Building a path from language user to sophisticated DSL creator in Racket

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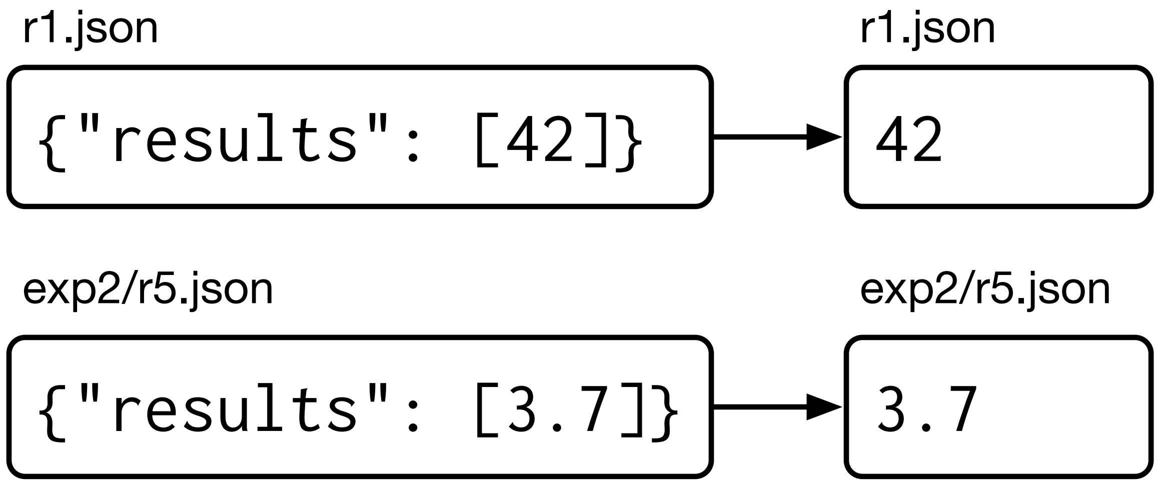
An extensible language
for language-oriented
programming.

```
#lang rash

(require match json)

(define (fix-file f)
  (write-json-file
   (match (read-json-file f)
     [(json { "results" [ v ] }) v]
     [v v])
   f))

find . -name *.json |>each-line fix-file
```



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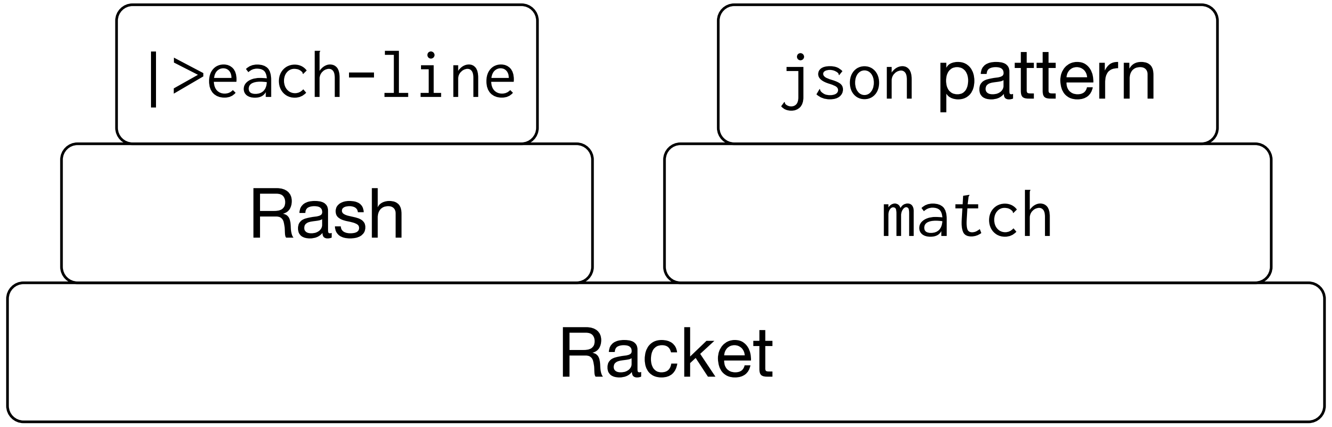
find . -name *.json |>each-line fix-file
```



This talk

How we build DSLs in Racket, via two techniques:

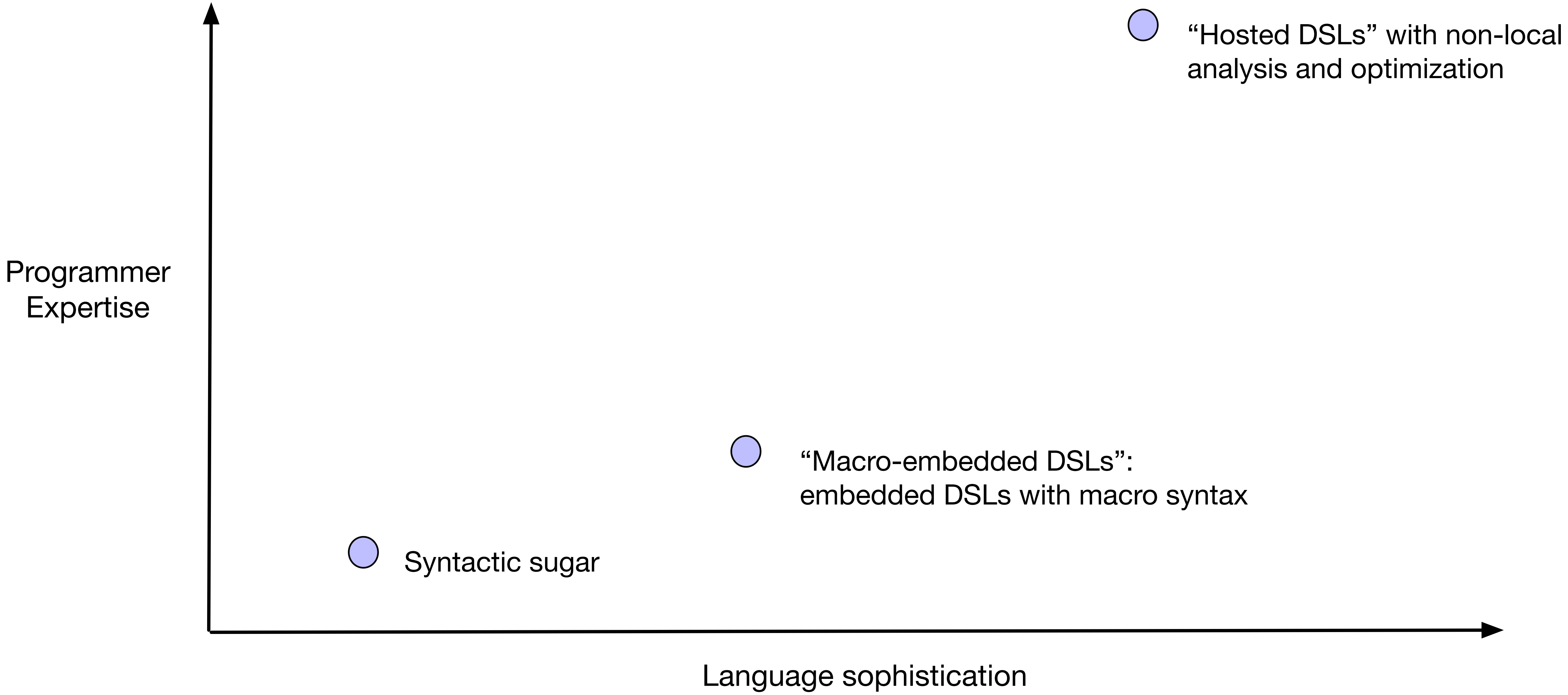
- "Macro-embedded DSLs"
- "Hosted DSLs"

Making sophisticated "hosted" DSLs easier to build:

- A new API for re-using parts of Racket's macro expander to build custom macro expanders for DSLs
- A new meta-language for creating hosted DSL front-ends
  (Work in progress)

Work with Matthias Felleisen and Alexis King

The path from programmer to DSL creator



Syntactic sugar via macros

```
(define (append l1 l2)
  (cond [(null? l1) l2]
        [(pair? l1)
         (let ([head (car l1)] [rest (cdr l1)])
           (cons head (append rest l2)))]))
```

```
(require "match-list.rkt")

(define (append l1 l2)
  (match-list l1
    [() l2]
    [(head rest) (cons head (append rest l2))]))
```

```
(define (append l1 l2)
  (cond [(null? l1) l2]
        [(pair? l1)
         (let ([head (car l1)] [rest (cdr l1)])
           (cons head (append rest l2)))]))
```

Defining `match-list`

```
#lang racket

(provide match-list)
(require (for-syntax syntax/parse))

(define (match-list-error) (error 'match-list […]))

(define-syntax match-list
  (lambda (stx)
    (syntax-parse stx
      [(_ e
          [() null-body ...+]
          [(head tail) pair-body ...+])
       #'(let ([v e])
           (cond [(null? v) null-body ...]
                 [(pair? v) (let ([head (car v)] [tail (cdr v)])
                              pair-body ...)]
                 [else (match-list-error)]))])))
```

Syntax export

Syntax definition

