# Expressive Genetic Programming

## Tutorial

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Lee Spector
School of Cognitive Science
Hampshire College
Amherst, MA 01002 USA
lspector@hampshire.edu
http://hampshire.edu/lspector


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# Instructor

**Lee Spector** is a Professor of Computer Science in the School of Cognitive Science at Hampshire College in Amherst, Massachusetts, and an adjunct professor in the Department of Computer Science at the University of Massachusetts, Amherst. He received a B.A. in Philosophy from Oberlin College in 1984 and a Ph.D. from the Department of Computer Science at the University of Maryland in 1992. His areas of teaching and research include genetic and evolutionary computation, quantum computation, and a variety of intersections between computer science, cognitive science, evolutionary biology, and the arts. He is the Editor-in-Chief of the journal *Genetic Programming and Evolvable Machines* (published by Springer) and a member of the editorial board of *Evolutionary Computation* (published by MIT Press). He is also a member of the SIGEVO executive committee and he was named a Fellow of the International Society for Genetic and Evolutionary Computation.

# Tutorial Description (1)

The language in which evolving programs are expressed can have significant impacts on the problem-solving capabilities of a genetic programming system. These impacts stem both from the absolute computational power of the languages that are used, as elucidated by formal language theory, and from the ease with which various computational structures can be produced by random code generation and by the action of genetic operators. Highly expressive languages can facilitate the evolution of programs for any computable function using, when appropriate, multiple data types, evolved subroutines, evolved control structures, evolved data structures, and evolved modular program and data architectures. In some cases expressive languages can even support the evolution of programs that express methods for their own reproduction and variation (and hence for the evolution of their offspring).

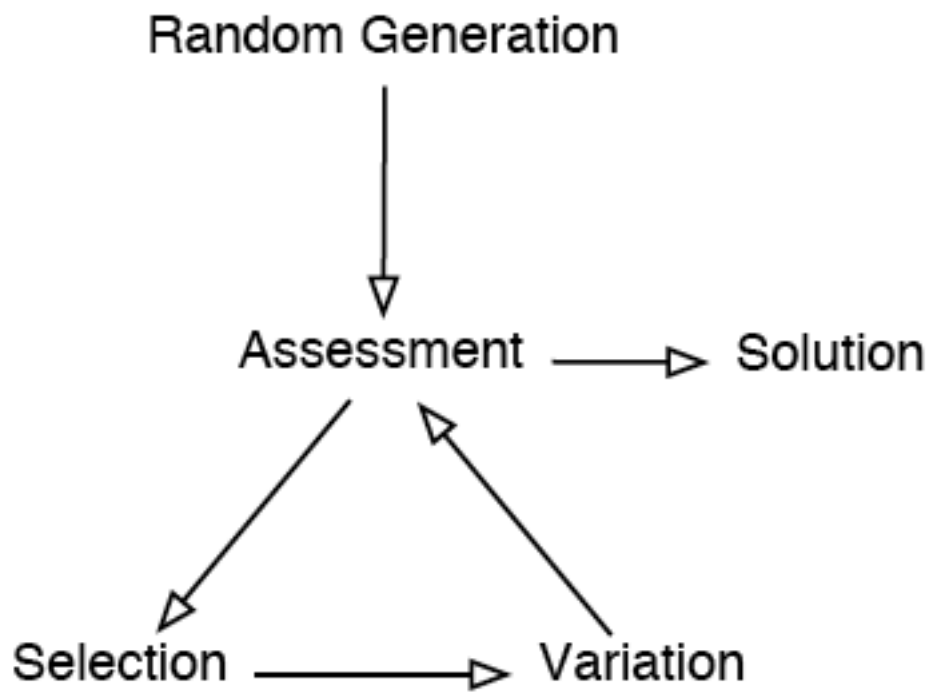
# Tutorial Description (2)

This tutorial will begin by presenting a range of approaches that have been taken for evolving programs in expressive programming languages. Within this context it will then provide a detailed introduction to the Push programming language, which was designed specifically for expressiveness and specifically for use in genetic programming systems. Push programs are syntactically unconstrained but can nonetheless make use of multiple data types and express arbitrary control structures, supporting the evolution of complex, modular programs in a particularly simple and flexible way. The Push language will be described and demonstrated, and over ten years of Push-based research, including the production of human-competitive results, will be briefly surveyed. The tutorial will conclude with a discussion of recent enhancements to Push that are intended to support the evolution of complex and robust software systems.

# Course Agenda

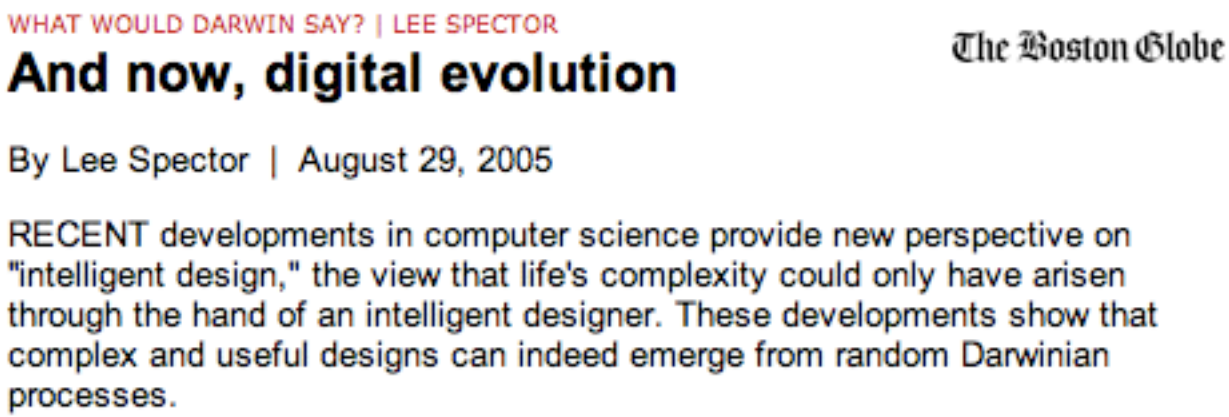
- Genetic Programming
- Evolving programs in expressive languages
- Expressivity, evolvability, and syntactic minimality
- **Push + DEMO**
- Expressing the evolution of expressive evolution

# Evolutionary Computation



# Evolution, the Designer

"Darwinian evolution is itself a designer worthy of significant respect, if not religious devotion." *Boston Globe* OpEd, Aug 29, 2005



WHAT WOULD DARWIN SAY? | LEE SPECTOR

**And now, digital evolution**

The Boston Globe

By Lee Spector | August 29, 2005

RECENT developments in computer science provide new perspective on "intelligent design," the view that life's complexity could only have arisen through the hand of an intelligent designer. These developments show that complex and useful designs can indeed emerge from random Darwinian processes.

# Genetic Programming (GP)

- Evolutionary computing to produce executable computer programs
- Programs are assessed by executing them
- Automatic programming; producing software

# Program Representations

- Lisp-style symbolic expressions (Koza, ...).
- Purely functional/lambda expressions (Walsh, Yu, ...).
- Linear sequences of machine/byte code (Nordin et al., ...).
- Artificial assembly-like languages (Ray, Adami, ...).
- Stack-based languages (Perkis, Spector, Stoffel, Tchernev, ...).
- Graph-structured programs (Teller, Globus, ...).
- Object hierarchies (Bruce, Abbott, Schmutter, Lucas, ...)
- Fuzzy rule systems (Tunstel, Jamshidi, ...)
- Logic programs (Osborn, Charif, Lamas, Dubossarsky, ...).
- Strings, grammar-mapped to arbitrary languages (O'Neill, Ryan, ...).

# Mutating Lisp

```
(+ (* X Y)
   (+ 4 (- Z 23)))

(+ (* X Y)
   (+ 4 (- Z 23)))

(+ (- (+ 2 2) Z)
   (+ 4 (- Z 23)))
```

# Recombining Lisp

Parent 1: `(+ (* X Y)`
`(+ 4 (- Z 23)))`

Parent 2: `(- (* 17 (+ 2 X))`
`(* (- (* 2 Z) 1)`
`(+ 14 (/ Y X))))`

Child 1: `(+ (- (* 2 Z) 1)`
`(+ 4 (- Z 23)))`

Child 2: `(- (* 17 (+ 2 X))`
`(* (* X Y)`
`(+ 14 (/ Y X))))`

# Symbolic Regression

A simple example

Given a set of data points, evolve a program that produces $y$ from $x$.

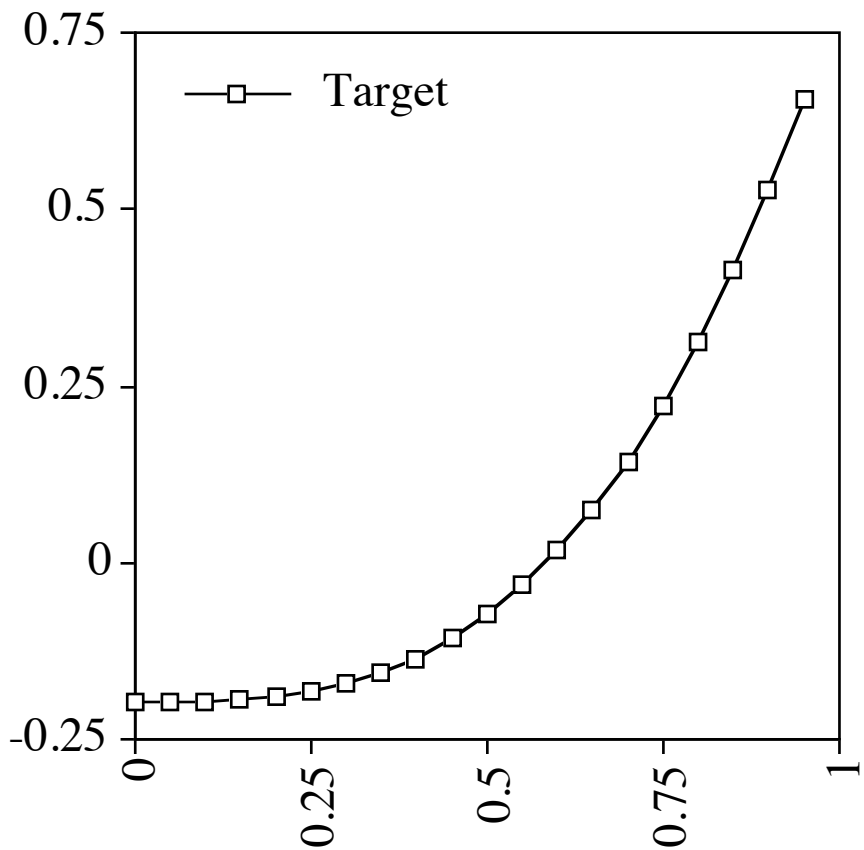
Primordial ooze: +, -, *, %, $x$, 0.1

Fitness = error (smaller is better)

# GP Parameters

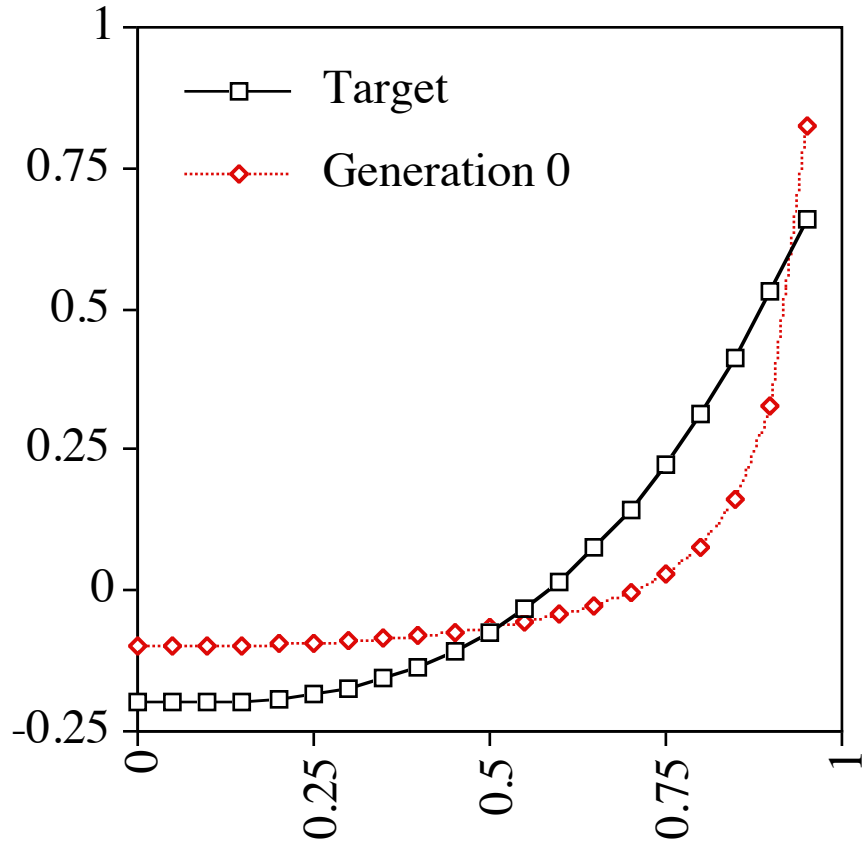
Maximum number of Generations: 51
Size of Population: 1000
Maximum depth of new individuals: 6
Maximum depth of new subtrees for mutants: 4
Maximum depth of individuals after crossover: 17
Fitness-proportionate reproduction fraction: 0.1
Crossover at any point fraction: 0.3
Crossover at function points fraction: 0.5
Selection method: FITNESS-PROPORTIONATE
Generation method:  RAMPED-HALF-AND-HALF
Randomizer seed: 1.2

# Evolving $y = x^3 - 0.2$



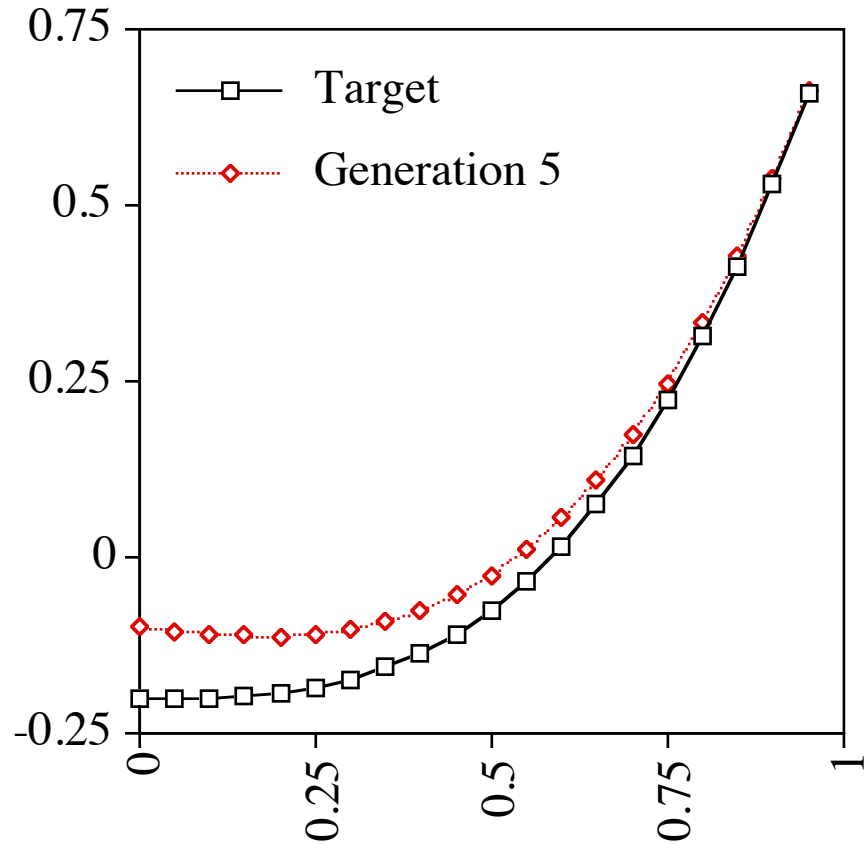
# Best Program, Gen 0

```
(- (% (* 0.1
         (* X X))
      (- (% 0.1 0.1)
         (* X X)))
   0.1)
```



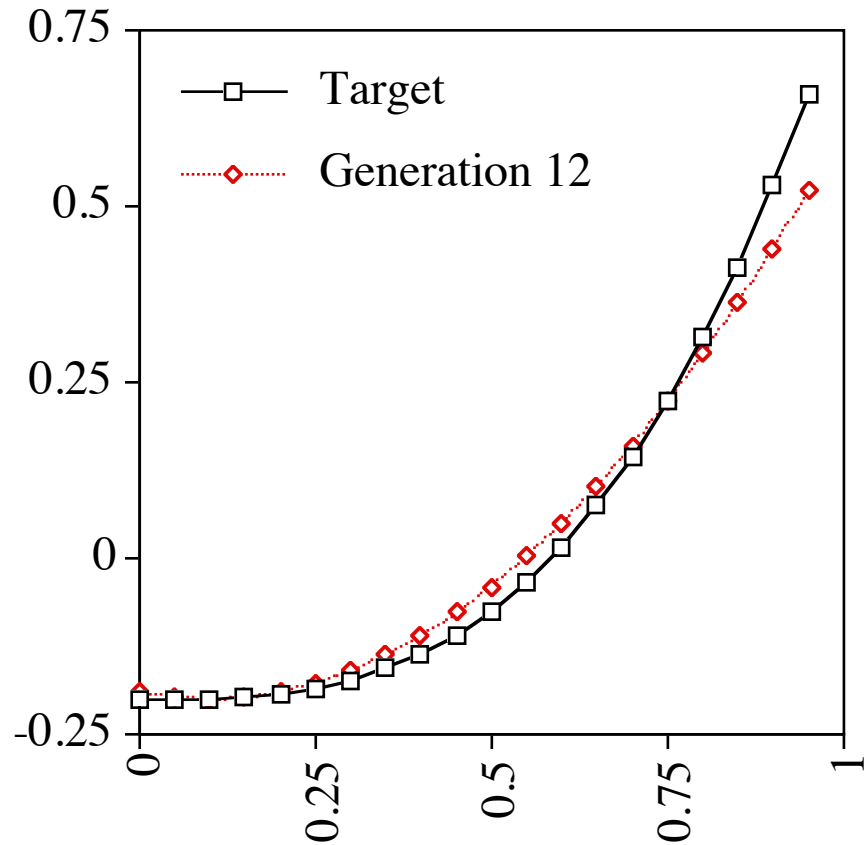
# Best Program, Gen 5

```
(- (* (* (% X 0.1)
         (* 0.1 X))
      (- X
         (% 0.1 X)))
   0.1)
```



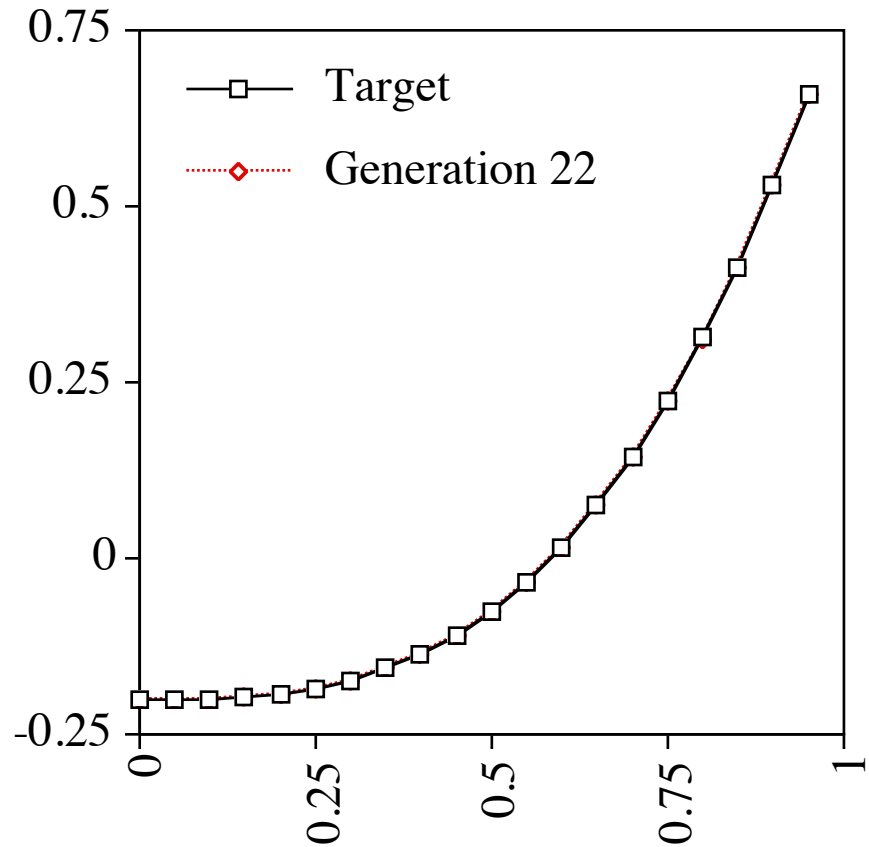
# Best Program, Gen 12

```
(+ (- (- 0.1
         (- 0.1
            (- (* X X)
               (+ 0.1
                  (- 0.1
                     (* 0.1
                        0.1))))))
      (* X
         (* (% 0.1
               (% (* (* (- 0.1 0.1)
                        (+ X
                           (- 0.1 0.1)))
                     X)
                  (+ X (+ (- X 0.1)
                          (* X X)))))
            (+ 0.1 (+ 0.1 X)))))
   (* X X))
```



# Best Program, Gen 22

```
(- (- (* X (* X X))
      0.1)
   0.1)
```



# Expressiveness

- Turing machine tables
- Lambda calculus expressions
- Partial recursive functions
- Register machine programs
- Assembly language programs
- etc.

# Evolvability

The fact that a computation *can* be expressed in a formalism does not imply that a correct expression can be produced in that formalism by a human programmer or by an evolutionary process.

# Data/Control Structure

- Data abstraction and organization

  Data types, variables, name spaces, data structures, ...

- Control abstraction and organization

  Conditionals, loops, modules, threads, ...

