# Optimizing R Language Execution via Aggressive Speculation

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# Safe Harbor Statement

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# What is R?

- A programming language
  - Convenient tool for common statistical tasks
  - A DSL for statistics
  - A general-purpose language: ability to implement algorithms, analyses

- A data analysis workbench
  - Data exploration and manipulation
  - Graphics capabilities for visualizing data
  - Interactions with typesetting systems and web servers for data presentation

- A data science ecosystem
  - Over 11k open source packages for multiple purposes
  - Application areas: statistics, geoscience, bioinformatics, health sciences, machine learning, ...

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# What is the challenge?

```
function(x) {
    for(i in 1:10000) {
        x[i] = i;
    }
    return(x);
}
```

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- Functions can have side effects
  - Function re-definition
  - Search path alteration

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dynamic lookup

function

function

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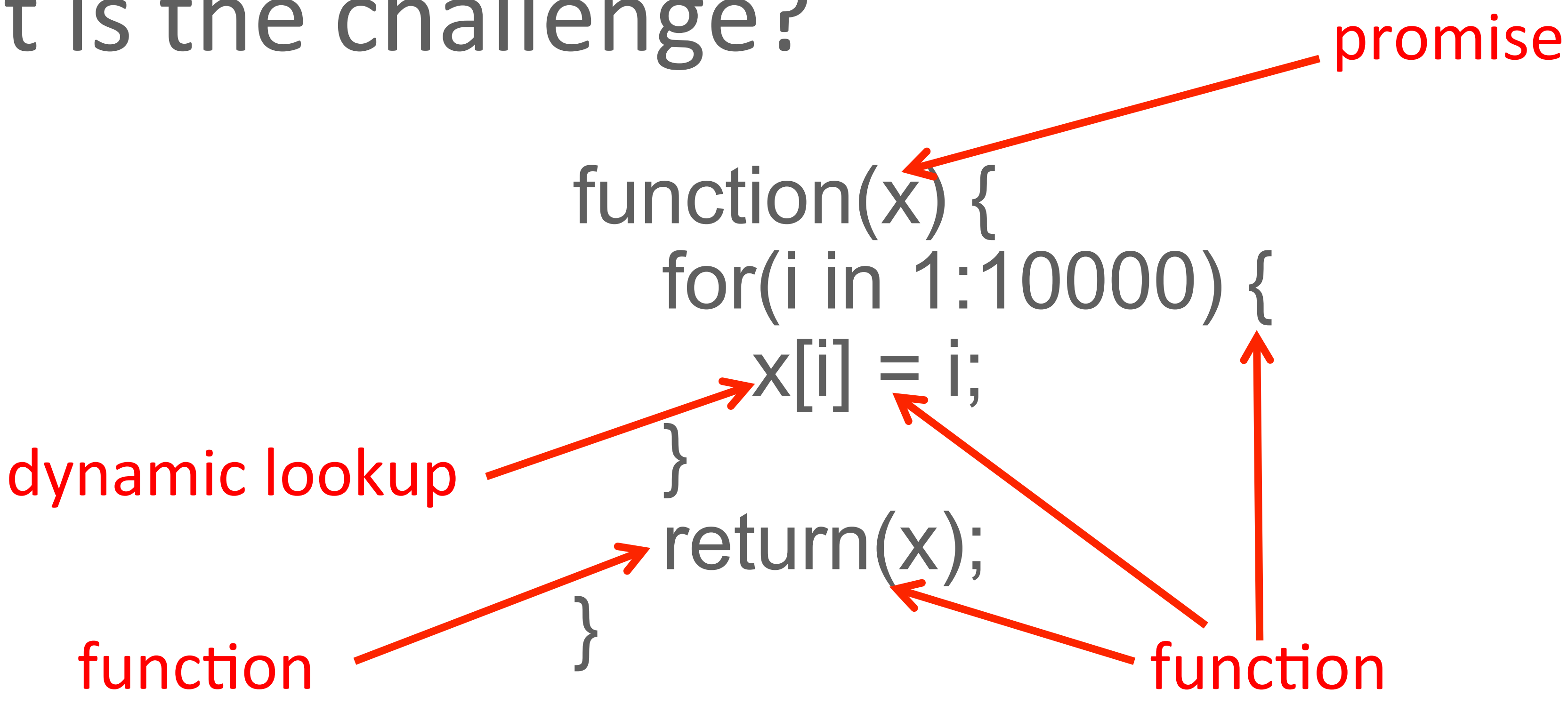


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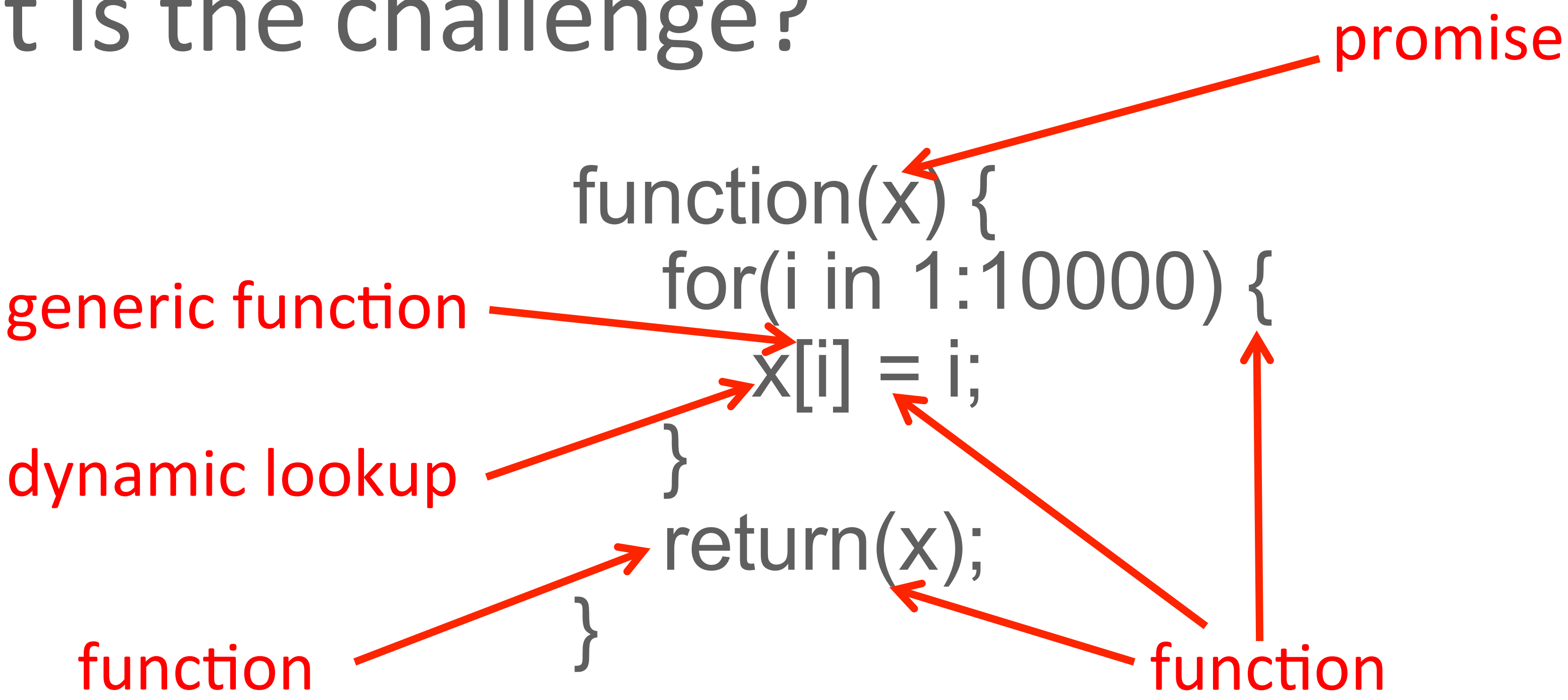


