

# Languages as Libraries

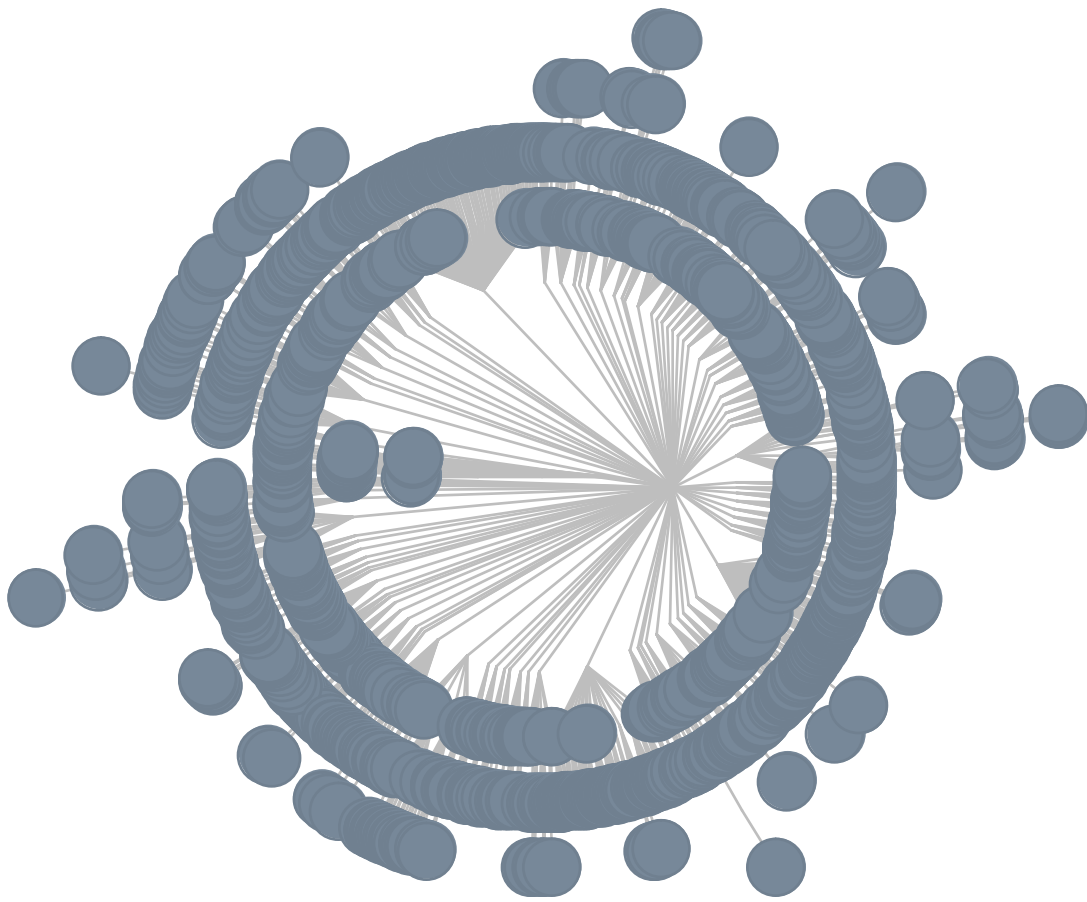
*or, implementing the next  
700 programming languages*

