Program Generation for ML Modules (Short Paper)

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Abstract
Program generation has been successful in various domains which need high performance and high productivity. Yet, programming-language supports for program generation need further improvement. An important omission is the functionality of generating modules in a type safe way. Inoue et al. have addressed this issue in 2016, but investigated only a few examples. We propose a language as an extension of (a small subset of) MetaOCaml in which one can manipulate and generate code of a module, and implement it based on a simple translation to MetaOCaml. We show that our language solves the performance problem in functor applications pointed out by Inoue et al., and that it provides a suitable basis for writing code generators for modules.

CCS Concepts  
• Software and its engineering  
• General programming languages  
• Theory of computation  
• Type theory;

Keywords  
Program Generation, Modules, Type Safety, Program Transformation

ACM Reference Format:  

1 Introduction
Multi-stage programming (MSP) is an attractive way to generate efficient code tailored to specific hardware, environment, or run-time parameters. After a number of studies for developing languages and systems for multi-stage programming (Scheme’s quasi quotation, hygienic macro, Template Haskell etc.), research on type systems for MSP has lead to full-blown programming languages for MSP: MetaOCaml [5, 12] and Scala Lightweight Modular Staging (LMS) [10]. In these languages, type safety of code generators has stronger implication than one would have expected: it subsumes the type safety of all generated code regardless of run-time parameters. Thus, these languages provide a solid basis for writing safe (or relatively safer) code generators. Recent successful examples include query engines [7], stream fusion [6] and generic programming [15].

Sticking to type safety sometimes leads to rather restricted expressivity of the language. One might want to generate not only code of expressions, but also code of types, declarations, and other syntactic objects such as modules, all of which have been considered difficult under statically typed MSP languages. In particular, guaranteeing type safety of generated code against types which do not exist at compile time would be difficult. Modules in ML-like languages involve declaration of types and values, hence, type safety for programs which generate (code of) a module is also challenging.

Inoue et al. [4] proposed the shift of MSP research from term generation to module generation. They have investigated the efficiency problem of indirect accesses in ML-style modules, and shown that the problem may be solved in a hypothetical extension with module generation. They also showed that their solution can be converted to a program written in the existing MetaOCaml, and at the end of the paper, they have questioned whether there exist compelling examples which really need such an extension.

In this paper, we investigate the same problem as theirs, and give a solution from a different angle. Specifically, we propose a lightweight extension of (a subset of) MetaOCaml where we can naturally and smoothly express manipulation of the code of a module, including splicing module components in another expression. This extension is arguably useful to express solutions for several inefficiency problems caused by module abstractions. Our extension is lightweight in the sense that we can translate away the extended functionality into the existing MetaOCaml.

The rest of this paper is organized as follows: §2 introduces the motivating example and the problem to be addressed in this paper, and the earlier work on the same problem. We show our solution to the motivating example in §3 and then

1Strictly speaking, type safety in these languages is guaranteed only for a certain sublanguage of these languages, typically a language without computational effects.
The module system in ML-like languages provides a powerful abstraction to structure a large program. It has been an active target of scientific research, and has found many interesting extensions with compelling applications such as first-class modules, modular implicits [14], and tagless final embedding [1]. On the practical side, the MirageOS\(^2\) is one of the most successful library operating systems which uses OCaml modules to implement operating system drivers.

A big problem of module abstraction is performance penalty in functor\(^3\) applications. Inoue et al. addressed this problem and gave a solution for a few examples, using program generation techniques. We shall illustrate the problem and their solutions below using the same example as theirs.

Inoue et al.’s leading example is a module which represents the set type for\(^4\) module types for modules\(^5\). A module of type \(\text{EQ}\) consists of a concrete type \(t\) and an implementation of \(\text{eq}\) whose type is \(t \rightarrow t \rightarrow \text{bool}\). A module of type \(\text{SET}\) consists of two types \(\text{elt}\) (for elements) and \(\text{set}\) (for the set of elements), and a function \(\text{member}\) (for the membership function). \(\text{MakeSet}\) is a functor which is given a module of type \(\text{EQ}\) (which specifies the type of elements of the set) and returns a module of type \(\text{SET}\). What \(\text{MakeSet}\) actually does is to implement the finite set as a list, and provides an implementation of the membership function. The last four lines apply the functor \(\text{MakeSet}\) to a module of type \(\text{EQ}\), which has \(\text{int}\) and the equality function\(^6\) over \(\text{int}\) as its components. By this application we obtain a concrete module of type \(\text{SET}\) whose element is of type \(\text{int}\).

