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PROGRAMMING WITH
REFINEMENT TYPES

AN INTRODUCTION TO LIQUIDHASKELL
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1

Introduction

One of the great things about Haskell is its brainy type system that allows one to enforce a variety of invariants at compile time, thereby nipping in the bud a large swathe of run-time errors.

Well-Typed Programs Do Go Wrong

Alas, well-typed programs do go quite wrong, in a variety of ways.

Division by Zero This innocuous function computes the average of a list of integers:

```
average :: [Int] -> Int
average xs = sum xs `div` length xs
```

We get the desired result on a non-empty list of numbers:

```
ghci> average [10, 20, 30, 40]
25
```

However, if we call it with an empty list, we get a rather unpleasant crash: ¹

```
ghci> average []
*** Exception: divide by zero
```

Missing Keys

Associative key-value maps are the new lists; they come “built-in” with modern languages like Go, Python, JavaScript and Lua; and of course, they’re widely used in Haskell too.

¹ We could write `average` more defensively, returning a `Maybe` or `Either` value. However, this merely kicks the can down the road. Ultimately, we will want to extract the `Int` from the `Maybe` and if the inputs were invalid to start with, then at that point we’d be stuck.
Alas, maps are another source of vexing errors that are tickled when we try to find the value of an absent key: 

```
ghci> m ! "javascript"
"*** Exception: key is not in the map"
```

**Segmentation Faults**

Say what? How can one possibly get a segmentation fault with a *safe* language like Haskell. Well, here’s the thing: every safe language is built on a foundation of machine code, or at the very least, C. Consider the ubiquitous vector library:

```
ghci> :m +Data.Vector
ghci> let v = fromList ["haskell", "ocaml"]
ghci> unsafeIndex v 0
"haskell"
```

However, invalid inputs at the safe upper levels can percolate all the way down and stir a mutiny down below: 

```
ghci> unsafeIndex v 3
'ghci' terminated by signal SIGSEGV ...
```

**Heart Bleeds**

Finally, for certain kinds of programs, there is a fate worse than death. *text* is a high-performance string processing library for Haskell, that is used, for example, to build web services.

```
ghci> :m +Data.Text Data.Text.Unsafe
ghci> let t = pack "Voltage"
ghci> takeWord16 5 t
"Volta"
```

A cunning adversary can use invalid, or rather, *well-crafted*, inputs that go well outside the size of the given text to read extra bytes and thus *extract secrets* without anyone being any the wiser.
The above call returns the bytes residing in memory immediately after the string `Voltage`. These bytes could be junk, or could be either the name of your favorite TV show, or, more worryingly, your bank account password.

**Refinement Types**

Refinement types allow us to enrich Haskell’s type system with predicates that precisely describe the sets of valid inputs and outputs of functions, values held inside containers, and so on. These predicates are drawn from special logics for which there are fast decision procedures called SMT solvers.

**By combining types with predicates** you can specify contracts which describe valid inputs and outputs of functions. The refinement type system guarantees at compile-time that functions adhere to their contracts. That is, you can rest assured that the above calamities cannot occur at run-time.

**LiquidHaskell** is a Refinement Type Checker for Haskell, and in this tutorial we’ll describe how you can use it to make programs better and programming even more fun.  

**Audience**

Do you

- know a bit of basic arithmetic and logic?
- know the difference between a nand and an xor?
- know any typed languages e.g. ML, Haskell, Scala, F# or (Typed) Racket?
- know what `forall a. a -> a` means?
- like it when your code editor politely points out infinite loops?
- like your programs to not have bugs?

Then this tutorial is for you!
Getting Started

As of July 2020, LiquidHaskell, version 0.8.10 onwards, is available as a GHC plugin.

This means, roughly, that you need simply

1. Add LH to your project dependencies, after which
2. GHC produces LH type errors whenever you compile the code, so that you can
3. View errors using your favorite editor’s existing Haskell tooling.

**LiquidHaskell Requires** (in addition to the cabal dependencies) a binary for an SMTLIB2 compatible solver, e.g. one of

- Z3 (which we recommend)
- CVC4
- MathSat

This Tutorial is written in literate Haskell and the code for it is available [here](https://github.com/ucsd-progsys/liquidhaskell-tutorial.git). Hence, we strongly recommend you grab the code, and follow along, and especially that you do the exercises, via two steps.

**Step 1** Clone the code repository,

```
git clone --recursive https://github.com/ucsd-progsys/liquidhaskell-tutorial.git
```

**Step 2:** Try building the code using

```
cabal v2-build
```

or

```
stack build --fast --file-watch
```

If your environment is set up correctly, compilation will stop with a Liquid type error:
Step 3: Iteratively edit-compile the code in src/ until it builds without any liquid type errors.

The above workflow will let you use whatever GHC/Haskell tooling you use for your favorite editor, to automatically display LH errors as well.

If you’d like to copy and paste code snippets into the web demo, instead of cloning the repo, note that you may need to pass --no-termination to liquid, or equivalently, add the pragma {-@ LIQUID "--no-termination" @-} to the top of the source file. (By default, liquid tries to ensure that all code it examines will terminate. Some of the code in this tutorial is written in such a way that termination is not immediately obvious to LH.)

Note: This tutorial is a work in progress, and we will be very grateful for feedback and suggestions, ideally via pull-requests on github.

Let’s begin!
2

Logic & SMT

As we shall see shortly, a refinement type is:

Refinement Types = Types + Logical Predicates

Let us begin by quickly recalling what we mean by “logical predicates” in the remainder of this tutorial. ¹ To this end, we will describe syntax, that is, what predicates look like, and semantics, which is a fancy word for what predicates mean.

Syntax

A logical predicate is, informally speaking, a Boolean valued term drawn from a restricted subset of Haskell. In particular, the expressions are drawn from the following grammar comprising constants, expressions and predicates.

A Constant² c is simply one of the numeric values:

\[ c := 0, 1, 2, \ldots \]

A Variable v is one of x, y, z, etc., these will refer to (the values of) binders in our source programs.

\[ v := x, y, z, \ldots \]

An Expression e is one of the following forms; that is, an expression is built up as linear arithmetic expressions over variables and constants and uninterpreted function applications.

¹ If you are comfortable with this material, e.g. if you know what the “S”, “M” and “T” stand for in SMT, and what QF-UFLIA stands for (i.e. the quantifier free theory of linear arithmetic and uninterpreted functions), then feel free skip to the next chapter.

² When you see := you should read it as “is defined to be”
Examples of Expressions include the following:

- $x + y - z$
- $2 * x$
- $1 + \text{size} \; x$

A Relation is one of the usual (arithmetic) comparison operators:

- $r := ==$ -- equality
- $=/=$ -- disequality
- $>==$ -- greater than or equal
- $<==$ -- less than or equal
- $>$ -- greater than
- $<$ -- less than

A Predicate is either an atomic predicate, obtained by comparing two expressions, or, an application of a predicate function to a list of arguments, or the Boolean combination of the above predicates with the operators && (and), || (or), ==> (implies $^3$), <=> (if and only if $^4$), and not.

Examples of Predicates include the following:

$^3$ Read $p \implies q$ as “if $p$ then $q$”

$^4$ Read $p \iff q$ as “if $p$ then $q$ and if $q$ then $p$”
• $x + y \leq 3$
• $null\ x$
• $x < 10 \Rightarrow y < 10 \Rightarrow x + y < 20$
• $0 < x + y \iff 0 < y + x$

**Semantics**

The syntax of predicates tells us what they *look* like, that is, what we can *write down* as valid predicates. Next, let us turn our attention to what a predicate *means*. Intuitively, a predicate is just a Boolean valued Haskell function with &&, ||, not being the usual operators and ==> and <=> being two special operators.

The Implication operator $\Rightarrow$ is equivalent to the following Haskell function. (For now, ignore the signature: it just says the output is a *Bool* that is equal to the *logical* implication between the inputs $p$ and $q$.)

\[
\begin{align*}
\text{False} \Rightarrow \text{False} &= \text{True} \\
\text{False} \Rightarrow \text{True} &= \text{True} \\
\text{True} \Rightarrow \text{True} &= \text{True} \\
\text{True} \Rightarrow \text{False} &= \text{False}
\end{align*}
\]

The If-and-only-if operator $\iff$ is equivalent to the Haskell function:\footnote{An observant reader may notice that $\iff$ is the same as $==$ if the arguments are of type *Bool*}

\[
\begin{align*}
\text{False} \iff \text{False} &= \text{True} \\
\text{False} \iff \text{True} &= \text{False} \\
\text{True} \iff \text{True} &= \text{True} \\
\text{True} \iff \text{False} &= \text{False}
\end{align*}
\]

An Environment is a mapping from variables to their Haskell types. For example, let $G$ be an environment defined as

\[
\begin{align*}
x &:: \text{Int} \\
y &:: \text{Int} \\
z &:: \text{Int}
\end{align*}
\]

which maps each variable $x$, $y$ and $z$ to the type *Int*. 
An Assignment under an environment, is a mapping from variables to values of the type specified in the environment. For example,

```plaintext
x := 1
y := 2
z := 3
```

is an assignment under G that maps x, y and z to the Int values 1, 2 and 3 respectively.

A Predicate Evaluates to either True or False under a given assignment. For example, the predicate

```plaintext
x + y > 10
```

evaluates to False given the above assignment but evaluates to True under the assignment

```plaintext
x := 10
y := 10
z := 20
```

A Predicate is Satisfiable in an environment if there exists an assignment (in that environment) that makes the predicate evaluate to True. For example, in G the predicate

```plaintext
x + y == z
```

is satisfiable, as the above assignment makes the predicate evaluate to True.

A Predicate is Valid in an environment if every assignment in that environment makes the predicate evaluate to True. For example, the predicate

```plaintext
x < 10 || x == 10 || x > 10
```

is valid under G as no matter what value we assign to x, the above predicate will evaluate to True.
Verification Conditions

LiquidHaskell works without actually executing your programs. Instead, it checks that your program meets the given specifications in roughly two steps.

1. First, LH combines the code and types down to a set of Verification Conditions (VC) which are predicates that are valid only if your program satisfies a given property.  

2. Next, LH queries an SMT solver to determine whether these VCs are valid. If so, it says your program is safe and otherwise it rejects your program.

The SMT Solver decides whether a predicate (VC) is valid without enumerating and evaluating all assignments. Indeed, it is impossible to do so as there are usually infinitely many assignments once the predicates refer to integers or lists and so on. Instead, the SMT solver uses a variety of sophisticated symbolic algorithms to deduce whether a predicate is valid or not. This process is the result of decades of work in mathematical logic and decision procedures; the Ph.D thesis of Greg Nelson is an excellent place to learn more about these beautiful algorithms.

We restrict the Logic to ensure that all our VC queries fall within the decidable fragment. This makes LiquidHaskell extremely automatic – there is no explicit manipulation of proofs, just the specification of properties via types and of course, the implementation via Haskell code! This automation comes at a price: all our refinements must belong to the logic above. Fortunately, with a bit of creativity, we can say a lot in this logic.

Examples: Propositions

Finally, let’s conclude this quick overview with some examples of predicates, in order to build up our own intuition about logic and validity. Each of the below is a predicate from our refinement logic. However, we write them as raw Haskell expressions that you may be more familiar with right now, and so that we can start to use LiquidHaskell to determine whether a predicate is indeed valid or not.
Let ‘TRUE’ be a refined type for Bool valued expressions that *always* evaluate to True. Similarly, we can define FALSE for Bool valued expressions that *always* evaluate to False.\(^8\)

\[
\begin{align*}
\{-@ \text{type TRUE} & = \{v: \text{Bool} \mid v \} \} @- \\
\{-@ \text{type FALSE} & = \{v: \text{Bool} \mid \neg v\} @- \
\end{align*}
\]

Thus, a *valid predicate* is one that has the type TRUE. The simplest example of a valid predicate is just True:

\[
\{-@ \text{ex0 :: TRUE @-} \\
\text{ex0} = \text{True}
\]

of course, False is *not valid*

\[
\{-@ \text{ex0’ :: TRUE @-} \\
\text{ex0’} = \text{False}
\]

We can get more interesting predicates if we use variables. For example, the following is valid predicate says that a Bool variable is either True or False.

\[
\{-@ \text{ex1 :: Bool -> TRUE @-} \\
\text{ex1 b} = b || \neg b
\]

Of course, a variable cannot be both True and False, and so the below predicate is valid:

\[
\{-@ \text{ex2 :: Bool -> FALSE @-} \\
\text{ex2 b} = b && \neg b
\]

The next few examples illustrate the $\Rightarrow$ operator. You should read $p \Rightarrow q$ as *if* $p$ is true then $q$ must also be true. Thus, the below predicates are valid as if both $a$ and $b$ are true, then well, $a$ is true, and $b$ is true.

\[
\{-@ \text{ex3 :: Bool -> Bool -> TRUE @-} \\
\text{ex3 a b} = (a && b) \Rightarrow a
\]

\[
\{-@ \text{ex4 :: Bool -> Bool -> TRUE @-} \\
\text{ex4 a b} = (a && b) \Rightarrow b
\]

**Exercise 2.1** (Implications and Or). *Of course, if we replace the && with || the result is not valid. Can you shuffle the variables around – without changing the operators – to make the formula valid?*
The following predicates are valid because they encode *modus ponens*: if you know that \( a \) implies \( b \) and you know that \( a \) is true, then it must be the case that \( b \) is also true:

\[
\{\text{@ ex6 :: Bool -> Bool -> TRUE @-}\}
\begin{align*}
\text{ex6 } a \ b &= (a \&\& (a \implies b)) \implies b
\end{align*}
\]

\[
\{\text{@ ex7 :: Bool -> Bool -> TRUE @-}\}
\begin{align*}
\text{ex7 } a \ b &= a \implies (a \implies b) \implies b
\end{align*}
\]

Recall that \( p \iff q \) (read \( p \) if and only if \( q \)) evaluates to True exactly when \( p \) and \( q \) evaluate to the *same* values (True or False). It is used to encode *equalities* between predicates. For example, we can write down De Morgan’s laws as the valid predicates:

\[
\{\text{@ exDeMorgan1 :: Bool -> Bool -> TRUE @-}\}
\begin{align*}
\text{exDeMorgan1 } a \ b &= \neg (a \lor b) \iff (\neg a \&\& \neg b)
\end{align*}
\]

**Exercise 2.2** (DeMorgan’s Law). *The following version of DeMorgan’s law is wrong. Can you fix it to get a valid formula?*

\[
\{\text{@ exDeMorgan2 :: Bool -> Bool -> TRUE @-}\}
\begin{align*}
\text{exDeMorgan2 } a \ b &= \neg (a \& b) \iff (\neg a \&\& \neg b)
\end{align*}
\]

**Examples: Arithmetic**

Next, let’s look at some predicates involving arithmetic. The simplest ones don’t have any variables, for example:

\[
\{\text{@ ax0 :: TRUE @-}\}
\begin{align*}
\text{ax0 } &= 1 + 1 = 2
\end{align*}
\]

Again, a predicate that evaluates to False is *not* valid:

\[
\{\text{@ ax0' :: TRUE @-}\}
\begin{align*}
\text{ax0'} &= 1 + 1 = 3
\end{align*}
\]

SMT Solvers determine Validity *without* enumerating assignments. For example, consider the predicate:
It is trivially valid; as via the usual laws of arithmetic, it is equivalent to $0 < 1$ which is True independent of the value of $x$. The SMT solver is able to determine this validity without enumerating the infinitely many possible values for $x$. This kind of validity checking lies at the heart of LiquidHaskell.

We can combine arithmetic and propositional operators, as shown in the following examples:

{-@ ax2 :: Int -> TRUE @-}
ax2 x = (x < 0) ==> (0 <= 0 - x)

{-@ ax3 :: Int -> Int -> TRUE @-}
ax3 x y = (0 <= x) ==> (0 <= y) ==> (0 <= x + y)

{-@ ax4 :: Int -> Int -> TRUE @-}
ax4 x y = (x == y - 1) ==> (x + 2 == y + 1)

{-@ ax5 :: Int -> Int -> Int -> TRUE @-}
ax5 x y z = (x <= 0 && x >= 0) 
  ==> (y == x + z) 
  ==> (y == z)

Exercise 2.3 (Addition and Order). The formula below is not valid. Do you know why? Change the hypothesis i.e. the thing to the left of the ==> to make it a valid formula.

{-@ ax6 :: Int -> Int -> TRUE @-}
ax6 x y = True ==> (x <= x + y)

Examples: Uninterpreted Function

We say that function symbols are uninterpreted in the refinement logic, because the SMT solver does not “know” how functions are defined. Instead, the only thing that the solver knows is the axiom of congruence which states that any function $f$, returns equal outputs when invoked on equal inputs.

We Test the Axiom of Congruence by checking that the following predicate is valid:
logic

congruence :: (Int -> Int) -> Int -> Int -> TRUE @-
congruence f x y = (x == y) ==> (f x == f y)

Again, remember we are not evaluating the code above; indeed we cannot evaluate the code above because we have no definition of f.

Still, the predicate is valid as the congruence axiom holds for any possible interpretation of f.

Here is a fun example; can you figure out why this predicate is indeed valid? (The SMT solver can...)

fx1 f x = (x == f (f (f x)))
      ==> (x == f (f (f (f (f x)))))
      ==> (x == f x)

To get a taste of why uninterpreted functions will prove useful, let’s write a function to compute the size of a list:

measure size @-}
{size :: [a] -> Int
size [] = 0
size (x:xs) = 1 + size xs

We can now verify that the following predicates are valid:

fx0 xs ys = (xs == ys) ==> (size xs == size ys)

Note that to determine that the above is valid, the SMT solver does not need to know the meaning or interpretation of size – merely that it is a function. When we need some information about the definition, of size we will put it inside the predicate. For example, in order to prove that the following is valid:

fx2 x xs = 0 < size ys
  where
    ys = x : xs

LiquidHaskell actually asks the SMT solver to prove the validity of a VC predicate which states that sizes are non-negative and that since ys equals x:xs, the size of ys is one more than xs. 9

9 Fear not! We will describe how this works soon
Recap

This chapter describes exactly what we, for the purposes of this book, mean by the term \textit{logical predicate}.

1. We defined a grammar – a restricted subset of Haskell corresponding to \texttt{Bool} valued expressions.

2. The restricted grammar lets us use SMT solvers to decide whether a predicate is \textit{valid} that is, evaluates to \texttt{True} for all values of the variables.

3. Crucially, the SMT solver determines validity \textit{without enumerating} and evaluating the predicates (which would take forever!) but instead by using clever symbolic algorithms.

Next, let’s see how we can use logical predicates to \textit{specify} and \textit{verify} properties of real programs.
3

Refinement Types

What is a Refinement Type? In a nutshell,

Refinement Types = Types + Predicates

That is, refinement types allow us to decorate types with logical predicates, which you can think of as boolean-valued Haskell expressions, that constrain the set of values described by the type. This lets us specify sophisticated invariants of the underlying values.

Defining Types

Let us define some refinement types:\(^1\)

```haskell
{-@ type Zero = {v:Int | v == 0} @-}
{-@ type NonZero = {v:Int | v /= 0} @-}
```

The \textbf{Value Variable} \(v\) denotes the set of valid inhabitants of each refinement type. Hence, \texttt{Zero} describes the set of \texttt{Int} values that are equal to 0, that is, the singleton set containing just 0, and \texttt{NonZero} describes the set of \texttt{Int} values that are \textit{not} equal to 0, that is, the set \(\{1, -1, 2, -2, \ldots\}\) and so on.\(^2\)

To use these types we can write:

```haskell
{-@ zero :: Zero @-}
zero = 0 :: Int
```

\(^1\) You can read the type of \texttt{Zero} as: “\(v\) is an Int such that \(v\) equals 0” and \texttt{NonZero} as : “\(v\) is an Int such that \(v\) does not equal 0”

\(^2\) We will use \texttt{@}-marked comments to write refinement type annotations in the Haskell source file, making these types, quite literally, machine-checked comments!
one   = 1 :: Int
two   = 2 :: Int
three = 3 :: Int

Errors

If we try to say nonsensical things like:

```haskell
nonsense :: Int
nonsense = one'  
where
{~@ one' :: Zero ~@}
one' = 1
```

LiquidHaskell will complain with an error message:

```plaintext
./liquidhaskell-tutorial/src/03-basic.lhs:72:3-6: Error: Liquid Type Mismatch
```

The message says that the expression 1 :: Int has the type

```
{v::Int | v == 1}
```

which is not (a subtype of) the required type

```
{v::Int | v == 0}
```

as 1 is not equal to 0.

Subtyping

What is this business of subtyping? Suppose we have some more refinements of Int
What is the type of zero? Zero of course, but also Nat:

```haskell
{-# zero' :: Nat #-}
zero' = zero
```

and also Even:

```haskell
{-# zero'' :: Even #-}
zero'' = zero
```

and also any other satisfactory refinement, such as

```haskell
{-# zero''' :: Lt100 #-}
zero''' = zero
```

Subtyping and Implication

Zero is the most precise type for 0::Int, as it is a subtype of Nat, Even and Lt100. This is because the set of values defined by Zero is a subset of the values defined by Nat, Even and Lt100, as the following logical implications are valid:

- \( v = 0 \Rightarrow 0 \leq v \)
- \( v = 0 \Rightarrow v \mod 2 = 0 \)
- \( v = 0 \Rightarrow v < 100 \)

In Summary the key points about refinement types are:

1. A refinement type is just a type decorated with logical predicates.
2. A term can have different refinements for different properties.
3. When we erase the predicates we get the standard Haskell types.

Writing Specifications

Let’s write some more interesting specifications.

\[\text{refinement types}\]

\[
\begin{align*}
\texttt{Nat} &= \{v:\text{Int} \mid 0 \leq v\} \\
\texttt{Even} &= \{v:\text{Int} \mid v \mod 2 = 0\} \\
\texttt{Lt100} &= \{v:\text{Int} \mid v < 100\}
\end{align*}
\]
Typing Dead Code We can wrap the usual error function in a function die with the type:

```haskell
{-# die :: {v: String | false} -> a #-}
die msg = error msg
```

The interesting thing about die is that the input type has the refinement false, meaning the function must only be called with Strings that satisfy the predicate false. This seems bizarre; isn’t it impossible to satisfy false? Indeed! Thus, a program containing die typechecks only when LiquidHaskell can prove that die is never called. For example, LiquidHaskell will accept

```haskell
cannotDie = if 1 + 1 == 3
    then die "horrible death"
    else ()
```

by inferring that the branch condition is always False and so die cannot be called. However, LiquidHaskell will reject

```haskell
canDie = if 1 + 1 == 2
    then die "horrible death"
    else ()
```

as the branch may (will!) be True and so die can be called.

