26 The Compiler Frontend: Parsing and Type Checking

Compiling source code into executable programs involves a fairly complex set of libraries, linkers, and assemblers. While Dune mostly hides this complexity from you, it's still useful to understand how these pieces work so that you can debug performance problems, or come up with solutions for unusual situations that aren't well handled by existing tools.

OCaml has a strong emphasis on static type safety and rejects source code that doesn't meet its requirements as early as possible. The compiler does this by running the source code through a series of checks and transformations. Each stage performs its job (e.g., type checking, optimization, or code generation) and discards some information from the previous stage. The final native code output is low-level assembly code that doesn't know anything about the OCaml modules or objects that the compiler started with.

In this chapter, we'll cover the following topics:

- An overview of the compiler codebase and the compilation pipeline, and what each stage represents
- Parsing, which goes from raw text to the abstract syntax tree
- PPX's, which further transform the AST
- Type-checking, including module resolution

The details of the remainder of the compilation process, which gets all the way to executable code comes next, in Chapter 27 (The Compiler Backend: Bytecode and Native code).

26.1 An Overview of the Toolchain

The OCaml tools accept textual source code as input, using the filename extensions `.ml` and `.mli` for modules and signatures, respectively. We explained the basics of the build process in Chapter 5 (Files, Modules, and Programs), so we'll assume you've built a few OCaml programs already by this point.

Each source file represents a *compilation unit* that is built separately. The compiler generates intermediate files with different filename extensions to use as it advances through the compilation stages. The linker takes a collection of compiled units and

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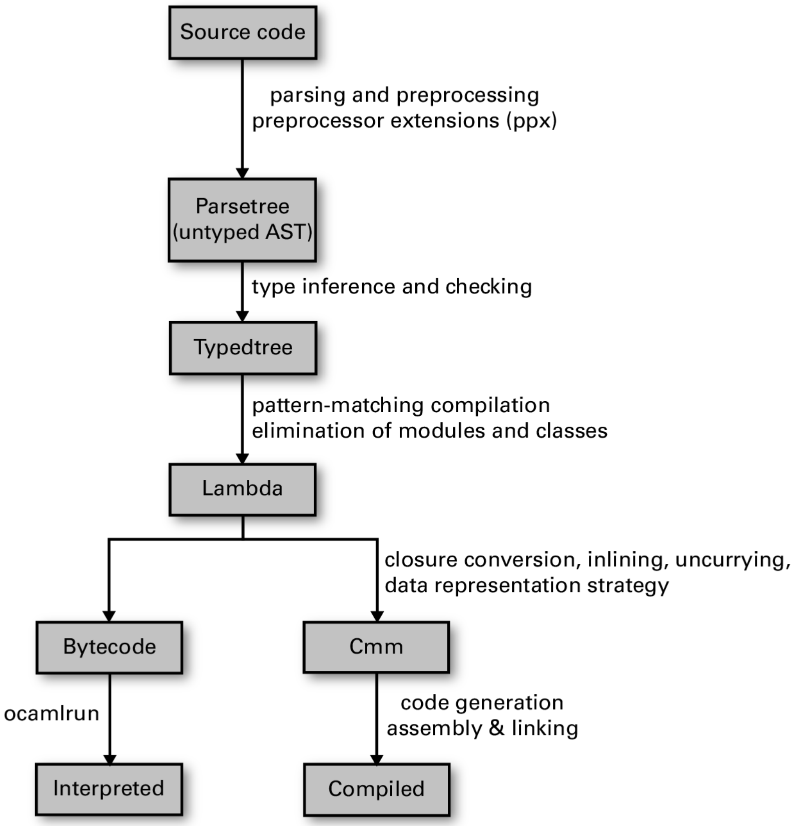
produces a standalone executable or library archive that can be reused by other applications.

The overall compilation pipeline looks like this:


Source code
parsing and preprocessing
preprocessor extensions (ppx)
Parsetree
(untyped AST)
type inference and checking
Typedtree
pattern-matching compilation
elimination of modules and classes
Lambda
closure conversion, inlining, uncurrying,
data representation strategy
Bytecode
Cmm
ocamlrun
code generation
assembly & linking
Interpreted
Compiled

Notice that the pipeline branches toward the end. OCaml has multiple compiler backends that reuse the early stages of compilation but produce very different final outputs. The *bytecode* can be run by a portable interpreter and can even be transformed into JavaScript (via js_of_ocaml[1]) or C source code (via OCamlCC[2]). The *native code* compiler generates specialized executable binaries suitable for high-performance applications.