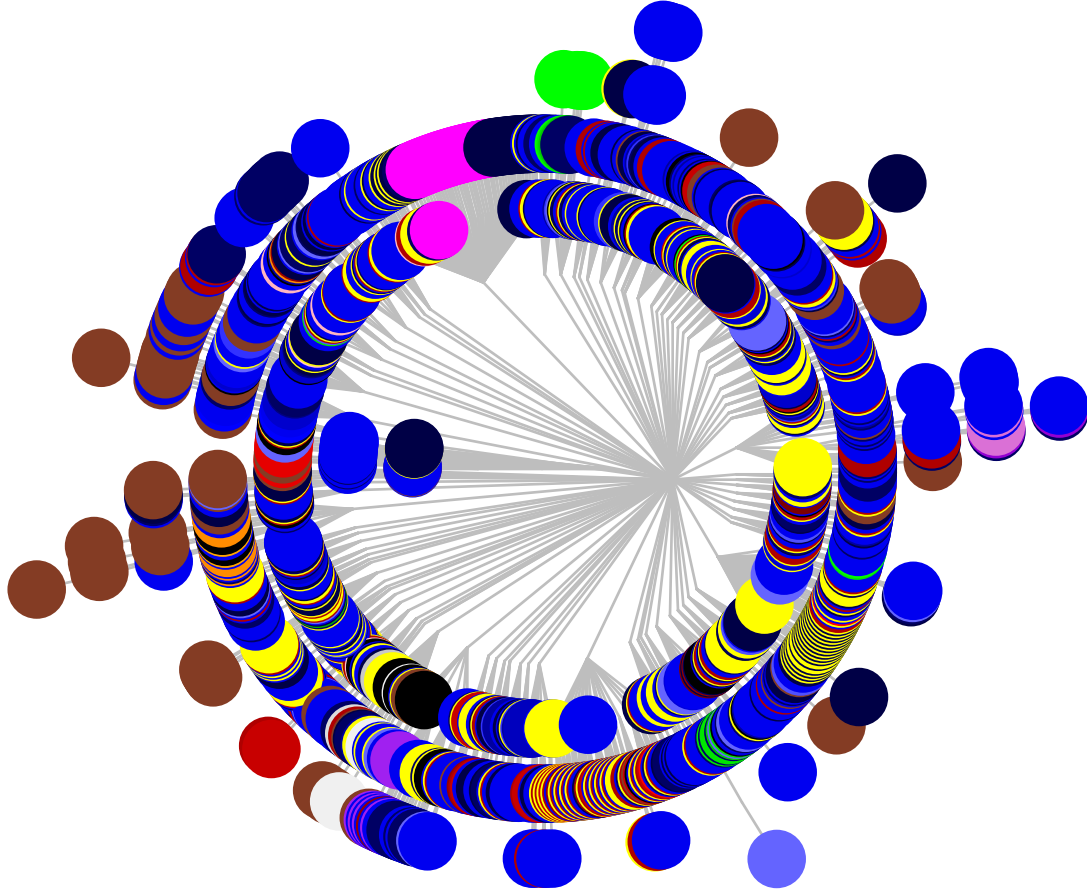
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“A domain specific language is the ultimate abstraction.”

— Paul Hudak





- |                           |                           |
|---------------------------|---------------------------|
| ● mzscheme                | ● deinprogramm/DMdA       |
| ● racket                  | ● htdp/asl                |
| ● racket/private          | ● htdp/isl+               |
| ● racket/unit             | ● htdp/bsl                |
| ● racket/private/base     | ● frtime/lang-utils       |
| ● #%kernel                | ● frtime/frtime-lang-only |
| ● racket/load             | ● frtime                  |
| ● racket/base             | ● syntax/module-reader    |
| ● racket/private/provider | ● web-server/insta        |
| ● racket/signature        | ● meta/web                |
| ● slideshow               | ● web-server              |
| ● racket/gui              | ● srfi/provider           |
| ● at-exp scheme/base      | ● typed/racket            |
| ● at-exp racket/base      | ● typed-scheme/minimal    |
| ● scribble/doc            | ● r6rs                    |
| ● scribble/manual         | ● r5rs                    |
| ● scribble/base/reader    | ● setup/infotab           |
| ● scribble/lp             | ● everything else         |

Racket ships more than  
40 documented languages

```
#lang racket ; An echo server
(define listener (tcp-listen 12345))
(let echo-server ()
  (define-values (in out) (tcp-accept listener))
  (thread (lambda () (copy-port in out)
              (close-output-port out)))
  (echo-server)))
```

A modern programming language

```
#lang web-server/insta
; A "hello world" web server
(define (start request)
  (response/xexpr
    '(html
      (body "Hello World"))))
```

A language for writing web servers

```
#lang lazy
; An infinite list:
(define fibs
  (list* 1 1 (map + fibs (cdr fibs))))
; Print the 1000th Fibonacci number:
(print (list-ref fibs 1000))
```

