FUN OF PROGRAMMING

the tao produced one
one produced two
two produced three
three produced all things

by

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Work In Progress

Preface

This is a book about hacking in ocaml. It's assumed that you already understand the underlying theory. Happy hacking Most parts are filled with code blocks, I will add some comments in the future. Still a book in progress. Don't distribute it.

☺

Acknowledgements

write later

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Todo list

Chapter 1

Tool Chain

1.1 Ocamlbuild

The reason for `ocamlbuild` in OCaml is to solve the complex scheme to when building camlp4. But it's very useful in other aspects as well.

The building process is done in the `_build` directory. `ocamlbuild` copies the `needed` source files and compiles them. In `_build`, `_log` file contains detailed building process. `ocamlbuild` automatically creates a symbol link to the executable in the current directory. Hygiene rules at start up (*.cmo, .cmi, or .o* should not appear outside of the `_build`). Sometimes when you want to mix c-stubs, you tag the *.o* object file `precious` or `-no-hygiene`

option	comment
-quiet	
-verbose <level>	
-documentation	show rules and flags for a **specific** `_tags` file
-clean	
-r	Traverse directories by default*true:traverse*
-I <path>	
-Is <path,...>	
-X <path>	*ignore* directory
-Xs <path,...>	
-lib <flag>	link to ocaml library *.cma*
-libs <flag,...>	
-mod <module>	link to ocaml module
-mods	
-pkg <package>	link to *ocamlfind package*
-pkgs <...>	
-lflag <flag>	ocamlc link flags
-lflags	
-cflag	ocamlc comple flags
-cflags	
-yaccflag	Add to ocamlyacc flags, you can hack for `menhir`

-yaccflags	
-lexflag	
-lexflags	
-pp	preprocessing flagss
-tag <tag>	add to default tags
-tags	
-show-tags	for *debugging*,`ocamlbuild -show-tags target`
-ignore <module,...>	
-no-hygiene	
-no-plugin	
-just-plugin	just build myocamlbuild.ml
-use-menhir	
-use-jocaml	
-use-ocamlfild	
-build-dir	set *build* directory (implies no-links)
-install-lib-dir <path>	
-install-bin-dir	
-ocamlc <command>	set the ocamlc command
-ocamlopt	
-ocamldoc	
-ocamlyacc	
-menhir	set the menhir tool (use it after -use-menhir)
-ocamllex	
-ocamlmktop	
-ocamlrun	
- -	supply arguments

Table 1.2: OCAMLBUILD FLAGS

The snippet below is a very simple example.

```
ocamlbuild -quiet xx.native -- args
ocamlbuild -quite -use-ocamlfind xx.native -- args
```

You can pass flags to `ocamlc` at compile time. i.e, `-cflags -I,+lablgtk,-rectypes`

You can link with *external* libraries(*.cma*). i.e, `-libs unix,num`. You may need add the options below to make it work if this not in OCaml's default search path `-cflags -I,/usr/local/lib/ocaml -lflags -I,/usr/local/lib/ocaml`

You can also build a library with specicfic modules included using `mllib` file

```
cat top_level.mllib
Dir_top_level_util
Dir_top_level
```

Then you can `ocamlbuild top_level.cma`, then you can use **ocamlobjinfo** to see exactly which modules are compacted into it.

```
ocamlobjinfo _build/top_level.cma | grep Unit
Unit name: Dir_top_level_util
Unit name: Dir_top_level
```

mlpack file

You can alo use `mlpack` file to do hierachical packing

You can also make use of `_tags` file for convenience. Every source tree may have a `_tags` file, and each target may have a set of tags .

```
bash-3.2$ocamlbuild -show-tags test.ml

Tags for "test.ml":
  {. extension:ml, file:test.ml, ocaml, pkg_camlp4.macro, pkg_menhirLib,
     pkg_ulex, predefine_ulex.ml, quiet, syntax_camlp4o, traverse, use_menhir .}

bash-3.2$ ocamlbuild -show-tags test.byte
Tags for "test.byte":
  {. byte, extension:byte, file:test.byte, ocaml, pkg_menhirLib, pkg_ulex,
     program, quiet, traverse, use_menhir .}

bash-3.2$ ocamlbuild -show-tags test.native
Tags for "test.native":
  {. extension:native, file:test.native, native, ocaml, pkg_menhirLib,
     pkg_ulex, program, quiet, traverse, use_menhir .}
```

Listing 1: OCAMLBUILD TAGS

You can digest the output to get a general idea of how tags file work. By preceding a tag with *a minus sign*, one can `remove` tags from one or more files.

The built-in `_tags` file as follows:

```
<**/*.ml>   or <**/*.mli> or <**/*.ml.depends> : ocaml
<**/*.byte> : ocaml, byte, program
<**/*.native>: ocaml, native, program
<**/*.cma>:ocaml, byte,library
<**/*.cmxa>:ocaml,native,library
<**/*.cmo>:ocaml,byte
<**/*.cmx>:ocaml,native
```

Listing 2: OCAMLBUILD DEFAULT TAGS

You can do some experiment do verify it, create a empty directory, and make a dummy ml file, then type `ocamlbuild -show-tags test.ml`, you will get the output as follows

```
Tags for "test.ml": {. extension:ml, file:test.ml, ocaml, quiet .}
```

`<**/*.ml>` means that `.ml` files in *current dir or sub dir*. A special tag made from the path name of the file relative to the toplevel of the project, is automatically defined for each file. Just as above `test.ml` will be tagged `file:test.ml`and also `extension:ml`

multiple directories

Considering multiple directories:

Suppose our directory structure is as follows

```
   |---bar
   |---baz
   |---foo
```

Our tags file is

```
<bar> or <baz> : include
bash-3.2$ cat foo/main.ml
open Printf
let _ = begin
  print_int Barfile.i;
  print_int Bazfile.j;
end
```

Here module `Barfile` and `Bazfile` lies in directries `bar,baz`. So, after typing ocamlbuild in `toplevel directory`, then your directory structure is as follows

```
   |-_build
   |---bar
   |---baz
   |---foo
   |-bar
   |-baz
   |-foo
```

What `ocamlbuild` did is explicit if you read `_log`

```
bash-3.2$ cat _build/_log
### Starting build.
# Target: foo/main.ml.depends, tags: { extension:ml, file:foo/main.ml, ocaml, ocamldep, quiet, traverse }
/opt/godi/bin/ocamldep.opt -modules foo/main.ml > foo/main.ml.depends
# Target: bar/barfile.ml.depends, tags: { extension:ml, file:bar/barfile.ml, ocaml, ocamldep, quiet, traverse }
/opt/godi/bin/ocamldep.opt -modules bar/barfile.ml > bar/barfile.ml.depends
# Target: baz/bazfile.ml.depends, tags: { extension:ml, file:baz/bazfile.ml, ocaml, ocamldep, quiet, traverse }
/opt/godi/bin/ocamldep.opt -modules baz/bazfile.ml > baz/bazfile.ml.depends
# Target: bar/barfile.cmo, tags: { byte, compile, extension:cmo, extension:ml, file:bar/barfile.cmo, file:bar/barfile.ml, implem
/opt/godi/bin/ocamlc.opt -c -I bar -I baz -o bar/barfile.cmo bar/barfile.ml
# Target: baz/bazfile.cmo, tags: { byte, compile, extension:cmo, extension:ml, file:baz/bazfile.cmo, file:baz/bazfile.ml, implem
/opt/godi/bin/ocamlc.opt -c -I baz -I bar -o baz/bazfile.cmo baz/bazfile.ml
# Target: foo/main.cmo, tags: { byte, compile, extension:cmo, extension:ml, file:foo/main.cmo, file:foo/main.ml, implem, ocaml,
/opt/godi/bin/ocamlc.opt -c -I foo -I baz -I bar -o foo/main.cmo foo/main.ml
# Target: foo/main.byte, tags: { byte, dont_link_with, extension:byte, file:foo/main.byte, link, ocaml, program, quiet, traverse
/opt/godi/bin/ocamlc.opt bar/barfile.cmo baz/bazfile.cmo foo/main.cmo -o foo/main.byte
# Compilation successful.
```

So, you can see that `-I` flags was added for each included directory and their source was copied to _build, `foo` was copied was due to our target `foo/main.byte`. They are still *flat* structure actually. Ocamlbuild still views each directory as source directory and do santity check. Each source tree should still be built using ocamlbuild, it's not easy to mix with other build tools. You can add `-I` flags by hand, but the relative path does not work. I did not find a perfect way to mix ocamlbuild with other build tools yet.

grouping targets

You can also group your targets `foo.itarget, foo.otarget`

```
cat foo.itarget
main.native
main.byte
stuff.docdir/index.html
```

Then you can say `ocamlbuild foo.otarget`

For preprocessing either `-pp` or tags `pp(cmd ...)`

For debugging and profiling either `.d.byte, .p.native` or `true:debug`

To build *documentation*, create a file called `foo.odocl`, then write the modules you want to document, then build the target `foo.docdir/index.html`. When you use *-keep-code* flag in myocamlbuild.ml(8), *only* document of exposed modules are kept, not very useful. Add such a line in your `myocamlbuild.ml` plugin

```
flag ["ocaml"; "doc"] & S[A"-keep-code"];
```

Or you can do it by hand

```
|ocamlbuild -ocamldoc 'ocamlfind ocamldoc -keep-code' foo.docdir/index.html
```

`ocamldep` seems to be **lightweight**. It's weird when you have `mli` file, `-keep-code` does not work.

Glob Patterns

With lex yacc, ocamlfind

`.mll .mly` supported by default, you can use menhir `-use-menhir` or add a line `true : use_menhir` Add a line in tags file

```
<*.ml> : pkg_sexplib.syntax, pkg_batteries.syntax, syntax_camlp4o
```

Here `syntax_camlp4o` is translated by myocamlbuild.ml(8) to `-syntax camlp4o` to pass to ocamlfind. Pkg needs **ocamlbuild plugin** support.

Examples with Syntax extension

```
<*.ml>: package(lwt.unix), package(lwt.syntax), syntax(camlp4o) # only needs lwt.syntax when prepossessing
"prog.byte": package(lwt.unix)
```

There are two style to cooperate with syntax extension, one way is above, combined with ocamlfind, in most case it works, but it is not very well considering you want to build `.ml.ppo` and other stuff. The other way is to use `pp` directly, you could simlink

your extension file to `camlp4 -where`. I found this way is more natural. There's another way which is used local(**??**), we will introduce it later.

We can see different styles here.

```
<pa_*r.{ml,cmo,byte}> : pkg_dynlink , pp(camlp4rf ), use_camlp4_full
<*_ulex.{byte,native}> : pkg_ulex
<*_ulex.ml> : syntax_camlp4o,pkg_ulex,pkg_camlp4.macro
<*_r.ml>:syntax_camlp4r,pkg_camlp4.quotations.r,pkg_camlp4.macro,pkg_camlp4.extend
pa_vector_r.ml:syntax_camlp4r,pkg_camlp4.quotations.r,pkg_camlp4.extend,pkg_sexplib.syntax
<pa_vector_r.{cmo,byte,native}>:pkg_dynlink,use_camlp4_full,pkg_sexplib
<*_o.ml> : syntax_camlp4o,pkg_sexplib.syntax
"map_filter_r.ml" : pp(camlp4r -filter map)
"wiki_r.ml" or "wiki2_r.ml"  : pp(camlp4rf -filter meta), use_camlp4_full
"wiki2_r.mli" : use_camlp4_full
```

Actually, you does not need *pp* here, ocamlbuild is smart enough to infer it as *.ml* tag.

The *.mli* file also needs tags. For syntax extension, **order matters**. For more information, check out **camlp4/examples** in the ocaml source tree. When you use `pp` flag, you need to specify the path to `pa_xx.cmo`, so symbol link may help. Since 3.12,, you can use `-use-ocamlfind` to activate. ocamlfind predicates can be activated with the `predicate(...)` tag.

```
<*.ml>: package(lwt.unix), package(lwt.syntax), syntax(camlp4o)
"prog.byte": package(lwt.unix)
```

ocamlbuild cares white space, **take care when write tags file**

1.1.1 Principles

Rules

A rule is composed of triple (Tags, Targets → Dependencies). `ocamlbuild` looks for all rules that are valid for this target. You can set `-verbose 10` to get the backtrace in case of a failure.

Link to Plugin API Documentation

There are 3 stages,(*hygiene*, *options*(parsing the command line options), *rules*(adding the default rules to the system)). You can add hooks to what you want.

```
{Before|After}_{options|hygiene|rules}
```

To change the options, simply refer to the `Options` module.

```
sub_modules "Ocamlbuild_plugin";;
module This_module_name_should_not_be_used :
    module Pathname :
        module Operators :
    module Tags :
        module Operators :
    module Command :
    module Outcome :
    module String :
    module List :
    module StringSet :
    module Options :
    module Arch :
    module Findlib :
```

Here `sub_modules` is a helper function which will be introduced later(some ideas, combined with ocamlgraph and camlp4-parser to generate a graph?).

1.1.2 Write plugin

Useful API: `Pathname.t,Tags.eltstring` List the tags of a file `tags_of_pathname` Tag a file `tag_file` Untag a file `tag_file "x.ml" ["-use_unix"] Arch.print_info`

```
rule;;
- : string ->
    ?tags:string list ->
    ?prods:string list ->
    ?deps:string list ->
    ?prod:string ->
    ?dep:string ->
    ?stamp:string ->
    ?insert:[ `after of string | `before of string | `bottom | `top ] ->
    Ocamlbuild_plugin.action -> unit
= <fun>
```

The first argument is the name of the rule(unique required), `~dep` is the dependency, `~prod` is the production. For example with

`~dep:"%.ml" ~prod:"%.byte"`

you can produce “bla.byte” from “bal.ml”. There are some predefined commands such as Unix commands(cp,mv,...).

```
flag ["ocaml"; "compile"; "thread"'] (A "-thread")
```

Listing 3: OCAMLBUILD plugin sample

It says when tags `ocaml, compile, thread` are met together, `-thread` option should be emitted.

```
(** module Command *)
type t =
  |Seq of t list
  (* A sequence of commands (like the ';' in shell) *)
  |Cmd of spec
  (* A command is made of command specifications (spec) *)
  |Echo of string list * pathname
  (* Write the given strings (w/ any formatting) to the given file *)
  |Nop
  (*The type t provides some basic combinators and command
    primitives. Other commands can be made of command specifications
    (spec).*)
type spec =
  |N (*No operation.        *)
  |S of spec list(* A sequence. This gets flattened in the last stages*)
  |A of string        (* An atom.*)
  |P of pathname(* A pathname.*)
  |Px of pathname
  (* A pathname, that will also be given to the call_with_target
     hook. *)
  |Sh of string
  (* A bit of raw shell code, that will not be escaped. *)
  |T of tags
  (* A set of tags, that describe properties and some semantics
     information about the command, afterward these tags will be replaced
     by command specs (flags for instance). *)
  |V of string
  (* A virtual command, that will be resolved at execution using
     resolve_virtuals *)
  |Quote of spec
  (* A string that should be quoted like a filename but isn't really
   one. *)
```

Listing 4: Command module interface

`module Options` contains refs to be configured

```
module type OPTIONS = sig
  type command_spec
```

```
val build_dir : string ref
val include_dirs : string list ref
val exclude_dirs : string list ref
val nothing_should_be_rebuilt : bool ref
val ocamlc : command_spec ref
val ocamlopt : command_spec ref
val ocamldep : command_spec ref
val ocamldoc : command_spec ref
val ocamlyacc : command_spec ref
val ocamllex : command_spec ref
val ocamlrun : command_spec ref
val ocamlmklib : command_spec ref
val ocamlmktop : command_spec ref
val hygiene : bool ref
val sanitize : bool ref
val sanitization_script : string ref
val ignore_auto : bool ref
val plugin : bool ref
val just_plugin : bool ref
val native_plugin : bool ref
val make_links : bool ref
val nostdlib : bool ref
val program_to_execute : bool ref
val must_clean : bool ref
val catch_errors : bool ref
val use_menhir : bool ref
val show_documentation : bool ref
val recursive : bool ref
val use_ocamlfind : bool ref

val targets : string list ref
val ocaml_libs : string list ref
val ocaml_mods : string list ref
val ocaml_pkgs : string list ref
val ocaml_cflags : string list ref
val ocaml_lflags : string list ref
val ocaml_ppflags : string list ref
val ocaml_yaccflags : string list ref
val ocaml_lexflags : string list ref
val program_args : string list ref
val ignore_list : string list ref
val tags : string list ref
val tag_lines : string list ref
val show_tags : string list ref

val ext_obj : string ref
```

```
  val ext_lib : string ref
  val ext_dll : string ref
  val exe : string ref

  val add : string * Arg.spec * string -> unit
end
```

Listing 5: Options module interface

Samples

Some Examples

```
open Ocamlbuild_plugin;;
open Command;;

let alphaCaml = A"alphaCaml";;

dispatch begin function
  | After_rules ->
      rule "alphaCaml: mla -> ml & mli"
        ~prods:["%.ml"; "%.mli"]
        ~dep:"%.mla"
        begin fun env _build ->
          Cmd(S[alphaCaml; P(env "%.mla")])
        end
  | _ -> ()
end
(**
   Extra efforts:
   The pointed directory contains the compiled files (.cmo, .cmi).
   $ ln -s /path/to/your/alphaCaml/directory/ alphaLib
   $ cat _tags
   "alphaLib": include, precious
   it's very nice to make the whole directory precious, this is a way to mix
   # different buiding unit.
 *)
```

Listing 6: Using αcaml

```
open Ocamlbuild_plugin;;
open Command;;
dispatch begin function
  | After_rules ->
      (* Add pa_openin.cmo to the ocaml pre-processor when use_opening is set *)
```

```
      flag ["ocaml"; "pp"; "use_openin"] (A"pa_openin.cmo");
      (* Running ocamldep on ocaml code that is tagged with use_openin will require
         the cmo.  Note that you only need this declaration when the syntax extension
         is part of the  sources to be compiled with ocamlbuild. *)
      dep ["ocaml"; "ocamldep"; "use_openin"] ["pa_openin.cmo"];
  | _ -> ()
end;;
```

```
"bar.ml": camlp4o, use_openin
<foo/*.ml> or <baz/**/*.ml>: camlp4r, use_openin
"pa_openin.ml": use_camlp4, camlp4o
```

```
open Ocamlbuild_plugin
open Unix
let version = "1.4.2+dev"
let time =
  let tm = Unix.gmtime (Unix.time ()) in
  Printf.sprintf "%02d/%02d/%04d %02d:%02d:%02d UTC"
    (tm.tm_mon + 1) tm.tm_mday (tm.tm_year + 1900)
    tm.tm_hour tm.tm_min tm.tm_sec
let make_version _ _ =
  let cmd =
    Printf.sprintf "let version = %S\n\
                    let compile_time = %S"
      version time  in
  (** Add a command *)
  Cmd (S [ A "echo"; Quote (Sh cmd); Sh ">"; P "version.ml" ])

let () = dispatch begin function
  | After_rules ->
      rule "version.ml" ~prod: "version.ml" make_version
  | _ -> ()
end
```

Listing 7: Ejecting Shell Command

```
open Ocamlbuild_plugin
let () =
  dispatch begin function
  | After_rules ->
    dep ["myfile"] ["other.ml"]
  | _ -> ()
  end
```

Listing 8: Add dependency

Mixing with C stubs

My point is that tag your c code precious, then mv it into _build directory. Then link it by hand.

```
_tags:
<single_write.o> : precious
Makefile:
_build/single_write.o: single_write.o
        test -d $(LIB) || mkdir $(LIB)
        cp single_write.o $(LIB)
# tag single_write.o precious
write.cma:  _build/single_write.o write.cmo
        cd $(LIB); ocamlc -custom -a -o single_write.o write.cmo
```

There's built in support, solution is:

```
    dep ["link"; "ocaml"; "use_plus_stubs"] ["plus_stubs.o"];
    flag["link"; "ocaml"; "byte"] (S[A"-custom"]);
```

OCamlbuild can invoke gcc to do the building process. The tags file is like this

```
<plus.{byte,native}> : use_plus_stubs
```

Notice that `-custom` is only for byte link, native link will link it by default. You can also enrich your *runtime* without linking to each byte file everytime.

```
  ocamlc -make-runtime -o new_ocamlrun progc.o a_c_library.a
  ocamlc -o vbcname.exe -use-runtime new_ocamlrun progocaml.cmo
```

Instead of new runtime, you can also build a toplevlel linking c functions

```
  ocamlmktop -custom -o ftop progc.o a_c_library.a ex.ml
```

So you see, you have 4 choices, enrich enriovment, toplevel, bytecode, native code

Another typical `myocamlbuild.ml` plugin.

1.1.3 OCamlbuild in the toplevel

```
#directory "+ocamlbuild";;
#load "ocamlbuildlib.cma";;
open Ocamlbuild_plugin
open Command
```

Now you can do a lot of amazing things in the toplevel and write complex plugin system.

1.1.4 Building interface files

```
<ppo.{cmo,mli}> : use_camlp4
```

Take care, Tags *.cmi* file does not make sense , tag *.mli* file

```
# Target: ppo.cmi, tags: { byte, compile, extension:mli, file:ppo.mli, interf, ocaml, quiet, traverse, use_camlp4 }
ocamlfind ocamlc -annot -c -I +camlp4 -o ppo.cmi ppo.mli
```

Interaction with Git

```
_log
_build
*.native
*.byte
*.d.native
*.p.byte
```

1.2 Godi,otags

1.2.1 CheatSheet

```
godi_make makesum
godi_make  install
godi_console info #installed software
godi_console list

godi_add ~/SourceCode/ML/godi/build/packages/All/godi-calendar-2.03.tgz
godi_console perform -build godi-ocaml-graphics  >.log 2 >1
godi_console perform (fetch, extract, patch, configure, build, install)
```

Listing 9: godi command

```
otags -r -q -a -o ~/tags/ocaml/TAGS /dest/to/your/source
```

Listing 10: otags command

1.3 Ocamlfind

Link to findlib

1.3.1 CheatSheet

```
\emph{ocamlfind browser -all } open documentation in ocamlbrowser
\emph{ocamlfind browser -package batteries}
```

Syntax extension support

```
ocamlfind ocamldep -package camlp4,xstrp4 -syntax camlp4r file1.ml file2.ml
```

ocamlfind can only handle flag `camlp4r`, `camlp4o`, so if you want to use other extensions, use -package camlp4,xstrp4, i.e. -package camlp4.macro

1.3.2 META file

```
name="toplevel"
description = "toplevel hacking"
requires = ""
archive(byte) = "dir_top_level.cmo"
archive(native) = "dir_top_level.cmx"
version = "0.1"
```

A simple Makefile for ocamlfind

```
all:
	@ocamlfind install toplevel META _build/*.cm[oxi]
clean:
	@ocamlfind remove toplevel
```

1.4 toplevel

1.4.1 directives

```
#directory ``_build'';;
#diretory ``+camlp4'';;
#load ``*.cma'';;
#trace fib;;
#labels false;;  # ignore labels in function types
#print_depth n;;
#print_length n;;
#warnings ``warning-list'';;
```

1.4.2 Module toploop

```
val run_script: Format.formatter -> string -> string array -> bool
val getvalue: string -> Obj.t
val directive_table:(string,directive_fun) Hashtbl.t
val print_exception_outcome : Format.formatter -> exn -> unit
val execute_phrase :
bool->formatter->Parsetree.toplevel_phrase->bool
val use_file : Format.formatter -> string -> bool
(** use_silently, parse_use_file *)
val print_value : Env.t -> Obj.t -> formatter ->
Types.type_expr ->  unit
```

Listing 11: module Toploop

```
input_name;;
val print_out_value : (formatter -> out_value -> unit) ref ;;
print_out_type  : (formatter -> out_type -> unit) ref ;;
print_out_class_type : (formatter -> out_class_type -> unit) ref ;;
print_out_module_type : (formatter -> out_module_type -> unit) ref;;
print_out_sig_item : (formatter -> out_sig_item -> unit) ref ;;
print_out_phrase : (formatter -> out_phrase -> unit) ref ;;
read_interactive_input :  (string -> string -> int -> int * bool)  ref;;
toplevel_startup_hook : (unit -> unit) ref
```

Listing 12: listing

module Toploop configurable refs

```
Toploop.run_script Format.std_formatter "test.ml" [|"ocaml"|];;
```

Listing 13: listing

Hacking Toploop sample

You can easily update directive table according to the source code we get. Here we get another parser, from ocaml-source *parsing* compared with camlp4.

```
dir_load
dir_use
dir_install_printer
dir_trace
dir_untrace
dir_untrace_all
dir_quit
dir_cd
load_file : Format.formatter -> string -> bool  (** using Dynlink internal*)
```

Listing 14: Module Topdirs

We can be more *flexible* without using directives using functions directly.

1.4.3 Env

```
    let env = !Toploop.toplevel_env
    (* ... blabbla ...     *)
    Toploop.toplevel_env := env
```

Listing 15: store toplevel env

```
    Toploop.initialize_toplevel_env ()
```

Listing 16: Clear toplevel

```
let exec_test s =
  let l = Lexing.from_string s in
  let ph = !Toploop.parse_toplevel_phrase l in
  let fmt = Format.make_formatter (fun _ _ _ -> ()) (fun _ -> ()) in
  try
    Toploop.execute_phrase false fmt ph
  with
      _ -> false
in
if not(exec_test "Topfind.reset;;") then (
  Topdirs.dir_load Format.err_formatter "/Users/bob/SourceCode/ML/godi/lib/ocaml/pkg-lib/findlib/findlib.cma";
  Topdirs.dir_load Format.err_formatter "/Users/bob/SourceCode/ML/godi/lib/ocaml/pkg-lib/findlib/findlib_top.cma";
);;
```

Listing 17: Hacking toploop sample from findlib

You can refer *Topfind.ml* for more. You can grep a module like this, but now, you can also use *otags*

```
se;;
- : ?ignore_module:bool -> (string -> bool) -> string -> string list =
se ~ignore_module:false (FILTER _*  "char" space* "->" space* "bool") "String";;
```

```
Hashtbl.add
    Toploop.directive_table
    "require"
    (Toploop.Directive_string
       (fun s ->
          protect load_deeply (Fl_split.in_words s)
       ))
;;
Hashtbl.add Toploop.directive_table "pwd"
(Toploop.Directive_none (fun _ ->
  print_endline (Sys.getcwd ())));;
#pwd;;
```

1.5 Ocamldoc

A special comment is associated to an element if it is placed before or after the element.

A special comment before an element is associated to this element if :

There is no blank line or another special comment between the special comment and the element. However, a regular comment can occur between the special comment and the element.

The special comment is not already associated to the previous element.

The special comment is not the first one of a toplevel module. A special comment after an element is associated to this element if there is no blank line or comment between the special comment and the element.

There are two exceptions: for type constructors and record fields in type definitions, the associated comment can only be placed after the constructor or field definition, without blank lines or other comments between them. The special comment for a type constructor with another type constructor following must be placed before the '|' character separating the two constructors.

Some elements support only a subset of all @-tags. Tags that are not relevant to the documented element are simply ignored. For instance, all tags are ignored when documenting type constructors, record fields, and class inheritance clauses. Similarly, a `@param` tag on a class instance variable is ignored

Markup language

```
text ::= (text_element)+
text_element ::=
| {[0-9]+ text}format text as a section header; the integer following
{ indicates the sectioning level.
  | {[0-9]+:label text} same, but also associate the name label to the
  current point. This point can be referenced by its fully-qualified
  label in a {! command, just like any other element.
    | {b text}set text in bold.
    | {i text}set text in italic.
    | {e text}emphasize text.
    | {C text}center text.
    | {L text}left align text.
    | {R text}right align text.
    | {ul list}build a list.
    | {ol list}build an enumerated list.
    | {{:string}text}put a link to the given address (given as a
    string) on the given text.
```

```
    | [string]set the given string in source code style.
    | {[string]}set the given string in preformatted source code
    style.
    | {v string v}set the given string in verbatim style.
    | {% string %}take the given string as raw LATEX code.
      | {!string}insert a reference to the element named
      string. string must be a fully qualified element name, for
      example Foo.Bar.t. The kind of the referenced element can be
      forced (useful when various elements have the same qualified
      name) with the following syntax: {!kind: Foo.Bar.t} where kind
      can be module, modtype, class, classtype, val, type, exception,
      attribute, method or section.
      | {!modules: string string ...}insert an index table for the
      given module names. Used in HTML only.
      | {!indexlist}insert a table of links to the various indexes
      (types, values, modules, ...). Used in HTML only.
      | {^ text}set text in superscript.
      | {_ text}set text in subscript.
      | escaped_stringtypeset the given string as is; special
      characters ('{', '}', '[', ']' and '@') must beescaped by a '\'
      | blank_lineforce a new line.

list ::=
  | ({- text})+
  | ({li text})+
```

Predefined tags

The folowing table gives the list of predefined @-tags, with their syntax and meaning. @author stringThe author of the element. One author by @author tag. There may be several @author tags for the same element.

@deprecated textThe text should describe when the element was deprecated, what to use as a replacement, and possibly the reason for deprecation.

@param id textAssociate the given description (text) to the given parameter name id. This tag is used for functions, methods, classes and functors.

@raise Exc textExplain that the element may raise the exception Exc.

@return textDescribe the return value and its possible values. This tag is used for functions and methods.

@see <url> textAdd a reference to the URL between '<' and '>' with the given text as comment.

@see 'filename' textAdd a reference to the given file name (written between single quotes), with the given text as comment.

@see “document name” textAdd a reference to the given document name (written between double quotes), with the given text as comment.

@since stringIndicate when the element was introduced.

@before v textAssociate the given description (text) to the given version v in order to document compatibility issues.

@version string: The version number for the element.

1.6 ocamlmktop

```
ocamlmktop -o or -I +camlp4 dynlink.cma camlp4rf.cma
```

1.7 Standard OCaml Develop Tools

ocaml	toplevel top
ocamlrun	bytecode interpreter
ocamlc	bytecode batch compiler
ocamlopt	native code batch compiler
ocamlc.opt	*optimized* bytecode batch compiler
ocamlopt.opt	*optimized* native code batch compiler
ocamlmktop	new *toplevel* constructor

Table 1.3: Ocaml Compiler Tools

The optimized compilers are themselves compiled with the Objective Caml native compiler. They compile *faster* but are otherwise *identical* to their unoptimized counterparts.

Compilation Unit For the interactive system, the unit of compilation corresponds to a phrase of the language. For the batch compiler, the unit of compilation is two files: the source file, and the interface file. The *compiled interface* is used for both the bytecode and native code compiler.

extension	meaning
.ml	source
.mli	interface
.cmi	compiled interface
.cmo	object file (byte)
.cma	library object file(bytecode)
.cmx	object file (native)
.cmxa	library object file(native)
.c	c source
.o	c object file (native)
.a	c library object file (native)

Table 1.4: ocaml file name extension

-a	construct a runtime library
-annot	save information in <filename>.annot
-c	compile *without* linking
-o name_of_executabular	specify the name of the executabular
-linkall	link with *all* libraries used
-i	*display all* compiled global declarations, generate .mli file
-pp	preprocessor
-unsafe	*turn off* index checking
-v	display version
-w list	choose among the list the level of warning message
-impl file	indicate that *file* is a caml source(.ml)
-intf file	as a caml interface(.mli)
-I dir	add directory in the list of directories
-thread	light process
-g, -noassert	linking with debug information
-custom, -cclib, -ccopt, -cc	standalone executeblel
-make-runtime, -use-runtime	runtime
-output-obj	output a c object file instead of an executable
-vmthread	VM-level thread support
-dparsetree	generate the parse output
-drawlambda	s-expression
-dlambda	s-experssion
-dinstr	generate asm

Table 1.5: ocamlc options

A/a	enable/disable all messages
F/f	partial application in a sequence
P/p	incomplete pattern matching
U/u	missing cases in pattern matching
X/x	enable/disable all other messages
M/m and V/v	for hidden object

Table 1.6: warning option

About warning messages (Table 1.6) , the compiler chooses the **(A)** by default. turn off some warnings sometimes is helpful, for example

```
ocamlbuild -cflags -w,aPF top_level.cma
```

-compact	optimize the produced code for space
-S	keeps the assembly code in a file
-inline level	set the aggressiveness of inlining
-S	keep assembly output

Table 1.7: ocamlopt option

-I dir	adds the directory
-unsafe	no bounds checking

Table 1.8: toplevel option

1.8 ocamlmktop

OCAMLMKTOP(Table 1.8) is ofen used for *pulling native object* code libraries(typically written in C) into a new toplevel. *-cclib libname, -ccopt optioin, -custom, -I dir -o exectuable*

For example:

```
ocamlmktop -custom -o mytoplevel graphics.cma \
   -cclib -I/usr/X11/lib -cclib -lX11
```

This *standalone* exe(-custom) wil be *linked* to the library X11(libX11.a) which in turn will be looked up in the path */usr/X11/lib*

A standalone exe is a program that *does not* depend on OCaml installation to run. The OCaml *native* compiler produces standalone executabulars by default. But *without -custom* option, the *bytecode* compiler produces an executabular which requires the *bytecode interpreter ocamlrun*

```
ocamlc test.ml -o a
ocamlc -custom test.ml -o b
-rwxr-xr-x   1 bob  staff    12225 Dec 23 16:31 a
-rwxr-xr-x   1 bob  staff   198804 Dec 23 16:31 b
```

You can see the size of `b`with the ocamlrun is way more bigger than `a`

```
bash-3.2$ cat a | head -n 1
#!/Users/bob/SourceCode/ML/godi/bin/ocamlrun
```

Without *-custom*, it depends on *ocamlrun*. With *-custom*, it contains the *Zinc* interpreter as well as the program bytecode, this file can be executed directly or copied to another machien(using the same CPU/Operating System). Still, the inclusion of machine code means that stand-alone executalbes are not protabular to other systems or other architectures.

Optimization It is necessary to not create *intermediate closures* in the case of application on several arguments. For example, when the function *add* is applied with two integers, it is not useful to create the first closure corresponding to the function of applying add to the first argument. It is necessary to note that the creation of a closure would *allocate* certain memory space for the environment and would require the recovery of that memory space in the future. *Automatic memory recovery* is the second major performance concern, along with environment.

1.9 Git

- ignore set

  ```
  _log _build *.native *.byte *.d.native *.p.byte
  ```

Chapter 2

Lexing

2.1 Lexing

Ulex support**unicode**, while ocamllex don't, the tags file is as follows

```
$ cat tags
<*_ulex.ml> : syntax_camlp4o,pkg_ulex
<*_ulex.{byte,native}> : pkg_ulex
```

Use default myocamlbuild.ml, like `ln -s ~/myocamlbuild.ml` and make a symbol link `pa_ulex.cma` to camlp4 directory,this is actually not necessary but sometimes for `debugging purpose`, as follows, this is pretty easy `camlp4o pa_ulex.cma -printer OCaml test_ulex`. So, you should do symbol link and write a very simple plugin like this

```
let _ =
  (** customize your plugin here *)
  let plugin = (fun _ -> begin
    (fun _ -> flag ["ocaml"; "pp"; "use_ulex"] (A"pa_ulex.cma")) +> after_rules;
  end
  )  in
  apply plugin
```

And your tags file should be like this

```
<test1.ml> : camlp4o, use_ulex
<test1.{cmo,byte,native}> : pkg_ulex
```

You can analyze the `_build/_log` to know how it works.

```
### Starting build.
# Target: test1.ml.depends, tags: { camlp4o, extension:ml,
# file:test1.ml, ocaml, ocamldep, quiet, traverse, use_ulex }
ocamlfind ocamldep -pp 'camlp4o pa_ulex.cma' -modules test1.ml >
# test1.ml.depends # cached
```

The nice thing is that you can `ocamlbuild test1.pp.ml` directly to view the source. A nice feature.

Ulex does not support `as` syntax as ocamllex. Its extended syntax is like this:

```
let regexp number = ['0'-'9'] +
let regexp line = [^'\n']* ('\n' ?)
let u8l = Ulexing.utf8_lexeme
let rec lexer1 arg1 arg2 .. = lexer
   |regexp -> action |..
and lexer2 arg1 arg2 .. = lexer
   |regexp -> action |...
```

Roll back

Ulexing.rollback lexbuf, so for string lexing, you can rollback one char, and *plugin your string lexer*, but *not generally usefull*, ulex *does not support shortest mode yet*. Sometimes the semantics of rolling back is not what you want as recursive descent parser.

Abstraction with macro package

Since you need inline to do macro prepossessing, so use syntax extension macro to **inline** your code,

```
<*_ulex.ml> : syntax_camlp4o,pkg_ulex,pkg_camlp4.macro
<*_ulex.{byte,native}> : pkg_ulex
```

Attention! Since you use ocamlbuild to build, then you need to copy you include files to `_build` if you use relative path in **INCLUDE** macro, otherwise you should use absolute path.

You can predefine some regexps (copied from ocaml source code) `parsing/lexer.ml`.

You can also use myocamlbuild plugin to write a dependency to avoid all these problems. But I am not sure which is one is better, copy paste or using `INCLUDE` macro. Maybe we are over-engineering.

2.1.1 Ulex interface

Roughly equivalent to the module Lexing, except that its lexbuffers handles Unicode code points OCaml type `int` in the range `0.. 0x10ffff` instead of bytes (OCamltype : `char`).

You can customize implementation for lex buffers, define a module L which implements *start,next,mark, and backtrack and the Error exception*. They need not work on a type named lexbuf, you can use the type name you want. Then, just do in your *ulex-processed* source, before the first lexer specification `module Ulexing = L` If you inspect the processed output by camlp4, you can see that the generated code *introducing Ulexing* very *late* and actually use very limited functions, other functions are just provided for your convenience, and it did not have any type annotations, so you really can customize it. I think probably ocamllex can do the similar trick.

```
(** Runtime support for lexers generated by [ulex].
  This module is roughly equivalent to the module Lexing from
  the OCaml standard library, except that its lexbuffers handles
  Unicode code points (OCaml type: [int] in the range
  [0..0x10ffff]) instead of bytes (OCaml type: [char]).

  It is possible to have ulex-generated lexers work on a custom
  implementation for lex buffers. To do this, define a module [L] which
  implements the [start], [next], [mark] and [backtrack] functions
  (See the Internal Interface section below for a specification),
  and the [Error] exception.
  They need not work on a type named [lexbuf]: you can use the type
  name you want. Then, just do in your ulex-processed source, before
  the first lexer specification:

  [module Ulexing = L]

  Of course, you'll probably want to define functions like [lexeme]
  to be used in the lexers semantic actions.
*)

type lexbuf
  (** The type of lexer buffers. A lexer buffer is the argument passed
    to the scanning functions defined by the generated lexers.
    The lexer buffer holds the internal information for the
    scanners, including the code points of the token currently scanned,
    its position from the beginning of the input stream,
    and the current position of the lexer. *)

exception Error
  (** Raised by a lexer when it cannot parse a token from the lexbuf.
    The functions [Ulexing.lexeme_start] (resp. [Ulexing.lexeme_end]) can be
    used to find to positions of the first code point of the current
    matched substring (resp. the first code point that yield the error). *)
```

```
exception InvalidCodepoint of int
  (** Raised by some functions to signal that some code point is not
    compatible with a specified encoding. *)

(** {6 Clients interface} *)

val create: (int array -> int -> int -> int) -> lexbuf
  (** Create a generic lexer buffer.  When the lexer needs more
    characters, it will call the given function, giving it an array of
    integers [a], a position [pos] and a code point count [n].  The
    function should put [n] code points or less in [a], starting at
    position [pos], and return the number of characters provided. A
    return value of 0 means end of input. *)

val from_stream: int Stream.t -> lexbuf
  (** Create a lexbuf from a stream of Unicode code points. *)

val from_int_array: int array -> lexbuf
  (** Create a lexbuf from an array of Unicode code points. *)

val from_latin1_stream: char Stream.t -> lexbuf
  (** Create a lexbuf from a Latin1 encoded stream (ie a stream
    of Unicode code points in the range [0..255]) *)

val from_latin1_channel: in_channel -> lexbuf
  (** Create a lexbuf from a Latin1 encoded input channel.
    The client is responsible for closing the channel. *)

val from_latin1_string: string -> lexbuf
  (** Create a lexbuf from a Latin1 encoded string. *)

val from_utf8_stream: char Stream.t -> lexbuf
  (** Create a lexbuf from a UTF-8 encoded stream. *)

val from_utf8_channel: in_channel -> lexbuf
  (** Create a lexbuf from a UTF-8 encoded input channel. *)

val from_utf8_string: string -> lexbuf
  (** Create a lexbuf from a UTF-8 encoded string. *)

type enc = Ascii | Latin1 | Utf8
val from_var_enc_stream: enc ref -> char Stream.t -> lexbuf
  (** Create a lexbuf from a stream whose encoding is subject
    to change during lexing. The reference can be changed at any point.
    Note that bytes that have been consumed by the lexer buffer
    are not re-interpreted with the new encoding.
```

```
    In [Ascii] mode, non-ASCII bytes (ie [>127]) in the stream
    raise an [InvalidCodepoint] exception. *)

val from_var_enc_string: enc ref -> string -> lexbuf
  (** Same as [Ulexing.from_var_enc_stream] with a string as input. *)

val from_var_enc_channel: enc ref -> in_channel -> lexbuf
  (** Same as [Ulexing.from_var_enc_stream] with a channel as input. *)

(** {6 Interface for lexers semantic actions} *)

(** The following functions can be called from the semantic actions of
  lexer definitions.  They give access to the character string matched
  by the regular expression associated with the semantic action. These
  functions must be applied to the argument [lexbuf], which, in the
  code generated by [ulex], is bound to the lexer buffer passed to the
  parsing function.

  These functions can also be called when capturing a [Ulexing.Error]
  exception to retrieve the problematic string. *)

val lexeme_start: lexbuf -> int
  (** [Ulexing.lexeme_start lexbuf] returns the offset in the
    input stream of the first code point of the matched string.
    The first code point of the stream has offset 0. *)

val lexeme_end: lexbuf -> int
(** [Ulexing.lexeme_end lexbuf] returns the offset in the input stream
   of the character following the last code point of the matched
   string. The first character of the stream has offset 0. *)

val loc: lexbuf -> int * int
(** [Ulexing.loc lexbuf] returns the pair
  [(Ulexing.lexeme_start lexbuf,Ulexing.lexeme_end lexbuf)]. *)

val lexeme_length: lexbuf -> int
(** [Ulexing.loc lexbuf] returns the difference
  [(Ulexing.lexeme_end lexbuf) - (Ulexing.lexeme_start lexbuf)],
  that is, the length (in code points) of the matched string. *)

val lexeme: lexbuf -> int array
(** [Ulexing.lexeme lexbuf] returns the string matched by
  the regular expression as an array of Unicode code point. *)

val get_buf: lexbuf -> int array
  (** Direct access to the internal buffer. *)
```

```
val get_start: lexbuf -> int
  (** Direct access to the starting position of the lexeme in the
      internal buffer. *)
val get_pos: lexbuf -> int
  (** Direct access to the current position (end of lexeme) in the
      internal buffer. *)

val lexeme_char: lexbuf -> int -> int
  (** [Ulexing.lexeme_char lexbuf pos] returns code point number [pos] in
      the matched string. *)

val sub_lexeme: lexbuf -> int -> int -> int array
(** [Ulexing.lexeme lexbuf pos len] returns a substring of the string
  matched by the regular expression as an array of Unicode code point. *)


val latin1_lexeme: lexbuf -> string
(** As [Ulexing.lexeme] with a result encoded in Latin1.
  This function throws an exception [InvalidCodepoint] if it is not possible
  to encode the result in Latin1. *)

val latin1_sub_lexeme: lexbuf -> int -> int -> string
(** As [Ulexing.sub_lexeme] with a result encoded in Latin1.
  This function throws an exception [InvalidCodepoint] if it is not possible
  to encode the result in Latin1. *)

val latin1_lexeme_char: lexbuf -> int -> char
(** As [Ulexing.lexeme_char] with a result encoded in Latin1.
  This function throws an exception [InvalidCodepoint] if it is not possible
  to encode the result in Latin1. *)


val utf8_lexeme: lexbuf -> string
(** As [Ulexing.lexeme] with a result encoded in UTF-8. *)

val utf8_sub_lexeme: lexbuf -> int -> int -> string
(** As [Ulexing.sub_lexeme] with a result encoded in UTF-8. *)


val rollback: lexbuf -> unit
(** [Ulexing.rollback lexbuf] puts [lexbuf] back in its configuration before
  the last lexeme was matched. It is then possible to use another
  lexer to parse the same characters again. The other functions
  above in this section should not be used in the semantic action
  after a call to [Ulexing.rollback]. *)

(** {6 Internal interface} *)
```

```
(** These functions are used internally by the lexers. They could be used
  to write lexers by hand, or with a lexer generator different from
  [ulex]. The lexer buffers have a unique internal slot that can store
  an integer. They also store a "backtrack" position.
*)

val start: lexbuf -> unit
(** [Ulexing.start lexbuf] informs the lexer buffer that any
  code points until the current position can be discarded.
  The current position become the "start" position as returned
  by [Ulexing.lexeme_start]. Moreover, the internal slot is set to
  [-1] and the backtrack position is set to the current position.
*)

val next: lexbuf -> int
(** [Ulexing.next lexbuf next] extracts the next code point from the
  lexer buffer and increments to current position. If the input stream
  is exhausted, the function returns [-1]. *)

val mark: lexbuf -> int -> unit
(** [Ulexing.mark lexbuf i] stores the integer [i] in the internal
  slot. The backtrack position is set to the current position. *)

val backtrack: lexbuf -> int
(** [Ulexing.backtrack lexbuf] returns the value stored in the
  internal slot of the buffer, and performs backtracking
  (the current position is set to the value of the backtrack position). *)
```

Ulex does not handle line position, you have only global char position, but we are using emacs, not matter too much

ATTENTION

When you use ulex to generate the code, make sure to write the interface by yourself, the problem is that when you use the default interface, it will generate `__table__`, and different file may overlap this name, when you open the module, it will cause a disaster, so the best to do is **write your .mli** file.

And when you write lexer, make sure you write the default branch, check the generated code, otherwise its behavior is weird.

```
camlp4of -parser macro pa_ulex.cma test_calc.ml -printer o
or
ocamlbuild basic_ulex.pp.ml
```

A basic Example

Here is the example of simple basic lexer

```
open Ulexing
open BatPervasives
let regexp op_ar = ['+' '-' '*' '/']
let regexp op_bool = ['!' '&' '|']
let regexp rel = ['=' '<' '>']


(** get string output, not int array *)
let lexeme = Ulexing.utf8_lexeme

let rec basic = lexer
  | [' '] -> basic lexbuf
  | op_ar | op_bool ->
    let ar = lexeme lexbuf in
    `Lsymbol ar
  | "<=" | ">="| "<>" | rel ->
    `Lsymbol (lexeme lexbuf)
  |("REM" | "LET" | "PRINT"
       | "INPUT" | "IF"| "THEN") ->
    `Lsymbol (lexeme lexbuf)
  | '-'?['0'-'9']+ ->
    `Lint (int_of_string (lexeme lexbuf))
  | ['A'-'z']+ ->
    `Lident (lexeme lexbuf)
  | '"' [^ '"'] '"' ->
    `Lstring (let s = lexeme lexbuf in
              String.sub s 1 (String.length s - 2))
  | eof -> raise End_of_file
  | _ ->
    (print_endline (lexeme lexbuf ^ "unrecognized");
    basic lexbuf)

let token_of_string str =
  str
  |> Stream.of_string
  |> from_utf8_stream
  |> basic
let tokens_of_string str =
  let output = ref [] in
  let lexbuf = str |> Stream.of_string |> from_utf8_stream in
  (try
    while true do
    let token = basic lexbuf in
    output:= token :: !output;
```

```
    print_endline (dump token)
    done
  with End_of_file -> ());
  List.rev (!output)
```

parser-help to coordinate menhir and ulex

```
let _ = tokens_of_string
  "a + b >= 3 > 3 < xx"
```

Notice that `ocamlnet` provides a fast `Ulexing module`, probably you can change its interal representation.

I have written a helper package to make lexer more available

2.2 Ocamlllex

ocamllex

1. *module Lexing*

```
se_str "from" "Lexing";;
```

```
val from_string : string -> lexbuf
val from_function : (string -> int -> int) -> lexbuf
val from_input : BatIO.input -> Lexing.lexbuf
val from_channel : BatIO.input -> Lexing.lexbuf
```

2. syntax

```
{header}
let ident = regexp ...
rule entrypoint [arg1 .. argn ] =
   parse regexp {action }
   | ..
   | regexp {action}
and entrypoint [arg1 .. argn] =
   parse ..
and ...
{trailer}
```

The parse keyword can be replaced by shortest keyword.

Typically, the header section contains the *open* directives required by the actions

All identifiers starting with `__ocaml_lex` are reserved for use by **ocamllex**

3. example for me, best practice is put some test code in the trailer part, and use *ocamlbuild fc_lexer.byte* – to verify, or write a makefile. you can write several indifferent rule in a file using and.

```
(* verbatim translate *)
rule translate = parse
  | "current_directory" {print_string (Sys.getcwd ()); translate lexbuf}
  | _ as c {print_char c ; translate lexbuf}
  | eof {exit 0}

{
```

```
  let _ =
    let chan = open_in "fc_lexer.mll" in begin
    translate (Lexing.from_channel chan );
    close_in chan
    end

}
```

```
Legacy.Printexc.print;;
- : ('a -> 'b) -> 'a -> 'b = <fun>
```

4. caveat

   the longest(shortest) win, then consider the order of each regexp later. Actions are evaluated after the *lexbuf* is bound to the current lexer buffer and the identifier following the keyword *as* to the matched string.

5. position

   The lexing engine manages only the *pos_cnum* field of *lexbuf.lex_curr_p* with the number of chars read from the start of lexbuf. you are responsible for the other fields to be accurate. i.e.

```
let incr_linenum lexbuf = Lexing.(
    let pos = lexbuf.lex_curr_p in
    lexbuf.lex_curr_p <- { pos with
      pos_lnum = pos.pos_lnum + 1; (* line number *)
     pos_bol = pos.pos_cnum; (* the offset of the beginning of the
     line *)
    })
```

6. combine with ocamlyacc

   normally just add *open Parse* in the header, and use the token defined in *Parse*

7. tips

   (a) keyword table

```
    {let keyword_table = Hashtbl.create 72
     let _ = ...
    }
    rule token = parse
    | ['A'-'z' 'a'-'z'] ['A'-'z' 'A'-'z' '0'-'9' '_'] * as id
```

```
    {try Hashtbl.find keyword_table id with Not_found -> IDENT id}
    | ...
```

(b) for sharing **why ocamllex sucks**
some complex regexps are not easy to write, like string, but sharing is hard. To my knowledge, cpp preprocessor is fit for this task here. camlp4 is not fit, it will check other syntax, if you use ulex, camlp4 will do this job. So, my Makefile is part like this

```
lexer :
  cpp fc_lexer.mll.bak > fc_lexer.mll
  ocamlbuild -no-hygiene fc_lexer.byte --
```

even so, sharing is still very hard, since the built in compiler used another way to write string lexing. painful too sharing. so ulex wins in both aspects. sharing in ulex is much easier.