Refining Function Types: Pre-conditions

Let’s use die to write a safe division function that only accepts non-zero denominators.

```haskell
divide' :: Int -> Int -> Int
divide' n 0 = die "divide by zero"
divide' n d = n `div'` d
```

From the above, it is clear to us that div is only called with non-zero divisors. However, LiquidHaskell reports an error at the call to "die" because, what if divide’ is actually invoked with a 0 divisor?

We can specify that will not happen, with a pre-condition that says that the second argument is non-zero:
To **verify** that `divide` never calls `die`, LiquidHaskell infers that "divide by zero" is not merely of type `String`, but in fact has the the refined type `{v: String | false}` in the context in which the call to `die` occurs. LiquidHaskell arrives at this conclusion by using the fact that in the first equation for `divide` the denominator is in fact `0 :: {v: Int | v == 0}` which *contradicts* the pre-condition (i.e. input) type. Thus, by contradiction, LiquidHaskell deduces that the first equation is *dead code* and hence `die` will not be called at run-time.

**Establishing Pre-conditions**

The above signature forces us to ensure that that when we *use* `divide`, we only supply provably `NonZero` arguments. Hence, these two uses of `divide` are fine:

```haskell
avg2 x y = divide (x + y) 2
avg3 x y z = divide (x + y + z) 3
```

**Exercise 3.1** (List Average). Consider the function `avg`:

1. **Why does LiquidHaskell flag an error at n?**
2. **How can you change the code so LiquidHaskell verifies it?**

```haskell
avg :: [Int] -> Int
avg xs = divide total n
  where
    total = sum xs
    n = length xs
```

**Refining Function Types: Post-conditions**

Next, let’s see how we can use refinements to describe the *outputs* of a function. Consider the following simple *absolute value* function

```haskell
{-@ divide :: Int -> NonZero -> Int @-}
divide _ 0 = die "divide by zero"
divide n d = n `div` d
```
abs :: Int -> Int
abs n
| 0 < n  = n
| otherwise = 0 - n

We can use a refinement on the output type to specify that the function returns non-negative values

{-@ abs :: Int -> Nat @-}

LiquidHaskell verifies that abs indeed enjoys the above type by deducing that n is trivially non-negative when 0 < n and that in the otherwise case, the value 0 - n is indeed non-negative.\(^5\)

Testing Values: Booleans and Propositions

In the above example, we compute a value that is guaranteed to be a Nat. Sometimes, we need to test if a value satisfies some property, e.g., is NonZero. For example, let’s write a command-line calculator:

calc = do putStrLn "Enter numerator"
n <- readLn
putStrLn "Enter denominator"
d <- readLn
putStrLn (result n d)
calc

which takes two numbers and divides them. The function result checks if d is strictly positive (and hence, non-zero), and does the division, or otherwise complains to the user:

result n d
| isPositive d = "Result = " ++ show (n `divide` d)
| otherwise = "Humph, please enter positive denominator!"

Finally, isPositive is a test that returns a True if its input is strictly greater than 0 or False otherwise:

isPositive :: Int -> Bool
isPositive x = x > 0
To verify the call to divide inside result we need to tell Liquid-Haskell that the division only happens with a NonZero value \( d \). However, the non-zero-ness is established via the test that occurs inside the guard \( \text{isPositive} \ d \). Hence, we require a post-condition that states that \( \text{isPositive} \) only returns \( \text{True} \) when the argument is positive:

\[
{-@ \text{isPositive} :: x:\text{Int} \rightarrow \{v:\text{Bool} \mid v \iff x > 0\}@-}
\]

In the above signature, the output type (post-condition) states that \( \text{isPositive} \ x \) returns \( \text{True} \) if and only if \( x \) was in fact strictly greater than \( 0 \). In other words, we can write post-conditions for plain-old \( \text{Bool} \)-valued \( \text{tests} \) to establish that user-supplied values satisfy some desirable property (here, \( \text{Pos} \) and hence \( \text{NonZero} \)) in order to then safely perform some computation on it.

**Exercise 3.2** (Propositions). What happens if you delete the type for \( \text{isPositive} \)? Can you change the type for \( \text{isPositive} \) (i.e. write some other type) while preserving safety?

**Exercise 3.3** (Assertions). Consider the following assert function, and two use sites. Write a suitable refinement type signature for \( \text{lAssert} \) so that \( \text{lAssert} \) and \( \text{yes} \) are accepted but \( \text{no} \) is rejected.

\[
{-@ \text{lAssert} :: \text{Bool} \rightarrow a \rightarrow a@-}
\]

\[
\begin{align*}
\text{lAssert True} & \equiv x = x \\
\text{lAssert False} & \equiv \text{die "yikes, assertion fails!"}
\end{align*}
\]

yes = lAssert (1 + 1 == 2) ()

no = lAssert (1 + 1 == 3) ()

*Hint:* You need a pre-condition that \( \text{lAssert} \) is only called with \( \text{True} \).

*Putting It All Together*

Let's wrap up this introduction with a simple truncate function that connects all the dots.

\[
\text{truncate} :: \text{Int} \rightarrow \text{Int} \rightarrow \text{Int}
\]

\[
\text{truncate} \; i \; \text{max} \; \begin{cases} 
  i' \leq \text{max}' & = i \\
  \text{otherwise} & = \text{max}' \ast (i \ ' \div \ i')
\end{cases}
\]

where
\[
\begin{align*}
  i' & = \text{abs} \; i \\
  \text{max}' & = \text{abs} \; \text{max}
\end{align*}
\]
The expression \( \text{truncate } i \ n \) evaluates to \( i \) when the absolute value of \( i \) is less than the upper bound \( \max \), and otherwise \( \text{truncates} \) the value at the maximum \( n \). LiquidHaskell verifies that the use of \( \text{divide} \) is safe by inferring that:

1. \( \max' < i' \) from the branch condition,
2. \( 0 \leq i' \) from the \( \text{abs} \) post-condition, and
3. \( 0 \leq \max' \) from the \( \text{abs} \) post-condition.

From the above, LiquidHaskell infers that \( i' \neq 0 \). That is, at the call site \( i' :: \text{NonZero} \), thereby satisfying the pre-condition for \( \text{divide} \) and verifying that the program has no pesky divide-by-zero errors.

**Recap**

This concludes our quick introduction to Refinement Types and LiquidHaskell. Hopefully you have some sense of how to

1. **Specify** fine-grained properties of values by decorating their types with logical predicates.
2. **Encode** assertions, pre-conditions, and post-conditions with suitable function types.
3. **Verify** semantic properties of code by using automatic logic engines (SMT solvers) to track and establish the key relationships between program values.
4 Polymorphism

Refinement types shine when we want to establish properties of polymorphic datatypes and higher-order functions. Rather than be abstract, let’s illustrate this with a classic use-case.

Array Bounds Verification aims to ensure that the indices used to retrieve values from an array are indeed valid for the array, i.e. are between 0 and the size of the array. For example, suppose we create an array with two elements:

```haskell
twoLangs = fromList ["haskell", "javascript"]
```

Let’s attempt to look it up at various indices:

```haskell
eeks = [ok, yup, nono]
where
  ok = twoLangs ! 0
  yup = twoLangs ! 1
  nono = twoLangs ! 3
```

If we try to run the above, we get a nasty shock: an exception that says we’re trying to look up `twoLangs` at index 3 whereas the size of `twoLangs` is just 2.

```
Prelude> :l 03-poly.lhs
[1 of 1] Compiling VectorBounds ( 03-poly.lhs, interpreted )
Ok, modules loaded: VectorBounds.
*VectorBounds> eeks
Loading package ... done.
"*** Exception: ./Data/Vector/Generic.hs:249 (!!): index out of bounds (3,2)
```
In a suitable Editor e.g. Vim or Emacs, or if you push the “play” button in the online demo, you will literally see the error *without* running the code. Let’s see how LiquidHaskell checks *ok* and *yup* but flags *nono*, and along the way, learn how it reasons about *recursion*, *higher-order functions*, *data types* and *polymorphism*.

**Specification: Vector Bounds**

First, let’s see how to specify array bounds safety by *refining* the types for the key functions exported by `Data.Vector`, i.e. how to

1. **define** the size of a Vector
2. **compute** the size of a Vector
3. **restrict** the indices to those that are valid for a given size.

**Imports**

We can write specifications for imported modules – for which we *lack* the code – either directly in the client’s source file or better, in `.spec` files which can be reused across multiple client modules.

**Include** directories can be specified when checking a file. Suppose we want to check some file `target.hs` that imports an external dependency `Data.Vector`. We can write specifications for `Data.Vector` inside `include/Data/Vector.spec` which contains:

```hs
-- | Define the size
measure vlen :: Vector a -> Int

-- | Compute the size
assume length :: x:Vector a -> {v: Int | v = vlen x}

-- | Lookup at an index
assume (!) :: x:Vector a -> {v: Nat | v < vlen x} -> a
```

Using this new specification is now a simple matter of telling LiquidHaskell to include this file:

```
$ liquid -i include/ target.hs
```

LiquidHaskell ships with specifications for `Prelude`, `Data.List`, and `Data.Vector` which it includes by default.
Measures are used to define properties of Haskell data values that are useful for specification and verification. Think of vlen as the actual size of a Vector regardless of how the size was computed.

Assumes are used to specify types describing the semantics of functions that we cannot verify e.g. because we don’t have the code for them. Here, we are assuming that the library function Data.Vector.length indeed computes the size of the input vector. Furthermore, we are stipulating that the lookup function (!) requires an index that is between 0 and the real size of the input vector x.

Dependent Refinements are used to describe relationships between the elements of a specification. For example, notice how the signature for length names the input with the binder x that then appears in the output type to constrain the output Int. Similarly, the signature for (!) names the input vector x so that the index can be constrained to be valid for x. Thus, dependency lets us write properties that connect multiple program values.

Aliases are extremely useful for defining abbreviations for commonly occurring types. Just as we enjoy abstractions when programming, we will find it handy to have abstractions in the specification mechanism. To this end, LiquidHaskell supports type aliases. For example, we can define Vectors of a given size N as:

```{-@ type VectorN a N = {v:Vector a | vlen v == N} @-}```

and now use this to type twoLangs above as:

```{-@ twoLangs :: VectorN String 2 @-}```
```twoLangs = fromList ["haskell", "javascript"]```

Similarly, we can define an alias for Int values between Lo and Hi:

```{-@ type Btwn Lo Hi = {v:Int | Lo <= v && v < Hi} @-}```

after which we can specify (!) as:

```(!) :: x:Vector a -> Btwn 0 (vlen x) -> a```
Verification: Vector Lookup

Let’s try to write some functions to sanity check the specifications. First, find the starting element – or head of a Vector:

```haskell
head :: Vector a -> a
head vec = vec ! 0
```

When we check the above, we get an error:

```
src/03-poly.lhs:127:23: Error: Liquid Type Mismatch
Inferred type
  VV : Int | VV == ?a && VV == 0
not a subtype of Required type
  VV : Int | VV >= 0 && VV < vlen vec
In Context
  VV : Int | VV == ?a && VV == 0
  vec : Vector a | 0 <= vlen vec
  ?a : Int | ?a == (0 : int)
```

LiquidHaskell is saying that 0 is not a valid index as it is not between 0 and vlen vec. Say what? Well, what if vec had no elements! A formal verifier doesn’t make off by one errors.

To fix the problem we can do one of two things.

1. **Require** that the input vec be non-empty, or
2. **Return** an output if vec is non-empty, or

Here’s an implementation of the first approach, where we define and use an alias NEVector for non-empty Vectors:

```haskell
{-@ type NEVector a = {v:Vector a | 0 < vlen v} @-}

{-@ head' :: NEVector a -> a @-}
head' vec = vec ! 0
```

**Exercise 4.1 (Vector Head).** Replace the undefined with an implementation of head’ which accepts all Vectors but returns a value only when the input vec is not empty.
head' :: Vector a -> Maybe a
head' vec = undefined

Exercise 4.2 (Unsafe Lookup). The function unsafeLookup is a wrapper around the (!) with the arguments flipped. Modify the specification for unsafeLookup so that the implementation is accepted by LiquidHaskell.

{-@ unsafeLookup :: Int -> Vector a -> a @-}
unsafeLookup index vec = vec ! index

Exercise 4.3 (Safe Lookup). Complete the implementation of safeLookup by filling in the implementation of ok so that it performs a bounds check before the access.

{-@ safeLookup :: Vector a -> Int -> Maybe a @-}
safeLookup x i
  | ok = Just (x ! i)
  | otherwise = Nothing
where
  ok = undefined

Inference: Our First Recursive Function

Ok, let’s write some code! Let’s start with a recursive function that adds up the values of the elements of an Int vector.

-- >>> vectorSum (fromList [1, -2, 3])
-- 2
vectorSum :: Vector Int -> Int
vectorSum vec = go 0 0
  where
    go acc i
      | i < sz = go (acc + (vec ! i)) (i + 1)
      | otherwise = acc
    sz = length vec

Exercise 4.4 (Guards). What happens if you replace the guard with i <= sz?

Exercise 4.5 (Absolute Sum). Write a variant of the above function that computes the absoluteSum of the elements of the vector.
Inference

LiquidHaskell verifies \texttt{vectorSum} – or, to be precise, the safety of the vector accesses \texttt{vec ! i}. The verification works out because LiquidHaskell is able to \textit{automatically infer} \footnote{In your editor, click on go to see the inferred type.}

\begin{align*}
\text{go} & : \text{Int} \to \{v : \text{Int} \mid 0 \leq v \land v \leq \text{sz}\} \to \text{Int}
\end{align*}

which states that the second parameter \(i\) is between 0 and the length of \texttt{vec} (inclusive). LiquidHaskell uses this and the test that \(i < \text{sz}\) to establish that \(i\) is between 0 and \(\text{vlen vec}\) to prove safety.

Note you need to run \texttt{liquid} with the option \texttt{--no-termination} or make sure your source file has \texttt{--@ LIQUID "--no-termination" @-}, otherwise the code \texttt{forgo'} fails the new default termination check. We will come back to this example later to see how to verify termination using metrics.

Exercise 4.6 (Off by one?). \textit{Why does the type of go have } \(v \leq sz\) \textit{and not } \(v < sz\) ?

\section*{Higher-Order Functions: Bottling Recursion in a loop}

Let’s refactor the above low-level recursive function into a generic higher-order loop.

\begin{align*}
\text{loop} & : \text{Int} \to \text{Int} \to \text{a} \to (\text{Int} \to \text{a} \to \text{a}) \to \text{a} \\
\text{loop lo hi base f} & = \text{go base lo} \\
\text{where} & \\
\text{go acc i} & \mid i < \text{hi} = \text{go (f i acc) (i + 1)} \\
\text{otherwise} & = \text{acc}
\end{align*}

We can now use \texttt{loop} to implement \texttt{vectorSum}:

\begin{align*}
\text{vectorSum'} & : \text{Vector Int} \to \text{Int} \\
\text{vectorSum'} \text{ vec} & = \text{loop 0 n 0 body} \\
\text{where} & \\
\text{body i acc} & = \text{acc} + (\text{vec ! i}) \\
\text{n} & = \text{length vec}
\end{align*}
Inference is a convenient option. LiquidHaskell finds:

\[
\text{loop} :: \text{lo} : \text{Nat} \to \text{hi} : (\text{Nat}|\text{lo} \leq \text{hi}) \to a \to (\text{Btwn} \, \text{lo} \, \text{hi} \to a \to a) \to a
\]

In English, the above type states that

- \(\text{lo}\) the loop lower bound is a non-negative integer
- \(\text{hi}\) the loop upper bound is a greater then or equal to \(\text{lo}\),
- \(f\) the loop body is only called with integers between \(\text{lo}\) and \(\text{hi}\).

It can be tedious to have to keep typing things like the above. If we wanted to make \(\text{loop}\) a public or exported function, we could use the inferred type to generate an explicit signature.

At the call \(\text{loop} \, 0 \, n \, 0 \, \text{body}\) the parameters \(\text{lo}\) and \(\text{hi}\) are instantiated with \(0\) and \(n\) respectively, which, by the way is where the inference engine deduces non-negativity. Thus LiquidHaskell concludes that body is only called with values of \(i\) that are between \(0\) and \((\text{vlen vec})\), which verifies the safety of the call \(\text{vec} \, ! \, i\).

Exercise 4.7 (Using Higher-Order Loops). Complete the implementation of \texttt{absoluteSum'} below. When you are done, what is the type that is inferred for \texttt{body}?

```haskell
-- >>> absoluteSum' (fromList [1, -2, 3])
-- 6
{-@ absoluteSum' :: Vector Int -> Nat @-}
absoluteSum' vec = loop 0 n 0 body
    where
        body i acc = undefined
        n = length vec

Exercise 4.8 (Dot Product). The following uses \texttt{loop} to compute \texttt{dotProducts}. Why does LiquidHaskell flag an error? Fix the code or specification so that LiquidHaskell accepts it.

```haskell
-- >>> dotProduct (fromList [1,2,3]) (fromList [4,5,6])
-- 32
{-@ dotProduct :: x:Vector Int -> y:Vector Int -> Int @-}
dotProduct x y = loop 0 sz 0 body
    where
        body i acc = acc + (x ! i) * (y ! i)
        sz = length x
```
Refinements and Polymorphism

While the standard Vector is great for dense arrays, often we have to manipulate sparse vectors where most elements are just 0. We might represent such vectors as a list of index-value tuples:

{-@ type SparseN a N = [(Btwn 0 N, a)] @-}

Implicitly, all indices other than those in the list have the value 0 (or the equivalent value for the type a).

The alias SparseN is just a shorthand for the (longer) type on the right, it does not define a new type. If you are familiar with the index-style length encoding e.g. as found in DML or Agda, then note that despite appearances, our Sparse definition is not indexed.

Sparse Products

Let’s write a function to compute a sparse product

{-@ sparseProduct :: x:Vector _ -> SparseN _ (vlen x) -> _ @-}
sparseProduct x y = go 0 y
  where
    go n [] = n
    go n ((i,v):y') = go (n + (x!i) * v) y'

LiquidHaskell verifies the above by using the specification to conclude that for each tuple (i, v) in the list y, the value of i is within the bounds of the vector x, thereby proving x ! i safe.

Folds

The sharp reader will have undoubtedly noticed that the sparse product can be more cleanly expressed as a fold:

foldl' :: (a -> b -> a) -> a -> [b] -> a

We can simply fold over the sparse vector, accumulating the sum as we go along

{-@ sparseProduct' :: x:Vector _ -> SparseN _ (vlen x) -> _ @-}
sparseProduct' x y = foldl' body 0 y
  where
    body sum (i,v) = sum + (x!i) * v
LiquidHaskell digests this without difficulty. The main trick is in how the polymorphism of foldl' is instantiated.

1. GHC infers that at this site, the type variable b from the signature of foldl' is instantiated to the Haskell type (Int, a).

2. Correspondingly, LiquidHaskell infers that in fact b can be instantiated to the refined (Btwn 0 (vlen x), a).

Thus, the inference mechanism saves us a fair bit of typing and allows us to reuse existing polymorphic functions over containers and such without ceremony.

Recap

This chapter gave you an idea of how one can use refinements to verify size related properties, and more generally, to specify and verify properties of recursive and polymorphic functions. Next, let’s see how we can use LiquidHaskell to prevent the creation of illegal values by refining data type definitions.
So far, we have seen how to refine the types of functions, to specify, for example, pre-conditions on the inputs, or post-conditions on the outputs. Very often, we wish to define datatypes that satisfy certain invariants. In these cases, it is handy to be able to directly refine the data definition, making it impossible to create illegal inhabitants.

**Sparse Vectors Revisited**

As our first example of a refined datatype, let’s revisit the sparse vector representation that we saw earlier. The SparseN type alias we used got the job done, but is not pleasant to work with because we have no way of determining the dimension of the sparse vector. Instead, let’s create a new datatype to represent such vectors:

```haskell
data Sparse a = SP { spDim :: Int, spElems :: [(Int, a)] }
```

Thus, a sparse vector is a pair of a dimension and a list of index-value tuples. Implicitly, all indices other than those in the list have the value 0 or the equivalent value type a.

**LEGAL**

Sparse vectors satisfy two crucial properties. First, the dimension stored in `spDim` is non-negative. Second, every index in `spElems` must be valid, i.e. between 0 and the dimension. Unfortunately, Haskell’s type system does not make it easy to ensure that illegal vectors are not representable.\(^1\)

\[^1\text{The standard approach is to use abstract types and smart constructors but even then there is only the informal guarantee that the smart constructor establishes the right invariants.}\]
Data Invariants LiquidHaskell lets us enforce these invariants with a refined data definition:

```haskell
{-@ data Sparse a = SP { spDim :: Nat
    , spElems :: [(Btwn 0 spDim, a)] } @-}
```

Where, as before, we use the aliases:

```haskell
{-@ type Nat = {v:Int | 0 <= v} @-}
{-@ type Btwn Lo Hi = {v:Int | Lo <= v && v < Hi} @-}
```

Refined Data Constructors The refined data definition is internally converted into refined types for the data constructor `SP`:

```haskell
-- Generated Internal representation
data Sparse a where
    SP :: spDim:Nat
    -> spElems:[(Btwn 0 spDim, a)]
    -> Sparse a
```

In other words, by using refined input types for `SP` we have automatically converted it into a smart constructor that ensures that every instance of a `Sparse` is legal. Consequently, LiquidHaskell verifies:

```haskell
okSP :: Sparse String
okSP = SP 5 [(0, "cat")
    , (3, "dog") ]
```

but rejects, due to the invalid index:

```haskell
badSP :: Sparse String
badSP = SP 5 [(0, "cat")
    , (6, "dog") ]
```

Field Measures It is convenient to write an alias for sparse vectors of a given size `N`. We can use the field name `spDim` as a measure, like `vlen`. That is, we can use `spDim` inside refinements\(^2\)

```haskell
{-@ type SparseN a N = {v:Sparse a | spDim v == N} @-}
```

Sparse Products Let’s write a function to compute a sparse product
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{-@ dotProd :: x:Vector Int -> SparseN Int (vlen x) -> Int @-}
dotProd x (SP _ y) = go 0 y
where
  go sum ((i, v): y') = go (sum + (x ! i) * v) y'
  go sum [] = sum

LiquidHaskell verifies the above by using the specification to conclude that for each tuple \((i, v)\) in the list \(y\), the value of \(i\) is within the bounds of the vector \(x\), thereby proving \(x ! i\) safe.

