** displacements in a list of tuples:

```
> sumTuples [(0,1),(1,0)]
(1,1)

> sumTuples [mapMove 'n', mapMove 'w']
(-1,1)
```

Implementation:

```
sumTuples :: [(Int,Int)] -> (Int,Int)
sumTuples [] = (0,0)
sumTuples ((x,y):ts) = (x + sumX, y + sumY)
  where
    (sumX, sumY) = sumTuples ts
```

travel itself:

```
travel :: [Char] -> [Char]
travel s
  | disp == (0,0) = "Got home"
  | otherwise = "Got lost; " ++ show (abs x + abs y) ++
                      " from home"
  where
    tuples = makeTuples s
    disp@(x,y) = sumTuples tuples -- note "as pattern"

    makeTuples :: [Char] -> [(Int, Int)]
    makeTuples [] = []
    makeTuples (c:cs) = mapMove c : makeTuples cs
```

As is, **mapMove** and **sumTuples** are at the top level but **makeTuples** is hidden inside **travel**. How should they be arranged?

Sidebar: top-level vs. hidden functions

```
travel s
   | disp == (0,0) = "Got home"
   | otherwise = "Got lost; " ...
  where
    tuples = makeTuples s
    disp = sumTuples tuples

    makeTuples [] = []
    makeTuples (c:cs) =
        mapMove c:makeTuples cs

    mapMove 'n' = (0,1)
    mapMove 's' = (0,-1)
    mapMove 'e' = (1,0)
    mapMove 'w' = (-1,0)
    mapMove c = error ...

    sumTuples [] = (0,0)
    sumTuples ((x,y):ts) = (x + sumX, y + sumY)
       where
          (sumX, sumY) = sumTuples ts
```

Top-level functions can be tested after code is loaded but functions inside a **where** block are not visible.

The functions at left are hidden in the **where** block but they can easily be changed to top-level using a shift or two with an editor.

Note: Types are not shown, to save space.

tally

Consider a function **tally** that counts character occurrences in a string:

```
> tally "a bean bag"
a 3
b 2
  2
g 1
n 1
e 1
```

Note that the characters are shown in order of decreasing frequency.

How can this problem be approached?

In a nutshell: `[('a',3),('b',2),(' ',2),('g',1),('n',1),('e',1)]`

tally, continued

Let's start by writing **incEntry c tuples**, which takes a list of (*character, count*) tuples and produces a new list of tuples that reflects the addition of the character **c**.

```
incEntry :: Char -> [(Char, Int)] -> [(Char, Int)]
```

Calls to **incEntry** with **'t', 'o', 'o'**:

```
> incEntry 't' []
[('t',1)]

> incEntry 'o' it
[('t',1),('o',1)]

> incEntry 'o' it
[('t',1),('o',2)]
```

```
{-  incEntry c tups

    tups is a list of (Char, Int) tuples that indicate how many
    times a character has been seen.  A possible value for tups:
        [('b',1),('a',2)]

    incEntry produces a copy of tups with the count in the tuple
    containing the character c incremented by one.

    If no tuple with c exists, one is created with a count of 1.
-}

incEntry::Char -> [(Char,Int)] -> [(Char,Int)]
incEntry c [ ] = [(c, 1)]
incEntry c ((char, count):entries)
  | c == char = (char, count+1) :  entries
  | otherwise = (char, count) :  incEntry c entries
```

Next, let's write **mkentries s**. It calls **incEntry** for each character in the string **s** in turn and produces a list of (*char, count*) tuples.

```
mkentries :: [Char] -> [(Char, Int)]
```

Usage:

```
> mkentries "tupple"
[('t',1),('u',1),('p',2),('l',1),('e',1)]

> mkentries "cocoon"
[('c',2),('o',3),('n',1)]
```

Code:

```
mkentries :: [Char] -> [(Char, Int)]
mkentries s = mkentries' s []
  where
    mkentries' [ ] entries = entries
    mkentries' (c:cs) entries =
      mkentries' cs (incEntry c entries)
```

```
{-  insert, isOrdered, and sort  provide an insertion sort -}
insert v [ ] = [v]
insert v (x:xs)
    | isOrdered (v,x) = v:x:xs
    | otherwise =  x:insert v xs

isOrdered ((_, v1), (_, v2)) = v1 > v2

sort [] = []
sort (x:xs) = insert x (sort xs)

> mkentries "cocoon"
[('c',2),('o',3),('n',1)]

> sort it
[('o',3),('c',2),('n',1)]
```

tally, continued

```
{- fmtEntries prints (char,count) tuples one per line -}
fmtEntries [] = ""
fmtEntries ((c, count):es) =
    [c] ++ " " ++ (show count) ++ "\n" ++ fmtEntries es

{- top-level function -}
tally s = putStr (fmtEntries (sort (mkentries s)))

> tally "cocoon"
o 3
c 2
n 1
```

- How does this solution exemplify functional programming? (slide 28+)

Running **tally** from the command line

Let's run it on lectura...

```
% code=/cs/www/classes/cs372/spring18/haskell

% cat $code/tally.hs
... everything we've seen before and now a main:
main = do
   bytes <- getContents  -- reads all of standard input
   tally bytes

% echo -n cocoon | runghc $code/tally.hs
o 3
c 2
n 1
```

tally from the command line, continued

$code/genchars N generates N random letters:

```
% $code/genchars 20
KVQaVPEmClHRbgdkmMsQ
```

Lets tally a million letters:

```
 % $code/genchars 1000000 |
        time runghc $code/tally.hs >out
21.79user 0.24system 0:22.06elapsed
% head -3 out
s  19553
V 19448
 J  19437
```

tally from the command line, continued

Let's try a compiled executable.

```
% cd $code
% ghc --make -rtsopts tally.hs
% ls -l tally
-rwxrwxr-x 1 whm whm 1118828 Jan 26 00:54 tally

% ./genchars 1000000 > 1m
% time ./tally < 1m > out
real   0m7.367s
user   0m7.260s
sys    0m0.076s
```

tally performance in other languages

Here are user CPU times for implementations of **tally** in several languages. The same one-million letter file was used for all timings.

Language	Time (seconds)
Haskell	7.260
Ruby	0.548
Icon	0.432
Python 2	0.256
C w/ `gcc -O3`	0.016

However, our **tally** implementation is very simplistic. An implementation of **tally** by an expert Haskell programmer, Chris van Horne, ran in 0.008 seconds. (See **spring18/haskell/tally-cwvh[12].hs**.)

Then I revisited the C version (**tally2.c**) and got to 3x faster than Chris' version with a one-billion character file.

Real world problem: "How many lectures?"

Here's an early question when planning a course for a semester:

"How many lectures will there be?"

How should we answer that question?

Google for a course planning app?

No! Let's write a Haskell program! ☺

classdays

One approach:

> > classdays *...arguments...*
> #1 H 1/15 *(for 2015...)*
> #2 T 1/20
> #3 H 1/22
> #4 T 1/27
> #5 H 1/29
> ...

What information do the arguments need to specify?

First and last day

Pattern, like M-W-F or T-H

How about holidays?

Arguments for **classdays**

Let's start with something simple:

```
> classdays (1,15) (5,6) [('H',5),('T',2)]
#1 H 1/15
#2 T 1/20
#3 H 1/22
#4 T 1/27
...
#32 T 5/5
>
```

The first and last days are represented with (*month*,*day*) tuples.

The third argument shows the pattern of class days: the first is a Thursday, and it's five days to the next class. The next is a Tuesday, and it's two days to the next class. Repeat!

Date handling

There's a **Data.Time.Calendar** module but writing two minimal date handling functions provides good practice.

```
> toOrdinal (12,31)
365     -- 12/31 is the last day of the year

> fromOrdinal 32
(2,1)   -- The 32nd day of the year is February 1.
```

What's a minimal data structure that could help us?

[(0,0),(1,31),(2,59),(3,90),(4,120),(5,151),(6,181),(7,212),(8,243),(9,273),(10,304),(11,334),(12,365)]

(1,31) *The last day in January is the 31st day of the year*

(7,212) *The last day in July is the 212th day of the year*

toOrdinal and fromOrdinal

```
offsets =
[(0,0),(1,31),(2,59),(3,90),(4,120),(5,151),(6,181),(7,212),(8,2
43),(9,273),(10,304),(11,334),(12,365)]

toOrdinal (month, day) = days + day
   where
      (_,days) = offsets!!(month-1)

fromOrdinal ordDay =
      fromOrdinal' (reverse offsets) ordDay
   where
      fromOrdinal' ((month,lastDay):t) ordDay
         | ordDay > lastDay = (month + 1, ordDay - lastDay)
         | otherwise = fromOrdinal' t ordDay
      fromOrdinal' [] _ = error "invalid month?"
```

```
> toOrdinal (12,31)
365
```

```
> fromOrdinal 32
(2,1)
```

Recall:

```
> classdays (1,15) (5,6) [('H',5),('T',2)]
#1 H 1/15
#2 T 1/20
...
```

Ordinal dates for `(1,15)` and `(5,6)` are `15` and `126`, respectively.