26.1.1 Obtaining the Compiler Source Code

Although it's not necessary to understand the examples, you may find it useful to have a copy of the OCaml source tree checked out while you read through this chapter. The source code is available from multiple places:

[1] http://ocsigen.org/js_of_ocaml
[2] https://github.com/ocaml-bytes/ocamlcc

- Stable releases as zip and tar archives from the OCaml download site[3]
- A Git repository with all the history and development branches included, browsable online at GitHub[4]

The source tree is split up into subdirectories. The core compiler consists of:

asmcomp/ Native-code compiler that converts OCaml into high performance native code executables.
bytecomp/ Bytecode compiler that converts OCaml into an interpreted executable format.
driver/ Command-line interfaces for the compiler tools.
file_formats/ Serializer and deserializers for on-disk files used by the compiler driver.
lambda/ The lambda conversion pass.
middle_end/ The clambda, closure and flambda passes.
parsing/ The OCaml lexer, parser, and libraries for manipulating them.
runtime/ The runtime library with the garbage collector.
typing/ The static type checking implementation and type definitions.

A number of tools and scripts are also built alongside the core compiler:

debugger/ The interactive bytecode debugger.
toplevel/ Interactive top-level console.
stdlib/ The compiler standard library, including the `Pervasives` module.
otherlibs/ Optional libraries such as the Unix and graphics modules.
tools/ Command-line utilities such as `ocamldep` that are installed with the compiler.
testsuite/ Regression tests for the core compiler.

We'll go through each of the compilation stages now and explain how they will be useful to you during day-to-day OCaml development.

26.2 Parsing Source Code

When a source file is passed to the OCaml compiler, its first task is to parse the text into a more structured abstract syntax tree (AST). The parsing logic is implemented in OCaml itself using the techniques described earlier in Chapter 20 (Parsing with OCamllex and Menhir). The lexer and parser rules can be found in the `parsing` directory in the source distribution.

26.2.1 Syntax Errors

The OCaml parser's goal is to output a well-formed AST data structure to the next phase of compilation, and so it fails on any source code that doesn't match basic syntactic

[3] http://ocaml.org/docs/install.html
[4] https://github.com/ocaml/ocaml

requirements. The compiler emits a *syntax error* in this situation, with a pointer to the filename and line and character number that's as close to the error as possible.

Here's an example syntax error that we obtain by performing a module assignment as a statement instead of as a let binding:

```
let () =
  module MyString = String;
  ()
```

The code results in a syntax error when compiled:

```
$ ocamlc -c broken_module.ml
File "broken_module.ml", line 2, characters 2-8:
2 |   module MyString = String;
      ^^^^^^
Error: Syntax error
[2]
```

The correct version of this source code creates the MyString module correctly via a local open, and compiles successfully:

```
let () =
  let module MyString = String in
  ()
```

The syntax error points to the line and character number of the first token that couldn't be parsed. In the broken example, the module keyword isn't a valid token at that point in parsing, so the error location information is correct.

26.2.2 Generating Documentation from Interfaces

Whitespace and source code comments are removed during parsing and aren't significant in determining the semantics of the program. However, other tools in the OCaml distribution can interpret comments for their own ends.

OCaml uses specially formatted comments in the source code to generate documentation bundles. These comments are combined with the function definitions and signatures, and output as structured documentation in a variety of formats. Tools such as odoc and ocamldoc can generate HTML pages, LaTeX and PDF documents, UNIX manual pages, and even module dependency graphs that can be viewed using Graphviz[5].

Here's a sample of some source code that's been annotated with docstring comments:

```
(** The first special comment of the file is the comment associated
   with the whole module. *)

(** Comment for exception My_exception. *)
exception My_exception of (int -> int) * int

(** Comment for type [weather]  *)
type weather =
  | Rain of int (** The comment for constructor Rain *)
```

[5] http://www.graphviz.org

```
  | Sun         (** The comment for constructor Sun *)

(** Find the current weather for a country
    @author Anil Madhavapeddy
    @param location The country to get the weather for.
*)
let what_is_the_weather_in location =
  match location with
  | `Cambridge  -> Rain 100
  | `New_york   -> Rain 20
  | `California -> Sun
```

The docstrings are distinguished by beginning with the double asterisk. There are formatting conventions for the contents of the comment to mark metadata. For instance, the `@tag` fields mark specific properties such as the author of that section of code.

There are two main tools used to manipulate docstring comments: the `ocamldoc` tool that is supplied with the compiler, and the odoc tool that is developed outside the compiler but is intended to be the long-term replacement. Try compiling the HTML documentation and UNIX man pages by running `ocamldoc` over the source file:

```
$ mkdir -p html man/man3
$ ocamldoc -html -d html doc.ml
$ ocamldoc -man -d man/man3 doc.ml
$ man -M man Doc
```

You should now have HTML files inside the `html/` directory and also be able to view the UNIX manual pages held in `man/man3`. There are quite a few comment formats and options to control the output for the various backends. Refer to the OCaml manual[6] for the complete list.

You can also use odoc to generate complete snapshots of your project via integration with dune, as described earlier in Chapter 22.2.2 (Browsing Interface Documentation).

26.3 Preprocessing with ppx

One powerful feature in OCaml is a facility to extend the standard language via *extension points*. These represent placeholders in the OCaml syntax tree and are ignored by the standard compiler tooling, beyond being delimited and stored in the abstract syntax tree alongside the normal parsed source code. They are intended to be expanded by external tools that select extension nodes that can interpret them. The external tools can choose to generate further OCaml code by transforming the input syntax tree, thus forming the basis of an extensible preprocessor for the language.

