Metaprogramming with Macros

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What are macros?

Macros in programming languages:

- C macros
- Lisp macros
- ...

What is the underlying notion?

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Macros in programming languages:

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- Lisp macros
- ...

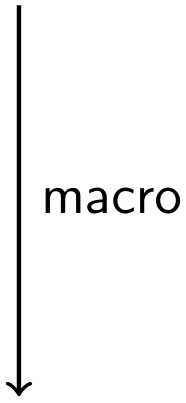
What is the underlying notion?

The notion of textual abstraction:

- Recognize pieces of text that match a specification
- Replace them according to a procedure

What are macros?

```
printf("Hello %s!", "World")
```




```
def formatter(arg1: Any) = "Hello " + arg1.toString + "!"
print(formatter("World"))
```

Why macros?

Work with lexical tokens or syntax trees, therefore are not bound by the semantics of the underlying programming language

Use cases:

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

Challenges in macrology

- Notation
- Variable capture
- Typechecking
- Syntax extensibility
- ...

The focus of this talk

Inadvertent variable capture:

- Macro expansions sometimes cause name clashes
- Some identifiers end up referring to variables from other scopes

Outline

The prelude of macros: introduces the running example

The chapter of bindings: illustrates the problem of variable capture

The trilogy of tongues: surveys macro systems that solve this problem

The vision of the days to come: presents the research proposal

A detour: how Lisp works

```
(if (calculate)
  (print "success")
  (error "does not compute"))
```

- S-expressions: atoms and lists
- `print` and `error` are one-argument functions
- `calculate` is a zero-argument function
- `if` is a special form
- All values can be used in conditions

Anaphoric `if`

```
(aif (calculate)
  (print it)
  (error "does not compute"))
```

```
(let* ((temp (calculate))
       (it temp))
  (if temp
    (print it)
    (error "does not compute")))
```

The aif macro

```
(aif (calculate)
  (print it)
  (error "does not compute"))

(defmacro aif args
```

```
(let* ((temp (calculate))
       (it temp))
  (if temp
    (print it)
    (error "does not compute")))
```

Low-level implementation

```
(aif (calculate)
  (print it)
  (error "does not compute"))

(defmacro aif args
  (list 'let* (list (list 'temp (car args))
                    (list 'it 'temp))
     (list 'if 'temp
       (cadr args)
       (caddr args))))

(let* ((temp (calculate))
       (it temp))
  (if temp
    (print it)
    (error "does not compute")))
```

Quasiquoting: static template

```
(aif (calculate)
  (print it)
  (error "does not compute"))

(defmacro aif args
  `(let* ((temp ...........)
          (it temp))
     (if temp
       ............
       ............)

(let* ((temp (calculate))
       (it temp))
  (if temp
    (print it)
    (error "does not compute")))
```

Quasiquoting: dynamic holes

```
(aif (calculate)
  (print it)
  (error "does not compute"))

(defmacro aif args
  `(let* ((temp ,(car args))
          (it temp))
     (if temp
       ,(cadr args)
       ,(caddr args))

(let* ((temp (calculate))
       (it temp))
  (if temp
    (print it)
    (error "does not compute")))
```

Macro by example (MBE)

```
(aif (calculate)
  (print it)
  (error "does not compute"))

(defmacro+ aif
  (aif cond then else)
  (let* ((temp cond)
         (it temp))
    (if temp
        then
        else)))

(let* ((temp (calculate))
       (it temp))
  (if temp
    (print it)
    (error "does not compute")))
```

Interlude

```
(defmacro+ aif
  (aif cond then else)
  (let* ((temp cond)
         (it temp))
    (if temp then else)))
```

- Macros are functions that transform syntax objects
- Quasiquotes = static templates + dynamic holes

The aif macro is buggy

```
(aif (calculate)
  (print it)
  (error "does not compute"))

(defmacro+ aif
  (aif cond then else)
  (let* ((temp cond)
         (it temp))
    (if temp then else)))
```

The aif macro is buggy

```
(aif (calculate)
  (print it)
  (error "does not compute"))

(defmacro+ aif
  (aif cond then else)
  (let* ((temp cond)
         (it temp))
    (if temp then else)))

(let* ((temp (calculate))
       (it temp))
  (if temp
    (print it)
    (error "does not compute")))
```