Lazy evaluation

```
#lang scribble/base
@; Generate a PDF or HTML document
@title{Bottles --- @italic{Abridged}}
@(apply itemList
  (for/list ([n (in-range 100 0 -1)])
    @item{@(format "~a" n) bottles.}))
```

A domain-specific language (and syntax) for documentation



```
#lang datalog
ancestor(A, B) :- parent(A, B).
ancestor(A, B) :-
    parent(A, C), D = C, ancestor(D, B).
parent(john, douglas).
parent(bob, john).
ancestor(A, B)?
```

Integrated logic programming

```
#lang typed/racket
(struct: person ([first : String]
                [last  : String]))
(: greeting (person -> String))
(define (greeting n)
  (format "~a ~a"
          (person-first n) (person-last n)))
(greeting (make-person "Bob" "Smith"))
```

Racket with static types and full interoperation

## All built with macros

- Comprehensions
- Recursive Modules
- Logic Programming
- Classes, Mixins, Traits
- Generic Methods a la CLOS
- Documentation
- Contracts
- Lazy Programming
- Web Programming
- Lexing + Parsing
- Teaching

## All built with macros

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- Teaching
- **Typechecking**

## Are Macros Hard?

No

Macros are just programming with trees

Yes

Macros are metaprogramming

## Are Macros Hard?

No

Macros are just programming with trees

Yes

Macros are metaprogramming

Maybe

Macros are our best tool for managing metaprogramming

# The Plan

Pre-history: Macros to 1985 (Lisp)

The Hygiene Revolution (Scheme)

A Rich Macro API (Racket)

On to Typed Racket

# Macros in Lisp



What is a macro?

```
(defmacro (let-pair . args)
  '(let ((, (car args) (car , (caddr args)))
        (, (cadr args) (cdr , (caddr args))))
    ,(caddr args)))
```

What is a macro?

```
(defmacro (let-pair . args)
  '(let ((, (car args) (car , (caddr args)))
        (, (cadr args) (cdr , (caddr args))))
    , (caddr args)))

(let-pair a b (cons 1 2) (+ a b))
```

## What is a macro?

```
(defmacro (let-pair . args)
  '(let ((, (car args) (car , (caddr args)))
        (, (cadr args) (cdr , (caddr args))))
    , (caddr args)))
```

```
(let-pair a b (cons 1 2) (+ a b))
```



```
(let ((a (car (cons 1 2)))
      (b (cdr (cons 1 2))))
  (+ a b))
```

## How Lisp macros work

To evaluate `(let-pair body)`:

1. Call the definition of `let-pair` with *body*
2. Then *evaluate* the result

It's great!

Abstract over everything

Build DSLs

Simple reasoning about macros

It's great!

Abstract over everything

Build DSLs

Simple reasoning about macros

It's terrible!

Hard to program: witness `caddr`s

Imagine the error messages

Inherently buggy

# Hygienic Macros in Scheme

## Pattern-matching macros

```
(define-syntax-rule (let-pair x y p body)
  (let ([x (car p)] [y (cdr p)]) body))

(let-pair a b (cons 1 2) (+ a b))
```

→

```
(let ((a (car (cons 1 2))))
      (b (cdr (cons 1 2))))
  (+ a b))
```

Macro by Example [Kohlbecker & Wand 87]



## The hygiene bug

```
(define-syntax-rule (let-pair x y p body)
  (let ([x (car p)] [y (cdr p)]) body))

(let-pair a b (cons 1 2) (+ a b))
```

## The hygiene bug

```
(define-syntax-rule (let-pair x y p body)
  (let* ([a p] [x (car a)] [y (cdr a)]) body))

(let-pair a b (cons 1 2) (+ a b))
```

## The hygiene bug

```
(define-syntax-rule (let-pair x y p body)
  (let* ([a p] [x (car a)] [y (cdr a)]) body))

(let-pair a b (cons 1 2) (+ a b))
```

→

```
(let* ([a (cons 1 2)]
      [a (car a)]
      [b (cdr a)])
  (+ a b))
```

Uh-oh

## The solution

```
(define-syntax-rule (let-pair x y p body)
  (let* ([a p] [x (car a)] [y (cdr a)]) body))

(let-pair a b (cons 1 2) (+ a b))
```

→

```
(let* ([a1 (cons 1 2)]
      [a (car a1)]
      [b (cdr a1)])
  (+ a b))
```

[Kohlbecker et al 88, Clinger & Rees 91]

It's great!

