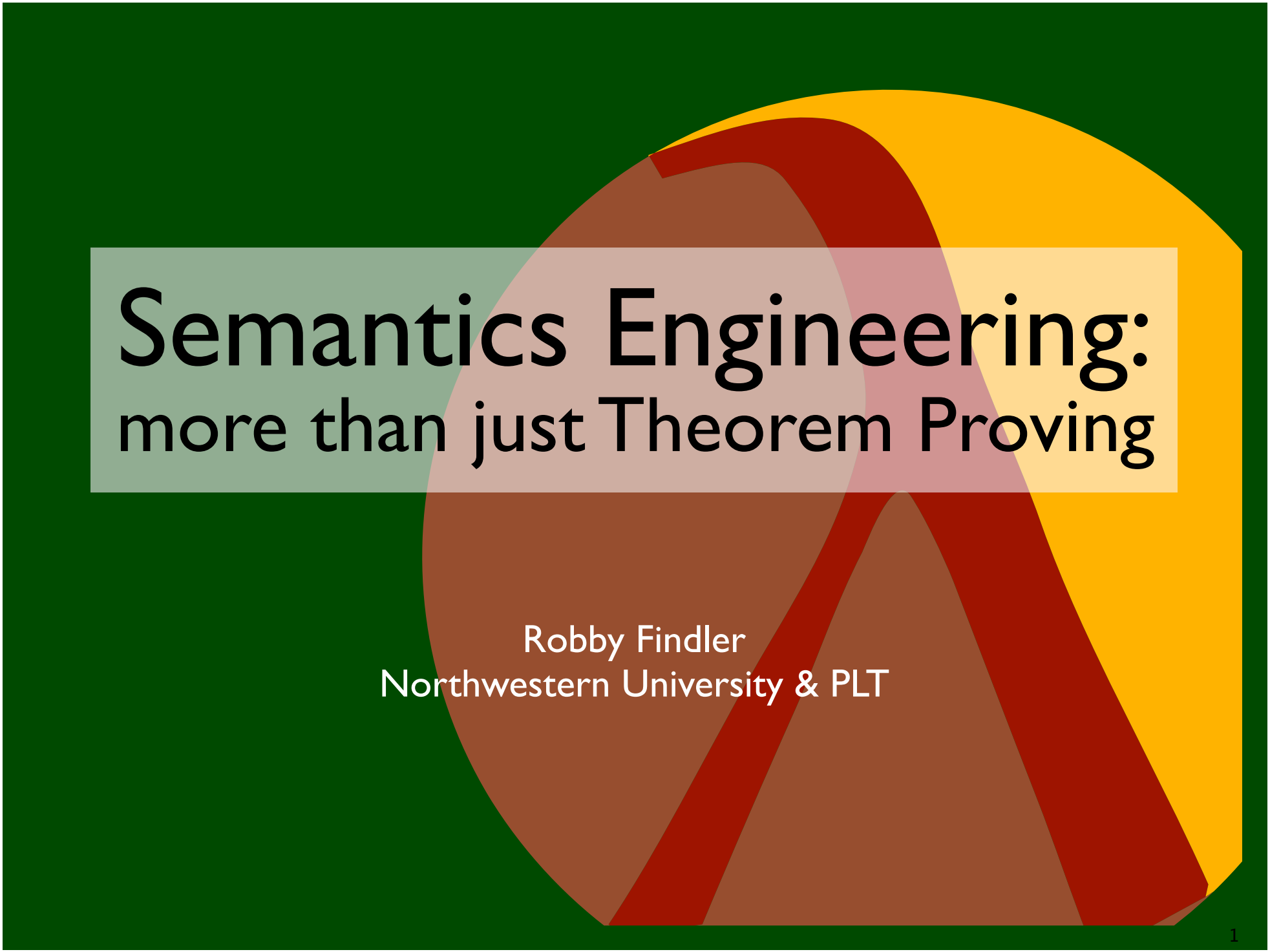
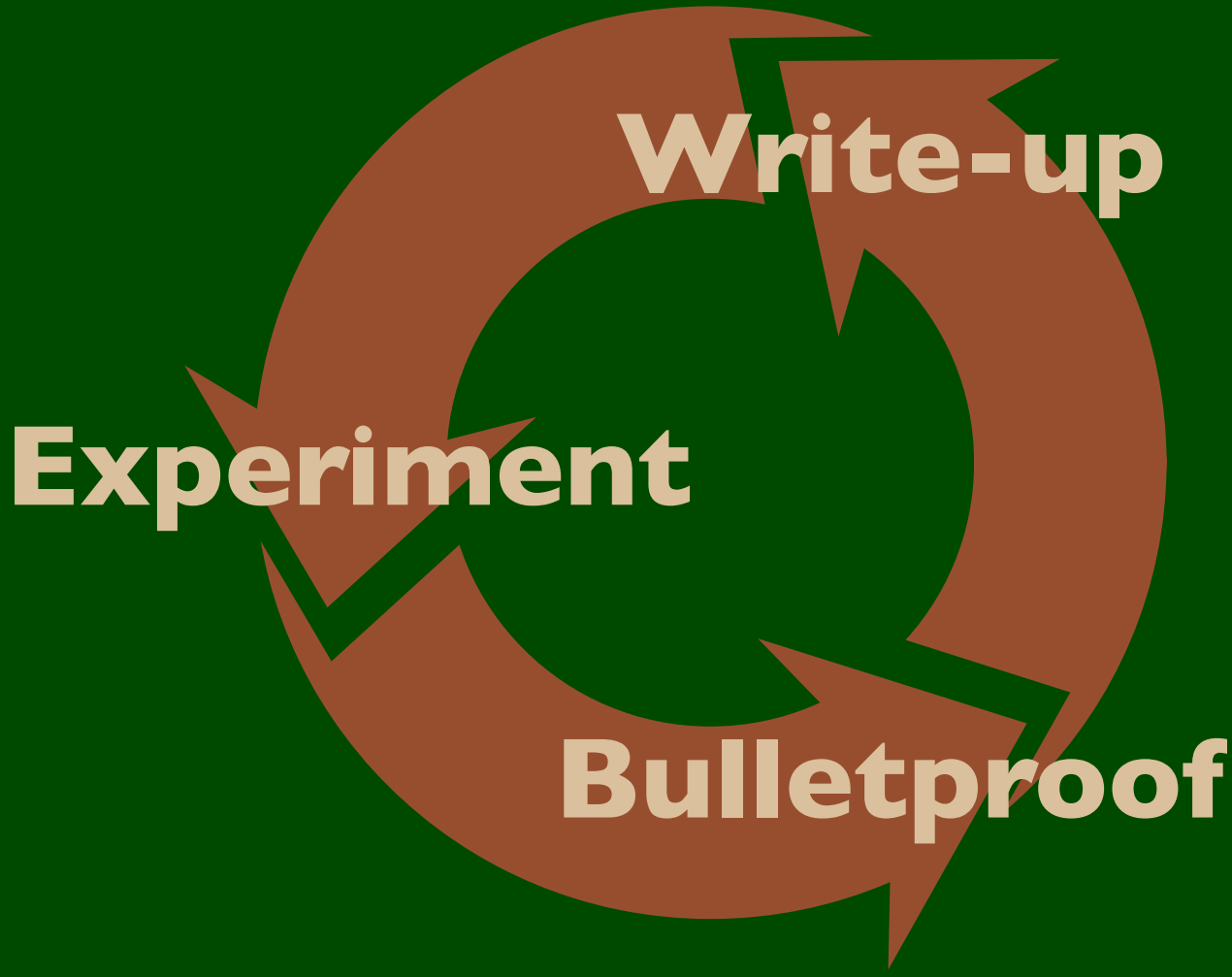

Semantics Engineering:
more than just Theorem Proving
Robby Findler
Northwestern University & PLT

Casey Klein

Semantics Lifecycle



Outline

- **An overview of Redex**
- **An in-class assignment**

Outline

- **An overview of Redex**
  - Operational semantics
  - Redex's DSL & tools
  - First-order class model
- **An in-class assignment**
  - Develop a higher-order variant of model
  - How good is random testing?
  - Plug for Racket's class system

$\mathcal{E}val$: program ⇸ answer

$\mathcal{E}val$(p) = a iff ⋯ p ⋯ a ⋯

$\mathcal{E}val$: program $\twoheadrightarrow$ answer

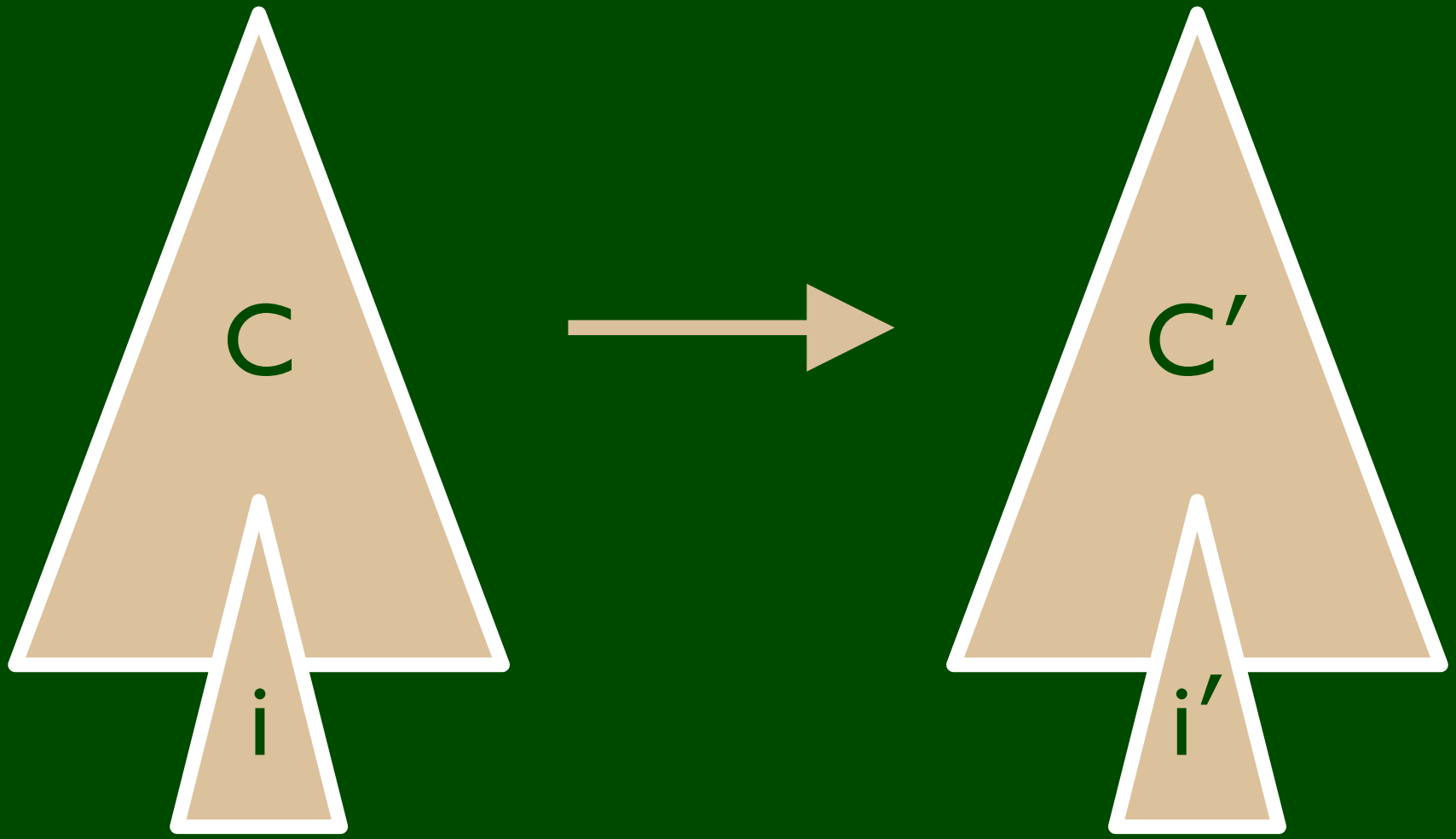
$\mathcal{E}val(p) = a$ iff $p \longrightarrow^{*} a$

