The calculator problem and the evolutionary synthesis of arbitrary software

CREST Open Workshop on Genetic Programming
for Software Engineering

October 14, 2013

Lee Spector
Hampshire College
Amherst, MA USA

Tests

↓

↓

Software

STAPLES
SPL-110
12345678
%
√
OFF
ON/C
MRC
M−
M+
CE
7
8
9
÷
4
5
6
×
1
2
3
−
0
•
=
+

Outline

- Arbitrary software
- Requirements and ways to meet them
- Tags, uniform variation, and lexicase selection
- The calculator problem
- Other problems and prospects

Arbitrary Software

- OS utilities
- Word processors
- Web browsers
- Accounting systems
- Image processing systems
- Everything

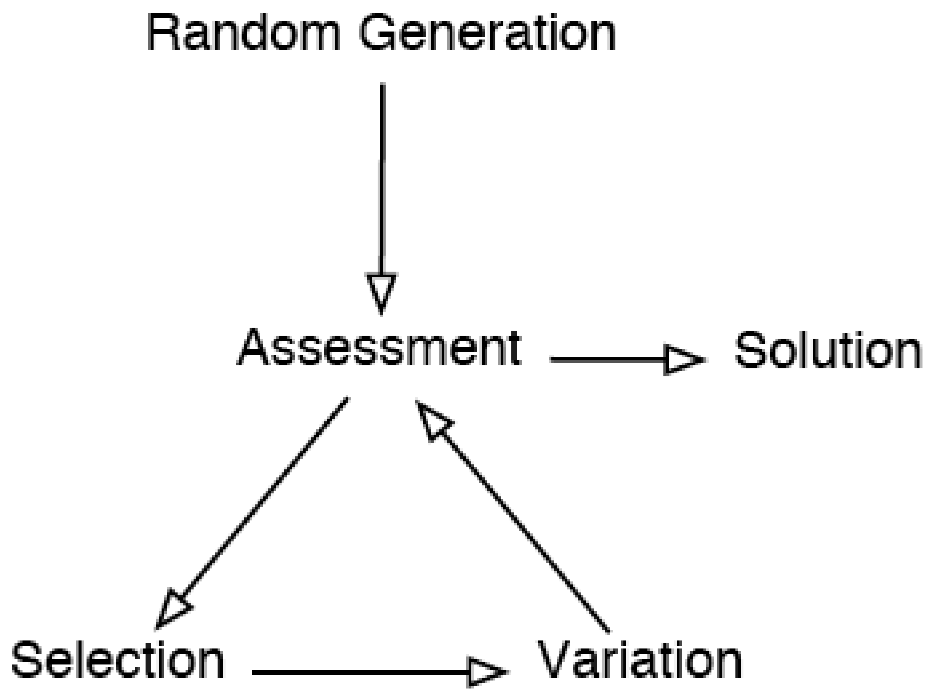
Arbitrary Software

- May be stateful, with multiple entry points
- May have a variety of interfaces involving a variety of types
- May require arbitrary Turing-computable functions
- Can be specified with behavioral tests

Requirements

- Represent and evolve arbitrary computable functions on arbitrary types (Push)
- Represent and evolve arbitrary computational architectures (e.g. modules, interfaces; tags and tagged entry points)
- Drive evolution with performance tests (lexicase selection)
- Permit self-adaptation of evolutionary mechanisms (flexible representations, autoconstruction)

Evolutionary Computation



Genetic Programming

- Evolutionary computing to produce executable computer programs
- Programs are assessed by executing them
- Automatic programming; producing software
- Potential (?): evolve software at all scales, including and surpassing the most ambitious and successful products of human software engineering

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, ...).

Evolvability

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

Push

- A programming language developed specifically for evolutionary computation, as the language in which evolving programs are expressed
- Intended to maximize the evolvability of arbitrary computational processes

Push

- Stack-based postfix language with one stack per type
- Types include: integer, float, Boolean, name, code, exec, vector, matrix, quantum gate, [add more as needed]
- Missing argument? NOOP
- Minimal syntax:
  program → instruction | literal | (program*)

Why Push?

