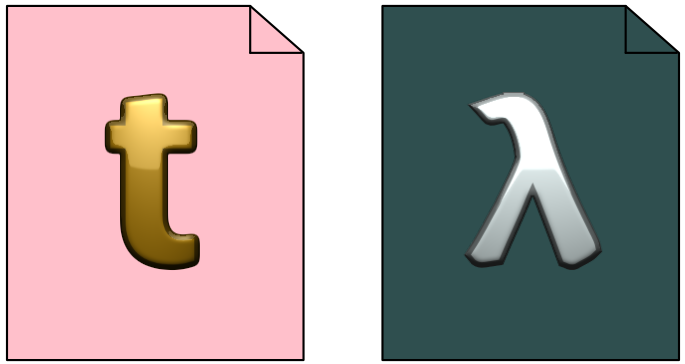
# A Spectrum of Type Soundness and Performance

Ben Greenman & Matthias Felleisen
Northeastern University

Is type soundness all-or-nothing?

Can adding types slow down a program?

# Migratory Typing



# Typed/Untyped Languages

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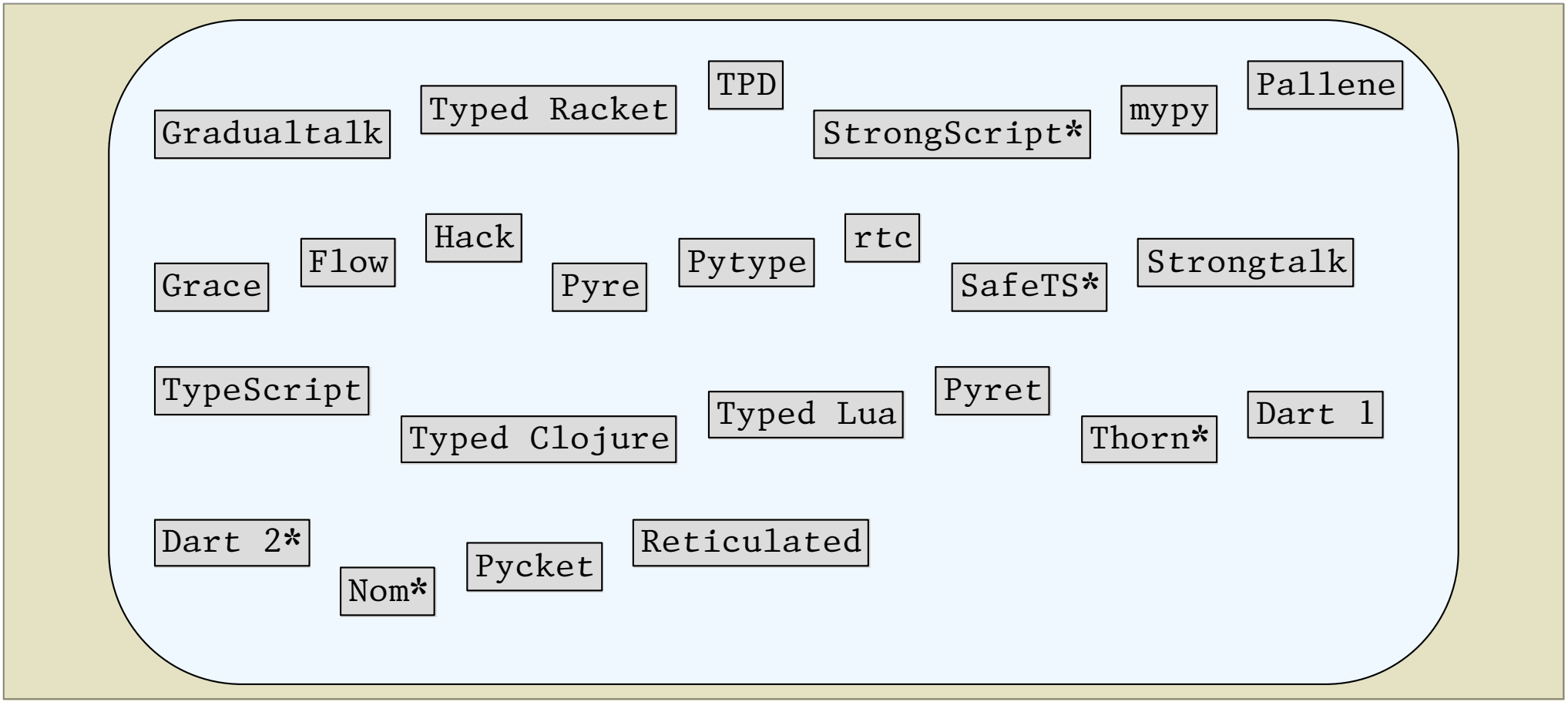
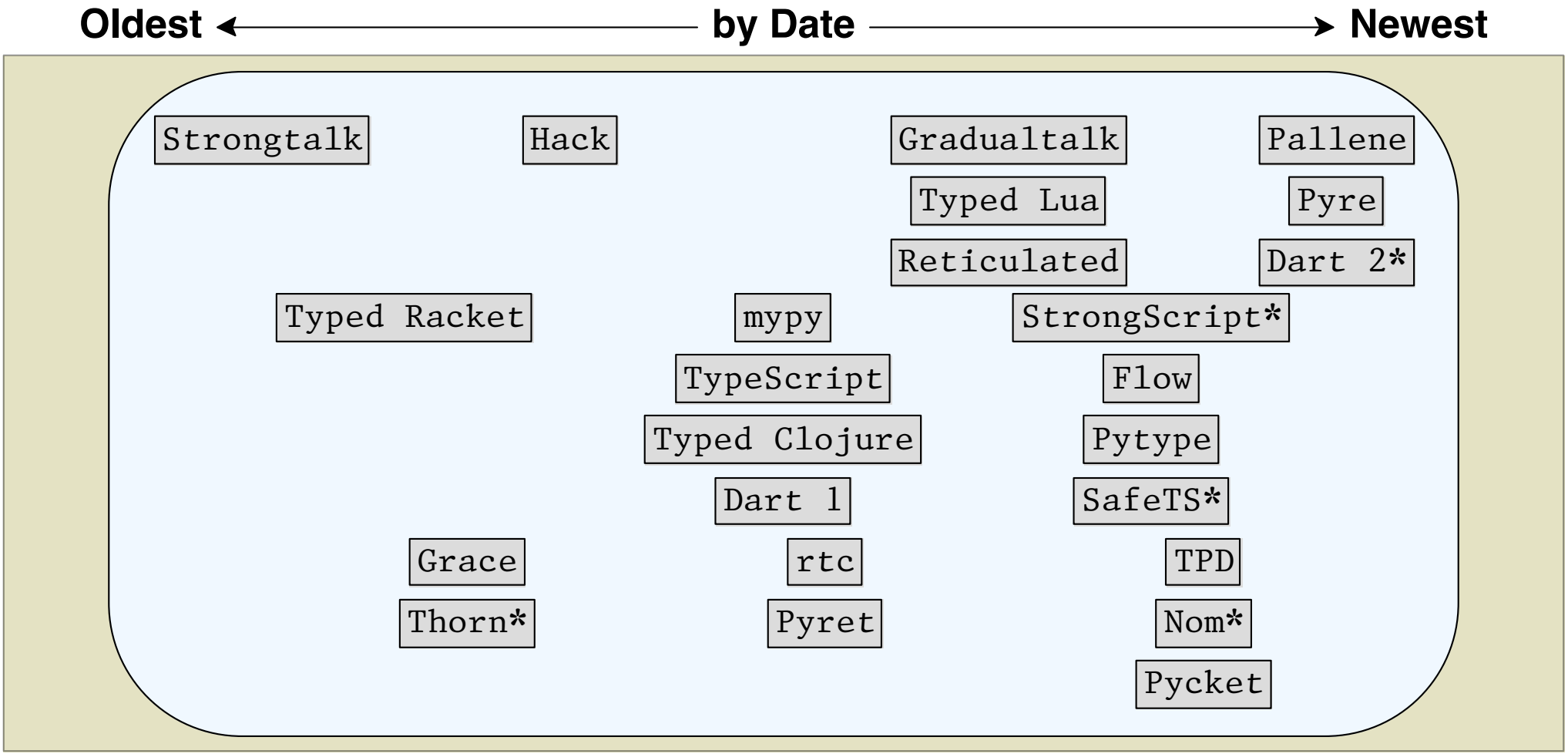
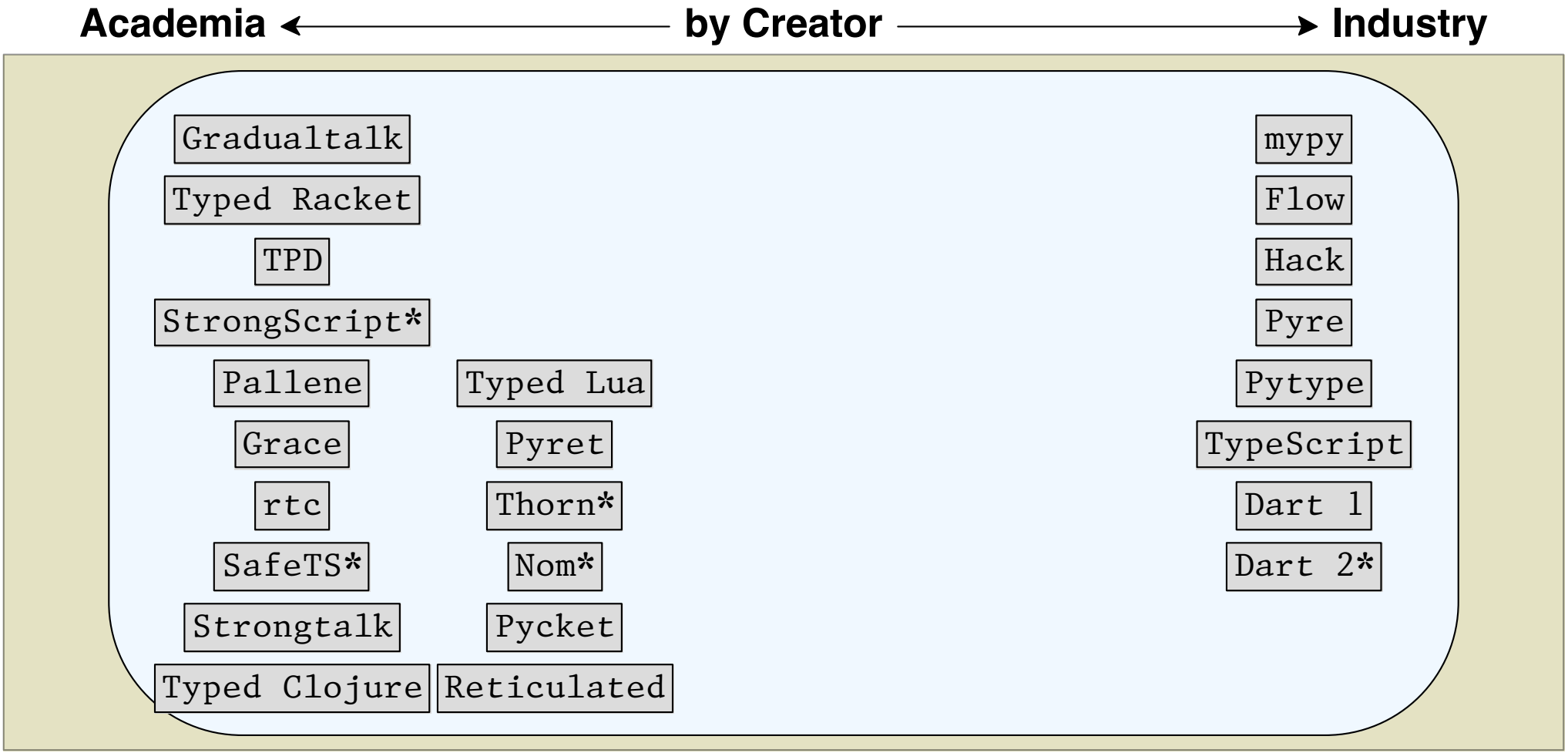



Oldest
by Date
Newest
Strongtalk
Hack
Gradualtalk
Pallene
Typed Lua
Pyre
Reticulated
Dart 2*
Typed Racket
mypy
StrongScript*
TypeScript
Flow
Typed Clojure
Pytype
Dart 1
SafeTS*
Grace
rtc
TPD
Thorn*
Pyret
Nom*
Pycket


Academia
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Gradualtalk
Typed Racket
TPD
StrongScript*
Pallene
Grace
rtc
SafeTS*
Strongtalk
Typed Clojure
Typed Lua
Pyret
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Nom*
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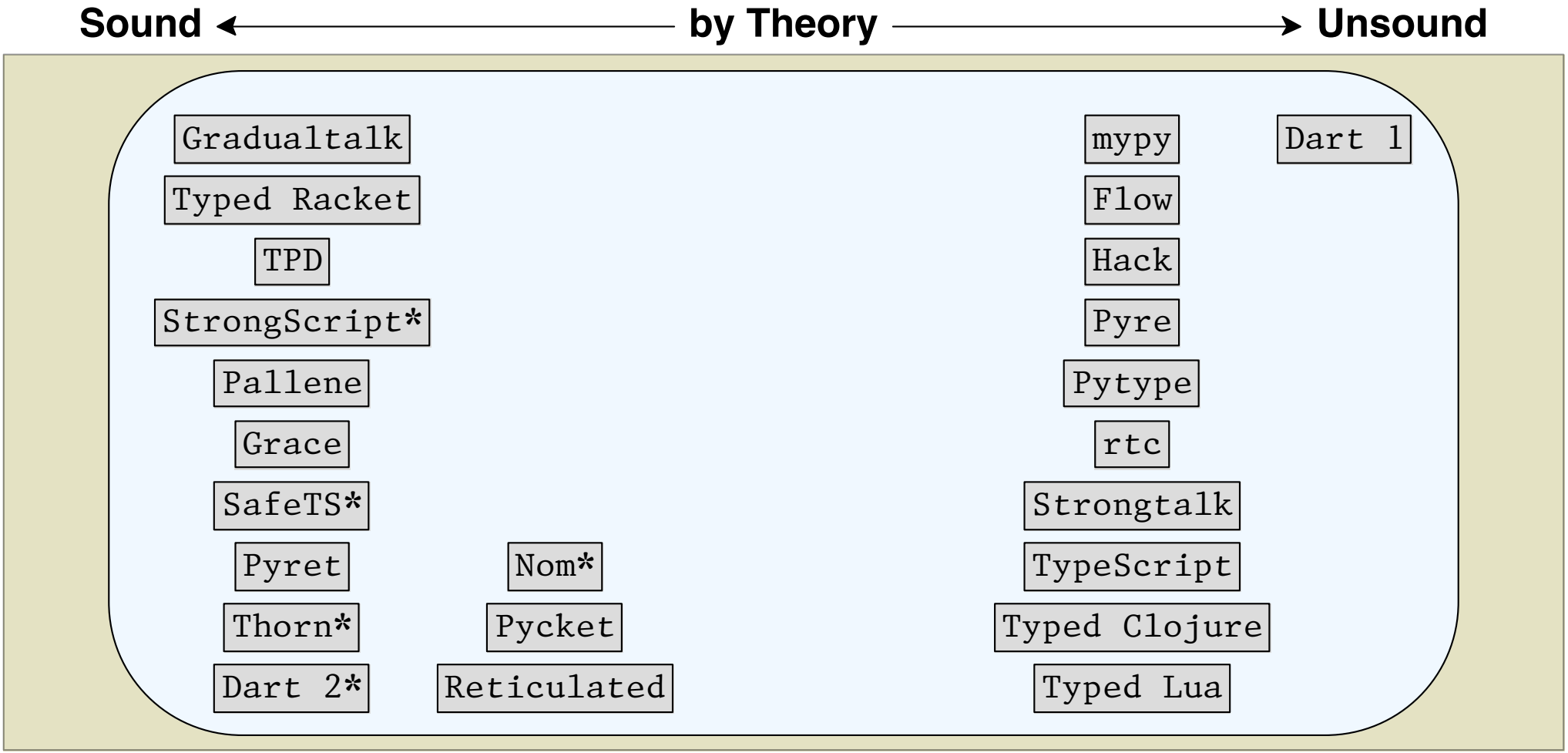
Reticulated
mypy
Flow
Hack
Pyre
Pytype
TypeScript
Dart 1
Dart 2*


Sound
by Theory
Unsound
Gradualtalk
Typed Racket
TPD
StrongScript*
Pallene
Grace
SafeTS*
Pyret
Thorn*
Dart 2*
Nom*
Pycket
Reticulated
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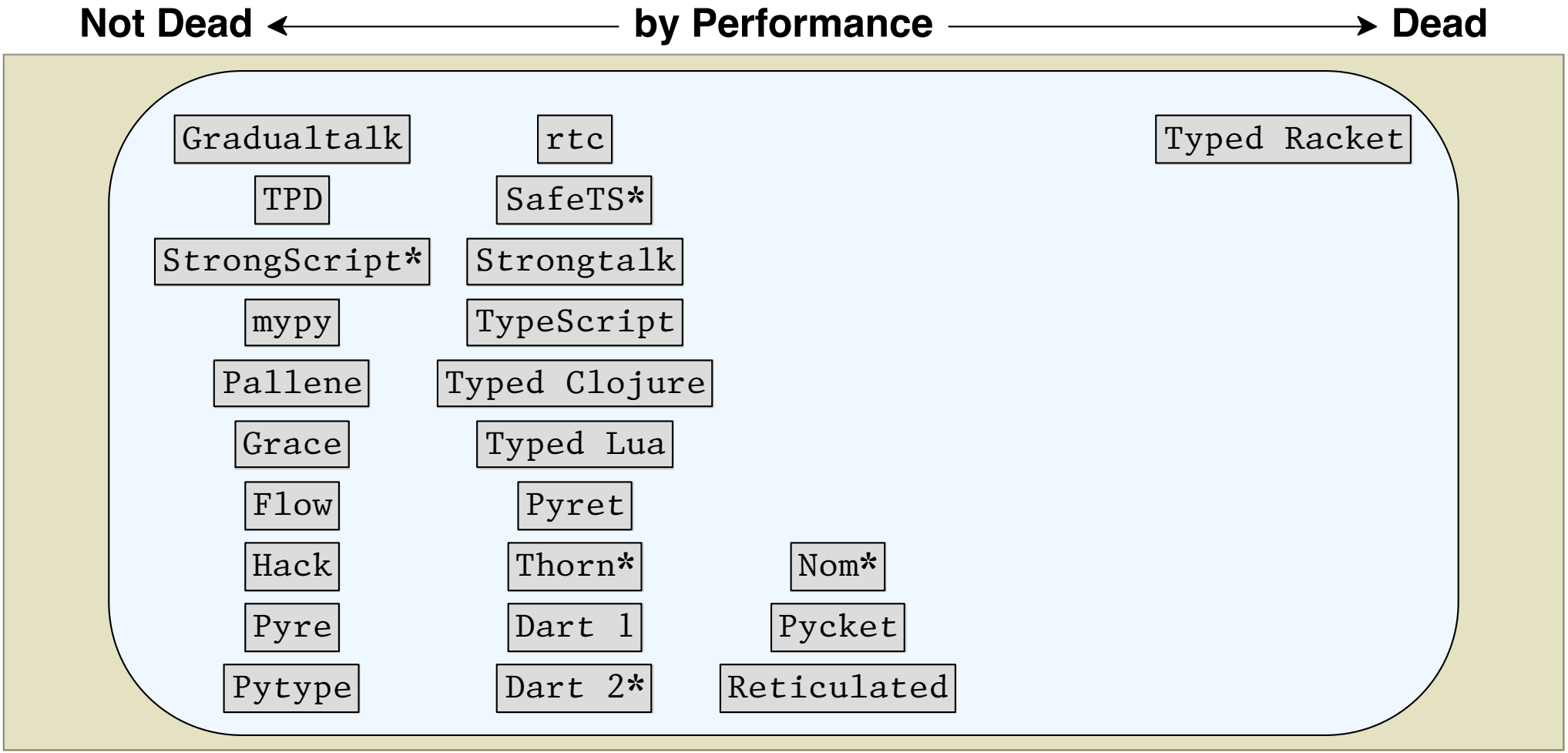
Pytype
rtc
Strongtalk
TypeScript
Typed Clojure
Typed Lua
Dart 1

