Kotlin Compiler Reading Notes

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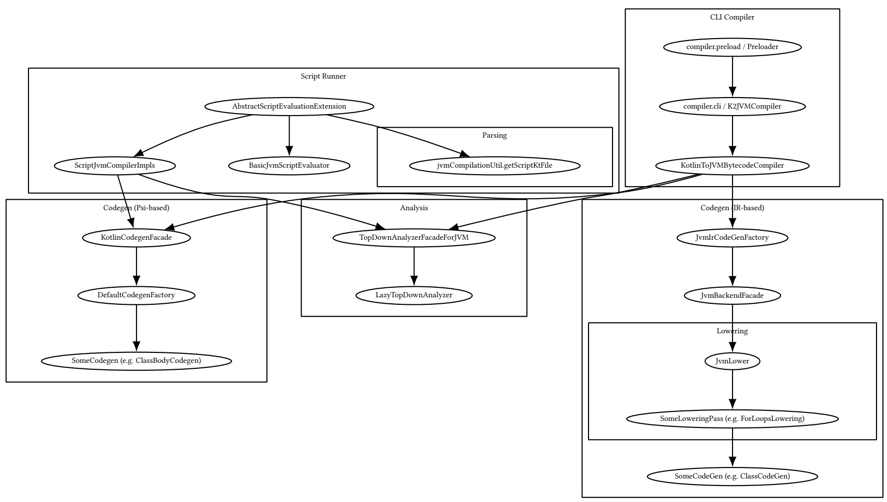
1 Methodology

It's often daunting to read through huge and complex codebase like the Kotlin compiler! Fortunately we have great tools at hand to deal with such complexity. In particular, IntelliJ Idea provides many priceless code navigation tools:

- Type Hierarchy (under Navigate)
- Structure (under View - Tool Windows)
- Find Usage
- Breakpoints

With these we'll be able to understand the compiler architecture and internals bit by bit...



1.1 Building From Source

Once you have the repo checked out, run `./gradlew dist` to build everything. This can take 10-20 minutes. Then you will be able to run tests, compiler.cli.cli-runner (i.e. the script runner), and compiler.preloader (i.e. the CLI compiler loader).

1.2 Tracing Compiler Execution

It's often useful to use the debugger to understand how the compiler pipeline works. This requires the ability to run custom code and to attach a debugger to the compiler process. One trick that I used was to add a local file to the cli-runner package (or compiler.preloader). This allows me to run or debug arbitrary code there while being able to link the code with the compiler. And since these these packages don't actually have source dependency on the whole compiler (only link to the dist jar), rebuilding is quite fast.

Another way is to link your code with a prebuilt compiler (e.g. add dependency "`org.jetbrains.kotlin:kotlin-compiler:1.3.70`"). I can't seem to fetch its sourceJar though...

2 Tl;dr: Pipeline

- Kotlin source
- KtElement (Psi)
- core.descriptor (ClassicTypeSystemContext)
- FirElement (nodes) / FirBasedSymbol (infotable?) (ConeTypeContext)
- IrElement (nodes) / IrSymbol (infotable?) (IrTypeSystemContext)

2.1 Pipeline for `kotlin` Script Runner

Note that the runner uses coroutine in its eval methods and therefore can be hard to trace.

Runner: AbstractScriptEvaluationExtension → ScriptJvmCompilerImpls Parse: jvmCompilationUtil.getScriptKtFile: text-based Kt source → KtFile (Psi-based KtElement) Analysis: TopDownAnalyzerFacadeForJVM → LazyTopDownAnalyzer Codegen (Psi-based): KotlinCodegenFacade → DefaultCodegenFactory → THINGCodegen (e.g. Package / Member / Script / ImplementationBody / ClassBody) Eval: AbstractScriptEvaluationExtension → BasicJvmScriptEvaluator

2.2 Pipeline for `kotlinc` Compiler

Runner: compiler.preloader / Preloader → compiler.cli / K2JVMCompiler → KotlinToJVMBytecodeCompiler (checks IR flag) Parse: Not sure Analysis: KotlinToJVMBytecodeCompiler.analyze → TopDownAnalyzerFacadeForJVM Codegen (Psi-based): KotlinToJVMBytecodeCompiler.generate → KotlinCodegenFacade Lowering (Ir-based): analysis is the same; but ktjvmbcc.generate is different? Uses JvmIrCodeGenFactory with a PhaseConfig. I.e., .generate → JvmIrCodeGenFactory → JvmBackendFacade → JvmLower → CompilerPhase.invokeToplevel(PhaseConfig, JvmBackendContext, IrModuleFragment) → a bunch of abstraction layers around lowering phases → SomeLoweringPass.lower Codegen (Ir-based): JvmBackendFacade → ClassCodeGen (IrFile.declarations should only contain IrClass after lowering) Write: KotlinToJVMBytecodeCompiler.writeOutputs