Abstract over everything

Build DSLs

Simple reasoning about  
macros

Pattern matching

Automatic Hygiene

It's great!

Abstract over everything

Build DSLs

Simple reasoning about  
macros

Pattern matching

Automatic Hygiene

It's terrible!

Limited language

Error messages still not good

## syntax-case and syntax objects

```
(define-syntax (let-pair stx)
  (syntax-case stx ()
    [(_ x y p body)
     #'(let* ([a p] [x (car a)] [y (cdr a)])
         body)])

(let-pair a b (cons 1 2) (+ a b))

→

(let* ([a p] [a (car p)] [b (cdr p)])
  (+ a b))
```

## syntax-case and syntax objects

```
(define-syntax (let-pair stx)
  (syntax-case stx ()
    [(_ x y p body)
     #'(let* ([a p] [x (car a)] [y (cdr a)])
         body)])

(let-pair 0 1 (cons 1 2) (+ a b))
```

→

let\*: bad syntax (not an identifier) in: 0



## syntax-case and syntax objects

```
(define-syntax (let-pair stx)
  (syntax-case stx ()
    [(_ x y p body)
     (and (identifier? #'x) (identifier? #'y))
     #'(let* ([a p] [x (car a)] [y (cdr a)])
         body)]))
```

```
(let-pair 0 1 (cons 1 2) (+ a b))
```



**let-pair: bad syntax**

## syntax-case and syntax objects

```
(define-syntax (let-pair stx)
  (syntax-case stx ()
    [(_ x y p body)
     (unless (identifier? #'x)
       (raise-syntax-error "expected ..."))
     #'(let* ([a p] [x (car a)] [y (cdr a)])
         body)))]))
```

```
(let-pair 0 1 (cons 1 2) (+ a b))
```



**let-pair: expected an identifier first**

It's great!

Abstract over everything

Pattern matching

Build DSLs

Automatic Hygiene

Use the full language

Good error reporting

It's great!

Abstract over everything	Pattern matching
Build DSLs	Automatic Hygiene
Use the full language	Good error reporting

What's left?

Hard to understand  
Scale up from macros to languages

Racket

## Macros and modules

`util`

```
#lang racket  
  
(define (f x) ...)  
(provide f)
```

`mac`

```
#lang racket  
  
(require (for-syntax util))  
(define-syntax (mac stx)  
  (f stx))
```

## A powerful API

Extensible macros

Static binding

Just-once evaluation

Certificates for integrity

...

## Source tracking

Report errors using the original program

```
(let ([x 1]
      [2 y])
      (+ x y))
```



## Source tracking

Report errors using the original program

```
(let ([x 1]
      [2 y])
  (+ x y))
```

## Tools and experience

```
(define-syntax let-pair
  (syntax-parser
    [(_ x:id y:id p:expr body:expr)
     #'(let* ([a p] [x (car a)] [y (cdr a)])
         body)]))
```

Declarative, Robust, Programmed

# Tools and experience

The screenshot shows the Racket Macro Stepper interface. The main window displays a code transformation:

```
(module anonymous-module racket
  (#%module-begin
   (#%app
    call-with-values
    (lambda () (let-values (((x) (%datum . 1))) x))
    print-values)))
→ Macro transformation
(module anonymous-module racket
  (#%module-begin
   (#%app call-with-values (lambda () (let-values (((x) '1)) x)) print-values)))
```

The right-hand pane, titled "Syntax Object", provides a detailed explanation of the transformation:

