GHC Reading Guide

- Exploring entrances and mental models to the source code -

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Rev. 0.01.1
WIP

NOTE:

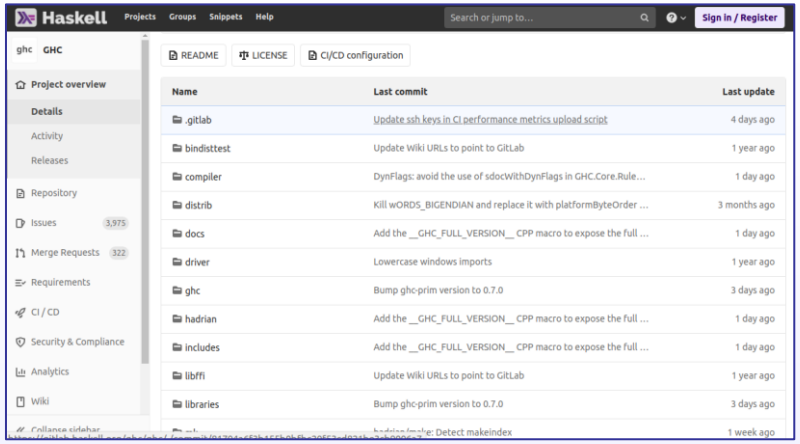
- This is not an official document by the ghc development team.
- Please refer to the official documents in detail.
- Don't forget “semantics”. It's very important.
- This is written for ghc 9.0.

Contents

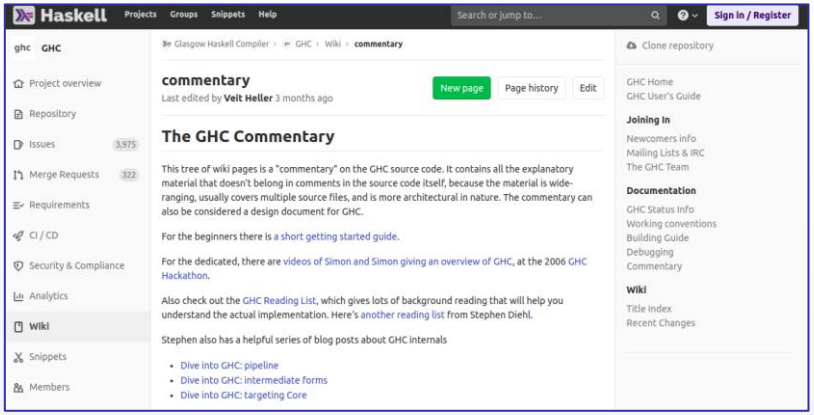
Introduction

Official resources are here

GHC source repository :
https://gitlab.haskell.org/ghc/ghc

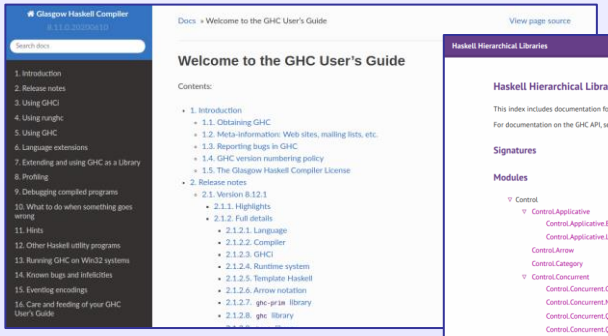


The GHC Commentary (for developers) :
https://gitlab.haskell.org/ghc/ghc/-/wikis/commentary

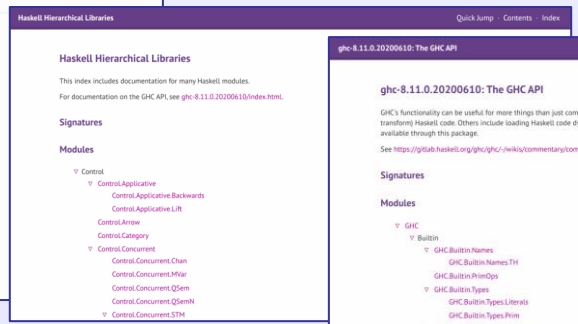


GHC Documentation (for users) :

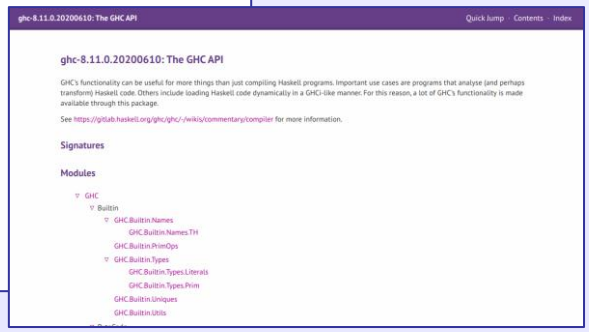
* master HEAD https://ghc.gitlab.haskell.org/ghc/doc/
* latest major release https://downloads.haskell.org/~ghc/latest/docs/html/
* version specified https://downloads.haskell.org/~ghc/9.0.1/docs/html/