With the Thursday-Tuesday pattern we'd see the ordinal dates progressing like this:

```
15,  20,  22,  27, 29, 34, 36, 41, ...
                    ...
  +5   +2   +5  +2   +5   +2  +5  ...
```

Imagine this series of calls to a helper, **showLecture**:

```
showLecture 1 15  'H'
showLecture 2  20 'T'
showLecture 3  22 'H'
showLecture 4  27  'T'
...
showLecture 32 125 'T'
```

Desired output:

```
#1 H 1/15
#2 T 1/20
#3 H 1/22
#4 T 1/27
...
#32 T 5/5
```

What computations do we need to transform

```
showLecture 1 15  'H'
```

into

```
"#1 H 1/15\n"?
```

We have: showLecture 1 15 'H'

We want: "#1 H 1/15"

1 is lecture #1; 15 is 15^{th} day of year

Let's write showOrdinal :: Integer -> [Char]

```
> showOrdinal 15
"1/15"

showOrdinal ordDay = show month ++ "/" ++ show day
  where
    (month,day) = fromOrdinal ordDay
```

Now we can write showLecture:

```
showLecture lecNum ordDay dayOfWeek =
    "#" ++ show lecNum ++ " " ++ [dayOfWeek] ++
     " " ++ showOrdinal ordDay ++ "\n"
```

Recall:

```
showLecture 1 15  'H'
showLecture 2  20 'T'
...
showLecture 32 125 'T'
```

Desired output:

```
#1 H 1/15
#2 T 1/20
...
#32 T 5/5
```

Let's "cons up" a list out of the results of those calls...

```
> showLecture 1 15 'H' :
  showLecture 2 20 'T' :
  "...more..." :  -- I literally typed "...more..."
  showLecture 32 125 'T' : []
["#1 H 1/15\n","#2 T 1/20\n", "...more...","#32 T
5/5\n"]
```

How close are the contents of that list to what we need?

Now lets imagine a recursive function **showLectures** that builds up a list of results from **showLecture** calls:

```
showLectures 1 15 126 [('H',5),('T',2)]            "#1 H 1/15\n"
  showLectures 2 20 126 [('T',2),('H',5)]          "#2 T 1/20\n"
      ...
    showLectures 32 125 126 [('T',2),('H',5)]      "#32 T 5/5\n"
      showLectures 33 127 126 [('H',5),('T',2)]
```

Result:

```
["#1 H 1/15\n","#2 T 1/20\n", ... ,"#33 H 5/5\n"]
```

Now let's write **showLectures:**

```
showLectures  lecNum thisDay lastDay
                 (pair@(dayOfWeek, daysToNext):pairs)
    | thisDay > lastDay = []
    | otherwise =  showLecture lecNum thisDay dayOfWeek
      :  showLectures (lecNum+1) (thisDay + daysToNext)
                  lastDay (pairs ++ [pair])
```

classdays—top-level

Finally, a top-level function to get the ball rolling:

```
classdays first last pattern = putStr (concat result)
    where
        result =
            showLectures 1 (toOrdinal first) (toOrdinal last) pattern
```

Usage:

```
> classdays (1,15) (5,6) [('H',5),('T',2)]
#1 H 1/15
#2 T 1/20
#3 H 1/22
...
#31 H 4/30
#32 T 5/5
```

Full source is in **spring18/haskell/classdays.hs**

Errors

Syntax errors

What syntax errors do you see in the following file?

```
% cat synerrors.hs
F x =
   | x < 0 == y + 10
   | x != 0 = y + 20
   otherwise = y + 30
  where
      g x:xs = x
      y =
      g [x] + 5
        g2 x = 10
```

Syntax errors, continued

What syntax errors do you see in the following file?

Function name starts with cap.

no = before guards

```
% cat synerrors.hs
F x =
    | x < 0 == y + 10
    | x != 0 = y + 20
    otherwise = y + 30
   where
       g x:xs = x
       y =
       g [x] + 5
         g2 x = 10
```

=, not == before result

use /= for inequality

missing | before **otherwise**

Needs parens: **(x:xs)**

continuation should be indented

violates *layout rule*

Type errors

In my opinion, producing understandable messages for type errors is what ghci is worst at.

If no polymorphic functions are involved, type errors are typically easy to understand.

```
> :type chr
chr :: Int -> Char

> chr 'x'
  Couldn't match expected type `Int' with actual
    type `Char'
   In the first argument of 'chr', namely 'x'
   In the expression: chr 'x'
   In an equation for 'it': it = chr 'x'
```

Type errors, continued

Code and error:

```
f x y
    | x == 0 = []
    | otherwise = f x
```

```
Couldn't match type 'p0 -> [a]' with '[a]'
    Expected type: t -> [a]
    Actual type: t -> p0 -> [a]
```

The first clause implies that `f` returns `[a]` but the second clause returns a partial application, of type `p0 -> [a]`, a contradiction.

Type errors, continued

Code:

```
countEO (x:xs)
   | odd x = (evens, odds+1)
   | otherwise = (evens+1, odds)
  where (evens,odds) = countEO
```

Error:

```
Couldn't match expected type '(a1, b)'
                 with actual type '[a] -> (a1, b)'
Probable cause: countEO is applied to too few arguments
  In the expression: countEO
```

What's the problem?

It's expecting a tuple, `(a1,b)` but it's getting a function, `[a] -> (a1,b)`

Typically, instead of errors about too few (or too many) function arguments, you get function types popping up in unexpected places.

Type errors, continued

Here's an example of omitting an operator:

```
> add3 x y z = x + y z
> add3 4 5 6
<interactive>:9:1: error:
Non type variable argument in the constraint:
Num (t -> a) (Use FlexibleContexts to permit this)
```

Looking at the type of **add3** sheds some light on the problem:

```
> :t add3
add3 :: Num a => a -> (t -> a) -> t -> a
```

A function type unexpectedly being inferred for **y** suggests we should look at how **y** is being used.

Try it: See if a type declaration for **add3** leads to a better error.

Type errors, continued

Is there an error in the following?

```
f [] = []
f [x] = x
f (x:xs) = x : f xs
```

A simple way to produce an infinite type:

```
x = head x
```

```
Occurs check: cannot construct the infinite type: a ~ [a]
    Expected type: [a]
    Actual type: [[a]]
In the expression: x : f xs
In an equation for 'f': f (x : xs) = x : f xs
```

("a is a list of as"--whm)

The second and third clauses are fine by themselves but together they create a contradiction.

Technique: Comment out clauses (and/or guards) to find the troublemaker, or incompatibilities between them.

Type errors, continued

Recall **ord :: Char -> Int.**

Note this error:

```
> ord 5
  No instance for (Num Char) arising from the literal `5'
```

The error "**No instance for (*TypeClass Type*)**" means that *Type* (**Char**, in this case) is not an instance of *TypeClass* (**Num**).

```
> :info Num
....
instance Num Word
instance Num Integer
instance Num Int
instance Num Float
instance Num Double
```

instance Num Char doesn't appear

Debugging

Debugging in general

My advice in a nutshell:

Don't need to do any debugging in Haskell!

My usual development process in Haskell:

1. Work out expressions at the `ghci` prompt.
2. Write a function using those expressions and put it in a file.
3. Test that function at the `ghci` prompt.
4. Repeat with the next function.

With conventional languages I might write dozens of lines of code before trying them out.

With Haskell I might write a half-dozen lines of code before trying them out.

The **trace** function

The **Debug.Trace** module has a **trace** function.

Observe:

```
> import Debug.Trace  -- put it in your ghci config file
> :t trace
trace :: String -> a -> a

> trace "a tuple" (True, 'x')
a tuple
(True,'x')
```

What's happening?

trace string value returns **value** but also outputs **string** as a side-effect. (!)

- Great for debugging!
- Completely subverts Haskell's isolation of the side-effects of output.

trace, continued

Here's a trivial function:

```
f 1 = 10
f n = n * 5 + 7
```

Let's augment it with tracing:

```
import Debug.Trace
f 1 = trace "f: first case" 10
f n = trace "f: default case" n * 5 + 7
```

Execution:

```
> f 1
f: first case
10

> f 3
f: default case
22
```

trace, continued

Let's add **trace** calls to **sumElems**:

```
sumElems [] = trace "sumElems []" 0
sumElems lst@(h:t) =
    trace ("sumElems " ++ show lst) h + sumElems t
```

Execution:

```
> sumElems [5,1,4,2,3]
sumElems []
sumElems [3]
sumElems [2,3]
sumElems [4,2,3]
sumElems [1,4,2,3]
sumElems [5,1,4,2,3]
15
```

Unfortunately, due to Haskell's lazy evaluation, the output's order is the opposite of what we'd expect. But it does show "progression".

trace, continued

Here's **countEO** with tracing:

```
import Debug.Trace
countEO [] = (0,0)
countEO list@(x:xs)
    | odd x = (evens, odds+1)
    | otherwise = (evens+1, odds)
  where
   result = countEO xs
   (evens,odds) =
    trace ("countEO " ++ show xs ++ " --> " ++ show result) result
```

Execution:

```
> countEO [3,2,4]
(countEO [] --> (0,0)
countEO [4] --> (1,0)
countEO [2,4] --> (2,0)
2,1)
```

Before tracing the **where** was:

```
(evens,odds) = countEO xs
```

trace, continued

Recall this clause for **buildingAtHeight**:

```
buildingAtHeight (width, height, ch) n =
    replicate width (if n > height then ' ' else ch)
```

Outputting **width**, **height**, and **ch** with labels is tedious:

```
buildingAtHeight (width, height, ch) n =
    trace ("width " ++ show width ++ ", height: " ++
       show height ++ ", ch: " ++ show ch)
    replicate width (if n > height then ' ' else ch)
```

Example of trace **output**: **width: 3, height: 2, ch: 'x'**

We can use a tuple to simplify the **trace** call:

```
buildingAtHeight (width, height, ch) n =
    trace (show ("width:", width, "height", height, "ch", ch))
    replicate width (if n > height then ' ' else ch)
```

Example of **trace** output: **("width:",3,"height",2,"ch:",'x')**

Sidebar: Tracing in Icon

Icon has a built-in tracing mechanism.

