An investigation into the benefits of using type-safe functional programming

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1 Purpose

The purpose of this project is to investigate how Haskell works and how its features benefit the developers. This investigation will show why Haskell as a high level language is better than standard imperative languages in terms of safety, expressiveness, high-level abstractions, modularity and performance. A lot of the concepts that Haskell uses can be found in other functional programming languages and even in some imperative languages. Over the course of this project I will demonstrate how Haskell works, explain its concepts, and compare that with more commonly used languages and concepts.

2 Analysis

When we pick a programming language for a project we want it to have several features that will make the process of building the project faster and easier. In this investigation project I will identify the most important features that a general purpose high-level programming language should have and show how Haskell implements them. First, let's identify the main features that make high-level programming languages different from the low-level ones.

2.1 Goal

2.1.1 Safety

Usually programmers spend a lot of time finding and fixing bugs, which is a huge problem because for businesses it is crucial to deliver code as fast as possible. But what's an even bigger problem is programs crashing in production. This can cause businesses to lose a lot money or, in the worst cases, shut down. So we want programming languages to prevent as many bugs as possible.

A lot of run-time issues happen because of state changes. In most languages variables are mutable and functions can have side effects, this means that we can accidentally change a global variable and cause the entire program to crash.

Here are some examples of methods that we can use to solve this problem: type systems, automated tests, code checkers. Let's take a look at every one of these approaches. Not all languages have type systems, but even the ones that do usually allow dangerous actions like implicit casting. Automated tests are great and they help a lot, but it is hard to test every single thing, especially if the part of the code that you are testing depends on the state. Non-standard code checkers can help, but often they can't prevent even simple run-time errors.

2.1.2 Expressiveness

We want to write the least amount of code possible. At the same time we want the code to be readable and elegant. As I mentioned above the development speed is very important and it reduces if we can quickly express ideas without writing too much code.

To solve this problem most languages just create special syntax for common things, for example instead of just having while loops they also support for loops. This can help, but this approach has two problems: it clutters up the language and it doesn't solve the problem generally, this approach only adds hacks for common specific things.

2.1.3 High level abstractions

High-level languages allow developers to think just about solving the business problem and minimize the amount of the code that specifies what exactly happens inside the computer. There are two areas that are fundamental in programming - resource management and sequencing.[1] Most modern languages have tools like garbage collectors that automatically deal with resource management, however, as most languages are imperative, they force the programmer to specify the order of computations. This is because the main idea of imperative programming is to allow programmers to write a sequence of instructions that computer will execute. The only thing imperative languages can do to abstract sequencing is introducing new keywords and libraries, thus cluttering the language.

We also want to be able to work with complex abstractions and general versions of different types. For example if the only important aspect of a data structure is that it can be parsed from a string then we don't want to work with a specific type, we want to use the most general case possible. Also this helps avoiding errors.

2.1.4 Modularity

We want to reuse as much code as possible. We also should be able to easily compose different parts of a program together. This is one of the main concepts of programming.

2.1.5 Performance

Depending on what we are developing we have different performance requirements, so we want programming languages to help us make efficient programs. Of course using a high-level language for writing low-level applications like drivers is usually a bad idea, but high-level languages should work as fast as possible without loosing benefits of high-level languages.

2.2 How Haskell works

2.2.1 Hello World and more.

```haskell
main :: IO ()
main = print "Hello World!"
```

Now let's write a console program that asks user to input their name and then prints "Hello <username>!" Haskell's IO parts of the program can look very similar to "normal" programming languages.

```haskell
main :: IO ()
main = do
    print "What's your name?"
    name <- getLine
    print ("Hello " ++ name ++ "!")
```

But we can write this in functional style.

```haskell
main :: IO ()
main = print "What's your name?" >> getLine >>= print . (++ "!") . ("Hello " ++)
```

We will come back to both of these examples later.

2.2.2 Pure functions

Haskell is very different from most languages. In Haskell all variables are immutable. This means that you don't really have variables, you only have constants. Also in Haskell all functions are pure. A pure function a function that any time it gets called with the same arguments returns the same result. Pure functions don't have side effects; they can't print something to console, read files or modify variables. Functions in Haskell are like functions in maths, they are just mappings between types. These properties make testing and debugging code much easier.

2.2.3 Lazy evaluation

Another aspect that makes Haskell very different from an average programming language is the fact that by default it uses lazy evaluation. This means that functions won't get evaluated until the result is needed. When a program gets executed it won't do unnecessary computations.

2.2.4 Defining functions

Let's define a function `f` that squares a number in both Python and Haskell. Here is how it would look like in Python:

```
def f(x, y):
    return x*x + y*y
```

And here is the Haskell version:

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

In Haskell to pass arguments into a function we don't use brackets and/or commas, we separate arguments with spaces. As you can see the definition is very simple and it doesn't use any unnecessary syntax like `def` or `return`. It's just the function name, arguments and what it returns.

In Haskell functions and types are the two primary things and everything is centered around them, so it makes sense why defining them is really easy.

2.2.5 Introduction to the type system

In Haskell you don't need to explicitly declare types of functions or variables, the compiler will derive them for you. However, explicitly declaring types of functions and variables is a good practice. Let's declare the type of the previous function and then write a main function to test `f`.

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

main = print (f 2 3)
```

But what if we want function `f` to work with all numbers and not just integers. The first solution is to remove the type declaration, in that case our file would look like this:

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

main = print (f 2.1 4)
```

GHC (Glasgow Haskell Compiler) is the default Haskell compiler. Haskell can be both compiled and interpreted, which is why there is an interactive environment - GHCi, which you can use to run Haskell code without making a file for it. It can also tell us the type of any defined function. Let's use it to find the type of `f`.

```
Prelude> :load sum_squares.hs
[1 of 1] Compiling Main             ( sum_squares.hs, interpreted )
Ok, modules loaded: Main.
**Main> :t f
f :: Num a => a -> a -> a
**Main>
```

OK, let's figure out what that type is.

Type	Value
Int	An integer
Int -> Int	A function that takes an integer and returns an integer
Float -> Int	A function that takes a float and returns an integer
a -> Int	A function that takes a value of any type and returns an integer
a -> a	A function that takes a value of any type and returns something of the same type

In Haskell type `a -> a -> a` is the same as `a -> (a -> a)`. This means that this is a function that takes an argument of any type and returns a function that takes an argument of the same type and returns something of the same type, so basically it's a function with two arguments. The benefit of this representation is that we can give the function only one argument and get a valid expression which is a function. This is called partial application.

When in a type declaration you see something starting with a small letter, it means that it's a type variable. Type variables give us parametric polymorphism. Also, for example, if you have a function that takes two arguments of any type, but both arguments have the same type, you can specify that using type variables.

But our function type is not just `a -> a -> a`, it also has prefix `Num a =>`. This means that `a` is in the type class `Num`. Type classes are like interfaces in OOP languages. They declare a list of signatures of variables, functions, and types. A type is in a type class if it implements all the members of the type class.

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

Here is the definition of the type class `Num`. In Haskell operators are just normal functions. By writing `Num a =>` we restrict all possible types to only allow the ones that implement the functions listed above.

So the type `Num a => a -> a -> a` means that it's a function that takes a number and returns a function that takes another number of the same type and then returns a number of the same type. Technically all functions in Haskell take only one argument. But any function that takes two arguments can be represented as a function that takes one argument and returns a function. So the expression `f 3 4` is equivalent to `(f 3) 4` and `f 3` is a function.

To define functions we can use another notation - lambda functions.

```
f = \x y -> x*x + y*y
```

2.2.6 Basic minimum of Haskell

I will use `<=>` to show that two expressions are equivalent. This is not a part of the Haskell syntax.

1. Arithmetic operations

   ```
   3 + 2 * 6 / 3 <=> 3 + ((2 * 6) / 3)
   ```

2. Logic

```
True || False <=> True
True && False <=> False
True == False <=> False
True /= False <=> True
```

3. Powers

```
x ^ n  -- for non-negative integer powers
x ** y -- for floating numbers
```

4. Lists

```
[] -- empty list
[1, 2, 3] -- a list of numbers
["foo", "bar"] -- a list of strings
1:[2, 3] <=> [1, 2, 3] -- (:) prepends an element to a list
1:2:[] <=> [1, 2]
[1,2] ++ [3,4] <=> [1, 2, 3, 4] -- (++) joins two lists
[1,2] ++ ["?"] -- compilation error
[1..4] <=> [1, 2, 3, 4]
[1,3..10] <=> [1, 3, 5, 7, 9]
[2,3,5,7..100] -- error, the compiler is not that smart
[5,4..1] <=> [5, 4, 3, 2, 1]
head [1,2,3] <=> 1
tail [1,2,3] <=> [2,3]
```

5. Strings

   In Haskell strings are just lists of chars.

```
'a' :: Char
"a" :: [Char] -- :: String
"ab" -- ['a', 'b']
```

   This is not very efficient, which is why in most cases people use other data types that represent strings.

6. Tuples

```
-- All of these tuples are valid
(2,"foo")
(3,'a',[2,3])
((2,"a"),"c",3)

fst (x, y) = x
snd (x, y) = y

fst (x, y, z) -- ERROR: fst :: (a, b) -> a
snd (x, y, z) -- ERROR: snd :: (a, b) -> b
```

2.2.7 More on the syntax

1. Infix and prefix notation

   ```
   square :: Num a => a -> a
   square x = x ^ 2
   ```

   Any infix operator can be used in prefix notation.

   ```
   square' x = (^) x 2
   square'' x = (^2) x
   ```

   We can remove `x` from the right hand side, this is called η-reduction.

   ```
   square''' = (^2)
   ```

   All these functions are identical.

   And functions in Haskell can be used in infix notation as well.

   ```
   add :: Num a => a -> a -> a
   add = (+)

   5 `add` 4 <=> add 5 4 <=> 9
   ```

2. Conditions

   Type class `Ord` is for types that can be ordered.

   ```
   absolute :: (Ord a, Num a) => a -> a
   absolute x = if x >= 0 then x else -x
   ```

   In Haskell if statements must always have `then` and `else`.

   Here is another way to write that function:

   ```
   absolute' x
     | x >= 0 = x
     | otherwise = -x
   ```

   In Haskell indentation is very important. Just like in Python programs with incorrect indentation will not work or, in some cases, will work, but not the way it was intended. Haskell uses spaces instead of tabs, if you try to use tabs then the program won't compile.

2.2.8 Higher order functions

Higher order functions are functions that take another function as an argument. Here are several examples:

```
filter :: (a -> Bool) -> [a] -> [a]
map    :: (a -> b) -> [a] -> [b]
(.)    :: (b -> c) -> (a -> b) -> a -> c
($)    :: (a -> b) -> a -> b
```

Function `filter` takes a function of type `a -> Bool` and a list `[a]`. It returns a list that only contains the elements of the given list that return `True` when the given function is applied.

```
filter :: (a -> Bool) -> [a] -> [a]
filter f (x:xs) = if f x then x : filter f xs else filter f xs
filter f []     = []

filter even [1..5] <=> [2, 4]
```

map takes a function and a list and applies the function to every element of the list.

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

map (*2) [1..5] <=> [2,4,6,8,10]
```

(.) is function composition and ($) is function application.

```
(.) :: (b -> c) -> (a -> b) -> a -> c
(.) f g x = f (g x)

($) :: (a -> b) -> a -> b
($) f x = f x


f g h x <=> (((f g) h) x)

f g $ h x   <=> f g (h x)
f $ g h x   <=> f (g h x) <=> f ((g h) x)
f $ g $ h x <=> f (g (h x))

(f . g) x     <=> f . g $ x     <=> f (g x)
(f . g . h) x <=> f . g . h $ x <=> f (g (h x))
```

2.2.9 Defining your own types

1. type

   type TypeName = AnotherType just makes a type synonym of String.

   ```
   type Name = String
   ```

   Name and String are the same type. This is useful for making type declarations more meaningful.

2. data

   data NewDataType = TypeConstructor AnotherType is how we make a new simple type. This code makes a type constructor which is a special function that allows us to create instances of the NewDataType. We don't need to write an implementation for this function, we get it by defining the type.

   ```
   TypeConstructor :: AnotherType -> NewDataType
   ```

   Now AnotherType and NewDataType are two different types even though they represent the same data. This means that if we have a function that takes an argument of type AnotherType then it won't compile if we pass it something of type NewDataType. To extract data we can use pattern matching on type constructors.

```haskell
toOriginalType :: NewDataType -> AnotherType
toOriginalType (TypeConstructor thing) = thing
```

Constructors can have multiple arguments or none at all. We can use the name of the type as the constructor name, which is what people usually do when there is only one constructor.

```haskell
data Thing = Thing

data StringPair = StringPair String String
```

We can have types with multiple constructors.

```haskell
data MaybeString = JustString String | NoString
```

This code creates a new type `MaybeString` with two constructors: `JustString` and `NoString`. We can do pattern matching on both of the constructors.

```haskell
hasString :: MaybeString -> Bool
hasString (JustString _) = True
hasString NoString       = False
```

In pattern matching we can replace a variable with an underscore if we don't use that variable.

```haskell
data Person = Person String Int

name :: Person -> String
name (Person str _) = str

age :: Person -> String
age (Person _ n) = n
```

Instead of writing functions `name` and `age` we can use fields and the compiler will generate them.

```haskell
data Person = Person { name :: String
                     , age  :: Int
                     }
```

This gives us the same `name` and `age` functions.

2.2.10 Recursive types

1. Lists

   List is a common example of a recursive type. Here is how we can define the list type:

   ```haskell
   data List a = Empty | Cons a (List a)
   ```

   Type `List` takes another type as an argument. We can see two constructors, here are their types:

   ```haskell
   Empty :: List a
   Cons  :: a -> List a -> List a
   ```

   Haskell allows the use of special characters in names, this gives us the definition of lists from the standard library:

```
data [] a = [] | a : [a]
```

If we tried to print our new list it wouldn't work, because we don't have a function for conversion to string defined for it. Haskell has function `show :: Show a => a -> String` which is defined in the type class `Show`. So we can make our `List` an instance of `Show`. However, for predefined type classes, we can use a simpler approach. We can just derive that instance.

```
data List a = Empty | Cons a (List a)
     deriving (Show)
```

We can also derive type class instances for `Read` (parsing strings), `Eq` (checking for equality), `Ord` (ordering), etc. This way we can get a lot of functions for free.

```
data List a = Empty | Cons a (List a)
     deriving (Show, Read, Eq, Ord)
```

2. Trees

   Here is another example of a recursive data type - binary trees.