The User's Guide

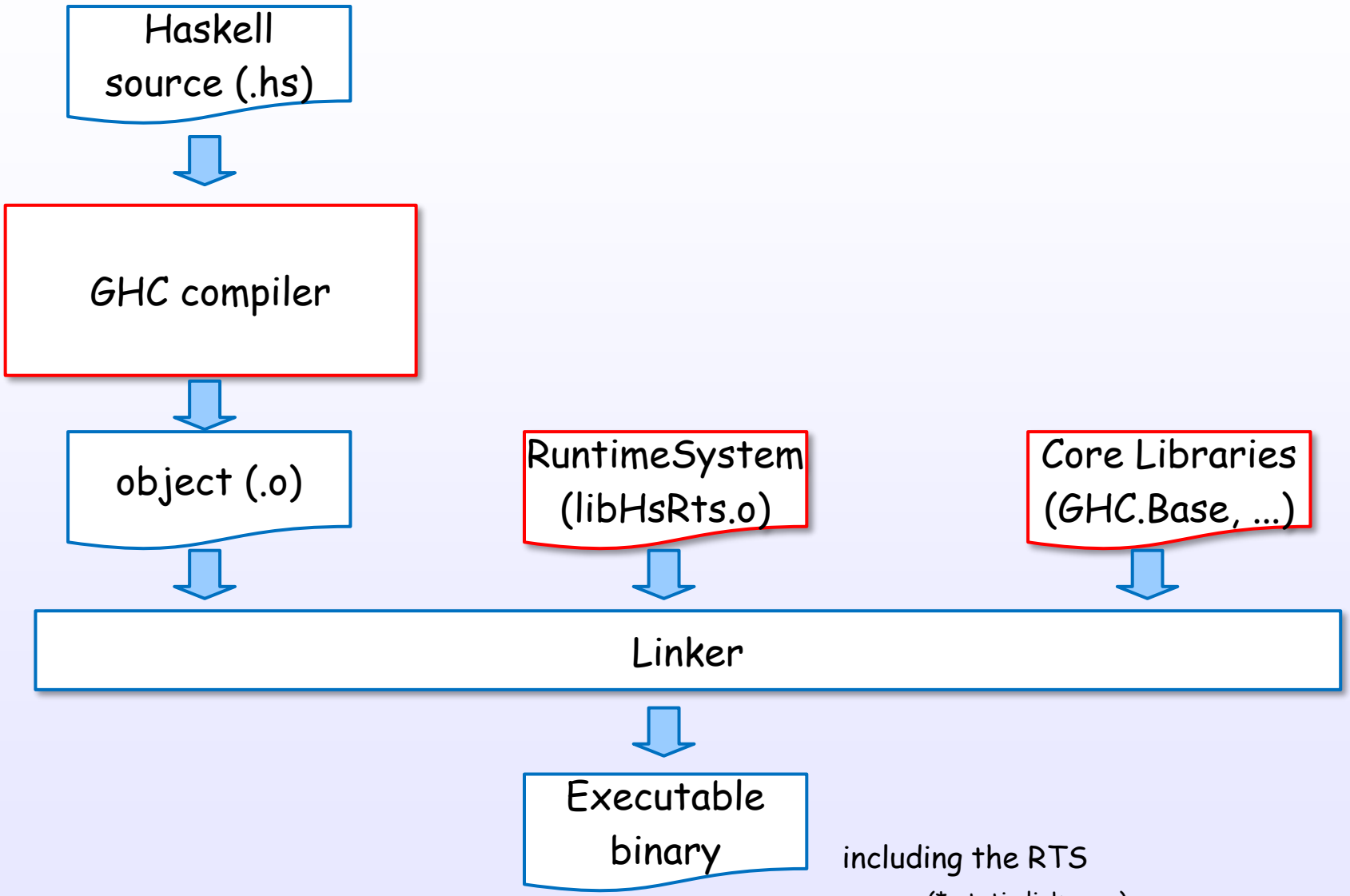


Core Libraries



GHC API

The GHC = Compiler + Runtime System (RTS) + Core Libraries



Each division is located in the GHC source tree

GHC source repository :
https://gitlab.haskell.org/ghc/ghc

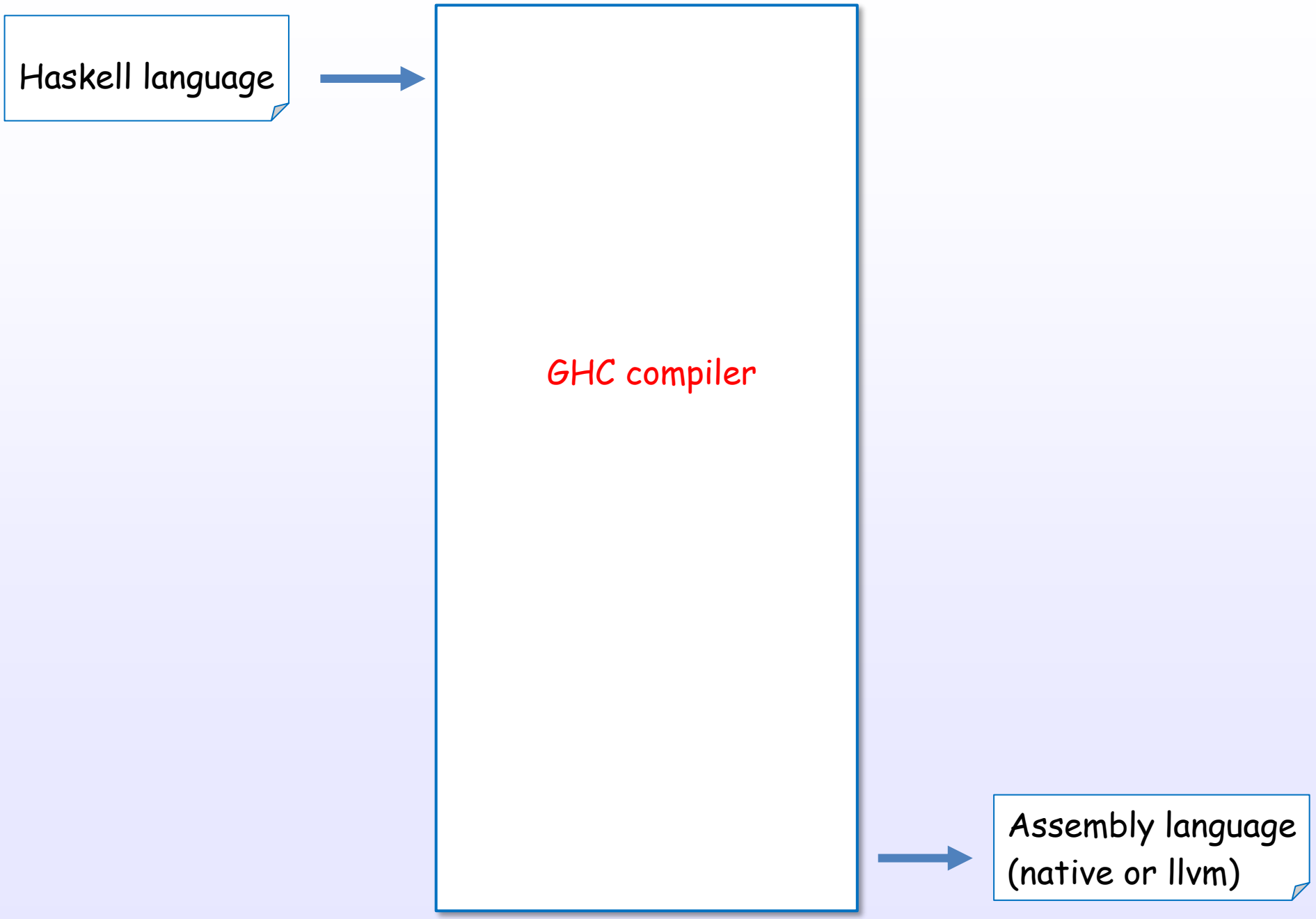
compiler/	... compiler sources
rts/	... runtime system sources
libraries/	... core library sources
ghc/	... compiler main
includes/	... include files
testsuite/	... test suites
nofib/	... performance tests
mk/	... build system
hadrian/	... hadrian build system
docs/	... documents
:	:

