C/CPS 506

Compara **Languages**

Prof. Ale

Topic 6: Type systems, pure functional with Haskell

Ryerson University

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Course Administration

Elixir assignment 9

Today

Type systems:

Intro to Has

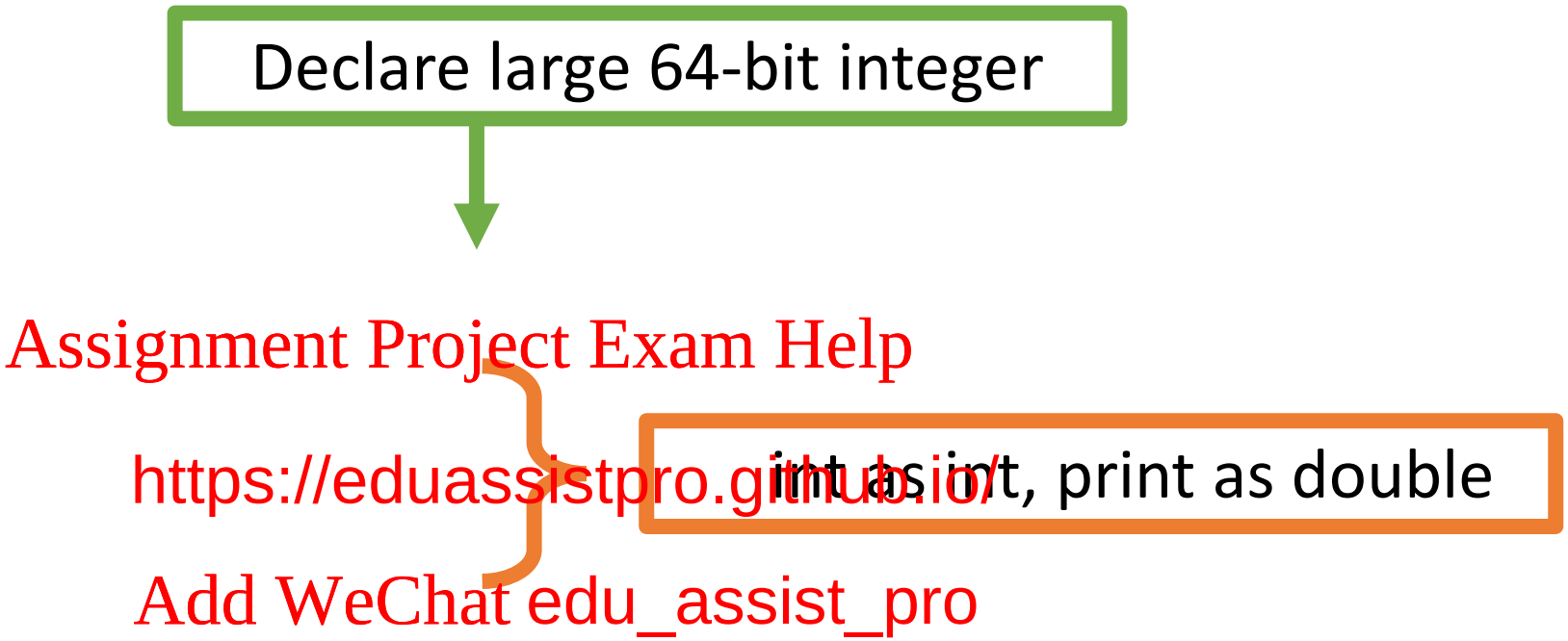
- Pure functional
- Typing in Haskell

Type System

- A set of rules that assigns a property called ***type*** to constructs of a program.
- These constructs include variables, functions, expressions, etc.

The whole point is to reduce bu

- For example, if a pattern of 3 [illegible] en encoded using 2s complement, we don't want to read it using IEEE 754
- And we *can* do this in many languages!



- The 2s comp bit pattern was read as an IEEE 754 double.
- (The integer constant was deliberately picked to produce a bit pattern that would yield 1.000000 as double)

Type Checking

Clearly, type checking isn't performed in the context of a **`printf`** statement in C++

- Think of type checking as a puzzle: pieces together.
- Does the output type of a fun the variable we're trying to store it in?
- Do the input arguments to a function match the types indicated in the parameter list?
- If no, will we allow implicit conversion?

Static VS Dynamic

When are types checked?

Statically typed languages perform type checking at *compile time*

- Checked while converting source code to machine (or byte) code

Dynamically typed l ecking at *run-time*

- Checked on the fly while instructi g executed.

Statically Typed languages: C/C++, Java, Haskell, Rust

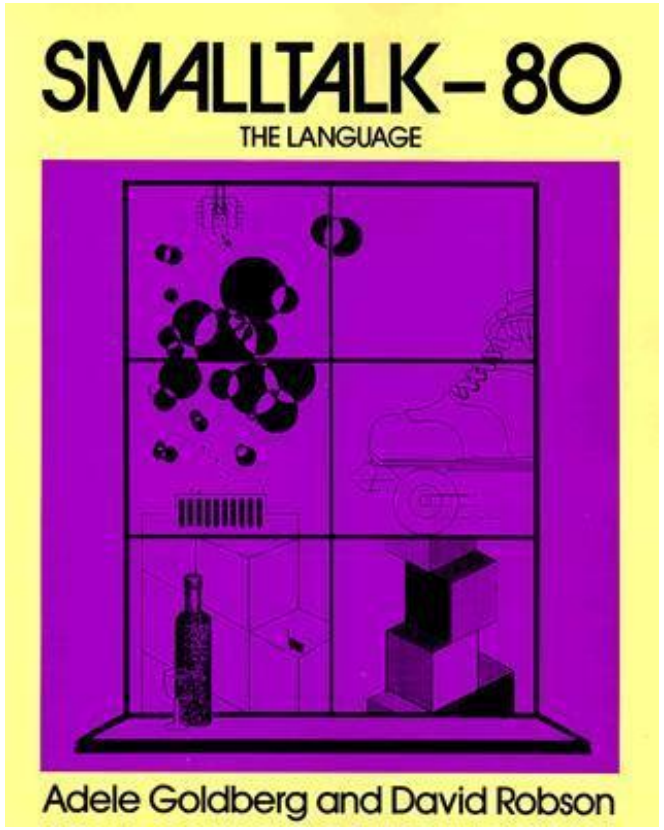
Dynamically Typed languages: Python, Smalltalk, Elixir

Static Type Checking

```
incompatible types: java.lang.String cannot be
converted to double
```

- In dynamically typed languages, every operation knows the types for which it is valid.
- Providing invalid arguments or operands will yield a run-time erro t be recoverable
- Such things can be anticipa itigated in various ways, such as verify xplicitly

Dynamic Type Checking




```
factorial: n
   | fac |
   fac := 1.
   n
      ifTrue: [1
         [:a | fac          .].
         ^fac
      ]
      ifFalse: [
         ^'Bad input'
      ].
```

- In Java, the parameter would be defined as **`int`**
- Compile error if arg isn't **`int`**, or
  't be implicitly cast as an **`int`**.