```
#lang racket

(provide match-list)
(require (for-syntax syntax/parse))

(define (match-list-error) (error 'match-list […]))

(define-syntax match-list
  (lambda (stx)
    (syntax-parse stx
      [(_ e
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         [(head tail) pair-body ...+])
       #'(let ([v e])
           (cond [(null? v) null-body ...]
                 [(pair? v) (let ([head (car v)] [tail (cdr v)])
                              pair-body ...)]
                 [else (match-list-error)]))])))
```

`Syntax -> Syntax` transformer function

```
#lang racket

(provide match-list)
(require (for-syntax syntax/parse))

(define (match-list-error) (error 'match-list […]))

(define-syntax match-list
  (lambda (stx)
    (syntax-parse stx
      [(_ e
         [() null-body ...+]
         [(head tail) pair-body ...+])
       #'(let ([v e])
           (cond [(null? v) null-body ...]
                 [(pair? v) (let ([head (car v)] [tail (cdr v)])
                              pair-body ...)]
                 [else (match-list-error)]))])))
```

```racket
#lang racket

(provide match-list)
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           (cond [(null? v) null-body ...]
                 [(pair? v) (let ([head (car v)] [tail (cdr v)])
                              pair-body ...)]
                 [else (match-list-error)]))])))
```

Import the `syntax-parse` meta-language for compile-time

```
#lang racket

(provide match-list)
(require (for-syntax syntax/parse))

(define (match-list-error) (error 'match-list […]))

(define-syntax match-list
  (lambda (stx)
    (syntax-parse stx
      [(_ e
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                 [(pair? v) (let ([head (car v)] [tail (cdr v)])
                              pair-body ...)]
                 [else (match-list-error)]))])))
```

Pattern

Template

```
#lang racket

(provide match-list)
(require (for-syntax syntax/parse))

(define (match-list-error) (error 'match-list […]))

(define-syntax match-list
  (lambda (stx)
    (syntax-parse stx
      [(_ e
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                 [(pair? v) (let ([head (car v)] [tail (cdr v)])
                              pair-body ...)]
                 [else (match-list-error)]))])))
```

Runtime support for the language feature

```
#lang racket

(provide match-list)
(require (for-syntax syntax/parse))

(define (match-list-error) (error 'match-list […]))

(define-syntax match-list
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           (cond [(null? v) null-body ...]
                 [(pair? v) (let ([head (car v)] [tail (cdr v)])
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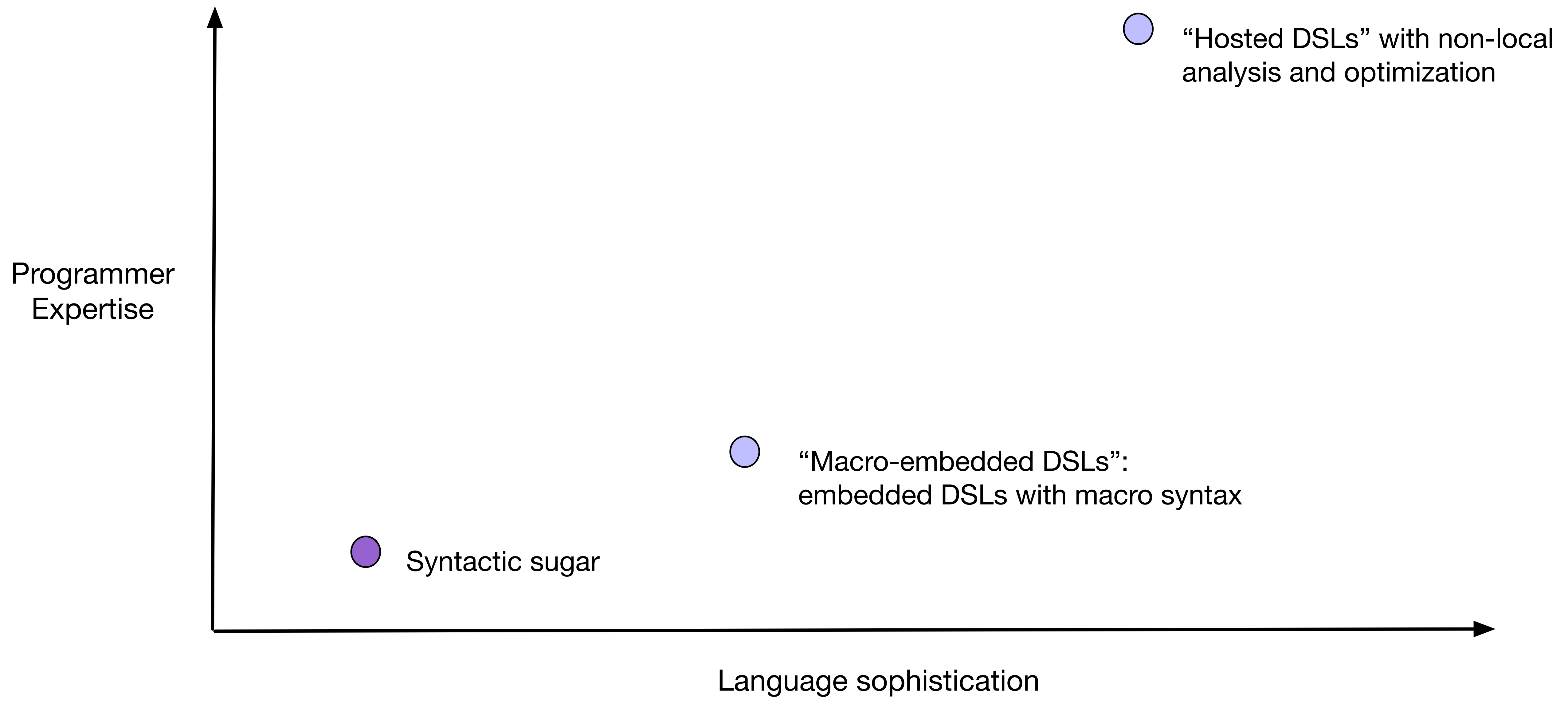
"Hosted DSLs" with non-local
analysis and optimization
Programmer
Expertise
"Macro-embedded DSLs":
embedded DSLs with macro syntax
Syntactic sugar
Language sophistication

Macro-embedded DSLs

An example DSL: miniKanren

```
(run 3 (l1 l2)
  (append l1 l2 '("a" "b")))
=> ;; evaluates to
((("a" "b") ())
 (("a") ("b"))
 (() ("a" "b")))
```

```
#lang racket

(require minikanren)

(define-relation (append l1 l2 l3)
  (conde
    [(== l1 '())
     (== l2 l3)]
    [(fresh (first rest result)
       (== (cons first rest) l1)
       (== (cons first result) l3)
       (append rest l2 result))]))
```

Embedding

Functions

```
#lang racket

(require minikanren)

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  (conde
    [(== l1 '())
     (== l2 l3)]
    [(fresh (first rest result)
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Embedding

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#lang racket

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```

Reuse of Racket

Embedding

Macros

```
#lang racket

(require minikanren)

(define-relation (append l1 l2 l3)
  (conde
    [(== l1 '())
     (== l2 l3)]
    [(fresh (first rest result)
       (== (cons first rest) l1)
       (== (cons first result) l3)
       (append rest l2 result))]))
```

```
(define-syntax conde
  (lambda (stx)
    (syntax-parse stx
      [(_ [g:goal ...+] ...+)
       #'(disj
          (lambda ()
            (conj g ...))
          …)])))
```

```
#lang racket

(require minikanren)

(define-relation (append l1 l2 l3)
  (conde
    [(== l1 '())
     (== l2 l3)]
    [(fresh (first rest result)
       (== (cons first rest) l1)
       (== (cons first result) l3)
       (append rest l2 result))]))
```

Consequences of macro-embedding

Mixing with host-language code

```
(define-relation (naturals v)
  (loop recur ([n 0])
    (conde
      [(== v n)]
      [(recur (+ n 1))])))
```

Mixing with host-language code

```
(define-relation (naturals v)
  (loop recur ([n 0])
    (conde
      [(== v n)]
      [(recur (+ n 1))])))
```

Useful when exploring extensions…

But can easily break the DSL’s semantics.

Extension using host-language macros

```
#lang racket

(require minikanren)

(define-syntax define-relation/match
  (lambda (stx)
    …))