1. Compiler

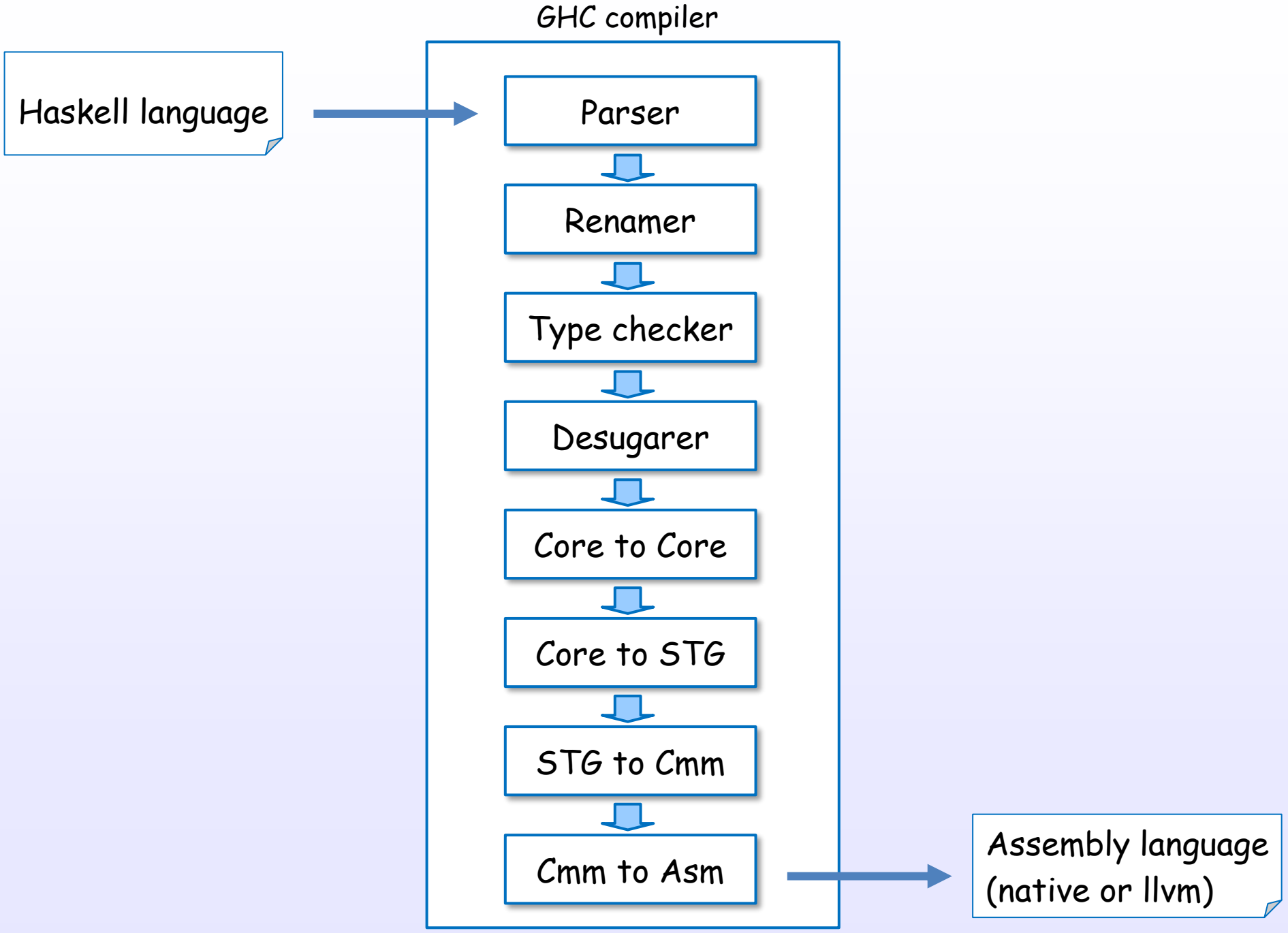
1. Compiler

Compilation pipeline

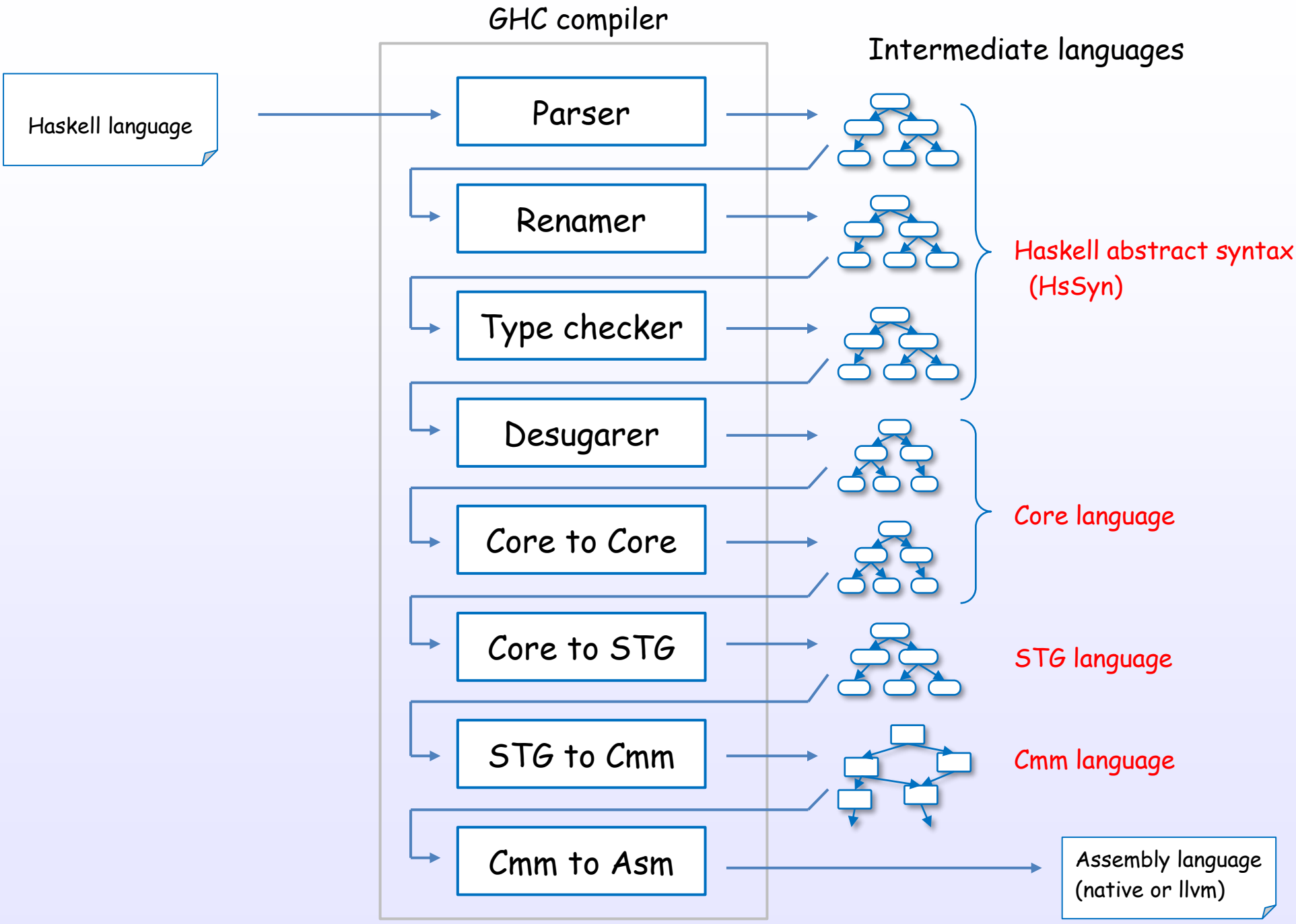
The GHC compiler



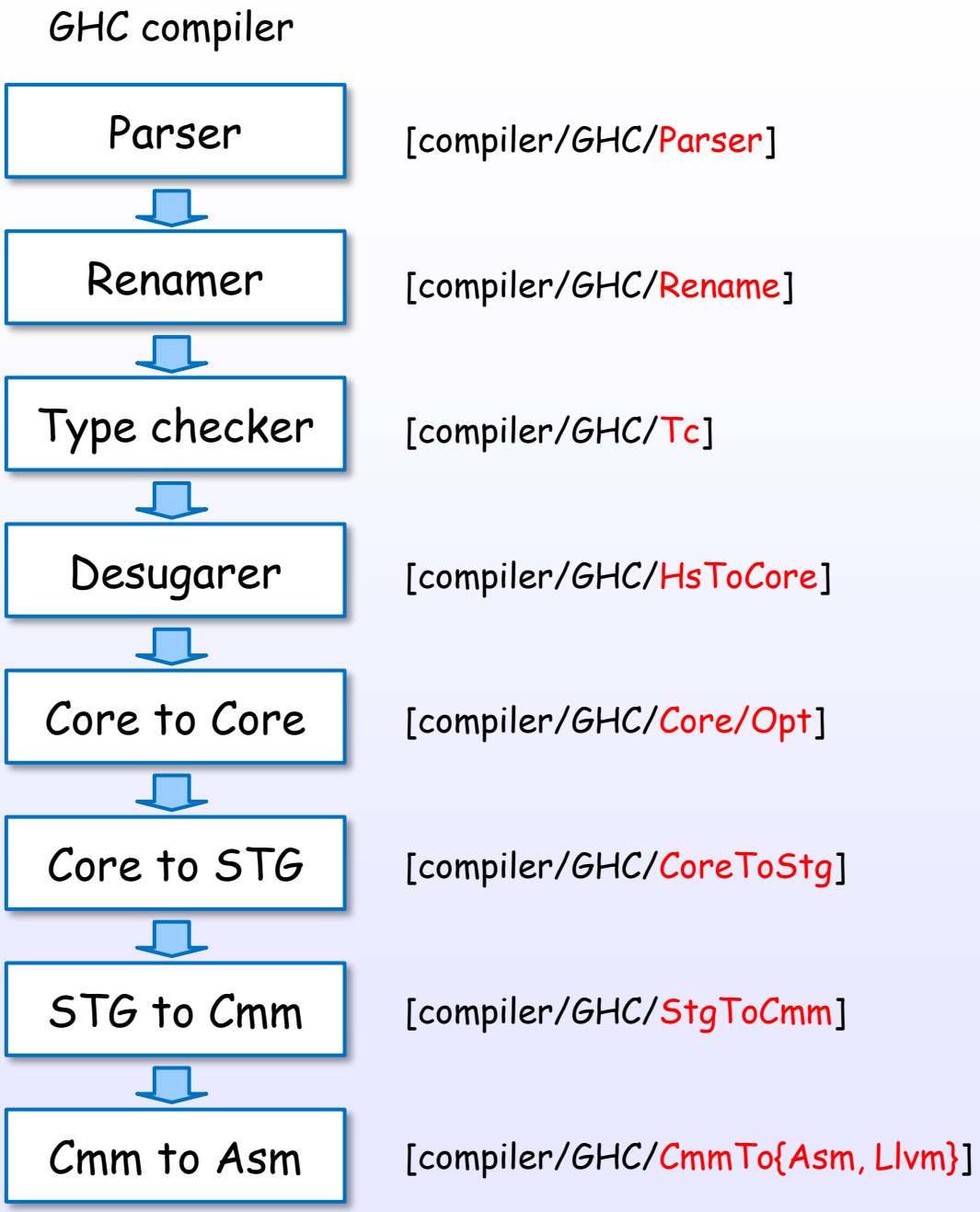
GHC compiler comprises pipeline stages



Pipeline stages process with intermediate languages



Each code is located in