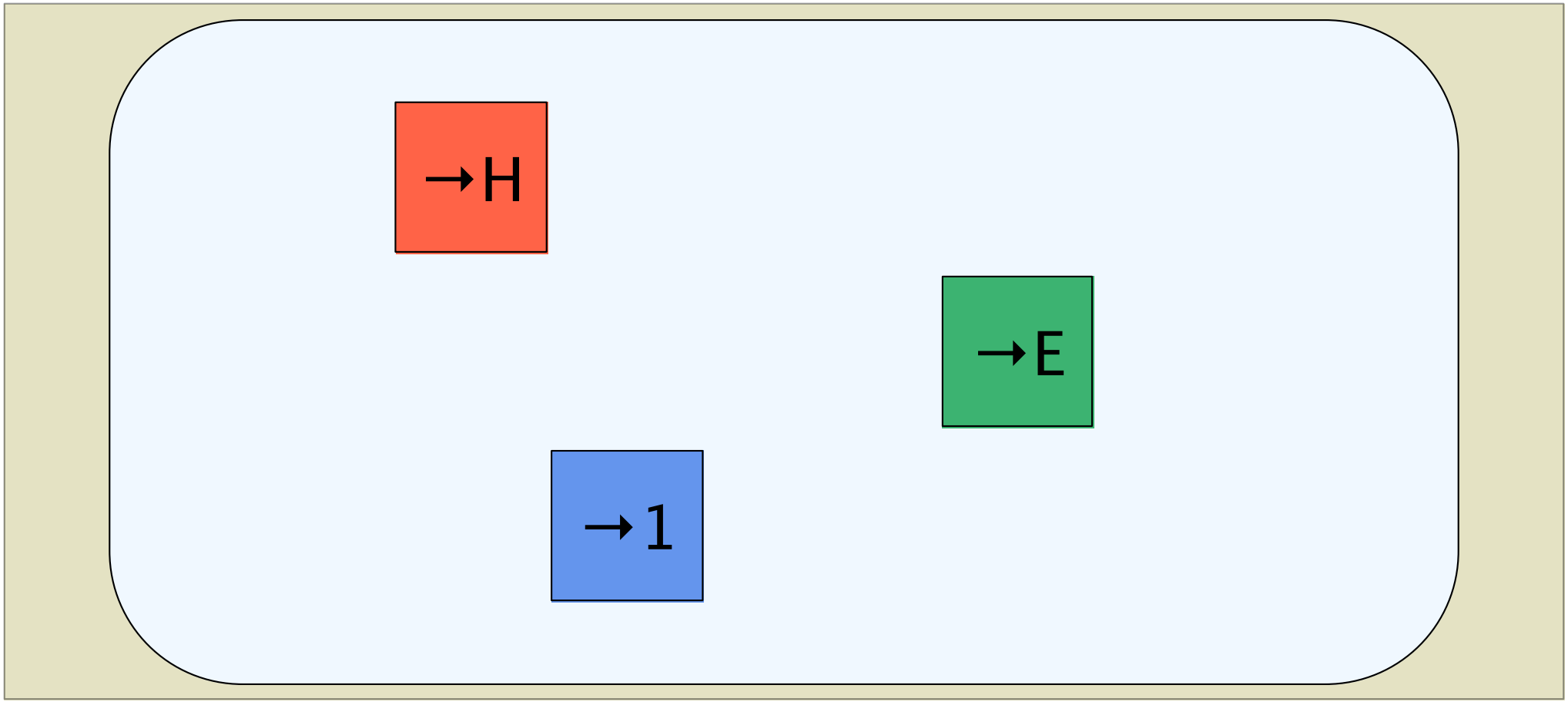


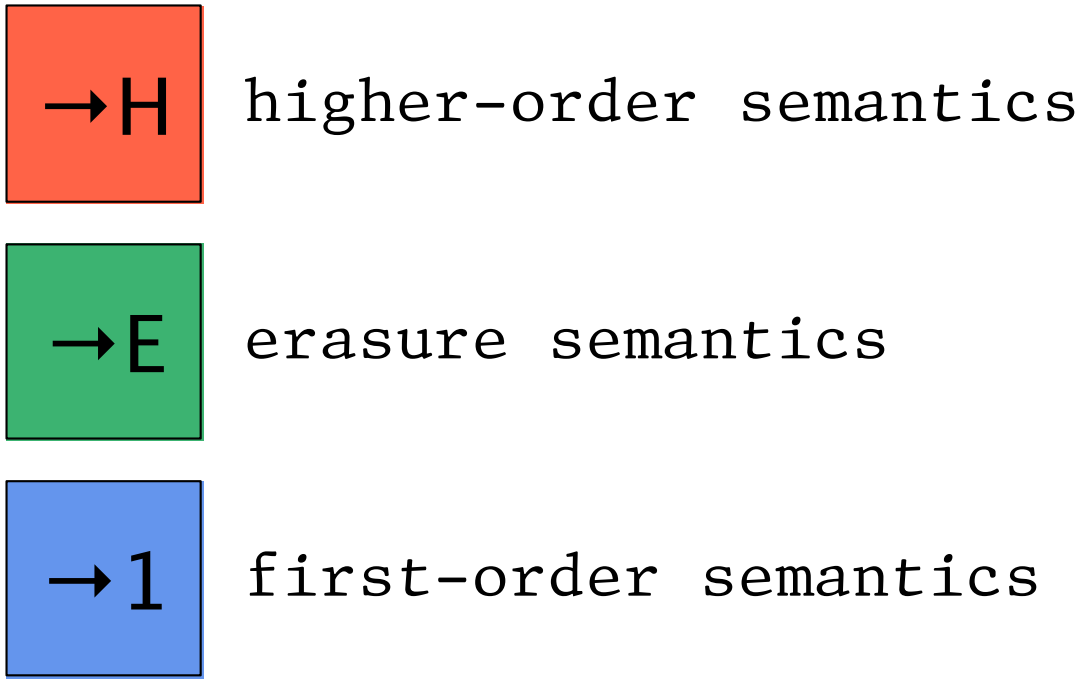

(the word 'dead' is used here in a technical sense)

# Chaos!

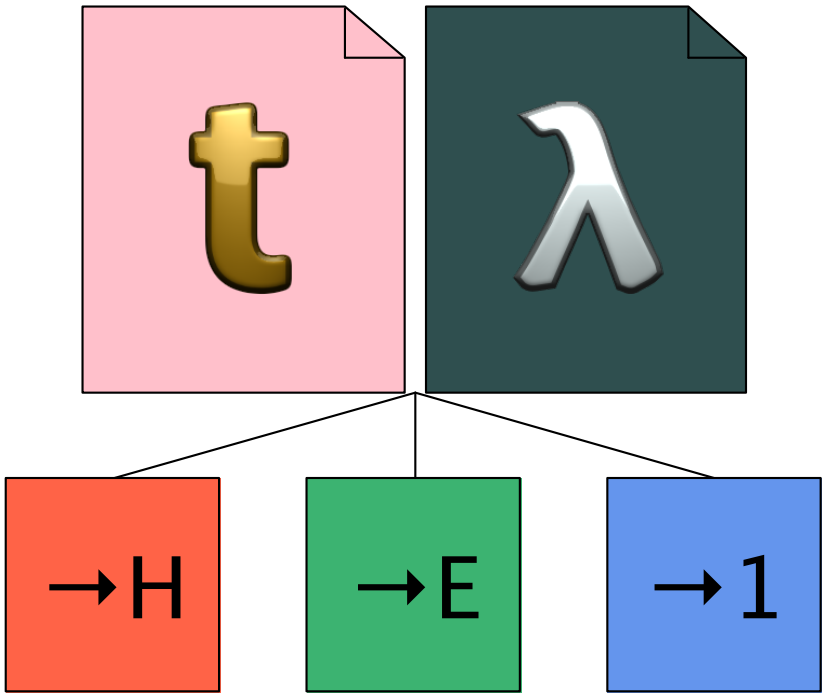
# KafKa: Gradual Typing for Objects


| | |
|---|---|
| **Who** | *Benjamin W Chung*, *Paley Li*, *Francesco Zappa Nardelli*, *Jan Vitek* |
| **Track** | ECOOP 2018 ECOOP Research Papers |


→H
→E
→1


→H
higher-order semantics
→E
erasure semantics
→1
first-order semantics

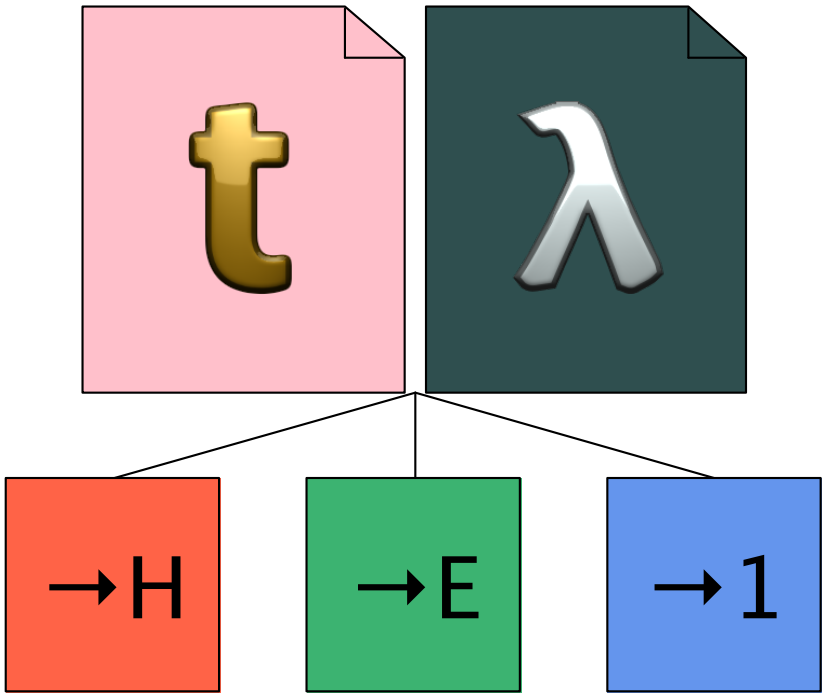
# Contributions (1/2)



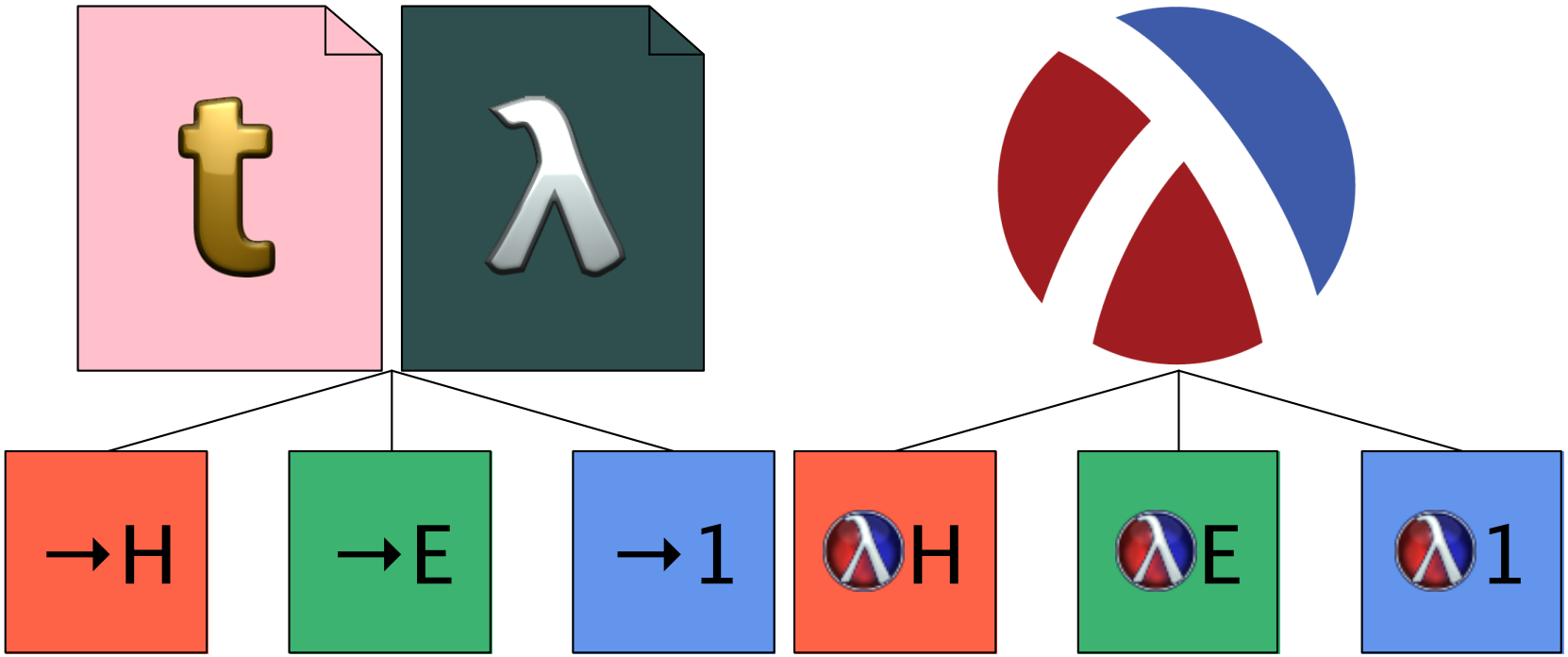

Model:

- one mixed-typed language
- one surface type system
- three semantics

# Contributions (2/2)



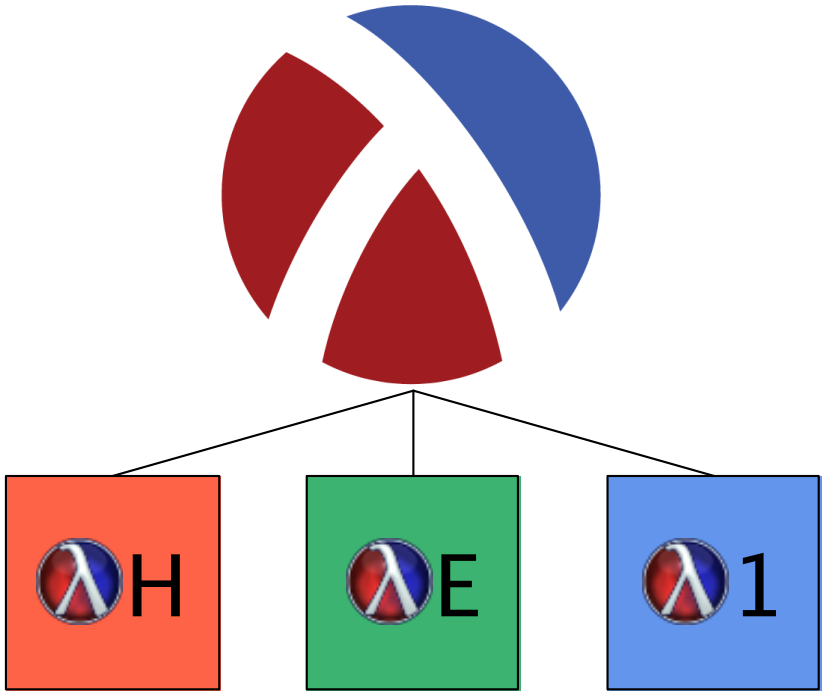
# Contributions (2/2)



# Contributions (2/2)

Implementation:

- Racket syntax/types
- three compilers
- the first controlled performance experiment



# Model

```
t = Nat | Int | t×t | t → t
Nat <: Int
```

$t = \mathtt{Nat} \mid \mathtt{Int} \mid t \times t \mid t \to t$

$\mathtt{Nat} <: \mathtt{Int}$

$v = n \mid i \mid \langle v, v \rangle \mid \lambda(x)e \mid \lambda(x{:}t)e$

$n \subset i$

$t$ = Nat | Int | $t \times t$ | $t \to t$

Nat <: Int

$v$ = $n$ | $i$ | $\langle v, v \rangle$ | $\lambda(x)e$ | $\lambda(x{:}t)e$

$n \subset i$

$e$ = .... | dyn $t$ $e$ | stat $t$ $e$

$t = \mathrm{Nat} \mid \mathrm{Int} \mid t \times t \mid t \to t$

$\mathrm{Nat} <: \mathrm{Int}$

$v = n \mid i \mid \langle v, v \rangle \mid \lambda(x)e \mid \lambda(x{:}t)e$

$n \subset i$

$e = .... \mid \mathrm{dyn}\ t\ e \mid \mathrm{stat}\ t\ e$

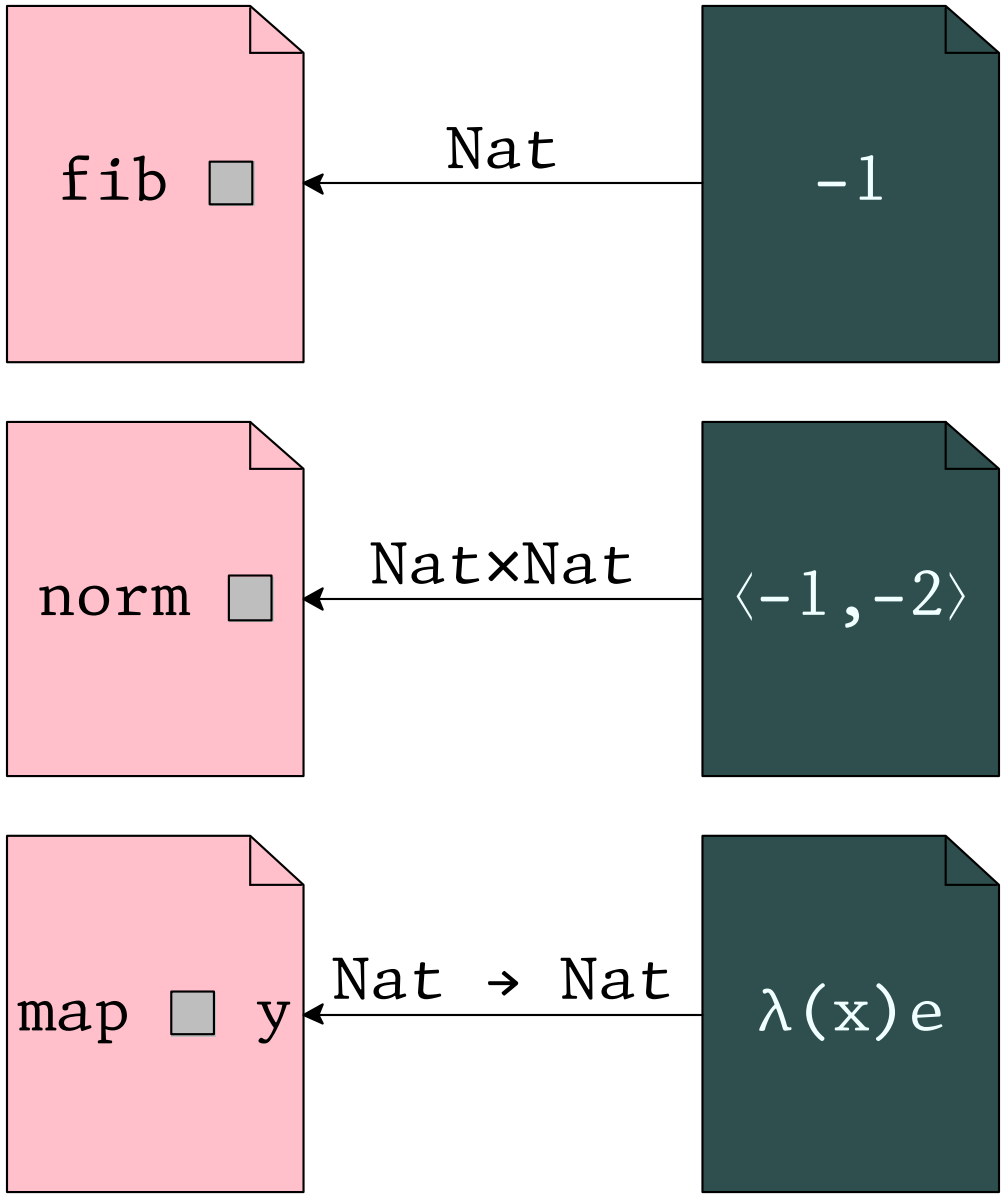
$$\frac{\vdash e}{\vdash \mathrm{dyn}\ t\ e : t} \qquad \frac{\vdash e : t}{\vdash \mathrm{stat}\ t\ e}$$