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# What is the challenge?

promise

generic function

dynamic lookup

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```

function

function

- Functions can have side effects
  - Function re-definition
  - Search path alteration
- Generic function’s dispatch depends on x’s metadata (attributes)

# What is FastR?

- An alternative R execution engine, developed under GPL v2 at Oracle Labs in collaboration with the academia
  - Started with Jan Vitek's group at Purdue
- Drop-in, fully compatible replacement for R's reference implementation GNU R
- Focused on improving performance of long-running R code
- Open-source: https://github.com/graalvm/fastr

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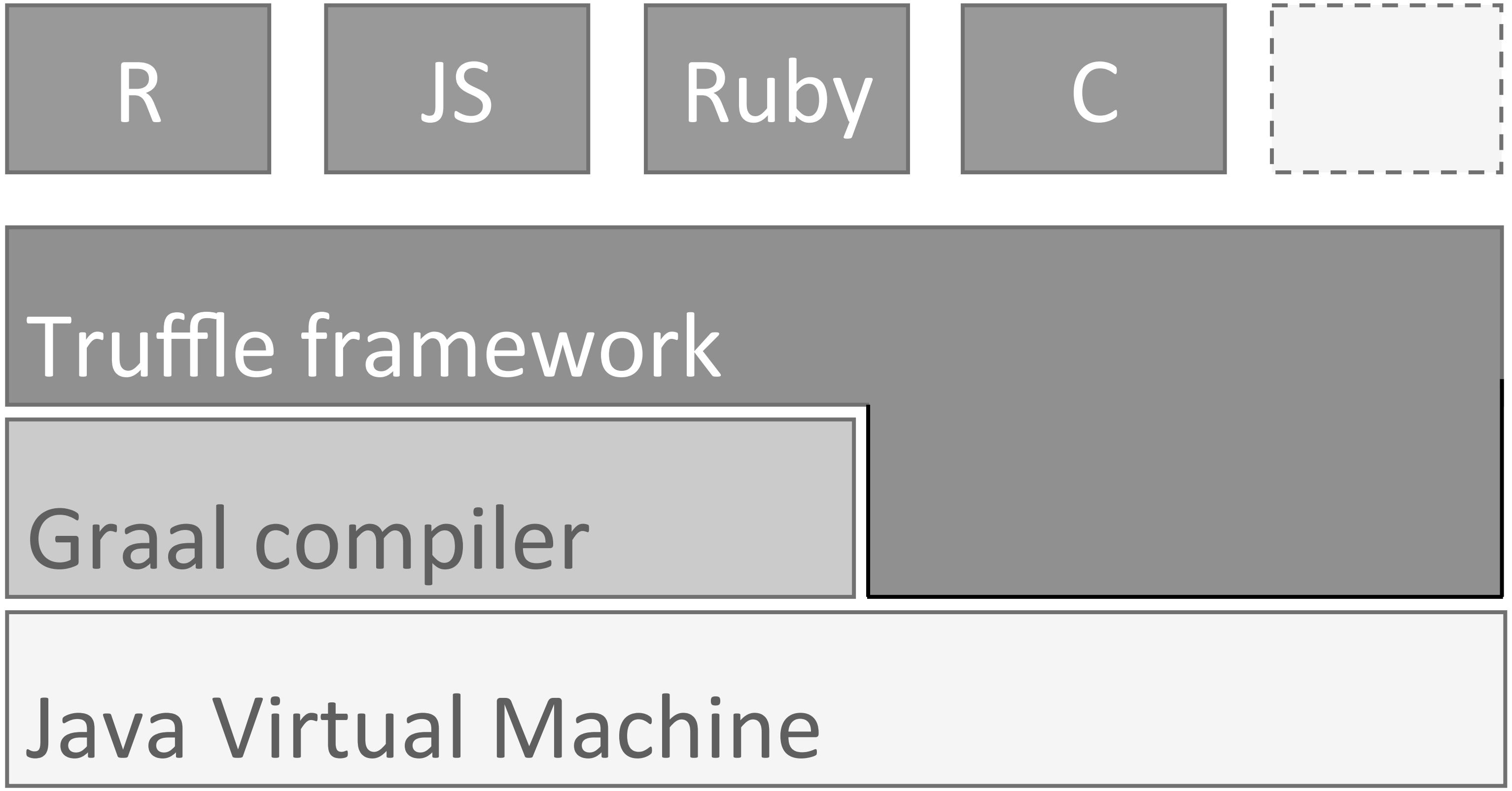
# System architecture