Here's **sumElems** in Icon:

```
% cat -n sumElems.icn
procedure main()
    sumElems([5,1,4,2,3])
end

procedure sumElems(L)
    if *L = 0 then
        return 0
    else
        return L[1] + sumElems(L[1:-1])
end
```

Sidebar, continued

Execution:

```
% TRACE=-1 icont sumElems.icn -x
...
               :       main()
sumElems.icn :     2  | sumElems(list_1 = [5,1,4,2,3])
sumElems.icn :     9  | | sumElems(list_2 = [5,1,4,2])
sumElems.icn :     9  | | | sumElems(list_3 = [5,1,4])
sumElems.icn :     9  | | | | sumElems(list_4 = [5,1])
sumElems.icn :     9  | | | | | sumElems(list_5 = [5])
sumElems.icn :     9  | | | | | | sumElems(list_6 = [])
sumElems.icn :     7  | | | | | | sumElems returned 0
sumElems.icn :     9  | | | | | sumElems returned 5
sumElems.icn :     9  | | | | sumElems returned 10
sumElems.icn :     9  | | | sumElems returned 15
sumElems.icn :     9  | | sumElems returned 20
sumElems.icn :     9  | sumElems returned 25
sumElems.icn :     3  main failed
```

I know of no better out-of-the-box tracing facility in any language.

ghci's debugger

ghci does have some debugging support but debugging is *expression-based*. Here's some simple interaction with it on **countEO**:

```
> :step countEO [3,2,4]
Stopped at countEO.hs:(1,1)-(6,29)
_result :: (t, t1) = _
> :step
Stopped at countEO.hs:3:7-11
_result :: Bool = _
x :: Integer = 3
> :step
Stopped at countEO.hs:3:15-29
_result :: (t, t1) = _
evens :: t = _
odds :: t1 = _
> :step
(Stopped at countEO.hs:6:20-29
_result :: (t, t1) = _
xs :: [Integer] = [2,4]
```

```
countEO [] = (0,0)
countEO (x:xs)
   | odd x = (evens, odds+1)
   | otherwise = (evens+1, odds)
  where
   (evens,odds) = countEO xs
```

_result shows type of current expression

Arbitrary expressions can be evaluated at the **>** prompt (as always).

PREVIEW CLE 4 NOW
(SLIDE 272)

Excursion:
A little bit with infinite lists
and lazy evaluation

Infinite lists

Here's a way we've seen to make an infinite list:

```
> [1..]
[1,2,3,4,5,6,7,8,9,10,11,12,13,14,15,16,17,18,19,^C
```

In essence, what does the following bind **f** to?

```
> f = (!!) [1,3..]
f :: (Num a, Enum a) => Int -> a
```

- Yes, we could say **f n = (n*2)+1** but that wouldn't be nearly as much fun! (This *is* <u>fun</u>ctional programming!)

- I want you to be cognizant of performance but don't let concerns about performance stifle creativity!

Lazy evaluation

Consider the following binding. Why does it complete?

```
> fives = [5,10..]
```

How will the following expression behave?

```
> take (head fives) fives
```

Lazy evaluation, continued

Here is an expression that is said to be *non-terminating:*

> **> length fives**
> *...when tired of waiting...*^C Interrupted.
> The value of **length fives** is said to be $\perp$ ("bottom").

But, we can bind a name to **length fives**:

```
> numFives = length fives
numFives :: Int
```

It completes because Haskell hasn't yet needed to compute a value for **length fives**.

What does the following do?

```
> numFives
```

Lazy evaluation, continued

We can use **:print** to explore lazy evaluation:

```
> fives = [5,10..]

> :print fives
fives = (_t1::[Integer])   -- ghci 7.8.3 behavior
fives = (_t1::(Enum a, Num a) => [a])  -- 8.2.2

> take 3 fives
[5,10,15]
```

What do you think **:print fives** will now show?

```
> :print fives
fives = 5 : 10 : 15 : (_t3::[Integer])   -- ghci 7.8.3
fives = (_t1::(Enum a, Num a) => [a]) -- 8.2.2
```

Lazy vs. non-strict

In fact, Haskell doesn't fully meet the requirements of lazy evaluation.
The word "lazy" appears only once in the Haskell 2010 Report.

What Haskell does provide is *non-strict evaluation*:
Function arguments are not evaluated until a value is needed.

Consider this function:

```
f x y z = if even x then y else z
```

What does the following expression produce?

```
> f 4 10 (length [1..])
```

Why does it complete?

Lazy vs. non-strict

At hand:

```
f x y z = if even x then y else z
```

How will the following behave?

```
> a = f 4 (length [1..]) 100
> b = a + 1
> c = [1,b]

2
> head c
1
> c
[1,^CInterrupted.
```

See ***wiki.haskell.org/Lazy_vs._non-strict*** for the fine points of lazy evaluation vs. non-strict evaluation. Google for more, too.

Sidebar: Evaluation in Java

How is the following Java expression evaluated?

```
x = f(g(x+3), h())
```

A model:

1. `t1 = x+3`
2. `t2 = g(t1)`
3. `t3 = h()`
4. `x = f(t2,t3)`

- Java uses strict evaluation
- Java guarantees* left to right evaluation of argument lists (JLS 15.7)
- Contrast: C does not guarantee L-to-R evaluation of argument lists.

What's a case in which Java's L-to-R guarantee makes a difference?

-
-

More with infinite lists

Speculate: Can infinite lists be concatenated?

```
> values = [1..] ++ [5,10..] ++ [1,2,3]
```

What will the following do?

```
> values > [1,2,3,5]
```

How far did evaluation of **values** progress?

```
values = 1 : 2 : 3 : 4 : (_t2::[Integer]) -- ghci 7.8.3
```

Infinite expressions

What does the following expression mean?

```
> threes = 3 : threes
```

How about the following?

```
> xys = ['x','y'] ++ xys

> take 5 xys

> xys !! 100000000
```

One more:

```
> x = 1 + x
> x
```

intsFrom

Problem: write a function **intsFrom** that produces the integers from a starting value. (No, you can't use **[n..]**!)

```
> intsFrom 1
[1,2,3,4,5,6,7,8,9,10,11,12,13,14,15,16,17,18,19,20,21,...

> intsFrom 1000
[1000,1001,1002,1003,1004,1005,1006,1007,1008,...

> take 5 (intsFrom 1000000)
[1000000,1000001,1000002,1000003,1000004]
```

Solution:

Does **length (intsFrom (minBound::Int))** terminate?

Collaborative Learning Exercise

Infinite experimentation

cs.arizona.edu/classes/cs372/spring18/cle-4-infexp.html

Note to self: do **push-cle 4**

Higher-order functions

Remember: Functions are values

Recall this fundamental characteristic of a functional language:

Functions are values that can be used as flexibly as values of other types.

Here are some more examples of that. What do the following do?

> (if 3 < 4 then head else last) "abc"

> funcs = (tail, (:) 100)

> nums = [1..10]

> fst funcs nums

> snd funcs nums

Lists of functions

Is the following valid?

```
> [take, tail, init]
```

What's the problem?

Puzzle: Make **[take, tail, init]** valid by adding two characters.

Comparing functions

Can functions be compared?

```
> add == plus
No instance for (Eq (Integer -> Integer -> Integer))
    arising from a use of `=='
In the expression: add == plus
```

You might see a proof based on this in CSC 473:

If we could determine if two arbitrary functions perform the same computation, we could solve *the halting problem*, which is considered to be unsolvable.

Because functions can't be compared, this version of **length** won't work for lists of functions: (Its type: (Num a, Eq t) => [t] -> a)

```
len list@(_h:t)
    | list == [] = 0
    | otherwise = 1 + len t
```

A simple *higher-order function*

Definition: A *higher-order function* is a function that (and/or)

- Has one or more arguments that are functions
- Returns a function

twice is a higher-order function with <u>two</u> arguments: **f** and **x**

```
twice f x = f (f x)
```

What does it do?

```
> twice tail [1,2,3,4,5]
```

```
> tail (tail [1,2,3,4,5])
```

.

twice, continued

At hand:

```
> twice f x = f (f x)
> twice tail [1,2,3,4,5]
[3,4,5]
```

Let's make the precedence explicit:

```
> ((twice tail) [1,2,3,4,5])
[3,4,5]
```

Consider a partial application...

```
> t2 = twice tail        -- like t2 x = tail (tail x)
> t2
<function>
it :: [a] -> [a]
```

twice, continued

At hand:

```
> twice f x = f (f x)
> twice tail [1,2,3,4,5]
[3,4,5]
```

Let's give **twice** a partial application!

```
> twice (drop 2) [1..5]
```

Let's make a partial application with a partial application!

```
> twice (drop 5)
<function>
> it ['a'..'z']
```

Try these!

```
twice (twice (drop 3)) [1..20]
twice (twice (take 3)) [1..20]
```

twice, continued

At hand:

```
twice f x = f (f x)
```

A *higher-order function* is...
a function that (1) has one or more arguments that are functions and/or (2) returns a function.

What's the the type of **twice**?

```
> :t twice
twice :: (t -> t) -> t -> t
```

Parentheses added to show precedence:

```
twice :: (t -> t) -> (t -> t)

            twice f  x  =  f (f x)
```

What's the correspondence between the elements of the clause and the elements of the type?

The **map** function

The Prelude's **map** function

Recall **double x = x * 2**

map is a Prelude function that applies a function to each element of a list, producing a new list:

```
> map double [1..5]


> map length (words "a few words")


> map head (words "a few words")
```

Is **map** a higher order function?

map, continued

At hand:

```
> map double [1..5]
[2,4,6,8,10]
```

Problem: Write **map**!

What is its type?

What's the relationship between the length of **map**'s input and output lists?

`map`, continued

Mapping (via `map`) is applying a transformation (a function) to each of the values in a list, always producing a new list of the same length.

```
> map chr [97,32,98,105,103,32,99,97,116]


> map isLetter it


> map not it


> map head (map show it) -- Note: show True is "True"
```

Sidebar: map can go parallel

Here's another map:

```
> map weather [85,55,75]
["Hot!","Cold!","Nice"]
```

This is equivalent:

```
> [weather 85, weather 55, weather 75]
["Hot!","Cold!","Nice"]
```

- If functions have no side effects, we can immediately turn a mapping into a parallel computation.
- We might start each function call on a separate processor and combine the values when all are done.

map and partial applications

What's the result of these?

```
> map (add 5) [1..10]
```

```
> map (drop 1) (words "the knot was cold")
```

```
> map (replicate 5) "abc"
```

map and partial applications, cont.