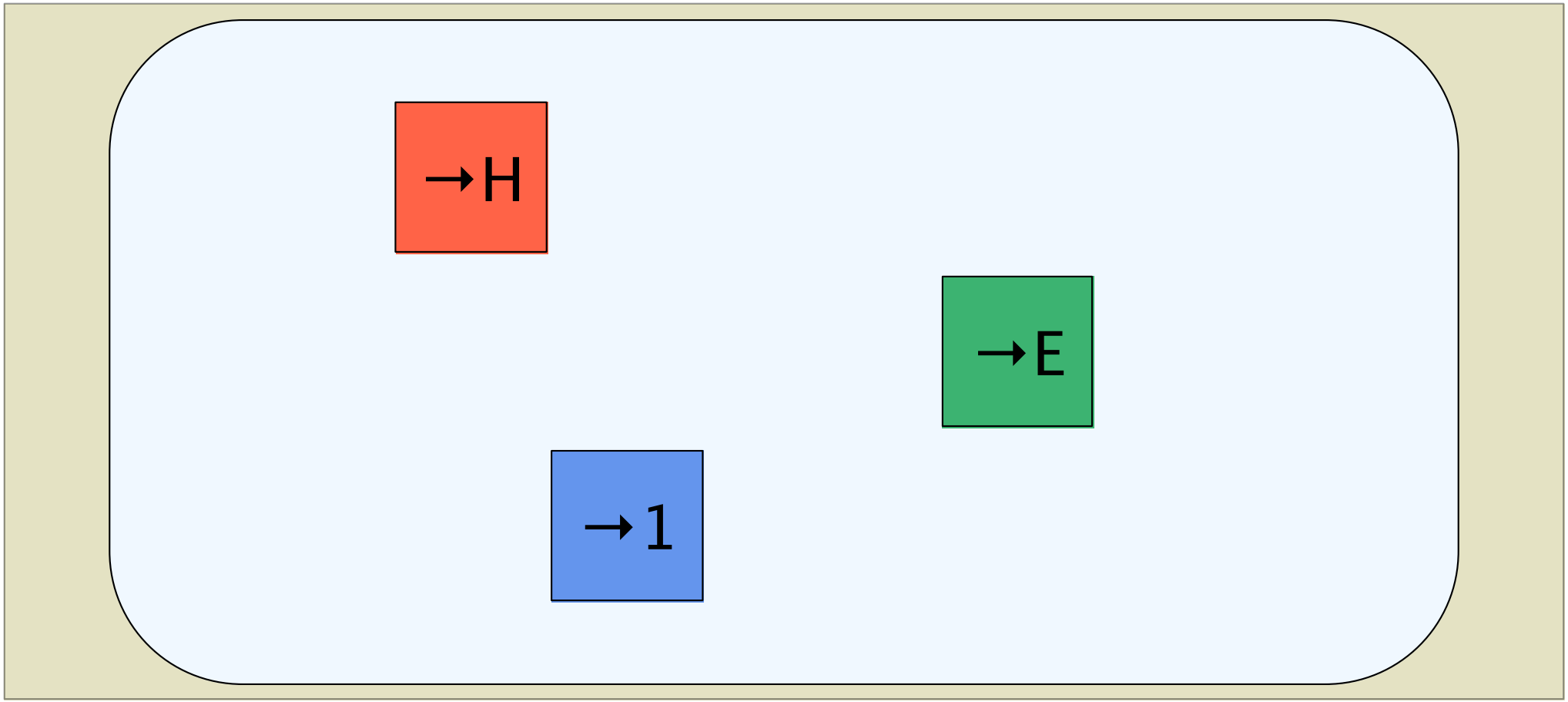
$$\Gamma = \left\{ \begin{array}{l} \texttt{fib : Nat} \to \texttt{Nat} \\ \texttt{norm : Nat}\times\texttt{Nat} \to \texttt{Nat} \\ \texttt{map : (Nat} \to \texttt{Nat)} \to \texttt{Nat}\times\texttt{Nat} \to \texttt{Nat}\times\texttt{Nat} \end{array} \right.$$

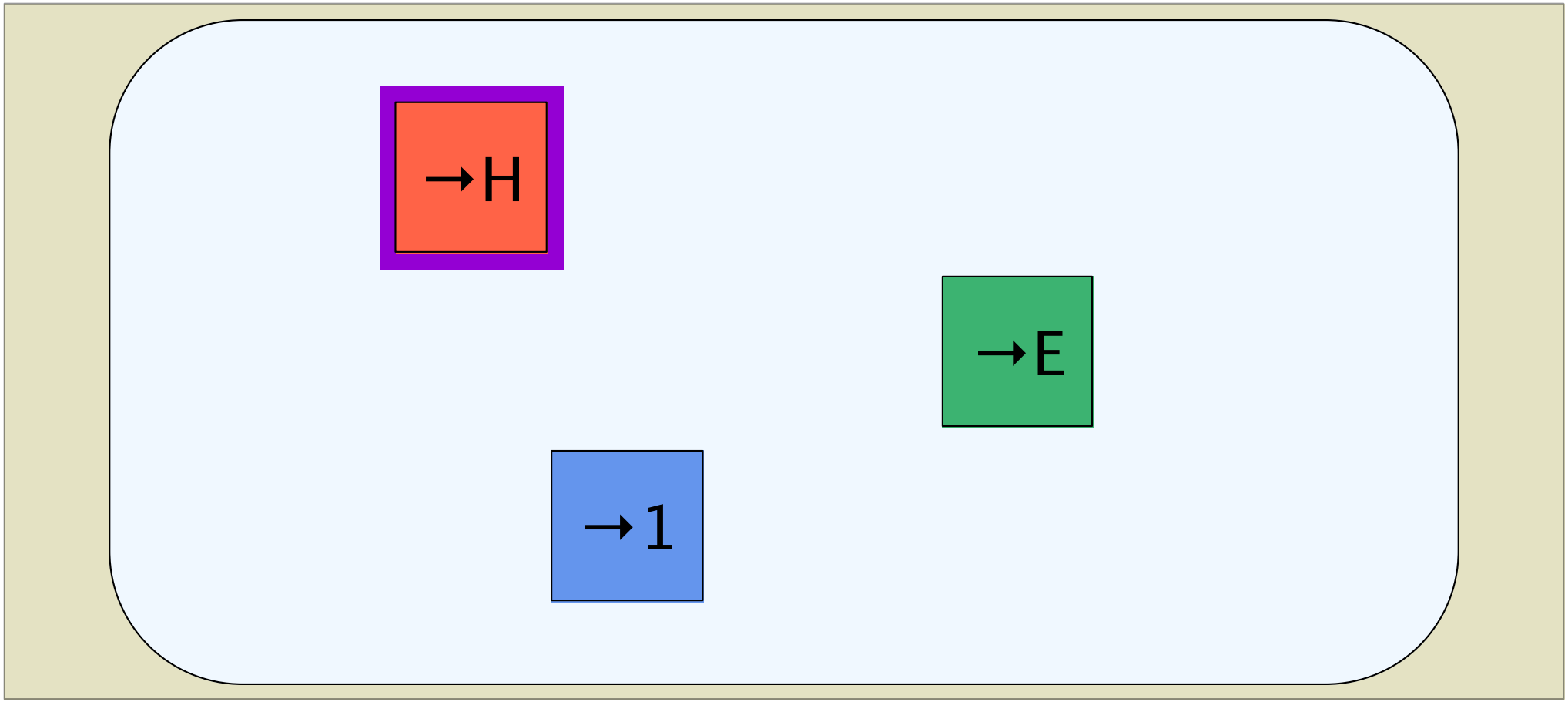
$\Gamma \vdash \texttt{fib (dyn Nat -1) : Nat}$

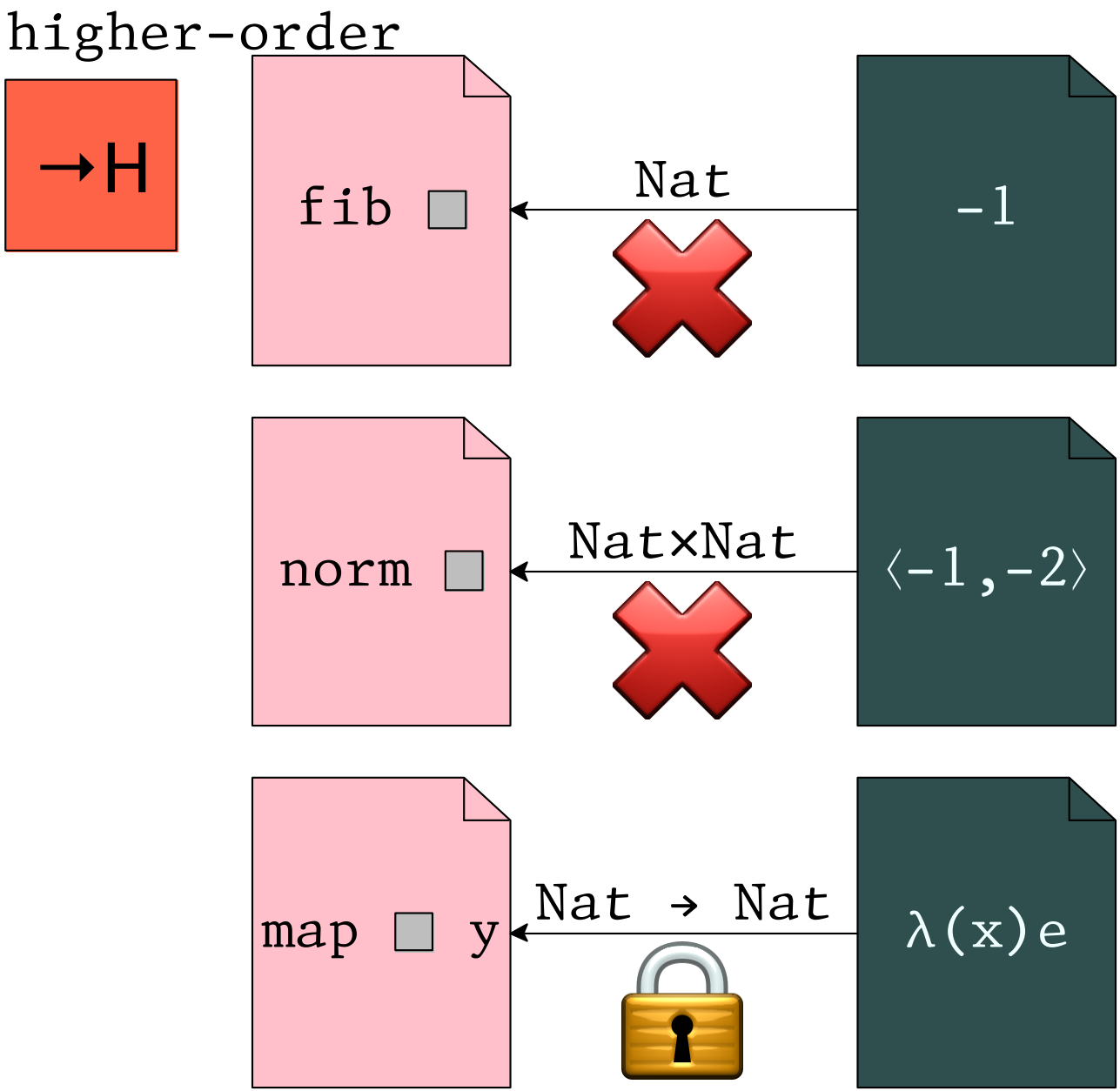
$\Gamma \vdash \texttt{norm (dyn Nat}\times\texttt{Nat } \langle\texttt{-1,-2}\rangle\texttt{) : Nat}$

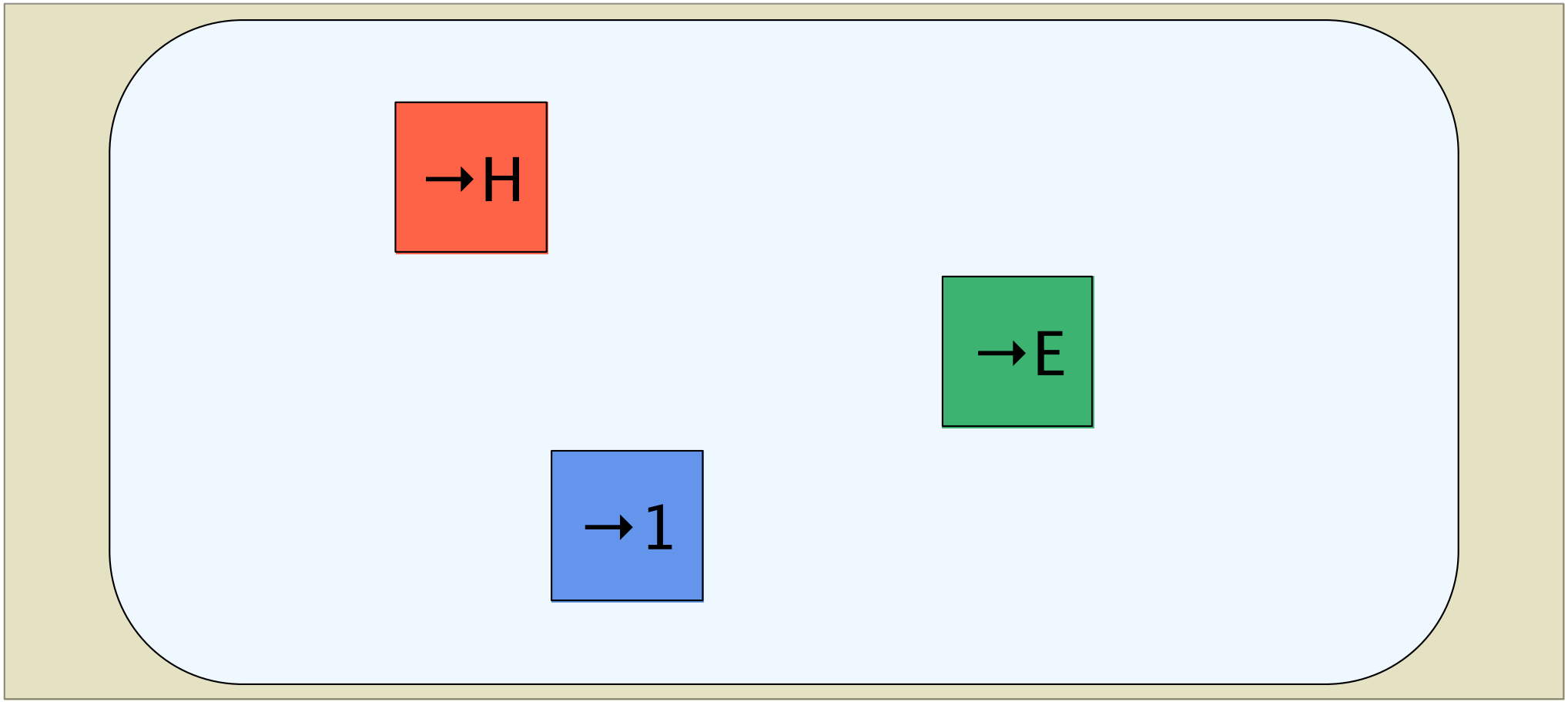
$\Gamma \vdash \texttt{map (dyn (Nat} \to \texttt{Nat) (}\lambda\texttt{(x)e)) y : Nat}\times\texttt{Nat}$

