Metaprogramming with Macros

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The essence of macros

Macros are programmable code transformers

Example

```
(defmacro let args
  (cons
   (cons 'lambda
         (cons (map car (car args))
               (cdr args)))
   (map cadr (car args))))
```

Here we declare *let*, a Lisp function. Since it is declared as a macro, it's automatically plugged into the Lisp evaluator.

We can say that the evaluator installs a macro transformer implemented by the body of the macro into a slot named *let*.

Example

```
(defmacro let args
  (cons
   (cons 'lambda
         (cons (map car (car args))
               (cdr args)))
   (map cadr (car args))))

(let ((x 40) (y 2)) (print (+ x y)))
```

When the evaluator encounters a form that is an application of *let*, it yields control to the corresponding macro transformer, passing it the tail of the form.

Example

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(defmacro let args
  (cons
   (cons 'lambda
         (cons (map car (car args))
               (cdr args)))
   (map cadr (car args))))

(let ((x 40) (y 2)) (print (+ x y)))

((lambda (x y) (print (+ x y))) (40 2))
```

The macro transformer takes the forms passed by the evaluator, and computes a resulting form (this is called *macro expansion*).

After that the evaluator proceeds with the form produced by macro expansion. The value of the new form is returned as the value of the original form.

Use cases

- Deeply embedded DSLs (database access, testing)
- Optimization (programmable inlining, fusion)
- Analysis (integrated proof-checker)
- Effects (effect containment and propagation)

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- Optimization (programmable inlining, fusion)
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- Effects (effect containment and propagation)

Actually these use cases come from our experience with macros in Scala, which we developed this year.

All the aforementioned scenarios are either already supported by Scala macros or will be supported in vNext!

Setting the stage

In this talk we'll be looking into macros for compiled programming languages, i.e. macros as extensions to compilers.

Different combinations of junction points (function applications, code annotations, custom grammar rules, etc) and tightness of the integration (parser, namer, typer, etc) produce different challenges.

Today we're going to focus on a particular challenge in macrology: tackling syntactic abstractions. These slides discuss the ways to represent, analyze and generate code.

Outline

Revisiting *let*

```
(defmacro let args
  (cons
   (cons 'lambda
         (cons (map car (car args))
               (cdr args)))
   (map cadr (car args))))

(let ((x 40) (y 2)) (print (+ x y)))

((lambda (x y) (print (+ x y))) (40 2))
```

The code here is quite impenetrable. Without color coding it would be hard to understand the supposed structure of input and output.

Improving *let*

```
(defmacro let (decls body)
  `((lambda ,(map car decls) ,body) ,@(map cadr decls)))

(let ((x 40) (y 2)) (print (+ x y)))

((lambda (x y) (print (+ x y))) (40 2))
```

This snippet represents a shift towards declarativeness. Arguments of let are now pattern-matched in the macro signature. The shape of resulting form is encoded in a template.

Backquote, the template-building operator, is called *quasiquote*. By default code inside the quasiquote is not evaluated and is copied into the output verbatim (note that we no longer have to quote `lambda`).

Comma and comma-at are called *unquote* operators. They temporarily cancel the effect of quasiquoting, demarcating "holes" in templates.

Pushing the envelope

```
(define-syntax let
  (syntax-rules ()
    ((let ((name expr) ...) body ...)
     ((lambda (name ...) body ...) expr ...))))