Chapter 3

Parsing

3.1 Ocamlyacc

We mainly cover menhir here.

A grammar is mainly composed of four elements(terminals, non-terminals, production rulls, start symbol)

Syntax

```
% {header
% }
%%
Grammar rules
%%
trailer
```

A tiny example as follows (It has a subtle bug, readers should find it)

```
% {
  open Printf
  let parse_error s =
    print_endline "error\
    print_endline s ;
    flush stdout
%}

%token <float> NUM
%token PLUS MINUS MULTIPLY
%token NEWLINE

%start input
%type <unit> input
%type <float> exp
%% /* rules and actions */

input: /* empty */ {}
    | input line {}
;

line: NEWLINE {}
    |exp NEWLINE  {printf
;

exp: NUM { $1 }
    |exp exp PLUS {$1 +.
    |exp exp MINUS {$1 -.
    |exp exp MULTIPLY {$1
    |exp exp DIVIDE {$1 /
    |exp exp CARET {$1 **
    |exp UMINUS {-. $1 }
;

%%
```

Notice that start non-terminal can be given *several*, then you will have a different .mli file, notice that it's different from ocamllex, ocamlyacc will generate a .mli file, so here we get the output interface as follows:

```
%type <type> nonterminal ... nonterminal
%start symbol ... symbol
```

```
type token =
  | NUM of (float)
  | PLUS
  | MINUS
  | MULTIPLY
  | DIVIDE
  | CARET
  | UMINUS
  | NEWLINE
val input :
  (Lexing.lexbuf  -> token) -> Lexing.lexbuf -> unit
val exp :
  (Lexing.lexbuf  -> token) -> Lexing.lexbuf -> float
```

Notice that we may use character strings as implicit terminals as in

```
expr : expr "+" expr {}
     | expr "*" expr {}
     | ... ;
```

They are directly processed by the parser without passing through the lexer. But it breaks the uniformity

Contextual Grammar

```
open Batteries

(**
   Grammar
   L := w C w
   w := (A|B)*
*)
type token = A |B |C

let rec parser1 = parser
  | [< 'A ; l = parser1 >] -> (parser [< 'A>] -> "a") :: l
  | [< 'B ; l = parser1 >] -> (parser [< 'B>] -> "b") :: l
  | [<>] -> []  (* always succeed *)
let parser2 lst str =
  List.fold_left (fun s p -> p str ^ s) ""  lst
let parser_L = parser
  | [< ls = parser1 ; 'C; r = parser2 ls >] ->
    r
let _ =
  [A;B;A;B;C;A;B;A;B]
  |>  Stream.of_list
  |>  parser_L
  |> print_endline
```

```
(* let a = *)
(*   let open A in *)
(*   let a = 3 in *)
(*   let b = 3 in *)
(*   let d = 3 in *)
(*   d *)

let a=
  let open Pervasives in
  let c = 5 in
  c
```

First gammar

```
1  /* empty corresponds Ctrl-d.*/
2  input : /*empty*/ {} | input line {};
```

Notice here we **preferred left-recursive** in yacc. The underlying theory for LALR prefers LR. because all the elements must be shifted onto the stack *before* the rule can be applied even once.

```
1  exp : NUM | exp exp PLUS | exp exp MINUS  ... ;
```

Here is our lexer

```
{
  open Rpcalc
  open Printf
  let first = ref true
}
let digit = ['0'-'9']
rule token = parse
  |[' ' '\t' ] {token lexbuf}
  |'\n' {NEWLINE}
  | (digit+ | "." digit+ | digit+ "." digit*) as num
      {NUM (float_of_string num)}
  |'+' {PLUS}
  |'-' {MINUS}
  |'*' {MULTIPLY}
  |'/' {DIVIDE}
  |'^' {CARET}
  |'n' {UMINUS}
  |_ as c  {printf "unrecognized char %c" c ; token lexbuf}
  |eof {
    if !first then begin first := false; NEWLINE end
    else raise End_of_file }

{
  let main ()  =
    let file = Sys.argv.(1) in
    let chan = open_in file in
    try
      let lexbuf = Lexing.from_channel chan in
      while true do
        Rpcalc.input token lexbuf
      done
    with End_of_file -> close_in chan

 let _ = Printexc.print main ()

}
```

We write driver function in lexer for convenience, since lexer depends on yacc. *Printex.print*

precedence associatitvity

Operator precedence is determined by the line ordering of the declarations;

%prec in the grammar section, the *%prec* simply instructs ocamlyacc that the rule */Minus exp* has the same precedence as NEG *%left,%right,%nonassoc*

1. The associatitvity of an operator op determines how repeated uses of the operator nest: whether x *op* y *op* z is parsed by grouping x with y or. nonassoc will consider it as an error

2. All the tokens declared in a single precedence declaration have equal precedence and nest together according to their associatitvity

```
%{
  open Printf
  open Lexing
  let parse_error s =
    print_endline "impossible happend! panic \n";
    print_endline s ;
    flush stdout
%}

%token NEWLINE
%token LPAREN RPAREN
%token <float> NUM
%token PLUS MINUS MULTIPLY DIVIDE CARET


%left PLUS MINUS MULTIPLY DIVIDE NEG
%right CARET

%start input
%start exp
%type <unit> input
%type <float> exp

%% /* rules and actions */


input: /* empty */ {}
    | input line {}
;

line: NEWLINE {}
    |exp NEWLINE  {printf "\t%.10g\n" $1 ; flush stdout}
;

exp: NUM { $1 }
    | exp PLUS exp                { $1 +. $3 }
    | exp MINUS exp                { $1 -. $3 }
    | exp MULTIPLY exp                { $1 *. $3 }
```

```
    | exp DIVIDE exp                { $1 /. $3 }
    | MINUS exp %prec NEG        { -. $2 }
    | exp CARET exp                 { $1 ** $3 }
    | LPAREN exp RPAREN                { $2 }
;

%%
```

Notice here the *NEG* is a place a holder, it takes the place, but it's not a token. since here we need *MINUS* has different levels.

Error Recovery

By default, the parser function raises exception after calling *parse_error* The ocamlyacc reserved word *error*

```
line: NEWLINE |exp NEWLINE | error NEWLINE {}
```

If an expression that cannot be evaluated is read, the error will be recognized by the third rule for line, and parsing will continue (parse_error is still called). This form of error recovery deals with syntax errors. There are also other kinds of errors.

Location Tracking

It's very easy. First, remember to use *Lexing.new_line* to track your line number, then use *rhs_start_pos, rhs_end_pos* to track the symbolposition. 1 is for the leftmost component.

```
            Parsing.(
              let start_pos = rhs_start_pos 3 in
              let end_pos = rhs_end_pos 3 in
              printf "%d.%d --- %d.%d: dbz"
                start_pos.pos_lnum (start_pos.pos_cnum -start_pos.pos_bol)
                end_pos.pos_lnum (end_pos.pos_cnum - end_pos.pos_bol);
              1.0
            )
```

For groupings, use the following function *symbol_start_pos, symbol_end_pos*

symbol_start_pos is set to the beginning of the leftmost component, and *symbol_end_pos* to the end of the rightmost component.

A complex Example

```
%{
```

```
  open Printf
  open Lexing
  let parse_error s =
    print_endline "impossible happend! panic \n";
    print_endline s ;
    flush stdout
  let var_table = Hashtbl.create 16
%}


%token NEWLINE
%token LPAREN RPAREN EQ
%token <float> NUM
%token PLUS MINUS MULTIPLY DIVIDE CARET
%token <string> VAR
%token <float->float>FNCT /* built in function */

%left PLUS MINUS
%left MULTIPLY DIVIDE
%left NEG

%right CARET
%start input
%start exp
%type <unit> input
%type <float> exp

%% /* rules and actions */


input: /* empty */ {}
    | input line {}
;

line: NEWLINE {}
    |exp NEWLINE  {printf "\t%.10g\n" $1 ; flush stdout}
    |error NEWLINE {}
;

exp: NUM { $1 }
    | VAR
        {try Hashtbl.find var_table $1
          with Not_found ->
            printf "unbound value '%s'\n" $1;
            0.0
        }
    | VAR EQ exp
```

```
        {Hashtbl.replace var_table $1 $3; $3}
    | FNCT LPAREN exp RPAREN
        { $1 $3 }
    | exp PLUS exp                { $1 +. $3 }
    | exp MINUS exp               { $1 -. $3 }
    | exp MULTIPLY exp               { $1 *. $3 }
    | exp DIVIDE exp
        { if $3 <> 0. then $1 /. $3
          else
            Parsing.(
              let start_pos = rhs_start_pos 3 in
              let end_pos = rhs_end_pos 3 in
              printf "%d.%d --- %d.%d: dbz"
                start_pos.pos_lnum (start_pos.pos_cnum -start_pos.pos_bol)
                end_pos.pos_lnum (end_pos.pos_cnum - end_pos.pos_bol);
              1.0
            )}
    | MINUS exp %prec NEG        { -. $2 }
    | exp CARET exp                { $1 ** $3 }
    | LPAREN exp RPAREN               { $2 }
;

%%



(** lexer file *)
{
  open Rpcalc
  open Printf
  let first = ref true
}


let digit = ['0'-'9']
let id = ['a'-'z']+
rule token = parse
  |[' ' '\t' ] {token lexbuf}
  |'\n' {Lexing.new_line lexbuf ; NEWLINE}
  | (digit+ | "." digit+ | digit+ "." digit*) as num
      {NUM (float_of_string num)}
  |'+' {PLUS}
  |'-' {MINUS}
  |'*' {MULTIPLY}
  |'/' {DIVIDE}
  |'^' {CARET}
  |'(' {LPAREN}
```

```
  |')' {RPAREN}
  |"sin" {FNCT(sin)}
  |"cos" {FNCT(cos) }
  |id as x {VAR x}
  |'=' {EQ}
  |_ as c  {printf "unrecognized char %c" c ; token lexbuf}
  |eof {
    if !first then begin first := false; NEWLINE end
    else raise End_of_file }


{
  let main ()  =
    let file = Sys.argv.(1) in
    let chan = open_in file in
    try
      let lexbuf = Lexing.from_channel chan in
      while true do
        Rpcalc.input token lexbuf
      done
    with End_of_file -> close_in chan

 let _ = Printexc.print main ()

}
```

In my opinion, the best practice is first modify .mly file, then change .mll file later

SHIFT REDUCE

A very nice tutorial shift-reduce

```
%token ID COMMA COLON
%token BOGUS /* NEVER LEX */
%start def
%type <unit>def
%%
def:    param_spec return_spec COMMA {}
        ;
param_spec:  ty {}
        |    name_list COLON ty {}
        ;

/*
return_spec:
             ty {}
        |    name COLON ty {}
```

```
        |    ID BOGUS {}   // This rule is never used
        ;
*/

/* another way to fix the prob */

return_spec : ty {}
        | ID COLON ty {}

ty:        ID {}
        ;
name:        ID {}
        ;
name_list:
              name {}
        |    name COMMA name_list {}
        ;




%{
%}


%token OPAREN CPAREN ID SEMIC DOT INT EQUAL

%start stmt
%type <int> stmt

%%
stmt: methodcall {0} | arrayasgn {0}
;

/*
previous
methodcall: target OPAREN CPAREN SEMIC {0}
;
target:  ID DOT ID {0} |ID {0}
;

our strategy was to remove the "extraneous" non-terminal in the
methodcall production, by moving one of the right-hand sides of target
to the methodcall production

*/
```

```
methodcall: target OPAREN CPAREN SEMIC {0} | ID OPAREN CPAREN SEMIC {0}
;
target:  ID DOT ID {0}
;
arrayasgn: ID OPAREN  INT CPAREN EQUAL INT SEMIC {0}
;




  %{
%}

%token RETURN ID SEMI EQ PLUS

%start methodbody
%type <unit> methodbody

%%

methodbody: stmtlist RETURN ID {}
;
/*
stmtlist: stmt stmtlist {} | stmt {}
;
the strategy here is simple, we use left-recursion instead of
right-recursion
*/

stmtlist: stmtlist stmt {} | stmt {}
;

stmt: RETURN ID SEMI {} | ID EQ ID PLUS ID {}
;

%{

%}

%token PLUS TIMES ID LPAREN RPAREN


%left PLUS
%left TIMES /* weird ocamlyacc can not detect typo TIMEs */

/*
here we add assiocaitivity and precedence
```

```
*/

%start expr
%type <unit> expr


%%

expr: expr PLUS expr {}
  | expr TIMES expr {}
  | ID {}
  | LPAREN expr RPAREN {}
;



%{

%}

%token ID EQ LPAREN RPAREN IF ELSE THEN


%nonassoc THEN
%nonassoc ELSE

/*
here we used a nice trick to
handle such ambiguity. set precedence of THEN, ELSE
both needed
*/

%start stmt
%type <unit> stmt

%%


stmt: ID EQ ID {}
  | IF LPAREN ID RPAREN THEN stmt {}
  | IF LPAREN ID RPAREN THEN stmt ELSE stmt {}


;
/*
It's tricky here we modify the grammar an unambiguous one
*/
```

```
/*
stmt      : matched {}
          | unmatched {}
          ;

matched   : IF '(' ID ')' matched ELSE matched {}
          ;

unmatched : IF '(' ID ')' matched {}
          | IF '(' ID ')' unmatched {}
          | IF '(' ID ')' matched ELSE unmatched {}
          ;
*/
%%
```

The prec trick is covered not correctly in this tutorial.

The symbols are declared to associate to the left, right, nonassoc. The symbols are *usually* tokens, they can also be *dummy* nonterminals, for use with the %prec directive in the rule.

1. Tokens and rules have precedences. The precedence of a *rule* is the precedence of its *rightmost* terminal. you can override this default by using the *%prec* directive in the rule

2. A reduce/reduce conflict is resolved in favor of the first ruel(in the order given by the source file)

3. A shift/reduce conflict is resolved by comparing the *predecence of the rule to be reduced* with the *precedence of the token to be shifted*. If the predecence of the rule is higher, then the rule will be reducecd; if the predecence of the token is higher then token will be shifted.

4. A shift/reduce conflict between a rule and a token with the same precedence will be resolved using the associativity.

5. when a shift/reduce can not be resolved, a warning, and in favor of *shift*

3.2 MENHIR Related

1. Syntax

```
specification ::= declaration . . . declaration %% rule . . . rule [ %%
    Objective Caml code ]
 declaration ::= %{ Objective Caml code %}
                        % parameter < uid : Objective Caml module type >
                        %token [ < Objective Caml type > ] uid . . . uid
                        %nonassoc uid . . . uid
                        %left uid . . . uid
                        %right uid . . . uid
                        %type < Objective Caml type > lid . . . lid
                        %start [ < Objective Caml type > ] lid . . . lid
rule ::= [%public] [%inline] lid [( id, ..., id)] : [|] group | ... | group
group ::= production | . . . | production { Objective Caml code } [ %prec id ]
production ::= producer . . . producer [ %prec id ]
 producer ::= [ lid = ] actual
actual ::= id [( actual, ..., actual)] [? | + | *]

\item parameter

  \begin{bluetext}
%parameter <uid: Objective module types>
```

   This causes the entire parser to be parameterized over the module.

2. multiple files (private and public,tokens aside)

3. parameterized rules

4. inline

5. standard library

Name	Recognizes	Produces	Comment
option(X)	ϵ | X	α option, if X : α	
ioption(X)			inlined
boption(X)			bool
loption(X)	ϵ |X	α list, if X : α list	
pair(X,Y)	X Y	$\alpha \times \beta$	
separated_pair(X,sep,Y)	X sep Y	$\alpha \times \beta$	
preceded(opening,X)	opening X	α, if X : α	
terminated(X,closing)	X closing	α, if X : α	
delimited(opening, X closing)	opening X closing	α, if X : α	
list(X)			
nonempty_list(X)			
separated_list(sep,X)			
sepearted_nonempty_list(sep,X)			

6. combined with ulex

   A typical tags file is as follows

```
true:use_menhir, pkg_ulex, pkg_pcre, pkg_menhirLib, pkg_batteries
<scanner.ml>: pkg_ulex, syntax_camlp4o
```

   You have to use

   Menhirlib.Convert

   API, here

```
(** support  ocamllex *)
type ('token, 'semantic_value) traditional =
    (Lexing.lexbuf -> 'token) -> Lexing.lexbuf -> 'semantic_value

(**
  This revised API is independent of any lexer generator. Here, the
   parser only requires access to the lexer, and the lexer takes no
   parameters. The tokens returned by the lexer *may*  need to contain
   position  information. *)

type ('token, 'semantic_value) revised =
```

```
    (unit -> 'token) -> 'semantic_value

(* A token of the revised lexer is essentially a triple of a token
   of the traditional lexer (or raw token), a start position, and
   and end position. The three [get] functions are accessors. *)

(* We do not require the type ['token] to actually be a triple type.
   This enables complex applications where it is a record type with
   more than three fields. It also enables simple applications where
   positions are of no interest, so ['token] is just ['raw_token]
   and [get_startp] and [get_endp] return dummy positions. *)

val traditional2revised:
  ('token -> 'raw_token) ->
  ('token -> Lexing.position) ->  (* get a a start position *)
  ('token -> Lexing.position) ->  (* get an end position *)
  ('raw_token, 'semantic_value) traditional ->
  ('token, 'semantic_value) revised

val revised2traditional:
  ('raw_token -> Lexing.position -> Lexing.position -> 'token) ->
  ('token, 'semantic_value) revised ->
  ('raw_token, 'semantic_value) traditional

(** concrete type used here *)
module Simplified : sig
  val traditional2revised:
    ('token, 'semantic_value) traditional ->
    ('token * Lexing.position * Lexing.position, 'semantic_value) revised
  val revised2traditional:
    ('token * Lexing.position * Lexing.position, 'semantic_value) revised ->
    ('token, 'semantic_value) traditional
end
```

7. example csss project

Chapter 4

Camlp4

Camlp4 stands for Preprocess-Pretty-Printer for `OCaml`, it's extremely powerful and hard to grasp as well. It is a source-to-source level translation tool.

predicate parsing stuff

4.1 Predicate Parser

```
a : a x | b (x can be anything)
=>
a : b r
r : x r | e
-------------------------
exp : exp op exp | prim
=>
exp : prim expR
expR : op exp expR | e
```

4.2 Basic Structure

4.2.1 Experimentation Environment

On Toplevel, you can load camlp4 via findlib as follows:

```
#camlp4r;
#load "camlp4rf.cma"
```

Using `ocamlobjinfo` to search modules [18]:

4.2.2 Camlp4 Modules

```
ocamlobjinfo `camlp4 -where`/camlp4fulllib.cma | grep -i unit
```

```
Camlp4_import Camlp4_config Camlp4 Camlp4AstLoader Camlp4DebugParser
Camlp4GrammarParser Camlp4ListComprehension Camlp4MacroParser
Camlp4OCamlParser Camlp4OCamlRevisedParser Camlp4QuotationCommon
Camlp4OCamlOriginalQuotationExpander Camlp4OCamlRevisedParserParser
Camlp4OCamlParserParser Camlp4OCamlRevisedQuotationExpander
Camlp4QuotationExpander Camlp4AstDumper Camlp4AutoPrinter
Camlp4NullDumper Camlp4OCamlAstDumper Camlp4OCamlPrinter
Camlp4OCamlRevisedPrinter Camlp4AstLifter Camlp4ExceptionTracer
Camlp4FoldGenerator Camlp4LocationStripper Camlp4MapGenerator
Camlp4MetaGenerator Camlp4Profiler Camlp4TrashRemover Camlp4Top
```

Listing 18: Camlp4 Modules

Using script (oco [19] with original syntax is ok, but when using ocr [20] with revised syntax, it will have some problems, i.e. .ocamlinit, and other startup files including findlib, so you'd better *not use* revised syntax in the toplevel. here I use .ocamlinitr (revised syntax) for ocr, but it still have some problem with findlib, which I think is internal, hard to solve, but it does not really matter.

Another way to solve this problem is to *customize your toplevel*.

```
bash-3.2$ cat /usr/local/bin/oco
ledit -x -h ~/.ocaml_history ocaml dynlink.cma camlp4of.cma -warn-error +a-4-6-27..29
```

Listing 19: oco

```
bash-3.2$ cat `which ocr`
ledit -x -h ~/.ocaml_history ocaml dynlink.cma camlp4rf.cma -init ~/.ocamlinitr -warn-error +a-4-6-27..29
```

Listing 20: ocr

Customize toplevel has some benefit, linking without scripts make you more roubst against *.ocamlinit*, we can customize *or*, and create a script *orr* in the shell.

4.2.3 Camlp4 Make Toplevel

```
  ocamlmktop -custom -o oraml -I +camlp4 dynlink.cma camlp4rf.cma \
  str.cma bigarray.cma unix.cma nums.cma -I `ocamlfind query
  batteries` batteries.cma
```

Listing 21: Customized toplevel with revised syntax

```
#! /usr/bin/env bash
oraml -init ~/.or
```

Listing 22: oramll

You can also have a try like this

```
open Camlp4.PreCast ;;
let _loc = Loc.ghost ;;
(**
   blabla...
   An idea, how about installing another pretty printer,
   the printer is awful, actually we have a printer already *)
```

Here are some experiments readers can have a try

```
open Camlp4.PreCast;
open BatPervasives;

value cons = ["A"; "B";"C"]
and _loc = Loc.ghost ;

value tys =
  <:ctyp< [ $list: (List.map (fun str -> <:ctyp< $uid:str$ >>) cons) $ ]
    >>
;

(** incomplete type *)
value  x = <:ctyp< A | B | C>>
;
(**
value x : ctyp =
  TyOr (TyId (IdUid "A"))
   (TyOr  (TyId  (IdUid  "B"))  (TyId  (IdUid  "C")))
*)
value  x = <:ctyp< [A | B | C]>>
;
(**
value x : ctyp =
  TySum
   (TyOr  (TyOr
   (TyId   (IdUid  "A"))
   (TyId   (IdUid  "B")))
     (TyId  (IdUid  "C")))
*)

<:str_item< type t = [A|B|C]>>;

(**
StTyp
 (TyDcl  "t" []
   (TySum
     (TyOr
       (TyOr
         (TyId
           (IdUid  "A"))
         (TyId
           (IdUid  "B")))
       (TyId
         (IdUid  "C"))))
   []) *)
```

Listing 23: Play with camlp4 AST Types

```
value match_case =
  <:match_case<  $list: List.map (fun c -> <:match_case< $uid:c$ -> $`str:c$ >> ) cons $  >>
;
(*
  McOr (
   McArr (
    PaId ( IdUid ( "A")),  ExNil   ExStr ( "A")),
   McOr (
    McArr (
     PaId ( IdUid ( "B")), ExNil   ExStr ( "B")),
    McArr (
     PaId (  IdUid ( "C")), ExNil  ExStr ( "C"))))
*)

value to_string = <:expr< fun [ $match_case$ ] >>;
(*
  ExFun (
  McOr (
    McArr (
    PaId ( IdUid ( "A")),  ExNil   ExStr ( "A")),
   McOr (
    McArr (
     PaId ( IdUid ( "B")), ExNil   ExStr ( "B")),
    McArr (
     PaId (  IdUid ( "C")), ExNil  ExStr ( "C")))))
*)

value pim = Printers.OCamlr.print_implem;
pim <:str_item< $exp: to_string $ >>;
(* fun [ A -> "A" | B -> "B" | C -> "C" ]; *)
value match_case2 =
  <:match_case< $list:
  List.map (fun c -> <:match_case< $`str:c$ -> $uid:c$ >> )
  cons $ >>;

pim  <:str_item< $exp: <:expr< fun [$match_case2$ | _ -> invalid_arg "haha"] >> $ >>  ;
(**
   fun [ "A" -> A | "B" -> B | "C" -> C | _ -> invalid_arg "haha" ];
 *)
```

Listing 24: Play with Camlp4 Ast Types Match Case

When you do antiquotation, in most cases, when inserting an AST rather than a string, usually you *do not* need tags, when you want to interpret a string as a piece of ast, probably you *need it.*

4.2.4 Command Options

```
bash-3.2$ camlp4 -where
/Users/bob/SourceCode/ML/godi/lib/ocaml/std-lib/camlp4
bash-3.2$ which camlp4
/Users/bob/SourceCode/ML/godi/bin/camlp4
```

You can grep all executables [??] relevant to camlp4 using a one-line bash as follows:

```
find $(dirname $(which ocaml)) -type f -perm -og+rx | grep camlp4 |
while read ss ; do echo $(basename $ss) ; done
```

```
camlp4 camlp4boot camlp4o camlp4o.opt camlp4of camlp4of.opt camlp4oof
camlp4oof.opt camlp4orf camlp4orf.opt camlp4prof camlp4r camlp4r.opt
camlp4rf camlp4rf.opt mkcamlp4 safe_camlp4
```

Listing 25: List of camlp4 executables

So the tools at hand are *camlp4, camlp4o, camlp4of, camlp4oof, camlp4orf, camlp4r, camlp4rf*

You can type *camlp4 -h* to enumerate all the command line options. Some pretty useful options are:

`-str`

`-loaded-modules`

`-parser <name>` load the parser *Camlp4Parsers/<name>.cm(o|a|xs)*

`-printer <name>` load the printer *Camlp4Printerss/<name>.cm(o|a|xs)*

`-filter <name>` load the filter *Camlp4Filters/<name>.cm(o|a|xs).*

`-printer o` means print in original syntax.

These command line options are all handled in *Camlp4Bin.ml*

`Camlp4o -h` There are options added by loaded object files. You can added by `Options.add` as well.

`-add_locations` Add locations as comment

`-no_comments`

`-curry-constr`

`-sep` Use this string between parsers

	host	embedded	reflective	3.09 equivalent
camlp4of	original	original	Yes	N/A
camlp4rf	revised	revised	Yes	N/A
camlp4r-parser rq	revised	revised	No	camlp4r q_MLast.cmo
camlp4orf	original	revised	No	camlp4o q_MLast.cmo
camlp4oof	original	original	No	N/A

Table 4.1: Module Components

4.2.5 Module Components

Table 4.1 list all components in camlp4 modules. That reflective is true means when extending the syntax of the host language will **also extend the embedded one**

- Camlp4r
  1. parser
     RP, RPP(RevisedParserParser)
  2. printer
     OCaml
- Camlp4rf (extended from camlp4r)
  1. parser
     RP,RPP, GrammarP, ListComprehension, MacroP, QuotationExpander
  2. printer
     OCaml
- Camlp4o (extended from camlp4r)
  1. parser
     OP, OPP, RP,RPP
- Camlp4of (extended from camlp4o)
  1. parser
     GrammarParser, ListComprehension, MacroP, QuotatuinExpander

2. printer

4.2.6 Simple Experiment

Without `ocamlbuild`, `ocamlfind`, a simple build would be like this

```
ocamlc -pp camlp4o.opt error.ml
```

4.3 Camlp4 SourceCode Exploration

Now we begin to explore the structure of camlp4 Source Code. First let's have a look at the directory structure of `camlp4` directory.

```
.
|-- boot
|-- build
|-- Camlp4
|   |-- Printers
|   `-- Struct
|       `-- Grammar
|-- Camlp4Filters
|-- Camlp4Parsers
|-- Camlp4Printers
|-- Camlp4Top
|-- examples
|-- man
|-- test
|   `-- fixtures
`-- unmaintained
```

4.3.1 Camlp4 PreCast

`Camlp4.PreCast (Camlp4/PreCast.ml)`

As above,Struct directory has module *Loc, Dynloader Functor, Camlp4Ast.Make, Token.Make, Lexer.Make, Grammar.Static.Make, Quotation.Make*

File `Camlp4.PreCast` Listing **?? Re-Export** such files

```
Struct.Loc Struct.Camlp4Ast Struct.Token Struct.Grammar.Parser
Struct.Grammar.Static Struct.Lexer Struct.DynLoader Struct.Quotation
Struct.AstFilters OCamlInitSyntax Printers.OCaml Printers.OCamlr
Printers.Null Printers.DumpCamlp4Ast Printers.DumpOCamlAst
```

```
(** Camlp4.PreCast.ml *)
module Id = struct
  value name = "Camlp4.PreCast";
  value version = Sys.ocaml_version;
end;
type camlp4_token = Sig.camlp4_token ==
  [ KEYWORD       of string
  | SYMBOL        of string (* *, +, +++*%, %#@... *)
```

```
  | LIDENT        of string (* lower case identifier *)
  | UIDENT        of string (* upper case identifier *)
  | ESCAPED_IDENT of string (* ( * ), ( ++##> ), ( foo ) *)
  | INT           of int and string  (* 'INT(i,is)  42, 0xa0, 0XffFFff, 0b1010101, 0O644, 0o644 *)
  | INT32         of int32 and string (* 42l, 0xa0l... *)
  | INT64         of int64 and string (* 42L, 0xa0L... *)
  | NATIVEINT     of nativeint and string (* 42n, 0xa0n... *)
  | FLOAT         of float and string (* 42.5, 1.0, 2.4e32 *)
  | CHAR          of char and string  (* with escaping *)
  | STRING        of string and string (* with escaping *)
  | LABEL         of string (* *)
  | OPTLABEL      of string
  | QUOTATION     of Sig.quotation (* << foo >> <:quot_name< bar >> <@loc_name<bar>>
    type quotation ={ q_name : string; q_loc : string;
    q_shift : int; q_contents : string; } *)
  | ANTIQUOT      of string and string    (* $foo$  $anti_name:foo$ $'anti_name:foo$ *)
  | COMMENT       of string
  | BLANKS        of string               (* some non newline blanks *)
  | NEWLINE                               (* interesting *)
  | LINE_DIRECTIVE of int and option string  (* #line 42, #foo "string" *)
  | EOI ];
module Loc = Struct.Loc;
module Ast = Struct.Camlp4Ast.Make Loc;
module Token = Struct.Token.Make Loc;
module Lexer = Struct.Lexer.Make Token;
module Gram = Struct.Grammar.Static.Make Lexer;
module DynLoader = Struct.DynLoader;
module Quotation = Struct.Quotation.Make Ast;

(** intersting, so you can make your own syntax totally but it's not
    easy to do this in toplevel, probably will crash. We will give a
    nice solution later *)

module MakeSyntax (U : sig end) = OCamlInitSyntax.Make Ast Gram Quotation;
module Syntax = MakeSyntax (struct end);
module AstFilters = Struct.AstFilters.Make Ast; (** Functorize *)
module MakeGram = Struct.Grammar.Static.Make;

module Printers = struct
  module OCaml = Printers.OCaml.Make Syntax;
  module OCamlr = Printers.OCamlr.Make Syntax;
  (* module OCamlrr = Printers.OCamlrr.Make Syntax; *)
  module DumpOCamlAst = Printers.DumpOCamlAst.Make Syntax;
  module DumpCamlp4Ast = Printers.DumpCamlp4Ast.Make Syntax;
  module Null = Printers.Null.Make Syntax;
end;
```

Listing 26: Camlp4 PreCast

4.3.2 OCamlInitSyntax

`OCamlInitSyntax` Listing 27 does not do too many things, first, it initialize all the entries needed later (they are all blank, to be extended by your functor), after initialization, it created a submodule `AntiquotSyntax`, and initialize two entries `antiquot_expr` and `antiquot_patt`, very easy.

```
(** File Camlp4.OCamlInitSyntax.ml
    Ast -> Gram -> Quotation -> Camlp4Syntax
    Given Ast, Gram, Quotation, we produce Camlp4Syntax
 *)
module Make (Ast     : Sig.Camlp4Ast)
            (Gram    : Sig.Grammar.Static with module Loc = Ast.Loc
                                           with type Token.t = Sig.camlp4_token)
            (Quotation : Sig.Quotation with module Ast = Sig.Camlp4AstToAst Ast)
: Sig.Camlp4Syntax with module Loc = Ast.Loc
                    and module Ast = Ast
                    and module Token = Gram.Token
                    and module Gram = Gram
                    and module Quotation = Quotation
= struct

  module Loc     = Ast.Loc;
  module Ast     = Ast;
  module Gram    = Gram;
  module Token   = Gram.Token;
  open Sig;

  (* Warnings *)
  type warning = Loc.t -> string -> unit;
  value default_warning loc txt = Format.eprintf "<W> %a: %s@." Loc.print loc txt;
  value current_warning = ref default_warning;
  value print_warning loc txt = current_warning.val loc txt;

  value a_CHAR = Gram.Entry.mk "a_CHAR";
  value a_FLOAT = Gram.Entry.mk "a_FLOAT";
  value a_INT = Gram.Entry.mk "a_INT";
  value a_INT32 = Gram.Entry.mk "a_INT32";
```

```
value a_INT64 = Gram.Entry.mk "a_INT64";
value a_LABEL = Gram.Entry.mk "a_LABEL";
value a_LIDENT = Gram.Entry.mk "a_LIDENT";
value a_NATIVEINT = Gram.Entry.mk "a_NATIVEINT";
value a_OPTLABEL = Gram.Entry.mk "a_OPTLABEL";
value a_STRING = Gram.Entry.mk "a_STRING";
value a_UIDENT = Gram.Entry.mk "a_UIDENT";
value a_ident = Gram.Entry.mk "a_ident";
value amp_ctyp = Gram.Entry.mk "amp_ctyp";
value and_ctyp = Gram.Entry.mk "and_ctyp";
value match_case = Gram.Entry.mk "match_case";
value match_case0 = Gram.Entry.mk "match_case0";
value binding = Gram.Entry.mk "binding";
value class_declaration = Gram.Entry.mk "class_declaration";
value class_description = Gram.Entry.mk "class_description";
value class_expr = Gram.Entry.mk "class_expr";
value class_fun_binding = Gram.Entry.mk "class_fun_binding";
value class_fun_def = Gram.Entry.mk "class_fun_def";
value class_info_for_class_expr = Gram.Entry.mk "class_info_for_class_expr";
value class_info_for_class_type = Gram.Entry.mk "class_info_for_class_type";
value class_longident = Gram.Entry.mk "class_longident";
value class_longident_and_param = Gram.Entry.mk "class_longident_and_param";
value class_name_and_param = Gram.Entry.mk "class_name_and_param";
value class_sig_item = Gram.Entry.mk "class_sig_item";
value class_signature = Gram.Entry.mk "class_signature";
value class_str_item = Gram.Entry.mk "class_str_item";
value class_structure = Gram.Entry.mk "class_structure";
value class_type = Gram.Entry.mk "class_type";
value class_type_declaration = Gram.Entry.mk "class_type_declaration";
value class_type_longident = Gram.Entry.mk "class_type_longident";
value class_type_longident_and_param = Gram.Entry.mk "class_type_longident_and_param";
value class_type_plus = Gram.Entry.mk "class_type_plus";
value comma_ctyp = Gram.Entry.mk "comma_ctyp";
value comma_expr = Gram.Entry.mk "comma_expr";
value comma_ipatt = Gram.Entry.mk "comma_ipatt";
value comma_patt = Gram.Entry.mk "comma_patt";
value comma_type_parameter = Gram.Entry.mk "comma_type_parameter";
value constrain = Gram.Entry.mk "constrain";
value constructor_arg_list = Gram.Entry.mk "constructor_arg_list";
value constructor_declaration = Gram.Entry.mk "constructor_declaration";
value constructor_declarations = Gram.Entry.mk "constructor_declarations";
value ctyp = Gram.Entry.mk "ctyp";
value cvalue_binding = Gram.Entry.mk "cvalue_binding";
value direction_flag = Gram.Entry.mk "direction_flag";
value direction_flag_quot = Gram.Entry.mk "direction_flag_quot";
value dummy = Gram.Entry.mk "dummy";
value entry_eoi = Gram.Entry.mk "entry_eoi";
```

```
value eq_expr = Gram.Entry.mk "eq_expr";
value expr = Gram.Entry.mk "expr";
value expr_eoi = Gram.Entry.mk "expr_eoi";
value field_expr = Gram.Entry.mk "field_expr";
value field_expr_list = Gram.Entry.mk "field_expr_list";
value fun_binding = Gram.Entry.mk "fun_binding";
value fun_def = Gram.Entry.mk "fun_def";
value ident = Gram.Entry.mk "ident";
value implem = Gram.Entry.mk "implem";
value interf = Gram.Entry.mk "interf";
value ipatt = Gram.Entry.mk "ipatt";
value ipatt_tcon = Gram.Entry.mk "ipatt_tcon";
value label = Gram.Entry.mk "label";
value label_declaration = Gram.Entry.mk "label_declaration";
value label_declaration_list = Gram.Entry.mk "label_declaration_list";
value label_expr = Gram.Entry.mk "label_expr";
value label_expr_list = Gram.Entry.mk "label_expr_list";
value label_ipatt = Gram.Entry.mk "label_ipatt";
value label_ipatt_list = Gram.Entry.mk "label_ipatt_list";
value label_longident = Gram.Entry.mk "label_longident";
value label_patt = Gram.Entry.mk "label_patt";
value label_patt_list = Gram.Entry.mk "label_patt_list";
value labeled_ipatt = Gram.Entry.mk "labeled_ipatt";
value let_binding = Gram.Entry.mk "let_binding";
value meth_list = Gram.Entry.mk "meth_list";
value meth_decl = Gram.Entry.mk "meth_decl";
value module_binding = Gram.Entry.mk "module_binding";
value module_binding0 = Gram.Entry.mk "module_binding0";
value module_declaration = Gram.Entry.mk "module_declaration";
value module_expr = Gram.Entry.mk "module_expr";
value module_longident = Gram.Entry.mk "module_longident";
value module_longident_with_app = Gram.Entry.mk "module_longident_with_app";
value module_rec_declaration = Gram.Entry.mk "module_rec_declaration";
value module_type = Gram.Entry.mk "module_type";
value package_type = Gram.Entry.mk "package_type";
value more_ctyp = Gram.Entry.mk "more_ctyp";
value name_tags = Gram.Entry.mk "name_tags";
value opt_as_lident = Gram.Entry.mk "opt_as_lident";
value opt_class_self_patt = Gram.Entry.mk "opt_class_self_patt";
value opt_class_self_type = Gram.Entry.mk "opt_class_self_type";
value opt_class_signature = Gram.Entry.mk "opt_class_signature";
value opt_class_structure = Gram.Entry.mk "opt_class_structure";
value opt_comma_ctyp = Gram.Entry.mk "opt_comma_ctyp";
value opt_dot_dot = Gram.Entry.mk "opt_dot_dot";
value row_var_flag_quot = Gram.Entry.mk "row_var_flag_quot";
value opt_eq_ctyp = Gram.Entry.mk "opt_eq_ctyp";
value opt_expr = Gram.Entry.mk "opt_expr";
```

```
value opt_meth_list = Gram.Entry.mk "opt_meth_list";
value opt_mutable = Gram.Entry.mk "opt_mutable";
value mutable_flag_quot = Gram.Entry.mk "mutable_flag_quot";
value opt_polyt = Gram.Entry.mk "opt_polyt";
value opt_private = Gram.Entry.mk "opt_private";
value private_flag_quot = Gram.Entry.mk "private_flag_quot";
value opt_rec = Gram.Entry.mk "opt_rec";
value rec_flag_quot = Gram.Entry.mk "rec_flag_quot";
value opt_sig_items = Gram.Entry.mk "opt_sig_items";
value opt_str_items = Gram.Entry.mk "opt_str_items";
value opt_virtual = Gram.Entry.mk "opt_virtual";
value virtual_flag_quot = Gram.Entry.mk "virtual_flag_quot";
value opt_override = Gram.Entry.mk "opt_override";
value override_flag_quot = Gram.Entry.mk "override_flag_quot";
value opt_when_expr = Gram.Entry.mk "opt_when_expr";
value patt = Gram.Entry.mk "patt";
value patt_as_patt_opt = Gram.Entry.mk "patt_as_patt_opt";
value patt_eoi = Gram.Entry.mk "patt_eoi";
value patt_tcon = Gram.Entry.mk "patt_tcon";
value phrase = Gram.Entry.mk "phrase";
value poly_type = Gram.Entry.mk "poly_type";
value row_field = Gram.Entry.mk "row_field";
value sem_expr = Gram.Entry.mk "sem_expr";
value sem_expr_for_list = Gram.Entry.mk "sem_expr_for_list";
value sem_patt = Gram.Entry.mk "sem_patt";
value sem_patt_for_list = Gram.Entry.mk "sem_patt_for_list";
value semi = Gram.Entry.mk "semi";
value sequence = Gram.Entry.mk "sequence";
value do_sequence = Gram.Entry.mk "do_sequence";
value sig_item = Gram.Entry.mk "sig_item";
value sig_items = Gram.Entry.mk "sig_items";
value star_ctyp = Gram.Entry.mk "star_ctyp";
value str_item = Gram.Entry.mk "str_item";
value str_items = Gram.Entry.mk "str_items";
value top_phrase = Gram.Entry.mk "top_phrase";
value type_constraint = Gram.Entry.mk "type_constraint";
value type_declaration = Gram.Entry.mk "type_declaration";
value type_ident_and_parameters = Gram.Entry.mk "type_ident_and_parameters";
value type_kind = Gram.Entry.mk "type_kind";
value type_longident = Gram.Entry.mk "type_longident";
value type_longident_and_parameters = Gram.Entry.mk "type_longident_and_parameters";
value type_parameter = Gram.Entry.mk "type_parameter";
value type_parameters = Gram.Entry.mk "type_parameters";
value typevars = Gram.Entry.mk "typevars";
value use_file = Gram.Entry.mk "use_file";
value val_longident = Gram.Entry.mk "val_longident";
value value_let = Gram.Entry.mk "value_let";
```

```
value value_val = Gram.Entry.mk "value_val";
value with_constr = Gram.Entry.mk "with_constr";
value expr_quot = Gram.Entry.mk "quotation of expression";
value patt_quot = Gram.Entry.mk "quotation of pattern";
value ctyp_quot = Gram.Entry.mk "quotation of type";
value str_item_quot = Gram.Entry.mk "quotation of structure item";
value sig_item_quot = Gram.Entry.mk "quotation of signature item";
value class_str_item_quot = Gram.Entry.mk "quotation of class structure item";
value class_sig_item_quot = Gram.Entry.mk "quotation of class signature item";
value module_expr_quot = Gram.Entry.mk "quotation of module expression";
value module_type_quot = Gram.Entry.mk "quotation of module type";
value class_type_quot = Gram.Entry.mk "quotation of class type";
value class_expr_quot = Gram.Entry.mk "quotation of class expression";
value with_constr_quot = Gram.Entry.mk "quotation of with constraint";
value binding_quot = Gram.Entry.mk "quotation of binding";
value rec_binding_quot = Gram.Entry.mk "quotation of record binding";
value match_case_quot = Gram.Entry.mk "quotation of match_case (try/match/function case)";
value module_binding_quot = Gram.Entry.mk "quotation of module rec binding";
value ident_quot = Gram.Entry.mk "quotation of identifier";
value prefixop = Gram.Entry.mk "prefix operator (start with '!', '?', '~')";
value infixop0 = Gram.Entry.mk "infix operator (level 0) (comparison operators, and some others)";
value infixop1 = Gram.Entry.mk "infix operator (level 1) (start with '^', '@')";
value infixop2 = Gram.Entry.mk "infix operator (level 2) (start with '+', '-')";
value infixop3 = Gram.Entry.mk "infix operator (level 3) (start with '*', '/', '%')";
value infixop4 = Gram.Entry.mk "infix operator (level 4) (start with \"**\") (right assoc)";

EXTEND Gram
  top_phrase:
    [ [ `EOI -> None ] ]
  ;
END;

module AntiquotSyntax = struct
  module Loc  = Ast.Loc;
  module Ast  = Sig.Camlp4AstToAst Ast;
  module Gram = Gram;
  value antiquot_expr = Gram.Entry.mk "antiquot_expr";
  value antiquot_patt = Gram.Entry.mk "antiquot_patt";
  EXTEND Gram
    antiquot_expr:
      [ [ x = expr; `EOI -> x ] ]
    ;
    antiquot_patt:
      [ [ x = patt; `EOI -> x ] ]
    ;
  END;
  value parse_expr loc str = Gram.parse_string antiquot_expr loc str;
```

```
    value parse_patt loc str = Gram.parse_string antiquot_patt loc str;
  end;

  module Quotation = Quotation;

  value wrap directive_handler pa init_loc cs =
    let rec loop loc =
      let (pl, stopped_at_directive) = pa loc cs in
      match stopped_at_directive with
      [ Some new_loc ->
        let pl =
          match List.rev pl with
          [ [] -> assert False
          | [x :: xs] ->
              match directive_handler x with
              [ None -> xs
              | Some x -> [x :: xs] ] ]
        in (List.rev pl) @ (loop new_loc)
      | None -> pl ]
    in loop init_loc;

  value parse_implem ?(directive_handler = fun _ -> None) _loc cs =
    let l = wrap directive_handler (Gram.parse implem) _loc cs in
    <:str_item< $list:l$ >>;

  value parse_interf ?(directive_handler = fun _ -> None) _loc cs =
    let l = wrap directive_handler (Gram.parse interf) _loc cs in
    <:sig_item< $list:l$ >>;

  value print_interf ?input_file:(_) ?output_file:(_) _ = failwith "No interface printer";
  value print_implem ?input_file:(_) ?output_file:(_) _ = failwith "No implementation printer";
end;
```

Listing 27: OCamlInitSyntax

4.3.3 Camlp4.Sig

For `Camlp4.Sig.ml`, all are signatures, there's even no `Camlp4.Sig.mli`.

4.3.4 Camlp4.Struct.Camlp4Ast.mlast

This file use macro`INCLUDE` to include `Camlp4.Camlp4Ast.parital.ml` for reuse.

4.3.5 AstFilters

Notice an interesting module `AstFilters` Listing 28, is defined by `Struct.AstFilters.Make`, which we see in `Camlp4.PreCast.ml??` It's very simple actually.

```
(**AstFilters.ml*)
module Make (Ast : Sig.Camlp4Ast)
: Sig.AstFilters with module Ast = Ast
= struct

  module Ast = Ast;

  type filter 'a = 'a -> 'a;

  value interf_filters = Queue.create ();
  value fold_interf_filters f i = Queue.fold f i interf_filters;
  value implem_filters = Queue.create ();
  value fold_implem_filters f i = Queue.fold f i implem_filters;
  value topphrase_filters = Queue.create ();
  value fold_topphrase_filters f i = Queue.fold f i topphrase_filters;

  value register_sig_item_filter f = Queue.add f interf_filters;
  value register_str_item_filter f = Queue.add f implem_filters;
  value register_topphrase_filter f = Queue.add f topphrase_filters;
end;
```

Listing 28: AstFilters

```
1 (** file Camlp4Ast.mlast   in the file we have *)
2 Camlp4.Struct.Camlp4Ast.Make : Loc -> Sig.Camlp4Syntax
3   module Ast = struct
4      include Sig.MakeCamlp4Ast Loc
5   end ;
```

Listing 29: Camlp4Ast Make

4.3.6 Camlp4.Register

Let's see what's in `Register` Listing 30module

```
(**
   Camlp4.Register.ml
*)
```

```
module PP = Printers;
open PreCast;

type parser_fun 'a =
  ?directive_handler:('a -> option 'a) -> PreCast.Loc.t -> Stream.t char -> 'a;

type printer_fun 'a =
  ?input_file:string -> ?output_file:string -> 'a -> unit;

(** a lot of parsers to be modified *)
value sig_item_parser = ref (fun ?directive_handler:(_) _ _ -> failwith "No interface parser");
value str_item_parser = ref (fun ?directive_handler:(_) _ _ -> failwith "No implementation parser");

value sig_item_printer = ref (fun ?input_file:(_) ?output_file:(_) _ -> failwith "No interface printer");
value str_item_printer = ref (fun ?input_file:(_) ?output_file:(_) _ -> failwith "No implementation printer");

(** a queue of callbacks *)
value callbacks = Queue.create ();

value loaded_modules = ref [];

(** iterate each callback*)
value iter_and_take_callbacks f =
  let rec loop () = loop (f (Queue.take callbacks)) in
  try loop () with [ Queue.Empty -> () ];

(** register module, add to the Queue *)
value declare_dyn_module (m:string) (f:unit->unit) =
  begin
    (* let () = Format.eprintf "declare_dyn_module: %s@." m in *)
    loaded_modules.val := [ m :: loaded_modules.val ];
    Queue.add (m, f) callbacks;
  end;

value register_str_item_parser f = str_item_parser.val := f;
value register_sig_item_parser f = sig_item_parser.val := f;
value register_parser f g =
  do { str_item_parser.val := f; sig_item_parser.val := g };
value current_parser () = (str_item_parser.val, sig_item_parser.val);

value register_str_item_printer f = str_item_printer.val := f;
value register_sig_item_printer f = sig_item_printer.val := f;
value register_printer f g =
  do { str_item_printer.val := f; sig_item_printer.val := g };
value current_printer () = (str_item_printer.val, sig_item_printer.val);

module Plugin (Id : Sig.Id) (Maker : functor (Unit : sig end) -> sig end) = struct
```

```
  declare_dyn_module Id.name (fun _ -> let module M = Maker (struct end) in ());
end;

module SyntaxExtension (Id : Sig.Id) (Maker : Sig.SyntaxExtension) = struct
  declare_dyn_module Id.name (fun _ -> let module M = Maker Syntax in ());
end;

module OCamlSyntaxExtension
  (Id : Sig.Id) (Maker : functor (Syn : Sig.Camlp4Syntax) -> Sig.Camlp4Syntax) =
struct
  declare_dyn_module Id.name (fun _ -> let module M = Maker Syntax in ());
end;

module SyntaxPlugin (Id : Sig.Id) (Maker : functor (Syn : Sig.Syntax) -> sig end) = struct
  declare_dyn_module Id.name (fun _ -> let module M = Maker Syntax in ());
end;

module Printer
  (Id : Sig.Id) (Maker : functor (Syn : Sig.Syntax)
                                 -> (Sig.Printer Syn.Ast).S) =
struct
  declare_dyn_module Id.name (fun _ ->
    let module M = Maker Syntax in
    register_printer M.print_implem M.print_interf);
end;

module OCamlPrinter
  (Id : Sig.Id) (Maker : functor (Syn : Sig.Camlp4Syntax)
                                 -> (Sig.Printer Syn.Ast).S) =
struct
  declare_dyn_module Id.name (fun _ ->
    let module M = Maker Syntax in
    register_printer M.print_implem M.print_interf);
end;

module OCamlPreCastPrinter
  (Id : Sig.Id) (P : (Sig.Printer PreCast.Ast).S) =
struct
  declare_dyn_module Id.name (fun _ ->
    register_printer P.print_implem P.print_interf);
end;

module Parser
  (Id : Sig.Id) (Maker : functor (Ast : Sig.Ast)
                                 -> (Sig.Parser Ast).S) =
struct
  declare_dyn_module Id.name (fun _ ->
```

```
    let module M = Maker PreCast.Ast in
    register_parser M.parse_implem M.parse_interf);
end;

module OCamlParser
  (Id : Sig.Id) (Maker : functor (Ast : Sig.Camlp4Ast)
                                 -> (Sig.Parser Ast).S) =
struct
  declare_dyn_module Id.name (fun _ ->
    let module M = Maker PreCast.Ast in
    register_parser M.parse_implem M.parse_interf);
end;

module OCamlPreCastParser
  (Id : Sig.Id) (P : (Sig.Parser PreCast.Ast).S) =
struct
  declare_dyn_module Id.name (fun _ ->
    register_parser P.parse_implem P.parse_interf);
end;

module AstFilter
  (Id : Sig.Id) (Maker : functor (F : Sig.AstFilters) -> sig end) =
struct
  declare_dyn_module Id.name (fun _ -> let module M = Maker AstFilters in ());
end;

sig_item_parser.val := Syntax.parse_interf;
str_item_parser.val := Syntax.parse_implem;

module CurrentParser = struct
  module Ast = Ast;
  value parse_interf ?directive_handler loc strm =
    sig_item_parser.val ?directive_handler loc strm;
  value parse_implem ?directive_handler loc strm =
    str_item_parser.val ?directive_handler loc strm;
end;

module CurrentPrinter = struct
  module Ast = Ast;
  value print_interf ?input_file ?output_file ast =
    sig_item_printer.val ?input_file ?output_file ast;
  value print_implem ?input_file ?output_file ast =
    str_item_printer.val ?input_file ?output_file ast;
end;

value enable_ocaml_printer () =
  let module M = OCamlPrinter PP.OCaml.Id PP.OCaml.MakeMore in ();
```

```
value enable_ocamlr_printer () =
  let module M = OCamlPrinter PP.OCamlr.Id PP.OCamlr.MakeMore in ();

(* value enable_ocamlrr_printer () =
  let module M = OCamlPrinter PP.OCamlrr.Id PP.OCamlrr.MakeMore in ();    *)

value enable_dump_ocaml_ast_printer () =
  let module M = OCamlPrinter PP.DumpOCamlAst.Id PP.DumpOCamlAst.Make in ();

value enable_dump_camlp4_ast_printer () =
  let module M = Printer PP.DumpCamlp4Ast.Id PP.DumpCamlp4Ast.Make in ();

value enable_null_printer () =
  let module M = Printer PP.Null.Id PP.Null.Make in ();
```

Listing 30: Camlp4 Register

Notice that functors Plugin, SyntaxExtension, OCamlSyntaxExtension, OCamlSyntaxExtension, SyntaxPlugin, they did the same thing essentially, they apply the second Funtor to Syntax(Camlp4.PreCast.Syntax).