**Folded Product** We can port the fold-based product to our new representation:

{-@ dotProd' :: x:Vector Int -> SparseN Int (vlen x) -> Int @-}
dotProd' x (SP _ y) = foldl' body 0 y
where
  body sum (i, v) = sum + (x ! i) * v

As before, LiquidHaskell checks the above by automatically instantiating refinements for the type parameters of \(\text{foldl}'\), saving us a fair bit of typing and enabling the use of the elegant polymorphic, higher-order combinators we know and love.

**Exercise 5.1 (Sanitization).** * Invariants are all well and good for data computed inside our programs. The only way to ensure the legality of data coming from outside, i.e. from the “real world”, is to write a sanitizer that will check the appropriate invariants before constructing a Sparse vector. Write the specification and implementation of a sanitizer fromList, so that the following typechecks:

**Hint:** You need to check that all the indices in elts are less than dim; the easiest way is to compute a new Maybe \([(\text{Int}, a)\)] which is Just the original pairs if they are valid, and Nothing otherwise.

{-@ test1 :: SparseN String 3 @-}
test1 = fromJust $ fromList 3 [(0, "cat"), (2, "mouse")]

**Exercise 5.2 (Addition).** Write the specification and implementation of a function plus that performs the addition of two Sparse vectors of the same dimension, yielding an output of that dimension. When you are done, the following code should typecheck:
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\[\text{plus} :: (\text{Num } a) \Rightarrow \text{Sparse } a \rightarrow \text{Sparse } a \rightarrow \text{Sparse } a\]
\[\text{plus } x \ y = \text{undefined}\]

\{-@ test2 :: \text{SparseN Int} 3 \ @-\}
\[\text{test2} = \text{plus } \text{vec1} \ \text{vec2}\]
\[\text{where}\]
\[\text{vec1} = \text{SP } 3 \ [(0, 12), (2, 9)]\]
\[\text{vec2} = \text{SP } 3 \ [(0, 8), (1, 100)]\]

\textit{Ordered Lists}

As a second example of refined data types, let’s consider a different problem: representing ordered sequences. Here’s a type for sequences that mimics the classical list:

\[\text{data IncList } a =\]
\[\quad \text{Emp}\]
\[\quad | (\langle \rangle) \{ \text{hd :: a, tl :: IncList } a \}\]

\textit{infixr } 9 :<

The Haskell type above does not state that the elements are in order of course, but we can specify that requirement by refining \text{every element in } \text{tl} \text{ to be greater than } \text{hd}:

\{-@ \text{data IncList } a =\}
\[\quad \text{Emp}\]
\[\quad | (\langle \rangle) \{ \text{hd :: a, tl :: IncList } \{ v :: a \mid \text{hd} \leq v \}\} \ @-\}

\textbf{Refined Data Constructors} Once again, the refined data definition is internally converted into a “smart” refined data constructor

\[\text{-- Generated Internal representation}\]
\[\text{data IncList } a \text{ where}\]
\[\quad \text{Emp} :: \text{IncList } a\]
\[\quad (\langle \rangle) :: \text{hd} :: a \rightarrow \text{tl:IncList } \{ v :: a \mid \text{hd} \leq v \} \rightarrow \text{IncList } a\]

which ensures that we can only create legal ordered lists.

\[\text{okList} = 1 :< 2 :< 3 :< \text{Emp} \quad \text{-- accepted by LH}\]
\[\text{badList} = 2 :< 1 :< 3 :< \text{Emp} \quad \text{-- rejected by LH}\]
It's all very well to specify ordered lists. Next, let's see how it's equally easy to establish these invariants by implementing several textbook sorting routines.

**Insertion Sort**

First, let's implement insertion sort, which converts an ordinary list \([a]\) into an ordered list IncList \(a\).

\[
\begin{align*}
\text{insertSort} & :: (\text{Ord } a) \Rightarrow [a] \rightarrow \text{IncList } a \\
\text{insertSort } [] & = \text{Emp} \\
\text{insertSort } (x:xs) & = \text{insert } \text{insertSort } xs
\end{align*}
\]

The hard work is done by insert which places an element into the correct position of a sorted list. LiquidHaskell infers that if you give insert an element and a sorted list, it returns a sorted list.

\[
\begin{align*}
\text{insert} & :: (\text{Ord } a) \Rightarrow a \rightarrow \text{IncList } a \rightarrow \text{IncList } a \\
\text{insert } y \text{ Emp} & = y :< \text{Emp} \\
\text{insert } y \text{ (x :< xs)} & |
\text{y <= x} = y :< x :< \text{xs} \\
\text{otherwise} & = x :< \text{insert } y \text{ xs}
\end{align*}
\]

**Exercise 5.3 (Insertion Sort).** Complete the implementation of the function below to use foldr to eliminate the explicit recursion in insertSort.

\[
\begin{align*}
\text{insertSort'} & :: (\text{Ord } a) \Rightarrow [a] \rightarrow \text{IncList } a \\
\text{insertSort'} \text{ xs} & = \text{foldr } f \text{ b } \text{xs} \\
\text{where} & \\
\text{f} & = \text{undefined} \quad \text{-- Fill this in} \\
\text{b} & = \text{undefined} \quad \text{-- Fill this in}
\end{align*}
\]

**Merge Sort** Similarly, it is easy to write merge sort, by implementing the three steps. First, we write a function that splits the input into two equal sized halves:

\[
\begin{align*}
\text{split} & :: [a] \rightarrow ([a], [a]) \\
\text{split } (x:y:zs) & = (x:xs, y:ys) \\
\text{where} & \\
\text{xs, ys} & = \text{split } zs \\
\text{split } \text{xs} & = (\text{xs, []})
\end{align*}
\]

Second, we need a function that combines two ordered lists
merge :: (Ord a) => IncList a -> IncList a -> IncList a
merge xs Emp = xs
merge Emp ys = ys
merge (x :< xs) (y :< ys)
  | x <= y = x :< merge xs (y :< ys)
  | otherwise = y :< merge (x :< xs) ys
merge _ _ = Emp

Finally, we compose the above steps to divide (i.e. split) and conquer (sort and merge) the input list:

mergeSort :: (Ord a) => [a] -> IncList a
mergeSort [] = Emp
mergeSort [x] = x :< Emp
mergeSort xs = merge (mergeSort ys) (mergeSort zs)
  where
    (ys, zs) = split xs

Exercise 5.4 (QuickSort). ** Why is the following implementation of quickSort rejected by LiquidHaskell? Modify it so it is accepted.

Hint: Think about how append should behave so that the quickSort has the desired property. That is, suppose that ys and zs are already in increasing order. Does that mean that append x ys zs are also in increasing order? No! What other requirement do you need? bottle that intuition into a suitable specification for append and then ensure that the code satisfies that specification.

quickSort :: (Ord a) => [a] -> IncList a
quickSort [] = Emp
quickSort (x:xs) = append x lessers greaters
  where
    lessers = quickSort [y | y <- xs, y < x ]
    greaters = quickSort [z | z <- xs, z >= x]

{-# append :: x:a -> IncList a
  -> IncList a
  -> IncList a
-}
**Ordered Trees**

As a last example of refined data types, let us consider binary search ordered trees, defined thus:

```haskell
data BST a = Leaf
           | Node { root :: a,
                  left :: BST a,
                  right :: BST a }
```

**Binary Search Trees**

enjoy the property that each root lies (strictly) between the elements belonging in the left and right subtrees hanging off the root. The ordering invariant makes it easy to check whether a certain value occurs in the tree. If the tree is empty i.e. a Leaf, then the value does not occur in the tree. If the given value is at the root then the value does occur in the tree. If it is less than (respectively greater than) the root, we recursively check whether the value occurs in the left (respectively right) subtree.

Figure 5.1 shows a binary search tree whose nodes are labeled with a subset of values from 1 to 9. We might represent such a tree with the Haskell value:

```haskell
okBST :: BST Int
okBST = Node 6
       (Node 2
        (Node 1 Leaf Leaf))
       (Node 4 Leaf Leaf))
       (Node 9
        (Node 7 Leaf Leaf)
        Leaf)
```

**Refined Data Type** The Haskell type says nothing about the ordering invariant, and hence, cannot prevent us from creating illegal BST values that violate the invariant. We can remedy this with a refined data definition that captures the invariant. The aliases BSTL and BSTR denote BSTs with values less than and greater than some X, respectively.

```haskell
{-# data BST a = Leaf
       | Node { root :: a,
              left :: BSTL a root
```
Refined Data Constructors As before, the above data definition creates a refined smart constructor for BST

data BST a where
  Leaf :: BST a
  Node :: r:a -> BST {v:a | v < r}
    -> BST {v:a | r < v}
    -> BST a

which prevents us from creating illegal trees

badBST =  Node 66
  (Node 4
    (Node 1 Leaf Leaf)
    (Node 69 Leaf Leaf)) -- Out of order, rejected
  (Node 99
    (Node 77 Leaf Leaf)
    Leaf)

Exercise 5.5 (Duplicates). Can a BST Int contain duplicates?

Membership

  Let’s write some functions to create and manipulate these trees.
  First, a function to check whether a value is in a BST:

mem :: (Ord a) => a -> BST a -> Bool
mem _ Leaf = False
mem k (Node k' l r)
  | k == k' = True
  | k < k'  = mem k l
  | otherwise = mem k r

Singleton Next, another easy warm-up: a function to create a BST with a single given element:
**Insertion** Let’s write a function that adds an element to a BST.\(^4\)

\[
\text{add} :: (\text{Ord } a) \Rightarrow a \rightarrow \text{BST } a \rightarrow \text{BST } a
\]

\[
\begin{align*}
\text{add } k' \text{ Leaf} &= \text{one } k' \\
\text{add } k' \text{ t@(Node } k \text{ l r)} &= \begin{cases} 
\text{Node } k \text{ (add } k' \text{ l) r} & \text{if } k' < k \\
\text{Node } k \text{ l (add } k' \text{ r)} & \text{if } k < k' \\
\text{t} & \text{otherwise}
\end{cases}
\end{align*}
\]

**Minimum** For our next trick, let’s write a function to delete the minimum element from a BST. This function will return a pair of outputs – the smallest element and the remainder of the tree. We can say that the output element is indeed the smallest, by saying that the remainder’s elements exceed the element. To this end, let’s define a helper type: \(^5\)

\[
\text{data MinPair } a = \text{MP } \{ \text{mElt} :: a, \text{rest} :: \text{BST } a \}
\]

We can specify that \text{mElt} is indeed smaller than all the elements in \text{rest} via the data type refinement:

\[
\{-@ \text{data MinPair } a = \text{MP } \{ \text{mElt} :: a, \text{rest} :: \text{BST } a \text{mElt} \} @-\}
\]

Finally, we can write the code to compute \text{MinPair}.

\[
\begin{align*}
\text{delMin} :: (\text{Ord } a) \Rightarrow \text{BST } a \rightarrow \text{MinPair } a \\
\text{delMin } \text{(Node } k \text{ Leaf } r) &= \text{MP } k \text{ r} \\
\text{delMin } \text{(Node } k \text{ l r)} &= \text{MP } k' \text{ (Node } k \text{ l' r)} \\
\text{where} & \text{MP } k' \text{ l'} \text{ = delMin } l \\
\text{delMin } \text{Leaf} &= \text{die } "\text{Don't say I didn't warn ya!}" \\
\end{align*}
\]

**Exercise 5.6** (Delete). Use \text{delMin} to complete the implementation of \text{del} which deletes a given element from a BST, if it is present.

\[
\begin{align*}
\text{del} :: (\text{Ord } a) \Rightarrow a \rightarrow \text{BST } a \rightarrow \text{BST } a \\
\text{del } k' \text{ t@(Node } k \text{ l r)} &= \text{undefined} \\
\text{del } \_ \text{ Leaf} &= \text{Leaf}
\end{align*}
\]
Exercise 5.7 (Safely Deleting Minimum). The function \( \text{delMin} \) is only sensible for non-empty trees. Read ahead to learn how to specify and verify that it is only called with such trees, and then apply that technique here to verify the call to die in \( \text{delMin} \).

Exercise 5.8 (BST Sort). Complete the implementation of \( \text{toIncList} \) to obtain a BST based sorting routine \( \text{bstSort} \).

\[
\begin{align*}
\text{bstSort} &: (\text{Ord} \ a) \Rightarrow [a] \rightarrow \text{IncList} \ a \\
\text{bstSort} &= \text{toIncList} \ . \ \text{toBST} \\
\text{toBST} &: (\text{Ord} \ a) \Rightarrow [a] \rightarrow \text{BST} \ a \\
\text{toBST} &= \text{foldr} \ \text{add} \ \text{Leaf} \\
\text{toIncList} &: \text{BST} \ a \rightarrow \text{IncList} \ a \\
\text{toIncList} (\text{Node} \ x \ l \ r) &= \text{undefined} \\
\text{toIncList} \ \text{Leaf} &= \text{undefined}
\end{align*}
\]

Hint: This exercise will be a lot easier after you finish the quickSort exercise. Note that the signature for \( \text{toIncList} \) does not use \text{Ord} and so you cannot (and need not) use a sorting procedure to implement it.

Recap

In this chapter we saw how LiquidHaskell lets you refine data type definitions to capture sophisticated invariants. These definitions are internally represented by refining the types of the data constructors, automatically making them “smart” in that they preclude the creation of illegal values that violate the invariants. We will see much more of this handy technique in future chapters.

One recurring theme in this chapter was that we had to create new versions of standard datatypes, just in order to specify certain invariants. For example, we had to write a special list type, with its own copies of nil and cons. Similarly, to implement \( \text{delMin} \) we had to create our own pair type.

This duplication of types is quite tedious. There should be a way to just slap the desired invariants on to \text{existing} types, thereby facilitating their reuse. In a few chapters, we will see how to achieve this reuse by abstracting refinements from the definitions of datatypes or functions in the same way we abstract the element type \( a \) from containers like \([a]\) or \( \text{BST} \ a \).
Boolean Measures

In the last two chapters, we saw how refinements could be used to reason about the properties of basic Int values like vector indices, or the elements of a list. Next, let's see how we can describe properties of aggregate structures like lists and trees, and use these properties to improve the APIs for operating over such structures.

Partial Functions

As a motivating example, let us return to the problem of ensuring the safety of division. Recall that we wrote:

```haskell
{-@ divide :: Int -> NonZero -> Int @-}
divide _ 0 = die "divide-by-zero"
divide x n = x `div` n
```

The Precondition asserted by the input type NonZero allows LiquidHaskell to prove that the die is never executed at run-time, but consequently, requires us to establish that wherever divide is used, the second parameter be provably non-zero. This requirement is not onerous when we know what the divisor is statically.

```haskell
avg2 x y = divide (x + y) 2
avg3 x y z = divide (x + y + z) 3
```

However, it can be more of a challenge when the divisor is obtained dynamically. For example, let’s write a function to find the number of elements in a list.
and use it to compute the average value of a list:

\[
\text{avgMany } xs = \frac{\text{total}}{\text{elems}}
\]

\[
\text{where}
\]

\[
\text{total} = \text{sum } xs
\]

\[
\text{elems} = \text{size } xs
\]

Uh oh. LiquidHaskell wags its finger at us!

```
src/04-measure.lhs:77:27-31: Error: Liquid Type Mismatch
Inferred type
  VV : Int | VV == elems

not a subtype of Required type
  VV : Int | 0 /= VV

In Context
  VV : Int | VV == elems
  elems : Int
```

We cannot prove that the divisor is NonZero, because it can be 0 – when the list is empty. Thus, we need a way of specifying that the input to `avgMany` is indeed non-empty!

**Lifting Functions to Measures**

How shall we tell LiquidHaskell that a list is non-empty? Recall the notion of measure previously introduced to describe the size of a `Data.Vector`. In that spirit, let’s write a function that computes whether a list is not empty:

\[
\text{notEmpty} :: [a] \to \text{Bool}
\]

\[
\text{notEmpty } [] = \text{False}
\]

\[
\text{notEmpty } (_:\_ :_) = \text{True}
\]

A measure is a total Haskell function,
1. With a *single* equation per data constructor, and

2. Guaranteed to *terminate*, typically via structural recursion.

We can tell LiquidHaskell to *lift* a function meeting the above requirements into the refinement logic by declaring:

```
{-@ measure notEmpty @-}
```

**Non-Empty Lists** can now be described as the *subset* of plain old Haskell lists \([a]\) for which the predicate `notEmpty` holds

```
{-@ type NEList a = {v:[a] | notEmpty v} @-}
```

We can now refine various signatures to establish the safety of the list-average function.

`Size` returns a non-zero value if the input list is not-empty. We capture this condition with an *implication* in the output refinement.

```
{-@ size :: xs:[a] -> {v:Nat | notEmpty xs => v > 0} @-}
```

`Average` is only sensible for non-empty lists. Happily, we can specify this using the refined `NEList` type:

```
{-@ average :: NEList Int -> Int @-}
average xs = divide total elems
  where
    total  = sum xs
    elems  = size xs
```

**Exercise 6.1** (Average, Maybe). Fix the code below to obtain an alternate variant `average'` that returns `Nothing` for empty lists:

```
average' :: [Int] -> Maybe Int
average' xs
 | ok         = Just $ divide (sum xs) elems
 | otherwise  = Nothing
  where
    elems   = size xs
    ok      = True  -- What expression goes here?
```
Exercise 6.2 (Debugging Specifications). An important aspect of formal verifiers like LiquidHaskell is that they help establish properties not just of your implementations but equally, or more importantly, of your specifications. In that spirit, can you explain why the following two variants of size are rejected by LiquidHaskell?

{-@ size1 :: xs:NEList a -> Pos @-}
size1 [] = 0
size1 (_:xs) = 1 + size1 xs

{-@ size2 :: xs:[a] -> {v:Int | notEmpty xs => v > 0} @-}
size2 [] = 0
size2 (_:xs) = 1 + size2 xs

A Safe List API

Now that we can talk about non-empty lists, we can ensure the safety of various list-manipulating functions which are only well-defined on non-empty lists and crash otherwise.

Head and Tail are two of the canonical dangerous functions, that only work on non-empty lists, and burn horribly otherwise. We can type them simple as:

{-@ head :: NEList a -> a @-}
head (x:_:_ = x
head [] = die "Fear not! 'twill ne'er come to pass"

{-@ tail :: NEList a -> [a] @-}
tail (_:xs) = xs
tail [] = die "Relaxeth! this too shall ne'er be"

LiquidHaskell uses the precondition to deduce that the second equations are dead code. Of course, this requires us to establish that callers of head and tail only invoke the respective functions with non-empty lists.

Exercise 6.3 (Safe Head). Write down a specification for null such that safeHead is verified. Do not force null to only take non-empty inputs, that defeats the purpose. Instead, its type should say that it works on all lists and returns False if and only if the input is non-empty.

Hint: You may want to refresh your memory about implies => and <= from the chapter on logic.
Groups

Let's use the above to write a function that chunks sequences into non-empty groups of equal elements:

```haskell
{-@ groupEq :: (Eq a) => [a] -> [NEList a] @-}
groupEq [] = []
groupEq (x:xs) = (x:ys) : groupEq zs
  where
    (ys, zs) = span (x ==) xs
```

By using the fact that each element in the output returned by `groupEq` is in fact of the form `x:ys`, LiquidHaskell infers that `groupEq` returns a `[NEList a]` that is, a list of **non-empty lists**.

To **Eliminate Stuttering** from a string, we can use `groupEq` to split the string into blocks of repeating `Char`s, and then just extract the first `Char` from each block:

```haskell
-- >>> eliminateStutter "ssstringssss liiiiiike thisss"
-- "strings like this"
eliminateStutter xs = map head $ groupEq xs
```

LiquidHaskell automatically instantiates the type parameter for `map` in `eliminateStutter` to `notEmpty v` to deduce that `head` is only called on non-empty lists.

**Foldl1** is one of my favorite folds; it uses the first element of the sequence as the initial value. Of course, it should only be called with non-empty sequences!

```haskell
{-@ foldl1 :: (a -> a -> a) -> NEList a -> a @-}
foldl1 f (x:xs) = foldl f x xs
foldl1 _ [] = die "foldl1!"
```
foldl :: (a -> b -> a) -> a -> [b] -> a
foldl _ acc [] = acc
foldl f acc (x:xs) = foldl f (f acc x) xs

To 

To Sum a non-empty list of numbers, we can just perform a foldl1 with the + operator: Thanks to the precondition, LiquidHaskell will prove that the die code is indeed dead. Thus, we can write

{-@ sum :: (Num a) => NEList a -> a @-}
sum [] = die "cannot add up empty list"
sum xs = foldl1 (+) xs

Consequently, we can only invoke sum on non-empty lists, so:

sumOk = sum [1,2,3,4,5] -- is accepted by LH, but
sumBad = sum [] -- is rejected by LH

Exercise 6.4 (Weighted Average). The function below computes a weighted average of its input. Unfortunately, LiquidHaskell is not very happy about it. Can you figure out why, and fix the code or specification appropriately?

{-@ wtAverage :: NEList (Pos, Pos) -> Int @-}
wtAverage wxs = divide totElems totWeight
  where
elems = map (\(w, x) -> w * x) wxs
weights = map (\(w, _) -> w ) wxs
totElems = sum elems
totWeight = sum weights
sum = foldl1 (+)

map :: (a -> b) -> [a] -> [b]
map _ [] = []
map f (x:xs) = f x : map f xs

Hint: On what variables are the errors? How are those variables’ values computed? Can you think of a better specification for the function(s) doing those computations?

Exercise 6.5 (Mitchell’s Risers). Non-empty lists pop up in many places, and it is rather convenient to have the type system track non-emptiness without having to make up special types. Consider the risers function, popularized by Neil Mitchell. safeSplit requires its input be non-empty;
but LiquidHaskell believes that the call inside *risers* fails this requirement.