# Structure via GP (1)

- Specialize GP techniques to directly support human programming language abstractions
- Strongly typed genetic programming
- Module acquisition/encapsulation systems
- Automatically defined functions
- Automatically defined macros
- Architecture altering operations

# Evolving Modular Programs

## With "automatically defined functions"

- All programs in the population have the same, pre-specified architecture
- Genetic operators respect that architecture
- Significant implementation costs
- Significant pre-specification
- Architecture-altering operations: more power and higher costs

# ADMs

- Macros implement control structures
- ADMs can be implemented via small tweaks to any system that supports ADFs
- Similar pros and cons to ADFs, but provide additional expressive power

# Control Structures (1)

Multiple evaluation

```
(defmacro do-twice (code)
`(progn ,code ,code))

(do-twice (incf x))
```

# Control Structures (2)

Conditional evaluation

```
(defmacro numeric-if (exp neg zero pos)
  `(if (< ,exp 0)
   ,neg
   (if (< 0 ,exp) ,pos ,zero)))

(numeric-if (foo) (bar) (baz) (bix))
```

# Structure via GP (2)

- Specialize GP techniques to **indirectly** support human programming language abstractions
- Map from unstructured genomes to programs in languages that support abstraction (e.g. via grammars)

# Structure via GP (3)

- Evolve programs in a minimal-syntax language that nonetheless supports a full range of data and control abstractions
- For example: orchestrate data flows via stacks, not via syntax
- Minimal syntax + maximal semantics
- **Push**

# Push

- Designed for program evolution
- Data flows via stacks, not syntax
- One stack per type:
  integer, float, boolean, string, code, exec, vector, ...
- Minimal syntax:
  program → instruction | literal | ( program* )
- Missing argument? NOOP

# Why Push?

- Highly expressive: data types, data structures, variables, conditionals, loops, recursion, modules, ...
- Elegant: minimal syntax and a simple, stack-based execution architecture
- Extensible
- Supports uniform variation
- Supports several forms of meta-evolution

# Plush

| Instruction | integer_eq | exec_dup | char_swap | integer_add | exec_if |
|---|---|---|---|---|---|
| Close? | 2 | 0 | 0 | 0 | 1 |
| Silence? | 1 | 0 | 0 | 1 | 0 |

# Sample Push Instructions

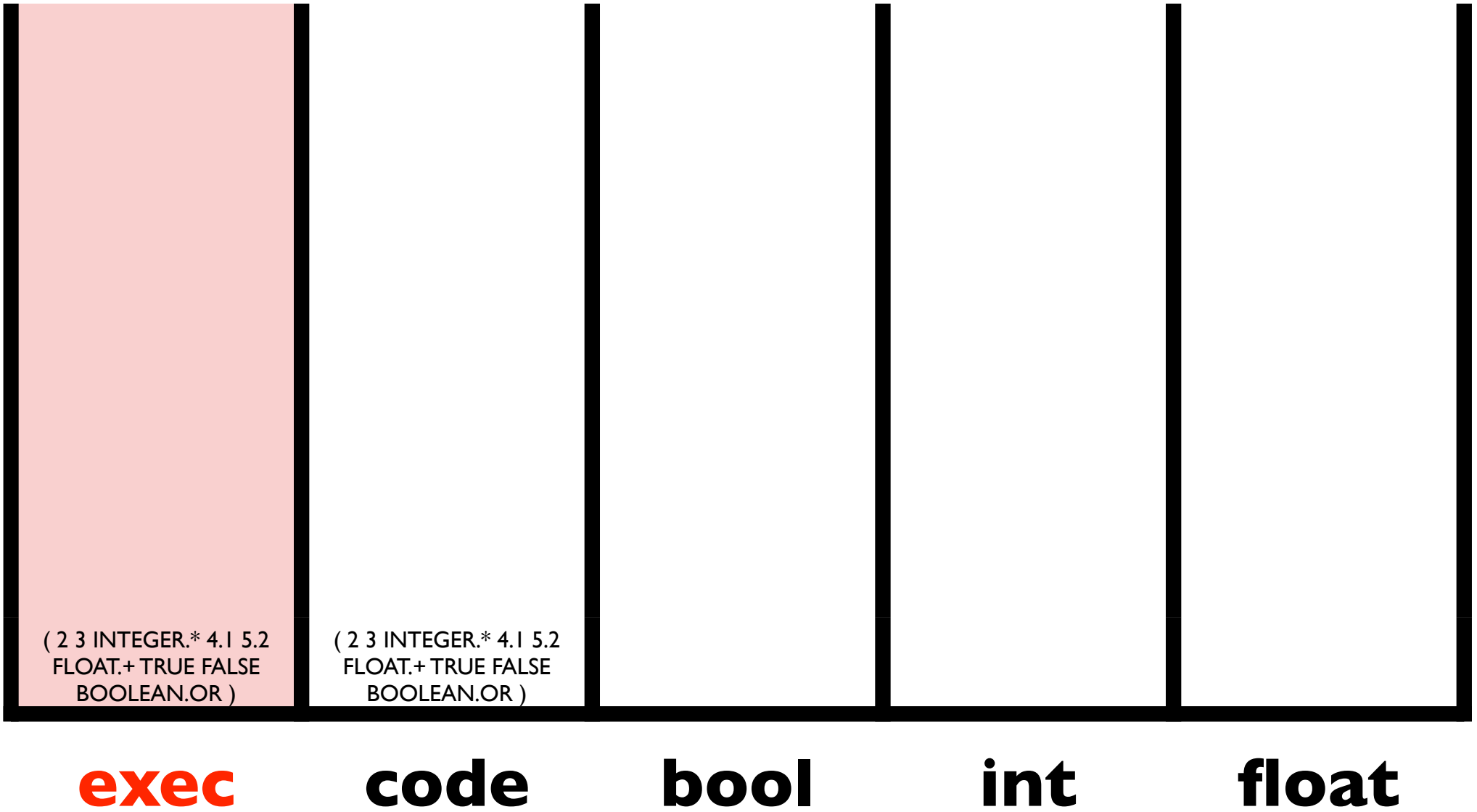
| | |
|---|---|
| Stack manipulation instructions (all types) | POP, SWAP, YANK, DUP, STACKDEPTH, SHOVE, FLUSH, = |
| Math (INTEGER and FLOAT) | +, −, /, *, >, <, MIN, MAX |
| Logic (BOOLEAN) | AND, OR, NOT, FROMINTEGER |
| Code manipulation (CODE) | QUOTE, CAR, CDR, CONS, INSERT, LENGTH, LIST, MEMBER, NTH, EXTRACT |
| Control manipulation (CODE and EXEC) | DO*, DO*COUNT, DO*RANGE, DO*TIMES, IF |

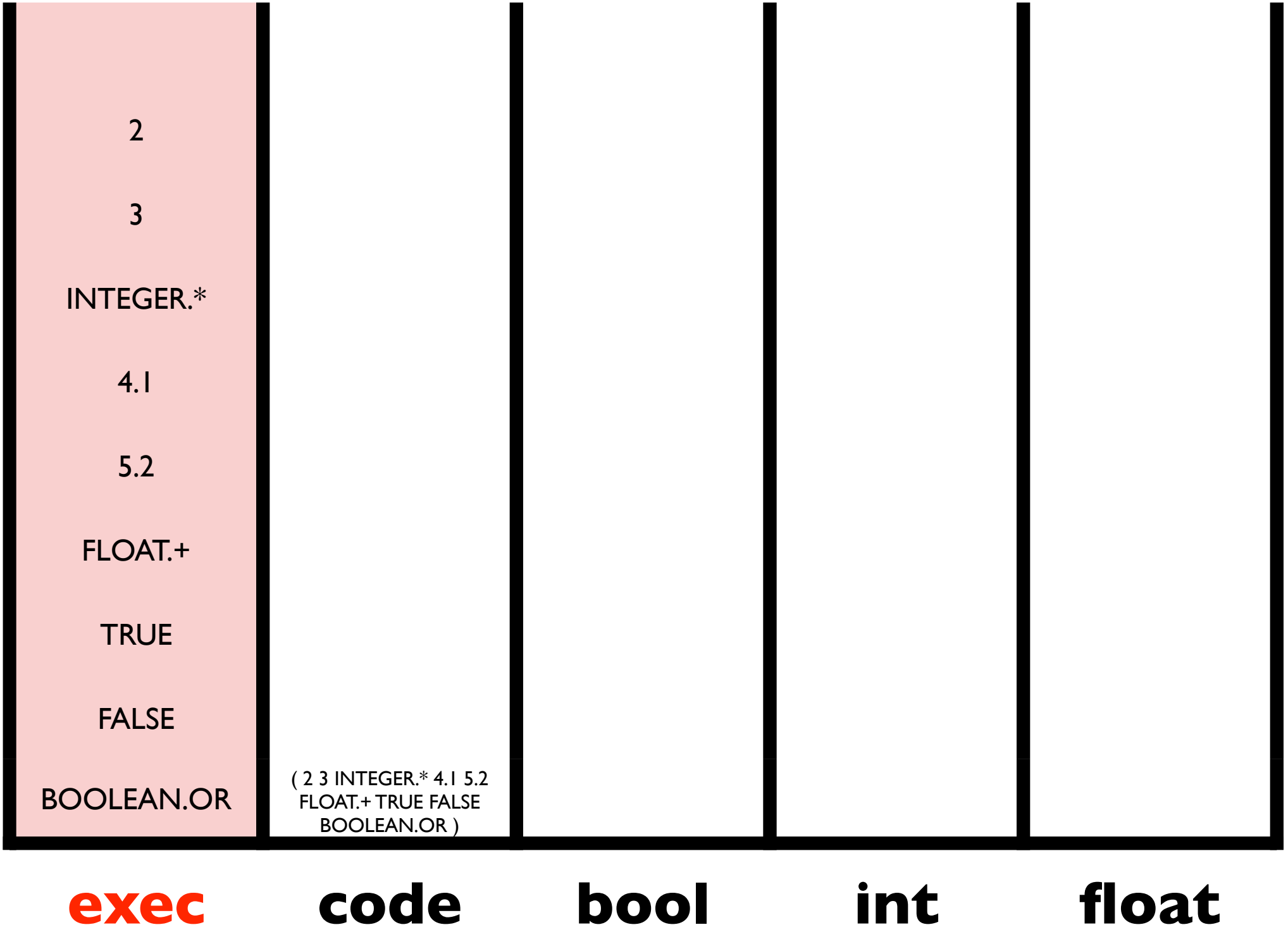
# Push(3) Semantics

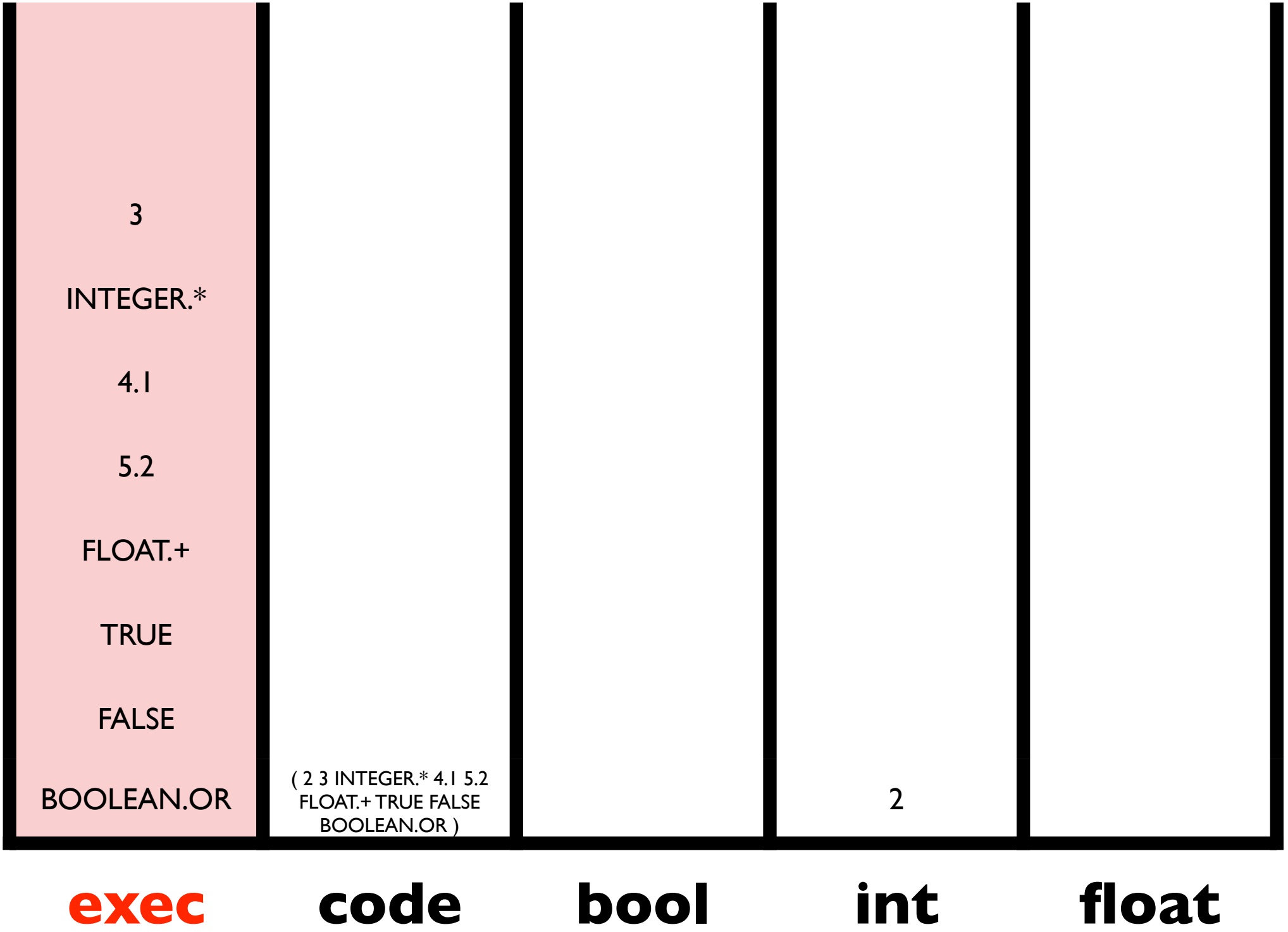
- To execute program $P$:

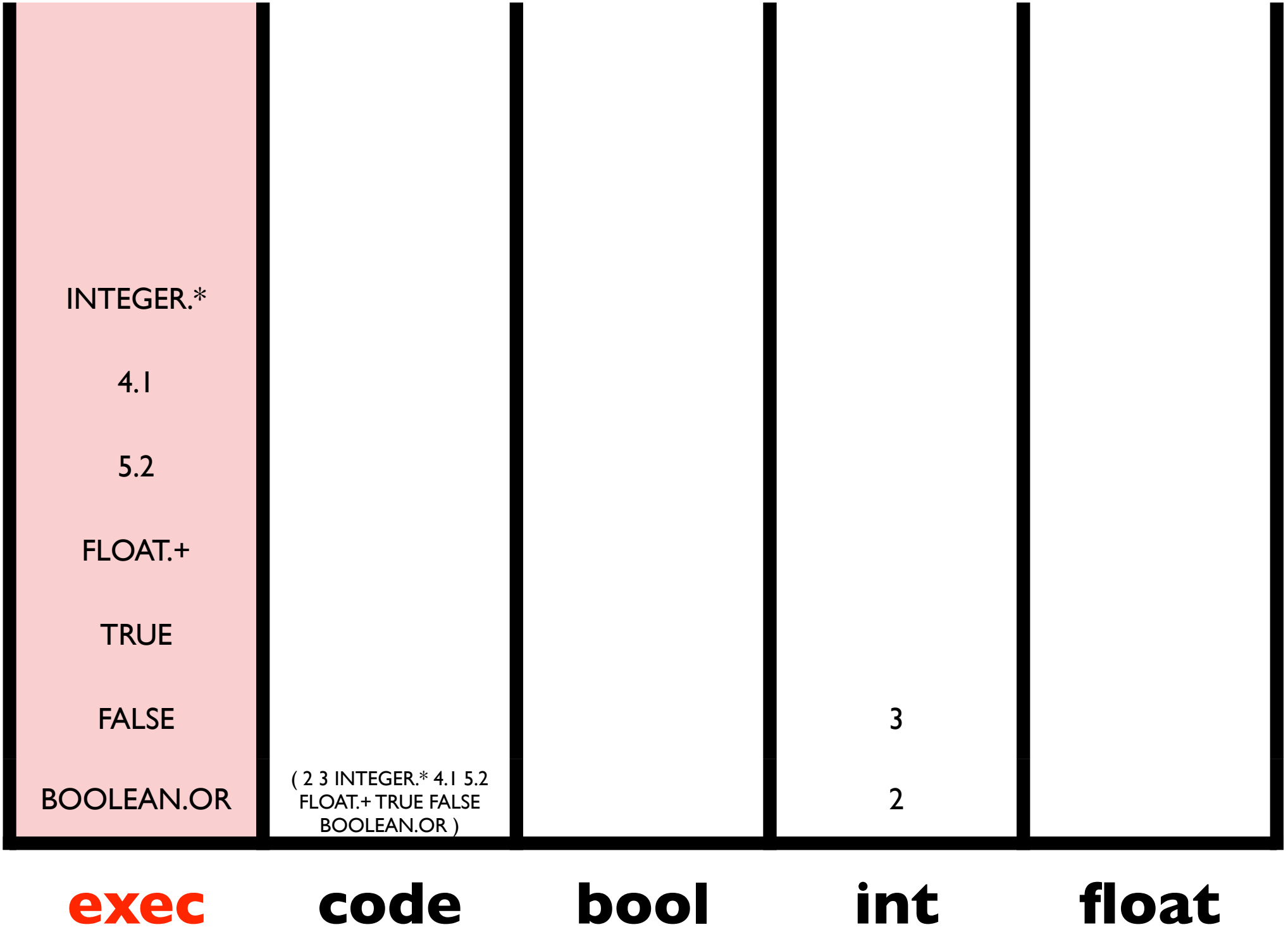
  1. Push $P$ onto the `EXEC` stack.
  2. While the `EXEC` stack is not empty, pop and process the top element of the `EXEC` stack, $E$:
     (a) If $E$ is an instruction: execute $E$ (accessing whatever stacks are required).
     (b) If $E$ is a literal: push $E$ onto the appropriate stack.
     (c) If $E$ is a list: push each element of $E$ onto the `EXEC` stack, in reverse order.

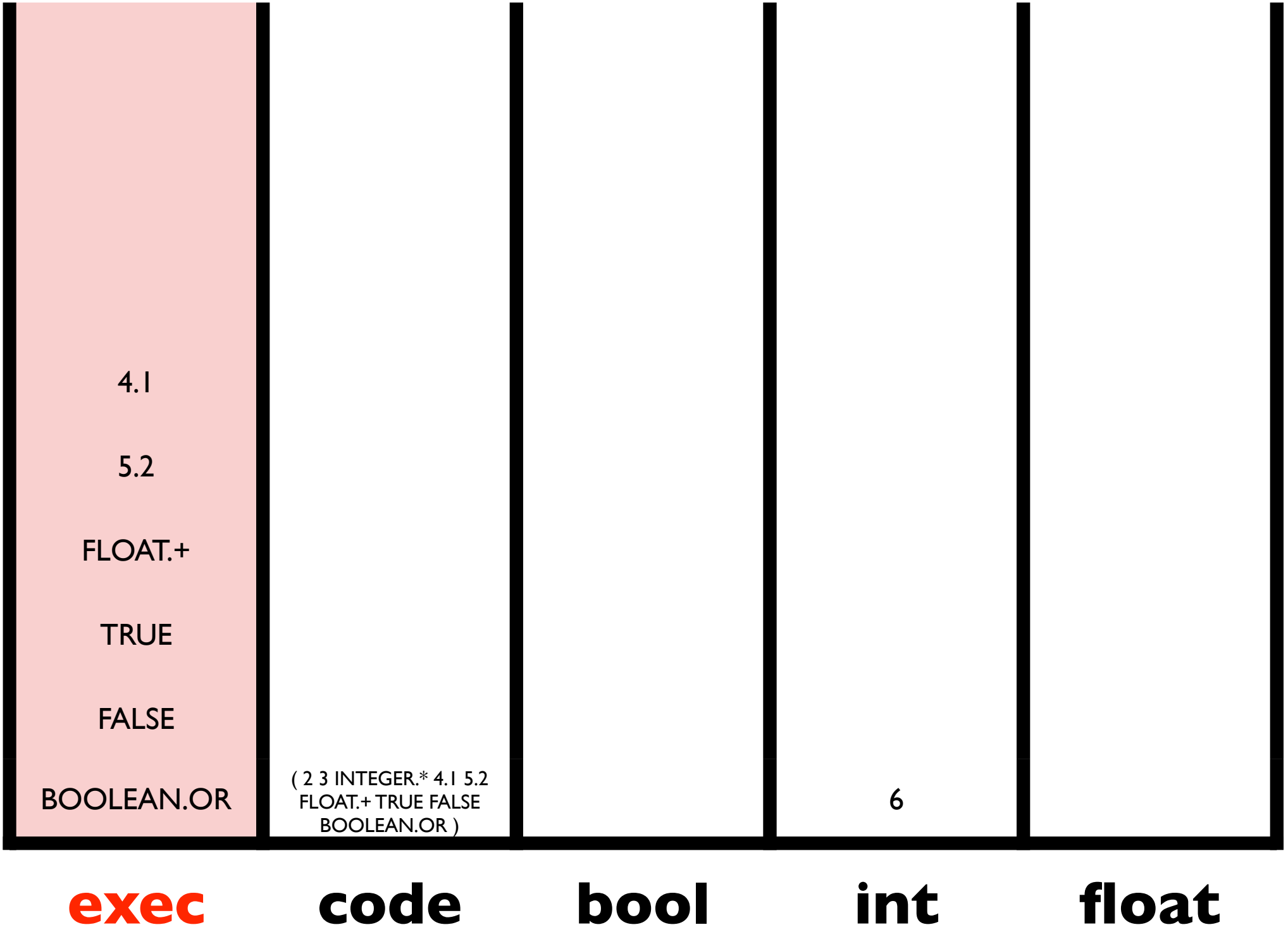
```
( 2 3 INTEGER.* 4.1 5.2 FLOAT.+
TRUE FALSE BOOLEAN.OR )
```