(let ((x 40) (y 2)) (print (+ x y)))

((lambda (x y) (print (+ x y))) (40 2))
```

This amazing notation comes from Scheme and is dubbed *macro by example* (MBE). With the ellipsis operator it naturally captures repetitions in the input form and translates them into the output.

`syntax-rules` is a shortcut that eliminates the syntactic overhead of quasiquoting at a cost of supporting unquotes only for variables bound in a match. However MBE per se doesn't prevent arbitrary unquoting. `syntax-case`, a low-level implementation of MBE, supports all the functionality provided by quasiquotes.

Typechecking quasiquotes: strict

```
-| fun plus x = <fn y => ~x + y>;
val plus = Fn : <int> -> <int -> int>

-| val w = <fn y => ~(plus <y>)>;
val w = <(fn a => (fn b => a %+ b))> : <int -> int -> int>
```

MetaML is a statically typechecked language with quasiquotes. Its typesystem guarantees that if a meta-program is well-typed then all possibly produced object-programs will be well-typed as well.

Unlike in lisps, quasiquotes in MetaML cannot have unbound free variables, which effectively means that meta-programs cannot introduce new bindings (e.g. it's not possible to express *let* as a macro). This is a sacrifice to the altar of strong type safety guarantees.

Typechecking quasiquotes: strict

```
mac (let seq x = e1 in e2 end) =
   $(let val x = ?e1 in ?e2 end)
```

MacroML is a macro system built on top of MetaML. It inherits typing discipline of its parents, but introduces a clever way to create certain bindings without compomising type safety.

In the example above `$` stands for "delay" and `?` stands for "force". Macro `seq` implements (wtf does it implement?).

To typecheck the fluent binding to `x`, MacroML tracks the name of the bindee parameter in the type of the body parameters such as `ei`.

Typechecking quasiquotes: lenient

```
macro using(name, expr, body) {
  <[
    def $name = $expr;
    try { $body } finally { $name.Dispose() }
  ]>
}

using(db, Database("localhost"), db.LoadData())
```

Nemerle allows quasiquotes to contain free variables, it even permits splicing into binding positions (like in `def $name = $expr`).

This makes it impossible to typecheck quasiquotes at their declaration site, but the result of macro expansion that uses such quasiquotes is typechecked anyways, so errors are still caught at compile-time.

Relaxed typechecking rules like in Nemerle have proven to be essential for a practical metaprogramming system.

Typechecking quasiquotes: the best of both worlds

The ideal typechecking discipline would allow programmers to freely mix typed and untyped quasiquotes.

In F# both quasiquoting (`<@...@>`) and splicing (`%`) operators have untyped versions (`<@@...@@>` and `%%` respectively).

Unfortunately they are only untyped in a sense that untyped splicing allows `Expr` instead of `Expr<'a>`. Untyped quasiquotes do perform typechecking using type inference to determine type bounds for holes, which are verified at runtime. As a result, `<@@ (%%x).Name @@>` won't typecheck, whereas `<@@ (%%x).ToString() @@>` will fail at runtime.

In a 15 year old paper, Mark Shields, Tim Sheard and Simon Peyton Jones propose a type system that can defer type inference to runtime. Their findings can probably be adapted to the task at hand.

Outline

Motivating example

```
(defmacro or (x y)
  `(let ((t ,x))
     (if t t ,y)))

(or 42 "strange")
```

One of the appealing features of macros is their ability to control evaluation order. For example, it's possible to write a short-circuiting `or` macro.

In this example, however, I would like to highlight the temporary variable that had to be introduced in order to prevent double evaluation.

The implementation is very simple. Yet it has two mistakes that can lead to subtle bugs. Let's take a closer look.

Mistake #1

```
(defmacro or (x y)
  `(let ((t ,x))
     (if t t ,y)))

(let ((t #t))
  (or #f t))
```

The first bug manifests itself when there's a variable named `t` at the call site, and it's used in the second argument of the `or` macro. We can say that a variable introduced during macro expansion shadows a binding from the macro use site.

Hygiene

Hygiene Condition for Macro Expansion.

Generated identifiers that become binding instances in the completely expanded program must only bind variables that are generated at the same transcription step.

—Eugene Kohlbecker
PhD Thesis

Breaking hygiene

```
(define-syntax forever
  (syntax-rules ()
    ((forever body ...)
     (call/cc (lambda (abort)
                (let loop () body ... (loop)))))))