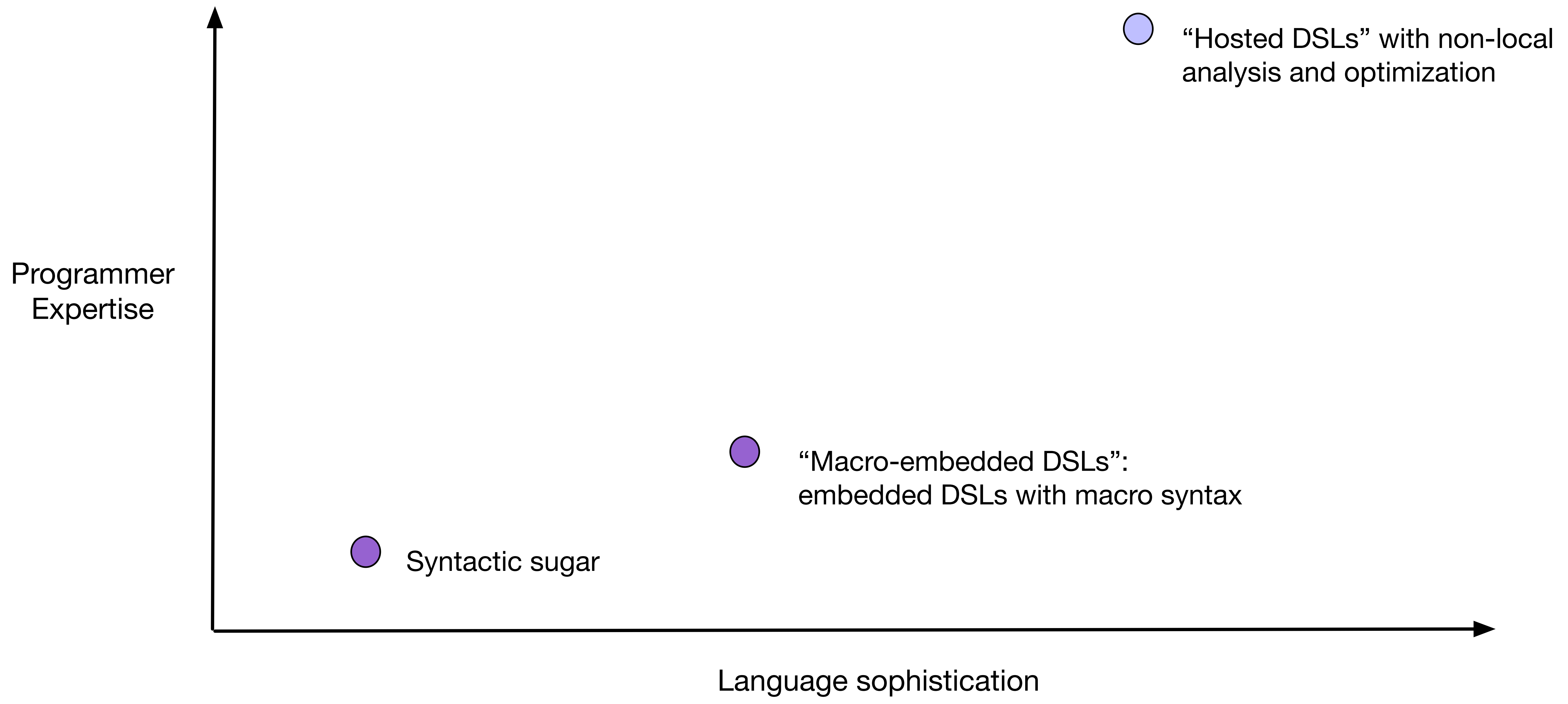
(define-relation/match (append l1 l2 l3)
  [('() _ _)
   (== l2 l3)]
  [((cons first rest) _ (cons first result))
   (append rest l2 result)])
```

Easy! Just functions and some lightweight macros.

To use the language, just import the library.

Can mix with host-language code.

Can extend with host-language macros.


“Hosted DSLs” with non-local
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Syntactic sugar
Language sophistication

More sophisticated DSLs

Custom:

- Grammar
- Binding structure
- Static semantics
- Optimizations

All non-local.

Macro-embedding only gives us what we can scrounge from the host language.

More sophisticated DSLs

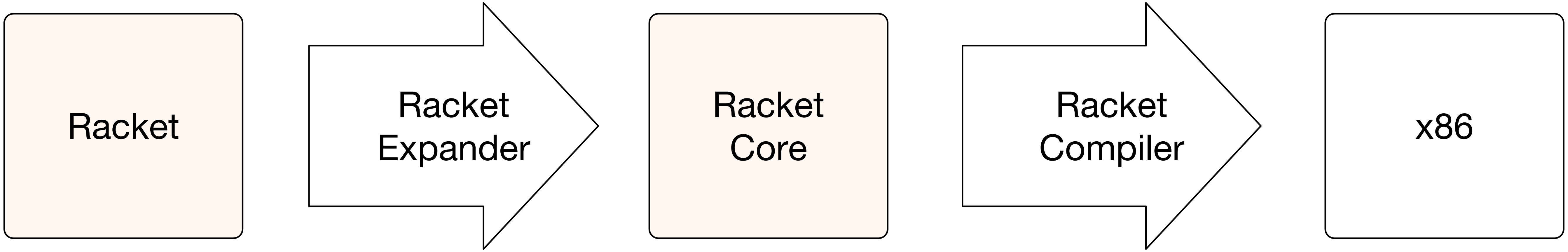
How to support these custom, non-local features…

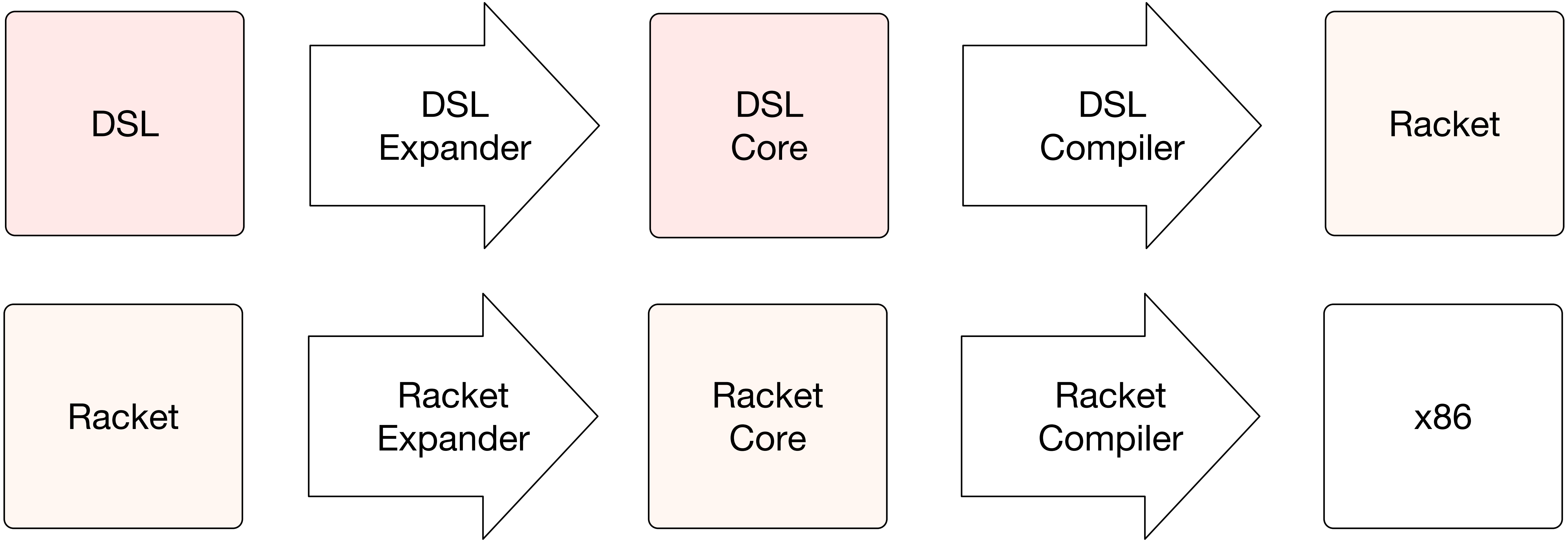
While keeping:

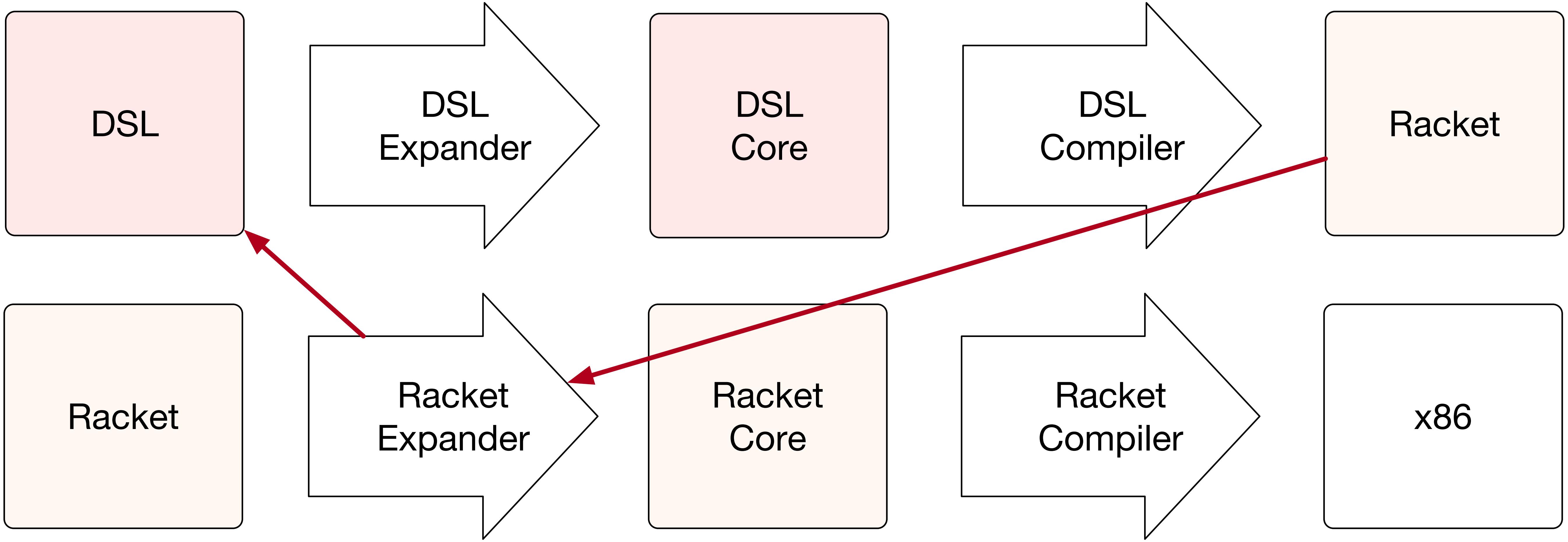
- Integration between DSLs and host
- “Languages as libraries”
- DSL extensibility via macros

Hosted DSLs

Use a traditional compiler,
but connected to the host-language
macro system.


Racket
Racket
Expander
Racket
Core
Racket
Compiler
x86


DSL
DSL Expander
DSL Core
DSL Compiler
Racket
Racket
Racket Expander
Racket Core
Racket Compiler
x86


DSL
DSL Expander
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DSL Compiler
Racket
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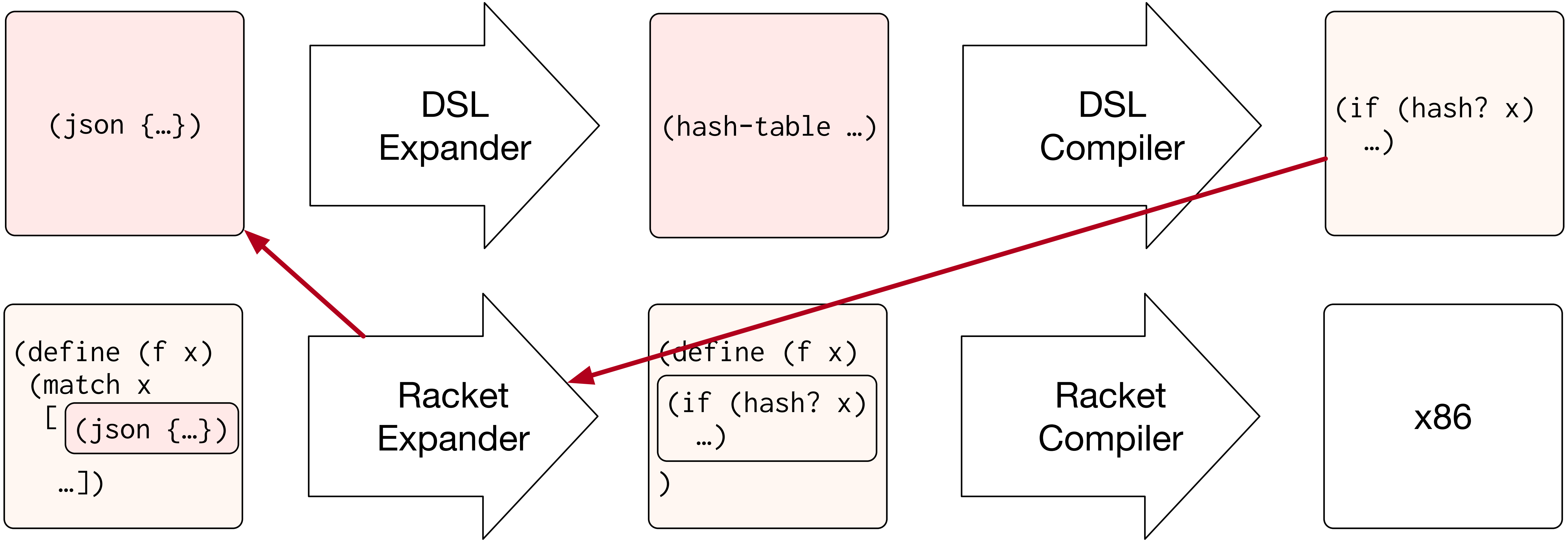
(json {…})
DSL Expander
(hash-table …)
DSL Compiler
(if (hash? x) …)
(define (f x) (match x [(json {…}) …])
Racket Expander
(define (f x) (if (hash? x) …))
Racket Compiler
x86

miniKanren core language