where

answer $\subset$ program

$\longrightarrow \subset$ program $\times$ program

Reduction



Semantics Recap

- Specify programs & answers (grammar)
- Specify evaluation contexts (grammar)
- Specify a reduction relation

```
p ::= (begin d ... e)
d ::= (define z c)
c ::= (class object%
        (init-field i)
        m ...
        (super-make-object))
m ::= (define/public (x y ...)
        e)
e ::= (make-object x e)
    | (send e x e ...)
    | x
    | this
    | number
    | (if0 e e e)
    | (+ e ...)
```

```
p ::= (begin d ... e)
d ::= (define z c)
c ::= (class object%
        (init-field i)
        m ...
        (super-make-object))
m ::= (define/public (x y ...)
        e)
e ::= (make-object x e)
    | (send e x e ...)
    | x
    | this
    | number
    | (if0 e e e)
    | (+ e ...)
```

```
(define-language Roo
  (p (begin d ... e))
  (d (define z c))
  (c (class object%
       (init-field i)
       m ...
       (super-make-object)))
  (m (define/public (x y ...)
       e))
  (e (make-object x e)
     (send e x e ...)
     x
     this
     number
     (if0 e e e)
     (+ e ...)))
```

```
p ::= (begin d ... e)
d ::= (define z c)
c ::= (class object%
        (init-field i)
        m ...
        (super-make-object))
m ::= (define/public (x y ...)
        e)
e ::= (make-object x e)
    | (send e x e ...)
    | x
    | this
    | number
    | (if0 e e e)
    | (+ e ...)
```

```
(define-language Roo
  (p (begin d ... e))
  (d (define z c))
  (c (class object%
       (init-field i)
       m ...
       (super-make-object)))
  (m (define/public (x y ...)
       e))
  (e (make-object x e)
     (send e x e ...)
     x
     this
     number
     (if0 e e e)
     (+ e ...))
  ((i x y z)
   variable-not-otherwise-mentioned))
```

A grammar associates non-terminals with patterns; parens are significant, indicating tree structure (aka "regular tree grammars")

```
(define-language Roo
  (p (begin d ... e))
  (d (define z c))
  (c (class object%
       (init-field i)
       m ...
       (super-make-object)))
  (m (define/public (x y ...)
       e))
  (e (make-object x e)
     (send e x e ...)
     x
     this
     number
     (if0 e e e)
     (+ e ...))
  ((i x y z)
   variable-not-otherwise-mentioned))
```

Some patterns, e.g. **number**, are like built-in non-terminals; in this case matching all Racket numbers

```
(define-language Roo
  (p (begin d ... e))
  (d (define z c))
  (c (class object%
       (init-field i)
       m ...
       (super-make-object)))
  (m (define/public (x y ...)
       e))
  (e (make-object x e)
     (send e x e ...)
     x
     this
     number
     (if0 e e e)
     (+ e ...))
  ((i x y z)
   variable-not-otherwise-mentioned))
```

The ellipsis is a Kleene star; a post-fix operator that allows zero or more repetitions of the pattern it follows

```
(define-language Roo
  (p (begin d ... e))
  (d (define z c))
  (c (class object%
       (init-field i)
       m ...
       (super-make-object)))
  (m (define/public (x y ...)
       e))
  (e (make-object x e)
     (send e x e ...)
     x
     this
     number
     (if0 e e e)
     (+ e ...))
  ((i x y z)
   variable-not-otherwise-mentioned))
```

These are the non-terminals; the definitions come from the grammar

```
(define-language Roo
  (p (begin d ... e))
  (d (define z c))
  (c (class object%
       (init-field i)
       m ...
       (super-make-object)))
  (m (define/public (x y ...)
       e))
  (e (make-object x e)
     (send e x e ...)
     x
     this
     number
     (if0 e e e)
     (+ e ...))
  ((i x y z)
   variable-not-otherwise-mentioned))
```

Which leaves the literals; this is a catch-all category and they act like keywords for the language

```
(define-language Roo
  (p (begin d ... e))
  (d (define z c))
  (c (class object%
       (init-field i)
       m ...
       (super-make-object)))
  (m (define/public (x y ...)
       e))
  (e (make-object x e)
     (send e x e ...)
     x
     this
     number
     (if0 e e e)
     (+ e ...))
  ((i x y z)
   variable-not-otherwise-mentioned))
```

This pattern matches any identifier except literals (making it sensitive to the language where it appears)

```
(define-language Roo
  (p (begin d ... e))
  (d (define z c))
  (c (class object%
       (init-field i)
       m ...
       (super-make-object)))
  (m (define/public (x y ...)
       e))
  (e (make-object x e)
     (send e x e ...)
     x
     this
     number
     (if0 e e e)
     (+ e ...))
  ((i x y z)
   variable-not-otherwise-mentioned))
```

Enough of Redex—now for the language; a program consists of definitions & an expression

```
(define-language Roo
  (p (begin d ... e))
  (d (define z c))
  (c (class object%
       (init-field i)
       m ...
       (super-make-object)))
  (m (define/public (x y ...)
       e))
  (e (make-object x e)
     (send e x e ...)
     x
     this
     number
     (if0 e e e)
     (+ e ...))
  ((i x y z)
   variable-not-otherwise-mentioned))
```

Definitions pair variables with classes

```
(define-language Roo
  (p (begin d ... e))
  (d (define z c))
  (c (class object%
       (init-field i)
       m ...
       (super-make-object)))
  (m (define/public (x y ...)
       e))
  (e (make-object x e)
     (send e x e ...)
     x
     this
     number
     (if0 e e e)
     (+ e ...))
  ((i x y z)
   variable-not-otherwise-mentioned))
```

Each class has a single initialization argument `i`, a bunch of methods, and a call to **`super-make-object`**; much of this is to mimic the syntactic structure of Racket's class system

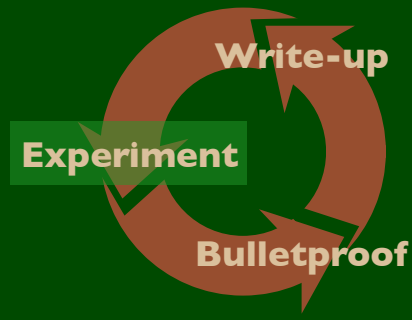
```
(define-language Roo
  (p (begin d ... e))
  (d (define z c))
  (c (class object%
       (init-field i)
       m ...
       (super-make-object)))
  (m (define/public (x y ...)
       e))
  (e (make-object x e)
     (send e x e ...)
     x
     this
     number
     (if0 e e e)
     (+ e ...))
  ((i x y z)
   variable-not-otherwise-mentioned))
```

Each method has a name **x**, multiple arguments **y**, and a body **e**

```
(define-language Roo
  (p (begin d ... e))
  (d (define z c))
  (c (class object%
       (init-field i)
       m ...
       (super-make-object)))
  (m (define/public (x y ...)
       e))
  (e (make-object x e)
     (send e x e ...)
     x
     this
     number
     (if0 e e e)
     (+ e ...))
  ((i x y z)
   variable-not-otherwise-mentioned))
```

Expressions either are object creation, method invocation, variables, the **`this`** keyword, numbers, conditionals, or addition expressions

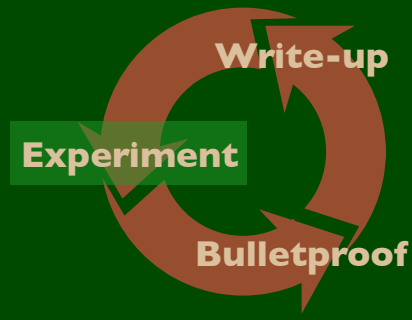
```
(define-language Roo
  (p (begin d ... e))
  (d (define z c))
  (c (class object%
       (init-field i)
       m ...
       (super-make-object)))
  (m (define/public (x y ...)
       e))
  (e (make-object x e)
     (send e x e ...)
     x
     this
     number
     (if0 e e e)
     (+ e ...))
  ((i x y z)
   variable-not-otherwise-mentioned))
```




```
> (redex-match Roo
               (+ e_1 e_2)
               (term (+ (if0 1 2 3)
                        4)))

(list
 (match
  (list
   (bind 'e_1 '(if0 1 2 3))
   (bind 'e_2 4))))
```

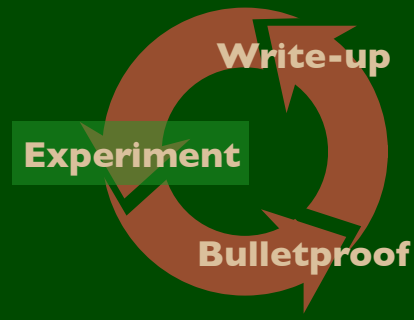
A **redex-match** expression accepts a language, a pattern, and a term; it tests the pattern against the expression and returns bindings for the pattern variables




```
> (redex-match Roo
               (+ e_1 e_2)
               (term (+ (if0 1 2 3)
                        4)))

(list
 (match
  (list
   (bind 'e_1 '(if0 1 2 3))
   (bind 'e_2 4))))
```