(forever (print 4) (print 2) (abort))
```

At times, though, it's useful to break hygiene and meld lexical contexts from different transcription steps.

We've seen one such example, when studying the `using` macro written in Nemerle. Here's another one that features a DSL for writing loops. Whenever we're inside a loop introduced by our DSL, we should be able to use `abort` to quit.

For this snippet to work, the binding created by `forever` must be non-hygienic, since `abort` is supposed to be accessible from `body`.

Mistake #2

```
(defmacro or (x y)
  `(let ((t ,x))
     (if t t ,y)))

(let ((let print))
  (or #f #t))
```

The second bug is, in a sense, dual to the first one. Previously, a binding introduced by a macro interfered with a binding at the macro use site. Now a binding introduced at the call site destroys a binding at the macro definition site.

Referential transparency

Macros defined in the high-level specification language are referentially transparent in the sense that a macro-introduced identifier refers to the binding lexically visible where the macro definition appears rather than to the top-level binding or to the binding visible where the macro call appears.

—Kent Dybvig et al.
Syntactic Abstractions in Scheme

State of the art

- Typical approaches to fixing the aforementioned problems are alpha-renaming and gensymming (from `gensym`).
- There are frameworks that provide hygiene and referential transparency automatically. Scheme is especially famous for pushing this research.
- These automatic frameworks usually have enough flexibility to allow for the use cases that require non-hygienic bindings.

Outline

printf

```
printf :: String -> Expr
printf s = gen (parse s) [| "" |]

gen :: [Format] -> Expr -> Expr
gen [] x = x
gen (D : xs) x = [| \n -> $(gen xs [| $x ++ show n |]) |]
gen (S : xs) x = [| \s -> $(gen xs [| $x ++ s |]) |]
gen (L s : xs) x = gen xs [| $x ++ $(lift s) |]

$(printf "Error: %s on line %d") msg line

(\s0 -> \n1 ->
  "Error: " ++ s0 ++ " on line " ++ show n1)
```

In Template Haskell macros don't need a special declaration form (unlike in Lisp, they are first-class), at a cost of requiring an explicit trigger for macro expansion.

printf

```
printf :: String -> Expr
printf s = gen (parse s) [| "" |]

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(\s0 -> \n1 ->
  "Error: " ++ s0 ++ " on line " ++ show n1)
```

Template Haskell has the notion of quasiquoting and unquoting (called *splicing* in authors' terms). Splicing outside quasiquotes (or an explicit call to `splice`) triggers macro expansion.

printf

```
printf :: String -> Expr
printf s = gen (parse s) [| "" |]

gen :: [Format] -> Expr -> Expr
gen [] x = x
gen (D : xs) x = [| \n -> $(gen xs [| $x ++ show n |]) |]
gen (S : xs) x = [| \s -> $(gen xs [| $x ++ s |]) |]
gen (L s : xs) x = gen xs [| $x ++ $(lift s) |]

$(printf "Error: %s on line %d") msg line

(\s0 -> \n1 ->
  "Error: " ++ s0 ++ " on line " ++ show n1)
```

Quasiquotes automatically alpha-rename introduced identifiers to ensure hygiene. Template Haskell also solves the referential transparency problem by implementing cross-stage persistence for static symbols.

printf

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printf s = gen (parse s) [| "" |]

gen :: [Format] -> Expr -> Expr
gen [] x = x
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gen (L s : xs) x = gen xs [| $x ++ $(lift s) |]

$(printf "Error: %s on line %d") msg line

(\s0 -> \n1 ->
  "Error: " ++ s0 ++ " on line " ++ show n1)
```

For non-static symbols, general case of cross-stage persistence is undecidable. However if the programmer knows how to reproduce a certain datum at runtime, he implements the `Lift` typeclass and calls `lift`.