**Apparent identifier binding**  
in the standard phase  
defined in: (quote (%kernel)  
as: %datum  
imported from: racket  
as: %datum  
via define-for-syntax  
in the transformer phase ("for-syntax")  
defined in: (quote (%kernel)  
as: %datum  
imported from: racket  
as: %datum  
via define-for-syntax  
in the template phase ("for-template")  
top-level or unbound

**Binding if used for %top**  
in the standard phase  
defined in: (quote (%kernel)  
as: %top  
imported from: racket  
as: %top  
via define-for-syntax  
in the transformer phase ("for-syntax")  
defined in: (quote (%kernel)  
as: %top  
imported from: racket  
as: %top

At the bottom, the "Macro hiding" section is visible, with options for "Custom ...", "Hide racket syntax", "Hide library syntax", and "Hide contracts (heuristic)".

## Tools and experience

15 years and 500,000 lines of macrology

[Flatt et al 02, 06, 09]

[Culpepper et al 04, 05, 07, 10]

[Eastlund et al 10]

[McCarthy et al 08]

# Typed Racket in 3 Slides

# Hello World

```
#lang racket  
(printf "Hello world\n")
```

```
hello
```

# Hello World

```
#lang typed/racket
```

```
(printf "Hello world\n")
```

```
hello
```

## Functions

```
#lang racket

; ack : Integer Integer -> Integer
(define (ack m n)
  (cond [(<= m 0) (+ n 1)]
        [(<= n 0) (ack (- m 1) 1)]
        [else (ack (- m 1) (ack m (- n 1)))]))

(ack 2 3)
```

ack



## Functions

```
#lang typed/racket
```

```
ack
```

```
(: ack : Integer Integer -> Integer)
(define (ack m n)
  (cond [(<= m 0) (+ n 1)]
        [(<= n 0) (ack (- m 1) 1)]
        [else (ack (- m 1) (ack m (- n 1)))]))

(ack 2 3)
```

## Modules

```
#lang racket  
  
; ack : Integer Integer -> Integer  
(define (ack m n)  
  (cond [(<= m 0) (+ n 1)]  
        [(<= n 0) (ack (- m 1) 1)]  
        [else (ack (- m 1) (ack m (- n 1)))])))
```

ack

```
#lang racket  
  
(require ack)  
  
(ack 2 3)
```

compute

## Modules

```
#lang typed/racket
```

```
ack
```

```
(: ack : Integer Integer -> Integer)
(define (ack m n)
  (cond [(<= m 0) (+ n 1)]
        [(<= n 0) (ack (- m 1) 1)]
        [else (ack (- m 1) (ack m (- n 1)))])))
```

```
#lang racket
```

```
compute
```

```
(require ack)
```

```
(ack 2 3)
```

## Modules

```
#lang racket
; ack : Integer Integer -> Integer
(define (ack m n)
  (cond [(<= m 0) (+ n 1)]
        [(<= n 0) (ack (- m 1) 1)]
        [else (ack (- m 1) (ack m (- n 1)))]))
```

ack

```
#lang typed/racket
(require [ack
         (Integer Integer -> Integer)])
(ack 2 3)
```

compute

## Modules

```
#lang typed/racket
```

```
ack
```

```
(: ack : Integer Integer -> Integer)
(define (ack m n)
  (cond [(<= m 0) (+ n 1)]
        [(<= n 0) (ack (- m 1) 1)]
        [else (ack (- m 1) (ack m (- n 1)))]))
```

```
#lang typed/racket
```

```
compute
```

```
(require ack)
```

```
(ack 2 3)
```

# Building Typed Racket

## Whole modules

Static semantics requires control

```
#lang typed/racket
```

```
ack
```

```
(: ack : Integer Integer -> Integer)
(define (ack m n)
  (cond [(<= m 0) (+ n 1)]
        [(<= n 0) (ack (- m 1) 1)]
        [else (ack (- m 1) (ack m (- n 1)))]))

(ack 2 3)
```

## Whole modules

Static semantics requires control

```
#lang typed/racket
```

```
ack
```

```
(#%module-begin
 (: ack : Integer Integer -> Integer)
 (define (ack m n)
  (cond [(<= m 0) (+ n 1)]
        [(<= n 0) (ack (- m 1) 1)]
        [else (ack (- m 1) (ack m (- n 1)))]))

(ack 2 3))
```