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

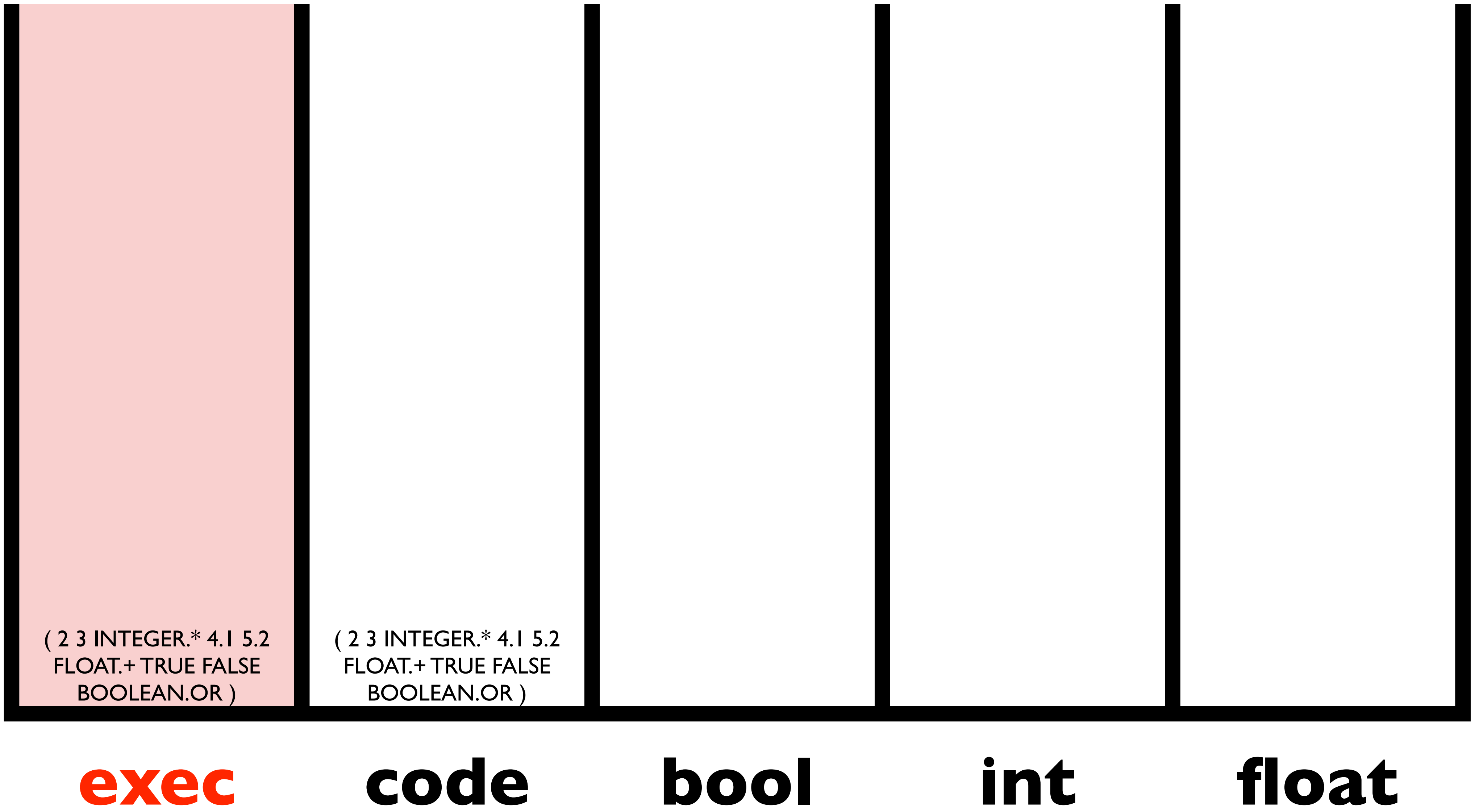
Sample Push Instructions

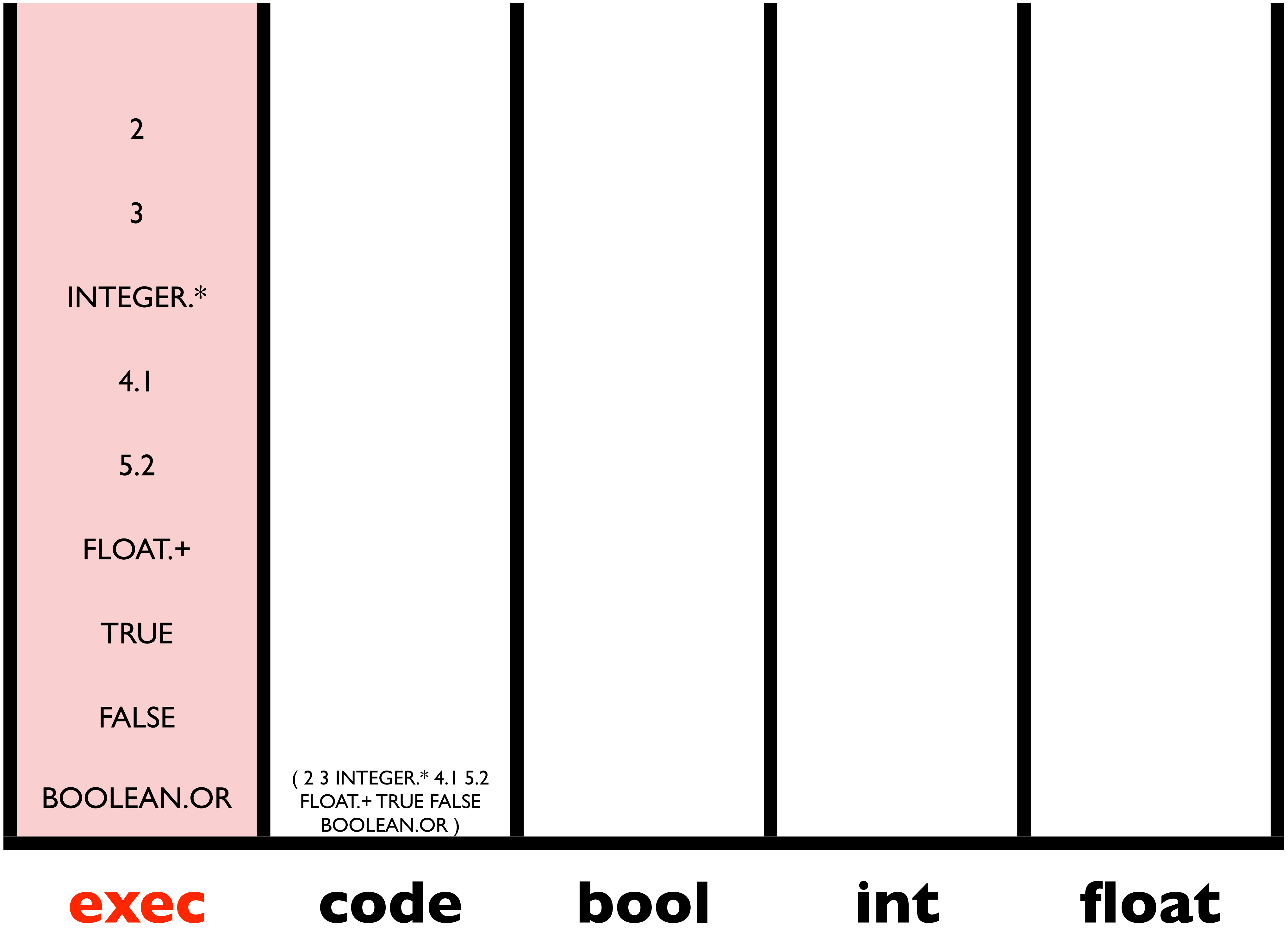
Stack manipulation instructions (all types)	`POP`, `SWAP`, `YANK`, `DUP`, `STACKDEPTH`, `SHOVE`, `FLUSH`, $=$
Math (`INTEGER` and `FLOAT`)	$+$, $-$, $/$, $*$, $>$, $<$, `MIN`, `MAX`
Logic (`BOOLEAN`)	`AND`, `OR`, `NOT`, `FROMINTEGER`
Code manipulation (`CODE`)	`QUOTE`, `CAR`, `CDR`, `CONS`, `INSERT`,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