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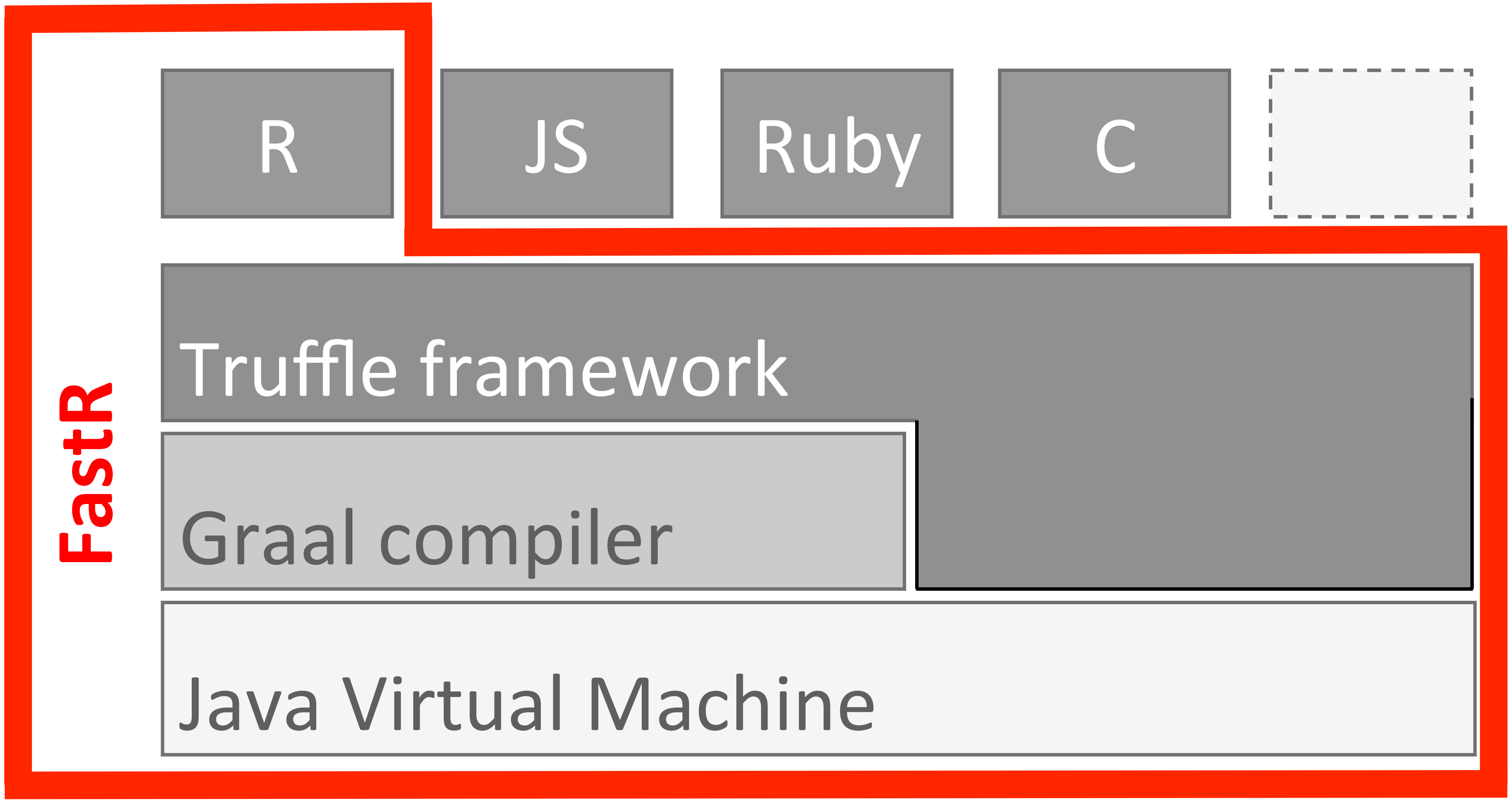
# System architecture



# Graal/Truffle technology stack

- Main components
  - Truffle framework to build Abstract Syntax Tree interpreters
  - Single Graal compiler to generate native code for all Truffle languages
- Competitive in peak performance to best-of-class of each language:
  - for Java (vs. HotSpot server compiler)
  - for dynamic languages (vs. V8)
  - for static languages (prototype, vs. GCC)
- Open source: https://github.com/graalvm

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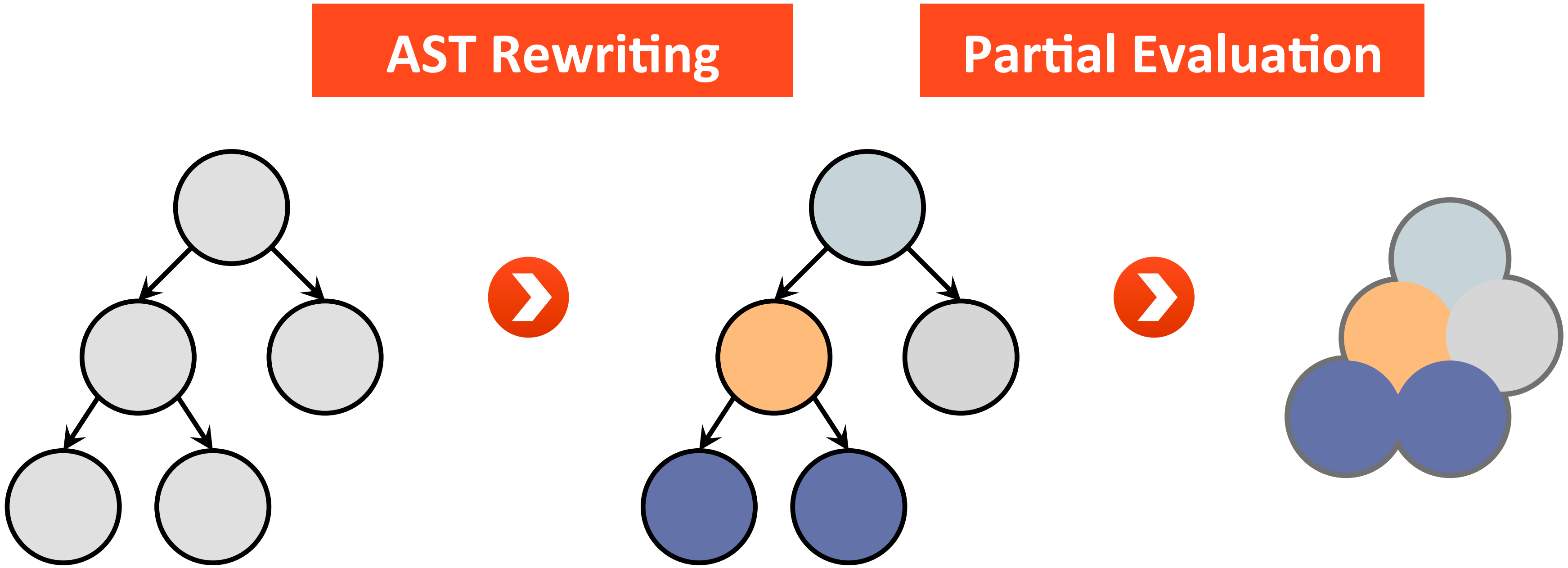
# From interpreted AST to native code