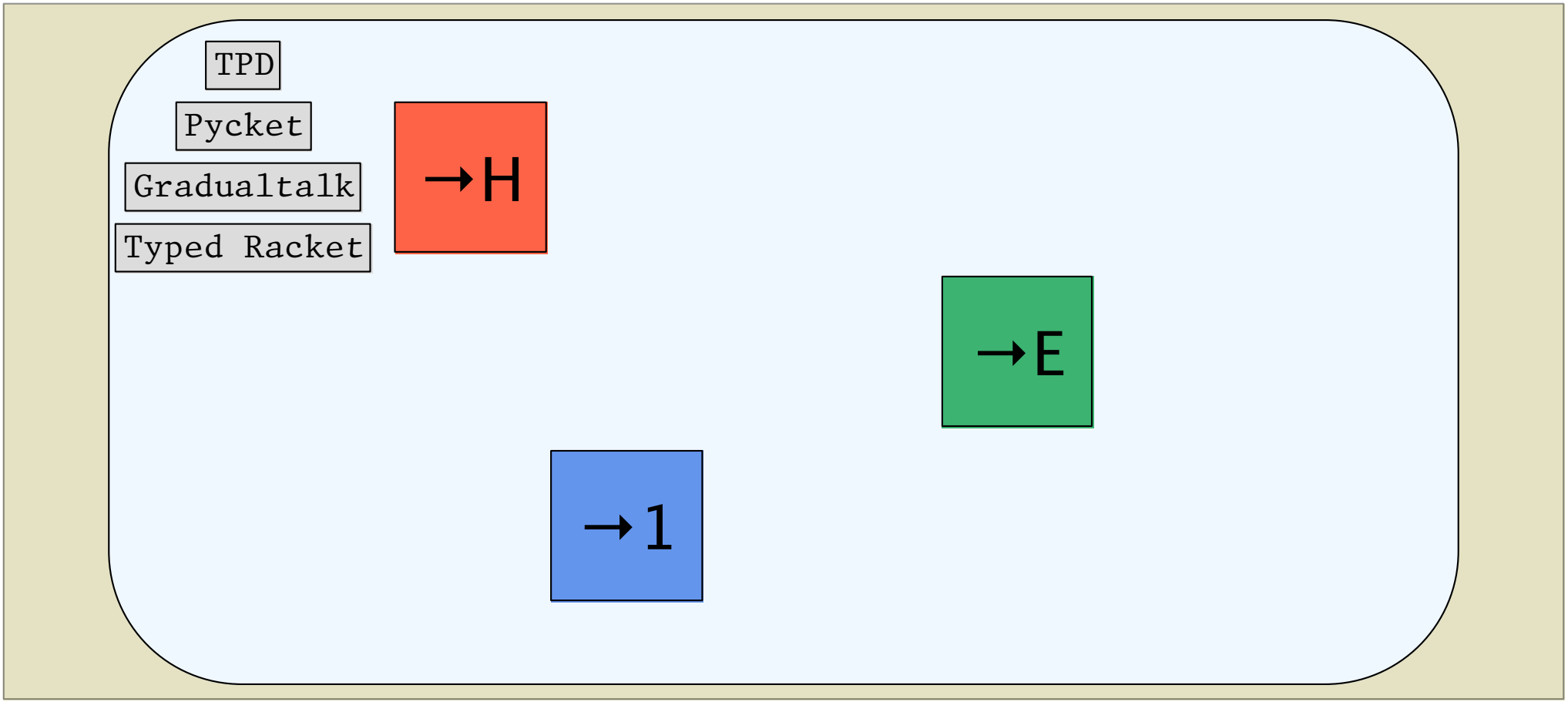

fib □
Nat
-1
norm □
Nat×Nat
⟨-1,-2⟩
map □ y
Nat → Nat
λ(x)e

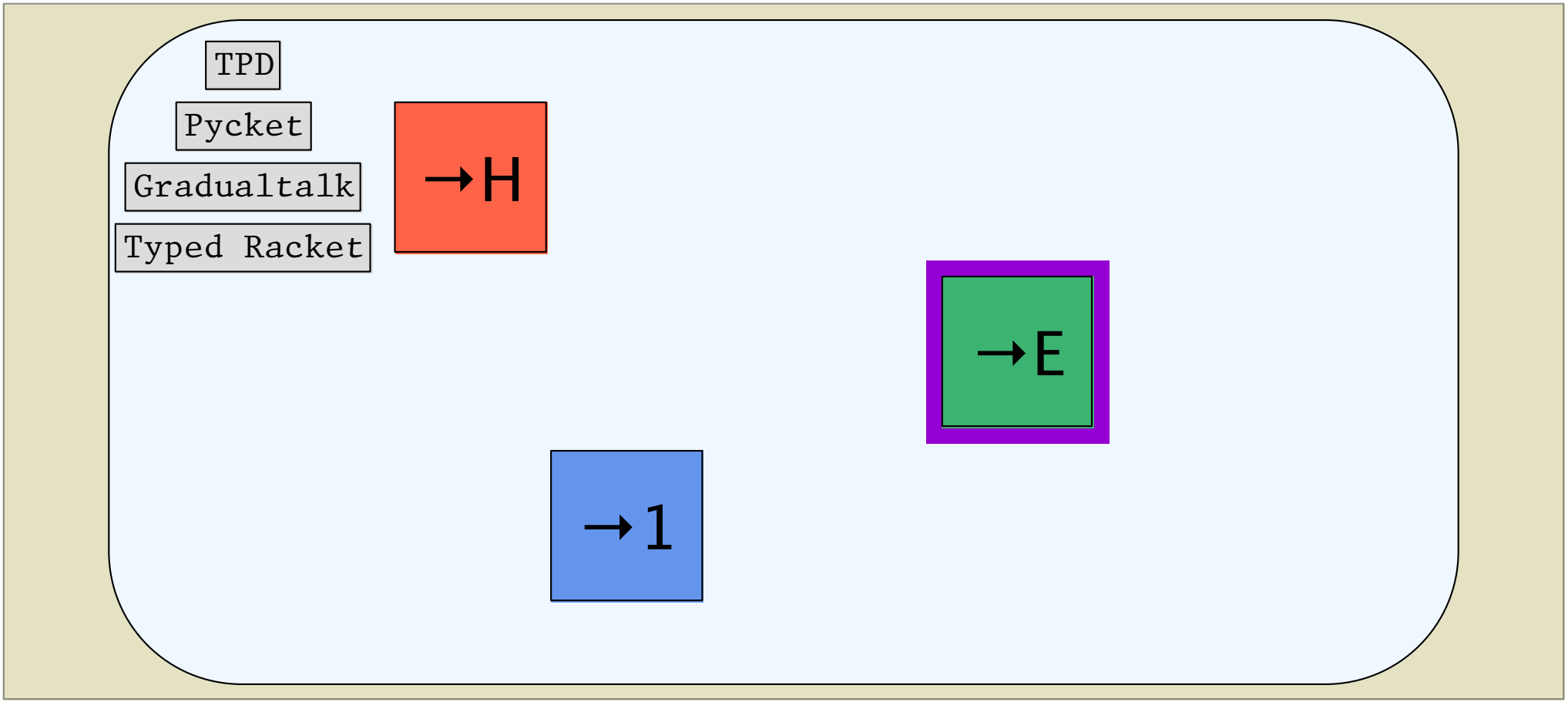

→H
→E
→1

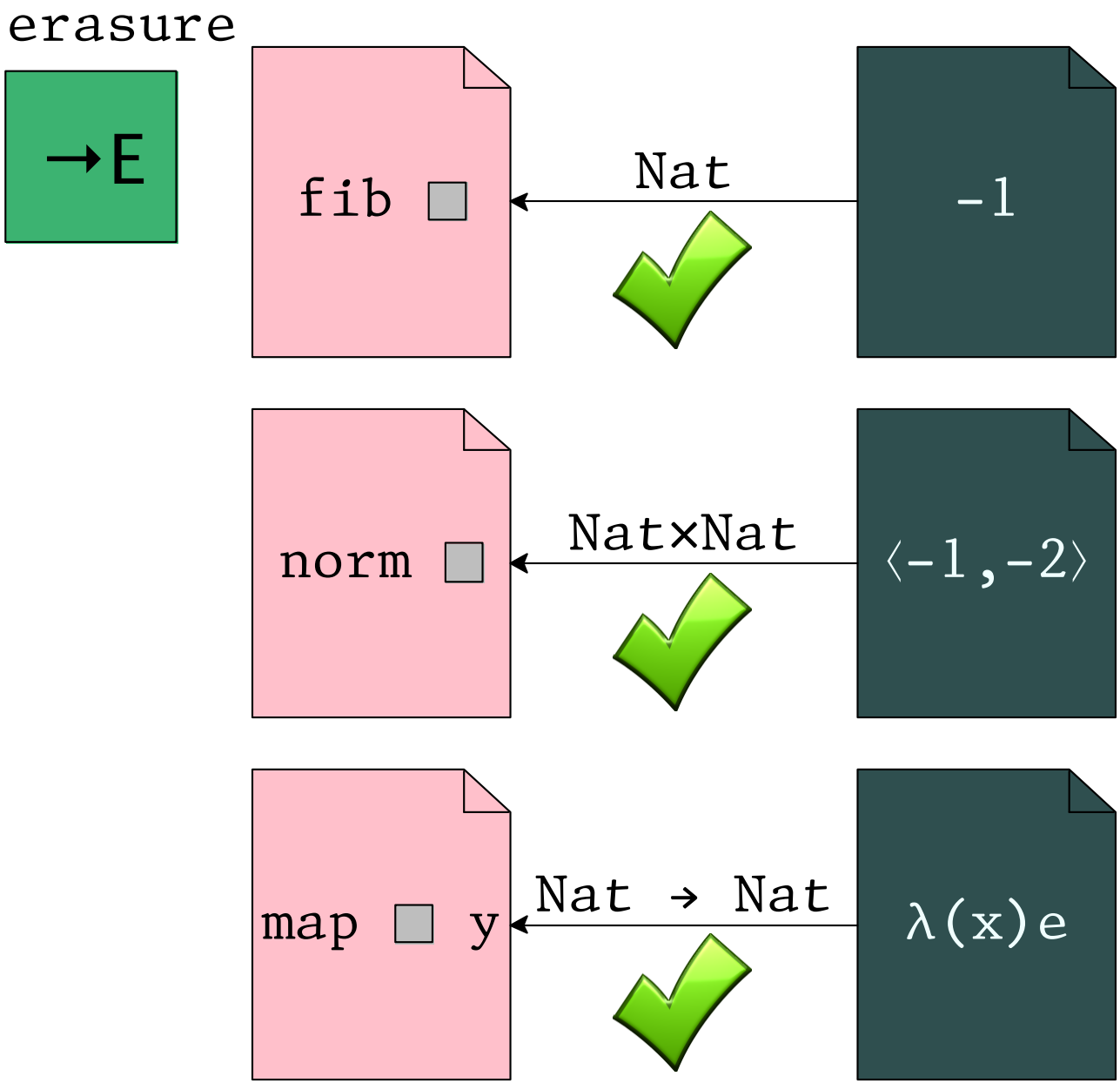

→H
→E
→1

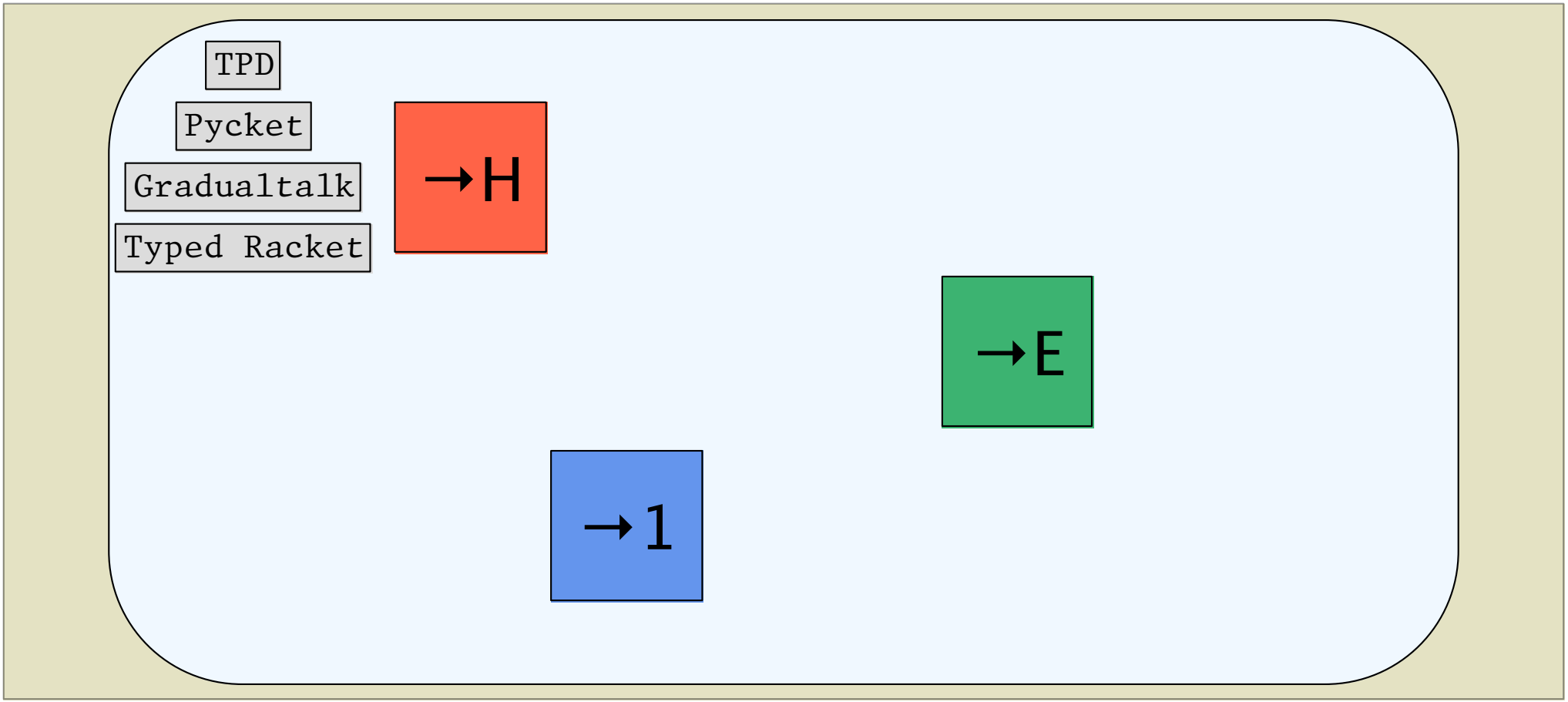

higher-order
→H
fib □
Nat
-1
norm □
Nat×Nat
⟨-1,-2⟩
map □ y
Nat → Nat
λ(x)e


→H
→E
→1


TPD
Pycket
Gradualtalk
Typed Racket
→H
→E
→1


TPD
Pycket
Gradualtalk
Typed Racket
→H
→E
→1


erasure
→E
fib □
Nat
-1
norm □
Nat×Nat
⟨-1,-2⟩
map □ y
Nat → Nat
λ(x)e


TPD
Pycket
Gradualtalk
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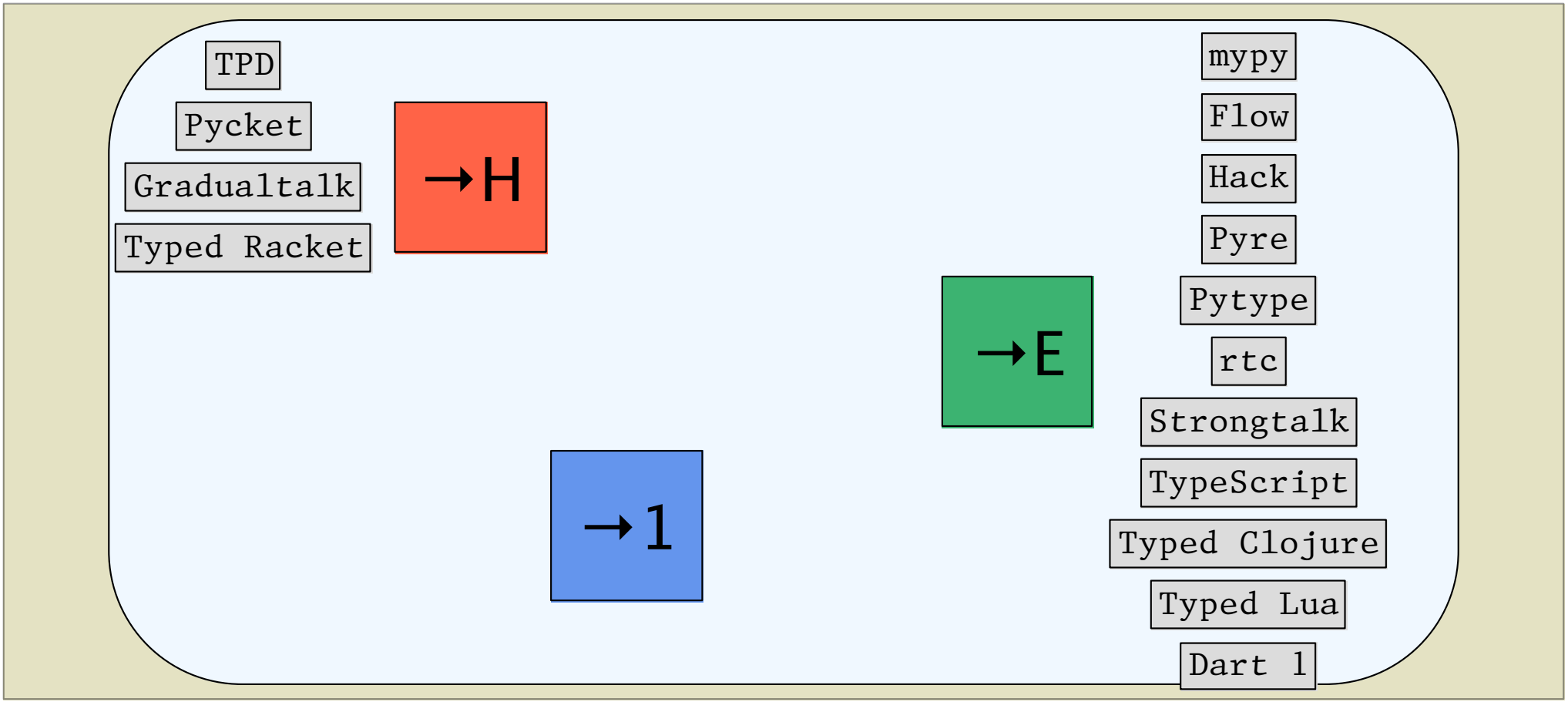
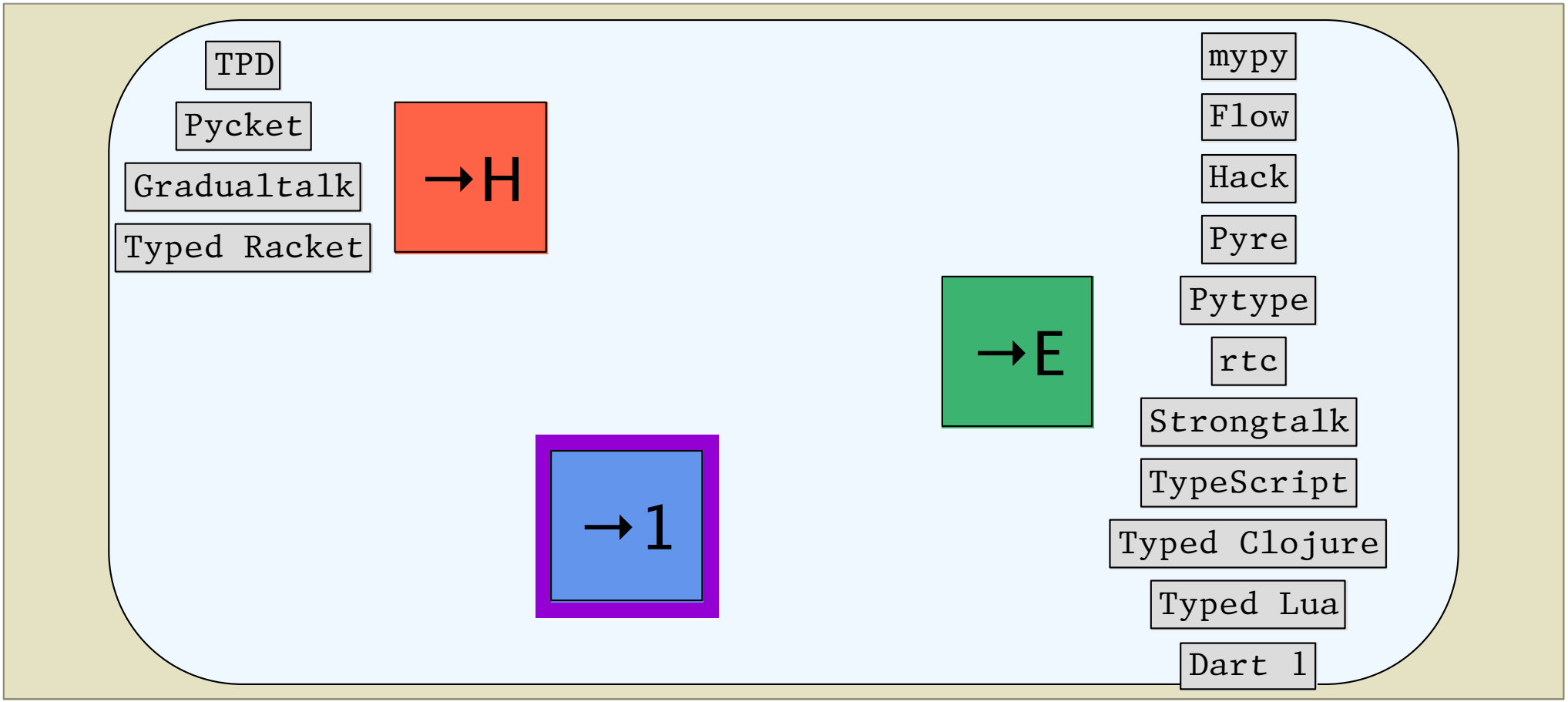
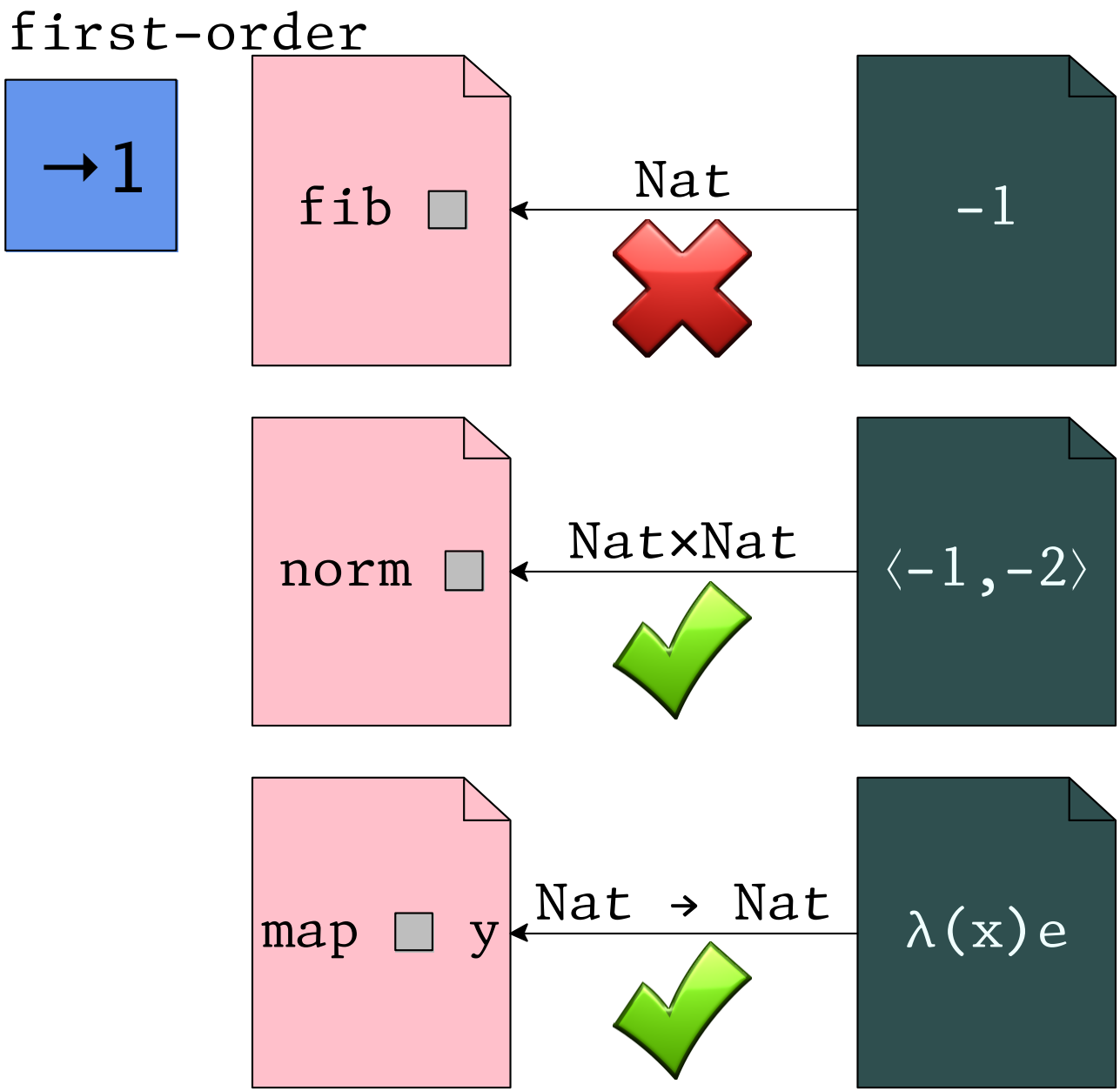
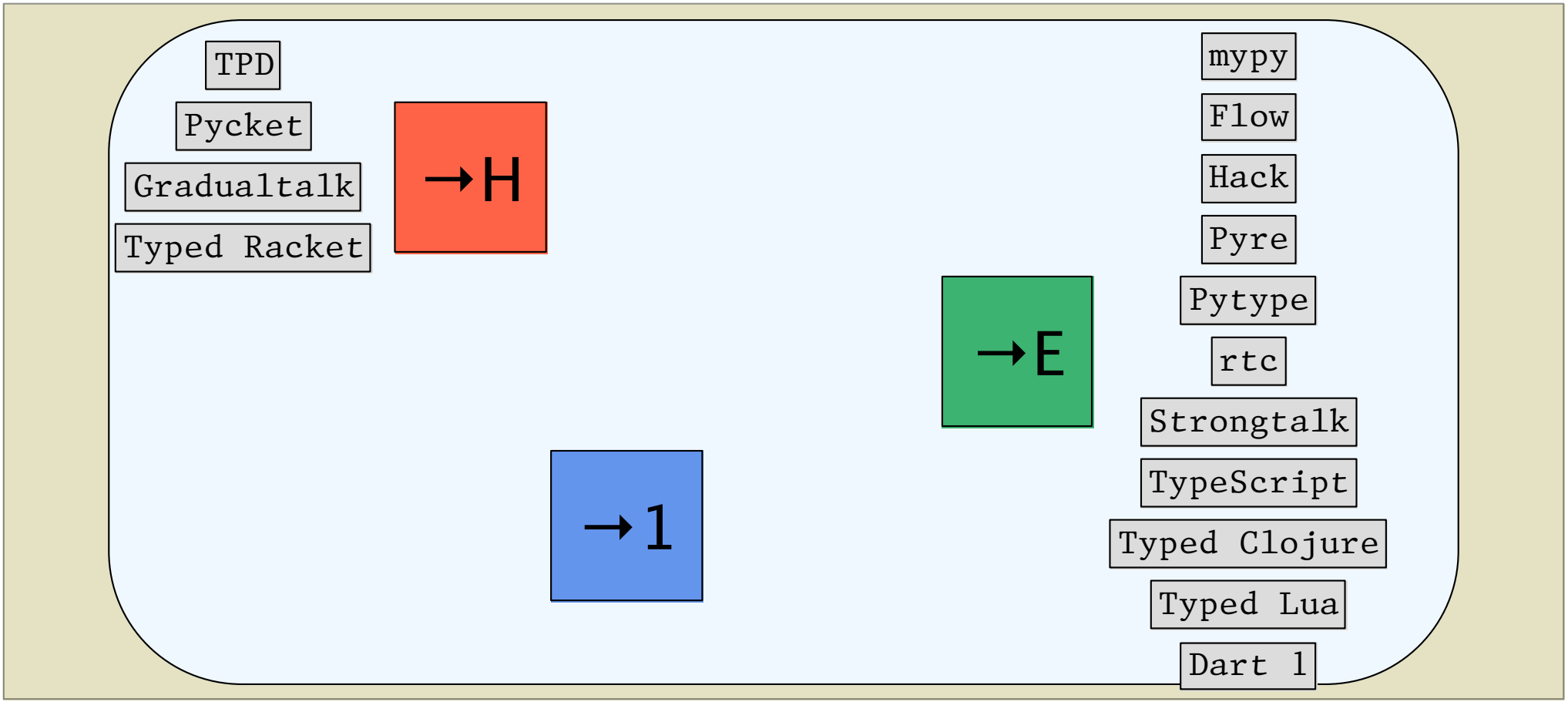
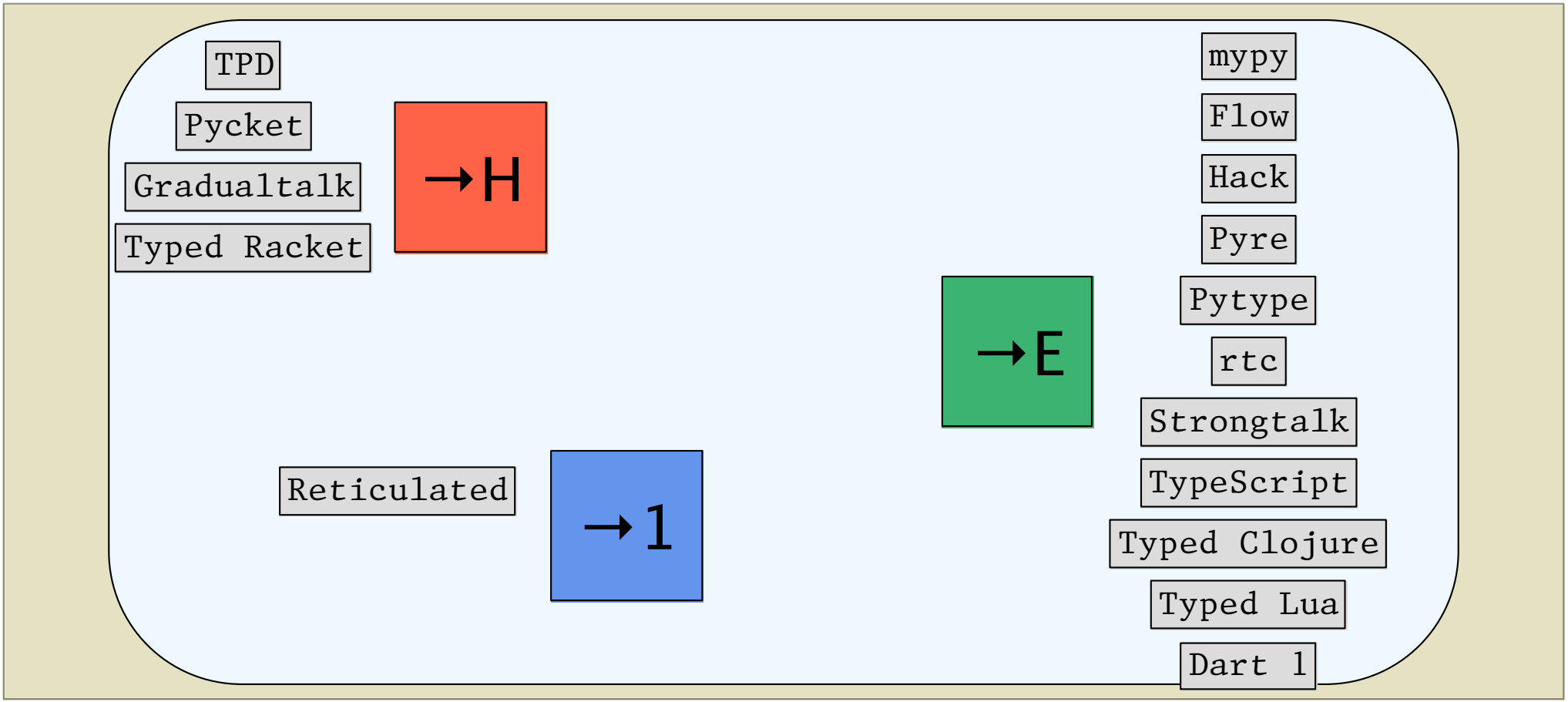
→H
→E
→1


TPD
Pycket
Gradualtalk
Typed Racket
→H
→E
→1
mypy
Flow
Hack
Pyre
Pytype
rtc
Strongtalk
TypeScript
Typed Clojure
Typed Lua
Dart 1


TPD
Pycket
Gradualtalk
Typed Racket
→H
→E
→1
mypy
Flow