Bug #1: Violation of hygiene

```
(let ((temp 451°F))
  (aif (calculate)
    (print it)
    (print temp)))

(defmacro+ aif
  (aif cond then else)
  (let* ((temp cond)
         (it temp))
    (if temp then else)))

(let ((temp 451°F))
  (let* ((temp (calculate))
         (it temp))
    (if temp
      (print it)
      (print temp))))
```

Bug #2: Violation of referential transparency

```
(let ((if hijacked))
  (aif (calculate)
    (print it)
    (error "does not compute")))

(defmacro+ aif
  (aif cond then else)
  (let* ((temp cond)
         (it temp))
    (if temp then else))) ;; core if

(let ((if hijacked))
  (let* ((temp (calculate))
         (it temp))
    (if temp ;; hijacked if
      (print it)
      (error "does not compute"))))
```

Old school solution

```
(defmacro+ aif
  (aif cond then else)
  (let ((temp (gensym)))
    (let* ((temp cond)
           (it temp))
      (if temp then else))))
```

Packages help with referential transparency

Three macro-enabled languages

Template Meta-programming for Haskell [Template Haskell]
by Tim Sheard and Simon Peyton Jones

Meta-programming in Nemerle [Nemerle]
by Kamil Skalski, Michal Moskal and Pawel Olszta.

Keeping it Clean with Syntax Parameters [Racket]
by Eli Barzilay, Ryan Culpepper and Matthew Flatt

All three languages:

- Solve the problems of hygiene and referential transparency
- Do that in their own interesting ways

Template Haskell: Introduction

```
$(aif [| calculate |]
   [| putStrLn (show it) |]
   [| error "does not compute" |])

aif :: Q Exp -> Q Exp -> Q Exp -> Q Exp
aif cond then' else' =
   [| let temp = $cond
          it = temp
      in if temp /= 0 then $then' else $else' |]
```

- No dedicated concept of macros
- Macro expansions are triggered explicitly with `$`
- There are quasiquotes `[| ... |]` and unquotes `$expr`
- Hygienic and referentially transparent

Template Haskell: The perils of hygiene

```
$(aif [| calculate |]
   [| putStrLn (show it) |]
   [| error "does not compute" |])

aif :: Q Exp -> Q Exp -> Q Exp -> Q Exp
aif cond then' else' =
   [| let temp = $cond
          it = temp
      in if temp /= 0 then $then' else $else' |]

let temp_a1mx = calculate
    it_a1my = temp_a1mx
in if (temp_a1mx /= 0)
   then putStrLn (show it)
   else error "does not compute"
```

Not in scope: ‘it’

Template Haskell: The Q monad

```
aif cond then' else' =
  [| let temp = $cond
         it = temp
     in if temp /= 0 then $then' else $else' |]

aif :: Q Exp -> Q Exp -> Q Exp -> Q Exp
aif cond' then'' else'' =
    do { ...
       ; temp <- newName "temp"
       ; it <- newName "it"
       ; let notEq = mkNameG_v "ghc-prim" "GHC.Classes" "/="
         in return (LetE ... (CondE (... then' else')) ...)
       }
```

Template Haskell: Breaking hygiene

```
$(aif [| calculate |]
   [| putStrLn (show $(dyn "it")) |]
   [| error "does not compute" |])

aif :: Q Exp -> Q Exp -> Q Exp -> Q Exp
aif cond then' else' =
   [| let temp = $cond
          it = temp
      in if temp /= 0 then $then' else $else' |]

let temp_a1mx = calculate
    it_a1my = temp_a1mx
in if (temp_a1mx /= 0)
   then putStrLn (show it_a1my)
   else error "does not compute"
```

Template Haskell: Summary

- Template Haskell is auto hygienic and referentially transparent
- The Q monad takes care of names
- Sometimes we need to break hygiene

Nemerle: Introduction

```
aif(calculate,
  WriteLine(it),
  throw Exception("does not compute"))

macro aif(cond, then, else_) {
  <[
    def temp = $cond;
    def it = temp;
    if (temp != 0) $then else $else_
  ]>
}
```

- Macros are declared explicitly, expansions are implicit
- There are quasiquotes `<[ ... ]>` and unquotes `$expr`
- Hygienic and referentially transparent