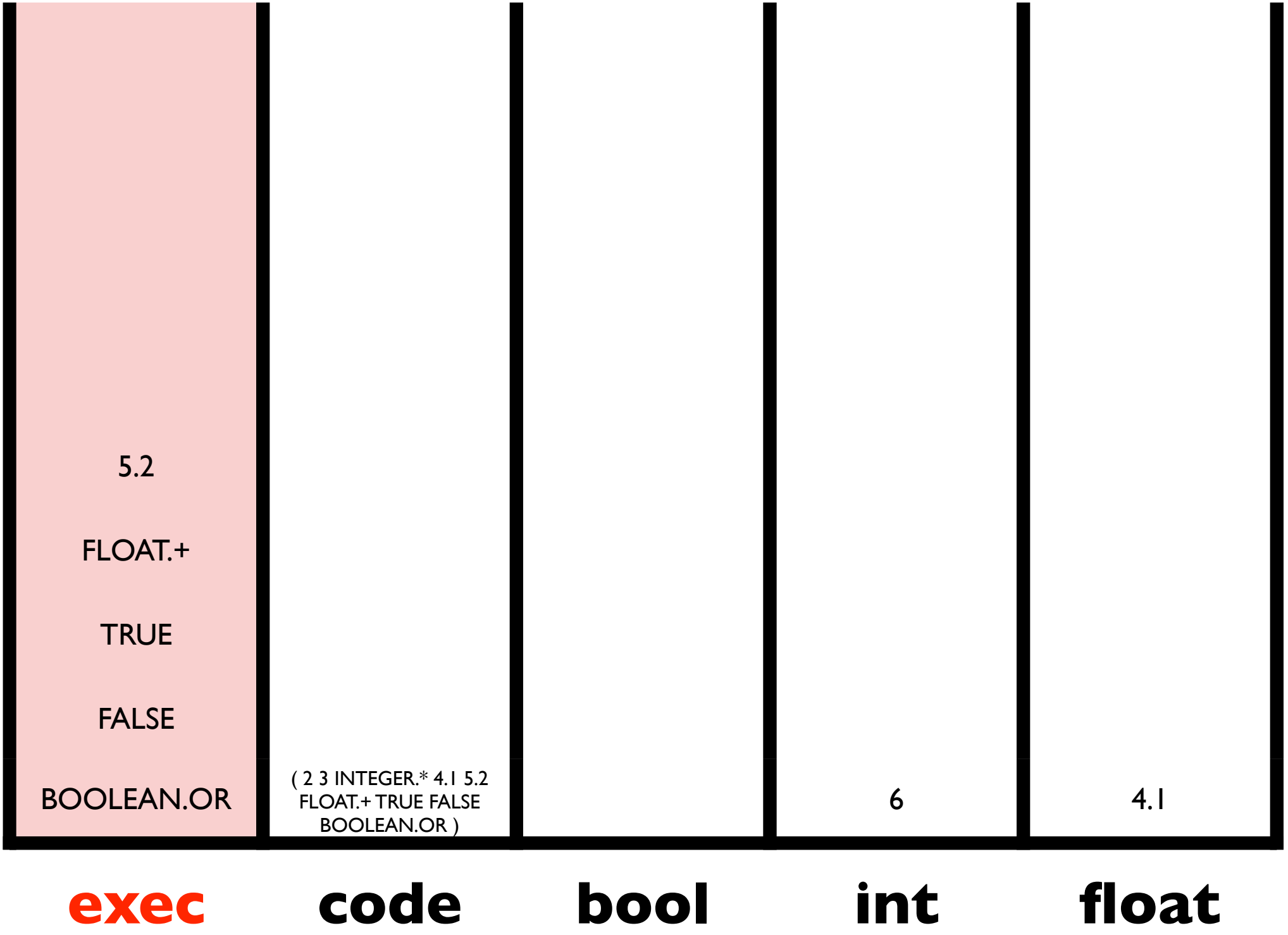


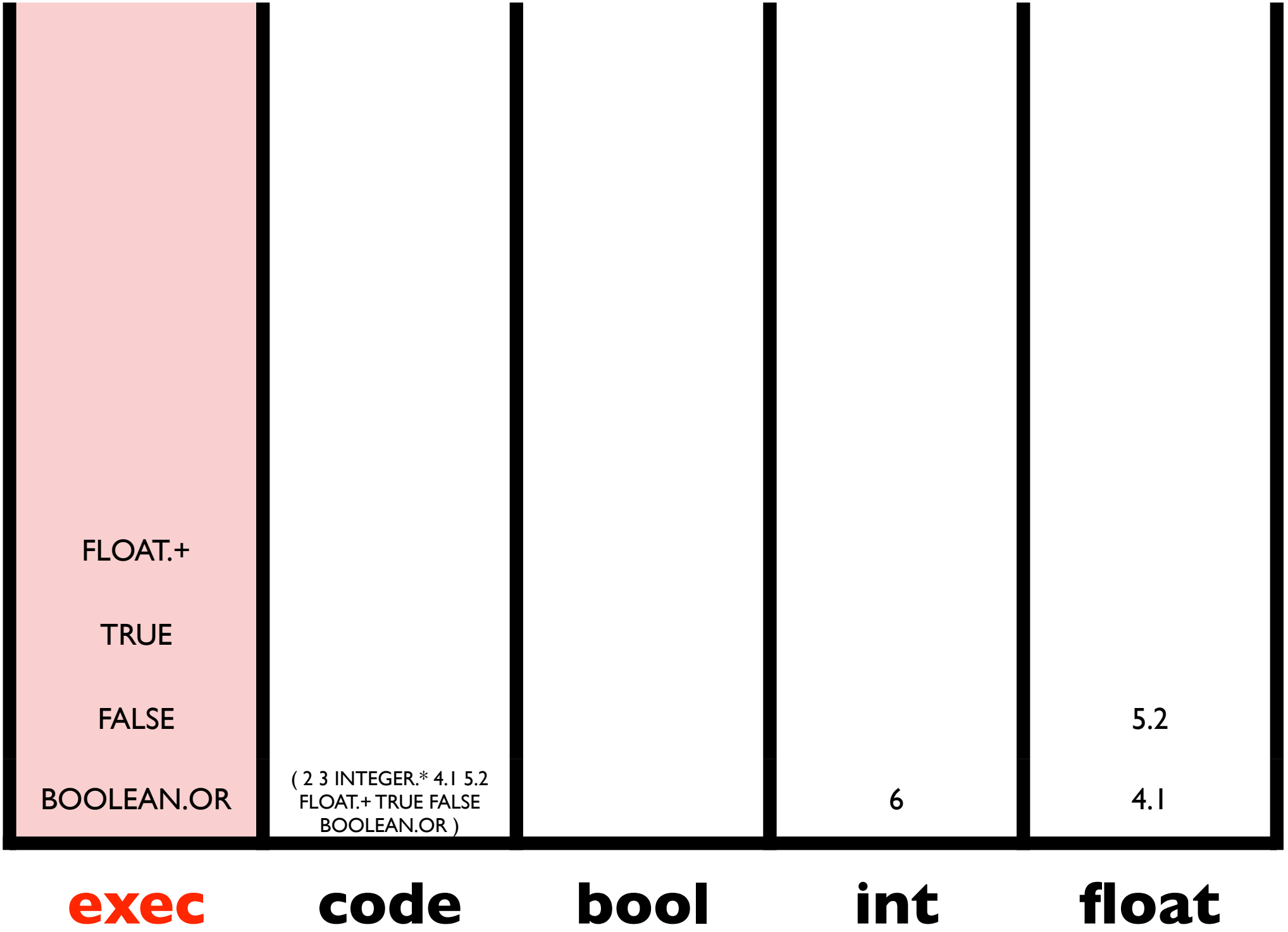

2
3
INTEGER.*
4.1
5.2
FLOAT.+
TRUE
FALSE
BOOLEAN.OR
( 2 3 INTEGER.* 4.1 5.2 FLOAT.+ TRUE FALSE BOOLEAN.OR )
exec
code
bool
int
float

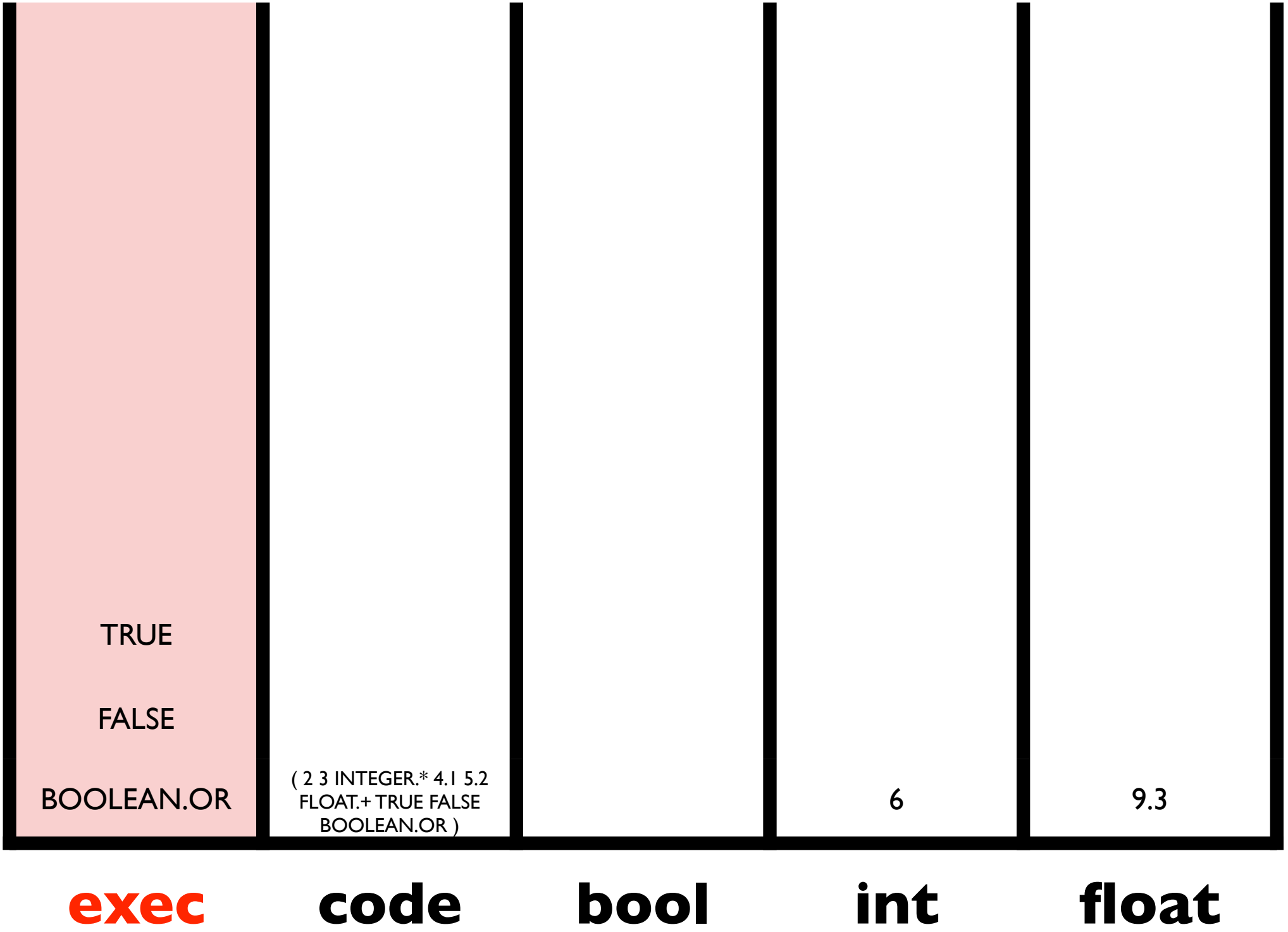

3
INTEGER.*
4.1
5.2
FLOAT.+
TRUE
FALSE
BOOLEAN.OR
( 2 3 INTEGER.* 4.1 5.2 FLOAT.+ TRUE FALSE BOOLEAN.OR )
2
exec
code
bool
int
float

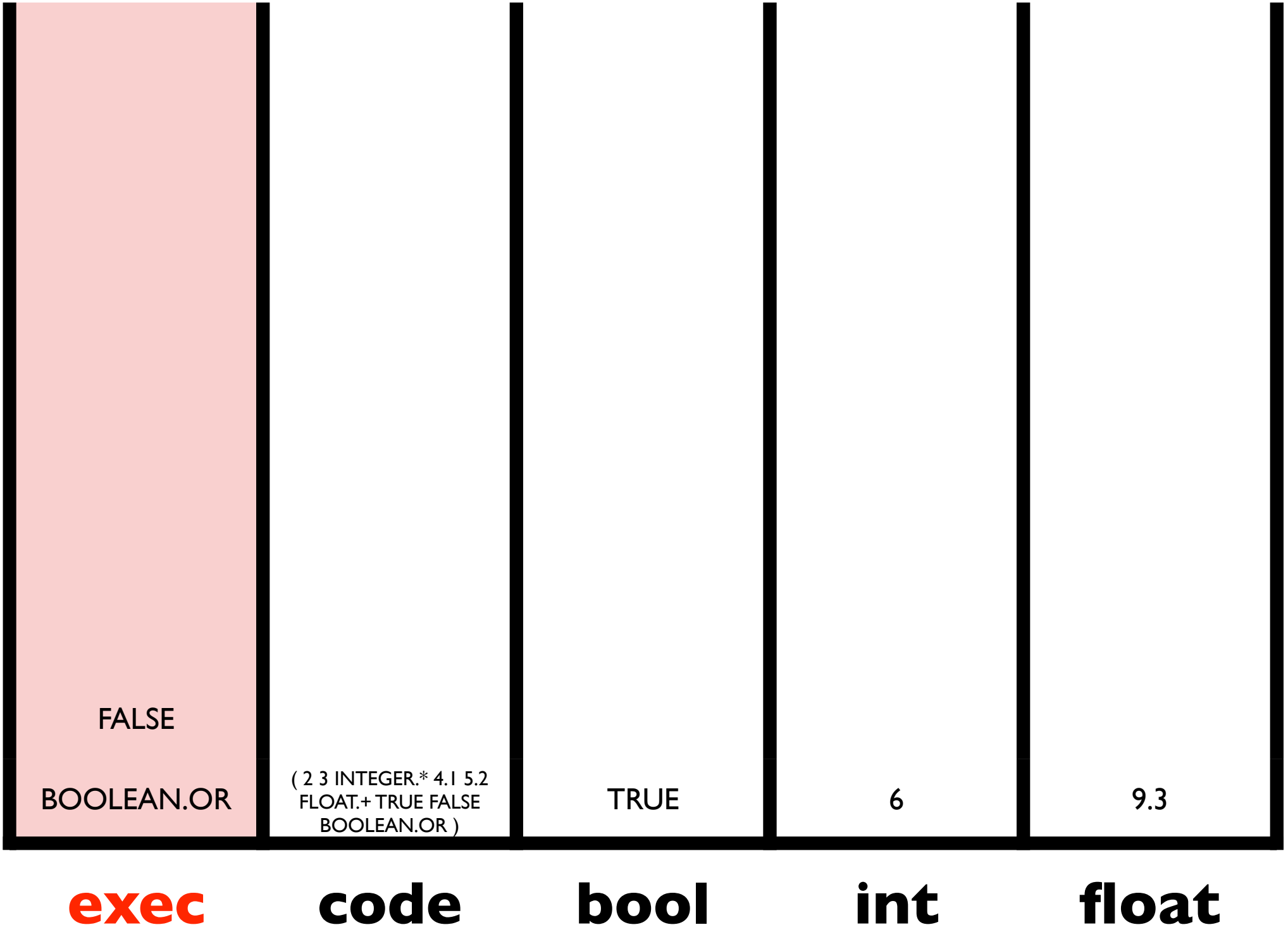

INTEGER.*
4.1
5.2
FLOAT.+
TRUE
FALSE
BOOLEAN.OR
( 2 3 INTEGER.* 4.1 5.2 FLOAT.+ TRUE FALSE BOOLEAN.OR )
3
2
exec
code
bool
int
float

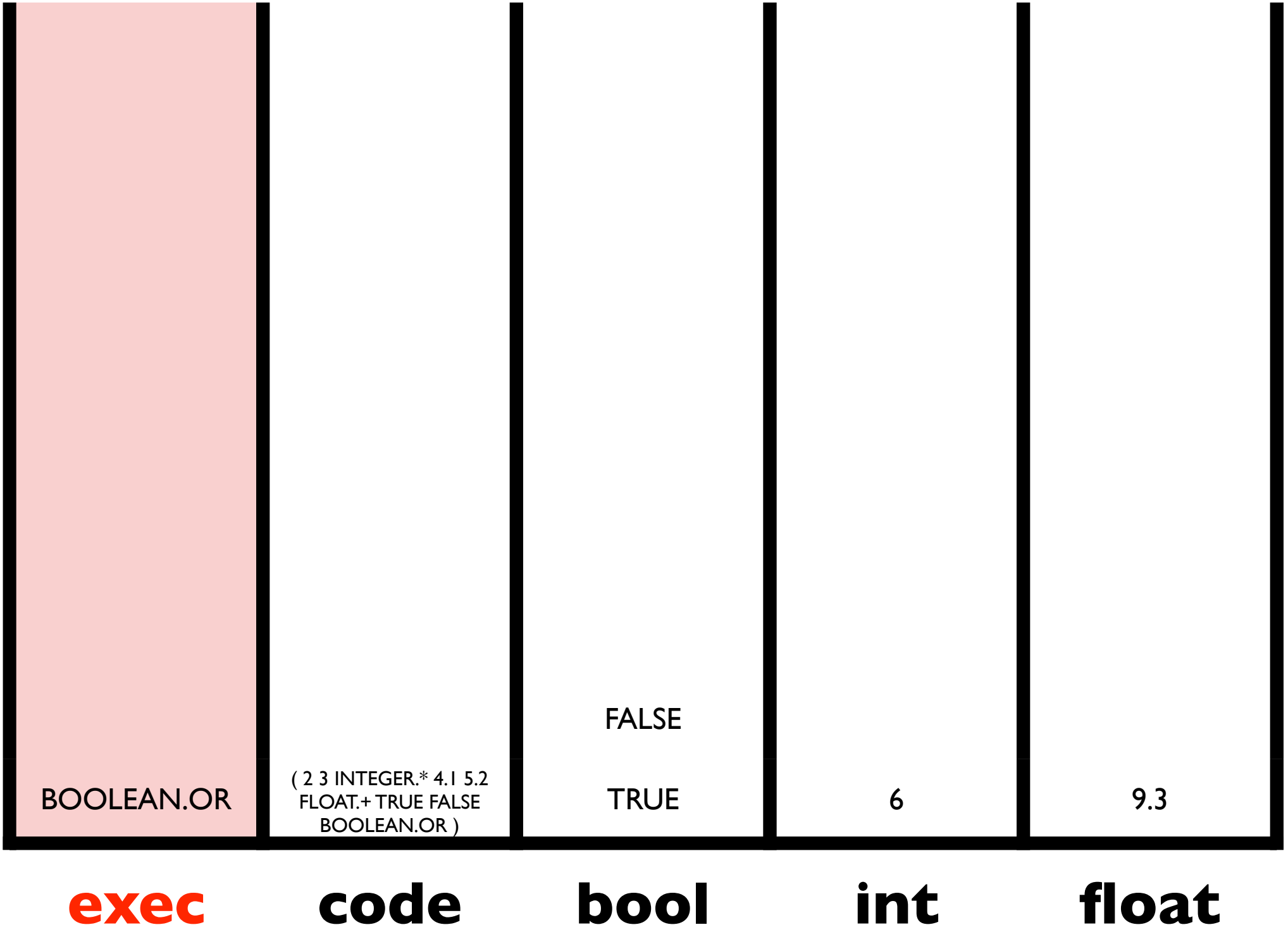

4.1
5.2
FLOAT.+
TRUE
FALSE
BOOLEAN.OR
( 2 3 INTEGER.* 4.1 5.2 FLOAT.+ TRUE FALSE BOOLEAN.OR )
6
exec
code
bool
int
float

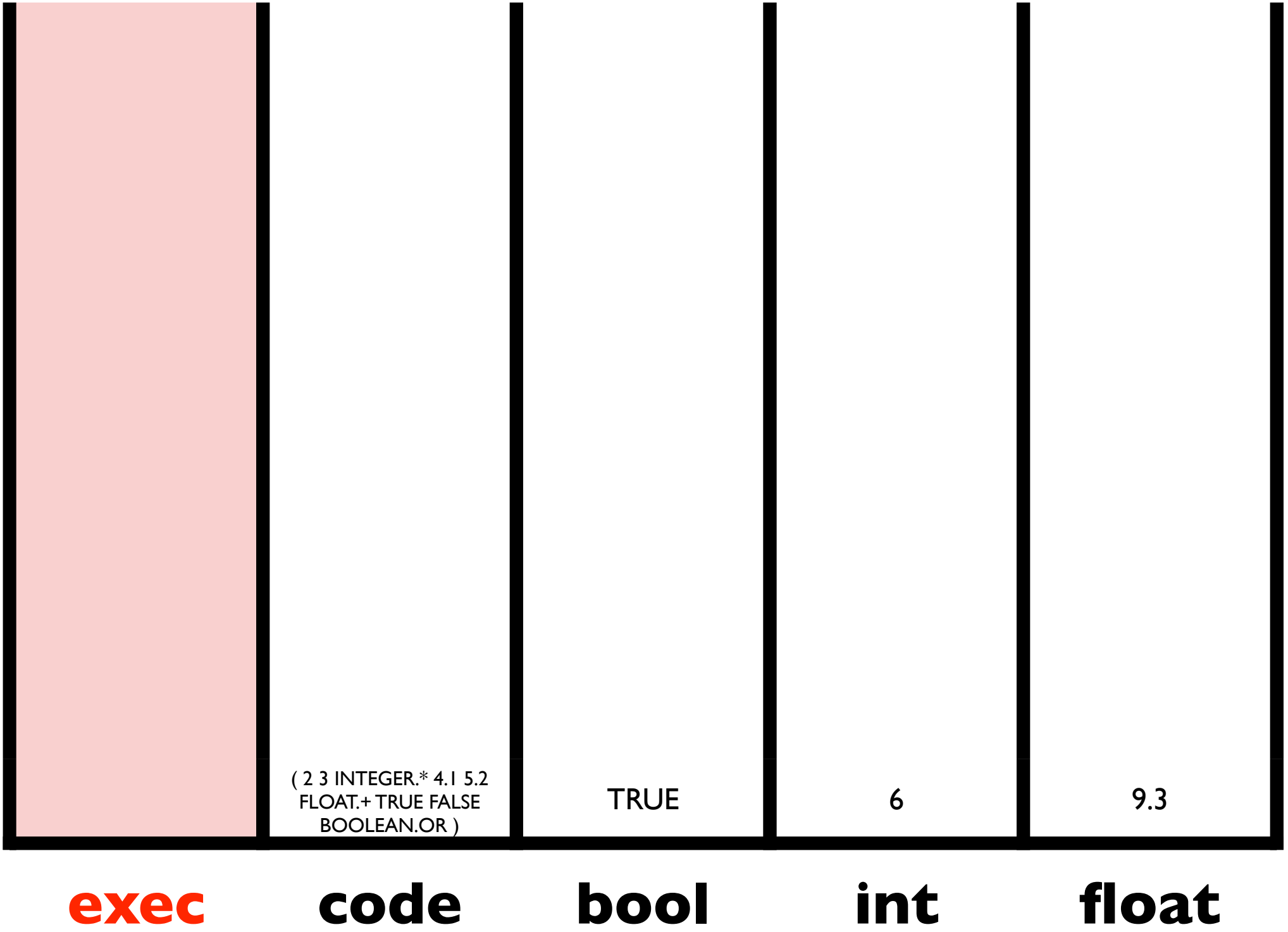

5.2
FLOAT.+
TRUE
FALSE
BOOLEAN.OR
( 2 3 INTEGER.* 4.1 5.2 FLOAT.+ TRUE FALSE BOOLEAN.OR )
6
4.1
exec
code
bool
int
float


FLOAT.+
TRUE
FALSE
BOOLEAN.OR
( 2 3 INTEGER.* 4.1 5.2 FLOAT.+ TRUE FALSE BOOLEAN.OR )
6
5.2
4.1
exec
code
bool
int
float


TRUE
FALSE
BOOLEAN.OR
( 2 3 INTEGER.* 4.1 5.2 FLOAT.+ TRUE FALSE BOOLEAN.OR )
6
9.3
exec
code
bool
int
float


FALSE
BOOLEAN.OR
( 2 3 INTEGER.* 4.1 5.2 FLOAT.+ TRUE FALSE BOOLEAN.OR )
TRUE
6
9.3
exec
code
bool
int
float


BOOLEAN.OR
( 2 3 INTEGER.* 4.1 5.2 FLOAT.+ TRUE FALSE BOOLEAN.OR )
FALSE
TRUE
6
9.3
exec
code
bool
int
float


( 2 3 INTEGER.* 4.1 5.2
FLOAT.+ TRUE FALSE
BOOLEAN.OR )
TRUE
6
9.3
exec
code
bool
int
float