Hack
Pyre
Pytype
rtc
Strongtalk
TypeScript
Typed Clojure
Typed Lua
Dart 1


first-order
→1
fib □
Nat
-1
norm □
Nat×Nat
⟨-1,-2⟩
map □ y
Nat → Nat
λ(x)e


TPD
Pycket
Gradualtalk
Typed Racket
→H
→E
→1
mypy
Flow
Hack
Pyre
Pytype
rtc
Strongtalk
TypeScript
Typed Clojure
Typed Lua
Dart 1


TPD
Pycket
Gradualtalk
Typed Racket
→H
mypy
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Hack
Pyre
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Strongtalk
TypeScript
Typed Clojure
Typed Lua
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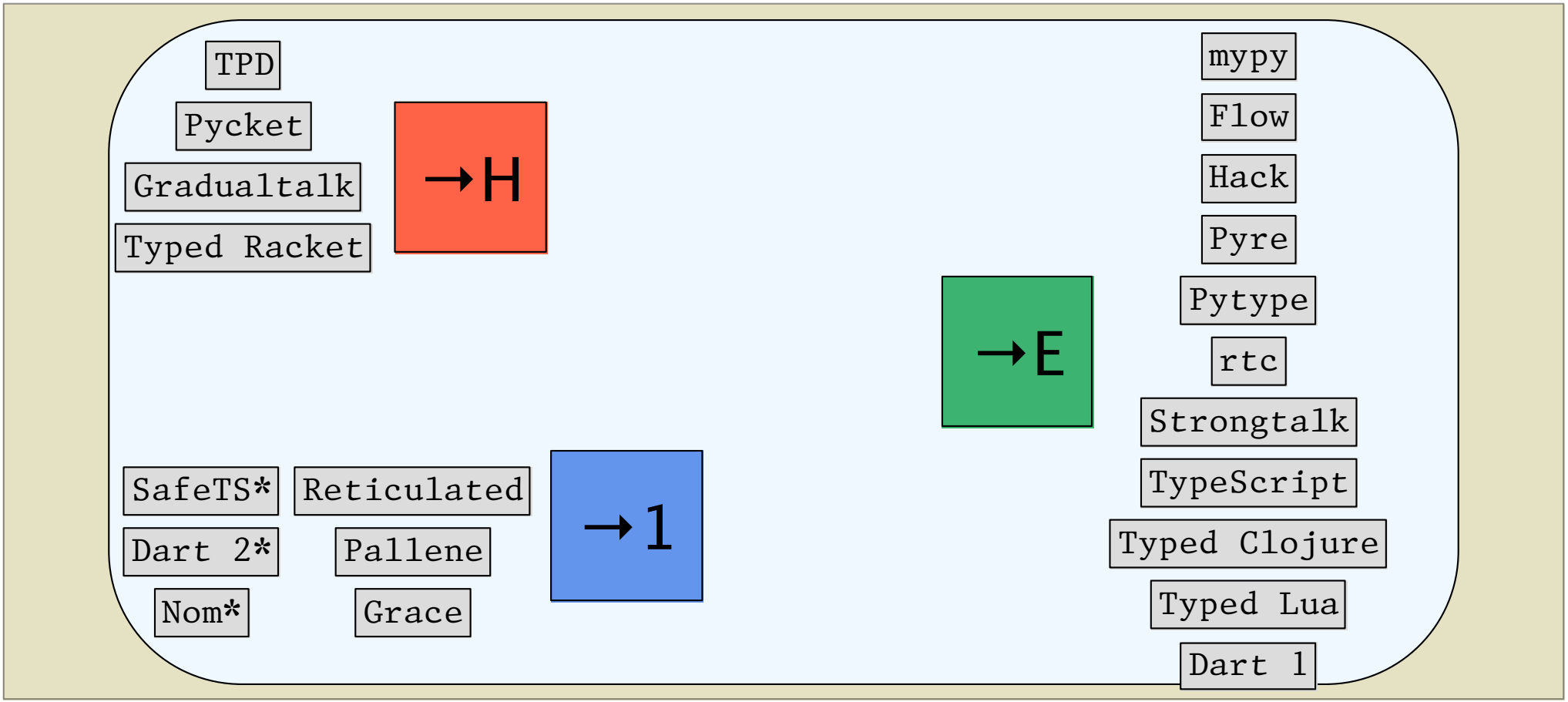
Reticulated
→1


TPD
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Gradualtalk
Typed Racket
→H
mypy
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Hack
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Strongtalk
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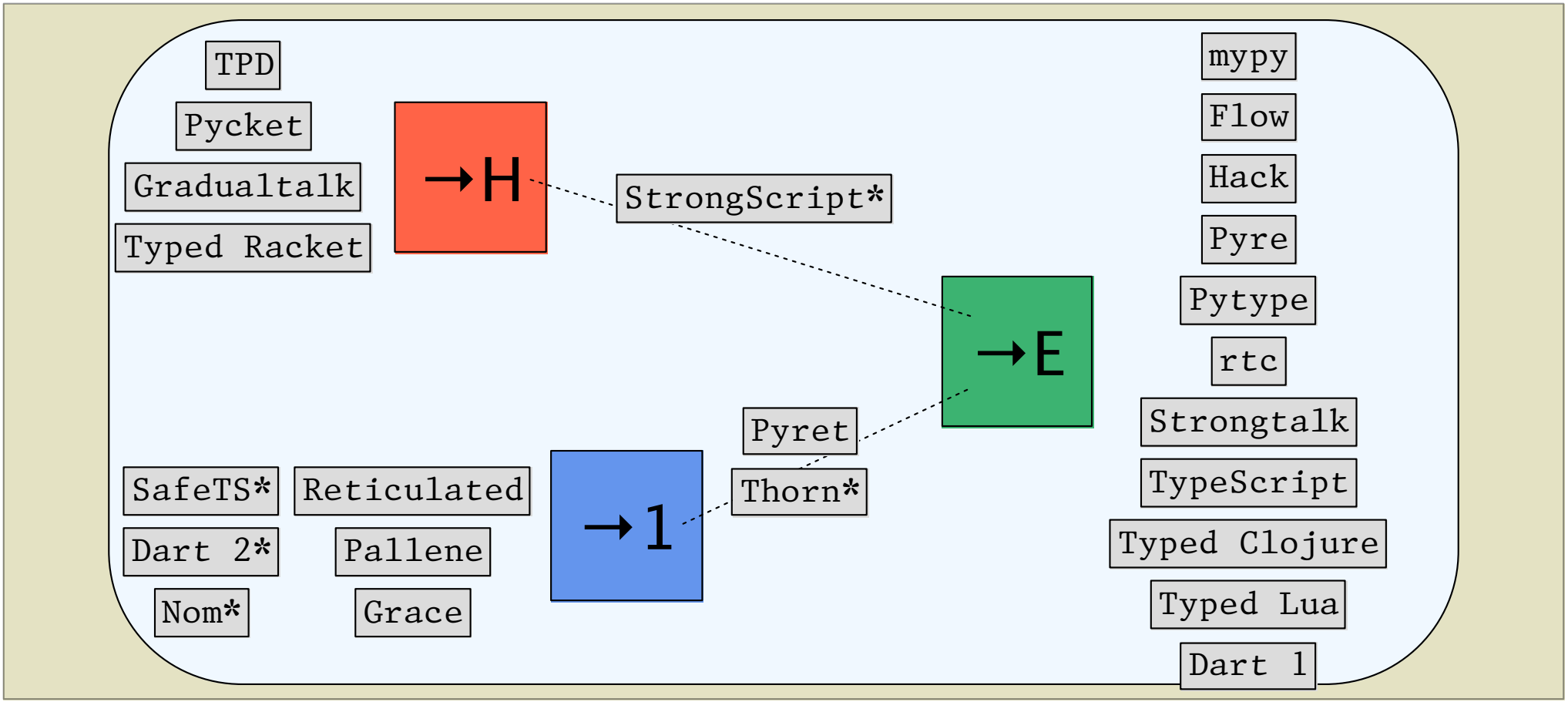
Typed Lua
Dart 1
→E
SafeTS*
Dart 2*
Nom*
Reticulated
Pallene
Grace
→1