There are two primary forms of extension points in OCaml: *attributes* and *extension nodes*. Let's first run through some examples of what they look like, and then see how to use them in your own code.

[6] https://ocaml.org/manual/native.html

26.3.1 Extension Attributes

Attributes supply additional information that is attached to a node in the OCaml syntax tree, and subsequently interpreted and expanded by external tools.

The basic form of an attribute is the `[@ ... ]` syntax. The number of `@` symbols defines which part of the syntax tree the attribute is bound to:

- a single `[@` binds using a postfix notation to algebraic categories such as expressions or individual constructors in type definitions.
- a double `[@@` binds to blocks of code, such as module definitions, type declarations or class fields.
- a triple `[@@@` appears as a standalone entry in a module implementation or signature, and are not tied to any specific source code node.

The OCaml compiler has some useful builtin attributes that we can use to illustrate their use without requiring any external tools. Let's first look at the use of the standalone attribute `@@@warning` to toggle an OCaml compiler warning.

```
# module Abc = struct

  [@@@warning "+non-unit-statement"]
  let a = Sys.get_argv (); ()

  [@@@warning "-non-unit-statement"]
  let b = Sys.get_argv (); ()
  end;;
Line 4, characters 11-26:
Warning 10 [non-unit-statement]: this expression should have type
    unit.
module Abc : sig val a : unit val b : unit end
```

The warning in our example is taken from the compiler manual page[7]. This warning emits a message if the expression in a sequence doesn't have type `unit`. The `@@@warning` nodes in the module implementation cause the compiler to change its behavior within the scope of that structure only.

An annotation can also be more narrowly attached to a block of code. For example, a module implementation can be annotated with `@@deprecated` to indicate that it should not be used in new code:

```
# module Planets = struct
    let earth = true
    let pluto = true
  end [@@deprecated "Sorry, Pluto is no longer a planet. Use the
    Planets2016 module instead."];;
module Planets : sig val earth : bool val pluto : bool end
# module Planets2016 = struct
    let earth = true
    let pluto = false
  end;;
module Planets2016 : sig val earth : bool val pluto : bool end
```

[7] https://ocaml.org/manual/native.html

In this example, the `@@deprecated` annotation is only attached to the `Planets` module, and the human-readable argument string redirects developers to the newer code. Now if we try to use the value that has been marked as deprecated, the compiler will issue a warning.

```
# let is_pluto_a_planet = Planets.pluto;;
Line 1, characters 25-38:
Alert deprecated: module Planets
Sorry, Pluto is no longer a planet. Use the Planets2016 module
    instead.
val is_pluto_a_planet : bool = true
# let is_pluto_a_planet = Planets2016.pluto;;
val is_pluto_a_planet : bool = false
```

Finally, an attribute can also be attached to an individual expression. In the next example, the `@warn_on_literal_pattern` attribute indicates that the argument to the type constructor should not be pattern matched upon with a constant literal.

```
# type program_result =
  | Error of string [@warn_on_literal_pattern]
  | Exit_code of int;;
type program_result = Error of string | Exit_code of int
# let exit_with = function
  | Error "It blew up" -> 1
  | Exit_code code -> code
  | Error _ -> 100;;
Line 2, characters 11-23:
Warning 52 [fragile-literal-pattern]: Code should not depend on the
    actual values of
this constructor's arguments. They are only for information
and may change in future versions. (See manual section 11.5)
val exit_with : program_result -> int = <fun>
```

26.3.2 Commonly Used Extension Attributes

We have already used extension points in Chapter 21 (Data Serialization with S-Expressions) to generate boilerplate code for handling s-expressions. These are introduced by a third-party library using the `(preprocess)` directive in a dune file, for example:

```
(library
 (name hello_world)
 (libraries core)
 (preprocess (pps ppx_jane))
```

This allows you to take advantage of a community of syntax augmentation. There are also a number of builtin attributes in the core OCaml compiler. Some are performance oriented and give directives to the compiler, whereas others will activate usage warnings. The full list is available in the attributes section[8] of the OCaml manual.

[8] https://ocaml.org/manual/attributes.html

26.3.3 Extension Nodes

While extension points are useful for annotating existing source code, we also need a mechanism to store generic placeholders within the OCaml AST for code generation. OCaml provides this facility via the *extension node* syntax.

The general syntax for an extension node is `[%id expr]`, where `id` is an identifier for a particular extension node rewriter and `expr` is the payload for the rewriter to parse. An infix form is also available when the payload is of the same kind of syntax. For example `let%foo bar = 1` is equivalent to `[%foo let bar = 1]`.

We've already seen extension nodes in use via the Core syntax extensions earlier in the book, where they act as syntactic sugar for error handling (`let%bind`), for command-line parsing (`let%map`) or inline testing (`let%expect_test`). Extension nodes are introduced via dune rules in the same fashion as extension attributes, via the `(preprocess)` attribute.

