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# An Optimising Compiler from Haskell to Java Bytecode

Computer Science Tripos – Part II

Robinson College

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# Declaration of Originality

I, Keith Collister of Robinson College, being a candidate for Part II of the Computer Science Tripos, hereby declare that this dissertation and the work described in it are my own work, unaided except as may be specified below, and that the dissertation does not contain material that has already been used to any substantial extent for a comparable purpose.

Signed:

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# Proforma

| | |
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The compiler is comprised of a number of stages and substages, as shown in Figure 3.1:

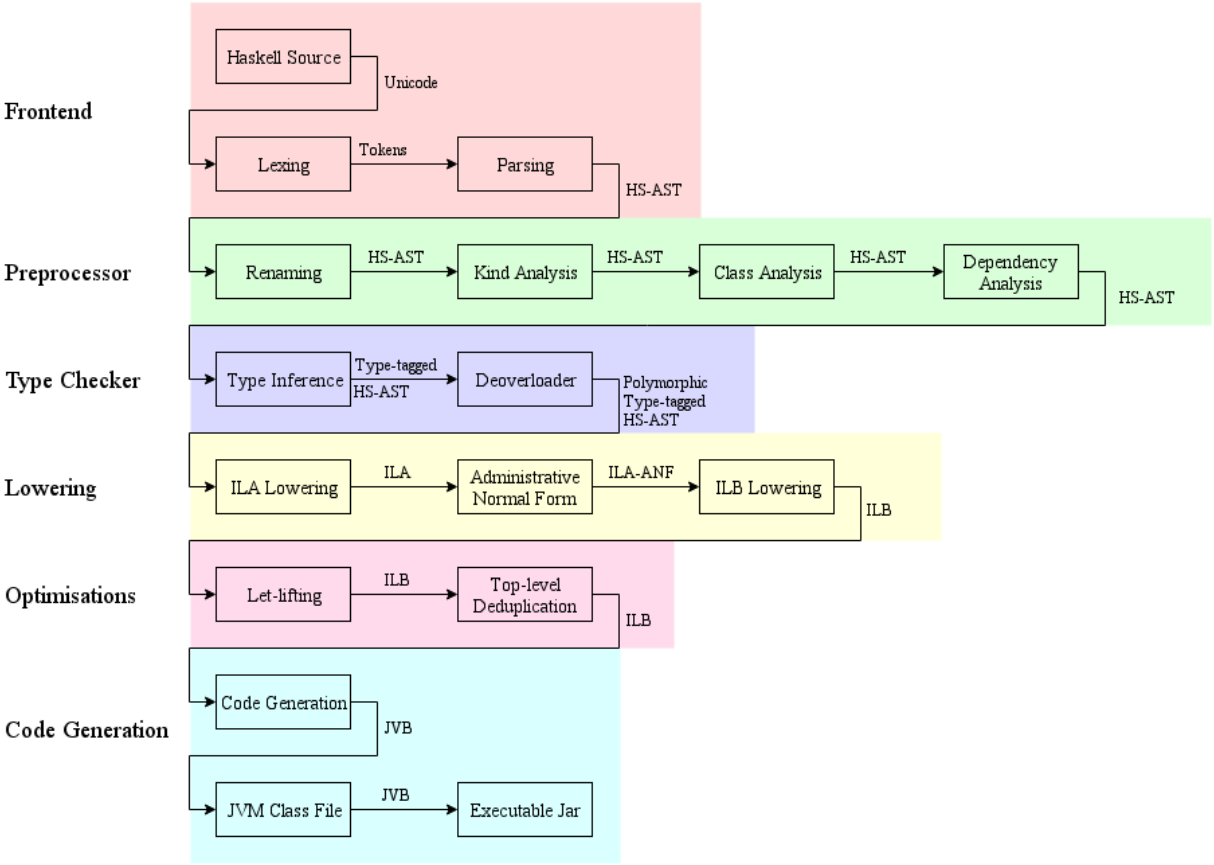



Figure 3.1

A brief overview of each stage is given here for a 'big picture' view of the compiler, followed by more detailed descriptions below.

### Frontend

The frontend consists of standard lexing and parsing from Haskell source code into an Abstract Syntax Tree (AST). A modified version of an existing library (haskell-src[1]) is used.

### Preprocessing

- The renamer renames each variable so that later stages can assume each variable name is unique: this reduces complexity by removing the possibility of variable shadowing (eg. `let x = 1 in let x = 2 in x`).

[1] https://github.com/hnefatl/haskell-src

- Kind and Class analysis both simply extract useful information about the declarations in the source so that stages of the type checker are simpler.
- Dependency analysis computes a partial order on the source declarations so that the typechecker can process them in a valid order.

**Type Checker**

- The type inference stage infers polymorphic overloaded types for each symbol, checks them against any user-provided type signatures, and alters the AST so that each expression is tagged with its type.
- Deoverloading converts polymorphic overloaded types to polymorphic types similar to those of System F, and alters the AST to implement typeclasses using dictionary-passing.

**Lowering**

The lowering stage transforms the Haskell source AST into Intermediate Language A (ILA), then rearranges that tree into Administrative Normal Form (ILA-ANF), before finally transforming it into Intermediate Language B (ILB).

**Optimisations**

Optimisations transform the intermediate languages into more efficient forms while preserving their semantics.

At time of writing these are done on ILB, might change to ILAANF so should update this accordingly.

If any more optimisations are implemented, update the diagram and here.

**Code Generation**

ILB is transformed into Java Bytecode (JVB), and a modified version of an existing library (hs-java[2]) is used to convert a logical representation of the bytecode into a set of class files, which are then packaged into an executable Jar file.

## 3.1 Implementation Details

### 3.1.1 Frontend

Lexing and parsing of Haskell source is performed using the `haskell-src`[3] library, which I have modified to provide some additional desirable features:

- Lexing and parsing declarations for built-in constructors like list and tuple definitions (eg. `data [] a = [] | a:[a]`).
- Parsing data declarations without any constructors (eg. `data Int`)[4]. This is a valuable way of introducing built-in types.

[2] https://github.com/hnefatl/hs-java

[3] https://hackage.haskell.org/package/haskell-src

[4] Declarations of this form are invalid in the original Haskell 1998 syntax, but valid in Haskell 2010: see https://wiki.haskell.org/Empty_type

- Adding `Hashable` and `Ord` typeclass instances to the syntax AST, so that syntax trees can be stored in associative containers.

The syntax supported is a strict superset of Haskell 1998 and a strict subset of Haskell 2010, but my compiler does not have support for all of the features implied by the scope of the syntax. For example, multi-parameter typeclasses are parsed correctly as a feature of Haskell 2010 but get rejected by the deoverloading stage.

```
1 class Convertable a b where
2     convert :: a -> b
3 instance Convertable Bool Int where
4     convert True = 1
5     convert False = 0
```

Figure 3.2: An example of a multi-parameter typeclass

### 3.1.2 Preprocessor

The preprocessing passes either make the Haskell source easier to deal with by later passes, or extract useful information to prevent subsequent passes from needing to extract information while applying transformations.

#### 3.1.2.1 Renaming

Haskell allows for multiple variables to share the same name within different scopes, which can increase the complexity of later stages in the pipeline. For example, when typechecking the following code we might conflate the two uses of `x`, and erroneously infer that they have the same type. A similar problem arises with variable shadowing, when the scopes overlap. The problem also applies to any type variables present in the source – the type variable `a` is distinct between the two type signatures:

```
1 id :: a -> a
2 id x = x
3
4 const :: a -> b -> a
5 const x _ = x
```

Additionally, variables and type variables are in different namespaces: the same token can refer to a variable and a type variable, even within the same scope. The following code is perfectly valid (but loops forever), despite the same name being used for a type variable and a variable:

```
1 x :: x
2 x = x
```

To eliminate the potential for subtle bugs stemming from this feature, the renamer pass gives each distinct variable/type variable in the source a unique name (in the above example, the variable `x` might be renamed to `v0` and the type variable renamed to `tv0`, provided those names haven't been already used).

Unique variable/type variable names are generated by prefixing the current value of an incrementing counter with either `v` for variable names or `tv` for type variable names. The renamer traverses the syntax tree maintaining a mapping from a syntactic variable/type variable name to an associated stack of unique semantic variable names (in Haskell, a `Map VariableName [UniqueVariableName]`):

- When processing the binding site of a new syntactic variable (eg. a let binding, a lambda argument, a pattern match...), a fresh semantic name is generated and pushed onto the stack associated with the syntactic variable.
- Whenever we leave the scope of a syntactic variable, we pop the top semantic name from the associated stack.
- When processing a use site of a syntactic variable, we replace it with the current top of the associated stack.

An analogously constructed mapping is maintained for type variables, but is kept separate from the variable mapping: otherwise the keys can conflict in code such as `x :: x`.