*Fix the specification for *risers* so that it is verified.*

```haskell
{-# risers :: (Ord a) => [a] -> [[a]] #-}
risers :: (Ord a) => [a] -> [[a]]
risers [] = []
risers [x] = [[x]]
risers (x:y:etc) |
| x <= y = (x:s) : ss |
| otherwise = [x] : (s : ss)
where
  (s, ss) = safeSplit $ risers (y:etc)
```

```haskell
{-# safeSplit :: NEList a -> (a, [a]) #-}
safeSplit (x:xs) = (x, xs)
safeSplit _ = die "don't worry, be happy"
```

**Recap**

In this chapter we saw how LiquidHaskell lets you

1. **Define** structural properties of data types,

2. **Use refinements** over these properties to describe key invariants that establish, at compile-time, the safety of operations that might otherwise fail on unexpected values at run-time, all while,

3. **Working with plain Haskell types**, here, Lists, without having to make up new types which can have the unfortunate effect of adding a multitude of constructors and conversions which often clutter implementations and specifications.

Of course, we can do a lot more with measures, so let’s press on!
Many of the programs we have seen so far, for example those in here, suffer from *indexitis*. This is a term coined by Richard Bird which describes a tendency to perform low-level manipulations to iterate over the indices into a collection, opening the door to various off-by-one errors. Such errors can be eliminated by instead programming at a higher level, using a *wholemeal approach* where the emphasis is on using aggregate operations, like `map`, `fold` and `reduce`.

*Wholemeal programming is no panacea* as it still requires us to take care when operating on different collections; if these collections are *incompatible*, e.g. have the wrong dimensions, then we end up with a fate worse than a crash, a possibly meaningless result. Fortunately, LiquidHaskell can help. Let’s see how we can use measures to specify dimensions and create a dimension-aware API for lists which can be used to implement wholemeal dimension-safe APIs.¹

### Wholemeal Programming

Indexitis begone! As an example of wholemeal programming, let’s write a small library that represents vectors as lists and matrices as nested vectors:

```haskell
data Vector a = V { vDim :: Int
                   , vElts :: [a]
               }
               deriving (Eq)

data Matrix a = M { mRow :: Int
                   , mCol :: Int
               }
```

¹ In a later chapter we will use this API to implement K-means clustering.
The Dot Product of two Vectors can be easily computed using a fold:

```haskell
dotProd :: (Num a) => Vector a -> Vector a -> a
dotProd vx vy = sum (prod xs ys)
  where
    prod = zipWith (\x y -> x * y)
    xs = vElts vx
    ys = vElts vy
```

Matrix Multiplication can similarly be expressed in a high-level, wholemeal fashion, by eschewing low level index manipulations in favor of a high-level iterator over the Matrix elements:

```haskell
matProd :: (Num a) => Matrix a -> Matrix a -> Matrix a
matProd (M rx _ xs) (M _ cy ys) = M rx cy elts
  where
    elts = for xs (\xi ->
               for ys (\yj ->
                     dotProd xi yj
                  )
               )
```

The Iteration embodied by the for combinator, is simply a map over the elements of the vector.

```haskell
for :: Vector a -> (a -> b) -> Vector b
for (V n xs) f = V n (map f xs)
```

Wholemeal programming frees us from having to fret about low-level index range manipulation, but is hardly a panacea. Instead, we must now think carefully about the compatibility of the various aggregates. For example,

- dotProd is only sensible on vectors of the same dimension; if one vector is shorter than another (i.e. has fewer elements) then we
will won’t get a run-time crash but instead will get some gibberish result that will be dreadfully hard to debug.

• \texttt{matProd} is only well defined on matrices of compatible dimensions; the number of columns of \( \mathbf{m} \) must equal the number of rows of \( \mathbf{y} \). Otherwise, again, rather than an error, we will get the wrong output.\footnote{In fact, while the implementation of \texttt{matProd} breezes past \texttt{GHC} it is quite wrong!}

\section*{Specifying List Dimensions}

In order to start reasoning about dimensions, we need a way to represent the \textit{dimension} of a list inside the refinement logic. \footnote{We could just use \texttt{vDim}, but that is a cheat as there is no guarantee that the field’s value actually equals the size of the list!}

\textbf{Measures} are ideal for this task. \textbf{Previously} we saw how we could lift Haskell functions up to the refinement logic. Lets write a measure to describe the length of a list: \footnote{Recall that these must be inductively defined functions, with a single equation per data-creator}

\begin{verbatim}
{-@ measure size @-}
{-@ size :: [a] -> Nat @-}
size []     = 0
size (_:rs) = 1 + size rs
\end{verbatim}

\textbf{Measures Refine Constructors}

As with \textit{refined data definitions}, the measures are translated into strengthened types for the type’s constructors. For example, the size measure is translated into:

\begin{verbatim}
data [a] where
  []    :: \{v: [a] | size v = 0\}
  (_:) :: a -> xs:[a] -> \{v:[a]|size v = 1 + size xs\}
\end{verbatim}

\textbf{Multiple Measures} may be defined for the same data type. For example, in addition to the size measure, we can define a \texttt{notEmpty} measure for the list type:

\begin{verbatim}
{-@ measure notEmpty @-}
notEmpty :: [a] -> Bool
notEmpty []     = False
notEmpty (_:_)= True
\end{verbatim}

\textbf{We Compose Different Measures}
simply by conjoining the refinements in the strengthened constructors. For example, the two measures for lists end up yielding the constructors:

```haskell
data [a] where
  [] :: {v: [a] | not (notEmpty v) && size v = 0}
  (:) :: a
    -> xs:[a]
    -> {v:[a] | notEmpty v && size v = 1 + size xs}
```

This is a very significant advantage of using measures instead of indices as in DML or Agda, as decouples property from structure, which crucially enables the use of the same structure for many different purposes. That is, we need not know a priori what indices to bake into the structure, but can define a generic structure and refine it a posteriori as needed with new measures.

We are almost ready to begin creating a dimension aware API for lists; one last thing that is useful is a couple of aliases for describing lists of a given dimension.

To make signatures symmetric let’s define an alias for plain old (unrefined) lists:

```haskell
type List a = [a]
```

A ListN is a list with exactly N elements, and a ListX is a list whose size is the same as another list X. Note that when defining refinement type aliases, we use uppercase variables like $N$ and $X$ to distinguish value parameters from the lowercase type parameters like $a$.

```haskell
{-@ type ListN a N = {v:List a | size v = N} @-}
{-@ type ListX a X = ListN a {size X} @-}
```

Lists: Size Preserving API

With the types and aliases firmly in our pockets, let us write dimension-aware variants of the usual list functions. The implementations are the same as in the standard library i.e. `Data.List`, but the specifications are enriched with dimension information.

**Exercise 7.1** (Map). MAP yields a list with the same size as the input. Fix the specification of map so that the prop_map is verified.
Exercise 7.2 (Reverse). \* We can reverse the elements of a list as shown below, using the tail recursive function \texttt{go}. Fix the signature for \texttt{go} so that LiquidHaskell can prove the specification for \texttt{reverse}.

\textit{Hint:} How big is the list returned by \texttt{go}?

\[
{-@ reverse :: xs:List a -> ListX a xs @}\]
\[
\text{reverse } xs = \text{go } [] \text{ } xs
\]
\[\text{where}\]
\[
\text{go } \text{acc } [] = \text{acc}
\]
\[
\text{go } \text{acc } (x:xs) = \text{go } (x:\text{acc}) \text{ } xs
\]

\texttt{\texttt{zipWith}} requires both lists to have the \textit{same} size, and produces a list with that same size. 5

\[
{-@ zipWith :: (a -> b -> c) -> xs:List a -> ListX b xs -> ListX c xs @}\]
\[
\text{zipWith } f (a:as) (b:bs) = f \text{ } a \text{ } b \text{ } : \text{zipWith } f \text{ } as \text{ } bs
\]
\[
\text{zipWith } _ [ ] [ ] = [ ]
\]
\[
\text{zipWith } _ _ _ = \text{die } "\text{no other cases}"
\]

\texttt{\texttt{unsafeZip}} The signature for \texttt{zipWith} is quite severe – it rules out the case where the zipping occurs only up to the shorter input. Here’s a function that actually allows for that case, where the output type is the \textit{shorter} of the two inputs:

\[
{-@ zip :: as:[a] -> bs:[b] -> \{v:[(a,b)] \mid \text{Tinier } v \text{ as bs}\} @}\]
\[
\text{zip } (a:as) (b:bs) = (a, b) \text{ } : \text{zip } as \text{ } bs
\]
\[
\text{zip } [] _ = [ ]
\]
\[
\text{zip } _ [] = [ ]
\]

The output type uses the predicate \texttt{Tinier} \texttt{Xs Ys Zs} which defines the length of \texttt{Xs} to be the smaller of that of \texttt{Ys} and \texttt{Zs}. 6

\[\text{5 As made explicit by the call to die, the input type rules out the case where one list is empty and the other is not, as in that case the former’s length is zero while the latter’s is not, and hence, different.}\]

\[\text{6 In logic, if } p \text{ then } q \text{ else } r \text{ is the same as } p \Rightarrow q \&\& \text{ not } p \Rightarrow r.\]
Exercise 7.3 (Zip Unless Empty). ** In my experience, zip as shown above is far too permissive and lets all sorts of bugs into my code. As middle ground, consider zipOrNull below. Write a specification for zipOrNull such that the code below is verified by LiquidHaskell.

```haskell
zipOrNull :: [a] -> [b] -> [(a, b)]
zipOrNull [] _ = []
zipOrNull _ [] = []
zipOrNull xs ys = zipWith (,) xs ys

{-@ test1 :: {v: _ | size v = 2} @-}
test1 = zipOrNull [0, 1] [True, False]

{-@ test2 :: {v: _ | size v = 0} @-}
test2 = zipOrNull [] [True, False]

{-@ test3 :: {v: _ | size v = 0} @-}
test3 = zipOrNull ["cat", "dog"] []
```

*Hint*: Yes, the type is rather gross; it uses a bunch of disjunctions ||, conjunctions && and implications =>.

### Lists: Size Reducing API

Next, let’s look at some functions that truncate lists, in one way or another.

**Take** lets us grab the first \(k\) elements from a list:

```haskell
{-@ take' :: n:Nat -> ListGE a n -> ListN a n @-}
take' 0 _ = []
take' n (x:xs) = x : take' (n-1) xs
take' _ _ = die "won't happen"
```

The alias `ListGE a n` denotes lists whose length is at least \(n\):

```haskell
{-@ type ListGE a N = {v:List a | N <= size v} @-}
```

Exercise 7.4 (Drop). **Drop** is the yang to take’s yin: it returns the remainder after extracting the first \(k\) elements. Write a suitable specification for it so that the below typechecks.
drop 0 xs = xs
drop n (_:xs) = drop (n-1) xs
drop _ _ = die "won't happen"

{-@ test4 :: ListN String 2 @-}
test4 = drop 1 ["cat", "dog", "mouse"]

Exercise 7.5 (Take it easy). The version take' above is too restrictive; it insists that the list actually have at least n elements. Modify the signature for the real take function so that the code below is accepted by LiquidHaskell.

take 0 _ = []
take _ [] = []
take n (x:xs) = x : take (n-1) xs

{-@ test5 :: [ListN String 2] @-}
test5 = [ take 2 ["cat", "dog", "mouse"]
    , take 20 ["cow", "goat"] ]

The Partition function breaks a list into two sub-lists of elements that either satisfy or fail a user supplied predicate.

partition :: (a -> Bool) -> [a] -> ([a], [a])
policy _ [] = ([], [])
policy f (x:xs)
    | f x = (x:ys, zs)
    | otherwise = (ys, x:zs)
where
    (ys, zs) = partition f xs

We would like to specify that the sum of the output tuple’s dimensions equal the input list’s dimension. Lets write measures to access the elements of the output:

{-@ measure fst @-}
fst (x, _) = x

{-@ measure snd @-}
snd (_, y) = y

We can now refine the type of partition as:
{-@ partition :: _ -> xs:_ -> {v:_ | Sum2 v (size xs)} @-}\[\]

where \(\text{Sum2} \ V \ N\) holds for a pair of lists dimensions add to \(N\):

{-@ predicate Sum2 X N = size (fst X) + size (snd X) = N @-}\[\]

**Exercise 7.6** (QuickSort). *Use partition to implement quickSort.*

```haskell
-- >> quickSort [1,4,3,2]
-- [1,2,3,4]

{-@ quickSort :: (Ord a) => xs:List a -> ListX a xs @-}\[\]
quickSort [] = []
quickSort (x:xs) = undefined

{-@ test10 :: ListN String 2 @-}\[\]
test10 = quickSort (drop 1 ["cat", "dog", "mouse"])
```

**Dimension Safe Vector API**

We can use the dimension aware lists to create a safe vector API.

**Legal Vectors** are those whose \(v\text{dim}\) field actually equals the size of the underlying list:

{-@ data Vector a = V { vDim :: Nat
, vElts :: ListN a vDim } @-}\[\]

When \(v\text{dim}\) is used a selector function, it returns the \(v\text{dim}\) field of \(x\).

{-@ vDim :: x:_ -> {v: Nat | v = vDim x} @-}\[\]

The refined data type prevents the creation of illegal vectors:

okVec = V 2 [10, 20] -- accepted by LH
badVec = V 2 [10, 20, 30] -- rejected by LH

As usual, it will be handy to have a few aliases.
To create a Vector safely, we can start with the empty vector \(v_{\text{Emp}}\) and then add elements one-by-one with \(v_{\text{Cons}}\):

\[
\begin{align*}
\text{vEmp} &:: \text{VectorN } a \ 0 \\
\text{vEmp} & = V\ 0\ []
\end{align*}
\]

\[
\begin{align*}
\text{vCons} &:: a \to x:\text{Vector } a \to \text{VectorN } a\ {v\text{Dim}\ x + 1} \\
v\text{Cons} \ x\ (V\ n\ xs) & = V\ (n^1)\ (x:xs)
\end{align*}
\]

To access vectors at a low-level, we can use equivalents of head and tail, which only work on non-empty Vectors:

\[
\begin{align*}
\text{vHd} &:: \text{VectorNE } a \to a \\
v\text{Hd}\ (V\ _\ (x:_)) & = x \\
v\text{Hd}\ _ & = \text{die} \ "\text{nope}"
\end{align*}
\]

\[
\begin{align*}
\text{vTl} &:: x:\text{VectorNE } a \to \text{VectorN } a\ {v\text{Dim}\ x - 1} \\
v\text{Tl}\ (V\ n\ (_:xs)) & = V\ (n^-1)\ xs \\
v\text{Tl}\ _ & = \text{die} \ "\text{nope}"
\end{align*}
\]

To iterate over a vector we can use the for combinator:

\[
\begin{align*}
\text{for} &:: x:\text{Vector } a \to (a \to b) \to \text{VectorX } b\ x \\
\text{for}\ (V\ n\ xs)\ f & = V\ n\ (\text{map}\ f\ xs)
\end{align*}
\]

Binary pointwise operations should only be applied to compatible vectors, i.e. vectors with equal dimensions. We can write a generic binary pointwise operator:

\[
\begin{align*}
\text{vBin} &:: (a \to b \to c) \to x:\text{Vector } a\ \to\ \text{VectorX } b\ x\ \to\ \text{VectorX } c\ x
\end{align*}
\]
The Dot Product of two vectors can be now implemented in a wholemeal and dimension safe manner, as:

{-@ dotProduct :: (Num a) => x:Vector a -> VectorX a x -> a @-}
dotProduct x y = sum $ vElts $ vBin (*) x y

Exercise 7.7 (Vector Constructor). Complete the specification and implementation of vecFromList which creates a Vector from a plain list.

vecFromList :: [a] -> Vector a
vecFromList xs = undefined

test6 = dotProduct vx vy -- should be accepted by LH
  where
    vx = vecFromList [1,2,3]
    vy = vecFromList [4,5,6]

Exercise 7.8 (Flatten). Write a function to flatten a nested Vector.

{-@ flatten :: n:Nat
    -> m:Nat
    -> VectorN (VectorN a m) n
    -> VectorN a {m * n}
    @-}
flatten = undefined

The Cross Product of two vectors can now be computed in a nice wholemeal style, by a nested iteration followed by a flatten.

{-@ product :: xs:Vector _
    -> ys:Vector _
    -> VectorN _ {vDim xs * vDim ys}
    @-}
product xs ys = flatten (vDim ys) (vDim xs) xys
  where
    xys = for ys $ \y ->
      for xs $ \x ->
        x * y
Dimension Safe Matrix API

The same methods let us create a dimension safe Matrix API which ensures that only legal matrices are created and that operations are performed on compatible matrices.

Legal Matrices are those where the dimension of the outer vector equals the number of rows \( m\text{Row} \) and the dimension of each inner vector is \( m\text{Col} \). We can specify legality in a refined data definition:

```haskell
{-@ data Matrix a =
    M { mRow :: Pos
        , mCol :: Pos
        , mElts :: VectorN (VectorN a mCol) mRow
    }
     @-}
```

Notice that we avoid disallow degenerate matrices by requiring the dimensions to be positive.

```haskell
{-@ type Pos = {v:Int | 0 < v} @-}
```

It is convenient to have an alias for matrices of a given size:

```haskell
{-@ type MatrixN a R C = {v:Matrix a | Dims v R C } @-}
{-@ predicate Dims M R C = mRow M = R && mCol M = C @-}
```

For example, we can use the above to write type:

```haskell
{-@ ok23 :: MatrixN _ 2 3 @-}
ok23 = M 2 3 (V 2 [ V 3 [1, 2], V 3 [4, 5, 6] ])
```

Exercise 7.9 (Legal Matrix). Modify the definitions of \textit{bad1} and \textit{bad2} so that they are legal matrices accepted by LiquidHaskell.

```haskell
bad1 :: Matrix Int
bad1 = M 2 3 (V 2 [ V 3 [1, 2], V 3 [4, 5, 6]])
```

```haskell
bad2 :: Matrix Int
bad2 = M 2 3 (V 2 [ V 2 [1, 2], V 2 [4, 5] ])
```
Exercise 7.10 (Matrix Constructor). * Write a function to construct a Matrix from a nested list.

```haskell
matFromList :: [[a]] -> Maybe (Matrix a)
matFromList []     = Nothing
matFromList xs@(xs:_)
    | ok        = Just (M r c vs)
    | otherwise = Nothing
    where
        r = size xs
        c = size xss
        ok = undefined
        vs = undefined
```

Exercise 7.11 (Refined Matrix Constructor). ** Refine the specification for matFromList so that the following is accepted by LiquidHaskell.

```haskell
{-# mat23 :: Maybe (MatrixN Integer 2 2) @-}
mat23    = matFromList [[1, 2], [3, 4]]
```

*Hint:* It is easy to specify the number of rows from xss. How will you figure out the number of columns? A measure may be useful.

Matrix Multiplication Finally, let’s implement matrix multiplication. You’d think we did it already, but in fact the implementation at the top of this chapter is all wrong (run it and see!) We cannot just multiply any two matrices: the number of columns of the first must equal to the rows of the second – after which point the result comprises the dotProduct of the rows of the first matrix with the columns of the second.

```haskell
{-# matProduct :: (Num a) => x:Matrix a -> y:(Matrix a | mCol x = mRow y) -> MatrixN a (mRow x) (mCol y) @-}
matProduct (M rx _ xs) my@(M _ cy _)
    = M rx cy elts
    where
        elts = for xs (\xi ->
                           for ys' (\yj ->
                                 dotProduct xi yj ))
```
To iterate over the *columns* of the matrix `my` we just transpose it so the columns become rows.

```haskell
-- >>> ok32 == transpose ok23
-- True
ok32 = M 3 2 (V 3 [ V 2 [1, 4] ], V 2 [2, 5], V 2 [3, 6])
```

**Exercise 7.12 (Matrix Transpose).** ★★ *Use the Vector API to complete the implementation of `txgo`. For inspiration, you might look at the implementation of `Data.List.transpose` from the prelude. Better still, don’t.*

```haskell
{-@ transpose :: m:Matrix a -> MatrixN a (mCol m) (mRow m) @-}
transpose (M r c rows) = M c r $ txgo c r rows

{-@ txgo :: c:Nat -> r:Nat
         -> VectorN (VectorN a c) r
         -> VectorN (VectorN a r) c
         @-}
txgo c r rows = undefined
```

*Hint:* As shown by `ok23` and `ok32`, transpose works by stripping out the heads of the input rows, to create the corresponding output rows.

**Recap**

In this chapter, we saw how to use measures to describe numeric properties of structures like lists (`Vector`) and nested lists (`Matrix`).

1. Measures are *structurally recursive* functions, with a single equation per data constructor,

2. Measures can be used to create refined data definitions that prevent the creation of illegal values,

3. Measures can then be used to enable safe wholemeal programming, via dimension-aware APIs that ensure that operators only apply to compatible values.

We can use numeric measures to encode various other properties of data structures. We will see examples ranging from high-level AVL trees, to low-level safe pointer arithmetic.
Elemental Measures

Often, correctness requires us to reason about the set of elements represented inside a data structure, or manipulated by a function. Examples of this abound: for example, we’d like to know that:

- **sorting** routines return permutations of their inputs – i.e. return collections whose elements are the same as the input set,
- **resource** management functions do not inadvertently create duplicate elements or drop elements from set of tracked resources.
- **syntax-tree** manipulating procedures create well-scoped trees where the set of used variables are contained within the set of variables previously defined.

SMT Solvers support very expressive logics. In addition to linear arithmetic and uninterpreted functions, they can efficiently decide formulas over sets. Next, let’s see how LiquidHaskell lets us exploit this fact to develop types and interfaces that guarantee invariants over the set of elements of a structures.

Talking about Sets

First, we need a way to talk about sets in the refinement logic. We could roll our own special Haskell type but for now, let’s just use the `Set` a type from the prelude’s `Data.Set`.

LiquidHaskell Lifts the basic set operators from `Data.Set` into the refinement logic. That is, the prelude defines the following logical functions that correspond to the Haskell functions of the same name:

1 See this for a brief description of how to work directly with the set operators natively supported by LiquidHaskell.
### Interpreted Operators

The above operators are *interpreted* by the SMT solver. That is, just like the SMT solver “knows”, via the axioms of the theory of arithmetic that:

\[ x = 1 + 1 \Rightarrow x = 2 \]

is a valid formula, i.e. holds for all \( x \), the solver “knows” that:

\[ x = (\text{singleton } 1) \Rightarrow y = (\text{singleton } 2) \Rightarrow x = (\text{intersection } x (\text{union } y x)) \]

This is because, the above formulas belong to a decidable Theory of Sets reduces to McCarthy’s more general Theory of Arrays. \(^2\) See this recent paper to learn how modern SMT solvers prove equalities like the above.

