# Pycket
# A Tracing JIT For a Functional Language

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# Problem: Racket is slow on generic code

Generic code:

```
(define (dot v1 v2)
  (for/sum ([e1 v1] [e2 v2])
    (* e1 e2)))
```

```
(time (dot v1 v2)) ;; 3864 ms
```

Hand optimized:

```
(define (dot-fast v1 v2)
  (define len (flvector-length v1))
  (unless (= len (flvector-length v2))
    (error 'fail))
  (let loop ([n 0] [sum 0.0])
    (if (unsafe-fx= len n) sum
        (loop (unsafe-fx+ n 1)
              (unsafe-fl+ sum (unsafe-fl* (unsafe-flvector-ref v1 n)
                                          (unsafe-flvector-ref v2 n)))))))
```

```
(time (dot-fast v1 v2)) ;; 268 ms
```

# Problem: Racket is slow on contracts

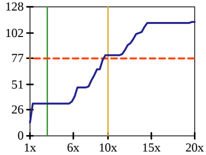
```
(define/contract (dot-safe v1 v2)
 ((vectorof flonum?) (vectorof flonum?) . -> . flonum?)
 (for/sum ([e1 v1] [e2 v2]) (* e1 e2)))

(time (dot-safe v1 v2)) ;; 8888 ms
```

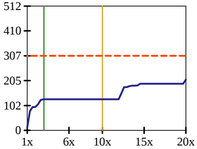
# Problem: Racket is slow wrt. gradual typing

*Is Sound Gradual Typing Dead?* Takikawa et al. POPL 2016

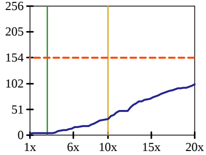
| **kcfa** | (7 modules) |
|---|---|
| typed/untyped ratio | 1.00x |
| max. overhead | 22.67x |
| mean overhead | 9.23x |
| 3-deliverable | 32 (25%) |
| 3/10-usable | 48 (38%) |



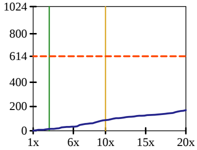
| **tetris** | (9 modules) |
|---|---|
| typed/untyped ratio | 0.97x |
| max. overhead | 117.28x |
| mean overhead | 33.34x |
| 3-deliverable | 128 (25%) |
| 3/10-usable | 0 (0%) |



| **snake** | (8 modules) |
|---|---|
| typed/untyped ratio | 0.92x |
| max. overhead | 121.51x |
| mean overhead | 32.30x |
| 3-deliverable | 4 (2%) |
| 3/10-usable | 28 (11%) |



| **synth** | (10 modules) |
|---|---|
| typed/untyped ratio | 1.03x |
| max. overhead | 85.90x |
| mean overhead | 39.69x |
| 3-deliverable | 15 (1%) |
| 3/10-usable | 73 (7%) |

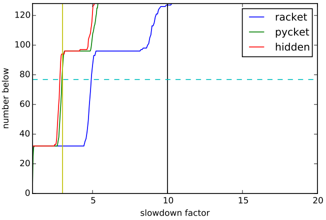


Pycket is a tracing JIT compiler which reduces the need for manual specialization and reduces contract overhead.

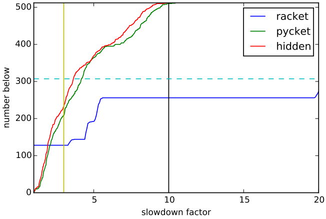
```
(time (dot v1 v2))      ;; 74 ms
(time (dot-fast v1 v2)) ;; 74 ms  (268 ms on Racket)
(time (dot-safe v1 v2)) ;; 95 ms
```