Type constants, such as `Bool` from `data Bool = False | True` and typeclass names like `Num` from `class Num a where ...`, are not renamed: these names are already guaranteed to be unique by the syntax of Haskell, and renaming them means we need to maintain more mappings and carry more state through the compiler as to what they've been renamed to.

### 3.1.3 Kind/Class Analysis

The typechecker and deoverloader require information about the kinds of any type constructors (the 'type of the type', eg. `Int :: *` and `Maybe :: * -> *`), and the methods provided by different classes. This is tricky to compute during typechecking as those passes traverse the AST in dependency order. Instead, we just perform a traversal of the AST early in the pipeline to aggregate the required information.

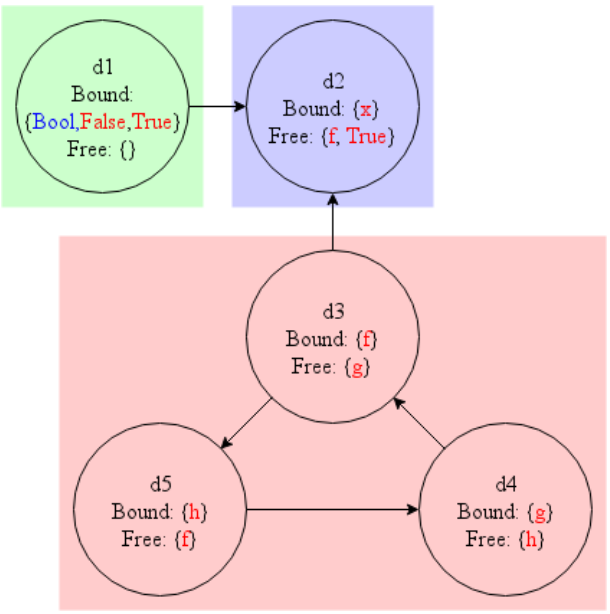
### 3.1.4 Dependency Analysis

When typechecking, the order of processing declarations matters: we can't infer the type of `foo = bar baz` until we've inferred the types of `bar` and `baz`. The dependency analysis stage determines the order in which the typechecker should process declarations.

We compute the sets of free/bound variables/type variables/type constants for each declaration, then construct a dependency graph – each node is a declaration, and there's an edge from $A$ to $B$ if any of the bound variables/type variables/type constants at $A$ are free in $B$. It is important to distinguish between variables/type variables and type constants, as otherwise name conflicts could occur (as we don't rename type constants). This separation is upheld in the compiler by using different types for each, and is represented in the dependency graph below by colouring variables red and constants blue.

The strongly connected components of the dependency graph correspond to sets of mutually recursive declarations, and the partial order between components gives us the order to typecheck

each set. For example, from the dependency graph in Figure 3.3 we know that: we need to typecheck $d_3$, $d_4$, and $d_5$ together as they're contained within the same strongly-connected component so are mutually recursive; we have to typecheck $d_2$ last, after both other components.




```
data Bool = False | True        d1
x = f True                      d2
f y = g y                       d3
g y = h y                       d4
h y = f y                       d5
```

Figure 3.3: Code labelled with declaration numbers, and the corresponding dependency graph. Variables are in red text, type constants in blue. Strongly connected components are highlighted.

Prettier graph: better colours/some other grouping style, and use a more latex-y font.

Typechecking declarations within the same component can proceed in an arbitrary order, we just need to ensure that the all of the type variables for the names bound by the declarations are available while processing each individual declaration.

This process works for languages without ad-hoc overloading, like SML. However, in Haskell there are some complications introduced by typeclasses:

- Typeclass member variables can be declared multiple times within the same scope. For example:

```
1 class Num a where
2     (+) :: a -> a -> a
3 instance Num Int where
4     x + y = ...
5 instance Num Float where
6     x + y = ...
```

Here the multiple declarations of + don't conflict: this is a valid program. However, the following program does have conflicting variables, as `x` is not a typeclass member and is not declared inside an `instance` declaration:

```
1 x = True
2 x = False
```

These declaration conflicts can be expressed as a binary symmetric predicate on declarations, as presented in Figure 3.4, where:

- `Sym` $x$ and `Type` $x$ represent top-level declaration and type-signature declarations for a symbol $x$, like $x$ `= True` and $x$ `:: Bool`.
- `ClassSym` $x$ $c$ and `ClassType` $x$ $c$ represent `Sym` $x$ and `Type` $x$ inside the declaration for a class $c$, like `class` $c$ `where { ` $x$ `= True ; ` $x$ `:: Bool }`.
- `InstSym` $x$ $c$ $t$ represents a `Sym` $x$ inside the declaration for a class instance $c\ t$, like `instance` $c$ $t$ `where { ` $x$ `= True }`.

| | `Sym` $x_1$ | `Type` $x_1$ | `ClassSym` $x_1$ $c_1$ | `ClassType` $x_1$ $c_1$ | `InstSym` $x_1$ $c_1$ $t_1$ |
|---|---|---|---|---|---|
| `Sym` $x_2$ | $x_1 = x_2$ | `False` | $x_1 = x_2$ | $x_1 = x_2$ | $x_1 = x_2$ |
| `Type` $x_2$ | | $x_1 = x_2$ | $x_1 = x_2$ | $x_1 = x_2$ | $x_1 = x_2$ |
| `ClassSym` $x_2$ $c_2$ | | | $x_1 = x_2$ | $x_1 = x_2 \wedge c_1 \neq c_2$ | $x_1 = x_2 \wedge c_1 \neq c_2$ |
| `ClassType` $x_2$ $c_2$ | | | | $x_1 = x_2$ | $x_1 = x_2 \wedge c_1 \neq c_2$ |
| `InstSym` $x_2$ $c_2$ $t_2$ | | | | | $x_1 = x_2 \wedge (c_1 \neq c_2 \vee t_1 = t_2)$ |

Figure 3.4: The conflict relation: the bottom triangle is omitted as the predicate is symmetric

Using this table we can see that the multiple declarations for `+` in the example above are `InstSym (+) Num Int` and `InstSym (+) Num Float` so do not conflict, while the declarations for `x` above are both `Sym x` so do conflict.

- Another complication introduced by typeclasses is that variable declarations such as `id = \\x -> x` are usually treated as being the unique binding definition of `id`, and any other uses within the same level of scope must be free rather than binding (otherwise we have conflicting definitions).

  However, we treat binding declarations inside `instance` declarations as actually being free uses rather than binding uses, so that the instance declaration forms a dependence on the class declaration where the variables are bound, ensuring it is typechecked first.

- The dependencies generated by this technique are *syntactic*, not *semantic*: this is a subtle but very important difference. The use of any ad-hoc overloaded variable generates dependencies on the class declaration that introduced the variable, but not the specific instance of the class that provides the definition of the variable used.

```
1 class Foo a where
2     foo :: a -> Bool
3 instance Foo Bool where
4     foo x = x
5 instance Foo [Bool] where
6     foo xs = all foo xs
```

The declaration of `foo` in `instance Foo [Bool]` semantically depends on the specific overload of `foo` defined in `instance Foo Bool`, and yet no dependency will be generated between the two instances as neither declaration binds `foo` (`foo` is treated as being free within the declarations as described above): they will only generate dependencies to `class Foo a` (and to the declaration of `Bool` and `all`).

Computing the semantic dependencies is too complicated to be done in this pass, so the problem is left and instead solved during the typechecking stage. A full explanation is given later, but the approach used is to defer typechecking instance declarations until a different declaration requires the information, and then attempt to typecheck the instance declaration then, in a Just-In-Time manner.

### 3.1.5 Type Checker

Type inference and checking is the most complex part of the compiler pipeline. The type system implemented is approximately System $F_\omega$ (the polymorphically typed lambda calculus with type constructors) along with algebraic data types, and type classes to provide ad-hoc overloading. The approximation is due to a number of alterations made by the Haskell Report to ensure that type inference is decidable.

This is a subset of the type system used by GHC (System $F_C$), as that compiler provides extensions such as GADTs and type families requiring a more complex type system.

```
data TypeVariable = TypeVariable TypeVariableName Kind
data TypeConstant = TypeConstant TypeVariableName Kind

data Type = TypeVar TypeVariable
          | TypeCon TypeConstant
          | TypeApp Type Type Kind

data Kind = KindStar
          | KindFun Kind Kind
```

A `Kind` is often described as the 'type of a type': we say that `True :: Bool`, but looking to a type system 'one level up' we can say `Bool :: ∗` where $*$ is the type of a type constructor that takes no parameters. The type constructor `Maybe` has kind $* \to *$, as it takes a single type parameter: applying it to a type of kind $*$ yields a type of kind $*$, such as `Maybe Int`. All Haskell values have a type with kind $*$: there are no values for types of other kinds. Kinds are used in the type system to enforce type correctness (or perhaps kind correctness), such as rejecting `Bool Bool` as an invalid type application.