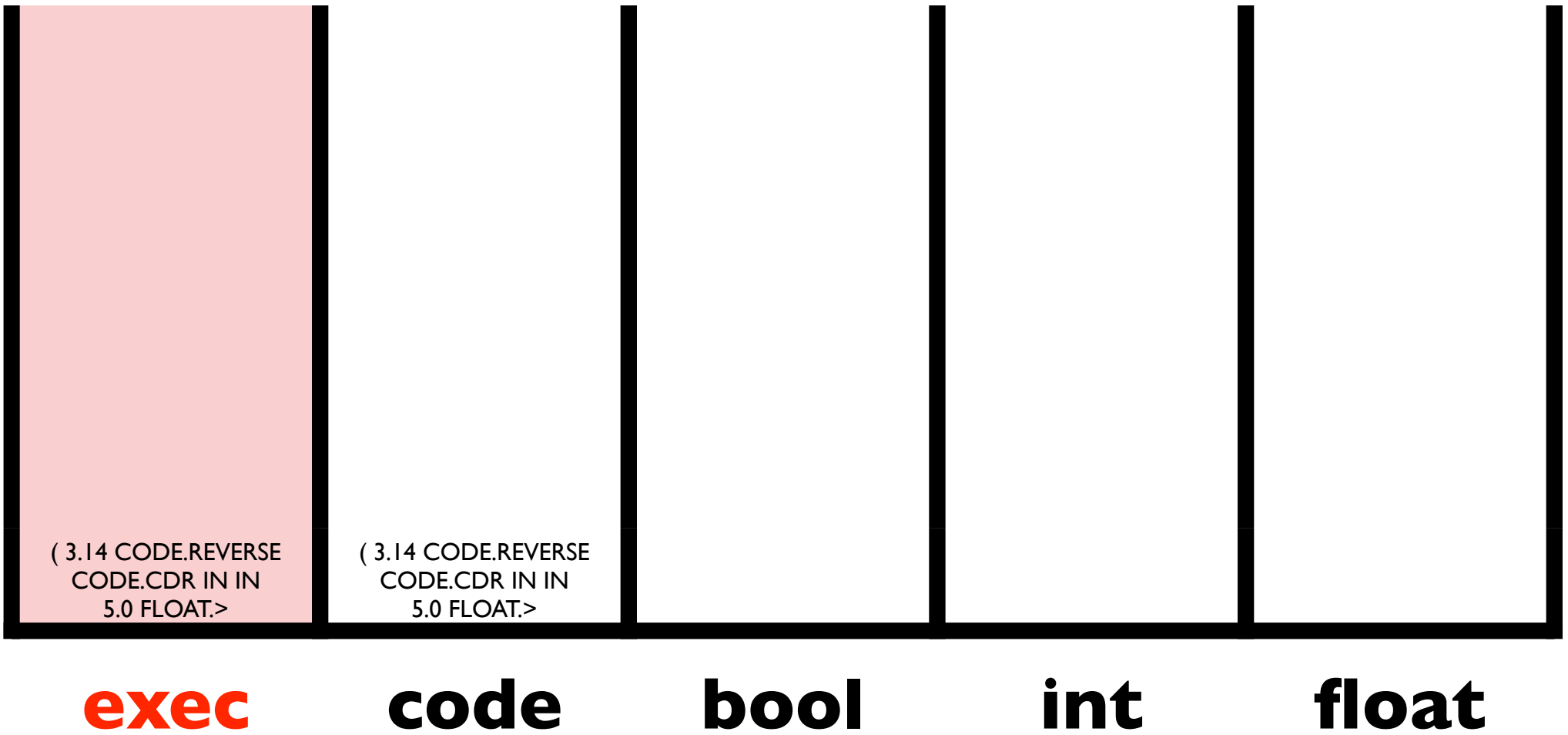
# Same Results

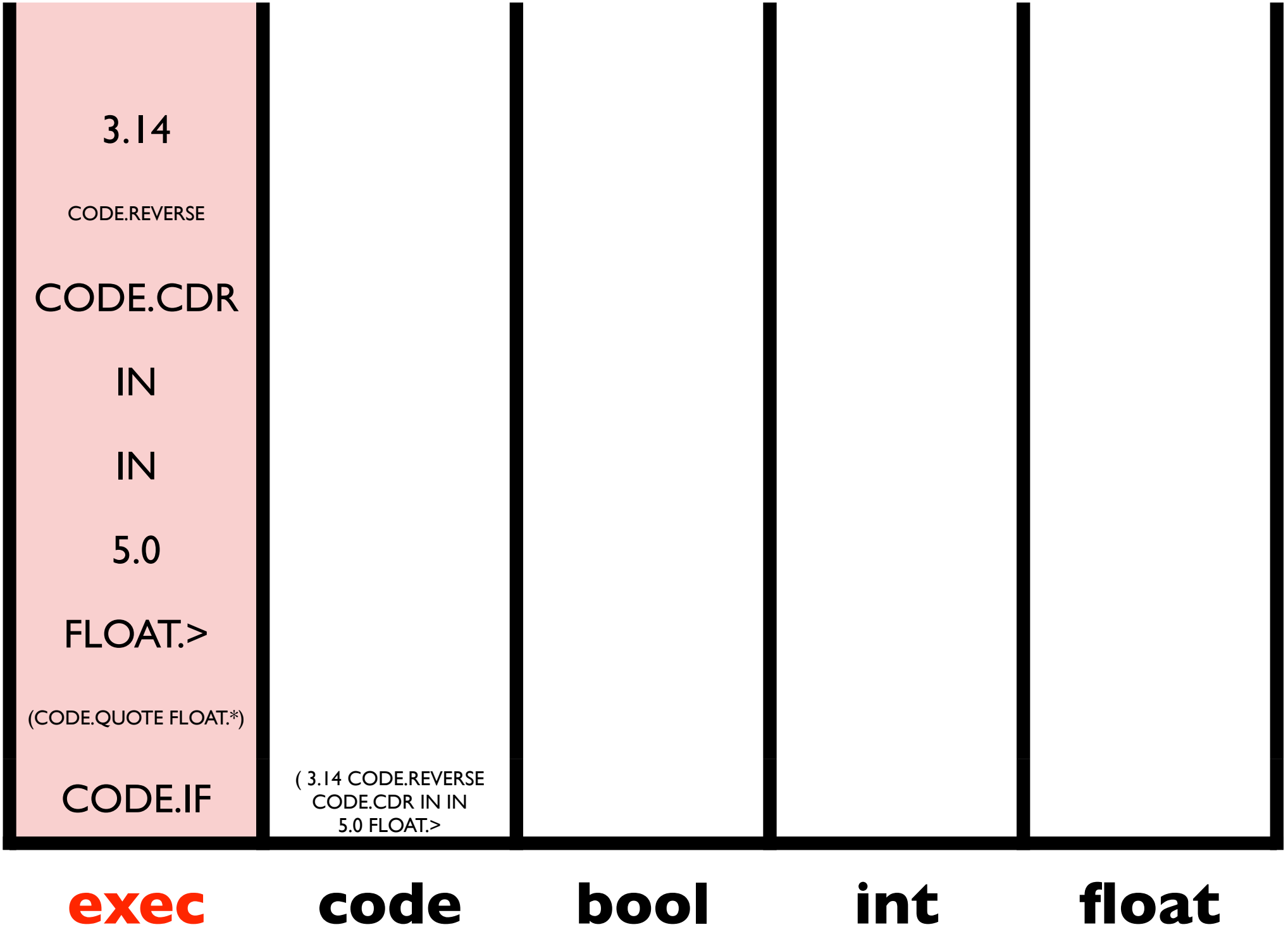
```
( 2 3 INTEGER.* 4.1 5.2 FLOAT.+
    TRUE FALSE BOOLEAN.OR )
```

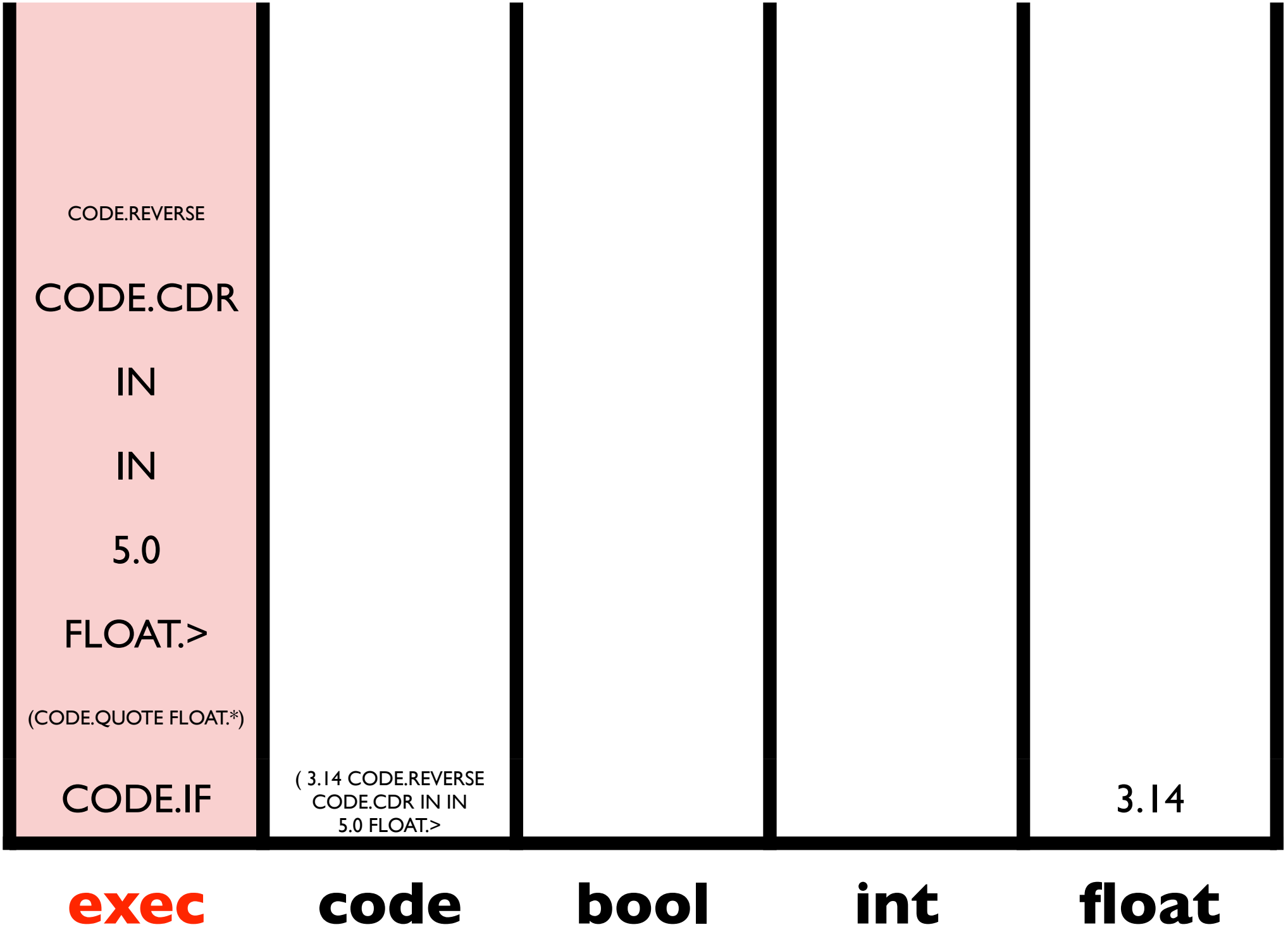
```
( 2 BOOLEAN.AND 4.1 TRUE INTEGER./ FALSE
  3 5.2 BOOLEAN.OR INTEGER.* FLOAT.+ )
```

```
( 3.14 CODE.REVERSE CODE.CDR IN IN 5.0
FLOAT.> (CODE.QUOTE FLOAT.*) CODE.IF )
```

IN=4.0




3.14
CODE.REVERSE
CODE.CDR
IN
IN
5.0
FLOAT.>
(CODE.QUOTE FLOAT.*)
CODE.IF
( 3.14 CODE.REVERSE
CODE.CDR IN IN
5.0 FLOAT.>
exec
code
bool
int
float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CODE.CDR
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5.0
FLOAT.>
(CODE.QUOTE FLOAT.*)
CODE.IF
( 3.14 CODE.REVERSE CODE.CDR IN IN 5.0 FLOAT.>
3.14
exec
code
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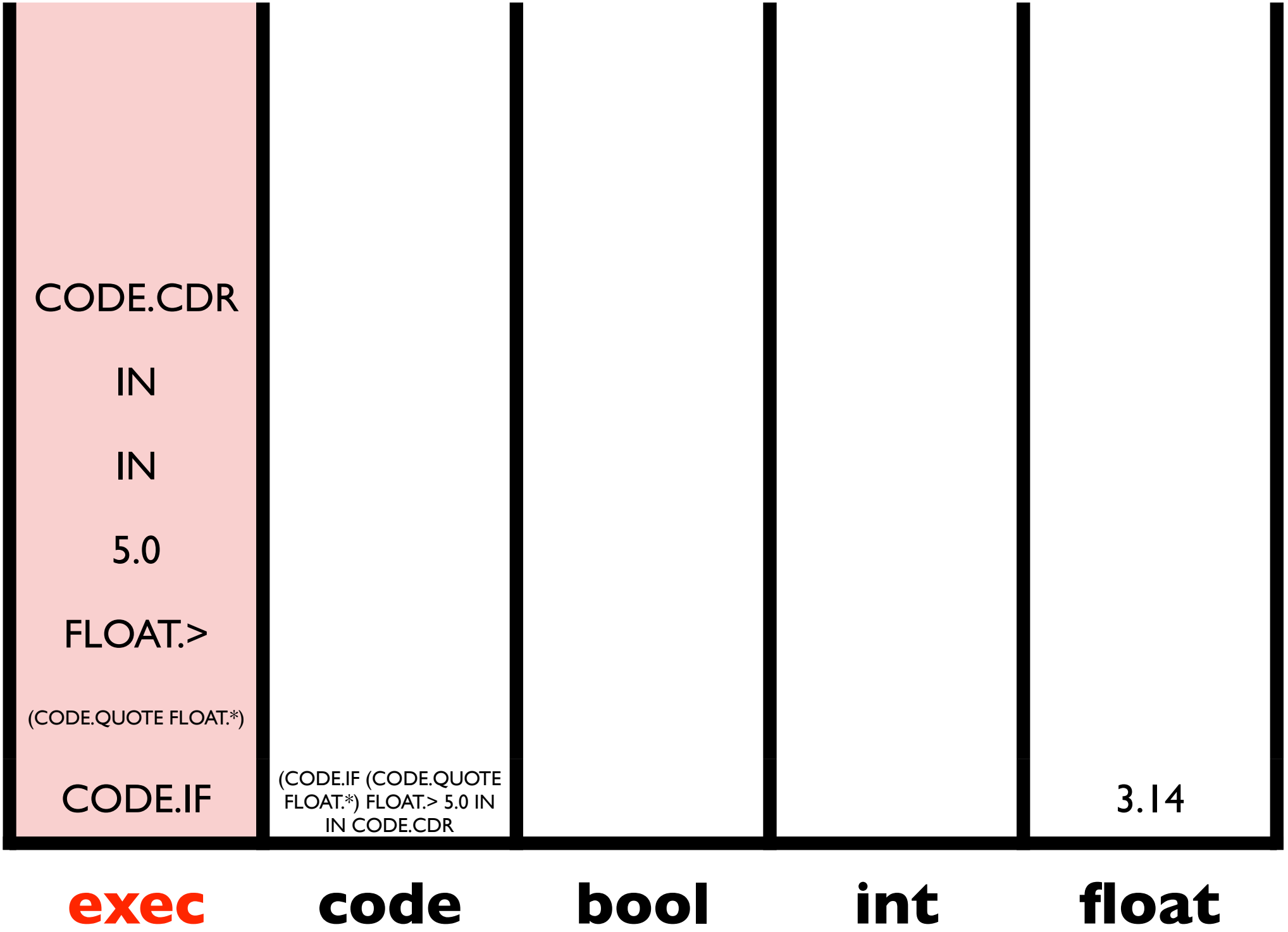
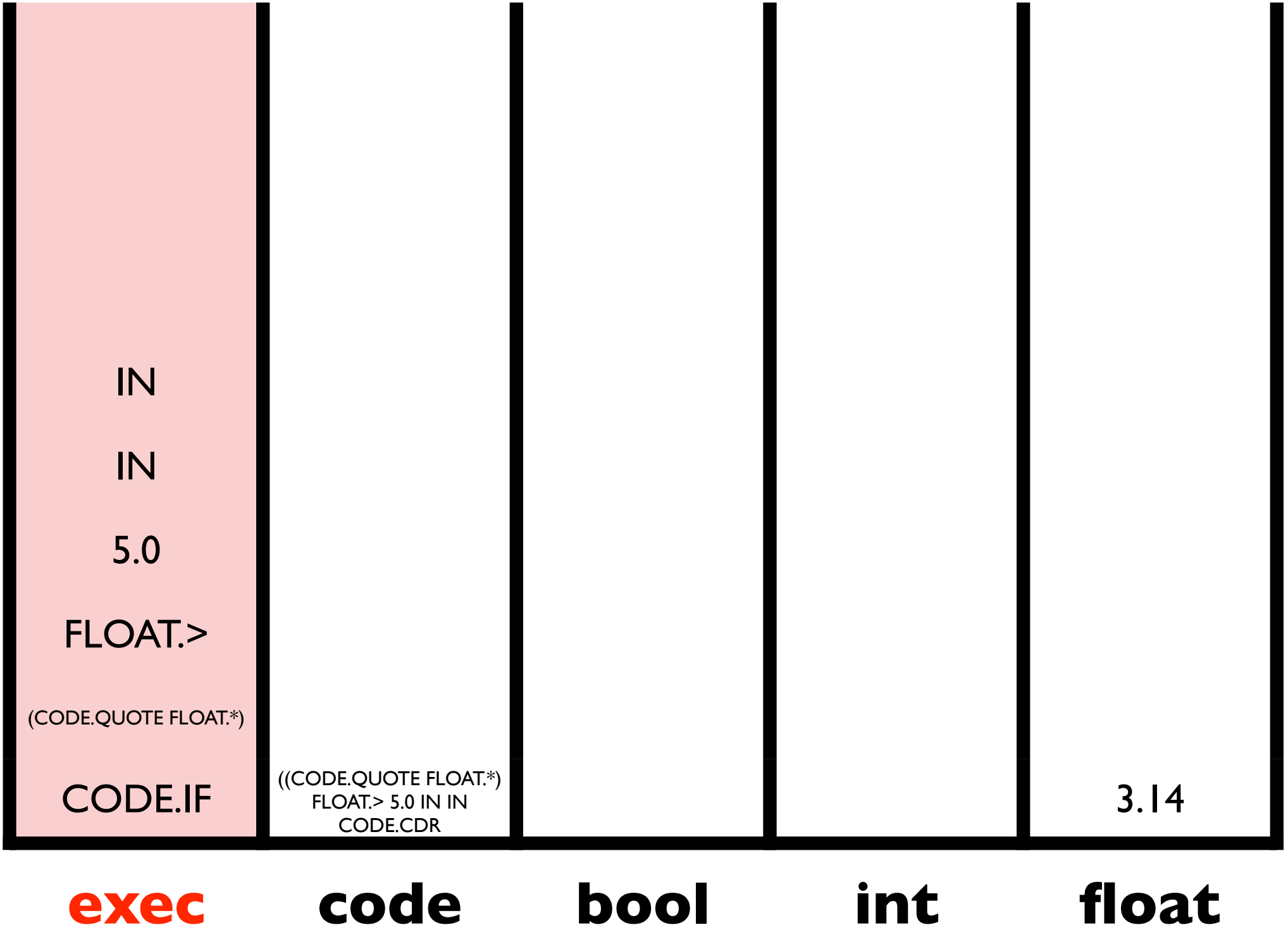

CODE.CDR
IN
IN
5.0
FLOAT.>
(CODE.QUOTE FLOAT.*)
CODE.IF
(CODE.IF (CODE.QUOTE FLOAT.*) FLOAT.> 5.0 IN IN CODE.CDR
3.14
exec
code
bool
int
float


IN
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FLOAT.>
(CODE.QUOTE FLOAT.*)
CODE.IF
((CODE.QUOTE FLOAT.*) FLOAT.> 5.0 IN IN CODE.CDR
3.14
exec
code
bool
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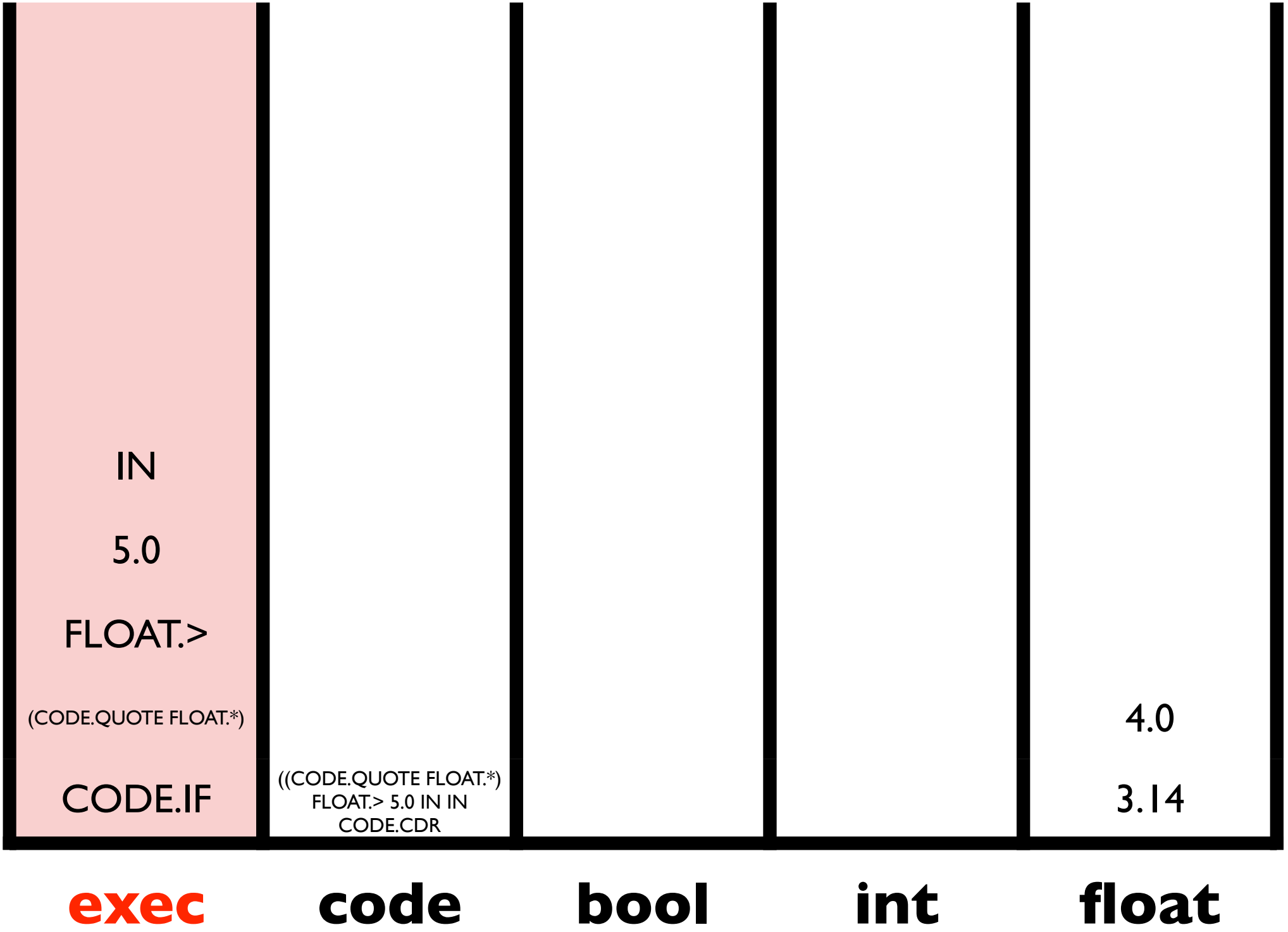
float