Interpreted AST (responsibility of the language creator)

Specialized AST

Compiled Code (guards for deoptimization)

# FastR – R as a Truffle language

- Superior performance without resorting to C and Fortran
  - Significant amounts of time are spent converting R to C code for performance
- Interoperability within the Graal/Truffle ecosystem
  - Transparent interop with JS, C, Ruby, …
- Research vehicle for data-heavy and parallel applications
  - Multi-tenancy, multi-thread execution of R applications, alternative internal data representations, etc.

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# Optimizing R

- Three fundamental optimization techniques
  - Caching: inline caches for function calls, but also caching information for other operations (e.g. argument matching)
  - Assumptions: used to monitor low probability events – costly invalidations but inexpensive (with system support) to check
  - Specialization: divide implementation of an operation into smaller pieces and speculate that only a limited set of code paths will be taken
- These techniques permeate the entire implementation: symbol lookup, function calls, lazy evaluation, vector accesses, etc.

# Example: lazy evaluation

- R uses a *call-by-need* lazy argument evaluation strategy
  - Each argument is a *promise* (code snippet + evaluation environment)
  - Argument value is computed (promise is *forced*) as late as possible and only if needed
- Problems
  - Promise creation and indirect argument value access incur overhead
  - Environments (variable/value mappings) are virtualized (into native stack frames) – storing them requires materialization and is expensive
  - Each program point where promise can be forced becomes a call site

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# Specialized promise implementation categories

- Eager promises – local variable used as parameter

```
x = 42; foo(x);         # extensible to include pure function calls as params
```

- Indirect promises – non-forced parameters passed to other calls

```
bar = function(x) { foo(x); }
```

- Default promises – arbitrarily complex code to be evaluated

```
foo(x + bar(y))
```

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# Lazy vs. eager evaluation

global environment

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global environment

lazy

```
foo = function(a) {
  x <<- 7;
  print(a);
}
```

# Lazy vs. eager evaluation


global environment

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```
foo = function(a) {
  x <<- 7;
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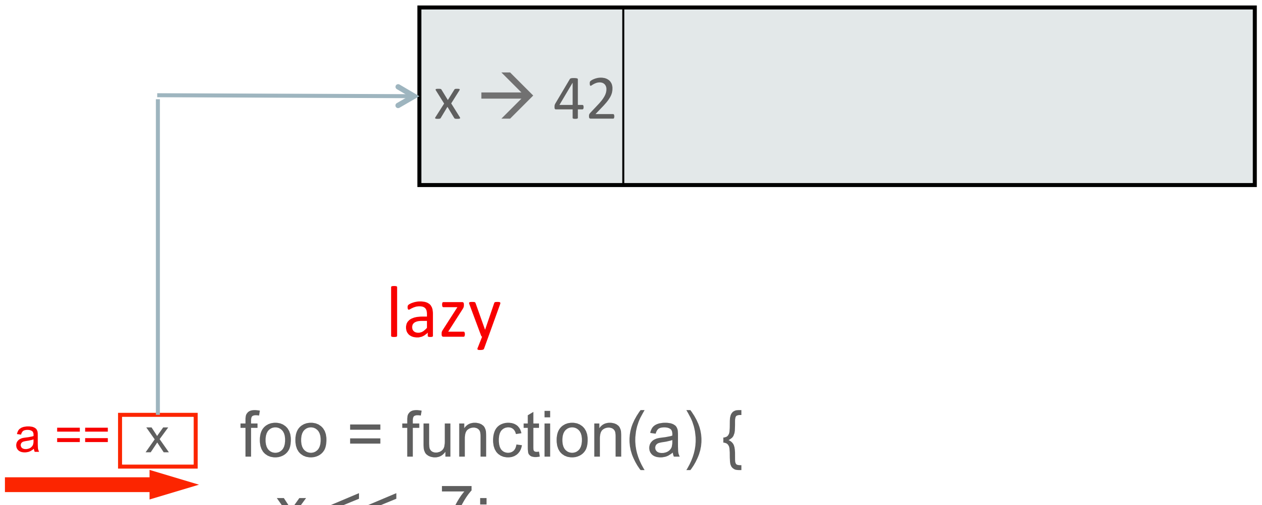
x = 42;
```

# Lazy vs. eager evaluation




global environment

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```

# Lazy vs. eager evaluation


global environment

lazy

a == x

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# Lazy vs. eager evaluation

x → 7

global environment

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# Lazy vs. eager evaluation


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foo(x);     # prints 7
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# Lazy vs. eager evaluation

| x → 7 | |
|---|---|

global environment

**lazy**

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foo = function(a) {
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x = 42;
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```

**eager**

```
bar = function(b) {
  y <<- 7;
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```

# Lazy vs. eager evaluation

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b == 42 →

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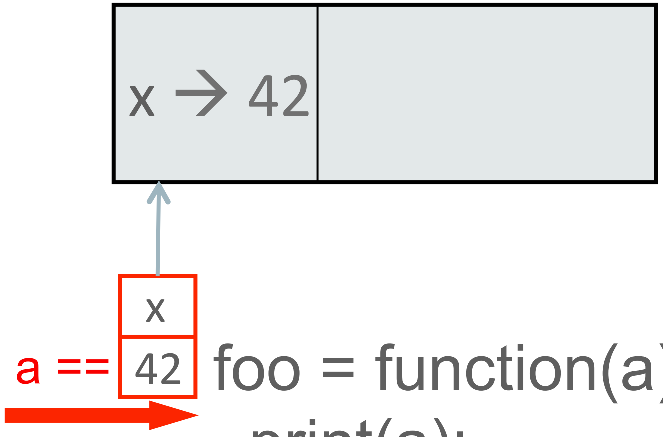
# Eager promises implementation