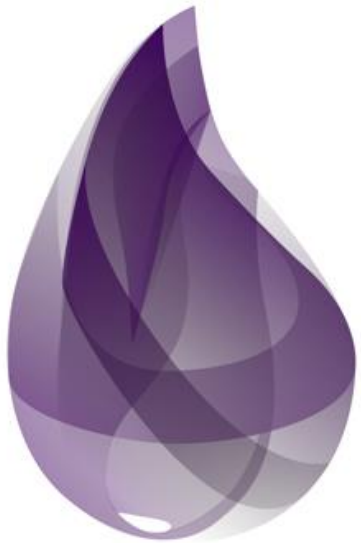
- Of course, polymorphism in Java complicates this.
- Still statically typed.

Dynamic Type Checking…?

```
#(1 2 3 4) + 18.2
```


- Does Smalltalk have type errors in the strict sense?
- Different obj messages.
- A “type error oesn’t have a method to handle a partial
- “Type” errors in Smalltalk are as a result of not finding a method (DNU, Did Not Understand).
- Above, the error occurs because the Array class doesn’t have an instance ***method*** for symbolic operator **#+**
- Smalltalk enthusiasts debate this.

Dynamic Type Checking



```
defmodule UserMath do
  def fib(n) when not is_integer(n) or n < 0 do
    :error
  end
  de
  de
  def fib(n), do: fib(n-1)
  def fac(n) when not is_integer(n) or n < 0 do
    :error
  end
  def fac(0), do: 1
  def fac(n), do: n*fac(n-1)

end
```

Static VS Dynamic

Advantages? Disadvantages?

Static:

- Reliably find errors at c
- Code will execute faste
  assumed to be correct at run time.
- Type-specific optimization can be performed at compile time.
- I.e., integer arithmetic is faster than floating point

Dynamic:

- pilers run faster
- n dynamically load
  - de
  - Smalltalk, MATLAB, iex
- Easier code reuse

Static VS Dynamic

Advantages? Disadvantages?

- There is much disagreement among programmers about just how much of a proble and scheme of things.
- Does the added c ically typed language make sense if type-related bugs a fraction?
- Of the type-related bugs that occ portion of those would have been solved by a type checker anyway?
- They aren't perfect after all.

Strong VS Weak Typing

Strong VS Weak (or *Loose*)

Refers to how strict statically typed languages are at compile time

There is actually no universally accepted definition of what
co typing

Of strongly typed

1974: “Whenever an object is pa calling function to a called function, its type must be ***compatible*** with the type declared in the called function."

Compatible is open to interpretation. Is float compatible with double? Integer with short integer?

Strong VS Weak (or *Loose*)

Refers to how strict statically typed languages are at compile time

1974: "Whenever an object is passed from a calling function to a called function, its type must be compatible with the type ction."

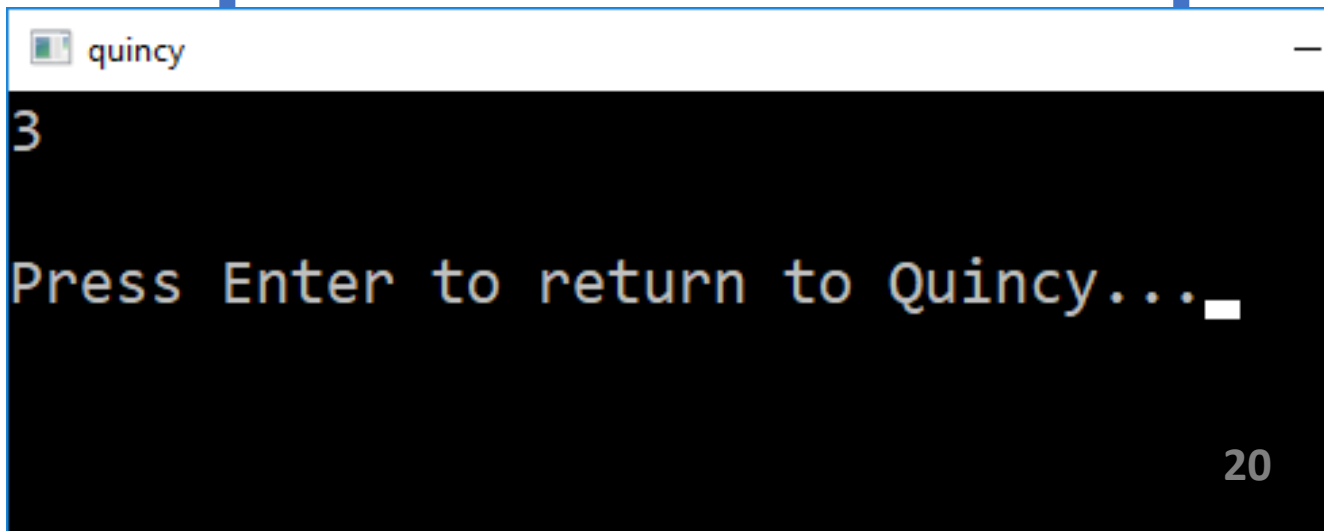
1977: "In a strongly typed lan ata area will have a distinct type and each process will state its ***communication requirements*** in terms of these types."

Parameter lists, return types, etc.

THE C PROGRAMMING LANGUAGE

Strong VS Weak (or *Loose*)

To what degree does a statically typed language allow implicit type conversion?



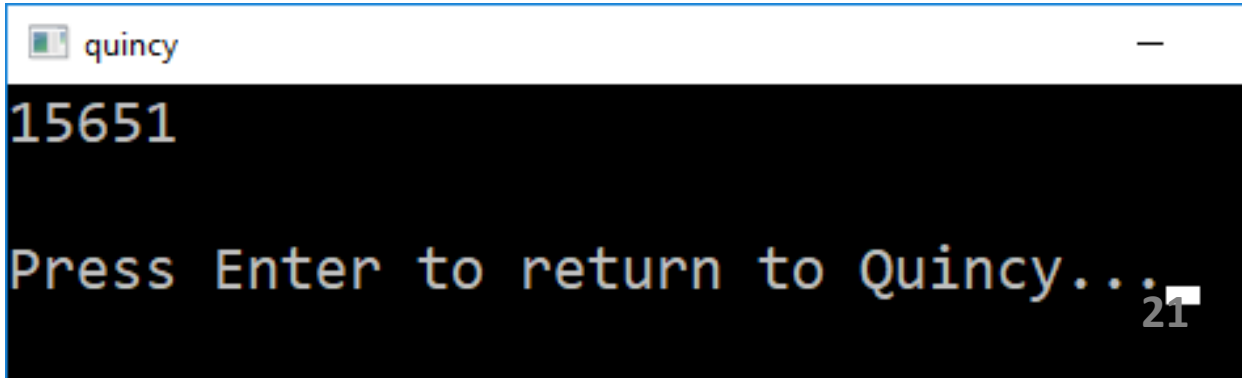
- C is weakly typed.
- Happy to perform all manner of implicit conversion without warning or error.