What's going on here?

```
> f = map double
> f [1..5]
```

```
> map f [[1..3],[10..15]]
```

Here's the above in one step:

```
> map (map double) [[1..3],[10..15]]
[[2,4,6],[20,22,24,26,28,30]]
```

Here's one way to think about it:

[<u>(map double)</u> [1..3], <u>(map double)</u> [10..15]]

Sections

Instead of using **map (add 5)** to add 5 to the values in a list, we should use a *section* instead: (it's the idiomatic way!)

```
> map (5+) [1,2,3]
[6,7,8]    -- [5+ 1, 5+ 2, 5+ 3]
```

More sections:

```
> map (10*) [1,2,3]


> map (++"*") (words "a few words")


> map ("*"++) (words "a few words")
```

Sections, continued

Sections have one of two forms:

(*infix-operator value*) Examples: `(+5)`, `(/10)`

(*value infix-operator*) Examples: `(5*)`, `("x"++)`

<u>Iff</u> the operator is commutative, the two forms are equivalent.

```
> map (3<=) [1..4]
```

`[3 <= 1, 3 <= 2, 3 <= 3, 3 <= 4]`

```
> map (<=3) [1..4]
```

`[1 <= 3, 2 <= 3, 3 <= 3, 4 <= 4]`

Sections aren't just for `map`; they're a general mechanism.

```
> twice (+5) 3
```

travel, revisited

Now that we're good at recursion...

Some of the problems on the next assignment will encourage working with higher-order functions by prohibiting you from <u>writing</u> any recursive functions!

Think of it as isolating muscle groups when weight training.

Here's a simple way to avoid what's prohibited:

<u>Pretend that you don't understand recursion!</u>

What's a base case? Is it related to baseball?
Why would a function call itself? How's it stop?
Is a recursive plunge refreshing?

If you were UNIX machines, I'd do `chmod 0` on an appropriate section of your brains.

travel revisited

Recall our traveling robot: (slide 214+)

```
> travel "nnee"
"Got lost"

> travel "nnss"
"Got home"
```

Recall our approach:

Argument value: "**nnee**"

Mapped to tuples: (0,1) (0,1) (1,0) (1,0)

Sum of tuples: (2,2)

How can we solve it without writing any recursive functions?

travel, continued

Recall:

```
> :t mapMove
mapMove :: Char -> (Int, Int)

> mapMove 'n'
(0,1)
```

Now what?

travel, continued

We have:

```
> disps = map mapMove "nneen"
[(0,1),(0,1),(1,0),(1,0),(0,1)]
```

We want: (2,3)

Any ideas?

travel, revisited

We have:

```
> disps= map mapMove "nneen"
[(0,1),(0,1),(1,0),(1,0),(0,1)]
> map fst disps
[0,0,1,1,0]
> map snd disps
[1,1,0,0,1]
```

We want: `(2,3)`

Ideas?

travel—Final answer

```
travel :: [Char] -> [Char]
travel s
   | totalDisp == (0,0) = "Got home"
   | otherwise = "Got lost"
  where
     disps = map mapMove s
     totalDisp = (sum (map fst disps),
                  sum (map snd disps))
```

Did we have to understand recursion to write this version of **travel**?

No.

Did we <u>write</u> any recursive functions?

No.

Did we <u>use</u> any recursive functions?

<u>Maybe</u>. But <u>using</u> recursive functions doesn't violate the prohibition at hand.

Filtering

Filtering

Another higher order function in the Prelude is **filter**:

> **> filter odd [1..10]**

> **> filter isDigit "(800) 555-1212"**

What's **filter f list** doing?

Note: Think of **filter** as filtering in, not filtering out.

What is the type of **filter**?

filter uses a *predicate*

filter's first argument (a function) is called a *predicate* because inclusion of each value is predicated on the result of calling that function with that value.

More...

```
> filter (<= 5) (filter odd [1..10])
```

```
> map (filter isDigit) ["br549", "24/7"]
```

```
> filter (`elem` "aeiou") "some words here"
```

Note that (`elem` ...) is a section.

```
elem :: Eq a => a -> [a] -> Bool
```

filter, continued

At hand:

```
> filter odd [1..10]
[1,3,5,7,9]

> :t filter
filter :: (a -> Bool) -> [a] -> [a]
```

Problem: Write **filter**!

Prelude functions that use predicates

Several Prelude functions use predicates. Here are two:

```
all :: (a -> Bool) -> [a] -> Bool
> all even [2,4,6,8]
True
> all even [2,4,6,7]
False

dropWhile :: (a -> Bool) -> [a] -> [a]
> dropWhile isSpace "  testing  "

> dropWhile isLetter it
```

How could we find other Prelude functions that use predicates?

map vs. filter

For reference:

```
> map double [1..10]
[2,4,6,8,10,12,14,16,18,20]

> filter odd [1..10]
[1,3,5,7,9]
```

map:

transforms a list of values

length *input* == length *output*

filter:

selects values from a list

0 <= length *output* <= length *input*

map and **filter** are in Python and JavaScript, to name two of many languages having them. (And, they're trivial to write!)

Anonymous functions

Anonymous functions

Imagine that for every number in a list we'd like to double it and then subtract five.

Here's one way to do it:

```
> f n = n * 2 - 5
> map f [1..5]
[-3,-1,1,3,5]
```

We could instead use an *anonymous function* to do the same thing:

```
> map (\n -> n * 2 - 5) [1..5]
[-3,-1,1,3,5]
```

What benefits does the anonymous function provide?

Anonymous functions, continued

At hand:

```
f n = n * 2 - 5
map f [1..5]
```

vs.

```
map (\n -> n * 2 - 5) [1..5]
```

an anonymous function

The most common use case for an anonymous function: (my guess)
Supply a simple "one-off" function to a higher-order function.

Anonymous functions...

- Directly associate a function's definition with its only use.
- Let us avoid the need to think up a good name for a function! ☺
- Can be likened to not using an intermediate variable:

```
int t = a * 3 + g(a+b);      // Java
return f(t);
```

vs.

```
return f(a * 3 + g(a+b));
```

Anonymous functions, continued

The general form of an anonymous function:

`\ pattern1 ... patternN -> expression`

Simple syntax suggestion: enclose the whole works in parentheses.

```
map (\n -> n * 2 - 5) [1..5]
```

These terms are synonymous with "anonymous function":

Lambda abstraction (H10)
Lambda expression
Just *lambda* (LYAH).

The \ character was chosen due to its similarity to λ (Greek lambda), used in the *lambda calculus*, another system for expressing computation.

Anonymous functions, continued

What will **ghci** say?

```
> \x y -> x + y * 2
```

\x y -> x + y * 2 is an <u>expression</u> whose value is a function.

Here are three ways to bind the name **double** to a function that doubles a number:

```
double x = x * 2

double = \x -> x * 2

double = (*2)
```

Anonymous functions, continued

Anonymous functions are commonly used with higher order functions such as **map** and **filter**.

```
> map (\w -> (length w, w)) (words "a test now")
```

```
> map (\c -> "{" ++ [c] ++ "}") "anon."
```

```
> filter (\x -> head x == last x) (words "pop top suds")
```

Analogy

From the previous slide:

```
> map (\w -> (length w, w)) (words "a test now")
[(1,"a"),(4,"test"),(3,"now")]
```

A rough Java analogy: (spring18/haskell/javamap.java)

```
ArrayList<Object []> result = new ArrayList<>();

for (String s: "a test now".split(" "))
    result.add(new Object[] {s.length(), s});
```

An anonymous function given to **map** is a bit like the body of an enhanced **for** in Java.

Challenge: Rewrite in Java the other two examples on the previous slide.

Sidebar: Three languages

A simple anonymous function in Haskell...

```
> \s -> s ++ "-" ++ show (length s)
<function>
> it "abc"
"abc-3"
```

Python...

```
>>> lambda s: s + '-' + str(len(s))
<function <lambda> at 0x10138af28>
>>> _('abc')              # underscore is like Haskell's it
'abc-3'
```

and JavaScript...

```
> f = function (s) { return s + '-' + s.length }
> f("abc")
"abc-3"
```

Larger example: `longest`

Example: longest line(s) in a file

Imagine a program to print the longest line(s) in a file, along with their line numbers:

```
% runghc longest.hs /usr/share/dict/web2
72632:formaldehydesulphoxylate
140339:pathologicopsychological
175108:scientificophilosophical
200796:tetraiodophenolphthalein
203042:thyroparathyroidectomize
```

Imagining that we don't understand recursion, how can we approach it in Haskell?

longest, continued

Let's work with a shorter file for development testing:

```
% cat longest.1
data
to
test
```

readFile in the Prelude lazily returns the full contents of a file as a string:

```
> readFile "longest.1"
"data\nto\ntest\n"
```

To avoid wading into input yet, let's focus on a function that operates on the full contents of a file as a single string:

```
> longest "data\nto\ntest\n"
"1:data\n3:test\n"
```

longest, continued

Let's work through a series of transformations of the data:

```
> bytes = "data\nto\ntest\n"

> lns = lines bytes
> lns
["data","to","test"]
```

Note: To save space in this example, we'll show the value bound immediately after each binding.

Let's use **zip3** and **map length** to create (length, line-number, line) triples:

```
> triples = zip3 (map length lns) [1..] lns
[(4,1,"data"),(2,2,"to"),(4,3,"test")]
```

longest, continued

We have (length, line-number, line) triples at hand:

```
> triples
[(4,1,"data"),(2,2,"to"),(4,3,"test")]
```

Let's use **Data.List.sort :: Ord a => [a] -> [a]** on them:

```
> sortedTriples = reverse (Data.List.sort triples)
[(4,3,"test"),(4,1,"data"),(2,2,"to")]a
```

Note that by having the line length first, the triples are sorted first by line length. Ties are resolved by line number, which is second.