- Promise caches eager value

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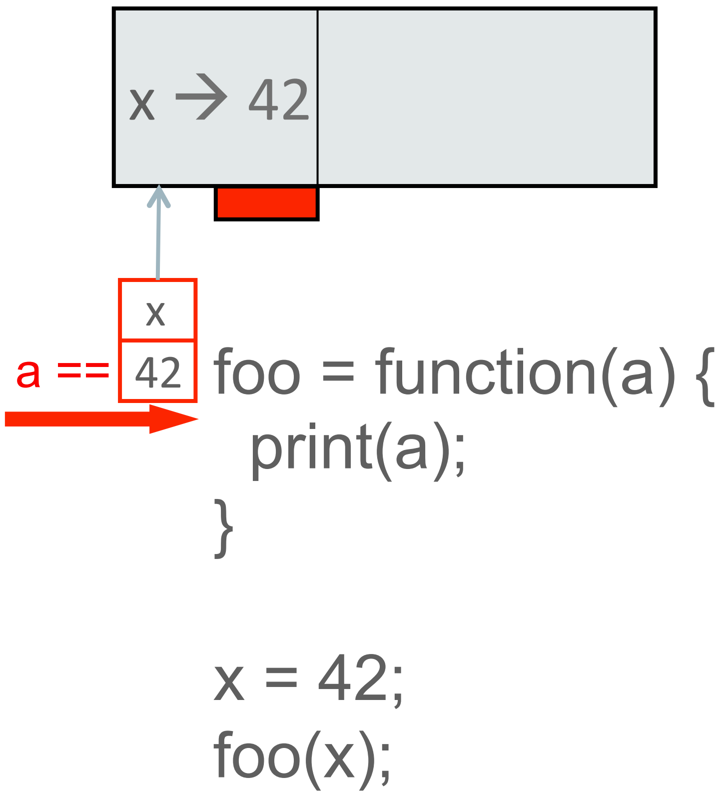

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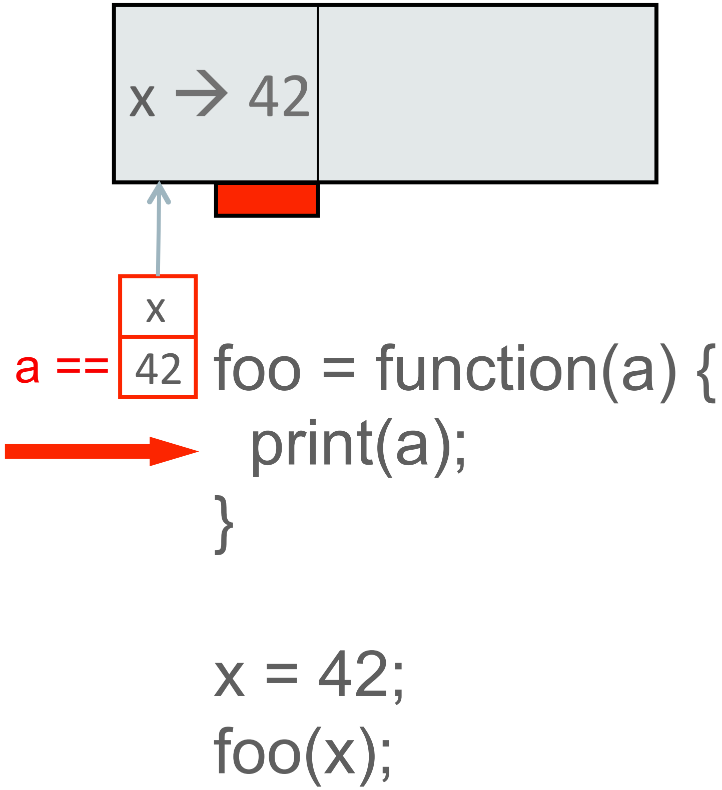

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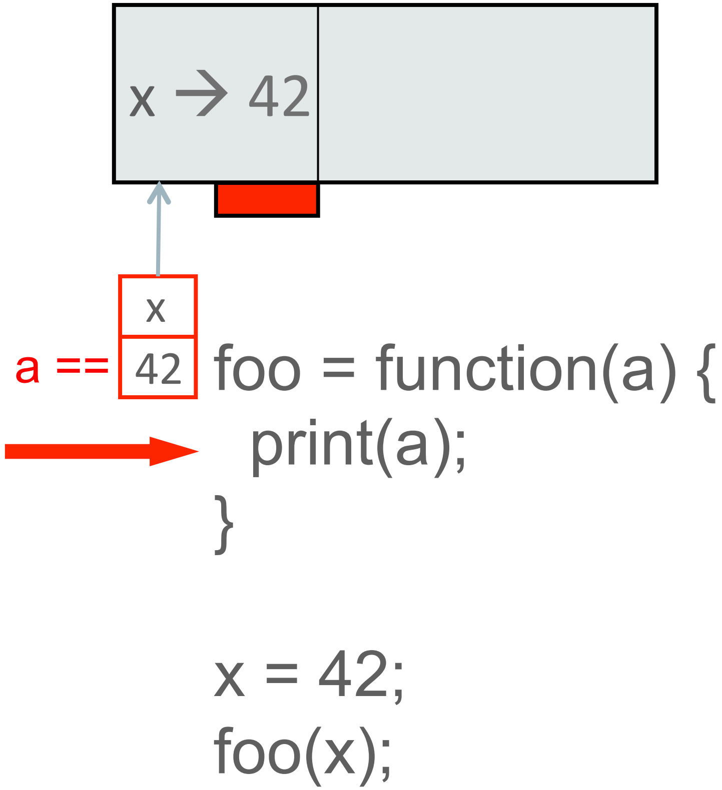