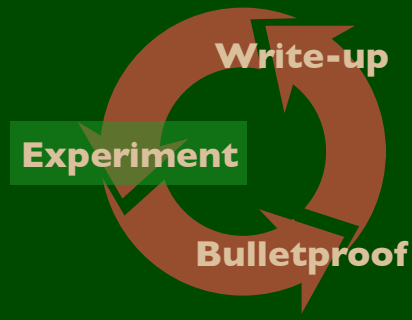
A **redex-match** expression accepts a language, a pattern, and a term; it tests the pattern against the expression and returns bindings for the pattern variables




```
> (redex-match Roo
               (+ e_1 e_2)
               (term (+ (if0 1 2 3)
                        4)))

(list
 (match
  (list
   (bind 'e_1 '(if0 1 2 3))
   (bind 'e_2 4))))
```

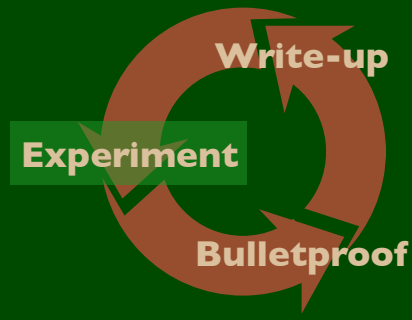
A **redex-match** expression accepts a language, a pattern, and a term; it tests the pattern against the expression and returns bindings for the pattern variables




```
> (redex-match Roo
               (+ e_1 e_2)
               (term (+ (if0 1 2 3)
                        4)))

(list
 (match
  (list
   (bind 'e_1 '(if0 1 2 3))
   (bind 'e_2 4))))
```

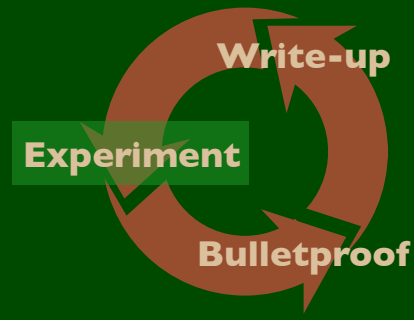
A **redex-match** expression accepts a language, a pattern, and a term; it tests the pattern against the expression and returns bindings for the pattern variables




```
> (redex-match Roo
                (+ e_1 e_2)
                (term (+ (if0 1 2 3)
                         4)))
```

```
(list
 (match
  (list
   (bind 'e_1 '(if0 1 2 3))
   (bind 'e_2 4))))
```

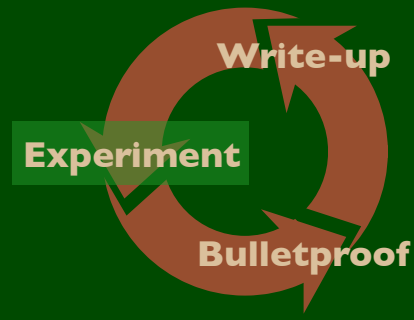
A **redex-match** expression accepts a language, a pattern, and a term; it tests the pattern against the expression and returns bindings for the pattern variables




```
> (redex-match Roo
               (+ e ...)
               (term (+ (if0 1 2 3)
                        4)))

(list
 (match
  (list
   (bind 'e '((if0 1 2 3) 4)))))
```

When a pattern variable is behind an ellipsis, it is bound to a list whose elements match pieces of the term




```
> (redex-match
   Roo
   (+ e_1 ... e_2 e_3 ...)
   (term (+ 1 2 3)))
(list
 (match
  (list
   (bind 'e_1 '(1 2))
   (bind 'e_2 3)
   (bind 'e_3 '())))
 (match
  (list
   (bind 'e_1 '(1))
   (bind 'e_2 2)
   (bind 'e_3 '(3))))
 (match
  (list
   (bind 'e_1 '())
   (bind 'e_2 1)
   (bind 'e_3 '(2 3)))))
```

Doubled ellipses are ambiguous; so here we get three possible matches, with `e_2` taking on either 1, 2, or 3, and `e_1` and `e_3` abosrbing the remaining numbers

Evaluation contexts, answers, and values

a ::= (**begin** d ... v)
v ::= (**make-object** x v)
| *number*
P ::= (**begin** d ... E)
E ::= (**make-object** x E)
| (**send** E x e ...)
| (**send** v x v ... E e ...)
| (**if0** E e e)
| (+ v ... E e ...)
| []

```
(a (begin d ... v))
(v (make-object x v)
   number)
(P (begin d ... E))
(E (make-object x E)
   (send E x e ...)
   (send v x v ... E e ...)
   (if0 E e e)
   (+ v ... E e ...)
   hole)
```

Evaluation contexts, answers, and values

The only new pattern here, **`hole`**, collaborates with **`in-hole`** to decompose terms into contexts and expressions at the hole

```
(a (begin d ... v))
(v (make-object x v)
   number)
(P (begin d ... E))
(E (make-object x E)
   (send E x e ...)
   (send v x v ... E e ...)
   (if0 E e e)
   (+ v ... E e ...)
   hole)
```

Evaluation contexts, answers, and values

An answer is the final result from a program, definitions plus a value

```
(a (begin d ... v))
(v (make-object x v)
   number)
(P (begin d ... E))
(E (make-object x E)
   (send E x e ...)
   (send v x v ... E e ...)
   (if0 E e e)
   (+ v ... E e ...)
   hole)
```

Evaluation contexts, answers, and values

Values are objects and numbers

```
(a (begin d ... v))
(v (make-object x v)
   number)
(P (begin d ... E))
(E (make-object x E)
   (send E x e ...)
   (send v x v ... E e ...)
   (if0 E e e)
   (+ v ... E e ...)
   hole)
```

Evaluation contexts, answers, and values

P stands for a program evaluation context; evaluation only happens in the main expression

```
(a (begin d ... v))
(v (make-object x v)
   number)
(P (begin d ... E))
(E (make-object x E)
   (send E x e ...)
   (send v x v ... E e ...)
   (if0 E e e)
   (+ v ... E e ...)
   hole)
```

Evaluation contexts, answers, and values

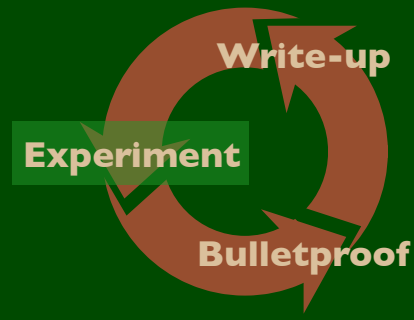
Expression evaluation can happen in the argument to `make-object`, in `send` expressions, `if0` expressions, and `+` expressions

```
(a (begin d ... v))
(v (make-object x v)
   number)
(P (begin d ... E))
(E (make-object x E)
   (send E x e ...)
   (send v x v ... E e ...)
   (if0 E e e)
   (+ v ... E e ...)
   hole)
```

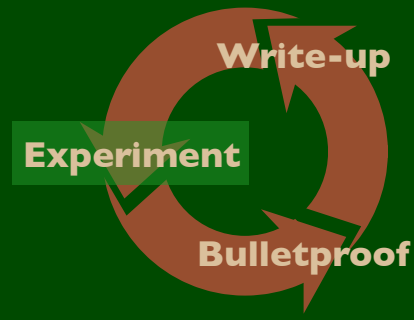
Evaluation contexts, answers, and values

Note that use of doubled ellipses forcing left-to-right order of evaluation

```
(a (begin d ... v))
(v (make-object x v)
   number)
(P (begin d ... E))
(E (make-object x E)
   (send E x e ...)
   (send v x v ... E e ...)
   (if0 E e e)
   (+ v ... E e ...)
   hole)
```




```
> (redex-match
   Roo
   (in-hole E (+ number_1 number_2))
   (term (if0 (+ 1 2) 3 4)))
(list
 (match
  (list
   (bind 'E (list 'if0 (hole) 3 4))
   (bind 'number_1 1)
   (bind 'number_2 2))))
```




```
> (redex-match
   Roo
   (in-hole E e)
   (term (if0 (+ 1 2) 3 4)))
(list
 (match
  (list
   (bind 'e '(+ 1 2))
   (bind 'E (list 'if0 (hole) 3 4))))
 (match
  (list
   (bind 'e 2)
   (bind 'E (list 'if0 (list '+ 1 (hole)) 3 4))))
 (match
  (list
   (bind 'e '(if0 (+ 1 2) 3 4))
   (bind 'E (hole))))
 (match
  (list
   (bind 'e 1)
   (bind 'E (list 'if0 (list '+ (hole) 2) 3 4)))))
```

$$P[\,\texttt{(+}\ \textit{number}\ \texttt{...)}\,] \longrightarrow P[\Sigma[\![\textit{number}\ \texttt{...}]\!]] \quad [+]$$

$$P[\,\texttt{(if0}\ 0\ e_1\ e_2\texttt{)}\,] \longrightarrow P[e_1] \quad [\text{if0t}]$$

$$P[\,\texttt{(if0}\ \textit{number}\ e_1\ e_2\texttt{)}\,] \longrightarrow P[e_2] \quad [\text{if0f}]$$

where $\textit{number} \neq 0$

```
(define num-rules
  (reduction-relation
   Roo
   (--> (in-hole P (+ number ...))
        (in-hole P (Σ number ...))
        "+")
   (--> (in-hole P (if0 0 e_1 e_2))
        (in-hole P e_1)
        "if0t")
   (--> (in-hole P (if0 number e_1 e_2))
        (in-hole P e_2)
        (side-condition (term (nonzero number)))
        "if0f")))
(define-metafunction Roo
  Σ : number ... -> number
  [(Σ number ...) ,(apply + (term (number ...)))])
```

```
(define num-rules
  (reduction-relation
   Roo
   (--> (in-hole P (+ number ...))
        (in-hole P (Σ number ...))
        "+")
   (--> (in-hole P (if0 0 e_1 e_2))
        (in-hole P e_1)
        "if0t")
   (--> (in-hole P (if0 number e_1 e_2))
        (in-hole P e_2)
        (side-condition (term (nonzero number)))
        "if0f")))
(define-metafunction Roo
  Σ : number ... -> number
  [(Σ number ...) ,(apply + (term (number ...)))])
```