IN
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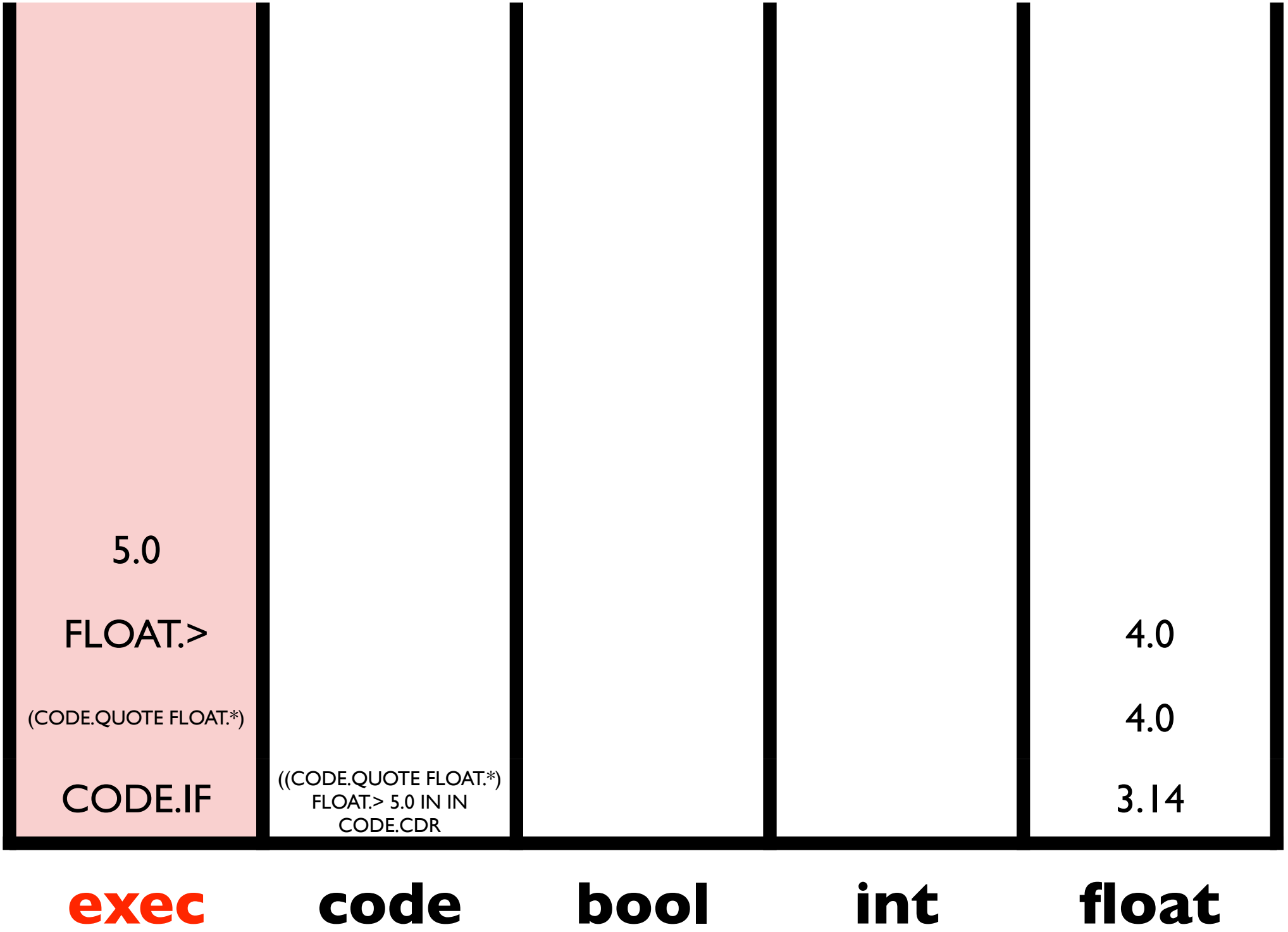
4.0
3.14
exec
code
bool
int
float


5.0
FLOAT.>
(CODE.QUOTE FLOAT.*)
CODE.IF
((CODE.QUOTE FLOAT.*) FLOAT.> 5.0 IN IN CODE.CDR
4.0
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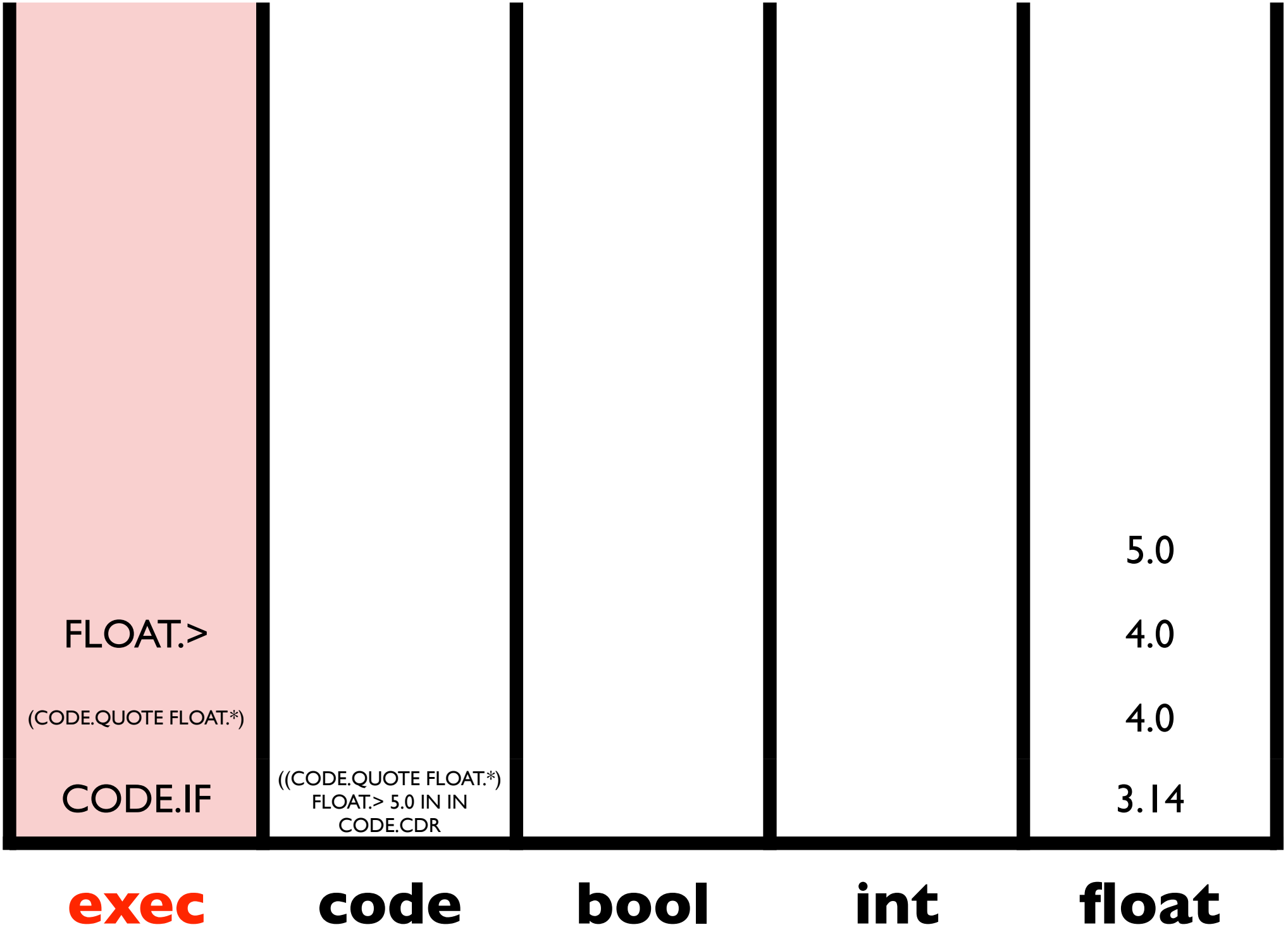
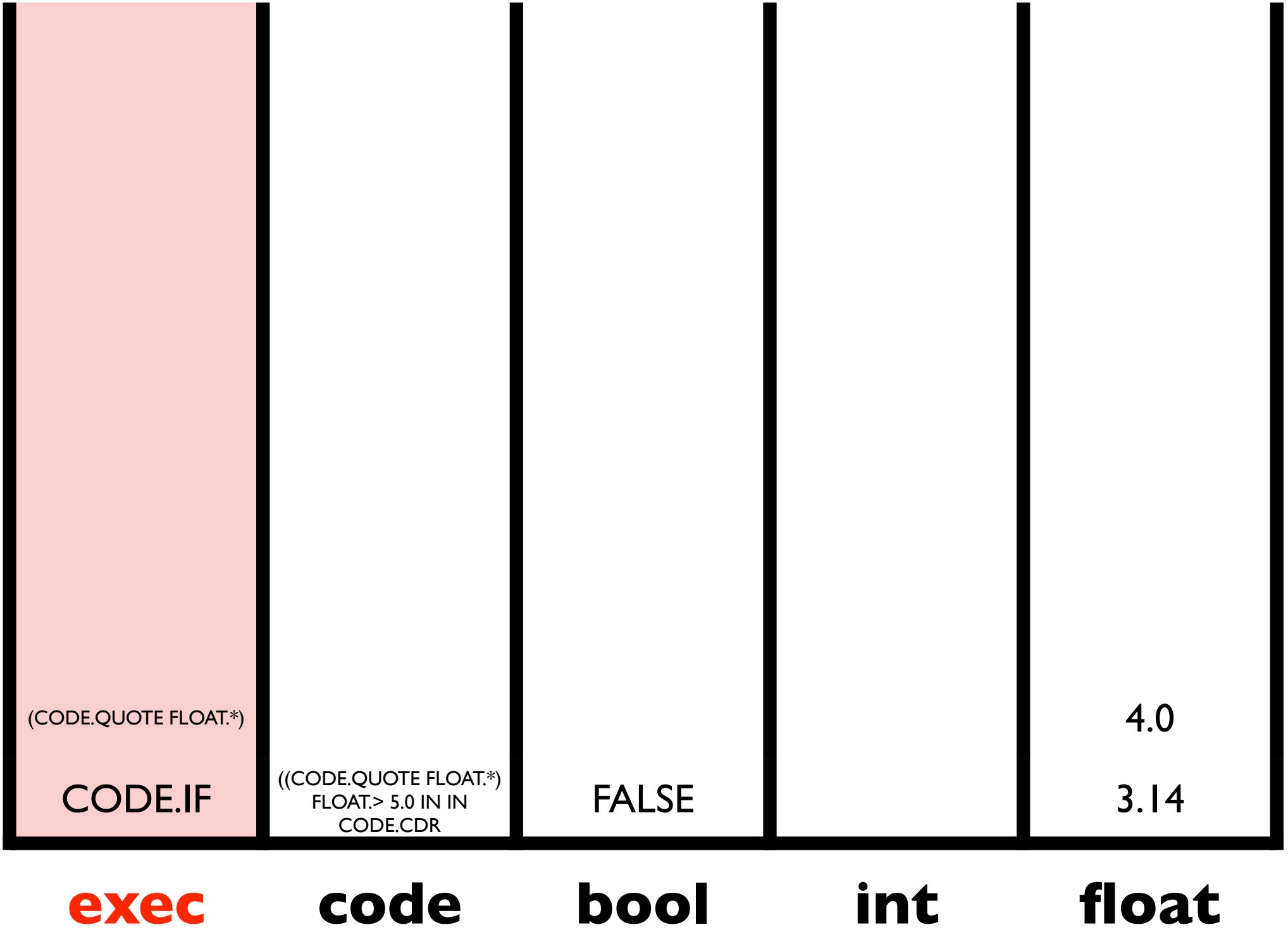
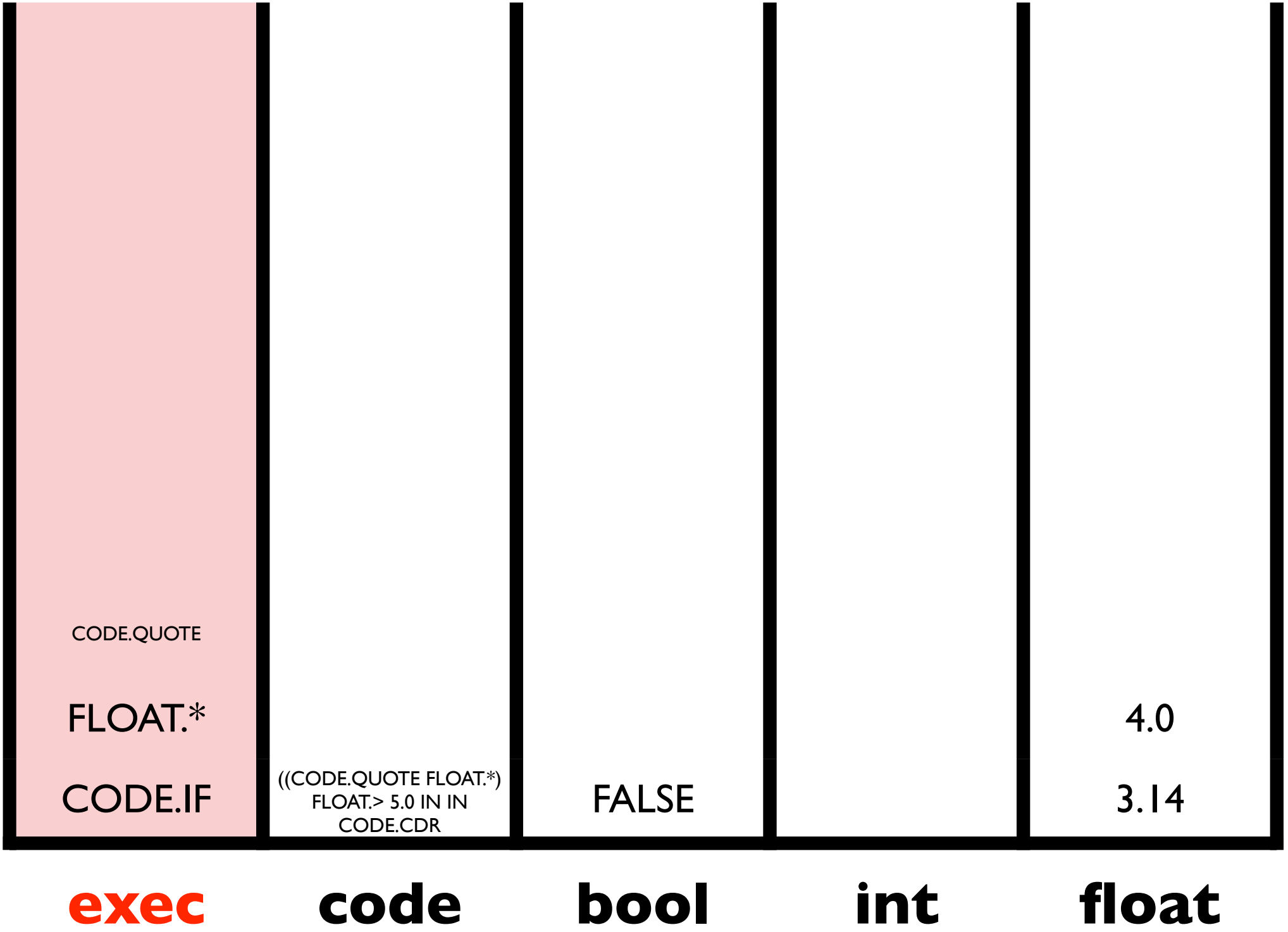
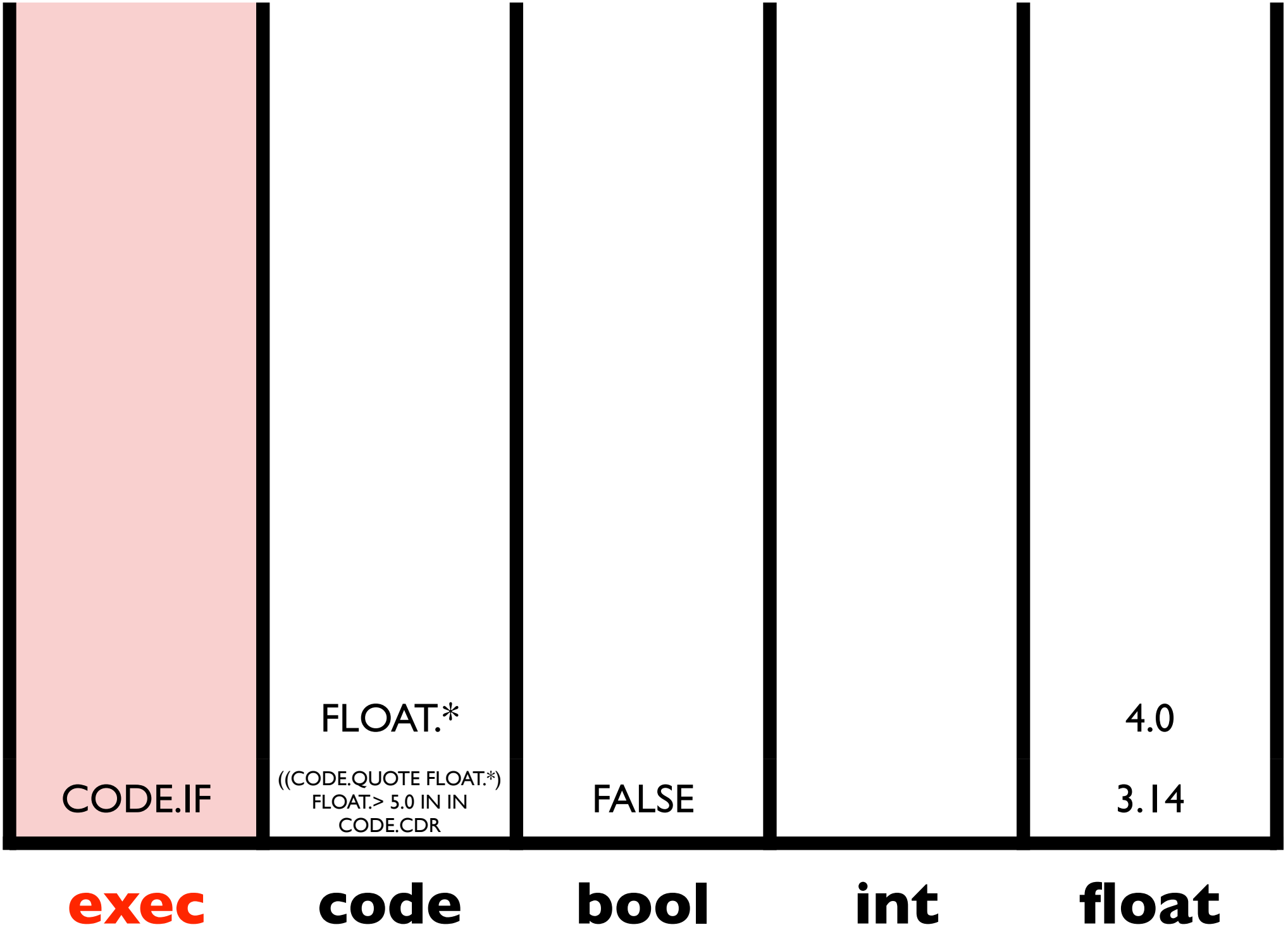
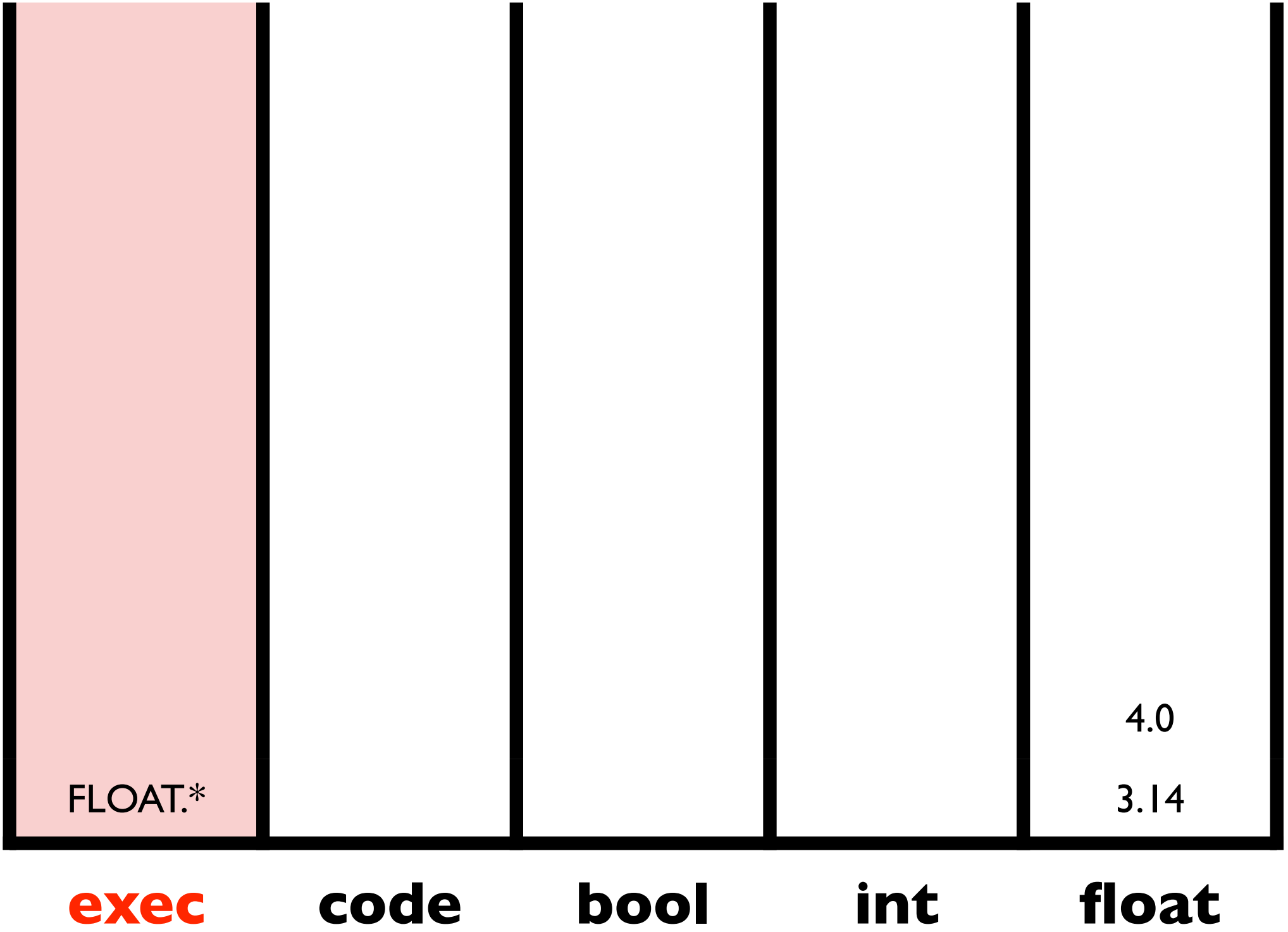
exec
code
bool
int
float