Functors Printer, OCamlPrinter, OCamlPrinter, they did the same thing, apply the Make to Syntax, then register it.

Functors Parser, OCamlParser, did the same thing.

Functors AstFilter did nothing interesting.

It sticks to the toplevel Listing

Listing 31: Camlp4 Register Part 2

It mainly hook some global variables, like `Camlp4.Register.loaded_modlules`, but there's no fresh meat in this file. To conclude, Register did nothing, except making your code more modular, or register your syntax extension.

As we said, another utility, you can inspect what modules you have loaded in toplevel:

```
1 Camlp4.Register.loaded_modules;;
2 - : string list ref =
3 {Pervasives.contents =
4   ["Camlp4GrammarParser"; "Camlp4OCamlParserParser";
5    "Camlp4OCamlRevisedParserParser"; "Camlp4OCamlParser";
6    "Camlp4OCamlRevisedParser"]}
```

4.3.7 Camlp4Ast

As the code Listing 32 demonstrate below, there are several categories including *ident, ctyp,patt,expr, module_type, sig_item, with_constr, binding, rec_binding, module_binding, match_case, module_expr,str_item, class_type, class_sig_item, class_expr, class_str_item,*. And there are antiquotations for each syntax category, i.e, *IdAnt,TyAnt,PaAnt,ExAnt,MtAnt, SgAnt, WcAnt, BiAnt, RbAnt,MbAnt,McAnt,MeAnt,StAnt,CtAnt,CgAnt, CeAnt, CrAnt*

```
(** CAMLP4AST RevisedSyntax *)
type loc = Loc.t
and meta_bool =
  [ BTrue
  | BFalse
  | BAnt of string ]
and rec_flag =
  [ ReRecursive
  | ReNil
  | ReAnt of string ]
and direction_flag =
  [ DiTo
  | DiDownto
  | DiAnt of string ]
and mutable_flag =
  [ MuMutable
  | MuNil
  | MuAnt of string ]
and private_flag =
  [ PrPrivate
  | PrNil
  | PrAnt of string ]
and virtual_flag =
  [ ViVirtual
  | ViNil
  | ViAnt of string ]
and override_flag =
  [ OvOverride
  | OvNil
  | OvAnt of string ]
and row_var_flag =
  [ RvRowVar
  | RvNil
  | RvAnt of string ]
and meta_option 'a =
  [ ONone
  | OSome of 'a
```

```
  | OAnt of string ]
and meta_list 'a =
  [ LNil
  | LCons of 'a and meta_list 'a
  | LAnt of string ]

and ident =
  [ IdAcc of loc and ident and ident (* i . i *)
(*  <:ident< a . b >>   Access in module
   IdAcc of Loc.t and ident and ident *)
  | IdApp of loc and ident and ident (* i i *)
(*  <:ident< a b >>
   Application
   IdApp of Loc.t and ident and ident ??? *)
  | IdLid of loc and string (* foo *)
(* <:ident< $lid:i$ >>
   Lowercase identifier
   IdLid of Loc.t and string
*)
  | IdUid of loc and string (* Bar *)
(* <:ident< $uid:i$ >>
   Uppercase identifier
   IdUid of Loc.t and string
*)
  | IdAnt of loc and string (* $s$ *)
(* <:ident< $anti:s$ >>
   Antiquotation
   IdAnt of Loc.t and string
*)
 ]
(*  <:ident< $list:x$ >>
   list of accesses
   Ast.idAcc_of_list x  use IdAcc to accumulate to a list
 *)
and ctyp =
  [ TyNil of loc
  (*<:ctyp< >>  Empty typeTyNil of Loc.t *)
  | TyAli of loc and ctyp and ctyp (* t as t *) (* list 'a as 'a *)
  (* <:ctyp< t as t >>  Type aliasing
     TyAli of Loc.t and ctyp and ctyp *)
  | TyAny of loc (* _ *)
  (*  <:ctyp< _ >> Wildcard TyAny of Loc.t *)
```

```
| TyApp of loc and ctyp and ctyp (* t t *) (* list 'a *)
(* <:ctyp< t t >> Application TyApp of Loc.t and ctyp and ctyp *)
| TyArr of loc and ctyp and ctyp (* t -> t *) (* int -> string *)
(* <:ctyp< t -> t >>Arrow TyArr of Loc.t and ctyp and ctyp       *)
| TyCls of loc and ident (* #i *) (* #point *)
(* <:ctyp< #i >> Class type TyCls of Loc.t and ident     ??? *)
| TyLab of loc and string and ctyp (* ~s:t *)
(* <:ctyp< ~s >>  Label type TyLab of Loc.t and string and ctyp    *)
| TyId  of loc and ident (* i *) (* Lazy.t *)
(* <:ctyp< $id:i$ >>  Type identifier of TyId of Loc.t and ident *)
(* <:ctyp< $lid:i$ >> TyId (_, IdLid (_, i)) *)
(* <:ctyp< $uid:i$ >>  TyId (_, IdUid (_, i)) *)
| TyMan of loc and ctyp and ctyp (* t == t *) (* type t = [ A | B ] == Foo.t *)
(* <:ctyp< t == t >>  Type manifest TyMan of Loc.t and ctyp and ctyp       *)

(* type t 'a 'b 'c = t constraint t = t constraint t = t *)
| TyDcl of loc and string and list ctyp and ctyp and list (ctyp * ctyp)
(* <:ctyp< type t 'a 'b 'c = t constraint t = t constraint t = t >>
   Type declaration
   TyDcl of Loc.t and string and list ctyp and ctyp and list (ctyp * ctyp) *)

(* < (t)? (..)? > *) (* < move : int -> 'a .. > as 'a  *)
| TyObj of loc and ctyp and row_var_flag
(* <:ctyp< < (t)? (..)? > >> Object type TyObj of Loc.t and ctyp and meta_bool       *)

| TyOlb of loc and string and ctyp (* ?s:t *)
(* <:ctyp< ?s:t >>  Optional label type TyOlb of Loc.t and string and ctyp       *)
| TyPol of loc and ctyp and ctyp (* ! t . t *) (* ! 'a . list 'a -> 'a *)
(* <:ctyp< ! t . t >> = Polymorphic type TyPol of Loc.t and ctyp and ctyp       *)
| TyQuo of loc and string (* 's *)
(* <:ctyp< 's >>' TyQuo of Loc.t and string       *)
| TyQuP of loc and string (* +'s *)
(* <:ctyp< +'s >> TyQuP of Loc.t and string       *)
| TyQuM of loc and string (* -'s *)
(* <:ctyp< -'s >> TyQuM of Loc.t and string       *)
| TyVrn of loc and string (* `s *)
(* <:ctyp< `s >> Polymorphic variant of TyVrn of Loc.t and string       *)
| TyRec of loc and ctyp (* { t } *) (* { foo : int ; bar : mutable string } *)
(* <:ctyp< { t } >>  Record TyRec of Loc.t and ctyp *)

| TyCol of loc and ctyp and ctyp (* t : t *)
(* <:ctyp< t : t >>Field declarationTyCol of Loc.t and ctyp and ctyp       *)
| TySem of loc and ctyp and ctyp (* t; t *)
(* <:ctyp< t; t >>Semicolon-separated type listTySem of Loc.t and ctyp and ctyp       *)
| TyCom of loc and ctyp and ctyp (* t, t *)
(* <:ctyp< t, t >>Comma-separated type listTyCom of Loc.t and ctyp and ctyp *)
| TySum of loc and ctyp (* [ t ] *) (* [ A of int and string | B ] *)
```

```
(* <:ctyp< [ t ] >>Sum typeTySum of Loc.t and ctyp       *)
| TyOf  of loc and ctyp and ctyp (* t of t *)  (* A of int *)
(* <:ctyp< t of t >>TyOf of Loc.t and ctyp and ctyp       *)
| TyAnd of loc and ctyp and ctyp (* t and t *)
(* <:ctyp< t and t >>TyAnd of Loc.t and ctyp and ctyp *)
| TyOr  of loc and ctyp and ctyp (* t | t *)
(* <:ctyp< t | t >>"Or" pattern between typesTyOr of Loc.t and ctyp and ctyp       *)
| TyPrv of loc and ctyp (* private t *)
(* <:ctyp< private t >>Private type TyPrv of Loc.t and ctyp       *)
| TyMut of loc and ctyp (* mutable t *)
(* <:ctyp< mutable t >>  Mutable type TyMut of Loc.t and ctyp       *)
| TyTup of loc and ctyp (* ( t ) *)  (* (int * string) *)
(* <:ctyp< ( t ) >> or <:ctyp< $tup:t$ >>  Tuple of TyTup of Loc.t and ctyp       *)
| TySta of loc and ctyp and ctyp (* t * t *)
(* <:ctyp< t * t >> TySta of Loc.t and ctyp and ctyp       *)
| TyVrnEq of loc and ctyp (* [ = t ] *)
(* <:ctyp< [ = t ] >>  TyVrnEq of Loc.t and ctyp       *)
| TyVrnSup of loc and ctyp (* [ > t ] *)
(* <:ctyp< [ > t ] >> open polymorphic variant type TyVrnSup of Loc.t and ctyp       *)
| TyVrnInf of loc and ctyp (* [ < t ] *)
(* <:ctyp< [ < t ] >>  closed polymorphic variant type with no known tags
    TyVrnInf of Loc.t and ctyp       *)
| TyVrnInfSup of loc and ctyp and ctyp (* [ < t > t ] *)
(*  <:ctyp< [ < t > t ] >> closed polymorphic variant type with some known tags
    TyVrnInfSup of Loc.t and ctyp and ctyp
*)
| TyAmp of loc and ctyp and ctyp (* t & t *)
(* <:ctyp< t & t >>conjuntive type in polymorphic variants
   TyAmp of Loc.t and ctyp and ctyp   *)
| TyOfAmp of loc and ctyp and ctyp (* t of & t *)
(* <:ctyp< $t1$ of & $t2$ >>Special (impossible) constructor (t1)
   that has both no arguments and arguments compatible with t2 at the
   same time.TyOfAmp of Loc.t and ctyp and ctyp *)
| TyPkg of loc and module_type (* (module S) *)
(* <:ctyp<(module S) >>  TyPkg of loc and module_type    *)
| TyAnt of loc and string (* $s$ *)
(* <:ctyp< $anti:s$ >>AntiquotationTyAnt of Loc.t and string       *)
(*<:ctyp< $list:x$ >>list of accumulated ctyps
depending on context,
Ast.tyAnd_of_list,
Ast.tySem_of_list,
Ast.tySta_of_list,
Ast.tyOr_of_list,
Ast.tyCom_of_list,
Ast.tyAmp_of_list

In a closed variant type <:ctyp< [ < $t1$ > $t2$ ] >> the type t2 must
```

```
    not be the empty type; use a TyVrnInf node in this case.

  Type conjuctions are stored in a TyAmp tree, use Camlp4Ast.list_of_ctyp and
  Camlp4Ast.tyAmp_of_list to convert from and to a list of types.

  Variant constructors with arguments and polymorphic variant
  constructors with arguments are both represented with a TyOf
  node. For variant types the first TyOf type is an uppercase
  identifier (TyId), for polymorphic variant types it is an TyVrn
  node.

  Constant variant constructors are simply represented as
  uppercase identifiers (TyId). Constant polymorphic variant
  constructors take a TyVrn node.  *)
]
and patt =
  [ PaNil of loc
  (* <:patt< >>Empty patternPaNil of Loc.t *)
  | PaId  of loc and ident (* i *)
  (* <:patt< $id:i$ >>IdentifierPaId of Loc.t and ident       *)
  (* <:patt< $lid:i$ >>PaId (_, IdLid (_, i)) *)
  (* <:patt< $uid:i$ >>PaId (_, IdUid (_, i)) *)
  | PaAli of loc and patt and patt (* p as p *) (* (Node x y as n) *)
  (* <:patt< ( p as p ) >>AliasPaAli of Loc.t and patt and patt       *)
  | PaAnt of loc and string (* $s$ *)
  (* <:patt< $anti:s$ >>AntiquotationPaAnt of Loc.t and string       *)
  | PaAny of loc (* _ *)
  (* <:patt< _ >>WildcardPaAny of Loc.t       *)
  | PaApp of loc and patt and patt (* p p *) (* fun x y -> *)
  (* <:patt< p p >>ApplicationPaApp of Loc.t and patt and patt       *)
  | PaArr of loc and patt (* [| p |] *)
  (* <:patt< [| p |] >>ArrayPaArr of Loc.t and patt       *)
  | PaCom of loc and patt and patt (* p, p *)
  (* <:patt< p, p >>Comma-separated pattern listPaCom of Loc.t and patt and patt       *)
  | PaSem of loc and patt and patt (* p; p *)
  (* <:patt< p; p >>Semicolon-separated pattern listPaSem of Loc.t and patt and patt       *)
  | PaChr of loc and string (* c *) (* 'x' *)
  (* <:patt< $chr:c$ >>CharacterPaChr of Loc.t and string       *)
  | PaInt of loc and string
  (* <:patt< $int:i$ >>IntegerPaInt of Loc.t and string       *)
  | PaInt32 of loc and string
  (* <:patt< $int32:i$ >>Int32PaInt32 of Loc.t and string       *)
  | PaInt64 of loc and string
  (* <:patt< $int64:i$ >>Int64PaInt64 of Loc.t and string       *)
  | PaNativeInt of loc and string
  (* <:patt< $nativeint:i$ >>NativeIntPaNativeInt of Loc.t and string       *)
  | PaFlo of loc and string
```

```
  (* <:patt< $flo:f$ >>FloatPaFlo of Loc.t and string       *)
  | PaLab of loc and string and patt (* ~s or ~s:(p) *)
  (* <:patt< ~s >> <:patt< s:(p) >>LabelPaLab of Loc.t and string and patt       *)

  (* ?s or ?s:(p) *)
  | PaOlb of loc and string and patt
  (* <:patt< ?s >> <:patt< ?s:(p) >>Optional labelPaOlb of Loc.t and string and patt       *)

  (* ?s:(p = e) or ?(p = e) *)
  | PaOlbi of loc and string and patt and expr
  (* <:patt< ?s:(p = e) >> <:patt< ?(p = e) >
     >Optional label with default valuePaOlbi of Loc.t and string and patt and expr       *)

  | PaOrp of loc and patt and patt (* p | p *)
  (* <:patt< p | p >>OrPaOrp of Loc.t and patt and patt       *)
  | PaRng of loc and patt and patt (* p .. p *)
  (* <:patt< p .. p >>Pattern rangePaRng of Loc.t and patt and patt *)
  | PaRec of loc and patt (* { p } *)
  (* <:patt< { p } >>RecordPaRec of Loc.t and patt *)
  | PaEq  of loc and ident and patt (* i = p *)
  (* <:patt< i = p >>EqualityPaEq of Loc.t and ident and patt       *)
  | PaStr of loc and string (* s *)
  (* <:patt< $str:s$ >>StringPaStr of Loc.t and string *)
  | PaTup of loc and patt (* ( p ) *)
  (* <:patt< ( $tup:p$ ) >>TuplePaTup of Loc.t and patt       *)
  | PaTyc of loc and patt and ctyp (* (p : t) *)
  (* <:patt< (p : t) >>Type constraintPaTyc of Loc.t and patt and ctyp       *)
  | PaTyp of loc and ident (* #i *)
  (* <:patt< #i >>PaTyp of Loc.t and ident
     used in polymorphic variants
  *)
  | PaVrn of loc and string (* `s *)
  (* <:patt< `s >>Polymorphic variantPaVrn of Loc.t and string   *)
  | PaLaz of loc and patt (* lazy p *)
  (* <:patt< lazy x >> *)
 ]
 (* <:patt< $list:x$ >>list of accumulated patts depending on context,
    Ast.paCom_of_list, Ast.paSem_of_list Tuple elements are wrapped in a
    PaCom tree. The utility functions Camlp4Ast.paCom_of_list and
    Camlp4Ast.list_of_patt convert from and to a list of tuple
    elements.  *)
and expr =
  [ ExNil of loc
      (* <:expr< >> *)
  | ExId  of loc and ident (* i *)
      (* <:expr< $id:i$ >> notice that antiquot id requires ident directly *)
      (* <:expr< $lid:i$ >> ExId(_,IdLid(_,i)) *)
```

```
    (* <:expr< $uid:i$ >> ExId(_, IdUid(_,i)) *)
| ExAcc of loc and expr and expr (* e.e *)
    (* <:expr< $e1$.$e2$ >> Access in module ? *)
| ExAnt of loc and string (* $s$ *)
    (* <:expr< $anti:s$ >> *)
| ExApp of loc and expr and expr (* e e *)
    (* <:expr< $e1$ $e2$ >> Application *)
| ExAre of loc and expr and expr (* e.(e) *)
    (* <:expr< $e$.($e$) >> Array access  *)
| ExArr of loc and expr (* [| e |] *)
    (* <:expr< [|$e$| ] Array declaration *)
| ExSem of loc and expr and expr (* e; e *)
    (* <:expr< $e$; $e$ >>  *)
| ExAsf of loc (* assert False *)
    (* <:expr< assert False >> *)
| ExAsr of loc and expr (* assert e *)
    (* <:expr< assert $e$ >>  *)
| ExAss of loc and expr and expr (* e := e *)
    (* <:expr< $e$ := $e$ >>  *)
| ExChr of loc and string (* 'c' *)
    (* <:exp< $`chr:s$ >> Character *)
| ExCoe of loc and expr and ctyp and ctyp (* (e : t) or (e : t :> t) *)
    (* <:expr< ($e$:> $t$) >> <:expr< ($e$ : $t1$ :> $t2$ ) >>
       The first ctyp is populated by TyNil
    *)
| ExFlo of loc and string (* 3.14 *)
    (* <:expr< $flo:f$ >> *)
    (* <:expr< $`flo:f$ >>  ExFlo(_,string_of_float f) *)

(* for s = e to/downto e do { e } *)
| ExFor of loc and string and expr and expr and direction_flag and expr
    (* <:expr< for $s$ = $e1$ to/downto $e2$ do { $e$  } >>  *)
| ExFun of loc and match_case (* fun [ mc ] *)
    (* <:expr< fun [ $a$ ] >>  *)
| ExIfe of loc and expr and expr and expr (* if e then e else e *)
    (* <:expr< if $e$ then $e$ else $e$ >>  *)
| ExInt of loc and string (* 42 *)
    (* <:expr< $int:i$ >> *)
    (* <:expr< $`int:i$ >> ExInt(_, string_of_int i) *)
| ExInt32 of loc and string
    (* <:expr< $int32:i$ >>
       <:expr< $`int32:i$ >>
    *)
| ExInt64 of loc and string
    (* <:expr< $int64:i$ >> *)
    (* <:expr< $`int64:i$ >>  *)
| ExNativeInt of loc and string
```

```
    (* <:expr< $nativeint:i$ >> <:expr< $`nativeint:i$ >>  *)
| ExLab of loc and string and expr (* ~s or ~s:e *)
    (* <:expr< ~ $s$ >> ExLab (_, s, ExNil) *)
    (* <:expr< ~ $s$ : $e$ >>  *)
| ExLaz of loc and expr (* lazy e *)
    (* <:expr< lazy $e$ >>  *)


| ExLet of loc and rec_flag and binding and expr
    (* <:expr< let $b$ in $e$ >> *)
    (* <:expr< let rec $b$ in $e$ >>    *)

| ExLmd of loc and string and module_expr and expr
    (* <:expr< let module $s$ = $me$ in $e$ >>  *)


| ExMat of loc and expr and match_case
    (* <:expr< match $e$ with [ $a$ ] >>  *)

(* new i *)
| ExNew of loc and ident
    (* <:expr< new $id:i$ >>  new object *)
    (* <:expr< new $lid:str$ >>  *)

(* object ((p))? (cst)? end *)
| ExObj of loc and patt and class_str_item
    (* <:expr< object ( ($p$))? ($cst$)? end >>  object declaration *)

(* ?s or ?s:e *)
| ExOlb of loc and string and expr
    (* <:expr< ? $s$ >>      Optional label  *)
    (* <:expr< ? $s$ : $e$ >>  *)

| ExOvr of loc and rec_binding
(* <:expr< {< $rb$  >} >>  *)

| ExRec of loc and rec_binding and expr
    (* <:expr< { $b$ } >> *)
    (* <:expr< {($e$ ) with $b$ } >>  *)
| ExSeq of loc and expr
    (* <:expr< do { $e$ } >> *)
    (* <:expr< $seq:e$ >> *)
    (* another way to help you figure out the type *)
    (* type let f e = <:expr< $seq:e$ >> in the toplevel            *)

| ExSnd of loc and expr and string
    (* <:expr< $e$ # $s$ >> METHOD call  *)
```

```
| ExSte of loc and expr and expr
    (* <:expr< $e$.[$e$] >> String access  *)

| ExStr of loc and string
    (* <:expr< $str:s$ >> "\n" -> "\n" *)
    (* <:expr< $`str:s$ >> "\n" -> "\\n" *)

| ExTry of loc and expr and match_case
    (* <:expr< try $e$ with [ $a$ ] >>  *)


| ExTup of loc and expr
    (* <:expr< ( $tup:e$ ) >>  *)

| ExCom of loc and expr and expr
    (* <:expr< $e$, $e$ >>  *)

(* (e : t) *)
| ExTyc of loc and expr and ctyp
    (* <:expr< ($e$ : $t$ ) Type constraint  *)

| ExVrn of loc and string
    (* <:expr< `$s$ >>  *)

| ExWhi of loc and expr and expr
    (* <:expr< while $e$ do { $e$ } >>  *)

| ExOpI of loc and ident and expr
    (* <:expr< let open $id:i$ in $e$ >>  *)

| ExFUN of loc and string and expr
    (* <:expr< fun (type $s$ ) -> $e$  >> *)
    (* let f x (type t) y z = e *)

| ExPkg of loc and module_expr
   (* (module ME : S) which is represented as (module (ME : S)) *)
]
and module_type =
  (**
     mt ::=
     | (* empty *)
     | ident
     | functor (s : mt) -> mt
     | 's
     | sig sg end
     | mt with wc
```

```
      | $s$
    *)
    [ MtNil of loc

    | MtId  of loc and ident
    (* i *)  (* A.B.C *)
    (* <:module_type< $id:ident$ >> named module type  *)

    | MtFun of loc and string and module_type and module_type
    (* <:module_type< functor ($uid:s$ : $mtyp:mta$ ) -> $mtyp:mtr$ >> *)

    | MtQuo of loc and string
    (* 's *)

    | MtSig of loc and sig_item
    (* sig sg end *)
    (* <:module_type< sig $sigi:sig_items$ end >>  *)

    | MtWit of loc and module_type and with_constr
    (* mt with wc *)
    (* <:module_type< $mtyp:mt$ with $with_constr:with_contr$ >>  *)
    | MtOf of loc and module_expr
    (* module type of m *)

    | MtAnt of loc and string
    (* $s$ *)
]
  (** Several with-constraints are stored in an WcAnd tree. Use
      Ast.wcAnd_of_list and Ast.list_of_with_constr to convert from and to a
      list of with-constraints.  Several signature items are stored in an
      SgSem tree. Use Ast.sgSem_of_list and Ast.list_of_sig_item to convert
      from and to a list of signature items. *)
and sig_item =
    (*
       sig_item, sg ::=
   | (* empty *)
   | class cict
   | class type cict
   | sg ; sg
   | #s
   | #s e
   | exception t
   | external s : t = s ... s
   | include mt
   | module s : mt
   | module rec mb
   | module type s = mt
```

```
 | open i
 | type t
 | value s : t
 | $s$
 lacking documentation !!
  *)
[ SgNil of loc

  (* class cict *)
  (* <:sig_item< class $s$ >>;; *)
  (* <:sig_item< class $typ:s$ >>;; *)
  | SgCls of loc and class_type

  (* class type cict *)
  (* <:sig_item< class type $s$ >>;; *)
  (* <:sig_item< class type $typ:s$ >>;;  *)
  | SgClt of loc and class_type

  (* sg ; sg *)
  | SgSem of loc and sig_item and sig_item

  (* # s or # s e ???  *)
  (* Directive  *)
  | SgDir of loc and string and expr

  (* exception t *)
  | SgExc of loc and ctyp

  (* external s : t = s ... s *)
  (*  <:sig_item< external $lid:id$ : $typ:type$ = $str_list:string_list$ >>
      another antiquot str_list
 *)
  | SgExt of loc and string and ctyp and meta_list string

  (* include mt *)
  | SgInc of loc and module_type

  (* module s : mt *)
  (* <:sig_item< module $uid:id$ : $mtyp:mod_type$ >>
     module Functor declaration
 *)
  (**
     <:sig_item< module $uid:mid$ ( $uid:arg$ : $mtyp:arg_type$ ) : $mtyp:res_type$ >>
     -->
     <:sig_item< module $uid:mid$ : functor ( $uid:arg$ : $mtyp:arg_type$ ) -> $mtyp:res_type$ >>
 *)
  | SgMod of loc and string and module_type
```

```
  (* module rec mb *)
  | SgRecMod of loc and module_binding

  (* module type s = mt *)
  (* <:sig_item< module type $uid:id$ = $mtyp:mod_type$ >>
     module type declaration
  *)
  (**
     <:sig_item< module type $uid:id$ >> abstract module type
     -->
     <:sig_item< module type $uid:id$ = $mtyp:<:module_type< >>$ >>
  *)
  | SgMty of loc and string and module_type

  (* open i *)
  | SgOpn of loc and ident

  (* type t *)
  (* <:sig_item< type $typ:type$ >>  *)
 (** <:sig_item< type $lid:id$ $p1$ ... $pn$ = $t$ constraint $c1l$
     = $c1r$ ... constraint $cnl$ = $cnr$ >>

     type declaration
     SgTyp
     of Loc.t and (TyDcl of Loc.t and id and [p1;...;pn] and t and
     [(c1l, c1r); ... (cnl, cnr)]) *)
 | SgTyp of loc and ctyp

  (* value s : t *)
  (* <:sig_item< value $lid:id$ : $typ:type$ >>  *)
  | SgVal of loc and string and ctyp

  | SgAnt of loc and string (* $s$ *) ]
(** An exception is treated like a single type constructor. For
    exception declarations the type should be either a type
    identifier (TyId) or a type constructor (TyOf).

    Abstract module type declarations (i.e., module type
    declarations without equation) are represented with the empty
    module type.

    Mutually recursive type declarations (separated by
    and) are stored in a TyAnd tree. Use Ast.list_of_ctyp and
    Ast.tyAnd_of_list to convert to and from a list of type
    declarations.
```

```
      The quotation parser for types (<:ctyp< ... >>) does not parse
      type declarations. Type declarations must therefore be embedded
      in a sig_item or str_item quotation.

      There seems to be no antiquotation syntax for a list of type
      parameters and a list of constraints inside a type
      declaration. The existing form can only be used for a fixed
      number of type parameters and constraints.

      Complete class and class type declarations (including name and
      type parameters) are stored as class types.

      Several "and" separated class or class type declarations are
      stored in a CtAnd tree, use Ast.list_of_class_type and
      Ast.ctAnd_of_list to convert to and from a list of class
      types.  *)
and with_constr =
    (**
       with_constraint, with_constr, wc ::=
   | wc and wc
   | type t = t
   | module i = i
    *)
  [ WcNil of loc

    (* type t = t *)
    (* <:with_constr< type $typ:type_1$ = $typ:type_2$ >>  *)
    | WcTyp of loc and ctyp and ctyp

    (* module i = i *)
    (* <:with_constr< module $id:ident_1$ = $id:ident_2$ >>  *)
    | WcMod of loc and ident and ident

    (* type t := t *)
    | WcTyS of loc and ctyp and ctyp

    (* module i := i *)
    | WcMoS of loc and ident and ident

    (* wc and wc *)
    (* <:with_constr< $with_constr:wc1$ and $with_constr:wc2$ >> *)
    | WcAnd of loc and with_constr and with_constr

    | WcAnt of loc and string (* $s$ *)
]
  (** Several with-constraints are stored in an WcAnd tree. Use
      Ast.wcAnd_of_list and Ast.list_of_with_constr to convert from and
```

```
      to a list of with-constraints. *)
and binding =
  (**  binding, bi ::=
   | bi and bi
   | p = e *)
  [ BiNil of loc

    (* bi and bi *) (* let a = 42 and c = 43 *)
    (* <:binding< $b1$ and $b2$ >>  *)
    | BiAnd of loc and binding and binding

    (* p = e *) (* let patt = expr *)
    (* <:binding< $pat:pattern$ = $exp:expression$ >>
       <:binding< $p$ = $e$ >> ;; both are ok
    *)
    (**
       <:binding< $pat:f$ $pat:x$ = $exp:ex$ >>
       -->
       <:binding< $pat:f$ = fun $pat:x$ -> $exp:ex$ >>

       <:binding< $pat:p$ : $typ:type$ = $exp:ex$ >>
       typed binding -->
       <:binding< $pat:p$ = ( $exp:ex$ : $typ:type$ ) >>

       <:binding< $pat:p$ :> $typ:type$ = $exp:ex$ >>
       coercion binding -->
       <:binding< $pat:p$ = ( $exp:ex$ :> $typ:type$ ) >>
    *)
    | BiEq  of loc and patt and expr

    | BiAnt of loc and string (* $s$ *)
    (**
       The utility functions Camlp4Ast.biAnd_of_list and
       Camlp4Ast.list_of_bindings convert between the BiAnd tree of
       parallel bindings and a list of bindings.  The utility
       functions Camlp4Ast.binding_of_pel and pel_of_binding convert
       between the BiAnd tree and a pattern * expression lis
    *)  ]
and rec_binding =
    (** record bindings
        record_binding, rec_binding, rb ::=
        | rb ; rb
        | x = e
    *)
  [ RbNil of loc

    (* rb ; rb *)
```

```
    | RbSem of loc and rec_binding and rec_binding

    (* i = e
       very simple
    *)
    | RbEq  of loc and ident and expr

    | RbAnt of loc and string (* $s$ *)
    ]

  and module_binding =
    (**
       Recursive module bindings
       module_binding, mb ::=
       | (* empty *)
       | mb and mb
       | s : mt = me
       | s : mt
       | $s$
    *)
    [ MbNil of loc

    (* mb and mb *)  (* module rec (s : mt) = me and (s : mt) = me *)
    | MbAnd of loc and module_binding and module_binding

    (* s : mt = me *)
    | MbColEq  of loc and string and module_type and module_expr

    (* s : mt *)
    | MbCol  of loc and string and module_type

    | MbAnt of loc and string (* $s$ *) ]

and match_case =
    (**
       match_case, mc ::=
       | (* empty *)
       | mc | mc
       | p when e -> e
       | p -> e
    (* a sugar for << p when e1 -> e2 >> where e1 is the empty expression *)
    <:match_case< $list:mcs$ >>list of or-separated match casesAst.mcOr_of_list
    *)
    [
      (* <:match_case< >>  *)
      McNil of loc
```

```
    (* a | a *)
    (* <:match_case< $mc1$ | $mc2$ >>            *)
    | McOr of loc and match_case and match_case

    (* p (when e)? -> e *)
    (* <:match_case< $p$ -> $e$ >>    *)
    (* <:match_case< $p$ when $e1$ or $e2$ >>    *)
    | McArr of loc and patt and expr and expr

    (* <:match_case< $anti:s$ >>    *)
    | McAnt of loc and string (* $s$ *) ]

and module_expr =
    (**
        module_expression, module_expr, me ::=
      | (* empty *)
      | ident
      | me me
      | functor (s : mt) -> me
      | struct st end
      | (me : mt)
      | $s$
      | (value pexpr : ptype)
    *)
    [
      (* <:module_expr< >>  *)
      MeNil of loc

    (* i *)
    (* <:module_expr< $id:mod_ident$ >>  *)
    | MeId  of loc and ident

    (* me me *)
    (* <:module_expr< $mexp:me$ $mexp:me$ >>         Functor application *)
    | MeApp of loc and module_expr and module_expr

    (* functor (s : mt) -> me *)
    (* <:module_expr< functor ($uid:id$ : $mtyp:mod_type$) -> $mexp:me$ >>  *)
    | MeFun of loc and string and module_type and module_expr

    (* struct st end *)
   (* <:module_expr< struct $stri:str_item$ end >>  *)
    | MeStr of loc and str_item

    (* (me : mt) *)
    (* <:module_expr< ($mexp:me$ : $mtyp:mod_type$ ) >>
       signature constraint
```

```
    *)
    | MeTyc of loc and module_expr and module_type

    (* (value e) *)
    (* (value e : S) which is represented as (value (e : S)) *)
    (* <:module_expr< (value $exp:expression$ ) >>
       module extraction

       <:module_expr< (value $exp:expression$ : $mtyp:mod_type$ ) >>
       -->
       <:module_expr<
       ( value $exp: <:expr< ($exp:expression$ : (module $mtyp:mod_type$ ) ) >> $ )
       >>
    *)
    | MePkg of loc and expr

    (* <:module_expr< $anti:string$ >>          *)
    | MeAnt of loc and string (* $s$ *)

(** Inside a structure several structure items are packed into a StSem
    tree. Use Camlp4Ast.stSem_of_list and Camlp4Ast.list_of_str_item to
    convert from and to a list of structure items.

    The expression in a module extraction (MePkg) must be a type
    constraint with a package type. Internally the syntactic class of
    module types is used for package types.
*)
]
  and str_item =
    (**
        structure_item, str_item, st ::=
   | (* empty *)
   | class cice
   | class type cict
   | st ; st
   | #s
   | #s e
   | exception t or exception t = i
   | e
   | external s : t = s ... s
   | include me
   | module s = me
   | module rec mb
   | module type s = mt
   | open i
   | type t
   | value b or value rec bi
```

```
| $s$
 *)
 [ StNil of loc

 (* class cice *)
 (* <:str_item< class $cdcl:class_expr$ >>  *)
 | StCls of loc and class_expr

 (* class type cict *)
 (**
   <:str_item< class type $typ:class_type$ >>
    --> class type definition
 *)
 | StClt of loc and class_type

 (* st ; st *)
 (* <:str_item< $str_item_1$; $str_item_2$ >>  *)
 | StSem of loc and str_item and str_item

 (* # s or # s e *)
 (* <:str_item< # $string$ $expr$ >>  *)
 | StDir of loc and string and expr

 (* exception t or exception t = i *)
 (* <:str_item< exception $typ:type$ >>   -> None *)
 (* <:str_item< exception $typ:type$ >> ->
    Exception alias -> Some ident
 *)
 | StExc of loc and ctyp and meta_option(*FIXME*) ident

 (* e *)
 (* <:str_item< $exp:expr$ >> toplevel expression          *)
 | StExp of loc and expr

 (* external s : t = s ... s *)
 (* <:str_item< external $lid:id$ : $typ:type$ = $str_list:string_list$ >>  *)
 | StExt of loc and string and ctyp and meta_list string

 (* include me *)
 (* <:str_item< include $mexp:mod_expr$ >>  *)
 | StInc of loc and module_expr

 (* module s = me *)
 (* <:str_item< module $uid:id$ = $mexp:mod_expr$ >>  *)
 | StMod of loc and string and module_expr

 (* module rec mb *)
```

```
    (* <:str_item< module rec $module_binding:module_binding$ >>  *)
    | StRecMod of loc and module_binding

    (* module type s = mt *)
    (* <:str_item< module type $uid:id$ = $mtyp:mod_type$ >> *)
    | StMty of loc and string and module_type

    (* open i *)
    (* <:str_item< open $id:ident$ >>  *)
    | StOpn of loc and ident

    (* type t *)
    (* <:str_item< type $typ:type$ >>  *)
    (**
       <:str_item< type $lid:id$ $p1$ ... $pn$ = $t$
       constraint $c1l$ = $c1r$ ... constraint $cnl$ = $cnr$ >>
       -->
       StTyp of Loc.t and
       (TyDcl of Loc.t and id and [p1;...;pn] and t and [(c1l, c1r); ... (cnl, cnr)])
    *)
    | StTyp of loc and ctyp

    (* value (rec)? bi *)
    (* <:str_item< value $rec:r$ $binding$ >>          *)
    (* <:str_item< value rec $binding$ >> *)
    (* <:str_item< value  $binding$ >> *)
    | StVal of loc and rec_flag and binding

    (* <:str_item< $anti:s$ >>          *)
    | StAnt of loc and string (* $s$ *)
(**
   <:str_item< module $uid:id$ ( $uid:p$ : $mtyp:mod_type$ ) = $mexp:mod_expr$ >>
   ---->
   <:str_item< module $uid:id$ =
   functor ( $uid:p$ : $mtyp:mod_type$ ) -> $mexp:mod_expr$ >>

   <:str_item< module $uid:id$ : $mtyp:mod_type = $mexp:mod_expr$ >>
   ---->
   <:str_item< module $uid:id$ = ($mexp:mod_expr$ : $mtyp:mod_type ) >>

   <:str_item< type t >>
   ---->
   <:str_item< type t = $<:ctyp< >>$ >>

   <:str_item< # $id$ >> (directive without arguments)
   ---->
   <:str_item< # $a$ $<:expr< >>$ >>
```

```
  A whole compilation unit or the contents of a structure is given as
  *one* structure item in the form of a StSem tree.

  The utility functions Camlp4Ast.stSem_of_list and
  Camlp4Ast.list_of_str_item convert from and to a list of structure
  items.

  An exception is treated like a single type constructor. For
  exception definitions the type should be either a type identifier
  (TyId) or a type constructor (TyOf). For execption aliases it
  should only be a type identifier (TyId).

  Abstract types are represented with the empty type.

  Mutually recursive type definitions (separated by and) are stored
  in a TyAnd tree. Use Ast.list_of_ctyp and Ast.tyAnd_of_list to
  convert to and from a list of type definitions.

  The quotation parser for types (<:ctyp< ... >>) does not parse type
  declarations. Type definitions must therefore be embedded in a
  sig_item or str_item quotation.

  There seems to be no antiquotation syntax for a list of type
  parameters and a list of constraints inside a type definition. The
  existing form can only be used for a fixed number of type
  parameters and constraints.

  Complete class type definitions (including name and type
  parameters) are stored as class types.

  Several "and" separated class type definitions are stored in a
  CtAnd tree, use Ast.list_of_class_type and Ast.ctAnd_of_list to
  convert to and from a list of class types.

  Several "and" separated classes are stored in a CeAnd tree, use
  Ast.list_of_class_exprand Ast.ceAnd_of_list to convert to and from
  a list of class expressions.

  Several "and" separated recursive modules are stored in a MbAnd
  tree, use Ast.list_of_module_binding and Ast.mbAnd_of_list to
  convert to and from a list of module bindings.

  Directives without argument are represented with the empty
  expression argument.  *)
]
```

```
and class_type =
  (** Besides class types, ast nodes of this type are used to
      describe *class type definitions*
      (in structures and signatures)
      and class declarations (in signatures).

      class_type, ct ::=
    | (* empty *)
    | (virtual)? i ([ t ])?
    | [t] -> ct
    | object (t) csg end
    | ct and ct
    | ct : ct
    | ct = ct
    | $s$
     *)
  [ CtNil of loc

    (* (virtual)? i ([ t ])? *)
    (* <:class_type< $virtual:v$ $id:ident$ [$list:p$ ] >> *)
    (* instanciated class type/ left hand side of a class *)
    (* declaration or class type definition/declaration  *)
    | CtCon of loc and virtual_flag and ident and ctyp

    (* [t] -> ct *)
    (* <:class_type< [$typ:type$] -> $ctyp:ct$ >>
         class type valued function
    *)
    | CtFun of loc and ctyp and class_type

    (* object ((t))? (csg)? end *)
    (* <:class_type< object ($typ:self_type$) $csg:class_sig_item$ end >> *)
    (* class body type *)
    | CtSig of loc and ctyp and class_sig_item

    (* ct and ct *)
    (* <:class_type< $ct1$ and $ct2$ >> *)
    (* mutually recursive class types *)
    | CtAnd of loc and class_type and class_type

    (* ct : ct *)
    (* <:class_type< $decl$ : $ctyp:ct$ >> *)
    (* class  c : object .. end   class declaration as in
       "class c: object .. end " in a signature
    *)
    | CtCol of loc and class_type and class_type
```

```
    (* ct = ct *)
    (* <:class_type< $decl$ = $ctyp:ct$ >> *)
    (* class type declaration/definition as in "class type c = object .. end " *)
    | CtEq  of loc and class_type and class_type


    (* $s$ *)
    | CtAnt of loc and string
    (**
       <:class_type< $id:i$ [ $list:p$] >>
       --->
       <:class_type< $virtual:Ast.BFalse$ $id:i$ [ $list:p$] >>

       <:class_type< $virtual:v$ $id:i$ >>
       --->
       <:class_type< $virtual:v$ $id:i$ [ $<:ctyp< >>$ ] >>

       <:class_type< object $x$ end >>
       --->
       <:class_type< object ($<:ctyp< >>$) $x$ end >>
    *)
(** CtCon is used for possibly instanciated/parametrized class
    type identifiers. They appear on the left hand side of class
    declaration and class definitions or as reference to existing
    class types. In the latter case the virtual flag is probably
    irrelevant.


    Several type parameters/arguments are stored in a TyCom tree, use
    Ast.list_of_ctyp and Ast.tyCom to convert to and from list of
    parameters/arguments.

    An empty type parameter list and an empty type argument is
    represented with the empty type.

    The self binding in class body types is represented by a type
    expression. If the self binding is absent, the empty type
    expression (<:ctype< >>) is used.

    Several class signature items are stored in a CgSem tree, use
    Ast.list_of_class_sig_item and Ast.cgSem_of_list to convert to and
    from a list of class signature items

*)
]
  and class_sig_item =
    (**
```

```
    class_signature_item, class_sig_item, csg ::=
| (* empty *)
| type t = t
| csg ; csg
| inherit ct
| method s : t or method private s : t
| value (virtual)? (mutable)? s : t
| method virtual (mutable)? s : t
| $s$
 *)
 [

   (* <:class_sig_item< >>  *)
   CgNil of loc

 (* <:class_sig_item< constraint $typ:type1$ = $typ:type2$ >>
    type constraint  *)
 | CgCtr of loc and ctyp and ctyp

 (* csg ; csg *)
 | CgSem of loc and class_sig_item and class_sig_item

 (* inherit ct *)
 (* <:classs_sig_item< inherit $ctyp:class_type$ >>  *)
 | CgInh of loc and class_type

 (* method s : t or method private s : t *)
 (* <:class_sig_item< method $private:pf$ $lid:id$:$typ:type$ >>    *)
 | CgMth of loc and string and private_flag and ctyp

 (* value (virtual)? (mutable)? s : t *)
 (* <:class_sig_item< value $mutable:mf$ $virtual:vf$ $lid:id$ : $typ:type$ >>  *)
 | CgVal of loc and string and mutable_flag and virtual_flag and ctyp

 (* method virtual (private)? s : t *)
 (* <:class_sig_item< method virtual $private:pf$ $lid:id$ : $typ:type$ >>   *)
 | CgVir of loc and string and private_flag and ctyp

 (* <:class_sig_item< $anti:a$ >>    *)
 | CgAnt of loc and string (* $s$ *)

 (**
    <:class_sig_item< type $typ:type_1$ = $typ:type_2$
    --->
    <:class_sig_item< constraint $typ:type_1$ = $typ:type_2$ >>

    The empty class signature item is used as a placehodler in
```

```
       empty class body types (class type e = object end )
    *)
]
and class_expr =
  (** Ast nodes of this type are additionally used to describe whole
      (mutually recursive) class definitions.


      class_expression, class_expr, ce ::=
   | (* empty *)
   | ce e
   | (virtual)? i ([ t ])?
   | fun p -> ce
   | let (rec)? bi in ce
   | object (p) (cst) end
   | ce : ct
   | ce and ce
   | ce = ce
   | $s$
  *)
  [
    CeNil of loc

    (* ce e *)
    (*
      <:class_expr< $cexp:ce$ $exp:exp$ >>

      application
    *)
    | CeApp of loc and class_expr and expr

    (* (virtual)? i ([ t ])? *)
    (* <:class_expr< $virtual:vf$ $id:ident$
       [ $typ:type_param$ ] >>

       instanciated class/ left hand side of class
       definitions.

       CeCon of Loct.t and vf and ident and type_param
    *)
    | CeCon of loc and virtual_flag and ident and ctyp

    (* fun p -> ce *)
    (* <:class_expr< fun $pat:pattern$ -> $cexp:ce$ >>
       class valued funcion

       CeFun of Loc.t and pattern and ce
```

```
*)
| CeFun of loc and patt and class_expr

(* let (rec)? bi in ce *)
(* <:class_expr< let $rec:rf$ $binding:binding$ in $cexp:ce$ >>  *)
| CeLet of loc and rec_flag and binding and class_expr

(* object ((p))? (cst)? end *)
(* <:class_expr< object ( $pat:self_binding$ ) $cst:class_str_items$ end >> *)
| CeStr of loc and patt and class_str_item

(* ce : ct
   type constraint
   <:class_expr< ($cexp:ce$ : $ctyp:class_type$) >>
*)
| CeTyc of loc and class_expr and class_type

(* ce and ce
   mutually recursive class definitions
*)
| CeAnd of loc and class_expr and class_expr

(**
   <:class_expr< $ci$ = $cexp:ce$ >>
   class definition as in class ci = object .. end
*)
| CeEq  of loc and class_expr and class_expr

(* $s$ *)
(** <:class_expr< $anti:s$ >> *)
| CeAnt of loc and string
(**
   <:class_expr< $id:id$ [$tp$] >>
   ----> non-virtual class/ instanciated class
   <:class_expr< $virtual:Ast.BFalse$ $id:id$ [$tp$ ] >>

   <:class_expr< $virtual:vf$ $id:id$ >>
   ---->
   <:class_expr< $virtual:vf$ $id:id$ [ $<:ctyp< >>$ ] >>

   <:class_expr< fun $pat:p1$ $pat:p2$ -> $cexp:ce$ >>
   ---->
   <:class_expr< fun $pat:p1$ -> fun $pat:p2$ -> $cexp:ce$ >>

   <:class_expr< let $binding:bi$ in $cexp:ce$ >>
   ---->
   <:class_expr< let $rec:Ast.BFalse$ $binding:bi$ in $cexp:ce$ >>
```

```
      <:class_expr< let $rec:Ast.BFalse$ $binding:bi$ in $cexp:ce$ >>
      ----->
      <:class_expr< object ( $<:patt< >>$ ) $cst:cst$ end >>
   *)
(** No type parameters or arguments in an instanciated class
   (CeCon) are represented with the empty type (TyNil).

   Several type parameters or arguments in an instanciated class
   (CeCon) are stored in a TyCom tree. Use Ast.list_of_ctyp and
   Ast.tyCom_of_list convert to and from a list of type parameters.

   There are three common cases for the self binding in a class
   structure: An absent self binding is represented by the
   empty pattern (PaNil).  An identifier (PaId) binds the
   object.  A typed pattern (PaTyc) consisting of an identifier
   and a type variable binds the object and the self type.

   More than one class structure item are stored in a CrSem
   tree. Use Ast.list_of_class_str_item and Ast.crSem_of_list to
   convert to and from a list of class items.
*)
]
and class_str_item =
   (**
      class_structure_item, class_str_item, cst ::=
  | (* empty *)
  | cst ; cst
  | type t = t
  | inherit(!)? ce (as s)?
  | initializer e
  | method(!)? (private)? s : t = e or method (private)? s = e
  | value(!)? (mutable)? s = e
  | method virtual (private)? s : t
  | value virtual (private)? s : t
  | $s$
   *)
 [
   CrNil of loc

   (* cst ; cst *)
   | CrSem of loc and class_str_item and class_str_item

   (* type t = t *)
   (* <:class_str_item< constraint $typ:type_1$ = $typ:type_2$ >>
      type constraint
   *)
```

```
    | CrCtr of loc and ctyp and ctyp

    (* inherit(!)? ce (as s)? *)
    (* <:class_str_item< inherit $!:override$ $cexp:class_cexp$ as $lid:id$ >>  *)
    | CrInh of loc and override_flag and class_expr and string

    (* initializer e *)
    (* <:class_str_item< initializer $exp:expr$ >>  *)
    | CrIni of loc and expr

    (** method(!)? (private)? s : t = e or method(!)? (private)? s = e *)
    (** <:class_str_item< method $!override$ $private:pf$ $lid:id$: $typ:poly_type$ =
        $exp:expr$ >>
    *)
    | CrMth of loc and string and override_flag and private_flag and expr and ctyp

    (* value(!)? (mutable)? s = e *)
    (** <:class_str_item< value $!:override$ $mutable:mf$ $lid:id$ = $exp:expr$ >>
       instance variable
    *)
    | CrVal of loc and string and override_flag and mutable_flag and expr

    (** method virtual (private)? s : t *)
    (** <:class_str_item< method virtual $private:pf$ $lid:id$ : $typ:poly_type$ >>
       virtual method
    *)
    | CrVir of loc and string and private_flag and ctyp

    (* value virtual (mutable)? s : t *)
    (* <:class_str_item< value virtual $mutable:mf$ $lid:id$ : $typ:type$ >> *)
    (* virtual instance variable  *)
    | CrVvr of loc and string and mutable_flag and ctyp

    | CrAnt of loc and string (* $s$ *)

(**
   << constraint $typ:type_1$ = $typ:type_2$ >>
   ----> type constraint
   << type $typ:type1$ = $typ:type2$ >>

   << inherit $!:override$ $cexp:class_exp$ >>
   ---> superclass without binding
   << inherit $!:override$ $cexp:class_exp$ as $lid:""$ >>

   <<inherit $cexp:class_exp$ as $lid:id$ >>
   ---> superclass without override
   <<inherit $!:Ast.OvNil$ $cexp:class_exp$ as $lid:id$ >>
```

```
<:class_str_item< method $private:pf$ $lid:id$ : $typ:poly_type$ = $exp:expr$ >>
non-overriding method
<:class_str_item< method $!:Ast.OvNil$
$private:pf$ $lid:id$ : $typ:poly_type$ = $exp:expr$ >>

<:class_str_item< method $private:pf$ $lid:id$ = $exp:expr$ >>
monomorphic method
<:class_str_item< method $private:pf$ $lid:id$ : $typ:<:ctyp< >>$ = $exp:expr$ >>

<:class_str_item< method $lid:id$ : $typ:poly_type$ = $exp:expr$ >>
public method
<:class_str_item< method $private:Ast.PrNil$ $lid:id$ : $typ:poly_type$ = $exp:expr$ >>

<:class_str_item< method $private:pf$ $lid:id$ :
$typ:poly_type$ $pat:pattern$ = $exp:expr$ >>
method arguments
<:class_str_item< method $private:pf$ $lid:id$ :
$typ:poly_type$ = fun $pat:pattern$ -> $exp:expr$ >>

<:class_str_item< method $private:pf$ $lid:id$ :
$typ:poly_type$ : $typ:res_type$ = $exp:expr$ >>
return type constraint
<:class_str_item< method $private:pf$ $lid:id$ :
$typ:poly_type$ = ($exp:expr$ : $typ:res_type$) >>

<:class_str_item< method $private:pf$ $lid:id$ :
$typ:poly_type$ :> $typ:res_type$ = $exp:expr$ >>
return type coercion
<:class_str_item< method $private:pf$ $lid:id$ :
$typ:poly_type$ = ($exp:expr$ :> $typ:res_type$ ) >>

<:class_str_item< value $mutable:mu$ $lid:id$ = $exp:expr$ >>
non-overriding instance variable
<:class_str_item< value $!:Ast.OvNil$ $mutable:mf$ $lid:id$ = $exp:expr$ >>

<:class_str_item< value $!:override$ $lid:id$ = $exp:expr$ >>
immutable instance variable
<:class_str_item< value $!:override$ $mutable:Ast.MuNil$ $lid:id$ = $exp:expr$ >>

<:class_str_item< value $!:override$ $mutable:mf$ $lid:id$ :
$typ:res_type$ = $exp:expr$ >>
type restriction<:class_str_item
< value $!:override$ $mutable:mf$ $lid:id$ =
($exp:expr$ : $typ:res_type$) >>

<:class_str_item< value $!:override$ $mutable:mf$ $lid:id$ :>
```

```
   $typ:res_type$ = $exp:expr$ >>
   simple value coercion
   <:class_str_item< value $!:override$ $mutable:mf$ $lid:id$ =
   ($exp:expr$ :> $typ:res_type$) >>

   <:class_str_item< value $!:override$ $mutable:mf$ $lid:id$ :
   $typ:expr_type$ :> $typ:res_type$ = $exp:expr$ >>
   complete value coercion
   <:class_str_item< value $!:override$ $mutable:mf$ $lid:id$ =
   ($exp:expr$ : $typ:expr_type$ :> $typ:res_type$) >>

   <:class_str_item< method virtual $lid:id$ : $typ:poly_type$ >>
   public virtual method
   <:class_str_item< method $private:Ast.PrNil$ virtual $lid:id$ : $typ:poly_type$ >>

   <:class_str_item< value $!:override$ virtual $lid:id$ : $typ:type$ >>
   immutable virtual value
   <:class_str_item< value $!:override$ virtual $mutable:Ast.MuNil$ $lid:id$
   : $typ:type$ >>

   A missing superclass binding is represented with the empty string
   as identifier.  Normal methods and explicitly polymophically typed
   methods are represented with the same ast node (CrMth). For a normal
   method the poly_type field holds the empty type (TyNil).
*)
];
```

Listing 32: Camlp4 Ast Definition

4.3.8 TestFile

Some test files are pretty useful(in the distribution of camlp4) like `test/fixtures/macro_test.ml`.