```
data BinTree a = Empty
               | Node a (BinTree a) (BinTree a)
               deriving (Show)
```

Because we used an arbitrary type variable `a` in the type declaration we can make a lot of different trees. For example we can make trees of trees.

2.2.11 Functors

The introduction up to this point is based on an article called "Learn Haskell Fast and Hard".[2]

Functor is one of the most important abstractions in Haskell. Basically, it is a type class that generalizes the `map` function.

```
class Functor f where
    fmap :: (a -> b) -> f a -> f b
```

The notion of functors comes from maths, and in maths there are laws for it. Unfortunately GHC doesn't support laws in type classes, so it's programmers' responsibility to make sure they work. The only relevant to Haskell law is that if we have two functions: `h :: a -> b` and `f :: b -> c` then for any functor `fmap (f . h)` should be the same as `fmap f . fmap h`. `<$>` is a infix operator for `fmap`.

```
f <$> x = fmap f x
```

Here are some examples of functors:

```
data Maybe a = Just a | Nothing

instance Functor Maybe where
    fmap f (Just x) = Just $ f x
    fmap _ Nothing  = Nothing

maybeFive :: Maybe Int
maybeFive = Just 5
```

```haskell
maybeSix :: Maybe Int
maybeSix = fmap (+1) maybeFive -- = Just 6

data [] a = [] | a : [a]

instance Functor [] where
    fmap f (x:xs) = f x : fmap f xs
    fmap _ []     = []
    -- fmap = map

data Either a b = Left a | Right b

instance Functor (Either a) where
    fmap f (Right x) = Right $ f x
    fmap _ (Left x)  = Left x

numberOrString :: Either Int String
numberOrString = Right "World"

numberOrHello :: Either Int String
numberOrHello = ("Hello " ++) <$> numberOrString -- Right "Hello World"

numOrStr :: Either Int String
numOrStr = Left 5

numOrHello :: Either Int String
numOrHello = ("Hello " ++) <$> numOrHello -- Left 5

data (,) a b = (,) a b

instance Functor ((,) a) where
    fmap f (x, y) = (x, f y)

pairOfNumbers :: (Int, Int)
pairOfNumbers = (2, 3)

incrementedPair :: (Int, Int)
incrementedPair = fmap (+1) pairOfNumbers -- = (2, 4)
```

2.2.12 Applicative functors

As you know `Maybe` is a functor. This is why we can do this:

```
Prelude> negate <$> Just 2
Just (-2)
```

But what if we want to add two `Maybe` numbers.

```
Prelude> :t (+) <$> Just 2
(+) <$> Just 2 :: Num a => Maybe (a -> a)
```

After we partially apply addition using `fmap` we get a function inside a functor. How to apply that function to our second `Maybe` number? Use applicative functors.

```
class Functor f => Applicative f where
    pure :: a -> f a
    <*>  :: f (a -> b) -> f a -> f b
```

`Maybe` is an applicative functor, hence we can do this:

```
Prelude> (+) <$> Just 2 <*> Just 3
Just 5
```

Applicative functors also have laws:

```
pure id  <*> v             <=> v                 -- identity
pure f   <*> pure x        <=> pure (f x)        -- homomorphism
u        <*> pure y        <=> pure ($ y) <*> u -- interchange
pure (.) <*> u <*> b <*> w <=> u <*> (v <*> w)   -- composition
```

Here are some examples of applicative functors:

```
data Maybe a = Just a | Nothing

instance Applicative Maybe where
    pure = Just
    (Just f) <*> (Just x) = Just $ f x
    _        <*> _        = Nothing

data [] a = [] | a : [a]

instance Applicative [] where
    pure x = [x]
    _      <*> [] = []
    []     <*> _  = []
    (f:fs) <*> l  = (f <$> l) ++ (fs <*> l)
    -- applied every function to every element of the list
```

2.2.13 Monads

```
headMay :: [a] -> Maybe a
headMay []    = Nothing
headMay (x:_) = Just x
```

Assume we have a list of lists and we want to safely get the first element of the first list. We can't use `head` as it will crash if you call it with an empty list, so we need to apply `headMay` twice. We can try using `fmap headMay . headMay`, but then we'll get this:

```
Prelude> :t fmap headMay . headMay
fmap headMay . headMay :: [[a]] -> Maybe (Maybe a)
```

We want to reduce `Maybe (Maybe a)` to just `Maybe a`. Another example is if we want to convert a list of lists into a single list. Both of these problems can be solved using monads. Here are some definitions:

```
const :: a -> b -> a
const x _ = x

class Applicative m => Monad m where
    (>>=) :: m a -> (a -> m b) -> m b
    (>>) :: m a -> m b -> m b
    x >> y = x >>= const y -- default implementation

instance Monad Maybe where
    (Just x) >>= f = f x
    Nothing  >>= _ = Nothing

instance Monad [] where
    (x:xs) >>= f = f x ++ (xs >>= f)
    []     >>= _ = []
```

Now for the first problem we can do this:

```
headMay l >>= headMay
```

`l` is the list of lists. And here is how we can solve the second problem:

```
Prelude> :t (>>= id)
(>>= id) :: Monad m => m (m b) -> m b
Prelude> [[1..5],[6..10]] >>= id
[1,2,3,4,5,6,7,8,9,10]
```

If we import `Control.Monad` we'll get several helper functions for working with monads.

```
join :: m (m a) -> m a
join = (>>= id)

(>=>) :: (a -> m b) -> (b -> m c) -> (a -> m c)
(>=>) f h = \x -> f x >>= h

Prelude> headMay l = if length l == 0 then Nothing else Just $ head l
Prelude> import Control.Monad
Prelude Control.Monad> :t join
join :: Monad m => m (m a) -> m a
Prelude Control.Monad> join [[1..5],[6..10]]
[1,2,3,4,5,6,7,8,9,10]
Prelude Control.Monad> :t headMay >=> headMay
headMay >=> headMay :: [[c]] -> Maybe c
```

2.2.14 IO

In Haskell functions are pure, however printing to console, reading/writing files, and other IO actions don't give the same results every time you call them. To deal with IO actions Haskell has a special monad - IO monad. This allows us to isolate pure and impure parts of the code. In our program we have `main` procedure which has type `IO ()`.

```
data () = ()
```

1. Printing to console

   ```
   putStr :: String -> IO ()   -- prints the given string
   putStrLn :: String -> IO () -- prints the given string and starts a new line
   print :: Show a => a -> IO ()
   print = putStrLn . show
   ```

   Now we can write a "Hello World" program.

   ```
   main :: IO ()
   main = print "Hello World!"
   ```

2. Reading user console input

   ```
   getChar :: IO Char
   getLine :: IO String
   ```

   Notice that these are not functions, they are IO actions. Now we can write a program that asks for the user's name and prints "Hello <username>!".

   ```
   main :: IO ()
   main = print "What's your name?" >> getLine >>= print . ("Hello " ++) . (++ "!")
   ```

3. Do notation

   We can use a simpler notation for monads that is more similar to imperative programming languages.

   ```
   main :: IO ()
   main = do print "What's your name?"
             name <- getLine
             print $ "Hello " ++ name ++ "!"
   ```

   In this case every line must be an IO action. This syntax is a nicer way of writing this:

   ```
   main :: IO ()
   main = print "What's your name?"
       >> getLine
      >>= \name -> print ("Hello " ++ name ++ "!")
   ```

   For the compiler these two things are identical. We can use do notation not only with the IO monad, but with any monad.

   ```
   headMay :: [a] -> Maybe a
   headMay (x:xs) = Just x
   headMay []     = Nothing

   headOfHead :: [[a]] -> Maybe a
   headOfHead l = do h <- headMay l
                     headMay h
   ```

2.3 Spec for the examples

To show that Haskell is better than other high-level programming languages I will solve several problems in Haskell and Ruby. Ruby is a high-level programming language, and it is almost the exact opposite of Haskell: it's imperative (although it supports some features from functional programming, as Haskell is one of the languages that Ruby was inspired by, I will avoid using them to show more differences between imperative and functional programming), dynamically typed, interpreted, and object oriented.

2.3.1 Example 1: Sorting a file

In this example I will write a script that reads numbers from a file, sorts them, and writes the sorted list to another file. Even though this investigation is about high-level languages, I decided to include a solution to this problem in a low-level language C. I did this to make a more representative performance comparison. In order to show this I will measure time taken for each of the scripts to process a file with one million random integers.

2.3.2 Example 2: reverse polish server

In this example I will implement a client-server system. The client takes an expression in reverse polish notation and an action (check or evaluate), then the expression gets sent to the server where the required action gets executed, finally the client shows the result of performing the given action on the given expression.

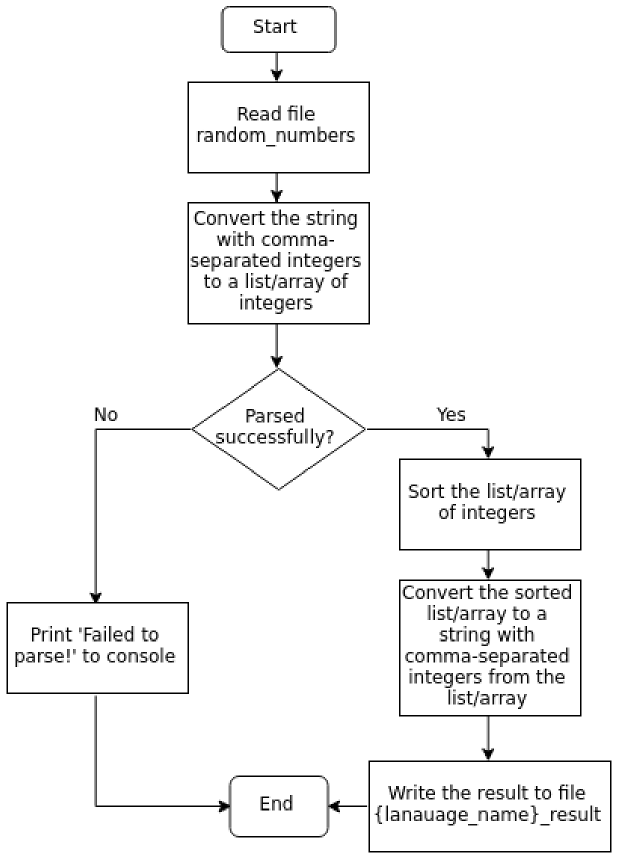
By comparing methods for defining and implementing an API this example is to show Haskell's safety, expressiveness, high-level abstractions, and modularity.

3 Sorting a file

3.1 Design

3.1.1 Algorithm

The script needs to read the file `"random_numbers"`, which contains comma-separated integers, parse the contents to get the list of integers, sort them, convert back to the original format, and write the result to the file `"{language}_result"` (where `{language}` is the name of the language that was used for the script).


Start
Read file random_numbers
Convert the string with comma-separated integers to a list/array of integers
Parsed successfully?
No
Yes
Sort the list/array of integers
Convert the sorted list/array to a string with comma-separated integers from the list/array
Print 'Failed to parse!' to console
Write the result to file {lanauage_name}_result
End

3.1.2 Tests

For testing the scripts I will write another script that generates a comma-separated list of integers in range $[1, 1000]$.

	Description	Test instructions	Expected result
1	Number generating script should work correctly.	Run the script to generate a file with 10 numbers. Inspect the file. Run the script again and inspect the new file.	Comma-separated list of integers in both files. The files should be different (though there is a small chance that the files will be the same , in this case just run the test again).
2	Outputs of the scripts for the same list of integers should be the same.	Generate a file with 10 integers, inspect it, run the script and inspect the output file. Generate a new file. Repeat the test.	Sorted comma-separated list of integers. With all the numbers from the randomly generated file.
3	Output of the sorting scripts for the same list of integers is the same.	Generate a file with 10 integers, run all 3 sorting scripts, check differences between the output files.	There should be no differences.

3.1.3 Benchmark

Generate a file with 1 million random integers, find how much time each script takes to execute.

3.2 Solution

3.2.1 Code

1. Haskell

```haskell
{-# LANGUAGE OverloadedStrings #-}

import qualified Data.ByteString.Lazy.Char8 as C
import           Data.List                  (sort)

main :: IO ()
main = C.readFile "random_numbers"
   >>= maybe (print "Failed to parse!")
             ( C.writeFile "haskell_result"
             . C.intercalate "," . fmap (C.pack . show) . sort . fmap fst
             ) . traverse C.readInt . C.split ','
```

The first line enables a language extension called `OverloadedStrings`. It allows us to use different types as strings. For example, in this script `"random_numbers"` is a standard string and "," is a byte string. The compiler can infer the right type of string from type definitions - the first argument of `C.readFile` is of type `String` and the first argument of `C.intercalate` is `ByteString`.

Then I imported two modules. The first one is from a library called `bytestring`. The default Haskell strings are very inefficient as they are just lists of characters, but there are different alternatives. One of them is using byte strings, which are arrays of bytes. There are two kinds of byte strings: strict and lazy. In this case I used a special version of lazy byte strings that interprets each byte as a character. The keyword `qualified` in the import statement means that the contents of the module won't be in the global namespace. `as C` means that we refer to the module as `C`. For example, we can write `C.pack` instead of `Data.ByteString.Lazy.Char8.pack`.

Secondly I imported sort function from the `Data.List` module. It's an implementation of the merge sort algorithm. One of classical examples of Haskell code, that shows how nice and expressive it is, is the Quicksort function.

```haskell
qsort :: Ord a => [a] -> [a]
qsort (x:xs) = qsort (filter (< x) xs) ++ [x] ++ qsort (filter (>= x) xs)
qsort []     = []
```

At first glance it looks similar to the quicksort algorithm, but it's actually less efficient. It uses the same idea - divide and conquer, however the performance of the original quicksort function relies on the very fast swap mechanism, which is not something we can easily do in Haskell. As Haskell uses immutable data structures it doesn't swap any values in memory, it creates new ones. This is why merge sort is usually more efficient than quicksort in Haskell.

In `main` I have a composition of many different functions. Let's quickly take a look at every one of them.

```haskell
C.readFile :: FilePath -> IO C.ByteString
```

`FilePath` is a type synonym for `String`. `C.readFile` takes a file path and returns the contents of the file as a byte string.

```haskell
C.split :: Char -> C.ByteString -> [C.ByteString]
```

This function breaks a byte string into pieces separated by the first argument, consuming the delimiter.

```haskell
C.readInt :: C.ByteString -> Maybe (Int, C.ByteString)
```

`C.readInt` reads an `Int` from the beginning of the given byte string. If it fails to do that then it returns `Nothing`, otherwise it returns the integer and the rest of the string.