THE C PROGRAMMING LANGUAGE

Strong VS Weak (or *Loose*)

In C, pointer arithmetic can be used to ***completely bypass*** the type system:

- We're using pointer arithmetic to read the first 2 bytes of an **`int`** as a **`short`**.
- ne with any two types.
- he rightmost 4 by
- det **`int`** etc.
- We can treat memory any way we want

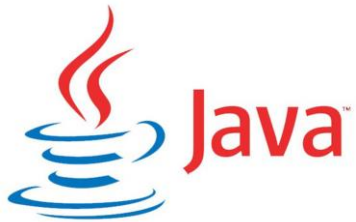


Strong VS Weak (or *Loose*)

C++ will give warnings where C did not, but still compiles and runs in this case:


```
guration: Debug Win32 ------

 warning C4244: 'initializing' : conversion from 'double' to 'int', possible loss of data
est\Debug\test.exe
-to-date, 0 skipped ==========
```



Strong VS Weak (or *Loose*)

Java will throw compile errors when a ***loss of precision*** occurs:

- No implicit rom floating point to integer
- Floating point constants are double precision
- Need to indicate single precision explicitly

Java will throw compile errors when a loss of precision occurs:

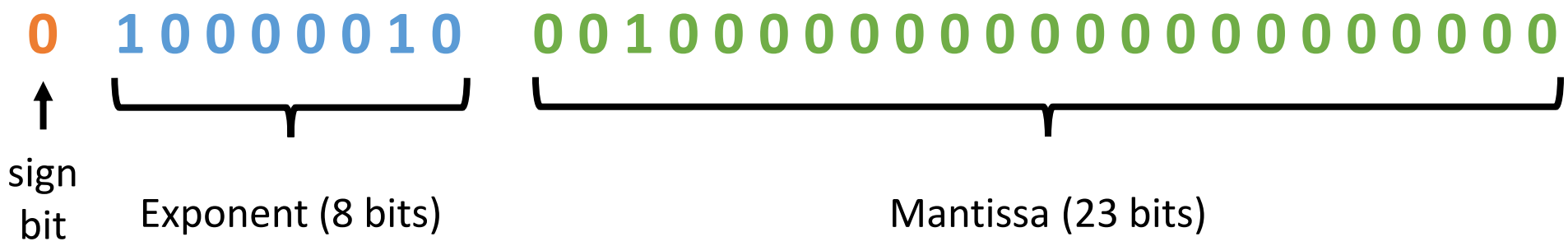
Careful! Loss of precision does not ***only*** occur when going from floating point type to integer type!

`int` is 32 bits two'

`float` is a 23-bit

here!

32-bit:



Imprecision of Floating Point

- Integers are represented *precisely.* The integer 42 is **exactly** 42.
- The single-precision (32 bits) floating point value 0.1 is ***actually*** 0.100000001490116119384765625
- *Double*-precision ues are more accurate, but still not perfe

But why?

- Floating point values exist on an infinite continuum.
- Between any two floating point values are an ***infinite*** number of additional floating point values.
- Integers are discrete. Between any two integers are a ***finite*** number of integers.

Imprecision of Floating Point

- A double-precision float is represented using 64 bits.
- A ***finite*** number of bits cannot represent an ***infinite*** number of floating point values.

0100101110000010100011011000110000111000011

- There are **2^64** ways to arrange 64 bits. A large number to be sure, but certainly not infinite.

Infinite Integers?

But there are an infinite number of integers!

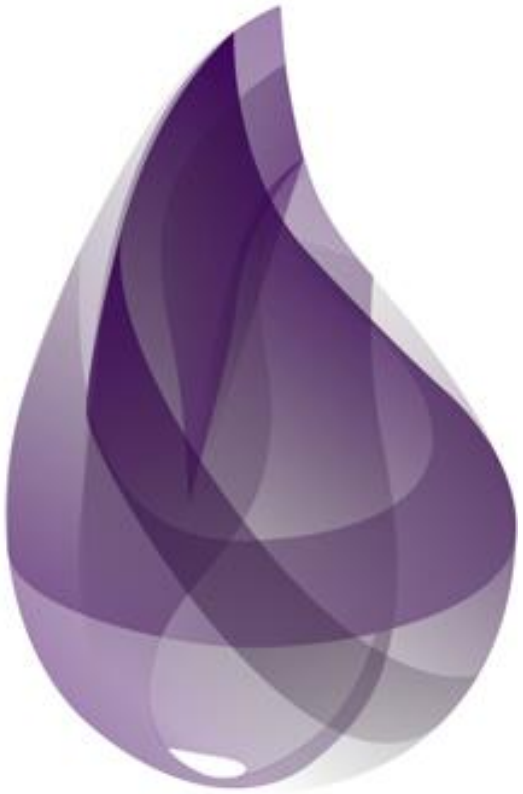
- 100% correct. We can't represent every possible integer either.
- Rather, there is integer has a range of −2,147,483,64
- Every integer within this range is precisely.
- Anything outside this range can't be represented using 32 bits
- If we try, we overflow.

IEEE-754

Functional Programming

Functional Programming

Functional Programming



Higher-order functions:

- Can return functions or accept them as arguments.

F

- ents, returned as values.
- Think of them st like integers or floats

Pure Functions:

- Functions that have no side effects. No interaction with world outside of local scope
- Easier to verify correctness, thread-safe when no data dependency is present.

Pure function

Impure function

Functional Programming

Strict (eager) VS. non-strict (lazy) evaluation:

- Strict: evaluate function arguments before invoking the function.
- Lazy: Evaluates arguments if their value is required to invoke the function.