TPD
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→H
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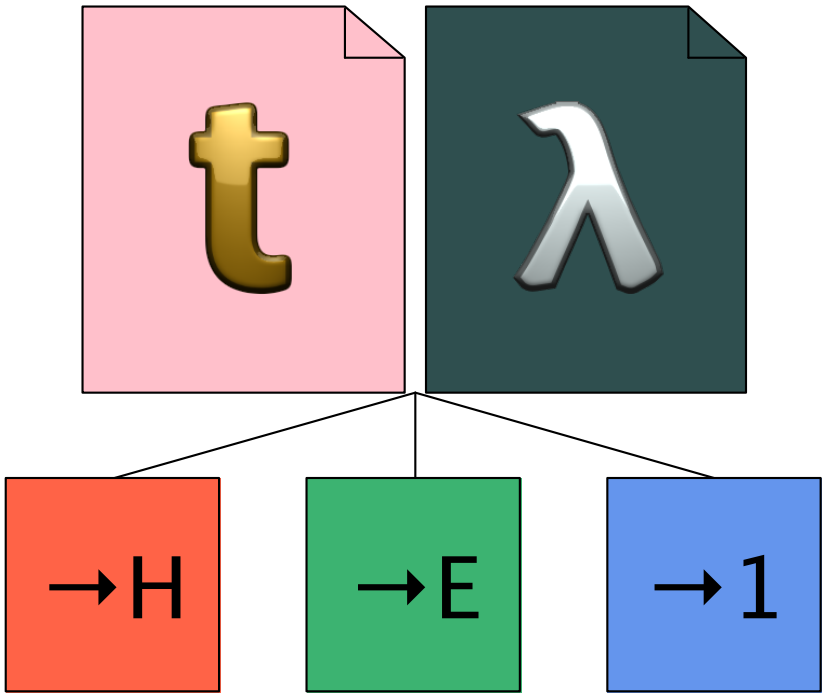
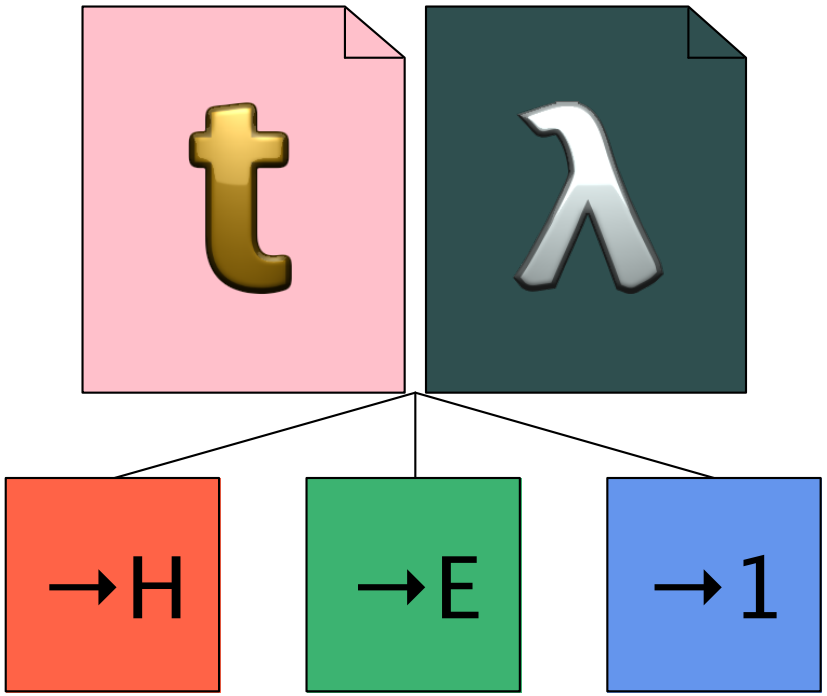
Typed Clojure
Typed Lua
Dart 1
→E
Pyret
Thorn*
→1
SafeTS*
Dart 2*
Nom*
Reticulated
Pallene
Grace

Is type soundness all-or-nothing?

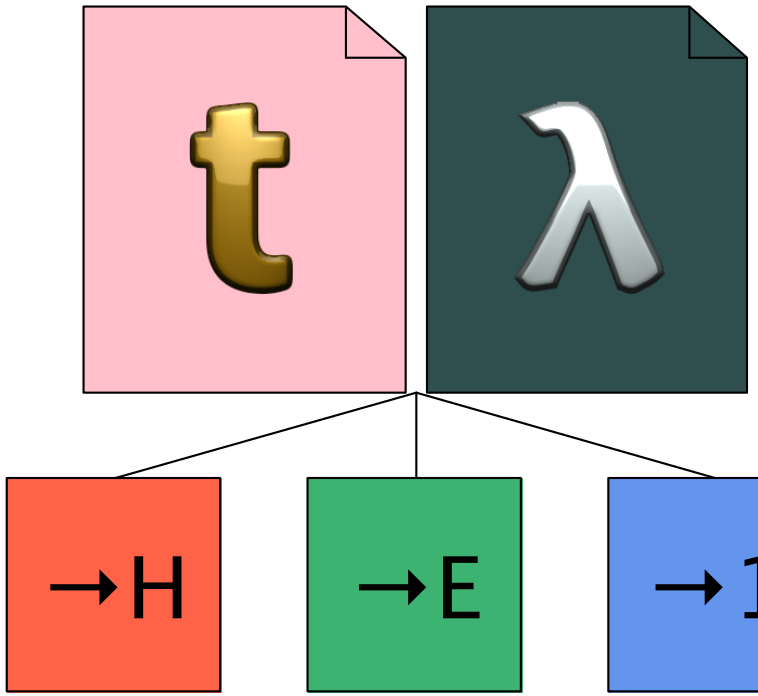



Same type soundness?



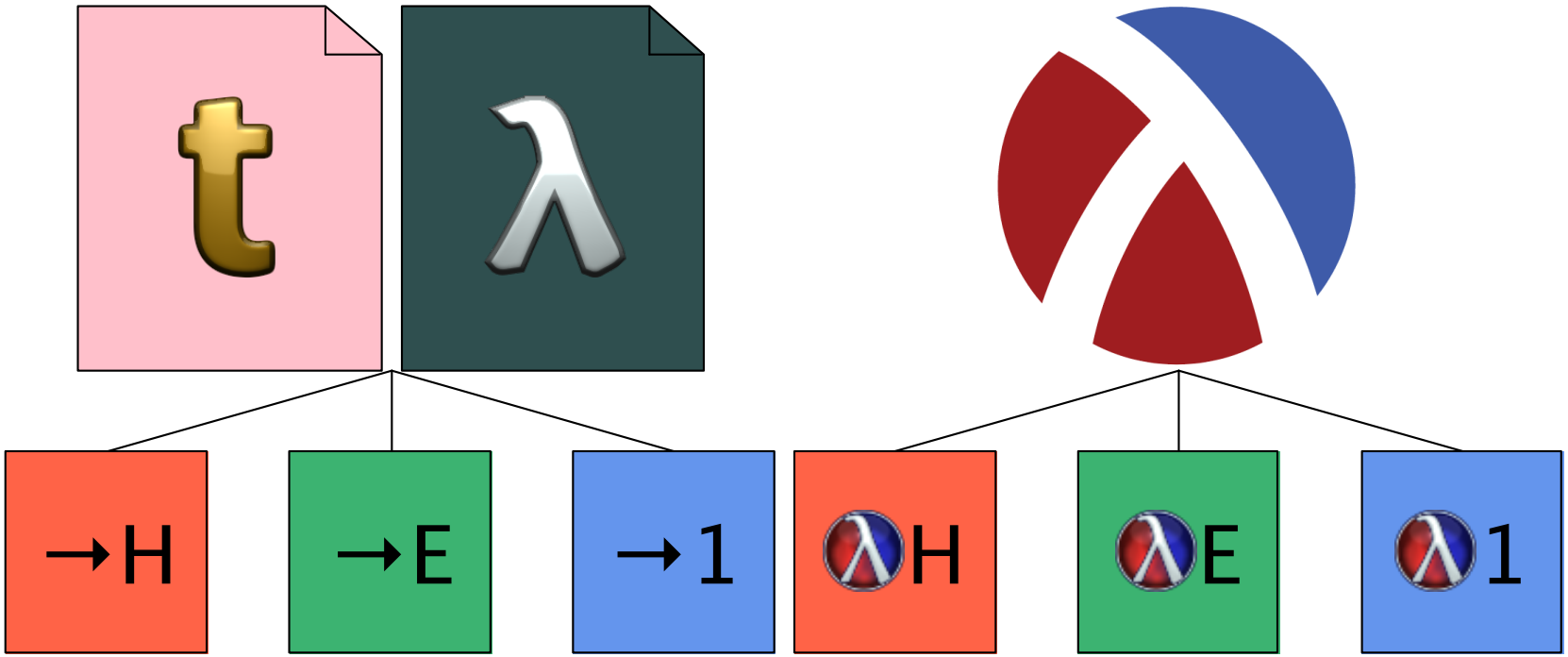

Same type soundness?

No!




- $\vdash_H e:t$ sound for $\to H$
- $\vdash_E e$ sound for $\to E$
- $\vdash_1 e:K(t)$ sound for $\to 1$