2.3 Source → KtElement

- See class KtVisitor for an overview of many Kotlin PsiElements
- compiler.psi defines KtElement and Stubs, also provides parser

  - Stubs represents the interface parts of a kt compilation unit (.h, .mli, .hi etc).
  - There's also a LighterASTNNode (KotlinLightParser) – what is it? (Flyweight pattern is like hash consing)
  - Some KtElements are related to types: e.g. KtTypeReference (some of them are not KtElements but stubs!)

- compiler.psi.KtPsiFactory is the entrypoint for creating KtFile (a PsiElement) from source text.

2.4 KtElement $\rightarrow$ DeclarationDescriptor

DeclarationDescriptor seems to be a high-level IR with type analyzed. It contains both the expr tree and the types.

2.4.1 LazyTopDownAnalyzer

compiler.frontend.LazyTopDownAnalyzer seems to be the psi analyzer. (Is there another analyzer that's not lazy?)

analyzeDeclarations returns an AnalysisResult which contains a ModuleDescriptor and a BindingContext.

2.5 DeclarationDescriptor $\rightarrow$ FIR

XXX: Not sure if this step is required or even exists.

FIR (compiler.fir) seems to be an intermediate yet still high-level IR.

- See generated class FirVisitor for an overview of many of the Fir exprs
- compiler.frontend (not sure which step it is in, but it at least does symbol resolution, type checking, (Psi $\rightarrow$ CFG?)
  - See key classes: AnalysisResult, BindingContext, BindingTrace (records the collected binding / type substs?)
- compiler.resolution: tower/ReceiverValue etc
- compiler.fir: cones (types and symbols used in Fir?), fir2ir (lowering to Ir), psi2fir (lowering Psi to Fir), resolve, jvm, tree (Fir definitions and impl for psi2fir)
  - cones: StandardClassIds contains a bunch of core Kt (read: not JVM) type Ids. They have a JVM-like fqname.

    SyntheticCallableId contains when/try/nullcheck synthetic call exprs
  - tree.gen contains all Fir expressions (see tree.tree-generator's readme for how they are generated), as well as extra info (FirTypeRef). And even on Fir level, the generic types are not yet erased (FirTypeProjectionWithVariance)

2.6 FIR $\rightarrow$ IR

XXX: Not sure if this step is required.

2.7 Example stacktrace for running a Kotlin script

E.g. `kotlin -e <expr>`

- CLIDriver
  - compiler.cli / K2JVMCompiler
  - plugins.scripting-compiler
  - compiler.cli / TopDownAnalyzerFacadeForJVM (analyzeFilesWithJavaIntegration)
- Analyzer
  - compiler.frontend / LazyTopDownAnalyzer.analyzeDeclarations
  - (HUGE) go through all stmts
  - BodyResolver.resolveBodies
  - DeclarationChecker.process
  - (HUGE) go through files, annotations, class's modifiers, idents, header (super+generic bounds); function, property, destructionDecl, typealias's modifiers and idents.

3 KtElement

KtFile and KtScript for toplevel decls, KtClass for `class Foo`, KtNamedFunction for `fun foo()`, KtProperty for `val foo`.

4 DeclarationDescriptor

See core.descriptors.DeclarationDescriptorVisitor for an overview.

DeclarationDescriptorVisitor sounds like an type-instantiated/abstracted wrapper of an element. Also has a bunch of annotations (AnnotationDescriptor) and a name. And is also a tree node (has parent: getContainingDecl)

4.1 Survey of Class Hierarchy

Looks that descriptors are something that's used throughout the whole compilation pipeline. They are more often used in frontend, but even in backend I can see some usage of them.

4.1.1 CallableD: VisD & NonRootD & Subst

Receiver types (dispatch / extension), arg types, return types, type params;

Parameter names, names may be unstable/synthesized (e.g. from JVM object code)

Parameter values (See 4.1.6)

Cross ref to overridden methods

UserDataKey<A>: stores typed user data

4.1.2 MemberD: VisD & NonRootD

Has member modifiers: expect / actual / external. And modality: final /sealed / open / abstract.