26.4 Static Type Checking

After obtaining a valid abstract syntax tree, the compiler has to verify that the code obeys the rules of the OCaml type system. Code that is syntactically correct but misuses values is rejected with an explanation of the problem.

Although type checking is done in a single pass in OCaml, it actually consists of three distinct steps that happen simultaneously:

automatic type inference An algorithm that calculates types for a module without requiring manual type annotations

module system Combines software components with explicit knowledge of their type signatures

explicit subtyping Checks for objects and polymorphic variants

Automatic type inference lets you write succinct code for a particular task and have the compiler ensure that your use of variables is locally consistent.

Type inference doesn't scale to very large codebases that depend on separate compilation of files. A small change in one module may ripple through thousands of other files and libraries and require all of them to be recompiled. The module system solves this by providing the facility to combine and manipulate explicit type signatures for modules within a large project, and also to reuse them via functors and first-class modules.

Subtyping in OCaml objects is always an explicit operation (via the `:>` operator). This means that it doesn't complicate the core type inference engine and can be tested as a separate concern.

26.4.1 Displaying Inferred Types from the Compiler

We've already seen how you can explore type inference directly from the toplevel. It's also possible to generate type signatures for an entire file by asking the compiler to do the work for you. Create a file with a single type definition and value:

```
type t = Foo | Bar
let v = Foo
```

Now run the compiler with the `-i` flag to infer the type signature for that file. This runs the type checker but doesn't compile the code any further after displaying the interface to the standard output:

```
$ ocamlc -i typedef.ml
type t = Foo | Bar
val v : t
```

The output is the default signature for the module that represents the input file. It's often useful to redirect this output to an `mli` file to give you a starting signature to edit the external interface without having to type it all in by hand.

The compiler stores a compiled version of the interface as a `cmi` file. This interface is either obtained from compiling an `mli` signature file for a module, or by the inferred type if there is only an `ml` implementation present.

The compiler makes sure that your `ml` and `mli` files have compatible signatures. The type checker throws an immediate error if this isn't the case. For example, if you have this as your `ml` file:

```
type t = Foo
```

and this as your `mli`:

```
type t = Bar
```

then, when you try to build, you'll get this error:

```
$ ocamlc -c conflicting_interface.mli conflicting_interface.ml
File "conflicting_interface.ml", line 1:
Error: The implementation conflicting_interface.ml
       does not match the interface conflicting_interface.cmi:
       Type declarations do not match:
         type t = Foo
       is not included in
         type t = Bar
       Constructors number 1 have different names, Foo and Bar.
       File "conflicting_interface.mli", line 1, characters 0-12:
         Expected declaration
       File "conflicting_interface.ml", line 1, characters 0-12:
         Actual declaration
[2]
```

Which Comes First: The ml or the mli?

There are two schools of thought on which order OCaml code should be written in. It's very easy to begin writing code by starting with an `ml` file and using the type inference to guide you as you build up your functions. The `mli` file can then be generated as described, and the exported functions documented.

If you're writing code that spans multiple files, it's sometimes easier to start by writing all the `mli` signatures and checking that they type-check against one another. Once the signatures are in place, you can write the implementations with the confidence that they'll all glue together correctly, with no cyclic dependencies among the modules.

As with any such stylistic debate, you should experiment with which system works best for you. Everyone agrees on one thing though: no matter in what order you write them, production code should always explicitly define an `mli` file for every `ml` file in the project. It's also perfectly fine to have an `mli` file without a corresponding `ml` file if you're only declaring signatures (such as module types).

Signature files provide a place to write succinct documentation and to abstract internal details that shouldn't be exported. Maintaining separate signature files also speeds up incremental compilation in larger code bases, since recompiling a `mli` signature is much faster than a full compilation of the implementation to native code.

26.4.2 Type Inference

Type inference is the process of determining the appropriate types for expressions based on their use. It's a feature that's partially present in many other languages such as Haskell and Scala, but OCaml embeds it as a fundamental feature throughout the core language.

OCaml type inference is based on the Hindley-Milner algorithm, which is notable for its ability to infer the most general type for an expression without requiring any explicit type annotations. The algorithm can deduce multiple types for an expression and has the notion of a *principal type* that is the most general choice from the possible inferences. Manual type annotations can specialize the type explicitly, but the automatic inference selects the most general type unless told otherwise.

OCaml does have some language extensions that strain the limits of principal type inference, but by and large, most programs you write will never *require* annotations (although they sometimes help the compiler produce better error messages).

Adding Type Annotations to Find Errors

It's often said that the hardest part of writing OCaml code is getting past the type checker—but once the code does compile, it works correctly the first time! This is an exaggeration of course, but it can certainly feel true when moving from a dynamically typed language. The OCaml static type system protects you from certain classes of bugs such as memory errors and abstraction violations by rejecting your program at compilation time rather than by generating an error at runtime. Learning how to navigate the type checker's compile-time feedback is key to building robust libraries and applications that take full advantage of these static checks.