```haskell
class Foldable t where
  foldr :: (a -> b -> b) -> b -> t a -> b
```

```haskell
class (Functor t, Foldable t) => Traversable t where
  traverse :: Applicative f => (a -> f b) -> t a -> f (t b)
```

`traverse` maps each element of a structure to an action, evaluates these actions from left to right, and collects the result.

```haskell
traverse C.readInt :: Traversable t => t C.ByteString -> Maybe (t (Int, C.ByteString))
```

List is in the `Traversable` type class, which is why we can compose this with `C.split ','`.

```haskell
traverse C.readInt . C.split ',' :: C.ByteString -> Maybe [(Int, C.ByteString)]
```

```haskell
maybe :: b -> (a -> b) -> Maybe a -> b
```

The type fully explains what the function does.

```haskell
C.pack :: [Char] -> C.ByteString
```

`C.pack` takes a string and converts it into a byte string.

```haskell
C.intercalate :: C.ByteString -> [C.ByteString] -> C.ByteString
```

`C.intercalate` joins a list of byte strings, putting the first argument between each element of the list.

```haskell
fmap fst :: Functor f => f (b1, b2) -> f b1
```

```haskell
sort . fmap fst :: Ord a => [(a, b)] -> [a]
```

```haskell
C.pack . show :: Show a => a -> C.ByteString
```

```haskell
fmap (C.pack . show) . sort . fmap fst :: (Ord a, Show a) => [(a, b)] -> [C.ByteString]
```

```haskell
C.intercalate "," . fmap (C.pack . show) . sort . fmap fst
  :: (Ord a, Show a) => [(a, b)] -> C.ByteString
```

```haskell
C.writeFile :: FilePath -> C.ByteString -> IO ()
```

`C.writeFile` takes a file path and a byte string and writes the byte string to the file, overwriting existing data or creating the file if it doesn't exist.

```
C.readFile "random_numbers" :: IO C.ByteString

maybe (print "Failed to parse!")
      ( C.writeFile "haskell_result"
      . C.intercalate "," . fmap (C.pack . show) . sort . fmap fst
      ) . traverse C.readInt . C.split ','
      :: C.ByteString -> IO ()

(>>=) :: Monad m => m a -> (a -> m b) -> m b
```

If we put all these things together we'll get `main`. In summary, it reads numbers from `"random_numbers"`, splits the string with comma separated integers into a list of byte strings with integers, then parses each integer, prints "Failed to parse!" in case it fails to parse, otherwise sorts the list of integers, converts each integer back into a byte string, joins the byte strings and writes the result to `"haskell_result"`.

2. Ruby

```ruby
input_file_name = 'random_numbers'
output_file_name = 'ruby_result'

buffer = ''
numbers = []

# open the input file
File.open(input_file_name) do |f|
  # for each character c in the file
  f.each_char do |c|
    if c == ','
      # convert the buffer to an integer and add to the list of numbers
      numbers << Integer(buffer)
      # empty the buffer
      buffer = ''
    else
      # add the character to the buffer
      buffer << c
    end
  end

  # convert the buffer to an integer and add to the list of numbers
  numbers << Integer(buffer)
end

# sort the numbers
numbers = numbers.sort

# open the output file
File.open(output_file_name, 'w') do |f|
  # remove the last number from the list
  last = numbers.pop
  # write all the remaining numbers with a comma after each of them to the output file
  numbers.each { |num| f.write "#{num}," }
  # write the last element
  f.write last
end
```

3. C

```c
#define SIZE (1000000)
#define INPUT_FILE ("random_numbers")
#define OUTPUT_FILE ("c_result")

#include <stdio.h>
#include <stdlib.h>
#include <string.h>
```

```c
// Just difference of two numbers
int cmpfunc(const void * a, const void * b)
{
  return (*(int*)a - *(int*)b);
}

int main()
{
  // Initializing the file pointer
  FILE *fs;

  // current char and buffer for digits
  char ch, buffer[32];
  int i = 0, arr[SIZE], j = 0;

  // Openning the file with file handler as fs
  fs = fopen(INPUT_FILE, "r");

  // Read the file unless the file encounters an EOF
  for(ch = fgetc(fs); ; ch = fgetc(fs)) {
    if(ch == ',') {
      // Converting the content of the buffer into an array position
      arr[j] = atoi(buffer);

      // Increamenting the array position
      j++;

      // Clearing the buffer, this function takes two
      // arguments, one is a character pointer and
      // the other one is the size of the character array
      bzero(buffer, 32);

      // setting the buffer index to 0
      i = 0;
    }
    else if (ch != EOF) {
      // add the next character to the buffer
      buffer[i] = ch;
      // increment the buffer index
      i++;
    }
    else { // end of the file
      // add the number from the buffer to
      arr[j] = atoi(buffer);

      // end the loop
      break;
    }
  }
```

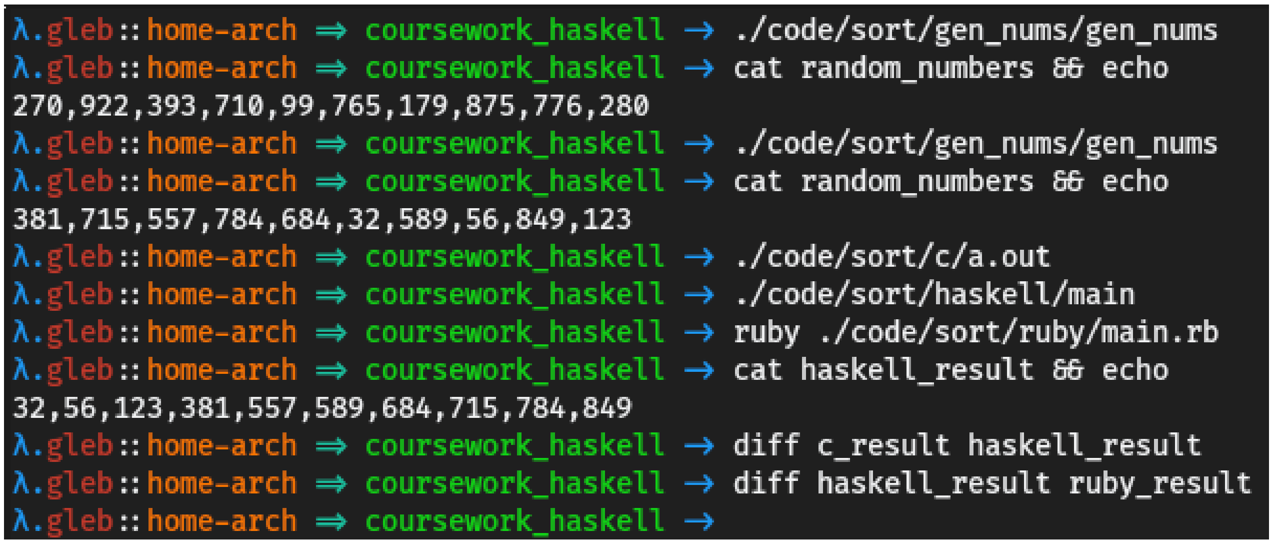
```
        // close the file
        fclose(fs);

        // sort the array
        qsort(arr, SIZE, sizeof(int), cmpfunc);

        // open the output file
        fs = fopen(OUTPUT_FILE, "w");

        // write every number (except the last one) with a comma after each
        for(i = 0; i < SIZE - 1; i++) {
          fprintf(fs, "%d,", arr[i]);
        }

        // write the last number
        fprintf(fs, "%d", arr[i]);

        // close the file
        fclose(fs);

        // return 0 (success code)
        return 0;
      }
```

3.2.2 Tests

I wrote a script that generates a list of random numbers in range $[1, 1000]$ and writes them to a file separated by commas to test the sorting script.

```
import Control.Monad
import System.Random

numOfNums :: Integer
numOfNums = 10

file :: FilePath
file = "random_numbers"

main :: IO ()
main =  join
     $  (\(r:rs) -> foldl (\p x -> p >> addToFile (',' : show x)) (writeFile file $ show r) rs)
    <$> foldl (\rs _ -> (:) <$> (randomRIO (1, 1000) :: IO Int) <*> rs) (return []) [1..numOfNums]
     where addToFile = appendFile file
```

I changed `SIZE` macro in the C script to `10` for the purpose of the test.



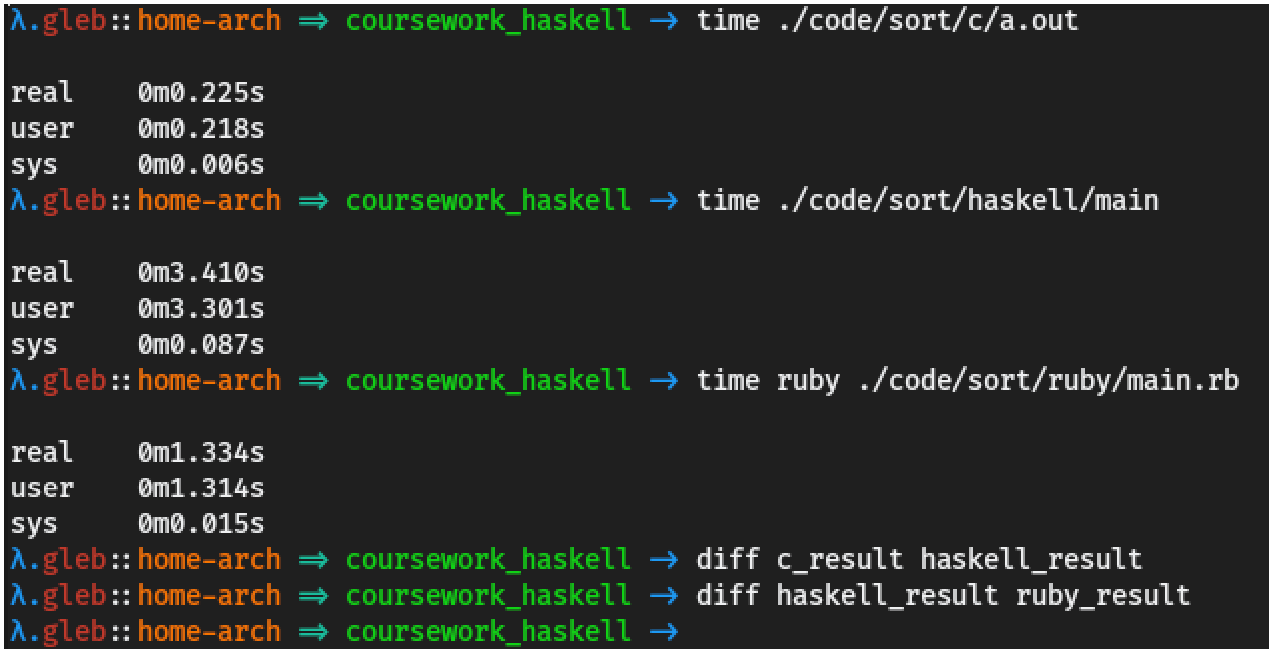
```
λ.gleb::home-arch ⇒ coursework_haskell → ./code/sort/gen_nums/gen_nums
λ.gleb::home-arch ⇒ coursework_haskell → cat random_numbers && echo
270,922,393,710,99,765,179,875,776,280
λ.gleb::home-arch ⇒ coursework_haskell → ./code/sort/gen_nums/gen_nums
λ.gleb::home-arch ⇒ coursework_haskell → cat random_numbers && echo
381,715,557,784,684,32,589,56,849,123
λ.gleb::home-arch ⇒ coursework_haskell → ./code/sort/c/a.out
λ.gleb::home-arch ⇒ coursework_haskell → ./code/sort/haskell/main
λ.gleb::home-arch ⇒ coursework_haskell → ruby ./code/sort/ruby/main.rb
λ.gleb::home-arch ⇒ coursework_haskell → cat haskell_result && echo
32,56,123,381,557,589,684,715,784,849
λ.gleb::home-arch ⇒ coursework_haskell → diff c_result haskell_result
λ.gleb::home-arch ⇒ coursework_haskell → diff haskell_result ruby_result
λ.gleb::home-arch ⇒ coursework_haskell →
```

I used some Linux commands to run the test. `cat` takes a file name and shows the file (if it exists). The scripts I wrote don't add a newline character at the end of files. To get a newline after the output of `cat`, I used `echo` command. It takes a string and prints it, I didn't give it any input, so it just print a newline. `diff` command shows differences between 2 files.

First I ran the first test to check that the number generating script works correctly. As you can see, it does. Then I ran all 3 sorting scripts, and did the second test on the output of the script written in Haskell. `haskell_result` contains the sorted list, so the test is passed. Then I ran test 3 and compared the 3 output files. `diff` command didn't show any differences, hence all the scripts work correctly.

3.2.3 Benchmark

I generated a file with one million random numbers (I changed macro `SIZE` in the C script back to a million) and measured the execution time using `time` command and tested that the output is correct by doing test 3 again.



```
λ.gleb::home-arch ⇒ coursework_haskell → time ./code/sort/c/a.out

real    0m0.225s
user    0m0.218s
sys     0m0.006s
λ.gleb::home-arch ⇒ coursework_haskell → time ./code/sort/haskell/main

real    0m3.410s
user    0m3.301s
sys     0m0.087s
λ.gleb::home-arch ⇒ coursework_haskell → time ruby ./code/sort/ruby/main.rb

real    0m1.334s
user    0m1.314s
sys     0m0.015s
λ.gleb::home-arch ⇒ coursework_haskell → diff c_result haskell_result
λ.gleb::home-arch ⇒ coursework_haskell → diff haskell_result ruby_result
λ.gleb::home-arch ⇒ coursework_haskell →
```

3.3 Evaluation

3.3.1 Safety

Let's take a look at the function `C.readInt`. It returns `Maybe (Int, C.ByteString)`. In most languages you can work with nullable types without checking if they are actually null, but Haskell doesn't allow that. It forces you to do something with the fact that a value can be `Nothing`. In this case I covered the case when it's `Nothing` by using the function `maybe` and providing the default behavior for that situation. If you want you can unsafely cast `Maybe a` to `a` using the function `fromJust` from the `Data.Maybe` module. However, the compiler won't make that decision for you and you'll have to explicitly tell it to do so.

If we ran the Ruby script and data in `random_numbers` file was incorrectly formatted then it would through an exception. In Ruby there are two ways of reading an integer from a string: `Integer` and method `String.to_i`. If we pass a string that doesn't represent an integer to `Integer`, it will throw an exception. If we call `.to_i` on that string then it will return `0` and we won't know if anything went wrong or not. Here is the Ruby script with exception handling:

```
input_file_name = 'random_numbers'
output_file_name = 'ruby_result'

buffer = ''
numbers = []

File.open(input_file_name) do |f|
  begin
  f.each_char do |c|
    if c == ','
      numbers << Integer(buffer)
      buffer = ''
    else
      buffer << c
    end
  end

  numbers << Integer(buffer)
  rescue(ArgumentError)
    puts 'Failed to parse!'
    exit
  end
end

numbers = numbers.sort

File.open(output_file_name, 'w') do |f|
  last = numbers.pop
  numbers.each { |num| f.write "#{num}," }
  f.write last
end
```

This requires more code and it delegates the task of checking whether fail cases were covered from the language to the developer. In Haskell you can write functions that can fail at run-time (but you can disable this using some compiler flags), but if you use a function that through the type system handles fail cases then the compiler will force you to deal with the fact that the function can fail. This makes Haskell a safe language.

3.3.2 Expressiveness

As you can see we didn't need a lot of code to solve the problem. If you take a look at the way the algorithm was described in English in 3.1.1 you'll see that the code I wrote does exactly that. We basically tell Haskell what we want to achieve and not how to achieve it.