Although the above usage of modules provides an elegant, modular framework for introducing sets, it has a serious performance penalty compared with a monolithic implementation of the module \(\text{IntSet}\) which does not use functors. The problem of the code in Fig. 1 lies in the phrase \(\text{Eq.eq}\) \(\text{elt}\) \(\text{elt}'\) where \(\text{Eq.eq}\) is a reference to the function \((=)\) (an indirect access to the compiled code of the function). Every time this phrase is evaluated, the actual content of \(\text{Eq.eq}\) is dereferenced, and this overhead is not negligible if the module component is dereferenced repeatedly. Inoue et al. have observed that the abstraction overhead can be eliminated by MetaML-style program generation for modules.

Fig. 2 shows their solution for the above problem written in a hypothetical extension of MetaOCaml. Since this code uses MetaOCaml, an extension of OCaml with the functionality of quasi-quotation for terms, we explain its basic operators first. \(<e>\) is the code for the term \(e\), for instance \(<3 + 5>\) is a code for the term \(3 + 5\). The term \((-e)\) is used for splicing. For instance, the code \(<2 + (3 + 5) * 4>\) will evaluate to \(<2 + (3 + 5) * 4>\) if the value of \(x\) is \(<3 + 5>\). The type of \(<3 + 5>\) is \(\text{int code}\), not \(\text{int}\). Although not included in our example,

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\(^2\)https://mirage.io

\(^3\)In ML, a functor is a function from modules to a module.

\(^4\)In ML, the type of modules is called a signature.

\(^5\)In OCaml the notation \((=)\) represents the prefix version of the function =, thus \((=) x y\) is equivalent to \(x = y\).

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\section{Motivating Example}

The module system in ML-like languages provides a powerful abstraction to structure a large program. It has been an active target of scientific research, and has found many interesting extensions with compelling applications such as first-class modules, modular implicits [14], and tagless final embedding [1]. On the practical side, the MirageOS\(^2\) is one of the most successful library operating systems which uses OCaml modules to implement operating system drivers.

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the term \texttt{run} \texttt{e} is used for compiling and running code. For instance, the code \texttt{run \(3 + 5\)} will evaluate to 6. The type of \texttt{run \(3 + 5\)} is \texttt{int}.

The program in Fig. 2 uses these annotations in two ways. The first, traditional way is the usage in \texttt{let eq (x : int code) y = \(<(\neg x) = (\neg y)>\)} where the annotations are used for terms. For instance, the term \texttt{eq \(<2+3\) \(<3+1\>\)} evaluates to the code value \(<(2+3) = (3+1)\>\). The second, untraditional way is the usage in \texttt{module MakeSetGen (Eq: EQ\_CODE) = \(<\text{ struct ... end}\)} where a concrete module appears inside brackets, namely we use code of a module. Since the current implementation of MetaOCaml does not allow code of a module, the above program can only be written in a hypothetical extension. If there were such an extended language, the program in Fig. 2 can solve the problem of indirect access; the functor \texttt{MakeSetGen} receives an argument of type \texttt{EQ\_CODE}, which is intuitively a code value of a module of type \texttt{EQ}, and returns a code value of a module of which the actual equality function (provided by the argument) is spliced at the place of \texttt{Eq.eq} in the code \(<(\neg x) = (\neg y)\). This splicing is done at program-generation time, and the result of program generation is a code value of a module. By running it, we obtain a module that does not suffer from the performance problem.

Inoue et al.’s paper left us the following two questions: (1) They found another solution obtained by translating the above program to a program in the standard MetaOCaml. They then asked if their hypothetical extension is really needed in realistic (and compelling) applications. (2) The program in Fig. 2 has a typing problem which is not fully settled in their paper. Is there any type-sound language to support module generation? The present paper tries to answer these two questions.

### 3 Our Solution

We propose an extension of (core) MetaOCaml which allows generation and manipulation of code of a module. Our extension is intentionally very small so that MetaOCaml programmers can easily understand it. Fig. 3 shows a solution to the leading example in the previous section written in our language, which we shall explain below.