There are a couple of tricks to make it easier to quickly locate type errors in your code. The first is to introduce manual type annotations to narrow down the source of your error more accurately. These annotations shouldn’t actually change your types and can be removed once your code is correct. However, they act as anchors to locate errors while you’re still writing your code.

Manual type annotations are particularly useful if you use lots of polymorphic variants or objects. Type inference with row polymorphism can generate some very large signatures, and errors tend to propagate more widely than if you are using more explicitly typed variants or classes.

For instance, consider this broken example that expresses some simple algebraic operations over integers:

```
let rec algebra =
  function
  | `Add (x,y) -> (algebra x) + (algebra y)
  | `Sub (x,y) -> (algebra x) - (algebra y)
  | `Mul (x,y) -> (algebra x) * (algebra y)
  | `Num x     -> x

let _ =
  algebra (
    `Add (
      (`Num 0),
      (`Sub (
          (`Num 1),
          (`Mul (
              (`Nu 3),(`Num 2)
            ))
        ))
    ))
```

There’s a single character typo in the code so that it uses `Nu` instead of `Num`. The resulting type error is impressive:

```
$ ocamlc -c broken_poly.ml
File "broken_poly.ml", lines 9-18, characters 10-6:
 9 | ..........(
10 |     `Add (
11 |       (`Num 0),
12 |       (`Sub (
13 |           (`Num 1),
14 |           (`Mul (
15 |               (`Nu 3),(`Num 2)
16 |             ))
17 |         ))
18 |     ))
Error: This expression has type
         [> `Add of
              ([< `Add of 'a * 'a
                | `Mul of 'a * 'a
                | `Num of int
                | `Sub of 'a * 'a
                > `Num ]
               as 'a) *
              [> `Sub of 'a * [> `Mul of [> `Nu of int ] * [> `Num of
    int ] ]
              ] ]
```

```
       but an expression was expected of type
         [< `Add of 'a * 'a | `Mul of 'a * 'a | `Num of int | `Sub of
    'a * 'a
          > `Num ]
         as 'a
       The second variant type does not allow tag(s) `Nu
[2]
```

The type error is perfectly accurate, but rather verbose and with a line number that doesn't point to the exact location of the incorrect variant name. The best the compiler can do is to point you in the general direction of the algebra function application.

This is because the type checker doesn't have enough information to match the inferred type of the algebra definition to its application a few lines down. It calculates types for both expressions separately, and when they don't match up, outputs the difference as best it can.

Let's see what happens with an explicit type annotation to help the compiler out:

```
type t = [
  | `Add of t * t
  | `Sub of t * t
  | `Mul of t * t
  | `Num of int
]

let rec algebra (x:t) =
  match x with
  | `Add (x,y) -> (algebra x) + (algebra y)
  | `Sub (x,y) -> (algebra x) - (algebra y)
  | `Mul (x,y) -> (algebra x) * (algebra y)
  | `Num x     -> x

let _ =
  algebra (
    `Add (
      (`Num 0),
      (`Sub (
          (`Num 1),
          (`Mul (
              (`Nu 3),(`Num 2)
            ))
        ))
    ))
```

This code contains exactly the same error as before, but we've added a closed type definition of the polymorphic variants, and a type annotation to the algebra definition. The compiler error we get is much more useful now:

```
$ ocamlc -i broken_poly_with_annot.ml
File "broken_poly_with_annot.ml", line 22, characters 14-21:
22 |               (`Nu 3),(`Num 2)
                   ^^^^^^^
Error: This expression has type [> `Nu of int ]
       but an expression was expected of type t
       The second variant type does not allow tag(s) `Nu
[2]
```

This error points directly to the correct line number that contains the typo. Once you fix the problem, you can remove the manual annotations if you prefer more succinct code. You can also leave the annotations there, of course, to help with future refactoring and debugging.

Enforcing Principal Typing

The compiler also has a stricter *principal type checking* mode that is activated via the `-principal` flag. This warns about risky uses of type information to ensure that the type inference has one principal result. A type is considered risky if the success or failure of type inference depends on the order in which subexpressions are typed.

The principality check only affects a few language features:

- Polymorphic methods for objects
- Permuting the order of labeled arguments in a function from their type definition
- Discarding optional labeled arguments
- Generalized algebraic data types (GADTs) present from OCaml 4.0 onward
- Automatic disambiguation of record field and constructor names (since OCaml 4.1)

Here's an example of principality warnings when used with record disambiguation.

```
type s = { foo: int; bar: unit }
type t = { foo: int }

let f x =
  x.bar;
  x.foo
```

Inferring the signature with `-principal` will show you a new warning:

```
$ ocamlc -i -principal non_principal.ml
File "non_principal.ml", line 6, characters 4-7:
6 |   x.foo
        ^^^
Warning 18 [not-principal]: this type-based field disambiguation is
    not principal.
type s = { foo : int; bar : unit; }
type t = { foo : int; }
val f : s -> int
```

This example isn't principal, since the inferred type for `x.foo` is guided by the inferred type of `x.bar`, whereas principal typing requires that each subexpression's type can be calculated independently. If the `x.bar` use is removed from the definition of `f`, its argument would be of type `t` and not `type s`.