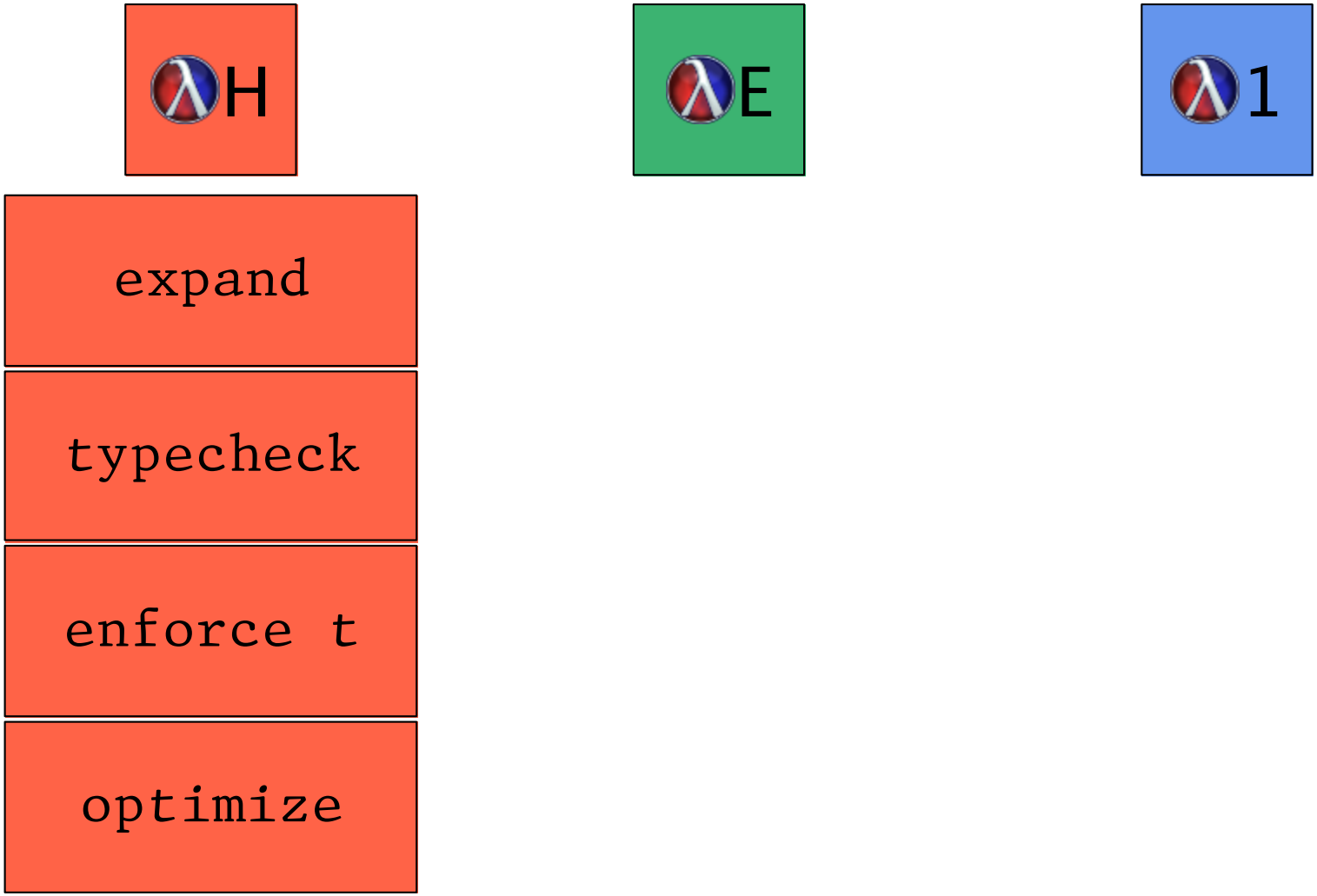
# Implementation

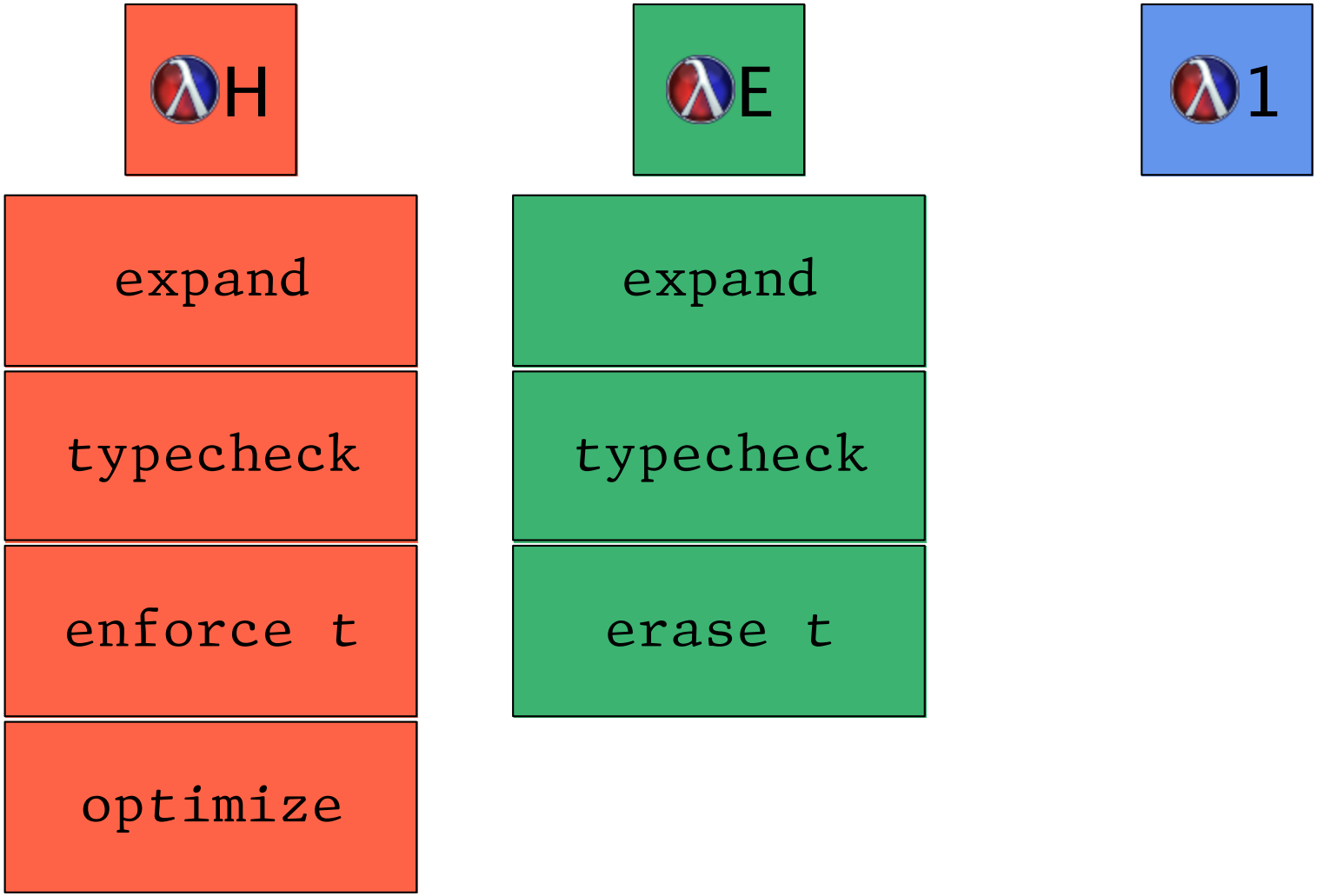

t
λ
→H
→E
→1
λH
λE
λ1

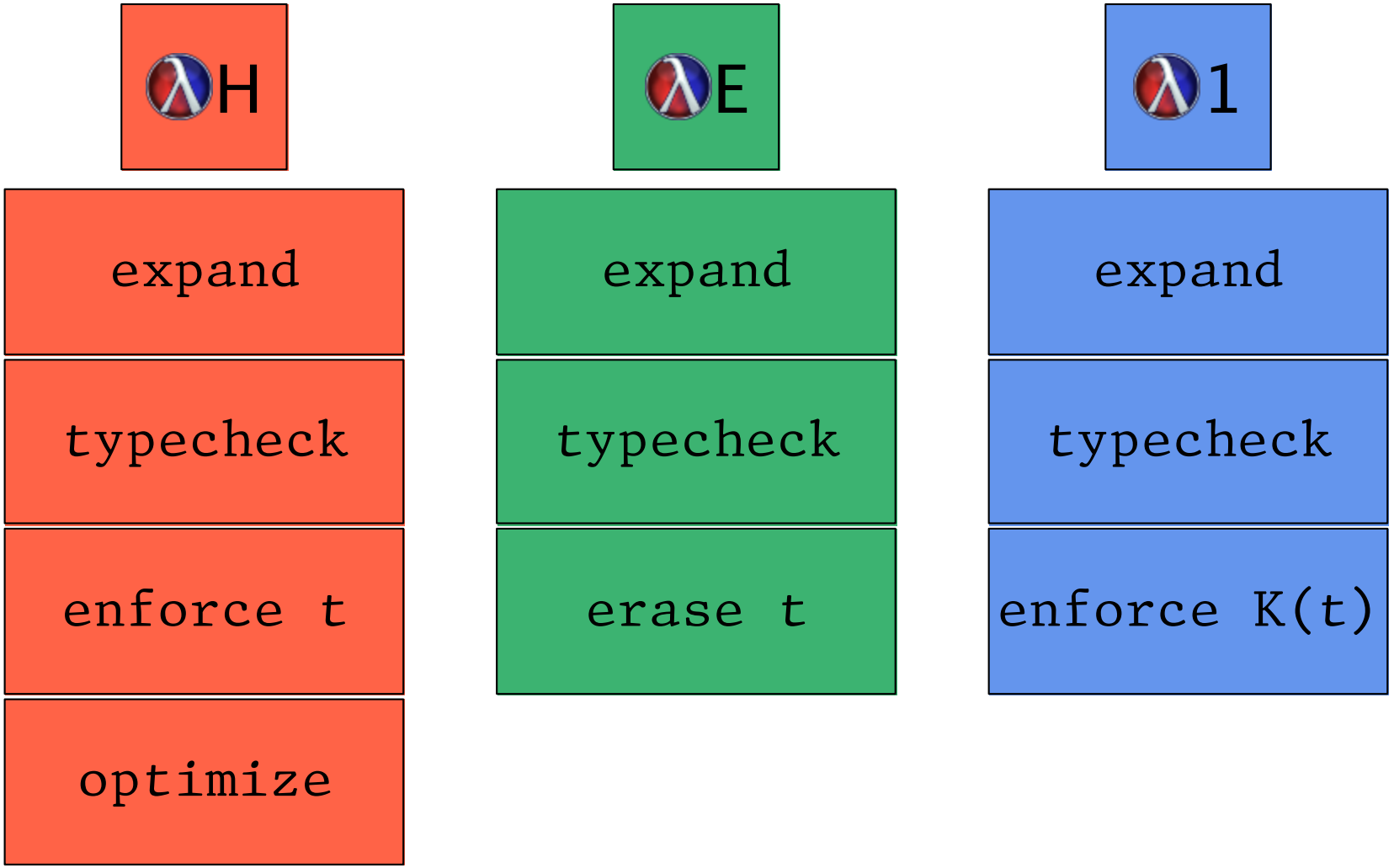

H

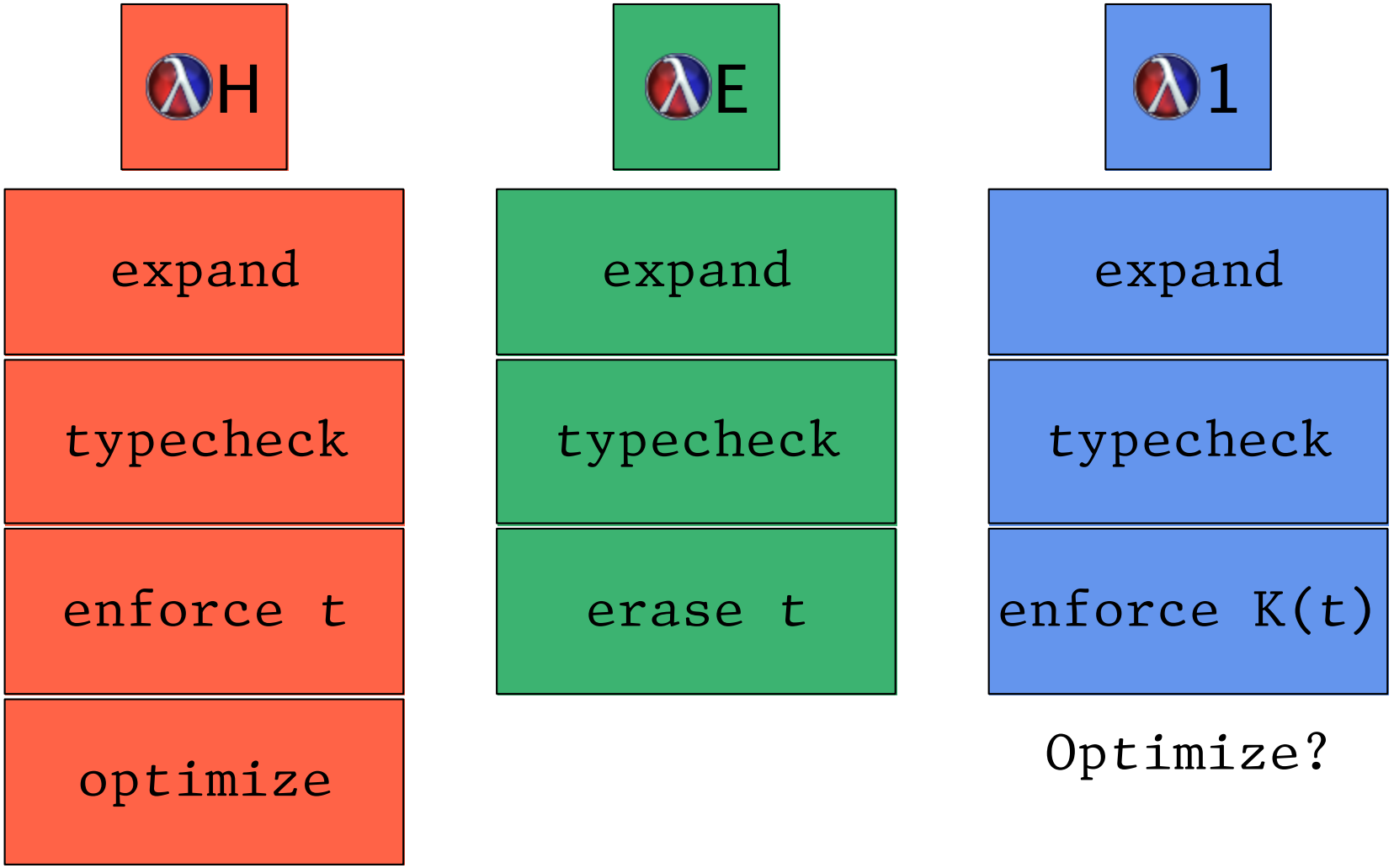

E


1


H
E
1
expand
typecheck
enforce t
optimize


H
expand
typecheck
enforce t
optimize
E
expand
typecheck
erase t
1


λH
expand
typecheck
enforce t
optimize
λE
expand
typecheck
erase t
λ1
expand
typecheck
enforce K(t)


λH
expand
typecheck
enforce t
optimize
λE
expand
typecheck
erase t
λ1
expand
typecheck
enforce K(t)
Optimize?

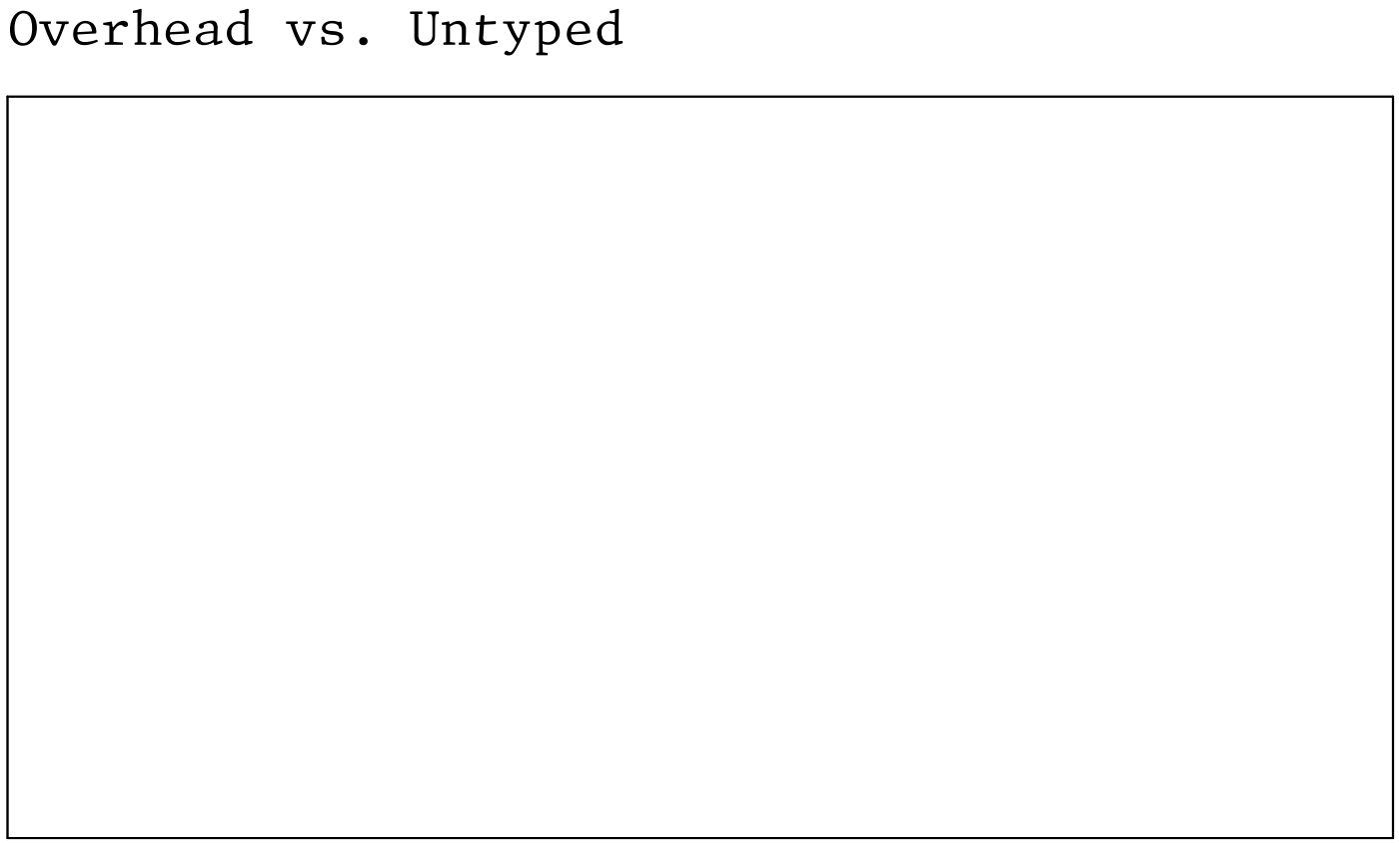
# Experiment

- 10 benchmark programs
- 2 to 10 modules each
- 4 to 1024 configurations each
- compare overhead to untyped

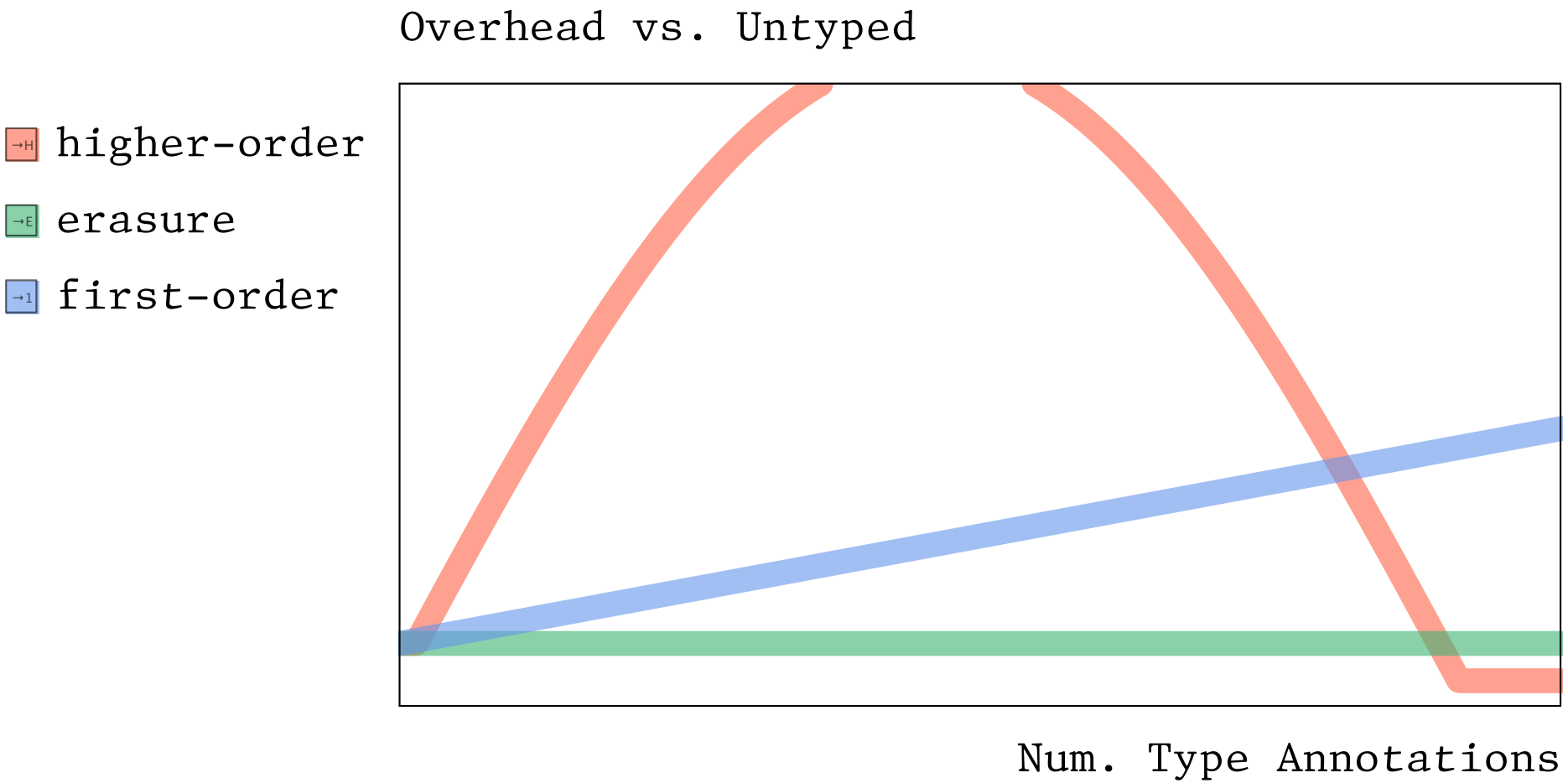
**docs.racket-lang.org/gtp-benchmarks**

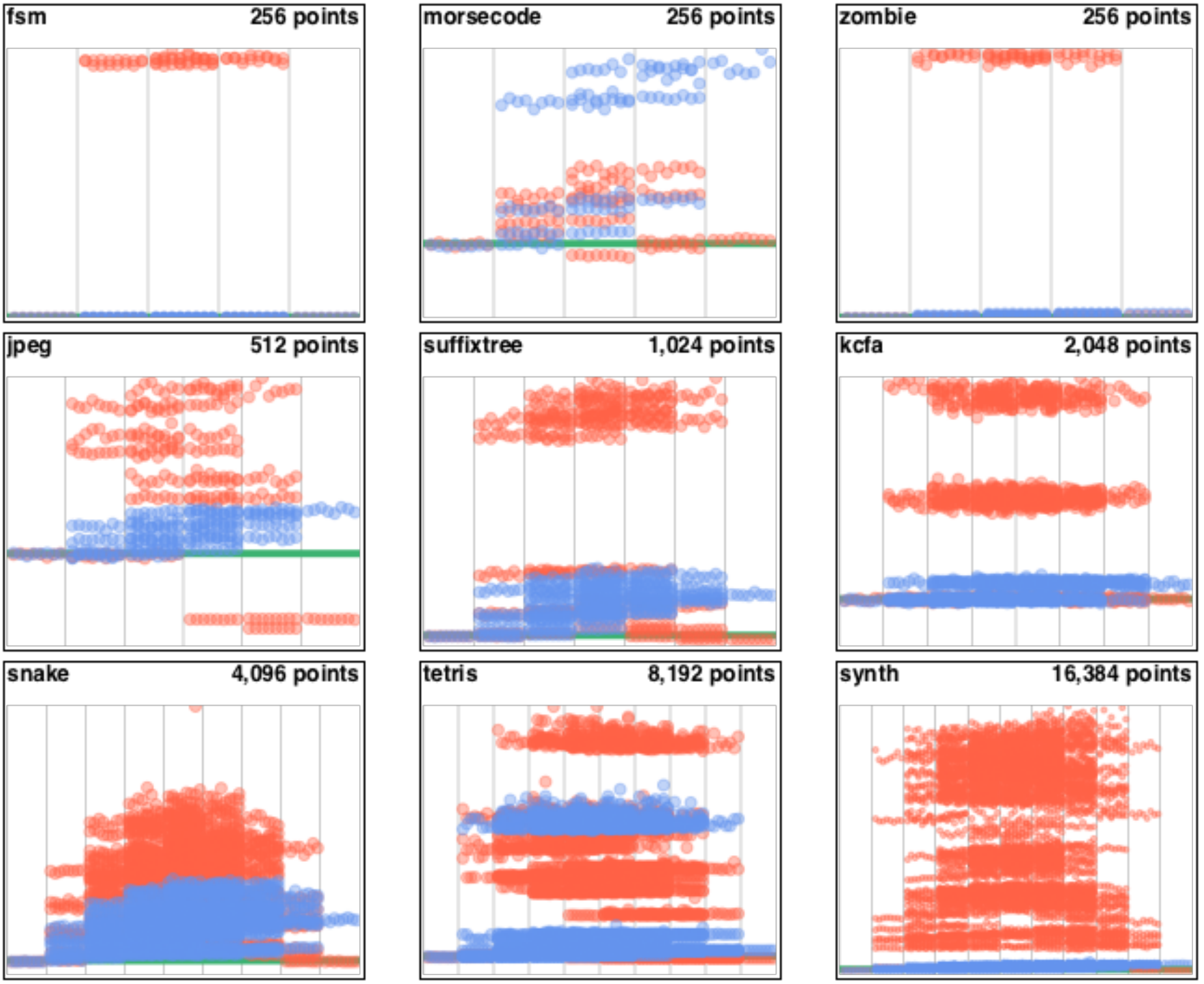
# Results

# Typical program



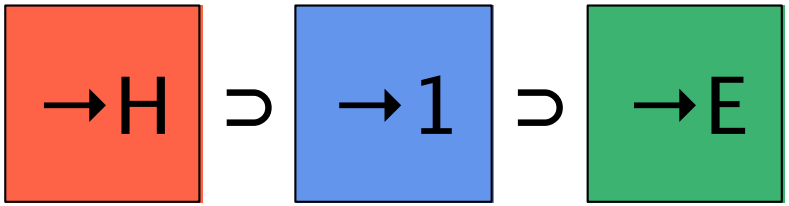
# Typical program




fsm
256 points
morsecode
256 points
zombie
256 points
jpeg
512 points
suffixtree
1,024 points
kcfa
2,048 points
snake
4,096 points
tetris
8,192 points
synth
16,384 points