We reverse the list to put the tuples in descending order.

longest, continued

At hand:

```
> sortedTriples
[(4,3,"test"),(4,1,"data"),(2,2,"to")]
```

We'll handle ties by using **takeWhile** to get all the triples with lines of the maximum length.

Let's use a helper function to get the first element of a 3-tuple:

```
> first (len, _, _) = len
> maxLength = first (head sortedTriples)
4
```

We'll be using **first** elsewhere but if we weren't, we'd bind **maxLength** using a pattern:

```
(maxLength,_,_):_ = sortedTriples
```

longest, continued

At hand:

```
> sortedTriples
[(4,3,"test"),(4,1,"data"),(2,2,"to")]

> maxLength
4
```

Let's use **takeWhile :: (a -> Bool) -> [a] -> [a]** to get the triples having the maximum length:

```
> maxTriples = takeWhile
    (\triple -> first triple  == maxLength) sortedTriples
[(4,3,"test"),(4,1,"data")]
```

anonymous function for **takeWhile**

longest, continued

At hand:

```
> maxTriples
[(4,3,"test"),(4,1,"data")]
```

Let's map an anonymous function to turn the triples into lines prefixed with their line number:

```
> linesWithNums =
      map (\(_,num,line) -> show num ++ ":" ++ line)
              maxTriples
["3:test","1:data"]
```

We can now produce a ready-to-print result:

```
> result = unlines (reverse linesWithNums)
"1:data\n3:test\n"
```

longest, continued

Let's package up our work into a function:

```
longest bytes = result
   where
      lns = lines bytes
      triples = zip3 (map length lns) [1..] lns
      sortedTriples = reverse (Data.List.sort triples)
      maxLength = first (head sortedTriples)
      maxTriples = takeWhile
         (\triple -> first triple  == maxLength) sortedTriples
      linesWithNums =
          map (\(_,num,line) -> show num ++ ":" ++ line)
          maxTriples
      result = unlines (reverse linesWithNums)

      first (x,_,_) = x
```

Look, Ma! No conditional code!

longest, continued

At hand:

```
> longest "data\nto\ntest\n"
"1:data\n3:test\n"
```

Let's add a **main** that handles command-line args and does I/O:

```
% cat longest.hs
import System.Environment (getArgs)
import Data.List (sort)

longest bytes = ...from previous slide...

main = do  -- 'do' "sequences" its expressions
   args <- getArgs  -- Get command line args as list
   bytes <- readFile (head args)
   putStr (longest bytes)
```

Execution:

```
$ runghc longest.hs /usr/share/dict/words # lectura
39886:electroencephalograph's
```

REPLACEMENTS! Discard 321+ in the old set

Composition

Function composition

Definition:

The *composition* of functions **f** and **g** is a function **c** that for all values of **x**, (**c x**) equals **(f (g x))**

Here is a function that applies two functions in turn:

```
compose f g x = f (g x)
```

How many arguments does **compose** have?

Its type:

```
(b -> c) -> (a -> b) -> a -> c
```

```
> compose init tail [1..5]
```

```
> compose signum negate 3
```

Composition, continued

Haskell binds the symbolic variable dot to a "compose" function:

```
> :t (.)
(.) :: (b -> c) -> (a -> b) -> a -> c
```

Dot is an operator whose operands are functions. Its result is a function.

```
> numwords = length  .  words

> numwords "just testing this"


> map numwords ["a test", "up & down", "done"]
```

Ponder this: Given '`compose f g x = f (g x)`', this works:

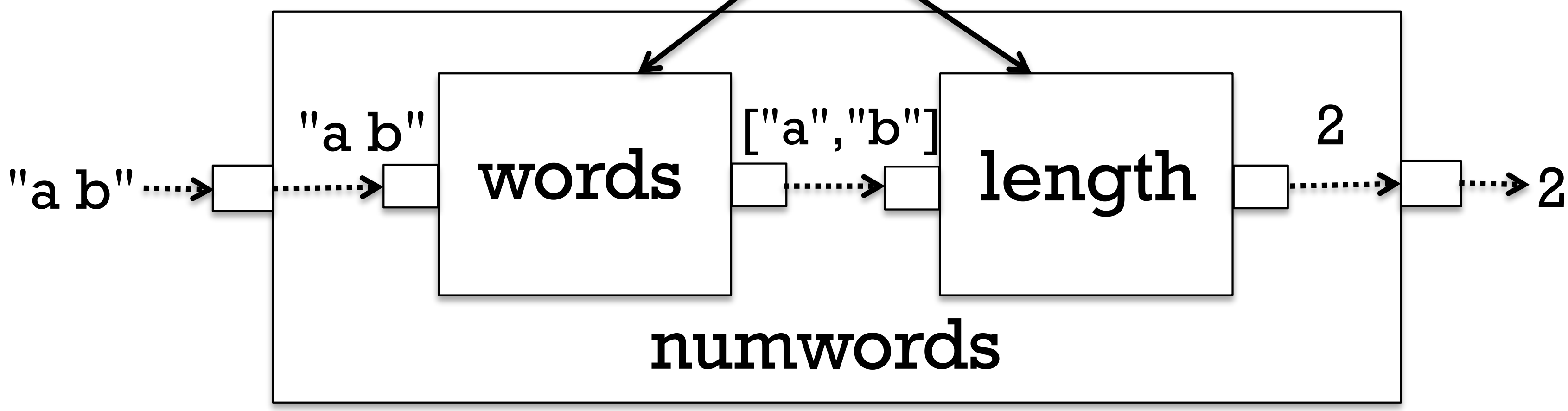
```
(.) = compose
```

Composition, continued

At hand:

numwords = length . words

A model:



Usage:

```
> numwords "a b"
2
```

Composition, continued

Problem: Using composition create a function that returns the next-to-last element in a list:

```
> ntl [1..5]
4

> ntl "abc"
'b'
```

Two solutions:

Composition, continued

Problem: Recall **twice f x = f (f x)**. Define **twice** as a composition.

Solution:

Problem: Use composition to create a function that reverses the words in a string:

```
> f "flip these words around"
"pilf eseht sdrow dnuora"
```

Hint: **unwords** is the inverse of **words**.

Solution:

Composition, continued

Problem: Create a function to <u>remove</u> the digits from a string:

```
> rmdigits "Thu Feb  6 19:13:34 MST 2014"
"Thu Feb   :: MST "
```

Solution:

Given the following, describe **f**:

```
> f = (*2) . (+3)

> map f [1..5]
```

Would an anonymous function be a better choice for **f**'s computation?

Composition, continued

Recalling the following, what's the type of **f**?

```
head :: [a] -> a
length :: [a] -> Int
words :: String -> [String]
show :: Show a => a -> String

f = head . show . length . words
```

Simple rule:

If a composition is valid, the type of the resulting function is based <u>only</u> on the input of the rightmost function and the output of the leftmost function.

What's the type of **f**?

Composition, continued

Consider the following:

```
> s = "It's on!"
> map head (map show (map not (map isLetter s)))
"FFTFTFFT"
```

Can we use composition to simplify it?

Question: Is

```
map f (map g x)
```

always equivalent to the following?

```
map (f . g) x
```

Mystery function

What would be a better name for the following function?

```
f2 = f . f
  where f = reverse . dropWhile isSpace
```

Credit: Eric Normand on Stack Overflow

Sidebar: A little Standard ML

```
- explode;
val it = fn : string -> char list

- implode;
val it = fn : char list -> string
```

```
- explode "abc";
val it = [#"a",#"b",#"c"] : char list

- implode it;
val it = "abc" : string
```

```
- rev;
val it = fn : 'a list -> 'a list
```

Problem: Write **revstr s**, which reverses the string **s**.

```
- revstr "backwards";
val it = "sdrawkcab" : string
```

Solution:

sml runs Standard ML on lectura

Point-free style
(video)

Point-free style

Recall **rmdigits**:

```
> rmdigits "Thu Feb  6 19:13:34 MST 2014"
"Thu Feb   :: MST "
```

What the difference between these two bindings for **rmdigits**?

```
rmdigits s = filter (not  .  isDigit) s

rmdigits = filter (not  .  isDigit)
```

The latter version is said to be written in *point-free style*.

<u>A point-free binding of a function **f** has NO parameters!</u>

Point-free style, continued

I think of point-free style as a natural result of fully grasping partial application and operations like composition.

Although it was nameless, we've already seen examples of point-free style, such as these:

```
nthOdd = (!!) [1,3..]
t2 = twice tail
numwords = length . words
ntl = head . tail . reverse
```

There's nothing too special about point-free style but it does save some visual clutter. <u>It is commonly used.</u>

The term "point-free" comes from topology, where a point-free function operates on points that are not specifically cited.

Point-free style, continued

Problem: Using point-free style, bind **len** to a function that works like the Prelude's **length**.

Handy:

```
> :t const
const :: a -> b -> a

> const 10 20
10

> const [1] "foo"
[1]
```

Solution:

```
len = sum . map (const 1)
```

See also: *Tacit programming* on Wikipedia

Hocus pocus with higher-order functions

Mystery function

What's this function doing?

```
f  a = g
   where
      g  b = a + b
```

Type?

```
f :: Num a => a -> a -> a
```

Interaction:

```
> f ' = f 10
> f ' 20
30

> f 3 4
7
```

DIY Currying

Fact:

Curried function definitions are really just *syntactic sugar*—they just save some clutter. They don't provide something we can't do without.

Compare these two completely equivalent declarations for **add**:

```
add x y = x + y
```

```
add x = add'
    where
        add' y = x + y
```

The **x** used in **add'** refers to the **x** parameter of **add**.

The result of the call **add 5** is essentially this function:

```
add' y = 5 + y
```

The combination of the code for **add'** and the binding for **x** is known as a *closure*. It contains what's needed for execution at a future time.