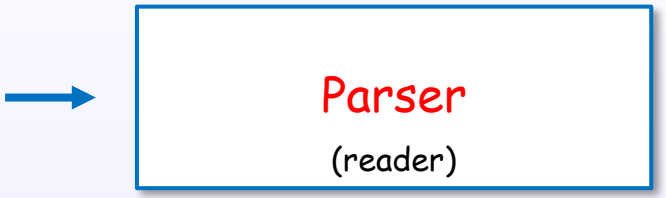
1. Compiler

Each pipeline stages

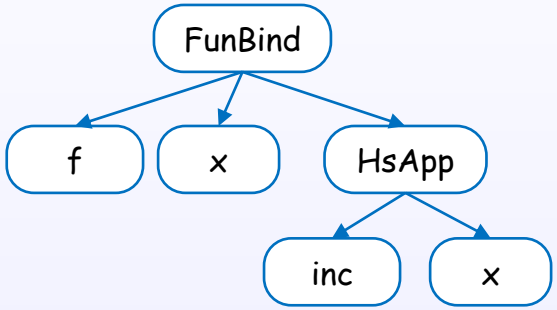
Parser

Haskell source

```
f x = inc x
```



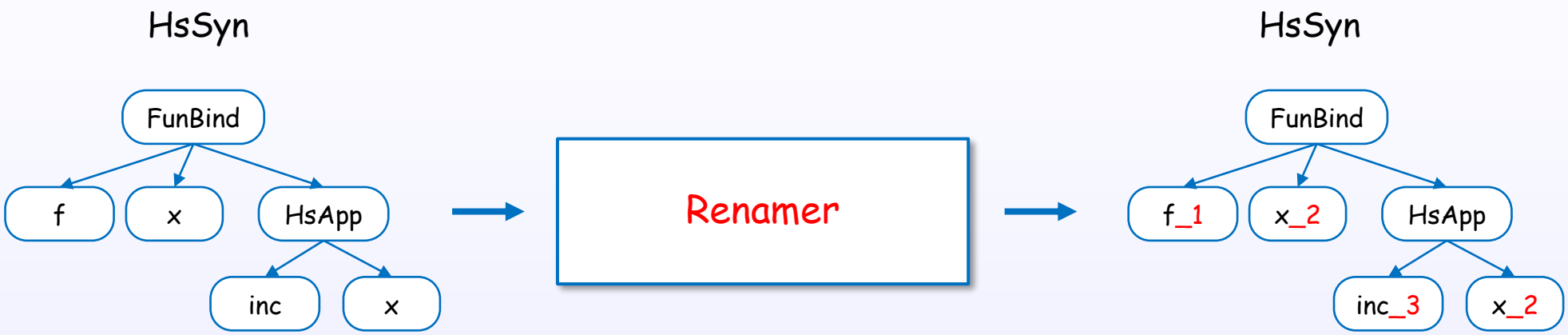
HsSyn
(Haskell Abstract Syntax)



Abstracted

- Parsing a Haskell source file
- Checking user syntax errors
- etc.