Type variables have an associated kind to allow for type constraints such as `pure :: Functor f =>` $\alpha \to f\alpha$, which says that `pure` can take a value of any type and embed it into a functor parametrised by that type: `f` has kind $* \to *$.

A 'simple type' is then represented as any tree of applications between type variables and type constants: these are types such as `Int -> Maybe Bool`. Haskell has more complex types, however: overloaded and polymorphic types.

```
data TypePredicate = IsInstance ClassName Type

data Qualified a = Qualified (Set TypePredicate) a
type QualifiedType = Qualified Type

data Quantified a = Quantified (Set TypeVariable) a
```

```
type QuantifiedType = Quantified QualifiedType
type QuantifiedSimpleType = Quantified Type
```

A qualified/overloaded type is a simple type with type constraints/predicates attached, such as `Eq α => α → α → Bool` (the constraint here being just `Eq α`). The constraints act as restrictions on the valid types that can fulfil the type variable, or equivalently predicates which must hold on the variables: the type signature is only valid for $\alpha$ that are instance of the `Eq` typeclass.

A quantified/polymorphic type is an overloaded type with a set of type variables that are universally quantified over the type, meaning they must later be instantiated to a specific type/type variable (universally quantified vaariables are 'placeholder' variables). Haskell type signatures are implicitly quantified over all the contained type variables, but some extensions add explicit syntax: `id :: α → α`, `id :: forall α. α → α`, and `id :: ∀α. α → α` all mean the same.

During type inference, types are almost always polymorphic and often overloaded (`(==) :: forall α. Eq α => α → α → Bool`, `(+) :: forall α. Num α => α → α → α`, `head :: [α] -> α`, ...). After deoverloading (section 3.1.5.2), types are never overloaded. This difference is enforced by using `QuantifiedType` and `QuantifiedSimpleType` respectively.

This is mentioned here as it's a good place to imply that things are really complicated and the following explanation makes simplifying assumptions, but it repeats stuff from the lexing+parsing section.

There are many types of 'declaration' in the Haskell grammar: pattern bindings like `x = 1` and `(y, z@(Just w)) = (1, Just True)`, function definitions like `f x = x`, and even declarations which contain other declarations, such as class and instance declarations. In the following descriptions, 'declaration' is assumed to refer to simple pattern binding declarations like `x = f y` unless otherwise mentioned: other declaration types are either easy to extend these approaches to, don't play much role in typechecking, or

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Section giving overview of substitution and unification?

### 3.1.5.1 Type Inference

The implementation is inspired by [3] and uses similar rules as the Hindley-Milner (HM) type inference algorithm presented in [1]. There are three passes over the source AST, each of which traverses the AST in dependency order as previously described in 3.1.4.

1. The first pass tags each subexpression with a type variable, then uses rules similar to the HM inference rules to infer the value of the type variable, usually using the type variables of subterms.

   Some expressions will generate constraints on type variables: using an overloaded function like `(+)` will first require instantiating the polymorphic type to an overloaded type ($\forall\alpha.\ \text{Num}\alpha \Rightarrow \alpha \to \alpha \to \alpha$ to $\text{Num}\beta \Rightarrow \beta \to \beta \to \beta$, where $\beta$ is a fresh unique type variable), then moving the constraints from the type to the set of constraints built up while traversing this declaration to get just $\beta \to \beta \to \beta$. This is the ground type that's unified with the type variable used to tag the use of `(+)`, and the constraint is stored for use after finishing traversing the declaration.

After a pattern binding declaration has been fully traversed, types are generated for all the variable names bound by the patterns. This involves adding explicit quantifiers and constraints to the simple type inferred for the top-level expression on the right-hand side of the binding. All free type variables in the simple type are added as universally quantified variables, and any constraints involving type variables that are free in the simple type are added as the qualifiers to the type.

There should also be a check called the ambiguity check here, but I've not implemented it: it's a bit complicated and at the time I'd overshot my typechecking time budget by multiple weeks. Not having implemented it allows some invalid programs to get through the type system and crash at runtime :(. Not mentioning leaves an obvious gap for people who know this subject, should I say I've not implemented it?

2. The second pass simply traverses the AST again and updates the type variables used to tag each with the final expression type generated by the unification during the first pass.

   This can't be done efficiently during the first pass: consider the expression $((+)^{t_1}\ \mathtt{x}^{t_2})^{t_3}$ where the $t_i$ are type variables tagging the expressions. Assume we've inferred that `x :: `$\alpha$ and `(+) ::` $\beta \to \beta \to \beta$ as described above, and that we've unified $t_1$ and $t_2$ with these types respectively. Inferring the type of the overall expression would proceed by unifying the type of the first formal argument of the function ($\beta$) with the first actual argument ($\alpha$), and then using this substitution to type the return value of the function as $\alpha \to \alpha \to \alpha$, which we can now unify with $t_3$. Had we previously updated the subterm's tags to be their inferred concrete types we'd now have to update them again: $\beta$ is no longer used as it's been unified with $\alpha$, but our subterms may still contains uses of it.

3. The third pass checks that any user-provided type signatures (such as the user explicitly annotating `5 :: Float`) are valid compared to what was actually inferred: if the user-provided tag is more general than the inferred tag, we reject the program.

   This could be done during the second pass, but was kept as a distinct pass for clarity in the code.

One departure from conventional polymorphic type systems is that Haskell's type system restricts polymorphism for some terms: let-bound variables are polymorphic over all their free type variables, while function parameters are never polymorphic. In practice, this means that in the code below, `f ::` $\forall\alpha.\ \alpha \to a$ whereas `g ::` $\alpha \to \alpha$. The difference in semantics ensures that type inference remains decidable.

```
1 let f x = x in const (f True) (f 1) :: Bool -- This is fine
2 (\\g -> const (g True) (g 1)) (\x -> x)     -- This fails to typecheck
```

Originally I had a big worked example here, but after refactoring the above I don't know if it's needed: depends on whether reading the above makes sense or whether a continuous worked example would make it clearer.

A tricky part of the typechecking process is dealing with typeclasses, as dependency order isn't semantically accurate for typeclass instance declarations: the problem is detailed in 3.1.4. To handle the potential issues, such declarations are processed in a lazy manner. If a declaration

requires an instance of a typeclass in order to typecheck then that typeclass is typechecked immediately, and all remaining instance declarations are processed after non-instance declarations have been processed.

An improvement to the current approach would be to implement the OutsideIn(X) framework given in [4]. This framework can work with Hindley-Milner type inference to handle more complex constraints than the current implementation, allowing support for GADTs and type families and handling type classes more flexibly than the current implementation.

#### 3.1.5.2 Deoverloader

The deoverloading stage performs a translation which eliminates typeclasses, resulting in an AST tagged with types that no longer have type contexts. The implementation of typeclasses chosen was dictionary passing.

To convert `add1 x = (+) x 1` with type $\forall\alpha.\ \text{Num}\ \alpha \Rightarrow \alpha \rightarrow \alpha$ to a non-overloaded function, we can add an extra argument that carries the 'implementation' of the Num $\alpha$ constraint, which we then pass down to the + function: `add1' dNum x = (+) dNum x 1`.

Alternative approaches than dictionary passing?

The approach used here is to perform a source-to-source transformation on the AST that replaces typeclass/instance declarations with datatype/value/function declarations.

```
1  class Eq a where
2      (==), (/=) :: a -> a -> Bool
3  instance Eq Bool where
4      (==) = ...
5      (/=) = ...
```

Typeclasses are replaced by datatypes equivalent to tuples with an element for each function defined by the class, and instances are replaced by values of the respective class' datatype, filling in the elements using the implementation provided by the instance declaration. Extractor functions are added which pull specific elements out of the datatype to get at the actual implementation of the function.

```
1  -- Implementation of the typeclass
2  data Eq a = Eq (a -> a -> Bool) (a -> a -> Bool)
3
4  -- The functions defined by the typeclass extract the implementation functions
5  (==), (/=) :: Eq a -> a -> a -> Bool
6  (==) (Eq eq _) = eq
7  (/=) (Eq _ neq) = neq
8
9  -- The implementation of the typeclass instance
10 dEqBool :: Eq Bool
11 dEqBool = Eq dEqBoolEq dEqBoolNeq
12
13 -- The function implementations defined in the instance
14 dEqBoolEq, dEqBoolNeq :: Bool -> Bool -> Bool
```

```
15 dEqBoolEq = ...
16 dEqBoolNeq = ...
```

To deoverload declarations using overloaded values, we essentially convert declarations of functions with types like Num $\alpha \Rightarrow \alpha \to \alpha$ to Num $\alpha \to \alpha \to \alpha$: we replace typeclass constraints with formal arguments to carry the implementation dictionaries. Similarly when using an expression of overloaded type, we add an actual argument to the call site for each typeclass constraint to account for the extra arguments we added to the definition.