```haskell
{-# LANGUAGE OverloadedStrings #-}

import qualified Data.ByteString.Lazy.Char8 as C
import Data.List (sort)

main :: IO ()
main = C.readFile "random_numbers" -- read the file "random_numbers"
   >>= maybe (print "Failed to parse!")
             ( C.writeFile "haskell_result" -- write the result to the file "haskell_result"
             . C.intercalate "," . fmap (C.pack . show) -- convert back to the original format
             . sort -- sort them
             . fmap fst ) . traverse C.readInt . C.split ',' -- parse comma-separated integers
```

In the Ruby solution, as you can see in the source code, the code represents a sequence of instructions which the computer needs to do. The Haskell version of the program has less code in it (even if we remove the comments) and the structure of the Haskell script is closer to the way the problem was defined in English, which shows us the expressiveness of the language.

3.3.3 Modularity

This script also shows how modular Haskell is. To solve the problem I just glue together 13 different functions using 2 operators. If we want to reuse some of the functionality we can easily extract the piece of code that does what we want from `main` and put it in another function. For example, let's say we want to reuse the code for parsing.

```haskell
{-# LANGUAGE OverloadedStrings #-}

import qualified Data.ByteString.Lazy.Char8 as C
import           Data.List                  (sort)

parse :: C.ByteString -> Maybe [Int]
parse = fmap (fmap fst) . traverse C.readInt . C.split ','

main :: IO ()
main = C.readFile "random_numbers"
   >>= maybe (print "Failed to parse!")
             ( C.writeFile "haskell_result"
             . C.intercalate "," . fmap (C.pack . show) . sort
             ) . parse
```

As you can see, in Haskell it's very easy to compose and decompose code.

3.3.4 Performance

As you can see in the benchmark results, Haskell didn't perform very well in this test. Why is that? I used `sort` function that applies mergesort algorithm on immutable lists. This is a problem for performance for several reasons: mergesort is not very fast (due to algorithm complexity), lists are not very fast (linked lists don't store all the data in one block, they use pointers to reference the next element), we need to allocate memory very often (because we're using an immutable sorting algorithm, so at each step of the algorithm `sort` creates new lists). I solved this problem by replacing the sort function. I used unboxed vectors (using `vector` library), safe (internal) mutations, and introspective sorting (using `vector-algorithms` library).

```haskell
{-# LANGUAGE OverloadedStrings #-}

import qualified Data.ByteString.Lazy.Char8   as C
import qualified Data.Vector.Algorithms.Intro as Alg
import qualified Data.Vector.Unboxed          as U

sort :: (Ord a, U.Unbox a) => [a] -> [a]
sort = U.toList . U.modify Alg.sort . U.fromList

main :: IO ()
main = C.readFile "random_numbers"
   >>= maybe (print "Failed to parse!")
             ( C.writeFile "haskell_result"
             . C.intercalate "," . fmap (C.pack . show) . sort . fmap fst
             ) . traverse C.readInt . C.split ','
```

1. Unboxed vectors

   `vector` library provides efficient arrays. Unboxed types are raw values. So boxed (default) vectors are arrays of pointers and unboxed vectors are arrays of raw values.

   ```haskell
   U.fromList :: U.Unbox a => [a] -> U.Vector a
   U.toList :: U.Unbox a => U.Vector a -> [a]
   ```

   As you can guess from the names and types `U.fromList` converts a list of values that can be represented as raw values to an unboxed vector and `U.toList` converts an unboxed vector to a list.

2. Introsort

   Introspective sorting or introsort is an optimised version of quicksort. From the description of the module `Data.Vector.Algorithms.Intro`:

   > This module implements various algorithms based on the introsort algorithm, originally described by David R. Musser in the paper *Introspective Sorting and Selection Algorithms*. It is also in widespread practical use, as the standard unstable sort used in the C++ Standard Template Library.
   >
   > Introsort is at its core a quicksort. The version implemented here has the following optimizations that make it perform better in practice:
   >
   > - Small segments of the array are left unsorted until a final insertion sort pass. This is faster than recursing all the way down to one-element arrays.
   > - The pivot for segment [l,u) is chosen as the median of the elements at l, u-1 and (u+l)/2. This yields good behavior on mostly sorted (or reverse-sorted) arrays.
   > - The algorithm tracks its recursion depth, and if it decides it is taking too long (depth greater than 2 * lg n), it switches to a heap sort to maintain O(n lg n) worst case behavior. (This is what makes the algorithm introsort).[3]

3. Safe internal mutations

   Let's take a look at types of `U.modify` and `Alg.sort`.

```
U.modify
  :: U.Unbox a =>
     (forall s. U.MVector s a -> GHC.ST.ST s ())
     -> U.Vector a -> U.Vector a
```

   First let's take a look at `ST` (state thread). `ST` is a monad, it can be described as a restricted `IO` monad or a monad for pure mutations. Some functions are more efficient with mutable memory, but global mutable memory is unsafe. This is why we have the `ST` monad. With `ST` you can use internal mutations, but the whole computation "thread" is not allowed to exchange mutable state with the outside world. Using this monad you can make functions that take in normal Haskell values, then allocate mutable memory, work with it, and return normal Haskell values back.

   `ST` type takes two types as arguments. The first argument is the scope. This is how we can be sure that the computation is pure. If the first argument is an arbitrary type variable then we know that the computation doesn't depend on the initial state, hence it is pure. The second argument is the output state. It is worth mentioning that `ST` provides **strict** state threads.

   `U.MVector s a` is a mutable vector of type `a` in scope `s`.

   `forall s.` means that `s` can be anything. In this case it's used not to make `U.modify` parametrically polymorphic in `c`, but to make sure that the function passed as an argument is parametrically polymorphic in `c`. This is done so that the scope of `ST` of the result type of the argument function has arbitrary type. In other words, this way we can be sure that the given function returns a pure computation.

   So `U.modify` takes a function that does a pure computation in `ST` and an unboxed vector, and it returns a new vector which is the result of applying the given computation to the given vector.

```
Alg.sort
  :: (Ord e, Data.Vector.Generic.Mutable.Base.MVector v e,
      Control.Monad.Primitive.PrimMonad m) =>
     v (Control.Monad.Primitive.PrimState m) e -> m ()
```

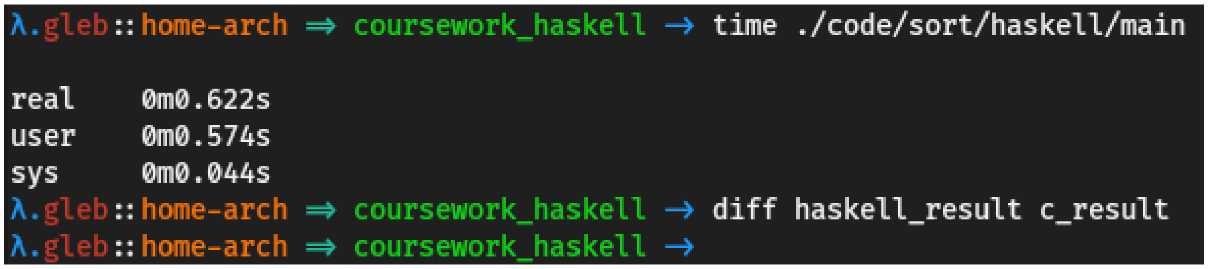
   `Data.Vector.Generic.Mutable.Base.MVector` is a class of mutable vectors and `U.MVector` is in it.

   `PrimMonad` is a type class for primitive state-transformer monads (`IO` and `ST`). `IO` and `ST` have many operations that are almost the same for both of the monads, which is why `PrimMonad` type class was created. This means that `Alg.sort` works with both `ST` and `IO`. `PrimState` is defined in the type class `PrimMonad`. It's an associated type giving the type of the state token (`s` in case of `ST s`).

   `Alg.sort` takes a mutable vector and sorts it, returning the unit type `()` wrapped in a state-transformer monad. So we can pass `Alg.sort` as an argument to `U.modify`.

```
U.modify Alg.sort :: (Ord a, U.Unbox a) => U.Vector a -> U.Vector a
```

4. The result of the optimizations