### Proving QuickCheck Style Properties

To get the hang of what’s going on, let’s do a few warm up exercises, using LiquidHaskell to prove various simple theorems about sets and operations over them.

We Refine The Set API to make it easy to write down theorems. That is, we give the operators in Data.Set refinement type signatures that precisely track their set-theoretic behavior:

<table>
<thead>
<tr>
<th>Measure</th>
<th>Signature</th>
</tr>
</thead>
<tbody>
<tr>
<td>empty</td>
<td>( v : \text{Set } a \mid v = \text{empty} )</td>
</tr>
<tr>
<td>member</td>
<td>( x : a \rightarrow s : \text{Set } a \rightarrow v : \text{Bool} \mid v \leftrightarrow \text{member } x s )</td>
</tr>
<tr>
<td>singleton</td>
<td>( x : a \rightarrow v : \text{Set } a \mid v = \text{singleton } x )</td>
</tr>
<tr>
<td>union</td>
<td>( x : \text{Set } a \rightarrow y : \text{Set } a \rightarrow v : \text{Set } a \mid v = \text{union } x y )</td>
</tr>
<tr>
<td>intersection</td>
<td>( x : \text{Set } a \rightarrow y : \text{Set } a )</td>
</tr>
</tbody>
</table>
We Can Assert Theorems as QuickCheck style properties, that is, as functions from arbitrary inputs to a Bool output that must always be True. Let’s define aliases for the Booleans that are always True or False.

{-@ type True = {v:Bool | v} @-}
{-@ type False = {v:Bool | not v} @-}

We can use True to state theorems. For example, the unexciting arithmetic equality above becomes:

{-@ prop_one_plus_one_eq_two :: _ -> True @-}
prop_one_plus_one_eq_two x = (x == 1 + 1) `implies` (x == 2)

Where implies is just the implication function over Bool

{-@ implies :: p:Bool -> q:Bool -> Implies p q @-}
implies False _ = True
implies _ True = True
implies _ _ = False

and Implies p q is defined as

{-@ type Implies P Q = {v: | v <-> (P => Q)} @-}

Exercise 8.1 (Bounded Addition). Write and prove a QuickCheck style theorem that: \( \forall x, y. x < 100 \land y < 100 \Rightarrow x + y < 200 \).

{-@ prop_x_y_200 :: _ -> _ -> True @-}
prop_x_y_200 x y = False -- fill in the theorem body

The Commutativity of Intersection can be easily stated and proved as a QuickCheck style theorem:

{-@ prop_intersection_comm :: _ -> _ -> True @-}
prop_intersection_comm x y
  = (x `intersection` y) == (y `intersection` x)
The Associativity of Union can similarly be confirmed:

```haskell
{-@ prop_union_assoc :: _ -> _ -> _ -> True @-}
prop_union_assoc x y z
  = (x `union` (y `union` z)) == (x `union` y) `union` z
```

The Distributivity Laws for Boolean Algebra can be verified by writing properties over the relevant operators. For example, let’s check that intersection distributes over union:

```haskell
{-@ prop_intersection_dist :: _ -> _ -> _ -> True @-}
prop_intersection_dist x y z
  = x `intersection` (y `union` z)
    ==
      (x `intersection` y) `union` (x `intersection` z)
```

Non-Theorems should be rejected. So, while we’re at it, let’s make sure LiquidHaskell doesn’t prove anything that isn’t true …

```haskell
{-@ prop_cup_dif_bad :: _ -> _ -> True @-}
prop_cup_dif_bad x y
  = pre `implies` (x == ((x `union` y) `difference` y))
  where
    pre = True -- Fix this with a non-trivial precondition
```

Exercise 8.2 (Set Difference). Why does the above property fail?

1. Use QuickCheck (or your own little grey cells) to find a counterexample for the property prop_cup_dif_bad.

2. Use the counterexample to assign pre a non-trivial (i.e. other than False) condition so that the property can be proved.

Thus, LiquidHaskell’s refined types offer a nice interface for interacting with the SMT solvers in order to prove theorems, while letting us use QuickCheck to generate counterexamples.³

³ The SBV and Leon projects describe a different DSL based approach for using SMT solvers from Haskell and Scala respectively.

Content-Aware List API

Lets return to our real goal, which is to verify properties of programs. First, we need a way to refine the list API to precisely track the set of elements in a list.
The Elements of a List can be described by a simple recursive measure that walks over the list, building up the set:

```haskell
{-# measure elts #-}
elts :: (Ord a) => [a] -> Set a
elts [] = empty
elts (x:xs) = singleton x `union` elts xs
```

Let's write a few helpful aliases for various refined lists that will then make the subsequent specifications pithy and crisp.

- A list with elements $S$

```haskell
{-# type ListS a S = {v:[a] | elts v = S} #-}
```

- An empty list

```haskell
{-# type ListEmp a = ListS a {Set_empty 0} #-}
```

- A list whose contents equal those of list $X$

```haskell
{-# type ListEq a X = ListS a {elts X} #-}
```

- A list whose contents are a subset of list $X$

```haskell
{-# type ListSub a X = {v:[a]| Set_sub (elts v) (elts X)} #-}
```

- A list whose contents are the union of lists $X$ and $Y$

```haskell
{-# type ListUn a X Y = ListS a {Set_cup (elts X) (elts Y)} #-}
```

- A list whose contents are exactly $X$ and the contents of $Y$

```haskell
{-# type ListUn1 a X Y = ListS a {Set_cup (Set_sng X) (elts Y)} #-}
```

The Measures strengthens the data constructors for lists. That is we get the automatically refined types for “nil” and “cons”:

```haskell
data [a] where
    [] :: ListEmp a
    (:') :: x:a -> xs:[a] -> ListUn1 a x xs
```

Let's take our new vocabulary out for a spin!
The `append` function returns a list whose elements are the union of the elements of the input Lists:

```haskell
{-# append' :: xs:_ -> ys:_ -> ListUn a xs ys #-}
append' [] ys = ys
append' (x:xs) ys = x : append' xs ys
```

**Exercise 8.3 (Reverse).** Write down a type for revHelper so that `reverse'` is verified by LiquidHaskell.

```haskell
{-# reverse' :: xs:[a] -> ListEq a xs #-}
reverse' xs = revHelper [] xs
revHelper acc [] = acc
revHelper acc (x:xs) = revHelper (x:acc) xs
```

**Exercise 8.4 (Halve).** Write down a specification for `halve` such that the subsequent "theorem" `prop_halve_append` is proved by LiquidHaskell.

```haskell
halve :: Int -> [a] -> ([a], [a])
halve 0 xs = ([], xs)
halve n (x:y:zs) = (x:xs, y:ys) where (xs, ys) = halve (n-1) zs
halve _ xs = ([], xs)

{-# prop_halve_append :: _ -> _ -> True #-}
prop_halve_append n xs = elts xs == elts xs'
  where
    xs' = append' ys zs
    (ys, zs) = halve n xs
```

*Hint: You may want to remind yourself about the dimension-aware signature for partition from the earlier chapter.*

**Exercise 8.5 (Membership).** Write down a signature for `elem` that suffices to verify `test1` and `test2`.

```haskell
{-# elem :: (Eq a) => a -> [a] -> Bool #-}
elem _ [] = False
elem x (y:ys) = x == y || elem x ys

{-# test1 :: True #-}
test1 = elem 2 [1, 2, 3]

{-# test2 :: False #-}
test2 = elem 2 [1, 3]
```
Permutations

Next, let’s use the refined list API to prove that various sorting routines return permutations of their inputs, that is, return output lists whose elements are the same as those of the input lists.\(^\dagger\)

**Insertion Sort** is the simplest of all the list sorting routines; we build up an (ordered) output list inserting each element of the input list into the appropriate position of the output:

\[
\begin{align*}
\text{insert} & \quad x \; [] = [x] \\
\text{insert} & \quad x \; (y:ys)
\begin{align*}
| \quad x \leq y & = x : y : ys \\
| \quad \text{otherwise} & = y : \text{insert} \; x \; ys
\end{align*}
\end{align*}
\]

Thus, the output of \text{insert} has all the elements of the input \(xs\), plus the new element \(x\):

\[\{-@ \text{insert} :: x:a \to xs:[a] \to \text{ListUn1} \; a \; x \; xs @-\}\]

The above signature lets us prove that the output of the sorting routine indeed has the elements of the input:

\[\{-@ \text{insertSort} :: (\text{Ord} \; a) \Rightarrow xs:[a] \to \text{ListEq} \; a \; xs @-\}\]

\[
\begin{align*}
\text{insertSort} & \quad [] = [] \\
\text{insertSort} & \quad (x:xs) = \text{insert} \; x \; (\text{insertSort} \; xs)
\end{align*}
\]

\**Exercise 8.6 (Merge).** Fix the specification of merge so that the subsequent property prop_merge_app is verified by LiquidHaskell.

\[\{-@ \text{merge} :: xs:[a] \to ys:[a] \to [a] @-\}\]

\[
\begin{align*}
\text{merge} & \quad [] \; ys = ys \\
\text{merge} & \quad xs \; [] = xs \\
\text{merge} & \quad (x:xs) \; (y:ys)
\begin{align*}
| \quad x \leq y & = x : \text{merge} \; xs \; (y:ys) \\
| \quad \text{otherwise} & = y : \text{merge} \; (x:xs) \; ys
\end{align*}
\end{align*}
\]

\[\{-@ \text{prop_merge_app} :: _ \to _ \to \text{True} @-\}\]

\[\text{prop_merge_app} \; xs \; ys = \text{elts} \; zs \; == \; \text{elts} \; zs'\]

\[\text{where}\]

\[zs = \text{append'} \; xs \; ys\]

\[zs' = \text{merge} \; xs \; ys\]

\(^\dagger\) Since we are focusing on the elements, let’s not distract ourselves with the ordering invariant and reuse plain old lists. See this for how to specify and verify order with plain old lists.
Exercise 8.7 (Merge Sort). ** Once you write the correct type for merge above, you should be able to prove the unexpected signature for mergeSort below.

1. Make sure you are able verify the given signature.

2. Obviously we don’t want mergeSort to return the empty list, so there’s a bug. Find and fix it, so that you cannot prove that the output is empty, but can instead prove that the output is \textbf{ListEq} \ a \ xs.

\[
\{-@ \text{mergeSort} :: (\text{Ord} \ a) => \text{x}:[a] -> \text{ListEmp} \ a @-\}
\]

\[
\text{mergeSort} \ [\] \ = \ []
\]

\[
\text{mergeSort} \ \text{xs} \ = \ \text{merge} \ (\text{mergeSort} \ \text{ys}) \ (\text{mergeSort} \ \text{zs})
\]

\[
\text{where}
\]

\[
(\text{ys}, \ \text{zs}) \ = \ \text{halve mid} \ \text{xs}
\]

\[
\text{mid} \ = \ \text{length} \ \text{xs} \ \text{`div`} \ 2
\]

Uniqueness

Often, we want to enforce the invariant that a particular collection contains \textit{no duplicates}; as multiple copies in a collection of file handles or system resources can create unpleasant leaks. For example, the \texttt{xmonad} window manager creates a sophisticated \texttt{zipper} data structure to hold the list of active user windows and carefully maintains the invariant that that the zipper contains no duplicates. Next, let’s see how to specify and verify this invariant using LiquidHaskell, first for lists, and then for a simplified zipper.

To \textbf{Specify Uniqueness} we need a way of saying that a list has \textit{no duplicates}. There are many ways to do so; the simplest is a \textit{measure}:

\[
\{-@ \text{measure unique @-}\}
\]

\[
\text{unique} \quad :: \ (\text{Ord} \ a) \Rightarrow \ [a] \Rightarrow \ \text{Bool}
\]

\[
\text{unique} \ [\] \ = \ \text{True}
\]

\[
\text{unique} \ (x:x:s) \ = \ \text{unique} \ \text{x} \ &\& \ \text{not} \ (\text{member} \ x \ (\text{elts} \ \text{x}))
\]

We can use the above to write an alias for duplicate-free lists

\[
\{-@ \text{type UList} \ a = \{v:[a] | \text{unique} \ v \}@-\}
\]

Let’s quickly check that the right lists are indeed unique
The Filter function returns a subset of its elements, and hence, preserves uniqueness. That is, if the input is unique, the output is too:

```
{-@ filter :: (a -> Bool) -> xs:UList a -> {v:ListSub a xs | unique v} @-}
filter _ [] = []
filter f (x:xs)
  | f x = x : xs'
  | otherwise = xs'
where
  xs' = filter f xs
```

Exercise 8.8 (Filter). It seems a bit draconian to require that filter only be called with unique lists. Write down a more permissive type for filter’ below such that the subsequent uses are verified by LiquidHaskell.

```
{-@ test3 :: UList _ @-}
test3 = filter' (> 2) [1,2,3,4]
{-@ test4 :: [ _ ] @-}
test4 = filter' (> 3) [3,1,2,3]
```

Exercise 8.9 (Reverse). When we reverse their order, the set of elements is unchanged, and hence unique (if the input was unique). Why does LiquidHaskell reject the below? Can you fix things so that we can prove that the output is a UList a? (When you are done, you should be able to remove the assume from the signature below, and still have LH verify the code.)
{-@ assume reverse :: xs:UList a -> UList a @-}
reverse :: [a] -> [a]
reverse = go []

where
{-@ go :: acc:[a] -> xs:[a] -> [a] @-}
go acc [] = acc
ngo acc (x:xs) = go (x:acc) xs

The `nub` function constructs a unique list from an arbitrary input by traversing the input and tossing out elements that are already seen:

{-@ nub :: [a] -> UList a @-}
nub xs = go [] xs

where
{-@ go :: UList a -> xs:[a] -> UList a / [len xs] @-}
go seen [] = seen
ngo seen (x:xs)
x `isin` seen = go seen xs
otherwise = go (x:seen) xs

The key membership test is done by `isin`, whose output is True exactly when the element is in the given list. 5

-- FIXME
{-@ predicate In X Xs = Set_mem X (elts Xs) @-}

{-@ isin :: x:_ -> ys:_ -> {v:Bool | v <=> In x ys } @-}
isin x (y:ys)
x == y = True
otherwise = x `isin` ys
isin _ [] = False

Exercise 8.10 (Append). ★ Why does appending two UList returns not return a UList? Fix the type signature below so that you can prove that the output is indeed unique.

{-@ append :: UList a -> UList a -> UList a @-}
append [] ys = ys
append (x:xs) ys = x : append xs ys

Exercise 8.11 (Range). ★★ range i j returns the list of Int between i and j. LiquidHaskell refuses to acknowledge that the output is indeed a UList. Fix the code so that LiquidHaskell verifies that it implements the given signature (and of course, computes the same result.)
Unique Zippers

A zipper is an aggregate data structure that is used to arbitrarily traverse the structure and update its contents. For example, a zipper for a list is a data type that contains an element (called focus) that we are currently focus-ed on, a list of elements to the left of (i.e. before) the focus, and a list of elements to the right (i.e. after) the focus.

data Zipper a = Zipper {
  focus :: a
,  left :: [a]
,  right :: [a]
}

xmonad is a wonderful tiling window manager, that uses a zipper to store the set of windows being managed. xmonad requires the crucial invariant that the values in the zipper be unique, that is, be free of duplicates.

We Refine Zipper to capture the requirement that legal zippers are unique. To this end, we state that the left and right lists are unique, disjoint, and do not contain focus.

{-# data Zipper a = Zipper {
  focus :: a
,  left :: {v: UList a | not (In focus v)}
,  right :: {v: UList a | not (In focus v) && Disj v left }
} #-}

{-# predicate Disj X Y = Disjoint (elts X) (elts Y) #-}
Our Refined Zipper Constructor makes illegal states unrepresentable. That is, by construction, we will ensure that every Zipper is free of duplicates. For example, it is straightforward to create a valid Zipper from a unique list:

```haskell
{-# differentiate :: UList a -> Maybe (Zipper a) #-

differentiate [] = Nothing

differentiate (x:xs) = Just $ Zipper x [] xs
```

**Exercise 8.12** (Deconstructing Zippers). ⋆ *Dually, the elements of a unique zipper tumble out into a unique list. Strengthen the types of reverse and append above so that LiquidHaskell accepts the below signatures for integrate:*

```haskell
{-# integrate :: Zipper a -> UList a #-

integrate (Zipper x l r) = reverse l `append` (x : r)
```

We can **shift the Focus** element to the left or right while preserving the uniqueness invariant. Here’s the code that shifts the focus to the left:

```haskell
focusLeft :: Zipper a -> Zipper a

focusLeft (Zipper t (l:ls) rs) = Zipper l ls (t:rs)

focusLeft (Zipper t [] rs) = Zipper x xs []
  where
    (x:xs) = reverse (t:rs)
```

To shift to the right, we simply reverse the elements and shift to the left:

```haskell
focusRight :: Zipper a -> Zipper a

focusRight = reverseZipper . focusLeft . reverseZipper

reverseZipper :: Zipper a -> Zipper a

reverseZipper (Zipper t ls rs) = Zipper t rs ls
```

To **Filter** elements from a zipper, we need to take care when the focus itself, or all the elements get eliminated. In the latter case, there is no Zipper and so the operation returns a Maybe:

```haskell
filterZipper :: (a -> Bool) -> Zipper a -> Maybe (Zipper a)

filterZipper p (Zipper f ls rs)
  = case filter p (f:rs) of
```

Thus, by using LiquidHaskell’s refinement types, and the SMT solvers native reasoning about sets, we can ensure the key uniqueness invariant holds in the presence of various tricky operations that are performed over Zippers.

Recap

In this chapter, we saw how SMT solvers can let us reason precisely about the actual contents of data structures, via the theory of sets. In particular, we saw how to:

- **Lift set-theoretic primitives** to refined Haskell functions from the Data.Set library,
- **Define measures** like elts that characterize the set of elements of structures, and unique that describe high-level application specific properties about those sets,
- **Specify and verify** that implementations enjoy various functional correctness properties, e.g. that sorting routines return permutations of their inputs, and various zipper operators preserve uniqueness.

Next, we present a variety of longer case-studies that illustrate the techniques developed so far on particular application domains.
Case Study: Okasaki’s Lazy Queues

Let’s start with a case study that is simple enough to explain without pages of code, yet complex enough to show off what’s cool about dependency: Chris Okasaki’s beautiful Lazy Queues. This structure leans heavily on an invariant to provide fast insertion and deletion. Let’s see how to enforce that invariant with LiquidHaskell.

Queues

A queue is a structure into which we can insert and remove data such that the order in which the data is removed is the same as the order in which it was inserted.

To efficiently implement a queue we need to have rapid access to both the front as well as the back because we remove elements from
former and insert elements into the latter. This is quite straightforward with explicit pointers and mutation – one uses an old school linked list and maintains pointers to the head and the tail. But can we implement the structure efficiently without having to stoop so low?

Chris Okasaki came up with a very cunning way to implement queues using a pair of lists – let’s call them front and back which represent the corresponding parts of the Queue.

- To insert elements, we just cons them onto the back list,
- To remove elements, we just un-cons them from the front list.

The catch is that we need to shunt elements from the back to the front every so often, e.g. we can transfer the elements from the back to the front, when:

1. a remove call is triggered, and
2. the front list is empty.

Okasaki’s first insight was to note that every element is only moved once from the back to the front; hence, the time for insert and remove could be \( O(1) \) when amortized over all the operations. This is perfect, except that some set of unlucky remove calls (which occur when the front is empty) are stuck paying the bill. They have a rather high latency up to \( O(n) \) where \( n \) is the total number of operations.
Okasaki’s second insight saves the day: he observed that all we need to do is to enforce a simple balance invariant:

\[ \text{Size of front} \geq \text{Size of back} \]

If the lists are lazy i.e. only constructed as the head value is demanded, then a single remove needs only a tiny \(O(\log n)\) in the worst case, and so no single remove is stuck paying the bill.

Let’s implement Queues and ensure the crucial invariant(s) with LiquidHaskell. What we need are the following ingredients:

1. A type for Lists, and a way to track their size,
2. A type for Queues which encodes the balance invariant
3. A way to implement the insert, remove and transfer operations.

**Sized Lists**

The first part is super easy. Let’s define a type:

```haskell
data SList a = SL { size :: Int, elems :: [a] }
```

We have a special field that saves the size because otherwise, we have a linear time computation that wrecks Okasaki’s careful analysis. (Actually, he presents a variant which does not require saving the size as well, but that’s for another day.)

How can we be sure that size is indeed the real size of elems? Let’s write a function to measure the real size:
Now, we can simply specify a refined type for SList that ensures that the real size is saved in the size field:

```haskell
{-@ data SList a = SL { size :: Nat , elems :: {v:[a] | realSize v = size} } @}```

As a sanity check, consider this:

```haskell
okList = SL 1 ["cat"]    -- accepted
badList = SL 1 []         -- rejected
```

**L E T S D E F I N E A N A L I S I S** for lists of a given size N:

```haskell
{-@ type SListN a N = {v:SList a | size v = N} @-}
```

Finally, we can define a basic API for SList.

To **C O N S T R U C T** lists, we use nil and cons:

```haskell
{-@ nil :: SListN a 0 @} 
nil = SL 0 []
{-@ cons :: a -> xs:SList a -> SListN a {size xs + 1} @} 
cons x (SL n xs) = SL (n+1) (x:xs)
```

**E xercise 9.1 (Destructing Lists).** We can **d e c o n s t r u c t** lists by writing a **h d** and **t l** function as shown below. Fix the specification or implementation such that the definitions typecheck.