Three reduction rules; the prefix operator `-->` introduces each one

```
(define num-rules
  (reduction-relation
   Roo
   (--> (in-hole P (+ number ...))
        (in-hole P (Σ number ...))
        "+")
   (--> (in-hole P (if0 0 e_1 e_2))
        (in-hole P e_1)
        "if0t")
   (--> (in-hole P (if0 number e_1 e_2))
        (in-hole P e_2)
        (side-condition (term (nonzero number)))
        "if0f")))
(define-metafunction Roo
  Σ : number ... -> number
  [(Σ number ...) ,(apply + (term (number ...)))])
```

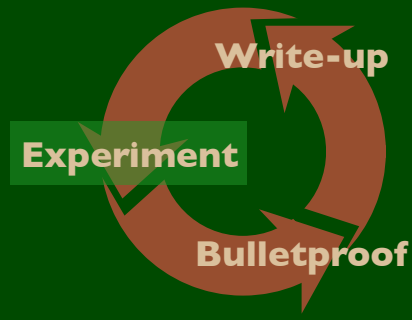
+ reduces via the metafunction Σ (redex supports unicode so Σ is just a regular identifier)

```
(define num-rules
  (reduction-relation
   Roo
   (--> (in-hole P (+ number ...))
        (in-hole P (Σ number ...))
        "+")
   (--> (in-hole P (if0 0 e_1 e_2))
        (in-hole P e_1)
        "if0t")
   (--> (in-hole P (if0 number e_1 e_2))
        (in-hole P e_2)
        (side-condition (term (nonzero number)))
        "if0f")))
(define-metafunction Roo
  Σ : number ... -> number
  [(Σ number ...) ,(apply + (term (number ...)))])
```

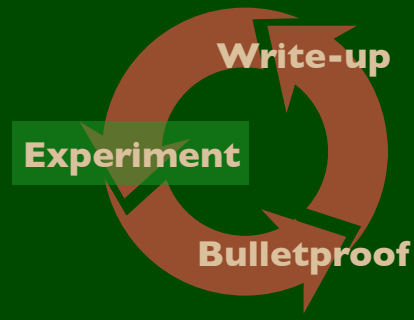
The comma means unquote, so we are just exploiting Racket's + to implement addition in the model

```
(define num-rules
  (reduction-relation
   Roo
   (--> (in-hole P (+ number ...))
        (in-hole P (Σ number ...))
        "+")
   (--> (in-hole P (if0 0 e_1 e_2))
        (in-hole P e_1)
        "if0t")
   (--> (in-hole P (if0 number e_1 e_2))
        (in-hole P e_2)
        (side-condition (term (nonzero number)))
        "if0f")))
(define-metafunction Roo
  Σ : number ... -> number
  [(Σ number ...) ,(apply + (term (number ...)))])
```

The first if0 rule uses the literal 0 but the second has to use a trivial metafunction (not shown) to test non-zeroness

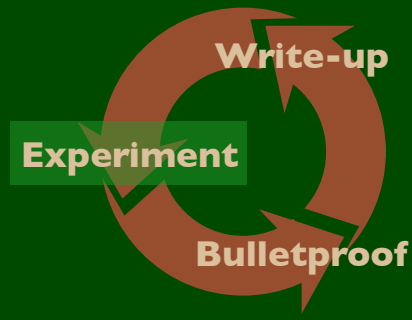


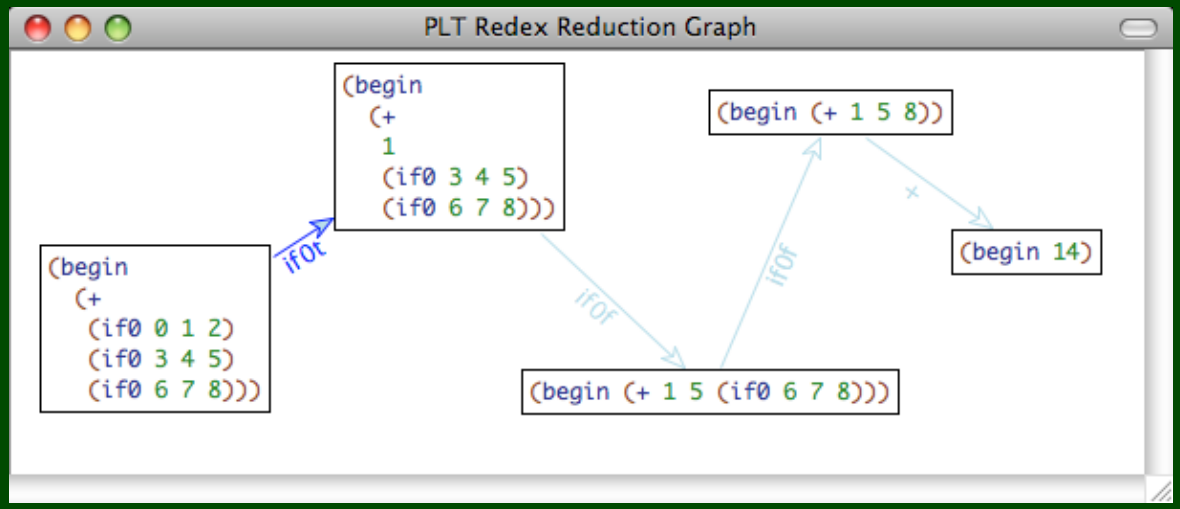

```
> (apply-reduction-relation
   num-rules
   (term (begin (if0 (+ 1 2) 3 4))))
'((begin (if0 3 3 4)))
```




```
> (traces
   num-rules
   (term (begin (+ (if0 0 1 2)
                   (if0 3 4 5)
                   (if0 6 7 8)))))
```

Run


Write-up
Experiment
Bulletproof


PLT Redex Reduction Graph
(begin
(+
(if0 0 1 2)
(if0 3 4 5)
(if0 6 7 8)))
if0r
(begin
(+
1
(if0 3 4 5)
(if0 6 7 8)))
if0r
(begin (+ 1 5 8))
x
(begin 14)
if0r
(begin (+ 1 5 (if0 6 7 8)))

```
(begin                                          (begin
  d1 ...                                          d1 ...
  (define z                                       (define z
    (class object%                                  (class object%
      (init-field i)                                  (init-field i)
      m1 ...                                          m1 ...
      (define/public (x y ...)                        (define/public (x y ...)
        e)                                              e)
      m2 ...                                          m2 ...
      (super-make-object)))                           (super-make-object)))
  d2 ...                                          d2 ...
  E[(send (make-object z vi)                      E[e{y := vy ...,
          x                                           i := vi,
          vy ...)])                                   this := (make-object z vi)}])
```

⟶ [send]

```
(begin
  d_1 ...
  (define z
    (class object%
      (init-field i)
      m_1 ...
      (define/public (x y ...) e)
      m_2 ...
      (super-make-object)))
  d_2 ...
  (in-hole E (send (make-object z v_i)
                   x
                   v_y ...)))
```

Begin reading at the bottom, in the main expression; this is a method invocation, with arguments `v_y ...` to an object of class `z` with init field `v_i`

```
(begin
  d_1 ...
   (define z
     (class object%
       (init-field i)
       m_1 ...
       (define/public (x y ...) e)
       m_2 ...
       (super-make-object)))
  d_2 ...
   (in-hole E (send (make-object z v_i)
                    x
                    v_y ...)))
```

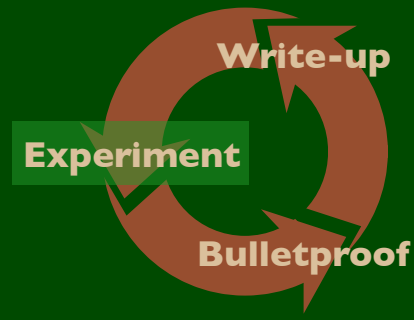
Since the z appears twice, it must be the same identifier; this forces the `d_1` and `d_2` to "absorb" all of the irrelevant class definitions

```
(begin
  d_1 ...
  (define z
    (class object%
      (init-field i)
      m_1 ...
      (define/public (x y ...) e)
      m_2 ...
      (super-make-object)))
  d_2 ...
  (in-hole E (send (make-object z v_i)
                   x
                   v_y ...)))
```

Ditto for `m_1` and `m_2` absorbing all of the irrelevant methods

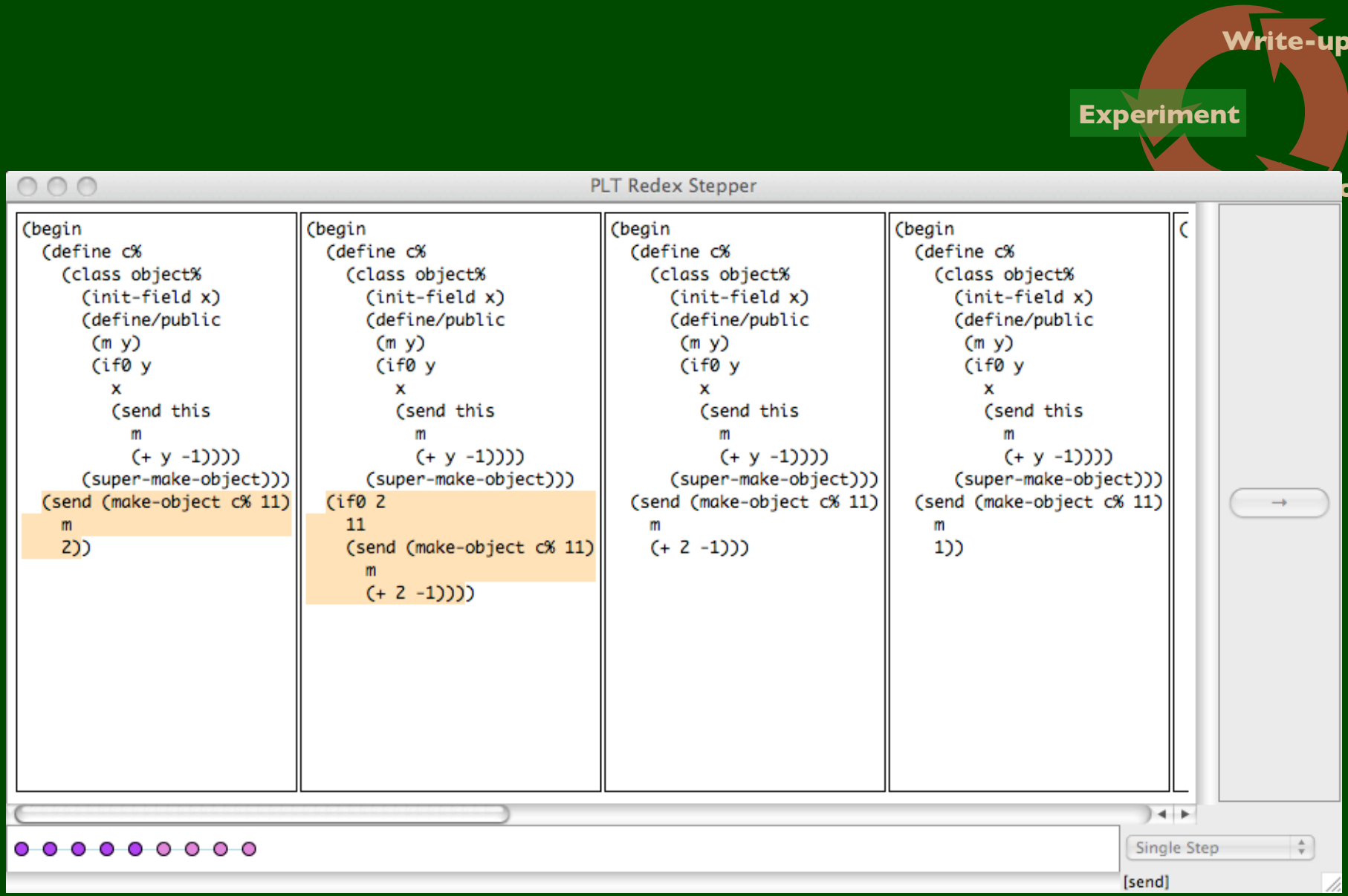
```
(begin
  d_1 ...
  (define z
    (class object%
      (init-field i)
      m_1 ...
      (define/public (x y ...) e)
      m_2 ...
      (super-make-object)))
  d_2 ...
  (in-hole E (substs-e e
                       (y v_y) ...
                       (i v_i)
                       (this
                        (make-object z v_i)))))
```

