Metaprogramming with Macros
don't forget to read the remaining papers!

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10 September 2012

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

```
(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.

Setting the stage

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

Combining different junction points (function applications, code annotations, custom grammar rules, etc) and integration capabilities (parser, namer, typer, etc) produces various interesting effects, but unfortunately our time is limited.

Therefore 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 in the small.

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 the 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). Ellipsis operator 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 lower level implementation of MBE, supports all the functionality provided by quasiquotes (we'll study it later).

Typechecking quasiquotes: strict

```
-| fun pow n = <fn x =>
    ~(if n = 0 then <1> else <x * (~(pow (n - 1)) x)>)>;
val pow = fn : int -> <int -> int>

-| val cube = (pow 3);
val cube = <(fn a => x %* x %* x %* 1)> : <int -> int>

-| (run cube) 5;
val it = 125 : int
```

MetaML is a staged language. Programs in MetaML can generate and run programs at runtime, these programs can do the same, and so on.

Quasiquotes here represent templates of the programs to be generated and delineate execution stages.

Due to its specific nature, MetaML requires strong guarantees from the type system. At runtime, if code generation fails because of an error in the meta-program, it's too late to report typechecking errors.

Typechecking quasiquotes: strict

```
-| fun pow n = <fn x =>
    ~(if n = 0 then <1> else <x * (~(pow (n - 1)) x)>)>;
val pow = fn : int -> <int -> int>

-| val cube = (pow 3);
val cube = <(fn a => x %* x %* x %* 1)> : <int -> int>

-| (run cube) 5;
val it = 125 : int
```

All quasiquotes in MetaML are typechecked and receive one of the <a> types (which means "code that evaluates to a value of type a"). Here `cube` is a quasiquote that represents a function from `int` to `int`.

Therefore, unlike in Lisps, quasiquotes in MetaML cannot have unbound free variables, which implies that meta-programs cannot modify bindings (e.g. in MetaML it's impossible to express `let` as a macro).

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.

Instead of arbitrary number of stages like in MetaML, it has only two stages: compile-time and runtime. Explicit `run` is removed and is carried out implicitly by macro expansion

MacroML inherits the typing discipline of its parent, 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 in place, but macro expansions are typechecked anyways, so errors are caught at compile-time (the luxury that a staged language like MetaML doesn't have).

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 "this can't be")
```

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 (generating fresh names).
- 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.
- Some languages are doing almost fine without renaming, which simplifies things at a cost of occasional non-hygienity.

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), but require an explicit trigger for 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)
```

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

```
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)
```

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). The 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 statically 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)
}
```

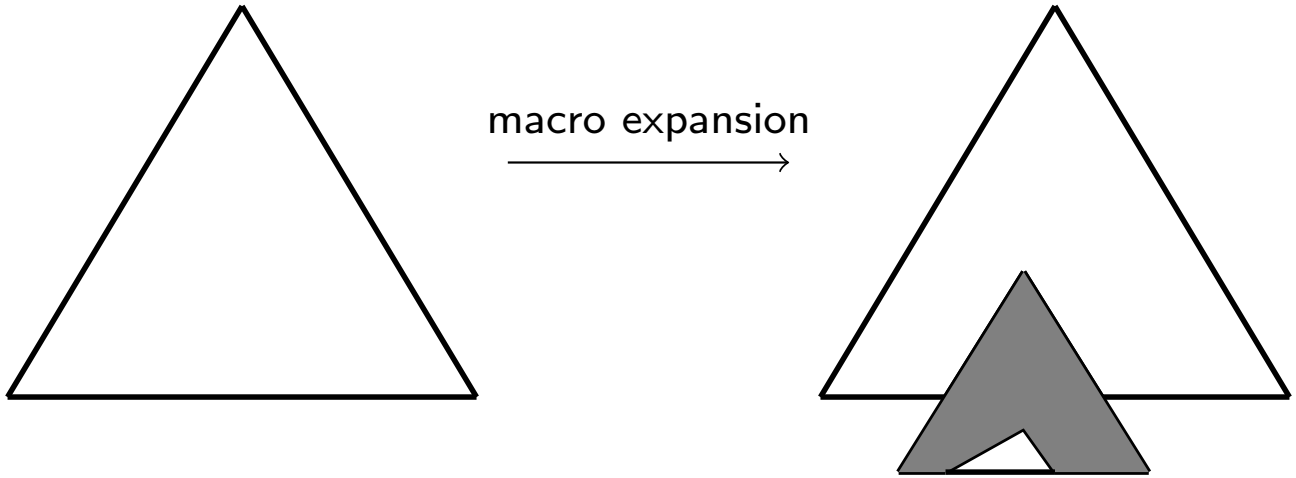
Designers of Nemerle were aware of the "too strongly typed" problem of quasiquotes in Template Haskell, so they decided not to typecheck them before they are used in macro expansions.