4.4 Extensible Parser

Camlp4's extensible parser is deeply combined with its own lexer, use menhir if it is very complex and not ocaml-oriented. It is very hard to debug in itself. So I suggest it is used to do simple ocaml-oriented parsing.

4.4.1 Examples

Listing 33 is a simple calculator example using camlp4 parser

```
open Camlp4.PreCast

let parser_of_entry entry  s =
  try Gram.parse entry (Loc.mk "<string>") (Stream.of_string  s)
  with
    Loc.Exc_located(loc, e) -> begin
      prerr_endline (Loc.to_string loc);
      let start_bol,stop_bol,
        start_off, stop_off =
        Loc.( start_bol loc,
             stop_bol loc,
             start_off loc,
             stop_off loc
            ) in
      let abs_start_off = start_bol + start_off in
      let abs_stop_off = stop_bol + stop_off in
      let err_location = String.sub s abs_start_off
          (abs_stop_off - abs_start_off + 1) in
      prerr_endline (sprintf "err: ^%s^" err_location);
      raise e ;
    end


let expr = Gram.Entry.mk "expr"
let expr_eoi = Gram.Entry.mk "expr_eoi"

let _ = begin
  EXTEND Gram GLOBAL: expr expr_eoi;
  expr_eoi:
    [ [x = expr ; `EOI -> x ] ];
  expr:
    [
     "add"
       [  x = SELF ; "+"; y = SELF -> x + y
```

```
      |  x = SELF ; "-"; y = SELF -> x - y]
    |"mult"
      [  x = SELF ; "*"; y = SELF -> x * y
      |  x = SELF ; "/"; y = SELF -> x / y]
    | "pow" RIGHTA
      [ x = SELF ; "**"; y = SELF -> int_of_float (float x ** float y)]
    |"simple"
     [ "("; x = SELF; ")" -> x
     | `INT(x,_) -> x ]
];
  END;
end

let parse_expr = parser_of_entry expr
let parse_expr_eoi = parser_of_entry expr_eoi
```

Listing 33: Simple Calc Parser

For oco (Listing 19) in **toplevel** , extensible parser works quite well in original syntax, so if you don't do quasiquoation in toplevel, feel free to use original syntax as a parser.

Some keywords for extensible paser

```
1  EXTEND END  LIST0 LIST1 SEP TRY SELF OPT  FIRST LAST  LEVEL AFTER BEFORE
```

Listing 34: CAMLP4 KEYWORDS

SELF represents either the **current level**, **the next level** or the **first level** depending on the **associativity** and the **position** of the SELF in the rule .

The identifier NEXT, which is a call to the next level of the current entry.

4.4.2 Mechanism

There are four generally four phases

I collection of new keywords, and update of the lexer associated to the grammar

II representation of the grammar as a tree data structure

III left-factoring of each precedence level

When there's a common perfix of symblos(a symbol is a keyword, token, or

entry), the parser does not branch until the common parser has been parsed. **that's how grammars are implemented, first the corresponding tree is generated, then the parser is generated for the tree.**

IV Greedy first

When one rule is a prefix of another. A token or keyword is *preferred* over epsilon, the empty string (this also holds for other ways that a grammar can match epsilon) factoring happens when the parser is built .

V Explicit token or keyword *trumps* an entry. So you have two prductions, with the same prefix, except the last one. one is another entry, and the other is a token, The parser will *first* try the token, if it succeeds, it stops, otherwise they try the entry. This sounds weird, but it is *reasonable*, after left-factorization, the parser *pays no cost* when it tries just a token, it's amazing that even more tokens, the token rule *still wins*, and even the token rule fails after consuming some tokens, it can *even* transfer to the entry rule. To notice, it seems that after factorization, the rule order *may* be changed.

VI the data structure representing the grammar is then passed as argument to a generic parser

It's really hard to understand how it really works. Here are some experiments I did. Listing 35 is a example to show how smart camlp4 is .

Listing 35: Smart Camlp4 Parser

All the dispatch magic hides in `Gram.extend` function (or `Insert.extend` function)]camlp4/Camlp4/Struct/Grammar/Insert.ml

```
    value extend entry (position, rules) =
      let elev = levels_of_rules entry position rules in
      do {
        entry.edesc := Dlevels elev;
        entry.estart :=
          fun lev strm ->
            let f = Parser.start_parser_of_entry entry in
            do { entry.estart := f; f lev strm };
        entry.econtinue :=
          fun lev bp a strm ->
            let f = Parser.continue_parser_of_entry entry in
            do { entry.econtinue := f; f lev bp a strm }
      };
```

Listing 36: Gram Extend

Factoring *only* happens in the same level within a rule.

You can do explicit backtracking by *npeek trick* (Listing 37), then you can switch to another branch by peeking some elements.

```
(* -*- Mode:caml; -*-
   *===----------------------------------------------------------------------===
   * Version: $Id: first.ml,v 0.0 2012/03/05 06:24:45 bobzhang1988 Exp $
   *===----------------------------------------------------------------------===*)
open Printf
open Camlp4.PreCast

let pr = Gram.Entry.print
let expr = Gram.Entry.mk "expr"
let test = Gram.Entry.of_parser "test"
  (fun strm ->
    match Stream.npeek 2 strm with
    |  [_ ; KEYWORD "xyzzy", _ ] -> raise Stream.Failure
    | _ -> ())

let _ = begin
  EXTEND Gram GLOBAL:expr ;
  g : [[ "plugh" ]] ;
  f1 : [[ g ; "quux" ]];
  f2 : [[g ; "xyzzy"]] ;
  expr :
    [[test ; f1 -> print_endline "1" | f2 -> print_endline "2" ]] ;
  END ;
  pr Format.std_formatter expr;
  Gram.parse_string expr (Loc.mk "<string>") "plugh xyzzy"
```

```
end
```

Listing 37: Explicit backtracking

Now we have a look at how left factorization is performed

(I) Left Factorization

Take rules as follows as an example

```
    "method"; "private"; "virtual"; l = label; ":"; t = poly_type
    "method"; "virtual"; "private"; l = label; ":"; t = poly_type
    "method"; "virtual"; l = label; ":"; t = poly_type
    "method"; "private"; l = label; ":"; t = poly_type; "="; e = expr
    "method"; "private"; l = label; sb = fun_binding
    "method"; l = label; ":"; t = poly_type; "="; e = expr
    "method"; l = label; sb = fun_binding
```

The rules are inserted in a tree and the result looks like:

```
"method"
   |-- "private"
   |       |-- "virtual"
   |       |       |-- label
   |       |             |-- ":"
   |       |                  |-- poly_type
   |       |-- label
   |             |-- ":"
   |             |    |-- poly_type
   |             |            |-- ":="
   |             |                 |-- expr
   |             |-- fun_binding
   |-- "virtual"
   |       |-- "private"
   |       |       |-- label
   |       |             |-- ":"
   |       |                  |-- poly_type
   |       |-- label
   |             |-- ":"
   |                  |-- poly_type
   |-- label
         |-- ":"
         |    |-- poly_type
         |            |-- "="
         |                 |-- expr
         |-- fun_binding
```

This tree is built as long as rules are inserted.

(II) *start and continue* At each entry level, the rules are separated into **two trees**:

(a) The tree of the rules not starting with neither the current entry name nor by "SELF"(start)

(b) The tree of the rules starting with the current entry or by SELF, this symbol **itself not being included** in the tree

They determine two functions :

(a) The function named "start", analyzing the first tree

(b) The function named "continue", taking, as parameter, a value previously parsed, and analyzing the second tree.

A call to an entry, correspond to a call to the **"start"** function of the **"first"** level of the entry.

For the "start", it tries its tree, if it works, it calls the "continue" function of the same level, giving the result of "start" as parameter. If this "continue" fails, return itself. (continue may do some more interesting stuff). If the "start" function fails, the "start" of the next level is tested until it fails.

For the "continue", it first tries the "continue" function of the **next** level. (here + give into *), if it fails or it's the last level, it then tries itself, giving the result as parameter. If it still fails, return its extra parameter.

A special case for rules ending with SELF or the current entry name. For this last symbol, there's a call to the "start" function of **the current level (RIGHTA) or the next level (OTHERWISE)**

When a SELF or the current entry name is encountered in the middle of the rule, there's a call to the start of the **first level** of the current entry.

Each entry has a start and continue

```
(* list of symbols, possible empty *)
LIST0 : LIST0 rule | LIST0 [ <rule definition> -> <action> ]
(* with a separator *)
LIST0 : LIST0 rule SEP <symbol>
| LIST0 [<rule definition > -> <action>] SEP <symbol>
  LIST1 rule
| LIST1 [<rule definition > -> <action > ]
| LIST1 rule SEP <symbol>
| LIST1 [<rule definition > -> <action >] SEP <symbol>
OPT <symbol>
SELF
TRY (* backtracking *)
FIRST LAST LEVEL level, AFTER level, BEFORE level
```

4.4.3 Parsing OCaml using Camlp4

Fully Utilize Camlp4 Parser and Printers

If we want to define our special syntax, we could do it like this Listing 38.

Here we see we could get any parser, any printer we want, very convenient. Notice `Gram.Entry` is **dynamic, extensible**

Otags Mini

```
open Camlp4.PreCast ;
open BatPervasives ;
module MySyntax = Camlp4.OCamlInitSyntax.Make Ast Gram Quotation ;
module M = Camlp4OCamlRevisedParser.Make MySyntax ;
(** load quotation parser *)
module M4 = Camlp4QuotationExpander.Make MySyntax ;

(** in toplevel, I did not find a way to introduce such module
    because it will change the state
    module N = Camlp4OCamlParser.Make MySyntax ;
    load o parser
*)

value my_parser = MySyntax.parse_implem;
value str_items_of_file file_name =
  file_name
  |> open_in
  |> BatStream.of_input
  |> my_parser (Loc.mk file_name)
```

```
    |> flip Ast.list_of_str_item [] ;

(** it has ambiguity in original syntax, so pattern match
    will be more natural in revised syntax
*)
value rec do_str_item str_item tags =
  match str_item with
  [ <:str_item< value $rec:_$ $binding$ >> ->
        let bindings = Ast.list_of_binding binding []
        in List.fold_right do_binding bindings tags
  |_ -> tags ]
and do_binding bi tags =
  match bi with
  [ <:binding@loc< $lid:lid$ = $_$ >> ->
    let line = Loc.start_line loc in
    let off = Loc.start_off loc in
    let pre = "let " ^ lid in
    [(pre,lid,line,off) :: tags ]
  | _ -> tags ];


value do_fn file_name =
    file_name
    |> str_items_of_file
    |> List.map (flip do_str_item [])
    |> List.concat ;
(**use MSyntax.parse_implem*)
value _ =
  do_fn "parser.ml"
  |> List.iter (fun (a, b, c, d) -> Printf.printf "%s-%s %d-%d \n" a b c d)  ;

(** output
   let my_parser-my_parser 14-423
   let str_items_of_file-str_items_of_file 15-464
   let do_str_item-do_str_item 25-733
   let do_binding-do_binding 31-958
   let do_fn-do_fn 41-1204
*)
```

Listing 39: Otags Mini

We use *OCamlInitSyntax.Make* instead of *MakeSyntax*, since it will introduce unnecessary abstraction type, which makes sharing code difficult.

Actually, we can use camlp4 parser to parse interfaces as well

```
let sig =
  let str = eval ‘‘moduleX = Camlp4.PreCast;;’’
  and _loc = Loc.ghost in
  Stream.of_string str |> Syntax.parse_intef _loc
```

Parsing Json AST

```
(** The problem for the toplevel is that you can not find the library
    of the parser?  Even if you succeed, it may change the hook of toplevel,
    not encouraged yet.
*)
open Camlp4.PreCast;

(** Set to Original Parser *)
module MSyntax=
    (Camlp4OCamlParser.Make
    (Camlp4OCamlRevisedParser.Make
    (Camlp4.OCamlInitSyntax.Make Ast Gram Quotation)));

(** Two styles of printers *)
module OPrinters = Camlp4.Printers.OCaml.Make(MSyntax);
module RPrinters = Camlp4.Printers.OCamlr.Make(MSyntax);


value  parse_exp = MSyntax.Gram.parse_string MSyntax.expr
  (MSyntax.Loc.mk "<string>");

(** Object-oriented paradigm *)
value print_expo =  (new OPrinters.printer ())#expr Format.std_formatter;
value print_expr = (new RPrinters.printer ())#expr Format.std_formatter;
value (|>) x f = f x;

value parse_and_print str = str
  |> parse_exp
  |> (fun x -> begin
    print_expo x;
    Format.print_newline ();
    print_expr x ;
    Format.print_newline ();
  end );

begin
  List.iter parse_and_print
    ["let a = 3 in fun x -> x + 3  ";
     "fun x -> match x with Some  y -> y | None -> 0 ";
    ];
end ;

(**
   output
let a = 3 in fun x -> x + 3
let a = 3 in fun x -> x + 3
fun x -> match x with | Some y -> y | None -> 0
fun x -> match x with [ Some y -> y | None -> 0 ]
*)
```

Listing 38: Camlp4 Self Parser Printer

4.5 STREAM PARSER

Here are some simple examples of stream parser, it's not powerful as camlp4 but lightweight.

```
let rec p = parser [< '"foo"; 'x ; '"bar">] -> x | [< '"baz"; y = p >] -> y;;
val p : string Batteries.Stream.t -> string = <fun>
```

```
camlp4of  -str "let rec p = parser [< '\"foo\"; 'x ; '\"bar\">] -> x | [< '\"baz\"; y = p >] -> y;;"
(** output
   normal pattern : first peek, then junk it
*)
let rec p (__strm : _ Stream.t) =
  match Stream.peek __strm with
  | Some "foo" ->
      (Stream.junk __strm;
       (match Stream.peek __strm with
        | Some x ->
            (Stream.junk __strm;
             (match Stream.peek __strm with
              | Some "bar" -> (Stream.junk __strm; x)
              | _ -> raise (Stream.Error ""))))
        | _ -> raise (Stream.Error "")))
  | Some "baz" ->
      (Stream.junk __strm;
       (try p __strm with | Stream.Failure -> raise (Stream.Error "")))
  | _ -> raise Stream.Failure
camlp4of -str "let rec p = parser [< x = q >] -> x | [< '\"bar\">] -> \"bar\""
(** output  *)
let rec p (__strm : _ Stream.t) =
  try q __strm
  with
  | Stream.Failure -> (* limited backtracking *)
      (match Stream.peek __strm with
       | Some "bar" -> (Stream.junk __strm; "bar")
       | _ -> raise Stream.Failure)
```

4.6 Grammar

We can Re-Raise the exception so it gets *printed* using *Printexc* . A literal string (like "foo") indicates a **KEYWORD** token. Using it in a grammar **registers the keyword** with the lexer. When it is promoted as a key word, it will no longer be used as a **LIDENT**, so for example, the parser parser, will **break some valid programs** before, because **parser** is now a keyword. This is the convention, to make things simple, you can find other ways to overcome the problem, but it's too complicated. you can also say (x= KEYWORD) or pattern match syntax ('LINDENT x) to get the actual token constructor. The parser **ignores** extra tokens after a success.

LEVELS They can be labeled following an entry, like *expr LEVEL "mul"*. However, explicitly specifying a level when calling an entry might *defeat* the start/continue mechanism.

NEXT LIST0 SEP OPT TRY NEXT refers to the entry being defined at the following level regardless of assocaitivity or position. LIST0 elem SEP sep . Both LIST0 and OPT can match the epsilon, but its *priority* is lower. For TRY, non-local backtracking, a *Stream.Error* will be *converted* to a *Stream.Failure*.

```
1    expr : [[ TRY f1 -> "f1" | f2 -> "f2" ]]
```

Nested rule (only one level can be applied)

```
1    [x = expr ; ["+" | "plus" ]; y = expr -> x + y ]
```

EXTEND is an expression (of type unit)
It can be evaluated at toplevel, but also inside a function, when the syntax extension takes place when the function is called.

Translated sample code (Listing 40)

```
open Camlp4.PreCast
module MGram = MakeGram(Lexer)
EXTEND MGram
   GLOBAL: m_expr ;
    m_expr :
     [[ "foo"; f  -> print_endline "first"
      | "foo" ; "bar"; "bax" -> print_endline "second"]
```

```
    ];
    f : [["bar"; "baz" ]];  END;;


(** translated code output
open Camlp4.PreCast
module MGram = MakeGram(Lexer)
let _ =
  let _ = (m_expr : 'm_expr MGram.Entry.t) in
  let grammar_entry_create = MGram.Entry.mk in
  let f : 'f MGram.Entry.t = grammar_entry_create "f"
  in
    (MGram.extend (m_expr : 'm_expr MGram.Entry.t)
       ((fun () ->
           (None,
            [ (None, None,
               [ ([ MGram.Skeyword "foo"; MGram.Skeyword "bar";
                    MGram.Skeyword "bax" ],
                  (MGram.Action.mk
                     (fun _ _ _ (_loc : MGram.Loc.t) ->
                        (print_endline "second" : 'm_expr))));
                 ([ MGram.Skeyword "foo";
                    MGram.Snterm (MGram.Entry.obj (f : 'f MGram.Entry.t)) ],
                  (MGram.Action.mk
                     (fun _ _ (_loc : MGram.Loc.t) ->
                        (print_endline "first" : 'm_expr)))) ]) ]))
         ());
     MGram.extend (f : 'f MGram.Entry.t)
       ((fun () ->
           (None,
            [ (None, None,
               [ ([ MGram.Skeyword "bar"; MGram.Skeyword "baz" ],
                  (MGram.Action.mk
                     (fun _ _ (_loc : MGram.Loc.t) -> (() : 'f)))) ]) ]))
         ()))
*)
```

Listing 40: Gram Transform output

If there are unexpected symbols after a correct expression, the trailing symbols are ignored.

```
1    let expr_eoi = Grammar.Entry.mk "expr_eoi" ;;
2    EXTEND expr_eoi : [[ e = expr ; EOI -> e]]; END ;;
```

The keywords are stored *in a hashtbl*, so it can be updated `dynamically`.

4.6.1 LEVEL

```
rule ::= list-of-symbols-seperated-by-semicolons -> action
level ::=  optional-label optional-associativity
[list-of-rules-operated-by-bars]
entry-extension ::=
identifier : optional-position  [ list-of-levels-seperated-by-bars ]
optional-position ::= FIRST | LAST | BEFORE label | AFTER label |
LEVEL label
```

4.6.2 Grammar Modification

When you extend an entry, by default the first level of the extension extends the first level of the entry. Listing 41 lists different usage of *EXTEND, EXTEND LAST, EXTEND LEVEL, EXTEND BEFORE.*

```
(* -*- Mode:caml; -*-
   *===----------------------------------------------------------------------===
   * Version: $Id: first.ml,v 0.0 2012/03/05 15:53:38 bobzhang1988 Exp $
   *===----------------------------------------------------------------------===*)
open Camlp4.PreCast
module MGram = MakeGram(Lexer)

let test = MGram.Entry.mk "test"
let p = MGram.Entry.print


let _ = begin
  MGram.Entry.clear test;
  EXTEND MGram GLOBAL: test;
  test:
    ["add" LEFTA
        [SELF; "+" ; SELF | SELF; "-" ; SELF]
    | "mult" RIGHTA
        [SELF; "*" ; SELF | SELF; "/" ; SELF]
    | "simple" NONA
        [ "("; SELF; ")"  | INT ] ];
  END;
  p Format.std_formatter test;
end

(** output
 test: [ "add" LEFTA
        [ SELF; "+"; SELF
```

```
        | SELF; "-"; SELF ]
      | "mult" RIGHTA
        [ SELF; "*"; SELF
        | SELF; "/"; SELF ]
      | "simple" NONA
        [ "("; SELF; ")"
        | INT ((_)) ] ]

*)


let _ = begin
  EXTEND MGram GLOBAL: test;
    test: [[ x = SELF ; "plus1plus" ; y = SELF ]];
  END ;
  p Format.std_formatter test
end
(** output
test: [ "add" LEFTA
    [ SELF; "plus1plus"; SELF
  | SELF; "+"; SELF
  | SELF; "-"; SELF ]
| "mult" RIGHTA
  [ SELF; "*"; SELF
  | SELF; "/"; SELF ]
| "simple" NONA
  [ "("; SELF; ")"
  | INT ((_)) ] ]
*)


let _ = begin
  EXTEND MGram  test: LAST
    [[x = SELF ; "plus1plus" ; y = SELF ]];
  END;
  p Format.std_formatter test
end
(** output
              test: [ "add" LEFTA
  [ SELF; "plus1plus"; SELF
  | SELF; "+"; SELF
  | SELF; "-"; SELF ]
| "mult" RIGHTA
  [ SELF; "*"; SELF
  | SELF; "/"; SELF ]
| "simple" NONA
  [ "("; SELF; ")"
```

```
  | INT ((_)) ]
| LEFTA
  [ SELF; "plus1plus"; SELF ] ]
*)


let _ = begin
  EXTEND MGram  test: LEVEL "mult" [[x = SELF ; "plus1plus" ; y = SELF ]]; END ;
  p Format.std_formatter test;
end
(** output
      test: [ "add" LEFTA
  [ SELF; "plus1plus"; SELF
  | SELF; "+"; SELF
  | SELF; "-"; SELF ]
| "mult" RIGHTA
  [ SELF; "plus1plus"; SELF
  | SELF; "*"; SELF
  | SELF; "/"; SELF ]
| "simple" NONA
  [ "("; SELF; ")"
  | INT ((_)) ]
| LEFTA
  [ SELF; "plus1plus"; SELF ] ]
*)


let _ = begin
  EXTEND MGram  test: BEFORE "mult" [[x = SELF ; "plus1plus" ; y = SELF ]];
  END ;
  p Format.std_formatter test;
end
(** output
        test: [ "add" LEFTA
  [ SELF; "plus1plus"; SELF
  | SELF; "+"; SELF
  | SELF; "-"; SELF ]
| LEFTA
  [ SELF; "plus1plus"; SELF ]
| "mult" RIGHTA
  [ SELF; "plus1plus"; SELF
  | SELF; "*"; SELF
  | SELF; "/"; SELF ]
| "simple" NONA
  [ "("; SELF; ")"
  | INT ((_)) ]
| LEFTA
```

```
  [ SELF; "plus1plus"; SELF ] ]
*)
```

Listing 41: Grammar modification

Grammar example You can do some search in the toplevel as follows

```
se (FILTER _* "val" _* "expr" space+ ":" ) "Syntax" ;;
```

```
Gram.Entry.print Format.std_formatter Syntax.expr;;
```

Example: Expr Parse Tree

Listing 42 is the expr parse tree.

```
expr:
[ ";" LEFTA
  [ seq_expr ]

| "top" RIGHTA
  [ "RE_PCRE"; regexp
  | "REPLACE"; regexp; "->"; sequence
  | "SEARCH"; regexp; "->"; sequence
  | "MAP"; regexp; "->"; sequence
  | "COLLECT"; regexp; "->"; sequence
  | "COLLECTOBJ"; regexp
  | "SPLIT"; regexp
  | "REPLACE_FIRST"; regexp; "->"; sequence
  | "SEARCH_FIRST"; regexp; "->"; sequence
  | "MATCH"; regexp; "->"; sequence
  | "FILTER"; regexp
  | "CAPTURE"; regexp
  | "function"; OPT "|"; LIST1 regexp_match_case SEP "|"
  (* syntax extension by mikmatch*)
  | "parser"; OPT parser_ipatt; parser_case_list
  | "parser"; OPT parser_ipatt; parser_case_list
  | "let"; "try"; OPT "rec"; LIST1 let_binding SEP "and"; "in"; sequence;
    "with"; LIST1 lettry_case SEP "|"
 (*  syntax extension mikmatch
     let try a = raise Not_found in a with Not_found -> 24;; *)
  | "let"; LIDENT "view"; UIDENT _; "="; SELF; "in"; sequence
```

```
(*   view patterns *)
  | "let"; "module"; a_UIDENT; module_binding0; "in"; expr LEVEL ";"
  | "let"; "open"; module_longident; "in"; expr LEVEL ";"
  | "let"; OPT "rec"; binding; "in"; sequence
  | "if"; SELF; "then"; expr LEVEL "top"; "else"; expr LEVEL "top"
  | "if"; SELF; "then"; expr LEVEL "top"
  | "fun"; fun_def
  | "match"; sequence; "with"; "parser"; OPT parser_ipatt; parser_case_list
  | "match"; sequence; "with"; "parser"; OPT parser_ipatt; parser_case_list
  | "match"; sequence; "with"; OPT "|"; LIST1 regexp_match_case SEP "|"
  | "try"; SELF; "with"; OPT "|"; LIST1 regexp_match_case SEP "|"
  | "try"; sequence; "with"; match_case
  | "for"; a_LIDENT; "="; sequence; direction_flag; sequence; "do";
    do_sequence
  | "while"; sequence; "do"; do_sequence
  | "object"; opt_class_self_patt; class_structure; "end" ]
| LEFTA
  [ "EXTEND"; extend_body; "END"
  | "DELETE_RULE"; delete_rule_body; "END"
  | "GDELETE_RULE"
  | "GEXTEND" ]

(* operators *)
| "," LEFTA
  [ SELF; ","; comma_expr ]

| ":=" NONA
  [ SELF; ":="; expr LEVEL "top"
  | SELF; "<-"; expr LEVEL "top" ]

| "||" RIGHTA
   [ SELF; infixop6; SELF ]

| "&&" RIGHTA
  [ SELF; infixop5; SELF ]

| "<" LEFTA
  [ SELF; infix operator (level 0) (comparison operators, and some others);
    SELF ]
| "^" RIGHTA
  [ SELF; infix operator (level 1) (start with '^', '@'); SELF ]
| "::" RIGHTA
  [ SELF; "::"; SELF ]
| "+" LEFTA
  [ SELF; infix operator (level 2) (start with '+', '-'); SELF ]
| "*" LEFTA
  [ SELF; "land"; SELF
```

```
  | SELF; "lor"; SELF
  | SELF; "lxor"; SELF
  | SELF; "mod"; SELF
  | SELF; infix operator (level 3) (start with '*', '/', '%'); SELF ]
| "**" RIGHTA
  [ SELF; "asr"; SELF
  | SELF; "lsl"; SELF
  | SELF; "lsr"; SELF
  | SELF; infix operator (level 4) (start with "**") (right assoc); SELF ]
| "unary minus" NONA
  [ "-"; SELF
  | "-."; SELF ]

(* apply *)
| "apply" LEFTA
  [ SELF; SELF
  | "assert"; SELF
  | "lazy"; SELF ]

| "label" NONA
  [ "~"; a_LIDENT
  | LABEL _; SELF
  | OPTLABEL _; SELF
  | "?"; a_LIDENT ]
| "." LEFTA
  [ SELF; "."; "("; SELF; ")"
  | SELF; "."; "["; SELF; "]"
  | SELF; "."; "{"; comma_expr; "}"
  | SELF; "."; SELF
  | SELF; "#"; label ]
| "~-" NONA
  [ "!"; SELF
  | prefix operator (start with '!', '?', '~'); SELF ]
| "simple" LEFTA
  [ "false"
  | "true"
  | "{"; TRY [ label_expr_list; "}" ]
  | "{"; TRY [ expr LEVEL "."; "with" ]; label_expr_list; "}"
  | "new"; class_longident
  | QUOTATION _
  | ANTIQUOT (("exp" | "" | "anti"), _)
  | ANTIQUOT ("`bool", _)
  | ANTIQUOT ("tup", _)
  | ANTIQUOT ("seq", _)
  | "`"; a_ident
  | "["; "]"
  | "["; sem_expr_for_list; "]"
```

```
  | "[|"; "|]"
  | "[|"; sem_expr; "|]"
  | "{<"; ">}"
  | "{<"; field_expr_list; ">}"
  | "begin"; "end"
  | "begin"; sequence; "end"
  | "("; ")"
  | "("; "module"; module_expr; ")"
  | "("; "module"; module_expr; ":"; package_type; ")"
  | "("; SELF; ";"; ")"
  | "("; SELF; ";"; sequence; ")"
  | "("; SELF; ":"; ctyp; ")"
  | "("; SELF; ":"; ctyp; ":>"; ctyp; ")"
  | "("; SELF; ":>"; ctyp; ")"
  | "("; SELF; ")"
  | stream_begin; stream_end
  | stream_begin; stream_expr_comp_list; stream_end
  | stream_begin; stream_end
  | stream_begin; stream_expr_comp_list; stream_end
  | a_INT
  | a_INT32
  | a_INT64
  | a_NATIVEINT
  | a_FLOAT
  | a_STRING
  | a_CHAR
  | TRY module_longident_dot_lparen; sequence; ")"
  | TRY val_longident ] ]
```

Listing 42: Expr Parse Tree

A syntax extension of `let try`

```
let try a = 3 in true with Not_found -> false || false;;
true
```

First, it uses start parser to parse *let try a = 3 in true with Not_found -> false*, then it calls the cont parser, and the next level cont parser, etc, and then it succeeds. This also applies to "apply" level.

When you modify the module *Camlp4.PreCast.Gram*, it will be reflected in the toplevel on the fly. And be careful, it's probably you never come back and need to restart the toplevel.

When two rules overlapping, the EXTEND statement replaces the old version by the new one and displays a warning.

```
se (FILTER _* "warning") "Syntax"
```

```
type warning = Loc.t -> string -> unit
val default_warning : warning
val current_warning : warning ref
val print_warning : warning
```

4.7 QuasiQuotations

There are a lot of metaphors introducing quasiquotations in camlp4 wiki, here we did not bother it. We just told you how to program.

Quotations are delimeters, since there are so many syntaxes in ocaml, so you need to delimit your syntax to make all up. Antiquotations are those make your syntax interact with outside scope. They are all expanders will be expanded by your hook.

```
1 [‘QUOTATION x -> Quotation.expand _loc x Quotation.DynAst.expr_tag ]
```

The *‘QUOTATION* token contains a record including the body of the quotation and the `tag`. The record is passed off to the Quotation module to be expanded. The expander parses the quotation string starting at some non-terminal(you specified), then runs the result through the antiquotation expander

```
1   |‘ANTIQUOT (‘‘exp’’ | ‘‘’’ | ‘‘anti’’ as n) s ->
2   <:expr< $anti:make_anti ~c:"expr" n s $>>
```

The antiquotation creates `a special AST node` to hold the body of the antiquotation, each type in the AST has a constructor (`ExAnt, TyAnt`, etc.) `c` means context here. Here we grep `Ant`, and the output is as follows

```
27 matches for "Ant" in buffer: Camlp4Ast.partial.ml
     5:     | BAnt of string ]
     9:     | ReAnt of string ]
    13:     | DiAnt of string ]
    17:     | MuAnt of string ]
    21:     | PrAnt of string ]
    25:     | ViAnt of string ]
    29:     | OvAnt of string ]
    33:     | RvAnt of string ]
    37:     | OAnt of string ]
    41:     | LAnt of string ]
    47:     | IdAnt of loc and string (* $s$ *) ]
    87:     | TyAnt of loc and string (* $s$ *)
    93:     | PaAnt of loc and string (* $s$ *)
   124:     | ExAnt of loc and string (* $s$ *)
   202:     | MtAnt of loc and string (* $s$ *) ]
   231:     | SgAnt of loc and string (* $s$ *) ]
   244:     | WcAnt of loc and string (* $s$ *) ]
   251:     | BiAnt of loc and string (* $s$ *) ]
   258:     | RbAnt of loc and string (* $s$ *) ]
   267:     | MbAnt of loc and string (* $s$ *) ]
   274:     | McAnt of loc and string (* $s$ *) ]
   290:     | MeAnt of loc and string (* $s$ *) ]
   321:     | StAnt of loc and string (* $s$ *) ]
```

```
337:     | CtAnt of loc and string ]
352:     | CgAnt of loc and string (* $s$ *) ]
372:     | CeAnt of loc and string ]
391:     | CrAnt of loc and string (* $s$ *) ];
```

4.7.1 Quotation Introduction

Take this as a simple example

```
camlp4rf -str 'value f = fun [ <:expr<$int:i$ >> -> i ];'
```

It will be expanded like this

```
let f = function | Ast.ExInt (_, i) -> i
```

```
camlp4rf -str 'value f = fun [ <:expr<$`int:i$ >> -> i ];'
```

And the output is like this

```
let f = function | Ast.ExInt (_, i) -> i
```

The underscore is *location*, so you see, the expander *just* make you happy, you can write programs directly if you don't like it.

```
<:expr< $int: "4"$ >>;;
- : Camlp4.PreCast.Ast.expr = Camlp4.PreCast.Ast.ExInt (<abstr>, "4")
<:expr< $`int: 4$ >>;; (** the same result *)
- : Camlp4.PreCast.Ast.expr = Camlp4.PreCast.Ast.ExInt (<abstr>, "4")
<:expr< $`flo:4.1323243232$ >>;;
- : Camlp4.PreCast.Ast.expr = Camlp4.PreCast.Ast.ExFlo (<abstr>, "4.1323243232")
# <:expr< $flo:"4.1323243232"$ >>;;
- : Camlp4.PreCast.Ast.expr = Camlp4.PreCast.Ast.ExFlo (<abstr>, "4.1323243232")
(** maybe the same for flo *)
```

4.7.2 Quotation Expander

```
    match_case:
      [ [ "["; l = LIST0 match_case0 SEP "|"; "]" -> Ast.mcOr_of_list l
        | p = ipatt; "->"; e = expr -> <:match_case< $p$ -> $e$ >> ] ]
    ;
    match_case0:
      [ [ `ANTIQUOT ("match_case"|"list" as n) s ->
            <:match_case< $anti:mk_anti ~c:"match_case" n s$ >>
        | `ANTIQUOT (""|"anti" as n) s ->
            <:match_case< $anti:mk_anti ~c:"match_case" n s$ >>
        | `ANTIQUOT (""|"anti" as n) s; "->"; e = expr ->
            <:match_case< $anti:mk_anti ~c:"patt" n s$ -> $e$ >>
        | `ANTIQUOT (""|"anti" as n) s; "when"; w = expr; "->"; e = expr ->
            <:match_case< $anti:mk_anti ~c:"patt" n s$ when $w$ -> $e$ >>
        | p = patt_as_patt_opt; w = opt_when_expr; "->"; e = expr -> <:match_case< $p$ when $w$ -> $e$ >>
      ] ]
```

The grammar rules indicate that the rule accept antiquotations here, and you can do insertion. Now let's take a furthur look at the antiquot expander

```
open Camlp4;                                        (* -*- camlp4r -*- *)
module Id = struct
  value name = "Camlp4QuotationCommon";
  value version = Sys.ocaml_version;
end;

module Make (Syntax : Sig.Camlp4Syntax)
            (TheAntiquotSyntax : (Sig.Parser Syntax.Ast).SIMPLE)
= struct
  open Sig;
  include Syntax; (* Be careful an AntiquotSyntax module appears here *)

  module MetaLocHere = Ast.Meta.MetaLoc;
  module MetaLoc = struct
    module Ast = Ast;
    value loc_name = ref None;
    value meta_loc_expr _loc loc =
      match loc_name.val with
      [ None -> <:expr< $lid:Loc.name.val$ >>
      | Some "here" -> MetaLocHere.meta_loc_expr _loc loc
      | Some x -> <:expr< $lid:x$ >> ];
    value meta_loc_patt _loc _ = <:patt< _ >>;
  end;
  module MetaAst = Ast.Meta.Make MetaLoc;
  module ME = MetaAst.Expr;
```

```
module MP = MetaAst.Patt;

value is_antiquot s =
  let len = String.length s in
  len > 2 && s.[0] = '\\' && s.[1] = '$';

value handle_antiquot_in_string s term parse loc decorate =
  if is_antiquot s then
    let pos = String.index s ':' in
    let name = String.sub s 2 (pos - 2)
    and code = String.sub s (pos + 1) (String.length s - pos - 1) in
    decorate name (parse loc code)
  else term;

value antiquot_expander = object
  inherit Ast.map as super;
  method patt = fun
    [ <:patt@_loc< $anti:s$ >> | <:patt@_loc< $str:s$ >> as p ->
        let mloc _loc = MetaLoc.meta_loc_patt _loc _loc in
        handle_antiquot_in_string s p TheAntiquotSyntax.parse_patt _loc (fun n p ->
          match n with
          [ "antisig_item" -> <:patt< Ast.SgAnt $mloc _loc$ $p$ >>
          | "antistr_item" -> <:patt< Ast.StAnt $mloc _loc$ $p$ >>
          | "antictyp" -> <:patt< Ast.TyAnt $mloc _loc$ $p$ >>
          | "antipatt" -> <:patt< Ast.PaAnt $mloc _loc$ $p$ >>
          | "antiexpr" -> <:patt< Ast.ExAnt $mloc _loc$ $p$ >>
          | "antimodule_type" -> <:patt< Ast.MtAnt $mloc _loc$ $p$ >>
          | "antimodule_expr" -> <:patt< Ast.MeAnt $mloc _loc$ $p$ >>
          | "anticlass_type" -> <:patt< Ast.CtAnt $mloc _loc$ $p$ >>
          | "anticlass_expr" -> <:patt< Ast.CeAnt $mloc _loc$ $p$ >>
          | "anticlass_sig_item" -> <:patt< Ast.CgAnt $mloc _loc$ $p$ >>
          | "anticlass_str_item" -> <:patt< Ast.CrAnt $mloc _loc$ $p$ >>
          | "antiwith_constr" -> <:patt< Ast.WcAnt $mloc _loc$ $p$ >>
          | "antibinding" -> <:patt< Ast.BiAnt $mloc _loc$ $p$ >>
          | "antirec_binding" -> <:patt< Ast.RbAnt $mloc _loc$ $p$ >>
          | "antimatch_case" -> <:patt< Ast.McAnt $mloc _loc$ $p$ >>
          | "antimodule_binding" -> <:patt< Ast.MbAnt $mloc _loc$ $p$ >>
          | "antiident" -> <:patt< Ast.IdAnt $mloc _loc$ $p$ >>
          | _ -> p ])
    | p -> super#patt p ];
  method expr = fun
    [ <:expr@_loc< $anti:s$ >> | <:expr@_loc< $str:s$ >> as e ->
        let mloc _loc = MetaLoc.meta_loc_expr _loc _loc in
        handle_antiquot_in_string s e TheAntiquotSyntax.parse_expr _loc (fun n e ->
          match n with
          [ "`int" -> <:expr< string_of_int $e$ >>
          | "`int32" -> <:expr< Int32.to_string $e$ >>
```

```
| "`int64" -> <:expr< Int64.to_string $e$ >>
| "`nativeint" -> <:expr< Nativeint.to_string $e$ >>
| "`flo" -> <:expr< Camlp4_import.Oprint.float_repres $e$ >>
| "`str" -> <:expr< Ast.safe_string_escaped $e$ >>
| "`chr" -> <:expr< Char.escaped $e$ >>
| "`bool" -> <:expr< Ast.IdUid $mloc _loc$ (if $e$ then "True" else "False") >>
| "liststr_item" -> <:expr< Ast.stSem_of_list $e$ >>
| "listsig_item" -> <:expr< Ast.sgSem_of_list $e$ >>
| "listclass_sig_item" -> <:expr< Ast.cgSem_of_list $e$ >>
| "listclass_str_item" -> <:expr< Ast.crSem_of_list $e$ >>
| "listmodule_expr" -> <:expr< Ast.meApp_of_list $e$ >>
| "listmodule_type" -> <:expr< Ast.mtApp_of_list $e$ >>
| "listmodule_binding" -> <:expr< Ast.mbAnd_of_list $e$ >>
| "listbinding" -> <:expr< Ast.biAnd_of_list $e$ >>
| "listbinding;" -> <:expr< Ast.biSem_of_list $e$ >>
| "listrec_binding" -> <:expr< Ast.rbSem_of_list $e$ >>
| "listclass_type" -> <:expr< Ast.ctAnd_of_list $e$ >>
| "listclass_expr" -> <:expr< Ast.ceAnd_of_list $e$ >>
| "listident" -> <:expr< Ast.idAcc_of_list $e$ >>
| "listctypand" -> <:expr< Ast.tyAnd_of_list $e$ >>
| "listctyp;" -> <:expr< Ast.tySem_of_list $e$ >>
| "listctyp*" -> <:expr< Ast.tySta_of_list $e$ >>
| "listctyp|" -> <:expr< Ast.tyOr_of_list $e$ >>
| "listctyp," -> <:expr< Ast.tyCom_of_list $e$ >>
| "listctyp&" -> <:expr< Ast.tyAmp_of_list $e$ >>
| "listwith_constr" -> <:expr< Ast.wcAnd_of_list $e$ >>
| "listmatch_case" -> <:expr< Ast.mcOr_of_list $e$ >>
| "listpatt," -> <:expr< Ast.paCom_of_list $e$ >>
| "listpatt;" -> <:expr< Ast.paSem_of_list $e$ >>
| "listexpr," -> <:expr< Ast.exCom_of_list $e$ >>
| "listexpr;" -> <:expr< Ast.exSem_of_list $e$ >>
| "antisig_item" -> <:expr< Ast.SgAnt $mloc _loc$ $e$ >>
| "antistr_item" -> <:expr< Ast.StAnt $mloc _loc$ $e$ >>
| "antictyp" -> <:expr< Ast.TyAnt $mloc _loc$ $e$ >>
| "antipatt" -> <:expr< Ast.PaAnt $mloc _loc$ $e$ >>
| "antiexpr" -> <:expr< Ast.ExAnt $mloc _loc$ $e$ >>
| "antimodule_type" -> <:expr< Ast.MtAnt $mloc _loc$ $e$ >>
| "antimodule_expr" -> <:expr< Ast.MeAnt $mloc _loc$ $e$ >>
| "anticlass_type" -> <:expr< Ast.CtAnt $mloc _loc$ $e$ >>
| "anticlass_expr" -> <:expr< Ast.CeAnt $mloc _loc$ $e$ >>
| "anticlass_sig_item" -> <:expr< Ast.CgAnt $mloc _loc$ $e$ >>
| "anticlass_str_item" -> <:expr< Ast.CrAnt $mloc _loc$ $e$ >>
| "antiwith_constr" -> <:expr< Ast.WcAnt $mloc _loc$ $e$ >>
| "antibinding" -> <:expr< Ast.BiAnt $mloc _loc$ $e$ >>
| "antirec_binding" -> <:expr< Ast.RbAnt $mloc _loc$ $e$ >>
| "antimatch_case" -> <:expr< Ast.McAnt $mloc _loc$ $e$ >>
| "antimodule_binding" -> <:expr< Ast.MbAnt $mloc _loc$ $e$ >>
```

```
            | "antiident" -> <:expr< Ast.IdAnt $mloc _loc$ $e$ >>
            | _ -> e ])
      | e -> super#expr e ];
  end;

  value add_quotation name entry mexpr mpatt =
    let entry_eoi = Gram.Entry.mk (Gram.Entry.name entry) in
    let parse_quot_string entry loc s =
      let q = Camlp4_config.antiquotations.val in
      let () = Camlp4_config.antiquotations.val := True in
      let res = Gram.parse_string entry loc s in
      let () = Camlp4_config.antiquotations.val := q in
      res in
    let expand_expr loc loc_name_opt s =
      let ast = parse_quot_string entry_eoi loc s in
      let () = MetaLoc.loc_name.val := loc_name_opt in
      let meta_ast = mexpr loc ast in
      let exp_ast = antiquot_expander#expr meta_ast in
      exp_ast in
    let expand_str_item loc loc_name_opt s =
      let exp_ast = expand_expr loc loc_name_opt s in
      <:str_item@loc< $exp:exp_ast$ >> in
    let expand_patt _loc loc_name_opt s =
      let ast = parse_quot_string entry_eoi _loc s in
      let meta_ast = mpatt _loc ast in
      let exp_ast = antiquot_expander#patt meta_ast in
      match loc_name_opt with
      [ None -> exp_ast
      | Some name ->
        let rec subst_first_loc =
          fun
          [ <:patt@_loc< Ast.$uid:u$ $_$ >> -> <:patt< Ast.$uid:u$ $lid:name$ >>
          | <:patt@_loc< $a$ $b$ >> -> <:patt< $subst_first_loc a$ $b$ >>
          | p -> p ] in
        subst_first_loc exp_ast ] in
    do {
      EXTEND Gram
        entry_eoi:
          [ [ x = entry; `EOI -> x ] ]
        ;
      END;
      Quotation.add name Quotation.DynAst.expr_tag expand_expr;
      Quotation.add name Quotation.DynAst.patt_tag expand_patt;
      Quotation.add name Quotation.DynAst.str_item_tag expand_str_item;
    };

  add_quotation "sig_item" sig_item_quot ME.meta_sig_item MP.meta_sig_item;
```

```
    add_quotation "str_item" str_item_quot ME.meta_str_item MP.meta_str_item;
    add_quotation "ctyp" ctyp_quot ME.meta_ctyp MP.meta_ctyp;
    add_quotation "patt" patt_quot ME.meta_patt MP.meta_patt;
    add_quotation "expr" expr_quot ME.meta_expr MP.meta_expr;
    add_quotation "module_type" module_type_quot ME.meta_module_type MP.meta_module_type;
    add_quotation "module_expr" module_expr_quot ME.meta_module_expr MP.meta_module_expr;
    add_quotation "class_type" class_type_quot ME.meta_class_type MP.meta_class_type;
    add_quotation "class_expr" class_expr_quot ME.meta_class_expr MP.meta_class_expr;
    add_quotation "class_sig_item"
                  class_sig_item_quot ME.meta_class_sig_item MP.meta_class_sig_item;
    add_quotation "class_str_item"
                  class_str_item_quot ME.meta_class_str_item MP.meta_class_str_item;
    add_quotation "with_constr" with_constr_quot ME.meta_with_constr MP.meta_with_constr;
    add_quotation "binding" binding_quot ME.meta_binding MP.meta_binding;
    add_quotation "rec_binding" rec_binding_quot ME.meta_rec_binding MP.meta_rec_binding;
    add_quotation "match_case" match_case_quot ME.meta_match_case MP.meta_match_case;
    add_quotation "module_binding"
                  module_binding_quot ME.meta_module_binding MP.meta_module_binding;
    add_quotation "ident" ident_quot ME.meta_ident MP.meta_ident;
    add_quotation "rec_flag" rec_flag_quot ME.meta_rec_flag MP.meta_rec_flag;
    add_quotation "private_flag" private_flag_quot ME.meta_private_flag MP.meta_private_flag;
    add_quotation "row_var_flag" row_var_flag_quot ME.meta_row_var_flag MP.meta_row_var_flag;
    add_quotation "mutable_flag" mutable_flag_quot ME.meta_mutable_flag MP.meta_mutable_flag;
    add_quotation "virtual_flag" virtual_flag_quot ME.meta_virtual_flag MP.meta_virtual_flag;
    add_quotation "override_flag" override_flag_quot ME.meta_override_flag MP.meta_override_flag;
    add_quotation "direction_flag" direction_flag_quot ME.meta_direction_flag MP.meta_direction_flag;

end;
```

Listing 43: Quotation Expander

In line 40, we define *antiquote_expander* which was inherited from *Ast.map* with overriding method *patt* and *expr*. Take a furthur look at method patt, we see it handles two kinds of constructor *(Ast.PaAnt _loc s | Ast.PaStr _loc s as p)* From line 125, we just *add_quotations* to the quotation expander.