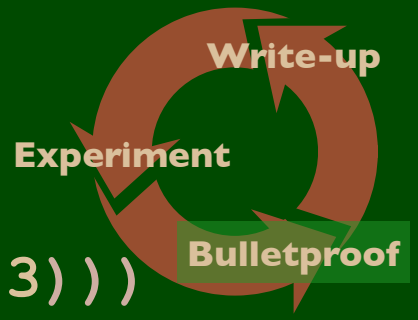
This, the right-hand side of the rule, is just like the left, except we replace method invoation with the body of the method, modulo appropriate substitutions



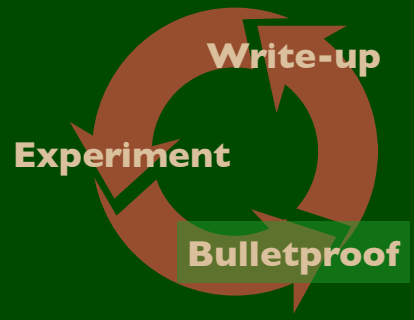

```
> (stepper
   red
   (term (begin
           (define c%
             (class object%
               (init-field x)
               (define/public (m y)
                 (if0 y
                      x
                      (send this m (+ y -1))))
               (super-make-object)))
           (send (make-object c% 11) m 2))))
```

Run


Write-up
Experiment
of
PLT Redex Stepper
(begin
(define c%
(class object%
(init-field x)
(define/public
(m y)
(if0 y
x
(send this
m
(+ y -1))))
(super-make-object)))
(send (make-object c% 11)
m
2))
(begin
(define c%
(class object%
(init-field x)
(define/public
(m y)
(if0 y
x
(send this
m
(+ y -1))))
(super-make-object)))
(if0 2
11
(send (make-object c% 11)
m
(+ 2 -1))))
(begin
(define c%
(class object%
(init-field x)
(define/public
(m y)
(if0 y
x
(send this
m
(+ y -1))))
(super-make-object)))
(send (make-object c% 11)
m
(+ 2 -1)))
(begin
(define c%
(class object%
(init-field x)
(define/public
(m y)
(if0 y
x
(send this
m
(+ y -1))))
(super-make-object)))
(send (make-object c% 11)
m
1))
(
→
Single Step
[send]

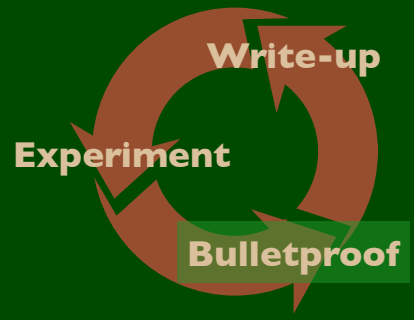



```
> (test-->> red
            (term (begin (if0 1 2 3)))
            (term (begin 3)))
> (test-->> red
            (term (begin (if0 0 1 2)))
            (term (begin 2)))
FAILED slides.rkt:124.11
expected: '(begin 2)
  actual: '(begin 1)
> (test-->> red
            (term (begin (+ 1 2 3 4)))
            (term (begin 10)))
> (test-results)
1 test failed (out of 3 total).
```



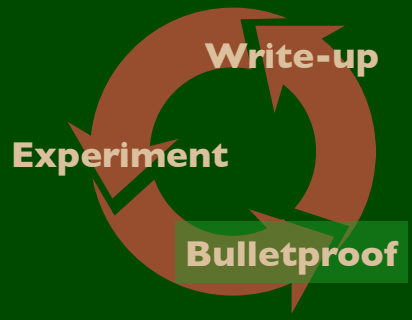

```
> (redex-check
   Roo
   p
    (equal? (eval-expr (term p))
            (reduce-expr (term p))))
```

redex-check accepts a language, a non-terminal, and a Racket expression, and makes up random examples of the pattern to test the Racket expression, looking for **#f**



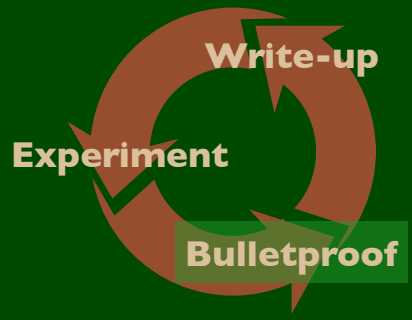

```
> (redex-check
   Roo
   p
    (equal? (eval-expr (term p))
            (reduce-expr (term p))))
```

redex-check accepts a language, a non-terminal, and a Racket expression, and makes up random examples of the pattern to test the Racket expression, looking for **#f**



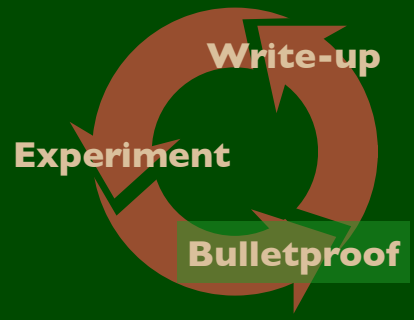

```
> (redex-check
   Roo
   p
   (equal? (eval-expr (term p))
           (reduce-expr (term p))))
```

redex-check accepts a language, a non-terminal, and a Racket expression, and makes up random examples of the pattern to test the Racket expression, looking for **#f**



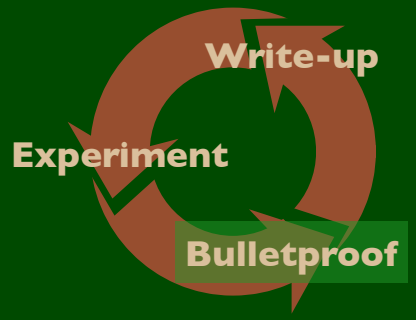

```
> (redex-check
   Roo
   p
   (equal? (eval-expr (term p))
           (reduce-expr (term p))))
```

redex-check accepts a language, a non-terminal, and a Racket expression, and makes up random examples of the pattern to test the Racket expression, looking for **#f**



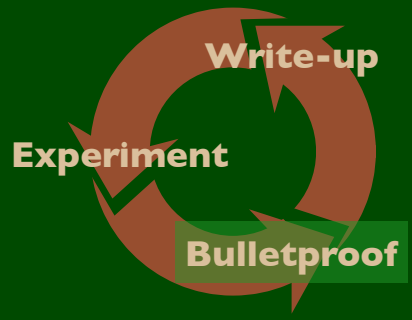

```
> (redex-check
   Roo
   p
    (equal? (eval-expr (term p))
            (reduce-expr (term p))))
```

redex-check accepts a language, a non-terminal, and a Racket expression, and makes up random examples of the pattern to test the Racket expression, looking for **#f**

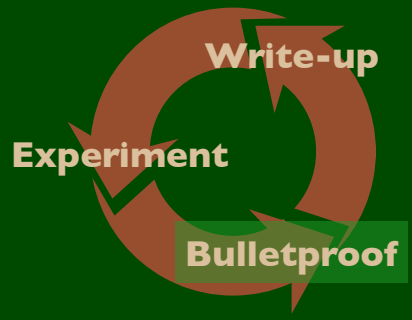



```
; reduce-expr : any -> (or/c 'error
;                            'object
;                            number?)
(define (reduce-expr e)
  (define results (apply-reduction-relation* red e))
  (define result (car results))
  (define value (last result))
  (if (redex-match Roo a result)
      (if (number? value)
          value
          'object)
      'error))

; eval-expr : any -> (or/c 'error 'object number?)
(define (eval-expr e)
  ; evaluate the expression using Racket
   )
```



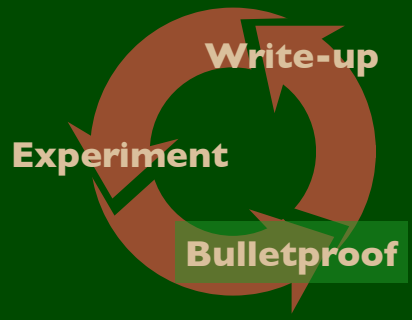

```
> (redex-check
   Roo
   p
    (equal? (eval-expr (term p))
            (reduce-expr (term p))))
```




```
> (redex-check
   Roo
   p
    (equal? (eval-expr (term p))
            (reduce-expr (term p))))
```

redex-check: checking (begin (define U (class object% (init-field JJp) (super-make-object))) (define FR (class object% (init-field x) (define/public (o) this) (define/public (k) this) (define/public (x) 0) (define/public (f) 6) (define/public (Q) 2) (super-make-object))) (make-object c (+ (make-object X 3) (send this hn) 2 (send 2 U) 0 this 0 -2 (make-object C -1) (if0 this 5 6) (+)))) raises an exception:

```
class: duplicate declared identifier in: x
```