For example, `foo x = x == 1` deoverloads to `add1 dEqa x = (==) dEqa x 1`: we add an extra formal argument to the function declaration, and insert it in the call site to `+`.

In order to know what variables to insert at call sites, the names of in-scope variables holding values of typeclass implementations are stored while traversing the AST. Initially the mapping contains the ground instances provided by top-level instance declarations (eg. {Num Int $\mapsto$ `dNumInt`, Eq Int $\mapsto$ `dEqInt`, ...}), and we update it to include any in-scope extra arguments we add to functions while deoverloading them. When we encounter an overloaded variable, we insert arguments for each type constraint by finding matching constraints within our mapping.

One special case in the process is the handling of literals. Whilst arbitrary expressions with overloaded types always require a dictionary to be passed (consider that the innocent-looking `x` in `let x = 1 + 2 in x` involves an application of `+` which requires a dictionary to provide the implementation), literals do not require a dictionary as they can never perform any computation.

### 3.1.6 Lowering and Intermediate Languages

There are two intermediate languages within the compiler, imaginatively named Intermediate Languages A and B (ILA and ILB respectively). There is also a minor language named ILA-Administrative Normal Form (ILA-ANF), which is simply a subset of ILA that helps restrict the terms to those in Administrative Normal Form (ANF).

For each: why needed, BNF grammar, strengths. Probably don't go into details of translation?

#### 3.1.6.1 Intermediate Language A

ILA is a subset of GHC's Core intermediate language, removing terms which are used for advanced language features like GADTs, as they are not supported by this compiler. Haskell 98 has hundreds of node types in its AST[5], whereas ILA has far fewer: this makes it far easier to transform. Below is the full definition of ILA:

Give BNF instead of Haskell ADTs?

```
1 data Expr = Var VariableName Type
2           | Con VariableName Type
3           | Lit Literal Type
4           | App Expr Expr
5           | Lam VariableName Type Expr
```

[5] `https://hackage.haskell.org/package/haskell-src/docs/Language-Haskell-Syntax.html`

Find version-independent link

```
6           | Let VariableName Type Expr Expr
7           | Case Expr [VariableName] [Alt Expr]
8           | Type Type
9
10 data Literal = LiteralInt Integer
11              | LiteralChar Char
12
13 data Alt a = Alt AltConstructor a
14
15 data AltConstructor = DataCon VariableName [VariableName]
16                     | Default
17
18 data Binding a = NonRec VariableName a
19                | Rec (Map VariableName a)
```

A Haskell program is lowered by this pass into a list of `Binding Expr`: a list of recursive or non-recursive bindings of expressions to variables.

Use paragraph to split this into better titled chunks

One notable feature of ILA is that it carries type information: leaf nodes such as `Var` are tagged with a type. GHC's Core IL is fully explicitly typed under a variant of System F, which allows for 'core linting' passes in-between transformations to ensure they maintain type-correctness. The type annotations on ILA are not sufficient for such complete typechecking, but do allow for some sanity checks and are necessary for lower stages of the compiler such as code generation.

ILA is still quite high-level, so many of the language constructs have similar semantics to their Haskell counterparts. The main benefit in this lowering pass is to collapse redundant Haskell syntax into a smaller grammar.

Most of these constructors have obvious usages, but some are more subtle: `Con` represents a data constructor such as `True` or `Just`. `App` is application of expressions, which covers both function applications and data constructor applications (eg. `App (Var "f" (Bool → Bool)) (Con "True" Bool)` and `App (Con "Just" (Int → Maybe Int)) (Var "x" Int)`).

Work out why spacing is weird here

`Lam` $x\ t\ e$ represents a lambda term like $\lambda x : t.\ e$, and `Let` $x\ t\ e_1\ e_2$ represents a term like let $x : t = e_1$ in $e_2$.

Lam and Let are most easily explained as lambda terms, but App is most easily demonstrated with some code, and the switch between explanation styles is a bit jarring.

`Case` $e\ vs\ as$ represents a multi-way switch on the value of an expression $e$ (the 'head' or 'scrutinee'), matching against a number of possible matches ('alts') from the list $as$, where the evaluated value of $e$ is bound to each of the variables in $vs$. The additional binding variables can be useful when the scrutinee expression is reused within some number of the alts.

`Type` isn't really used afaik, it's a leftover from when I was trying to do System F style types. Should see if I can remove it.

The alts in a `Case` expression, of the form `Alt` $c\ b$, match the value of evaluating the scrutinee against the data constructor $c$, then evaluates the $b$ from whichever alt matched.

`AltConstructor` represents the potential matches: either a data constructor with a number of variables to be bound, or a 'match-anything' default value.

Many syntax features in Haskell are just syntactic sugar, and are simple to desugar (list literals like `[1, 2]` are desugared to `1:2:[]`). Others are slightly more involved, such as converting `if x then y else z` expressions into `case x of { True -> y ; False -> z }` (`Bool`is just defined as an ADT in Haskell, there's no special language support for it).

Other language features are non-trivial to lower, such as the rich syntax Haskell uses for pattern matching. An example pattern match could be `Just x@(y:z) = Just [1, 2]`, binding `x = [1, 2]`, `y = 1`, and `z = [2]`. Multiple pattern matches can also be related, as in function definitions:

```
1 f (x, Just y) = x + y
2 f (x, Nothing) = x
```

Additionally, pattern matches can occur in a number of places: pattern-binding declarations such as `let (x, y) = z in ...`, functions definitions like the example above, lambda expressions, and `case` expressions (`case Just 1 of { Nothing -> ... ; Just x -> ... }`). The heterogeneity of use sites demands a flexible approach to translating pattern matches that can be reused for each instance.

My initial implementation worked correctly for single-pattern uses, such as the `let` example above, but didn't support multiple parallel patterns as used in `case` expressions and function definitions. The current implementation is now based off the approach given in Chapter 5 of [5], which is a more general version of my initial algorithm.

Feel like this needs a little bit more. Probably give a very brief overview, explain that everything's converted into case statements in the end, etc.

Finally, note that in Haskell a pattern will eventually match against a data constructor, a literal, or anything (with the wildcard pattern `_`). However, in the grammar for ILA's `AltConstructor`, there's no constructor corresponding to literals. This is due to `case` expressions generally only making sense for data constructors, where there are a finite number of constructors to check a value against for a given datatype. On the other hand, literals normally have a cumbersomely large (or infinite) number of 'constructors' (one can imagine the `Int` type, which is bounded, as being defined as `data Int = ... | -1 | 0 | 1 | ...`, but `Integer` cannot be defined in this way as it is unbounded). As a result, literals are 'pattern matched' by using equality checks from the `Eq` typeclass: the expression `case x of { 0 -> y ; 1 -> z ; _ -> w }` is essentially translated to `if x == 0 then y else if x == 1 then z else w`, which is then lowered into `case` expressions match on `True` and `False` as described above.

#### 3.1.6.2 Intermediate Language A - Administrative Normal Form

Administrative Normal Form (ANF) is a style of writing programs in which all arguments to functions must be trivial (a variable, literal, or other irreducible 'value' like a lambda expression). ANF is an alternative to Continuation Passing Style (CPS) as a style of intermediate language but can perform transformations in a single pass that would take multiple passes on a CPS program[2].

This compiler uses ANF as it lends itself well to conceptualising lazy evaluation: as each complex expression is referred to through a variable, if the expression is evaluated by one com-

putation then all other references to the variable transparently reference the resulting value, rather than a duplicate of the computation.

ILA-ANF is a subset of ILA which uses a more restricted grammar to enforce more invariants on the language and guide the AST into ANF. The full definition of ILA-ANF is given below, and reuses the definitions of `Binding` and `Alt` from ILA.

In the case of ILA-ANF, 'trivial' terms are taken to be variables, data constructors, and literals. Note that this excludes lambda terms, which is somewhat unusual. Instead, lambda terms must immediately be bound to a variable: this restriction is enforced by the `AnfRhs` term in the grammar below.

Why lambda terms not trivial? General design-decision explanation. Makes thunk model explicit + easier to generate code?

```
data AnfTrivial = Var VariableName Type
                | Con VariableName Type
                | Lit Literal Type
                | Type Type

data AnfApplication = App AnfApplication AnfTrivial
                    | TrivApp AnfTrivial

data AnfComplex = Let VariableName Type AnfRhs AnfComplex
                | Case AnfComplex Type [VariableName] [Alt AnfComplex]
                | CompApp AnfApplication
                | Trivial AnfTrivial

data AnfRhs = Lam VariableName Type AnfRhs
            | Complex AnfComplex
```

An ILA program is lowered from a list of `Binding Expr` to a list of `Binding AnfRhs` by this pass. The translation is quite simple compared to the other lowering passes – most of the terms are similar to those in ILA (including carrying type information), with notable exceptions being the introduction of `AnfApplication`, which restricts application arguments to purely trivial terms, and `AnfRhs`, to enforce that lambda terms can only be bound to variables.