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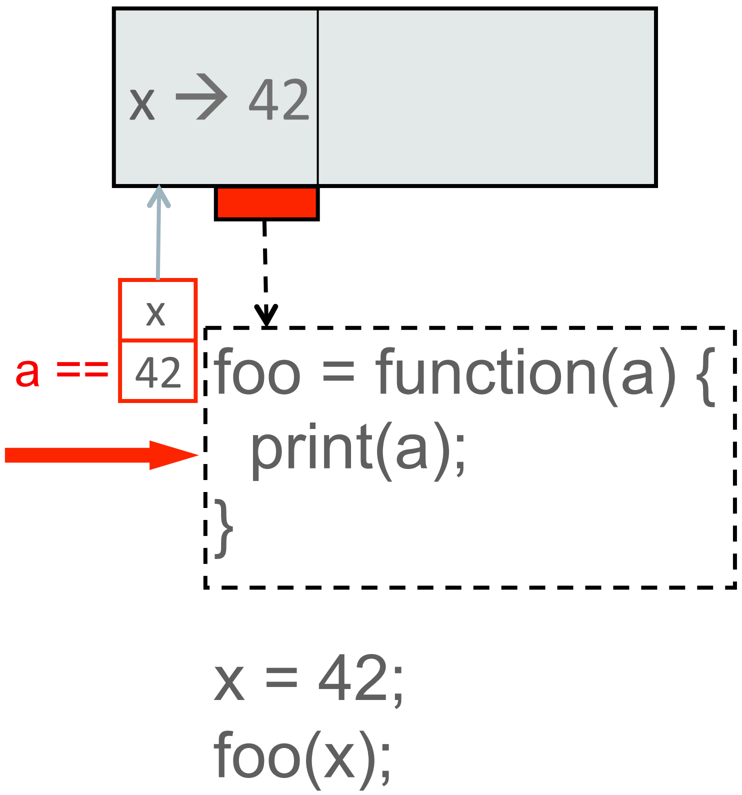

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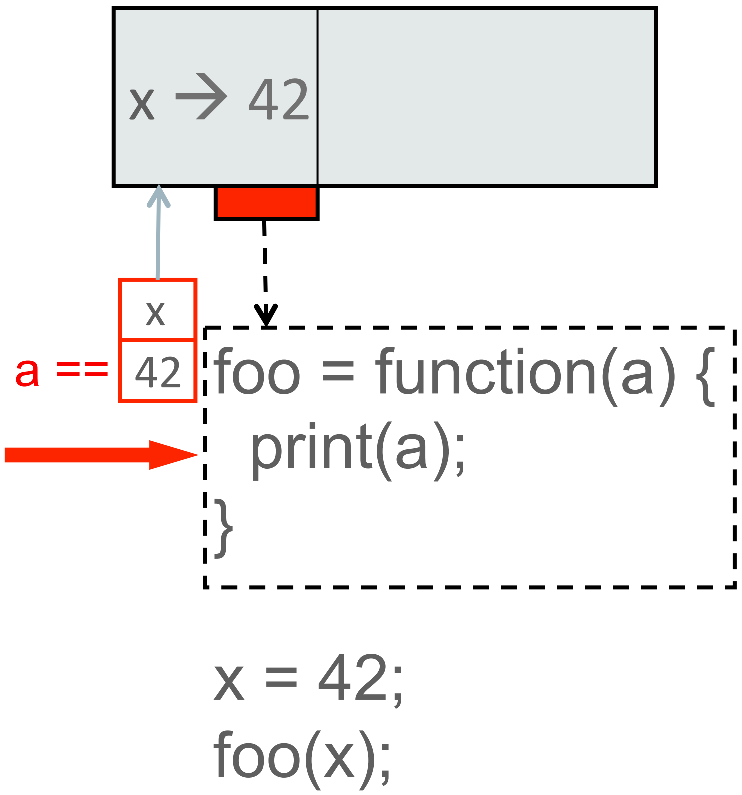
  - Compiler can unbox cached eager value



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global env (depth 1)

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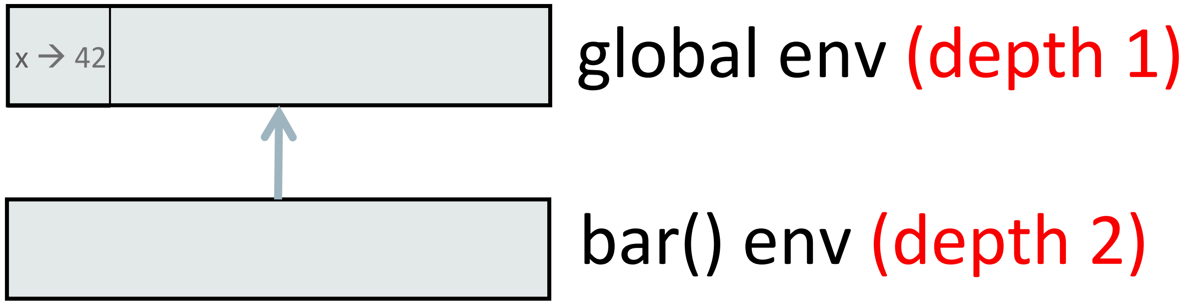

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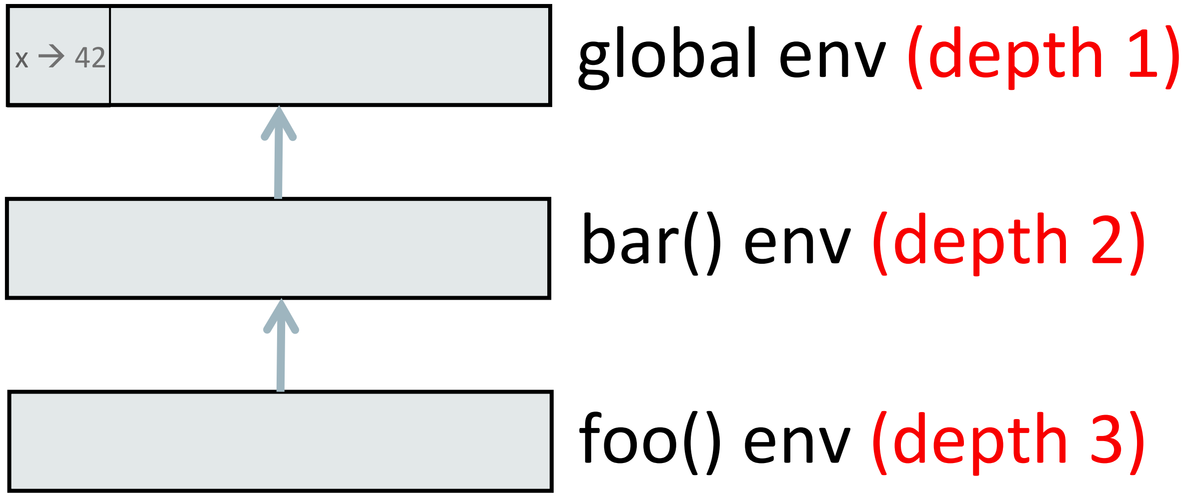