Elixir largely performs strict evaluation
(some exceptions, recall `Stream`, `Range`)

Functional Programming

Strict (eager) VS. non-strict (lazy) evaluation:

- Strict: evaluate function arguments before invoking the function.
- Lazy: Evaluates arguments if their value is required to invoke the function.

https://www.haskell.org/

A great intro to Haskell syntax

Haskell: Functional Programming cranked up to 11

History

- Named after logician Haskell Curry
  interest in lazy functional
  lowing
- There
  g consensus to define
  an op
  for such languages

History

- Haskell 1.0 was defined in 1990
  - Continued with version 1.1, 1.2, 1.3, etc.
  - Culminated with *Haskell 98* published in July 2010
- Next version controversial features pre led via compiler flags
  - Though progress seems to have stalled worked on – Haskell 2020
  - Perhaps it should be called Haskell 202X

Features

Purely Functional:

- Every function is *pure*
- Even side-effect inducing operations are
  e code
  only expressions
- Canno
  riables (local or global)
- Suppo
  atching
- Side effects are handled using *monads*

Features

Statically Typed:

- Every expression has a type
  - Determined at compile time
- g an expressions must match
- ile error

Type Inf

- Types don't have to be written out explicitly
  - Though you can if you want
- They will be inferred at compile time

Features

Lazy Evaluation:

- Functions don't evaluate their arguments
- Control constructs written as functions

ins of functions together

ver takes place unless a result

Concurrency:

- GHC (Haskell compiler) includes high performance parallel garbage collector
- Light-weight concurrency library

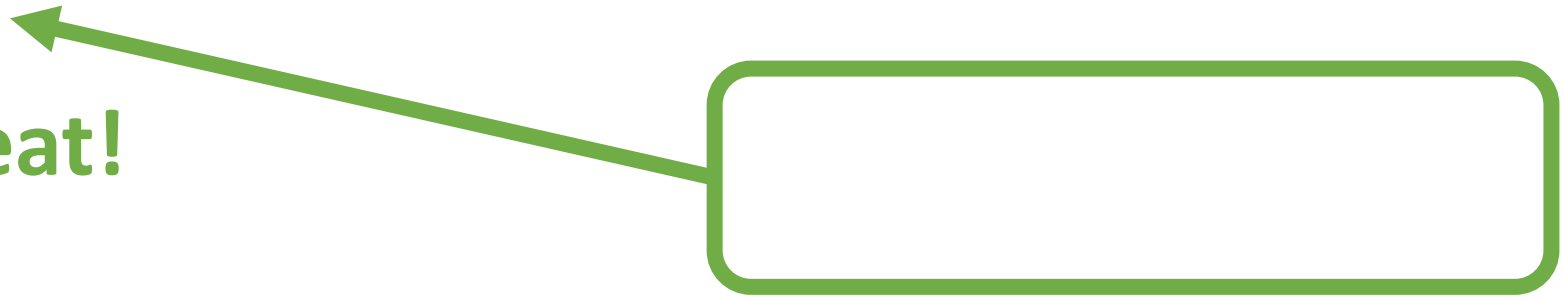
Haskell in Industry?

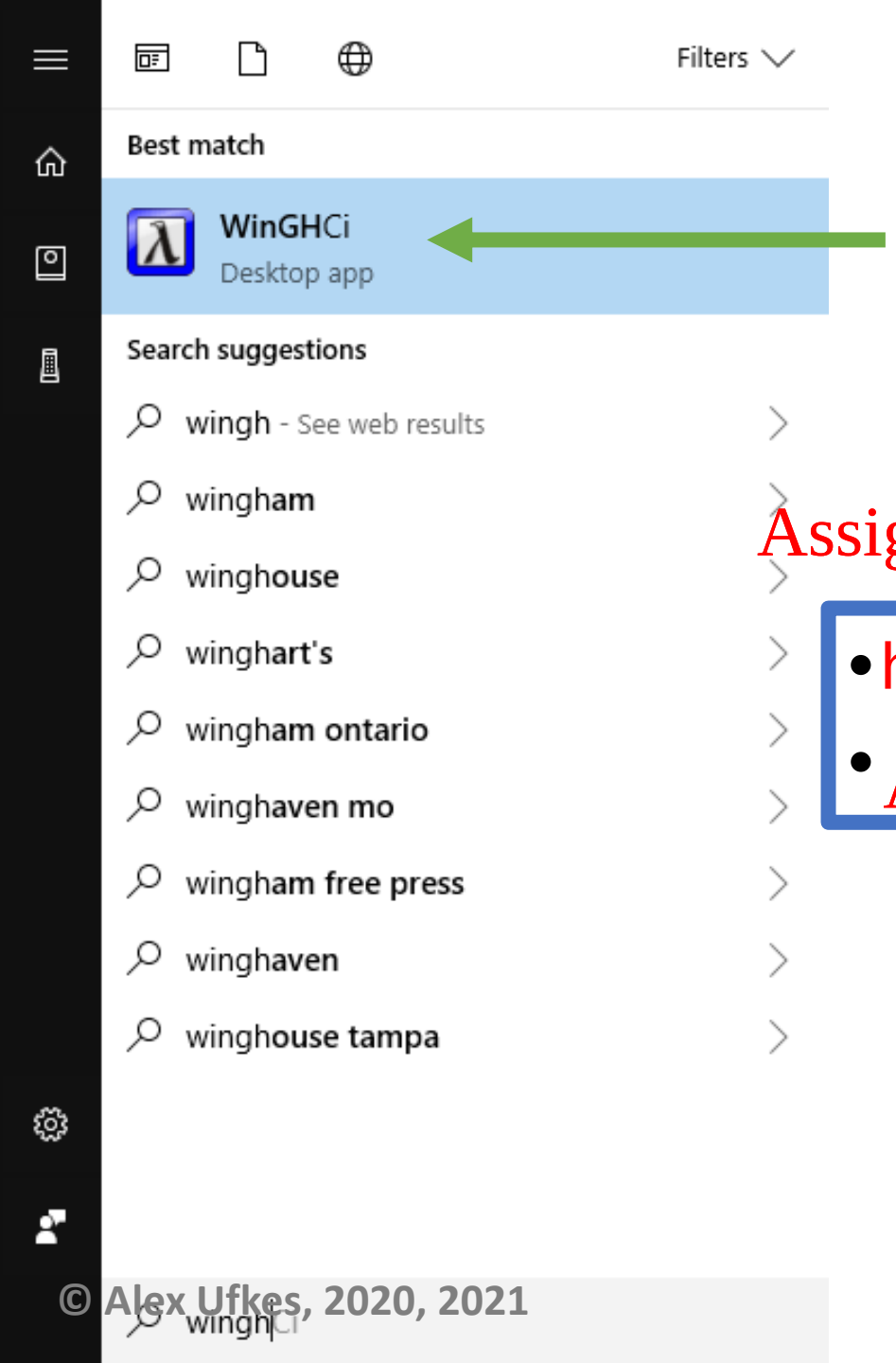
Notable companies that use or have used Haskell:

- Nvidia
- AT&T
- Ericsson
- Facebook
- Google
- Intel
- Microsoft

Typically Haskell is used on specialized internal projects or research. Not necessarily company-wide.