```
term := literal
      | lvar
      | (cons term term)

goal := (== term term)
      | (fresh1 (lvar ...) goal)
      | (disj2 goal goal)
      | (conj2 goal goal)
      | (relname term ...)
```

miniKanren core language

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term := literal
      | lvar
      | (cons term term)

goal := (== term term)
      | (fresh1 (lvar ...) goal)
      | (disj2 goal goal)
      | (conj2 goal goal)
      | (relname term ...)
```

miniKanren syntactic sugar

```
term := ...
      | (quasiquote quoted)

goal := ...
      | (fresh (lvar ...) goal ...)
      | (conde [goal ...] ...)
```

miniKanren core language

```
term := literal
      | lvar
      | (cons term term)

goal := (== term term)
      | (fresh1 (lvar ...) goal)
      | (disj2 goal goal)
      | (conj2 goal goal)
      | (relname term ...)
```

miniKanren syntactic sugar

```
term := ...
      | (quasiquote quoted)

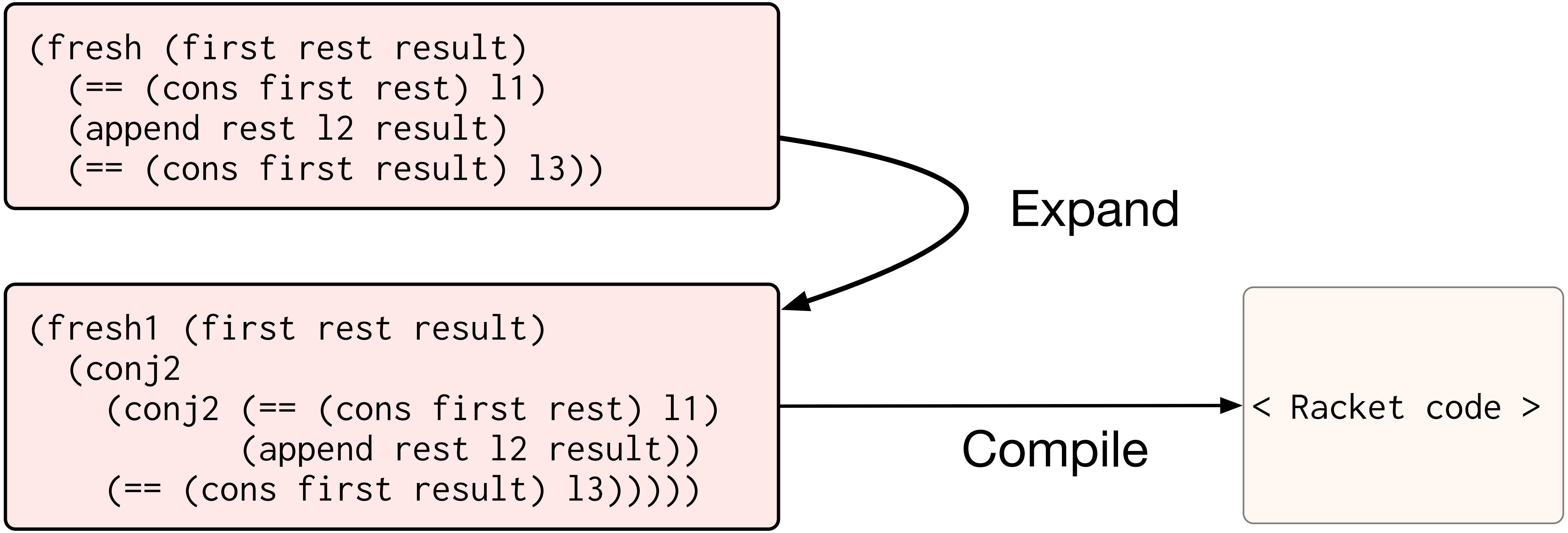
goal := ...
      | (fresh (lvar ...) goal ...)
      | (conde [goal ...] ...)
```

Racket “interface macros”

```
racket-def := ...
            | (define-relation (relname lvar ...) goal)

racket-exp := ...
            | (run n (lvar ...) goal)
```

```
(define-relation (append l1 l2 l3)
  (conde
    [(== l1 '())
     (== l2 l3)]
    [(fresh (first rest result)
       (== (cons first rest) l1)
       (append rest l2 result)
       (== (cons first result) l3))]))
```