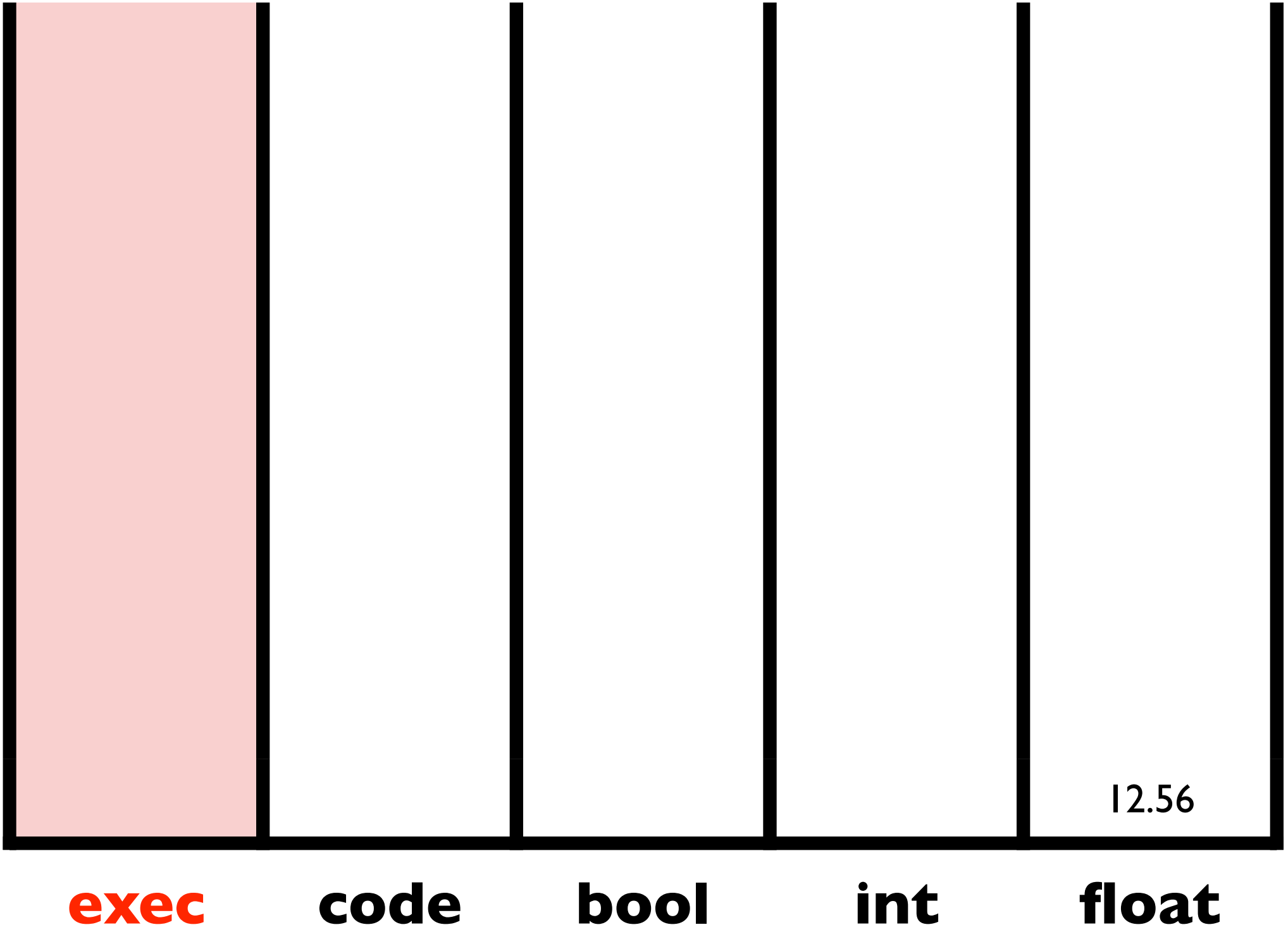

FLOAT.>
(CODE.QUOTE FLOAT.*)
CODE.IF
((CODE.QUOTE FLOAT.*) FLOAT.> 5.0 IN IN CODE.CDR
5.0
4.0
4.0
3.14
exec
code
bool
int
float


(CODE.QUOTE FLOAT.*)
CODE.IF
((CODE.QUOTE FLOAT.*) FLOAT.> 5.0 IN IN CODE.CDR
FALSE
4.0
3.14
exec
code
bool
int
float

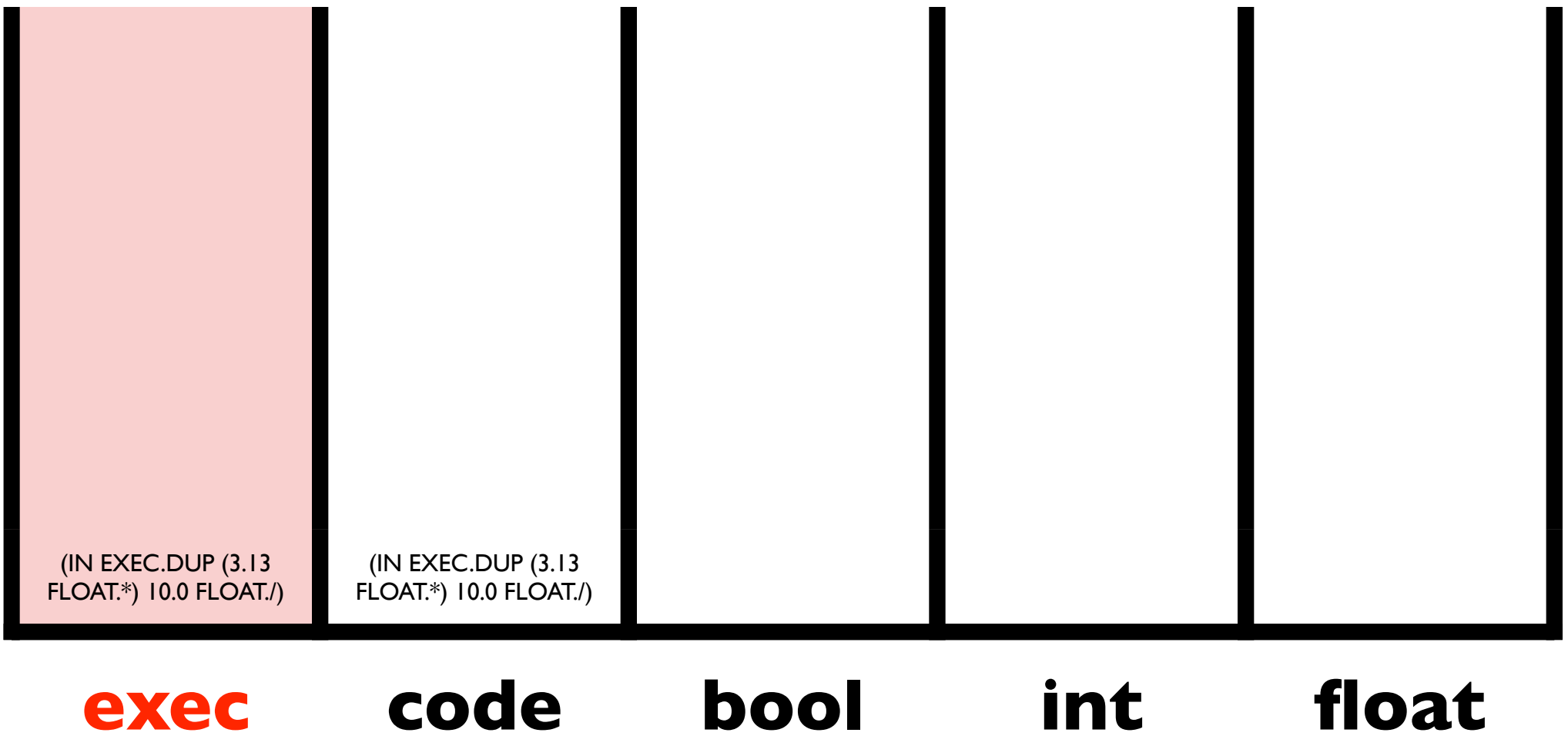

CODE.QUOTE
FLOAT.*
CODE.IF
((CODE.QUOTE FLOAT.*) FLOAT.> 5.0 IN IN CODE.CDR
FALSE
4.0
3.14
exec
code
bool
int
float

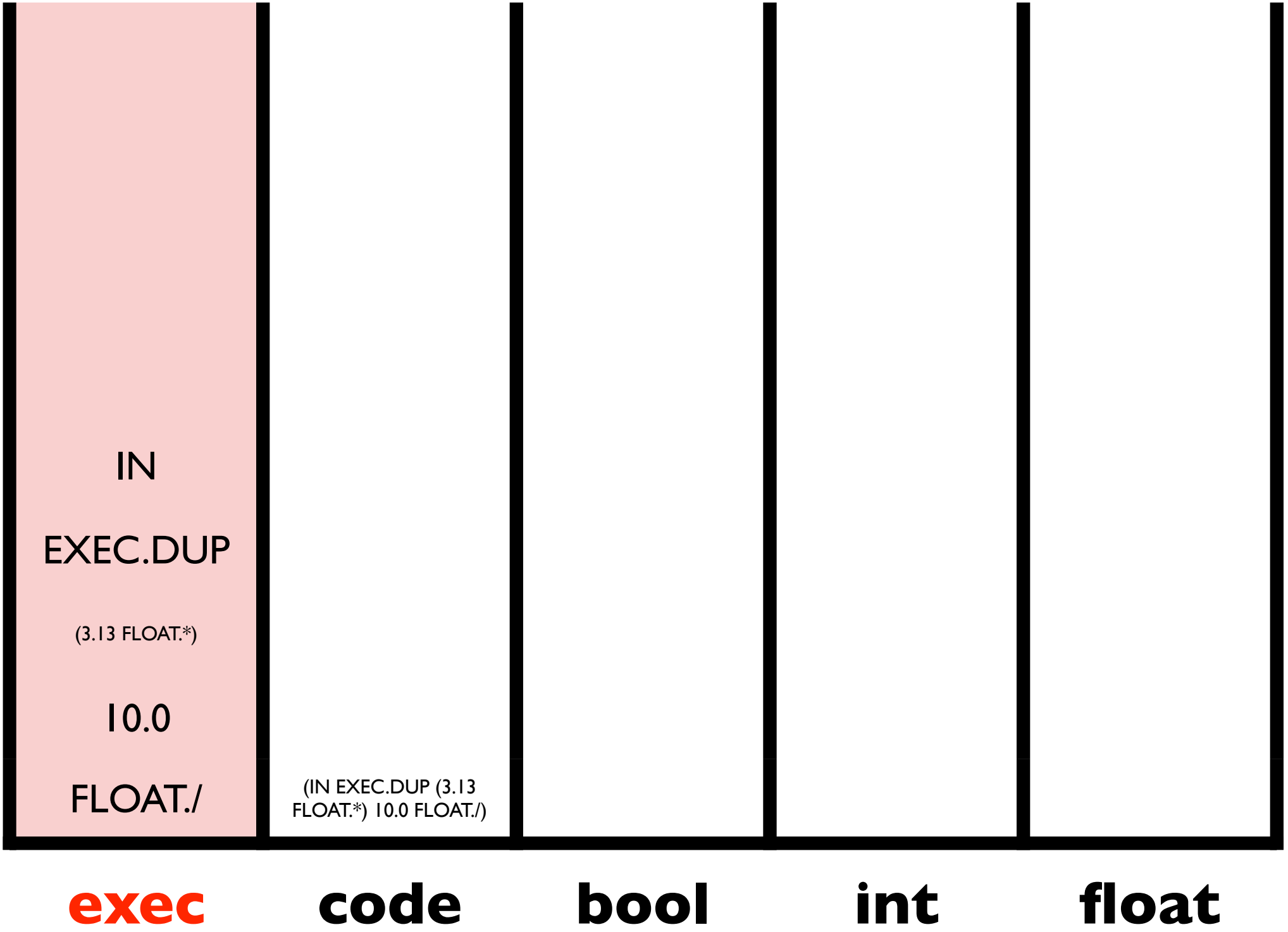

FLOAT.*
4.0
CODE.IF
((CODE.QUOTE FLOAT.*) FLOAT.> 5.0 IN IN CODE.CDR
FALSE
3.14
exec
code
bool
int
float

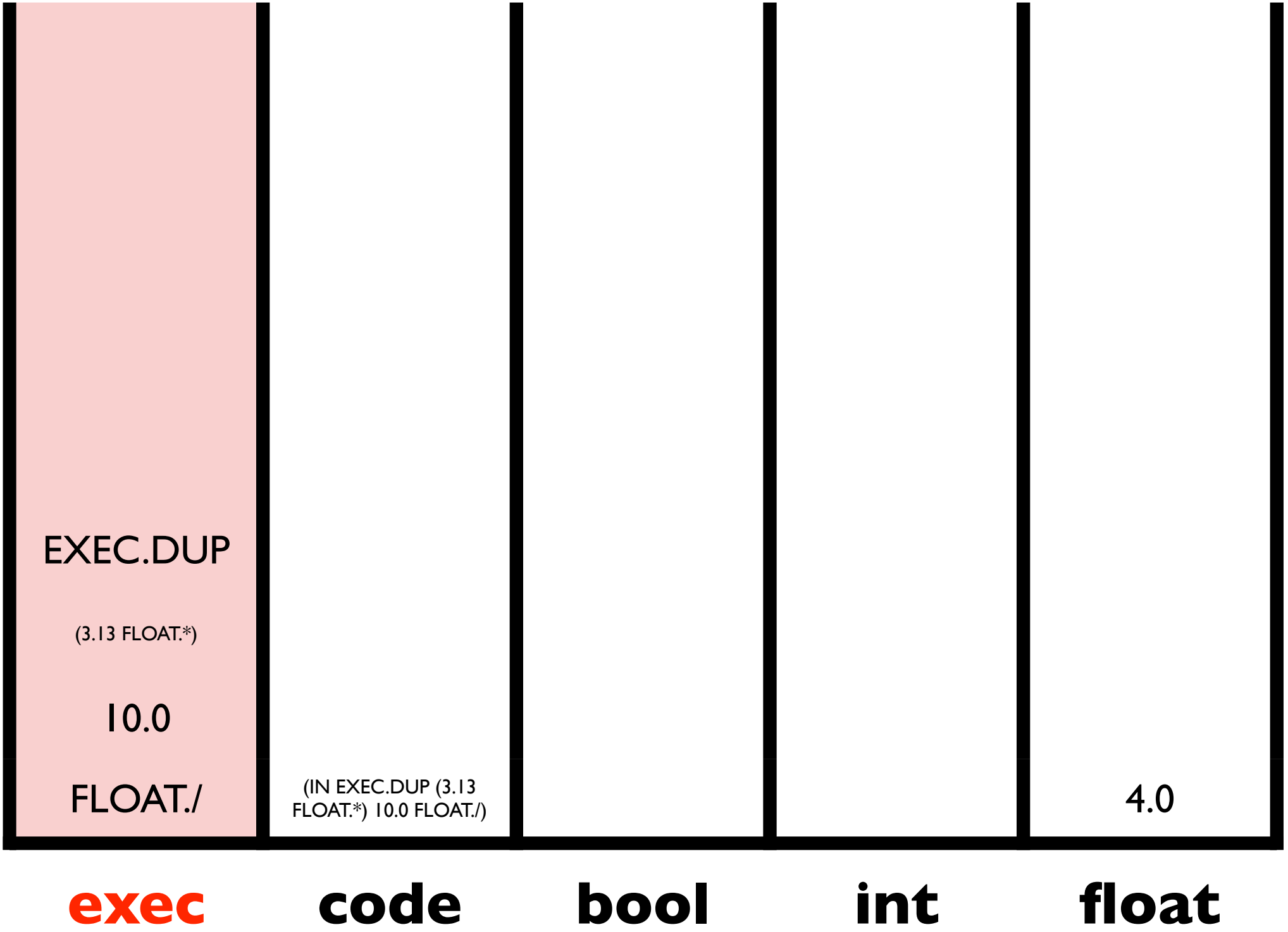

FLOAT.*
4.0
3.14
exec
code
bool
int
float

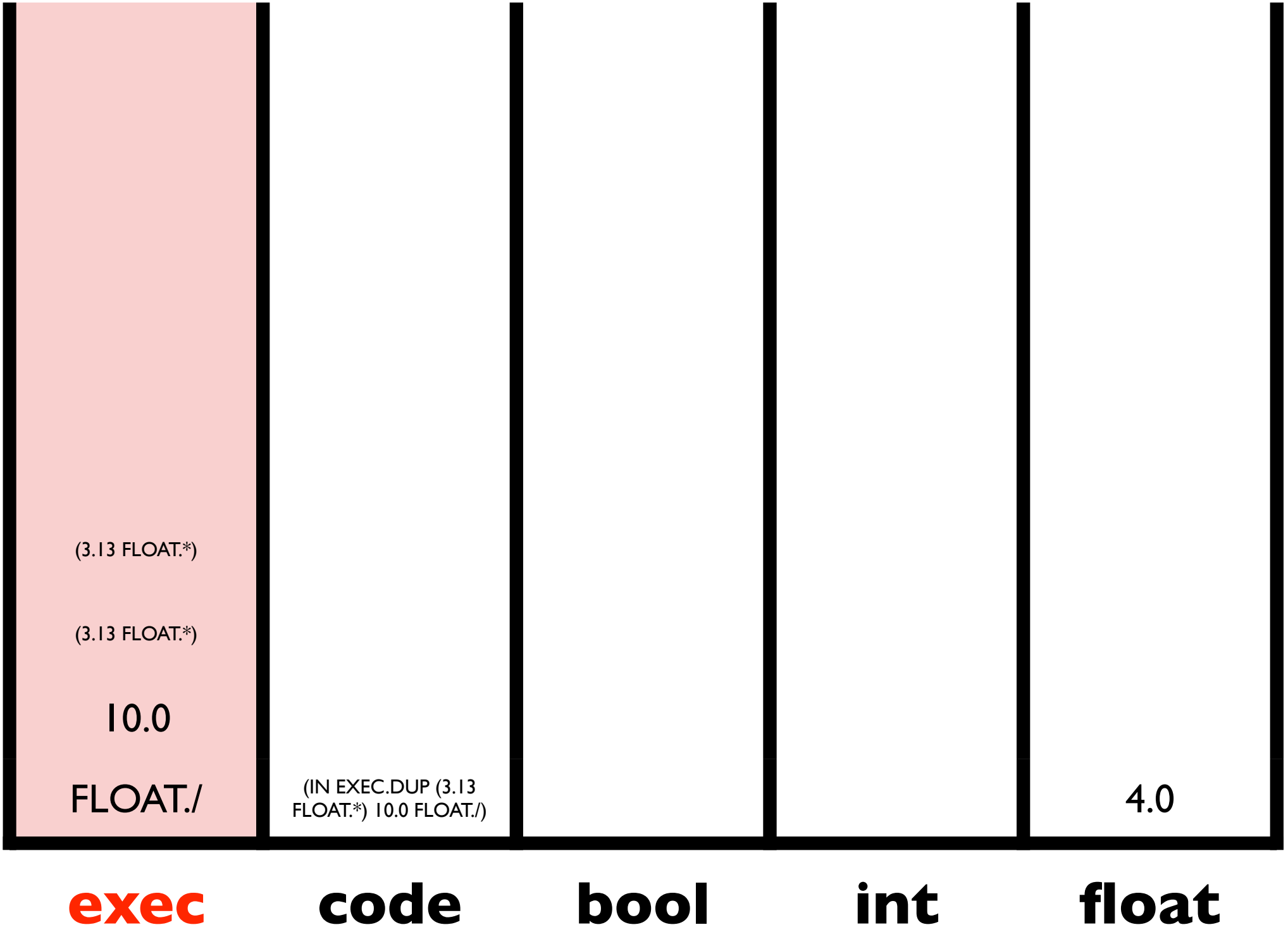

12.56
exec
code
bool
int
float

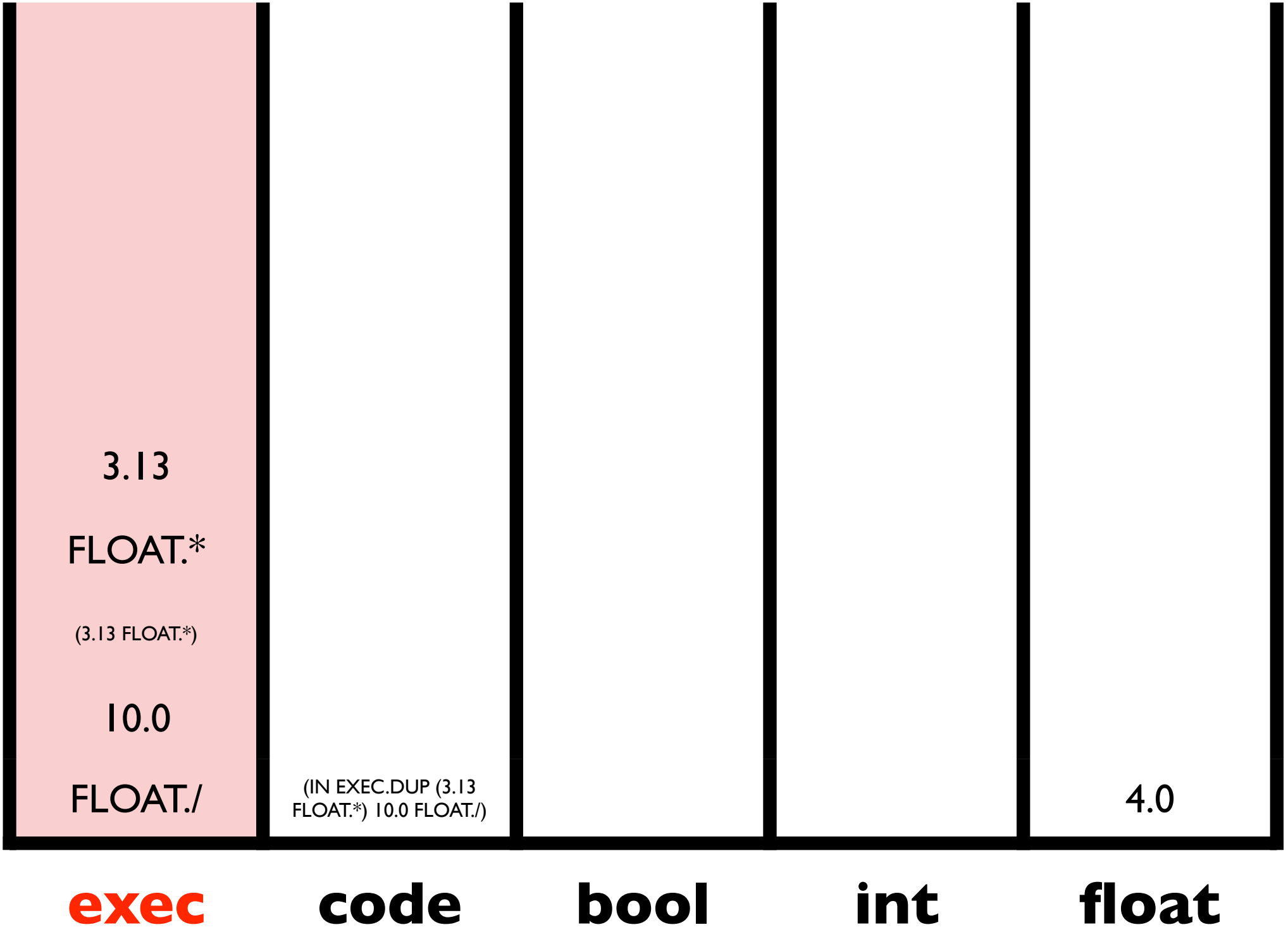
```
(IN EXEC.DUP (3.13 FLOAT.*)
10.0 FLOAT./)

IN=4.0
```