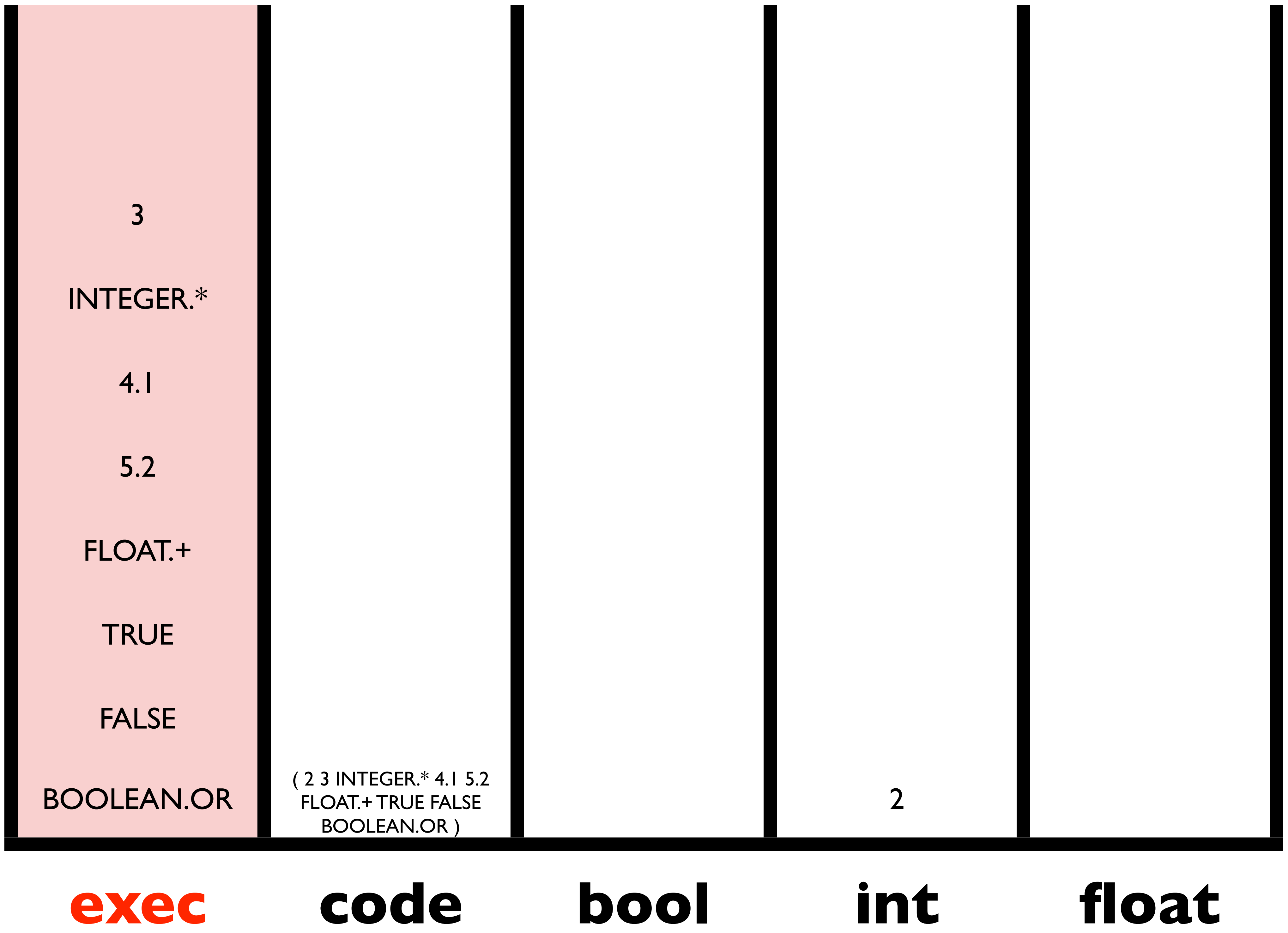
Push(3) Semantics

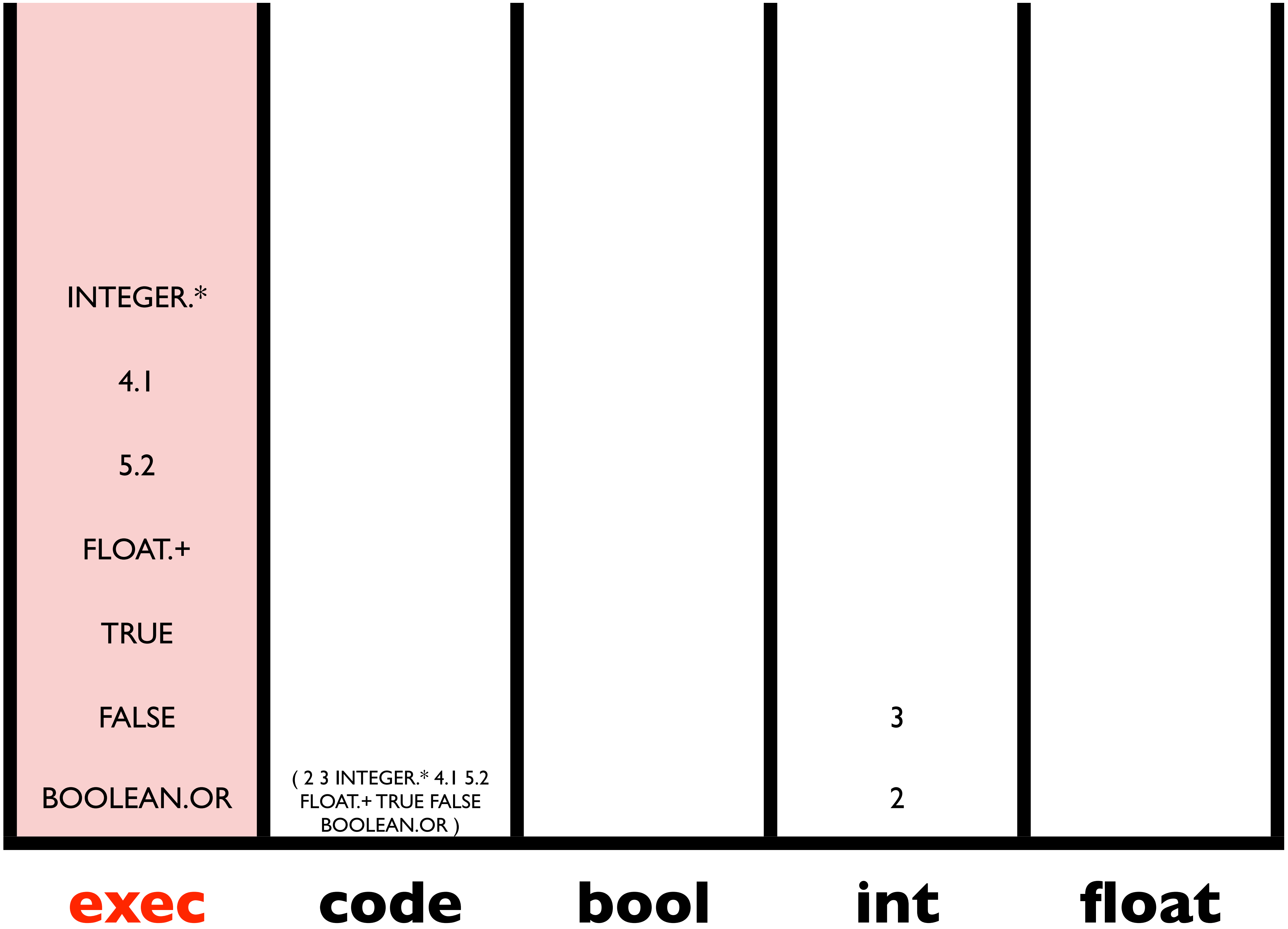
- To execute program P:
  1. Push P onto the `EXEC` stack.
  2. While the `EXEC` stack is not empty, pop and process the top element of the `EXEC` stack, E:
     (a) If E is an instruction: execute E (accessing whatever stacks are required).
     (b) If E is a literal: push E onto the appropriate stack.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

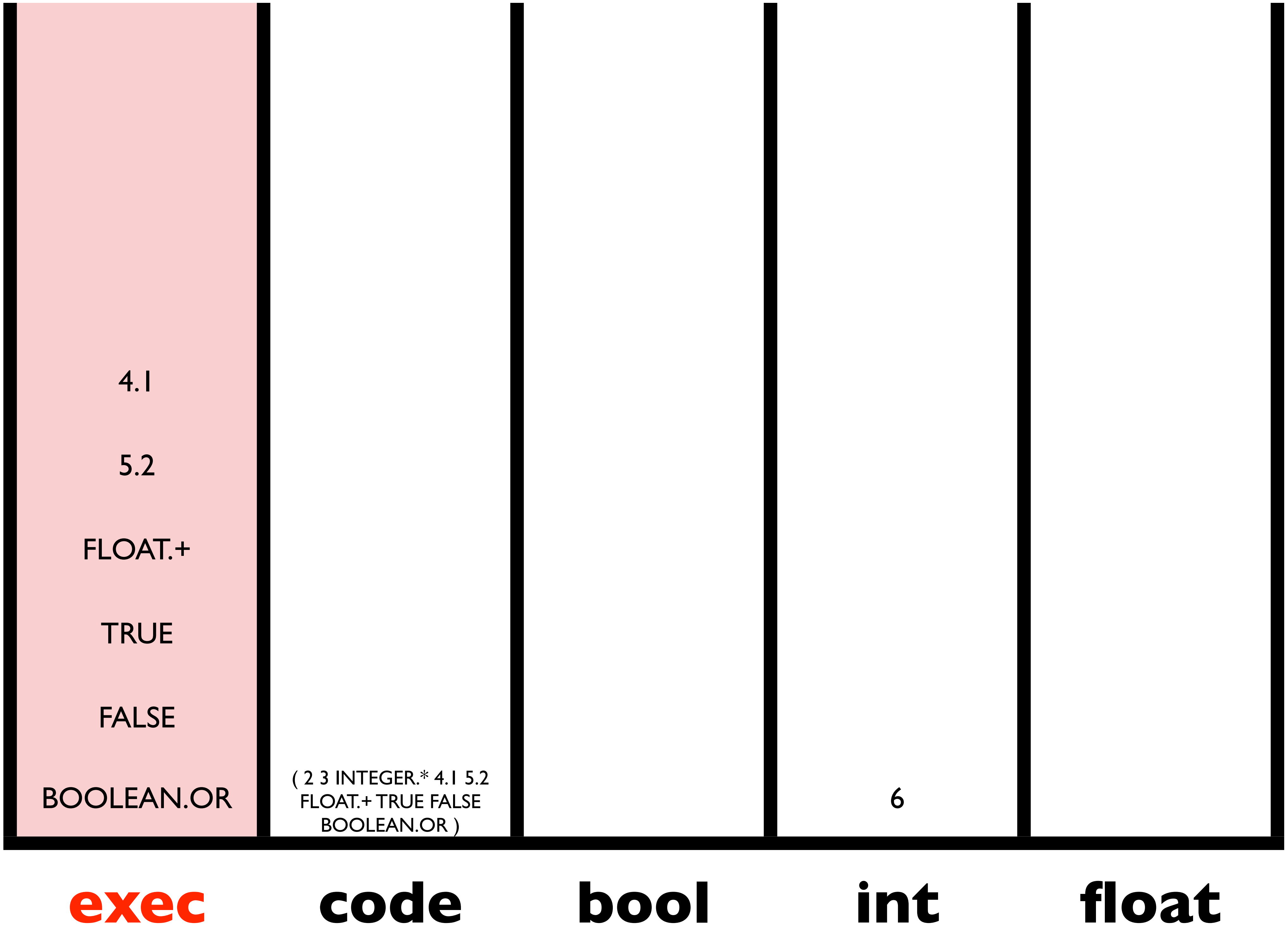
```
( 2 3 INTEGER.* 4.1 5.2 FLOAT.+
TRUE FALSE BOOLEAN.OR )
```

