

# Metaprogramming with Macros

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10 September 2012

# What are macros?

Macros in programming languages:

- ▶ C macros
- ▶ Lisp macros
- ▶ ...

What is the underlying concept?

# What are macros?

Macros in programming languages:

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- ▶ Lisp macros
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What is the underlying concept?

Macros realize the notion of textual abstraction:

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

# Why macros?

Work with 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)
- ▶ ...

# Macrology

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

# Outline

The prelude of macros

The chapter of bindings

The trilogy of tongues

The vision of the days to come

## 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
- ▶ Impressive power for minimal investments from the compiler

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## 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)))
```

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

## Old school

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

And please don't rename core forms

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## Template Haskell

```
$(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' |]
```

## Template Haskell

```
$(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_almx = calculate
```

```
    it_almy = temp_almx
```

```
in if (temp_almx /= 0)
```

```
    then putStrLn (show it)
```

```
    else error "does not compute"
```

Not in scope: 'it'

## 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"  
      ; cond <- cond'  
      ; then' <- then''  
      ; else' <- else''  
      ; let notEq = mkNameG_v "ghc-prim" "GHC.Classes" "/="   
      in return  
      (LetE [ValD (VarP temp) (NormalB cond) [],  
             ValD (VarP it) (NormalB (VarE temp)) []]  
        (Conde (... (VarE notEq) ...) then' else'))  
  }
```

## 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"  
      ; cond <- cond'  
      ; then' <- then''  
      ; else' <- else''  
      ; let notEq = mkNameG_v "ghc-prim" "GHC.Classes" "/="   
      in return  
      (LetE [ValD (VarP temp) (NormalB cond) [],  
             ValD (VarP it) (NormalB (VarE temp)) []]  
        (Conde (... (VarE notEq) ...) then' else'))  
  }
```



## 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_almx = calculate  
  it_almy = temp_almx  
in if (temp_almx /= 0)  
  then putStrLn (show it_almy)  
  else error "does not compute"
```

## Summary: Template Haskell

- ▶ Quasiquotes in Template Haskell are automatically hygienic and referentially transparent
- ▶ That's because they are lifted into the Q monad, which takes care of names (fresh names for locals, fully qualified names for globals)
- ▶ Sometimes we need to break hygiene

## Nemerle

```
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_  
  ]>  
}
```

## Nemerle

```
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'

## 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("...")
```

## Coloring algorithm: normal code gets a vanilla color

```
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("...")
```

## Coloring algorithm: each expansion gets unique colors

```
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("...")
```

## Coloring algorithm: at the end of the day

```
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("...")
```



## Coloring algorithm: inherit use site

```
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;
    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("...")
```

## Summary: Nemerle

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

# Racket

A Lisp, descendent from Scheme

25 years of hygienic macros, a bunch of macro systems

Language features written using macros (classes, modules, etc)

Q: "How to turn macros into proper abstractions?"

# Racket

```
(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))))
```

# Racket

```
(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

```
(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")))
```

## Doesn't scale

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

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

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

## Doesn't scale

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

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

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



## Doesn't scale

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

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

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

## Solution: dynamic variables

```
(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))))))
```

## Summary: overall

- ▶ There are algorithms that take care of hygiene and referential transparency
- ▶ These algorithms can work in automatic mode, but are flexible enough to give the programmer full control
- ▶ Like a silver bullet
- ▶ Nevertheless sometimes even better solutions come from integration with language features

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- ▶ Since this semester 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

# 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]
```

# Research proposal

Marry macros and high-level language features:

- ▶ Macros + functions → programmable inlining, specialization, fusion
- ▶ Macros + annotations → code contracts
- ▶ Macros + path-dependent types → controlled effects
- ▶ Macros + implicits → static verification
- ▶ ...