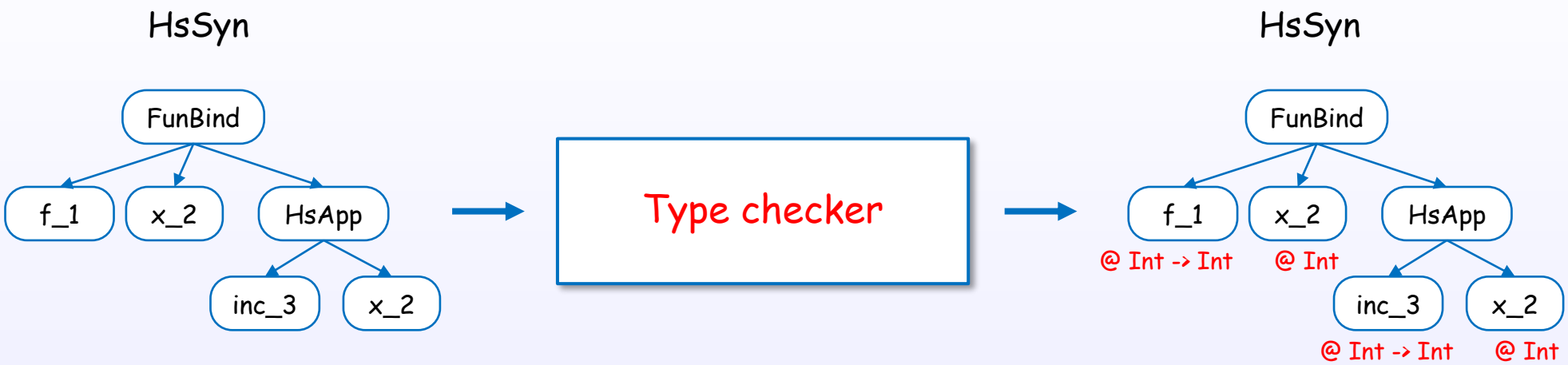
Renamer



Unique named

- Resolving all of the identifiers
- Rearranging infix expressions
- Checking user scope errors
- Building global environments
- etc.

Type checker



Explicitly typed

- Resolving/Inferring types
- Decorating AST with types
- Checking user type errors
- etc.

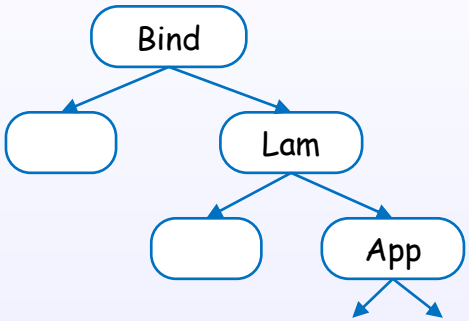
Desugarer

Squeezed into λ calculus

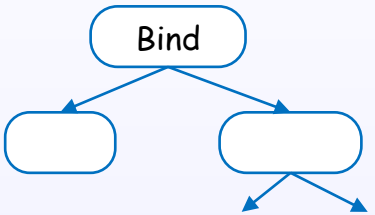
- Desugaring HsSyn to Core
- Checking pattern-match overlap
- etc.

Core to Core

Core language



Core language

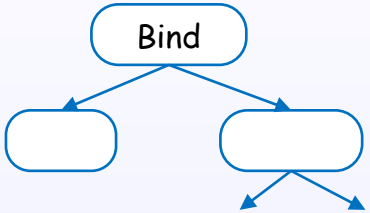


Optimized

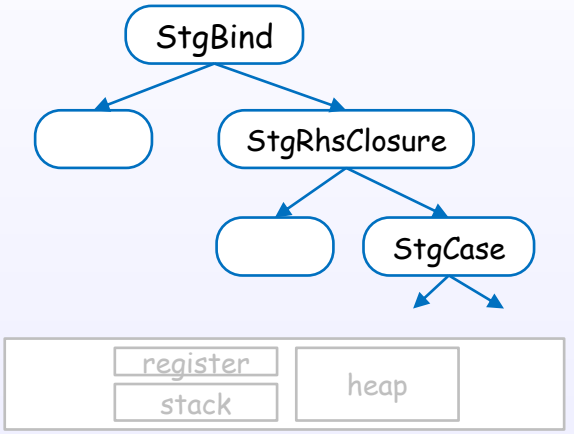
- Optimizing Core (simplifier, ...)
- Checking typechecker's result with Lint
- Tidying Core to Core
- etc.

Core to Stg

Core language



STG language

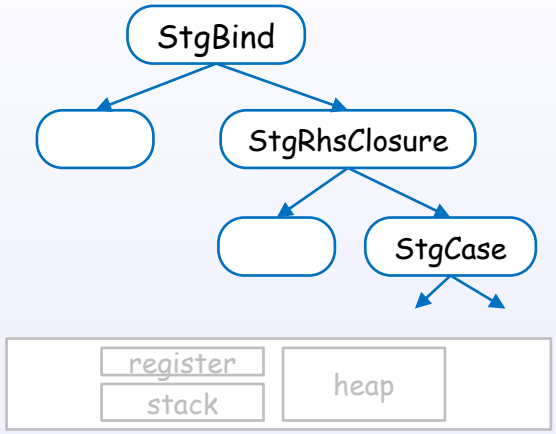


- Transforming Core to STG
- etc.

Operationally mapped

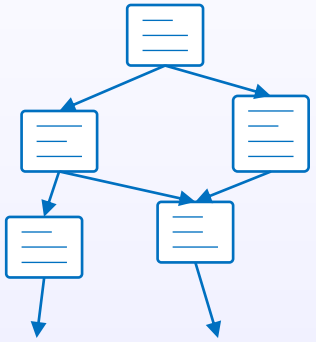
STG to Cmm

STG language



STG to Cmm
(code gen)

Cmm language

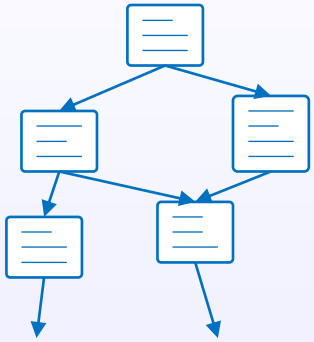


- Optimizing STG
- Transforming STG to Cmm
- etc.