Sidebar: Syntactic sugar

In 1964 Peter Landin coined the term "syntactic sugar".

A language construct that makes something easier to express but doesn't add a new capability is called *syntactic sugar*. It simply makes the language "sweeter" for human use.

Two examples from C:

- "**abc**" is equivalent to a **char** array initialized with {'a', 'b', 'c', '\0'}
- **a[i]** is equivalent to ***(a + i)**

What's an example of syntactic sugar in Java?

Syntactic sugar, continued

In Haskell a list like **[5, 2, 7]** can be expressed as **5:2:7:[]**.

Is that square-bracket list literal notation syntactic sugar?

What about **[1..]**, **[1,3..]**, **['a'..'z']**?

The **Enum** type class has **enumFrom**, **enumFromTo**, etc.

Recall these equivalent bindings for **double**:

```
double x = x * 2
double = \x -> x * 2
```

Is the first form just syntactic sugar?

Are anonymous functions syntactic sugar?

Syntactic sugar, continued

"Syntactic sugar causes cancer of the semicolon."
—Alan J. Perlis.

Another Perlis quote:

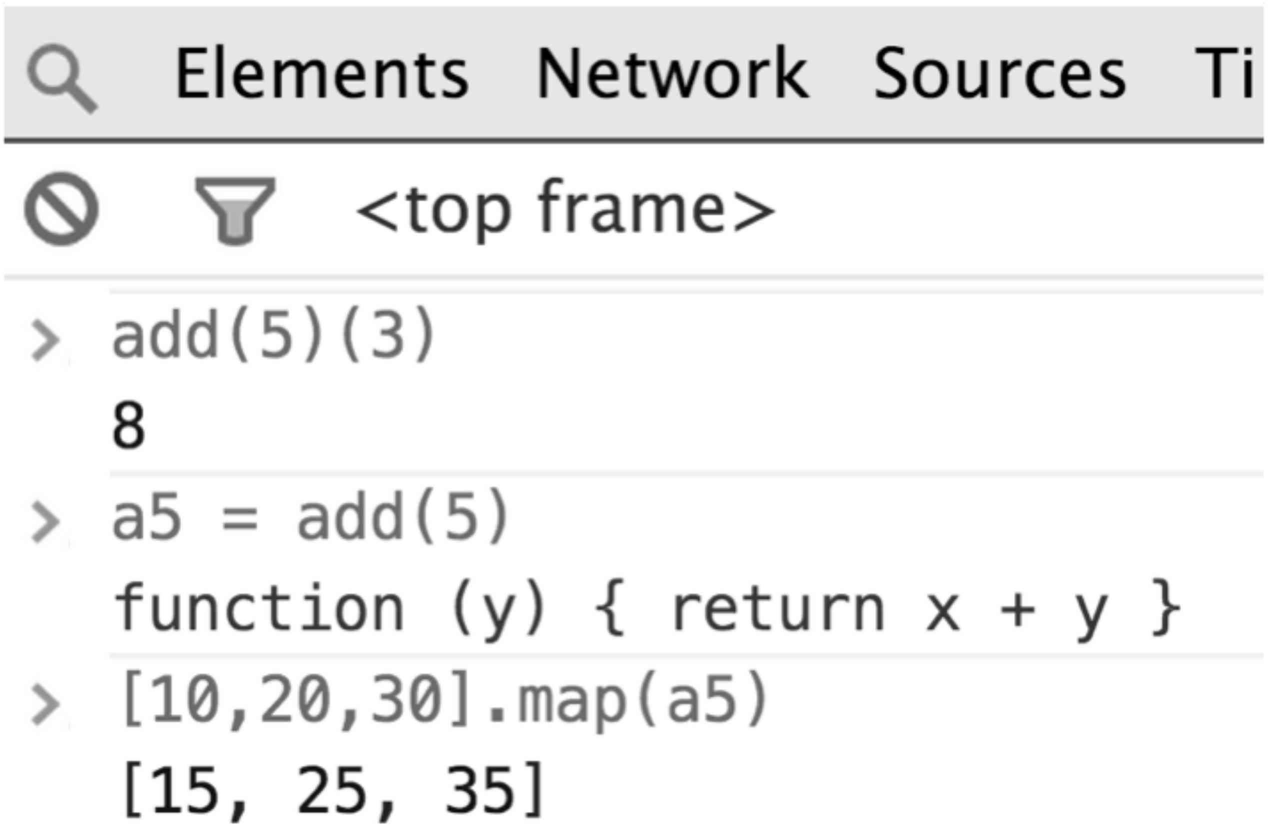
"A language that doesn't affect the way you think about programming is not worth knowing."

Perlis was the first recipient of the ACM's Turing Award.

DIY currying in JavaScript

JavaScript doesn't provide the syntactic sugar of curried function definitions but we can do this:

```
function add(x) {
    return function (y) { return x + y }
}
```



Try it in Chrome!

View>Developer> JavaScript Console brings up a console.

Type in the code for **add**.

DIY currying in Python

```
>>> def add(x):
...         return lambda y: x + y
...

>>> f = add(5)

>>> type(f)
<type 'function'>

>>> map(f, [10,20,30])
[15, 25, 35]
```

Another mystery function

Here's another mystery function:

```
> m f x y = f y x

> :type m
m :: (t1 -> t2 -> t) -> t2 -> t1 -> t
```

Can you devise a call to **m**?

REPLACEMENTS! Discard 345+ in the old set

flip

At hand:

```
m f x y = f y x
```

m is actually a Prelude function named **flip**:

```
> :t flip
flip :: (a -> b -> c) -> b -> a -> c
```

Recall **take :: Int -> [a] -> [a]**

```
> flip take [1..10] 3
[1,2,3]

> ftake = flip take
> ftake [1..10] 3
[1,2,3]
```

flip, continued

At hand:

```
flip f x y = f y x

> map (flip take "Haskell") [1..7]
["H","Ha","Has","Hask","Haske","Haskel","Haskell"]
```

Problem: write a function that behaves like this:

```
> f 'a'
["a","aa","aaa","aaaa","aaaaa",...infinitely...
```

Solution:

flip, continued

From assignment 3:

```
> splits "abcd"
[("a","bcd"),("ab","cd"),("abc","d")]
```

Some students used the Prelude's **splitAt**:

```
> splitAt 2 [10,20,30,40]
([10,20],[30,40])
```

Problem: Write a non-recursive version of **splits**.

Solution:

The $ operator

$ is the "application operator". Here's what **:info** shows:

```
> :info ($)
($) :: (a -> b) -> a -> b
infixr 0 $      -- right associative infix operator with very
                -- low precedence
```

The following binding of **$** uses an infix syntax:

```
f $ x  =  f x        -- Equivalent: ($) f x = f x
```

Usage:

```
> negate $ 3 + 4
-7
```

What's the point of it?

The $ operator, continued

$ is a low precedence, right associative operator that applies a function to a value:

```
f $ x  =  f x
```

Because **+** has higher precedence than **$**, the expression

```
negate $ 3 + 4
```

groups like this:

```
negate $ (3 + 4)
```

Problem: Rewrite the following with parentheses instead of **$**

```
filter (>3) $ map length $ words "up and down"
```

Don't confuse **$** with **.** (composition)!

Currying the uncurried

Problem: We're given a function whose argument is a 2-tuple but we wish it were curried so we could map a partial application of it.

```
g :: (Int, Int) -> Int
g (x,y) = x^2 + 3*x*y + 2*y^2

> g (3,4)
77
```

Solution: Curry **g** with **curry** from the Prelude!

```
> map (curry g 3) [1..10]
[20,35,54,77,104,135,170,209,252,299]
```

Your problem: Write **curry**! (And don't peek ahead!)

Currying the uncurried, continued

At hand:

```
g :: (Int, Int) -> Int
> g (3,4)
77
> map (curry g 3) [1..10]
[20,35,54,77,104,135,170,209,252,299]
```

Here's **curry**:

```
curry :: ((a, b) -> c) -> a -> b -> c
curry f x y = f (x,y)
```

Usage:

```
> cg = curry g
> :type cg
cg :: Int -> Int -> Int

> cg 3 4
77
```

Currying the uncurried, continued

At hand:

```
curry :: ((a, b) -> c) -> a -> b -> c
curry f x y = f (x, y)

> map (curry g 3) [1..10]
[20,35,54,77,104,135,170,209,252,299]
```

The key: **(curry g 3)** is a partial application of **curry**!

Call: **curry g 3**

Dcl: **curry f x y = f (x, y)**

= g (3, y)

Curying the uncurried, continued

At hand:

```
curry :: ((a, b) -> c) -> (a -> b -> c)
```
(parentheses added)

```
curry f x y = f (x, y)
```

```
> map (curry g 3) [1..5]
[20,35,54,77,104]
```

Effectively turns

```
g (x,y) = x^2 + 3*x*y + 2*y^2
```

into

Let's get **flip** into the game!

```
> map (flip (curry g) 4) [1..5]
[45,60,77,96,117]
```

The counterpart of **curry** is **uncurry**:

```
> uncurry (+) (3,4)
```

A **curry** function for JavaScript

```
function curry(f) {
    return function(x) {
        return function (y) { return f(x,y) }
        }
    }
```

```
Elements   Network   Sources   Timeline   Profiles   Resourc
<top frame>
> function add(x,y) {return x + y}
  undefined
> c_add = curry(add)
  function (x) { return function (y) { return f(x,y) } }
> add_5 = c_add(5)
  function (y) { return f(x,y) }
> [10,20,30].map(add_5)
  [15, 25, 35]
```

Folding

Reduction

We can *reduce* a list by a binary operator by inserting that operator between the elements in the list:

[1,2,3,4] reduced by + is 1 + 2 + 3 + 4

["a","bc", "def"] reduced by ++ is "a" ++ "bc" ++ "def"

Imagine a function **reduce** that does reduction by an operator.

```
> reduce (+) [1,2,3,4]


> reduce (++) ["a","bc","def"]


> reduce max [10,2,4]
```

-- think of 10 `max` 2 `max` 4

Reduction, continued

At hand:

```
> reduce (+) [1,2,3,4]
10
```

An implementation of **reduce**:

```
reduce _ [] = error "emptyList"
reduce _ [x] = x
reduce op (x:xs) = x `op` reduce op xs
```

Does **reduce + [1,2,3,4]** do

```
((1 + 2) + 3) + 4
```

or

```
1 + (2 + (3 + 4))
```

?