# Pycket tames overhead from gradual typing

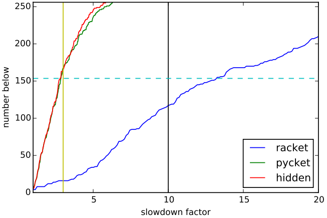
kcfa



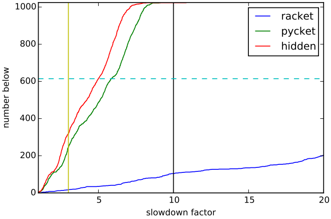
tetris



snake



synth



Idea: Apply dynamic language JIT compiler to Racket

Take: Racket

$+$

Apply: RPython Project

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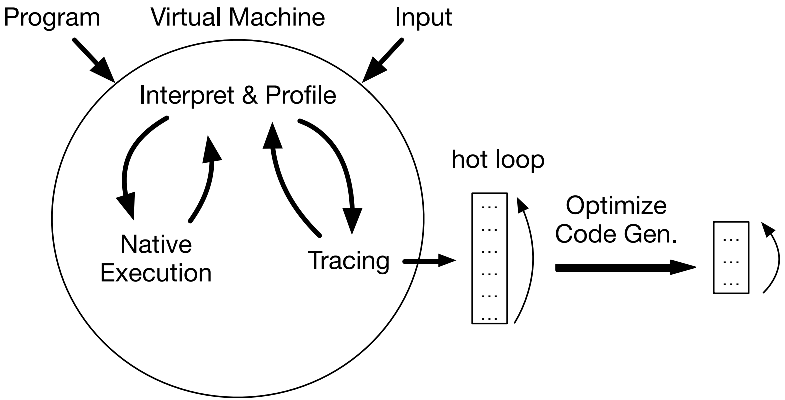
Pycket

# Background: Tracing JIT Compilation



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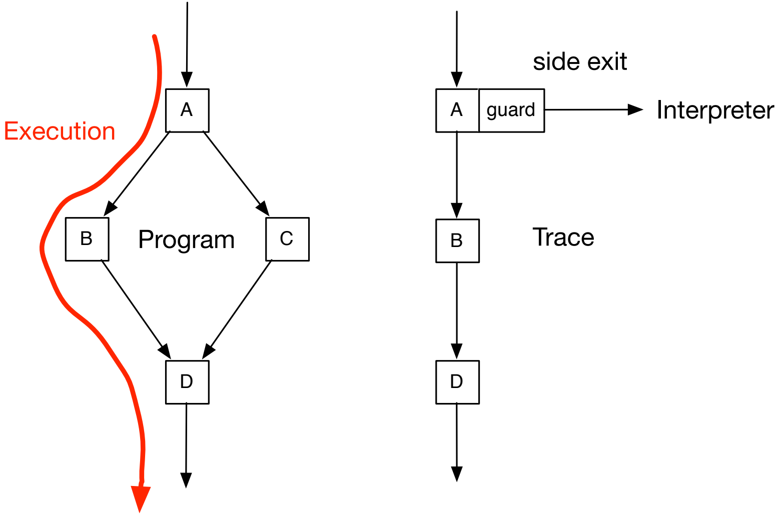
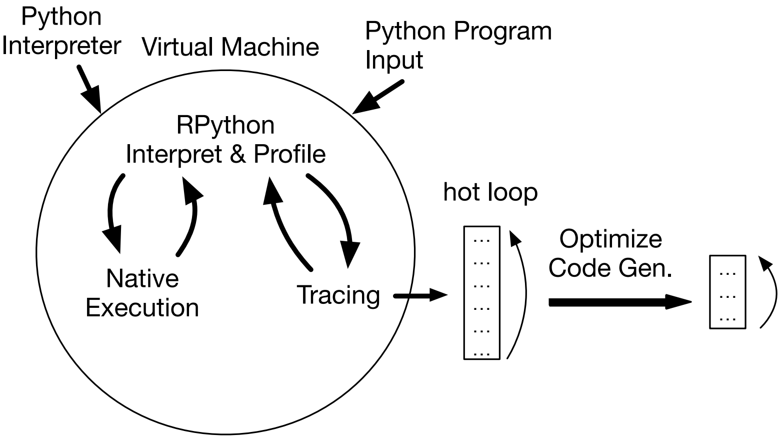
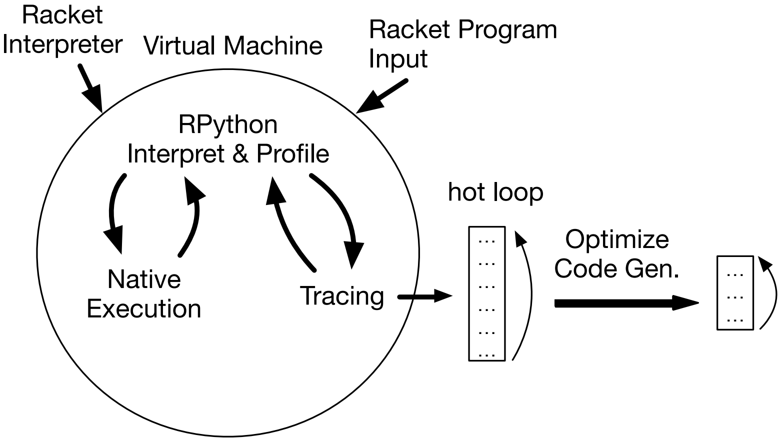