You can fix this either by permuting the order of the type declarations, or by adding an explicit type annotation:

```
type s = { foo: int; bar: unit }
type t = { foo: int }

let f (x:s) =
  x.bar;
  x.foo
```

There is now no ambiguity about the inferred types, since we've explicitly given the argument a type, and the order of inference of the subexpressions no longer matters.

```
$ ocamlc -i -principal principal.ml
type s = { foo : int; bar : unit; }
type t = { foo : int; }
val f : s -> int
```

The dune equivalent is to add the flag `-principal` to your build description.

```
(executable
  (name principal)
  (flags :standard -principal)
  (modules principal))

(executable
  (name non_principal)
  (flags :standard -principal)
  (modules non_principal))
```

The `:standard` directive will include all the default flags, and then `-principal` will be appended after those in the compiler build flags.

```
$ dune build principal.exe
$ dune build non_principal.exe
File "non_principal.ml", line 6, characters 4-7:
6 |   x.foo
        ^^^
Error (warning 18 [not-principal]): this type-based field
    disambiguation is not principal.
[1]
```

Ideally, all code should systematically use `-principal`. It reduces variance in type inference and enforces the notion of a single known type. However, there are drawbacks to this mode: type inference is slower, and the `cmi` files become larger. This is generally only a problem if you extensively use objects, which usually have larger type signatures to cover all their methods.

If compiling in principal mode works, it is guaranteed that the program will pass type checking in non-principal mode, too. Bear in mind that the `cmi` files generated in principal mode differ from the default mode. Try to ensure that you compile your whole project with it activated. Getting the files mixed up won't let you violate type safety, but it can result in the type checker failing unexpectedly very occasionally. In this case, just recompile with a clean source tree.

26.4.3 Modules and Separate Compilation

The OCaml module system enables smaller components to be reused effectively in large projects while still retaining all the benefits of static type safety. We covered the basics of using modules earlier in Chapter 5 (Files, Modules, and Programs). The module language that operates over these signatures also extends to functors and first-class modules, described in Chapter 11 (Functors) and Chapter 12 (First-Class Modules), respectively.

This section discusses how the compiler implements them in more detail. Modules are essential for larger projects that consist of many source files (also known as *compilation units*). It's impractical to recompile every single source file when changing just one or two files, and the module system minimizes such recompilation while still encouraging code reuse.

The Mapping Between Files and Modules

Individual compilation units provide a convenient way to break up a big module hierarchy into a collection of files. The relationship between files and modules can be explained directly in terms of the module system.

Create a file called `alice.ml` with the following contents:

```
let friends = [ Bob.name ]
```

and a corresponding signature file:

```
val friends : Bob.t list
```

These two files produce essentially the same result as the following code.

```
module Alice : sig
  val friends : Bob.t list
end = struct
  let friends = [ Bob.name ]
end
```

Defining a Module Search Path

In the preceding example, `Alice` also has a reference to another module `Bob`. For the overall type of `Alice` to be valid, the compiler also needs to check that the `Bob` module contains at least a `Bob.name` value and defines a `Bob.t` type.

The type checker resolves such module references into concrete structures and signatures in order to unify types across module boundaries. It does this by searching a list of directories for a compiled interface file matching that module's name. For example, it will look for `alice.cmi` and `bob.cmi` on the search path and use the first ones it encounters as the interfaces for `Alice` and `Bob`.

The module search path is set by adding `-I` flags to the compiler command line with the directory containing the `cmi` files as the argument. Manually specifying these flags gets complex when you have lots of libraries, and is the reason why tools like `dune` and `ocamlfind` exist. They both automate the process of turning third-party package names and build descriptions into command-line flags that are passed to the compiler command line.

By default, only the current directory and the OCaml standard library will be searched for `cmi` files. The `Stdlib` module from the standard library will also be opened by default in every compilation unit. The standard library location is obtained by running `ocamlc -where` and can be overridden by setting the `CAMLLIB` environment variable. Needless to say, don't override the default path unless you have a good reason to (such as setting up a cross-compilation environment).

Inspecting Compilation Units with ocamlobjinfo

For separate compilation to be sound, we need to ensure that all the `cmi` files used to type-check a module are the same across compilation runs. If they vary, this raises the possibility of two modules checking different type signatures for a common module with the same name. This in turn lets the program completely violate the static type system and can lead to memory corruption and crashes.

