Modular macros

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We propose an OCaml language extension for type-safe compile-time code generation.

1. Macros

Programming often involves a choice between efficiency and abstraction. One on the one hand, using high-level abstractions can lead to an elegant program with suboptimal performance. On the other, optimising for performance often means abandoning reusability and manifest correctness.

As an example, consider the following definition of Printf-style format strings:

```
let rec printk : (a, b). (string expr → b expr) → (a, b) fmt → a
function
  Int → fun s → $(k << string_of_int s >>) >>
  Lit s → k (lift_string s)
  | Cat (l, r) → printk (fun x → printk (fun y → k << $x ^ $y >>) r) l

let sprintf fmt = printk (fun x → x) fmt
```

Here is a second of definition of `printk`, written as a code-generating macro:

```
macro rec printk : type a b. (string expr → b expr) → (a, b) fmt → a
function
  Int → fun k → function
    Int → fun s → $(k << string_of_int s >>) >>
    Lit s → k (lift_string s)
    | Cat (l, r) → printk (fun x → printk (fun y → k (x ^ y)) r) l

let sprintf fmt = printk (fun x → x) fmt
```

This definition of `printk` involves two new expression constructs, borrowed from MetaOCaml. Quoting an expression by placing it between brackets `<< >>` delays its evaluation, turning it into a piece of code that can later be used as part of a larger program. Splicing a quoted expression into a larger piece of code is performed with the `$` operator. The typing is straightforward: if `e` has type `t` then `<<e>>` has type `t expr`; conversely, if `e'` has type `t expr` then `$e'` has type `t`. As in MetaOCaml, quotations allow type-safe programming with open code, but we direct the interested reader to the MetaOCaml literature (e.g. [2]) for the details.

Inspired by Racket [1], we divide the evaluation of programs written using macros into two phases (and sometimes more, but we stick to two here). Expressions are evaluated either at runtime (phase 0) or during compilation (phase 1). In this abstract we use colour to highlight the phase distinction, colouring those expressions black whose evaluation is delayed until phase 0, and leaving those expressions black whose evaluation is delayed until phase 0. Evidently, in the definition of `printk`, only black expressions will remain in the program after macro expansion. There is a family of functions `string_expr, int_expr, and so on`, which turn values into expressions suitable for use at a later phase.

Evaluation phases, macro bindings, quotation and splicing together form a coherent system. Macros (bound with `macro`) can only be used directly in expressions at phase 1, whereas functions (bound with `let`) can only be used directly in expressions at phase 0. Quoting allows references to phase 0 definitions in phase 1 expressions, whilst splicing allows construction of phase 0 expressions using phase 1 definitions.

The same `sprintf` definition can now be used to create a macro:

```
macro sprintf fmt = printk (fun x → x) fmt
```

but it now generates code rather than printing its arguments directly:

```
# sprintf p 3 4
- : string = "(3,4)"
```

The generated code can be inserted into a larger program using the splicing operator:
module Power : sig
  function for a particular exponent.
end

This definition highlights a difference between macros and MetaOCaml. In MetaOCaml, splices are only permitted within a quotation. With macros, splices can occur at the top level of a program, allowing insertion of generated code into a file which is to be evaluated at phase 0.

2. Modular macros

Like other OCaml program elements — values, types, exceptions, and so on — macros belong to modules, and play a full part in the module system: a macro can be referred to by a path, included within another module, hidden by signature ascription, and so on. The combination of macros and modules raises two questions of particular interest: first, what happens when a macro expands to code which includes identifiers hidden by a signature? And second, what is the meaning of a macro passed via a functor argument?

2.1 Macros out of modules: ascription and path closures

An expression inside a quotation can refer to any in-scope identifier that is in scope when a quotation is created need not be available when the expression is evaluated. However, an expression inside a quotation can refer to any in-scope identifier — macros belong to modules, and play a full part in the module system.

Like other OCaml program elements — values, types, exceptions, and so on — macros belong to modules, and play a full part in the module system, having been hidden by the signature: $\text{Power.power} = \text{show_mtimes} 1 \text{M.show} \text{mtimes} 1$

With a naive implementation, calling power would generate code containing references to the square function, which is not in scope outside the Power module, having been hidden by the signature:

module Power : sig
  macro power : int → (int → int) expr
end

How can we ensure that identifiers available in the environment where a quotation was created can be safely used in a different context? There is a clear analogy to the question of how to treat free variables used in local functions, and the issue can be solved using an analogous technique: closures.

A closure in a language with lexical scope consists of the code of a function together with the values of the free variables used by the function. Analogously, a path closure for a macro consists of the definition of the macro along with the set of free identifiers used in the macro definition. A macro exported from a module therefore itself behaves as a module which exports a binding for each identifier used by the macro.

module Power : sig
  module Closure1 :
    val square : int → int
end

macro power : int → (int → int) expr
end

Invoking the macro generates code which refers to elements of the module:

module F_staged(M : MONOID) = struct
  let rec mtimes = function
  | [] → $(M.one)
  | x :: xs → $(Mmul <<x>> << mtimes xs>>)
end

The functor $F$ defines two functions, mtimes and show_mtimes, which use macros and functions from $M$. However, there is an apparent difficulty: in OCaml functor application takes place at runtime (phase 0), which is too late to perform macro expansion.

Once again, there is a known technique which can be generalized to solve the difficulty. A one-parameter functor in regular OCaml can be decomposed into a curried two-parameter functor which accepts static arguments (i.e. the type components) via the first argument and the dynamic arguments (i.e. the value components) via the second. The dynamic arguments may depend on the static arguments, but there are no dependencies in the other direction. Extending this scheme to support macros involves adding the macro components to the static parameter; for example, the functor $F$ may be decomposed as follows:

module F_staged(M_static : sig
  type t
  macro one : t expr
  macro mul : t expr → t expr → t expr
  end
  macro M_dynamic : sig
  val show : M_static.t → string
end)

Each functor argument is applied in a particular phase. For example, an application $F(\text{Int})$ is decomposed into an application $F_staged(\text{Int}\_static)(\text{Int}\_dynamic)$, where the first part of the application takes place during phase 1 and the second part takes place during phase 0.

2.3 Module lifting

Macro definitions are one way to construct functions that can be used during compilation (phase 1). A second source of
compile-time functions comes from importing compiled modules during compilation, making their values available for use in macros. Racket supports cross-phase module lifting using the require-for-syntax construct. Since OCaml does not use explicit require statements we instead use a command-line argument; for example, the following makes the values from phase 0 of the Power module available for use in phase 1 of math.ml:

```
ocamlc -k power.cmo math.ml
```

3. Acknowledgements

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References