Now we want to manipulate lambda ast, we just translate the concrete syntax to the syntax we want.

Lambda Example

```
open Format
open Camlp4.PreCast
```

```
let parser_of_entry entry  s =
  try Gram.parse entry (Loc.mk "<string>") (Stream.of_string  s)
  with
    Loc.Exc_located(loc, e) -> begin
      prerr_endline (Loc.to_string loc);
      let start_bol,stop_bol,
        start_off, stop_off =
        Loc.( start_bol loc,
             stop_bol loc,
             start_off loc,
             stop_off loc
            ) in
      let abs_start_off = start_bol + start_off in
      let abs_stop_off = stop_bol + stop_off in
      let err_location = String.sub s abs_start_off
          (abs_stop_off - abs_start_off + 1) in
      prerr_endline (sprintf "err: ^%s^" err_location);
      raise e ;
    end


let lambda = Gram.Entry.mk "lambda"
let lambda_eoi = Gram.Entry.mk "lambda_eoi"

let _ = begin
  EXTEND Gram GLOBAL: lambda lambda_eoi;
  lambda_eoi:
    [ [x = lambda ; `EOI -> x ] ];
  lambda:
    [
     "top" (** str antiquot -> string literal *)
       [ "fun"; x=LIDENT; "->" ; y=SELF ->
         <:expr< `Lambda ( $ <:expr< `Id $str:x$ >> $, $y$ ) >>  ]
  | "app"
      [x=SELF;y=SELF -> <:expr< `App ($x$,$y$ ) >> ]
  |"simple"
      [ "("; x = SELF; ")" -> x
      | x = LIDENT ->  <:expr< `Id $str:x$ >> ]
];
  END;
end

let parse_lambda = parser_of_entry lambda
let parse_lambda_eoi = parser_of_entry lambda_eoi


let mk_quotation ~entry ~tag_name ()=
```

```
  let expand_expr _loc _loc_name_opt quotation_contents  =
    let open Camlp4_config in
    let old = !antiquotations in
    let ()  = antiquotations := true in
    let res = Gram.parse_string entry _loc quotation_contents in
    let ()  = antiquotations := old in
    let () =
      match _loc_name_opt with
      |None -> print_endline "None"
      |Some s -> print_endline (sprintf "Some %s" s) in
    res in
  let expand_str_item _loc _loc_name_opt quotation_contents  =
    let open Camlp4_config in
    let old = !antiquotations in
    let () = antiquotations := true in
    let res = Gram.parse_string entry _loc quotation_contents in
    let () = antiquotations := old in
    <:str_item< $exp:res$ >> in
  let open Syntax.Quotation in begin
    add tag_name DynAst.expr_tag expand_expr;
    add tag_name DynAst.str_item_tag expand_str_item;
  end

let () =
  mk_quotation ~entry:lambda_eoi ~tag_name:"lam"  ()
```

Listing 44: Lambda Extension

Listing?? try to use built in caml syntax to save you time. We use antiquotation syntax, that is, going back to host language. You use *Syntax.AntiquotSyntax.parse_expr* and *Syntax.AntiquotSyntax.parse_patt* here since it's *reflexitive*, it will be the same as your host language syntax, not fixed to original syntax or revised syntax.' Another thing to notice, here we transform string input *directly* into camlp4 AST, normally you may transform your string input into your ast, and then transform your ast into camlp4 Ast using filter. It's very easy to test our modules, just using toplevel

Here we notice that there are a lot of tags Listing 45. Tags mean the position where you can expand your code.

```
type 'a tag = 'a Camlp4.PreCast.Quotation.DynAst.tag
val ctyp_tag : Ast.ctyp tag
val patt_tag : Ast.patt tag
val expr_tag : Ast.expr tag
val module_type_tag : Ast.module_type tag
val sig_item_tag : Ast.sig_item tag
val with_constr_tag : Ast.with_constr tag
val module_expr_tag : Ast.module_expr tag
val str_item_tag : Ast.str_item tag
val class_type_tag : Ast.class_type tag
val class_sig_item_tag : Ast.class_sig_item tag
val class_expr_tag : Ast.class_expr tag
val class_str_item_tag : Ast.class_str_item tag
val match_case_tag : Ast.match_case tag
val ident_tag : Ast.ident tag
val binding_tag : Ast.binding tag
val rec_binding_tag : Ast.rec_binding tag
val module_binding_tag : Ast.module_binding tag
```

Listing 45: DynAst Tag

4.8 Ast Transformation

Using concrete syntax instead of the abstract one is useful for

1. Independent of the internal representation

2. Have more concise programs

The beauty lies that you can *compose* bigger AST using smaller ones without learning about the internal AST constructor.

```
open Camlp4.PreCast;
value gen _loc patts exprs =
    <:match_case<
      $list: List.map2 (fun p e -> <:match_case< $p$ -> $e$ >> )
      patts exprs $ >> ;
(**
let gen _loc patts exprs =
  Ast.mcOr_of_list
    (List.map2 (fun p e -> Ast.McArr (_loc, p, (Ast.ExNil _loc), e)) patts
       exprs)
*)


(** a tedious way *)
value gen2 patts exprs =
    let cases = List.fold_right2 begin fun p e acc ->
      let _loc = Loc.merge (Ast.loc_of_patt p) (Ast.loc_of_expr e) in
      <:match_case< $p$ -> $e$ | $acc$ >>
    end patts exprs <:match_case@here< >>
      (** here is handled specifically
          (Loc.of_tuple ("ghost-location", 1, 0, 0, 1, 0, 0, true))
      *)
    in
    let _loc = Ast.loc_of_match_case cases in
    <:expr< fun [ $cases$ ] >>
    ;

value data_con_args _loc n t =
        let rec self n =
          if n <= 0 then <:ctyp< >>
          else <:ctyp<  $t$  and $self (n-1)$ >> (** minor location error ??? *)
        in
        self n ;
```

```
value data_con _loc n t =
  <:ctyp< $uid:"C" ^ string_of_int n $ of $data_con_args _loc n t $ >>
;

value gen_type _loc n t =
  let rec self n =
    if n <= 0
    then <:ctyp< >>
    else <:ctyp<   $self (n-1)$ | $data_con _loc n t $  >>
  (* <:ctyp<   [ $self (n-1)$ | $data_con _loc n t $ ] >> *)
  in
  <:ctyp< [ $ self n $ ] >>
  (* <:ctyp<  $ self n $  >>
     subtle difference try and you will know why
  *)
;

value filter = fun
  [ <:ctyp@_loc< gen_type $lid:x$ >>
  | <:ctyp@_loc< $lid:x$ gen_type >> ->
    (** Scanf.sscanf *)
    Scanf.sscanf x "%[^0-9]%d" begin fun _ n -> begin
      (* prerr_endline (string_of_int n); *)
      gen_type _loc n  <:ctyp< $lid:x$ >>
    end
   end
  | t -> t
  ];

AstFilters.register_str_item_filter (Ast.map_ctyp filter )#str_item;

(**
   ocamlc -c -pp 'camlp4o -I _build compose.cmo'  test.ml
   camlp4o -I _build compose.cmo -str 'type t7 = gen_type t7'
7
type t7 =
  | C1 of t7
  | C2 of t7 * t7
  | C3 of t7 * t7 * t7
  | C4 of t7 * t7 * t7 * t7
  | C5 of t7 * t7 * t7 * t7 * t7
  | C6 of t7 * t7 * t7 * t7 * t7 * t7
  | C7 of t7 * t7 * t7 * t7 * t7 * t7 * t7
*)
```

Listing 46: Compose Bigger Ast

Notice that Ast.Filter does not work well in the toplevel, Quotations work well in the toplevel. Revised syntax is more robust handling ambiguity:

1. Tuples `(t1 * .. * tN)`
2. Sum-types `[ C1 of t1 | C2 of t2 ..| Cn of tn ]`
3. Records `{f1:t1; f2:t2; fn:tn}`
4. Polymorphic Variants `[< ‘c1 of t1 | .. | ‘cN of tN ]`

Notice they have different separator, and delimiter, you can build an *incomplete* ast when you have no delimiters

4.9 Quotation Cont

4.9.1 Quotation module

```
type 'a expand_fun = Loc.t -> string option -> string -> 'a
(** the second argument is _loc,
for example: <:lam@_loc< >> , camlp4 will pass the second
argument Some ``_loc''
*)
```

In previous camlp4, Quotation provides a string to string transformation, then it default uses `Syntax.expr` or `Syntax.patt` to parse the returned string. following drawbacks

- needs a **more** parsing phase
- the resulting string may be syntactically incorrect, difficult to **debug**

When without antiquotaions, a parser is enought, other things are quite mechanical

A comprehensive Example Suppose we have already defined an AST, and did the parser, meta part(4.12.1). The parser part is simple, as follows

```
module MGram = MakeGram(Lexer)
let json_parser = MGram.Entry.mk "json"
let json_eoi = MGram.Entry.mk "json_eoi"
let _ =   let open Jq_ast in begin
  EXTEND MGram  GLOBAL : json_parser ;
  json_parser :
     [["null" -> Jq_null
     |"true" -> Jq_bool true
     |"false" -> Jq_bool false
     | n = [x = INT -> x | y = FLOAT -> y  ] -> Jq_number (float_of_string n )
     | s = STRING -> Jq_string s
     | "["; xs = LISTO SELF SEP "," ; "]" -> Jq_array xs
     | "{"; kvs = LISTO [s = STRING; ":"; v = json_parser -> (s,v)] SEP ",";
     "}" -> Jq_object kvs
     ]] ; END ;
  EXTEND MGram  GLOBAL: json_eoi ;
  json_eoi : [[x = json_parser ; EOI -> x ]] ;
  END ;
```

```
  MGram.parse_string json_eoi (Loc.mk "<string>") "[true,false]"
end
```

Now we do a mechanical installation to get a quotation expander All need is as follows:

```
let (|>) x f = f x
let parse_quot_string _loc s =
  MGram.parse_string  json_eoi _loc s
let expand_expr _loc _ s =  s
  |> parse_quot_string _loc
  |> MetaExpr.meta_t _loc
(** to make it able to appear in the toplevel *)
let expand_str_item _loc _ s =
   (** exp antiquotation insert an expression as str_item *)
   <:str_item@_loc< $exp: expand_expr _loc None s $ >>
let expand_patt _loc _ s  =  s
  |> parse_quot_string _loc
  |> MetaPatt.meta_t _loc
let _  = let open Syntax.Quotation in begin
  add "json" DynAst.expr_tag expand_expr ;
  add "json" DynAst.patt_tag expand_patt ;
  add "json" DynAst.str_item_tag expand_str_item ;
  default := "json";
end
```

You could also refactor you code as follows:

```
(** make quotation from a parser *)
let install_quotation my_parser (me,mp) name =
  let expand_expr _loc _ s = s |>  my_parser _loc |> me _loc in
  let expand_str_item _loc _ s =  <:str_item@_loc< $exp: expand_expr
    _loc None s $>> in
  let expand_patt _loc _ s = s |> my_parser _loc |> mp _loc in
  let open Syntax.Quotation in begin
    add name DynAst.expr_tag expand_expr ;
    add "json" DynAst.patt_tag expand_patt ;
    add "json" DynAst.str_item_tag expand_str_item;
  end
```

4.10 Antiquotation Expander

The meta filter treat any other constructor **ending in Ant** specially.

Instead of handling this way:

```
  |Jq_Ant(loc,s) -> <:expr< Jq_Ant ($meta_loc loc$, $meta_string s$) >>
```

They have:

```
  |Jq_Ant(loc,s) -> ExAnt(loc,s)
```

They translate it directly to *ExAnt* or *PaAnt*.

```
let try /(_* Lazy as x) ":" (_* as rest ) / = "ghsoghosghsog ghsohgo"
in (x,rest)
with Match_failure _ -> ("","");;
```

Notice that `Syntax.AntiquotSyntax.(parse_expr,parse_patt)` `Syntax.(parse_implem, parse_in` provides the parser as a host language. The normal part is as follows:

And also, `Syntax.AntiquotSyntax` only provides `parse_expr,parse_patt` corresponding to two postions where quotations happen.

```
open Camlp4.PreCast
module Jq_ast = struct
  type float' = float
  type t =
      Jq_null
    |Jq_bool of bool
    |Jq_number of float'
    |Jq_string of string

    |Jq_array of t
    |Jq_object of t
    |Jq_colon of t * t  (* to make an object *)
    |Jq_comma of t * t  (* to make an array *)
    |Jq_Ant of Loc.t * string
    |Jq_nil (* similiar to StNil *)
  let rec t_of_list lst = match lst with
    |[] -> Jq_nil
    | b::bs -> Jq_comma (b, t_of_list bs)
end
let (|>) x f = f x
```

```
module MetaExpr = struct
  let meta_float' _loc f = <:expr< $`flo:f$ >>
  include Camlp4Filters.MetaGeneratorExpr(Jq_ast)
end
module MetaPatt = struct
  let meta_float' _loc f = <:patt< $`flo:f$ >>
  include Camlp4Filters.MetaGeneratorPatt(Jq_ast)
end
```

Here we define the AST in a special way for the convenience of inserting code. The parser is modified:

```
module MGram = MakeGram(Lexer)
let json  = MGram.Entry.mk "json"
let json_eoi = MGram.Entry.mk "json_eoi"

let _ = let open Jq_ast in begin
  EXTEND  MGram  GLOBAL: json_eoi  json ;
  json_eoi : [[ x = json ; EOI -> x ]];
  json :
    [[ "null" -> Jq_null
     |"true" -> Jq_bool true
     |"false" -> Jq_bool false
     (** register special tags for anti-quotation*)
     | `ANTIQUOT (""|"bool"|"int"|"floo"|"str"|"list"|"alist" as n , s) ->
       Jq_Ant(_loc, n ^ ": " ^ s )
     | n = [ x = INT-> x | x =  FLOAT -> x ] -> Jq_number (float_of_string n)
     | "["; es = SELF ; "]" -> Jq_array es
     | "{";  kvs = SELF ;"}" -> Jq_object kvs
     | k= SELF; ":" ; v = SELF -> Jq_colon (k, v)
     | a = SELF; "," ; b = SELF -> Jq_comma (a, b)
     | -> Jq_nil  (* camlp4 parser epsilon has a lower priority *)
     ]];
  END ;
end
```

```
let destruct_aq s  =
  let try  /(_* Lazy as  name ) ":" (_* as content)/ = s
  in  name,content
  with Match_failure _ -> invalid_arg (s  ^ "in destruct_aq")
```

```
let aq_expander = object
  inherit Ast.map as super
  method expr = function
    |Ast.ExAnt(_loc, s) ->
      let n, c = destruct_aq s in
      (** use host syntax to parse the string  *)
      let e = Syntax.AntiquotSyntax.parse_expr _loc c in  begin
        match n with
        |"bool" -> <:expr< Jq_ast.Jq_bool $e$ >> (* interesting *)
        |"int" -> <:expr< Jq_ast.Jq_number (float $e$ ) >>
        |"flo" -> <:expr< Jq_ast.Jq_number $e$ >>
        |"str" -> <:expr< Jq_ast.Jq_string $e$ >>
        | "list" -> <:expr< Jq_ast.t_of_list $e$ >>
        |"alist" ->
          <:expr<
            Jq_ast.t_of_list
            (List.map (fun (k,v) -> Jq_ast.Jq_colon (Jq_ast.Jq_string k, v))
            $e$ )
          >>
        |_ -> e
      end
    |e -> super#expr e
  method patt = function
    | Ast.PaAnt(_loc,s) ->
      let n,c = destruct_aq s in
      Syntax.AntiquotSyntax.parse_patt _loc c  (* ignore the tag *)
    | p -> super#patt p
end


let parse_quot_string _loc s =
  let q = !Camlp4_config.antiquotations in
  (** checked by the lexer to allow antiquotation
      the flag is initially set to false, so antiquotations
      appearing outside a quotation won't be parsed
      *)
  Camlp4_config.antiquotations := true ;
  let res =  MGram.parse_string  json_eoi _loc s in
  Camlp4_config.antiquotations := q ;
  res

let expand_expr _loc _ s =   s
  |> parse_quot_string _loc
  |> MetaExpr.meta_t _loc
  (** aq_expander inserted here *)
  |> aq_expander#expr
```

```
let expand_str_item _loc _ s =
  (**insert an expression as str_item *)
   <:str_item@_loc< $exp: expand_expr _loc None s $ >>

let expand_patt _loc _ s  = s
  |> parse_quot_string _loc
  |> MetaPatt.meta_t _loc
  (** aq_expander inserted here *)
  |> aq_expander#patt
let _  = let open Syntax.Quotation in  begin
  add "json" DynAst.expr_tag expand_expr ;
  add "json" DynAst.patt_tag expand_patt ;
  add "json" DynAst.str_item_tag expand_str_item ;
  default := "json";
end
```

The procedure is as follows:

```
<< $ << 1 >> $>>  (* parsing (my parser) *)
Jq_Ant(_loc, "<< 1 >> ") (* lifting  (mechnical) *)
Ex_Ant(_loc, "<< 1 >>") (* parsing  (the host parser *)
<:expr< Jq_number 1. >>   (* antiquot_expand (my anti_expander ) *)
<:expr < Jq_number 1. >>
```

4.11 Revised syntax

```
'\''
'''
let x = 3
value  x = 42 ; (str_item) (do't forget ;)
let x = 3 in x + 8
let x = 3 in x + 7 (expr)

-- signature
val x : int
value x : int ;

-- abstract module types
module type MT
module type MT = 'a

-- currying functor
type t = Set.Make(M).t
type t = (Set.Make M).t

--
e1;e2;e3
do{e1;e2;e3}

--
while e1 do e2 done
while e1 do {e2;e3 }
for i = e1 to e2 do e1;e2 done
for i = e1 to e2 do {e1;e2;e3}

--
() always needed

x::y
[x::y]
x::y::z
[x::[y::[z::t]]]
x::y::z::t
[x;y;z::t]

match e with
[p1 -> e1
|p2 -> e2];
```

```
fun x -> x
fun [x->x]


value rec  fib = fun [
0|1  -> 1
|n -> fib (n-1) + fib (n-2)
];


fun x y (C z) -> t
fun x y -> fun [C z -> t]
-- the curried pattern matching can be done with "fun", but
-- only irrefutable

-- legall

fun []

match e with []

try e with []


-- pattern after "let" and "value" must be irrefutable

let f (x::y) = ...
let f = fun [ [x::y] ->  ... ]


x.f <- y
x.f := y
x:=!x + y
x.val := x.val + y

--
int list
list int


('a,bool) foo
foo 'a bool (*camlp4o -str "type t = ('a,bool) foo" -printer r  -> type t = foo 'a bool*)

type 'a foo = 'a list list
type foo 'a = list (list a)

int * bool
```

```
(int * bool )
```

```
-- abstract type are represented by a unbound type variable
type 'a foo
type foo 'a = 'b
```

```
type t = A of i | B
type t = [A of i | B]
```

```
-- empty is legal
type foo = []
```

```
type t= C of t1 * t2
type t = [C of t1 and t2]
```

```
C (x,y)
C x y
```

```
type t = D of (t1*t2)
type t = [D of (t1 * t2)]
```

```
D (x,y)
D (x,y)
```

```
type t = {mutable x : t1 }
type t = {x : mutable t1}
```

```
if a then b
if a then b else ()
```

```
a or b & c
a || b && c
```

```
(+)
\+
```

```
  (mod)
  \mod



  (*  new syntax
     it's possible to group together several declarations
     either in an interface or in an implementation by enclosing
     them between "declare" and "end" *)

declare
  type foo = [Foo of int | Bar];
  value f : foo -> int ;
end ;


   [<'1;'2;s;'3>]
   [:`1; `2 ; s; `3 :]

   parser [
     [: `Foo  :] -> e
     |[: p = f :] -> f ]


   parser []
   match e with parser []


   -- support where syntax
   value e = c
     where c = 3 ;


   -- parser
   value x = parser [
   [: `1; `2  :] -> 1
   |[: `1; `2 :] -> 2
   ];

   -- object
   class ['a,'b] point
   class point ['a,'b]


   class c = [int] color
   class c = color [int]
```

```
-- signature
class c : int -> point
class c : [int] -> point


method private virtual
method virtual private

--
object val x = 3 end
object value x = 3; end


object constraint 'a = int end
object type 'a = int ; end

-- label type
module type X = sig val x : num:int -> bool  end ;
module type X = sig value x : ~num:int -> bool ; end;

--
~num:int
?num:int
```

Inside a `<< do { ... } >>` you can use `<< let var = expr1; expr2 >>` like `<< let var = expr1 in expr2>>` .

The main goal is to facilitate imperative coding inside a « do »:

```
do {
 let x = 42;
 do_that_on x;
 let y = x + 2;
 play_with y;
}
```

That's nice but undocumented **Without** such a syntax the regular one will make you nest `do { ... }` notations.

```
do {
 foo 1;
 let x = 43 in do {
    bar x;
 };
 (* x should be out of the scope *)
}
```

Alas `<< let ... in >>` and `<< let ... ; >>` have the same semantics inside a `<< do { ... } >>` what I regret because `<< let ... in >>` is not local anymore.

In plain OCaml it's different since `<< ; >>` is a binary operator so you must see `<< let a = () in a; a >>` like `<< let a = () in (a; a) >>`.

Another utility to learn some revised syntax

```
camlp4o -printer r -str '{ s with foo = bar }'
{(s) with foo = bar;};

camlp4o -printer r -str 'type t = [`A | `B ]'

type t = [= `A | `B ];
```

4.12 Filters in camlp4

4.12.1 Map Filter

The filter *Camlp4MapGenerator* reads *OCaml* type definitions and generate a class that implements a map traversal. The generated class have a method per type you can override to implement a *map traversal*. It needs to read the `definition` of the type.

Camlp4 uses the **filter** iteself to bootstrap.

```
(** file Camlp4Ast.mlast *)
class map = Camlp4MapGenerator.generated;
class fold = Camlp4FoldGenerator.generated;
```

As above, `Camlp4.PreCast.Ast` has a corresponding map traversal object, which could be used by you: (the class was generated by our filter) `Ast.map` is a class

```
let b = new Camlp4.PreCast.Ast.map ;;
val b : Camlp4.PreCast.Ast.map = <obj>
```

4.12.2 Filter Examples

Using filters is a declarative way of doing ast transformation, the input is a legal syntax construct(not necessarily leagal ocaml ast), the output is a legal ocaml AST.

Example: Map Filter

You can also generate map traversal for ocaml type. *put your type definition before* you macro, as Listing 47

```
open Printf;
type a =
  [ A of b
  | C]
and b =
  [ B of a
  | D ]
;

class map = Camlp4MapGenerator.generated;

let v = object
  inherit map as super;
  method! b x =
    match super#b x with
    [ D -> B C
    | x -> x];
  end in
assert (v#b D = B (C));
```

Listing 47: Map Filter Example

Without filter, you would write the transformer by hand like this

```
(** The processed output of ast_map *)
type a = | A of b | C and b = | B of a | D

class map =
  object ((o : 'self_type))
    method b : b -> b = function | B _x -> let _x = o#a _x in B _x | D -> D
    method a : a -> a = function | A _x -> let _x = o#b _x in A _x | C -> C
    method unknown : 'a. 'a -> 'a = fun x -> x
  end

let _ =
  let v =
    object
      inherit map as super
      method! b = fun x -> match super#b x with | D -> B C | x -> x
    end
  in assert ((v#b D) = (B C))
```

Listing 48: Map Filter by Hand

Camlp4 use the filter in `antiquot_expander`, for example in *Camlp4Parsers/Camlp4QuotationCommon* 43, in the definition of `add_quotation`.

Using Register Filter has some limitations, like it first parse the whole file, and then transform each *structure item* one by one, so the code generated before will *not have* an effect on the later code. This is probably what not you want.

Linking Problem

You syntax extension may depends on other modules, make sure your `pa_xx.cma` contains all the modules statically. You can write a `pa_xx.mllib`, or link the module to `cma` file by hand.

For instance, you `pa_filter.cma` depends on `Util`, then you will `ocalmc -a pa_filter.cmo util.cmo` then you could use `camlp4o -parser pa_filter.cma`, it works. If you write `pa_xx.mllib` file, it would be something like

```
pa_filter
util
```

If you want to use other libraries to write syntax extension, make sure you link *all* libraries, including recursive dependency, i.e, the require field of batteries.

```
ocamlc -a  -I +num -I `ocamlfind query batteries` nums.cma unix.cma
bigarray.cma str.cma batteries.cma pa_filter.cma -o x.cma
```

You must link all the libraries *recursively*, even you don't need it at all. This is the defect of the OCaml compiler. `-linkall` here links submodules, recursive linking needs you say it clearly, you can find some help in the META file.

We can also test our filter seriously as follows `camlp4of -parser _build/filter.cmo filter_test.ml`

Example: Add Zero

```
open Camlp4.PreCast;
let simplify = object
  inherit Ast.map as super;
  method expr e =
    match super#expr e with
    [ <:expr< $x$ + 0 >> | <:expr< 0 + $x$  >> ->  x
    | x -> x ];
end in AstFilters.register_str_item_filter simplify#str_item
;
```

Listing 49: Ast Filter Add Zero

It's actually *a nested pattern match* as follows

To make life easier, you can write like this

In the module `Camlp4.PreCast.AstFilters`, which is generated by `Camlp4.Struct.AstFilters`
there are some utiliies to do filtering over the ast. It's actually very simple.

```
1    type 'a filter = 'a -> 'a
2    val register_sig_item_filter : Ast.sig_item filter -> unit
3    val register_str_item_filter : Ast.str_item filter -> unit
4    val register_topphrase_filter : Ast.str_item filter -> unit
5    val fold_interf_filters : ('a -> Ast.sig_item filter -> 'a) -> 'a -> 'a
6    val fold_implem_filters : ('a -> Ast.str_item filter -> 'a) -> 'a -> 'a
7    val fold_topphrase_filters :
8      ('a -> Ast.str_item filter -> 'a) -> 'a -> 'a
```

Fold filter

```
1  class x = Camlp4FoldGenerator.generated ;
```

Meta filter

Meta filter needs a module name, however, it also needs the source of the definition of the module. (Since OCaml does not have type reflection). There are some problems here, first you want to separate the type definition in another file, this could be achieved while using macro `INCLUDE`, and `Camlp4Trash`, however, you also want to make your type definition to using another syntax extension, i.e, `sexplib`,

`deriving`, `deriving` will *generate a bunch of modules and types*, which conflicts with our `Meta filter`. So, be careful here.

However, the problem can not be solved for meta filter, it can be solved for `map, fold` filter, for the meta filter, it will introduce the name of `Camlp4Trash` into the source tree, so you can not trash the module otherwise it will not compile. The only way to do it is to write your own `TrashModule` ast filter.

Fortunately, it's not hard to roll your own filter. First

```
(**
   camlp4of -filter map -filter fold -filter trash  -filter meta -parser Pa_type_conv.cma pa_sexp_conv.cma pa_json_ast.ml -printe
*)
open Sexplib.Std

type float' = float
and t =
  | Jq_null
  |Jq_bool of bool
  |Jq_number of float'
  |Jq_string of string
  |Jq_array of t list
  |Jq_object of (string*t) list
with sexp

open Camlp4.PreCast
open Json_ast

module Camlp4TrashX = struct
    INCLUDE "json_ast.ml"
end

open Camlp4TrashX

class map = Camlp4MapGenerator.generated

class fold = Camlp4FoldGenerator.generated



module MetaExpr = struct
  let meta_float' _loc f =
    <:expr< $`flo:f$ >>
  include Camlp4Filters.MetaGeneratorExpr(Camlp4TrashX)
end
```

```
module MetaPatt  = struct
  let meta_float' _loc f =
    <:patt< $`flo:f$ >>
  include Camlp4Filters.MetaGeneratorPatt(Camlp4TrashX)
end
```

Notice that we have `Camlp4TrashX`, you can not trash it, due to the fact that the generated code needs it.

Lift filter

These functions are what *Camlp4AstLifter uses* to lift the AST, and also how *quotations are implemented* A example of meta filter could be found here . Here we do a interesting experiment, lift a ast for serveral times

By the *lift filter* you can see its **internal representation**, textual code does not gurantee its correctness, but the AST representation could gurantee its correctness.

```
camlp4o -filter lift -filter lift  test_lift.ml -printer o > test_lift_1.ml
camlp4o -filter lift -filter lift  test_lift_1.ml -printer o > test_lift_2.ml
```

You can lift it several times to see it grows exponentially

Macro Filter

```
DEFINE PI = 3.1415926
DEFINE F(x) = x +. x

let _  =
  IFDEF DEBUG THEN
    print_float PI
  ENDIF;
  print_float (F(PI));
  print_endline "";
  IFDEF DEBUG THEN
    print_endline "DEBUG"
  ELSE
    print_endline "RELEASE"
  END
```

Listing 50: Example Macro

4.12.3 Example Tuple Map

```
open Camlp4.PreCast ;
value rec duplicate n t _loc =
    if n <= 0 then invalid_arg "duplicate n < 0"
    else
      let arr = Array.init n (fun x -> x) in
      let lst = Array.(
        to_list (mapi (fun i _ -> <:patt< $lid: "x" ^ string_of_int i $ >> ) arr )) in
      let patt = <:patt< $tup:Ast.paCom_of_list lst $ >> in
      <:expr< fun $patt$ -> $tup:Ast.exCom_of_list
          (Array.(
           to_list (mapi (fun i _ ->
             <:expr< $lid:t$ $lid:"x" ^ string_of_int i $ >> ) arr ))) $ >> ;
value map_filter = object
  inherit Ast.map as super ;
  method! expr e =
    match e with
    [ <:expr@_loc< Tuple.map $lid:f$ $tup:xs$ >> ->
      <:expr< $tup: Ast.(exCom_of_list  (List.map (fun e -> <:expr< $lid:f$ $e$ >> )
                          (list_of_expr xs []))) $ >>
     (** we can do the same as the second branch, but here we do inlining *)
    | <:expr@_loc< Tuple.map $lid:f$ $int:num$ >> ->
        let n = int_of_string num in
        super#expr
          (duplicate n f _loc)
    | <:expr@_loc< Tuple.map $_$ >> ->
        failwith ("Tuple.map not transformed, supported two forms\n"^
                  "Tuple.map lid tup \n"^
                  "Tuple.map lid n \n")
    | others -> super#expr others ]
        ;
end ;

AstFilters.register_str_item_filter map_filter#str_item;

(**
```

Listing 51: Example Tuple Map

4.12.4 Location Strip filter

Replace location with `Loc.ghost`

Might be useful when you compare two asts? YES! idea? how to use lifter at toplevel, how to beautify our code, without the horribling output? (I mean, the qualified name is horrible, but you can solve it by open the Module)

4.12.5 Camlp4Profiler

Inserts profiling code

4.12.6 Camlp4TrashRemover

```
open Camlp4;

module Id = struct
  value name    = "Camlp4TrashRemover";
  value version = Sys.ocaml_version;
end;

module Make (AstFilters : Camlp4.Sig.AstFilters) = struct
  open AstFilters;
  open Ast;

  register_str_item_filter
    (Ast.map_str_item
      (fun
       [ <:str_item@_loc< module Camlp4Trash = $_$ >> ->
           <:str_item<>>
       | st -> st ]))#str_item;

end;

let module M = Camlp4.Register.AstFilter Id Make in ();
```

4.12.7 Camlp4ExceptionTracer

4.13 Examples

4.13.1 Pa_python

```
(* Author: bobzhang1988@seas215.wlan.seas.upenn.edu        *)
(* Version: $Id: test.ml,v 0.0 2012/02/12 19:48:30 bobzhang1988 Exp $ *)
(* open BatPervasives *)

(* ocamlbuild -lflags -linkall translate.cma *)
(* camlp4o -I _build translate.cma -impl test.py -printer o *)
open Printf
open Camlp4.PreCast

open Camlp4

(**
   1. Define your own ast
      There's need to add location to your ast.
      This can locate the error position during type-check time
      If you only care syntax-error location, then it's not necessary
   2. Parse to your ast
   3. Translate yor ast to ocaml ast
      two ways to translate
      a. meta-expr
         mechanical, but not very useful, just make your concrete syntax
         a little easy
      b. do some transformation
         semantics changed
   4. define quotation syntax for your syntax tree
      not necessary but make your life easier
*)

(**
   concrete_syntax
   stmt:
      def id = expr
      print exprs
   expr:
      string-literal
      id

   exprs: expr list
*)


(* module MGram = MakeGram(Lexer) *)
```

```
module MGram = Gram

type  stmt =
    Def of Loc.t *  id * expr
  | Print of Loc.t * expr list
and  expr =
  | Var of Loc.t * id
  | String of Loc.t * string
and id = string
and prog =
  | Prog of Loc.t * stmt list

let pys = MGram.Entry.mk "pys"
let pys_eoi = MGram.Entry.mk "pys_eoi"

let _ = begin
  MGram.Entry.clear pys;
  MGram.Entry.clear pys_eoi;
  EXTEND MGram GLOBAL: pys_eoi;
  pys_eoi:
    [ [ prog= pys ; EOI -> prog ]];
  END;
  EXTEND MGram GLOBAL:pys;
    pexpr: [
      [ s = STRING -> String(_loc, s)
        (** here we want  "\n" be comprehended as "\n", so we don't
            escape.
            *)
      | id = LIDENT -> Var(_loc, id)
      ]
    ];
    pys:
      [ [ stmts = LIST0 [ p = py ;  ";" -> p  ]  -> Prog(_loc, stmts)] ];
    py:
      [
        [ "def"; id=LIDENT; "="; e = pexpr -> begin
          (* prerr_endline "def"; *)
          Def (_loc, id, e);
        end
        | "print"; es = LIST1 pexpr SEP "," ->
           Print(_loc, es)
        ]
      ];
  END;
end

let pys_parser  str =
```

```
  MGram.parse_string pys_eoi (Loc.mk "<string>") str

let a =
  pys_parser "def a = \"3\"; def b =  \"4\"; def c =  \"5 \"; print a,b,c; "

(** Parser is ok now.  Now Ast Transformer, if we defined quotation
    for our own syntax. That would be easier *)
```

Now we transform the ast to the semantics what we want, we write Ast transformation using revised syntax(robust, and disambiguous) .

```
(* Author: bobzhang1988@seas215.wlan.seas.upenn.edu        *)
(* Version: $Id: translate.ml,v 0.0 2012/02/12 20:28:50 bobzhang1988 Exp $ *)


(** Revised Syntax *)

(* open BatPervasives; *)
open Printf;
open Test;
open Camlp4;
open Camlp4.PreCast;


value rec concat  (asts : list Ast.expr) : Ast.expr  =
    match asts with
   [ [] -> assert False
   | [h] -> h
   | [h::t ] ->
     let _loc = Ast.loc_of_expr h in
     <:expr< $h$ ^ $concat t$  >>
   ]
;

value rec translate (p: prog ) :Ast.str_item =
  match p with
      [ Prog(_loc,stmts) ->
        <:str_item< $list: List.map translate_stmt stmts $ >>
      ]
and translate_stmt (st:stmt) =
    match st with
    [ Def (_loc, id, expr) ->
      <:str_item< value $lid:id$ = $translate_expr expr$ ;>>
    | Print (_loc, exprs) ->
      <:str_item< print_endline $concat  (List.map translate_expr exprs) $;
        >>
```

```
    ]
and translate_expr (e:expr) =
    match e with
    [ Var (_loc, id) -> <:expr<$lid:id$ >>
    | String (_loc,s) -> <:expr<$str:s$ >>    (* Check whether needs escaped later*)
    ]
;

begin
  Gram.Entry.clear Syntax.str_item ;
  let open Syntax in begin
  EXTEND Gram GLOBAL:str_item;
    str_item : [ [ s = pys_eoi -> translate s ] ];
  END ;
  (* Gram.Entry.print Format.std_formatter expr; *)
  end ;
end;
```

```
(* module Pa_python (Syntax:Sig.Camlp4Syntax) = struct *)
(*   (\* open Syntax; *\) *)
(*   prerr_endline "why is it not invoked"; *)
(*   open Camlp4.PreCast.Syntax; *)
(*   Gram.Entry.clear str_item ; *)
(*   EXTEND Gram *)
(*     str_item : [ [ s = pys_eoi -> *)
(*       begin *)
(*         prerr_endline "here"; *)
(*         translate s; *)
(*       end ] ]; *)
(*   END ; *)
(*   include Syntax ; *)
(* end ; *)
```

```
(* prerr_endline "weird"; *)
(* let module M = Camlp4.Register.OCamlSyntaxExtension Id Pa_python in (); *)

(** Here we use MGram, they are _actually_ the same, but
    Syntax.Gram.Entry.t is not the same as
    Test.Prog Test.MGram.Entry.t
*)

(* Without functors *)
(* This is the most straightforward. We complete our code from above as follows: *)
```

Notice, we could either modify using functor interface(tedious, maybe robust, but it does not gurantee anything)

Test file is like this

```
def a = "3";
def b = "4";
def c = "5\n";

print a, b, c;
```

And out put

```
let a = "3"

let b = "4"

let c = "5\n"

let _ = print_endline (a ^ (b ^ c))
```

Everything seems pretty easy, but be careful! When you use camlp4 extensions, use ocamlobjinfo to examine which modules are exactly linked, normally you only need to link your own module file, don't try to link other modules, otherwise you will get trouble.

ocamlbuild is not that smart, use `ocamlbuild -clean` to keep your source tree clean.

The myocamlbuild.ml file now seems rather trival to write

```
(fun _ -> begin
  flag ["ocaml"; "pp"; "use_python"]
    (S[A"test.cmo"; A"translate.cmo"
  flag ["ocaml"; "pp"; "use_list"]
    (S[A"pa_list.cmo"]);
end ) +> after_rules;
(fun _ -> begin
  dep ["ocamldep";  "use_python"] ["
  dep ["ocamldep";  "use_list"] ["pa
  Options.ocaml_lflags := "-linkall"

 end ) +> after_rules;
```

Make sure you know which module you linked.

4.13.2 Pa_list

```
open Camlp4.PreCast
(** open Batteries  *)
(** So the first one adds [%] to the simple level; it's added as two
    terminals because the lexer splits [%] into two tokens [% and ];
    this isn't a problem, we'll just recognize them in sequence, but
    it does allow [% (* foo *) ] to stand for lazy nil.*)

let _ = let open Syntax in begin
  EXTEND Gram GLOBAL: patt;
  patt: LEVEL "simple"
    [
      [ "[%" ; "]" ->  <:patt< lazy Nil >> ] ];
  patt: LEVEL "::"
    [ [ p1 = SELF; "%::"; p2 = SELF ->
    <:patt< lazy Cons ($p1$,  $p2$ ) >>
      ] ];
  END;
end

(**
open Camlp4.PreCast

(** open Batteries  *)
(** So the first one adds [%] to the simple level; it's added as two
    terminals because the lexer splits [%] into two tokens [% and ];
    this isn't a problem, we'll just recognize them in sequence, but
    it does allow [% (* foo *) ] to stand for lazy nil.*)
let _ = let open Syntax
  in
```

```
let _ = (patt : 'patt Gram.Entry.t)
in
  (Gram.extend (patt : 'patt Gram.Entry.t)
     ((fun () ->
         ((Some (Camlp4.Sig.Grammar.Level "simple")),
          [ (None, None,
             [ ([ Gram.Skeyword "[%"; Gram.Skeyword "]" ],
                (Gram.Action.mk
                   (fun _ _ (_loc : Gram.Loc.t) ->
                      (Ast.PaLaz (_loc,
                         (Ast.PaId (_loc, (Ast.IdUid (_loc, "Nil"))))) :
                       'patt)))) ]) ]))
        ());
   Gram.extend (patt : 'patt Gram.Entry.t)
     ((fun () ->
         ((Some (Camlp4.Sig.Grammar.Level "::")),
          [ (None, None,
             [ ([ Gram.Sself; Gram.Skeyword "%::"; Gram.Sself ],
                (Gram.Action.mk
                   (fun (p2 : 'patt) _ (p1 : 'patt) (_loc : Gram.Loc.t)
                      ->
                      (Ast.PaLaz (_loc,
                         (Ast.PaApp (_loc,
                            (Ast.PaApp (_loc,
                               (Ast.PaId (_loc,
                                  (Ast.IdUid (_loc, "Cons")))),
                               p1)),
                            p2))) :
                       'patt)))) ]) ]))
        ()))


*)
```

Notice that here for `pa_list.cmo`, we did not need to link `batteries`, since at executation time, it did not bother `Batteries` at all. Read the commented output, you see at this phase, that `Nil` was acutally translated into `"Nil"`. So actually you don't bother Batteries at all. Even you said `open Batteries`, ocaml compiler was not that stupid to link it.

The test file is also interesting.

This extension illustrates an example to tell us how to extend your parser. Remember, Camlp4 is a source to source level pretty-printer. So you don't need to be

responsible for which library will be linked at the time of writing syntax extension. The user may make sure such module or value really exist.

4.13.3 Pa_abstract

```
open Camlp4.PreCast
open Camlp4

let abstract = ref true

(** open Syntax for Gram *)
let _ = let open Syntax in begin
  EXTEND Gram  GLOBAL: ctyp;
  ctyp: [[ LIDENT "semi"; LIDENT "opaque"; t = SELF ->
    (* <:ctyp< 's >>TyQuo of Loc.t and string *)
    if !abstract
    (* Abstract types are represented with the empty type. *)
    then <:ctyp< >>
    (* then <:ctyp< 'abstract >> *)
    else t
       ]];
  END;
end

let _ =  begin
  Camlp4.Options.add "-abstract" (Arg.Set abstract)
 "Use abstract types for semi opaque ones";
  Options.add "-concrete" (Arg.Clear abstract)
 "Use concrete types for semi opaque ones";
end

type t = semi opaque int

(**
   camlp4o -I _build pa_abstract.cmo test_pa_abstract.ml -abstract -printer o
   type t
   ocamlbuild -pp 'camlp4o -I _build pa_abstract.cmo -abstract ' test_pa_abstract.cmo
*)
```

This example shows how to customize your options for your syntax extension.

4.13.4 Pa_apply

```
open Camlp4.PreCast
let _ =
  AstFilters.register_str_item_filter
  (Ast.map_expr
    (function
      <:expr@loc< $e1$ & $e2$ >> -> <:expr@loc< $e1$ $e2$ >>
     | e -> e ))#str_item

(* To force it to be inlined. If not it's not well typed. *)
let ( & ) = ( )
let test = fun f g h x -> f & g & h x
```

This is a dirty way to write a filter plugin, you may write a formal way which uses the interface of `Camlp4.Register`.

4.13.5 Pa_ctyp

```
open Camlp4.PreCast;

module Caml =
  Camlp4OCamlParser.Make
    (Camlp4OCamlRevisedParser.Make
    (Camlp4.OCamlInitSyntax.Make Ast Gram Quotation ));
module Printers = Camlp4.Printers.OCaml.Make Caml;
open Caml; (** Use all from Caml*)
(** File PreCast.ml
    (** Camlp4.PreCast.Syntax is global and shared
    *)
    module Loc = Struct.Loc;
    module Ast = Struct.Camlp4Ast.Make Loc;
    module Token = Struct.Token.Make Loc;
    module Lexer = Struct.Lexer.Make Token;
    module Gram = Struct.Grammar.Static.Make Lexer;
    module DynLoader = Struct.DynLoader;
    module Quotation = Struct.Quotation.Make Ast;
    module MakeSyntax (U : sig end) = OCamlInitSyntax.Make Ast Gram Quotation;
    module Syntax = MakeSyntax (struct end);
    module AstFilters = Struct.AstFilters.Make Ast;
    module MakeGram = Struct.Grammar.Static.Make;

    module Printers = struct
      module OCaml = Printers.OCaml.Make Syntax;
      module OCamlr = Printers.OCamlr.Make Syntax;
```

```
     (* module OCamlrr = Printers.OCamlrr.Make Syntax; *)
     module DumpOCamlAst = Printers.DumpOCamlAst.Make Syntax;
     module DumpCamlp4Ast = Printers.DumpCamlp4Ast.Make Syntax;
     module Null = Printers.Null.Make Syntax;
end;
*)

value function_type = "'a -> 'b ";

let printer = (new Printers.printer ()) in
let print_class_str_item = printer#class_sig_item Format.std_formatter in
let print_ctyp = printer#ctyp Format.std_formatter in
let quant = ["'a"; "'b"] in
let parse_ctyp = Gram.parse_string Caml.ctyp (Loc.mk "<string>") in
let _loc = Loc.ghost in
let quant : Ast.ctyp =
  List.fold_right
    (fun t acc -> <:ctyp< $parse_ctyp t$ $acc$ >>) quant <:ctyp< >> in
let function_type =
  parse_ctyp function_type in
print_ctyp function_type;
(* print_class_str_item <:class_str_item< method $x$ : ! $list:quant$ . $function_type$ = $expression$ >> ; *)

(* 'a -> 'b *)
```

This example shows how to make use of the existing parser or printer of camlp4.