(fresh (first rest result)
  (== (cons first rest) l1)
  (append rest l2 result)
  (== (cons first result) l3))
Expand
(fresh1 (first rest result)
  (conj2
    (conj2 (== (cons first rest) l1)
           (append rest l2 result))
    (== (cons first result) l3))))
Compile
< Racket code >

```
(fresh (first rest result)
  (== (cons first rest) l1)
  (append rest l2 result)
  (== (cons first result) l3))
```

Expand

```
(fresh1 (first rest result)
  (conj2
    (conj2 (== (cons first rest) l1)
           (append rest l2 result))
    (== (cons first result) l3)))))
```

Transform

(Improve search behavior)

```
(fresh1 (first rest result)
  (conj2
    (conj2 (== (cons first rest) l1)
           (== (cons first result) l3))
    (append rest l2 result)))))
```

Compile

< Racket code >

Benefits:

- Enforced DSL grammar
  miniKanren terms and goals are separated
- Enforced DSL static semantics
  Relation arity
- Domain-specific analysis and transformation
  Unification lifting

Integration Between Languages

```
(define-relation (naturals v)
  (loop recur ([n 0])
    (conde
      [(== v n)]
      [(recur (+ n 1))])))
```

Integration Between Languages

```
(define-relation (naturals v)
  (racket
    (loop recur ([n 0])
      (mkgoal
        (conde
          [(== v n)]
          [(racket (recur (+ n 1)))])))))
```

Integration Between Languages

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(define-relation (naturals v)
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```

`loop` body scope

Relation body scope

Integration Between Languages

```
(define-relation (naturals v)
  (racket
    (loop recur ([n 0])
      (mkgoal
        (conde
          [(== v n)]
          [(racket (recur (+ n 1)))])))))
```

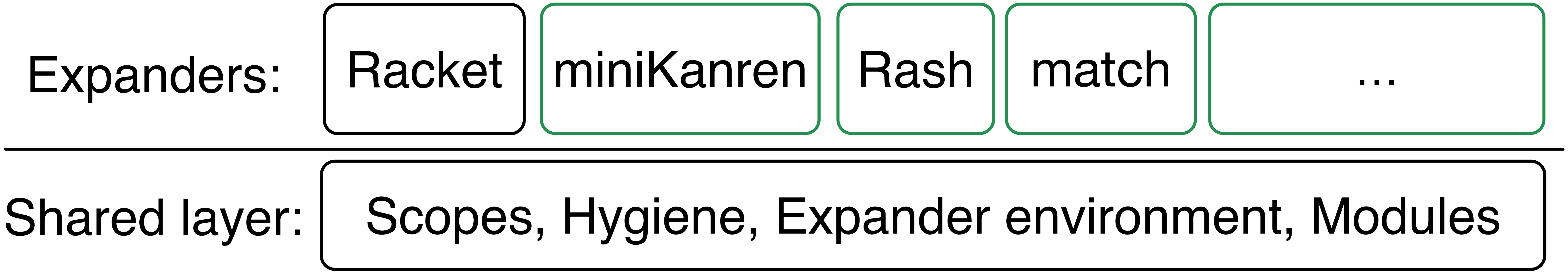
Cross-language name reference

`loop` body scope

Relation body scope

Separate out and expose the language-independent parts of Racket's expander, and reuse them in DSL expanders.

Expanders:	Racket	miniKanren	Rash	match	...
Shared layer:	Scopes, Hygiene, Expander environment, Modules				



New API to make this shared layer easy to reuse.

Reuse: Scope

```
(define-relation (naturals v)
  (racket
    (loop recur ([n 0])
      (mkgoal
        (conde
          [(== v n)]
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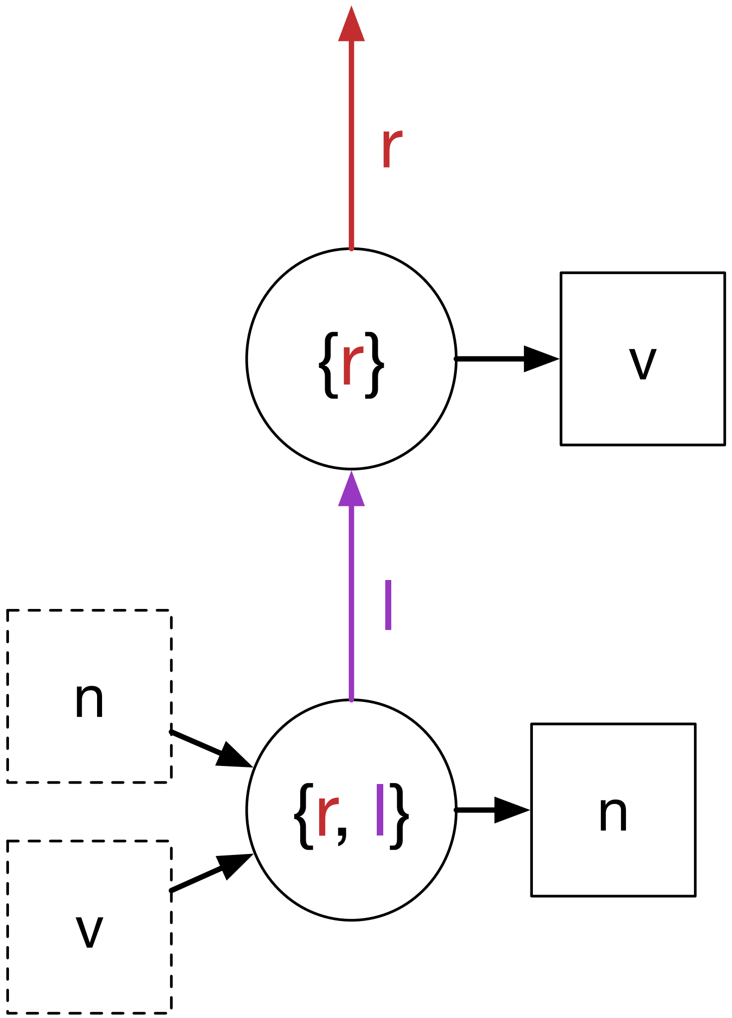
```



```
(define-relation (naturals v)
  (racket
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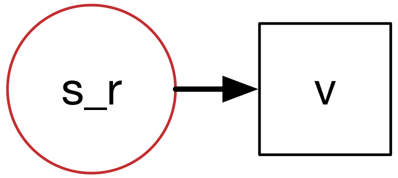
(define-relation (naturals v)
  (racket
   (loop recur ([n 0])
     (mkgoal
       (conde
         [(== v n)]
         [(racket (recur (+ n 1)))])))))
```

```
expOk(s_r, (loop recur ([n 0])
             (mkgoal
               (conde
                 [(== v n)]
                 [(racket (recur (+ n 1)))]))))
```



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  (racket
   (loop recur ([n 0])
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       (conde
         [(== v n)]
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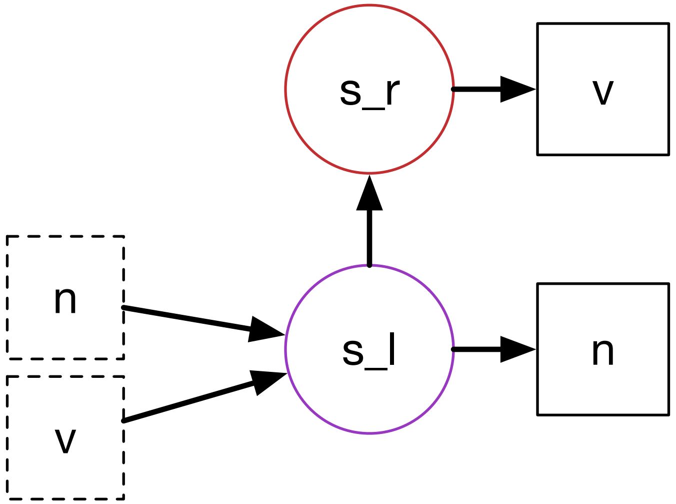

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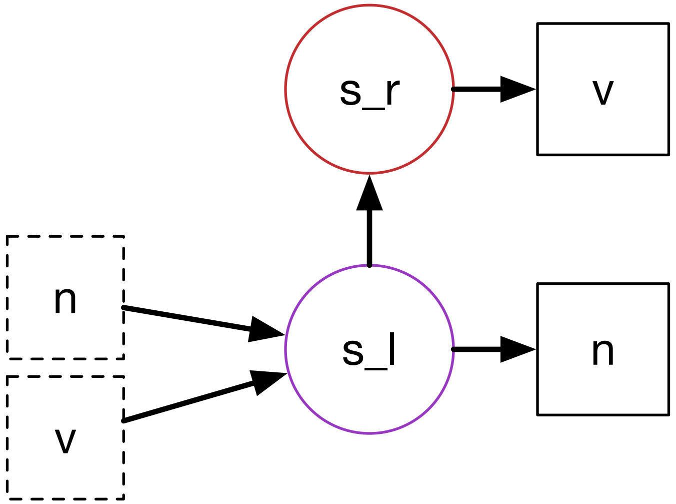
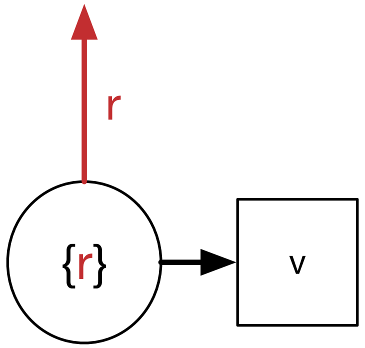



```
(expand #'(loop recur ([n_{r} 0])
            (mkgoal
              (conde
                [(== v_{r} n)]
                [(racket (recur (+ n_{r} 1)))]))))
```