# Implications

# Theory Implications

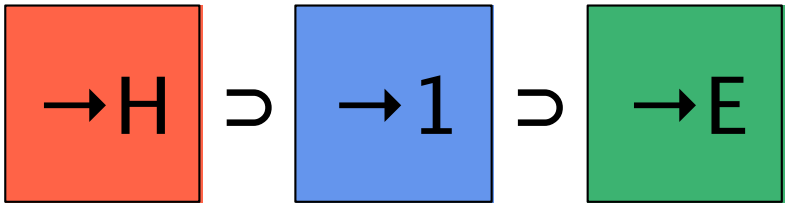



→H progress + preserves types

→E progress

→1 progress + preserves type constructors

# Theory Implications




→H progress + preserves types

→E progress

→1 progress + preserves type constructors

- →H refines →1

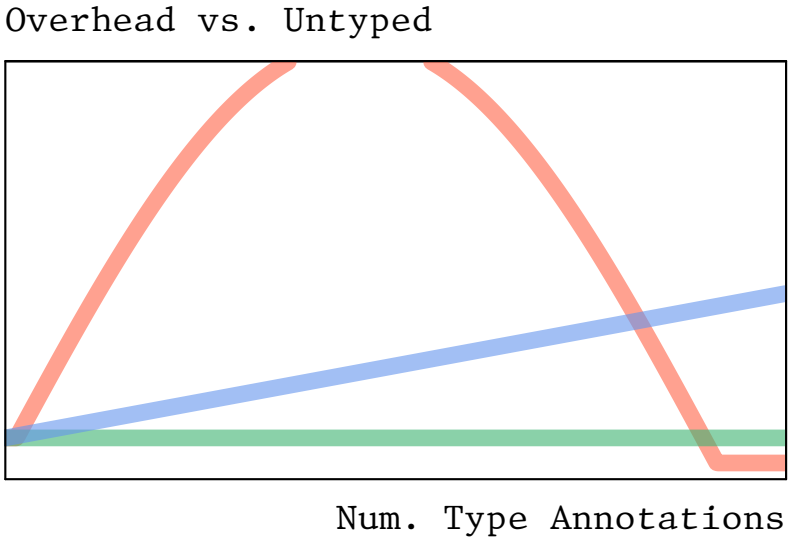
- →1 refines →E

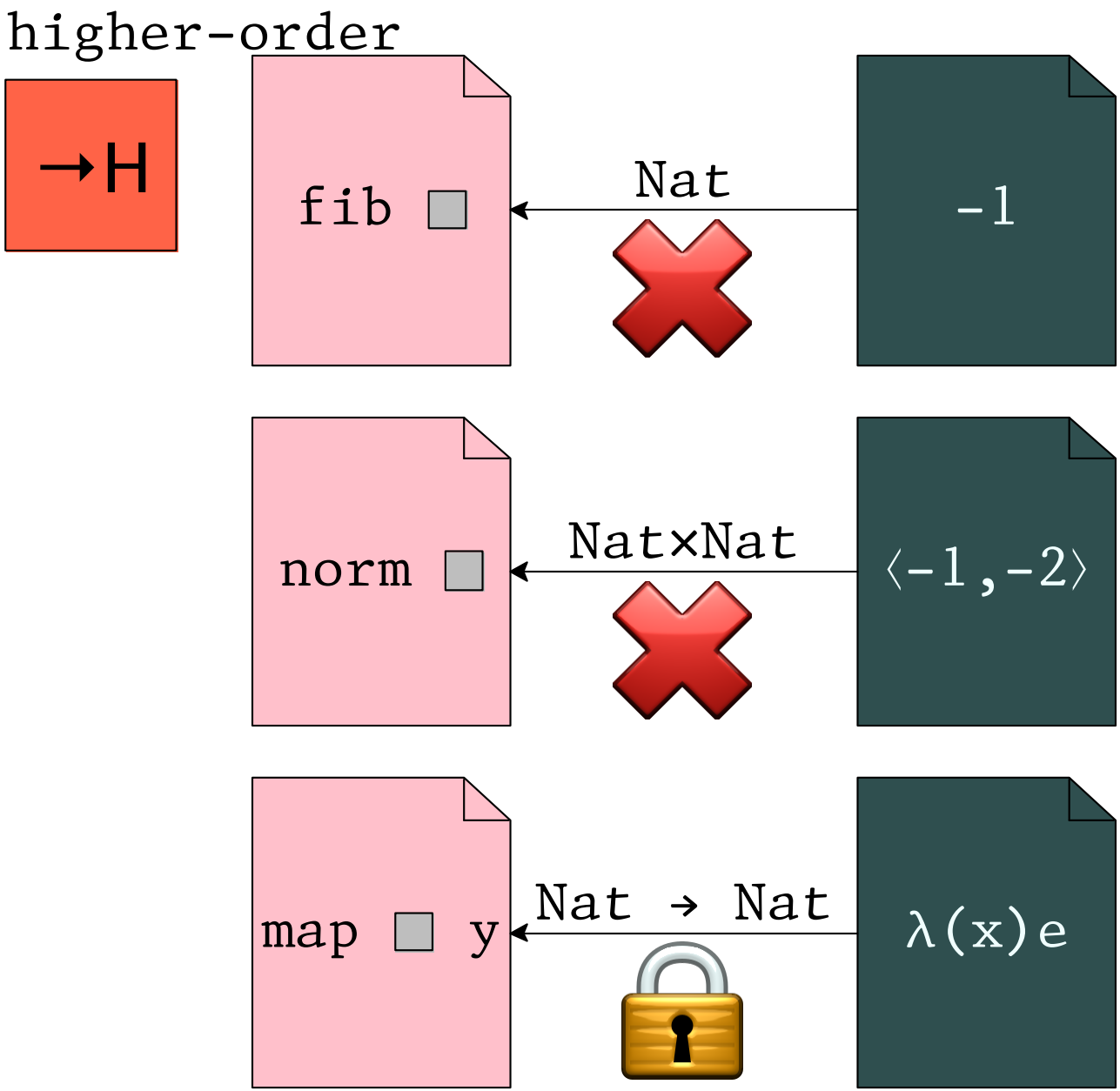
# Performance Implications

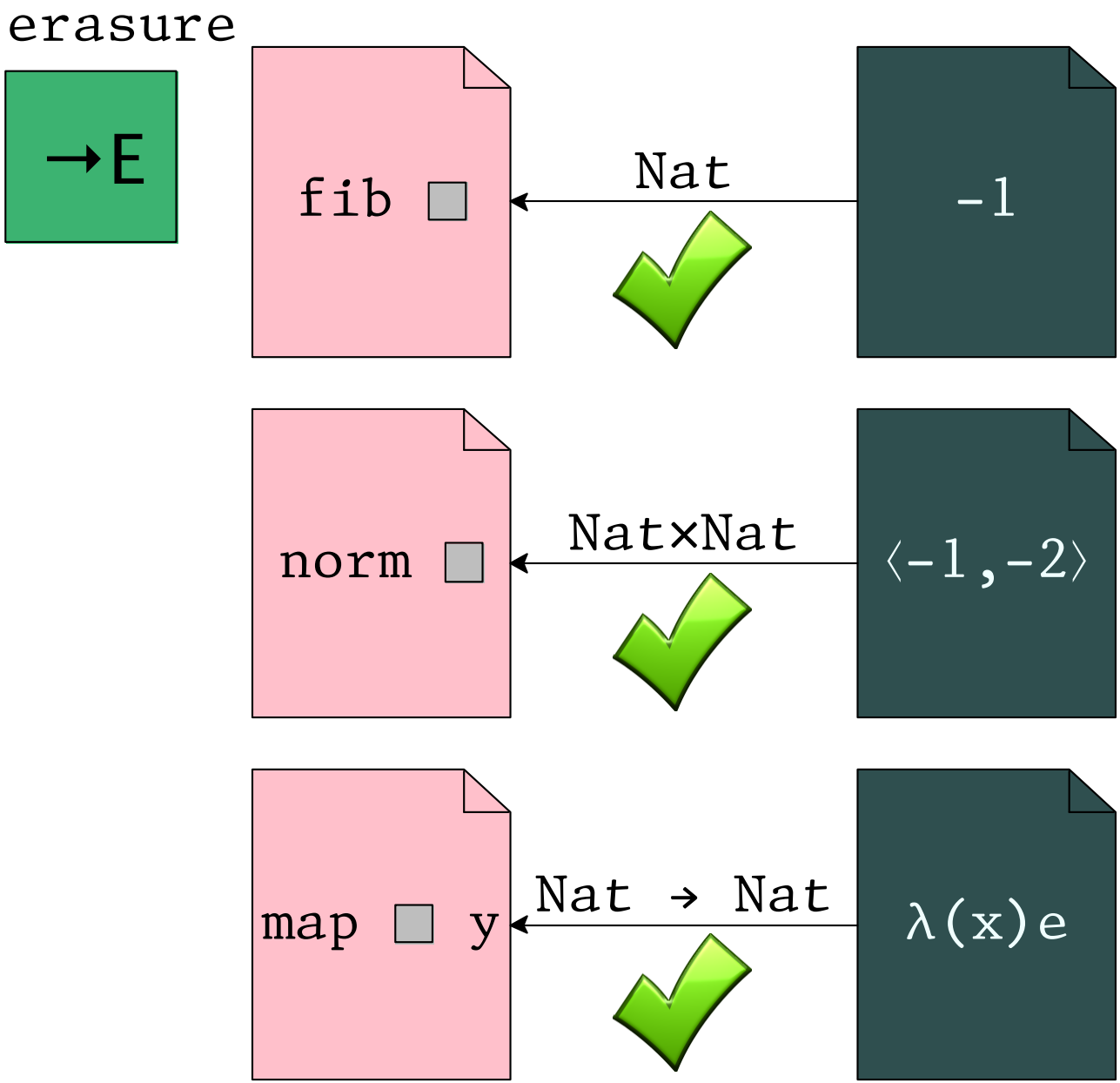
→H add types to 'packages'

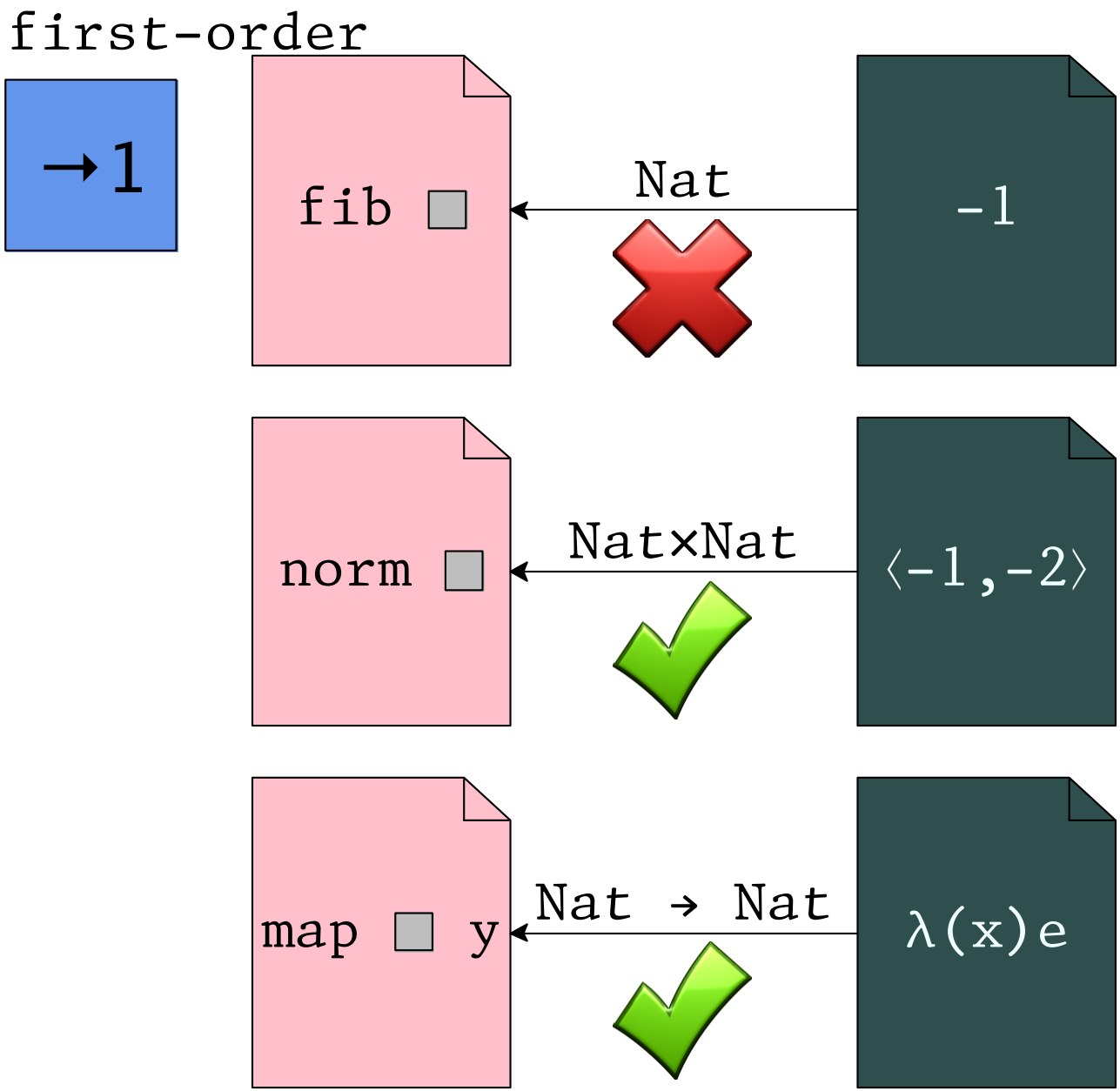
→E add types anywhere

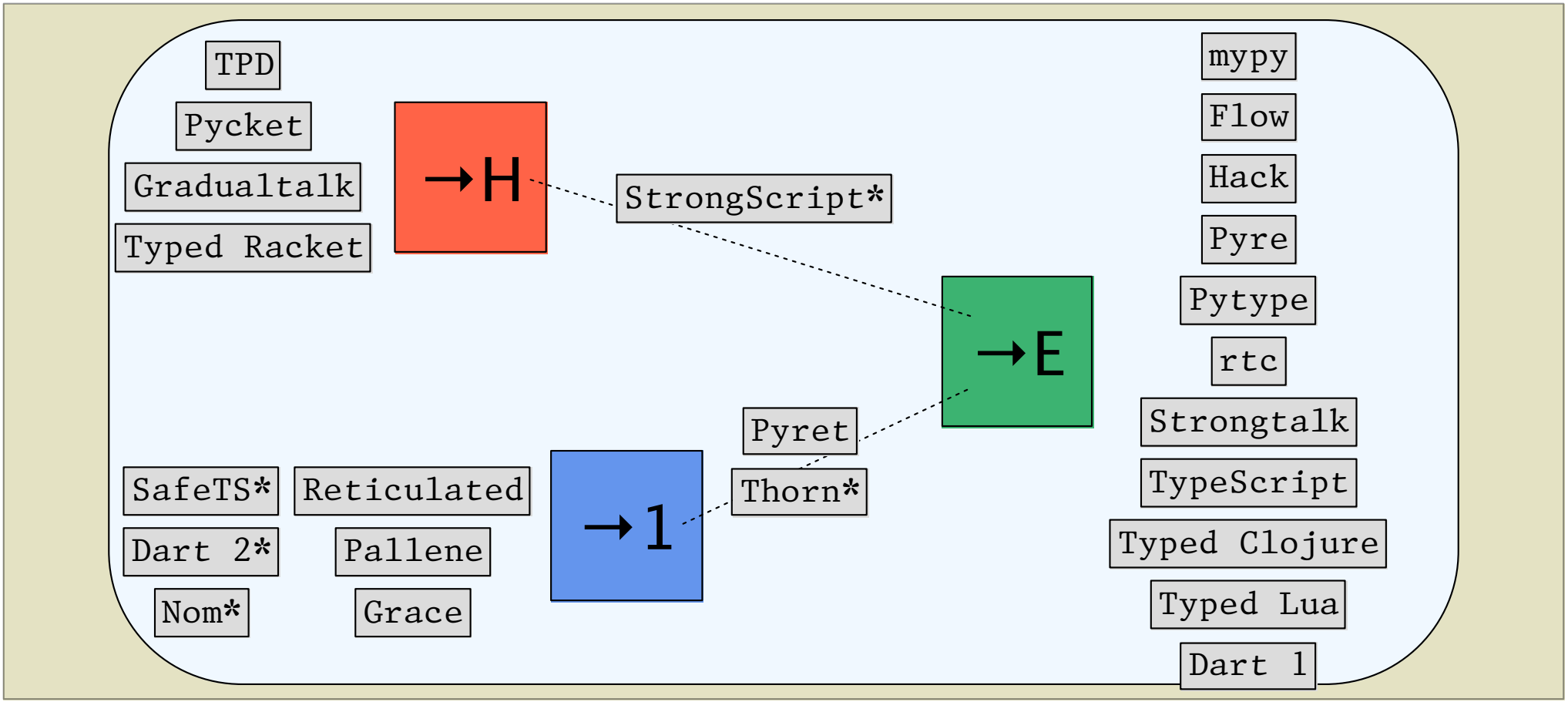
→1 add types sparingly

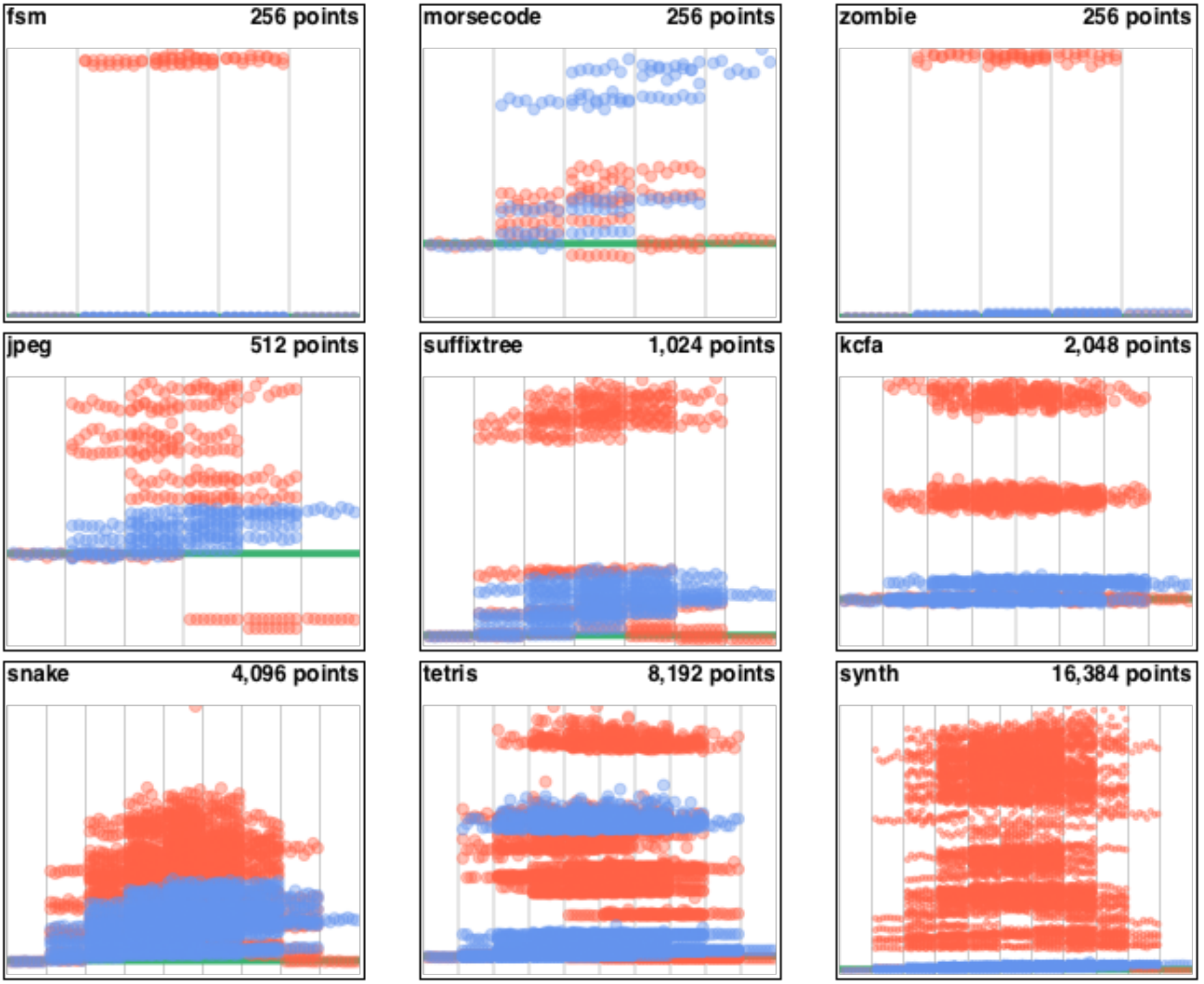



higher-order
→H
fib □
Nat
-1
norm □
Nat×Nat
⟨-1,-2⟩
map □ y
Nat → Nat
λ(x)e


erasure
→E
fib □
Nat
-1
norm □
Nat×Nat
⟨-1,-2⟩
map □ y
Nat → Nat
λ(x)e


first-order
→1
fib □
Nat
-1
norm □
Nat×Nat
⟨-1,-2⟩
map □ y
Nat → Nat
λ(x)e


TPD
Pycket
Gradualtalk
Typed Racket
→H
StrongScript*
mypy
Flow
Hack
Pyre
Pytype
rtc
Strongtalk
TypeScript
Typed Clojure
Typed Lua
Dart 1
→E
Pyret
Thorn*
→1
SafeTS*
Dart 2*
Nom*
Reticulated
Pallene
Grace


fsm
256 points
morsecode
256 points
zombie
256 points
jpeg
512 points
suffixtree
1,024 points
kcfa
2,048 points
snake
4,096 points
tetris
8,192 points
synth
16,384 points

Is type soundness all-or-nothing?

What invariants should the language guarantee?

Can adding types slow down a program?

Yes, through interaction with untyped code (or data)