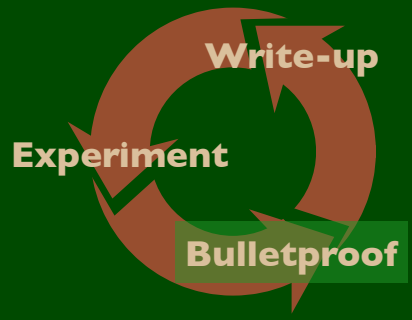

```
> (redex-check
   Roo
   p
    (equal? (eval-expr (term p))
            (reduce-expr (term p))))
```

redex-check: checking

```
(begin (define FR (class object%
                    (init-field x)
                    (define/public (x) 0)
                    (super-make-object)))
       0)
```

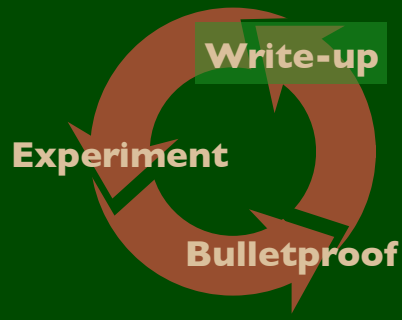
raises an exception:

```
class: duplicate declared identifier in: x
```




```
> (redex-check
   Roo
   p
   (with-handlers ((exn:fail:syntax?
                    (λ (x) #t)))
     (equal? (eval-expr (term p))
             (reduce-expr (term p)))))
```

redex-check: no counterexamples in 1000 attempts




```
> (render-reduction-relation num-rules)
```

P[`(+` *number* `...)`] [+]

⟶ P[Σ[[*number* `...`]]]

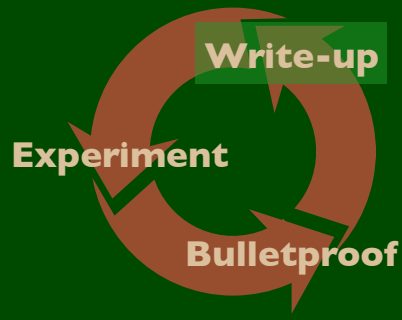
P[`(if0` 0 e_1 e_2`)`] [if0t]

⟶ P[e_1]

P[`(if0` *number* e_1 e_2`)`] [if0f]

⟶ P[e_2]

where nonzero[[*number*]]



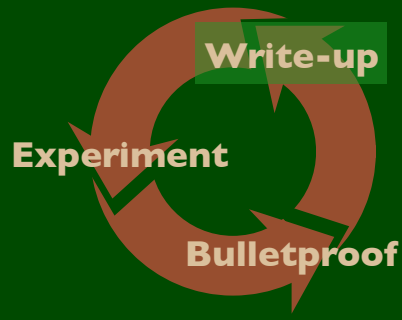

```
> (parameterize ([rule-pict-style 'horizontal])
    (render-reduction-relation num-rules))
```

$P[\,\texttt{(+}\ number\ \ldots\texttt{)}\,] \longrightarrow P[\Sigma[[number\ \ldots]]]$ [+]

$P[\,\texttt{(if0}\ 0\ e_1\ e_2\texttt{)}\,] \longrightarrow P[e_1]$ [if0t]

$P[\,\texttt{(if0}\ number\ e_1\ e_2\texttt{)}\,] \longrightarrow P[e_2]$ [if0f]

where nonzero$[[number]]$




```
> (parameterize ([rule-pict-style 'horizontal])
    (with-rewriters
     (render-reduction-relation num-rules)))
```

$P[\,(\texttt{+}\ number\ \ldots)\,] \longrightarrow P[\Sigma[[number\ \ldots]]]$ [+]

$P[\,(\texttt{if0}\ 0\ e_1\ e_2)\,] \longrightarrow P[e_1]$ [if0t]

$P[\,(\texttt{if0}\ number\ e_1\ e_2)\,] \longrightarrow P[e_2]$ [if0f]

where $number \neq 0$

Assignment: Generalize the model to first-class classes (i.e., classes as values)

The next few slides show a model that we went through together in the live talk. It starts with the complete version of the first-order calculus and then adjusts definitions so that any expression can appear on the right-hand side, and then makes classes be expressions. It then exploits Redex's testing facilities to find bugs in the model.

To try this yourself, download:

`www.eecs.northwestern.edu/~robby/talks/fool2010-hw.rkt`

It contains the complete code from the model but with two changes:

- `e` now contains `c` and
- definitions are of the form `(define x e)`.

Run it to see the first counter example.

0.rkt

```
p ::= (begin d ... e)
d ::= (define z c)
c ::= (class object%
        (init-field i)
        m ...
        (super-make-object))
m ::= (define/public (x y ...)
        e)
e ::= (make-object x e)
    | (send e x e ...)
    | x
    | this
    | number
    | (if0 e e e)
    | (+ e ...)
a ::= (begin d ... v)
v ::= (make-object x v)
    | number
P ::= (begin d ... E)
E ::= (make-object x E)
    | (send E x e ...)
    | (send v x v ... E e ...)
    | (if0 E e e)
    | (+ v ... E e ...)
    | []
x, y, z ::= variable-not-otherwise-mentioned
```

```
(begin
  d1 ...
  (define z
    (class object%
      (init-field i)
      m1 ...
      (define/public (x y ...)
        e)
      m2 ...
      (super-make-object)))
  d2 ...
  E[(send (make-object z v1)
          x
          vy ...)])
```

```
P[(+ number ...)]                    [+]
⟶ P[Σ[[number ...]]]

P[(if0 0 e1 e2)]                     [if0t]
⟶ P[e1]

P[(if0 number e1 e2)]                [if0f]
⟶ P[e2]
  where number ≠ 0
```

```
(begin                                          [send]
  d1 ...
  (define z
    (class object%
      (init-field i)
      m1 ...
      (define/public (x y ...)
        e)
      m2 ...
      (super-make-object)))
  d2 ...
  E[e{y := vy ...,
      i := vi,
      this := (make-object z vi)}])
```

l.rkt

```
p ::= (begin d ... e)
d ::= (define z e)
c ::= (class object%
        (init-field i)
        m ...
        (super-make-object))
m ::= (define/public (x y ...)
        e)
e ::= c
    | (make-object x e)
    | (send e x e ...)
    | x
    | this
    | number
    | (if0 e e e)
    | (+ e ...)
a ::= (begin d ... v)
v ::= (make-object x v)
    | number
P ::= (begin d ... E)
E ::= (make-object x E)
    | (send E x e ...)
    | (send v x v ... E e ...)
    | (if0 E e e)
    | (+ v ... E e ...)
    | []
x, y, z ::= variable-not-otherwise-mentioned
```

```
(begin
  d1 ...
  (define z
    (class object%
      (init-field i)
      m1 ...
      (define/public (x y ...)
        e)
      m2 ...
      (super-make-object)))
  d2 ...
  E[(send (make-object z v1)
          x
          vy ...)])
```

```
P[(+ number ...)]                    [+]
⟶ P[Σ[[number ...]]]

P[(if0 0 e1 e2)]                     [if0t]
⟶ P[e1]

P[(if0 number e1 e2)]                [if0f]
⟶ P[e2]
  where number ≠ 0
```

```
⟶ (begin                                          [send]
    d1 ...
    (define z
      (class object%
        (init-field i)
        m1 ...
        (define/public (x y ...)
          e)
        m2 ...
        (super-make-object)))
    d2 ...
    E[e{y := vy ...,
        i := vi,
        this := (make-object z vi)}])
```

1.rkt Error

```
p ::= (begin d ... e)
d ::= (define z e)
c ::= (class object%
        (init-field i)
        m ...
        (super-make-object))
m ::= (define/public (x y ...)
        e)
e ::= c
    | (make-object x e)
    | (send e x e ...)
    | x
    | this
    | number
    | (if0 e e e)
    | (+ e ...)
a ::= (begin d ... v)
v ::= (make-object x v)
    | number
P ::= (begin d ... E)
E ::= (make-object x E)
    | (send E x e ...)
    | (send v x v ... E e ...)
    | (if0 E e e)
    | (+ v ... E e ...)
    | []
x, y, z ::= variable-not-otherwise-mentioned
```

```
(begin
  d1 ...
  (define z
    (class object%
      (init-field i)
      m1 ...
      (define/public (x y ...)
        e)
      m2 ...
      (super-make-object)))
  d2 ...
  E[ (send (make-object z v)
           x
           v ...) ])
⟶ P[ (+ number ...) ]                [+]
⟶ P[ (if0 0 e1 e2) ]                 [if0t]
⟶ P[ (if0 number e1 e2) ]            [if0f]
⟶ P[e2]
   where number ≠ 0
```

```
⟶ (begin                                          [send]
    d1 ...
    (define z
      (class object%
        (init-field i)
        m1 ...
        (define/public (x y ...)
          e)
        m2 ...
        (super-make-object)))
    d2 ...
    E[ e{ y := v1
          ...
          i := vi
          this := (make-object z vi) } ])
```

```
(begin
  (class object%
    (init-field bB)
    (super-make-object)))
```

2.rkt

```
p ::= (begin d ... e)
d ::= (define z e)
c ::= (class object%
        (init-field i)
        m ...
        (super-make-object))
m ::= (define/public (x y ...)
        e)
e ::= c
    | (make-object x e)
    | (send e x e ...)
    | x
    | this
    | number
    | (if0 e e e)
    | (+ e ...)
a ::= (begin d ... v)
v ::= (make-object x v)
    | number
    | c
P ::= (begin d ... E)
E ::= (make-object x E)
    | (send E x e ...)
    | (send v x v ... E e ...)
    | (if0 E e e)
    | (+ v ... E e ...)
    | []
x, y, z ::= variable-not-otherwise-mentioned
```

```
(begin
  d1 ...
  (define z
    (class object%
      (init-field i)
      m1 ...
      (define/public (x y ...)
        e)
      m2 ...
      (super-make-object)))
  d2 ...
  E[(send (make-object z vi)
          x
          vy ...)])
```

⟶

```
(begin
  d1 ...
  (define z
    (class object%
      (init-field i)
      m1 ...
      (define/public (x y ...)
        e)
      m2 ...
      (super-make-object)))
  d2 ...
  E[e{y := vy ...,
      i := vi,
      this := (make-object z vi)}])
```

[send]

```
P[(+ number ...)]
⟶ P[Σ[[number ...]]]
```

[+]

```
P[(if0 0 e1 e2)]
⟶ P[e1]
```

[if0t]

```
P[(if0 number e1 e2)]
⟶ P[e2]
  where number ≠ 0
```

[if0f]