In general, when would the grouping matter?

foldl1 and foldr1

In the Prelude there's no reduce but there is foldl1 and foldr1.

```
> foldl1 (+) [1..4]


> foldl1 max "maximum"


> foldl1 (/) [1,2,3]
0.16666666666666666   -- behaves like left associative: (1 / 2) / 3

> foldr1 (/) [1,2,3]           -- behaves like right associative: 1 / (2 / 3)
1.5
```

The types of both foldl1 and foldr1 are (a -> a -> a) -> [a] -> a.

foldl1 vs. foldl

Another folding function is foldl (no 1). Let's compare the types of foldl1 and foldl:

```
foldl1 :: (a -> a -> a) -> [a] -> a
foldl :: (a -> b -> a) -> a -> [b] -> a
```

What's different between them? (Eyes on the screen!)

First difference: foldl requires one more argument:

```
> foldl (+) 0 [1..10]
55

> foldl (+) 100 []


> foldl1 (+) []
```

foldl1 vs. foldl, continued

Again, the types:

```
foldl1 :: (a -> a -> a) -> [a] -> a
foldl :: (a -> b -> a) -> a -> [b] -> a
```

Second difference:

foldl can fold a list of values into a different type! (This is BIG!)

Examples:

```
> foldl f1 0 ["just","a","test"]
3                         -- folded strings into a number

> foldl f2 "stars: " [3,1,2]
"stars: ******"           -- folded numbers into a string

> foldl f3 0 [(1,1),(2,3),(5,10)]
57
```

foldl

For reference:

```
foldl :: (a -> b -> a) -> a -> [b] -> a
```

Here's another view of the type: (acm_t stands for accumulator type)

```
foldl :: (acm_t -> elem_t -> acm_t) -> acm_t -> [elem_t] -> acm_t
```

foldl takes three arguments:

1. A function that takes an accumulated value and an element value and produces a new accumulated value
2. An initial accumulated value
3. A list of elements

Recall:

```
> foldl f1 0 ["just","a","test"]
3

> foldl f2 "stars: " [3,1,2]
"stars: ******"
```

Recall:

```
> foldl f1 0 ["just","a","test"]
3
```

Here are the computations that foldl did to produce that result

```
> f1 0 "just"
1
> f1 it "a"
2
> f1 it "test"
3
```

Let's do it in one expression, using backquotes to infix f1:

```
> ((0  `f1`  "just")  `f1`  "a")  `f1`  "test"
3
```

Note the parallels between these two.

1 + 2 + 3 + 4 is the reduction we started this section with.

foldl, continued

At hand:

```
> f1 0 "just"
1
> f1 it "a"
2
> f1 it "test"
3
```

For reference:

```
> foldl f1 0 ["just","a","test"]
3
```

Problem: Write a function `f1` that behaves like above.

Starter:

```
f1 :: acm_t -> elem_t -> acm_t
f1 acm elem =
```

Congratulations! You just wrote a *folding function*!

Recall:

```
> foldl f2 "stars: " [3,1,2]
"stars: ******"
```

Here's what foldl does with f2 and the initial value, "stars: ":

```
> f2 "stars: " 3
"stars: ***"
> f2 it 1
"stars: ****"
> f2 it 2
"stars: ******"
```

Write f2, with this starter:

```
f2 :: acm_t -> elem_t -> acm_t
f2 acm elem =
```

Look! Another folding function!

Folding abstracts a common pattern of computation:
A series of values contribute one-by-one to an accumulating result.

<u>The challenge of folding</u> is to envision a function that takes **<u>nothing</u>** but an accumulated value (acm) and a single list element (elem) and produces a result that reflects the contribution of elem to acm.

```
f2 acm elem = acm ++ replicate elem '*'
```

SUPER IMPORTANT: <u>A folding function never sees the list!</u>

We then call foldl with (1) the folding function, (2) an appropriate initial value, and (3) a list of values.

```
foldl f2 "stars: " [3,1,2]
```

foldl <u>orchestrates</u> the computation by making a series of calls to the folding function.

```
> (("stars: " `f2` 3) `f2` 1) `f2` 2
"stars: ******"
```

foldl, continued

Recall:

```
> foldl f3 0 [(1,1),(2,3),(5,10)]
57
```

Here are the calls that foldl will make:

```
> f3 0 (1,1)
1
> f3 it (2,3)
7
> f3 it (5,10)
57
```

Problem: write f3!

foldl, continued

Remember that

```
foldl f 0 [10,20,30]
```

is like

```
((0 `f` 10) `f` 20) `f` 30
```

Here's an implementation of foldl:

```
foldl f acm [] = acm
foldl f acm (elem:elems) =  foldl f (acm `f` elem) elems
```

We can implement foldl1 in terms of foldl:

```
foldl1 f (x1:xs) = foldl f x1 xs
foldl1 _ [] = error "emptyList"
```

A non-recursive countEO

Let's use folding to implement our even/odd counter non-recursively.

```
> countEO [3,4,7,9]
(1,3)
```

Often, a good place to start on a folding is to figure out what the initial accumulator value should be. What should it be for countEO?

Given countEO [3,4,7,9], what will be the calls to the folding function?

Problem: Write the folding function

Problem: Write countEO as a foldl with f

Folds with anonymous functions

If a folding function is simple, an anonymous function is typically used.

Let's redo our three earlier folds with anonymous functions:

```
> foldl (\acm _ -> acm + 1) 0 ["just","a","test"]
3

> foldl (\acm elem -> acm ++ replicate elem '*') "stars: " [3,1,2]
"stars: ******"

> foldl (\acm (a,b) -> acm + a * b) 0 [(1,1),(2,3),(5,10)]
57
```

foldr

The counterpart of foldl is foldr. Compare their meanings:

```
foldl f zero [e1, e2, ..., eN] == (...((zero `f` e1) `f` e2) `f`...)`f` eN

foldr f zero [e1, e2, ..., eN] == e1 `f` (e2 `f` ... (eN `f` zero)...)
```

"zero" represents the computation-specific initial accumulated value. Note that with foldl, zero is leftmost; but with foldr, zero is rightmost.

Their types, with long type variables:

```
foldl :: (acm -> val -> acm) -> acm -> [val] -> acm
foldr :: (val -> acm -> acm) -> acm -> [val] -> acm
```

Mnemonic aid:

foldl's folding function has the accumulator on the left.

foldr's folding function has the accumulator on the right.

foldr, continued

Because cons (:) is right-associative, folds that produce lists are often done with foldr.

Imagine a function that keeps the odd numbers in a list:

```
> keepOdds [5,4,2,3]
[5,3]
```

Implementation, with fold<u>r</u>:

```
keepOdds list = foldr f [] lista
    where
        f elem acm
            | odd elem = elem : acm
            | otherwise = acm
```

What are the calls to the folding function?

filter and map with folds?

keepOdds could have been defined using filter:

```
keepOdds = filter odd
```

Can we implement filter as a fold?

```
filter predicate list = foldr f [] list
    where
        f elem acm
            | predicate elem = elem : acm
            | otherwise = acm
```

How about implementing map as a fold?

Is folding One Operation to Implement Them All?

paired with a fold

Recall **paired** from assignment 3:

```
> paired "((())())"
True
```

Can we implement **paired** with a fold?

A progression of folds

Let's do a progression of folds related to finding vowels in a string.

First, let's count vowels in a string with a fold:

```
> foldr (\val acm ->
          acm + if  val `elem` "aeiou" then 1 else 0)  0  "ate"
2
```

anonymous folding function

Next, let's produce both a count and the vowels themselves:

Note: s/val/letter/g

```
> foldr (\letter acm@(n, vows) ->
          if  letter `elem` "aeiou" then (n+1, letter:vows)
                                     else acm) (0,[]) "ate"
(2,"ae")
```

A progression of folds, continued

Finally, let's write a function that produces a list of vowels and their positions:

```
> vowelPositions "Down to Rubyville!"
[('o',1),('o',6),('u',9),('i',13),('e',16)]
```

Solution:

```
vowelPositions s = reverse result
  where (result, _) =
    foldl (\acm@(vows, pos) letter ->
          if  letter `elem` "aeiou" then ((letter,pos):vows,pos+1)
                                    else (vows,pos+1))
      ([],0) s
```

The **foldl** produces a 2-tuple whose first element is the result, a list, but in reverse order.

This is another function that's a fold with a *wrapper*, like **paired**, earlier.

map vs. filter vs. folding

map:

transforms a list of values

length *input* == length *output*

filter:

selects values from a list

0 <= length *output* <= length *input*

folding

Input: A list of values and an initial value for accumulator

Output: <u>A value of any type and complexity</u>

True or false?

Any operation that processes a list can be expressed in a terms of a fold, perhaps with a simple wrapper.

We can fold a list of anythings into anything!

Far-fetched folding:

Refrigerators in Gould-Simpson to
((grams fat, grams protein, grams carbs), calories)

Keyboards in Gould-Simpson to
[("a", #), ("b", #), ..., ("$", #), ("CMD", #)]

[Backpack] to
(# pens, pounds of paper,
[(title, author, [page #s with the word "computer")])

[Furniture]
to a structure of 3D vertices representing a *convex hull* that could hold any single piece of furniture.

User-defined types

A **Shape** type

A new type can be created with a **data** declaration.