```haskell
{-@ tl :: xs:SList a -> SListN a {size xs - 1} @} 
tl (SL n (_:xs)) = SL (n-1) xs 
tl _ = die "empty SList"
{-@ hd :: xs:SList a -> a @} 
```
Hint: When you are done, okHd should be verified, but badHd should be rejected.

{-@ okList :: SListN String 1 @-}
okHd = hd okList  -- accepted
badHd = hd (tl okList)  -- rejected

Queue Type

It is quite straightforward to define the Queue type, as a pair of lists, front and back, such that the latter is always smaller than the former:

{-@ data Queue a = Q { front :: SList a , back :: SListLE a (size front) } @-}
data Queue a = Q { front :: SList a , back :: SList a }

The alias SListLE a L corresponds to lists with at most N elements:

{-@ type SListLE a N = {v:SList a | size v <= N} @-}

As a quick check, notice that we cannot represent illegal Queues:

okQ = Q okList nil  -- accepted, |front| > |back|
badQ = Q nil okList  -- rejected, |front| < |back|

Queue Operations

Almost there! Now all that remains is to define the Queue API. The code below is more or less identical to Okasaki's (I prefer front and back to his left and right.)
The Empty Queue is simply one where both front and back are both empty:

\[
\text{emp} = \text{Q} \text{ nil nil}
\]

To Remove an element we pop it off the front by using \( \text{hd} \) and \( \text{tl} \). Notice that the remove is only called on non-empty Queues, which together with the key balance invariant, ensures that the calls to \( \text{hd} \) and \( \text{tl} \) are safe.

\[
\text{remove} (\text{Q} \ f \ b) = (\text{hd} \ f, \ \text{makeq} \ (\text{tl} \ f) \ b)
\]

**Exercise 9.2** (Whither pattern matching?). *Can you explain why we (or Okasaki) didn’t use pattern matching here, and have instead opted for the explicit \( \text{hd} \) and \( \text{tl} \)?*

**Exercise 9.3** (Queue Sizes). *If you did the List Destructing exercise above, then you will notice that the code for remove has a type error: namely, the calls to \( \text{hd} \) and \( \text{tl} \) may fail if the \( f \) list is empty.*

1. Write a measure to describe the queue size,
2. Use it to complete the definition of QueueN below, and
3. Use it to give remove a type that verifies the safety of the calls made to \( \text{hd} \) and \( \text{tl} \).

*Hint:* When you are done, \text{okRemove} should be accepted, \text{badRemove} should be rejected, and \text{emp} should have the type shown below:

\[
\begin{align*}
\text{-- | Queues of size 'N'} \\
\text{record QueueN a N = \{v:Queue a | true\} @-}
\end{align*}
\]

\[
\begin{align*}
\text{okRemove} & = \text{remove example2Q} \quad \text{-- accept} \\
\text{badRemove} & = \text{remove example0Q} \quad \text{-- reject}
\end{align*}
\]

\[
\begin{align*}
\text{-- @ emp :: QueueN \_ \_ 0 @-}
\end{align*}
\]

\[
\begin{align*}
\text{-- @ example2Q :: QueueN \_ \_ 2 @-} \\
\text{example2Q} & = \text{Q} \ (1 \ `\text{cons}` \ (2 \ `\text{cons}` \ nil)) \ nil
\end{align*}
\]

\[
\begin{align*}
\text{-- @ example0Q :: QueueN \_ \_ 0 @-} \\
\text{example0Q} & = \text{Q} \ \text{nil} \ \text{nil}
\end{align*}
\]
To Insert an element we just cons it to the back list, and call the smart constructor makeq to ensure that the balance invariant holds:

\[
\text{insert } e \ (Q \ f \ b) = \text{makeq } f \ (e \ \text{`cons'} \ b)
\]

Exercise 9.4 (Insert). Write down a type for insert such that replicate and okReplicate are accepted by LiquidHaskell, but badReplicate is rejected.

\{
{\text{-@ replicate :: n:Nat \to a \to QueueN a n @-}}
replicate \emptyset \ _ = \text{emp}
replicate n \ x = \text{insert } x \ (\text{replicate } (n-1) \ x)
\}

\{
{\text{-@ okReplicate :: QueueN } \_ \ _ 3 @-}
okReplicate \ = \text{replicate } 3 \ \text{"Yeah!"} \ -- \text{accept}
\}

\{
{\text{-@ badReplicate :: QueueN } \_ \ _ 3 @-}
badReplicate \ = \text{replicate } 1 \ \text{"No!"} \ -- \text{reject}
\}

To Ensure the Invariant we use the smart constructor makeq, which is where the heavy lifting happens. The constructor takes two lists, the front f and back b and if they are balanced, directly returns the Queue, and otherwise transfers the elements from b over using the rotate function rot described next.

\{
{\text{-@ makeq :: f:SList a \to b:SList a \to QueueN a \{size f + size b\} @-}}
\text{makeq } f \ b
| \text{size } b \leq \text{size } f = Q \ f \ b
| \text{otherwise} \ = Q \ (\text{rot } f \ b \ \text{nil}) \ \text{nil}
\}

Exercise 9.5 (Rotate). ⭐⭐ The Rotate function rot is only called when the back is one larger than the front (we never let things drift beyond that). It is arranged so that it the hd is built up fast, before the entire computation finishes; which, combined with laziness provides the efficient worst-case guarantee. Write down a type for rot so that it typechecks and verifies the type for makeq.

Hint: You may have to modify a precondition in makeq to capture the relationship between f and b.

\{
\text{rot } f \ b \ acc
| \text{size } f \ == \emptyset = \text{hd } b \ \text{`cons'} \ acc
| \text{otherwise} = \text{hd } f \ \text{`cons'} \ (\text{rot } (\text{tl } f) \ (\text{tl } b) \ (\text{hd } b \ \text{`cons'} \ acc))
\}
Exercise 9.6 (Transfer). Write down a signature for `take` which extracts \( n \) elements from its input \( q \) and puts them into a new output Queue. When you are done, `okTake` should be accepted, but `badTake` should be rejected.

```haskell
take :: Int -> Queue a -> (Queue a, Queue a)
take 0 q = (emp, q)
take n q = (insert x out, q''
where
  (x , q') = remove q
  (out, q'') = take (n-1) q'

{-@ okTake :: (QueueN _ 2, QueueN _ 1) @-}
okTake = take 2 exampleQ -- accept
badTake = take 10 exampleQ -- reject

exampleQ = insert "nal" $ insert "bob" $ insert "alice" $ emp
```

Recap

Well there you have it; Okasaki’s beautiful lazy Queue, with the invariants easily expressed and checked with LiquidHaskell. This example is particularly interesting because

1. The refinements express invariants that are critical for efficiency,
2. The code introspects on the size to guarantee the invariants, and
3. The code is quite simple and we hope, easy to follow!
Case Study: Associative Maps

Recall the following from the introduction:

ghci> :m +Data.Map
ghci> let m = fromList [ ("haskell", "lazy")
                                   , ("javascript", "eager")]

ghci> m ! "haskell"
"lazy"

ghci> m ! "python"
"*** Exception: key is not in the map

The problem illustrated above is quite a pervasive one; associative maps pop up everywhere. Failed lookups are the equivalent of NullPointerException exceptions in languages like Haskell. It is rather difficult to use Haskell’s type system to precisely characterize the behavior of associative map APIs as ultimately, this requires tracking the dynamic set of keys in the map.

In this case study, we’ll see how to combine two techniques, measures and refined data types, to analyze programs that implement and use associative maps (e.g. Data.Map or Data.HashMap).

Specifying Maps

Let’s start by defining a refined API for Associative Maps that tracks the set of keys stored in the map, in order to statically ensure the safety of lookups.

Types First, we need a type for Maps. As usual, let’s parameterize the type with k for the type of keys and v for the type of values:
data Map k v  -- Currently left abstract

Keys To talk about the set of keys in a map, we will use a measure

measure keys :: Map k v -> Set k

that associates each Map to the Set of its defined keys. Next, we use
the above measure, and the usual Set operators to refine the types
of the functions that *create, add* and *lookup* key-value bindings, in
order to precisely track, within the type system, the keys that are
dynamically defined within each Map. ¹

Empty Maps have no keys in them. Hence, we type the empty Map as:

emp :: {m:Map k v | Empty (keys m)}

ADD The function `set` takes a key `k` a value `v` and a map `m` and returns
the new map obtained by extending `m` with the binding `k \rightarrow v`. Thus,
the set of keys of the output Map includes those of the input plus the
singleton `k`, that is:

set :: k:k -> v -> m:Map k v -> {n: Map k v| AddKey k m n}

predicate AddKey K M N = keys N = Set_cup (Set_sng K) (keys M)

QUERY Finally, queries will only succeed for keys that are defined a
given Map. Thus, we define an alias:

predicate HasKey K M = In K (keys M)

and use it to type `mem` which *checks* if a key is defined in the Map and
get which actually returns the value associated with a given key.

<table>
<thead>
<tr>
<th>Check if key is defined</th>
</tr>
</thead>
<tbody>
<tr>
<td>mem :: k:k -&gt; m:Map k v -&gt; {v:Bool</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Lookup key's value</th>
</tr>
</thead>
<tbody>
<tr>
<td>get :: k:k -&gt; {m:Map k v</td>
</tr>
</tbody>
</table>
Using Maps: Well Scoped Expressions

Rather than jumping into the implementation of the above Map API, let’s write a client that uses Maps to implement an interpreter for a tiny language. In particular, we will use maps as an environment containing the values of bound variables, and we will use the refined API to ensure that lookups never fail, and hence, that well-scoped programs always reduce to a value.

Expressions Let’s work with a simple language with integer constants, variables, binding and arithmetic operators:

```
type Var = String

data Expr = Const Int
  | Var Var
  | Plus Expr Expr
  | Let Var Expr Expr
```

Values We can use refinements to formally describe values as a subset of Expr allowing us to reuse a bunch of code. To this end, we simply define a (measure) predicate characterizing values:

```
{-# measure val #-}
val :: Expr -> Bool
val (Const _) = True
val (Var _) = False
val (Plus _ _) = False
val (Let _ _ _ ) = False
```

and then we can use the lifted measure to define an alias for Val denoting values:

```
{-# type Val = {v:Expr | val v} #-}
```

we can use the above to write simple operators on Val, for example:

```
{-# plus :: Val -> Val -> Val #-}
plus (Const i) (Const j) = Const (i+j)
plus _ _ _ = die "Bad call to plus"
```

Environments let us save values for the local i.e. let-bound variables; when evaluating an expression Var x we simply look up the value
of $x$ in the environment. This is why Maps were invented! Let’s define our environments as Maps from Variables to Values:

```haskell
{-@ type Env = Map Var Val @-}
```

The above definition essentially specifies, inside the types, an *eager* evaluation strategy: LiquidHaskell will prevent us from sticking unevaluated `Expr`s inside the environments.

Evaluation proceeds via a straightforward recursion over the structure of the expression. When we hit a `Var` we simply query its value from the environment. When we hit a `Let` we compute the bound expression and tuck its value into the environment before proceeding within.

```haskell
eval _ i@ (Const _) = i
eval g (Var x) = get x g
eval g (Plus e1 e2) = plus (eval g e1) (eval g e2)
eval g (Let x e1 e2) = eval g' e2
  where
g' = set x v1 g
v1 = eval g e1
```

The above `eval` seems rather unsafe; what’s the guarantee that `get x g` will succeed? For example, surely trying:

```
ghci> eval emp (Var "x")
```

will lead to some unpleasant crash. Shouldn’t we *check* if the variables is present and if not, fail with some sort of `Variable Not Bound` error? We could, but we can do better: we can prove at compile time, that such errors will not occur.

**Free Variables** are those whose values are *not* bound within an expression, that is, the set of variables that *appear* in the expression, but are not *bound* by a dominating `Let`. We can formalize this notion as a (lifted) function:

```haskell
{-@ measure free @-}
free :: Expr -> (Set Var)
free (Const _) = empty
free (Var x) = singleton x
free (Plus e1 e2) = xs1 `union` xs2
```
where
xs1 = free e1
xs2 = free e2
free (Let x e1 e2) = xs1 `union` (xs2 `difference` xs)
where
xs1 = free e1
xs2 = free e2
xs = singleton x

An Expression is Closed with respect to an environment G if all the free variables in the expression appear in G, i.e. the environment contains bindings for all the variables in the expression that are not bound within the expression. As we’ve seen repeatedly, often a whole pile of informal hand-waving, can be succinctly captured by a type definition that says the free variables in the Expr must be contained in the keys of the environment G:

{-@ type ClosedExpr G = {v:Expr | Subset (free v) (keys G)} @-}

Closed Evaluation never goes wrong, i.e. we can ensure that eval will not crash with unbound variables, as long as it is invoked with suitable environments:

{-@ eval :: g:Env -> ClosedExpr g -> Val @-}

We can be sure an Expr is well-scoped if it has no free variables. Let’s use that to write a “top-level” evaluator:

{-@ topEval :: {v:Expr | Empty (free v)} -> Val @-}
topEval = eval emp

Exercise 10.1 (Wellformedness Check). Complete the definition of the below function which checks if an Expr is well formed before evaluating it:

{-@ evalAny :: Env -> Expr -> Maybe Val @-}
evalAny g e | ok = Just $ eval g e
| otherwise = Nothing
where
ok = undefined

Proof is all well and good, in the end, you need a few sanity tests to kick the tires. So:
tests = [v1, v2]

where
  v1 = topEval e1  -- Rejected by LH
  v2 = topEval e2  -- Accepted by LH
  e1 = (Var x)
      `Plus` c1
  e2 = Let x c10 e1
  x = "x"
  c1 = Const 1
  c10 = Const 10

Exercise 10.2 (Closures).  ** Extend the language above to include functions. That is, extend Expr as below, (and eval and free respectively.)

data Expr = ... | Fun Var Expr | App Expr Expr

Just focus on ensuring the safety of variable lookups; ensuring full type-safety (i.e. every application is to a function) is rather more complicated and beyond the scope of what we’ve seen so far.

Implementing Maps: Binary Search Trees

We just saw how easy it is to use the Associative Map API to ensure the safety of lookups, even though the Map has a “dynamically” generated set of keys. Next, let’s see how we can implement a Map library that respects the API using Binary Search Trees

Data Type First, let’s provide an implementation of the hitherto abstract data type for Map. We shall use Binary Search Trees, wherein, at each Node, the left (resp. right) subtree has keys that are less than (resp. greater than) the root key.

{-@ data Map k v = Node { key :: k
, value :: v
, left :: Map {v:k | v < key} v
, right :: Map {v:k | key < v} v } @-}

Recall that the above refined data definition yields strengthened data constructors that statically ensure that only legal, binary-search ordered trees are created in the program.
Defined Keys Next, we must provide an implementation of the notion of the keys that are defined for a given Map. This is achieved via the lifted measure function:

```haskell
{-@ measure keys @-}
keys :: (Ord k) => Map k v -> Set k
keys Tip = empty
keys (Node k _ l r) = ks `union` kl `union` kr
  where
    kl = keys l
    kr = keys r
    ks = singleton k
```

Armed with the basic type and measure definition, we can start to fill in the operations for Maps.

Exercise 10.3 (Empty Maps). To make sure you are following, fill in the definition for an empty Map:

```haskell
{-@ emp :: {m:Map k v | Empty (keys m)} @-}
emp = undefined
```

Exercise 10.4 (Insert). To add a key k' to a Map we recursively traverse the Map zigging left or right depending on the result of comparisons with the keys along the path. Unfortunately, the version below has an (all too common!) bug, and hence, is rejected by LiquidHaskell. Find and fix the bug so that the function is verified.

```haskell
{-@ set :: (Ord k) => k:k -> v -> m:Map k v -> {n: Map k v | AddKey k m n} @-}
set k' v' (Node k v l r)
  | k' == k = Node k v' l r
  | k' < k  = set k' v l
  | otherwise = set k' v r
set k' v' Tip = Node k' v' Tip Tip
```

Lookup Next, let’s write the mem function that returns the value associated with a key k'. To do so we just compare k' with the root key, if they are equal, we return the binding, and otherwise we go down the left (resp. right) subtree if sought for key is less (resp. greater) than the root key. Crucially, we want to check that lookup never fails, and hence, we implement the Tip (i.e. empty) case with die gets LiquidHaskell to prove that that case is indeed dead code, i.e. never happens at run-time.
{-@ get' :: (Ord k) => k:k -> m:{Map k v| HasKey k m} -> v @-}
get' k' m@(Node k v l r)
  | k' == k  = v
  | k' <  k  = get' k' l
  | otherwise = get' k' r
get'_  _ Tip  = die "Lookup Never Fails"

Unfortunately the function above is rejected by LiquidHaskell. This is a puzzler (and a bummer!) because in fact it is correct. So what gives? Well, let’s look at the error for the call get' k' l

`src/07-case-study-associative-maps.lhs:411:25: Error: Liquid Type Mismatch
Inferred type
   VV : Map a b | VV == l
not a subtype of Required type
   VV : Map a b | Set_mem k' (keys VV)
In Context
   VV : Map a b | VV == l
   k  : a
   l  : Map a b
   k' : a`

LiquidHaskell is unable to deduce that the key k’ definitely belongs in the left subtree l. Well, let’s ask ourselves: why must k’ belong in the left subtree? From the input, we know `HasKey k` m i.e. that k’ is somewhere in m. That is one of the following holds:

1. k’ == k or,
2. HasKey k’ l or,
3. HasKey k’ r.

As the preceding guard k’ == k fails, we (and LiquidHaskell) can rule out case (1). Now, what about the Map tells us that case (2) must hold, i.e. that case (3) cannot hold? The BST invariant, all keys in r exceed k which itself exceeds k’. That is, all nodes in r are disequal to k’ and hence k’ cannot be in r, ruling out case (3). Formally, we need the fact that:

\[ \forall \text{key}, t.t :: \text{Map} \{ \text{key'}:k | \text{key'} \neq \text{key} \} \ v \Rightarrow \neg(\text{HasKey key} t) \]

Conversion Lemmas Unfortunately, LiquidHaskell cannot automatically deduce facts like the above, as they relate refinements of a
container’s type parameters (here: key′ ≠ key, which refines the Maps first type parameter) with properties of the entire container (here: HasKey key t). Fortunately, it is easy to state, prove and use facts like the above, via lemmas which are just functions. ³

Defining Lemmas To state a lemma, we need only convert it into a type by viewing universal quantifiers as function parameters, and implications as function types:

```haskell
{-# lemma_notMem :: key:k -> m:Map {k:k | k /= key} v -> {v:Bool | not (HasKey key m)} @-#
  lemma_notMem _ Tip = True
  lemma_notMem key (Node _ _ l r) = lemma_notMem key l &&
    lemma_notMem key r
```

Proving Lemmas Note how the signature for lemma_notMem corresponds exactly to the missing fact from above. The “output” type is a Bool refined with the proposition that we desire. We prove the lemma simply by traversing the tree which lets LiquidHaskell build up a proof for the output fact by inductively combining the proofs from the subtrees.

Using Lemmas To use a lemma, we need to instantiate it to the particular keys and trees we care about, by “calling” the lemma function, and forcing its result to be in the environment used to typecheck the expression where we want to use the lemma. Say what? Here’s how to use lemmas to verify get:

```haskell
{-# get :: (Ord k) => k:k -> m:{Map k v | HasKey k m} -> v @-#
  get k' (Node k v l r)
    | k' == k   = v
    | k' < k    = assert (lemma_notMem k' r) $
      get k' l
    | otherwise = assert (lemma_notMem k' l) $
      get k' r
  get _ Tip   = die "Lookup failed? Impossible."
```

³ Why does LiquidHaskell not automatically deduce this information? This is tricky to describe. Intuitively, because there is no way of automatically connecting the traversal corresponding to keys with the type variable k. I wish I had a better way to explain this rather subtle point; suggestions welcome!
assert \_ x = x

**Ghost Values** This technique of materializing auxiliary facts via *ghost values* is a well known idea in program verification. Usually, one has to take care to ensure that ghost computations do not interfere with the regular computations. If we had to actually execute `lemma_notMem` it would wreck the efficient logarithmic lookup time, assuming we kept the trees *balanced*, as we would traverse the *entire* tree instead of just the short path to a node.  

*Laziness* comes to our rescue: as the ghost value is (trivially) not needed, it is never computed. In fact, it is straightforward to entirely *erase* the call in the compiled code, which lets us freely assert such lemmas to carry out proofs, without paying any runtime penalty. In an eager language we would have to do a bit of work to specifically mark the computation as a ghost or *irrelevant* but in the lazy setting we get this for free.

**Exercise 10.5** (Membership Test). *Capisce?* Fix the definition of `mem` so that it verifiably implements the given signature.

```haskell
{-@ mem :: (Ord k) => k:k -> m:Map k v
       -> {v:_ | v <=> HasKey k m} @-}
mem k (Node k _ l r) | k' == k = True
                     | k' < k = mem k' l
                     | otherwise = mem k' r
mem _ Tip = False
```

**Exercise 10.6** (Fresh). ** To make sure you really understand this business of ghosts values and proofs, complete the implementation of the following function which returns a fresh integer that is distinct from all the values in its input list:

```haskell
{-@ fresh :: xs:[Int] -> {v:Int | not (Elem v xs)} @-}
fresh = undefined
```

To refresh your memory, here are the definitions for `Elem` we saw earlier

```haskell
{-@ predicate Elem X Ys = In X (elems Ys) @-}
{-@ measure elems @-}
elems [] = empty
elems (x:xs) = (singleton x) `union` (elems xs)
Recap

In this chapter we saw how to combine several of the techniques from previous chapters in a case study. We learned how to:

1. Define an API for associative maps that used refinements to track the set of keys stored in a map, in order to prevent lookup failures, the NullPointerException errors of the functional world,

2. Use the API to implement a small interpreter that is guaranteed to never fail with UnboundVariable errors, as long as the input expressions were closed,

3. Implement the API using Binary Search Trees; in particular, using ghost lemmas to assert facts that LiquidHaskell is otherwise unable to deduce automatically.
Case Study: Pointers & Bytes

A large part of the allure of Haskell is its elegant, high-level ADTs that ensure that programs won’t be plagued by problems like the infamous SSL heartbleed bug. However, another part of Haskell’s charm is that when you really really need to, you can drop down to low-level pointer twiddling to squeeze the most performance out of your machine. But of course, that opens the door to the heartbleeds.

Wouldn’t it be nice to have our cake and eat it too? Wouldn’t it be great if we could twiddle pointers at a low-level and still get the nice safety assurances of high-level types? Let’s see how LiquidHaskell lets us have our cake and eat it too.