The solution uses first-class modules (standard in OCaml and MetaOCaml) plus three new operators \$\$, \% and \texttt{run\_module} for manipulating code of a module. First-class modules are standard since OCaml 3.12, which allow manipulation of modules as first-class values that can be passed to and returned from functions. A module \(M\) is turned to an expression by \texttt{(module m : M)} where \(M\) is the type of \(m\), and the expression \(e\) is turned back to a module by \texttt{(val e)}. As modules are turned to expressions, the functor \texttt{MakeSet} in Fig. 1 can be represented by the function \texttt{makeSet}.

The $ operator converts code of a module to a module of code. Consider the program phrase $\texttt{seq.t}$. Since \texttt{eq} has type $(\texttt{module EQ})$ \texttt{code}$,^{6}$ it refers to code of a module of type \texttt{EQ}. It is not possible to extract its components such as the type \texttt{t} and the value \texttt{eq}, since MetaOCaml does not allow destruction of code values in any way. Hence we need the new operator $ to covert \texttt{eq} to a module of code, namely, a module whose value component is code. Then we can extract each component by simply applying the dot notation to \texttt{seq}, and \texttt{seq.eq} refers to the \texttt{eq} component. (Note that \texttt{seq.eq} is parsed to $(\texttt{seq}.\texttt{eq})$.)

We think that the existence of the $ operator in our language is harmless by the following reasons. First, we have concrete semantics for our language, via the translation to core MetaOCaml. Second, the $ operator already exists in our intended semantics. Let us assume that our target language does not have any computational effects (which is in fact true in our current setting), and we interpret the type $A$ \texttt{code}$ as \texttt{unit} \rightarrow A$, which should be one possible interpretation. Then the type $(A \times B)$ \texttt{code}$ is isomorphic to the type $(A \texttt{code}) \times (B \texttt{code})$, and similarly the type $(x : A; y : B)$ \texttt{code}$ is isomorphic to the type $(x : A \texttt{code}; y : B \texttt{code})$. Since modules in MetaOCaml are internally represented as records, it is natural to expect that the type \texttt{code} of a module is isomorphic to the type $\text{for a module of code}$, namely, a module whose components have code types.$^{5}$ The \$ operator is a syntactic operator for one direction of this “isomorphism”. Admittedly, this naïve argument is insufficient as a mathematical justification, and we think that it is sufficient as an intuitive guidance for our language design.

The % operator is the typed version of Cross-Stage Persistence (CSP). MetaOCaml allows a present-stage value such as $\texttt{fun x \rightarrow x * x}$ to be embedded in code (a future-stage

\[\begin{align*}
\text{let makeSet (type a)} \\
(\text{eq: (module EQ with type t = a) code}) = \\
<\text{(module struct}} \\
\text{type elt = \%($\text{eq.t}$) list} \\
\text{let rec member elt = function} \\
| [] \rightarrow \text{false} \\
| \text{elt' :: set' \rightarrow} \\
\quad \neg(\text{seq.eq}) \text{elt elt'} \\
| \text{|| member elt set'} \\
\text{end : SET with type elt = a) > module IntSet = run_module} \\
(\text{val makeSet} <\text{(module struct}} \\
\text{type t = int} \\
\text{let eq = (\neg)} \\
\text{end: EQ with type t = int}>)
\end{align*}\]

Figure 3. Our Solution for MakeSet

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6We ignore the sharing constraint “with type t = a” in this discussion, since it is not quite relevant.
7This holds if we ignore dependency between components of modules.
8Similarly we can consider “isomorphism” between code of X and code of Y: X = tuple, list, and other similar data structures.
value), by which the value goes across the stage boundary. (Note the difference from splicing which allows us to embed code such as `<fun x → x * x>` in another code.) Taha and Nieelsen [13] used the notation `%e` for CSPing the value of `e`, and we borrow it to denote CSP for types. The phrase `type set = %<seq.t> list` in Fig. 3 means that, if `seq.t` evaluates to `int * bool` list, the type set is `int * bool` list. If the `%` operator is omitted, then the phrase `eq.t` is not evaluated since it appears inside brackets. The `%` operator lets the phrase be evaluated and then replaced by the result of evaluation. The novelty of our `%` operator is to allow CSP for types. Note that we have no other operators that manipulate types, in particular, we do not allow code of types in our language. This is crucial in our design which differentiate our language from Inoue et al.’s.