4.1.3 CallableMemberD: CallableD & MemberD

Kind: decl / delegation / fakeOverride / synthesized (what's the last two?)

4.1.4 ValueD: CallableD

Has a KotlinType.

4.1.5 VarD: ValueD

Has isVar (wat), isLateinit, isConst, and an optional compileTimeInitializer.

4.1.6 ParamD: ValueD

Represents a parameter that can be supplied to a callableD.

ReceiverParamD: ParamD Has a ReceiverValue.

ValueParamD: ParamD & VarD Has a index, hasDefaultValue, varargElementType, isCrossinline / Noinline (why on param?)

4.1.7 VarDWithAccessors

Has optional getter / setter typed VarAccessorD.

4.1.8 FunD: CallableMemberD

initialSignatureD: the initial D before renaming (didn't find SimpleFunctionD.rename)

hiddenToOvercomeSignatureClash: hack to handle corner case signature clash (said see nio.CharBuffer); also hiddenEverywhereBesideSupercalls: see 4.1.9.

Function modifiers: infix/inline/operator/suspend/tailrec

4.1.9 FunDImpl: NonRootDImpl & FunD

Base impl for function modifiers. Setters set the local modifier (mostly happen during conversion from KtElement), while some getters (infix, operator) respect super class methods.

Base impl for substitution (doSubstitute), and substituted value param. Worth reading.

Base impl for initialize.

Only here documents hiddenToOvercomeSignatureClash and hiddenEverywhereBesideSupercalls: former makes the function completely hidden (even in super-call), latter permits super-call and propagates to overriden methods

4.1.10 ConD: FunD

containingD: ClassifierDWithTypeParams (what is this?)

constructedClass: ClassD

4.1.11 ClassConD: ConD

Just a bunch of return type specializations

4.1.12 ClassConDImpl: FunDImpl & ClassConD

Default (`<init>`) or synthesized.

Has a way to calculate dispatchReceiverParam. If inner, init's receiver is outer class instance (Whereas Java's outer class instance is passed as a param. Though in compiled code there's no difference, just at descriptor level they are different.); else null.

CommonizedClassConD: ClassConDImpl ClassConDImpl with source and originalD stripped.

DefaultClassConD: ClassConDImpl Read as (default constructor) of given class, not default implementation of (any class constructor). So this is just the no-param constructor of a class. Its visibility depends on the classD's visibility.

DeserClassConD: ClassConDImpl & DeserCallableMemberD ProtoBuf based deserialized ClassConD. Holds a bunch of TypeTable, NameResolver, ContainerSource etc to help with further deserialization (so this is also in some sense lazy).

JClassConD: ClassConDImpl & JCallableMemberD A Java imported class's constructor. Since this is from JVM object code, it provides property impl of hasStableParamNames / hasSynthesizedParamNames.

enhance() implementation makes a copy with enhanced receiver param and value params.

SamAdapterClass: ClassConDImpl & SamAdapterD<JavaClassConD> A synthetic ClassConD that wraps another ClassConD.

4.2 DFactory

In core.descriptors / resolve.

5 FIR

Front-end IR (not sure what this means), enabled by CommonConfigurationKeys .USE_FIR (This also implies using IR. But use-ir doesn't imply using FIR).

compiler.fir.resolve: ResolutionStage sounds like something pipeline-related

6 IR

IR (compiler.ir) seems to be an lower-level IR. This is an experimental IR that's intended to be used across all Kotlin backends. Also see this writeup.

A sample IR lowering pass can be found here. Looks that the compiler API provides a convenient IrBuilder, and a visitor style IrTransformer.

6.1 Playing with IR

This is enabled by passing `-Xuse-ir` as a CLI option to the compiler. IR backend currently doesn't support the script runner – KotlinToJVMBytecodeCompiler will ignore use-ir on kts files; Also ScriptCodegen calls KotlinTypeMapper.mapType which is not intended to be called with IR backend.

6.2 compiler.ir.tree

IrSymbol definitions. See IrSymbolVisitor for an overview. Looks that they have descriptors attached.

6.3 Phases

compiler.ir.backend.common defines CompilerPhase that's chainable. See PhaseBuilders.kt and JvmLower.kt.