In fact they went even further - quasiquotes are not only untyped, but they also don't get their bindings resolved until 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.

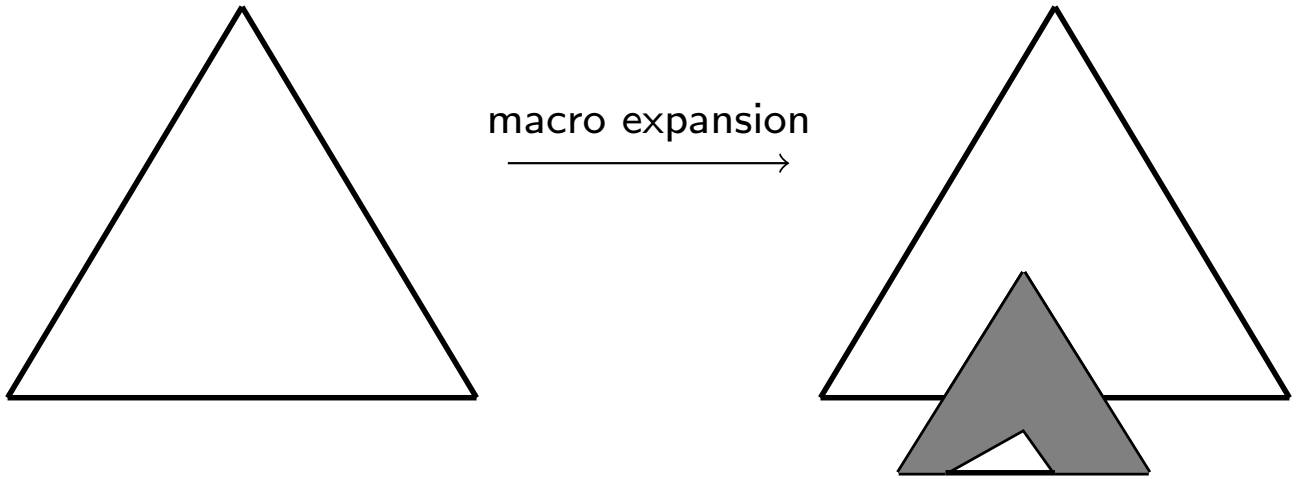
Hygiene



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

Overview

```
(define-syntax (let stx)
  (syntax-case stx ()
    ((let ((name expr) ...) body ...)
     #'((lambda (name ...) body ...) expr ...))))

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

Racket is a Scheme. It inherits and develops its macro system. In fact all Lispy examples in these slides are Racket-based.

An important tradition in Scheme community is a strive towards hygiene. Both Kohlbecker and Dybvig, who we quoted when studying hygiene and referential transparency, did their research in Scheme.

For example, `syntax-case` introduced in Scheme is automatically hygienic. `defmacro`, which dates back to Lisp, is not.

Notation

```
(define-syntax (let stx)
  (syntax-parse stx
    ((let ((name:identifier expr:expr) ...) body:expr ...)
     #:fail-when (check-duplicate #'(var ...))
                 "duplicate variable name"
     #'((lambda (name ...) body ...) expr ...))))

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

`syntax-parse` is a development of the `syntax-case` family of macro transformers. On top of the normal capabilities of `syntax-case` it lets the programmers define syntax specifications that improve error checking and reporting.

These specifications are first-class in a sense that they can be abstracted with `define-syntax-class` and composed from the ground up.

Hygiene

Racket Reference promotes usage of pattern-based syntax matching with `syntax-case`, which automatically separates lexical contexts of macro use and macro definition (Schemes use marks for this purpose, which were a direct inspiration for colors in Nemerle).

Raw S-expressions are abstracted behind syntax objects that carry information about sources and positions (and, therefore, lexical contexts), modules, visibility etc.

Default way of creating syntax objects is syntax quote `#'`, which uses the lexical context of its call site, ensuring hygiene.

In cases when it's necessary to break hygiene (i.e. to make an identifier `a` visible in the scope of an identifier `b`) it is conventional to use something like `(datum-> syntax #'b 'a)` and then splice the return value into the macro expansion.

Revisiting `forever`

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

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

This code from the previous discussion on hygiene will not work, because `syntax-*` macro transformers are hygienic by default.

`abort` introduced by the macro expansion will be alpha-renamed, which will prevent the body of `forever` from seeing it.

Unhygienic `forever`

```
(define-syntax (forever stx)
  (syntax-case stx ()
    ((forever body ...)
     (with-syntax ((abort (datum->syntax #'forever 'abort)))
       #'(call/cc (lambda (abort)
                    (let loop () body ... (loop))))))))

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

Here `datum->syntax` takes a raw S-expression `'abort` that represents the name we want to introduce unhygienically and creates a corresponding syntax object linked to the lexical context of the macro use site represented by `#'forever`.

When this syntax object is spliced into the template, it becomes visible to the body of the application of `forever`.

Doesn't scale

```
(define-syntax while
  (syntax-rules ()
    ((while test body ...)
     (forever (unless test (abort)) body ...))))