2.rkt Error

$p ::=$ `(begin` $d \ldots e$ `)`
$d ::=$ `(define` $z\ e$ `)`
$c ::=$ `(class object%`
`(init-field` i `)`
$m \ldots$
`(super-make-object))`
$m ::=$ `(define/public (`$x\ y \ldots$`)`
e `)`
$e ::= c$
| `(make-object` $x\ e$ `)`
| `(send` $e\ x\ e \ldots$ `)`
| x
| `this`
| *number*
| `(if0` $e\ e\ e$ `)`
| `(+` $e \ldots$ `)`
$a ::=$ `(begin` $d \ldots v$ `)`
$v ::=$ `(make-object` $x\ v$ `)`
| *number*
| c
$P ::=$ `(begin` $d \ldots E$ `)`
$E ::=$ `(make-object` $x\ E$ `)`
| `(send` $E\ x\ e \ldots$ `)`
| `(send` $v\ x\ v \ldots E\ e \ldots$ `)`
| `(if0` $E\ e\ e$ `)`
| `(+` $v \ldots E\ e \ldots$ `)`
| `[]`
$x, y, z ::=$ *variable-not-otherwise-mentioned*

`(begin`
$d_1 \ldots$
`(define` z
`(class object%`
`(init-field` i `)`
$m_1 \ldots$
`(define/public (`$x\ y \ldots$`)`
e `)`
$m_2 \ldots$
`(super-make-object)))`
$d_2 \ldots$
E[`(send (make-object` $z\ v_i$ `)`

$\longrightarrow$ `(begin` [send]
$d_1 \ldots$
`(define` z
`(class object%`
`(init-field` i `)`
$m_1 \ldots$
`(define/public (`$x\ y \ldots$`)`
e `)`
$m_2 \ldots$
`(super-make-object)))`
$d_2 \ldots$
E[e{$y := v_y \ \ldots$,
$i := v_i$,
`this :=` `(make-object` $z\ v_i$ `)` }])

```
(begin
  (define c (send 0 G))
  3)
```

P[`(if0` *number* $e_1\ e_2$ `)`] [if0f]
$\longrightarrow P[e_2]$
where *number* $\neq 0$

3.rkt

```
p ::= (begin d ... e)
d ::= (define z e)
c ::= (class object%
        (init-field i)
        m ...
        (super-make-object))
m ::= (define/public (x y ...)
        e)
e ::= c
    | (make-object x e)
    | (send e x e ...)
    | x
    | this
    | number
    | (if0 e e e)
    | (+ e ...)
a ::= (begin (define x v) ... v)
v ::= (make-object x v)
    | number
    | c
P ::= (begin d ... E)
E ::= (make-object x E)
    | (send E x e ...)
    | (send v x v ... E e ...)
    | (if0 E e e)
    | (+ v ... E e ...)
    | []
x, y, z ::= variable-not-otherwise-mentioned
```

```
(begin
  d1 ...
  (define z
    (class object%
      (init-field i)
      m1 ...
      (define/public (x y ...)
        e)
      m2 ...
      (super-make-object)))
  d2 ...
  E[ (send (make-object z v1)
           x
           vy ...) ])
```

⟶

```
(begin
  d1 ...
  (define z
    (class object%
      (init-field i)
      m1 ...
      (define/public (x y ...)
        e)
      m2 ...
      (super-make-object)))
  d2 ...
  E[ e{y := vy ...,
       i := vi,
       this := (make-object z vi)} ])
```

[send]

```
P[ (+ number ...) ]
⟶ P[Σ[[number ...]]]
```

[+]

```
P[ (if0 0 e1 e2) ]
⟶ P[e1]
```

[if0t]

```
P[ (if0 number e1 e2) ]
⟶ P[e2]
  where number ≠ 0
```

[if0f]

3.rkt Error

```
p ::= (begin d ... e)
d ::= (define z e)
c ::= (class object%
        (init-field i)
        m ...
        (super-make-object))
m ::= (define/public (x y ...)
        e)
e ::= c
    | (make-object x e)
    | (send e x e ...)
    | x
    | this
    | number
    | (if0 e e e)
    | (+ e ...)
a ::= (begin (define x v) ...
v ::= (make-object x v)
    | number
    | c
P ::= (begin d ... E)
E ::= (make-object x E)
    | (send E x e ...)
    | (send v x v ... E e ...)
    | (if0 E e e)
    | (+ v ... E e ...)
    | []
x, y, z ::= variable-not-otherwise-mentioned
```

```
(begin                                  ⟶ (begin                                  [send]
  d1 ...                                    d1 ...
  (define z                                 (define z
    (class object%                            (class object%
      (init-field i)                            (init-field i)
      m1 ...                                    m1 ...
      (define/public (x y ...)                  (define/public (x y ...)
        e)                                        e)
      m2 ...                                    m2 ...
      (super-make-object)))                     (super-make-object)))
  d2 ...                                    d2 ...
  E[(send (make-object z v_i)               E[e{y := v_y ...,
          x                                     i := v_i,
          v_y ...)])                            this := (make-object z v_i)}])
```

(begin (define g (+)) (+))

```
P[(if0 0 e1 e2)]                [if0t]
⟶ P[e1]

P[(if0 number e1 e2)]           [if0f]
⟶ P[e2]
  where number ≠ 0
```

4.rkt

```
p ::= (begin d ... e)
d ::= (define z e)
c ::= (class object%
        (init-field i)
        m ...
        (super-make-object))
m ::= (define/public (x y ...)
        e)
e ::= c
    | (make-object x e)
    | (send e x e ...)
    | x
    | this
    | number
    | (if0 e e e)
    | (+ e ...)
a ::= (begin (define x v) ... v)
v ::= (make-object x v)
    | number
    | c
P ::= (begin (define x v) ...
             (define x E)
             (define x e) ...
             e)
    | (begin (define x v) ...
             E)
E ::= (make-object x E)
    | (send E x e ...)
    | (send v x v ... E e ...)
    | (if0 E e e)
    | (+ v ... E e ...)
    | []
x, y, z ::= variable-not-otherwise-mentioned
```

```
(begin
  d1 ...
  (define z
    (class object%
      (init-field i)
      m1 ...
      (define/public (x y ...)
        e)
      m2 ...
      (super-make-object)))
  d2 ...
  E[(send (make-object z v1)
          x
          vy ...)])
```

⟶

```
(begin
  d1 ...
  (define z
    (class object%
      (init-field i)
      m1 ...
      (define/public (x y ...)
        e)
      m2 ...
      (super-make-object)))
  d2 ...
  E[e{y := vy ...,
      i := vi,
      this := (make-object z vi)}])
```

[send]

```
P[(+ number ...)]
⟶ P[Σ[[number ...]]]
```

[+]

```
P[(if0 0 e1 e2)]
⟶ P[e1]
```

[if0t]

```
P[(if0 number e1 e2)]
⟶ P[e2]
  where number ≠ 0
```

[if0f]

4.rkt Error

```
p ::= (begin d ... e)
d ::= (define z e)
c ::= (class object%
        (init-field i)
        m ...
        (super-make-object))
m ::= (define/public (x y ...)
        e)
e ::= c
    | (make-object x e)
    | (send e x e ...)
    | x
    | this
    | number
    | (if0 e e e)
    | (+ e ...)
a ::= (begin (define x v) ... v)
v ::= (make-object x v)
    | number
    | c
P ::= (begin (define x v) ...
             (define x l)
             (define x e) ...
             e)
    | (begin (define x v) ...
             E)
E ::= (make-object x E)
    | (send E x e ...)
    | (send v x v ... E e ...)
    | (if0 E e e)
    | (+ v ... E e ...)
    | []
x, y, z ::= variable-not-otherwise-mentioned
```

```
(begin
  d1 ...
  (define z
    (class object%
      (init-field i)
      m1 ...
      (define/public (x y ...)
        e)
      m2 ...
      (super-make-object)))
  E[(send (make-object z v)
          x e ...)])
```

```
⟶ (begin
    d1 ...
    (define z
      (class object%
        (init-field i)
        m1 ...
        (define/public (x y ...)
          e)
        m2 ...
        (super-make-object)))
    d2 ...
    E[e{y := v1 ...
        i := v0
        this := (make-object z v)}])
```

[send]

```
(begin
  (define R
    (make-object R
      (class
        object%
        (init-field h)
        (super-make-object))))
  7)
```

5.rkt

```
p ::= (begin d ... e)
d ::= (define z e)
c ::= (class object%
        (init-field i)
        m ...
        (super-make-object))
m ::= (define/public (x y ...)
        e)
e ::= c
    | (make-object x e)
    | (send e x e ...)
    | x
    | this
    | number
    | (if0 e e e)
    | (+ e ...)
a ::= (begin (define x v) ... v)
v ::= (make-object c v)
    | number
    | c
P ::= (begin (define x v) ...
             (define x E)
             (define x e) ...
             e)
    | (begin (define x v) ...
             E)
E ::= (make-object x E)
    | (send E x e ...)
    | (send v x v ... E e ...)
    | (if0 E e e)
    | (+ v ... E e ...)
    | []
x, y, z ::= variable-not-otherwise-mentioned
```

```
(begin
  d1 ...
  (define z
    (class object%
      (init-field i)
      m1 ...
      (define/public (x y ...)
        e)
      m2 ...
      (super-make-object)))
  d2 ...
  E[(send (make-object z v1)
          x
          vy ...)])
```

⟶

```
(begin
  d1 ...
  (define z
    (class object%
      (init-field i)
      m1 ...
      (define/public (x y ...)
        e)
      m2 ...
      (super-make-object)))
  d2 ...
  E[e{y := vy ...,
      i := vi,
      this := (make-object z vi)}])
```

[send]

```
P[(+ number ...)]
⟶ P[Σ[[number ...]]]
```

[+]

```
P[(if0 0 e1 e2)]
⟶ P[e1]
```

[if0t]

```
P[(if0 number e1 e2)]
⟶ P[e2]
  where number ≠ 0
```

[if0f]

5.rkt Error

```
p ::= (begin d ... e)
d ::= (define z e)
c ::= (class object%
        (init-field i)
        m ...
        (super-make-object))
m ::= (define/public (x y ...)
        e)
e ::= c
    | (make-object x e)
    | (send e x e ...)
    | x
    | this
    | number
    | (if0 e e e)
    | (+ e ...)
a ::= (begin (define x v) ... v)
v ::= (make-object c v)
    | number
    | c
P ::= (begin (define x v) ...
             (define x E)
             (define x e) ...
             e)
    | (begin (define x v) ...
             E)
E ::= (make-object x E)
    | (send E x e ...)
    | (send v x v ... E e ...)
    | (if0 E e e)
    | (+ v ... E e ...)
    | []
x, y, z ::= variable-not-otherwise-mentioned
```

```
(begin
  d1 ...
  (define z
    (class object%
      (init-field i)
      m1 ...
      (define/public (x y ...)
        e)
      m2 ...
      (super-make-object)))
  d2 ...
  E[(send (make-object z v1)
          x
          vy ...)])
```