6.4 IrSymbol vs IrElement

IrElement seems to be the implementation part while IrSymbol is more about the declaration part. E.g. IrClassImpl vs IrClassSymbolImpl. The former contain the concrete class members (init, methods) while the latter contains ClassD.

IrSymbol can be bound or not (what does this mean?), has a owner (an IrElement), an IdSignature (what's this?), and visibility (isPublicApi).

7 Type System

7.1 Types

Kotlin compiler uses Marker Interface pattern extensively in type definitions. See TypeSystemContext.kt (KotlinTypeMarker, TypeArgumentMarket etc).

KotlinType is the base class for all types in Kotlin. It has a tycon, list of tyargs, nullability (so nullability is built-in to any type – can this be problematic?). It also has a MemberScope ("what are the members in this type-based namespace?", see 8) and a refine(KotlinTypeRefiner) method.

7.2 core.type-system

type system core (equality, bounds checking etc). However this is more of an interface module – the actual impls are in core.descriptors, fir and ir modules.

7.3 TypeSystemTypeFactoryContext

Contains a bunch of common type factories:

- flexibleType has lower/upper bounds
- simpleType has tycon, tyargs, nullablep
- tyarg has ty and variance
- star has tyarg (why?)
- there's also an error type used in diagnosis

7.4 TypeCheckerProviderContext

- modular axioms (errorType unifiable with all types etc)
- what is a stub type? (Probably PsiStub related?)

7.5 TypeSystemCommonSuperTypesContext

Used to check if two type has common super types, and lowest-common ancestor utils.

typeDepth is a safe overestimation of the depth (from 'Any').

Seems to also be used in Fir.

7.6 TypeSystemInferenceExtensionContext

Inference related.

7.6.1 Questions

- What is a isCapturedTypeConstructor?
- What is a singleBestRepresentative?
- What is a noInferAnnotation?
- What is mayBeTypeVariable?
- What is a defaultType?
- Read impl of isUnit vs isUnitTypeConstructor
- Read impl of createCapturedType
- Read impl of createStubType
- Read impl createEmptySubstitutor, typeSubstitutorByTypeConstructor, safeSubstitute

7.7 TypeSystemContext

- fastCorrespondingSupertypes has no actual impl? (No, it's just that intellij's search functionality fail to find overridden extension methods)
- isCommonFinalClassConstructor is implemented in three (Psi, Fir, Ir) stage's TypeSystemContext:
  - ClassicTypeSystemContext: get ClassDescriptor from TypeConstructor's declarationDescriptor, then check it's final but not (enum or annotation). So the method really checks that the tycon is "final" but is not a uncommon (enum/annotation) class.
  - ConeTypeContext: Does almost the same thing, but also return true if is anonymous object (final by design). Works on FirBasedSymbol (some sort of class infotable?). Check that this is a FirRegularClassSymbol, whose FirRegularClass is final but not uncommon.
  - IrTypeSystemContext: Check this is a IrClassSymbol whose owner is final and not uncommon.

    So basically ClassDescriptor, FirRegularClass and IrClassSymbol.owner are the same thing across three stages.

    Sounds that reading the common implemented methods of these three TySysCtx impl classes would be super helpful to understand the stages.

7.8 Type System for Fir

Read ConeTypeContext

7.9 Type System for Ir

Read IrTypeSystemContext

7.10 compiler.resolution/.inference

Type inference? constraint system, subst, fresh tycon, tyvar etc

7.11 compiler.frontend/.types

TypeIntersector (unify), DeferredType (I guess this is for when inference can't proceed at some first, and will retry when it has more information. Not really fully bidirectional (H-M style) type inference, but an approximation)

7.12 types.expressions

Contains a bunch of KtElement visitors that does type recon/checking:

- ExpressionTypingVisitorDispatcher
- ControlStructureTypingVisitor
- FunctionsTypingVisitor
- BasicExpressionTypingVisitor (constants etc)
  - This actually does a bit of parsing/validation work… e.g. understore on int literals.
  - Also uses ConstantExpressionEvaluator to check for possible compile time constants (this indeed sounds like something a parser would do).
    Folds boolean && and `||`
    Look up simple unary and binary func in OperationsMapGenerated

8 Resolution

Package: compiler.resolution

8.1 Scopes

core.descriptor / ResolutionScope: contains information about what identifier it contributes to a given lookup location. Identifiers have separate namespaces: variable, function, and classifier (type).

compiler.resolution / LexicalScope is a ResolutionScope that has a parent, a ownerD, a LexicalScopeKind (what kind of syntactical structure created this scope?)