Instruction blocked

Cmm to Assembly

Cmm language



Cmm to Asm

(native code gen)

Assembly/LLVM language

```
add   $0x2, %rbx
jmpq  *0x0(%rbp)
   :
```

Machine coded

- Optimizing Cmm
- Generating Asm
- etc.

Intermediate language syntax

HsSyn (Haskell abstract syntax)

[compiler/GHC/Hs/Decls.hs]

```
data HsDecl p
  = TyClD ...          -- Type or Class Declaration
  | InstD ...          -- Instance declaration
  | DerivD ...         -- Deriving declaration
  | ValD ...           -- Value declaration
  | SigD ...           -- Signature declaration
  | KindSigD ...       -- Standalone kind signature
  | DefD ...           -- 'default' declaration
  | ForD ...           -- Foreign declaration
  | WarningD ...       -- Warning declaration
  | AnnD ...           -- Annotation declaration
  | RuleD ...          -- Rule declaration
  | SpliceD ...        -- Splice declaration
  | DocD ...           -- Documentation comment declaration
  | RoleAnnotD ...     -- Role annotation declaration
  | XHsDecl ...
```

[compiler/GHC/Hs/Binds.hs]

```
data HsBindLR idL idR
  = FunBind ...        -- Function-like Binding
  | PatBind ...        -- Pattern Binding
  | VarBind ...        -- Variable Binding
  | AbsBinds ...       -- Abstraction Bindings
  | PatSynBind ...     -- Patterns Synonym Binding
  | XHsBindsLR ...
```

[compiler/GHC/Hs/Expr.hs]

```
data HsExpr p
  = HsVar ...
  | HsUnboundVar ...
  | HsConLikeOut ...
  | HsRecFld ...
  | HsOverLabel ...
  | HsIPVar ...
  | HsOverLit ...
  | HsLit ...
  | HsLam ...
  | HsLamCase ...
  | HsApp ...
  | HsAppType ...
  | OpApp ...
  | NegApp ...
  | HsPar ...
  | SectionL ...
  | SectionR ...
  | ExplicitTuple
  | ExplicitSum
  | HsCase ...
  | HsIf ...
  | HsMultiIf ...
  | HsLet ...
  | HsDo ...
  | ExplicitList
  | RecordCon
  | RecordUpd
  | ExprWithTySig
  | ArithSeq
      :
```

An abstract syntax corresponding to Haskell user source.

Core language

[compiler/GHC/Core.hs]

```
type CoreProgram = [CoreBind]
type CoreBndr = Var
type CoreExpr = Expr CoreBndr
type CoreArg  = Arg  CoreBndr
type CoreBind = Bind CoreBndr
type CoreAlt  = Alt  CoreBndr

data Expr b
  = Var   Id                          -- Variable
  | Lit   Literal                     -- Literal
  | App   (Expr b)  (Arg b)           -- Application
  | Lam   b  (Expr b)                 -- Lambda abstraction
  | Let   (Bind b)  (Expr b)          -- Variable binding
  | Case  (Expr b)  b  Type  [Alt b]  -- Pattern match
  | Cast  (Expr b)  Coercion          -- Cast
  | Tick  (Tickish Id)  (Expr b)      -- Internal note
  | Type  Type                        -- Type
  | Coercion Coercion                 -- Coercion
```

A tiny explicitly-typed functional language.
Only ten data constructors based on System FC.

STG language

[compiler/GHC/Stg/Syntax.hs]

```
data GenStgTopBinding pass
  = StgTopLifted (GenStgBinding pass)  |  StgTopStringLit Id ByteString

data GenStgBinding pass
  = StgNonRec (BinderP pass) (GenStgRhs pass)  |  StgRec  [(BinderP pass, GenStgRhs pass)]

data GenStgRhs pass
  = StgRhsClosure  (XRhsClosure pass)  CostCentreStack  !UpdateFlag  [BinderP pass]  (GenStgExpr pass)
  | StgRhsCon        CostCentreStack DataCon [StgArg]

data GenStgExpr pass
  = StgApp           Id  [StgArg]
  | StgLit           Literal
  | StgConApp        DataCon  [StgArg]  [Type]
  | StgOpApp         StgOp  [StgArg]  Type
  | StgLam           (NonEmpty  (BinderP pass))  StgExpr
  | StgCase          (GenStgExpr pass)  (BinderP pass)  AltType  [GenStgAlt  pass]
  | StgLet           (XLet pass)  (GenStgBinding pass)  (GenStgExprpass)
  | StgLetNoEscape   (XLetNoEscape pass)  (GenStgBinding pass)  (GenStgExpr pass)
  | StgTick          (Tickish Id)  (GenStgExpr pass)
```

A very small purely-functional language with the abstract machine (STG-machine) semantics.

Cmm language

[compiler/GHC/Cmm.hs]

```
type CmmProgram = [CmmGroup]
type CmmGroup   = GenCmmGroup CmmStatics CmmTopInfo CmmGraph
type CmmGraph = GenCmmGraph CmmNode
```

[compiler/GHC/Cmm/Node.hs]

```
data CmmNode e x where
  CmmEntry ...                                          -- Entry
  CmmComment ...                                        -- Comment
  CmmTick ...                                           -- Tick annotation
  CmmUnwind ...                                         -- Unwind pseudo-instruction
  CmmAssign :: !CmmReg -> !CmmExpr -> CmmNode O O       -- Assign to register
  CmmStore ...                                          -- Assign to memory location
  CmmUnsafeForeignCall ...                              -- An unsafe foreign call
  CmmBranch ...                                         -- Goto another block
  CmmCondBranch ...                                     -- Conditional branch
  CmmSwitch ...                                         -- Switch
  CmmCall ...                                           -- A native call or tail call
  CmmForeignCall ...                                    -- A safe foreign call
```