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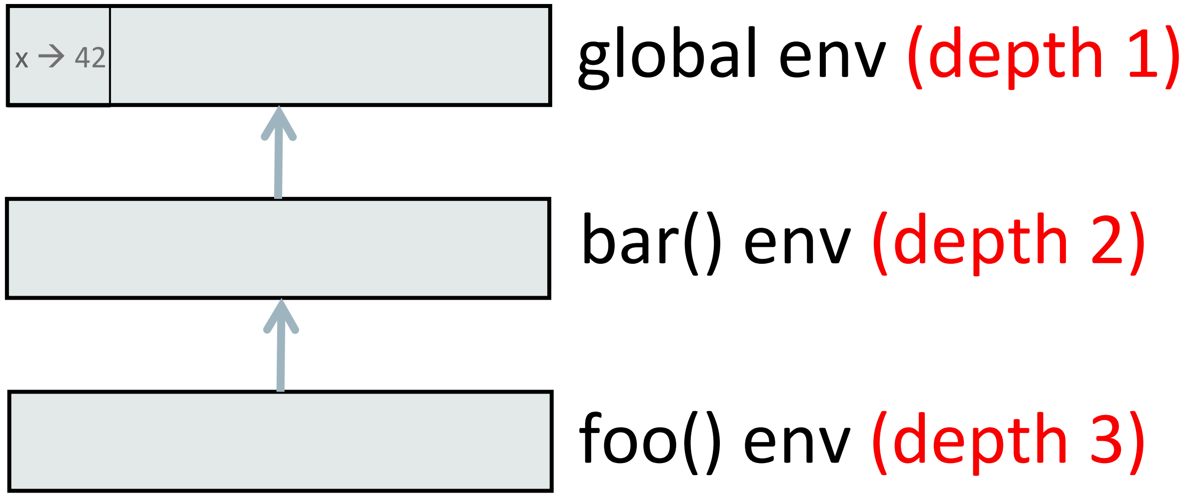


- Store environment depth with a promise

# Other promises

- Default promises
  - Environment stored with a promise
  - Inline caches used to reduce overhead of evaluating promises carrying the same code snippets
- Indirect promises
  - Technically – instance of eager promises (no costly meta data)
  - Practically – wrappers around other promise types
  - Evaluation cost the same as of the promise they are wrapping

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# Lazy evaluation optimization results

- Two benchmark suites
  - B25: matrix calculations + simple R computation tasks
  - Shootout: small applications consisting mostly of R code
- Estimated optimization potential measured in number of promises
- Three configurations to measure impact of the optimizations (peak performance plotted on logarithmic scale)
  - Eager promises optimization only
  - Caching for default promises only
  - Eager promises and caching combined

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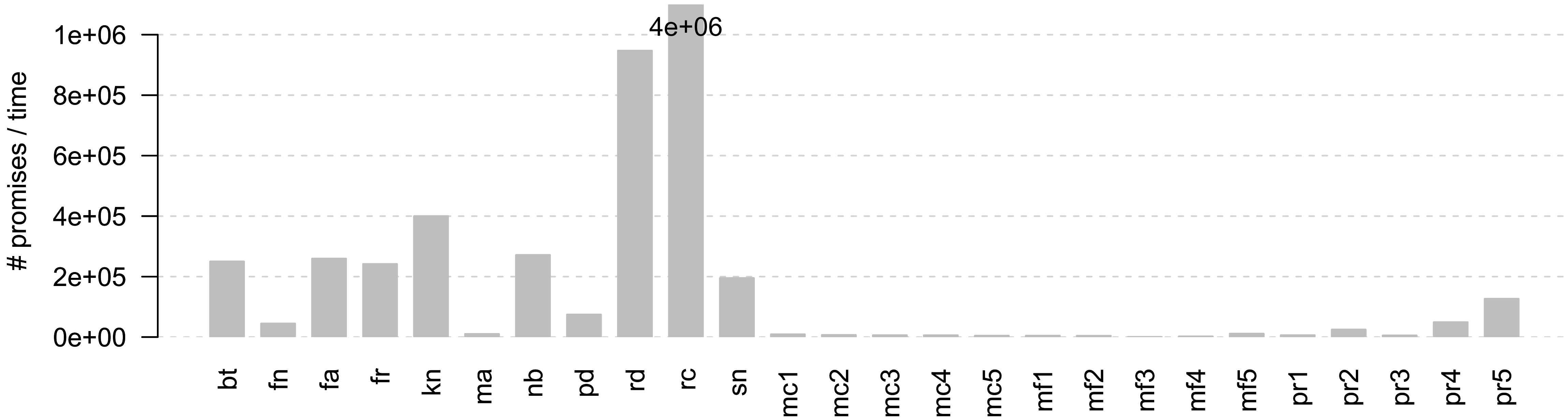
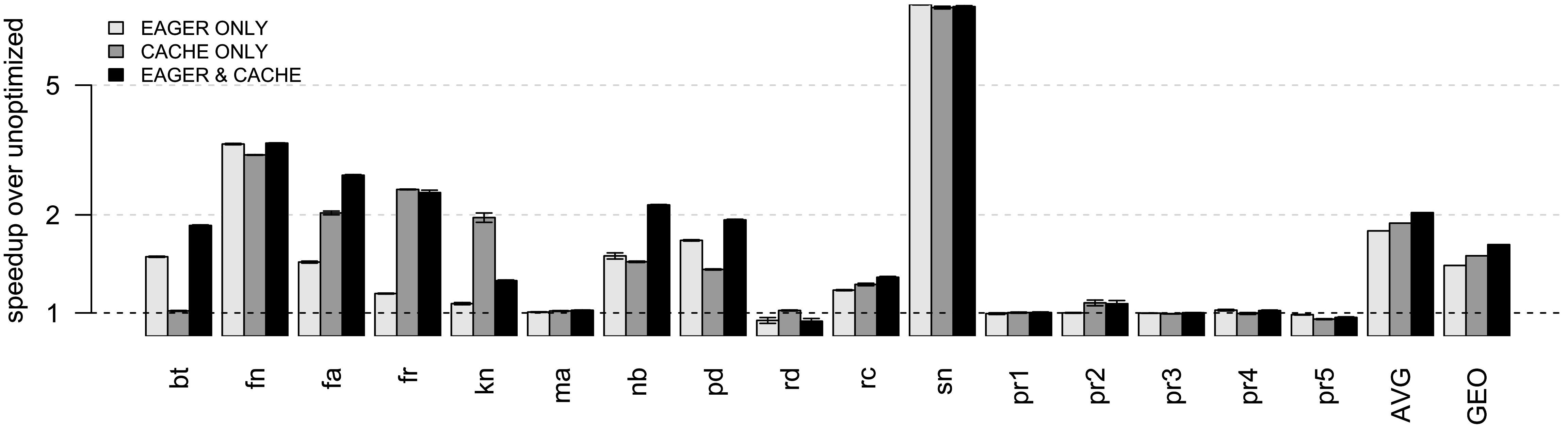
# Promise statistics