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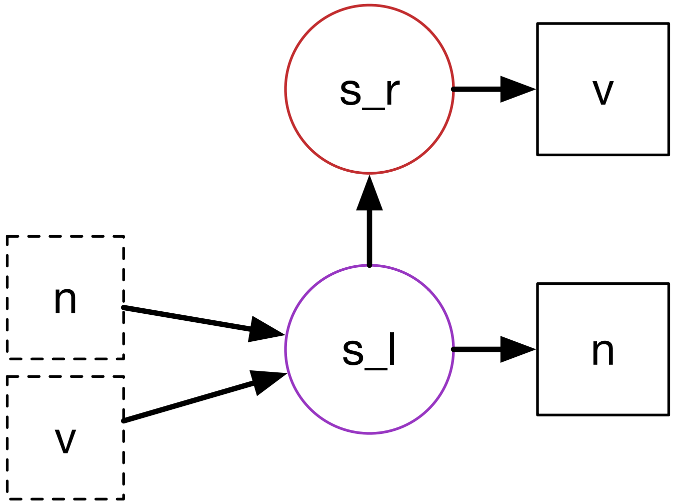
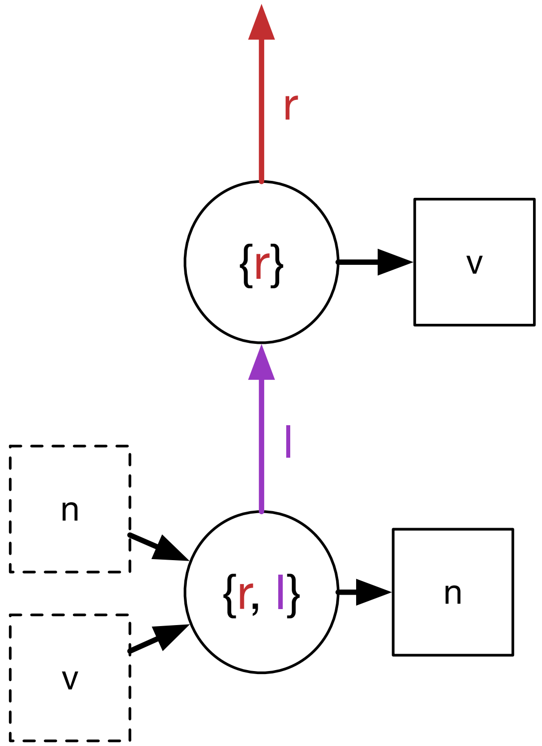



```
(expand #'(loop recur ([n_{r} 0])
            (mkgoal
              (conde
                [(== v_{r} n)]
                [(racket (recur (+ n_{r} 1)))]))))
=>
#'(loop recur ([n_{r,l} 0])
    (mkgoal
     (conde
       [(== v_{r,l} n)]
       [(racket (recur (+ n_{r,l} 1)))])))
```



Scope in the presence of macros: hygiene

We want programmers to be able to extend both Racket and DSLs with macros.

```
(define-relation (naturals v)
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Expansion…

- Moves syntax between scopes and modules
- Combines syntax from different origins

Like the need to avoid capture in λ substitution, but more subtle.

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```

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Like the need to avoid capture in λ substitution, but more subtle.

Automatic hygiene motivates Racket’s model of scope.

Scope in the presence of macros: hygiene

What if `loop` is defined by a macro?

```
(loop recur ([x init]) b)
->
(let ([v init])
  (letrec ([recur (lambda (x) b)])
    (recur v)))
```

```
(define-relation (naturals v)
  (racket
    (loop recur ([n 0])
      (mkgoal
        (conde
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          [(racket (recur (+ n 1)))]))))))
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(define-relation (naturals v)
 (racket
  (loop recur ([n 0])
    (mkgoal
      (conde
        [(== v n)]
        [(racket (recur (+ n 1)))])))))
```

Expands to

```
(define-relation (naturals v)
 (racket
  (let ([v 0])
    (letrec ([recur
              (lambda (n)
                (mkgoal
                  (conde
                    [(== v n)]
                    [(racket (recur (+ n 1)))])))])
    (recur v)))))
```

Scope in the presence of macros: hygiene

What if `loop` is defined by a macro?

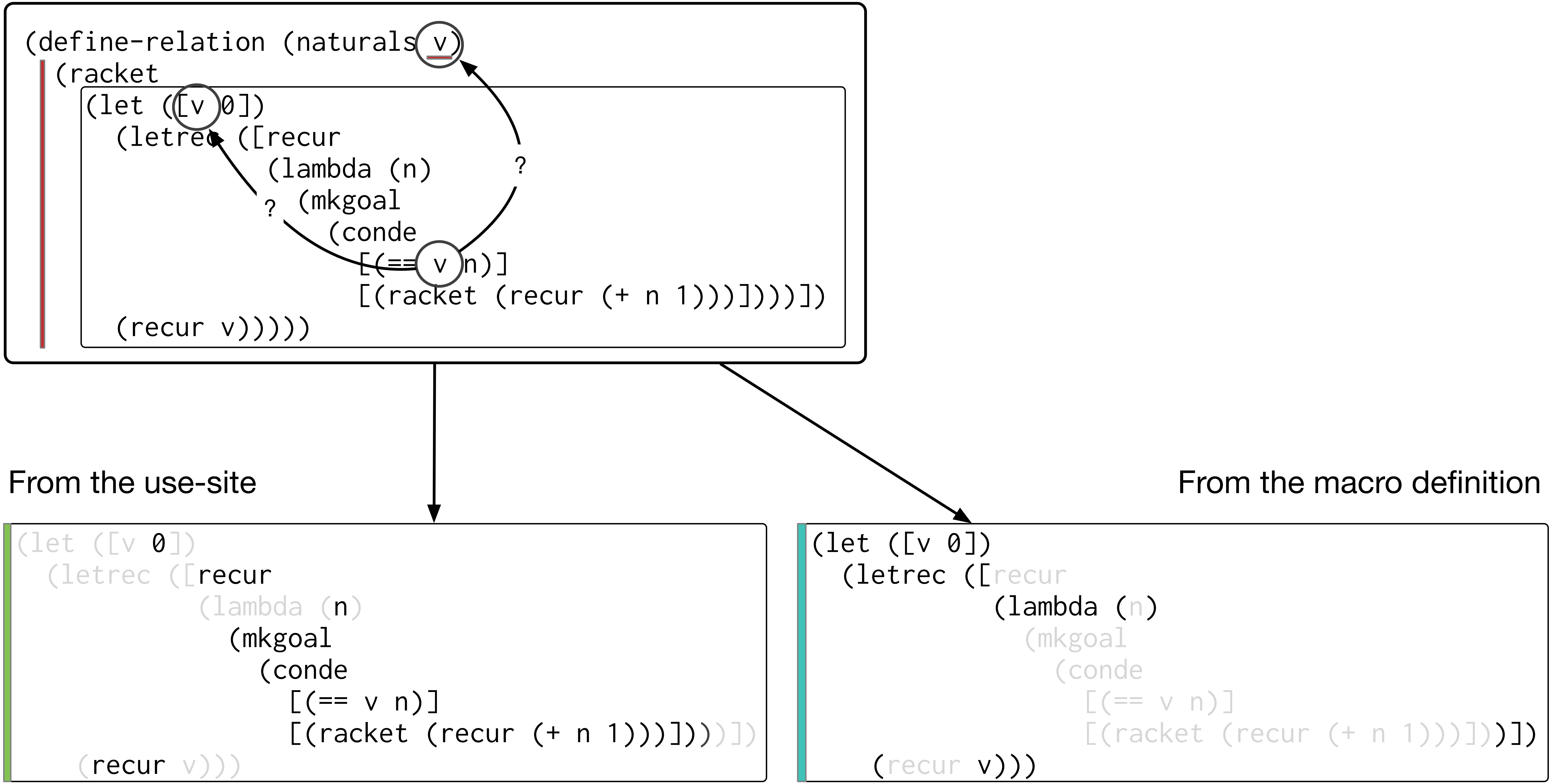
```
(loop recur ([x init]) b)
->
(let ([v init])
  (letrec ([recur (lambda (x) b)])
    (recur v)))
```