# Background: The PyPy Meta-Tracing JIT



# The Pycket Meta-Tracing JIT



# Our Racket Interpreter: The CEK Machine

$$e ::= x \mid \lambda x.\, e \mid (e\ e) \mid \mathsf{letcc}\, x.\, e \mid e@e$$

$$\kappa ::= [] \mid \mathsf{arg}(e, \rho)::\kappa \mid \mathsf{fun}(v, \rho)::\kappa \mid \mathsf{ccarg}(e, \rho)::\kappa \mid \mathsf{cc}(\kappa)::\kappa$$

$$v ::= \lambda x.\, e \mid \kappa$$

$$\langle x, \rho, \kappa\rangle \longmapsto \langle \rho(x), \rho, \kappa\rangle$$

$$\begin{aligned}
\langle (e_1\ e_2), \rho, \kappa\rangle &\longmapsto \langle e_1, \rho, \mathsf{arg}(e_2, \rho)::\kappa\rangle \\
\langle v_1, \rho, \mathsf{arg}(e_2, \rho')::\kappa\rangle &\longmapsto \langle e_2, \rho', \mathsf{fun}(v_1, \rho)::\kappa\rangle \\
\langle v_2, \rho, \mathsf{fun}(\lambda x.\, e, \rho')::\kappa\rangle &\longmapsto \langle e, \rho'[x \mapsto v_2], \kappa\rangle
\end{aligned}$$

$$\langle \mathsf{letcc}\, x.\, e, \rho, \kappa\rangle \longmapsto \langle e, \rho[x \mapsto \kappa], \kappa\rangle$$

$$\begin{aligned}
\langle (e_1@e_2), \rho, \kappa\rangle &\longmapsto \langle e_1, \rho, \mathsf{ccarg}(e_2, \rho)::\kappa\rangle \\
\langle \kappa_1, \rho, \mathsf{ccarg}(e_2, \rho')::\kappa\rangle &\longmapsto \langle e_2, \rho', \mathsf{cc}(\kappa_1) :: \kappa\rangle \\
\langle v_2, \rho, \mathsf{cc}(\kappa_1)::\kappa)\rangle &\longmapsto \langle v_2, \rho, \kappa_1\rangle
\end{aligned}$$

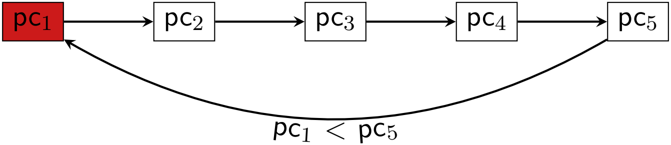
*Programming Languages and Lambda Calculi.* Flatt and Felleisen. 2007

# Challenges particular to Racket

- Detect loops for trace compilation in a higher-order language without explicit loop constructs
- Reduce the need for manual specialization
- Reduce the overhead imposed by contracts

# Loop finding: cyclic paths

Record cycles in control flow



Default RPython strategy

# Tracing cycles in the control flow is insufficient

The CEK machine has no notion of a program counter,
can try to use AST nodes instead.

```
(define (my-add a b) (+ a b))
(define (loop a b)
  (my-add a b)
  (my-add a b)
  (loop a b))
```