4.13.6 Pa_exception_wrapper

```
open Camlp4.PreCast;

value rec aux =
    let add_debug_expr e =
      let _loc = Loc.make_absolute (Ast.loc_of_expr e) in
      let msg = "Exception tracer at " ^
        Loc.to_string _loc ^ " (%s)@." in
      <:expr<
        try $e$
        with exc ->
          do {
            Format.eprintf $str:msg$ (Printexc.to_string exc);
            raise exc
          } >> in
    let map_pwe (patt, owhen, expr) =
      (patt, owhen, add_debug_expr expr) in
```

```
    map_pwe
and map_expr =
 fun
 [ <:expr@_loc< fun [ $ms$ ] >> ->
   let mcs = Ast.list_of_match_case ms [] in
   let mcs' = Ast.mcOr_of_list (List.map (fun [
   <:match_case< $p$ when $e1$ -> $e2$ >>
       ->
         let (p',e1',e2') = aux (p,e1,e2) in
         <:match_case<$p'$ when $e1'$ -> $e2'$ >>
   ]) mcs ) in
   <:expr< fun [ $mcs'$ ]>>
 | x -> x ];


(*
  value make_absolute x =
  debug loc "make_absolute: %a@\n" dump x in
  let pwd = Sys.getcwd () in
  if Filename.is_relative x.file_name then
    { (x) with file_name = Filename.concat pwd x.file_name }
  else x;
*)

AstFilters.register_str_item_filter (Ast.map_expr map_expr)#str_item  ;


let a = Array.make 10 0
let f () = a.(11)

(** only one match case in the toplevel *)
let f2 x = match x with
  | 0 -> 1
  | 1 -> 2
  | 2 -> 3

(** 3 match cases in the toplevel *)
let f3 = function
  | 0 -> 1
  | 1 -> 2
  | 3 -> 4
let g = f
let h = g
let main = h ()

(**
   camlp4of -I _build pa_exception_wrapper.cmo test_pa_exception_wrapper.ml -printer o
```

```
let a = Array.make 10 0

let f () =
  try a.(11)
  with
  | exc ->
      (Format.eprintf
         "Exception tracer at File "/Users/bobzhang1988/Writing/ocaml-book/camlp4/examples/test_pa_exception_wrapper.ml"
         (Printexc.to_string exc);
       raise exc)

(** only one match case in the toplevel *)
let f2 x =
  try match x with | 0 -> 1 | 1 -> 2 | 2 -> 3
  with
  | exc ->
      (Format.eprintf
         "Exception tracer at File "/Users/bobzhang1988/Writing/ocaml-book/camlp4/examples/test_pa_exception_wrapper.ml"
         (Printexc.to_string exc);
       raise exc)

(** 3 match cases in the toplevel *)
let f3 =
  function
  | 0 ->
      (try 1
       with
       | exc ->
           (Format.eprintf
              "Exception tracer at File "/Users/bobzhang1988/Writing/ocaml-book/camlp4/examples/test_pa_exception_wrappe
              (Printexc.to_string exc);
            raise exc))
  | 1 ->
      (try 2
       with
       | exc ->
           (Format.eprintf
              "Exception tracer at File "/Users/bobzhang1988/Writing/ocaml-book/camlp4/examples/test_pa_exception_wrappe
              (Printexc.to_string exc);
            raise exc))
  | 3 ->
      (try 4
       with
       | exc ->
           (Format.eprintf
              "Exception tracer at File "/Users/bobzhang1988/Writing/ocaml-book/camlp4/examples/test_pa_exception_wrappe
              (Printexc.to_string exc);
```

```
            raise exc))

let g = f

let h = g

let main = h ()




*)
```

4.13.7 Pa_exception_tracer

```
open Camlp4;
module Id = struct
  value name    = "Camlp4ExceptionTracer";
  value version = Sys.ocaml_version;
end;

module Make (AstFilters : Camlp4.Sig.AstFilters) = struct
  open AstFilters;
  open Ast;
  value add_debug_expr e =
    let _loc = Ast.loc_of_expr e in
    let msg = "camlp4-debug: exc: %s at " ^ Loc.to_string _loc ^ "@." in
    <:expr<
        try $e$
        with
        [ Stream.Failure | Exit as exc -> raise exc
        | exc -> do {
            if Debug.mode "exc" then
              Format.eprintf $`str:msg$ (Printexc.to_string exc) else ();
            raise exc
          } ] >>;

  (** finer grained transform *)
  value rec map_match_case =
    fun
    [ <:match_case@_loc< $m1$ | $m2$ >> ->
      (** split into each bracnh *)
        <:match_case< $map_match_case m1$ | $map_match_case m2$ >>
    | <:match_case@_loc< $p$ when $w$ -> $e$ >> ->
        <:match_case@_loc< $p$ when $w$ -> $add_debug_expr e$ >>
```

```
    | m -> m ];

  value filter = object
    inherit Ast.map as super;
    method expr = fun
    [ <:expr@_loc< fun [ $m$ ] >> -> <:expr< fun [ $map_match_case m$ ] >>
    | x -> super#expr x ];
    method str_item = fun
    [ <:str_item< module Debug = $_$ >> as st -> st
    | st -> super#str_item st ];
  end;

  register_str_item_filter filter#str_item;

end;

let module M = Camlp4.Register.AstFilter Id Make in ();
```

4.13.8 Pa_freevars

4.13.9 Pa_freevars_filter

4.13.10 Pa_global_handler

4.13.11 Pa_holes

4.13.12 Pa_minimm

4.13.13 Pa_plus

4.13.14 Pa_zero

4.13.15 Pa_printer

```
(* Author: bobzhang1988@vpl472.wlan.library.upenn.edu        *)
(* Version: $Id: pa_printer.ml,v 0.0 2012/02/15 18:19:14 bobzhang1988 Exp $ *)
open Printf

module Id = struct
  let name = "Printer How to"
  let version = "$Id: how to version 1$ "
end
```

```
let (^$) f x = f x

(** Camlp4.Sig.Syntax.Ast is not very powerful,
    many interfaces are not exposed
*)
module Make (Syntax: Camlp4.Sig.Syntax) :
  Camlp4.Sig.Printer(Syntax.Ast).S = struct
    module Ast = Syntax.Ast
    let opt_string = function
      | None -> "<None>"
      | Some s -> s
    let info ?input_file ?output_file name =
      eprintf
        "printer on %s\n input: %s\n output: %s\n"
        name
        (opt_string input_file)
        (opt_string output_file)
    let print_interf ?input_file ?output_file (ast:Ast.sig_item) = begin
      (* let n = List.length (^$ Ast.list_of_str_item ast [] in  *)
      info ?input_file ?output_file "signature";
      (* eprintf "%d sig_items\n"; *)
    end
    let print_implem ?input_file ?output_file (ast:Ast.str_item) = begin
      (* let n = List.length (^$ Ast.list_of_str_item ast [] in *)
      info ?input_file ?output_file "structure";
      (* eprintf "%d str_items\n"; *)
    end
  end
module M = Camlp4.Register.Printer(Id) (Make)

(**
   camlp4o -I _build  pa_printer.cmo pa_printer.ml

 printer on structure
 input: pa_printer.ml
 output: <None>

*)
```

4.13.16 Parse_arith

4.13.17 Pa_estring

```
(*
 * pa_estring.ml
```

```
 * -------------
 * Copyright : (c) 2008, Jeremie Dimino <jeremie@dimino.org>
 * Licence   : BSD3
 *
 * This file is a part of estring.
 *)

open Printf
open Camlp4.Sig
open Camlp4.PreCast

type specifier = string

type context = {
  mutable next_id : int;
  mutable shared_exprs : (Loc.t * string * Ast.expr) list;
}

let lookup tbl key =
  try
    Some(Hashtbl.find tbl key)
  with
      Not_found -> None

(* +----------------------+
   | Lists with location |
   +----------------------+ *)

type 'a llist =
  | Nil of Loc.t
  | Cons of Loc.t * 'a * 'a llist

let loc_of_llist = function
  | Nil loc -> loc
  | Cons(loc, x, l) -> loc

let rec llength_rec acc = function
  | Nil _ -> acc
  | Cons(_, _, ll) -> llength_rec (acc + 1) ll

let llength ll = llength_rec 0 ll

let rec lfoldr f g = function
  | Nil loc -> g loc
  | Cons(loc, x, l) -> f loc x (lfoldr f g l)

let rec list_of_llist = function
```

```
  | Nil _ -> []
  | Cons(_, x, l) -> x :: list_of_llist l

let rec llist_of_list loc = function
  | [] -> Nil loc
  | x :: l -> Cons(loc, x, llist_of_list (Loc.move `start 1 loc) l)

let rec ldrop n l =
  if n <= 0 then
    l
  else match l with
    | Cons(_, _, l) -> ldrop (n - 1) l
    | l -> l

let rec ltake n l =
  if n <= 0 then
    Nil (loc_of_llist l)
  else match l with
    | Cons(loc, x, l) -> Cons(loc, x, ltake (n - 1) l)
    | l -> l

let rec lappend ll1 ll2 = match ll1 with
  | Nil _ -> ll1
  | Cons(loc, x, ll) -> Cons(loc, x, lappend ll ll2)

let llist_expr f ll = lfoldr (fun _loc x acc -> <:expr< $f _loc x$ :: $acc$ >>) (fun _loc -> <:expr< [] >>) ll
let llist_patt f ll = lfoldr (fun _loc x acc -> <:patt< $f _loc x$ :: $acc$ >>) (fun _loc -> <:patt< [] >>) ll

(* +--------------------+
   | Strings unescaping |
   +--------------------+ *)

(* String appears in the camlp4 ast as they apears in the source
   code. So if we want to process a string then we need to first
   unescape it. Camlp4 provide such a function
   (Camlp4.Struct.Token.Eval.string) but the problem is that we do not
   know exactly the location of unescaped characters:

   For instance: "\tx\tA" will be unescaped in " x A", and the
   position of "A" in the resulting string will be changed.

   So here is an implementation of an unescaping function which also
   compute the location of each unescaped characters. *)

module Unescape =
struct
  let add n loc = Loc.move `start n loc
```

```
let inc loc = add 1 loc
let addl n loc = Loc.move_line n loc
let incl loc = addl 1 loc
let resetl loc = addl 0 loc

let dec x = Char.code x - Char.code '0'
let hex = function
  | '0'..'9' as x -> Char.code x - Char.code '0'
  | 'a'..'f' as x -> Char.code x - Char.code 'a' + 10
  | 'A'..'F' as x -> Char.code x - Char.code 'A' + 10
  | x -> assert false

let rec skip_indent cont loc = function
  | (' ' | '\t') :: l -> skip_indent cont (inc loc) l
  | l -> cont loc l

let skip_opt_linefeed cont loc = function
  | '\n' :: l -> cont (incl loc) l
  | l -> cont loc l

let rec string loc = function
  | [] -> Nil loc
  | '\\' :: l ->
      let loc = inc loc in
      begin match l with
        | '\n' :: l -> skip_indent string (incl loc) l
        | '\r' :: l -> skip_opt_linefeed (skip_indent string) (resetl loc) l
        | 'n' :: l -> Cons(loc, '\n', string (inc loc) l)
        | 'r' :: l -> Cons(loc, '\r', string (inc loc) l)
        | 't' :: l -> Cons(loc, '\t', string (inc loc) l)
        | 'b' :: l -> Cons(loc, '\b', string (inc loc) l)
        | '\\' :: l -> Cons(loc, '\\', string (inc loc) l)
        | '"' :: l  -> Cons(loc, '"', string (inc loc) l)
        | '\'' :: l -> Cons(loc, '\'', string (inc loc) l)
        | ' ' :: l -> Cons(loc, ' ', string (inc loc) l)
        | ('0'..'9' as c1) :: ('0'..'9' as c2) :: ('0'..'9' as c3) :: l ->
            Cons(loc,
                 char_of_int (100 * (dec c1) + 10 * (dec c2) + (dec c3)),
                 string (add 3 loc) l)
        | 'x'
          :: ('0'..'9' | 'a'..'f' | 'A'..'F' as c1)
          :: ('0'..'9' | 'a'..'f' | 'A'..'F' as c2) :: l ->
            Cons(loc,
                 char_of_int (16 * (hex c1) + (hex c2)),
                 string (add 3 loc) l)
        | _ -> Loc.raise loc (Stream.Error "illegal backslash")
      end
```

```
    | '\r' :: l -> Cons(loc, '\r', string (resetl loc) l)
    | '\n' :: l -> Cons(loc, '\n', string (incl loc) l)
    | ch :: l -> Cons(loc, ch, string (inc loc) l)
end

let unescape loc str =
  let l = ref [] in
  for i = String.length str - 1 downto 0 do
    l := str.[i] :: !l
  done;
  Unescape.string loc !l

(* +------------------------+
   | Specifier registration |
   +------------------------+ *)

module String_set = Set.Make(String)

let specifiers = ref String_set.empty
let add_specifier spec =
  specifiers := String_set.add spec !specifiers

let expr_specifiers = Hashtbl.create 42
let patt_specifiers = Hashtbl.create 42
let when_specifiers = Hashtbl.create 42

let register_expr_specifier specifier f =
  add_specifier specifier;
  Hashtbl.add expr_specifiers specifier f

let register_patt_specifier specifier f =
  add_specifier specifier;
  Hashtbl.add patt_specifiers specifier f

let register_when_specifier specifier f =
  add_specifier specifier;
  Hashtbl.add when_specifiers specifier f

(* +-----------------------------+
   | String specifier recognition |
   +-----------------------------+ *)

(* Strings with a specifier are recognized using a token filter. This
   is to avoid recognizing things like [u "string"], [X.u"string"].

   Strings with a specifier are replaced by an identifier of the form
   "__estring_string_NNN_XXX". *)
```

```
let strings = Hashtbl.create 42
  (* Mapping identifier of the form "__estring_XXX" -> specifier + string literal *)

let estring_prefix = sprintf "__estring_string_%d_" (Oo.id (object end))
  (* Prefix for identifiers referring to strings with specifier. The
     [Oo.id (object end)] is a trick to generate a fresh id so several
     estring instances can works together. *)

let gen_string_id =
  let nb = ref 0 in
  fun () ->
    let x = !nb in
    nb := x + 1;
    estring_prefix ^ string_of_int x

let wrap_stream stm =
  (* The previous token *)
  let previous = ref EOI in

  let func pos =
    try
      let prev = !previous
      and tok, loc = Stream.next stm in

      previous := tok;

      match tok with
        | (LIDENT id | UIDENT id) when prev <> KEYWORD "." && String_set.mem id !specifiers ->
            begin match Stream.peek stm with
              | Some(STRING(s, orig), loc) ->
                  Stream.junk stm;
                  let string_id = gen_string_id () in
                  Hashtbl.add strings string_id (id, orig);
                  Some(LIDENT string_id, loc)
              | _ ->
                  Some(tok, loc)
            end

        | _ ->
            Some(tok, loc)
    with
        Stream.Failure -> None
  in
  Stream.from func

(* +--------------------+
```

```
   | Strings conversion |
   +--------------------+ *)

let register_shared_expr context expr =
  let id = "__estring_shared_" ^ string_of_int context.next_id in
  context.next_id <- context.next_id + 1;
  let _loc = Ast.loc_of_expr expr in
  context.shared_exprs <- (_loc, id, expr) :: context.shared_exprs;
  <:ident< $lid:id$ >>

let is_special_id id =
  let rec aux1 i =
    if i = String.length estring_prefix then
      aux2 i
    else
      i < String.length id && id.[i] = estring_prefix.[i] && aux1 (i + 1)
  and aux2 i =
    (i < String.length id) && match id.[i] with
      | '0' .. '9' -> aux3 (i + 1)
      | _ -> false
  and aux3 i =
    if i = String.length id then
      true
    else match id.[i] with
      | '0' .. '9' -> aux3 (i + 1)
      | _ -> false
  in
  aux1 0

let expand_expr context _loc id =
  match lookup strings id with
    | Some(specifier, string) -> begin
        match lookup expr_specifiers specifier with
          | Some f ->
              f context _loc string
          | None ->
              Loc.raise _loc (Failure "pa_estring: this specifier can not be used here")
      end

    | None ->
        <:expr< $lid:id$ >>

let expand_patt context _loc id =
  match lookup strings id with
    | Some(specifier, string) -> begin
        match lookup patt_specifiers specifier with
          | Some f ->
```

```
            f context _loc string
          | None ->
            Loc.raise _loc (Failure "pa_estring: this specifier can not be used here")
      end

    | None ->
        <:patt< $lid:id$ >>

(* Replace extended strings with identifiers and collect conditions *)
let map_match context (num, conds) = object
  inherit Ast.map as super

  method patt p = match super#patt p with
    | <:patt@_loc< $lid:id$ >> as p when is_special_id id -> begin
        match lookup strings id with
          | Some(specifier, string) -> begin
              match lookup when_specifiers specifier with
                | Some f ->
                    let id = <:ident< $lid:"__estring_var_" ^ string_of_int !num$ >> in
                    incr num;
                    conds := f context _loc id string :: !conds;
                    <:patt< $id:id$ >>

                | None ->
                    expand_patt context _loc id
            end

          | None ->
              p
      end

    | p -> p
end

let map context = object(self)
  inherit Ast.map as super

  method expr e = match super#expr e with
    | <:expr@_loc< $lid:id$ >> when is_special_id id -> expand_expr context _loc id
    | e -> e

  method patt p = match super#patt p with
    | <:patt@_loc< $lid:id$ >> when is_special_id id -> expand_patt context _loc id
    | p -> p

  method match_case = function
    | <:match_case@_loc< $p$ when $c$ -> $e$ >> ->
```

```
        let conds = ref [] in
        let p = (map_match context (ref 0, conds))#patt p
        and c = self#expr c and e = self#expr e in
        let gen_mc first_cond conds =
          <:match_case< $p$ when $List.fold_left (fun acc cond -> <:expr< $cond$ && $acc$ >>) first_cond conds$ -> $e$ >>
        in
        begin match c, !conds with
          | <:expr< >>, [] ->
              <:match_case< $p$ when $c$ -> $e$ >>

          | <:expr< >>, c :: l ->
              gen_mc c l

          | e, l ->
              gen_mc e l
        end

    | mc ->
        super#match_case mc
end

let map_expr e =
  let context = { next_id = 0; shared_exprs = [] } in
  let e = (map context)#expr e in
  List.fold_left
    (fun acc (_loc, id, expr) -> <:expr< let $lid:id$ = $expr$ in $acc$ >>)
    e context.shared_exprs

let rec map_class_expr = function
  | Ast.CeAnd(loc, e1, e2) ->
      Ast.CeAnd(loc, map_class_expr e1, map_class_expr e2)
  | Ast.CeEq(loc, name, e) ->
      let context = { next_id = 0; shared_exprs = [] } in
      let e = (map context)#class_expr e in
      let e =
        List.fold_left
          (fun acc (_loc, id, expr) -> <:class_expr< let $lid:id$ = $expr$ in $acc$ >>)
          e context.shared_exprs
      in
      Ast.CeEq(loc, name, e)
  | ce ->
      ce

let rec map_binding = function
  | <:binding@_loc< $id$ = $e$ >> ->
      <:binding< $id$ = $map_expr e$ >>
  | <:binding@_loc< $a$ and $b$ >> ->
```

```
      <:binding< $map_binding a$ and $map_binding b$ >>
  | x ->
      x

let map_def = function
  | Ast.StVal(loc, is_rec, binding) ->
      Ast.StVal(loc, is_rec, map_binding binding)
  | Ast.StExp(loc, expr) ->
      Ast.StExp(loc, map_expr expr)
  | Ast.StCls(loc, ce) ->
      Ast.StCls(loc, map_class_expr ce)
  | x ->
      x

(* +--------------+
   | Registration |
   +--------------+ *)

let _ =
  (* Register the token filter for specifiers *)
  Gram.Token.Filter.define_filter (Gram.get_filter ()) (fun filter stm -> filter (wrap_stream stm));

  let map = (Ast.map_str_item map_def)#str_item in

  (* Register the mapper for implementations *)
  AstFilters.register_str_item_filter map;

  (* Register the mapper for the toplevel *)
  AstFilters.register_topphrase_filter map
```

4.13.18 Pa_holes

4.14 Useful links

Abstract_Syntax_Tree

elehack

meta-guide

camlp4

zheng.li

pa-do

Wiki

yutaka

4.15 Camlp4 CheatSheet

4.15.1 Camlp4 Transform Syntax

```
camlp4of -str "let a = [x| x <- [1.. 10] ] "
```

```
let a = [ 1..10 ]
```

```
camlp4o -str 'true && false'
```

```
true && false
```

```
(** camlp4of -str "let q = <:str_item< let f x = x >>"*)
let q =
  Ast.StSem (_loc,
    (Ast.StVal (_loc, Ast.ReNil,
       (Ast.BiEq (_loc,
          (Ast.PaId (_loc, (Ast.IdLid (_loc, "f")))),
          (Ast.ExFun (_loc,
             (Ast.McArr
                (_loc,
                (Ast.PaId (_loc, (Ast.IdLid (_loc, "x")))),
                (Ast.ExNil _loc), (Ast.ExId (_loc, (Ast.IdLid (_loc, "x"))))))))))),
    (Ast.StNil _loc))
```

`camlp4of -p r -str 'you code'` is a good way to learn the corresponding revised syntax.

You can also *customize* you options in your filter as sample code Listing 52

Example: semi opaque

```
open Format
open Camlp4.PreCast
open Camlp4
let abstract = ref true

(** Abstract types are represented with the empty type.
 *)
let _ =
  let open Syntax in begin
```

```
    EXTEND Gram  GLOBAL: ctyp;
    ctyp: [[ LIDENT "semi"; LIDENT "opaque"; t = SELF ->
      (* <:ctyp< 's >>TyQuo of Loc.t and string *)
      if !abstract

      then <:ctyp< >>
        (* then <:ctyp< 'abstract >> *)
      else t
           ]];
    END;
  end

let _ =  begin
  Camlp4.Options.add "-abstract" (Arg.Set abstract)
    "Use abstract types for semi opaque ones";
  Options.add "-concrete" (Arg.Clear abstract)
    "Use concrete types for semi opaque ones";
end
(**
   camlp4o -I _build pa_abstract.cmo -str 'type t  = semi opaque string' -printer r
 *)
```

Listing 52: Camlp4 Options

4.15.2 Parsing

Create a yasnippet, saves you a lot of time.

Chapter 5

Libraries

5.1 batteries

syntax extension Not of too much use , **Never use it in the toplevel**

- comprehension (M.filter, concat, map, filter_map, enum, of_enum)
  since it's at preproccessed stage, you can use some trick
  `let module Enum = List in` will change the semantics
  `let open Enum in` doesn't make sense, since it uses qualified name inside

5.1.1 Dev

- make changes in both .ml and .mli files

5.1.2 BOLT

5.2 Mikmatch

Directly supported in toplevel Regular expression *share* their own namespace.

1. compile

```
"test.ml" : pp(camlp4o -parser pa_mikmatch_pcre.cma)
<test.{cmo,byte,native}> : pkg_mikmatch_pcre
-- myocamlbuild.ml use default
```

2. toplevel

```
ocaml
#camlp4o ;;
#require "mikmatch_pcre" ;; (* make sure to follow the order strictly *)
```

3. debug

```
camlp4of -parser pa_mikmatch_pcre.cma -printer o test.ml
(* -no_comments does not work     *)
```

4. structure

   regular expressions can be used to match strings, it must be preceded by the RE keyword, or placed between slashes (/../).

```
    match ... with pattern -> ...
    function pattern -> ...
    try ... with pattern -> ...
    let /regexp/ = expr in expr
    let try (rec) let-bindings in expr with pattern-match
    (only handles exception raised by let-bindings)
    MACRO-NAME regexp -> expr ((FILTER | SPLIT) regexp)
```

```
let x = (function (RE digit+) -> true | _ -> false) "13232";;
val x : bool = true
# let x = (function (RE digit+) -> true | _ -> false) "1323a2";;
val x : bool = true
# let x = (function (RE digit+) -> true | _ -> false) "x1323a2";;
val x : bool = false
```

```
let get_option () = match Sys.argv with
     [| _ |] -> None
    |[| _ ; RE (lower+ as key) "=" (_* as data) |] -> Some(key,data)
    |_ -> failwith "Usage: myprog [key=val]";;
val get_option : unit -> (string * string) option = <fun>
```

```
let option = try get_option () with Failure (RE "usage"~) -> None ;;
val option : (string * string) option = None
```

5. **sample regex** built in regexes

```
    lower, upper, alpha(lower|upper), digit, alnum, punct
    graph(alnum|punct), blank,cntrl,xdigit,space
    int,float
    bol(beginning of line)
    eol
    any(except newline)
    bos, eos
```

```
let f = (function (RE int as x : int) -> x ) "132";;
val f : int = 132
let f = (function (RE float as x : float) -> x ) "132.012";;
val f : float = 132.012
let f = (function (RE lower as x ) -> x ) "a";;
val f : string = "a"
let src = RE_PCRE int ;;
val src : string * 'a list = ("[+\\-]?(?:0(?:[Xx][0-9A-Fa-f]+|(?:[Oo][0-7]+|[Bb][01]+))|[0-9]+)", [])
let x = (function (RE _* bol "haha") -> true | _ -> false) "x\nhaha";;
val x : bool = true
```

```
RE hello = "Hello!"
RE octal  = ['0'-'7']
RE octal1 = ["01234567"]
RE octal2 = ['0' '1' '2' '3' '4' '5' '6' '7']
RE octal3 = ['0'-'4' '5'-'7']
RE octal4 = digit # ['8' '9']  (* digit is a predefined set of characters *)
RE octal5 = "0" | ['1'-'7']
RE octal6 = ['0'-'4'] | ['5'-'7']
RE not_octal = [ ^ '0'-'7'] (* this matches any character but an octal digit *)
RE not_octal' = [ ^ octal]  (* another way to write it *)
```

```
RE paren' = "(" _* Lazy ")"
(* _ is wild pattern, paren is built in *)
let p = function (RE (paren' as x )) -> x ;;
```

```
p "(xx))";;
- : string = "(xx)"
# p "(x)x))";;
- : string = "(x)"
```

```
RE anything  = _*          (* any string, as long as possible *)
RE anything' = _* Lazy     (* any string, as short as possible *)
RE opt_hello  = "hello"?       (* matches hello if possible, or nothing *)
RE opt_hello' = "hello"? Lazy (* matches nothing if possible, or hello *)
RE num = digit+         (* a non-empty sequence of digits, as long as possible;
                           shortcut for: digit digit* *)
RE lazy_junk = _+ Lazy (* match one character then match any sequence
                           of characters and give up as early as possible *)

RE at_least_one_digit = digit{1+}      (* same as digit+ *)
RE at_least_three_digits = digit{3+}
RE three_digits = digit{3}
RE three_to_five_digits = digit{3-5}
RE lazy_three_to_five_digits = digit{3-5} Lazy

let test s = match s with
    RE "hello" -> true
  | _ -> false
```

It's important to know that matching process will try *any* possible combination until the pattern is matched. However the combinations are tried from left to right, and repeats are either greedy or lazy. (greedy is default). laziness triggered by the presence of the Lazy keyword.

6. fancy features of regex

   (a) normal

```
let x = match "hello world" with
  RE "world" -> true
 | _ -> false;;
```

```
val x : bool = false
```

(b) pattern match syntax (the let constructs can be used directly with a regexp pattern, but **let RE ... = ...** does not look nice, the sandwich notation (/.../) has been introduced)

```
Sys.ocaml_version;;
- : string = "3.12.1"
# RE num = digit + ;;
```

```
RE num = digit + ;;

let  /(num as major : int ) "." (num as minor : int)

( "." (num as patchlevel := fun s -> Some (int_of_string s))
| ("" as patchlevel := fun s -> None ))

( "+" (_*  as additional_info := fun s -> Some s )
| ("" as additional_info  := fun s -> None )) eos

/ = Sys.ocaml_version ;;
```

we always use **as** to extract the information.

```
val additional_info : string option = None
val major : int = 3
val minor : int = 12
val patchlevel : int option = Some 1
```

(c) File processing (Mikmatch.Text)

```
val iter_lines_of_channel : (string -> unit) -> in_channel -> unit
val iter_lines_of_file : (string -> unit) -> string -> unit
val lines_of_channel : in_channel -> string list
val lines_of_file : string -> string list
val channel_contents : in_channel -> string
val file_contents : ?bin:bool -> string -> string
val save : string -> string -> unit
val save_lines : string -> string list -> unit
exception Skip
val map : ('a -> 'b) -> 'a list -> 'b list
val rev_map : ('a -> 'b) -> 'a list -> 'b list
val fold_left : ('a -> 'b -> 'a) -> 'a -> 'b list -> 'a
val fold_right : ('a -> 'b -> 'b) -> 'a list -> 'b -> 'b
val map_lines_of_channel : (string -> 'a) -> in_channel -> 'a list
val map_lines_of_file : (string -> 'a) -> string -> 'a list
```

(d) **Mikmatch.Glob** (pretty useful)

```
val scan :
  ?absolute:bool ->
  ?path:bool ->
  ?root:string ->
  ?nofollow:bool -> (string -> unit) -> (string -> bool) list -> unit
val lscan :
  ?rev:bool ->
  ?absolute:bool ->
  ?path:bool ->
  ?root:string list ->
  ?nofollow:bool ->
  (string list -> unit) -> (string -> bool) list -> unit
val list :
  ?absolute:bool ->
  ?path:bool ->
  ?root:string ->
  ?nofollow:bool -> ?sort:bool -> (string -> bool) list -> string list
val llist :
  ?rev:bool ->
  ?absolute:bool ->
  ?path:bool ->
  ?root:string list ->
  ?nofollow:bool ->
  ?sort:bool -> (string -> bool) list -> string list list
```

here we want to get `~/.*/*.conf` file X.list (predicates corresponding to each layer .

```
let xs = let module X = Mikmatch.Glob in X.list ~root:"/Users/bob" [FILTER "." ; FILTER _* ".conf" eos ] ;;
val xs : string list = [".libfetion/libfetion.conf"]
```

```
let xs =
  let module X = Mikmatch.Glob in
  X.list ~root:"/Users/bob" [const true; FILTER _* ".pdf" eos ]
  in print_int (List.length xs) ;;
```

```
455
```

(e) Lazy or Greedy

```
match "acbde (result), blabla... " with
RE _* "(" (_* as x) ")" -> print_endline x | _ -> print_endline "Failed";;
```

```
result
```

```
 match "acbde (result),(bla)bla... " with
 RE _* Lazy "(" (_* as x) ")" -> print_endline x | _ -> print_endline "Failed";;
```

```
result),(bla
```

```
let / "a"? ("b" | "abc" ) as x / = "abc" ;; (* or patterns, the same as before*)
val x : string = "ab"
# let / "a"? Lazy ("b" | "abc" ) as x / = "abc" ;;
val x : string = "abc"
```

In place conversions of the substrings can be performed, using either the predefined converters *int*, *float*, or custom converters

```
let z  = match "123/456" with RE (digit+ as x : int ) "/" (digit+ as y : int) -> x ,y ;;
val z : int * int = (123, 456)
```

Mixed pattern

```
let z = match 123,45, "6789" with i,_, (RE digit+ as j : int) | j,i,_ -> i * j + 1;;
val z : int = 835048
```

(f) Backreferences

Previously matched substrings can be matched again using backreferences.

```
let z =  match "abcabc" with RE _* as x !x -> x ;;
val z : string = "abc"
```

(g) Possessiveness prevent backtracking

```
let x = match "abc" with RE _* Possessive _ -> true | _ -> false;;
val x : bool = false
```

(h) macros

i. FILTER macro

```
let f = FILTER int eos;;
val f : ?share:bool -> ?pos:int -> string -> bool = <fun>
# f "32";;
- : bool = true
# f "32a";;
- : bool = false
```

ii. REPLACE macro

```
let remove_comments = REPLACE "#" _* Lazy eol -> "" ;;
val remove_comments : ?pos:int -> string -> string = <fun>
# remove_comments "Hello #comment \n world #another comment" ;;
- : string = "Hello \n world "
let x = (REPLACE "," -> ";;" ) "a,b,c";;
val x : string = "a;;b;;c"
```

iii. REPLACE_FIRST macro

iv. SEARCH(_FIRST) COLLECT COLLECTOBJ MACRO

```
let search_float = SEARCH_FIRST float as x : float -> x ;;
val search_float : ?share:bool -> ?pos:int -> string -> float = <fun>
search_float "bla bla -1.234e12 bla";;
- : float = -1.234e+12
let get_numbers = COLLECT float as x : float -> x ;;
val get_numbers : ?pos:int -> string -> float list = <fun>
get_numbers "1.2   83  nan  -inf 5e-10";;
- : float list = [1.2; 83.; nan; neg_infinity; 5e-10]
let read_file = Mikmatch.Text.map_lines_of_file (COLLECT float as x : float -> x );;
val read_file : string -> float list list = <fun>

(** Negative assertions *)
let get_only_numbers =  COLLECT < Not alnum . > (float as x : float) < . Not alnum > -> x
```

```
let list_words = COLLECT (upper | lower)+ as x -> x ;;
val list_words : ?pos:int -> string -> string list = <fun>
# list_words "gshogh sghos sgho ";;
- : string list = ["gshogh"; "sghos"; "sgho"]
RE pair = "(" space* (digit+ as x : int) space* ","  space* ( digit + as y : int ) space* ")";;
 # let get_objlist = COLLECTOBJ pair;;
val get_objlist : ?pos:int -> string -> < x : int; y : int > list =
```

v. SPLIT macro

```
let ys = (SPLIT space* [",;"] space* ) "a,b,c, d, zz;";;
val ys : string list = ["a"; "b"; "c"; "d"; "zz"]
let f = SPLIT space* [",;"] space* ;;
val f : ?full:bool -> ?pos:int -> string -> string list = <fun>
```

Full is false by default. When true, it considers the regexp as a separator between substrings even if the first or the last one is empty. will add some whitespace trailins

```
f ~full:true "a,b,c,d;"  ;;
- : string list = ["a"; "b"; "c"; "d"; ""]
```

vi. MAP macro (a weak lexer) (MAP regexp -> expr)
splits the given string into fragments: the fragments that do not match the pattern are returned as *'Text s*. Fragments that match the pattern are replaced by the result of expr

```
let f = MAP ( "+" as x = `Plus ) -> x ;;
val f : ?pos:int -> ?full:bool -> string -> [> `Plus | `Text of string ] list =
let x =  (MAP ',' -> `Sep ) "a,b,c";;
val x : [> `Sep | `Text of string ] list = [`Text "a"; `Sep; `Text "b"; `Sep; `Text "c"]
```

```
let f = MAP ( "+" as x = `Plus ) | ("-" as x = `Minus) | ("/" as x = `Div)
  | ("*" as x = `Mul) | (digit+ as x := fun s -> `Int (int_of_string s))
  | (alpha [alpha digit] *  as x := fun s -> `Ident s) -> x ;;
```

```
val f :
  ?pos:int ->
  ?full:bool ->
  string ->
  [> `Div
   | `Ident of string
   | `Int of int
   | `Minus
   | `Mul
   | `Plus
   | `Text of string ]
list = <fun>
```

```
# f "+-*/";;
```

```
- : [> `Div
     | `Ident of string
     | `Int of int
     | `Minus
     | `Mul
     | `Plus
     | `Text of string ]
    list
=
[`Text ""; `Plus; `Text ""; `Minus; `Text ""; `Mul; `Text ""; `Div; `Text ""]
```

```
let xs = Mikmatch.Text.map (function `Text (RE space* eos) -> raise Mikmatch.Text.Skip | token -> token) (f "+-
val xs :
  [> `Div
   | `Ident of string
   | `Int of int
   | `Minus
   | `Mul
   | `Plus
   | `Text of string ]
  list = [`Plus; `Minus; `Mul; `Div]
```

vii. lexer (ulex is faster and more elegant)

```
let get_tokens = f |- Mikmatch.Text.map (function `Text (RE space* eos)
-> raise Mikmatch.Text.Skip | `Text x -> invalid_arg x | x
-> x) ;;

val get_tokens :
  string ->
  [> `Div
   | `Ident of string
   | `Int of int
   | `Minus
   | `Mul
   | `Plus
   | `Text of string ]
  list = <fun>

get_tokens "a1+b3/45";;
- : [> `Div
     | `Ident of string
     | `Int of int
     | `Minus
     | `Mul
     | `Plus
     | `Text of string ]
    list
= [`Ident "a1"; `Plus; `Ident "b3"; `Div; `Int 45]
```

viii. SEARCH macro (location)

```
let locate_arrows = SEARCH %pos1 "->" %pos2 ->  Printf.printf "(%i-%i)" pos1 (pos2-1);;
val locate_arrows : ?pos:int -> string -> unit = <fun>
# locate_arrows "gshogho->ghso";;
(7-8)- : unit = ()
let locate_tags = SEARCH "<" "/"? %tag_start (_* Lazy as tag_contents) %tag_end ">" -> Printf.printf "
```

(i) debug

```
let src = RE_PCRE <Not alnum . > (float as x : float ) < . Not alnum > in print_endline (fst src);;
(?<![0-9A-Za-z])([+\-]?(?:(?:[0-9]+(?:\.[0-9]*)?|\.[0-9]+)(?:[Ee][+\-]?[0-9]+)?|(?:[Nn][Aa][Nn]|[Ii][Nn][Ff]
```

(j) ignore the case

```
match "OCaml" with RE "O" "caml"~ -> print_endline "success";;
success
```

(k) zero-width assertions

```
RE word =  < Not alpha . >    alpha+ < . Not alpha>
RE word' = < Not alpha . >    alpha+ < Not alpha >
```

```
RE triplet = <alpha{3} as x>
let print_triplets_of_letters = SEARCH triplet -> print_endline x
print_triplets_of_letters "helhgoshogho";;
```

```
hel
elh
lhg
hgo
gos
osh
sho
hog
ogh
gho
- : unit = ()
```

```
(SEARCH alpha{3} as x -> print_endline x ) "hello world";;
```

```
hel
wor
```

```
(SEARCH <alpha{3} as x> -> print_endline x ) "hello world";;
```

```
hel
ell
llo
wor
orl
rld
```

```
(SEARCH alpha{3} as x -> print_endline x ) ~pos:2 "hello world";;
```

```
llo
wor
```

(l) dynamic regexp

```
let get_fild x = SEARCH_FIRST @x "=" (alnum* as y) -> y;;
val get_fild : string -> ?share:bool -> ?pos:int -> string -> string = <fun>
# get_fild "age" "age=29 ghos";;
```

```
- : string = "29"
```

(m) reuse

using macro INCLUDE

(n) view patterns

```
let view XY = fun obj -> try Some (obj#x, obj#y) with _ -> None ;;
val view_XY : < x : 'a; y : 'b; .. > -> ('a * 'b) option = <fun>
# let test_orign = function
   %XY (0,0) :: _ -> true
  |_ -> false
;;
      val test_orign : < x : int; y : int; .. > list -> bool = <fun>


let view Positive = fun x -> x > 0
let view Negative = fun x -> x <= 0

let test_positive_coords = function
  %XY ( %Positive, %Positive ) -> true
  | _ -> false

  (** lazy pattern is already supported in OCaml *)
let test x = match x with
    lazy v -> v

type 'a lazy_list = Empty | Cons of ('a * 'a lazy_list lazy_t)


let f = fun (Cons (_ , lazy (Cons (_, lazy (Empty)) ) )) -> true ;;
let f = fun %Cons (x1, %Cons (x2 %Empty)) -> true  (* simpler *)
```

implementation let view X = f is translated into: let view_X = f

Similarly, we have local views: let view X = f in ...

Given the nature of camlp4, this is the simplest solution that allows us to make views available to other modules, since they are just functions, with a standard name. When a view X is encountered in a pattern, it uses the view_X function. The compiler will complain if doesn't have the right type, but not the preprocessor.

About inline views: since views are simple functions, we could insert functions directly in patterns. I believe it would make the pattern really difficult to read, especially since views are expected to be most useful in already complex patterns.

About completeness checking: our definition of views doesn't allow the compiler to warn against incomplete or redundants pattern-matching. We have the same situation with regexps. What we define here are incomplete or overlapping views, which have a broader spectrum of applications than views which are defined as sum types.

(o) tiny use

```
se (FILTER _* "map_lines_of_file" ) "Mikmatch";;
val map_lines_of_file : (string -> 'a) -> string -> 'a list
```

```
let _  = Mikmatch.map_lines_of_file
  (function x ->
    match x with
      | RE "\xbegin{ocamlcode}" -> "\n" ^ x
      | RE "\xend{ocamlcode}" -> x ^ ''\n''
      | _  -> x  )
  "/Users/bob/SourceCode/Notes/ocaml-hacker.tex"
  |> List.enum
  |> File.write_lines "/Users/bob/SourceCode/Notes/ocaml-hacker-back-up.tex";;
```

5.3 pa-do

5.4 num

- delimited overloading

5.5 caml-inspect

It's mainly used to debug programs or presentation. blog

1. usage

```
#require "inspect";;
open Inspect ;;

Sexpr.(dump (test_data ()))
Sexpr.(dump dump) (** can dump any value, including closure *)
Dot.(dump_osx dump_osx)
```

2. *module Dot*

```
dump
dump_to_file
dump_with_formatter
dump_osx
```

3. *module Sexpr*

```
dump
dump_to_file
dump_with_formatter
```

4. principle

   OCaml values all share a *common low-level* representation. The basic building block that is used by the runtime-system(which is written in the C programming languag) to represent any value in the OCaml universe is the value type. Values are always *word-sized*. A word is either 32 or 64 bits wide(*Sys.word_size*)

   A value can either be a pointer to a block of values in the OCaml heap, a pointer to an object outside of the heap, or an unboxed integer. Naturally, blocks in the heap are garbage-collected.

   To distinguish between unboxed integers and pointers, the system uses the least-significant bit of the value as a flag. If the LSB is set, the value is unboxed. If the LSB is cleared, the value is a pointer to some other region of memory. This

encoding also explains why the int type in OCaml is only 31 bits wide (63 bits wide on 64 bit platforms).

Since blocks in the heap are garbage-collected, they have strict structure constraints. Information like the tag of a block and its size(in words) is encoded in the header of each block.

There are two categories of blocks with respect to the garbage collector:

(a) Structured blocks
May only contain well-formed values, as they are recursively traversed by the garbage collector.

(b) Raw blocks
are not scanned by the garbage collector, and can thus contain arbitrary values.

Structured blocks have tag values lower than *Obj.no_scan_tag*, while raw blocks have tags equal or greater than *Obj.no_scan_tag*.

The type of a block is its tag, which is stored in the block header.(*Obj.tag*)

```
Obj.( let f ()= repr |- tag in no_scan_tag, f () 0, f () [|1.;2.|], f
() (1,2) ,f ()[|1,2|]);;
```

```
- : int * int * int * int * int = (251, 1000, 254, 0, 0)
```

```
se_str "_tag" "Obj";;
```

```
external tag : t -> int = "caml_obj_tag"
external set_tag : t -> int -> unit = "caml_obj_set_tag"
val lazy_tag : int
val closure_tag : int
val object_tag : int
val infix_tag : int
val forward_tag : int
val no_scan_tag : int
val abstract_tag : int
val string_tag : int
val double_tag : int
val double_array_tag : int
val custom_tag : int
val final_tag : int
val int_tag : int
val out_of_heap_tag : int
val unaligned_tag : int
```

(a) *0 to Obj.no_scan_tag-1* A structured block (an array of Caml objects). Each field is a value.

(b) *Obj.closure_tag*: A closure representing a functional value. The first word is a pointer to a piece of code, the remaining words are values containing the environment.

(c) *Obj.string_tag*: A character string.

(d) *Obj.double_tag*: A double-precision floating-point number.

(e) *Obj.double_array_tag*: An array or record of double-precision floating-point numbers.

(f) *Obj.abstract_tag*: A block representing an abstract datatype.

(g) *Obj.custom_tag*: A block representing an abstract datatype with user-defined finalization, comparison, hashing, serialization and deserialization functions attached

(h) *Obj.object_tag*: A structured block representing an object. The first field is a value that describes the class of the object. The second field is a unique object id (see *Oo.id*). The rest of the block represents the variables of the

object.

(i) *Obj.lazy_tag, Obj.forward_tag*: These two block types are used by the runtime-system to implement lazy-evaluation.

(j) *Obj.infix_tag*: A special block contained within a closure block

5. representation

   For atomic types

   (a) int, char (ascii code) : Unboxed integer values

   (b) float : Blocks with tag *Obj.dobule_tag*

   (c) string : Blocks with tag *Obj.string_tag*

   (d) int32, int64, nativeint : Blocks with *Obj.custom_tag*

   For Tuples and records: Blocks with tag 0

```
Obj.((1,2) |> repr |> tag);;
- : int = 0
```

   For normal array(except float array), Blocks with tag 0

   For Arrays and records of floats: Block with tag *Obj.double_array_tag*

   For concrete types,

   (a) Constant ctor : Represented by unboxed integers(0,1,...).

   (b) Non-Constant ctor: Block with a tag lower than *Obj.no_scan_tag* that encodes the constructor, numbered in order of declaration, starting at 0.

   For objects: Blocks with tag *Obj.object_tag*. The first field refers to the class of the object and its associated method suite. The second field contains a unique object ID. The remaining fields are the instance variables of the object.

   For polymorphic variants: Variants are similar to constructed terms. There are a few differences

(a) Variant constructors are identified by their hash value

(b) Non-constant variant constructors are not flattened. They are always block of size 2, where the first field is the hash. The second field can either contain a single value or a pointer to another structured block(just like a tuple)

5.6 ocamlgraph

ocamlgraph is a sex library which deserve well-documentation.

1. simple usage in the module *Graph.Pack.Digraph*

```
se_str "label" "PDig.V";;
```

```
type label = int
val create : label -> t
val label : t -> label
```

Follow this file, you could know how to build a graph, A nice trick, to bind open command to use graphviz to open the file, then it will do the sync automatically

and you can *#u "open *.dot"*, so nice

```
module PDig = Graph.Pack.Digraph
let g = PDig.Rand.graph ~v:10 ~e:20 ()
(* get dot output file *)
let _ = PDig.dot_output g "g.dot"
(* use gnu/gv to show *)
let show_g = PDig.display_with_gv;;

let g_closure = PDig.transitive_closure ~reflexive:true g
(** get a transitive closure *)
let _ = PDig.dot_output g_closure "g_closure.dot"

let g_mirror = PDig.mirror g
let _ = PDig.dot_output g_mirror "g_mirror.dot"

let g1 = PDig.create ()
let g2 = PDig.create ()


let [v1;v2;v3;v4;v5;v6;v7 ] = List.map PDig.V.create [1;2;3;

let _ = PDig.( begin
  add_edge g1 v1 v2;
  add_edge g1 v2 v1;
  add_edge g1 v1 v3;
  add_edge g1 v2 v3;
  add_edge g1 v5 v3;
  add_edge g1 v6 v6;
  add_vertex g1 v4
  end
)

let _ = PDig.( begin
  add_edge g2 v1 v2;
  add_edge g2 v2 v3;
  add_edge g2 v1 v4;
  add_edge g2 v3 v6;
  add_vertex g2 v7
end
)

let g_intersect = PDig.intersect g1 g2
let g_union = PDig.union g1 g2

let _ =
  PDig.(
    let f = dot_output in begin
    f g1 "g1.dot";
    f g2 "g2.dot";
    f g_intersect "g_intersect.dot";
    f g_union "g_union.dot"
    end
  )
```

```
module PDig = Graph.Pack.Digraph
sub_modules "PDig";;
```

```
    module V :
    module E :
    module Mark :
    module Dfs :
    module Bfs :
    module Marking : sig val dfs : t -> unit val has_cycle : t -> bool end
    module Classic :
    module Rand :
    module Components :
    module PathCheck :
    module Topological :
```

Different modules have corresponding algorithms

2. hierachical

```
sub_modules "Graph" (** output too big *)
```

idea. can we draw a tree graph for this??

Graph.Pack requires its label being integer

```
sub_modules "Graph.Pack"
```

```
module Digraph :
    module V :
    module E :
    module Mark :
    module Dfs :
    module Bfs :
    module Marking :
    module Classic :
    module Rand :
    module Components :
    module PathCheck :
    module Topological :
module Graph :
    module V :
    module E :
    module Mark :
    module Dfs :
    module Bfs :
    module Marking :
    module Classic :
    module Rand :
    module Components :
    module PathCheck :
    module Topological :
```

3. hierachical for undirected graph

```
Graph.Pack.(Di)Graph
Undirected imperative graphs with edges and vertices labeled with integer.
Graph.Imperative.Matrix.(Di)Graph
Imperative Undirected Graphs implemented with adjacency matrices, of course integer(Matrix)


Graph.Imperative.(Di)Graph
Imperative Undirected Graphs.
Graph.Persistent.(Di)Graph
Persistent Undirected Graphs.
```

Here we have functor *Graph.Imperative.Graph.Concrete*, *Graph.Imperative.Graph.Abstract*, *Graph.Imperative.Graph.ConcreteLabeled*, *Graph.Imperative.Graph.AbstractLabeled*

we see that

```
module Abstract:
functor (V : Sig.ANY_TYPE) -> Sig.IM  with type V.label = V.t and type E.label
    = unit

module AbstractLabeled:
functor (V : Sig.ANY_TYPE) ->
functor (E : Sig.ORDERED_TYPE_DFT) -> Sig.IM  with type V.label = V.t and type
    E.label = E.t

module Concrete:
functor (V : Sig.COMPARABLE) -> Sig.I  with type V.t = V.t and type V.label = V
    .t and type E.t = V.t * V.t
    and type E.label = unit

module ConcreteBidirectional:
functor (V : Sig.COMPARABLE) -> Sig.I  with type V.t = V.t and type V.label = V
    .t and type E.t = V.t * V.t
and type E.label = unit

module ConcreteBidirectionalLabeled:
functor (V : Sig.COMPARABLE) ->
functor (E : Sig.ORDERED_TYPE_DFT) -> Sig.I  with type V.t = V.t and type V.
    label = V.t
and type E.t = V.t * E.t * V.t and type E.label = E.t

module ConcreteLabeled:
functor (V : Sig.COMPARABLE) ->
functor (E : Sig.ORDERED_TYPE_DFT) -> Sig.I  with type V.t = V.t and type V.
    label = V.t
      and type E.t = V.t * E.t * V.t and type E.label = E.t
```

so, as soon as you want to label your vertices with strings and your edges with floats, you should use functor. Take ConcreteLabeled as an example

```
module V = struct
  type t = string
  let compare = Pervasives.compare
  let hash = Hashtbl.hash
  let equal = (=)
end
module E = struct
  type t = float
  let compare = Pervasives.compare
  let default = 0.0
end
module X = Graph.Imperative.Graph.ConcreteLabeled (V) (E);;
module Y = Graph.Imperative.Digraph.ConcreteLabeled (V) (E);;

(**
    val add_edge : t -> vertex -> vertex -> unit
    val add_edge_e : t -> edge -> unit
    val remove_edge : t -> vertex -> vertex -> unit
    val remove_edge_e : t -> edge -> unit

    Not only that, but the V and E structure will work for
    persistent and directed graphs that are concretelabeled,
```

```
    and you can switch by replacing Imperative with Persistent
    , and Graph with Digraph.
    *)

module W = struct
  type label = float
  type t = float
  let weight x = x (* edge label -> weight *)
  let compare = Pervasives.compare
  let add = (+.)
  let zero = 0.0
  end

module Dijkstra = Graph.Path.Dijkstra (X) (W);;
```

4. another example (edge unlabeled, directed graph)

```
1  open Graph
2  module V = struct
3    type t = string
4    let compare = Pervasives.compare
5    let hash = Hashtbl.hash
6    let equal = (=)
7  end
8  module G = Imperative.Digraph.Concrete (V)
9  let g = G.create ()
10 let _ = G.( begin
11   add_edge g "a" "b";
12   add_edge g "a" "c";
13   add_edge g "b" "d";
14   add_edge g "b" "d"
15 end )
16 module Display = struct
17   include G
18   let vertex_name v = (V.label v)
19   let graph_attributes _ = []
20   let default_vertex_attributes _ = []
21   let vertex_attributes _ = []
22   let default_edge_attributes _ = []
23   let edge_attributes _ = []
24   let get_subgraph _ = None
25 end
26 module Dot_ = Graphviz.Dot(Display)
27 let _ =
28   let out = open_out "g.dot" in
29   finally (fun _ -> close_out out) (fun g ->
30     let fmt =
31       (out |> Format.formatter_of_output) in
32     Dot_.fprint_graph fmt g ) g
```

It seems that Graphviz.Dot is used to display directed graph, Graphviz.Neato is used to display undirected graph.

here is a useful example to visualize the output generated by ocamldep.

```
open Batteri
open Graph
module V = s
  type t = s
  let compar
  let hash =
  let equal
end
module Strin
module Displa
  include St
  open Strin
  let vertex
  let graph_
  let defaul
  let vertex
  let defaul
  let edge_a
  let get_su
end

module Displa


let dot_outp
  let out =
  finally (f
    let fmt
      (out |
    DisplayG


let g_of_edg
  let g = cr
  let _ = St
  g
)

let line = "

let edges_of
  try
    let (a::
      Pcre.s
    let v_a
      let _
      a  in
    let v_bs
      (Pcre.
    let edge
    edges
  with exn -

let lines_st
```

5.7 pa-monad

1. debug
   tags file

```
  "monad_test.ml" : pp(camlp4o -parser pa_monad.cmo)
  camlp4o -parser pa_monad.cmo monad_test.ml -printer o

  (** filter *)

  let a = perform let b = 3 in  b
  let bind x f = f x
  let c = perform c <-- 3 ; c
  (* output
  let a = let b = 3 in b
  let bind x f = f x
  let c = bind 3 (fun c -> c)
  *)



let bind x f = List.concat (List.map f x)
let return x = [x]
let bind2 x f = List.concat (List.map f x)

let c = perform
    x <-- [1;2;3;4];
    y <-- [3;4;4;5];
    return (x+y)


let d = perform with bind2 in
    x <-- [1;2;3;4];
    y <-- [3;4;4;5];
    return (x+y)

let _ = List.iter print_int c
let _ = List.iter print_int d

(*
let bind x f = List.concat (List.map f x)
let return x = [ x ]
let bind2 x f = List.concat (List.map f x)
let c =
  bind [ 1; 2; 3; 4 ]
    (fun x -> bind [ 3; 4; 4; 5 ] (fun y -> return (x + y)))
let d =
  bind2 [ 1; 2; 3; 4 ]
    (fun x -> bind2 [ 3; 4; 4; 5 ] (fun y -> return (x + y)))
let _ = List.iter print_int c
let _ = List.iter print_int d
*)
```

2. translation rule

   it's simple. **perform** or **perform with bind in** then it will translate all

phrases ending with *;; x <– me;* will be translated into *me »= (fun x ->); me;* will be translated into *me »= (fun _ -> ...)* you should refer *pa_monad.ml* for more details *perform with exp1 and exp2 in exp3* uses the first given expression as bind and the second as match-failure function. *perform with module Mod in exp* use the function named bind from module Mod. In addition ues the module's failwith in refutable patterns

```
let a = perform with (flip Option.bind) in a <-- Some 3;  b<-- Some 32; Some (a+ b) ;;
val a : int option = Some 35
```

it will be translated into

```
let a =
  flip Option.bind (Some 3)
    (fun a -> flip Option.bind (Some 32) (fun b -> Some (a + b)))
```

3. ParameterizedMonad

```
class ParameterizedMonad m where
  return :: a -> m s s a
  (>>=) :: m s1 s2 t -> (t -> m s2 s3 a) -> m s1 s3 a

data Writer cat s1 s2 a = Writer {runWriter :: (a, cat s1 s2)}

instance (Category cat) => ParameterizedMonad (Writer cat) where
  return a = Writer (a,id)
  m >>= k = Writer $ let
    (a,w) = runWriter
    (b,w') = runWriter (k a)
    in (b, w' . w)
```

```
module State : sig
  type ('a,'s) t = 's -> ('a * 's)
  val return : 'a -> ('a,'s) t
  val bind : ('a,'s ) t -> ('a -> ('b,'s) t ) -> ('b,'s) t
  val put : 's -> (unit,'s) t
  val get :  ('s,'s) t
end = struct
 type ('a,'s) t = ('s -> ('a * 's))
```

```
 let return v = fun s -> (v,s)
 let bind (v : ('a,'s) t) (f : 'a -> ('b,'s) t) : ('b,'s) t = fun s ->
   let a,s' = v s in
   let a',s'' = f a s' in
   (a',s'')
 let put s = fun _ -> (), s
 let get = fun s -> s,s
end


module PState : sig
  type ('a, 'b, 'c) t = 'b -> 'a * 'c
  val return : 'a -> ('a,'b,'b) t
  val bind : ('b,'a,'c)t -> ('b -> ('d,'c, 'e) t ) -> ('d,'a,'e) t
  val put : 's -> (unit,'b,'s)t
  val get : ('s,'s,'s) t
end  = struct
 type ('a,'s1,'s2) t = 's1 -> ('a * 's2)
 let return v = fun s -> (v,s)
 let bind v f = fun s ->
   let a,s' = v s in
   let a',s'' = f a s' in
   (a',s'')
 let put s = fun _ -> (), s
 let get = fun s -> s,s
end
```

```
let v = State.( perform  x <-- return 1 ; y <-- return 2 ; let _ =
print_int (x+y) in return (x+y) );;
```

```
val v : (int, '_a) State.t = <fun>
```

```
let v = State.( perform x <-- return 1 ; y <-- return 2 ; z <-- get ; put (x+y+z) ;
  z<-- get ; let _ = print_int z in return (x+y+z));;
```

```
 val v : (int, int) State.t = <fun>
```

```
  v 3;;
6- : int * int = (9, 6)
```

```
let v = PState.( perform x <-- return 1 ; y <-- return 2 ; z <-- get ; put (x+y+z) ;
z<-- get ; let _ = print_int z in return (x+y+z));;
```

```
val v : (int, int, int) PState.t = <fun>
```

```
v 3 ;;
6- : int * int = (9, 6)
```

```
let v = PState.( perform x <-- return 1 ; y <-- return 2 ; z <-- get ;
put (string_of_int (x+y+z)) ; return z );;
```

```
val v : (int, int, string) PState.t = <fun>
```

```
# v 3;;
v 3;;
- : int * string = (3, "6")
```

5.8 bigarray

This implementation allows efficient sharing of large numerical arrays between Caml code and C or Fortran numerical libraries. Your are encouraged to `open Bigarray`. Big arrays support the ad-hoc polymorphic operations (comparison, hashing,marshall)

Element kinds

The abstract type `type ('a,'b) kind` captures type 'a for values read or written in the array, while 'b which represents the actual content of the big array.