8.2 Tower

i.e. ImplicitScopeTower. Some sort of multi-level scopes? Can't understand this part.

9 Analysis

Package: compiler.frontend

9.1 compiler.frontend.LazyTopDownAnalyzer

9.1.1 TopDownAnalysisContext

Stores the toplevel declarations (in typed maps) found during analysis.

9.2 BindingTrace

Has a BindingContext. Is writable. Can record/inquiry KotlinType for a KtElement. Impls: BindingTraceContext and ObservingBindingTrace

9.3 BindingContext

Sounds like a read-only counterpart to the BindingTrace.

9.4 Smartcasting

compiler.frontend smartcasts.DataFlowInfo: bunch of maps to stores the data flow analysis result useful for smart casts.

DataFlowValue: one instance of a value in a dataflow

DataFlowValue.Kind: classify exprs into smart cast enabled, possible, or disabled ones. Quite intuitive.

IdentifierInfo: represents both qualifier and ident name. what is this for?

10 Codegen

There are currently two codegen systems and both target JS, JVM, etc. They differ in the choice of IR.

- The existing production codegen uses KtElement (Psi node) as the IR. JVM codegen lives in compiler.backend / codegen (e.g. ClassBodyCodeGen); JS codegen lives in js.js.translator (e.g. PropertyTranslator).

- The other "experimental" codegen uses compiler.ir as the IR. All targets specific code lives in compiler.ir.backend.TARGET.

10.1 Psi-based Codegen

10.1.1 JVM

ExpressionCodeGen Generates JVM bytecode directly from KtElement. This is a KtVisitor<StackValue[2]>. Has an InstructionAdapter (JVM bytecode emitter).

StackValue Sounds like a helper class to represent operands on the JVM stack. Has a couple subclasses.

ClassBodyCodeGen Generate class body from a KtPureClassOrObject with a ClassDescriptor. Also does bridge generation.

FunctionCodeGen Generate class body from a KtPureClassOrObject with a ClassDescriptor. Also does bridge generation.

10.1.2 JS

e.S. js.js.translator / PropertyTranslator. Looks that it directly translates descriptor + Psi (KtElement) into JS statement / expressions.

Also see FunctionBodyTranslator – takes a FunD and a KtElement (KtDeclWithBody).

10.2 IR-based Codegen

10.2.1 JVM

ClassCodegen Takes an IrClass and generates into a JvmBackendContext.

11 Unsolved Questions

- What is a LazyTypeParameterDescriptor?
- What is a core.descriptors.MemberScope?
- What's the diff between TypeCheckerContext and TypeSystemContext?

Nomenclature

Bridge Kotlin's way (i.e. doesn't require Java 8) of representing default implementation for interfaces in generate code. See compiler.backend-common / impl.kt's code doc.

Commonization Seems to be a klib process to strip source and original information from descriptors. For example see CommonizedClassConD. Maybe this is to reduce storage size for these Ds in klibs?

Con Constructor. Can be either a type constructor, or a value / class constructor like `<init>`

D DeclarationDescriptor or just Descriptor. See the DeclarationDescriptor section

Deser Deserialization. See core.deserialization – The compiler is able to serialize / deserialize descriptors. And it seems to be done lazily – Many deserialized descriptors still hold TypeTable / NameResolver / VersionRequirementTable to help with further deserialization.

FIR "Front-end IR", an intermediate level IR, below KtElement and above IR. See 5.

Fun Function

Impl Implementation

IR Can either be a general term (Intermediate Representation), or specifically Kotlin compiler's new experimental lowlevel IR (see 6).

J Java

Param Parameter

PSI JetBrain's universal parse tree API. See its doc here.

Stub In the context of PSI, this is the interface part of a PSI tree. It's initially calculated from PSI trees and then cached for efficient retrival. See JetBrain's doc.

Subst Substitution, usually in the context of type checking / reconstruction / unification algorithms. See Wikipedia: Unification and nLab: Substitution.

TyCon Type constructor. Basically a type-level function that takes zero or more types, and returns another type. E.g. List is a tycon: ∀ `a, List<a>`

Var Variable

Vis Visibility, as in public / private / internal etc.