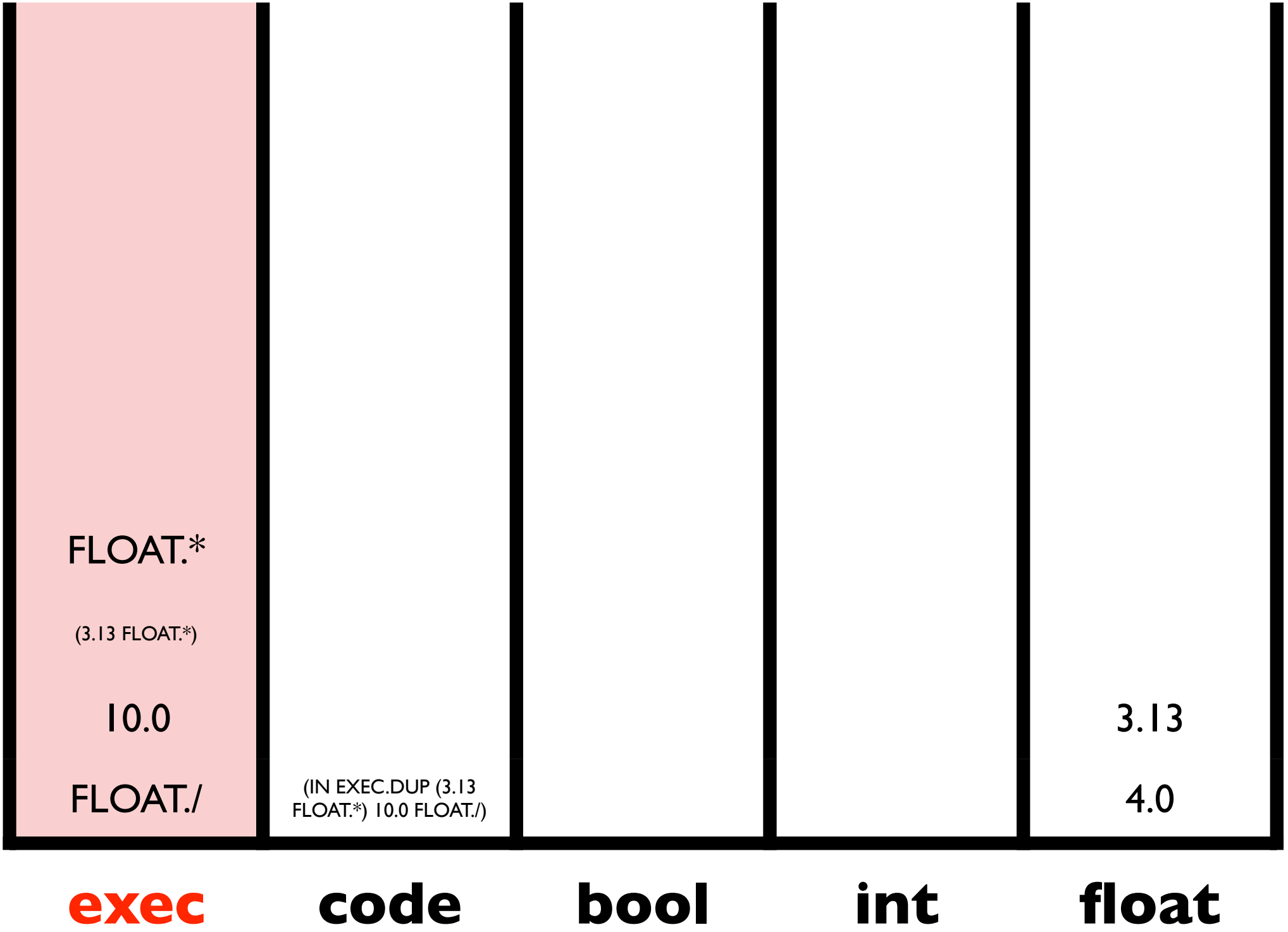


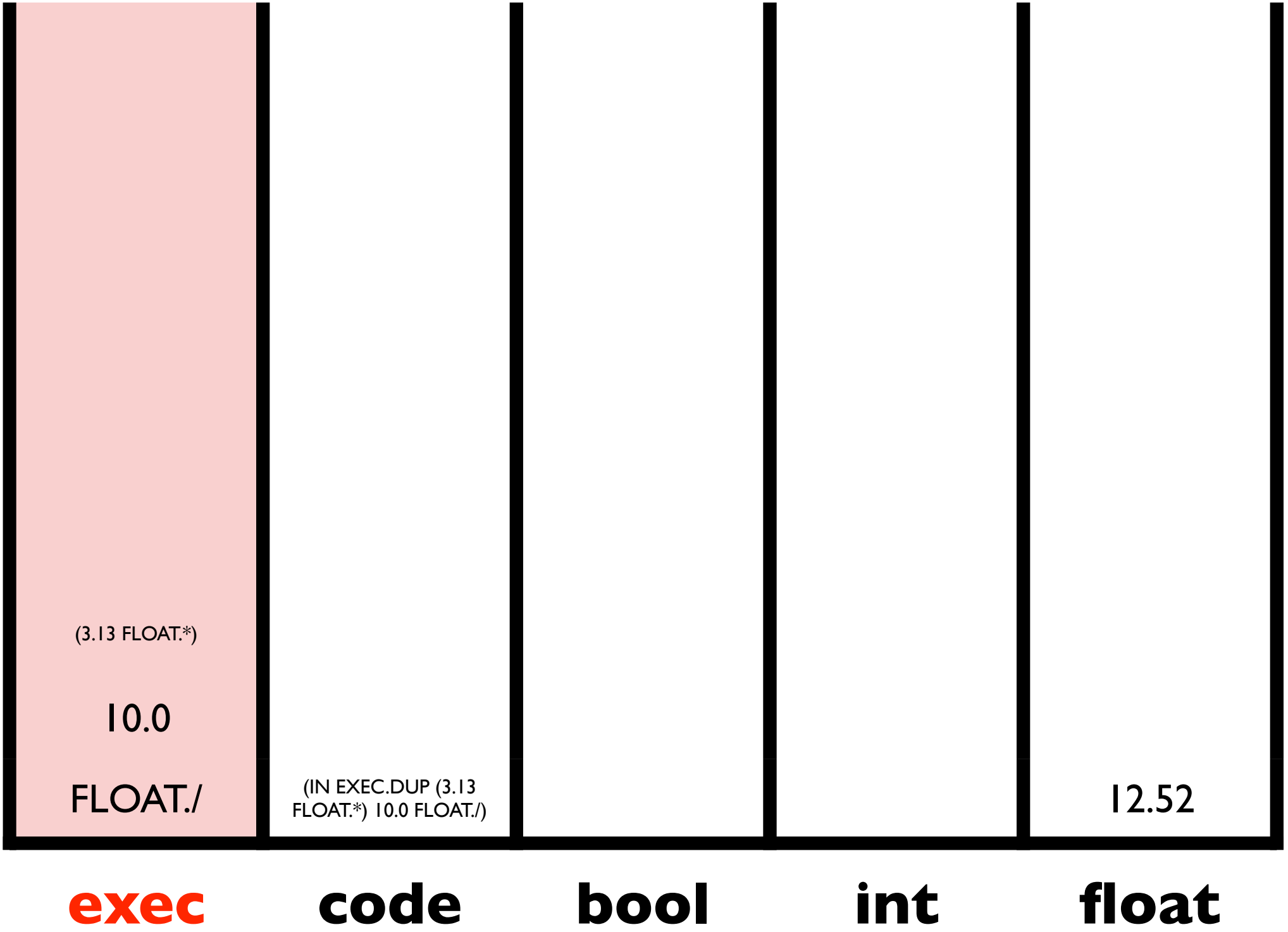

IN
EXEC.DUP
(3.13 FLOAT.*)
10.0
FLOAT./
(IN EXEC.DUP (3.13 FLOAT.*) 10.0 FLOAT./)
exec
code
bool
int
float

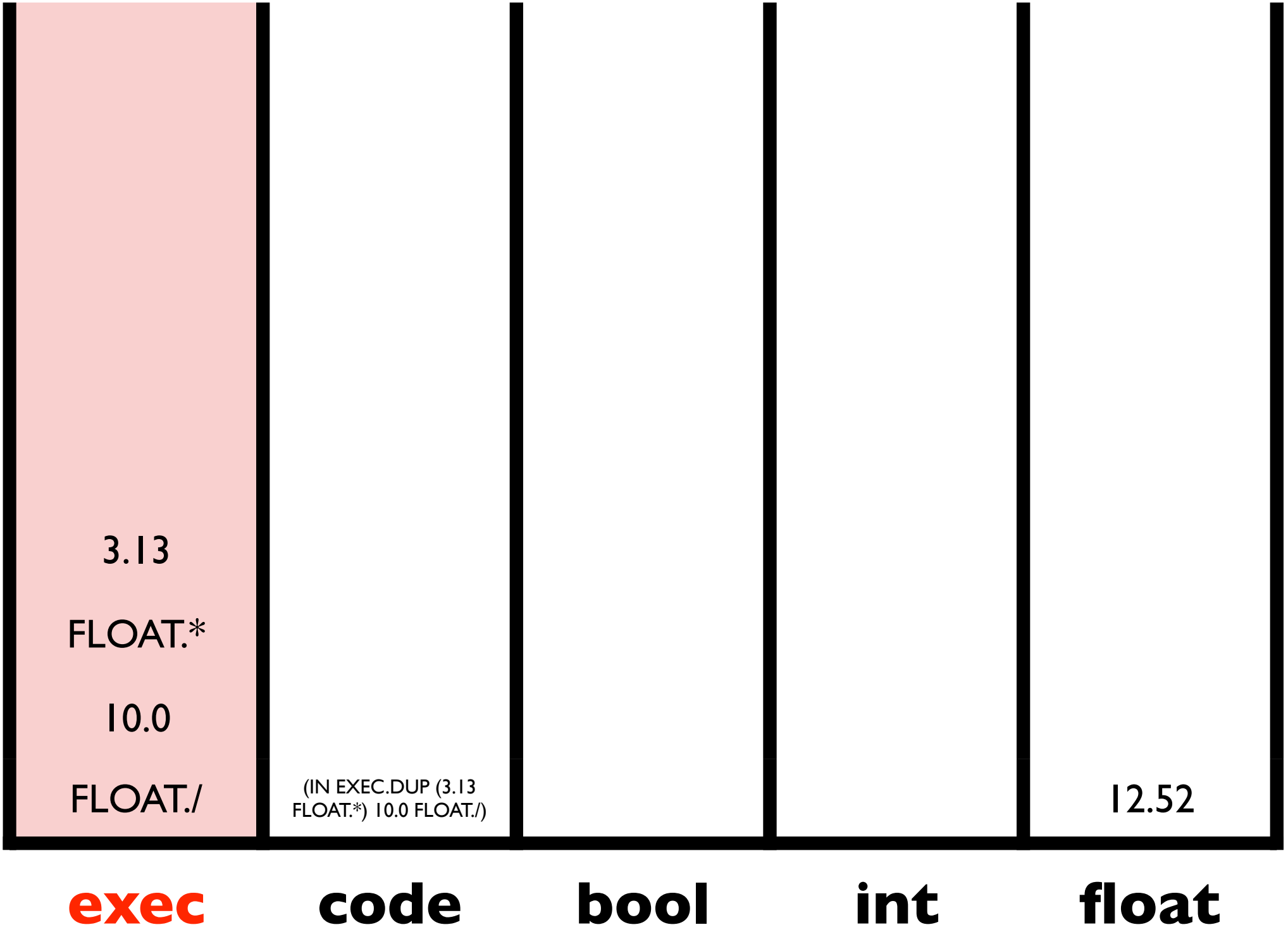

EXEC.DUP
(3.13 FLOAT.*)
10.0
FLOAT./
(IN EXEC.DUP (3.13 FLOAT.*) 10.0 FLOAT./)
4.0
exec
code
bool
int
float

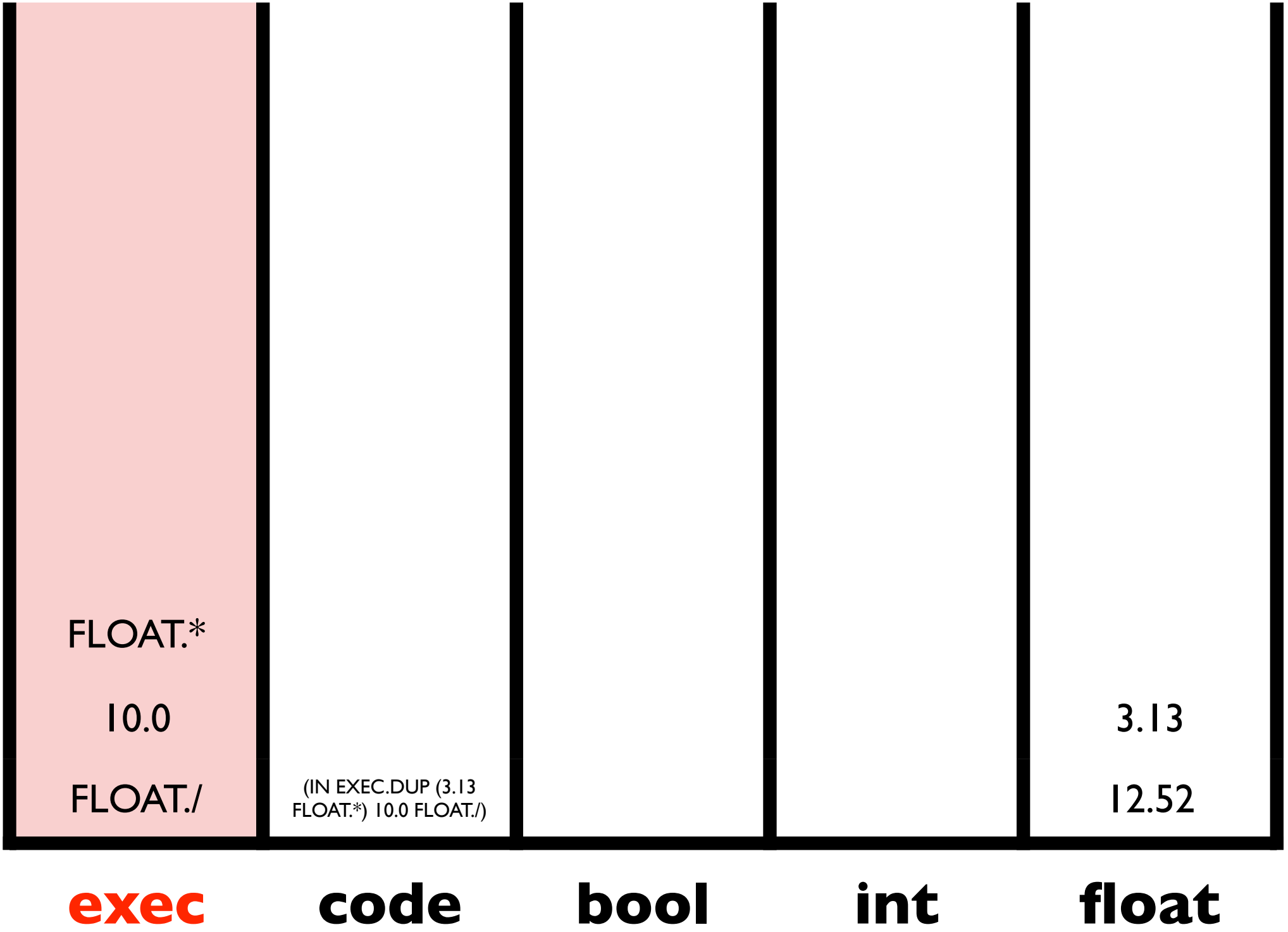

(3.13 FLOAT.*)
(3.13 FLOAT.*)
10.0
FLOAT./
(IN EXEC.DUP (3.13 FLOAT.*) 10.0 FLOAT./)
4.0
exec
code
bool
int
float

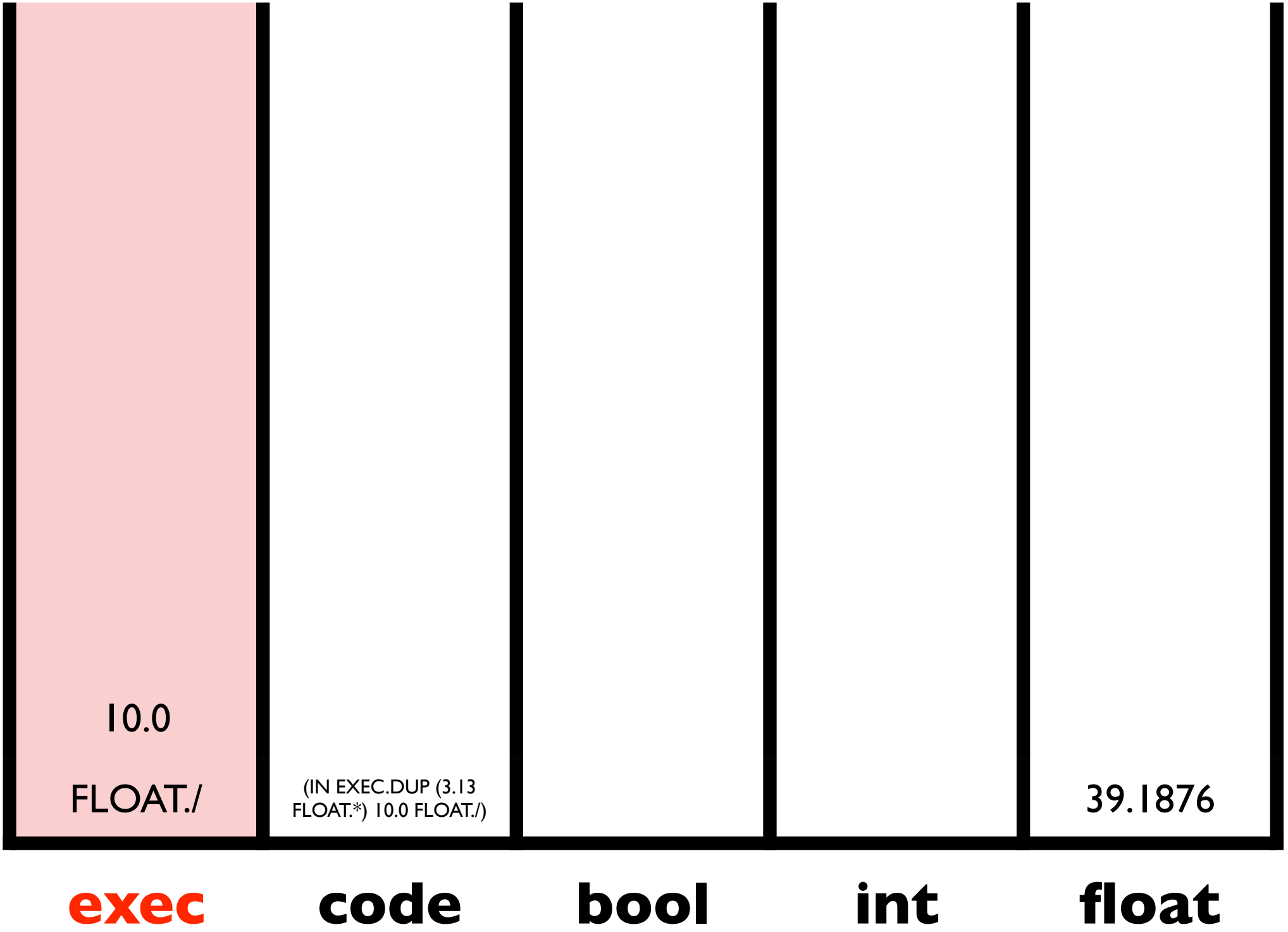

3.13
FLOAT.*
(3.13 FLOAT.*)
10.0
FLOAT./
(IN EXEC.DUP (3.13 FLOAT.*) 10.0 FLOAT./)
4.0
exec
code
bool
int
float

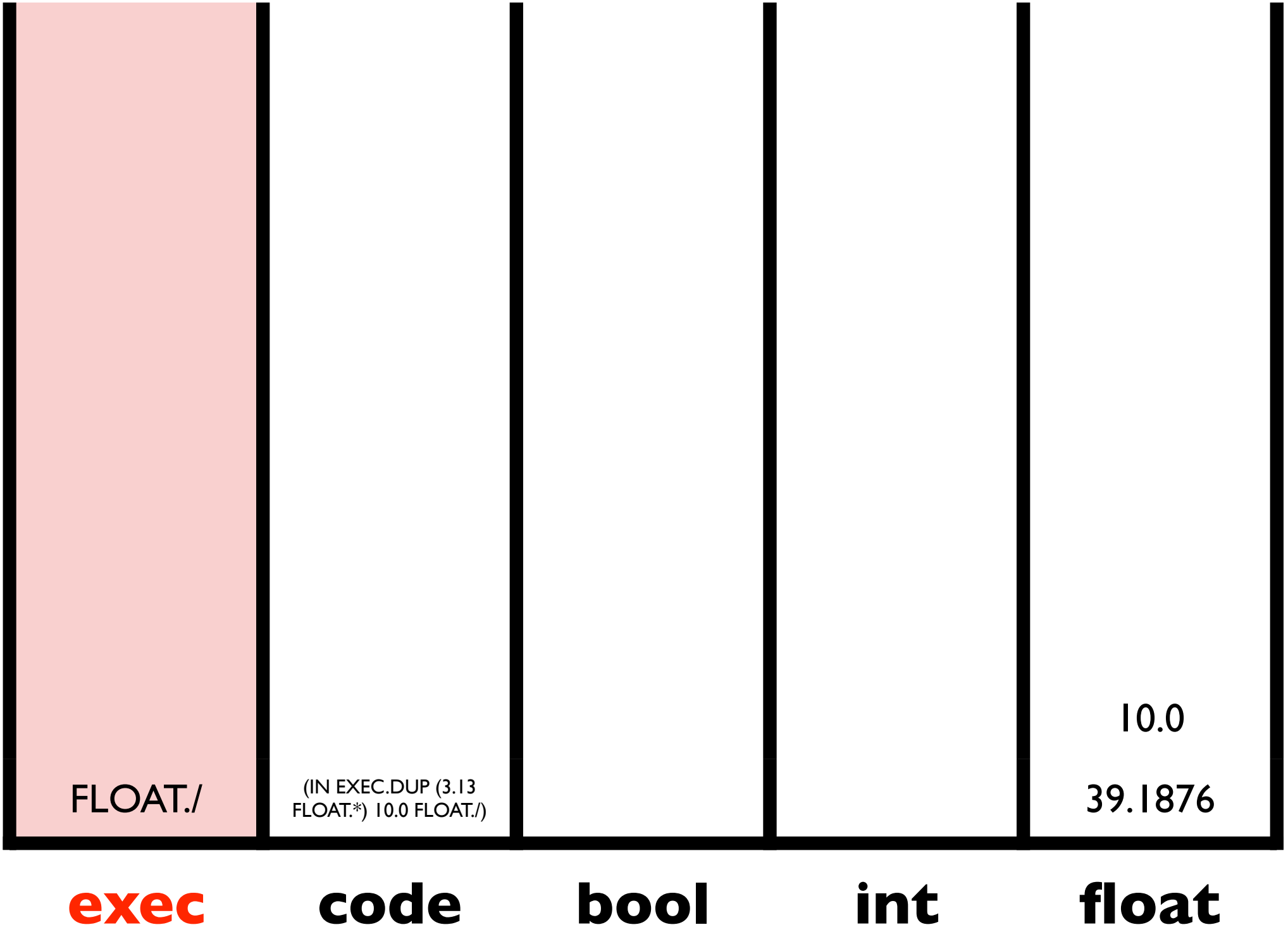

FLOAT.*
(3.13 FLOAT.*)
10.0
FLOAT./
(IN EXEC.DUP (3.13 FLOAT.*) 10.0 FLOAT./)
3.13
4.0
exec
code
bool
int
float