Begin tracing at a hot node and continue until that node is reached again

`(+ a b)`

# Tracing cycles in the control flow is insufficient

```
(define (my-add a b) (+ a b))
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```

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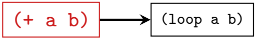

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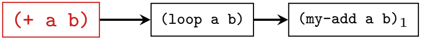

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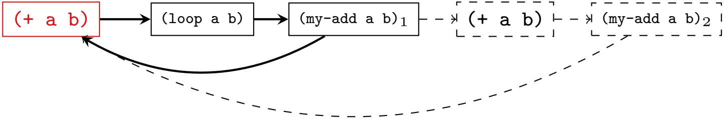
Begin tracing at a hot node and continue until that node is reached again



(+ a b)

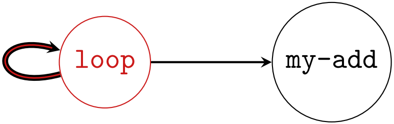
(loop a b)

(my-add a b)$_1$

(+ a b)

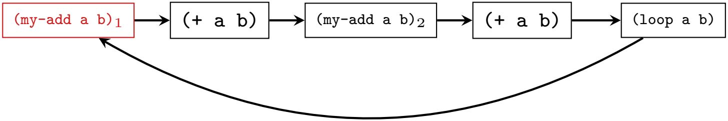
(my-add a b)$_2$

# The Callgraph



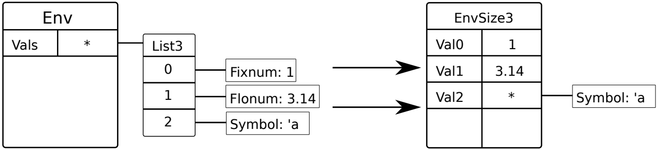
Newer definition: A *loop* is a cycle in the program's call graph.

1. Build the callgraph during execution
2. Mark functions in a cycle as a loop



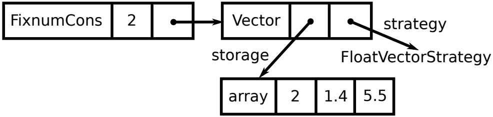
# Data Structure Specialization

Unbox small, fixed-size arrays of Racket values



# Specialized Mutable Objects

Optimistically specialize the representation of homogeneous containers



When a mutating operation invalidates the current strategy, the storage is rewritten — this is fortunately infrequent

[Bolz et al., OOPSLA 2013]

# Pycket: What Works?

- File IO

  ```
  (open-input-file "list.txt")
  (open-output-file "brain.dat")
  ```

- Numeric tower

  ```
  number? complex? real? rational? integer? ...
  ```

- Contracts

  ```
  (define-contract ...)
  ```

- Typed Racket

  ```
  #lang typed/racket
  ```

- Primitive Functions ($\sim 900/1400$)

# Pycket: What Doesn’t Work?

- FFI
- Scribble