## Whole modules

Static semantics requires control

```
#lang typed/racket
(#%module-begin
 (: ack : Integer Integer -> Integer)
 (define (ack m n)
  (cond [(<= m 0) (+ n 1)]
        [(<= n 0) (ack (- m 1) 1)]
        [else (ack (- m 1) (ack m (- n 1)))]))

(ack 2 3))
```

ack

## Defining A Language

```
(define-syntax (%module-begin stx)
  (syntax-parse stx
    [(_ forms ...)
     (let ()
       (for ([f (syntax->list #'(forms ...))])
         (typecheck f))
       #'(%plain-module-begin forms ...))])])
```

## Typechecking

```
(define (typecheck f)
  (syntax-parse f
    ; variables
    [v:identifier
     (lookup-type #'v)]
    ; abstractions
    [(lambda (x) e)
     (define t (syntax-property #'x 'type-label))
     (set-type! #'x t)
     (typecheck #'e)]
    ; about 10 more cases
    ....))
```

## Typechecking

```
(define (typecheck f)
  (syntax-parse f
    ; variables
    [v:identifier
     (lookup-type #'v)]
    ; abstractions
    [(lambda (x) e)
     (define t (syntax-property #'x 'type-label))
     (set-type! #'x t)
     (typecheck #'e)]
    ; about 10 more cases
    ....))
```

## Defining A Language

```
(define-syntax (%module-begin stx)
  (syntax-parse stx
    [(_ forms ...)
     (let ()
       (for ([f (syntax->list #'(forms ...))])
         (typecheck f)))
     #'(%plain-module-begin forms ...))])
```

## local-expand

Core forms support arbitrary macros

```
(: ack : Integer Integer -> Integer)
(define (ack m n)
  (cond [(<= m 0) (+ n 1)]
        [(<= n 0) (ack (- m 1) 1)]
        [else (ack (- m 1) (ack m (- n 1)))]))
```

Discover static semantics by expansion

## Defining A Language

```
(define-syntax (%module-begin stx)
  (syntax-parse stx
    [(_ forms ...)
     (let ([forms* (local-expand #'(forms ...))]
           (for ([f (rest (syntax->list forms*))])
                 (typecheck f))
           #'(%plain-module-begin #, forms*))])])])
```

## Typechecking

```
(define (typecheck f)
  (syntax-parse f
    ; variables
    [v:identifier
     (lookup-type #'v)]
    ; abstractions
    [(lambda (x) e)
     (define t (syntax-property #'x 'type-label))
     (set-type! #'x t)
     (typecheck #'e)]
    ; about 10 more cases
    ....))
```

Syntax properties provide side-channels



## Defining A Language

```
(define-syntax (%module-begin stx)
  (syntax-parse stx
    [(_ forms ...)
     (let ([forms* (local-expand #'(forms ...))]
           (for ([f (rest (syntax->list forms*))])
                (typecheck f))
           #'(%plain-module-begin #, forms*))])])])
```

## Defining A Language

```
(define-syntax (#%module-begin stx)
  (syntax-parse stx
    [(_ forms ...)
     (let ([forms* (local-expand #'(forms ...))]
           (for ([f (rest (syntax->list forms*))])
                 (typecheck f))
           (let ([forms** (optimize forms*)])
                 #'(plain-module-begin #, forms**)))]))])
```

# Optimization

Express guarantees as rewritings

```
(: norm : Float Float -> Float)
(define (norm x y)
  (sqrt (+ (sqr x) (sqr y))))
```

# Optimization

Express guarantees as rewritings

```
(: norm : Float Float -> Float)
(define (norm x y)
  (unsafe-flsqrt
   (unsafe-fl+ (unsafe-fl* x x) (unsafe-fl* y y))))
```

## The take-away

Language are powerful abstractions

Racket helps us build new, integrated languages

Whole-module control

Local expansion

Optimization via rewriting



Thanks!

Available from  
[racket-lang.org](http://racket-lang.org)

Supported by the Mozilla Foundation