# Impact of lazy evaluation optimizations



# Overall system performance

- Same two benchmark suites – b25 and shootout
- Five runtime configurations
  - GNU R “base” (default configuration)
  - GNU R “BC” (bytecode compiler)
  - Renjin (alternative R implementation from BeDataDriven)
  - TERR (alternative R implementation from TIBCO)
  - FastR
- Plotted peak performance on a logarithmic scale

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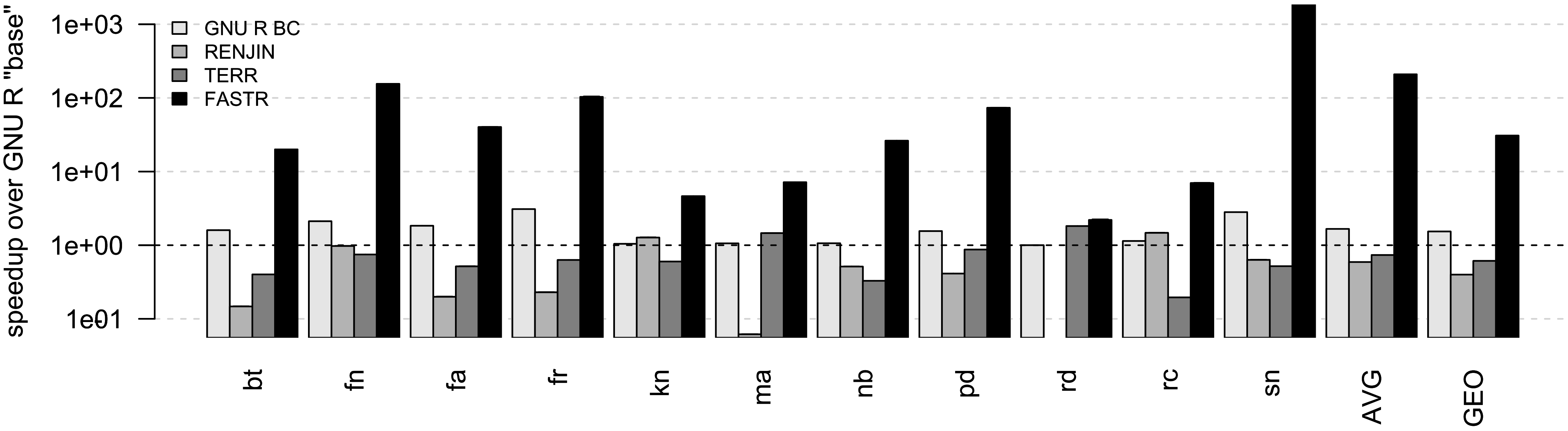
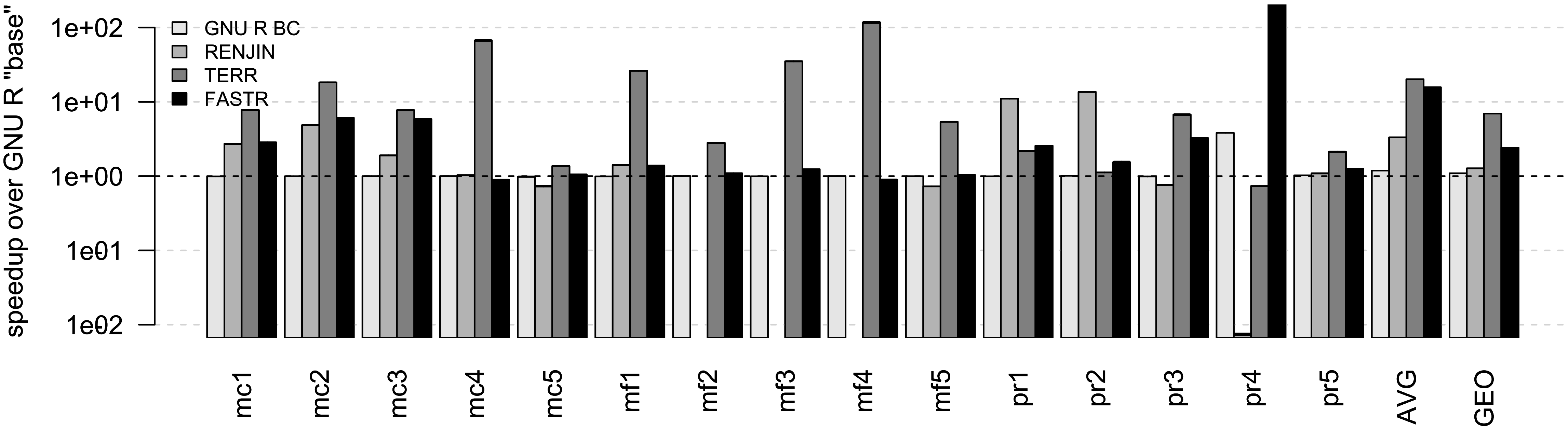
# Shootout benchmark suite




FastR’s average speedup: ~208.7 (geometric mean: ~30.8)

# B25 benchmark suite




- FastR's average speedup: ~15.7 (geometric mean: ~2.4)

# Project status

- Implemented all important language features, including lazy evaluation, calls to C/Fortran, S3 and S4 object models
- FastR can load over 2000 unmodified CRAN packages and run selected production applications in parallel
- Missing features include portions of native interface and selected builtins
- Bottom line – semantic compatibility is high but work ongoing on completeness and experimental features (e.g. autoparallelization)

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Jaroslav Tulach
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Christian Wirth
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Robert Seilbeck
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