Nemerle: The perils of hygiene

```
aif(calculate,
  WriteLine(it),
  throw Exception("does not compute"))

macro aif(cond, then, else_) {
  <[
    def temp = $cond;
    def it = temp;
    if (temp != 0) $then else $else_
  ]>
}

def calculate = 42;
def temp_1087 = calculate;
def it_1088 = temp_1087;
if (temp_1087 != 0) WriteLine(it) else throw Exception("...")

error: unbound name ‘it’
```

Nemerle: Coloring algorithm

```
def calculate = 42;
aif(calculate,
  WriteLine(it),
  throw Exception("does not compute"))

macro aif(cond, then, else_) {
  <[
    def temp = $cond;
    def it = temp;
    if (temp != 0) $then else $else_
  ]>
}

def calculate = 42;
def temp = calculate;
def it = temp;
if (temp != 0) WriteLine(it) else throw Exception("...")
```

Nemerle: Coloring algorithm

```
def calculate = 42;                    // vanilla color
aif(calculate,
  WriteLine(it),
  throw Exception("does not compute"))

macro aif(cond, then, else_) {
  <[
    def temp = $cond;
    def it = temp;
    if (temp != 0) $then else $else_
  ]>
}

def calculate = 42;
def temp = calculate;
def it = temp;
if (temp != 0) WriteLine(it) else throw Exception("...")
```

Nemerle: Coloring algorithm

```
def calculate = 42;                        // vanilla color
aif(calculate,
  WriteLine(it),
  throw Exception("does not compute"))

macro aif(cond, then, else_) {             // expansion color
  <[
    def temp = $cond;
    def it = temp;
    if (temp != 0) $then else $else_
  ]>
}

def calculate = 42;
def temp = calculate;
def it = temp;
if (temp != 0) WriteLine(it) else throw Exception("...")
```

Nemerle: Coloring algorithm

```
def calculate = 42;                    // vanilla color
aif(calculate,
  WriteLine(it),
  throw Exception("does not compute"))

macro aif(cond, then, else_) {         // expansion color
  <[
    def temp = $cond;
    def it = temp;
    if (temp != 0) $then else $else_
  ]>
}

def calculate = 42;                    // bind using colors
def temp = calculate;
def it = temp;
if (temp != 0) WriteLine(it) else throw Exception("...")
```

Nemerle: Breaking hygiene

```
def calculate = 42;                          // vanilla color
aif(calculate,
  WriteLine(it),
  throw Exception("does not compute"))

macro aif(cond, then, else_) {               // expansion color
  <[
    def temp = $cond;
    def $("it": usesite) = temp;             // recolor the variable
    if (temp != 0) $then else $else_
  ]>
}

def calculate = 42;                          // bind using colors
def temp = calculate;
def it = temp;
if (temp != 0) WriteLine(it) else throw Exception("...")
```

Nemerle: Summary

- Nemerle takes care of hygiene with a coloring algorithm
- No complex translation algorithms are necessary
- As another bonus programmer can fine-tune colors with `MacroColors`
- Referential transparency works as well

Racket: Introduction

```
(aif (calculate)
  (print it)
  (error "does not compute"))

(define-syntax (aif stx)
  (syntax-case stx ()
    ((aif cond then else)

       #'(let ((temp cond)
               (it temp)))
           (if temp then else)))))
```

- A Lisp, descendent from Scheme
- 25 years of hygienic macros, a bunch of macro systems
- Language features written using macros (classes, modules, etc)

Racket: The perils of hygiene

```
(aif (calculate)
  (print it)
  (error "does not compute"))

(define-syntax (aif stx)
  (syntax-case stx ()
    ((aif cond then else)

      #'(let ((temp cond)
              (it temp)))
          (if temp then else)))))

(let* ((temp (calculate))
       (it temp))
  (if temp
    (print it)
    (error "does not compute")))
```

Racket: Breaking hygiene

```
(aif (calculate)
  (print it)
  (error "does not compute"))

(define-syntax (aif stx)
  (syntax-case stx ()
    ((aif cond then else)
     (with-syntax ((it (datum->syntax #'aif 'it)))
       #'(let ((temp cond)
               (it temp)))
           (if temp then else))))))

(let* ((temp (calculate))
       (it temp))
  (if temp
    (print it)
    (error "does not compute")))
```