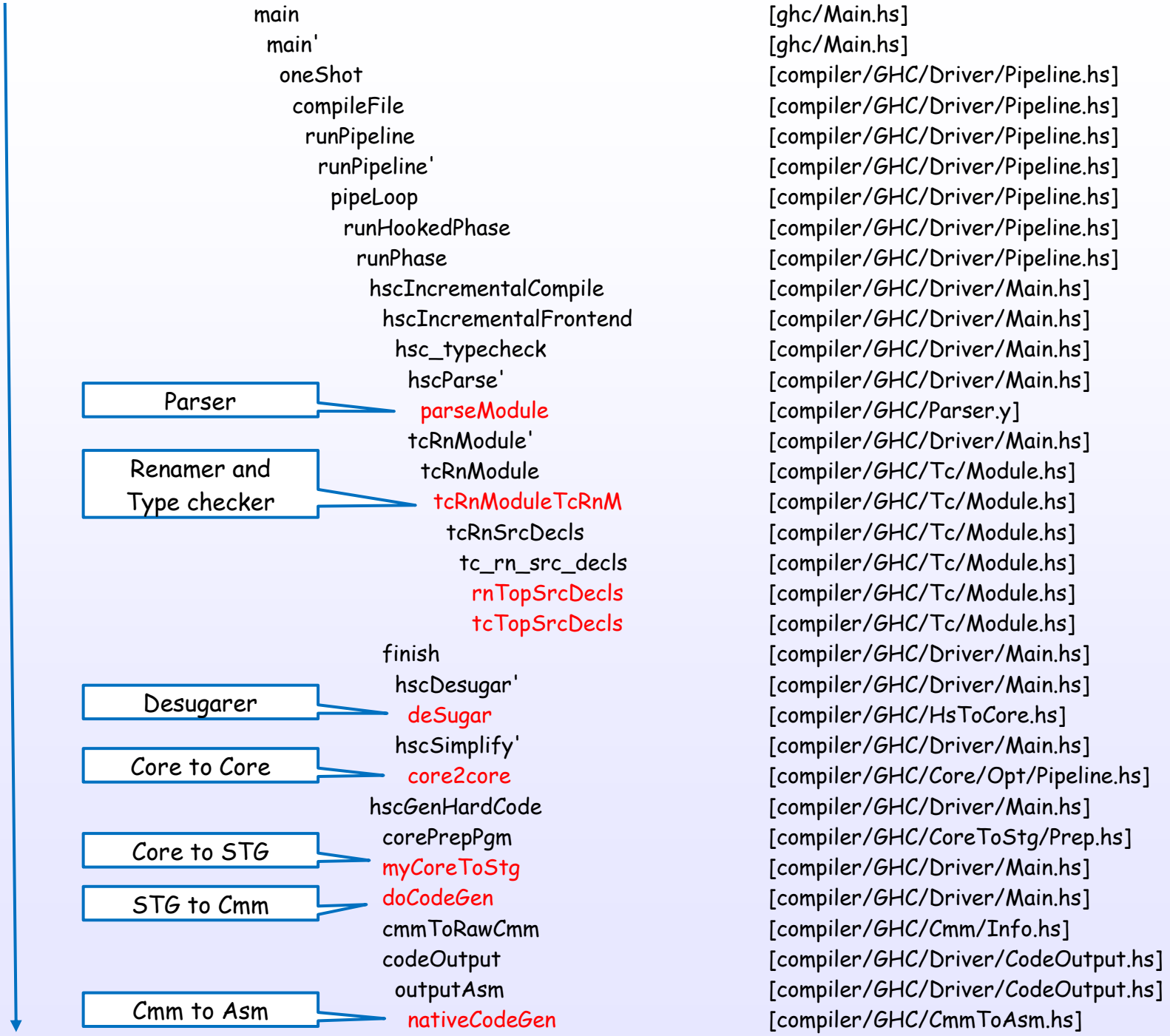
[compiler/GHC/Cmm/Expr.hs]

```
data CmmExpr
  = CmmLit        CmmLit                  -- Literal
  | CmmLoad       !CmmExpr  !CmmType      -- Read memory location
  | CmmReg        !CmmReg                 -- Contents of register
  | CmmMachOp     MachOp  [CmmExpr]       -- Machine operation (+, -, *, etc.)
  | CmmStackSlot  Area  {-# UNPACK #-} !Int
  | CmmRegOff     !CmmReg  Int
```

A low-level imperative language with an explicit stack.

Call graph

An example of a call graph



Appendix

Dump intermediate languages

Dump parser output:

```
$ ghc  -ddump-parsed
$ ghc  -ddump-parsed-ast
```

Dump renamer output:

```
$ ghc  -ddump-rn
$ ghc  -ddump-rn-ast
```

Dump type-checker output:

```
$ ghc  -ddump-tc
$ ghc  -ddump-tc-ast
    :
```

Dump Core:

```
$ ghc  -ddump-ds-preopt
$ ghc  -ddump-ds
$ ghc  -ddump-simpl
$ ghc  -ddump-prep
    :
```

Dump STG:

```
$ ghc  -ddump-stg-final
    :
```

Dump Cmm:

```
$ ghc  -ddump-cmm
$ ghc  -ddump-opt-cmm
    :
```

Dump asm/llvm:

```
$ ghc  -ddump-asm
$ ghc  -ddump-llvm
```

Each intermediate language can be dumped using ghc's flags.
See the user's guide in detail :

https://downloads.haskell.org/~ghc/latest/docs/html/users_guide/debugging.html#dumping-out-compiler-intermediate-structures

Additional useful flags for dumps

Use ghc's flags when you need more detailed information :

```
-fprint-explicit-kinds              : Print out kind applications
-fprint-explicit-coercions          : Print out details of coercions
-fprint-typechecker-elaboration     : Print out extra gubbins the type-checker inserts
-fprint-explicit-runtime-reps       : Don't simplify away RuntimeRep arguments
    :
```

See the user's guide in detail :

https://downloads.haskell.org/~ghc/latest/docs/html/users_guide/using.html#verbosity-options

Use ghc's flags when you want to suppress some information :

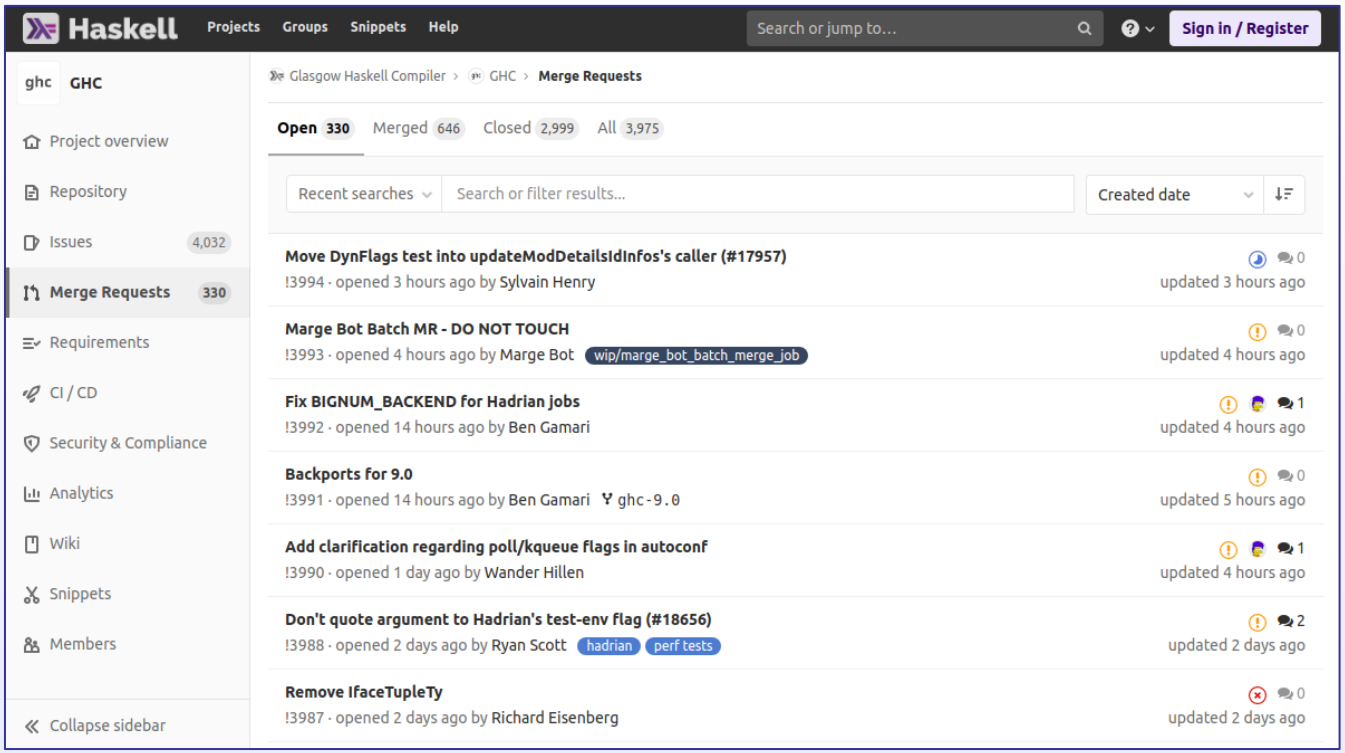
```
-dsuppress-module-prefixes          : Suppress the printing of module qualification prefixes
-dsuppress-coercions                : Suppress the printing of coercions
-dsuppress-uniques                  : Suppress the printing of uniques
-dsuppress-type-applications        : Suppress type applications
    :
```