Installing Haskell:





- https://eduassistpro.github.io/ just like Elixir.
- Haskell's i

Hello, World!


```
Prelude> main
Hello, World!
Prelude>
```

putStrLn == System.out.println()
putStr == System.out.print()

efine a main function.
hen executing a Haskell program, main is the entry point

- Just like C or Java

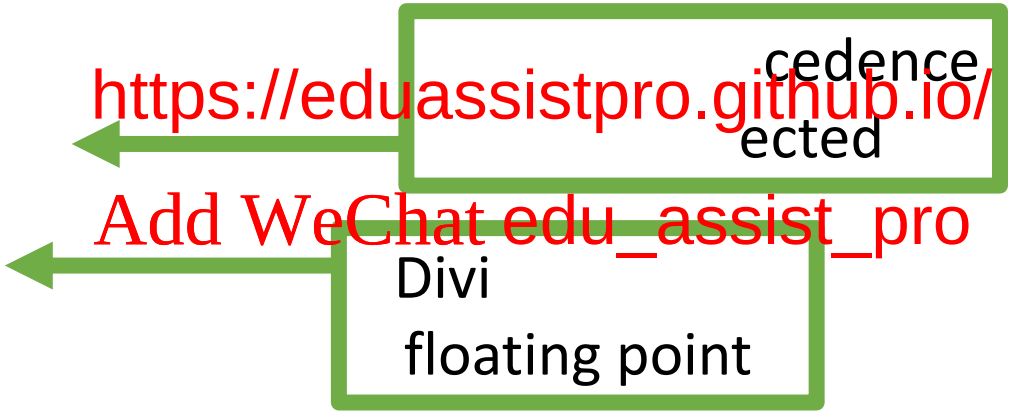
Execute main function

Compiling Haskell

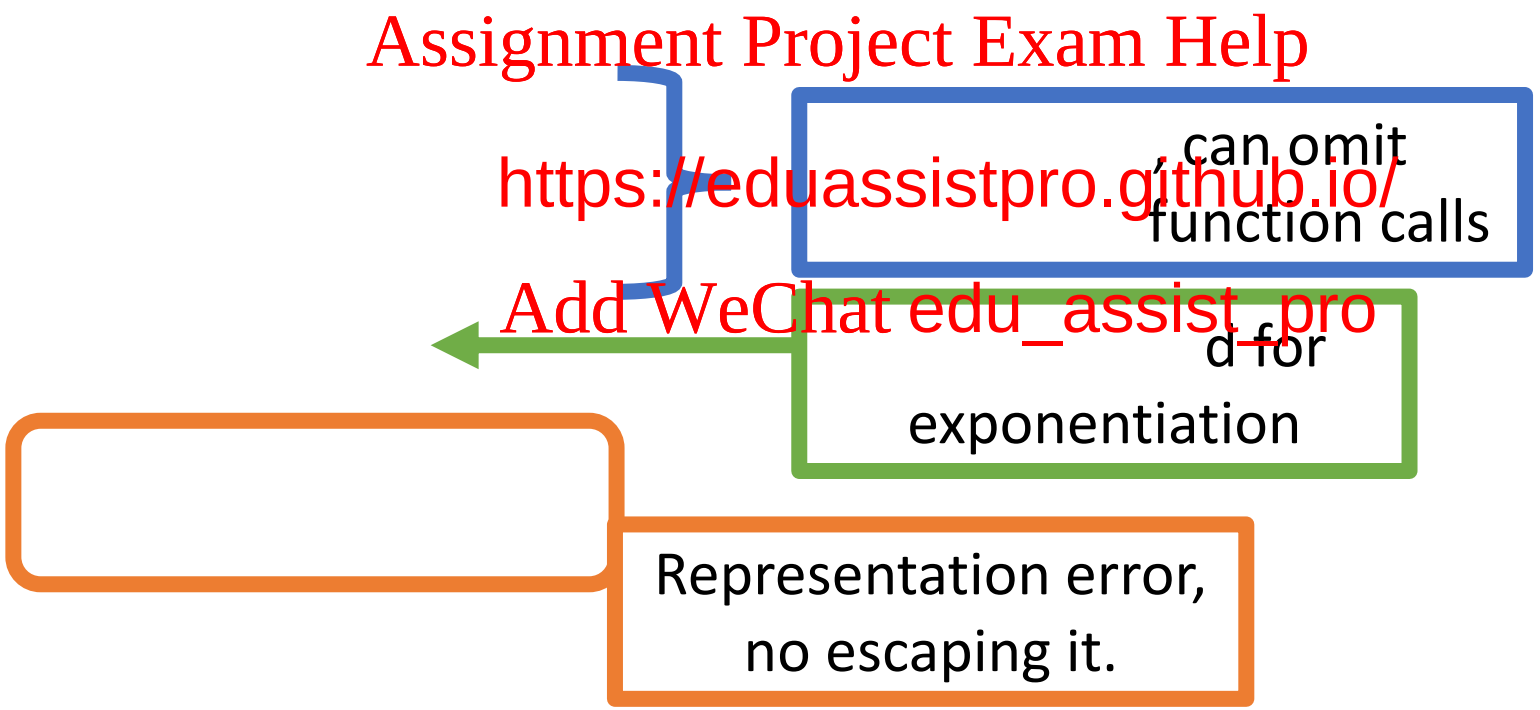
Notepad++ features Haskell syntax highlighting!

As with E nd in the interactive shell until it edious.

Literals & Arithmetic



Literals & Arithmetic



Tuples

- orts tuples.
- he same types.

There a nctions for accessing first and second elements. Great for coordinates.

`fst` and **`snd`** only work on pair tuples!

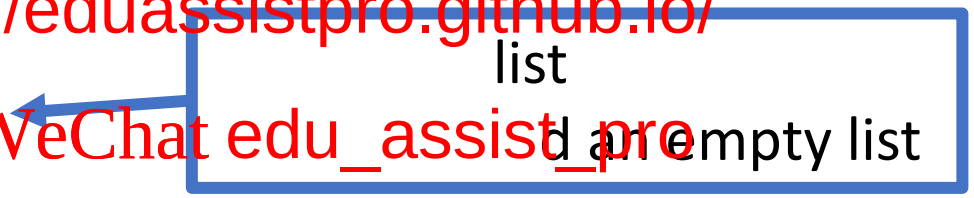
Lists

Must be ***homogeneous***:

r literals get
floating point
do not

Lists

Elements can be added to the *beginning* of a list with the **cons** (:) operator



In fact, when we write **[1, 2, 3]** the compiler is *actually* doing **1:2:3:[]**
[1, 2, 3] notation is *syntactic sugar.*

Lists & Tuples

Tuples can be heterogeneous, lists must be homogeneous.