```
λ.gleb::home-arch ⇒ coursework_haskell → time ./code/sort/haskell/main

real	0m0.622s
user	0m0.574s
sys	0m0.044s
λ.gleb::home-arch ⇒ coursework_haskell → diff haskell_result c_result
λ.gleb::home-arch ⇒ coursework_haskell →
```

As you can see this significantly improved performance. If this still isn't fast enough for you, there are other optimizations that can be done: you can use the foreign function interface to call C functions, reduce the number of different conversions in the script, completely get rid of lists, etc. This shows that Haskell can have decent performance. Depending on what application you're developing you can optimize Haskell to get the performance you need. It's still slower than low-level languages like C, but if you really need certain parts of your code to perform really well then you can use foreign function interface and call C code from Haskell.

3.3.5 Abstractions

This example also shows what Haskell's high level abstractions can do. A good example of the language's use of high-level abstractions from the optimized version of the script is how Haskell uses type system to ensure that a state mutating computation is pure using `ST` monad. The type system plays a big role in Haskell. Haskell's type system is very strict, but at the same time it uses type variables and type classes, making the language very flexible and allowing you to define the most general versions of functions, variables, etc.

4 Reverse Polish server

4.1 Design

4.1.1 Algorithm

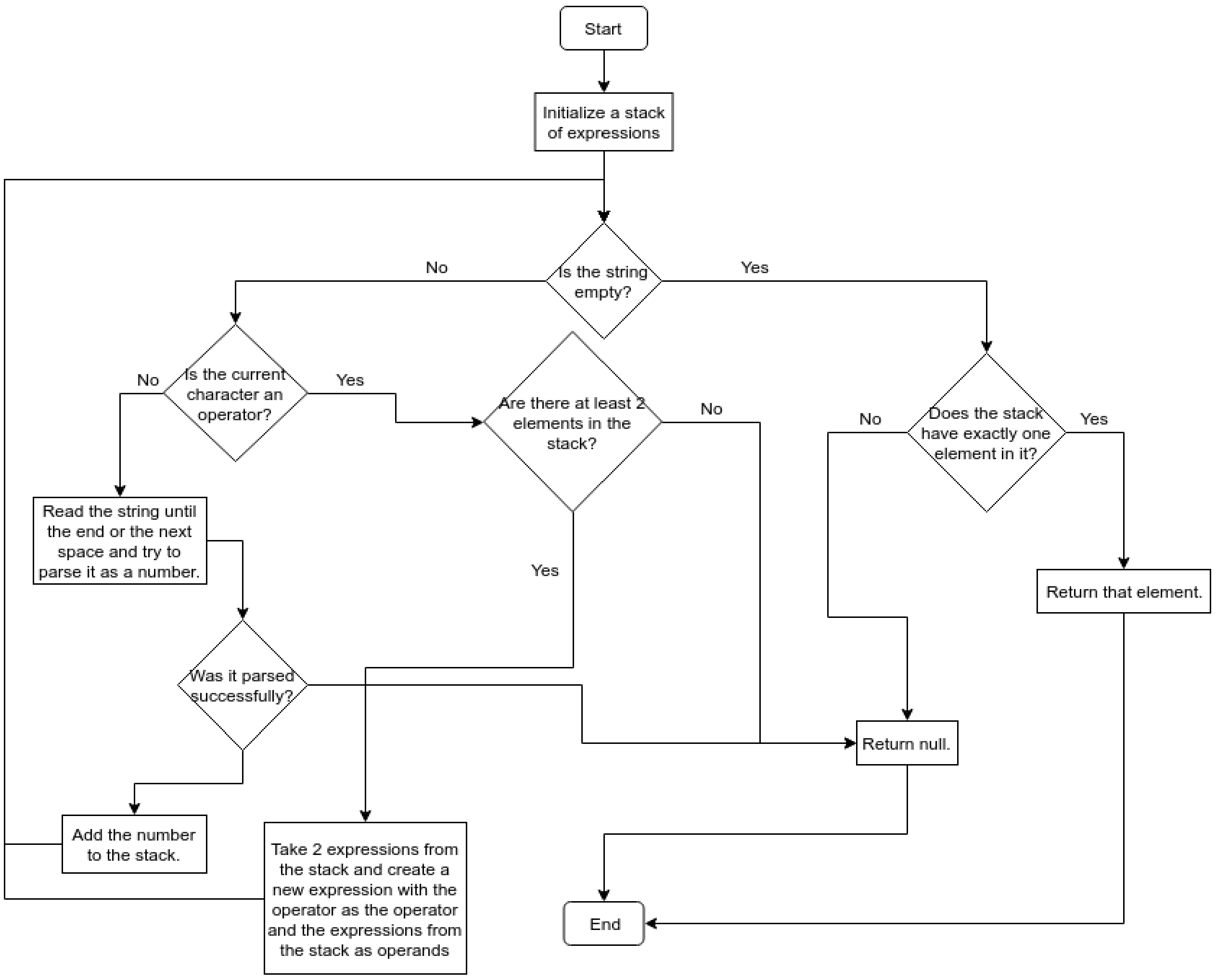
In the script there needs be a data type that represents a simple mathematical expression (in terms of numbers and operators `+`, `-`, `*`, `/`). For this data type a function that evaluates the expression must be defined. If the function is called on a number then this number gets returned, if the function is called on an expression then the function gets recursively called on the operands and the current operator is applied to the two results.

There must be a function that takes a string and reads the expression in reverse polish notation that is stored in it. The function returns a nullable expression of the expression type. The function uses a stack of expressions. When it sees an operator in the input it takes two expressions from the stack and constructs a new expression with the operator it read as the operator and the two expressions as the operands and puts the new expression in the stack. The function treats the rest of the input as numbers delimited by spaces. After the function finishes going through the entire input string if there is only one element in the stack then it returns it, otherwise it return a null value because the expression is invalid.

These functions are then used to implement the following API endpoints:

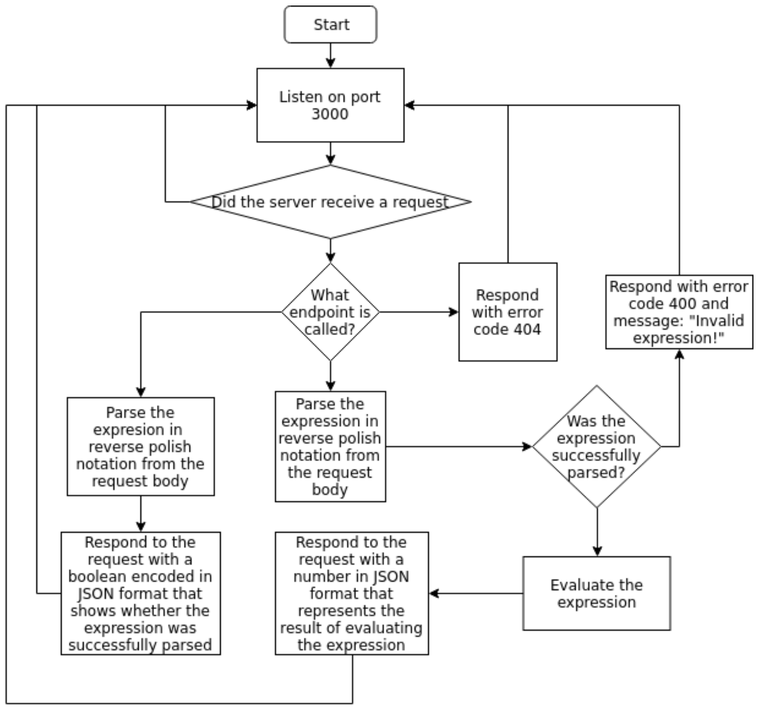
- POST: /check - extracts an expression in reverse polish notation in JSON format from the request body and returns a response with a boolean in JSON format. If the given expression is valid then the server responds with `true`, if the given expression is invalid then the server responds with `false`.
- POST: /evaluate - extracts an expression in reverse polish notation in JSON format from the request body and returns a response with code 200 and response body containing the result of evaluating the expression if the expression is valid, otherwise returns a response with error code 400 (Bad Request) and error message "invalid".

Parsing expressions in reverse polish notation:



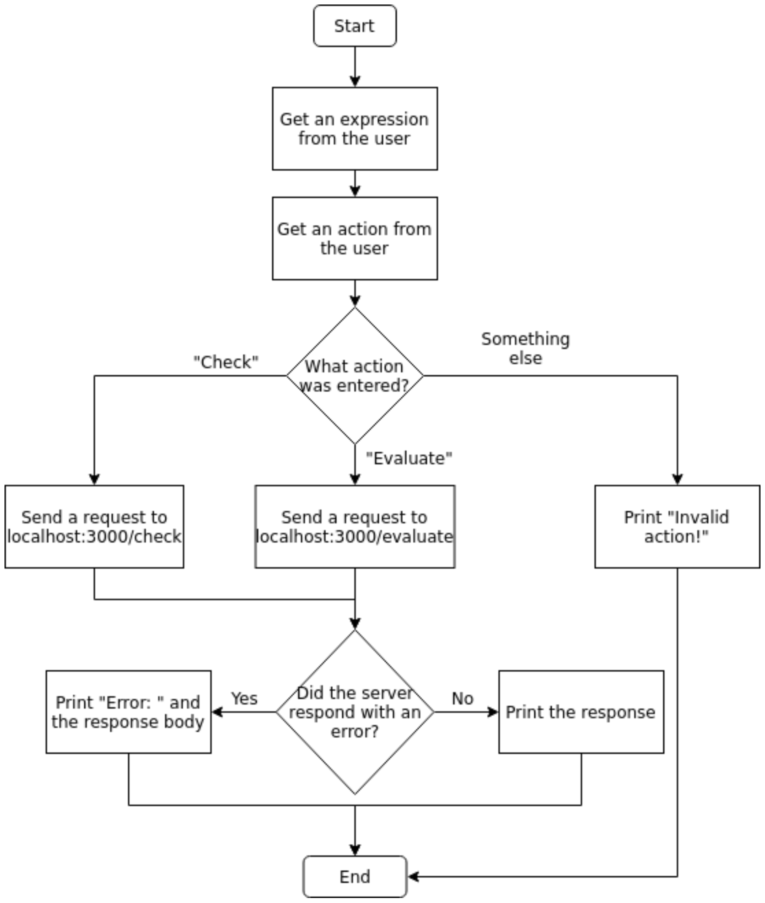
Start
Initialize a stack of expressions
Is the string empty?
No
Yes
Is the current character an operator?
No
Yes
Are there at least 2 elements in the stack?
No
Yes
Does the stack have exactly one element in it?
No
Yes
Read the string until the end or the next space and try to parse it as a number.
Was it parsed successfully?
Return that element.
Return null.
Add the number to the stack.
Take 2 expressions from the stack and create a new expression with the operator as the operator and the expressions from the stack as operands
End

Server:



Start
Listen on port 3000
Did the server receive a request
What endpoint is called?
Respond with error code 404
Respond with error code 400 and message: "Invalid expression!"
Parse the expresion in reverse polish notation from the request body
Parse the expression in reverse polish notation from the request body
Was the expression successfully parsed?
Respond to the request with a boolean encoded in JSON format that shows whether the expression was successfully parsed
Respond to the request with a number in JSON format that represents the result of evaluating the expression
Evaluate the expression

Client:


Start
Get an expression from the user
Get an action from the user
What action was entered?
"Check"
"Evaluate"
Something else
Send a request to localhost:3000/check
Send a request to localhost:3000/evaluate
Print "Invalid action!"
Did the server respond with an error?
Yes
No
Print "Error: " and the response body
Print the response
End

4.1.2 Tests

	Description	Test instructions	Expected result
1	Check action should return true for valid expressions.	Run the script several times with the check action and the following expressions: "1 1 +", "15 7 1 1 + - / 3 * 2 1 1 + + -".	True for every input.
2	Check action should return false for invalid expressions.	Run the script several times with the check action and the following inputs: "1 + 1", "1 1 1 +", "1 test +", "".	False for every input.
3	Evaluation action should evaluate given expression and return the result for valid expressions.	Run the script several times with the evaluate action and the same inputs as in the first test.	2.0, 5.0 respectively.

Continued on next page

Continued from previous page

	Description	Test instructions	Expected result
4	Evaluation action should return error "Invalid Expression!" for invalid expressions.	Run the script several times with the evaluate action and inputs from the second test.	Error: "Invalid expression!"

4.1.3 Benchmark

Call /evaluate with expression "15 7 1 1 + - / 3 * 2 1 1 + + -" 1000 times for each server and measure how much times it takes.

4.2 Solution

4.2.1 Code

1. Haskell

   (a) Server
   To implement the server I created two files: one for the API and one for the implementation of the API. First I defined the API:

```haskell
{-# LANGUAGE DataKinds     #-}
{-# LANGUAGE TypeOperators #-}

module API where

import           Data.Proxy
import           Servant

type API = "check" :> ReqBody '[JSON] String :> Post '[JSON] Bool
      :<|> "evaluate" :> ReqBody '[JSON] String :> Post '[JSON] Float

api :: Proxy API
api = Proxy
```

In the beginning of the script I enable two language extensions. `DataKinds` language extensions promotes values to types. The same way as values have types, types have kinds.

```
Prelude> :set -XDataKinds -- this is how you enable language extensions in ghci
Prelude> :t 5
5 :: Num p => p
Prelude> :t (+)
(+) :: Num a => a -> a -> a
Prelude> :k Int
Int :: *
Prelude> :k Either
Either :: * -> * -> *
```

`DataKinds` allows us to use values as types and types as kinds (we still can use them the regular way though).

```
Prelude> :set -XDataKinds
Prelude> data Response = Response
Prelude> :t Response
Response :: Response
Prelude> :k 'Response
'Response :: Response
```

`TypeOperators` lets us define a type as an operator.

```haskell
{-# LANGUAGE TypeOperators #-}

data path :> a
data l :<|> r = l :<|> r
```

Notice that `:>` doesn't have any type constructors. This means that there are no values of this type, but we can still use this type operator for type-level computations.

```
Prelude> :k (:>)
(:>) :: * -> * -> *
Prelude> data l :<|> r = l :<|> r
Prelude> :t (:<|>)
(:<|>) :: l -> r -> l :<|> r
Prelude> :k (:<|>)
(:<|>) :: * -> * -> *
```

These type operators are defined in a library called Servant, which I used to implement the server and the client. Using this library you can define your API in terms of types. Using these type operators and other types provided by Servant we can define the API. Here are the types that I used:

- `Post` is a type that represents a post request. It takes a type-level list of content types (response formats, like JSON or XML) and the type of the response (this type must be in the type classes that convert values of this type to formats from the content type type-level list).
- `JSON` is a content type. It doesn't have a constructor and it only exists for representing the content type at the type level.
- `ReqBody` is a data type that takes a type-level list of content types (request formats that it can accept) and the type of the value that is encoded in one of the content types.

So the type `API` represents the API defined in the design section (4.1.1).

- POST: /check - takes a string in JSON format, returns a boolean in JSON format
- POST: /evaluate - takes a string in JSON format, returns a float in JSON format

Of course this type only defines the endpoints, the actual server logic goes into the implementation. `API` is a type and sometimes we need to use the API definition as a value. In Haskell we can't pass types as arguments to functions, which is why we need `Proxy`. Here is how it's defined:

```haskell
{-# LANGUAGE KindSignatures #-}
{-# LANGUAGE PolyKinds #-}

data Proxy (t :: k) = Proxy
```

`KindSignatures` extension enables explicit kind declarations and `PolyKinds` enables kind polymorphism.

```
Prelude> data Proxy t = Proxy
Prelude> :k Proxy
Proxy :: * -> *
Prelude> :set -XPolyKinds
Prelude> :set -XKindSignatures
Prelude> data Proxy (t :: k) = Proxy
Prelude> :k Proxy
Proxy :: k -> *
```

This allows us to pass a value, which is always `Proxy`, and pass a type by explicitly stating the type of the value that we pass.
Now let's take a look at the implementation of the API.

```haskell
{-# LANGUAGE DataKinds         #-}
{-# LANGUAGE OverloadedStrings #-}
{-# LANGUAGE TypeOperators     #-}

import           Data.Proxy
import           Network.Wai
import           Network.Wai.Handler.Warp
import           Safe
import           Servant

import qualified Data.Text.IO             as TIO

import qualified API

infixl 6 :+:
infixl 6 :-:
infixl 7 :*:
infixl 7 :/:

data Expr a = Expr a :+: Expr a
            | Expr a :-: Expr a
            | Expr a :*: Expr a
            | Expr a :/: Expr a
            | Number a
            deriving Show

eval :: (Num a, Fractional a) => Expr a -> a
eval (x :+: y)  = eval x + eval y
eval (x :-: y)  = eval x - eval y
eval (x :*: y)  = eval x * eval y
eval (x :/: y)  = eval x / eval y
eval (Number x) = x

parse :: (Read a, Fractional a) => String -> Maybe (Expr a)
parse = flip parseAccum [] . words
  where parseAccum :: (Read a, Num a) => [String] -> [Expr a] -> Maybe (Expr a)
        parseAccum []       [x]        = Just x
        parseAccum ("+":cs) (x1:x2:xs) = parseAccum cs $ x1 :+: x2 : xs
        parseAccum ("-":cs) (x1:x2:xs) = parseAccum cs $ x1 :-: x2 : xs
        parseAccum ("*":cs) (x1:x2:xs) = parseAccum cs $ x1 :*: x2 : xs
        parseAccum ("/":cs) (x1:x2:xs) = parseAccum cs $ x1 :/: x2 : xs
        parseAccum (str:cs) exprs = readMay str >>= parseAccum cs . (: exprs) . Number
        parseAccum _        _          = Nothing
```

```haskell
server :: Server API.API
server = maybe (return False) (const $ return True) . parse
    :<|> maybe invalid return . fmap eval . parse
    where invalid = throwError err400 { errBody = "Invalid expression!" }

app :: Application
app = serve API.api server

main :: IO ()
main = run 3000 app
```

First I defined 4 operators which I then used as type constructors. `infixl` assigns priority to an operator. I used the same priority for `:+:`, `:-:`, `:*:`, `:/:` as Haskell uses by default for `+`, `-`, `*`, `/`, respectively.

Then I defined a data type (`Expr`) that represents a simple mathematical expression. It's a recursive data type and it's either a number or addition/subtraction/multiplication/division of two expressions. Function `eval` evaluates `Expr`.

`parse` takes a string with an expression in reverse polish notation and parses it to get an expression of type `Expr`. It uses several functions for that:

```haskell
flip :: (a -> b -> c) -> b -> a -> c -- defined in Prelude

words :: String -> [String] -- defined in Prelude
-- breaks a string up into a list of words, which were delimited by white space

readMay :: Read a => String -> Maybe a -- defined in Safe (library `safe`)
-- parses a string, returns Nothing if fails
```

To implement `parse` I wrote a simple local recursive function `parseAccum`. It takes a list of strings with terms of the given expression in reverse polish notation and a list of expressions of type `Expr a`, which is used as a stack. If the list of strings is empty and there is only one element in the stack then it means that we successfully parsed the given expression, so `parseAccum` just returns the expression from the stack. If the current element of the list of strings is an operator then `parseAccum` takes two top elements from the stack, constructs a new expression with the given operator, puts the new expression in the stack, and recursively calls `parseAccum` on the rest of the list and the new stack. If the current element of the list is not an operator then it must be a number, so `parseAccum` attempts to read a number from the list and if it succeeds then it puts the number into the stack and calls `parseAccum` on the rest of the list and the new stack. In any other case it returns Nothing.

`server` is the implementation of `API`. `Server` is a type family, which is like a type-level function. This way it can figure out what type the implementation of the API should have for any `API` type. The API I defined has two endpoints, both of which take data from request body, which is why the actual type is