Bindings

```
cross2a :: Expr -> Expr -> Expr
cross2a f g = [| \(x,y) -> ($f x, $g y) |]

cross2c :: Expr -> Expr -> Expr
cross2c f g =
  do { x <- gensym "x"
     ; y <- gensym "y"
     ; ft <- f
     ; gt <- g
     ; return (Lam [Ptup [Pvar x, Pvar y]]
                   (Tup  [App ft (Var x)
                         ,App gt (Var y)]))
     }
```

At the low level of Template Haskell lie plain ADTs that represent program fragments. Quotation monad can make low-level ASTs hygienic (but also may ignore hygiene). High level of syntactic abstraction is represented by quasiquotes, which translate to the hygienic quotation monad.

Typechecking

- Quasiquotes are expanded in *re*namer (later in the pipeline bindings are frozen), and they must not contain unbound free symbols.
- Every quotation is then sanity-checked in typer to reject nonsense like `[| "hello" && True |]`. Having passed the check, quotations pass the type check and are assigned the `Q Exp` type.
- After quotations are typechecked, macros are expanded, and the compilation goes on just as if the programmer had written the expanded program in the first place.

A retrospective write-up from TH developers indicates that:

- There is a real need for strongly typed quotes `TExp a` (for more robustness).
- Normal quotes shouldn't be typechecked at all (to allow for more flexibility, with an important particular case of splicing into binding positions).

Outline

Overview

```
macro identity(e) {
  <[ def f(x) { x }; f($e) ]>
}

identity(f(1))

{
  def f_42(x_43) { x_43 };
  f_42(f(1))
}
```

Macros in Nemerle are Lisp-like in a sense that they are second-class, but are transparent to the user.

Unlike Lisp, Nemerle is statically typed and has rich syntax. Macros provide extension points to both of these aspects. They can change syntax and control typechecking (alas, outside the scope of this talk).

Overview

```
macro identity(e) {
  <[ def f(x) { x }; f($e) ]>
}

identity(f(1))

{
  def f_42(x_43) { x_43 };
  f_42(f(1))
}
```

Nemerle has quasiquotes and unquotes (called *splices* like in Template Haskell). They provide automatic alpha-renaming to preserve hygiene. Cross-stage persistence is only supported for static symbols.

Typechecking

```
cache(e: Expr): Expr * Expr {
  | <[ $o.$m ]> => (<[ def tmp = $o ]>, <[ tmp.$m ]>)
  | <[ $o[$i] ]> => (<[ def (tmp1, tmp2) = ($o, $i) ]>,
                     <[ tmp1[tmp2] ]>)
  | _ => (<[ () ]>, e)
}
```

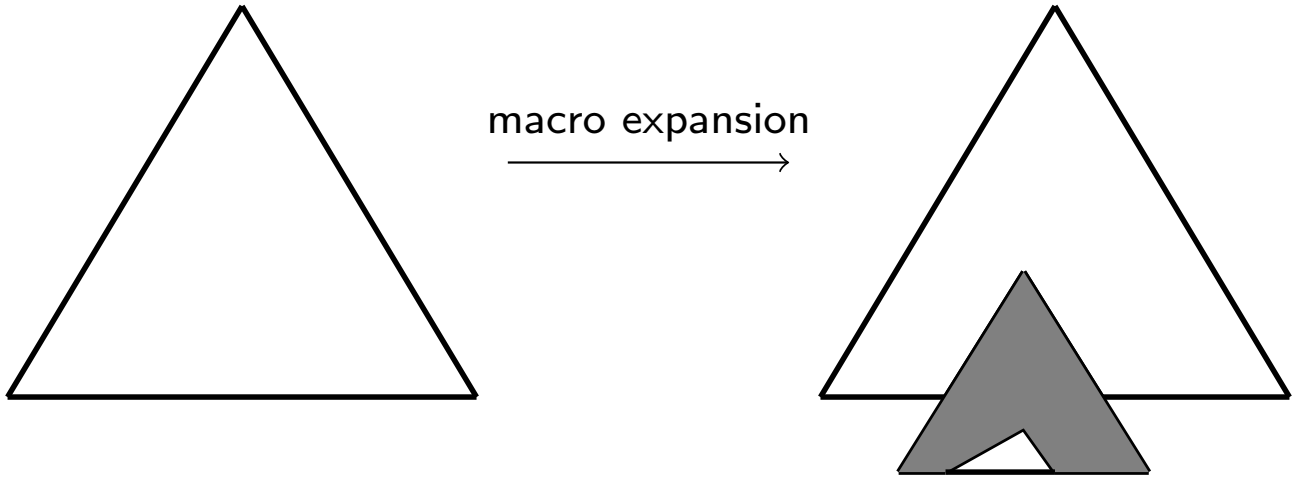
Designers of Nemerle were aware of the "too strongly typed" problem of quasiquotes in Template Haskell, so they decided not to typecheck them before they are used in macro expansions.