However! We can have lists of tuples, each tuple is heterogeneous.

Lists & Tuples

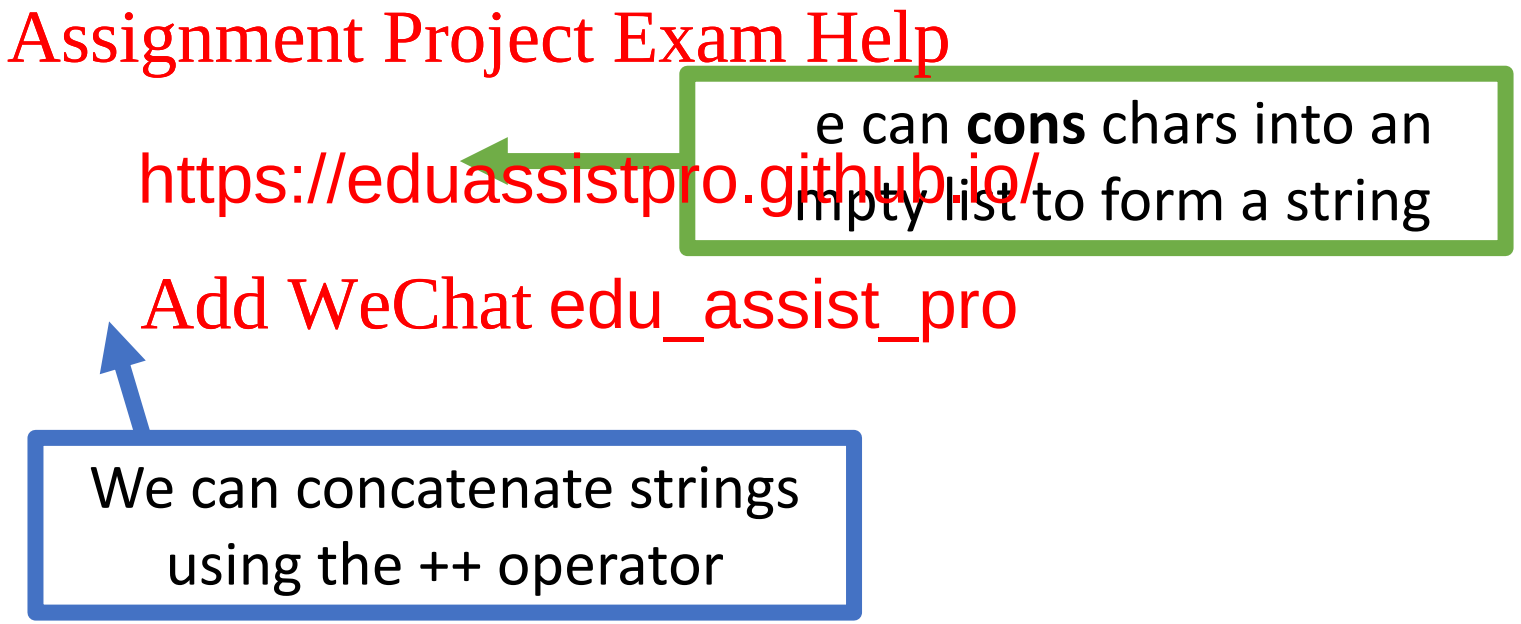
Tuples can be heterogeneous, lists must be homogeneous.

However #2!

of tuples, each tuple
ve the same format:

Strings

Strings are simply lists of chars:



Strings

Concatenate multiple types? Java lets us…

Strings

`show()` and **`read()`** functions

Convert non-string argument to string

Read numeric a string (like *sscanf* in C)

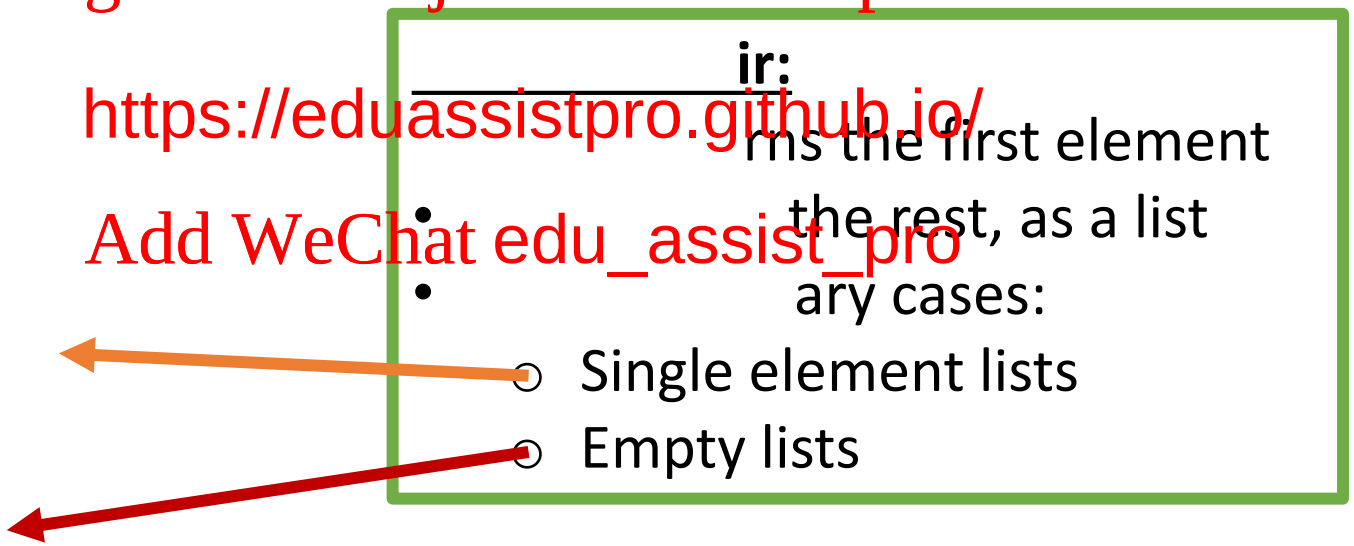
Error when no numeric value is present

Operations on Lists

- In functional programming, computation is done in large part by operating on lists.
- We sa in Elixir.
- Haske ations.