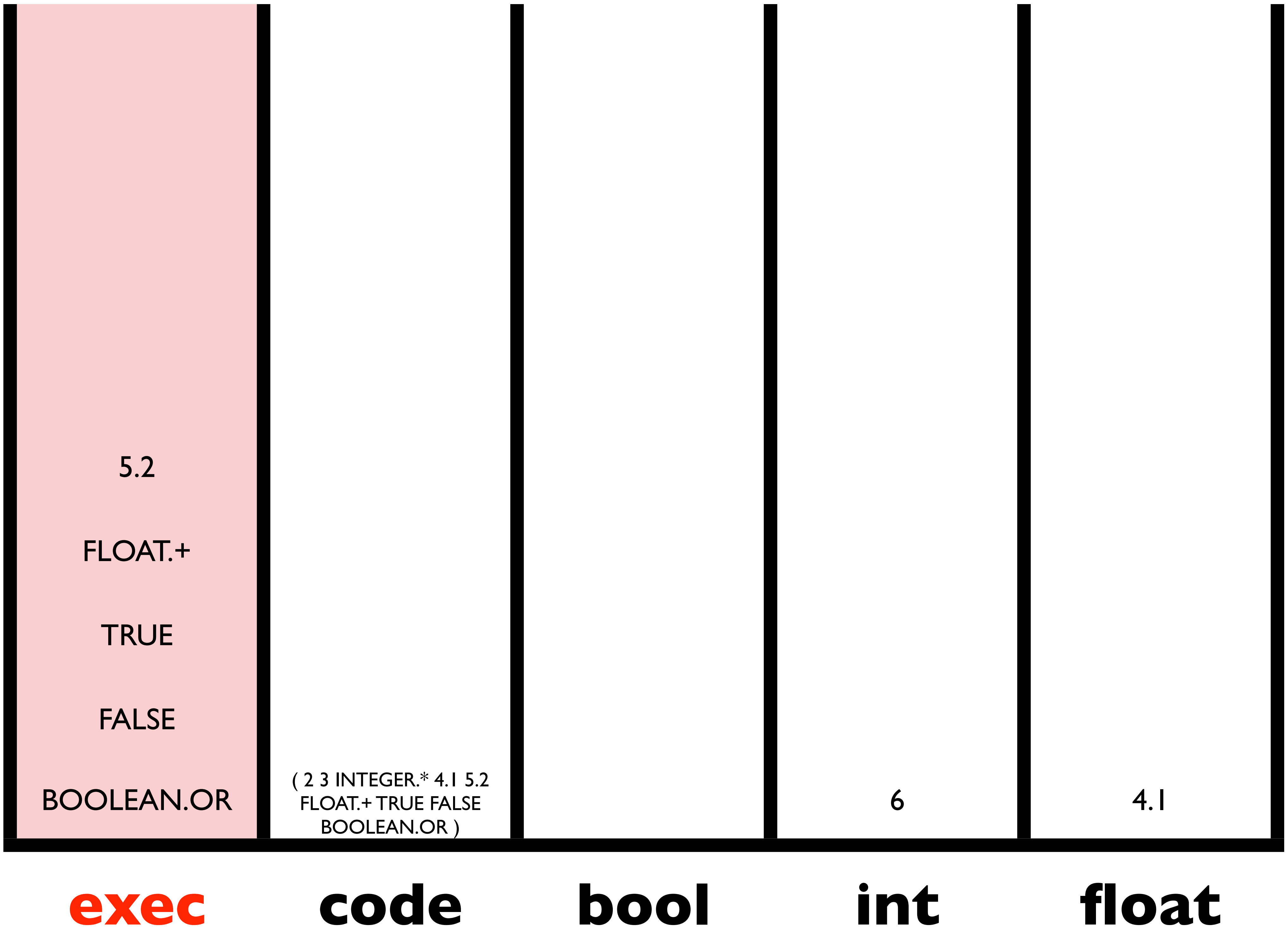

(2 3 INTEGER.* 4.1 5.2 FLOAT.+ TRUE FALSE BOOLEAN.OR)
(2 3 INTEGER.* 4.1 5.2 FLOAT.+ TRUE FALSE BOOLEAN.OR)
exec
code
bool
int
float


