Part 1

Identifier Address

Suppose that

```
{let {[x 88]}
  {+ x y}}
```

appears in a program; the body is eventually evaluated:

```
           ...
{+ x y}
```

where will `x` be in the environment?

Answer: always at the beginning:

```
x = 88    ...
```

Identifier Address

Suppose that

```
{let {[y 1]}
  {+ x y}}
```

appears in a program; the body is eventually evaluated:

```
...
{+ x y}
```

where will `y` be in the environment?

Answer: always at the beginning:

```
y = 1    ...
```

Identifier Address

Suppose that

```
{let {[y 1]}
  {let {[x 2]}
    {+ x y}}}
```

appears in a program; the body is eventually evaluated:

```
...
{+ x y}
```

where will `y` be in the environment?

Answer: always second:

```
x = 2   y = 1   ...
```

Identifier Address

Suppose that

```
{let {[y 1]}
  {let {[x 88]}
    {* {+ x y} 17}}}
```

appears in a program; the body is eventually evaluated:

```
{+ x y}
```

```
...
```

where will `x` and `y` be in the environment?

Answer: always first and second:

```
x = 88   y = 1    ...
```

Identifier Address

Suppose that

```
{let {[y 1]}
  {let {[w 10]}
    {let {[z 9]}
      {let {[x 0]}
        {+ x y}}}}}
```

appears in a program; the body is eventually evaluated:

```
...
{+ x y}
```

where will **`x`** and **`y`** be in the environment?

Answer: always first and fourth:

```
x = 0    z = 9    w = 10    y = 1    ...
```

Identifier Address

Suppose that

```
{let {[y {let {[r 9]} {* r 8}}]}
  {let {[w 10]}
    {let {[z {let {[q 9]} q}]}
      {let {[x 0]}
        {+ x y}}}}}
```

appears in a program; the body is eventually evaluated:

```
...
{+ x y}
```

where will **`x`** and **`y`** be in the environment?

Answer: always first and fourth:

```
x = 0    z = 9    w = 10    y = 1    ...
```

Lexical Scope

- For any expression, we can tell which identifiers will be in the environment at run time
- The order of the environment is predictable

Part 2

Compilation of Variables

A compiler can transform an **`Exp`** expression to an expression without identifiers — only lexical addresses

```
; compile : Exp ... -> ExpD
```

```
(define-type Exp
  (numE [n : Number])
  (addE [l : Exp]
        [r : Exp])
  (multE [l : Exp]
         [r : Exp])
  (idE [n : Symbol])
  (lamE [n : Symbol]
        [body : Exp])
  (appE [fun : Exp]
        [arg : Exp]))
```

```
(define-type ExpD
  (numD [n Number])
  (addD [l : ExpD]
        [r : ExpD])
  (multD [l : ExpD]
         [r : ExpD])
  (atD [pos : Number])
  (lamD [body : ExpD])
  (appD [fun : ExpD]
        [arg : ExpD]))
```

Compile Examples

```
(compile 1 ...) ⇒ 1

(compile {+ 1 2} ...) ⇒ {+ 1 2}
```

`(compile x ...)` ⇒ *compile: free identifier*

```
(compile {lambda {x} {+ 1 x}} ...)
⇒ {lambda {+ 1 {at 0}}}

(compile {lambda {y} {lambda {x} {+ x y}}} ...)
⇒ {lambda {lambda {+ {at 0} {at 1}}}}
```

Implementing the Compiler

```
(define (compile [a : Exp] [env : EnvC])
  (type-case Exp a
    [(numE n) (numD n)]
    [(plusE l r) (plusD (compile l env)
                        (compile r env))]
    [(multE l r) (multD (compile l env)
                        (compile r env))]
    [(idE n) (atD (locate n env))]
    [(lamE n body-expr)
     (lamD
      (compile body-expr
               (extend-env (bindE n)
                           env)))]
    [(appE fun-expr arg-expr)
     (appD (compile fun-expr env)
           (compile arg-expr env))]))
```

Compile-Time Environment

Mimics the run-time environment, but without values:

```
(define-type BindingC
  (bindE [name : Symbol]))

(define-type-alias EnvC (Listof BindingC))

(define (locate name env)
  (cond
   [(empty? env) (error 'locate "free variable")]
   [else (if (symbol=? name (bindC-name (first env)))
             0
             (+ 1 (locate name (rest env))))]))
```

`interp` for Compiled

Almost the same as **`interp`** for **`Exp`**:

```
(define (interp a env)
  (type-case ExpD a
    [(numD n) (numV n)]
    [(plusD l r) (num+ (interp l env)
                       (interp r env))]
    [(multD l r) (num* (interp l env)
                       (interp r env))]
    [(atD pos) (list-ref env pos)]
    [(lamD body-expr)
     (closV body-expr env)]
    [(appD fun-expr arg-expr)
     (let ([fun-val (interp fun-expr env)]
           [arg-val (interp arg-expr env)])
       (interp (closV-body fun-val)
               (cons arg-val
                     (closV-env fun-val))))]))
```