#### 3.1.6.3 Intermediate Language B

ILB is the final intermediate language of this compiler and is inspired by GHC's STG (Spineless Tagless G-Machine) IL. ILB maintains the ANF style from ILA-ANF. It has a number of extremely useful features for code generation: the only term that performs any evaluation of an expression is the `ExpCase` $e\ t\ vs\ as$ term (which evaluates $e$ then branches to one of the $as$), and the only term which performs any memory allocation is the `ExpLit` $v\ r\ e$ term, which allocates memory on the heap to represent a datatype/literal/uneveluated expression then evaluates $e$.

Additionally, this language makes lazy evaluation 'explicit', in the sense that expressions to be evaluated are always encapsulated within an `RhsClosure` (thanks to ANF style which names each subexpression) that can be implemented as a not-yet-evaluated thunk.

```
data Arg = ArgLit Literal
         | ArgVar VariableName

data Exp = ExpLit Literal
         | ExpVar VariableName
         | ExpApp VariableName [Arg]
         | ExpConApp VariableName [Arg]
         | ExpCase Exp Type [VariableName] [Alt Exp]
         | ExpLet VariableName Rhs Exp

data Rhs = RhsClosure [VariableName] Exp
```

ILB is similar in grammar to ILA-ANF, and the translation pass is relatively simple. There are some key differences between the languages, that reflect the changes from a relatively high-level IL down to a lower-level one:

Didn't use bullet points for the previous IL explanations: change them?

- There are now two terms for applications, one for functions (`ExpApp`) and one for data constructors (`ExpConApp`). The distinction is necessary for code generation, when a function application results in a jump to new executable code while a constructor application creates a new heap object.

  `ExpConApp` also requires all its arguments to be present: it cannot be a partial application. Haskell treats datatype constructors as functions, so the following is a valid program:

  ```
  data Pair a b = Pair a b
  x = Pair 1
  y = x 2
  ```

  At the implementation level however, functions and data constructors are necessarily very different, so distinguishing them within this IL makes code generation easier.

  Include how they're distinguished? Or too much detail?

- Right-hand side terms in ILA (`AnfRhs`) were either lambda expressions or a let-binding/case expression/...– in ILB, the only right-hand side term is a `RhsClosure`. A closure with no arguments is essentially a thunk, a term that exists purely to delay computation of an expression, while a closure with arguments is the familiar lambda term.

  ILB's `RhsClosure` takes a list of arguments, whereas ILA-ANF's lambda terms only take a single argument (multiple-argument functions are just nested single-argument lambdas). This is another translation aimed at making code generation easier. Single-argument lambdas allow for simpler logic when handling partial application in higher-level languages, but is inefficient in implementation. ILB is the ideal IL to perform this switch from the high-level convenient-to-modify grammar to a lower-level efficient representation.

- ILB only allows variables in many of the places where ILA-ANF allowed variables, literals, or 0-arity data constructors (like `True`). This is another step towards making laziness

explicit, by keeping expressions simple so that only one step of the evaluation needs to happen at a time.

### 3.1.7 Code Generation

Left optimisations until after codegen: cover the main pipeline first then the optional stages later?

Code generation is, from the surface, quite a mechanically simple process. ILB is a small language, so there aren't many terms to lower into bytecode. Implementing the semantics of these terms in Java Bytecode is complex, however.

The `hs-java` library was used to provide a Haskell representation of bytecode that could then be serialised to a Java `.class` file, but a number of modifications were made to the library by me to add support for Java 8 features required by the compiler, as well as a number of smaller improvements: the forked project can be found at `https://github.com/hnefatl/hs-java`.

A number of Java classes have been written to provide the 'primitives' used by generated bytecode: including the implementation of Haskell's primitive datatypes like `Int` and `Char`, as well as the base class for all ADTs definable within the language (`BoxedData`, described later). The compiler is aware of these 'builtin' classes and uses a set of 'hooks' when generating code to provide Java implementations of Haskell functions. This is covered in more detail later.

#### 3.1.7.1 Weak Head Normal Form

A Haskell expression is in weak head normal form (WHNF) if it is either a partially applied function (including lambda terms), a fully/partially applied data constructor, or a literal. Any arguments need not have been evaluated.

Evaluation of an expression up to WHNF corresponds to a form of non-strict evaluation: partial applications of functions or any data constructor applications don't force their arguments to be evaluated, but when a function is applied to all its arguments, it reduces to the body without necessarily having evaluated its arguments. In particular, the evaluation of a Haskell program is equivalent to evaluation to WHNF.

The following Haskell expressions are either valid or invalid WHNF terms, as indicated:

```
1  1                -- In WHNF
2  (+) 1            -- In WHNF
3  1 + 2            -- Not in WHNF
4  3                -- In WHNF
5  Just             -- In WHNF
6  Just True        -- In WHNF
7  (\\x -> x) 1     -- Not in WHNF
8  (+) (1 + 2)      -- In WHNF
9  (1 + 2) + 3      -- Not in WHNF
```

#### 3.1.7.2 Heap Objects

Literals, datatype values and closures are all represented at runtime by values on the heap, as they are all first-class values in Haskell, and will be referred to as 'objects': this intentionally

overloads the terminology used by Java for an instance of a class, as the two concepts are essentially interchangeable here as Java objects are heap-allocated.

Thunks are represented simply as closures without arguments: all of the closure logic described below is the same between thunks and functions.

All objects on the heap inherit from a common abstract base class, `HeapObject`:

```
public abstract class HeapObject implements Cloneable {
    public abstract HeapObject enter();

    @Override
    public Object clone() throws CloneNotSupportedException {
        return super.clone();
    }
}
```

The abstract `enter` method evaluates the object to WHNF and returns a reference to the result, and the `clone` method simply returns a shallow copy of the object. This method is critically for implementing function applications, described later.

### Literals

Literals are builtin types that can't be defined as an Haskell ADT, such as `Int`. Any such type is a subclass of the `Data` class, which is itself a subclass of the `HeapObject` class that a rather boring implementation of the abstract `enter` method. Any literal is already in WHNF, so evaluation to WHNF is trivial:

```
public abstract class Data extends HeapObject {
    @Override
    public HeapObject enter() {
        return this;
    }
}
```

Here is an example literal implementation for `Integer`, Haskell's arbitrary precision integral value type. It is implemented using Java's `BigInteger` class to perform all the computation. The copious uses of underscores is explained in the JVM Sanitisation section below.

```
import java.math.BigInteger;

public class _Integer extends Data {
    public BigInteger value;
    public static _Integer _make_Integer(BigInteger x) {
        _Integer i = new _Integer();
        i.value = x;
        return i;
```

```
    }
    public static _Integer _make_Integer(String x) {
        return _make_Integer(new BigInteger(x));
    }

    public static _Integer add(_Integer x, _Integer y) {
        return _make_Integer(x.value.add(y.value));
    }
    public static _Integer sub(_Integer x, _Integer y) { ... }
    public static _Integer mult(_Integer x, _Integer y) { ... }
    public static _Integer div(_Integer x, _Integer y) { ... }
    public static _Integer negate(_Integer x) { ... }

    public static boolean eq(_Integer x, _Integer y) { ... }

    public static String show(_Integer x) { ... }
}
```

The `_make_Integer(String)` function allows a Java `_Integer` object to be constructed from a Java string representation, which is used by the compiler to construct `Integer` values:

Brief two-line bytecode demonstrating this

The `add`, `sub`, etc. methods are Java implementations of the functions required by Haskell's `Num`, `Eq` and `Show` typeclass instances for `Integer`. The section on Hooks covers this aspect of code generation in more detail.

### Datatypes

An Haskell ADT can be represented simply by a class generated by the compiler which inherits from the `BoxedData` builtin abstract class:

```
public abstract class BoxedData extends Data {
    public int branch;
    public HeapObject[] data;
}
```

The `branch` field is used to identify which constructor of the type has been used, and the `data` field contains any arguments given to the constructor. An example generated class[6] for the datatype `data Maybe a = Nothing | Just a` might be:

```
public class _Maybe extends BoxedData {
    public _make_Nothing() {
        _Maybe x = new _Maybe();
        x.branch = 0;
```

[6]The compiler doesn't generate a class described in Java source as shown, it just generates the bytecode for the class directly.

```
        x.data = new HeapObject[] {};
        return x;
    }
    public _make_Just(HeapObject val) {
        _Maybe x = new _Maybe();
        x.branch = 1;
        x.data = new HeapObject[] { val };
        return x;
    }
}
```

Note that as `BoxedData` inherits from `Data`, the `enter` method has the same simple implementation – as any data value is already in WHNF.

### Closures

Closures are the most complicated objects stored on the heap. There are three main lifecycle stages of a closure:

- Creation: construction of a new closure representing a function of a given arity, without any arguments having been applied yet but possibly including values of free variables in scope of the closure.
- Argument application: this may be a partial application or a total application, or even an over-application: consider `id (+1) 5`, which evaluates to `6`. `id` has arity 1, but is applied to 2 arguments here.
- Evaluation: after a total application, reducing the function to its body (as specified by WHNF reduction).