Three primary list-processing functions: **`map`**, **`filter`**, **`foldr`** (and **`foldl`**)

Head & Tail



`map`

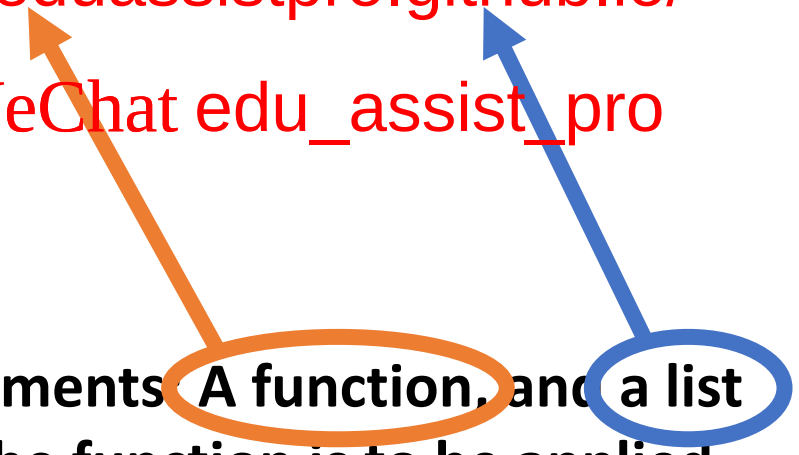
Similar to Elixir's **`Enum.map`**

- First class function, doe suggests.
- Alphabetical characters are upped, everything else is left the same.

Recall: map operates on lists, but a string is just a list of characters

`map`

Similar to Elixir's **`Enum.map`**



Map takes two arguments: A function, and a list of values to which the function is to be applied.

`filter`

"Remove" items from a list based on some criteria:

Function **List**

`foldl, foldr`

Replaces the cons operator with some other function. This takes some explaining.

Is actually s

```
1:2:3:4:5:[]
```

By the compiler.

`foldl, foldr`

Replaces the cons operator with some other function. This takes some explaining.

Recall that the list:

```
[1, 2, 3, 4, 5]
```

Is actually seen as:

```
1:2:3:4:5:[]
```

By the compiler.

`foldr` replaces the cons operator with a function of our choosing.

- This is `lum.reduce` in Elixir.
- The empty list is replaced with some initial value.

`foldl, foldr`

Replaces the cons operator with some other function. This takes some explaining.

- **`foldr`** in effect replaces the cons operator with another .
- This is s Elixir.
- The empty list is replac e initial value.


```
foldr (+) 0 [1, 2, 3, 4, 5]
```

Three arguments: **function**, **initial value**, **list**

foldl, foldr

Replaces the cons operator with some other function. This takes some explaining.


```
foldr (+) 0 [1, 2, 3, 4, 5]
```


```
foldr (+) 0          :5:[]
```


```
1 + 2 + 3 + 4 + 5 + 0
```

```
15
```

foldl, foldr


```
120
Prelude>
```

foldr to perform factorial!

`foldl` VS `foldr`

`foldr` is *right associative*. Meaning:

```
foldr (+) 0 [1, 2, 3, 4, 5]
```



```
1 + 2 + 3 +         + 0
```


Is actually:

```
(1 + (2 + (3 + (4 + (5 + 0)))))
```

Doesn't matter for addition, but subtraction…

`foldl` VS `foldr`

`foldr` is *right associative*. Meaning:

```
foldr (-) 1 [4, 8, 5]
```



```
  4 - 8 -
```


Is actually:

```
(4 - (8 - (5 - 1 )))
```

```
0
```

`foldl` VS `foldr`

`foldl` is *left associative*. Meaning:

```
foldl (-) 1 [4, 8, 5]
```



```
  1 - 4 -
```


Is actually:

```
(((1 - 4) - 8) - 5)
```

```
-16
```

`foldl` VS `foldr`

List Generation

Syntactic sugar:

List declaration:
```
list = [1, 2, 3, 4, 5, 6, 7, 8, 9]
```

Can be written:

Specify interval:
```
list = [1,
       = [1,3,5,7,9]
```


Interval is discerned from difference between first two elements

Infinite Lists?

Try it, but be ready to interrupt

Infinite Lists?

Haskell is lazy!

ind x to the expression
nerate an infinite list.
n't have to *evaluate*
to do so!

- Displaying the list, however, requires evaluation.

Why? How?

Infinite Lists?

- Finding the length of the list requires counting the elements.
- Be ready to interrupt.

- Grab first three elements of list
- Doesn't matter if infinite, we're only evaluating first three items

Infinite Lists?

We're allowed to perform operations on a *finite subset* of an infinite list.

- **`zip`** "zips" two lists together into tuples.
- If one list is finite, the other can be infinite.

Types in Haskell

Statically Typed:

- Haskell uses static type checking.
- Every expression is assigned a type.
- If a function xpected type, a com

Type Inference

- Like Python, and unlike Java, we need not specify type.
- It is inferred by the context: X = “Hello”, X is a string.
- However, we can explicitly specify types.
- Good practice when we know what types we want; compiler will give errors upon type mismatch.

Types in Haskell

`:t` can be used to reveal type:


```
+ :: Num a => a -> a -> a
1.0 :: Fractional a => a
```

- ‘a’ is a **Char**
- “Hello” is a **[Char]**
- **[Char]** = **String**
- t is a **Bool**

`Num p => p ?`

p is a *type v* e value can be any type in type nteger, Float, etc.)

- Haskell is free to treat 7 as it sees fit, so long as it does so in a way that adheres to the operations defined in type class **`Num`**.

Typeclasses?

Types as generic as possible

- If we expli… a variable as integer, it can't be p… nction requiring float.
- However, if we generically infer it to be a **Num**, it can be used anywhere any other member of Num is allowed.

Types in Haskell

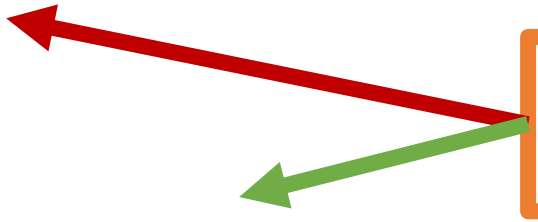
We can explicitly indicate types:


```
Prelude> :t 5::Int
5::Int :: Int
Prelude> :t 5.0::Double
5.0::Double :: Double
Prelude>
```

- Us a type
- My advice for you is to start by letting the inference engine figure it out.
- **At this point, it knows better than you.**

Types in Haskell

We can explicitly indicate types:



When defining a name, can indicate type explicitly:

Type Classes

Type polymorphism and type variables:

Recall: Overloading

- In langu tor is overload ferent types.
- Numeric type equality a uality are performed differently.
- In general, if we want to compare two values of type α, we use an ***α-compare***
- α is a *type variable*, because its value is a type.

Type Classes

Consider the equality (==) operator:

Takes two parameters, each of the same type (call it a), and returns a Boolean

This operator pes, just some.

Thus, we can associate == with a specific ***type class*** containing those types for which == is defined.

This type class is called **Eq** in Haskell.

`Eq` Type Class

(==) is defined for types in typeclass **`Eq`**

- (==) ta of type **a**, where **a** is a pe class **`Eq`**
- It returns **`Bool`**

- If a concrete type, **a**, belongs to a certain type class, we say **a** is an *instance* of that type class.
- **`Int`** is an instance of **`Eq`**, for example.