Timing Effect of Compilation

Given

```
(define c {{{{lambda {x}
               {lambda {y}
                 {lambda {z} {+ {+ x x} {+ x x}}}}}
             1}
            2}
           3})
(define d (compile c mt-env))
```

then

```
(interp d empty)
```

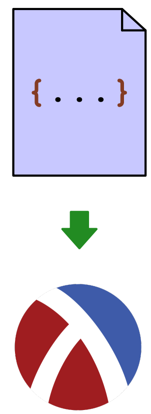
is significantly faster than

```
(interp c mt-env)
```

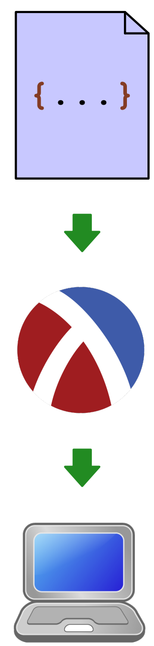
Using the built-in `list-ref` simulates machine array indexing, but don't take timings too seriously

Part 3

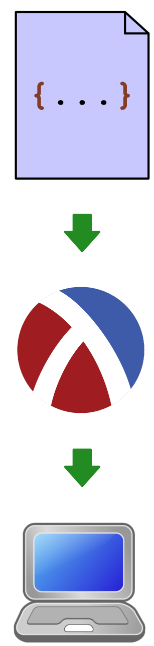
From Racket to Machine Code



From Racket to Machine Code

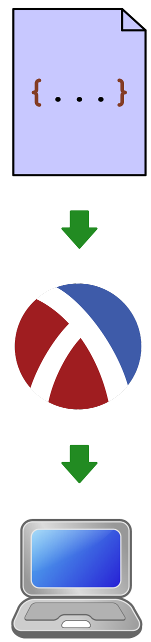


From Racket to Machine Code



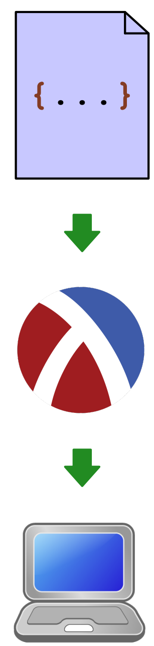
- Everything must be a number

From Racket to Machine Code



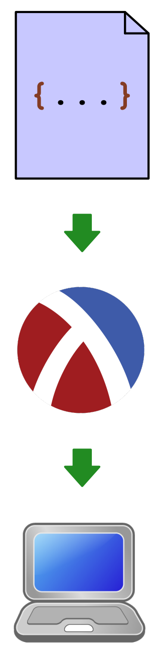
- Everything must be a number
- No **`define-type`** or **`type-case`**

From Racket to Machine Code



- Everything must be a number
- No **`define-type`** or **`type-case`**
- No implicit continuations

From Racket to Machine Code



- Everything must be a number
- No **`define-type`** or **`type-case`**
- No implicit continuations
- No implicit allocation

Part 4

From Racket to Machine Code

Step 1:

```
          Exp → ExpD

{lambda {x}        {lambda
  {+ 1 x}}          {+ 1 {at 0}}}
```

Eliminates all run-time names

From Racket to Machine Code

Step 2:

`interp` → **`interp`** + **`continue`**

Eliminates implicit continuations

From Racket to Machine Code

Step 3:

function calls → regsiters and **`goto`**

From Racket to Machine Code

Step 3:

function calls → regsiters and **`goto`**

```
(interp l
        env
        (plusSecondK r
                     env
                     k))
```

```
(begin
  (set! expr-reg l)
  (set! k-reg (plusSecondK r
                           env-reg
                           k-reg))
  (interp))
```

Makes argument passing explicit

Part 5

From Racket to Machine Code

Step 4:

```
(multSecondK r           →  (malloc3 3
             env-reg                 (ref expr-reg 2)
             k-reg)                  env-reg
                                     k-reg)
```

From Racket to Machine Code

Step 4:

```
doneK        → 1
plusSecondK  → 2
...
numD         → 8
plusD        → 9
...
numV         → 15
closV        → 16
```

From Racket to Machine Code

Step 4:

```
(type-case Cont k-reg          →  (case (ref k-reg 0)
  ...                                ...
  [(multSecondK r env k)             [(3)
   ... r                              ... (ref k-reg 1)
   ... env                            ... (ref k-reg 2)
   ... k ..]                          ... (ref k-reg 3) ...]
  ...)                               ...)
```

From Racket to Machine Code

Step 4:

```
(define memory (make-vector 1500 0))
(define ptr-reg 0)

(define (malloc3 tag a b c)
  (begin
    (vector-set! memory ptr-reg tag)
    (vector-set! memory (+ ptr-reg 1) a)
    (vector-set! memory (+ ptr-reg 2) b)
    (vector-set! memory (+ ptr-reg 3) c)
    (set! ptr-reg (+ ptr-reg 4))
    (- ptr-reg 4)))
```

Makes all allocation explicit

Makes everything a number