The `run_module` operator runs code of a module and it is similar to the `run` primitive in MetaOCaml, which works for code of a term.

We claim that the program in Fig. 3 is natural and easy to write and understand. First it perfectly fits the MetaML-style program generation framework. In this framework, given an ordinary program, one only has to add annotations such as `<...>` and `~(...)` to appropriate places in the program, based on binding-time analysis (the process is called staging). In our language, one need to add `%` and `$` in addition to these annotations, but still the resulting program after staging is quite similar to the original program.

Besides the basics of MetaOCaml and ML-style modules, all we need to understand our language are the first-class modules and the new operators `$`, `%` and `run_module`. But as the program in Fig. 3 shows, they are really lightweight. The first one simply converts code of a module to a code of module and the second embeds the type dereferenced by a type component of a module and it is similar to the implicit CSP for values in MetaOCaml. The last one is similar to the `run` primitive.

4 Our Language

Our language is an extension of core MetaOCaml which does not include computational effects such as references and exceptions, but includes first-class modules. We omit the explanation of the standard part; see Harper and Lillibridge [3] and Leroy [8] for module calculi.

Fig. 5 defines the syntax of modules (`m`), module components (`c`), simple expressions (`e`), and general expressions (`g`). We distinguish simple expressions from general expressions to avoid nested modules (a module which contains another module as its component) for simplicity. Simple expressions are standard lambda expressions such as variables and primitive operations `p(e, · · · , e)`, selection for module component `x.x`, expressions for staging `<e>`, `!e` and `~e`, or the new expression `$x.x$` introduced in this work. A general expression may contain a module expression and related expressions. The expression `module m : M` is an expression converted from a module `m` where the type of module `M` is made explicit. The expression `<g>` may be code of a module. We also have an expression `run_module g` for running a module. The example in Fig. 3 can be written as a general expression in this syntax.

The type system of our language is based on Davies’ λO [2] which allows manipulation of open code and no stage errors may happen for typeable terms. Although λO does not prevent open code from being executed (the scope extrusion problem [9, 13]), the situation is not worse than the current MetaOCaml and Scala LMS. It is left for future work to make our language to be scope safe.

For simplicity we restrict the number of stages to two where the stage 0 is the present stage and the stage 1 is the next (future) stage. Each typing judgment is associated with its stage such as `$E ⊢_i e : σ$ for $i = 0$, 1. Due to lack of space we cannot list the typing rules. Instead, we show a few examples of typing rules and a typing derivation. Let the types of Fig. 4 be $M_1$ (left) and $M_2$ (right). Then $M_1$ is the type for code of a module and $M_2$ is the type for a module consisting of a type and code values. Then, the `$` operator has the following typing rule where the superscript 0 indicates the stage:

\[
(x : M_1)_0 \in E \quad E \vdash^0 \$x : M_2
\]

Namely, the `$` operator merely converts a variable\(^{10}\) of type $M_1$ to an expression of type $M_2$. Using the above rule, we

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\(^{10}\)We have restricted the syntax so that the argument of `$` must be a variable.
can derive the type for each component of the module, for instance, the type of the component v2 is derived as follows:

\[ E \vdash^0 \sigma :: \star \]
\[ E \vdash^1 \%\sigma :: \star \]

where \( \star \) is the (unique) kind, namely, \( \sigma :: \star \) means \( \sigma \) is a well-formed type. Using this rule, we can derive well-formedness of a type component as follows:

\[ E \vdash^0 \% M_2 \]
\[ E \vdash^1 \% (\%M_2) :: \star \]

Since the last judgment of the above derivation has the type component as follows:

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The translation is not quite correct for modules whose components have dependency. Consider the following code snippet:

```
let m = <(module struct
    let v1 = 10 + 20 + 30
    let v2 = v1 + v1
end) >
```

By translating this program, we would get:

```
let m = (module struct
    let v1 = <10 + 20 + 30 >
    let v2 = <let v1 = ~(v1) in
           v1 + v1 >
end)
```

but then v2 has a free reference to v1 at the stage 1. To solve the problem, we refine the translation by inserting let expressions in the following way:

```
let m = (module struct
    let v1 = <10 + 20 + 30 >
    let v2 = <let v1 = ~(v1) in
           v1 + v1 >
end)
```

Now v2 has no free references and can be used in other code by splicing. Thus, we have resolved dependency via let-insertion. The above strategy fixes the problem of the naïve translation, yet it has a problem: generated code may become excessively large for some cases. It is our ongoing work to improve the size of generated code, which will be reported elsewhere.