```haskell
server :: ([Char] -> Handler Bool) :<|> ([Char] -> Handler Float)
```

`Handler` is a monad from Servant. In this case I don't have any impure computations in the implementation of the server, so I just used `return` to get the result that matches the type definition. The implementations for /check and /evaluate are separated by `:<|>`. The function for /check attempts to parse the given expression and then converts `Maybe (Expr Double)` (unspecified arbitrary numbers from `Fractional` default to `Double`) to `Handler Bool` using functions `maybe`, `const`, and `return`. The function for /evaluate takes an expression, attempts to parse it, evaluates it and returns in the right type if `parse` didn't return `Nothing`, otherwise it sends a response with HTTP error 400 (Bad request) and message "Invalid expression!".

`app` converts the API type and the implementation of the API to `Application`, which is a type defined in `Network.Wai` (from library `wai` - web application interface). We need to do this because Servant doesn't provide any functions for running the server, it allows you to plug your Servant code into different web servers. WAI provides a common protocol for communication between web applications and web servers. Now that we have a WAI web application we can run it using `run` function from `Network.Wai.Handler.Warp` (from library `warp`), which is a web server for WAI applications. `main` IO action runs the application on port 3000.

(b) Client

```haskell
{-# LANGUAGE DataKinds     #-}
{-# LANGUAGE TypeOperators #-}

import           Data.Proxy
import           Network.HTTP.Client
import           Safe
import           Servant.API
import           Servant.Client      as SC
import           System.IO

import           API                 (api)

check :: String -> ClientM Bool
evaluate :: String -> ClientM Float

check :<|> evaluate = client api

baseUrl :: BaseUrl
baseUrl = BaseUrl Http "localhost" 3000 ""

data Action = Check | Evaluate deriving (Show, Read)

printResponse :: Show b => Either ServantError b -> IO ()
printResponse = either (putStrLn . ("Error: " ++) . show . SC.responseBody) print

performAction :: String -> Action -> IO ()
performAction expr action =
  let manager = flip ClientEnv baseUrl <$> newManager defaultManagerSettings
  in manager >>= \m -> case action of
                         Check    -> printResponse =<< runClientM (check expr) m
                         Evaluate -> printResponse =<< runClientM (evaluate expr) m

main :: IO ()
main = do expr <- prompt "Expression: "
          action <- prompt "Action (Check or Evaluate): "
          maybe (print "Invalid action!") (performAction expr) $ readMay action
          where prompt str = putStr str >> hFlush stdout >> getLine
```

Using Servant you can generate documentation and client side code from your API type. So I declared functions `check` and `evaluate` and then used pattern matching to assign the automatically derived implementations from the API type. `ClientM` is the monad in which client functions run.

`API` type doesn't contain any data about where the web server is hosted, so to run the derived querying functions you need to specify base URL. I defined a variable `baseUrl` that stores URI scheme, host, port, and base path.

Then I defined a data type that represents an action (`Check` or `Evaluate`) and derived instances of `Show` and `Read` for it.

```haskell
runClientM :: ClientM a -> ClientEnv -> IO (Either ServantError a)
```

As you can see `runClientM`, the function used for running queries, returns `IO (Either ServantError a)`. To show responses I wrote a function `printResponse`.

```haskell
either :: (a -> c) -> (b -> c) -> Either a b -> c
SC.responseBody :: ServantError -> Data.ByteString.Lazy.Internal.ByteString
```

`printResponse` prints the response if no errors occurred and prints `"Error: <error message>"` if the server responded with an error.

```haskell
data ClientEnv = ClientEnv { Servant.Common.Req.manager :: Manager
                           , Servant.Common.Req.baseUrl :: BaseUrl
                           } -- Defined in ‘Servant.Common.Req’
newManager :: ManagerSettings -> IO Manager
defaultManagerSettings :: ManagerSettings

flip ClientEnv baseUrl <$> newManager defaultManagerSettings :: IO ClientEnv
```

`performAction` takes an expression and an action. It queries the server to perform the right action and then prints the response using `printResponse`.

`main` prompts user for an expression and an action, parses the action using `readMay` and performs the action if it is valid, otherwise it prints "Invalid action!". I defined a local function `prompt` that takes a string, prints it, and reads a line from the user. `hFlush` causes any buffered items to get sent immediately to the operating system. We need to call `hFlush` because by default due to Haskell's use of lazy IO the standard output data gets sent to the OS only after we print a new line or the buffer is full.

2. Ruby

   (a) Server

   For the Ruby version of the server I used a popular framework for developing web application called Ruby on Rails. I generated a new rails project and a new controller. Rails uses MVC (model, view, controller) model. Models are used for working with data, views render data, and controllers have the logic of the application.

```
$ rails new ruby --api
$ rails generate controller Main
```

   This application is very simple, so all I need is one controller, so I changed `config/routes.rb` to tell Rails to use `MainController` class for all requests.

```ruby
Rails.application.routes.draw do
  post '/:action(/:id)', controller: 'main' # route all requests to the main controller
end
```

   Then I wrote `MainController`.

```ruby
# class that handles HTTP requests
class MainController < ApplicationController
  # /check
  def check
  # .nil? returns true if the object is nil
  # parse the expression from the request and return boolean
  # in JSON format that shows if the expression is valid or not
  render json: !parse(JSON.parse(request.body.read)).nil?
end

# /evaluate
def evaluate
  # check if the expression is valid
  if (expr = parse(JSON.parse(request.body.read))).nil?
    # if it's invalid respond with an error
    render body: 'Invalid expression!', status: 400
  else
    # evaluate the expression and return the result in JSON
    render json: eval_expr(expr)
  end
end

# everything below is private
private

# class that represents a simple mathematical expression
class Expr
  # getters and setters for a binary operator and two operands
  attr_accessor :operator, :operand1, :operand2

  # simple class constructor
  def initialize(operator, operand1, operand2)
    self.operator = operator
    self.operand1 = operand1
    self.operand2 = operand2
  end
end

# function for evaluating expressions
def eval_expr(expr)
  # return nil if the given expression is nil
  nil if expr.nil?

  case expr
  when Expr # when the expression is an instance of Expr
    # evaluate the operands and apply the operator to the results
    case expr.operator
    when '+'
      eval_expr(expr.operand1) + eval_expr(expr.operand2)
    when '-'
      eval_expr(expr.operand1) - eval_expr(expr.operand2)
    when '*'
      eval_expr(expr.operand1) * eval_expr(expr.operand2)
    when '/'
```

```
      eval_expr(expr.operand1) / eval_expr(expr.operand2)
    end
  else
    # when the expression is not an instance of Expr it should be a number
    # return the number
    expr
  end
end

# function for parsing expressions
def parse(str)
  exprs = []  # array of expressions used as a stack
  buffer = '' # buffer for parsing numbers

  # loop through each character
  str.each_char do |d|
    # we can apply operators only if there are at least two expressions in the stack
    if exprs.length >= 2
      # if the current character is an operator then take first two elements
      # from the stack, construct a new expression, and put it in the stack
      case d
      when '+'
        exprs.unshift Expr.new '+', exprs.shift, exprs.shift
      when '-'
        exprs.unshift Expr.new '-', exprs.shift, exprs.shift
      when '*'
        exprs.unshift Expr.new '*', exprs.shift, exprs.shift
      when '/'
        exprs.unshift Expr.new '/', exprs.shift, exprs.shift
      when ' '
        # if the buffer isn't empty then there is a number in it
        unless buffer.empty?
          begin # try
            x = Float(buffer) # convert to float
            exprs.unshift x   # put in the stack
            buffer = ''       # empty the buffer
          rescue(ArgumentError) # catch parsing exception
            # the expression is invalid, break the loop
            break
          end
        end
      else
        # put the character in the buffer
        buffer << d
      end
    else # less than two elements in the stack
      # only need to check if the character is ' '
      case d
      when ' '
        # the same behavior in case of a space
```

```
          unless buffer.empty?
            begin
              x = Float(buffer)
              exprs.unshift x
              buffer = ''
            rescue(ArgumentError)
              break
            end
          end
        else
          # put the character in the buffer
          buffer << d
        end
      end
    end

    # if the buffer is empty and the expressions stack has only one element
    # return the expression
    exprs.shift if exprs.length == 1 && buffer.empty?

    # expressions in reverse polish notation should have an operator at the end,
    # so if the buffer isn't empty then the expression is invalid.
  end
end
```

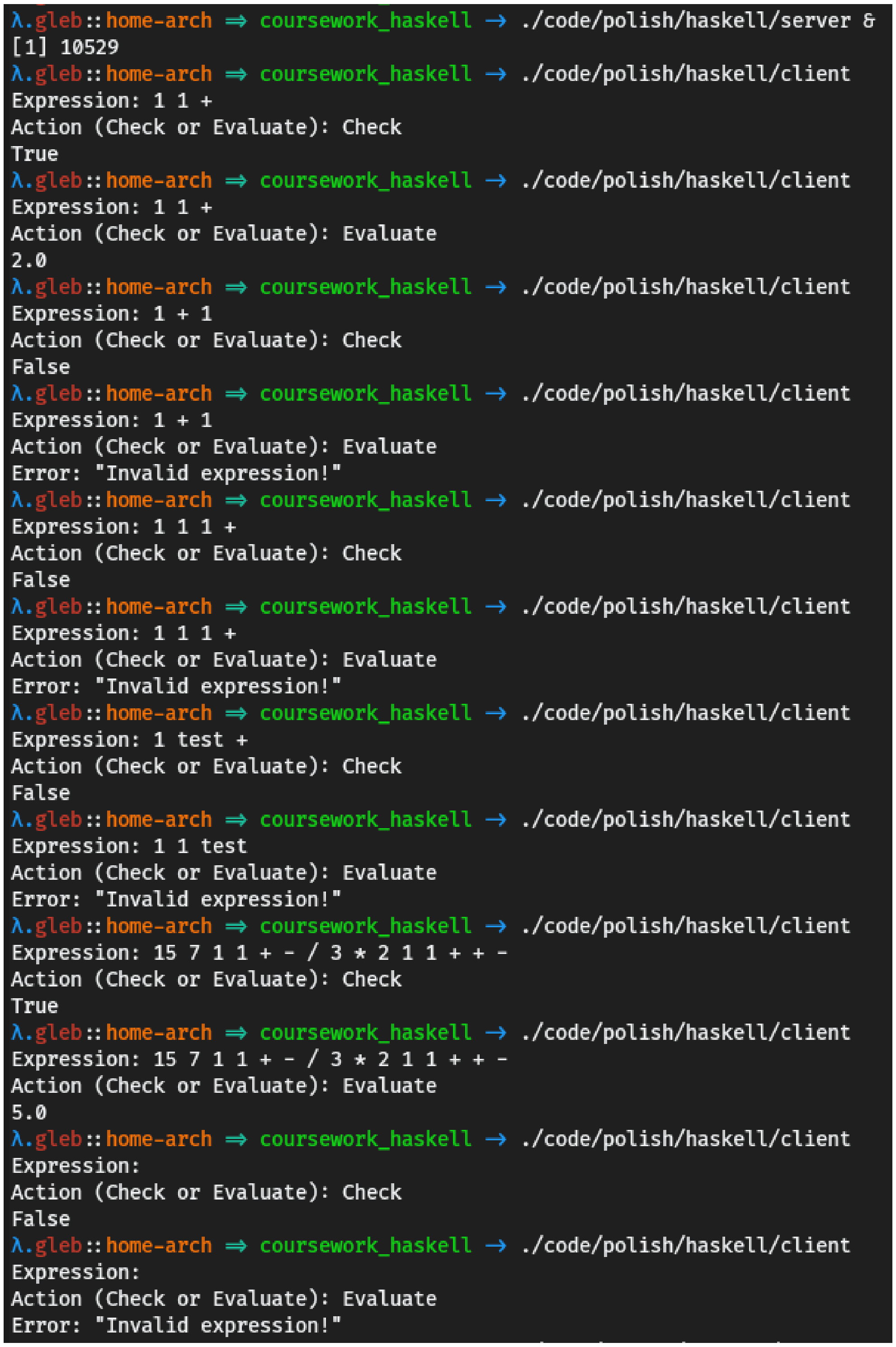
(b) Client

```
require 'excon' # library for HTTP
require 'json'  # library for JSON

# function for querying /check
def post_check(excon, body)
  excon.request(
    method: :post,
    path: '/check',
    headers: { 'Content-Type' => 'application/json' },
    body: body
  )
end

# function for querying /evaluate
def post_evaluate(excon, body)
  excon.request(
    method: :post,
    path: '/evaluate',
    headers: { 'Content-Type' => 'application/json' },
    body: body
  )
end

# expression input
print 'Expression: '
expr = JSON.generate gets.chomp # .chomp removes carriage return characters (like \n)