Here's a simple **Shape** type whose instances represent circles or rectangles:

```
data Shape =
   Circle Double |            -- just a radius
   Rect Double Double         -- width and height
          deriving Show
```

The shapes have dimensions but no position.

Circle and **Rect** are *data constructors*.

"**deriving Show**" declares **Shape** to be an instance of the **Show** type class, so that values can be shown using some simple, default rules.

Shape is called an *algebraic type* because instances of **Shape** are built using other types.

Shape, continued

Instances of **Shape** are created by calling the data constructors:

```
> r1 = Rect 3 4
> r1
Rect 3.0 4.0

> r2 = Rect 5 3

> c1 = Circle 2

> shapes = [r1, r2, c1]

> shapes
[Rect 3.0 4.0,Rect 5.0 3.0,Circle 2.0]
```

```
data Shape =
   Circle Double |
   Rect Double Double
      deriving Show
```

Lists must be homogeneous—why are both **Rect**s and **Circle**s allowed in the same list?

Shape, continued

The data constructors are just functions—we can use all our function-fu with them!

```
data Shape =
   Circle Double |
   Rect Double Double
      deriving Show
```

```
> :t Circle
Circle :: Double -> Shape

> :t Rect
Rect :: Double -> Double -> Shape

> map Circle [2,3] ++ map (Rect 3) [10,20]
[Circle 2.0,Circle 3.0,Rect 3.0 10.0,Rect 3.0 20.0]
```

Shape, continued

Functions that operate on algebraic types use patterns based on the type's data constructors.

```
data Shape =
    Circle Double |
    Rect Double Double
        deriving Show
```

```
area (Circle r) = r ** 2 * pi
area (Rect w h) = w * h
```

Usage:

```
> r1
Rect 3.0 4.0

> area r1
12.0

> shapes
[Rect 3.0 4.0,Rect 5.0 3.0,Circle 2.0]

> map area shapes
[12.0,15.0,12.566370614359172]

> sum $ map area shapes
39.56637061435917
```

Shape, continued

Let's make the **Shape** type an instance of the **Eq** type class.

What does **Eq** require?

```
> :info Eq
class Eq a where
  (==) :: a -> a -> Bool
  (/=) :: a -> a -> Bool
```

Default definitions from **Eq**:

```
(==) a b = not $ a /= b
(/=)  a b = not $ a == b
```

We'll say that two shapes are equal if their areas are equal.

```
instance Eq Shape where
   (==) r1 r2 = area r1 == area r2
```

Usage:

```
> Rect 3 4 == Rect 6 2
True

> Rect 3 4 == Circle 2
False
```

Shape, continued

Let's see if we can find the biggest shape:

```
> maximum shapes
 No instance for (Ord Shape) arising from a use of
`maximum'
   Possible fix: add an instance declaration for (Ord
Shape)
```

What's in **Ord**?

```
> :info Ord
class Eq a => Ord a where
  compare :: a -> a -> Ordering
  (<) :: a -> a -> Bool
  (>=) :: a -> a -> Bool
  (>) :: a -> a -> Bool
  (<=) :: a -> a -> Bool
  max :: a -> a -> a
  min :: a -> a -> a
```

Eq a => Ord a requires would-be **Ord** classes to be instances of **Eq**. (Done!)

Like **==** and **/=** with **Eq**, the operators are implemented in terms of each other.

Shape, continued

Let's make **Shape** an instance of the **Ord** type class:

```
instance Ord Shape where
   (<) r1 r2 = area r1 < area r2          -- < and <= are sufficient
   (<=) r1 r2 = area r1 <= area r2
```

Usage:

```
> shapes
[Rect 3.0 4.0,Rect 5.0 3.0,Circle 2.0]

> map area shapes
[12.0,15.0,12.566370614359172]

> maximum shapes
Rect 5.0 3.0

> Data.List.sort shapes
[Rect 3.0 4.0,Circle 2.0,Rect 5.0 3.0]
```

Note that we didn't need to write functions like **sumOfAreas** or **largestShape**—we can express those in terms of existing operations

Shape all in one place

Here's all the **Shape** code: (in **shape.hs**)

```
data Shape =
    Circle Double |
    Rect Double Double deriving Show

area (Circle r) = r ** 2 * pi
area (Rect w h) = w * h

instance Eq Shape where
    (==) r1 r2 = area r1 == area r2

instance Ord Shape where
    (<) r1 r2 = area r1 < area r2
    (<=) r1 r2 = area r1 <= area r2
```

What would be needed to add a **Figure8** shape and a **perimeter** function?

How does this compare to a **Shape/Circle/Rect** hierarchy in Java?

The type **Ordering**

Let's look at the **compare** function:

```
> :t compare
compare :: Ord a => a -> a -> Ordering
```

Ordering is a simple algebraic type, with only three values:

```
> :info Ordering
data Ordering = LT | EQ | GT

> [r1,r2]
[Rect 3.0 4.0,Rect 5.0 3.0]

> compare r1 r2
LT

> compare r2 r1
GT
```

What is **Bool**?

What do you suppose **Bool** really is?

Bool is just an algebraic type with two values:

```
> :info Bool
data Bool = False | True
```

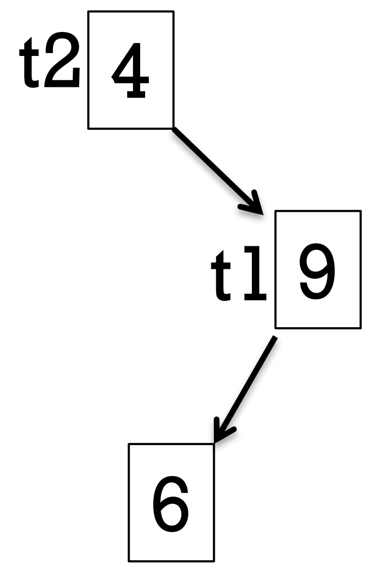
Bool is an example of Haskell's extensibility. Instead of being a primitive type, like **boolean** in Java, it's defined in terms of something more basic.

A binary tree

Here's an algebraic type for a binary tree: (in **tree.hs**)

```
data Tree a = Node a (Tree a) (Tree a)
            | Empty
              deriving Show
```

The **a** is a type variable. Our **Shape** type used **Double** values but Tree can hold values of any type!




```
> t1 = Node 9 (Node 6 Empty Empty) Empty
> t1
Node 9 (Node 6 Empty Empty) Empty

> t2 = Node 4 Empty t1
> t2
Node 4 Empty (Node 9 (Node 6 Empty Empty) Empty)
```

Tree, continued

Here's a function that inserts values, maintaining an ordered tree:

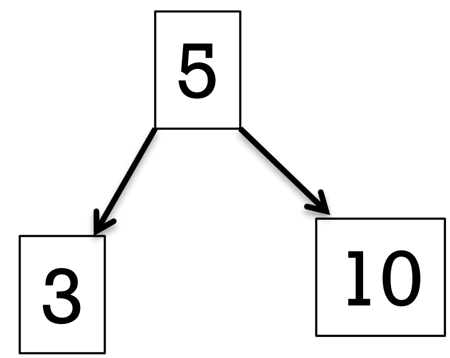
```
insert Empty v = Node v Empty Empty
insert (Node x left right) value
    | value <= x = (Node x (insert left value) right)
    | otherwise = (Node x left (insert right value))
```

Let's insert some values...

```
> t = Empty
> insert t 5
Node 5 Empty Empty

> insert it 10
Node 5 Empty (Node 10 Empty Empty)

> insert it 3
Node 5 (Node 3 Empty Empty) (Node 10 Empty Empty)
```



Note that each insertion rebuilds some portion of the tree!

Tree, continued

Here's an in-order traversal that produces a list of values:

```
inOrder Empty = []
inOrder (Node val left right) =
    inOrder left ++ [val] ++ inOrder right
```

What's an easy way to insert a bunch of values?

```
> t = foldl insert Empty [3,1,9,5,20,17,4,12]
> inOrder t
[1,3,4,5,9,12,17,20]

> inOrder $ foldl insert Empty "tim korb"
" bikmort"

> inOrder $ foldl insert Empty [Rect 3 4, Circle 1, Rect 1 2]
[Rect 1.0 2.0,Circle 1.0,Rect 3.0 4.0]
```

Maybe

Here's an interesting type:

```
> :info Maybe
data Maybe a = Nothing | Just a
```

Speculate: What's the point of it?

Here's a function that uses it:

```
> :t Data.List.find
Data.List.find :: (a -> Bool) -> [a] -> Maybe a
```

How could we use it?

```
> find even [3,5,6,8,9]
Just 6

> find even [3,5,9]
Nothing

> case (find even [3,5,9]) of { Just _ -> "got one"; _ -> "oops!"}
"oops!"
```

In conclusion...

If we had a whole semester...

If we had a whole semester to study functional programming, here's what might be next:

- More with infinite data structures (like **`x = 1:x`**)
- How lazy/non-strict evaluation works
- Implications and benefits of referential transparency (which means that the value of a given expression is always the same).
- Functors (structures that can be mapped over)
- Monoids (a set of things with a binary operation over them)
- Monads (for representing sequential computations)
- Zippers (a structure for traversing and updating another structure)
- And more!

Jeremiah Nelson and Jordan Danford are great local resources for Haskell!

Even if you never use Haskell again...

Recursion and techniques with higher-order functions can be used in most languages. Some examples:

JavaScript, Python, PHP, all flavors of Lisp, and lots of others:
Functions are "first-class" values; anonymous functions are supported.

C
Pass a function pointer to a recursive function that traverses a data structure.

C#
Excellent support for functional programming with the language itself, and LINQ, too.

Java 8
Lambda expressions are in!

OCaml
"an industrial strength programming language supporting functional, imperative and object-oriented styles" – OCaml.org
http://www.ffconsultancy.com/languages/ray_tracer/comparison.html

Killer Quiz!