Racket: The aunless macro

```
(aunless (not (calculate))
  (print it)
  (error "does not compute"))

(define-syntax (aunless stx)
  (syntax-case stx ()
    ((aunless cond then else)
     #'(aif (not cond) then else))))

(let* ((temp (not (not (calculate))))
       (it temp))
  (if temp
    (print it)
    (error "does not compute")))
```

Racket: Being unhygienic doesn't scale

```
(aunless (not (calculate))
  (print it)
  (error "does not compute"))

(define-syntax (aunless stx)
  (syntax-case stx ()
    ((aunless cond then else)
     #'(aif (not cond) then else))))

(let* ((temp (not (not (calculate))))
       (it temp))
  (if temp
    (print it)
    (error "does not compute")))
```

Racket: Being unhygienic doesn't scale

```
(aunless (not (calculate))
  (print it)
  (error "does not compute"))

(define-syntax (aunless stx)
  (syntax-case stx ()
    ((aunless cond then else)
     #'(aif (not cond) then else))))

(let* ((temp (not (not (calculate))))
       (it temp))
  (if temp
    (print it)
    (error "does not compute")))
```

Racket: Syntax parameters

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

(define-syntax (aif stx)
  (syntax-case stx ()
    ((aif cond then else)
     #'(let ((temp cond))
         (syntax-parameterize
           ((it (syntax-rules () ((_) temp))))
         (if temp then else))))))
```

- `it` becomes a compile-time dynamic variable
- Therefore its scope overarches all potential expansions
- High-level language feature (dynamic variables) + macros = win

Summary

Macros:

- Macros provide impressive power for their simplicity
- But they also give rise to unusual problems
- One of these problems involves mixed up bindings

Summary

Macros:

- Macros provide impressive power for their simplicity
- But they also give rise to unusual problems
- One of these problems involves mixed up bindings

Bindings:

- Automatic hygiene and referential transparency are real
- Sometimes it is necessary to break hygiene
- There are ways of doing that
- Sometimes these ways are too low-level

Summary

Macros:

- Macros provide impressive power for their simplicity
- But they also give rise to unusual problems
- One of these problems involves mixed up bindings

Bindings:

- Automatic hygiene and referential transparency are real
- Sometimes it is necessary to break hygiene
- There are ways of doing that
- Sometimes these ways are too low-level

Future work:

- Integration with other language features provides unexpected insights

Scala macros

- Since this spring Scala has macros
- Even better: macros are an official part of the language in the next production release 2.10.0
- Now it's time to put the pens down and think about the future
- The future is in integration with other language features

Implicits

```
def serialize[T](x: T): Pickle
```

Implicits

```
trait Serializer[T] {
  def write(pickle: Pickle, x: T): Unit
}

def serialize[T](x: T)(s: Serializer[T]): Pickle
```

Implicits

```
trait Serializer[T] {
  def write(pickle: Pickle, x: T): Unit
}

def serialize[T](x: T)(implicit s: Serializer[T]): Pickle

implicit object ByteSerializer extends Serializer[Byte] {
  def write(pickle: Pickle, x: Byte) = pickle.writeByte(x)
}
```

Implicits

```
trait Serializer[T] {
  def write(pickle: Pickle, x: T): Unit
}

def serialize[T](x: T)(implicit s: Serializer[T]): Pickle

implicit def generator: Serializer[T] = macro impl[T]
def impl[T](c: Context): c.Expr[Serializer[T]] = ...
```

Research proposal

Marry macros and high-level language features:

- Macros + functions $\rightarrow$ programmable inlining, specialization, fusion
- Macros + annotations $\rightarrow$ code contracts, statically-typed decorators
- Macros + implicits $\rightarrow$ static verification
- ...

Backup slides

Macros for database access: SLICK

```
@table("COFFEES") case class Coffee(
  @column("COF_NAME") name: String,
  @column("SUP_ID") supID: Int,
  @column("PRICE") price: Double
)
val coffees = Queryable[Coffee]

val l = for { c <- coffees if c.supID == 101 }
yield (c.name, c.price)

backend.result(l, session)
 .foreach { case (n, p) => println(n + ": " + p) }
```

- Deeply embedded domain-specific language
- Constructs like field access and method calls are overloaded
- Underlying macros save ASTs till runtime and translate them to SQL

Macros for testing: ScalaMock