HeartBleeds in Haskell

Modern Languages like Haskell are ultimately built upon the foundation of C. Thus, implementation errors could open up unpleasant vulnerabilities that could easily slither past the type system and even code inspection. As a concrete example, let’s look at a function that uses the ByteString library to truncate strings:

```haskell
chop' :: String -> Int -> String
chop' s n = s'
  where
    b   = pack s          -- down to low-level
    b'  = unsafeTake n b  -- grab n chars
    s'  = unpack b'       -- up to high-level
```

First, the function packs the string into a low-level bytestring b, then it grabs the first n characters from b and translates them back into a high-level String. Let’s see how the function works on a small test:
ghci> let ex = "Ranjit Loves Burritos"

We get the right result when we chop a valid prefix:

ghci> chop' ex 10
"Ranjit Lov"

But, as illustrated in Figure 11.1, the machine silently reveals (or more colorfully, bleeds) the contents of adjacent memory or if we use an invalid prefix:

ghci> chop' ex 30
"Ranjit Loves Burritos\NUL\201\&1j\DC3\SOH\NUL"

Figure 11.1: Can we prevent the program from leaking secrets via overflows?

Types against Overflows Now that we have stared the problem straight in the eye, look at how we can use LiquidHaskell to prevent the above at compile time. To this end, we decompose the system into a hierarchy of levels (i.e. modules). Here, we have three levels:

1. Machine level Pointers
2. Library level ByteString
3. User level Application

Our strategy, as before, is to develop an refined API for each level such that errors at each level are prevented by using the typed interfaces for the lower levels. Next, let’s see how this strategy lets us safely manipulate pointers.

Low-level Pointer API

To get started, let’s look at the low-level pointer API that is offered by GHC and the run-time. First, let’s see who the dramatis personae are and how they might let heartbleeds in. Then we will see how to batten down the hatches with LiquidHaskell.
Pointers are an (abstract) type `Ptr a` implemented by GHC.

```haskell
data Ptr a
```

Foreign Pointers are *wrapped* pointers that can be exported to and from C code via the Foreign Function Interface.

```haskell
data ForeignPtr a
```

To create a pointer we use `mallocForeignPtrBytes n` which creates a `Ptr` to a buffer of size `n` and wraps it as a `ForeignPtr`.

```haskell
mallocForeignPtrBytes :: Int -> ForeignPtr a
```

To unwrap and actually use the `ForeignPtr` we use

```haskell
withForeignPtr :: ForeignPtr a -- pointer
               -> (Ptr a -> IO b) -- action
               -> IO b -- result
```

That is, `withForeignPtr fp act` lets us execute an action `act` on the actual `Ptr` wrapped within the `fp`. These actions are typically sequences of *dereferences*, i.e. reads or writes.

To dereference a pointer, i.e. to read or update the contents at the corresponding memory location, we use `peek` and `poke` respectively. \(^2\)

```haskell
peek :: Ptr a -> IO a -- Read
poke :: Ptr a -> a -> IO () -- Write
```

For fine-grained access we can directly shift pointers to arbitrary offsets using the pointer arithmetic operation `plusPtr p off` which takes a pointer `p` an integer `off` and returns the address obtained shifting `p` by `off`:

```haskell
plusPtr :: Ptr a -> Int -> Ptr b
```
Example. That was rather dry; let’s look at a concrete example of how one might use the low-level API. The following function allocates a block of 4 bytes and fills it with zeros:

```haskell
zero4 = do fp <- mallocForeignPtrBytes 4
          withForeignPtr fp $ \p -> do
          poke (p `plusPtr` 0) zero
          poke (p `plusPtr` 1) zero
          poke (p `plusPtr` 2) zero
          poke (p `plusPtr` 3) zero
          return fp
          where
          zero = 0 :: Word8
```

While the above is perfectly all right, a small typo could easily slip past the type system (and run-time!) leading to hard to find errors:

```haskell
zero4' = do fp <- mallocForeignPtrBytes 4
           withForeignPtr fp $ \p -> do
           poke (p `plusPtr` 0) zero
           poke (p `plusPtr` 1) zero
           poke (p `plusPtr` 2) zero
           poke (p `plusPtr` 8) zero
           return fp
           where
           zero = 0 :: Word8
```

A Refined Pointer API

Wouldn’t it be great if we had an assistant to helpfully point out the error above as soon as we wrote it? We will use the following strategy to turn LiquidHaskell into such an assistant:

1. Refine pointers with allocated buffer size,
2. Track sizes in pointer operations,
3. Enforce pointer are valid at reads and writes.

To Refine Pointers with the size of their associated buffers, we can use an abstract measure, i.e. a measure specification without any underlying implementation.

\[^3\text{In Vim or Emacs or online, you’d see the error helpfully highlighted.}\]
case study: pointers & bytes

-- | Size of `Ptr`
measure plen :: Ptr a -> Int

-- | Size of `ForeignPtr`
measure fplen :: ForeignPtr a -> Int

It is helpful to define aliases for pointers of a given size \(N\):

\[
type \text{PtrN} \ a \ N = \{v:\text{Ptr} \ a \mid \text{plen} \ v = N\}
\]

\[
type \text{ForeignPtrN} \ a \ N = \{v:\text{ForeignPtr} \ a \mid \text{fplen} \ v = N\}
\]

Abstract Measures are extremely useful when we don’t have a concrete implementation of the underlying value, but we know that the value exists. Here, we don’t have the value – inside Haskell – because the buffers are manipulated within C. However, this is no cause for alarm as we will simply use measures to refine the API, not to perform any computations.  

This is another ghost specification.

To Refine Allocation we stipulate that the size parameter be non-negative, and that the returned pointer indeed refers to a buffer with exactly \(n\) bytes:

\[
\text{mallocForeignPtrBytes :: } n:\text{Nat} \to \text{ForeignPtrN} \ a \ n
\]

To Refine Unwrapping we specify that the action gets as input, an unwrapped \(\text{Ptr}\) whose size equals that of the given \(\text{ForeignPtr}\).

\[
\text{withForeignPtr :: } \text{fp:ForeignPtr} \ a
\to \ (\text{PtrN} \ a \ (\text{fplen} \ \text{fp}) \to \text{IO} \ b)
\to \ \text{IO} \ b
\]

This is a rather interesting higher-order specification. Consider a call \(\text{withForeignPtr \ fp \ act}\). If the act requires a \(\text{Ptr}\) whose size exceeds that of \(\text{fp}\) then LiquidHaskell will flag a (subtyping) error indicating the overflow. If instead the act requires a buffer of size less than \(\text{fp}\) then it is always safe to run the act on a larger buffer. For example, the below variant of \(\text{zero4}\) where we only set the first three bytes is fine as the act, namely the function \(\text{\_} \ p \to \ldots\), can be typed with the requirement that the buffer \(p\) has size 4, even though only 3 bytes are actually touched.
To Refine Reads and Writes we specify that they can only be done if the pointer refers to a non-empty (remaining) buffer. That is, we define an alias:

\[
\text{type OkPtr } a = \{ v : \text{Ptr } a | 0 < \text{plen } v \} \]

that describes pointers referring to non-empty buffers (of strictly positive plen), and then use the alias to refine:

\[
\begin{align*}
\text{peek :: OkPtr } a & \rightarrow \text{IO } a \\
\text{poke :: OkPtr } a & \rightarrow a \rightarrow \text{IO } ()
\end{align*}
\]

In essence the above type says that no matter how arithmetic was used to shift pointers around, when the actual dereference happens, the size remaining after the pointer must be non-negative, so that a byte can be safely read from or written to the underlying buffer.

To Refine the Shift operations, we simply check that the pointer remains within the bounds of the buffer, and update the plen to reflect the size remaining after the shift:  

\[
\text{plusPtr :: } p : \text{Ptr } a \rightarrow \text{off : BNat } (\text{plen } p) \rightarrow \text{PtrN } b (\text{plen } p - \text{off})
\]

using the alias BNat, defined as:

\[
\text{type BNat } N = \{ v : \text{Nat } | v \leq N \}
\]

Types Prevent Overflows Let's revisit the zero-fill example from above to understand how the refinements help detect the error:

\[
\begin{align*}
\text{zero3 = do } & \text{fp <- mallocForeignPtrBytes 4} \\
& \text{withForeignPtr fp }$ \_ p \rightarrow \text{ do} \\
& \text{poke (p `plusPtr` 0) zero} \\
& \text{poke (p `plusPtr` 1) zero} \\
& \text{poke (p `plusPtr` 2) zero} \\
& \text{return fp}
\end{align*}
\]

\[
\begin{align*}
\text{where} \\
\text{zero } = 0 :: \text{Word8}
\end{align*}
\]

\[5\] This signature precludes left or backward shifts; for that there is an analogous minusPtr which we elide for simplicity.

\[6\] Did you notice that we have strengthened the type of plusPtr to prevent the pointer from wandering outside the boundary of the buffer? We could instead use a weaker requirement for plusPtr that omits this requirement, and instead have the error be flagged when the pointer was used to read or write memory.
exBad = do fp <- mallocForeignPtrBytes 4
   withForeignPtr fp $ \p -> do
      poke (p `plusPtr` 0) zero
      poke (p `plusPtr` 1) zero
      poke (p `plusPtr` 2) zero
      poke (p `plusPtr` 5) zero -- LH complains
   return fp
   where
      zero = 0 :: Word8

Let's read the tea leaves to understand the above error:

Error: Liquid Type Mismatch
Inferred type
   VV : {VV : Int | VV == ?a && VV == 5}

not a subtype of Required type
   VV : {VV : Int | VV <= plen p}

in Context
   zero : {zero : Word8 | zero == ?b}
   VV : {VV : Int | VV == ?a && VV == (5 : int)}
   fp : {fp : ForeignPtr a | fplen fp == ?c && 0 <= fplen fp}
   p : {p : Ptr a | fplen fp == plen p && ?c <= plen p && ?b <= plen p && zero <= plen p}
   ?a : {?a : Int | ?a == 5}
   ?c : {?c : Int | ?c == 4}
   ?b : {?b : Integer | ?b == 0}

The error says we're bumping \( p \) up by \( VV == 5 \) using \( \text{plusPtr} \) but the latter \textit{requires} that bump-offset be within the size of the buffer referred to by \( p \), i.e. \( VV <= \text{plen } p \). Indeed, in this context, we have:

\[
\begin{align*}
\ p & : {p : Ptr a | fplen fp == plen p && ?c <= plen p && ?b <= plen p && zero <= plen p} \\
\ fp & : {fp : ForeignPtr a | fplen fp == ?c && 0 <= fplen fp}
\end{align*}
\]

that is, the size of \( p \), namely \( \text{plen } p \) equals the size of \( fp \), namely \( \text{fplen } fp \) (thanks to the \textit{withForeignPtr} call). The latter equals to \( ?c \) which is 4 bytes. Thus, since the offset 5 is not less than the buffer size 4, LiquidHaskell cannot prove that the call to \( \text{plusPtr} \) is safe, hence the error.
Assumptions vs Guarantees

At this point you ought to wonder: where is the code for peek, poke or mallocForeignPtrBytes and so on? How can we be sure that the types we assigned to them are in fact legitimate?

Frankly, we cannot as those functions are externally implemented (in this case, in C), and hence, invisible to the otherwise all-seeing eyes of LiquidHaskell. Thus, we are assuming or trusting that those functions behave according to their types. Put another way, the types for the low-level API are our specification for what low-level pointer safety. We shall now guarantee that the higher level modules that build upon this API in fact use the low-level function in a manner consistent with this specification.

Assumptions are a Feature and not a bug, as they let us to verify systems that use some modules for which we do not have the code. Here, we can assume a boundary specification, and then guarantee that the rest of the system is safe with respect to that specification. 7

ByteString API

Next, let’s see how the low-level API can be used to implement to implement ByteStrings, in a way that lets us perform fast string operations without opening the door to overflows.

A ByteString is implemented as a record of three fields:

data ByteString = BS {
  bPtr :: ForeignPtr Word8
  , bOff :: !Int
  , bLen :: !Int
}

• bPtr is a pointer to a block of memory,

• bOff is the offset in the block where the string begins,

• bLen is the number of bytes from the offset that belong to the string.

7 If we so desire, we can also check the boundary specifications at runtime, but that is outside the scope of LiquidHaskell.
These entities are illustrated in Figure 11.2; the green portion represents the actual contents of a particular ByteString. This representation makes it possible to implement various operations like computing prefixes and suffixes extremely quickly, simply by pointer arithmetic.

In a Legal ByteString the start (bOff) and end (bOff + bLen) offsets lie inside the buffer referred to by the pointer bPtr. We can formalize this invariant with a data definition that will then make it impossible to create illegal ByteStrings:

```haskell
{-@ data ByteString = BS { 
  bPtr :: ForeignPtr Word8,
  bOff :: {v:Nat| v <= fplen bPtr},
  bLen :: {v:Nat| v + bOff <= fplen bPtr}
 } @-}
```

The refinements on bOff and bLen correspond exactly to the legality requirements that the start and end of the ByteString be within the block of memory referred to by bPtr.

For brevity let’s define an alias for ByteStrings of a given size:

```haskell
{-@ type ByteStringN N = {v:ByteString | bLen v = N} @-}
```

Legal ByteStrings can be created by directly using the constructor, as long as we pass in suitable offsets and lengths. For example,

```haskell
{-@ good1 :: IO (ByteStringN 5) @-}

good1 = do fp <- mallocForeignPtrBytes 5
           return (BS fp 0 5)
```

creates a valid ByteString of size 5; however we need not start at the beginning of the block, or use up all the buffer, and can instead create
ByteStrings whose length is less than the size of the allocated block, as shown in good2 whose length is 2 while the allocated block has size 5.

```haskell
{-@ good2 :: IO (ByteStringN 2) @-}
good2 = do fp <- mallocForeignPtrBytes 5
          return (BS fp 3 2)
```

**Illegal ByteStrings** are rejected by LiquidHaskell. For example, bad1’s length is exceeds its buffer size, and is flagged as such:

```haskell
bad1 = do fp <- mallocForeignPtrBytes 3
          return (BS fp 0 10)
```

Similarly, bad2 does have 2 bytes but not if we start at the offset of 2:

```haskell
bad2 = do fp <- mallocForeignPtrBytes 3
          return (BS fp 2 2)
```

**Exercise 11.1** (Legal ByteStrings). Modify the definitions of bad1 and bad2 so they are accepted by LiquidHaskell.

Measures are generated from Fields in the datatype definition. As GHC lets us use the fields as accessor functions, we can refine the types of those functions to specify their behavior to LiquidHaskell. For example, we can type the (automatically generated) field-accessor function bLen so that it actually returns the exact size of the ByteString argument.

```haskell
{-@ bLen :: b:ByteString -> {v: Nat | v = bLen b} @-}
```

To Safely Create a ByteString the implementation defines a higher order create function, that takes a size n and accepts a fill action, and runs the action after allocating the pointer. After running the action, the function tucks the pointer into and returns a ByteString of size n.

```haskell
{-@ create :: n:Nat -> (Ptr Word8 -> IO ()) -> ByteStringN n @-}
create n fill = unsafePerformIO $ do
  fp <- mallocForeignPtrBytes n
  withForeignPtr fp fill
  return (BS fp 0 n)
Exercise 11.2 (Create). ⋆ Why does LiquidHaskell reject the following function that creates a ByteString corresponding to "GHC"?

```haskell
bsGHC = create 3 $ \p -> do
  poke (p `plusPtr` 0) (c2w 'G')
  poke (p `plusPtr` 1) (c2w 'H')
  poke (p `plusPtr` 2) (c2w 'C')
```

*Hint:* The function writes into 3 slots starting at p. How big should `plen p` be to allow this? What type does LiquidHaskell infer for `p` above? Does it meet the requirement? Which part of the `specification` or `implementation` needs to be modified so that the relevant information about `p` becomes available within the `do`-block above? Make sure you figure out the above before proceeding.

To **Pack** a String into a ByteString we simply call `create` with the appropriate fill action: 8

```haskell
pack str = create' n $ \p -> go p xs
  where
    n = length str
    xs = map c2w str
    go p (x:xs) = poke p x >> go (plusPtr p 1) xs
    go _ [] = return ()
```

Exercise 11.3 (Pack). * We can compute the size of a ByteString by using the function: Fix the specification for `pack` so that (it still typechecks!) and furthermore, the following QuickCheck style property is proved.

```haskell
{-@ prop_pack_length :: String -> TRUE @-}
prop_pack_length xs = bLen (pack xs) == length xs
```

*Hint:* Look at the type of `length`, and recall that `len` is a numeric measure denoting the size of a list.

The magic of inference ensures that `pack` just works. Notice there is a tricky little recursive loop `go` that is used to recursively fill in the ByteString and actually, it has a rather subtle type signature that LiquidHaskell is able to automatically infer.

Exercise 11.4 (Pack Invariant). Exercise 11.1. ⋆ Still, we’re here to learn, so can you write down the type signature for the `pLoop` so that the below variant of `pack` is accepted by LiquidHaskell (Do this without cheating by peeping at the type inferred for `go` above!)
packEx str = create' n $ \p -> pLoop p xs
  where
    n = length str
    xs = map c2w str

{-# pLoop :: (Storable a) => p:Ptr a -> xs:[a] -> IO () #-}
pLoop p (x:xs) = poke p x >> pLoop (plusPtr p 1) xs
pLoop _ [] = return ()

Hint: Remember that \texttt{n} \texttt{\texttt{xs}} denotes the size of the list \texttt{xs}.

Exercise 11.5 (Unsafe Take and Drop). The functions \texttt{unsafeTake} and \texttt{unsafeDrop} respectively extract the prefix and suffix of a ByteString from a given position. They are really fast since we only have to change the offsets. But why does LiquidHaskell reject them? Can you fix the specifications so that they are accepted?

{-@ unsafeTake :: n:Nat -> b:_ -> ByteStringN n @-}
unsafeTake n (BS x s _) = BS x s n

{-@ unsafeDrop :: n:Nat -> b:_ -> ByteStringN {bLen b - n} @-}
unsafeDrop n (BS x s l) = BS x (s + n) (l - n)

Hint: Under what conditions are the returned ByteStrings legal?

To \texttt{Unpack} a ByteString into a plain old String, we essentially run \texttt{pack} in reverse, by walking over the pointer, and reading out the characters one by one till we reach the end:

unpack :: ByteString -> String
unpack (BS _ _ 0) = []
unpack (BS ps s l) = unsafePerformIO
  $ withForeignPtr ps
  $ \p -> go (p `plusPtr` s) (l - 1) []

  where
    {-@ go :: p:_ -> n:_ -> acc:_ -> IO {v:_ | true } #-}
g o p \theta acc = peekAt p \theta >>= \e -> return (w2c e : acc)
g o p n acc = peekAt p n >>= \e -> go p (n-1) (w2c e : acc)
peekAt p n = peek (p `plusPtr` n)

Exercise 11.6 (Unpack). \texttt{\textbullet} Fix the specification for \texttt{unpack} so that the below QuickCheck style property is proved by LiquidHaskell.
**Case Study: Pointers & Bytes**

```haskell
{-# prop_unpack_length :: ByteString -> TRUE #-}
prop_unpack_length b = bLen b == length (unpack b)
```

*Hint:* You will also have to fix the specification of the helper `go`. Can you determine the output refinement should be (instead of just `true`?)

How big is the output list in terms of `p`, `n` and `acc`.

**Application API**

Finally, let’s revisit our potentially “bleeding” `chop` function to see how the refined `ByteString` API can prevent errors. We require that the prefix size `n` be less than the size of the input string `s`:

```haskell
{-# chop :: s: b: String -> n:BNat (len s) -> String #-
chop s n = s'
where
  b    = pack s -- down to low-level
  b'   = unsafeTake n b -- grab n chars
  s'   = unpack b' -- up to high-level
```

Overflows are prevented by LiquidHaskell, as it rejects calls to `chop` where the prefix size is too large which is what led to the overflow that spilled the contents of memory after the string (cf. Figure 11.1). In the code below, the first use of `chop` which defines `ex6` is accepted as `6 <= len ex` but the second call is rejected as `30 > len ex`.

```haskell
demo = [ex6, ex30]
where
  ex   = ['L','I','Q','U','I','D']
  ex6  = chop ex 6 -- accepted by LH
  ex30 = chop ex 30 -- rejected by LH
```

Fix the specification for `chop` so that the following property is proved:

```haskell
{-# prop_chop_length :: String -> Nat -> TRUE #-
prop_chop_length s n
  | n <= length s  = length (chop s n) == n
  | otherwise      = True
```
Exercise 11.7 (Checked Chop). In the above, we know statically that the string is longer than the prefix, but what if the string and prefix are obtained dynamically, e.g. as inputs from the user? Fill in the implementation of `ok` below to ensure that `chop` is called safely with user specified values:

```haskell
safeChop :: String -> Int -> String
safeChop str n = chop str n
    | ok = chop str n
    | otherwise = ""
    where
        ok = True

queryAndChop :: IO String
queryAndChop = do
    putStrLn "Give me a string:"
    str <- getLine
    putStrLn "Give me a number:"
    ns <- getLine
    let n = read ns :: Int
    return $ safeChop str n
```

Nested ByteStrings

For a more in-depth example, let’s take a look at `group`, which transforms strings like "foobaaar" into lists of strings like ["f", "oo", "b", "aaa", "r"]. The specification is that `group` should produce a

1. list of non-empty ByteStrings,
2. the sum of whose lengths equals that of the input string.

Non-empty ByteStrings are those whose length is non-zero:

```haskell
{-# predicate Null B = bLen B == 0 #-}
{-# type ByteStringNE = {v:ByteString | not (Null v)} #-}

We can use these to enrich the API with a null check

```haskell
{-# null :: b:_ -> {v:Bool | v <=< Null b} #-}
null (BS _ _ l) = l == 0

This check is used to determine if it is safe to extract the head and tail of the ByteString. we can use refinements to ensure the safety of the operations and also track the sizes. ¿

\* `peekByteOff p i` is equivalent to `peek (plusPtr p i).`
The `group` function recursively calls `spanByte` to carve off the next group, and then returns the accumulated results:

```haskell
{-@ group :: b:_ -> {v: [ByteStringNE] | bsLen v = bLen b} @-}
group xs
| null xs = []
| otherwise = let y = unsafeHead xs
               (ys, zs) = spanByte y (unsafeTail xs)
               in (y `cons` ys) : group zs
```

The first requirement, that the groups be non-empty is captured by the fact that the output is a `[ByteStringNE]`. The second requirement, that the sum of the lengths is preserved, is expressed by a writing a numeric measure:

```haskell
{-@ measure bsLen @-}
bsLen :: [ByteString] -> Int
bsLen [] = 0
bsLen (b:bs) = bLen b + bsLen bs
```

`spanByte` does a lot of the heavy lifting. It uses low-level pointer arithmetic to find the first position in the `ByteString` that is different from the input character `c` and then splits the `ByteString` into a pair comprising the prefix and suffix at that point. (If you filled in the relevant type signatures above, the below code should typecheck even after you delete the assume from the specification.)