OCaml guards against this by recording a MD5 checksum in every `cmi`. Let's examine our earlier `typedef.ml` more closely:

```
$ ocamlc -c typedef.ml
$ ocamlobjinfo typedef.cmi
File typedef.cmi
Unit name: Typedef
Interfaces imported:
    cdd43318ee9dd1b187513a4341737717    Typedef
    9b04ecdc97e5102c1d342892ef7ad9a2    Pervasives
    79ae8c0eb753af6b441fe05456c7970b    CamlinternalFormatBasics
```

`ocamlobjinfo` examines the compiled interface and displays what other compilation units it depends on. In this case, we don't use any external modules other than `Pervasives`. Every module depends on `Pervasives` by default, unless you use the `-nopervasives` flag (this is an advanced use case, and you shouldn't normally need it).

The long alphanumeric identifier beside each module name is a hash calculated from all the types and values exported from that compilation unit. It's used during type-checking and linking to ensure that all of the compilation units have been compiled consistently against one another. A difference in the hashes means that a compilation unit with the same module name may have conflicting type signatures in different modules. The compiler will reject such programs with an error similar to this:

```
$ ocamlc -c foo.ml
File "foo.ml", line 1, characters 0-1:
Error: The files /home/build/bar.cmi
       and /usr/lib/ocaml/map.cmi make inconsistent assumptions
       over interface Map
```

This hash check is very conservative, but ensures that separate compilation remains type-safe all the way up to the final link phase. Your build system should ensure that you never see the preceding error messages, but if you do run into it, just clean out your intermediate files and recompile from scratch.

26.4.4 Wrapping Libraries with Module Aliases

The module-to-file mapping described so far rigidly enforces a 1:1 mapping between a top-level module and a file. It's often convenient to split larger modules into separate files to make editing easier, but still compile them all into a single OCaml module.

Dune provides a very convenient way of doing this for libraries via automatically generating a toplevel *module alias* file that places all the files in a given library as submodules within the toplevel module for that library. This is known as *wrapping* the library, and works as follows.

Let's define a simple library with two files `a.ml` and `b.ml` that each define a single value.

```
let v = "hello"
```

```
let w = 42
```

The dune file defines a library called `hello` that includes these two modules.

```
(library
  (name hello)
  (modules a b))
(executable
  (name test)
  (libraries hello)
  (modules test))
```

If we now build this library, we can look at how dune assembles the modules into a `Hello` library.

```
$ dune build
$ cat _build/default/hello.ml-gen
(** @canonical Hello.A *)
module A = Hello__A


(** @canonical Hello.B *)
module B = Hello__B
```

Dune has generated a `hello.ml` file which forms the toplevel module exposed by the library. It has also renamed the individual modules into internal mangled names such as `Hello__A`, and assigned those internal modules as aliases within the generated `hello.ml` file. This then allows a user of this library to access the values as `Hello.A`. For example, our test executable contains this:

```
let v = Hello.A.v
let w = Hello.B.w
```

One nice aspect about this module alias scheme is that a single toplevel module provides a central place to write documentation about how to use all the submodules exposed by the library. We can manually add a `hello.ml` and `hello.mli` to our library that does exactly this. First add the `hello` module to the dune file:

```
(library
  (name hello)
  (modules a b hello))
(executable
  (name test)
  (libraries hello)
  (modules test))
```

Then the `hello.ml` file contains the module aliases (and any other code you might want to add to the toplevel module).

```
module A = A
module B = B
```

Finally, the hello.mli interface file can reference all the submodules and include documentation strings:

```
(** Documentation for module A *)
module A : sig
  (** [v] is Hello *)
  val v : string
end

(** Documentation for module B *)
module B : sig
  (** [w] is 42 *)
  val w : int
end
```

If you want to disable this behavior of dune and deliberately include multiple toplevel modules, you can add (wrapped false) to your libraries stanza. However, this is discouraged in general due to the increased likelihood of linking clashes when you have a lot of library dependencies, since every module that is linked into an executable must have a unique name in OCaml.

26.4.5 Shorter Module Paths in Type Errors

Core uses the OCaml module system quite extensively to provide a complete replacement standard library. It collects these modules into a single Std module, which provides a single module that needs to be opened to import the replacement modules and functions.

There's one downside to this approach: type errors suddenly get much more verbose. We can see this if you run the vanilla OCaml toplevel (not utop).

```
$ ocaml
# List.map print_endline "";;
Error: This expression has type string but an expression was expected
    of type
         string list
```

This type error without Core has a straightforward type error. When we switch to Core, though, it gets more verbose:

```
$ ocaml
# open Core;;
# List.map ~f:print_endline "";;
Error: This expression has type string but an expression was expected
    of type
         'a Core.List.t = 'a list
```

The default List module in OCaml is overridden by Core.List. The compiler does its best to show the type equivalence, but at the cost of a more verbose error message.

The compiler can remedy this via a so-called short paths heuristic. This causes the compiler to search all the type aliases for the shortest module path and use that as the preferred output type. The option is activated by passing -short-paths to the compiler, and works on the toplevel, too.

```
$ ocaml -short-paths
# open Core;;
# List.map ~f:print_endline "foo";;
Error: This expression has type string but an expression was expected
    of type
        'a list
```

The utop enhanced toplevel activates short paths by default, which is why we have not had to do this before in our interactive examples. However, the compiler doesn't default to the short path heuristic, since there are some situations where the type aliasing information is useful to know, and it would be lost in the error if the shortest module path is always picked.