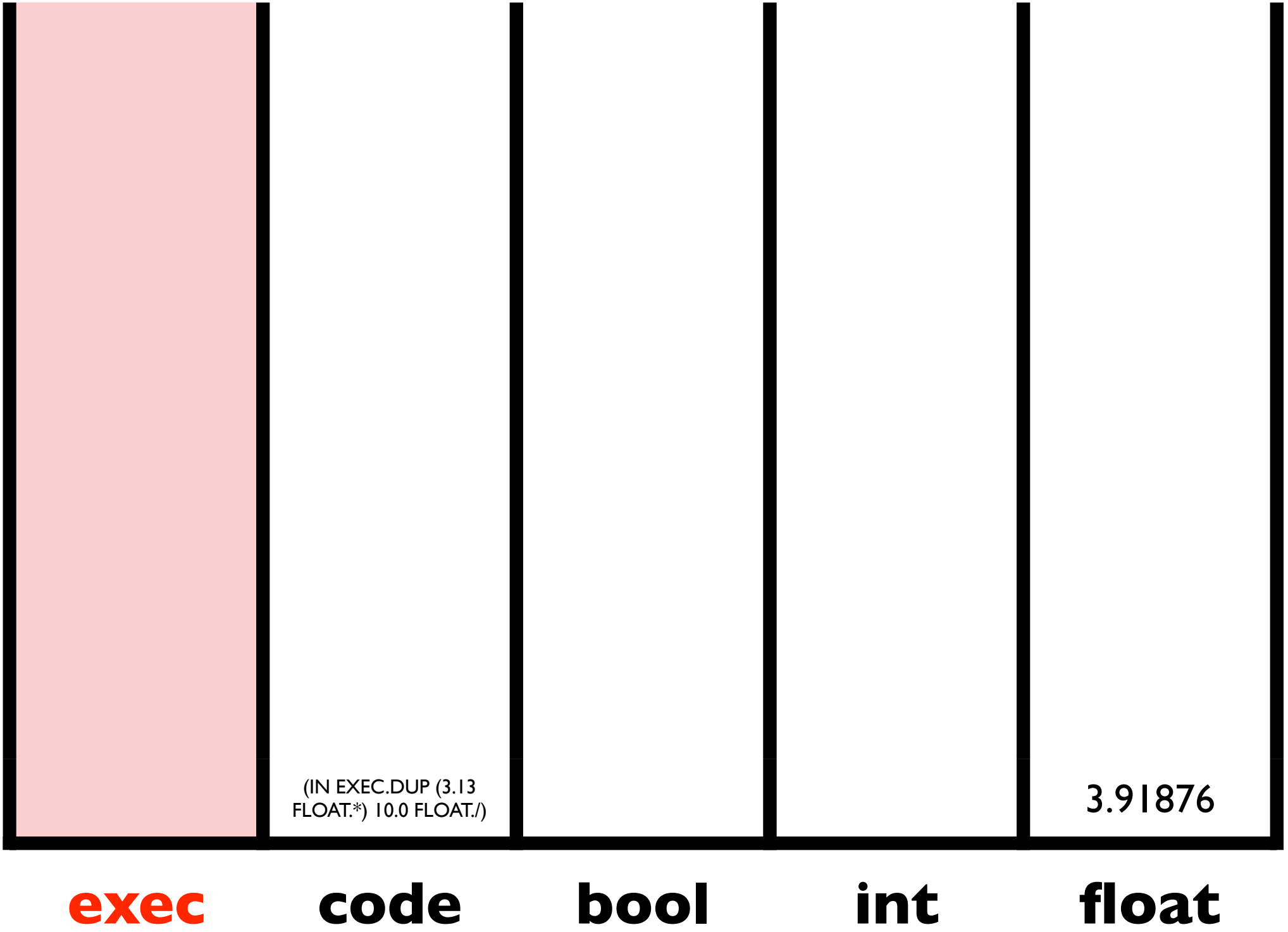

(3.13 FLOAT.*)
10.0
FLOAT./
(IN EXEC.DUP (3.13 FLOAT.*) 10.0 FLOAT./)
12.52
exec
code
bool
int
float


3.13
FLOAT.*
10.0
FLOAT./
(IN EXEC.DUP (3.13 FLOAT.*) 10.0 FLOAT./)
12.52
exec
code
bool
int
float


FLOAT.*
10.0
FLOAT./
(IN EXEC.DUP (3.13 FLOAT.*) 10.0 FLOAT./)
3.13
12.52
exec
code
bool
int
float


10.0
FLOAT./
(IN EXEC.DUP (3.13 FLOAT.*) 10.0 FLOAT./)
39.1876
exec
code
bool
int
float


FLOAT./
(IN EXEC.DUP (3.13 FLOAT.*) 10.0 FLOAT./)
10.0
39.1876
exec
code
bool
int
float


(IN EXEC.DUP (3.13
FLOAT.*) 10.0 FLOAT./)
3.91876
exec
code
bool
int
float

# The Odd Problem

- Integer input
- Boolean output
- Was the input odd?
- `((code.nth) code.atom)`

# Combinators

- Standard *K*, *S*, and *Y* combinators:
  - `EXEC.K` removes the second item from the `EXEC` stack.
  - `EXEC.S` pops three items (call them `A`, `B`, and `C`) and then pushes `(B C)`, `C`, and then `A`.
  - `EXEC.Y` inserts `(EXEC.Y` *T*`)` under the top item (*T*).
- A *Y*-based "while" loop:

```
( EXEC.Y
  ( <BODY/CONDITION> EXEC.IF
  ( ) EXEC.POP ) )
```

# Iterators

`CODE.DO*TIMES, CODE.DO*COUNT, CODE.DO*RANGE`

`EXEC.DO*TIMES, EXEC.DO*COUNT, EXEC.DO*RANGE`

Additional forms of iteration are supported through code manipulation (e.g. via `CODE.DUP CODE.APPEND CODE.DO`)

# Evolving Modular Programs

## With Code Manipulation

- Transform code as data on “code” stack
- Execute transformed code with `code.do`, etc.
- Simple uses of modules can be evolved easily

# Evolving Modular Programs

## With Execution Stack Manipulation

- Code queued for execution is stored on an "execution stack"
- Allow programs to duplicate and manipulate code that on the stack
- Example: `(3 exec.dup (1 integer.+))`

# Evolving Modular Programs

## With Named Modules

- Uses Push's "name" stack
- Example:

```
(plus1 exec.define (1 integer.+))
...
plus1
```

- Coordinating definitions/references is tricky

# Holland's Tags

- Initially arbitrary identifiers that come to have meaning over time
- Matches may be inexact
- Appear to be present in some form in many different kinds of complex adaptive systems
- Examples range from immune systems to armies on a battlefield
- A general tool for the support of emergent complexity

# Evolving Modular Programs

## With tags

- Include instructions that tag code (modules)
- Include instructions that recall and execute modules by *closest matching* tag
- If a single module has been tagged then all tag references will recall modules
- The number of tagged modules can grow incrementally over evolutionary time
- **Expressive and evolvable**

# Tags in Push

- Tags are integers embedded in instruction names
- Instructions like `tag.exec.123` tag values
- Instructions like `tagged.456` recall values by *closest matching* tag
- If a single value has been tagged then all tag references will recall (and execute) values
- The number of tagged values can grow incrementally over evolutionary time

# Tags in Trees

- Example:

```
(progn (tag.123 (+ a b))
       (+ tagged.034 tagged.108))
```

- Must do something about endless recursion
- Must do something about return values of tagging operations and references prior to tagging
- Non-trivial to support arguments in a general way
- Utility not clear from experiments conducted to date

# Auto-simplification

Loop: Make it randomly simpler

If it's as good or better: keep it

Otherwise: revert

GECCO-2014 poster showed that this can efficiently and reliably reduce the size of the evolved programs

GECCO-2014 student paper explored its utility in a genetic operator

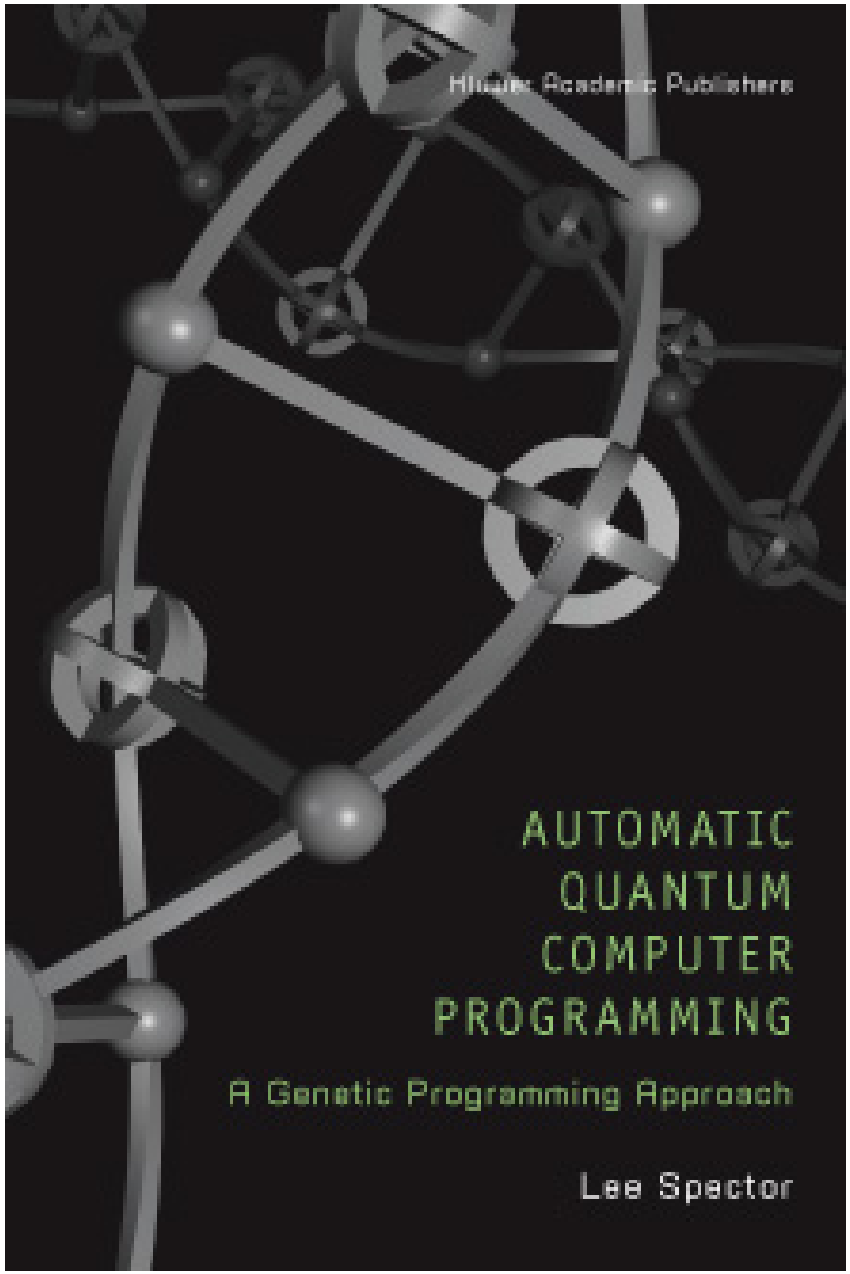
DEMO

# Problems Solved by PushGP in the GECCO-2005 Paper on Push3

- Reversing a list
- Factorial (many algorithms)
- Fibonacci (many algorithms)
- Parity (any size input)
- Exponentiation
- Sorting

# 29 Synthesis Benchmarks

- Number IO, Small or Large, For Loop Index, Compare String Lengths, Double Letters, Collatz Numbers, Replace Space with Newline, String Differences, Even Squares, Wallis Pi, String Lengths Backwards, Last Index of Zero, Vector Average, Count Odds, Mirror Image, Super Anagrams, Sum of Squares, Vectors Summed, X-Word Lines, Pig Latin, Negative to Zero, Scrabble Score, Word Stats, Checksum, Digits, Grade, Median, Smallest, Syllables
- PushGP has solved all of these except for the ones in blue
- Presented in a GECCO-2015 GP track paper



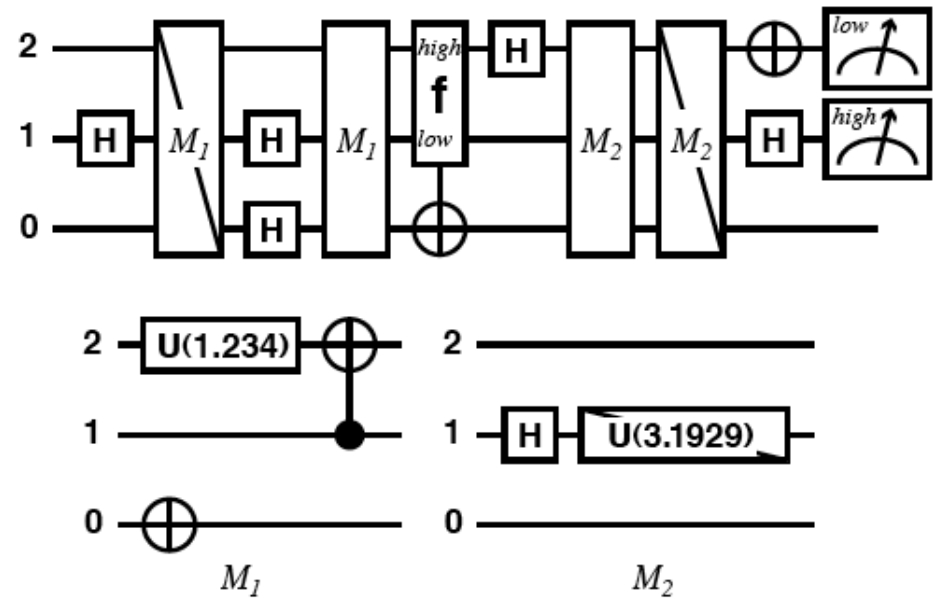




*Figure 8.7.* A gate array diagram for an evolved version of Grover's database search algorithm for a 4-item database. The full gate array is shown at the top, with $M_1$ and $M_2$ standing for the smaller gate arrays shown at the bottom. A diagonal line through a gate symbol indicates that the matrix for the gate is transposed. The "f" gate is the oracle.

# Humies 2004
# GOLD MEDAL

# Genetic Programming for Finite Algebras

Lee Spector
Cognitive Science
Hampshire College
Amherst, MA 01002
lspector@hampshire.edu

David M. Clark
Mathematics
SUNY New Paltz
New Paltz, NY 12561
clarkd@newpaltz.edu

Ian Lindsay
Hampshire College
Amherst, MA 01002
iml04@hampshire.edu

Bradford Barr
Hampshire College
Amherst, MA 01002
bradford.barr@gmail.com

Jon Klein
Hampshire College
Amherst, MA 01002
jk@artificial.com

Humies 2008

GOLD MEDAL

# Autoconstructive Evolution

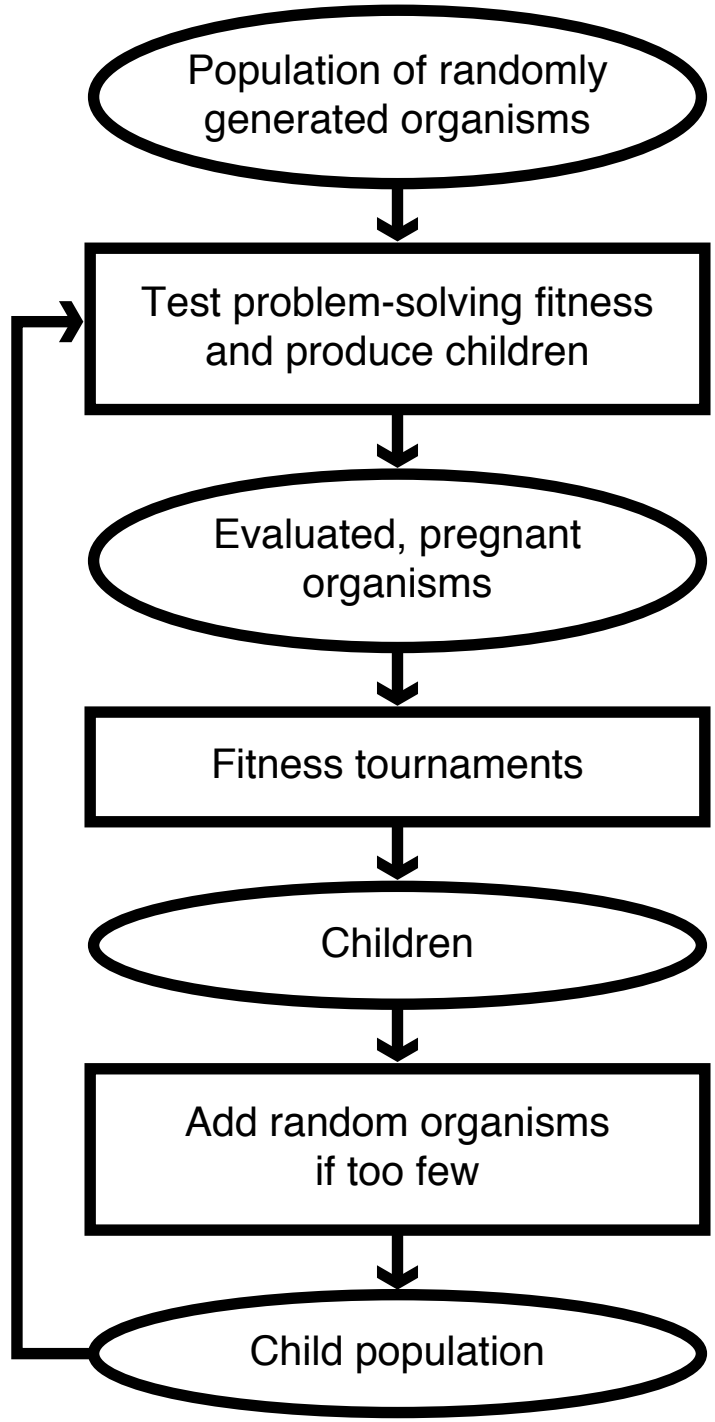
- Individuals make their own children
- Agents thereby control their own mutation rates, sexuality, and reproductive timing
- The machinery of reproduction and diversification (i.e., the machinery of evolution) evolves
- Radical self-adaptation

# Related Work

- MetaGP: but (1) programs and reproductive strategies dissociated and (2) generally restricted reproductive strategies
- ALife systems such as Tierra, Avida, SeMar: but (1) hand-crafted ancestors, (2) reliance on cosmic ray mutation, and (3) weak problem solving
- Evolved self-reproduction: but generally exact reproduction, non-improving (exception: Koza, but very limited tools for problem solving *and* for construction of offspring)

# Pushpop

- A soup of evolving Push programs
- Reproductive procedures emerge ex nihilo:
  - No hand-designed “ancestor”
  - Children constructed by any computable process
  - No externally applied mutation procedure or rate
  - Exact clones are prohibited, but near-clones are permitted.
- Selection for problem-solving performance


Population of randomly generated organisms
Test problem-solving fitness and produce children
Evaluated, pregnant organisms
Fitness tournaments
Children
Add random organisms if too few
Child population

# Pushpop Results

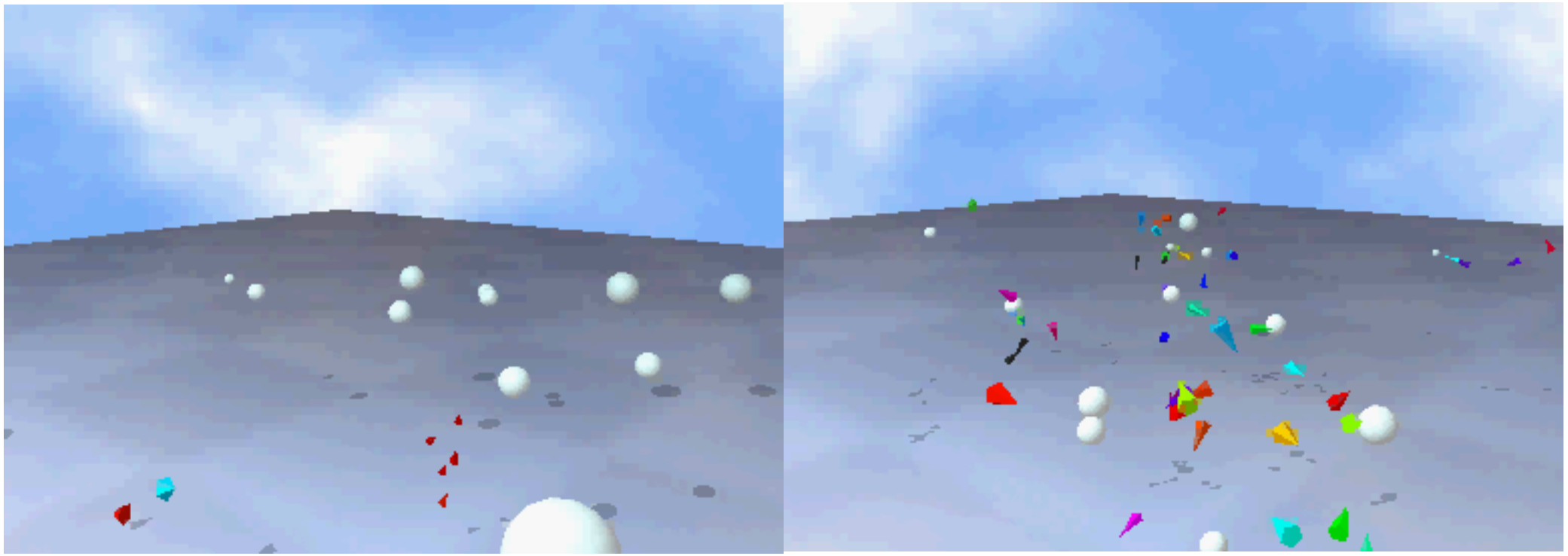
- In adaptive populations:
  - Species are more numerous
  - Diversification processes are more reliable
- Selection can promote diversity
- Provides a possible explanation for the evolution of diversifying reproductive systems

# SwarmEvolve 2.0

- Behavior (including reproduction) controlled by evolved Push programs
- Color, color-based agent discrimination controlled by agents
- Energy conservation
- Facilities for communication, energy sharing
- Ample user feedback (e.g. diversity metrics, agent energy determines size)

| Instruction(s) | Description |
|---|---|
| DUP, POP, SWAP, REP, =, NOOP, PULL, PULLDUP, CONVERT, CAR, CDR, QUOTE, ATOM, NULL, NTH, +, *, /, >, <, NOT, AND, NAND OR, NOR, DO*, IF | Standard Push instructions (See [11]) |
| VectorX, VectorY, VectorZ, VPlus, VMinus, VTimes, VDivide, VectorLength, Make-Vector | Vector access, construction, and manipulation |
| RandI, RandF, RandV, RandC | Random number, vector, and code generators |
| SetServoSetpoint, SetServoGain, Servo | Servo-based persistent memory |
| Mutate, Crossover | Stochastic list manipulation (parameters from stacks) |
| Spawn | Produce a child with code from code stack |
| ToFood | Vector to energy source |
| FoodIntensity | Energy of energy source |
| MyAge, MyEnergy, MyHue, MyVelocity, MyLocation, MyProgram | Information about self |
| ToFriend, FriendAge, FriendEnergy, FriendHue, FriendVelocity, FriendLocation, FriendProgram | Information about closest agent of similar hue |
| ToOther, OtherAge, OtherEnergy, OtherHue, OtherVelocity, OtherLocation, OtherProgram | Information about closest agent of non-similar hue |
| FeedFriend, FeedOther | Transfer energy to closest agent of indicated category |

# SwarmEvolve 2.0



Winner, Best Paper Award, AAAA Track, GECCO-2003

# Expressiveness and Assessment

- Expressive languages ease representation of programs that over-fit training sets
- Expressive languages ease representation of programs that work only on subsets of training sets
- Lexicase selection may help: Select parents by starting with a pool of candidates and then filtering by performance on individual fitness cases, considered one at a time

# Future Work

- Expression of variable scope and environments (implemented in Push, but not yet studied systematically)
- Expression of concurrency and parallelism
- Applications for which expressiveness is likely to be essential, e.g. complete software applications, agents in complex, dynamic environments
- Epigenetics

# Conclusions

- GP in expressive languages may allow for the evolution of complex software
- Minimal-syntax languages can be expressive, and GP systems that evolve programs in such languages can be unusually simple and powerful
- Push is expressive, evolvable, successful, and extensible
- http://pushlanguage.org

# Thanks

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