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

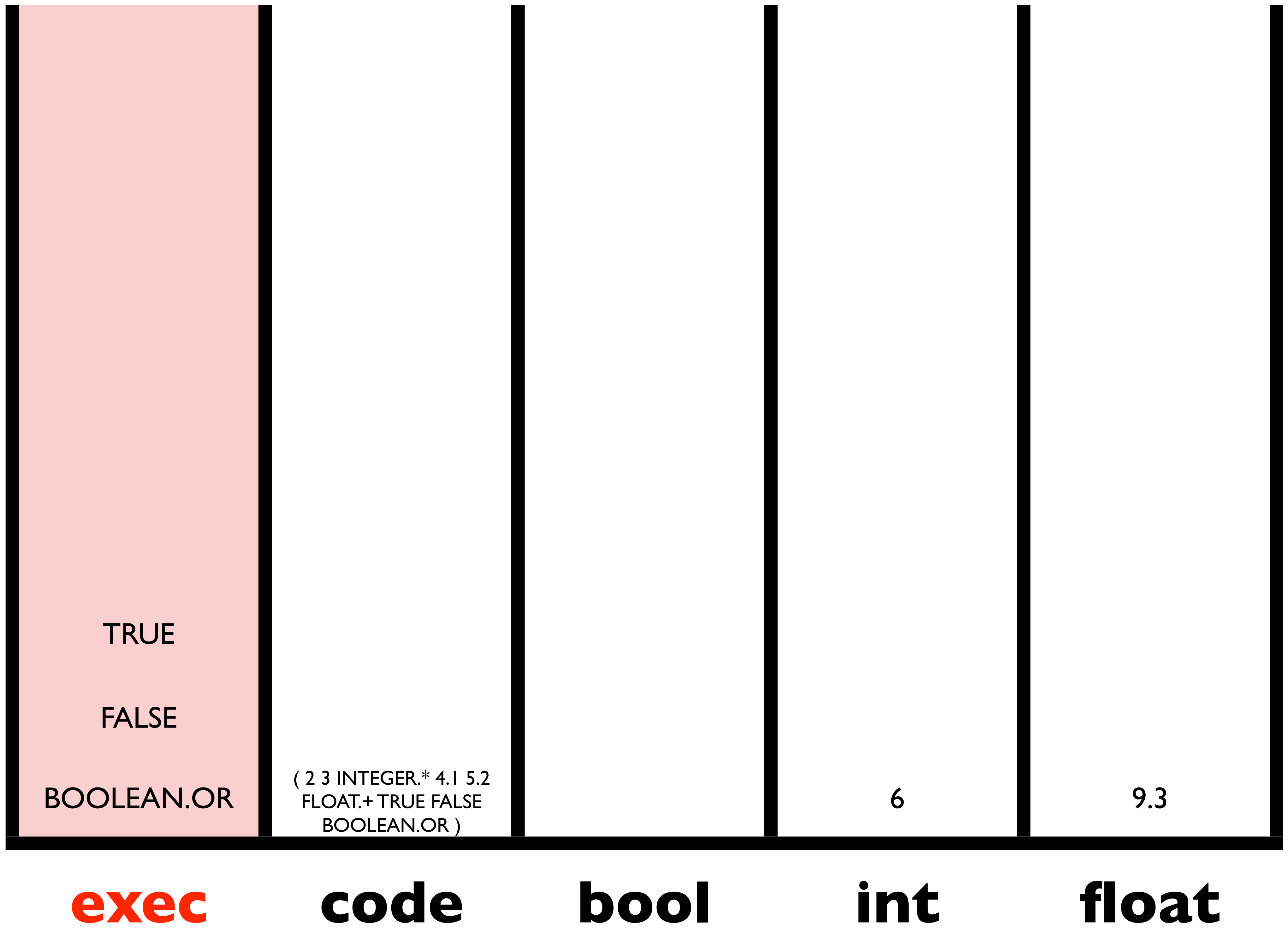

3
INTEGER.*
4.1
5.2
FLOAT.+
TRUE
FALSE
BOOLEAN.OR
(2 3 INTEGER.* 4.1 5.2 FLOAT.+ TRUE FALSE BOOLEAN.OR)
2
exec
code
bool
int
float