You'll need to choose for yourself if you prefer short paths or the default behavior in your own projects, and pass the -short-paths flag to the compiler if you need

26.5 The Typed Syntax Tree

When the type checking process has successfully completed, it is combined with the AST to form a *typed abstract syntax tree*. This contains precise location information for every token in the input file, and decorates each token with concrete type information.

The compiler can output this as compiled cmt and cmti files that contain the typed AST for the implementation and signatures of a compilation unit. This is activated by passing the -bin-annot flag to the compiler.

The cmt files are particularly useful for IDE tools to match up OCaml source code at a specific location to the inferred or external types. For example, the merlin and ocaml-lsp-server opam packages both use this information to provide you with tooltips and docstrings within your editor, as described earlier in Chapter 22.2.1 (Using Visual Studio Code).

26.5.1 Examining the Typed Syntax Tree Directly

The compiler has a couple of advanced flags that can dump the raw output of the internal AST representation. You can't depend on these flags to give the same output across compiler revisions, but they are a useful learning tool.

We'll use our toy typedef.ml again:

```
type t = Foo | Bar
let v = Foo
```

Let's first look at the untyped syntax tree that's generated from the parsing phase:

```
$ ocamlc -dparsetree typedef.ml 2>&1
[
  structure_item (typedef.ml[1,0+0]..[1,0+18])
    Pstr_type Rec
```

```
      [
        type_declaration "t" (typedef.ml[1,0+5]..[1,0+6])
      (typedef.ml[1,0+0]..[1,0+18])
          ptype_params =
            []
          ptype_cstrs =
            []
          ptype_kind =
            Ptype_variant
              [
                (typedef.ml[1,0+9]..[1,0+12])
                  "Foo" (typedef.ml[1,0+9]..[1,0+12])
                  []
                  None
                (typedef.ml[1,0+13]..[1,0+18])
                  "Bar" (typedef.ml[1,0+15]..[1,0+18])
                  []
                  None
              ]
          ptype_private = Public
          ptype_manifest =
            None
      ]
    structure_item (typedef.ml[2,19+0]..[2,19+11])
      Pstr_value Nonrec
      [
        <def>
          pattern (typedef.ml[2,19+4]..[2,19+5])
            Ppat_var "v" (typedef.ml[2,19+4]..[2,19+5])
          expression (typedef.ml[2,19+8]..[2,19+11])
            Pexp_construct "Foo" (typedef.ml[2,19+8]..[2,19+11])
            None
      ]
  ]
```

This is rather a lot of output for a simple two-line program, but it shows just how much structure the OCaml parser generates even from a small source file.

Each portion of the AST is decorated with the precise location information (including the filename and character location of the token). This code hasn't been type checked yet, so the raw tokens are all included.

The typed AST that is normally output as a compiled `cmt` file can be displayed in a more developer-readable form via the `-dtypedtree` option:

```
$ ocamlc -dtypedtree typedef.ml 2>&1
[
  structure_item (typedef.ml[1,0+0]..typedef.ml[1,0+18])
    Tstr_type Rec
    [
      type_declaration t/81 (typedef.ml[1,0+0]..typedef.ml[1,0+18])
        ptype_params =
          []
        ptype_cstrs =
          []
        ptype_kind =
          Ttype_variant
```

```
              [
                (typedef.ml[1,0+9]..typedef.ml[1,0+12])
                  Foo/82
                  []
                  None
                (typedef.ml[1,0+13]..typedef.ml[1,0+18])
                  Bar/83
                  []
                  None
              ]
          ptype_private = Public
          ptype_manifest =
            None
      ]
    structure_item (typedef.ml[2,19+0]..typedef.ml[2,19+11])
      Tstr_value Nonrec
      [
        <def>
          pattern (typedef.ml[2,19+4]..typedef.ml[2,19+5])
            Tpat_var "v/84"
          expression (typedef.ml[2,19+8]..typedef.ml[2,19+11])
            Texp_construct "Foo"
            []
      ]
  ]
```

The typed AST is more explicit than the untyped syntax tree. For instance, the type declaration has been given a unique name (`t/1008`), as has the `v` value (`v/1011`).

You'll rarely need to look at this raw output from the compiler unless you're building IDE tools, or are hacking on extensions to the core compiler itself. However, it's useful to know that this intermediate form exists before we delve further into the code generation process next, in Chapter 27 (The Compiler Backend: Bytecode and Native code).

There are several new integrated tools emerging that combine these typed AST files with common editors such as Emacs or Vim. The best of these is Merlin[9], which adds value and module autocompletion, displays inferred types and can build and display errors directly from within your editor. There are instructions available on its homepage for configuring Merlin with your favorite editor, or its bigger sibling `ocaml-lsp-server` is described earlier in Chapter 22.2.1 (Using Visual Studio Code).

[9] https://github.com/def-lkb/merlin