In fact they went even further - quasiquotes are not only untyped, but they also don't get their free variables resolved until being used (with an exception for references to static symbols). This defies one of the aspects of referential transparency, but in return provides flexibility, e.g. splicing into binding positions at zero implementation cost.

Hygiene

Nemerle assigns colors to every identifier in the program.

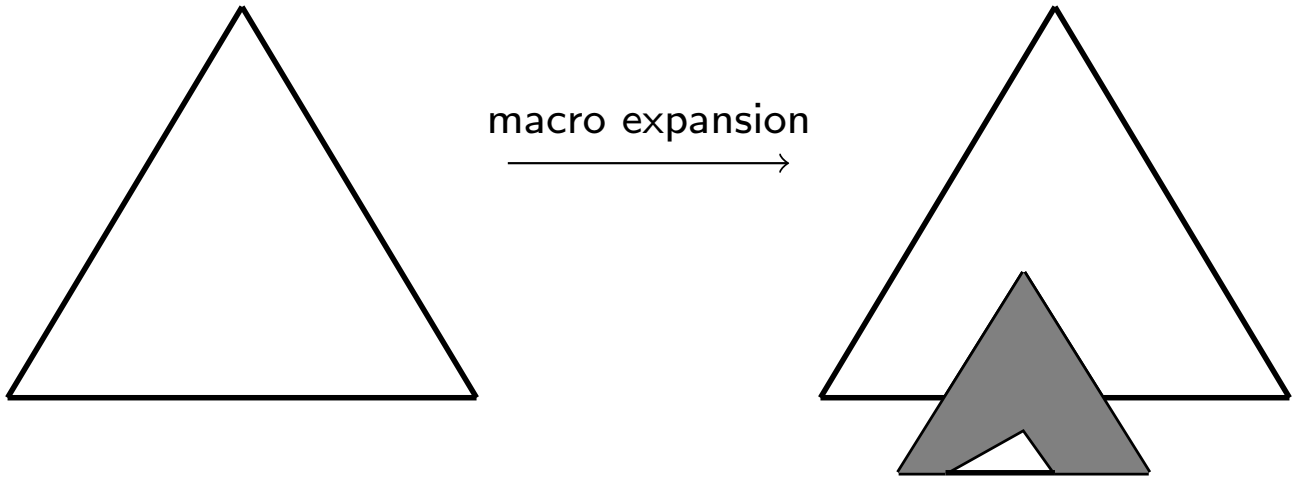
Hygiene



Given `u`, the color of the use site, and `m`, a fresh color assigned to the current macro expansion:

- Most identifiers introduced in that expansion get colored with `m`
- Macro arguments and `$(name: usesite)` splices get colored with `u`
- `$(name: dyn)` splices become polychromatic
- Colors can also be tinkered with manually

Hygiene



After all colors are resolved it is easy to bind identifiers:

- Use refers to the nearest preceding declaration of the matching color (polychromatics match any color, others only match their own)
- Unbound identifiers are looked up in global scope.

Outline

Outline