# action input
print 'Action (Check or Evaluate): '
action = gets.chomp

# creating an instance of excon with base url http://localhost:3000
excon = Excon.new('http://localhost:3000')

case action # identifying the action
when 'Check'
  res = post_check(excon, expr)
  print 'Error: ' if res.status != 200
  puts res.body
when 'Evaluate'
  res = post_evaluate(excon, expr)
  print 'Error: ' if res.status != 200
  puts res.body
else
  puts 'Invalid action!'
end
```

4.2.2 Tests

1. Haskell

   I ran all the tests from the test table and got the expected result for each test.

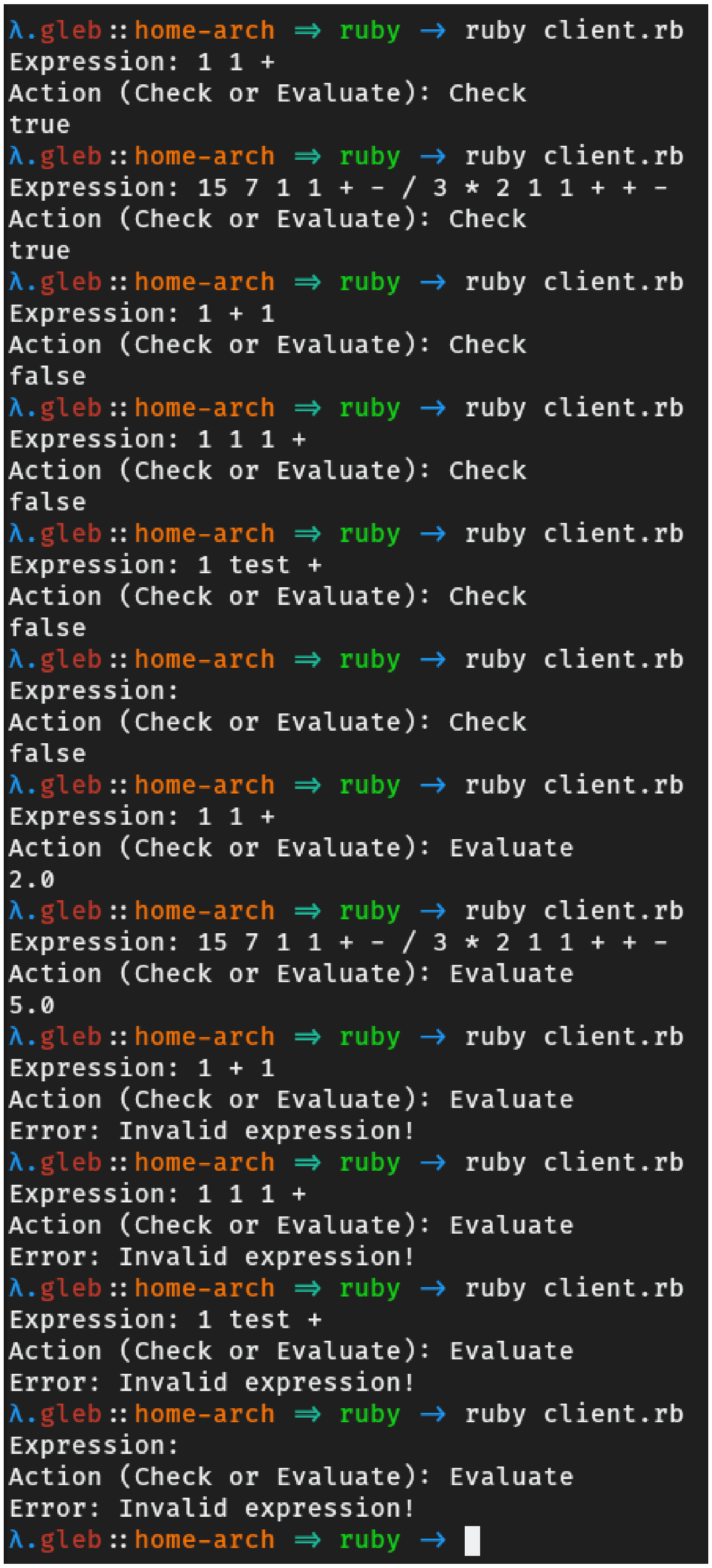


```
λ.gleb::home-arch ⇒ coursework_haskell → ./code/polish/haskell/server &
[1] 10529
λ.gleb::home-arch ⇒ coursework_haskell → ./code/polish/haskell/client
Expression: 1 1 +
Action (Check or Evaluate): Check
True
λ.gleb::home-arch ⇒ coursework_haskell → ./code/polish/haskell/client
Expression: 1 1 +
Action (Check or Evaluate): Evaluate
2.0
λ.gleb::home-arch ⇒ coursework_haskell → ./code/polish/haskell/client
Expression: 1 + 1
Action (Check or Evaluate): Check
False
λ.gleb::home-arch ⇒ coursework_haskell → ./code/polish/haskell/client
Expression: 1 + 1
Action (Check or Evaluate): Evaluate
Error: "Invalid expression!"
λ.gleb::home-arch ⇒ coursework_haskell → ./code/polish/haskell/client
Expression: 1 1 1 +
Action (Check or Evaluate): Check
False
λ.gleb::home-arch ⇒ coursework_haskell → ./code/polish/haskell/client
Expression: 1 1 1 +
Action (Check or Evaluate): Evaluate
Error: "Invalid expression!"
λ.gleb::home-arch ⇒ coursework_haskell → ./code/polish/haskell/client
Expression: 1 test +
Action (Check or Evaluate): Check
False
λ.gleb::home-arch ⇒ coursework_haskell → ./code/polish/haskell/client
Expression: 1 1 test
Action (Check or Evaluate): Evaluate
Error: "Invalid expression!"
λ.gleb::home-arch ⇒ coursework_haskell → ./code/polish/haskell/client
Expression: 15 7 1 1 + - / 3 * 2 1 1 + + -
Action (Check or Evaluate): Check
True
λ.gleb::home-arch ⇒ coursework_haskell → ./code/polish/haskell/client
Expression: 15 7 1 1 + - / 3 * 2 1 1 + + -
Action (Check or Evaluate): Evaluate
5.0
λ.gleb::home-arch ⇒ coursework_haskell → ./code/polish/haskell/client
Expression:
Action (Check or Evaluate): Check
False
λ.gleb::home-arch ⇒ coursework_haskell → ./code/polish/haskell/client
Expression:
Action (Check or Evaluate): Evaluate
Error: "Invalid expression!"
```

`./server &` executes binary file `server` in the background.

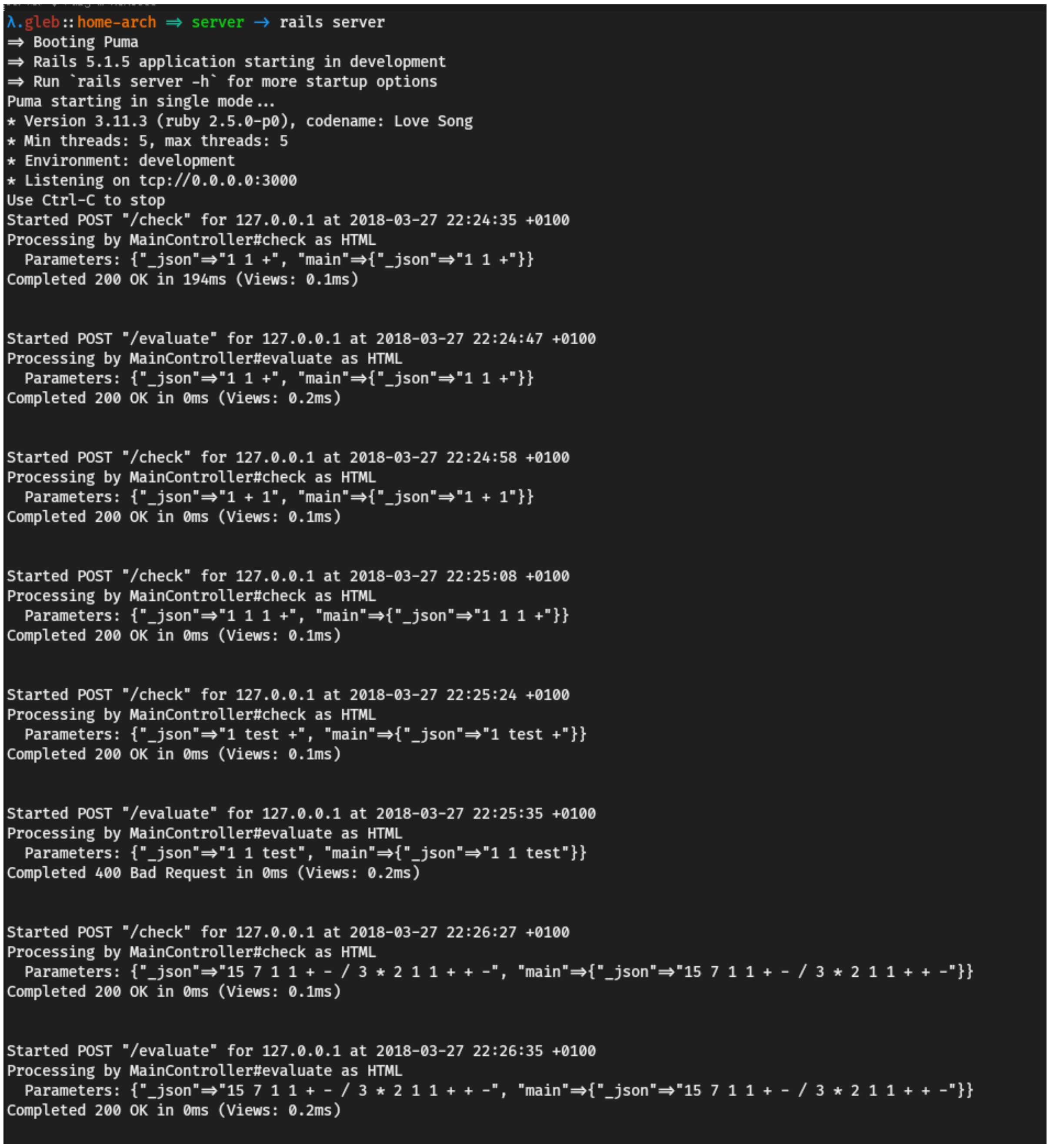
2. Ruby

   I ran all the tests from the test table and got the expected result for each test.



```
λ.gleb::home-arch ⇒ ruby → ruby client.rb
Expression: 1 1 +
Action (Check or Evaluate): Check
true
λ.gleb::home-arch ⇒ ruby → ruby client.rb
Expression: 15 7 1 1 + - / 3 * 2 1 1 + + -
Action (Check or Evaluate): Check
true
λ.gleb::home-arch ⇒ ruby → ruby client.rb
Expression: 1 + 1
Action (Check or Evaluate): Check
false
λ.gleb::home-arch ⇒ ruby → ruby client.rb
Expression: 1 1 1 +
Action (Check or Evaluate): Check
false
λ.gleb::home-arch ⇒ ruby → ruby client.rb
Expression: 1 test +
Action (Check or Evaluate): Check
false
λ.gleb::home-arch ⇒ ruby → ruby client.rb
Expression:
Action (Check or Evaluate): Check
false
λ.gleb::home-arch ⇒ ruby → ruby client.rb
Expression: 1 1 +
Action (Check or Evaluate): Evaluate
2.0
λ.gleb::home-arch ⇒ ruby → ruby client.rb
Expression: 15 7 1 1 + - / 3 * 2 1 1 + + -
Action (Check or Evaluate): Evaluate
5.0
λ.gleb::home-arch ⇒ ruby → ruby client.rb
Expression: 1 + 1
Action (Check or Evaluate): Evaluate
Error: Invalid expression!
λ.gleb::home-arch ⇒ ruby → ruby client.rb
Expression: 1 1 1 +
Action (Check or Evaluate): Evaluate
Error: Invalid expression!
λ.gleb::home-arch ⇒ ruby → ruby client.rb
Expression: 1 test +
Action (Check or Evaluate): Evaluate
Error: Invalid expression!
λ.gleb::home-arch ⇒ ruby → ruby client.rb
Expression:
Action (Check or Evaluate): Evaluate
Error: Invalid expression!
λ.gleb::home-arch ⇒ ruby →
```

I started the server in another window, because it shows logs that I don't need for the tests.



```
λ.gleb::home-arch ⇒ server → rails server
⇒ Booting Puma
⇒ Rails 5.1.5 application starting in development
⇒ Run `rails server -h` for more startup options
Puma starting in single mode...
* Version 3.11.3 (ruby 2.5.0-p0), codename: Love Song
* Min threads: 5, max threads: 5
* Environment: development
* Listening on tcp://0.0.0.0:3000
Use Ctrl-C to stop
Started POST "/check" for 127.0.0.1 at 2018-03-27 22:24:35 +0100
Processing by MainController#check as HTML
  Parameters: {"_json"⇒"1 1 +", "main"⇒{"_json"⇒"1 1 +"}}
Completed 200 OK in 194ms (Views: 0.1ms)


Started POST "/evaluate" for 127.0.0.1 at 2018-03-27 22:24:47 +0100
Processing by MainController#evaluate as HTML
  Parameters: {"_json"⇒"1 1 +", "main"⇒{"_json"⇒"1 1 +"}}
Completed 200 OK in 0ms (Views: 0.2ms)


Started POST "/check" for 127.0.0.1 at 2018-03-27 22:24:58 +0100
Processing by MainController#check as HTML
  Parameters: {"_json"⇒"1 + 1", "main"⇒{"_json"⇒"1 + 1"}}
Completed 200 OK in 0ms (Views: 0.1ms)


Started POST "/check" for 127.0.0.1 at 2018-03-27 22:25:08 +0100
Processing by MainController#check as HTML
  Parameters: {"_json"⇒"1 1 1 +", "main"⇒{"_json"⇒"1 1 1 +"}}
Completed 200 OK in 0ms (Views: 0.1ms)


Started POST "/check" for 127.0.0.1 at 2018-03-27 22:25:24 +0100
Processing by MainController#check as HTML
  Parameters: {"_json"⇒"1 test +", "main"⇒{"_json"⇒"1 test +"}}
Completed 200 OK in 0ms (Views: 0.1ms)


Started POST "/evaluate" for 127.0.0.1 at 2018-03-27 22:25:35 +0100
Processing by MainController#evaluate as HTML
  Parameters: {"_json"⇒"1 1 test", "main"⇒{"_json"⇒"1 1 test"}}
Completed 400 Bad Request in 0ms (Views: 0.2ms)


Started POST "/check" for 127.0.0.1 at 2018-03-27 22:26:27 +0100
Processing by MainController#check as HTML
  Parameters: {"_json"⇒"15 7 1 1 + - / 3 * 2 1 1 + + -", "main"⇒{"_json"⇒"15 7 1 1 + - / 3 * 2 1 1 + + -"}}
Completed 200 OK in 0ms (Views: 0.1ms)


Started POST "/evaluate" for 127.0.0.1 at 2018-03-27 22:26:35 +0100
Processing by MainController#evaluate as HTML
  Parameters: {"_json"⇒"15 7 1 1 + - / 3 * 2 1 1 + + -", "main"⇒{"_json"⇒"15 7 1 1 + - / 3 * 2 1 1 + + -"}}
Completed 200 OK in 0ms (Views: 0.2ms)
```

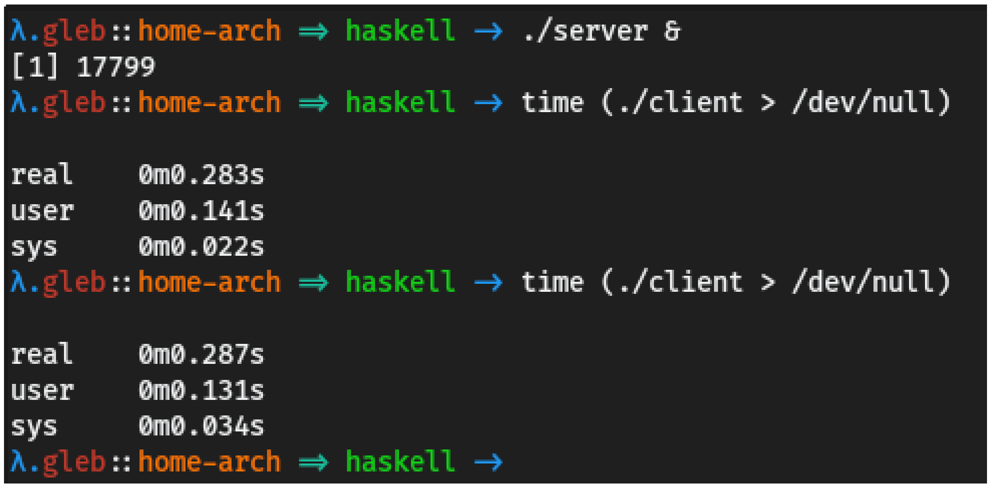
4.2.3 Benchmark

I modified the Haskell version of the client side to compare performances of the server.