```haskell
{-@ assume spanByte :: Word8 -> b:ByteString -> ByteString2 b @-}
spanByte c ps@(BS x s ln)
  = unsafePerformIO
    $ withForeignPtr x $ \p ->
      go (p `plusPtr` s) 0
where
  go p i
```
| i >= ln | return (ps, empty) |
| otherwise | do c' <- peekByteOff p i |
|           | if c /= c' |
|           | then return (splitAt i) |
|           | else go p (i+1) |

splitAt i = (unsafeTake i ps, unsafeDrop i ps)

LiquidHaskell infers that $0 \leq i \leq 1$ and therefore that all of the memory accesses are safe. Furthermore, due to the precise specifications given to unsafeTake and unsafeDrop, it is able to prove that the output pair’s lengths add up to the size of the input ByteString.

```haskell
{-# type ByteString2 B
   = {v:_ | bLen (fst v) + bLen (snd v) = bLen B} #-}
```

**Recap: Types Against Overflows**

In this chapter we saw a case study illustrating how measures and refinements enable safe low-level pointer arithmetic in Haskell. The take away messages are that we can:

1. *compose* larger systems from layers of smaller ones,
2. *refine* APIs for each layer, which can be used to
3. *design and validate* the layers above.

We saw this recipe in action by developing a low-level Pointer API, using it to implement fast ByteStrings API, and then building some higher-level functions on top of the ByteStrings.

The **Trusted Computing Base** in this approach includes exactly those layers for which the code is *not* available, for example, because they are implemented outside the language and accessed via the FFI as with mallocForeignPtrBytes and peek and poke. In this case, we can make progress by *assuming* the APIs hold for those layers and verify the rest of the system with respect to that API. It is important to note that in the entire case study, it is only the above FFI signatures that are *trusted*; the rest are all verified by LiquidHaskell.
Case Study: AVL Trees

One of the most fundamental abstractions in computing is that of a collection of values – names, numbers, records – into which we can rapidly insert, delete and check for membership.

Trees offer an attractive means of implementing collections in the immutable setting. We can order the values to ensure that each operation takes time proportional to the path from the root to the datum being operated upon. If we additionally keep the tree balanced then each path is small (relative to the size of the collection), thereby giving us an efficient implementation for collections.

As in real life

maintaining order and balance is rather easier said than done. Often we must go through rather sophisticated gymnastics to ensure everything is in its right place. Fortunately, LiquidHaskell can help. Lets see a concrete example, that should be familiar from your introductory data structures class: the Georgy Adelson-Velsky and Landis’ or AVL Tree.

AVL Trees

An AVL tree is defined by the following Haskell datatype:\(^1\)

```haskell
data AVL a =
  Leaf
| Node { key :: a -- value
      , l :: AVL a -- left subtree
      , r :: AVL a -- right subtree
}
```

\(^1\) This chapter is based on code by Michael Beaumont.
While the Haskell type signature describes any old binary tree, an AVL tree like that shown in Figure 12.1 actually satisfies two crucial invariants: it should be binary search ordered and balanced.

A Binary Search Ordered tree is one where at each Node, the values of the left and right subtrees are strictly less and greater than the values at the Node. In the tree in Figure 12.1 the root has value 50 while its left and right subtrees have values in the range 9–23 and 54–76 respectively. This holds at all nodes, not just the root. For example, the node 12 has left and right children strictly less and greater than 12.

A Balanced tree is one where at each node, the heights of the left and right subtrees differ by at most 1. In Figure 12.1, at the root, the heights of the left and right subtrees are the same, but at the node 72 the left subtree has height 2 which is one more than the right subtree.

The Invariants Lead To Fast Operations.

Order ensures that there is at most a single path of left and right moves from the root at which an element can be found; balance ensures that each such path in the tree is of size $O(\log n)$ where $n$ is the numbers of nodes. Thus, together they ensure that the collection operations are efficient: they take time logarithmic in the size of the collection.

Specifying AVL Trees

The tricky bit is to ensure order and balance. Before we can ensure anything, let’s tell LiquidHaskell what we mean by these terms, by defining legal or valid AVL trees.

To Specify Order we just define two aliases AVL.L and AVL.R – read AVL-left and AVL-right – for trees whose values are strictly less than and greater than some value $x$: 
The real height of a tree is defined recursively as $0$ for leaves and one more than the larger of left and right subtrees for nodes. Note that we cannot simply use the $ah$ field because that’s just some arbitrary Int – there is nothing to prevent a buggy implementation from just filling that field with $0$ everywhere. In short, we need the ground truth: a measure that computes the actual height of a tree.\footnote{FIXME: The inline pragma indicates that the Haskell functions can be directly lifted into and used inside the refinement logic and measures.}

```haskell
{-@ measure realHeight @-}
realHeight :: AVL a -> Int
realHeight Leaf = 0
realHeight (Node _ l r _) = nodeHeight l r

{-@ inline nodeHeight @-}
nodeHeight l r = 1 + max hl hr
  where
    hl = realHeight l
    hr = realHeight r

{-@ inline max @-}
max :: Int -> Int -> Int
max x y = if x > y then x else y
```

A reality check predicate ensures that a value $v$ is indeed the real height of a node with subtrees $l$ and $r$:

```haskell
{-@ inline isReal @-}
isReal v l r = v == nodeHeight l r
```

A node is $n$-balanced if its left and right subtrees have a (real) height difference of at most $n$. We can specify this requirement as a predicate $\text{isBal l r n}$

```haskell
{-@ inline isBal @-}
isBal l r n = 0 - n <= d && d <= n
  where
    d = realHeight l - realHeight r
```
A legal AVL Tree can now be defined via the following refined data type, which states that each Node is 1-balanced, and that the saved height field is indeed the real height:

```
{-@ data AVL a = Leaf
    | Node { key :: a
           , l  :: AVL a key
           , r  :: {v:AVL a key | isBal l v 1}
           , ah :: {v:Nat | isReal v l r}
           } @-}
```

**Smart Constructors**

Let’s use the type to construct a few small trees which will also be handy in a general collection API. First, let’s write an alias for trees of a given height:

```
-- | Trees of height N
{-@ type AVLN a N = {v: AVL a | realHeight v = N} @-}

-- | Trees of height equal to that of another T
{-@ type AVLT a T = AVLN a {realHeight T} @-}
```

An Empty collection is represented by a Leaf, which has height 0:

```
{-@ empty :: AVLN a 0 @-}
empty = Leaf
```

**Exercise 12.1 (Singleton).** Consider the function `singleton` that builds an AVL tree from a single element. Fix the code below so that it is accepted by LiquidHaskell.

```
{-@ singleton :: a -> AVLN a 1 @-}
singleton x = Node x empty empty 0
```

As you can imagine, it can be quite tedious to keep the saved height field `ah` in sync with the real height. In general in such situations, which arose also with lazy queues, the right move is to eschew the data constructor and instead use a smart constructor that will fill in the appropriate values correctly. ³

The Smart Constructor `node` takes as input the node’s value `x`, left and right subtrees `l` and `r` and returns a tree by filling in the right value for the height field.
Exercise 12.2 (Constructor). Unfortunately, LiquidHaskell rejects the above smart constructor `node`. Can you explain why? Can you fix the code (implementation or specification) so that the function is accepted?

Hint: Think about the (refined) type of the actual constructor `Node`, and the properties it requires and ensures.

Inserting Elements

Next, let’s turn our attention to the problem of adding elements to an AVL tree. The basic strategy is this:

1. Find the appropriate location (per ordering) to add the value,
2. Replace the `Leaf` at that location with the singleton value.

If you prefer the spare precision of code to the informality of English, here is a first stab at implementing insertion:

Unfortunately `insert0` does not work. If you did the exercise above, you can replace it with `mkNode` and you will see that the above function is rejected by LiquidHaskell. The error message would essentially say that at the calls to the smart constructor, the arguments violate the balance requirement.
Insertion Increases The Height of a sub-tree, making it too large relative to its sibling. For example, consider the tree t0 defined as:

```haskell
ghci> let t0 = Node { key = 'a'
          , l  = Leaf
          , r  = Node {key = 'd'
                        , l  = Leaf
                        , r  = Leaf
                        , ah = 1 }
          , ah = 2}
```

If we use `insert0` to add the key 'e' (which goes after 'd') then we end up with the result:

```haskell
ghci> insert0 'e' t0
Node { key = 'a'
          , l  = Leaf
          , r  = Node { key = 'd'
                        , l  = Leaf
                        , r  = Node { key = 'e'
                                      , l  = Leaf
                                      , r  = Leaf
                                      , ah = 1 }
                        , ah = 1 }
          , ah = 2 }
```

In the above, illustrated in Figure 12.2 the value 'e' is inserted into the valid tree t0; it is inserted using `insR0`, into the right subtree of t0 which already has height 1 and causes its height to go up to 2 which is too large relative to the empty left subtree of height 0.

LiquidHaskell catches the imbalance by rejecting `insert0`. The new value y is inserted into the right subtree r, which (may already be bigger than the left by a factor of 1). As insert can return a tree with arbitrary height, possibly much larger than 1 and hence, LiquidHaskell rejects the call to the constructor `node` as the balance requirement does not hold.

Two lessons can be drawn from the above exercise. First, `insert` may increase the height of a tree by at most 1. So, second, we need a way to rebalance sibling trees where one has height 2 more than the other.
Rebalancing Trees

The brilliant insight of Adelson-Velsky and Landis was that we can, in fact, perform such a rebalancing with a clever bit of gardening. Suppose we have inserted a value into the left subtree l to obtain a new tree l' (the right case is symmetric.)

The relative heights of l' and r fall under one of three cases:

• (RightBig) r is two more than l',
• (LeftBig) l' is two more than r, and otherwise
• (NoBig) l' and r are within a factor of 1,

We can specify these cases as follows.

{-@ inline leftBig @-}
leftBig l r = diff l r == 2

{-@ inline rightBig @-}
rightBig l r = diff r l == 2

{-@ inline diff @-}
diff s t = getHeight s - getHeight t

the function getHeight accesses the saved height field.

{-@ measure getHeight @-}
g getHeight Leaf = 0
getHeight (Node _ _ _ n) = n

In insL, the RightBig case cannot arise as l' is at least as big as l, which was within a factor of 1 of r in the valid input tree t. In NoBig, we can safely link l' and r with the smart constructor as they satisfy the balance requirements. The LeftBig case is the tricky one: we need a way to shuffle elements from the left subtree over to the right side.

What is a LeftBig tree? Let's split into the possible cases for l', immediately ruling out the empty tree because its height is 0 which cannot be 2 larger than any other tree.

• (NoHeavy) the left and right subtrees of l' have the same height,
• \textit{(LeftHeavy)} the left subtree of $l'$ is bigger than the right,
• \textit{(RightHeavy)} the right subtree of $l'$ is bigger than the left.

The \textbf{Balance Factor} of a tree can be used to make the above cases precise. Note that while the \texttt{getHeight} function returns the saved height (for efficiency), thanks to the invariants, we know it is in fact equal to the realHeight of the given tree.

\begin{verbatim}
{-@ measure balFac @-}
balFac Leaf    = 0
balFac (Node _ l r _) = getHeight l - getHeight r
\end{verbatim}

\textbf{Heaviness} can be encoded by testing the balance factor:

\begin{verbatim}
{-@ inline leftHeavy @-}
leftHeavy t = balFac t > 0

{-@ inline rightHeavy @-}
rightHeavy t = balFac t < 0

{-@ inline noHeavy @-}
noHeavy t = balFac t == 0
\end{verbatim}

Adelson-Velsky and Landis observed that once you’ve drilled down into these three cases, the shuffling suggests itself.

\begin{figure}[h]
\centering
\includegraphics[width=0.8\textwidth]{figure12.3.png}
\caption{Rotating when in the \textit{LeftBig, NoHeavy} case.}
\end{figure}

In the \textit{NoHeavy} case, illustrated in Figure 12.3, the subtrees $ll$ and $lr$ have the same height which is one more than that of $r$. Hence, we can link up $lr$ and $r$ and link the result with $l$. Here’s how you would implement the rotation. Note how the preconditions capture the exact case we’re in: the left subtree is \textit{NoHeavy} and the right subtree is smaller than the left by 2. Finally, the output type captures the exact height of the result, relative to the input subtrees.
In the LeftHeavy case, illustrated in Figure 12.4, the subtree $ll$ is larger than $lr$; hence $lr$ has the same height as $r$, and again we can link up $lr$ and $r$ and link the result with $l$. As in the NoHeavy case, the input types capture the exact case, and the output the height of the resulting tree.

In the RightHeavy case, illustrated in Figure 12.5, the subtree $lr$ is larger than $ll$. We cannot directly link it with $r$ as the result would again be too large. Hence, we split it further into its own subtrees.
lr1 and lr2 and link the latter with r. Again, the types capture the
requirements and guarantees of the rotation.

{-@ balLR :: x:a
    -> l:{AVLL a x | rightHeavy l}
    -> r:{AVLR a x | leftBig l r}
    -> AVLT a l
    @-}
balLR v (Node lv ll (Node lrv lr1 lr2 _) _) r
= node lrv (node lv ll lr1) (node v lr2 r)

The RightBig cases are symmetric to the above cases where the left
subtree is the larger one.

Exercise 12.3 (RightBig, NoHeavy). Fix the implementation of balR0 so
that it implements the given type.

{-@ balR0 :: x:a
    -> l: AVLL a x
    -> r: {AVLR a x | rightBig l r && noHeavy r}
    -> AVLN a {realHeight r + 1}
    @-}
balR0 v l r = undefined

Exercise 12.4 (RightBig, RightHeavy). Fix the implementation of balRR so
that it implements the given type.

{-@ balRR :: x:a
    -> l: AVLL a x
    -> r: {AVLR a x | rightBig l r && rightHeavy r}
    -> AVLT a r
    @-}
balRR v l r = undefined

Exercise 12.5 (RightBig, LeftHeavy). Fix the implementation of balRL so
that it implements the given type.

{-@ balRL :: x:a
    -> l: AVLL a x
    -> r: {AVLR a x | rightBig l r && leftHeavy r}

    @-}
To **correctly insert** an element, we recursively add it to the left or right subtree as appropriate and then determine which of the above cases hold in order to call the corresponding *rebalance* function which restores the invariants.

```haskell
{-# insert :: a -> s:AVL a -> {t: AVL a | eqOrUp s t} #-}
insert y Leaf = singleton y
insert y (Node x _ _ _) | y < x = insL y t
                            | y > x = insR y t
                            | otherwise = t
```

The refinement, `eqOrUp` says that the height of `t` is the same as `s` or goes up by at most 1.

```haskell
{-# inline eqOrUp #-}
eqOrUp s t = d == 0 || d == 1
  where
d = diff t s
```

**The hard work** happens inside `insL` and `insR`. Here’s the first; it simply inserts into the left subtree to get `l'` and then determines which rotation to apply.

```haskell
{-# insL :: x:a
        -> t:(AVL a | x < key t && 0 < realHeight t) -> {v: AVL a | eqOrUp t v} #-}
insL a (Node v l r _) | isLeftBig && leftHeavy l' = balLL v l' r
                      | isLeftBig && rightHeavy l' = balLR v l' r
                      | otherwise = node v l' r
  where
    isLeftBig = leftBig l' r
    l' = insert a l
```

**Exercise 12.6 (InsertRight).** *The code for insR is symmetric. To make sure you’re following along, why don’t you fill it in?*
Refactoring Rebalance

Next, let’s write a function to delete an element from a tree. In general, we can apply the same strategy as insert:

1. remove the element without worrying about heights,
2. observe that deleting can decrease the height by at most 1,
3. perform a rotation to fix the imbalance caused by the decrease.

We painted ourselves into a corner with insert: the code for actually inserting an element is intermingled with the code for determining and performing the rotation. That is, see how the code that determines which rotation to apply – leftBig, leftHeavy, etc. – is inside the insL which does the insertion as well. This is correct, but it means we would have to repeat the case analysis when deleting a value, which is unfortunate.

Instead let’s refactor the rebalancing code into a separate function, that can be used by both insert and delete. It looks like this:

```haskell
{-# bal :: x:a
    -> l:AVLL a x
    -> r:{AVLR a x | isBal l r 2}
    -> {t:AVL a | reBal l r t}
  #-}

bal v l r
| isLeftBig && leftHeavy l = balLL v l r
| isLeftBig && rightHeavy l = balLR v l r
| isLeftBig = balL0 v l r
| isRightBig && leftHeavy r = balRL v l r
| isRightBig && rightHeavy r = balRR v l r
| isRightBig = balR0 v l r
| otherwise = node v l r
where
```
The bal function is a combination of the case-splits and rotation calls made by insL (and ahem, insR); it takes as input a value x and valid left and right subtrees for x whose heights are off by at most 2 because as we will have created them by inserting or deleting a value from a sibling whose height was at most 1 away. The bal function returns a valid AVL tree, whose height is constrained to satisfy the predicate \( \text{reBal} l r t \), which says:

- (bigHt) The height of t is the same or one bigger than the larger of l and r, and
- (balHt) If l and r were already balanced (i.e. within 1) then the height of t is exactly equal to that of a tree built by directly linking l and r.

```haskell
{-@ inline reBal @-}
reBal l r t = bigHt l r t && balHt l r t

{-@ inline balHt @-}
balHt l r t = not (isBal l r 1) || isReal (realHeight t) l r

{-@ inline bigHt @-}
bigHt l r t = lBig && rBig
  where
  lBig = not (hl >= hr) || (eqOrUp l t)
  rBig = (hl >= hr) || (eqOrUp r t)
  hl = realHeight l
  hr = realHeight r
```

Insert can now be written very simply as the following function that recursively inserts into the appropriate subtree and then calls bal to fix any imbalance:

```haskell
{-@ insert' :: a -> s:AVL a -> {t: AVL a | eqOrUp s t} @-}
insert' a t@(Node v l r n)
  | a < v     = bal v (insert' a l) r
  | a > v     = bal v l (insert' a r)
  | otherwise = t
insert' a Leaf = singleton a
```
Deleting Elements

Now we can write the `delete` function in a manner similar to `insert`: the easy cases are the recursive ones; here we just delete from the subtree and summon `bal` to clean up. Notice that the height of the output `t` is at most 1 less than that of the input `s`.

```haskell
{-@ delete :: a -> s:AVL a -> {t:AVL a | eqOrDn s t} @-}
delete y (Node x l r _) |
  y < x = bal x (delete y l) r |
  x < y = bal x l (delete y r) |
  otherwise = merge x l r
delete _ Leaf = Leaf

{-@ inline eqOrDn @-}
eqOrDn s t = eqOrUp t s
```

The tricky case is when we actually find the element that is to be removed. Here, we call `merge` to link up the two subtrees `l` and `r` after hoisting the smallest element from the right tree `r` as the new root which replaces the deleted element `x`.

```haskell
{-@ merge :: x:a -> l:AVLL a x -> r:{AVLR a x | isBal l r 1} -> {t:AVL a | bigHt l r t} @-}
merge _ Leaf r = r
merge _ l Leaf = l
merge x l r  = bal y l r'
  where
    (y, r') = getMin r
```

`getMin` recursively finds the smallest (i.e. leftmost) value in a tree, and returns the value and the remainder tree. The height of each remainder `l'` may be lower than `l` (by at most 1.) Hence, we use `bal` to restore the invariants when linking against the corresponding right subtree `r`.

```haskell
getMin (Node x Leaf r _) = (x, r)
getMin (Node x l r _)    = (x', bal x l' r)
  where
    (x', l') = getMin l
```
Functional Correctness

We just saw how to implement some tricky data structure gymnastics. Fortunately, with LiquidHaskell as a safety net we can be sure to have gotten all the rotation cases right and to have preserved the invariants crucial for efficiency and correctness. However, there is nothing in the types above that captures “functional correctness”, which, in this case, means that the operations actually implement a collection or set API, for example, as described here. Let’s use the techniques from that chapter to precisely specify and verify that our AVL operations indeed implement sets correctly, by:

1. **Defining** the set of elements in a tree,
2. **Specifying** the desired semantics of operations via types,
3. **Verifying** the implementation.  

We’ve done this once before already, so this is a good exercise to solidify your understanding of that material.

The **Elements** of an AVL tree can be described via a measure defined as follows:

```haskell
{-@ measure elems @-}
elems :: (Ord a) => AVL a -> S.Set a
elems (Node x l r _) = (S.singleton x)`S.union`
                    (elems l)`S.union`
                    (elems r)
elems Leaf = S.empty
```

Let us use the above measure to specify and verify that our AVL library actually implements a Set or collection API.

**Exercise 12.7 (Membership).** Complete the implementation of the implementation of member that checks if an element is in an AVL tree:

```haskell
{-@ member :: (Ord a) => x:a -> t:AVL a -> {v: Bool | v <=> hasElem x t} @-}
member x t = undefined

{-@ type BoolP P = {v:Bool | v <=> P} @-}
{-@ inline hasElem @-}
hasElem x t = True
{-@ FIXME hasElem x t = S.member x (elems t) @-}
```
Exercise 12.8 (Insertion). Modify `insert` to obtain a function `insertAPI` that states that the output tree contains the newly inserted element (in addition to the old elements):

```haskell
{-@ insertAPI :: (Ord a) => a -> s:AVL a -> {t:AVL a | addElem x s t} @-}
insertAPI x s = insert' x s
```

```haskell
{-@ inline addElem @-}
addelem :: Ord a => a -> AVL a -> AVL a -> Bool
addelem x s t = True
    -- FIXME addElem x s t = (elems t) == (elems s) \$ union \$(S.singleton x)
```

Exercise 12.9 (Insertion). Modify `delete` to obtain a function `deleteAPI` that states that the output tree contains the old elements minus the removed element:

```haskell
{-@ deleteAPI :: (Ord a) => a -> s:AVL a -> {t: AVL a | delElem x s t} @-}
deleteAPI x s = delete x s
```

```haskell
{-@ inline delElem @-}
delElem :: Ord a => a -> AVL a -> AVL a -> Bool
delElem x s t = True
    -- FIXME delElem x s t = (elems t) == (elems s) \$ difference \$(S.singleton x)