(while #t (abort)
```

Unfortunately this approach doesn't scale, because it doesn't compose with other macros. In the example above, `abort` in the body of `while` is in a lexical context different from `forever` and will not see `abort`.

One of the solutions would be to bind `abort` in the body of `while` bringing it to the requried context. Another one implies passing `abort` explicitly when calling `while` and derived macros. In both cases, however, each macro use site imposes a boilerplate penalty.

Solution

```
(define-syntax-parameter abort (syntax-rules ()))

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

Unlike Nemerle, Racket doesn't have polychromatic identifiers, but it does have dynamic variables (`fluid-let` and `fluid-syntax-let`).

Here `abort` is exposed along with `forever`, so it's in the lexical scope of both `forever` and its usages, regardless of the intermediate macro expansions. This solves the visibility problem.

Outline

vCurrent

```
def assert(cond: Boolean, msg: Any) = macro m
def m(c: Ctx)(cond: c.Expr[Boolean], msg: c.Expr[Any]) =
  if (assertionsEnabled)
    // if (!cond) raise(msg)
    If(Select(cond.tree, newTermName("!")),
        Apply(Ident(newTermName("raise")), List(msg.tree)),
        Literal(Constant(())))
  else
    Literal(Constant(())

assert(2 + 2 == 4, "this can't be")
```

The Scala macros experiment started as a minimalistic macro system. We didn't admit a special notation for quasiquoting, neither we supported hygiene. Since Scala is a production-grade language, this was also a careful first step in popularizing compile-time metaprogramming.

vCurrent

```
def raise(msg: Any) = throw new AssertionError(msg)

def assert(cond: Boolean, msg: Any) = macro m
def m(c: Ctx)(cond: c.Expr[Boolean], msg: c.Expr[Any]) =
  if (assertionsEnabled)
    c.reify(if (!cond.splice) raise(msg))
  else
    c.reify(())

object Test extends App {
  def raise(msg: Any) = { /* referential transparency */ }
  assert(2 + 2 == 3, "this can be")
}
```

Later we came up with the idea of `reify`, which turns out (possibly parameterized) statically-typed templates of Scala code into syntax objects. In a sense this notion is very similar to MacroML.

vCurrent

```
def raise(msg: Any) = throw new AssertionError(msg)

def assert(cond: Boolean, msg: Any) = macro m
def m(c: Ctx)(cond: c.Expr[Boolean], msg: c.Expr[Any]) =
  if (assertionsEnabled)
    c.reify(if (!cond.splice) raise(msg))
  else
    c.reify(())

object Test extends App {
  def raise(msg: Any) = { /* referential transparency */ }
  assert(2 + 2 == 3, "this can be")
}
```

`reify` is the middle-man between raw unhygienic templates and syntax objects. It's a good place to implement support for hygiene and referential transparency.

vCurrent

```
abstract class Universe extends Symbols
                           with Types
                           with Trees
                           with ...
{
  def reify[T](expr: T): Expr[T] =
    macro Reifiers.reifyTree[T]
}
```

A curious fact about `reify` is that it is just a macro, yet it provides a quasiquoting and hygiene facility without touching the compiler.

Macros in Scala start from a minimalistic core, but are capable of becoming hygienic and referentially transparent. That's why we call our macro system *self-cleaning*.

Adoption

We dedicated a lot of time to making macros release-worthy.

Since March 2012 macros are a part of Scala's mainline, and the upcoming release of 2.10.0 will include macros as an experimental feature.

Projects and ideas

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

Future work

- Lenient typing (currently arguments to macro expansions and, consequently, reified templates are statically typed, which has proven to be a problem when writing interesting macros).
- Synergy with the type system (implicit macros, type macros, macro annotations and their combinations enable some of the interesting techniques described above).
- Minimalizing Scala (macros have already allowed us to remove an entire phase and to implement full-fledged type reification - this can be pushed even further).

Questions

1. Is it ok to copy/paste snippets and drawings from the papers being studied?
2. Examples. Are they any good?
3. Minimal size of the write-up?

Backup slides

1. How is one supposed to debug macros?
2. Why the need for analytic macros?
3. Dynamic typing as staged type inference
4. Hygiene in Clojure
5. Example of a type macro in Nemerle
6. Example of a syntax macro in Nemerle
7. Implicit macros (Heather's example)
8. Type macros
9. Macro annotations
10. Slide about descartes
11. Slide about an integrated prover
12. Macros in Tex
13. define-syntax-class
14. Slide about ScalaMock3