```haskell
repeatAction :: Monad m => Integer -> m () -> m ()
repeatAction n a = foldr (const (>> a)) (return ()) [1..n]

performAction :: String -> Action -> IO ()
performAction expr action =
  let manager = flip ClientEnv baseUrl <$> newManager defaultManagerSettings
  in manager >>= \m -> case action of
                         Check    -> printResponse =<< runClientM (check expr) m
                         Evaluate -> repeatAction 1000 $ printResponse =<< runClientM (evaluate expr)

main :: IO ()
main = performAction "15 7 1 1 + - / 3 * 2 1 1 + + -" Evaluate
```

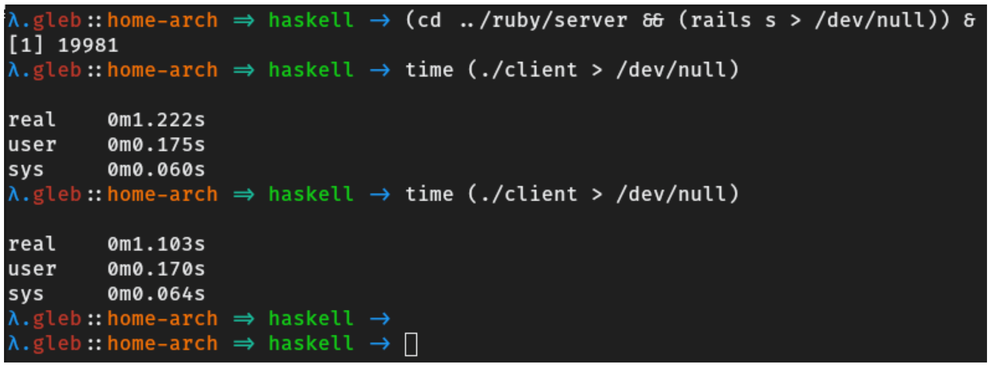
To run the benchmark I used several Linux commands. `>` operator forwards output of a program to a file. `/dev/null` is the null device - a device file that discards all data written to it but reports that the write operation succeeded. `&&` operator takes two commands, and runs the second command if the first successfully finished. Here are the results of the benchmark

1. Haskell



```
λ.gleb::home-arch ⇒ haskell → ./server &
[1] 17799
λ.gleb::home-arch ⇒ haskell → time (./client > /dev/null)

real    0m0.283s
user    0m0.141s
sys     0m0.022s
λ.gleb::home-arch ⇒ haskell → time (./client > /dev/null)

real    0m0.287s
user    0m0.131s
sys     0m0.034s
λ.gleb::home-arch ⇒ haskell →
```

2. Ruby



```
λ.gleb::home-arch ⇒ haskell → (cd ../ruby/server && (rails s > /dev/null)) &
[1] 19981
λ.gleb::home-arch ⇒ haskell → time (./client > /dev/null)

real    0m1.222s
user    0m0.175s
sys     0m0.060s
λ.gleb::home-arch ⇒ haskell → time (./client > /dev/null)

real    0m1.103s
user    0m0.170s
sys     0m0.064s
λ.gleb::home-arch ⇒ haskell →
λ.gleb::home-arch ⇒ haskell → ▯
```

4.3 Evaluation

4.3.1 Safety

In this example I defined an API using types. This approach ensures that the implementation of the server corresponds to the API definition. For example, we can be absolutely sure that /check takes a string and returns a boolean. In the ruby version of the server we don't have that safety. We can accidentally return the result in a wrong format or return nothing at all. Also, with this approach you only use the parameters of the request that you specified in the API type. For example if all you need from a request is the body then you define the type with `ReqBody` and get the contents of the request body. If the request data that you can access is restricted by the type then there are less mistakes you can possibly make when you implement the API. When you are implementing your API using Servant you only think about the logic of your code, things like encoding and decoding data are done automatically through type classes. This also reduces the number of possible bugs.

4.3.2 Expressiveness

Just by looking at the number of lines of code that I wrote we can see how Haskell is more expressive.

Language	Lines of code (client + server)
Haskell	108
Ruby	179

Keep in mind that this is all the Haskell code, but I didn't include 380 lines of ruby code in different configuration files generated by the framework. The reason I didn't include them is that Ruby on Rails framework is an overkill for the problem that I was solving. The Haskell version of the code not only uses less amount of code, but it is also almost exactly matches the algorithms' descriptions in English in 4.1.1. For example, let's take a look at the `parse` function.

```haskell
parse :: (Read a, Fractional a) => String -> Maybe (Expr a)
parse = flip parseAccum [] . words
  where parseAccum :: (Read a, Num a) => [String] -> [Expr a] -> Maybe (Expr a)
        parseAccum []        [x]         = Just x
        -- "if there is one element in the stack then return it"

        parseAccum ("+":cs) (x1:x2:xs) = parseAccum cs $ x1 :+: x2 : xs
        parseAccum ("-":cs) (x1:x2:xs) = parseAccum cs $ x1 :-: x2 : xs
        parseAccum ("*":cs) (x1:x2:xs) = parseAccum cs $ x1 :*: x2 : xs
        parseAccum ("/":cs) (x1:x2:xs) = parseAccum cs $ x1 :/: x2 : xs
        -- "when it sees an operator in the input it takes two expressions
        -- from the stack and constructs a new expression with the operator
        -- it read as the operator and the two expressions as the operands
        -- and puts the new expression in the stack"

        parseAccum (str:cs) exprs = readMay str >>= parseAccum cs . (: exprs) . Number
        -- the function treats the rest of the input as numbers

        parseAccum _         _           = Nothing
        -- the expression is invalid
```

As I mentioned in the evaluation of safety the implementation of the API contains only the logic of the application. This feature not only makes the code safer, but also makes it more expressive. This shows that Haskell is very expressive.

4.3.3 High level abstractions

Defining an API in terms of types is a great example of Haskell's high level abstractions. In most languages even if you have a type system you can't do anything like this. First of all you can't define readable type-level grammar. Also even if you somehow manage to define types that can be used for constructing a type that represents an arbitrary REST API, the constructed type will be useless because the majority of languages don't support type-level functions. So you won't be able to type check the implementation of your API.

The point I made about only describing logic in the implementation of the server is also relevant to this discussion. The way Servant encodes and decodes data to the right formats just by looking at the type definition of your API is also a great example of using abstractions in Haskell. But you can go even further and define an API type using type variables and then implement it once for an arbitrary type variable that is constraint by type classes that are required for encoding, decoding, etc. This can be useful if, for example, you need the same CRUD (create, read, update delete) API for several entities. All these features of the type system give Haskell support for all kinds of different abstractions.

4.3.4 Modularity

The fact that you can use types to define APIs is good for modularity. You can define parts of your API and then compose them. Also you can use the approach I mentioned in the previous section. For example if you have two projects that have APIs `API1` and `API2` respectively and implementation of the APIs `server1` and `server2` then merging these projects into one bigger project will take very little code.

```haskell
type API = API1 :<|> API2

server :: Server API
server = server1 :<|> server2
```

And then, of course, you need to remove code that serves the original apps and serve the new app. On the other hand, with Ruby on Rails the easiest way to achieve this would be to make a service app that calls the APIs, but this will be slow and hard to maintain. You can also use mountable engines, which is hard.

As you can see defining APIs using types is good for modularity. Haskell itself is very modular. And its high level abstractions allow developers to use standard (more or less) tools when they develop libraries. So, for example, grammar for defining APIs can be embedded directly into the language. This means that you can write modular code and then easily reuse it. You can also extend the grammar by providing the required type class instances for your types and type combinators. This shows that Haskell has good modularity.

4.3.5 Performance

The benchmark shows that the Haskell version of the server is more than 3 times faster than the Ruby version. However, this comparison is not very fair because for the Ruby version of the server I used a big framework, which was unnecessary.

5 Conclusion

5.1 Safety

Haskell allows you to encode logic in types. The benefits of this approach is that at compile time your code is checked and it must follow the types, so if your logic is encoded in types then the compiler checks that your code follows your logic. I showed this with the web server example, there I encoded the API in types. Then when I implemented the API the compiler checked that the code implements the specified API.

Using Haskell you can avoid almost all run-time errors. For example, if you have a function that can fail then you encode that fail in types by wrapping the result in `Maybe`, `Either a` or another monad. This way when you actually use the function the compiler will force you to check that the function didn't fail, otherwise the code won't type check.

Immutability also makes a big role in making Haskell a very safe language. A lot of the errors in imperative languages are caused by state change. In most languages you can change a global variable in one function without realizing that this will break another function.

If you declare the type of your function or variable before the value then the number of possible ways in which you can write this variable or function is significantly reduced. There are few ways of writing the right code and many ways of writing incorrect code, in most languages the number of ways to write incorrect code is infinite. Haskell reduces the number of ways in which you can write your code, making it harder to write code that compiles, but doesn't work as it should.

```
data Bool = True | False

not :: Bool -> Bool
```

There are four ways of defining the function `not` (2 possible inputs and 2 possible outputs for each of them). In languages like Ruby there are infinitely many ways of defining a function like this, just because the language doesn't have a type system and it uses impure functions. In languages like C# there are still infinitely many ways of defining `not`. The type system reduces the number of possible inputs and outputs, but you still can do any impure computations inside the function. You can choose to write some code that is not directly related to the function `not` and crash the application, for example by just dividing by zero. In Haskell to cause a problem this way you would need to put the division somewhere in the code and also force Haskell to evaluate the division, because Haskell won't evaluate the expression with division by zero as the result of the function doesn't depend on it. This is another example of how in Haskell it's harder to write incorrect code. Another example is `maybe` function.

```
maybe :: b -> (a -> b) -> Maybe a -> b
```

There are only two ways of defining this function (return the first argument or do the right thing). Because the function's type uses arbitrary type variables you can't just construct a new value of type `b` or do modify somehow the first two arguments. And sometimes type declaration uniquely defines what the function does. Below there are three functions that you can't implement incorrectly.

```
id :: a -> a
const :: a -> b -> a
flip :: (a -> b -> c) -> b -> a -> c
```

All these examples show how Haskell's type system and immutability make your code safer.

5.2 Expressiveness

Haskell types not only make code safer, but they also make it more readable. Type signature significantly reduces the number of possible implementations of the function, so if you know the name and the type of a function then more often than not you can tell what the function does without looking at the implementation. This helps a lot when you are working in a team and you want to use a function written by another person. It also makes it easier to use libraries. By defining types using `newtype` and `type` you can make it even easier to understand what functions do without using any more data at run time.

As you saw in the examples, Haskell usually requires less code to solve a problem. The reason for this is the minimalist syntax and features like partial application, pattern matching, custom operators, etc. Also, in both cases the code was close to the description of the problem in English. This shows that Haskell is a very expressive language.

5.3 High level abstractions

In Haskell the type system is very strict and safe, but at the same time it's very flexible. Using algebraic data types, type variables, type classes, and other tools you can model very complex logic with types. An API defined in terms of types is a good example of that - it's flexible, extensible, and safe. It also allows you to generate client side code from your API type, which makes the system even more abstract.

In Haskell, unlike imperative languages, sequencing task is removed. You only care what the program needs to compute, not how or when it will compute it. Haskell tools like `deriving` allow you to generate functions for your custom data types. Extensions like `GeneralizedNewtypeDeriving`, `DeriveGeneric`, `DeriveAnyClass`, etc extend this mechanism even further and allow you to derive instances for non-standard type classes. `TemplateHaskell` extension adds compile-time metaprogramming facilities. This means you can write type safe Haskell code that modifies type safe Haskell code (usually adds functions).

These features allow you to focus on the logic of the application you are developing and let Haskell do the rest of the work. And if you are unhappy with the way Haskell does something then you can usually specify how you want the code work, for example by using different compiler flags. This makes Haskell a very abstract language.

5.4 Modularity

Lazy evaluation makes code more modular. For example, you can implement a function that finds maximum of a list as `maximum = head . sort`. Thanks to lazy evaluation this won't sort the entire list. Without lazy evaluation we can't efficiently use these 2 functions to implement `maximum`. So lazy evaluation improves modularity.

The type system also improves modularity, because you can easily and safely compose types, functions, etc. Ad-hoc polymorphism and parametric polymorphism allow developers to write the most general version of functions, making them more reusable. The syntax plays a big role in making Haskell code more modular, as it makes things like function composition very easy. You can see this in the first example, where my main IO action is one expression, that uses more than 10 functions.

These features make Haskell code reusable.

5.5 Performance

In both examples Haskell performed better than Ruby. In the first example I did some optimizations, but for most of the code I kept things simple. High-level programming languages don't have to be very fast and they are usually slower than low-level programming languages, however, as Jan Stolarek showed in his blog, Haskell code can be as fast as C code.[4] Also Haskell has a foreign function interface that lets you call C code from Haskell. Facebook's spam filtering system is implemented in Haskell and C++ and it handles millions of requests per second. In conclusion, Haskell's performance is good for most use cases, and if for some parts of your program you need higher performance then you can use the foreign function interface and implement it in C.

5.6 Final conclusion

As I showed in this investigation, there are a lot of benefits to using Haskell for developing applications. It's safety, expressiveness, level of abstraction, modularity, and performance allow programmers to quickly and easily write code that is safe, stable, easy to refactor, and has low defect rate. Of course it has some disadvantages, like the fact that currently not many software developers know Haskell or that it can be hard to learn as most coders are not used to thinking about problems in functional/declarative manner. In conclusion, if one's team of developers can work in Haskell then for developing most kinds of applications (except for drivers, 3d games, and other applications that require the best possible performance) Haskell will be one of the best programming languages to use.

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