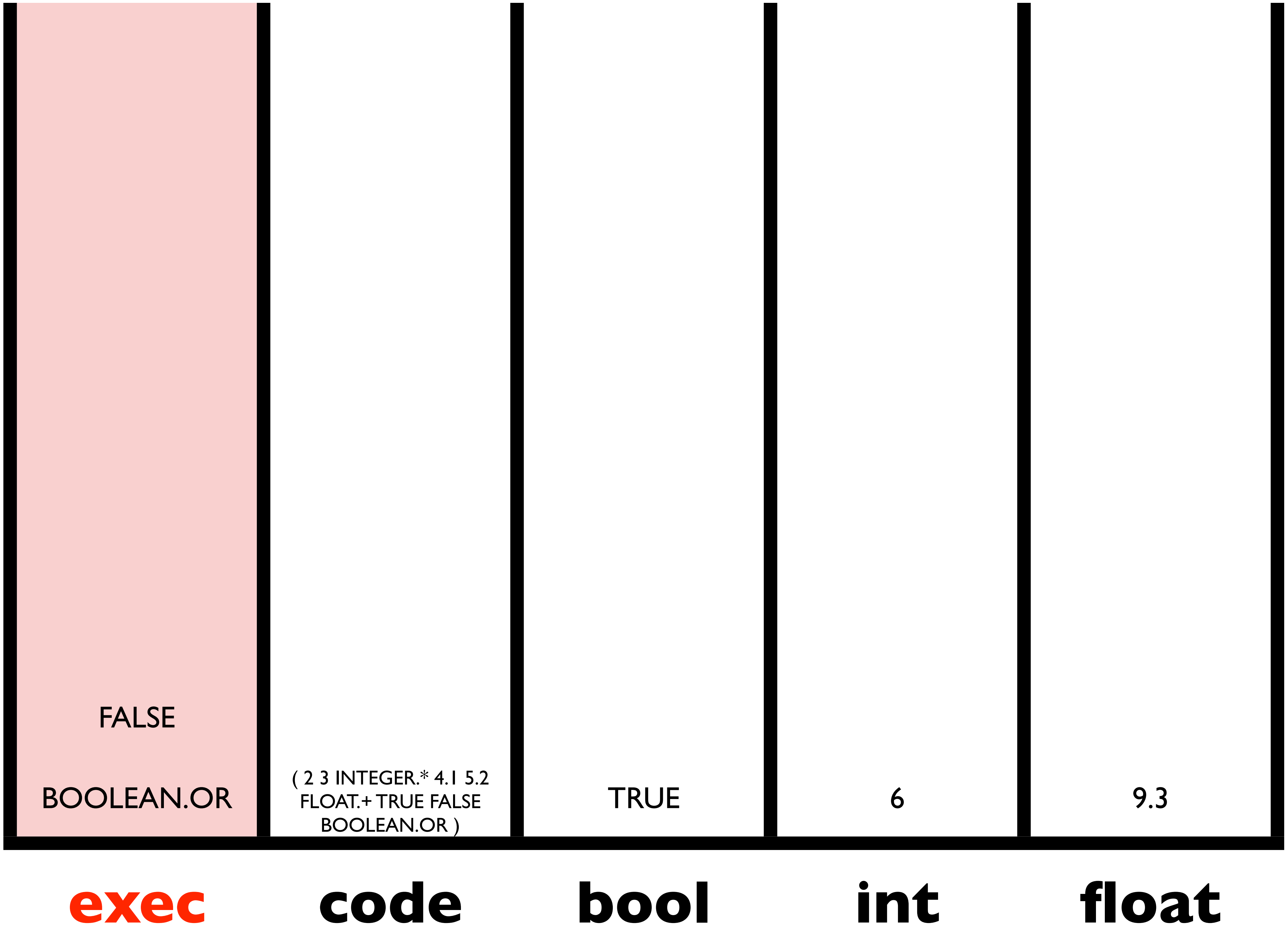

INTEGER.*
4.1
5.2
FLOAT.+
TRUE
FALSE
BOOLEAN.OR
(2 3 INTEGER.* 4.1 5.2 FLOAT.+ TRUE FALSE BOOLEAN.OR)
3
2
exec
code
bool
int
float