```
val w = mock[Warehouse]
inSequence {
  w.expects.hasInventory("Talisker", 50).returning(true)
  w.expects.remove("Talisker", 50).once
}

val order = new Order("Talisker", 50)
order.fill(w)
assert(order.isFilled)
```

- Deeply-embedded domain-specific language
- Macro types generate mocks at compile-time
- Boilerplate generation is completely automatic

Macros for inlining: Scala collections

```
def filter(p: T => Boolean): Repr = ...

def filter(p: T => Boolean): Repr = macro inline {
  ... the original body of filter ...
}
```

- The `filter` function transparently becomes a macro
- This doesn't break source compatibility
- The original body of `filter` remains the same
- Yet the underlying macro is now in full control of inlining

Macros for fusion: Courtesy of Paul Phillips

```
def inc(x: Int) = x + 1
def f = List(1, 2, 3) map inc map inc map inc
def g = List(1, 2, 3) map inc map inc map inc fuse
```

- Desktop fusion achieved!
- How to deal with side effects?
- Also what about data flow analysis?

Macros for verification: Courtesy of Alexander Kuklev

```
trait SemiGroup[T] extends Eq[T] {
  def ∘(a: T, b: T): T
  def associativity(a: T, b: T, c: T):
    ✓((a ∘ (b ∘ c)) == ((a ∘ b) ∘ c))
}

def reduce[T](op: (T, T) => T): T

def reduce[T](op: (T, T) => T)(implicit evidence:
  ✓((a: T, b: T, c: T) => op(op(a, b), c) == op(a, op(b, c)))
): T
```

- Facts are encoded with the ✓ macro
- Proofs are requested with implicit parameters
- Proofs can either be inferred by implicit macros or provided by hand

Scala in the present: Macro defs

```
object Asserts {
  def assertionsEnabled = ...
  def raise(msg: Any) = throw new AssertionError(msg)

  def assert(cond: Boolean, msg: Any) = macro impl
  def impl(c: Context)
          (cond: c.Expr[Boolean], msg: c.Expr[Any]) =
    if (assertionsEnabled)
      c.reify(if (!cond.eval) raise(msg.eval))
    else
      c.reify(())
}
```

- Separate macro definitions and implementations
- `reify` ensures hygiene and referential transparency
- `reify` also implements the notion of quasiquoting

Scala in the future: Type macros

```
type MySqlDb(connString: String) = macro ...

type MyDb = Base with MySqlDb("Server=127.0.0.1")

import MyDb._
val products = new MyDb().products
products.filter(p => p.name.startsWith("foo")).toList
```

- Generalize macros from term refs to symbol refs
- Type macros can generate arbitrary amounts of publicly visible defs
- Enables an astounding multitude of techniques
- The problem of erasure

Scala in the future: Macro annotations

```
class atomic extends MacroAnnotation {
  def complete(defn: _) = macro("generate a backing field")
  def typeCheck(defn: _) = macro("return defn itself")
}

@atomic var fld: Int
```

- Statically-typed analogue of Python's decorators
- Operates on arbitrary definitions
- Two-step expansion: macro-level + micro-level

Typechecking disciplines: 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
```

- Each quasiquote is typechecked in isolation
- All quasiquotes are assigned "code of something" types
- E.g. right-hand side of `pow` is a code of function from `int` to `int`
- Hence no pattern matching and no new bindings

Typechecking disciplines: Lenient

```
[| 'a' + True |] -- rejected

printf :: String -> Expr -- allowed
$(printf "Error: %s on line %d") "urk" 341

f :: Q Type -> Q [Dec] -- rejected
f t = [d| data T = MkT $t; g (MkT x) = x + 1 |]
```

- Quasiquotes are sanity-checked early, fully typechecked later
- But require their bindings to be established in advance
- Not flexible enough, e.g. no splicing into binding positions

Typechecking disciplines: Deferred

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

- Quasiquotes are not typechecked at all
- Typechecking only happens after macro expansion
- This gives ultimate flexibility at the cost of delayed error detection