```
(define-relation (naturals v)
  (racket
    (loop recur ([n 0])
      (mkgoal
        (conde
          [(== v n)]
          [(racket (recur (+ n 1)))])))))
```

Expands to

```
(define-relation (naturals v)
  (racket
    (let ([v 0])
      (letrec ([recur
                 (lambda (n)
                   (mkgoal
                     (conde
                       [(== v n)]
                       [(racket (recur (+ n 1)))])))])
      (recur v)))))
```

```
(define-relation (naturals v)
  (racket
    (let ([v 0])
      (letrec ([recur
                 (lambda (n)
                   (mkgoal
                     (conde
                       [(== v n)]
                       [(racket (recur (+ n 1)))])))])
        (recur v)))))
```


(define-relation (naturals v)
(racket
(let ([v 0])
(letrec ([recur
(lambda (n)
(mkgoal
(conde
[(== v n)]
[(racket (recur (+ n 1)))])))])
(recur v)))))
?
?
From the use-site
From the macro definition
(let ([v 0])
(letrec ([recur
(lambda (n)
(mkgoal
(conde
[(== v n)]
[(racket (recur (+ n 1)))])))])
(recur v)))
(let ([v 0])
(letrec ([recur
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(conde
[(== v n)]
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(define-relation (naturals v)
  (racket
    (let ([v 0])
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                (lambda (n)
                  (mkgoal
                    (conde
                      [(== v n)]
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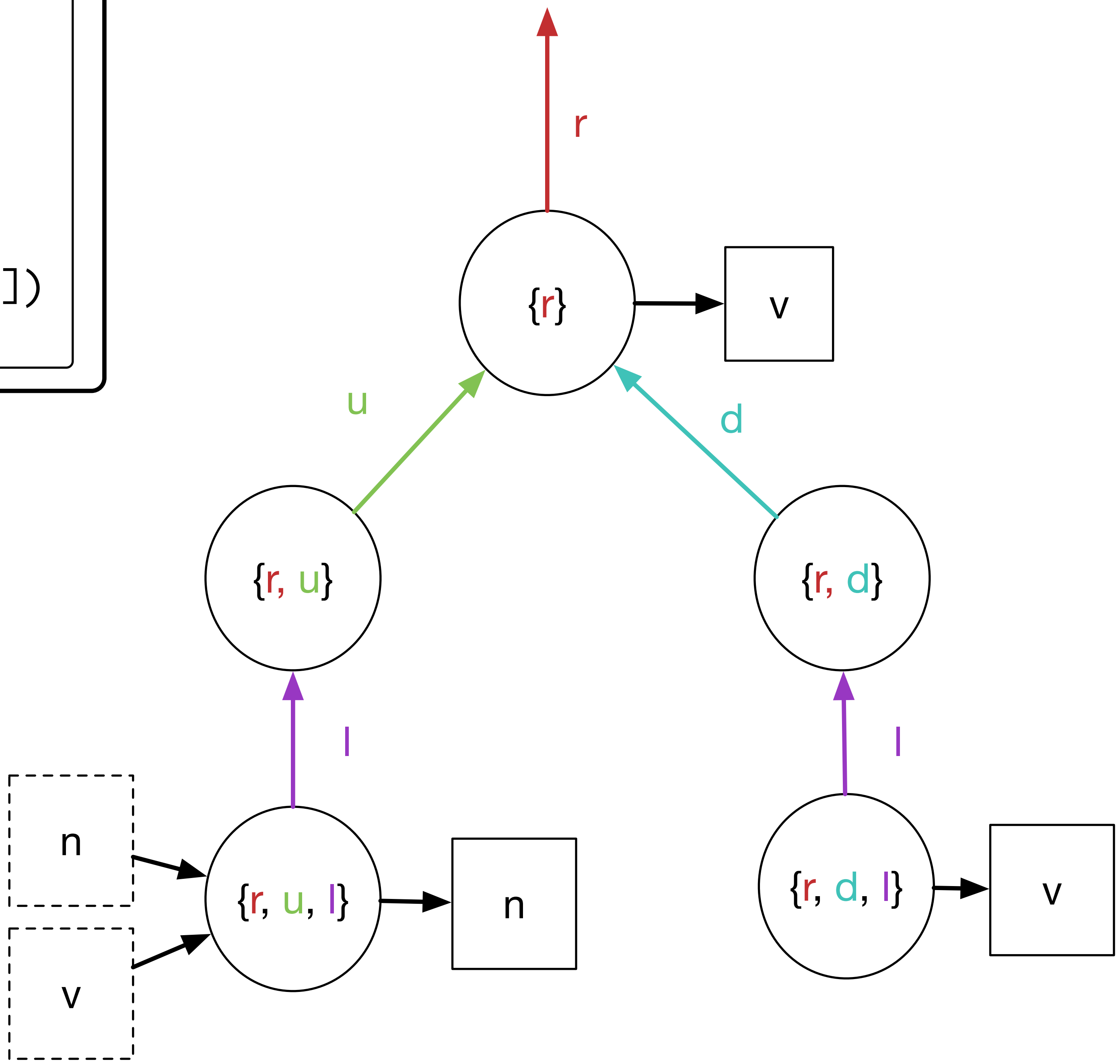
      (recur v)))))
```



Statix

- Scope:
  ```
  new s_let
  s_let -P-> s
  ```
- Binding:
  ```
  !lvar[x] in s_let
  x in s_let |-> [(_,_)]
  ```

extDSL API

- Scope:
  ```
  (with-scope s_let …)
  (add-scope #'body s_let)
  ```
- Binding:
  ```
  (bind! #'x (lvar))
  (lookup #'x)
  ```
- Hygiene:
  ```
  (apply-as-transformer f arg …)
  ```

(Break and questions)

Reuse: Expander Environment

```
define ->
  (rkt-macro #<procedure>)
x ->
  (racket-var)
```

```
(define x 5)
; ->
(define-values (x) 5)
x
```

Reuse: Expander Environment

```
define ->
  (rkt-macro #<procedure>)
x ->
  (racket-var)
conde ->
  (goal-macro #<procedure>)
append ->
  (relation 3)
l1, l2, l3 ->
  (lvar)
```

```
(define x 5)
; ->
(define-values (x) 5)
x

(define-relation (append l1 l2 l3)
  (conde
     …))

(run* (l1 l2)
  (append l1 l2 '(1 2)))
```

Reuse: Modules and Separate Compilation

Expander Environment

```
append ->
  (relation 3)
```

mk/lists

```
(provide append)
(define-relation (append l1 l2 l3)
  …)
```

Reuse: Modules and Separate Compilation

Expander Environment

```
append ->
  (relation 3)
```

`mk/lists`

```
(provide append)
(define-relation (append l1 l2 l3)
  …)
```

`mk/tests/lists`

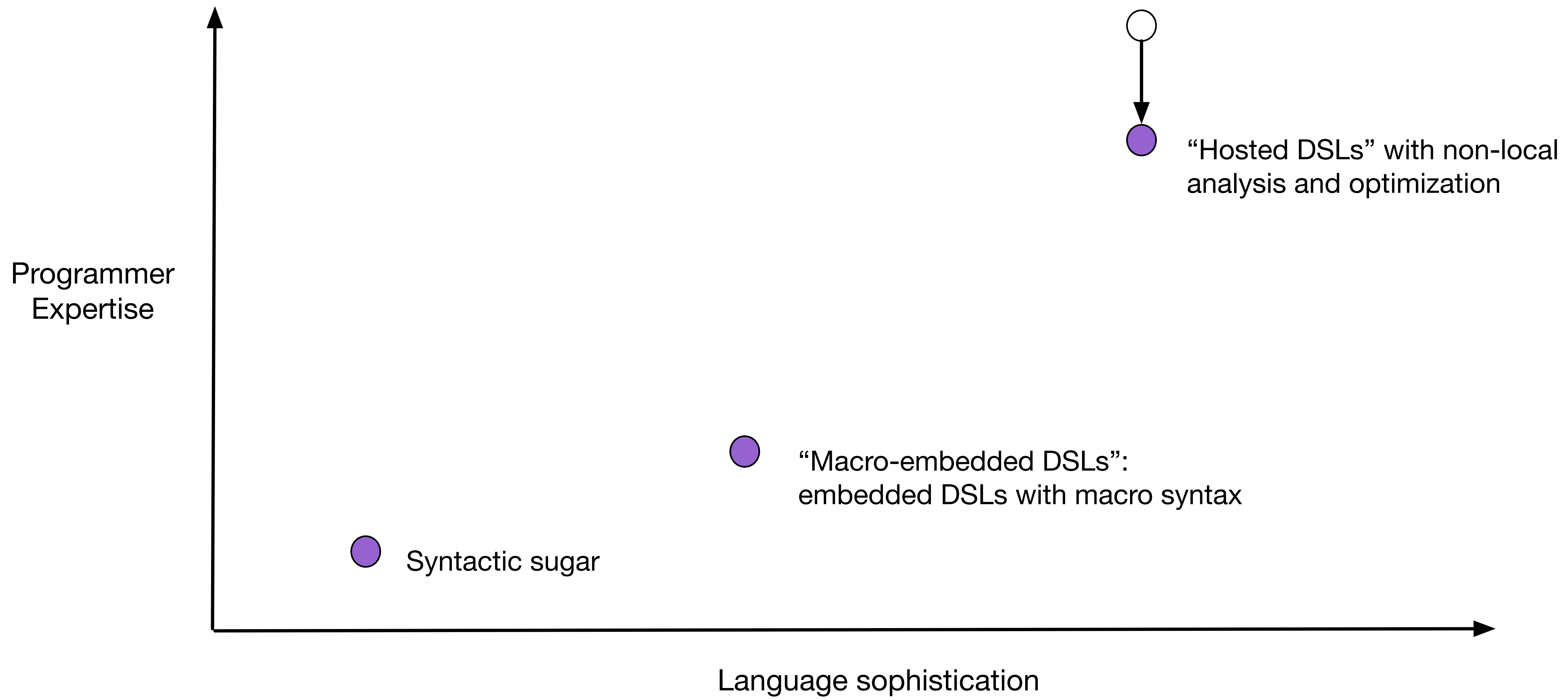
```
(require mk/lists)
(run* (l1 l2)
  (append l1 l2 '(1 2)))
```