Num Type Class

- This allows nu s freedom to be an integer or floating point as the compiler sees fit.
- **`Num`** class contains all numbers, and certain operations over them such as addition.

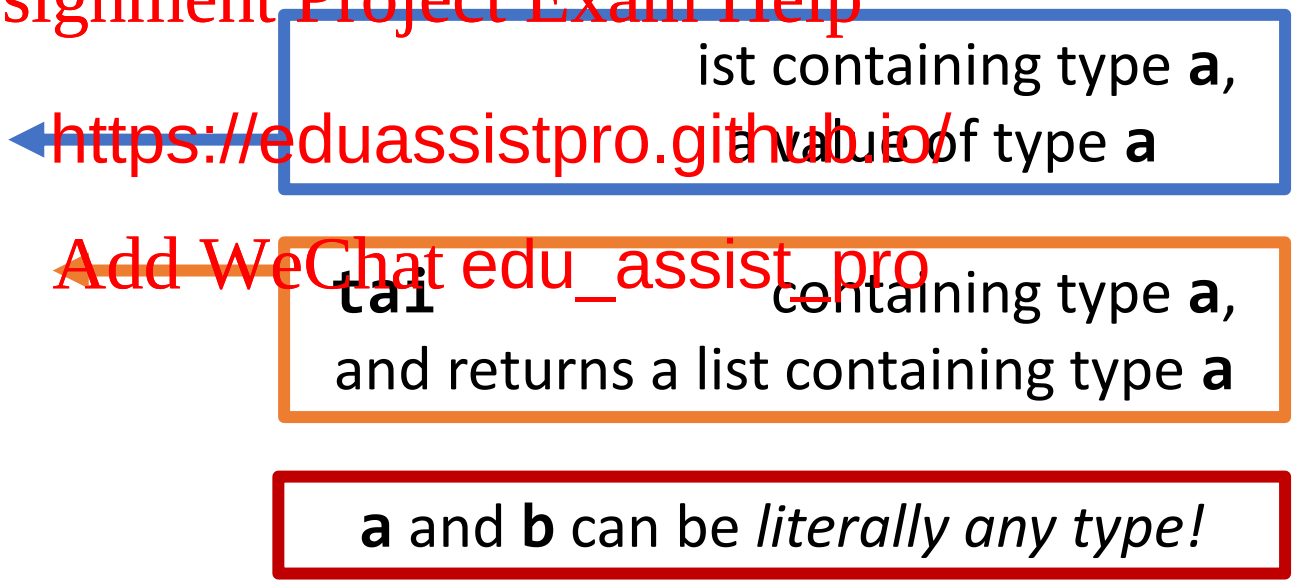
Num Type Class

- **p** iable
- The type of 5 is **p**, and **p** is a member of type class **Num**

Show Type Class

The members of the **Show** class have functions which convert their value to a String.

Function Types



Function Types

- _____ tring, returns ***IO action***.
- function
- ut, IO() is output.
- More on IO actions later.

Same as [Char]

We'll create our own types soon, and see how to add t lasses.

Functions in Haskell

As expected of a pure functional language, functions are central in Haskell

- If we're compiling our
  de into an executable,
  e need a main.
- If we're using the GHCi shell, we don't.

Functions in Haskell

Let's start simple:

Define function called **square** that takes one argument **x**

square x = x*x, where **x** is the input argument

Functions in Haskell

Let's start simple:

function **square**
ypical fashion

Functions in Haskell

Functions in Haskell


```
19
Prelude>
```

Passing in four args

Functions in Haskell

hat we're do **square** and
s ing and adding)…

- Haskell determined that input and output type should be instances of typeclass **Num**.
- **(+)** and **(*)** are both defined for all types in typeclass **Num**.

Haskell Modules

This is getting tedious to type interactively.

Let's cr le!

- Simil s in Elixir
- We can load the module in GHCi
- Access its functions and expressions

Loading a Module

When we make changes to Test module, can reload with 1 click!

Loading a Module

Use **`:load`** in terminal GHCi:

Use **`:reload`** for previously loaded module

Control Structures

if then else


```
        f 67
1
Prelude> f 0
1
Prelude> f (-6)
0
Prelude> f -6

<interactive>:203:1: error:
    • Non type-variable argument in the constr
aint: Num (a -> p)
```

- Brackets required around negative arguments
- Otherwise it thinks you're subtracting 6 from f

Control Structures

```
if then else if then else
```

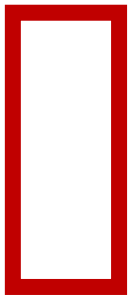

- Here we have a function named
  takes one argument x
  egative
  sitive
  - 0 if x is 0

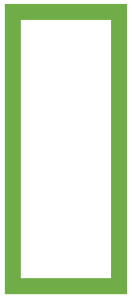
- If/else construct in Haskell is similar to most other languages.
- It must include a **then** and an **else**

Control Structures

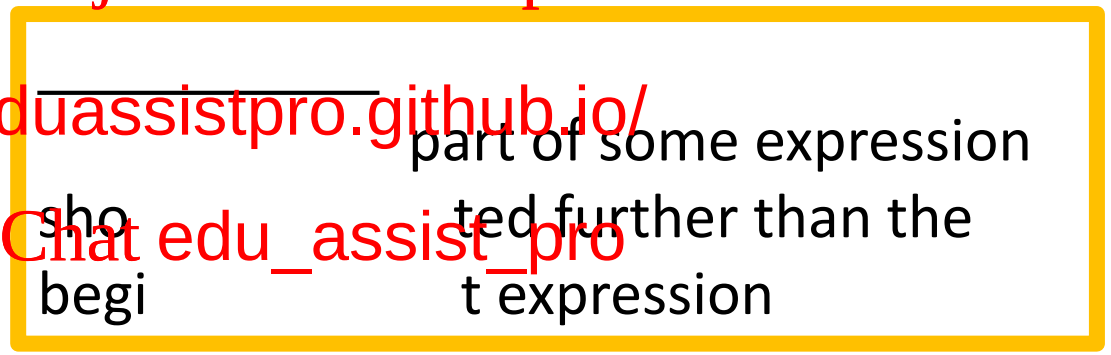
```
if then else if then else
```


We can now format across multiple lines.
HOWEVER: Indentation matters in Haskell!





Indenting in Haskell



https://en.wikibooks.org/wiki/Haskell/Indentation

If all that weren’t enough, Tabs don’t work properly u aces exactly.

Haskell Tutorials/References:

https://en.wikiboo ther_Haskell_Tutorial

http://cheatsheet.codesto heatSheet.pdf