Array layouts

5.9 sexplib

Basic Usage

```
#require "sexplib.top";;
```

```
open Sexplib.Std
type t = A of int list | B with sexp;;
module S = Sexp;;
module C = Conv;;
```

```
 sub_modules "Sexplib";;
module This_module_name_should_not_be_used :
    module Type :
    module Parser :
    module Lexer :
    module Pre_sexp :
        module Annot :
        module Parse_pos :
        module Annotated :
        module Of_string_conv_exn :
    module Sexp_intf :
        module type S =
            module Parse_pos :
            module Annotated :
            module Of_string_conv_exn :
    module Sexp :
        module Parse_pos :
        module Annotated :
        module Of_string_conv_exn :
    module Path :
    module Conv :
        module Exn_converter :
    module Conv_error :
    module Exn_magic :
    module Std :
        module Hashtbl :
            module type HashedType =
            module type S =
            module Make :
        module Big_int :
        module Nat :
        module Num :
        module Ratio :
        module Lazy :
```

Build It's pretty easy to build with sexplib. Just write one line code in your `myocamlbuild.ml`

```
    flag ["ocaml"; "pp"; "use_sexp"]
      (S[A"Pa_type_conv.cma"; A"pa_sexp_conv.cma"]);
```

Debug

```
camlp4o -parser Pa_type_conv.cma pa_sexp_conv.cma   sexp.ml -printer o
```

You can deriving a `string_of_t` function pretty using by making use of `Sexplib.Std.string_of_sexp`

```
open Sexplib.Std
type ('a,'b) term =
  | Term of 'a * ('a,'b) term list
  | Var of 'b
with sexp
let print_term (t:(string,string) term) =
  print_string ^$
    string_of_sexp ^$
    sexp_of_term sexp_of_string sexp_of_string t
```

Modules

`Sexp` Contains all I/O-functions for Sexp, module `Conv` helper functions converting OCaml-valus of `standard-types` to Sexp. Moduel `Path` supports sub-expression extraction and substitution.

Sexp

```
type t = Sexplib.Type.t = Atom of string | List of t list
```

Syntax

`with sexp` or `with sexp_of` or `with of_sexp`. `signatures` are also well supported. When packed, you should use `TYPE_CONV_PATH` to make the location right. Common utilities are exported by `Std`.

we hope `sexp_of_t |- t_of_sexp` to be an `id` function

```
let f = exp_of_int |- int_of_exp
Enum.( let a = range ~until:max_int min_int in
       fold2 (fun l r a -> a & (l=r)) true a
```

5.10 bin-prot

5.11 fieldslib

5.12 variantslib

5.13 delimited continuations

Continuatioins A conditional banch selects a continuation from the two possible futures; rasing an exception discards. Traditional way to handle continuations explicitly in a program is to transform a program into cps style. Continuation captured by call/cc is the **whole** continuation that includes all the future computation.. In practice, most of the continuations that we want to manipulate are only a part of computation. Such continuations are called **delimited continuations** or **partial continuations**.

1. cps transform
   there are multiple ways to do cps transform, here are two.

```
[x] --> x
[\x. M] --> \k . k (\x . [M])
[M N] --> \k. [M] (\m . m [N] k)
```

```
[x] --> \k . k x
[\x. M] --> \k. k (\x.[M])
[M N] --> \k. [M] (\m . [N] (\n. m n k))


[callcc (\k. body)] = \outk. (\k. [body] outk) (\v localk. outk v)
```

2. experiment

```
#load "delimcc.cma";;
```

```
Delimcc.shift;;
- : 'a Delimcc.prompt -> (('b -> 'a) -> 'a) -> 'b = <fun>
```

```
reset (fun () -> M ) --> push_prompt p (fun () -> M )
shift (fun k -> M) --> shift p (fun k -> M )
```

in racket you should have *(require racket/control)* and then *(reset expr ...+)*

(shift id expr ...+)

```
module D = Delimcc
(** set the prompt *)
let p = D.new_prompt ()
let (reset,shift),abort  = D.( push_prompt &&& shift &&& abort ) p;;
let foo x = reset (fun () -> shift (fun cont -> if x = 1 then cont 10 else 20 ) + 100 )
```

```
foo 1 ;;
- : int = 110
foo 2  ;;
- : int = 20
5 * reset (fun () -> shift (fun k -> 2 * 3 ) + 3 * 4 );;
- : int = 30
reset (fun () -> 3 + shift (fun k -> 5 * 2) ) - 1 ;;
- : int = 9
```

```
val p : '_a D.prompt = <abstr>
val reset : (unit -> '_a) -> '_a = <fun>
val shift : (('_a -> '_b) -> '_b) -> '_a = <fun>
val abort : '_a -> 'b = <fun>
```

```
let p = D.new_prompt ()
let (reset,shift),abort  = D.( push_prompt &&& shift &&& abort ) p;;
```

```
reset (fun () -> if (shift (fun k -> k(2 = 3))) then "hello" else "hi ") ^ "world";;
- : string = "hi world"
reset (fun () -> if (shift (fun k -> "laji")) then "hello" else "hi ") ^ "world";;
- : string = "lajiworld"
reset (fun _ -> "hah");;
- : string = "hah"
```

```
let make_operator () =
  let p = D.new_prompt () in
  let (reset,shift),abort = D.( push_prompt &&& shift &&& abort) p in
  p,reset,shift,abort
```

Delimited continuations seems not able to handle answer type polymorphism.

```
exception Str of [`Found of int | `NotFound]
```

```
let times lst  =
  let rec times_aux lst = match lst with
    | [] -> 1
    | 0 :: xs -> shift (fun _ -> 0 )
    | x :: xs -> begin
      (* printf "entering %d\n" x ; *)
      let v = x * times_aux xs in
      (* printf "exiting %d\n" x ;  *)
      v
    end in
  reset (fun () -> times_aux lst )
```

Store the continuation, the type system is not friendly to the continutations, but fortunately we have *side effects* at hand, we can store it. (This is pretty hard in Haskell)

```
let p,reset,shift,abort = make_operator() in
  let c = ref None in
  begin
   reset (fun () -> 3 + shift (fun k -> c:= Some k ;  0) - 1)  ;
   Option.get (!c) 20
   end ;;
          Characters 81-139:
     reset (fun () -> 3 + shift (fun k -> c:= Some k ;  0) - 1)  ;
     ^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^
     Warning 10: this expression should have type unit.
```

```
- : int = 22
```

```
let cont =
  let p,reset,shift,abort = make_operator() in
  let c = ref None in
  let rec id lst = match lst with
    | [] -> shift (fun k -> c:=Some k ; [] )
    |x :: xs -> x :: id xs in
  let xs = reset (fun () -> id [1;2;3;4]) in
  xs, Option.get (!c);;
```

```
val cont : int list * (int list -> int list) = ([], <fun>)
```

```
# let a,b = cont ;;
val a : int list = []

val b : int list -> int list = <fun>
# b [];;
- : int list = [1; 2; 3; 4]
```

```
type tree = Empty | Node of  tree * int  * tree
let walk_tree =
  let cont = ref None in
  let p,reset,shift,abort = make_operator() in
  let yield n = shift (fun k -> cont := Some k; print_int n ) in
  let rec walk2 tree = match tree with
    |Empty -> ()
    |Node (l,v,r) ->
      walk2 l ;
      yield v ;
      walk2 r in
  fun tree -> (reset (fun _ -> walk2 tree ), cont);;
```

```
val walk_tree : tree_t -> unit * ('_a -> unit) option Batteries.ref =
```

```
# let _, cont = walk_tree tree1 ;;
1val cont : ('_a -> unit) option Batteries.ref = {contents = Some <fun>}
# Option.get !cont ();;
2- : unit = ()
# Option.get !cont ();;
3- : unit = ()
# Option.get !cont ();;
- : unit = ()
# Option.get !cont ();;
- : unit = ()
```

It's quite straightforward to implement yield using delimited continuation, since each time shifting will escape the control, and you store the continuation, later it can be resumed.

```
(** defer the continuation *)
shift (fun k -> fun () -> k "hello")
```

By wrapping continuations, we can **access the information outside** of the enclosing reset while staying within reset lexically.

suppose this type check

```
let f x = reset (fun () -> shift (fun k -> fun () -> k "hello") ^ "world" ) x
f : unit -> string
```

3. Answer type modification (serious) in the following context, `reset (fun () -> [...] ^  "word" )` the value returned by reset appears to be a string. An answer type is a type of the enclosing *reset*.

4. reorder delimited continuations
   if we apply a continuation at the tail position, the captured computation is simply resumed. If we apply a continuation at the non-tail position, we can perform additional computation after resumed computation finishes.

   Put differently, we can switch the execution order of the surrounding context.

```
let p,reset,shift,abort = make_operator () in
    reset (fun () -> 1 + (shift (fun k -> 2 * k 3 )));;
```

```
- : int = 8
```

```
let p,reset,shift,abort = make_operator () in
   let either a b = shift (fun k -> k a ; k b ) in
   reset (fun () ->
   let x = either  0  1 in
   print_int x ; print_newline ());;
```

```
 0
 1
```

5. useful links
   sea side
   shift and reset tutorial
   shift reset tutorial

racket control operators

caml-shift-paper.pdf

caml-shift-talk

5.14 shcaml

A shell library. (you can refer `Shell` module of shell package)

All modules in the system are submodules of the `Shcaml` module, except ofr the module `Shtop`

5.15 deriving

Build

For debuging

```
cd `camlp4 -where`
ln -s `ocamlfind query deriving-ocsigen`/pa_deriving.cma
```

So you could type `camlp4o -parser pa_deriving.cma test.ml`

Toplevel `#require "deriving-ocsigen.syntax";;`
For building, a typical tags file is as follows.

```
true : pkg_deriving-ocsigen
<test.ml> : syntax_camlp4o, pkg_deriving-ocsigen.syntax
```

```
type 'a tree =
  | Leaf of 'a
  | Node of 'a * 'a tree * 'a tree
deriving (Show,Eq,Typeable, Functor)

let _ = begin
  print_string (Show.show<int tree> (Node (3, Leaf 4, Leaf 5)));
end
```

5.16 Modules

- BatEnum
  - utilities

```
range ~until:20 3
filter, concat, map, filter_map
(--), (--^) (|>) (@/) (/@)
No_more_elements (*interface for dev to raise (in Enum.make next)*)
icons, lcons, cons
```

  - don't play effects with enum
  - idea??? how about divide enum to two; one is just for iterator the other is for lazy evaluation. (iterator is lazy???)

- Set (*one comparison, one container*)

```
Set.IntSet
Set.CharSet
Set.RopeSet
Set.NumStringSet
```

for polymorphic set

```
split
union
empty
add
```

why polymorphic set is dangerous? Because in Haskell, *Eq a =>* is implicitly you want to make your comparison method is unique, otherwise you union two sets, how to make sure they use the same comparison, here we use abstraction types, one comparison, one container we can not override polymorphic = behavior, polymorphic = is pretty bad practice for complex data structure, mostly not you want, so write compare by yourself

As follows, compare is the right semantics.

```
# Set.IntSet.(compare (of_enum (1--5))  (of_enum (List.enum [5;3;4;2;1])));;
- : int = 0
# Set.IntSet.(of_enum (1--5) = of_enum (List.enum [5;3;4;2;1]));;
- : bool = false
```

- caveat
  - module syntax

```
module Enum = struct
  include Enum include Labels include Exceptionless
end
```

    floating nested modules up (Enum.include, etc) include Enum, will expose all Enum have to the following context, so Enum.Labels is as Labels, so you can now include Labels, but *Labels.v will override Enum.v*, maybe you want it, and *module Enum still has Enum.Labels.v*, we just duplicated the nested module into toplevel

Chapter 6

Runtime

6.1 ocamlrun

ocamlrun

The ocamlrun command comprises three main parts: the bytecode interpreter, the memory allocator and garbage collector, and a set of c functions that implement primitive operations such as input/output.

Back Trace -b When the program aborts due to an uncaught exception, print a detailed "back trace" of the execution, showing where the exception was raised and which function calls were outstanding at this point. The back trace is printed only if the bytecode executable contains debugging information, i.e. was compiled and linked with the -g option to ocamlc set. This is equivalent to setting the b flag in the `OCAMLRUNPARAM` environment variable.

-I Include the search dir for dynamically loaded libraries.

-p Print the names of the primitives known to this version of ocaml

-v Direct the `memory manager` to print some progress messages. equivalent to setting `v=63` in the `OCAMLRUNPARAM`

The following environment variables are also consulted

`CAML_LD_LIBRARY_PATH` `OCAMLLIB` `OCAMLRUNPARAM`

For `OCAMLRUNPARAM` This variable must be a sequence of parameter specifications. A parameter specification is an option letter followed by an = sign, a decimal number (or an hexadecimal number prefixed by 0x), and an optional multiplier. There are nine options, six of which correspond to the fields of the control record documented in Module `Gc`.

b (backtrace) Trigger the printing of a stack backtrace when an uncaught exception aborts the program. This option takes no argument.

p (parser trace) Turn on debugging support for ocamlyacc-generated parsers. When this option is on, the pushdown automaton that executes the parsers prints a trace of its actions. This option takes no argument.

s (minor_heap_size) Size of the minor heap. (in words)

i (major_heap_increment) Default size increment for the major heap. (in words)

o (space_overhead) The major GC speed setting.

O (max_overhead) The heap compaction trigger setting.

v (verbose) What GC messages to print to stderr. This is a sum of values selected from the following: 1 (= 0x001) Start of major GC cycle. 2 (= 0x002) Minor collection and major GC slice. 4 (= 0x004) Growing and shrinking of the heap. 8 (= 0x008) Resizing of stacks and memory manager tables. 16 (= 0x010) Heap compaction. 32 (= 0x020) Change of GC parameters. 64 (= 0x040) Computation of major GC slice size. 128 (= 0x080) Calling of finalisation functions 256 (= 0x100) Startup messages (loading the bytecode executable file, resolving shared libraries).

l (stack_limit) The limit (in words) of the stack size.

h The initial size of the major heap (in words).

The multiplier is k, M, or G, for multiplication by 2^10, 2^20, and 2^30 respectively. For example, on a 32-bit machine, under bash the command export OCAMLRUNPARAM='b,s=256k,v=0x015' tells a subsequent ocamlrun to print backtraces for uncaught exceptions, set its initial minor heap size to 1 megabyte and print a message at the start of each major GC cycle, when the heap size changes, and when compaction is triggered.

6.2 FFI

Basic Part Only one thing to notice is that for bytecode, if the number of arguments is greater than five, the C function's first parameter will get an array containing all of the arguments, and the c function's second parameter will get the number of arguments.

In this case, you may need to discriminate byte code from native code. Syntax is like this:

```
external caml_name: type = "byte_code" "native_code"
```

The simple example is like this

```
/* notice the first is a poiter */
value
plus_six_bc(value* ar, value n){
  int i=0;
  long res =0;
  for(; i< n ;++i){
    res+=Long_val(ar[i]);
  }
  return Val_long(res);
}

value
plus_six_nc(value i1, value i2, value i3,
            value i4, value i5, value i6){
  return Val_long(Long_val(i1)+ Long_val(i2) + Long_val(i3)+
                  Long_val(i4) + Long_val(i5) + Long_val(i6));
}
```

Listing 53: Plus Stubs

```
(* -*- Mode:Tuareg; -*-
   *====---------------------------------------------------------------------===
   * Version: $Id: plus.ml,v 0.0 2012/02/22 04:38:27 bobzhang1988 Exp $
   *====---------------------------------------------------------------------===*)
open Printf
external unsafe_plus : int -> int -> int -> int -> int -> int -> int =
  "plus_six_bc"  "plus_six_nc"


let _ = begin
  print_int (unsafe_plus 1 2 3 4 5 6);
end
```

6.2.1 Data representation

C Part For the data discrimination, ocaml provides a lot of C macros in `<caml/values.h>`.

It's illustrated very clearly in the header file:

word: Four bytes on 32 and 16 bit architectures, eight bytes on 64 bit architectures.

long: A C integer having *the same number of bytes as* a word.

val: The ML representation of something. A long or a block or a pointer outside the heap. If it is a block, it is the (encoded) address of an object, if it is a long, it is encoded as well.

block: Something allocated. It always has a header and some fields or some number of bytes (a multiple of the word size).

field: A word-sized val which is part of a block.

bp: Pointer to the first *byte* of a block. (a char *)

op: Pointer to the first *field* of a block. (a value *)

hp: a pointer to the header of a block. (a char *)

int32: Four bytes on all architectures.

int64: Eight bytes on all architectures.

A block size is always a multiple of the word size, and at least one word plus the header.

bosize: Size (in bytes) of the "bytes" part.

wosize: Size (in words) of the "fields" part.

bhsize: Size (in bytes) of the block with its header.

whsize: Size (in words) of the block with its header.

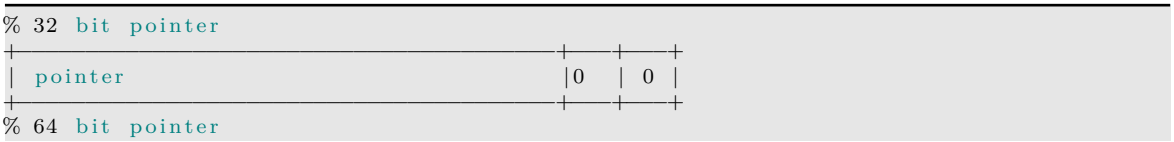
hd: A header.

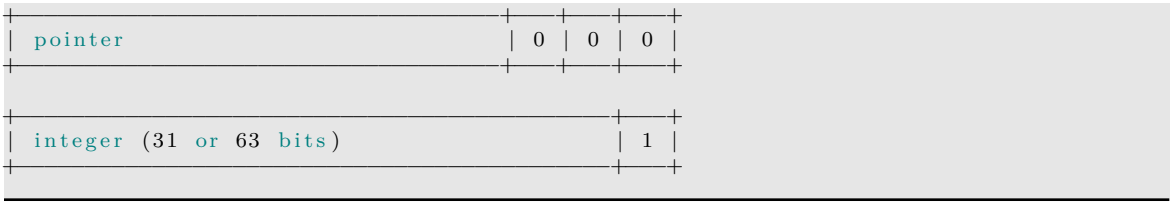
tag: The value of the tag field of the header.

color: The value of the color field of the header. This is for use only by the GC.

It's easy to discriminate whether is long or block by the lowest bit.

hat's why ocaml int is 31 bit.



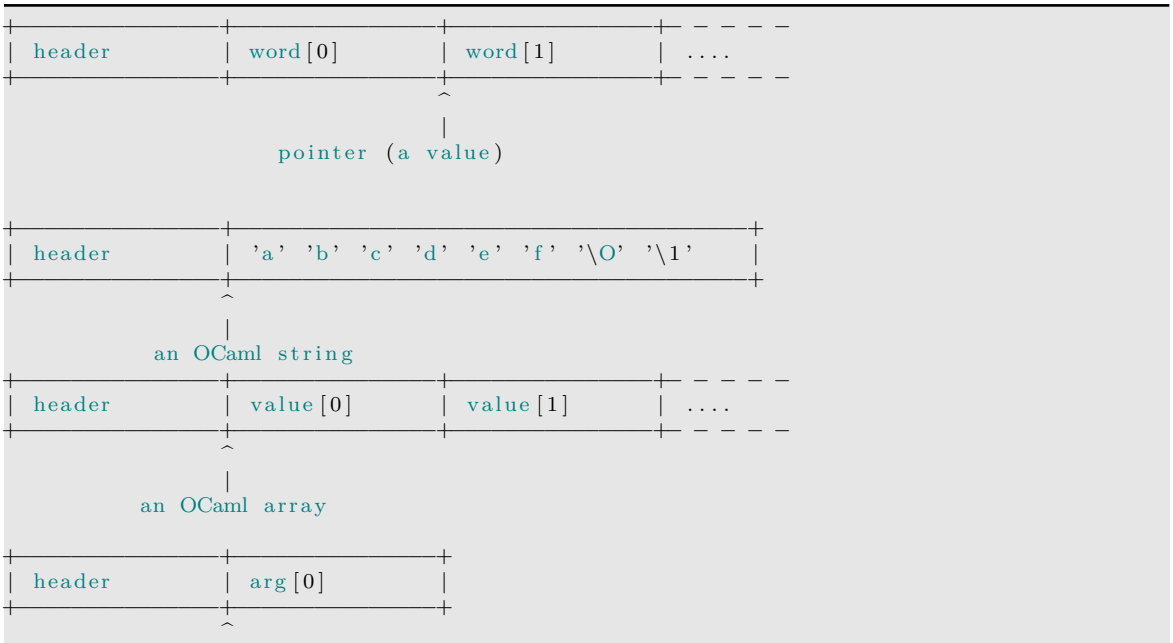


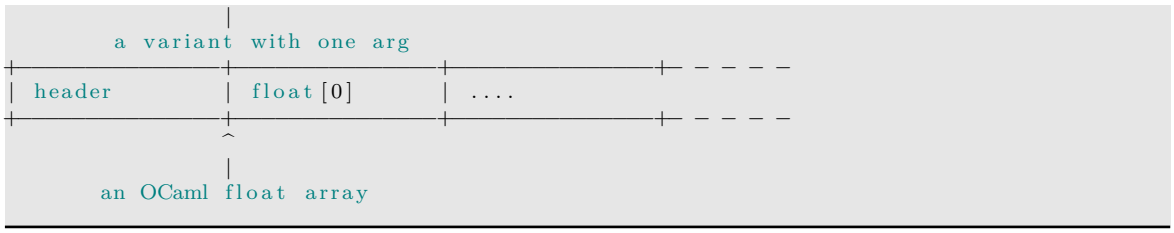
So if you need 32/64bit, you may need consult Bigarray. There are other data conversion macroslike `Type_val`, `Val_type`, which is straightforward.

For blocks the structure of the header is interesting: For 16-bit and 32-bit architectures:

For 64-bit architectures:

Here are some more examples of lay out





So, it's easy to understand that 32 platform, it's wosize 22bits long : the reason for the annoying 16MByte limit for string. The tag field is interesting

The tag byte is multipurpose, in the variant-with-parameter example above, it tells you which variant it is. In the string case, it contains a little bit of runtime type information. In other cases it can tell the gc that it's a lazy value or opaque data that the gc should not scan Table 6.1 illustrate how tags are used to encode different data types.

So we can write a c function to walk through ocaml data as follows:

```
void print_block(value v, int m){
  margin(m);printf("\n");
  int size, i,tag;
  if(Is_long(v)){
    margin(m);
    printf("immediate value\n");
    margin(m);
    printf("v as c integer: (%ld); as ocaml int: (%ld);"
           "as ocaml char: (%c)\n", (long)v, (Long_val(v)), (char)(Long_val(v)));
    return;
  }
  else {
    size = Wosize_val(v);
    tag = Tag_val(v);
    margin(m);
    printf("memory block: size=%d --\n", size);
    switch (tag){
    case Closure_tag:
      margin(m);
      printf("closure with %d closure variables\n", size-1);

      margin(m+4);
      printf("code pointer: %p\n",Code_val(v)); // Field 0
      for(i=1;i<size;++i){
        print_block(Field(v,i),(m+4)); //
      }
```

int, char	immediate value, shifted left by 1 bit, with LSB=1
(), [], false	stored as OCaml int 0 (native 1)
true	stored as OCaml int 1
type t = Foo | Bar | Baz (no parameters)	stored as OCaml int 0,1,2
type t = Foo | Bar of int	the varient with no parameters are stored as OCaml int 0,1,2, etc. counting just the variants that have no parameters. The variants with parameters are stored as blocks, counting just the variants with parameters. The parameters are stored as words in the block itself. Note there is a limit around *240 variants with parameters that applies to each type*, but no limit on the number of variants without parameters you can have. *this limit arises because of the size of the tag byte and the fact that some of high numbered tags are reserved*
list [1;2;3]	This is represented as 1::2::3::[] where [] is a value in OCaml int 0, and h::t is a block with tag 0 and two parameters. This representation is exactly the same as if list was a variant
tuples, struct and array	These are all represented identically, as a simple array of values, the tag is 0. The only difference is that an array can be allocated with variable size, but structs and tuples always have a fixed size.
struct or array where every elements is a float	These are treated as a special case. The tag has special value `Dyn_array_tag` (254) so that the GC knows how to deal with these. *Note this exception does not apply to tuples that contains floats, beware anyone who would declare a vector as (1.0,2.0).*
any string	strings are byte arrays in OCaml, but they have quite a clever representation to make it very efficient to get their length, and at the same time make them directly compatible with C strings. The tag is `String_tag` (252).

Table 6.1: Runtime type representation

```
      break;
    case String_tag:
      margin(m);
      printf("string: as c string: %s as ocaml string: "
             /* (char*)v, (String_val(v))); */
             // String_val just do pointer arithmetic, does not keep the semantics of ocaml
             ,(char*)v);
      explore_string(v);
      printf("\n");
      break;
    case Double_tag:
      margin(m);printf("float: %g \n", Double_val(v));
      break;
    case Double_array_tag:
      margin(m);printf("float array:\n");
      for(i=0;i<size/Double_wosize;++i){ // for 64 bit Double_wosize=1
        margin(m);printf(" %g",Double_field(v,i));
      }    break;
    case Abstract_tag:
      margin(m);printf("Not traced by GC tag \n");
      break;
    case Custom_tag:
      margin(m);printf("Custom tag\n");
      break;
    default:
      if(tag>=No_scan_tag){margin(m);printf("No_scan_tag or above\n"); break;}
      else{
        margin(m);
        printf("unknown structured block (tag=%d):\n", Tag_val(v));
        for(i=0;i<size;i++){print_block(Field(v,i),m+4);}
        break;
      }
    }
    return;
  }
}
```

You can see the last three ocaml values are exactly the same when in the layer of run time.

```
(* -*- Mode:Tuareg; -*-
   *===----------------------------------------------------------------------===
   * Version: $Id: inspect.ml,v 0.0 2012/02/22 22:37:31 bobzhang1988 Exp $
   *===----------------------------------------------------------------------===*)
open Printf
open Util
```

```
external inspect : 'a -> 'a = "inspect"

let rec fib  = function
  | 0 | 1 -> 1
  | n -> fib (n-1) + fib (n-2)

(* let i = inspect |- ignore      *)

let f  =  fun x y z -> x + y + z
let f2 = fun x y z -> x + y * z
type foo = {x:int;y:int;z:int}
type foo1 =
    C1 of int * int * int
  | C2 of int
  | C3
  | C4 of int * int
let s = "aghosh\000aghoshgo"
let w : int Weak.t= Weak.create 10
let _ = begin
  inspect 3 |> ignore;
  inspect 3.0 |> ignore ;
  inspect 'a' |> ignore;
  [|1;1;0|] |> inspect |> ignore;
  (1,true,()) |> inspect |> ignore ;
  {x=1;y=1;z=0} |> inspect |> ignore;
  C1(1,1,0) |> inspect |> ignore;
  [|1.0;1.0;0.0|] |> inspect |> ignore;
  inspect [1.0;1.0;0.0] |> ignore;

  fib |> inspect |> ignore ;

  f |> inspect |> ignore;
  f 2 |> inspect |> ignore ;
  f 1 2 |> inspect |> ignore ;
  f2 1 2 |> inspect |> ignore ;
  let g = let x = 1 and y = 2 in fun z -> x + y + z in g |> inspect |> ignore;
  inspect |> inspect |> ignore;
  s |> inspect |> ignore;
  w |> inspect |> ignore;
  stdout |> inspect ;
end
```

The dumped result is interesting, and worthwhile to digest.(output of bytecode)

```
immediate value
v as c integer: (7); as ocaml int: (3);as ocaml char: (^C)
```

```
memory block: size=1 --
float: 3

immediate value
v as c integer: (195); as ocaml int: (97);as ocaml char: (a)

memory block: size=3 --
unknown structured block (tag=0):
....
....immediate value
....v as c integer: (3); as ocaml int: (1);as ocaml char: (^A)
....
....immediate value
....v as c integer: (3); as ocaml int: (1);as ocaml char: (^A)
....
....immediate value
....v as c integer: (1); as ocaml int: (0);as ocaml char: (^@)

memory block: size=3 --
unknown structured block (tag=0):
....
....immediate value
....v as c integer: (3); as ocaml int: (1);as ocaml char: (^A)
....
....immediate value
....v as c integer: (3); as ocaml int: (1);as ocaml char: (^A)
....
....immediate value
....v as c integer: (1); as ocaml int: (0);as ocaml char: (^@)

memory block: size=3 --
unknown structured block (tag=0):
....
....immediate value
....v as c integer: (3); as ocaml int: (1);as ocaml char: (^A)
....
....immediate value
....v as c integer: (3); as ocaml int: (1);as ocaml char: (^A)
....
....immediate value
....v as c integer: (1); as ocaml int: (0);as ocaml char: (^@)

memory block: size=3 --
unknown structured block (tag=0):
....
....immediate value
....v as c integer: (3); as ocaml int: (1);as ocaml char: (^A)
....
....immediate value
....v as c integer: (3); as ocaml int: (1);as ocaml char: (^A)
....
....immediate value
....v as c integer: (1); as ocaml int: (0);as ocaml char: (^@)

memory block: size=3 --
float array:
 1 1 0
memory block: size=2 --
unknown structured block (tag=0):
....
```

```
....memory block: size=1 --
....float: 1
....
....memory block: size=2 --
....unknown structured block (tag=0):
........
........memory block: size=1 --
........float: 1
........
........memory block: size=2 --
........unknown structured block (tag=0):
............
............memory block: size=1 --
............float: 0
............
............immediate value
............v as c integer: (1); as ocaml int: (0);as ocaml char: (^@)

memory block: size=1 --
closure with 0 closure variables
....code pointer: 0x7ff451015578

memory block: size=1 --
closure with 0 closure variables
....code pointer: 0x7ff451015870

memory block: size=3 --
closure with 2 closure variables
....code pointer: 0x7ff45101586c
....
....memory block: size=1 --
....closure with 0 closure variables
........code pointer: 0x7ff451015870
....
....immediate value
....v as c integer: (5); as ocaml int: (2);as ocaml char: (^B)

memory block: size=4 --
closure with 3 closure variables
....code pointer: 0x7ff45101586c
....
....memory block: size=1 --
....closure with 0 closure variables
........code pointer: 0x7ff451015870
....
....immediate value
....v as c integer: (3); as ocaml int: (1);as ocaml char: (^A)
....
....immediate value
....v as c integer: (5); as ocaml int: (2);as ocaml char: (^B)

memory block: size=4 --
closure with 3 closure variables
....code pointer: 0x7ff451015844
....
....memory block: size=1 --
....closure with 0 closure variables
........code pointer: 0x7ff451015848
....
....immediate value
....v as c integer: (3); as ocaml int: (1);as ocaml char: (^A)
```

```
....
....immediate value
....v as c integer: (5); as ocaml int: (2);as ocaml char: (^B)

memory block: size=3 --
closure with 2 closure variables
....code pointer: 0x7ff451015680
....
....immediate value
....v as c integer: (3); as ocaml int: (1);as ocaml char: (^A)
....
....immediate value
....v as c integer: (5); as ocaml int: (2);as ocaml char: (^B)

memory block: size=1 --
closure with 0 closure variables
....code pointer: 0x7ff451015624

memory block: size=2 --
string: as c string: aghosh as ocaml string: aghosh(#0)aghoshgo(#0)

memory block: size=11 --
Not traced by GC tag

memory block: size=2 --
Custom tag
```

For partial evaluation under the *bytecode*, it has some special optimization, the field 0 is still code pointer, then if it doesn't closure any variable, its block size 1, if it contains any variable, its block size will be 2 + n. The second field is a code pointer points to the real code. And both the *first* field and the *second* field across the same name of partial function could be *shared*. (the first describes how to apply the parameters, the second describes the real code). So a closure block size could be $\{1, 3, 4, 5, \cdots\}$.

Notice `String_val` just do pointer arithmetic, does not keep the semantics of ocaml string.(ocaml is null-terminated string(null appended), but null is allowed to appear in the string) It was illustrated as follows:

```
value
explore_string(value s){
  char* st = String_val(s) ;
  int len = Bosize_val(s);
  int i=0;
  int code ;
  for(i=0;i<len;++i){
    code = (int) st[i];
    if(code>31 && code <128 ){
      putchar((char)code);
    }
    else {
```

```
      printf("(#%d)",code);
    }
  }
  return Val_unit;
}
```

OCaml Part We could also play with module Obj

```
Obj.("gshogh" |> repr |> tag);;
- : int = 252
let a = [|1;2;3|] in Obj.(a|>repr|>tag);;
- : int = 0
Obj.(a |> repr |> size);;
- : int = 3
```

String has a clever algorithm

```
Obj.( "ghsoghoshgoshgoshgoshogh"|> repr |> size);;
- : int = 4 (4*8 = 32 )
"ghsoghoshgoshgoshgoshogh" |> String.length;;
24 (padding 8 bits)
```

Like all heap blocks, strings contain a header defining the size of the string in machine words.

```
("aaaaaaaaaaaaaaaa"|>String.length);;
- : int = 16
# Obj.("aaaaaaaaaaaaaaaa"|>repr |> size);;
- : int = 3
```

padding will tell you how many words are padded actually

The null-termination comes handy when passing a string to C, but is not relied upon to compute the length (in Caml), allowing the string to contain nulls.

```
repr : 'a -> t (id)
obj : t -> 'a (id)
magic : 'a -> 'b (id)
is_block : t -> bool = "caml_obj_is_block"
is_int : t -> bool = "%obj_is_int"
tag : t -> int ="caml_obj_tag" % get the tag field
set_tag : t -> int -> unit = "caml_obj_set_tag"
size : t -> int = "%obj_size" % get the size field
field : t -> int -> t = "%obj_field" % handle the array part
set_field : t -> int -> t -> unit = "%obj_set_field"
double_field : t -> int -> float
set_double_field : t -> int -> float -> unit
new_block : int -> int -> t = "caml_obj_block"
dup : t -> t = "caml_obj_dup"
truncate : t -> int -> unit = "caml_obj_truncate"
add_offset : t -> Int32.t -> t = "caml_obj_add_offset"
marshal : t -> string
Obj.( None |> repr |> is_int);;
- : bool = true
Obj.(" ghsogho" |> repr |> is_block);;
- : bool = true
Obj.(let f x = x |> repr |> is_block in (f Bar, f (Baz 3)));;
- : bool * bool = (false, true)
```

6.2.2 Caveats

The input-output don't share their file buffers. try to use `fflush(stdout)`

Chapter 7

GC

Should be re-written later

1. heap

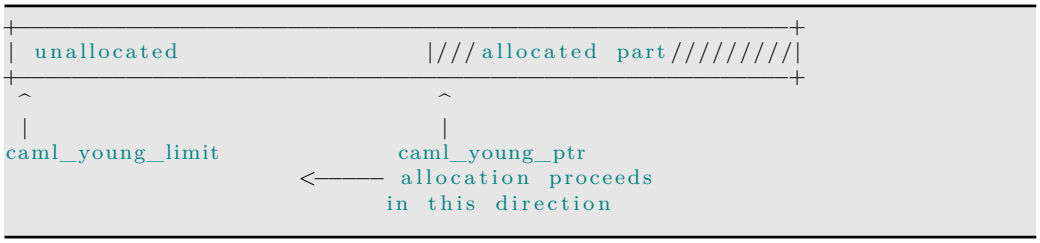
   Most OCaml blocks are created in the minor(young) heap.

   (a) minor heap (*32K words for 32 bit, 64K for 64 bit by default*) in my mac, i use "ledit ocaml -init x" to avoid loading startup scripts, then

```
Gc.stat ()
```

```
{Gc.minor_words = 104194.; Gc.promoted_words = 0.; Gc.major_words = 43979.;
 Gc.minor_collections = 0; Gc.major_collections = 0; Gc.heap_words = 126976;
 Gc.heap_chunks = 1; Gc.live_words = 43979; Gc.live_blocks = 8446;
 Gc.free_words = 82997; Gc.free_blocks = 1; Gc.largest_free = 82997;
 Gc.fragments = 0; Gc.compactions = 0; Gc.top_heap_words = 126976;
 Gc.stack_size = 52}
```

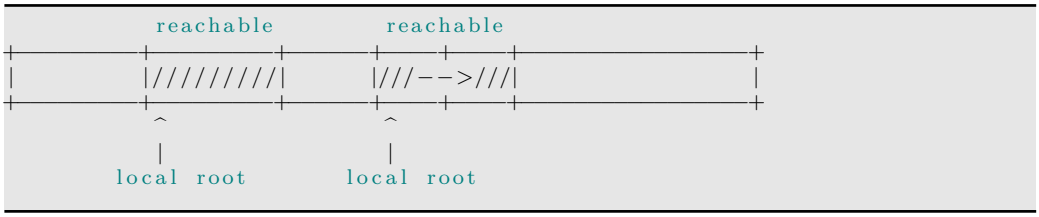
```
78188 lsr 16 ;;
- : int = 1
```



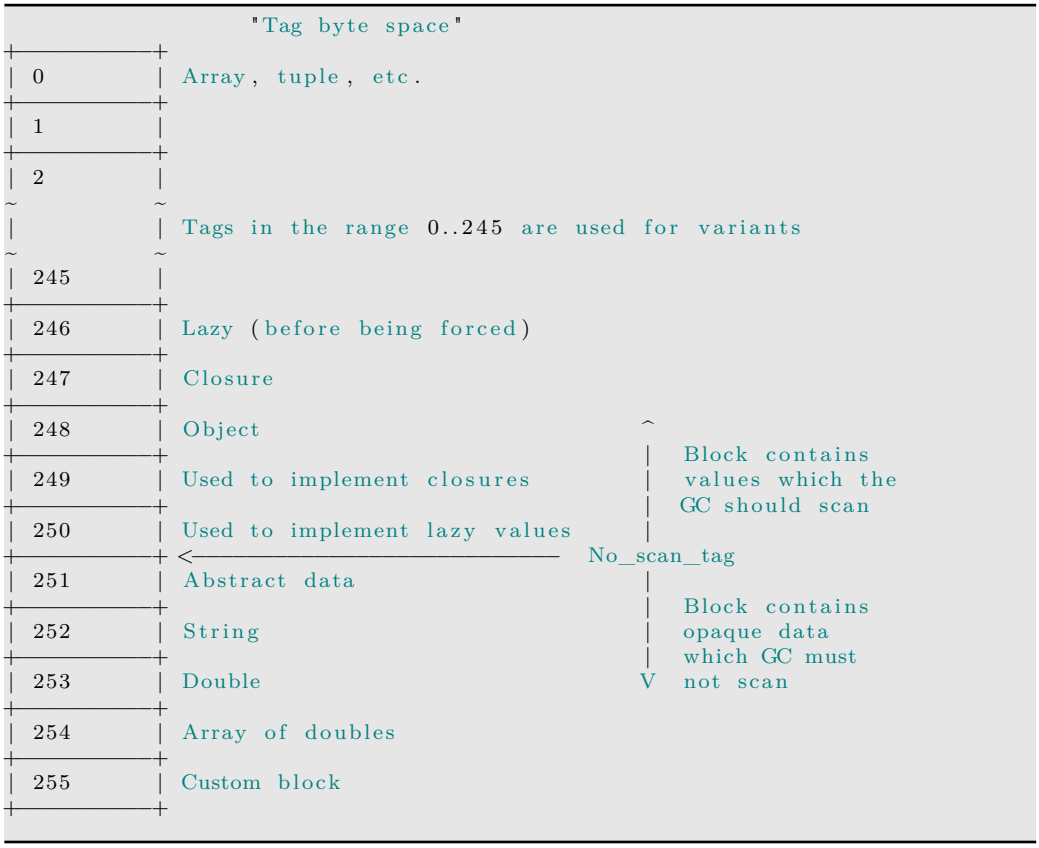
   Consider *the array of two elements*, the total size of this object *will be 3 words (header + 2 words)*, so 24 bytes for 64-bit , so the fast path for allocation is subtract size from caml_young_ptr. If caml_young_ptr < caml_young_limit, then take the slow path through the garbage collector. The fast path just **five machine instructions and no branches**. But even five instructions are costly in inner loops, be careful.

   (b) major heap

   when the minor heap runs out, it triggers a **minor collection**. The minor collection starts at all the local roots and *oldifies* them, basically copies them by reallocating those objects (recursively) **to the major heap**. After this, any object left in the minor heap **are unreachable**, so the minor heap can be reused by resetting **caml_young_ptr** .



At runtime the garbage collector *always* knows what is a pointer, and what is an int or opaque data (like a string). Pointers get scanned so the GC can find unreachable blocks. Ints and opaque data must not be scanned. *This is the reason for having a tag bit for integer-like values*, and one of the uses of the tag byte in the header.



so, in the normal course of events, a small, long-lived object will start on the minor heap and be copied into the major heap. **Large objects go straight to the major heap** But there is another important structure

used in the major heap, called the **page table**. The garbage collector must at all times know which pieces of memory belong to the major heap, and which pieces of memory do not, and it uses the page table to track this. One reason **why we always want to know where the major heap lies** is so we can avoid scanning pointers which point to C structs outside the OCaml heap. The GC will not stray beyond its own heap, and treats all pointers outside as opaque (it doesn't touch them or follow them). In OCaml 3.10 the page table was implemented as a simple bitmap, with 1 bit per page of virtual memory (major heap chunks are always page-aligned). This was unsustainable for 64 bit address spaces where memory allocations can be very very **far apart**, so in OCaml 3.11 this was changed to a sparse hash table. Because of the page table, C pointers can be stored directly as values, which saves time and space. (However, if your C pointer later gets freed, you must NULL the value-the reason is that the same memory address might later get malloced for the OCaml major heap, thus *suddenly* becoming a *valid* address again. THIS usually results in crash). In a functional language **which does not allow any mutable references**, there's one guarantee you can make which is there could **never be a pointer going from the major heap to something in the minor heap**, so when an object in an immutable language graduates from the minor heap to the major heap, it is fixed forever(until it becomes unreachable), and can not point back to the minor heap. But ocaml is impure, so if the minor heap collection worked exactly as previous, then the outcome wouldn't be good, maybe some object is not pointed at **by any local root**, so it would be *unreachable* and would *disappear*, leaving a **dangling pointer**. **one solution would be to check the major heap, but that would be massively time-consuming: minor-collections are supposed to be very quick** What OCaml does instead is to have a separate *refs* list. This contains a list of pointers that point **from the major heap to the minor heap**. During a minor heap collection, the refs list is consulted for additional roots(and after the minor heap collection, the refs list can be

started anew).

The refs list however has to be updated, and it gets **updated potentially every time we modify a mutable field in a struct**. The code calls the c function **caml_modify** which both mutates the struct a nd decides whether this is a major→minor pointer to be added to the refs list.

If you use mutable fields then this is **much slower** than a simple assignment. However, **mutable integers** are ok, and don't trigger the extra call. You can also **mutate fields** yourself, eg. from c functions or using Obj, **provied you can guarantee that this won't generate a pointer between the major and minor heaps**.

The OCaml gc does not collect the major heap in one go. It spreads the work over small **slices**, and splices are grouped into whole *phases* of work. *A slice* is just a defined amount of work.

The phases are mark and sweep, and some additional sub-passes dealing with weak pointers and finalization.

Finally there is *a compaction phase* which is triggered when there is no other work to do and the estimate of free space in the heap has reached some threshold. This is tunable. You can schedule when to compact the heap – while waiting for a key-press or between frames in a live simulation.

There is also a penalty for doing a slice of the major heap – for example if the minor heap is exhausted, then some activity in the major heap is unavoidable. However if you make the **minor heap large enough**, you can completely control when GC work is done. You can also move *large structures out of the major heap entirely*,

2. module Gc

```
Gc.compact () ;;
let checkpoint p = Gc.compact () ; prerr_endline ("checkpoint at poisition " ^
    p )
```

The checkpoint function does two things: *Gc.compact ()* does a full major round of garbage collection and compacts the heap. This is the most aggressive

form of Gc available, and it's highly likely to *segfault* if the heap is corrupted. *prerr_endline* prints a message to stderr and crucially also flushes stderr, so you will see the message printed immediately.

you **should** grep for `caml_heap_check` in byterun for details

```
void caml_compact_heap (void)
{
  char *ch, *chend;
                                          Assert (caml_gc_phase == Phase_idle);
  caml_gc_message (0x10, "Compacting heap...\n", 0);

#ifdef DEBUG
  caml_heap_check ();
#endif


#ifdef DEBUG
void caml_heap_check (void)
{
  heap_stats (0);
}
#endif


#ifdef DEBUG
  ++ major_gc_counter;
  caml_heap_check ();
#endif
```

3. tune

   problems can arise when you're building up ephemeral data structures which are larger than the minor heap. The data structure won't stay around overly long, but it is a bit too large. Triggering major GC slices more often can cause static data to be walked and re-walked more often than is necessary. tuning sample

```
let _ =
  let gc = Gc.get () in
    gc.Gc.max_overhead <- 1000000;
    gc.Gc.space_overhead <- 500;
    gc.Gc.major_heap_increment <- 10_000_000;
    gc.Gc.minor_heap_size <- 10_000_000;
    Gc.set gc
```

Chapter 8

Object-oriented

8.1 Simple Object Concepts

```
let poly = object
  val vertices = [|0,0;1,1;2,2|]
  method draw = "test"
end
(**
   val poly : < draw : string > = <obj>
*)
```

obj#method, the actual method gets called is determined at runtime.

```
let draw_list  =   List.iter (fun x -> x#draw)
(**
   val draw_list : < draw : unit; _.. > list -> unit = <fun>
*)
```

.. is a row variable

```
type 'a blob = <draw : unit;  ..> as 'a
(* type 'a blob = 'a constraint 'a = < draw : unit; .. >   *)
```

{<>} represents a **functional update** (only fields), which produces a new object

Some other examples

```
type 'a blob = 'a constraint 'a = < draw : unit > ;;
(* type 'a blob = 'a constraint 'a = < draw : unit >   *)

type 'a blob = 'a constraint 'a = < draw : unit ; .. > ;;
(* type 'a blob = 'a constraint 'a = < draw : unit; .. > *)


let transform =
    object
      val matrix = (1.,0.,0.,0.,1.,0.)
      method new_scale sx sy =
```

```
        {<matrix= (sx,0.,0.,0.,sy,0.)>}
      method new_rotate theta =
        let s,c=sin theta, cos theta in
        {<matrix=(c,-.s,0.,s,c,0.)>}
      method new_translate dx dy=
        {<matrix=(1.,0.,dx,0.,1.,dy)>}
      method transform (x,y) =
        let (m11,m12,m13,m21,m22,m23)=matrix in
        (m11 *. x +. m12 *. y +. m13,
         m21 *. x +. m22 *. y +. m23)
    end ;;

(**
  val transform :
  < new_rotate : float -> 'a; new_scale : float -> float -> 'a;
    new_translate : float -> float -> 'a;
    transform : float * float -> float * float >
  as 'a = <obj>
*)


let new_collection () =  object
  val mutable items = []
  method add item = items <- item::items
  method transform mat =
    {<items = List.map (fun item -> item#transform mat) items>}
end ;;

(*
val new_collection :
  unit ->
  (< add : (< transform : 'c -> 'b; .. > as 'b) -> unit;
     transform : 'c -> 'a >
   as 'a) =
  <fun>
*)

let test_init =object
```

Something to Notice

Field expression **could not** refer to other fields, nor to itself, after you get the object you can have initializer. The object *does not exist* when the field values are be computed. For the initializer, you can call `self#blabla`

```
let test_init =object
```

```
    val x = 1
    val mutable x_plus_1 = 0
    initializer begin
      print_endline "hello ";
      x_plus_1 <- x + 1;
    end
end ;;

(**
hello
val test_init : <  > = <obj>
*)
```

Private method

```
let test_private = object
  val x = 1
  method private print =
    print_int x
end ;;
(* val test_private : <  > = <obj> *)
```

Subtyping

Supports *width and depth subtyping, contravariant and covariant* for subtyping of recursive object types, *first assume it is right* then prove it using such assumption. Sometimes, type annotation and coersion both needed, when t2 is recursive or t2 has polymorphic structure.

```
1  e : t1 :> t2
```

Simulate narrowing(downcast)

```
type animal = < eat : unit; v : exn >
type dog = < bark : unit; eat : unit; v : exn >
type cat = < eat : unit; meow : unit; v : exn >
exception Dog of dog
exception Cat of cat

let fido : dog = object(self)
  method v=Dog self
  method eat = ()
  method bark = ()
```

```
end;;

let miao : cat = object(self)
  method v = Cat self
  method eat = ()
  method meow = ()
end;;

let _ = begin
  let test o = match o#v with
    | Dog o' -> print_endline "Dog"
    | Cat o' -> print_endline "Cat"
    | _ -> print_endline "not handled"
  in
  test fido;
  test miao;
end
(**
   Dog
   Cat
*)
```

It's doable, since `exn` is open and its tag is global, and you can store the tag information uniformly. But onething to notice is that you can not write safe code, since exn is extensible, you can not guarantee that you match is exhuastive.