Expander Environment

```
append ->
  (relation 3)
```

Benefits of reuse

- Scope and binding work across languages
- DSL macros behave like host-language macros
- DSLs reuse host’s module system
- IDE understands DSL scope and binding



“Hosted DSLs” with non-local analysis and optimization
Programmer Expertise
“Macro-embedded DSLs”: embedded DSLs with macro syntax
Syntactic sugar
Language sophistication

Remaining problem: DSL expanders are low-level, procedural, and demand deep understanding of Racket’s macro system.

Declaring a language.

```
(define-variable-class lvar)
(define-variable-class relname)

(define-nonterminal term
  literal
  lvar
  (cons term term))

(define-nonterminal goal
  (== term term)
  (fresh (v:lvar ...+) g:goal)
    #:binding { (! v) g }
  (disj2 goal goal)
  (conj2 goal goal)
  (relname term ...+))
```

Binding specifications

```
(define-variable-class lvar)
(define-variable-class relname)

(define-nonterminal term
  literal
  lvar
  (cons term term))

(define-nonterminal goal
  (== term term)
  (fresh (v:lvar ...+) g:goal)
    #:binding { (! v) g }
  (disj2 goal goal)
  (conj2 goal goal)
  (relname term ...+))
```

Declaring extension points

```
(define-variable-class lvar)
(define-variable-class relname)

(define-extension-class goal-macro)

(define-nonterminal term
  (quote datum)
  literal
  lvar
  (cons term term))

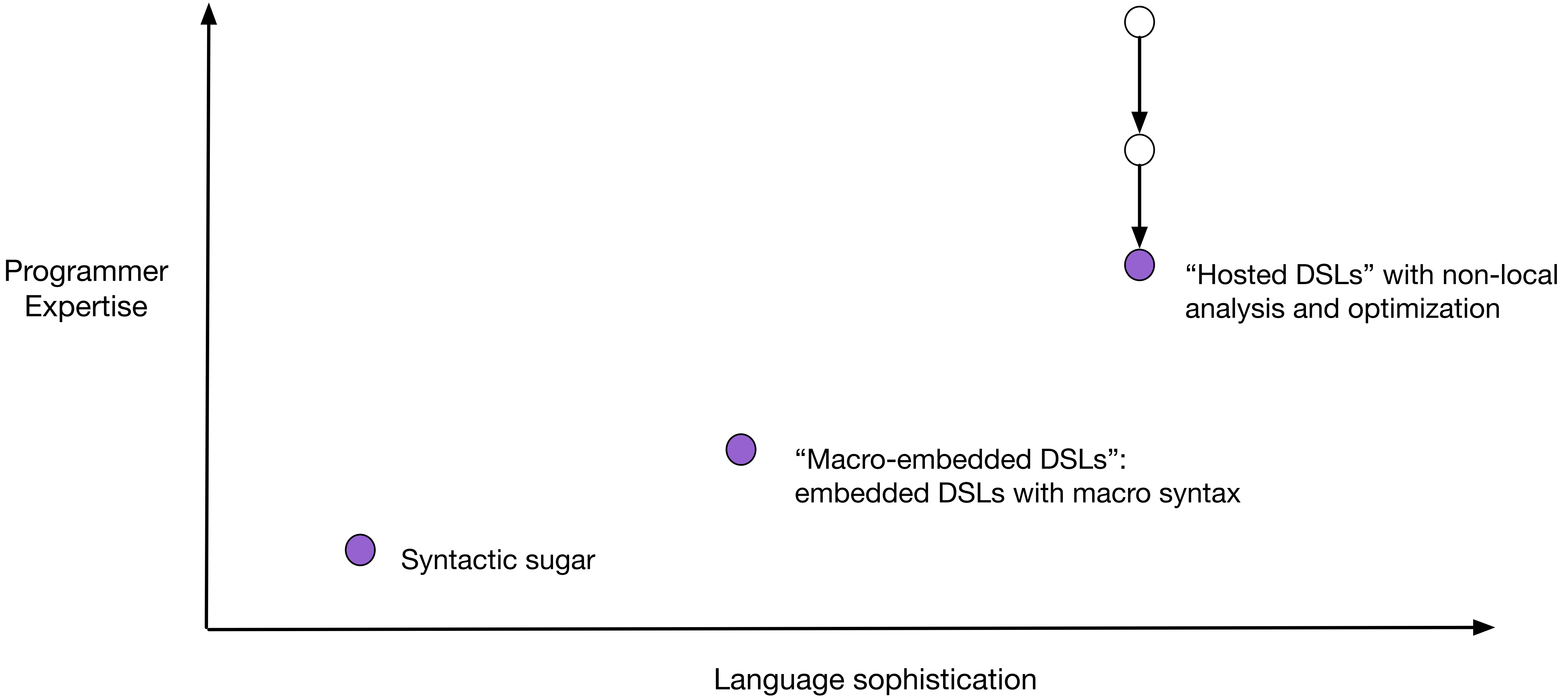
(define-nonterminal goal
  #:allow-extension goal-macro
  (== term term)
  (fresh (lvar ...+) goal ...+)
    #:binding { (! lvar) goal }
  (disj goal ...+)
  (conj goal ...+)
  (relname term ...+))
```

Key goal: make simple, untyped languages easy.

How can we

- integrate type rules
- handle dependent binding structures

without making the common case complicated?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This talk:

- Macro-embedding is easy and great for simple DSLs and design exploration.
- Custom DSL expanders and compilers enable more sophisticated features, and can integrate with the host via our new API.

- In progress: Declarative definition of extensible hosted DSLs, using language workbench ideas.

This talk:

- Macro-embedding is easy and great for simple DSLs and design exploration.
- Custom DSL expanders and compilers enable more sophisticated features, and can integrate with the host via our new API.

- In progress: Declarative definition of extensible hosted DSLs, using language workbench ideas.

Questions?

Details of binding specification…

Binding specifications

```
(fresh (first rest result)
  (conj2
    (conj2
      (== (cons first rest) l1)
      (== (cons first result) l3))
    (append rest l2 result)))
```

Binding specifications

```
(fresh (first rest result)
  (conj2
    (conj2
      (== (cons first rest) l1)
      (== (cons first result) l3))
    (append rest l2 result)))
```

```
(fresh (v:lvar ...+) g:goal)
  #:binding { (! v) g }
```

Exported bindings

```
(match '(1 2 3)
  [(cons first (cons second tail))
   second]
  [_ (error)])
```

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```

```
(define-nonterminal match-clause
  [p:pat e:racket-expr]
    #:binding { (! p) e })
```

Exported bindings

```
(match '(1 2 3)
  [(cons first (cons second tail))
   second]
  [_ (error)])
```

```
(define-nonterminal match-clause
  [p:pat e:racket-expr]
    #:binding { (! p) e })

(define-nonterminal pat
  literal
  v:pvar
    #:binding (^ v)
  (cons p1:pat p2:pat)
    #:binding (^ p1 p2))
```

Mutually recursive bindings

```
(block
  (define f
    (lambda (x) (g x)))
  (define g
    (lambda (x) (f x)))
  (f 5))
```

Mutually recursive bindings

```
(block
  (define f
    (lambda (x) (g x)))
  (define g
    (lambda (x) (f x)))
  (f 5))
```

```
(define-nonterminal def-or-expr
  (define v:rlvar e:expr)
    #:binding (^ v)
  e:expr)
```

Mutually recursive bindings

```
(block
  (define f
    (lambda (x) (g x)))
  (define g
    (lambda (x) (f x)))
  (f 5))
```

```
(define-nonterminal def-or-expr
  (define v:rlvar e:expr)
    #:binding (^ v)
  e:expr)

(define-nonterminal expr
  …
  (block body:def-or-expr ...)
    #:binding { (! body) body })
```