These behaviours are provided by the `Function` builtin class:

Formatting + it's quite a lot of code, but I think necessary to understand the details below.

```
import java.util.ArrayList;
import java.util.function.BiFunction;

public class Function extends HeapObject {
    private BiFunction<HeapObject[], HeapObject[], HeapObject> inner;
    private HeapObject[] freeVariables;
    private ArrayList<HeapObject> arguments;
    private int arity = 0;

    public Function(BiFunction<HeapObject[], HeapObject[], HeapObject> inner,
                    int arity, HeapObject[] freeVariables) {
        this.inner = inner;
        this.arity = arity;
        this.freeVariables = freeVariables;
        arguments = new ArrayList<>();
```

```
16      }
17
18      @Override
19      public HeapObject enter() {
20          if (arguments.size() < arity) { // Partial application
21              return this;
22          }
23          else if (arguments.size() > arity) { // Over-applied
24              try {
25                  Function result = (Function)inner
26                      .apply(
27                          arguments.subList(0, arity).toArray(new HeapObject[0]),
28                          freeVariables)
29                      .enter()
30                      .clone();
31                  for (HeapObject arg : arguments.subList(arity, arguments.size()))
32                      result.addArgument(arg);
33                  return result;
34              }
35              catch (CloneNotSupportedException e) {
36                  throw new RuntimeException(e);
37              }
38          }
39          else { // Perfect application
40              return inner.apply(
41                  arguments.toArray(new HeapObject[0]), freeVariables
42              ).enter();
43          }
44      }
45
46      public void addArgument(HeapObject arg) {
47          arguments.add(arg);
48      }
49
50      @Override
51      public Object clone() throws CloneNotSupportedException {
52          Function f = (Function)super.clone();
53          f.inner = inner;
54          f.arity = arity;
55          f.freeVariables = freeVariables.clone();
56          f.arguments = new ArrayList<>(arguments);
57          return f;
58      }
59  }
```

A function $f$ (either defined locally or at the top-level) in Haskell of arity $n_a$ and using $n_{fv}$ free variables is translated into two Java functions:

- `_f Impl`, which takes two arrays of `HeapObject`s as arguments, one holding the arguments for the Haskell function (of length $n_a$) and one holding the free variables used by the Haskell function (of length $n_{fv}$), and returns a `HeapObject` representing the result of applying the function.
- `_make_f`, which takes $n_{fv}$ arguments representing the free variables of the Haskell function, and returns a Java `Function` object representing the closure, where the `inner` field points to the `_f Impl` function.

`Function`'s `freeVariables` field has type `HeapObject[]` as we know at initialisation time exactly how many free variables the function has, and it doesn't change. The `arguments` field is an `ArrayList<HeapObject>` so that we can handle partial applications and over-applications by only adding arguments when they're applied.

Haskell function applications are lowered into bytecode that:

1. Fetches the function, either by calling the appropriate `_make_` function with the free variables, or just loading a local variable if the function has already been partially applied and stored or passed as a function argument.
2. **Clones** the `Function` object. This step is subtle but vital, as each argument applied to the function mutates the `Function` object by storing additional arguments.

   If we're using a local closure like `let add1 = (+) 1 in add1 2 * add1 3` then `add1` will be a local `Function` object with `inner` pointing to the implementation of `(+)` and one applied argument (a `Data` instance representing 1). Both `add1 2` and `add1 3` will mutate the object to add the argument being applied (see the next step for details), which leads to the `Function` object after `add1 3` having 3 stored arguments.

   Cloning the function essentially maintains the same references to arguments and free variables, but creates new (non-shared) containers to hold them, avoiding the above issue.

   This is a shallow clone – if we used a deep clone, recursively cloning the arguments and free variables, then we'd lose the performance benefit of graph reduction where we can use an already computed value instead of recomputing it ourselves, and increase memory usage.
3. Invokes `addArgument` on the cloned object for each argument in the application, storing them later use.
4. Invokes `enter` on the function object. This will reduce the object to WHNF, which has three cases:

   - The function is partially applied, so hasn't yet received all of the necessary arguments to be evaluated. Such a function is already in WHNF, so we can just return it.
   - The function has exactly the right number of arguments, so WHNF demands we reduce it. This is implemented by calling the `inner` function that performs the actual implementation of the Haskell function with the free variables and arguments we've stored, then ensuring the result has been evaluated to WHNF by calling `enter`, then returning it.
   - The function is over-applied. This case looks complicated, it's two simple steps. We pretend we have an application of exactly the right number of arguments as in the

above case, then instead of returning the result we cast it to a `Function` object and perform a normal function application with all the leftover arguments.

All of the functions defined in a Haskell program are compiled into their pairs of Java functions within a single class, the 'main' class. Datatypes are compiled into their own classes which are then referenced by the main class. This approach to function compilation differs from the approaches taken by Scala and Kotlin (other languages targeting the JVM), which compile lambda expressions into anonymous classes.

In Haskell, the vast majority of expressions are function applications by the time the source has reached ILB. To provide lazy semantics, each expression has to be evaluatable without forcing other expressions, so each function implementation is quite small. This results in a lot of functions being generated. Using anonymous classes to implement Haskell functions would result in hundreds or thousands of small Java classes, whereas using Java functions results in far fewer classes and more functions inside a single class.

This is meant to be a reflective design discussion: say something about it being interesting to compare tradeoffs in performance and size? Also cost of class loading?

#### 3.1.7.3 JVM Sanitisation

Haskell[7], Java[8], and JVB[9] all allow different sets of strings as valid identifiers: for example, in Java and JVB `Temp` is a valid variable name, but in Haskell it's not (identifiers with uppercase Unicode start characters are reserved for constructor names like `True`). `+` is a valid identifier in Haskell and JVB, but not in Java.

Additionally name conflicts can occur between builtin classes used by the compiler (eg. `Function` and `Data`) and constructor names in the Haskell source (eg. `data Function = Function`).

JVM Sanitisation is a name conversion process used in the code generator to prevent conflicts and invalid variable names when everything's been lowered into JVB:

- All names that have come from Haskell source are prefixed with an underscore, and any builtin classes are forbidden from starting with an underscore. This prevents name clashes.
- Any non-alphanumeric (Unicode) characters in a Haskell source identifier are replaced by their Unicode codepoint in hexadecimal, flanked on either side by $ symbols. This is more restrictive than necessary, as JVB allows most unicode characters, but is a safe and simple defence against conflicts. Using $ symbols to mark the start and end of a sanitised character ensures that identifiers are uniquely decodable and prevents two distinct identifiers from clashing when sanitised (without delimiters, the valid Haskell identifiers $\pi$ and `CF80` are sanitised into the same identifier: `_CF80`. With the delimiters, $\pi$ is sanitised into `_$CF80$`).

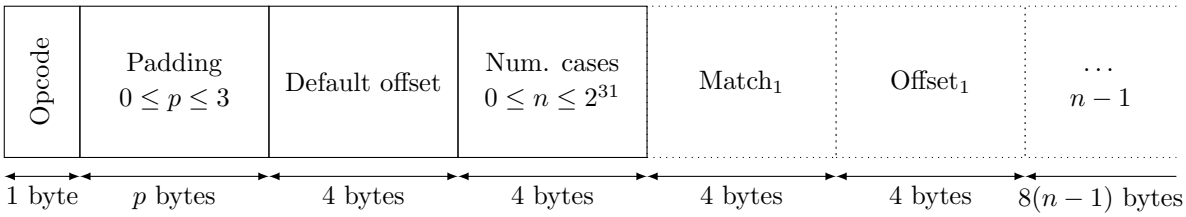
#### 3.1.7.4 Notable Instructions

As mentioned earlier, the `hs-java` library is used to generate Java `.class` files from an in-memory representation of JVB, but support for a number of instructions were added to it: this section describes some of the more interesting ones that are heavily used by the compiler.

[7] `https://www.haskell.org/onlinereport/lexemes.html`
[8] `https://docs.oracle.com/javase/specs/jls/se8/html/jls-3.html#jls-3.8`
[9] `https://docs.oracle.com/javase/specs/jvms/se8/html/jvms-4.html#jvms-4.2.2`

`lookupswitch`

The `lookupswitch` instruction is a low-level implementation of a `switch` statement in Java: it compares an `int` on the top of the stack ('scrutinee') with a set of values, jumping to an address paired with each value or to a default address if no values match. The interesting part of this instruction is that the length varies between usages:




- The first byte of the instruction is the opcode, `0xab`.
- Up to 3 bytes of padding follow, such that the next byte (the first byte of the 'Default offset' chunk) is an address that's a multiple of four bytes. JVM instruction addressing is local to a function, so the first instruction in a method has address 0.
- The subsequent 4 bytes constitute a signed `int` that gives the offset to jump to if the scrutinee doesn't match any of the values given in the instruction.