You can also implement using polymorphic variants, this is essentially the same thing, since `Polymorphic Variants` is also global and extensible.

```
type 'a animal = <eat:unit; tag : 'a >;;


let fido : [< `Dog of int] animal = object method eat = () method tag = `Dog 3 end;;
(* val fido : [ `Dog of int ] animal = <obj> *)


let fido : 'a animal = object method eat = () method tag = `Dog 3 end;;

(* val fido : [> `Dog of int ] animal = <obj> *)



let miao : [> `Cat of int] animal = object method eat = () method tag = `Cat 2 end;;
(* val miao : [> `Cat of int ] animal = <obj> *)
```

```
let aims =  [fido;miao];;
(* [> `Cat of int | `Dog of int ] animal list = [<obj>; <obj>] *)


List.map (fun v -> match v#tag with `Cat a -> a |`Dog a -> a) [fido;miao];;
(* - : int list = [3; 2] *)
```

8.2 Modules vs Objects

1. Objects (data entirely hidden)

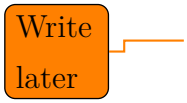
2. Self recursive type is so natural in objects, isomorphic-like equivalence is free in oo.

3. Example

```
let list_obj initial = object
  val content = initial
  method cons x = {< content = x :: content >}
end


(** module style *)
module type PolySig = sig
  type poly
  val create : (float*float) array -> poly
  val draw : poly -> unit
  val transform : poly -> poly
end
;;

module Poly :PolySig = struct
  type poly = (float * float) array
  let create vertices = vertices
  let draw vertices = ()
  let transform matrix = matrix
end;;


(** class style *)
class type poly  = object
 method create : (float*float) array -> poly
 method draw :  unit
```

```
 method transform : poly
end;;

class poly_class  = object (self:'self)
  val mutable vertices : (float * float ) array = [||]
  method create vs = {< vertices = vs >}
  method draw = ()
  method transform = {< vertices = vertices >}
end;;

(** makes the type not that horrible. First class objects, but not
    first class classes
*)
let a_obj : poly = new poly_class


(** oo-style *)
type blob = < draw : unit -> unit; transform : unit -> blob >;;

(** functional style *)
type blob2 = {draw:unit-> unit; transform:unit-> blob2};;
```

8.3 More about class


Write
later

Chapter 9

Language Features

9.1 Stream Expression

Link to streams

Stream Expression

```
let rec walk dir =
  let items =
    try
      Array.map (fun fn ->
        let path = Filename.concat dir fn in
        try if Sys.is_directory path then `Dir path else `File path
        with e -> `Error(path,e) ) (Sys.readdir dir)
    with e -> [| `Error (dir,e) |] in
  Array.fold_right
    (fun item rest -> match item with
      |`Dir path -> [< 'item ; walk path; rest >]
      | _ -> [< 'item; rest >]) items [< >]
(**

val walk :
  string ->
  [> `Dir of string | `Error of string * exn | `File of string ] Stream.t

ocamlbuild test_stream.pp.ml

let rec walk dir =
  let items =
    try
      Array.map
        (fun fn ->
           let path = Filename.concat dir fn
           in
             try if Sys.is_directory path then `Dir path else `File path
             with | e -> `Error (path, e))
        (Sys.readdir dir)
    with | e -> [| `Error (dir, e) |]
  in
    Array.fold_right
      (fun item rest ->
         match item with
         | `Dir path ->
             Stream.icons item (Stream.lapp (fun _ -> walk path) rest)
         | _ -> Stream.icons item rest)
      items Stream.sempty
*)
open Batteries
```

```
let _ =
  Stream.( walk   "/Users/bobzhang1988"
             |> take 10 |> iter
                 (
                   (function `Dir s -> "dir :" ^ s
                     | `File s -> "file: " ^ s
                     | `Error (s,e) -> "error: " ^ s ^ " " ^ Printexc.to_string e
                    )  |- print_string |- print_newline)
  );;
```

Module Stream

```
Stream.npeek;;
- : int -> 'a Batteries.Stream.t -> 'a list = <fun>
Stream.next;;
- : 'a Stream.t -> 'a = <fun>
```

```
1 let lines_stream_of_channel chan = Stream.from (fun _ ->
2     try Some (input_line chan) with End_of_file -> None );;
3 val lines_stream_of_channel : BatIO.input -> string Batteries.Stream.t =
```

It raises *Stream.Failure* on an empty stream, i.e. *Stream.next*

```
1 let line_stream_of_string string =
2   Stream.of_list (Str.( split (regexp "\n") string))
```

Constructing streams

```
Stream.from
Stream.of_list
Stream.of_string (* char t *)
Stream.of_channel (* char t *)
```

Consuming streams

```
Stream.peek
Stream.junk
```

```
let paragraph lines =
  let rec next para_lines i =
    match Stream.peek lines,para_lines with
    | None, [] -> None
    | Some "", [] ->
      Stream.junk lines (* still a white paragraph *)
      next para_lines i
    | Some "", _ | None, _ ->
      Some (String.concat "\n" (List.rev para_lines)) (* a new paragraph*)
    | Some line, _ ->
      Stream.junk lines ;
      next (line :: para_line ) i in
  Stream.from (next [])
let stream_fold f stream init =
    let result = ref init in
    Stream.iter (fun x -> result := f x !result) stre  am; !result;;
val stream_fold : ('a -> 'b -> 'b) -> 'a Batteries.Stream.t -> 'b -> 'b =
  <fun>
let stream_concat streams =
  let current_stream = ref None in
  let rec next i =
    try
      let stream = match !current_stream with
        | Some stream -> stream
        | None ->
          let stream = Stream.next streams in
          current_stream := Some stream ;
          stream in
      try Some (Stream.next stream)
      with Stream.Failure -> (current_stream := None ; next i)
    with Stream.Failure -> None in
  Stream.from next
```

Copying or sharing streams

This was called *dup* in Enum

```
(** create 2 buffers to store some pre-fetched value *)
let stream_tee stream =
  let next self other i =
    try
      if Queue.is_empty self
      then
        let value = Stream.next stream in
        Queue.add value other ;
        Some value
      else
        Some (Queue.take self)
    with Stream.Failure -> None in
  let q1,q2 = Queue.create (), Queue.create () in
  (Stream.from (next q1 q2), Stream.from (next q2 q1))
```

Convert arbitray data types to streams

If the datat type defines an *iter* function, and you don't mind using threads, you can use a *producer-consumer* arrangement to invert control.

```
let elements iter coll =
  let channel = Event.new_channel () in
  let producer () =
    let _ = iter (fun x -> Event.( sync (send channel (Some x )))) coll in
    Event.( sync (send channel None)) in
  let consumer i =
    Event.( sync (receive channel)) in
  ignore (Thread.create producer ()) ;
  Stream.from consumer
val elements : (('a -> unit) -> 'b -> 'c) -> 'b -> 'a Batteries.Stream.t =
```

Keep in mind that these techniques spawn producer threads which carry a few risks: they only terminate when they have finished iterating, and any change to the original data structure while iterating may produce unexpected results.

9.2 GADT

```
type _ expr =
  | Int : int -> int expr
  | Add : (int -> int -> int) expr
  | App : ('a -> 'b ) expr * 'a expr -> 'b expr


let rec eval : type t . t expr -> t = function
  | Int n -> n
  | Add -> (+)
  | App (f,x) -> eval f (eval x)


(** tagless data structure *)
type _ ty =
  | Tint : int ty
  | Tbool : bool ty
  | Tpair : 'a ty * 'b ty -> ('a * 'b) ty

(** inside pattern matching, type inference progresses from left to
    right, allowing subsequent patterns to benift from type equations
    generated in the previous ones.
    This implies that d has type int on the first line,...
*)
let rec print : type a . a ty -> a -> string = fun t d ->
  match t, d with
    |Tint, n -> string_of_int n
    |Tbool,true -> "true"
    |Tbool,false -> "false"
    |Tpair (ta,tb), (a,b) ->
      "(" ^ print ta a ^ ", " ^ print tb b ^ ")"

let f = print (Tpair (Tint,Tbool))
```

read ml 2011 workshop paper

9.3 First Class Module

First class mdoule

```
module type ID = sig val id : 'a -> 'a end

let f m =
    let module Id = (val m : ID) in
    (Id.id 1, Id.id true);;

(* val f : (module ID) -> int * bool = <fun>   *)

f (module struct let id x = print_endline "ID!"; x end : ID);;
(*
  ID!
  ID!
*)
```

Here the argument `m` is a module. This is already possible with objects and records, but now modules are also allowed. We introduce three syntaxes

```
(your_module : Sig) (*packing*)

(val def : Sig) (*unpacking*)

(module Sig) (*type*)
```

Runtime choices, Type-safe plugins

Parametric algorithms

Read the slides by Jacques Garrigue

```
module type Number = sig
  type t
  val int : int -> t
  val (+) : t -> t -> t
  val (/) : t -> t -> t
end

let average (type t) number arr =
  let module N = (val number : Number with type t = t) in
  N.(
    let r = ref (int 0) and len = Array.length arr in
    for i = 0 to Pervasives.(len - 1) do
      r := !r + arr.(i)
```

```
    done;
    !r / int (Array.length arr)
  )

(* val average : (module Number with type t = 'a) -> 'a array -> 'a = <fun>     *)

let f =
  average
    (module struct
      type t = int
      let (+) = (+)
      let (/) = (/)
      let int = fun x -> x
    end : Number with type t = int);;
(* val f : int array -> int = <fun> *)
```

Notice `with type t = int` is necessary here.

The next is a fancy example to illustrate lebiniz equivalence, readers should try to digest it. Something to reminder, now the simple type may be a very complex module type.

```
type ('a, 'b) eq = (module EqTC with type a = 'a and type b = 'b)))
```

```
(** First class module to encode *)
module type TyCon = sig
  type 'a tc
end


module type WeakEQ =
sig
  type ('a, 'b) eq
  val refl : unit -> ('a, 'a) eq
  val symm : ('a, 'b) eq -> ('b, 'a) eq
  val trans : ('a, 'b) eq -> ('b, 'c) eq -> ('a, 'c) eq
  val cast : ('a, 'b) eq -> 'a -> 'b
end

module WeakEq : WeakEQ =
struct
  type ('a, 'b) eq = ('a -> 'b) * ('b -> 'a)
  let refl () = (fun x -> x), (fun x -> x)
  let symm  (f, g)        = (g, f)
  let trans (f, g) (j, k) = (fun x -> j (f x)), (fun x -> g (k x))
  let cast  (f, g)        = f
end
```

```
module type EQ =
sig
  type ('a, 'b) eq
  val refl : unit -> ('a, 'a) eq

  module Subst (TC : TyCon) :  sig
    val subst : ('a, 'b) eq -> ('a TC.tc, 'b TC.tc) eq
  end
  val cast : ('a, 'b) eq -> 'a -> 'b
end

module Eq : EQ = struct

  (** EqTC can be seen as a high-order kind, parameterized by two type
      variables a b. This is the limitation of ocaml, since type
      variable as a parameter can only appear in [type 'a t], the type
      variable will be *universally quantified* when it appears in
      other places *)
  module type EqTC =  sig
    type a
    type b
    (** You see the definition of [TC], it could be parameterized
        here *)
    module Cast : functor (TC : TyCon) ->  sig
      val cast : a TC.tc -> b TC.tc
    end
  end

  type ('a, 'b) eq = (module EqTC with type a = 'a and type b = 'b)

  let refl (type t) () =  (module struct
    type a = t
    type b = t
    module Cast (TC : TyCon) =
    struct
      let cast v = v
    end
  end : EqTC with type a = t and type b = t)

  let cast (type s) (type t) s_eq_t =
    let module S_eqtc = (val s_eq_t : EqTC with type a = s and type b = t) in
    let module C = S_eqtc.Cast(struct type 'a tc = 'a end) in
    C.cast

  module Subst (TC : TyCon) =  struct
    (** We have (s,t) eq, now we want to construct a proof of (s TC.t,
```

```
        t Tc.t) eq .
        i.e, a Sc.t -> b Sc.t, s Tc.t Sc.t -> t Tc.t Sc.t *)
    let subst (type s) (type t) s_eq_t =
      (module
       struct
         type a = s TC.tc
         type b = t TC.tc
         module S_eqtc = (val s_eq_t : EqTC with type a = s and type b = t)
         module Cast (SC : TyCon) =
         struct
           module C = S_eqtc.Cast(struct type 'a tc = 'a TC.tc SC.tc end)
           let cast = C.cast
         end
       end : EqTC with type a = s TC.tc and type b = t TC.tc)
  end
end

include Eq

let symm : 'a 'b. ('a, 'b) eq -> ('b, 'a) eq =
  fun (type a) (type b) a_eq_b ->
    let module S = Subst (struct type 'a tc = ('a, a) eq end) in
    cast (S.subst a_eq_b) (refl ())


let trans : 'a 'b 'c. ('a, 'b) eq -> ('b, 'c) eq -> ('a, 'c) eq =
  fun (type a) (type b) (type c) a_eq_b b_eq_c ->
    let module S = Subst(struct type 'a tc = (a, 'a) eq end) in
    cast (S.subst b_eq_c) a_eq_b

(** Our implementation of equality seems sufficient for the common
    examples, but has one apparent limitation, described below.  A few
    examples seem to require an inverse of Leibniz's law.  For
    injectivty type constructors t, we would like to have ('a t, 'b t)
    eq -> ('a, 'b) eq For example, given a proof that two function
    types are equal, we would like to extract proofs that the domain
    and codomain types are equal: ('a -> 'b, 'c -> 'd) eq -> ('a, 'c)
    eq * ('b, 'd) eq GADTs themselves support type decomposition in
    this way.  Unfortunately, injectivity is supported only for
    WeakEq.eq.  We may always get WeakEq.eq from EQ.eq.
*)
let degrade : 'r 's. ('r, 's) eq -> ('r, 's) WeakEq.eq =
  fun (type r) (type s) r_eq_s ->
    let module M = Eq.Subst(struct type 'a tc = ('a, r) WeakEq.eq end) in
    WeakEq.symm (cast (M.subst r_eq_s) (WeakEq.refl ()))
```

9.4 Pahantom Types

A simple example

```
module type S = sig
  type 'a expr
  val int : int -> int expr
  val bool : bool -> bool expr
  val add : int expr -> int expr -> int expr
  val app : ('a -> 'b ) expr -> ('a expr -> 'b expr)
  val lam : ('a expr -> 'b expr ) -> ('a -> 'b) expr
end



module M : S= struct
  type term =
      Int of int
    | Bool of bool
    | Add of term * term
    | App of term * term
    | Lam of (term -> term)

  type 'a expr =  term (* The phantom type *)
  let int : int -> int expr = fun i ->  (Int i)
  let bool : bool -> bool expr = fun b ->  (Bool b)

  let add : int expr -> int expr -> int expr =
    fun ( e1) ( e2) ->  (Add(e1,e2))

  let app : ('a -> 'b) expr -> ('a expr -> 'b expr) =
    fun ( e1) ( e2) ->  (App(e1,e2))

  let lam : ('a expr -> 'b expr) -> ('a -> 'b) expr =
    fun f ->  (Lam(fun x -> let ( b) = f ( x) in b))
end


open M

(*
  lam (fun x -> app x x );;
                        ^
Error: This expression has type ('a -> 'b) M.expr
       but an expression was expected of type 'a M.expr
*)
```

```
module Length : sig
  type 'a t = private float
  val meters : float -> [`Meters] t
  val feet : float -> [`Feet] t
  val (+.) : 'a t -> 'a t -> 'a t
  val to_float : 'a t -> float
end = struct
  type 'a t = float
  external meters : float -> [`Meters] t = "%identity"
  external feet : float -> [`Feet] t = "%identity"
  let (+.) = (+.)
  external to_float : 'a t -> float = "%identity"
end
```

```
let meters, feet = Length.( meters,feet)
let m1 = meters 10.
let m2 = meters 20.
open Printf

let _ =
  printf "10m + 20m = %g\n" Length.(( ( m1 +. m2 ) :> float ))

let f1 = feet 40.
let f2 = feet 50.

let _ =   printf "40ft + 50ft = %g\n" (Length.( (( f1 +. f2) :> float )))

  (*printf "10m + 50ft = %g\n" (to_float (m1 +. f2)) (* error *) *)


module Connection : sig
  type 'a t

  (** we return a closed Readonly type *)
  val connect_readonly : unit -> [`Readonly] t

  (** we reeturn  a closed ReadWrite both type *)
  val connect : unit -> [`Readonly|`Readwrite] t

  (** read only or greater *)
  val status : [>`Readonly] t -> int

  val destroy : [>`Readwrite] t -> unit
end = struct
```

```
  type 'a t = int
  let count = ref 0
  let connect_readonly () = incr count; !count
  let connect () = incr count; !count
  let status c = c
  let destroy c = ()
end

module C = String.Cap


(** closed type here when you want it to be read only *)
let read : [ `Read] C.t = C.of_string "aghsogho"

(**
   error
   let _ = C.set s 0 'a'  ; s
*)

let a =
  C.set read 0 'b' ;
  C.get read 0


(** open for write and read *)
let write : [> `Write] C.t    = C.of_string "aghso"

let _ =
  C.set write 0 'a';
  print_char (C.get write 0);
  C.to_string write

(** now
write;;
- : [ `Read | `Write ] C.t = <abstr>
*)

module type S = sig
  type 'a perms
  type 'a t
  val read_only : [`Readable] perms
  val write_only : [`Writable] perms
  val read_write : [> `Readable | `Writable] perms
  (** interesting 'a perms -> 'a t, both perms and t are phantom
      types *)
  val map_file : string -> 'a perms -> int -> 'a t
  val get : [>`Readable] t -> int -> char
```

```
  val set : [>`Writable] t -> int -> char -> unit
end

(**
   Array1.map_file;;
   - : Unix.file_descr ->
   ?pos:int64 ->
   ('a, 'b) Batteries.Bigarray.kind ->
   'c Batteries.Bigarray.layout ->
   bool -> int -> ('a, 'b, 'c) Batteries.Bigarray.Array1.t

   Array1.get;;
   - : ('a, 'b, 'c) Batteries.Bigarray.Array1.t -> int -> 'a = <fun>p

   Array1.set;;
   - : ('a, 'b, 'c) Batteries.Bigarray.Array1.t -> int -> 'a -> unit = <fun>

*)
module M : S= struct
  open Unix
  open Bigarray
  type bytes = (int,int8_unsigned_elt,c_layout) Bigarray.Array1.t
  type 'a perms = int
  type 'a t = bytes
  let read_only = 1
  let write_only = 2
  let read_write = 3
  let openflags_of_perms n = match n with
    | 1 -> O_RDONLY, 0o400
    | 2 -> O_WRONLY, 0o200
    | 3 -> O_RDWR, 0o600
    | _ -> invalid_arg "access_of_openflags"
  let access_of_openflags  = function
    | O_RDONLY -> [R_OK;F_OK]
    | O_WRONLY -> [W_OK; F_OK]
    | O_RDWR -> [R_OK; W_OK;F_OK]
    | _ -> invalid_arg "access_of_openflags"

  let map_file filename perms sz =
    let oflags,fperm = openflags_of_perms perms in
    try
      access filename (access_of_openflags oflags);
      let fd = openfile filename [oflags;O_CREAT] fperm in
      Array1.map_file fd int8_unsigned c_layout false sz
    with
        _ ->
          invalid_arg "map_file: not even a valid permission"
```

```
  let  get a i = Char.chr (Array1.get a i)
  let set a i c = Array1.set a i (Char.code c)

end
```

A fancy example.

```
(** several tricks used in this file *)
module DimArray : sig
  type dec  (* = private unit *)
  type 'a d0 (* =  private unit *)
  and 'a d1  (* = private unit *)
  and 'a d2 (* = private unit *)
  and 'a d3 (* = private unit *)
  and 'a d4 (* = private unit *)
  and 'a d5 (* = private unit *)
  and 'a d6 (* = private unit *)
  and 'a d7 (* = private unit *)
  and 'a d8 (* = private unit *)
  and 'a d9 (* = private unit *)
  type zero (* = private unit  *)
  and nonzero (* = private unit*)
  type ('a, 'z) dim0 (* = private int*)
  type 'a dim = ('a, nonzero) dim0
  type ('t, 'd) dim_array = private ('t array)

  val dec :            ((dec, zero) dim0 -> 'b) -> 'b
  val d0 : 'a dim        -> ('a d0 dim -> 'b) -> 'b
  val d1 : ('a, 'z) dim0 -> ('a d1 dim -> 'b) -> 'b
  val d2 : ('a, 'z) dim0 -> ('a d2 dim -> 'b) -> 'b
  val d3 : ('a, 'z) dim0 -> ('a d3 dim -> 'b) -> 'b
  val d4 : ('a, 'z) dim0 -> ('a d4 dim -> 'b) -> 'b
  val d5 : ('a, 'z) dim0 -> ('a d5 dim -> 'b) -> 'b
  val d6 : ('a, 'z) dim0 -> ('a d6 dim -> 'b) -> 'b
  val d7 : ('a, 'z) dim0 -> ('a d7 dim -> 'b) -> 'b
  val d8 : ('a, 'z) dim0 -> ('a d8 dim -> 'b) -> 'b
  val d9 : ('a, 'z) dim0 -> ('a d9 dim -> 'b) -> 'b
  val dim : ('a, 'z) dim0 -> ('a, 'z) dim0
  val to_int : ('a, 'z) dim0 -> int
  (* arrays with static dimensions *)

  val make : 'd dim -> 't -> ('t, 'd) dim_array
  val init : 'd dim -> (int -> 'a) -> ('a, 'd) dim_array
  val copy : ('a, 'd) dim_array -> ('a, 'd) dim_array
  (* other array operations go here ... *)
  val get : ('a, 'd) dim_array -> int -> 'a
```

```
  val set : ('a, 'd) dim_array -> int -> 'a -> unit
  val combine :
    ('a, 'd) dim_array -> ('b, 'd) dim_array -> ('a -> 'b -> 'c) ->
    ('c, 'd) dim_array
  val length : ('a, 'd) dim_array -> int
  val update : ('a, 'd) dim_array -> int -> 'a -> ('a, 'd) dim_array
  val iter : f:('a -> unit) -> ('a, 'd) dim_array -> unit
  val map : f:('a -> 'b) -> ('a, 'd) dim_array -> ('b, 'd) dim_array
  val iteri : f:(int -> 'a -> unit) -> ('a, 'd) dim_array -> unit
  val mapi : f:(int -> 'a -> 'b) -> ('a, 'd) dim_array ->
    ('b, 'd) dim_array
  val fold_left : f:('a -> 'b -> 'a) -> init:'a -> ('b,'d) dim_array -> 'a
  val fold_right : f:('b -> 'a -> 'a) -> ('b, 'd) dim_array -> init:'a ->
    'a
  val iter2 :
    f:('a -> 'b -> unit) -> ('a,'d) dim_array -> ('b, 'd) dim_array ->
    unit
  val map2 :
    f:('a -> 'b -> 'c) -> ('a, 'd) dim_array -> ('b, 'd) dim_array ->
    ('c, 'd) dim_array
  val iteri2 :
    f:(int -> 'a -> 'b -> unit) -> ('a,'d) dim_array -> ('b, 'd)
    dim_array ->
    unit
  val mapi2 :
    f:(int -> 'a -> 'b -> 'c) -> ('a, 'd) dim_array -> ('b, 'd)
    dim_array ->
    ('c, 'd) dim_array
  val to_array : ('a, 'd) dim_array -> 'a array
end = struct
  include Array
  include Array.Labels
  (** some functions should be overriden later *)
  type dec = unit
  type 'a d0 = unit
  type 'a d1 = unit
  type 'a d2 = unit
  type 'a d3 = unit
  type 'a d4 = unit
  type 'a d5 = unit
  type 'a d6 = unit
  type 'a d7 = unit
  type 'a d8 = unit
  type 'a d9 = unit
  type zero = unit
  type nonzero = unit
```

```
  type ('a, 'z) dim0 = int (* Phantom type *)
  type 'a dim = ('a, nonzero) dim0

  let dec k = k 0

  let d0 d k = k (10 * d + 0)
  let d1 d k = k (10 * d + 1)
  let d2 d k = k (10 * d + 2)
  let d3 d k = k (10 * d + 3)
  let d4 d k = k (10 * d + 4)
  let d5 d k = k (10 * d + 5)
  let d6 d k = k (10 * d + 6)
  let d7 d k = k (10 * d + 7)
  let d8 d k = k (10 * d + 8)
  let d9 d k = k (10 * d + 9)

  let dim d = d

  let to_int d = d

  type ('t, 'd) dim_array = 't array

  let make d x = Array.make (to_int d) x
  let init d f = Array.init (to_int d) f
  let copy x = Array.copy  x
  (* other array operations go here ... *)
  let get : ('a, 'd) dim_array -> int -> 'a = fun a d ->
    Array.get a d

  let set : ('a, 'd) dim_array -> int -> 'a -> unit = fun a d v ->
    Array.set a d v

  let unsafe_get : ('a, 'd) dim_array -> int -> 'a = fun a d ->
    Array.unsafe_get a d

  let unsafe_set : ('a, 'd) dim_array -> int -> 'a -> unit = fun a d v ->
    Array.unsafe_set a d v

  let combine :
      ('a, 'd) dim_array -> ('b, 'd) dim_array -> ('a -> 'b -> 'c) -> ('c,
'd) dim_array =
        fun a b f ->
          Array.init (Array.length a) (fun i -> f a.(i) b.(i))

  let length : ('a, 'd) dim_array -> int = fun a -> Array.length a

  let update : ('a, 'd) dim_array -> int -> 'a -> ('a, 'd) dim_array =
```

```
    fun a d v -> let result = Array.copy a in (Array.set result d v;
result)


  let rec iteri2 ~f a1 a2 =
    for i = 0 to length a1 - 1 do
      f i (unsafe_get a1 i) (unsafe_get a2 i)
    done
  let map2 ~f = map2 f
  let mapi2 ~f a1 a2 =
    let l = length a1 in
    if l = 0 then [||] else
    (let r = Array.make l (f 0 (unsafe_get a1 0) (unsafe_get a2 0)) in
     for i = 1 to l - 1 do
       unsafe_set r i (f i (unsafe_get a1 i) (unsafe_get a2 i))
     done;
     r)

  let to_array : ('a, 'd) dim_array -> 'a array = fun d -> d

end;;

open DimArray
let d10 = dec d1   d0 dim
let a = make d10 0.
let b = make d10 1.


module S : sig
  type 'a t = private ('a array)
  val of_float_array : 'a array -> 'a t
end = struct
  type 'a t = 'a array
  let of_float_array = fun x -> x
end
```

9.4.1 Useful links

jones

- jambo
- caml
- jane

9.5 Positive types

9.6 Private Types

Private types

Private type stand between abstract type and concrete types. You can coerce your private type back to the concrete type (zero-performance), but backward is **not allowed**.

For ordinary private type, you can still do pattern match, print the result in toplevel, and debugger. A big advantage for private type abbreviation is that for parameterized type(like container) coercion, you can still do the coercion pretty fast(optimization), and some parameterized types(not containers) can still do such coercions while abstract types can not do. Since ocaml does not provide ad-hoc polymorphism, or type functions like Haskell, this is pretty straight-forward.

```
module Int = struct
  type t = int
  let of_int x = x
  let to_int  x = x
end

module Priv : sig
  type t = private int
  val of_int : int -> t
  val to_int : t -> int
end = Int


module Abstr : sig
  type t
  val of_int : int -> t
  val to_int : t -> int
end = Int

let _ =
  print_int (Priv.of_int 3 :> int)

let _ =
  List.iter (print_int|-print_newline)
    ([Priv.of_int 1; Priv.of_int 3] :> int list)

(** non-container type *)
type 'a f =
  |A of (int -> 'a)
```

```
  |B

(** this is is hard to do when abstract types *)
let  a =
  ((A (fun x -> Priv.of_int x )) :> int f)
```

9.7 Subtyping

9.8 Explicit Nameing Of Type Variables

The type constructor it introduces can be used in places where a type variable is `not allowed`.

```
let f (type t) () =
    let module M = struct exception E of t end in
    (fun x -> M.E x ), (function M.E x -> Some x | _ -> None);;
val f : unit -> ('a -> exn) * (exn -> 'a option) = <fun>
```

The exception defined in local module can not be captured by other exception handler except wild catch.

Another example:

```
let sort_uniq (type s) (cmp : s -> s -> int) =
    let module S = Set.Make(struct type t = s let compare = cmp end) in
    fun l -> S.elements (List.fold_right S.add l S.empty);;
val sort_uniq : ('a -> 'a -> int) -> 'a list -> 'a list = <fun>
```

The functor needs a type constructor(type variable is not allowed)

9.9 The module Language

write later

Chapter 10

subtle bugs

10.1 Reload duplicate modules

polymorphic comparison

this is fragile when you load some modules like syntax extension, or toploop modules.

use *ocamlobjinfo* to see which modules are loaded exactly

Polymorphic comparisons

jane

caml_alloc returns value which is typedefed to intnat which in turn is long which is 64bit on LP64.

When prototype(without alloc.h) is missing, it is assumed to be `int caml_alloc();` assigning the return value of this call to value will sign extend it with devasting results(upper 32bit lost forever).

```
value -> intnat -> long
```

10.2 debug

```
(** The backtrace lists the program locations where the most-recently
    raised exception was raised and where it was propagated through
    function calls. *)
let f () = raise Not_found

let g () = let _ = f () in  3

let _ =
  try g ();
      assert false
  with Not_found ->
    prerr_endline "fuck";
    Printexc.print_backtrace stdout;


(**
   OCAMLRUNPARAM=b ./trace.d.byte
   fuck
   Raised at file "trace.ml", line 2, characters 17-26
   Called from file "trace.ml", line 4, characters 19-23
   Called from file "trace.ml", line 7, characters 6-10

*)
```

10.3 Debug Cheat Sheet

Chapter 11

Interoperating With C

Write later

Chapter 12

Pearls

12.1 Write Printf-Like Function With Ksprintf

```
let failwithf format = ksprintf failwith format
(*  val failwithf : ('a, unit, string, 'b) format4 -> 'a = <fun> *)
```

12.2 Optimization

`let a,b = ...` allocates a tuple `(a,b)` before discarding it, rewriting as `let a= ... and b = ... in .` ocaml does not support moving pointer Optimization, for example, `fib.(i)` will be translated to `fib + i * sizeof (int)`, quite expensive, try to avoid it, even `ref` is faster.

12.3 Weak Hashtbl

Weak Hash Weak pointer is like an ordinary pointer, but it doesn't "count" towards garbage collection. In other words if a value on the heap is only pointed at by weak pointers, then the garbage collector may free that value as if nothing was pointing to it'

A weak hash table uses weak pointers to avoid the garbage collection problem above. Instead of storing a permanent pointer to the keys or values, a weak hash table stores only a weak pointer, allowing the garbage collector to free nodes as normal

It probably isn't immediately obvious, but there are 3 variants of the weak hash table, to do with whether the key, the value or both are weak. (The fourth "variant", where both key and value are strong, is just an ordinary Hashtbl). Thus the OCaml standard library "weak hash table" has only weak values. The Hweak library has weak keys and values. And the WeakMetadata library (weakMetadata.ml, weakMetadata.mli) is a version of Hweak modified by me which has only weak keys.

12.4 Bitmatch

12.5 Interesting Notes

Ocsigen can load the code dynamically (both bytecode and native code) without having to restart the application (in fact, this is the default: static linking is a recent addition). You can use omake -P to have OMake monitor the filesystem and rebuild as you edit, in the background. Also, with a rule to the tell ocsigen to reload your application code (via the command FIFO), you can be running the new code the second you save it.

12.6 Polymorphic Variant

```
(* Author: bobzhang1988@seas215.wlan.seas.upenn.edu        *)
(* Version: $Id: pv.ml,v 0.0 2012/02/12 03:59:37 bobzhang1988 Exp $ *)
open BatPervasives
open Printf

let classify_chars s =
  let rec classify_chars_at p =
    if p < String.length s then
      let c = s.[p] in
      let cls =
        match c with
          | '0' .. '9' -> `Digit c
          | 'A' .. 'Z' | 'a' .. 'z' -> `Letter c
          | _ -> `Other c in
      cls :: classify_chars_at (p+1)
    else []
  in
  classify_chars_at 0
(* val classify_chars :
  string -> [> `Digit of char | `Letter of char | `Other of char ] list
*)


let recognize_numbers l =
  let rec recognize_at m acc =
    match m with
      | `Digit d :: m' ->
        let d_v = Char.code d - Char.code '0' in
        let acc' =
          match acc with
            | Some v -> Some(10*v + d_v)
            | None -> Some d_v in
        recognize_at m' acc'
      (** here makes the input and output the same time *)
      | x :: m' ->
        ( match acc with
          | None -> x :: recognize_at m' None
          | Some v -> (`Number v) :: x :: recognize_at m' None
        )
      | [] ->
        ( match acc with
          | None -> []
          | Some v -> (`Number v) :: []
        )
  in
```

```
  recognize_at l None
(** val recognize_numbers :
    ([> `Digit of char | `Number of int ] as 'a ) list -> 'a list

    Note that the type of the recognize_numbers
    function does not reflect all what we could know about the
    function. We can be sure that the function will never return a
    `Digit tag, but this is not expressed in the function type. We have
    run into one of the cases where the O'Caml type system is not
    powerful enough to find this out, or even to write this knowledge
    down. In practice, this is no real limitation - the types are
    usually a bit weaker than necessary, but it is unlikely that weaker
    types cause problems.'
*)


let analysis = classify_chars |- recognize_numbers
(**
   val analysis:
     string ->
     [> `Digit of char | `Letter of char | `Number of int | `Other of char ]  list

   It is no problem that classify_chars emits tags that are completely
   unknown to recognize_numbers. And both functions can use the same
   tag, `Digit, without having to declare in some way that they are
   meaning the same. It is sufficient that the tag is the same, and
   that the attached value has the same type.
*)


let number_value1 t =
  match t with
    | `Number n -> n
    | `Digit d -> Char.code d - Char.code '0'

let number_value2 t =
  match t with
    | `Number n -> n
    | `Digit d -> Char.code d - Char.code '0'
    | _ -> failwith "This is not a number"

(**
   val number_value1 : [< `Digit of char | `Number of int ] -> int = <fun>
   val number_value2 : [> `Digit of char | `Number of int ] -> int = <fun>
*)

type classified_char =
```

```
  [ `Digit of char | `Letter of char | `Other of char ]

type number_token =
  [ `Digit of char | `Number of int ]

(**
   Note that there is no ">" or "<" sign in such definitions - it
   would not make sense to say something about whether more or less
   tags are possible than given, because the context is missing.
*)

type classified_number_token = [classified_char  | number_token ]
(**
   type classified_number_token =
    [ `Digit of char | `Letter of char | `Number of int | `Other of char ]
*)

let rec sum l =
  match l with
    | x :: l' ->
      ( match x with
        | `Digit _ | `Number _ ->
              number_value1 x + sum l'
        | _ ->
              sum l' )
    | [] ->
      0
(**
   Warning 11: this match case is unused.
   val sum : [ `Digit of char | `Number of int ] list -> int = <fun>
*)

let rec sum2 l =
  match l with
    | x :: l' ->
      ( match x with
        | (`Digit _ | `Number _) as y ->
              number_value1 y + sum2 l'
        | _ ->
              sum2 l'
      )
    | [] ->
      0
(**
val sum2 : [> `Digit of char | `Number of int ] list -> int = <fun>
*)
let rec sum3 l =
```

```
  match l with
    | #number_token as y :: l' ->
      number_value1 y + sum3 l'
    | _ :: l' -> sum3 l'
    | [] -> 0

(**
 val sum3 : [> number_token ] list -> int = <fun>
*)

(** Internally, the tags are represented by hash values of the names
    of the tags. So the tags are simply reduced to integers at
    runtime. Compared with the normal variant types, there is some
    additional overhead for tags with values. In particular, for
    storing `X value one extra word is needed in comparison with the
    normal variant X value.  *)
```

Chapter 13

XX

13.0.1 tricks

- ocamlobjinfo
  analyzing ocaml obj info

```
ocamlobjinfo ./_build/src/batEnum.cmo
File ./_build/src/batEnum.cmo
Unit name: BatEnum
Interfaces imported:
  720848e0b508273805ef38d884a57618  Array
  c91c0bbb9f7670b10cdc0f2dcc57c5f9  Int32
  42fecddd710bb96856120e550f33050d  BatEnum
  d1bb48f7b061c10756e8a5823ef6d2eb  BatInterfaces
  81da2f450287aeff11718936b0cb4546  BatValue_printer
  6fdd8205a679c3020487ba2f941930bb  BatInnerIO
  40bf652f22a33a7cfa05ee1dd5e0d7e4  Buffer
  c02313bdd8cc849d89fa24b024366726  BatConcurrent
  3dee29b414dd26a1cfca3bbdf20e7dfc  Char
  db723a1798b122e08919a2bfed062514  Pervasives
  227fb38c6dfc5c0f1b050ee46651eebe  CamlinternalLazy
  9c85fb419d52a8fd876c84784374e0cf  List
  79fd3a55345b718296e878c0e7bed10e  Queue
  9cf8941f15489d84ebd11297f6b92182  CamlinternalOO
  b64305dcc933950725d3137468a0e434  ArrayLabels
  64339e3c28b4a17a8ec728e5f20a3cf6  BatRef
  3aeb33d11433c95bb62053c65665eb76  Obj
  3b0ed254d84078b0f21da765b10741e3  BatMonad
  aaa46201460de222b812caf2f6636244  Lazy
Uses unsafe features: YES
Primitives declared in this module:

ocamlobjinfo /Users/bob/SourceCode/ML/godi/lib/ocaml/std-lib/camlp4/camlp4lib.
    cma |grep Unit
Unit name: Camlp4_import
Unit name: Camlp4_config
Unit name: Camlp4
```

obj has many Units, each Unit itself also import some interfaces. ideas: you can parse the result to get an dependent graph.

- operator associativity
  the **first** char decides @ → right ; ^ → right

```
# let (^|) a b = a - b;;
val ( ^| ) : int -> int -> int = <fun>
# 3 ^| 2 ^| 1;;
- : int = 2
```

- literals

```
30l => int32
30L => int64
30n => nativeint
```

- `{re ;_}` some labels were intentionally omitted
  this is a new feature in recent ocaml, it will emit an warning otherwise

- Emacs
  there are some many tricks I can only enum a few

  - capture the shell command *C-u M-!* to capture the shell-command *M-|* shell-command-on-region

- **dirty** compiling

```
# let ic = Unix.open_process_in "ocamlc test.ml 2>&1";;
val ic : in_channel = <abstr>
# input_line ic;;
- : string = "File \"test.ml\", line 1, characters 0-1:"
# input_line ic;;
- : string = "Error: I/O error: test.ml: No such file or directory"
# input_line ic;;
Exception: End_of_file.
```

- toplevellib.cma (toplevel/toploop.mli)

- memory profiling
  You can override a little ocaml-benchmark to measure the allocation rate of the GC. This gives you a pretty good understanding on the fact you are allocating too much or not.

```
(** Benchmark extension   @author Sylvain Le Gall
 *)

open Benchmark;;
type t =
  {
    benchmark: Benchmark.t;
    memory_used: float;
  }
;;

let gc_wrap f x =
 (* Extend sample to add GC stat *)
 let add_gc_stat memory_used samples =
   List.map
     (fun (name, lst) ->
        name,
        List.map
          (fun bt ->
             {
               benchmark = bt;
               memory_used = memory_used;
             }
          )
          lst
     )
     samples
 in
(* Call throughput1 and add GC stat *)
 let () =
   print_string "Cleaning memory before benchmark"; print_newline ();
   Gc.full_major ()
 in
 let allocated_before =
   Gc.allocated_bytes ()
 in
 let samples =
   f x
 in
 let () =
   print_string "Cleaning memory after benchmark"; print_newline ();
   Gc.full_major ()
 in
 let memory_used =
   ((Gc.allocated_bytes ()) -. allocated_before)
 in
   add_gc_stat memory_used samples
;;

let throughput1
     ?min_count ?style
     ?fwidth    ?fdigits
     ?repeat    ?name
     seconds
```

```
.ml.mli:
  rm -f $@
  $(OB) $(basename $@).inferred.mli
  cp _build/$(basename $@).inferred.mli $@
```

13.0.2 ocaml blogs

ygrek
michal
eigenclass
syntax
jambon
Xavier Clerc
Zheng li
xleroy/teaching
alaska
erratique
duther
David Teller
john harisson
Mike Gordon
Robert Keller
alexott
Yoann Padioleau
garrigue
jun
llvm
incubaid
heniz
memcheck
danmey
yutaka
Lindig

Chapter 14

Topics

14.1 First Order Unification

Unification is widely used in automated reasoning, logic programming and programming language type system implementation.

14.1.1 First-order terms

Given a set of *variable symbols* $X = \{x, y, z, \cdots\}$, a set of distinct *constant symbols* $C = \{a, b, c, \cdots\}$ a set of distinct *function symbols* $F = \{f, g, h, \cdots\}$. Term is defined as any expression that can be generated by a finite number of applications of the following rules:

1. Basis: any variable , and also any constant is a term
2. Induction: if $t_1, \cdots, t_k$ are terms then $f(t_1, \cdots, t_k)$ is term for finite $k, 0 < k$.

For brevity, the constant symbols are regarded as function symbols taking zero arguments, the induction rule is relaxed to allow terms with zero arguments , and $a()$ is regarded as syntactically equal to a . Mathematicians fix the arity of a function symbol while typically in syntactic unification problems, a function symbol may have any number of arguments, and possibly may have different number of arguments in different arguments.

First order unification is the syntactic unification of first-order terms, while higher order unification is the unification of higher-order terms. First-order unification is especially widely used in logic programming, programming language type system design, especially in type inferencing algorithms based on the Hindley-Milner type system, and automated reasoning. Higher-order unification is also widely used in proof assistants, for example Isabelle and Twelf, and restricted forms of higher-order unification (higher-order pattern unification) are used in some programming language implementations, such as lambdaProlog, as higher-order patterns are expressive, yet their associated unification procedure retains theoretical properties closer to first-order unification. Semantic unification is widely used in SMT solvers and term rewriting algorithms.

It is well known that if two terms have a unfier, they also have a *most general unifier*

14.1.2 Substitution

A substitution is defined as a finite set of mappings from variables to terms where each mapping must be *unique*, because mapping the same variable to two different terms would be ambiguous. A substitution may be applied to a term u and is written $u\{x_0 \to t_0, \cdots, x_k \to t_k\}$, which means *simultaneously* replace every occurrence of each variable x_i in the term u with the term t_i for $0 \leq i \leq k$. E.g. $f(x, a, g(z), y)\{x \to h(a, y), z \to b\} = f(h(a, y), a, g(b), y)$. A unifier U is called a *most general unifer* for L, if $\forall\ U'$ of L, $\exists$ substitution s, $subst(U', L) = subst(s, subst(U, L))$.

14.1.3 Unification in Various areas

Unification in Prolog

- A variable which is uninstantiated-i.e. no previous unifications were performed on it-can be unified with an atom, a term, or another uninstantiated variable, thus effectively becoming its alias. In many modern Prolog dialects and in first-order logic, a variable cannot be unified with a term that contains it; this is the so called occurs check.
- Two atoms can only be unified if they are identical.
- Similarly, a term can be unified with another term if the top function symbols and arities of the terms are identical and if the parameters can be unified simultaneously. Note that this is a recursive behavior.

Unification in HM type inference

- Any type variable unifies with any type expression, and is instantiated to that expression. A specific theory might restrict this rule with an occurs check.
- Two type constants unify only if they are the same type

- Two type constructions unify only if they are applications of the same type constructor and all of their component types recursively unify.

Due to its declarative nature, the order in a sequence of unifications is (usually) unimportant.

14.1.4 Occurs check

If there is ever an attempt to unify a variable x with a term with a function symbol containing x as a strict subterm $x = f(\cdots, x, \cdots)$, x would have to be an infinite term, which contradicts the strict definition of terms that requires a *finite* number of applications of the induction rule. e.g $x = f(x)$ does not represent a strictly valid term.

14.1.5 Unification Examples

Prolog Notation	Unify Substitution	Explaination
f(X)=f(Y)	X → Y	X and Y are aliased
f(g(X),X) = f(Y,a)	X → a, Y → g(a)	
X = f(X)	should fail	enforced by *occurs check*
X=Y,Y=a	X → a , Y → a	

14.1.6 Algorithm

Unification algorithms can either perform occurs checks as soon as a variable has to be unified with a non-variable term or postpone all occurs checks to the end. The first kind check is *inline* and the second is called *post* occurs checks. The second performs

well.

$$G \cup \{t \sim t\} \Rightarrow G \tag{14.1}$$

$$G \cup \{f(s_0, \cdots, s_k) \sim f(t_0, \cdots, t_k)\} \Rightarrow G \cup \{s_0 \sim t_0, \cdots, s_k \sim t_k\} \tag{14.2}$$

$$G \cup \{f(s_0, \cdots, s_k) \sim g(t_0, \cdots, t_m)\} \Rightarrow \bot \; iff \neq g \vee k \neq m \tag{14.3}$$

$$G \cup \{x \sim t\} \Rightarrow Gx \rightarrow t \cup x \sim t if x \in Vars(G) \wedge x \notin Vars(t) \tag{14.4}$$

$$G \cup \{x \sim f(s_0, \cdots, s_k)\} \Rightarrow \bot \; if x \in Vars(f(s_0, \cdots, s_k)) \tag{14.5}$$

The set of variables in a term t is written as $Vars(t)$, and the et of variables in all terms on `LHS` or `RHS` of potential equations in a problem `G` is written as `Vars(G)`. For brevity, constant symbols are regarded as function symbols having zero arguments.

Robinson Algorithm

```
Function robOccursCheck(x,t,delta)
INPUT:
  Variable x, term t, substitution delta
OUTPUT:
  false or true
BEGIN
  let S be a stack, initially containing t
  while (S is non-empty) do
    t := pop(S);
    foreach variable y in t do
      if x = y then
        return false
      if y is bound in delta  then
        push y <* delta onto S
    od
  od
  return true
END
```

```
FUNCTION ROB(s,t)
INPUT:
  Term s and t
OUTPUT:
  substitution or failure
BEGIN
  let S be an empty stack of pairs of terms, initially containing
(s,t)
  let delta be the empty substitution
  while (S is non-empty) do
     (s,t) := pop (S);
     while (s is a variable bound by delta) s := s <* delta
     while (t is a variable bound by detal) t := t <* delta
     if s <> t then
       case(s,t) of
         (x,y) => add x -> y to delta
         (x,u) =>
               if robOccursCheck(x,u,delta)
               then
                 add x -> u to delta
                 apply x -> u to each term in delta
               else failure
         (u,x) =>
               if robOccursCheck(x,u,delta)
               then
                 add x -> u to delta
                 apply x -> u to each term in data
               else failure

         (f(s1,..,sn),f(t1,...,tn)) =>
```

```
                push (s1,t1), ... , (sn,tn) onto S
        end
    od
    return delta
END
```

14.2 LLVM

```
ocamlfind ocamlc llvm.cma llvm_analysis.cma llvm_bitwriter.cma -cc g++ -linkpkg first.cmo -o first.byte
```

This is equivalent to

```
+ ocamlc.opt -cc g++ -o first.byte -verbose llvm.cma llvm_analysis.cma llvm_bitwriter.cma first
```

`-linkpkg` is an option of `ocamlfind`. Link the packages in.

```
  ocaml_lib ~extern:true "llvm";
  ocaml_lib ~extern:true "llvm_analysis";
  ocaml_lib ~extern:true "llvm_bitwriter";
  flag ["link";"ocaml";"g++";] (S[A"-cc"; A"g++"]);
```

`ocaml_lib` will create the tag `use_llvm`.

Build a toplevel

```
ocamlfind ocamlmktop -custom -o olvm unix.cma llvm.cma \
llvm_analysis.cma llvm_bitwriter.cma  llvm_executionengine.cma \
llvm_target.cma llvm_scalar_opts.cma -cc g++ -linkpkg
```