  ```
  #lang scribble/base
  ```
- DrRacket
- Web

  ```
  #lang web-server/insta
  ```
- Threads

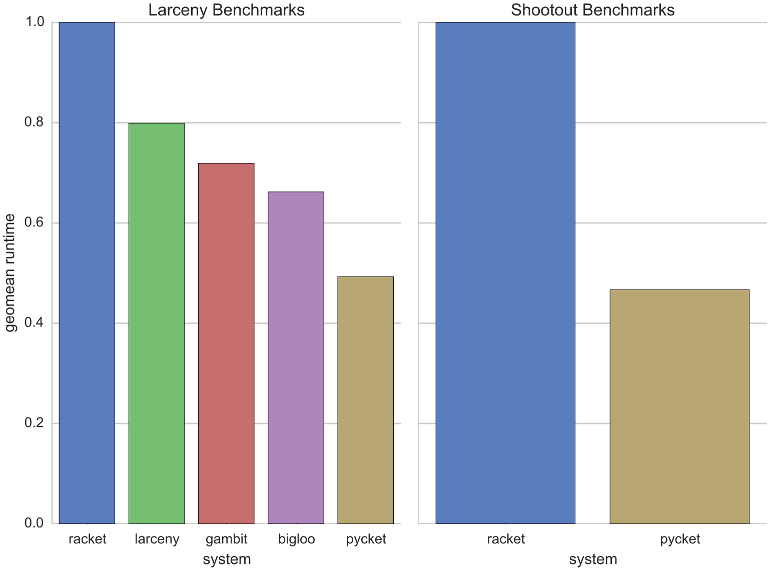
  ```
  (thread (  () ...))
  ```
- Lesser used primitives

# Performance Caveats

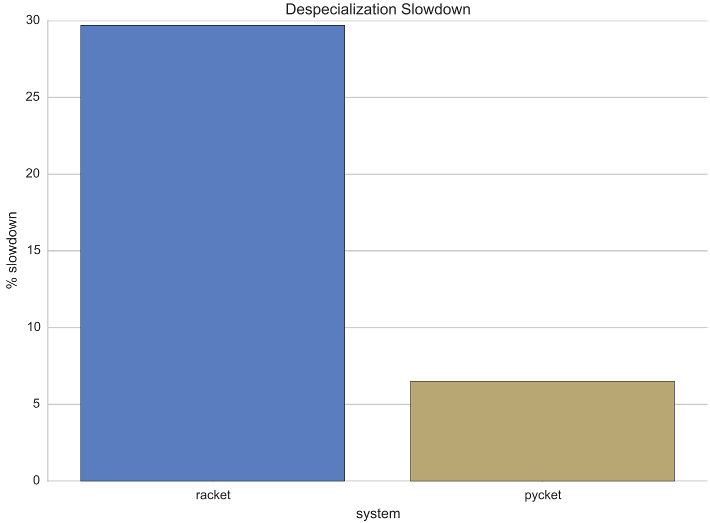
| Fast | Slow |
|---|---|
| Tight loops | Branchy/irregular control flow |
| Numeric Computations | Code not easily expressed as loops |
| | Interpreters |
| | Short-running programs |

# Benchmarks

# Overall Performance



# Specialization



# Contracts and Chaperones

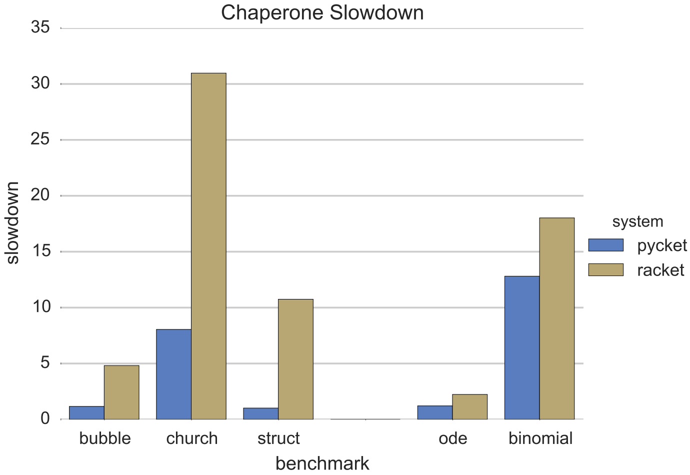
```
(define (dot v1 v2)
  (for/sum ([e1 v1] [e2 v2]) (* e1 e2)))

(define/contract (dotc v1 v2)
  ((vectorof flonum?) (vectorof flonum?) . -> . flonum?)
  (for/sum ([e1 v1] [e2 v2]) (* e1 e2)))
```

- Pycket supports Racket's implementation of higher-order software contracts via *impersonators* and *chaperones*
- Used to support Type Racket's implementation of gradual typing
- Overhead = Enforcement Cost + Extra Indirection

[Strickland, Tobin-Hochstadt, Findler, Flatt 2012]

# Benchmarks: Contracts



# Future Improvements

- Improve chaperone/impersonator performance and space usage
- Explore interaction between ahead-of-time and just-in-time optimizations
- Green threads and inter-thread optimizations
- Improve performance on complicated control flow
- Support more of Racket

# Thank You

- Dynamic language JIT compilation is a viable implementation strategy for functional languages
- Novel loop detection method for trace compilation of a higher-order language
- Significant reduction in contract overhead
- Significant reduction in the need for manual specialization

https://github.com/samth/pycket