  For this description, 'offset' means 'signed relative address difference from the address of the opcode of the instruction to the address of the target': if a `lookupswitch` instruction has opcode at address 10 and is 30 bytes long, the offset used to jump to the immediately subsequent instruction would be 30.
- The following 4 bytes form another signed `int` that's restricted to non-negative values, representing the number of value-offset pairs to match the scrutinee against, $n$.
- Next come $n$ pairs of 4-byte values, each describing an `int` value to match the scrutinee against and an offset to jump to if the values match.

JVB uses variable-length instructions: the `nop` (no-op) instruction is just an opcode (`0x00`), a single byte, whereas the `goto` instruction is 3 bytes (the opcode, `0xa7`, followed by a two-byte operand forming the address to jump to).

The `lookupswitch` instruction is especially interesting because the length changes between uses of the same instruction: $n$ and $p$ effect the length of the instruction at runtime.

`invokedynamic`

Left because the code generation section looks like it's getting way too long: can write later if needed

- Basics of instruction, why needed (creation of `BiFunction` objects for `Function`).
- Boostrap methods, class attributes

#### 3.1.7.5 Hooks

Many standard functions operating on primitive types like `Int` and `Char`, such as `(+)` and `(==)`, cannot be implemented in Haskell. These operations need to be implemented at the same level as `Int` is implemented, in bytecode. However, *some* form of definition has to be given in the Haskell source: we want to be able to write:

```
1 instance Num Int where
2     (+) = ...
```

... in order to allow typechecking to see that `Int` is an instance of `Num`, but we can't provide any reasonable implementation.

Hooks solve this problem by allowing for methods implemented in bytecode to be injected during code generation, making them callable just like any function compiled from Haskell source. For example, integer addition is defined as

```
1 instance Num Int where
2     (+) = primNumIntAdd
3 primNumIntAdd :: Int -> Int -> Int
```

A hook is then added to the compiler that generates functions named `_makeprimNumIntAdd` and `_primNumIntAddImpl`, as described in 3.1.7.2. The implementation of `_primNumIntAddImpl` is provided in the hook definition, and simply forwards its arguments to the `_Int::add` function shown in 3.1.7.2. The functions generated by the hook are, at the bytecode level, indistinguishable from functions generated by any other expression so can be called by any other function without issue.

Compare to GHC's approach? Looks similar

### 3.1.8 Optimisations

Many JVM implementations perform low-level optimisations on the bytecode while just-in-time compiling it to native machine code. The Jikes JVM, as of 2006[10], performs method inlining, common subexpression elimination, copy/constant propagation, peephole passes, instruction reordering and loop unrolling, as well as adaptive optimisations such as selective optimisation to improve startup time.

This somewhat reduces the need to perform low-level optimisations within the compiler, so focus is instead given to higher-level optimisations.

#### 3.1.8.1 Let-lifting

Let lifting aims to move let-bound variables and functions 'up' the AST, to as close to the top-level as possible while preserving the semantics. This can reduce the number of heap allocations and eliminate the need for initialisation code, saving on program size and execution time.

Example?

[10] http://www.complang.tuwien.ac.at/andi/ACACES06.pdf

Lifting variables and functions to the top level is desirable as they can be referenced immediately by other code without needing to initialise them: this eliminates initialisation code and in the case of variables additionally prevents allocating a new thunk on the heap. Lifting expressions as high as possible but not all the way to the top doesn't have any immediate advantages, but exposes benefits after the Binding Deduplication pass, described in 3.1.8.2.

Let lifting is an ILB to ILB transformation, as ILB exposes the most uses of let-bindings: almost every subexpression in a computation is let-bound to a variable as ILB requires that all function applications only use trivial arguments. This provides a lot of freedom to move bindings around.

Nomal let lifting involves lifting functions out of scope of their free variables then adding the free vars as arguments: mine doesn't do this as I didn't have time to look into how to balance adding more arguments versus removing free variables

#### 3.1.8.2 Binding Deduplication

The binding deduplication pass eliminates any bindings where the right-hand side of the binding is syntactically identical to that of another in-scope binding, and replaces references to the eliminated binding with references to the existing one. This is a rather unusual optimisation to perform but it has significantly positive effects on program size, and can reduce computation.

As the intermediate languages are mostly in ANF, there are a great deal of let-bindings. In particular, simple expressions like `True && True` in Haskell are converted into `let v1 = True in let v2 = True in (&&) v1 v2` in ILB. This is necessary in general in order to provide lazy evaluation, but in simple cases like this it introduces obvious redundancy. Binding deduplication removes the redundancy by transforming the ILB version into `let v1 = True in (&&) v1 v1`. This reduces code size and removes a heap allocation, and if the redundant expression had been more complex it would also have allowed for the value to only be computed once, instead of twice.

This optimisation is an ILB to ILB transformation like let-lifting, for similar reasons. In addition, this transformation is performed after let-lifting as it produces better results than before: after lifting bindings as high as possible there are more in-scope bindings at any program point, which increases the potential for bindings to be removed by this pass.

Name-drop 'phase ordering' at some point to sound smart?

#### 3.1.8.3 Code generation

General smart codegen choices to prevent needless inefficiencies: using `lookupswitch` instead of chained `ifeq`s, global closures etc. are just referenced instead of being created like local closures, ...

Not planning to write yet: would like to sneakily implement unused code elimination in the *tons* of time I have available and write that up instead, as a 'proper optimisation technique'.

# Chapter 4

# Evaluation

# Chapter 5

# Conclusion

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[5] Philip Wadler and Simon Peyton Jones. *The Implementation of Functional Programming Languages*. Prentice Hall, 1987.

# Appendix A

# Project Proposal

Computer Science Tripos: Part II Project Proposal

# An Optimising Compiler from Haskell to Java Bytecode

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## Introduction and Description of the Work

The goal of this project is to implement an optimising compiler from a subset of the Haskell language to Java bytecode. A variety of optimisations will be implemented to explore their effect on compilation and execution time, as well as on the size of the produced bytecode.

Haskell is a functional, pure, and non-strict language seeing increasing usage in industry and academia. Purity makes programs much simpler to reason about: a programmer can usually tell from the type of a function exactly what it can do, which makes it easier to avoid bugs.

Java Bytecode was chosen as the target language as it is portable and mature. While not as performant as native machine code, bytecode produced by the compiler built during this project can be interpreted on almost any platform, rather than being restricted to e.g. only machines with an x86-64 processor. Other bytecodes like python bytecode are less well known, and lack existing Haskell libraries that provide an abstraction over them. Compiling to LLVM IR was considered, but would require implementing a garbage collector which is a significant piece of work that is not aligned with the aims of this project.

Similar projects exist, like Frege[1] and Eta[2], that both aim to provide a fully-featured Haskell compiler for programs running on the JVM, with the ability to interoperate with Java. The Eta project aims to accelerate the uptake of Haskell in industry by interfacing with a widely used imperative language[3]. The motivation behind this project is instead simply individual learning – Haskell has a number of aspects which are not covered in undergraduate courses, such as type classes and lazy evaluation, which I am very interested in learning how to implement.

[1] https://github.com/Frege/frege
[2] https://eta-lang.org/
[3] https://eta-lang.org/docs/user-guides/eta-user-guide/introduction/what-is-eta#motivation

## Starting Point

I intend to use Haskell to develop the compiler, and Python or Bash for quick utility scripts – I have experience with all of these languages.

I have preread the 2018 Optimising Compilers course[4] as preparation: my schedule involves writing optimisations before the module is lectured.

## Resources Required

I will use my personal laptop to develop this project: a ThinkPad 13 running NixOS. I will use Git for version control, host the code on a public repository on GitHub, and use TravisCI for automated tests. I also intend to keep a backup repository on an MCS machine – my personal DS-Filestore allowance should be sufficient.

Should my laptop break or otherwise become unusable to complete the project, I have an older laptop running Debian 9 that I can use. It should only cost a few days to get it set up with a Haskell development environment.

I intend to use the GHC compiler[5] with the Stack toolchain[6] for development (both are available under BSD-style licences).

## Substance and Structure of the Project

The aim of the project is to develop an optimising compiler that can translate simple programs written in Haskell into Java bytecode that can be interpreted on platforms supporting the Java Runtime Environment.

Haskell is a very feature-rich language, and those features are often highly dependent on each other: simple things often touch many aspects of the language (for example, the simple numeric literal `5` which would have type `int` in C instead has type `Num t => t` in Haskell, involving type classes and type constraints). I intend to implement typeclasses[7], aspects of functions (currying, partial application, recursion), arithmetic, boolean operations, lists (and functions for manipulating them such as `map` and `foldl`). The implementation of many of these features will be different from in conventional languages due to the impact of typeclasses and laziness. These features should cover most of the novel aspects of Haskell that are feasible to be implemented, so should be the most educational to implement.