⟶

```
(begin
  d1 ...
  (define z
    (class object%
      (init-field i)
      m1 ...
      (define/public (x y ...)
        e)
      m2 ...
      (super-make-object)))
  d2 ...
  E[e{y := vy ...,
      i := vi,
      this := (make-object z vi)}])
```

[send]

Test case (on line 196)

P[(if0 0 e1 e2)] [if0t]

⟶ P[e1]

P[(if0 number e1 e2)] [if0f]

⟶ P[e2]

where number ≠ 0

6.rkt

```
p ::= (begin d ... e)
d ::= (define z e)
c ::= (class object%
        (init-field i)
        m ...
        (super-make-object))
m ::= (define/public (x y ...)
        e)
e ::= c
    | (make-object x e)
    | (send e x e ...)
    | x
    | this
    | number
    | (if0 e e e)
    | (+ e ...)
a ::= (begin (define x v) ... v)
v ::= (make-object c v)
    | number
    | c
P ::= (begin (define x v) ...
             (define x E)
             (define x e) ...
             e)
    | (begin (define x v) ...
             E)
E ::= (make-object v E)
    | (make-object E e)
    | (send E x e ...)
    | (send v x v ... E e ...)
    | (if0 E e e)
    | (+ v ... E e ...)
    | []
x, y, z ::= variable-not-otherwise-mentioned
```

```
P[ (send (make-object
           (class object%
             (init-field i)
             m1 ...
             (define/public (x y ...)
               e)
             m2 ...
             (super-make-object))
           vi)
         x
         vy ...) ]
```

⟶

```
P[e{y := vy ...,
    i := vi,
    this := (make-object
              (class object%
                (init-field i)
                m1 ...
                (define/public (x y ...)
                  e)
                m2 ...
                (super-make-object))
              vi) }]
```

[send]

```
P[ (+ number ...) ]
⟶ P[Σ[[number ...]]]
```

[+]

```
P[ (if0 0 e1 e2) ]
⟶ P[e1]
```

[if0t]

```
P[ (if0 number e1 e2) ]
⟶ P[e2]
  where number ≠ 0
```

[if0f]

```
(begin d1 ...
       (define x v)
       d2 ...
       E[x])
```

⟶

```
(begin d1 ...
       (define x v)
       d2 ...
       E[v])
```

6.rkt Error

```
p ::= (begin d ... e)
d ::= (define z e)
c ::= (class object%
        (init-field i)
        m ...
        (super-make-object))
m ::= (define/public (x y ...)
        e)
e ::= c
    | (make-object x e)
    | (send e x e ...)
    | x
    | this
    | number
    | (if0 e e e)
    | (+ e ...)
a ::= (begin (define x v) ... v)
v ::= (make-object c v)
    | number
    | c
P ::= (begin (define x v) ...
             (define x E)
             (define x e) ...
             e)
    | (begin (define x v) ...
             E)
E ::= (make-object v E)
    | (make-object E e)
    | (send E x e ...)
    | (send v x v ... E e ...)
    | (if0 E e e)
    | (+ v ... E e ...)
    | []
x, y, z ::= variable-not-otherwise-mentioned
```

```
P[ (send (make-object
           (class object%
             (init-field i)
             m1 ...
             (define/public (x y ...)
               e)
             m2 ...
             (super-make-object))
           vi)
         x
         vy ...)]
```

```
⟶ P[e{y := vy ...,
      i := vi,
      this := (make-object
                (class object%
                  (init-field i)
                  m1 ...
                  (define/public (x y ...)
                    e)
                  m2 ...
                  (super-make-object))
                vi)}]
```

[send]

```
P[ (if0 0 e1 e2) ]
⟶ P[e1]
```

[if0t]

```
P[ (if0 number e1 e2) ]
⟶ P[e2]
where number ≠ 0
```

[if0f]

```
P[ (+ number1 number2) ]
⟶ P[number3]
where number3 = (+ number1 number2)
```

[+]

```
P[ (begin d1 ...
          (define x v)
          d2 ...
          E[x])]
⟶ P[ (begin d1 ...
            (define x v)
            d2 ...
            E[v])]
```

[substs]

substs-e gets a non-“e” as argument in test cases

7.rkt

```
p ::= (begin d ... e)
d ::= (define z e)
c ::= (class object%
        (init-field i)
        m ...
        (super-make-object))
m ::= (define/public (x y ...)
        e)
e ::= c
    | (make-object e e)
    | (send e x e ...)
    | x
    | this
    | number
    | (if0 e e e)
    | (+ e ...)
a ::= (begin (define x v) ... v)
v ::= (make-object c v)
    | number
    | c
P ::= (begin (define x v) ...
             (define x E)
             (define x e) ...
             e)
    | (begin (define x v) ...
             E)
E ::= (make-object v E)
    | (make-object E e)
    | (send E x e ...)
    | (send v x v ... E e ...)
    | (if0 E e e)
    | (+ v ... E e ...)
    | []
x, y, z ::= variable-not-otherwise-mentioned
```

```
P[ (send (make-object
           (class object%
             (init-field i)
             m1 ...
             (define/public (x y ...)
               e)
             m2 ...
             (super-make-object))
           vi)
         x
         vy ...) ]
```

⟶

```
P[e{y := vy ...,
    i := vi,
    this := (make-object
              (class object%
                (init-field i)
                m1 ...
                (define/public (x y ...)
                  e)
                m2 ...
                (super-make-object))
              vi) }]
```

[send]

```
P[ (+ number ...) ]
⟶ P[Σ[[number ...]]]
```

[+]

```
P[ (if0 0 e1 e2) ]
⟶ P[e1]
```

[if0t]

```
P[ (if0 number e1 e2) ]
⟶ P[e2]
  where number ≠ 0
```

[if0f]

```
(begin d1 ...
       (define x v)
       d2 ...
       E[x])
```

⟶

```
(begin d1 ...
       (define x v)
       d2 ...
       E[v])
```

7.rkt Error

```
p ::= (begin d ... e)
d ::= (define z e)
c ::= (class object%
        (init-field i)
        m ...
        (super-make-object))
m ::= (define/public (x y ...)
        e)
e ::= c
    | (make-object e e)
    | (send e x e ...)
    | x
    | this
    | number
    | (if0 e e e)
    | (+ e ...)
a ::= (begin (define x v) ... v)
v ::= (make-object c v)
    | number
    | c
P ::= (begin (define x v) ...
             (define x E)
             (define x e) ...
             e)
    | (begin (define x v) ...
             E)
E ::= (make-object v E)
    | (make-object E e)
    | (send E x e ...)
    | (send v x v ... E e ...)
    | (if0 E e e)
    | (+ v ... E e ...)
    | []
x, y, z ::= variable-not-otherwise-mentioned
```

```
P[ (send (make-object
           (class object%
             (init-field i)
             m1 ...
             (define/public (x y ...)
               e)
             m2 ...
             (super-make-object))
           v1 ... vi)
   x
   v) ] ]
```

```
(begin
  (define z 0)
  (define HV z)
  (class object%
    (init-field ÷)
    (super-make-object)))
```

```
P[ (+ number ...) ]   [+]   (begin d1 ...
                              (define x v)
                              d2 ...
                              E[x])
P[ (if0 0 e1 e2) ]    [if0t]
P[ (if0 number e1 e2) ]  [if0f]
where number ≠ 0
```

$$P[e\{y := v_y \ \ldots,\ i := v_i,\ \texttt{this} := (\texttt{make-object}\ (\texttt{class object\%}\ (\texttt{init-field}\ i)\ m_1 \ldots\ (\texttt{define/public}\ (x\ y \ldots)\ e)\ m_2 \ldots\ (\texttt{super-make-object}))\ v_i \ldots)\}] \longrightarrow P[(\texttt{begin}\ d_1 \ldots\ (\texttt{define}\ x\ v)\ d_2 \ldots\ E[v])]$$ [send]

8.rkt

```
p ::= (begin d ... e)
d ::= (define z e)
c ::= (class object%
        (init-field i)
        m ...
        (super-make-object))
m ::= (define/public (x y ...)
        e)
e ::= c
    | (make-object e e)
    | (send e x e ...)
    | x
    | this
    | number
    | (if0 e e e)
    | (+ e ...)
a ::= (begin (define x v) ... v)
v ::= (make-object c v)
    | number
    | c
P ::= (begin (define x v) ...
             (define x E)
             (define x e) ...
             e)
    | (begin (define x v) ...
             E)
E ::= (make-object v E)
    | (make-object E e)
    | (send E x e ...)
    | (send v x v ... E e ...)
    | (if0 E e e)
    | (+ v ... E e ...)
    | []
x, y, z ::= variable-not-otherwise-mentioned
```

```
P[ (send (make-object
           (class object%
             (init-field i)
             m1 ...
             (define/public (x y ...)
               e)
             m2 ...
             (super-make-object))
           vi)
         x
         vy ...) ]
```

⟶

```
P[e{y := vy ...,
    i := vi,
    this := (make-object
              (class object%
                (init-field i)
                m1 ...
                (define/public (x y ...)
                  e)
                m2 ...
                (super-make-object))
              vi) }]
```

[send]

```
P[ (+ number ...) ]
⟶ P[Σ[[number ...]]]
```

[+]

```
P[ (if0 0 e1 e2) ]
⟶ P[e1]
```

[if0t]

```
P[ (if0 number e1 e2) ]
⟶ P[e2]
  where number ≠ 0
```

[if0f]

```
(begin d1 ...
       (define x v)
       d2 ...
       E[x])
⟶ (begin d1 ...
         (define x v)
         d2 ...
         E[v])

(begin d1 ...
       (define x v)
       d2 ...
       (define y E[x])
       d3 ...
       e)
⟶ (begin d1 ...
         (define x v)
         d2 ...
         (define y E[v])
         d3 ...
         e)
```

Racket's class system

There's more to the Racket class system, e.g.:

- The superclass position is an expression ⇒ mixins
- `define-local-member-name`
  (exploiting scope for abstraction)
- inner + super

See Flatt et al [APLAS 2006] or the docs for more

Thank you.

Three parting thoughts:

Semantics Engineering is more than just Theorem Proving;

Random testing gives *no* guarantees, yet is incredibly useful;

Check out Racket's class system:
`http://racket-lang.org/`