See the user's guide in detail :

https://downloads.haskell.org/~ghc/latest/docs/html/users_guide/debugging.html#suppressing-unwanted-information

Patches are good entrances to dive into GHC

Merge Requests (Pull requests) :
https://gitlab.haskell.org/ghc/ghc/-/merge_requests



The merge-requests page is a mine of practical codes.

References

References

Overview:

The Architecture of Open Source Applications: The Glasgow Haskell Compiler
https://www.aosabook.org/en/ghc.html

GHC Commentary: The Compiler
https://gitlab.haskell.org/ghc/ghc/-/wikis/commentary/compiler

Compiling one module: GHC.Driver.Main
https://gitlab.haskell.org/ghc/ghc/-/wikis/commentary/compiler/hsc-main

A Haskell Compiler
https://www.scs.stanford.edu/11au-cs240h/notes/ghc-slides.html

Dive into GHC
https://www.stephendiehl.com/posts/ghc_01.html

Write a GHC extension in 30 minutes
https://www.youtube.com/watch?v=bhhE2DxbrJM

The GHC Commentary
https://gitlab.haskell.org/ghc/ghc/-/wikis/commentary

The GHC reading list
https://gitlab.haskell.org/ghc/ghc/-/wikis/reading-list

References

Parser:

The Parser
https://gitlab.haskell.org/ghc/ghc/-/wikis/commentary/compiler/parser

Syntactic ambiguity resolution in the GHC parser
https://blog.shaynefletcher.org/2020/04/syntactic-ambiguity-resolution-in-ghc.html

The HsSyn types
https://gitlab.haskell.org/ghc/ghc/-/wikis/commentary/compiler/hs-syn-type

Renamer:

The renamer
https://gitlab.haskell.org/ghc/ghc/-/wikis/commentary/compiler/renamer

The Name type
https://gitlab.haskell.org/ghc/ghc/-/wikis/commentary/compiler/name-type

Type checker:

The GHC Commentary: Checking Types
https://gitlab.haskell.org/ghc/ghc/-/wikis/commentary/compiler/type-checker

The GHC reading list: Types and type inference
https://gitlab.haskell.org/ghc/ghc/-/wikis/reading-list#types-and-type-inference

References

Desugarer, Core:

Into the Core - Squeezing Haskell into Nine Constructors
https://www.youtube.com/watch?v=uR_VzYxvbxg
https://www.erlang-factory.com/static/upload/media/1488806820775921euc2016intothecoresimonpeytonjones.pdf

The Core type
https://gitlab.haskell.org/ghc/ghc/-/wikis/commentary/compiler/core-syn-type

Core-to-Core optimization pipeline
https://gitlab.haskell.org/ghc/ghc/-/wikis/commentary/compiler/core-to-core-pipeline

System FC, as implemented in GHC
https://gitlab.haskell.org/ghc/ghc/blob/master/docs/core-spec/core-spec.pdf

The GHC reading list: Optimisations
https://gitlab.haskell.org/ghc/ghc/-/wikis/reading-list#optimisations

Haskell to Core: Understanding Haskell Features Through Their Desugaring
https://serokell.io/blog/haskell-to-core

References

STG, Code generator:

Implementing lazy functional languages on stock hardware: the Spineless Tagless G-machine Version 2.5
https://www.microsoft.com/en-us/research/wp-content/uploads/1992/04/spineless-tagless-gmachine.pdf

Making a Fast Curry: Push/Enter vs. Eval/Apply for Higher-order Languages
https://www.microsoft.com/en-us/research/wp-content/uploads/2016/07/eval-apply.pdf

Faster Laziness Using Dynamic Pointer Tagging
https://simonmar.github.io/bib/papers/ptr-tagging.pdf

The STG syntax data types
https://gitlab.haskell.org/ghc/ghc/-/wikis/commentary/compiler/stg-syn-type

I know kung fu: learning STG by example
https://gitlab.haskell.org/ghc/ghc/-/wikis/commentary/compiler/generated-code

Overview of GHC's code generator
https://gitlab.haskell.org/ghc/ghc/-/wikis/commentary/compiler/code-gen/overview

GHC illustrated
https://takenobu-hs.github.io/downloads/haskell_ghc_illustrated.pdf

References

Cmm:

I know kung fu: learning STG by example
https://gitlab.haskell.org/ghc/ghc/-/wikis/commentary/compiler/generated-code

Cmm syntax
https://gitlab.haskell.org/ghc/ghc/-/wikis/commentary/compiler/cmm-syntax

cmm type [outdated]
https://gitlab.haskell.org/ghc/ghc/-/wikis/commentary/compiler/cmm-type

The C-- Language Specification Version 2.0
https://www.cs.tufts.edu/~nr/c--/extern/man2.pdf

Understanding the RealWorld
https://www.well-typed.com/blog/95/

Native/LLVM code generator:

Native Code Generator (NCG) [outdated]
https://gitlab.haskell.org/ghc/ghc/-/wikis/commentary/compiler/backends/ncg

The LLVM backend
https://gitlab.haskell.org/ghc/ghc/-/wikis/commentary/compiler/backends/llvm

Low Level Virtual Machine for Glasgow Haskell Compiler
https://llvm.org/pubs/2009-10-TereiThesis.pdf

Happy haskelling!

Here is the slide: https://github.com/takenobu-hs/haskell-ghc-reading-guide