We have implemented our language using the above translation. The performance of our implementation is shown in the next section.

### 6 Experiments and Performance

We have conducted an experiment for micro benchmarks using the implementation of our language. The case study shown in this section was taken from Suzuki et al.'s normalizer for language-integrated query (SQL-query language integrated with a functional language) [11]. They used the tagless-final embedding for domain-specific languages, and expressed each normalization step as a functor, and used a recursive functor to iterate normalization steps. Thus, functor applications are repeatedly used in their normalizer and their overhead is not negligible. We have implemented a simplified normalizer in our language, and measured its performance. Here we show its core part, and the complete code is shown in the first author’s page.

```ocaml
module type S = sig
  type int_t
  type obs_t
  val int : int -> int_t
  val add : int_t -> int_t -> int_t
...
end
let suppressAddZeroPE =
  fun (m: (module S with ..) code) ->
    <(module struct
      type int_t = $m.int_t * bool
      type obs_t = int
      let int = fun n1 ->
               (~($m.int) n1 , n1 = 0)
      let add = fun n1 ->
               fun n2 ->
               match (n1 , n2) with
               | (n1 , b1) , (n2 , b2) ->
                   if (b1 && b2) then
                     (~($m.int) 0 , true)
                   else
                     ~($m.add) n1 n2
               ...
    end: S with type obs_t = int)>

let rec fix depth m =
  if depth <= 0 then m
  else fix (depth - 1)
      (suppressAddZeroPE m)
```

The function suppressAddZeroPE realizes a program transformation for the zero-suppression optimization such as \(x + 0\) to \(x\). It is given an expression of type \((\text{module } S)\) code (which specifies the signature of the object language) and returns code of a module after performing the optimization. We apply the transformation iteratively to obtain the fully optimized form, hence we use a recursive function in the code. The number of iteration is given by the parameter depth. Note that this kind of control is easily implemented in our language, while it may be difficult for a fully-automatic static analyzer which would try to infinitely inline a module (or never inline it).

Our translator turns the above code into a MetaOCaml program (a code generator). Then we run it in MetaOCaml to obtain an OCaml program, and by executing it we obtain the final result. We have measured the execution time (the last step) of the above implementation, and that of a naïve implementation of the same program transformation which does not use code generation for modules. (We do not include the time for code generation in measurement.) The result is shown in Table 1 where the unit is second, and we run it on MacOS X 10.11.2, Memory 8GB, BER MetaOCaml N104 (OCaml 4.04.0), byte code compiler.

<table>
<thead>
<tr>
<th>depth</th>
<th>Naïve</th>
<th>Ours</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>0.0501</td>
<td>0.0064</td>
</tr>
<tr>
<td>4</td>
<td>0.0933</td>
<td>0.0108</td>
</tr>
<tr>
<td>6</td>
<td>0.1284</td>
<td>0.0159</td>
</tr>
<tr>
<td>8</td>
<td>0.1692</td>
<td>0.0174</td>
</tr>
<tr>
<td>10</td>
<td>0.2167</td>
<td>0.0232</td>
</tr>
</tbody>
</table>

The first row shows the value of the depth parameter (the number of iterations), and the second and the third show the performance of the naïve one and that of our implementation.

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We have proposed an extension of (core) MetaOCaml where
one can write program generators that can manipulate and
generate code of a module in the type-safe way. We believe
that our extension naturally fits the style of MetaML-like
multi-stage programming, thus allowing one to write module
manipulation easily and naturally. We have shown that the
MakeSet example and a simplified example of Suzuki et al.'s
tagless-final program transformation are expressible in our
language, and that the performance of generated modules is
improved.

We briefly state future work. First, we put several restric-
tions to our language and eliminating these restrictions will
be an interesting research topic. For instance, we allow only
two stages, which means that we cannot write a code gen-
erator which generates yet another code generator. We also
do not allow nested modules in the source language. Sec-
ond, we sticked to the MetaML-style type-safe approach to
program generation, and did not allow run-time generation
and manipulation of code of types. Several authors includ-
ing Inoue et al.[4] have already argued that allowing it may
further improve expressivity of generators and performance of
generated code. It is left for future investigation.

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