The project also aims to implement some optimisations to improve the performance of the of the compiler. These include classical optimisations like peephole analysis, but also strictness analysis[8], which is exclusively useful for lazy languages, so again offers good educational value. I intend to research and implement existing impactful techniques, rather than try to invent new optimisation techniques.

As Haskell is a lazy language, one of the major challenges will be to design a way to represent and perform lazy computation. This might be achieved using "thunks", in-memory representations of pending computations. GHC keeps track of thunks at runtime using a directed graph.

[4] https://www.cl.cam.ac.uk/teaching/1718/OptComp/
[5] https://www.haskell.org/ghc/
[6] https://github.com/commercialhaskell/stack
[7] http://homepages.inf.ed.ac.uk/wadler/papers/classhask/classhask.ps
[8] https://www.cl.cam.ac.uk/~am21/papers/sofsem92b.ps.gz

As the focus of the project is on the implementation of various language features and optimisations operating on them, I intend to use an existing library for lexing and parsing (`haskell-src`[9]) which can produce an AST from Haskell 98 – similarly, the actual assembly of the textual bytecode will be handled by the `hs-java` library[10]. This will allow for more time to be devoted to those parts of the project which are more aligned with the aim.

Tests are a vital part of any engineering project. During the work on the project, I will write and maintain a test suite to ensure the various components of the compiler work as expected and guard against regressions. I intend to use the `tasty` framework[11] which provides a standard interface to `HUnit`[12] (for unit and regression tests) and `QuickCheck`[13] (for wonderful property-based tests) to implement this test suite.

## Success Criteria

The primary goal of the project is to produce a compiler that can translate source code written in a small subset of Haskell into Java bytecode suitable for execution by the JVM, attempting simple optimisations during the translation process.

The compiler should be able to reject ill-formed programs for syntactic or type errors (within the scope of the subset of Haskell implemented), and convert well-formed programs into Java bytecode. The resulting bytecode should perform computation non-strictly.

I also hope to identify the cases in which the optimisations produce code that uses fewer resources than when non-optimised (either CPU time, memory, or disk space).

## Evaluation

To evaluate the success criteria, I plan to use a suite of test programs designed to probe various areas of the compiler, based off GHC's `nofib`[14] repository. Some tests from that suite will likely use features that my compiler does not support, and I intend to modify or discard them depending on how close they are to being supported.

Additional test programs will also be written, to specifically demonstrate features of the compiler: for example a simple program like `let l = 1:l in take 5 l` (with result `[1,1,1,1,1]`) is a good demonstration of lists and laziness. These might be carefully crafted, e.g. to demonstrate the effect of the peephole pass on non-optimised versus optimised code. Combined, these sets of programs should form a broad range of inputs to ensure that the compiler behaves as expected.

Specific metrics that I aim to capture data about are the time taken to compile a program with and without optimisations enabled, the execution time and memory footprint of non-optimised and optimised output bytecode, and the size of output bytecode (number of instructions or raw byte size). These should allow for critical evaluation on a number of axes, such as "speed-up of optimised bytecode over non-optimised" against "extra time taken during compilation" or "change in output size". The effects of strictness analysis should also be visible by comparing the memory usage of bytecode running with and without the optimisation enabled.

[9] https://hackage.haskell.org/package/haskell-src
[10] https://hackage.haskell.org/package/hs-java
[11] https://hackage.haskell.org/package/tasty
[12] https://hackage.haskell.org/package/HUnit
[13] https://hackage.haskell.org/package/QuickCheck
[14] https://github.com/ghc/nofib

To gather data about the performance of the compiler, I intend to use the rich profiling options built in to GHC, together with the `criterion`[15] and `weigh`[16] packages for reproducible benchmarks.

To gather data about the performance of the emitted bytecode, I intend to leverage mature JVM tooling by using an existing JVM profiler such as JProfiler or Java VisualVM.

## Extensions

There are many interesting extensions to the proposed work:

- There are many more features to Haskell than those mentioned in this proposal, ranging from syntactic sugar to features in their own right: infix operators, operator sections, point-free notation, user-defined datatypes, type instances, monads, GADTs, user input/output, etc.

  Increasing the size of the implemented subset of Haskell would allow for writing more interesting programs, and also exploring the effectiveness of existing optimisations on the new changes.

- There also exist many more optimisations that could be investigated: there are over 60 "big picture" optimisations listed on the GHC's "using optimisations" page[17].

- One of the greatest attractions of pure languages is the relative ease with which they can be parallelised: any sub-expressions can be evaluated at any time without effecting the result of the computation. GHC provides a concurrency extension to make such parallel programming easy – it would be interesting to implement such a feature but likely far beyond the scope of this project.

- The Haskell Prelude[18] is the "standard library" of Haskell: as it is written in Haskell, it might be possible to compile parts of it using the compiler developed during this project, allowing it to be used in programs. However, this would require quite a significant level of support for the language in the compiler.

- A very cool demonstration for the project would be to compile the project using the compiler developed during the project (bootstrapping). This would require extensive language support though (at the very least, support for monads), which is likely infeasible to be completed.

- One potential advantage of using the JVM as a target is that it may be possible to provide a foreign function interface between Java code and Haskell code.

- Using the JVM will impose a performance impact compared to compiling to native machine code – this overhead is hard to measure and reduces the informativeness of comparisons to other compilers like GHC. It would be beneficial to find a way of calculating this overhead, to improve the quality of data obtained during evaluation.

[15] https://hackage.haskell.org/package/criterion
[16] https://hackage.haskell.org/package/weigh
[17] https://downloads.haskell.org/~ghc/master/users-guide/using-optimisation.html
[18] https://www.haskell.org/onlinereport/standard-prelude.html

## Schedule

I intend to treat tests as part of a feature: when the schedule lists a certain feature as being deliverable in a slot, that implicitly includes suitable tests for it.

- **15th Oct – 21st Oct**

  General project setup: creating a version-controlled repository of code with continuous integration to run tests.

  Create a simple frontend for converting a given file into an AST using the `haskell-src` package.

- **22nd Oct – 11th Nov**

  Implement a type checking pass over the AST, *including support for typeclasses*. This is one of the most uncertain duration parts of the project, because while the Hindley-Milner type system is well understood and frequently implemented, the extension of type classes seems less comprehensively covered, although there are still some strong leads[19].

  After this work, the frontend should be functional and the compiler should be able to reject ill-formed source code either due to syntactic or type errors.

- **12th Nov – 2nd Dec**

  Create a simple (non-optimising) backend for experimenting with lazy evaluation. This should just perform a minimally-featured translation from the frontend's AST to executable bytecode (supporting e.g. basic arithmetic and conditional expressions), but performing evaluation *lazily*.

- **3rd Dec – 16th Dec**

  The goal of this week is to implement a peephole pass to collapse sequences of instructions into more efficient versions. The sequences to be collapsed will need to be decided at the time, based on inspection of the bytecode produced by the compiler, and more peephole rules can be added as other transformations are implemented.

  After this work is complete, the absolutely minimal success criteria should have been met, taking pressure off the rest of the planned work.

- **17th Dec – 23rd Dec**

  This week is a slack week, to catch up on anything that fell behind, or to spend time cleaning up any parts of the existing implementation that are messy/fragile/poorly designed.

- **24th Dec – 13th Jan**

  Implement user-defined functions, supporting currying, partial application, recursion, and laziness. Depending on how long this takes, this may be a convenient time to implement a number of smaller related features, such as pattern matching, `case` expressions, `let ... in ...` expressions, `... where ...` expressions, etc.

- **14th Jan – 3rd Feb**

  Progress report and presentation.

[19] http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.53.3952&rep=rep1&type=pdf

Introduce lists: these are one of the most frequently used data structures in Haskell, and form the basis for many algorithms. They also give many opportunities to demonstrate that the implementation of lazy evaluation works correctly (e.g. by careful analysis of expressions like `let l = 1:l in take 5 l`, which should give `[1,1,1,1,1]`).

- **4th Feb – 24th Feb**

  Implement strictness analysis, and accompanying optimisations. The optimisation opportunities revealed by strictness analysis should reduce compiled code size and memory usage, by eagerly evaluating expressions that are guaranteed to require evaluation during program execution.

- **25th Feb – 24th Mar**

  During these weeks, I intend to focus on writing the dissertation.

  Implement some micro-benchmarks to demonstrate the effectiveness of the optimisations, for use in the evaluation section.

- **25th Mar – 14th Apr**

  In these weeks I hope to balance work on the dissertation with revision.

  Near the start of this work chunk, I intend to submit a full draft to my DoS and Supervisor.

- **15th Apr – 28th Apr**

  I now expect to switch fully to revision, making only critical changes to the dissertation.

  At the end of these weeks I hope to submit the dissertation and concentrate fully on revision and the final term.