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

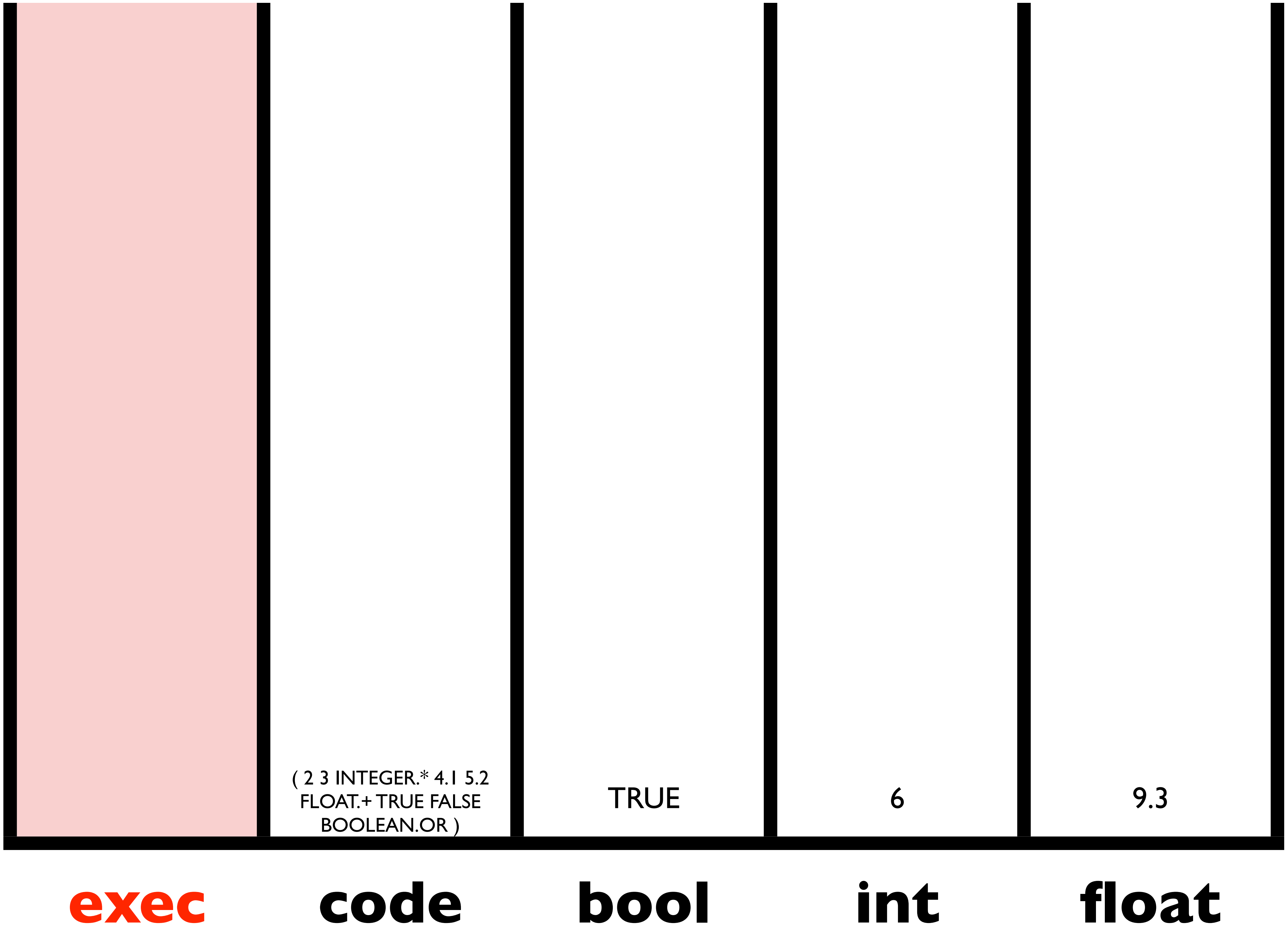

5.2
FLOAT.+
TRUE
FALSE
BOOLEAN.OR
(2 3 INTEGER.* 4.1 5.2 FLOAT.+ TRUE FALSE BOOLEAN.OR)
6
4.1
exec
code
bool
int
float

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


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

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


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

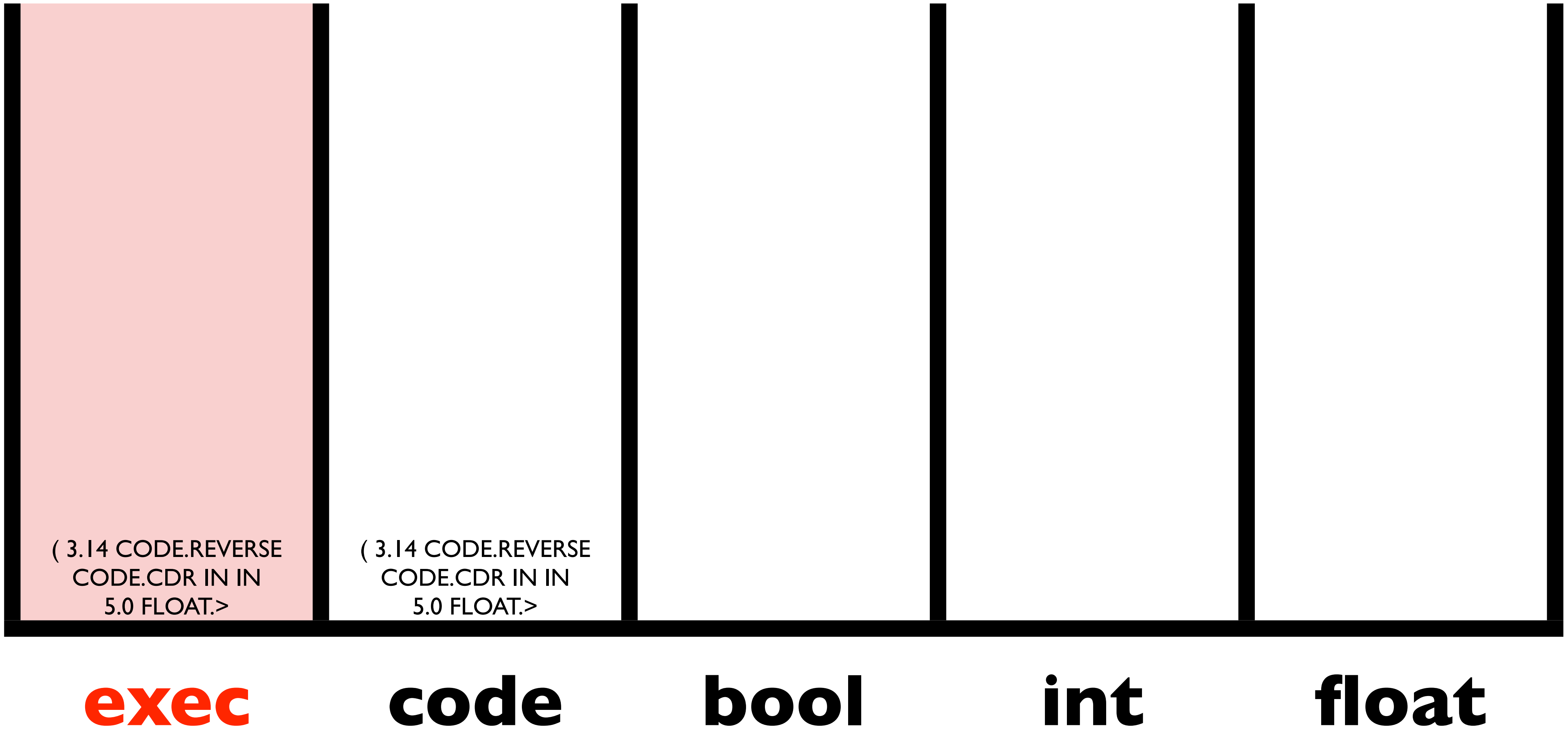
Same Results

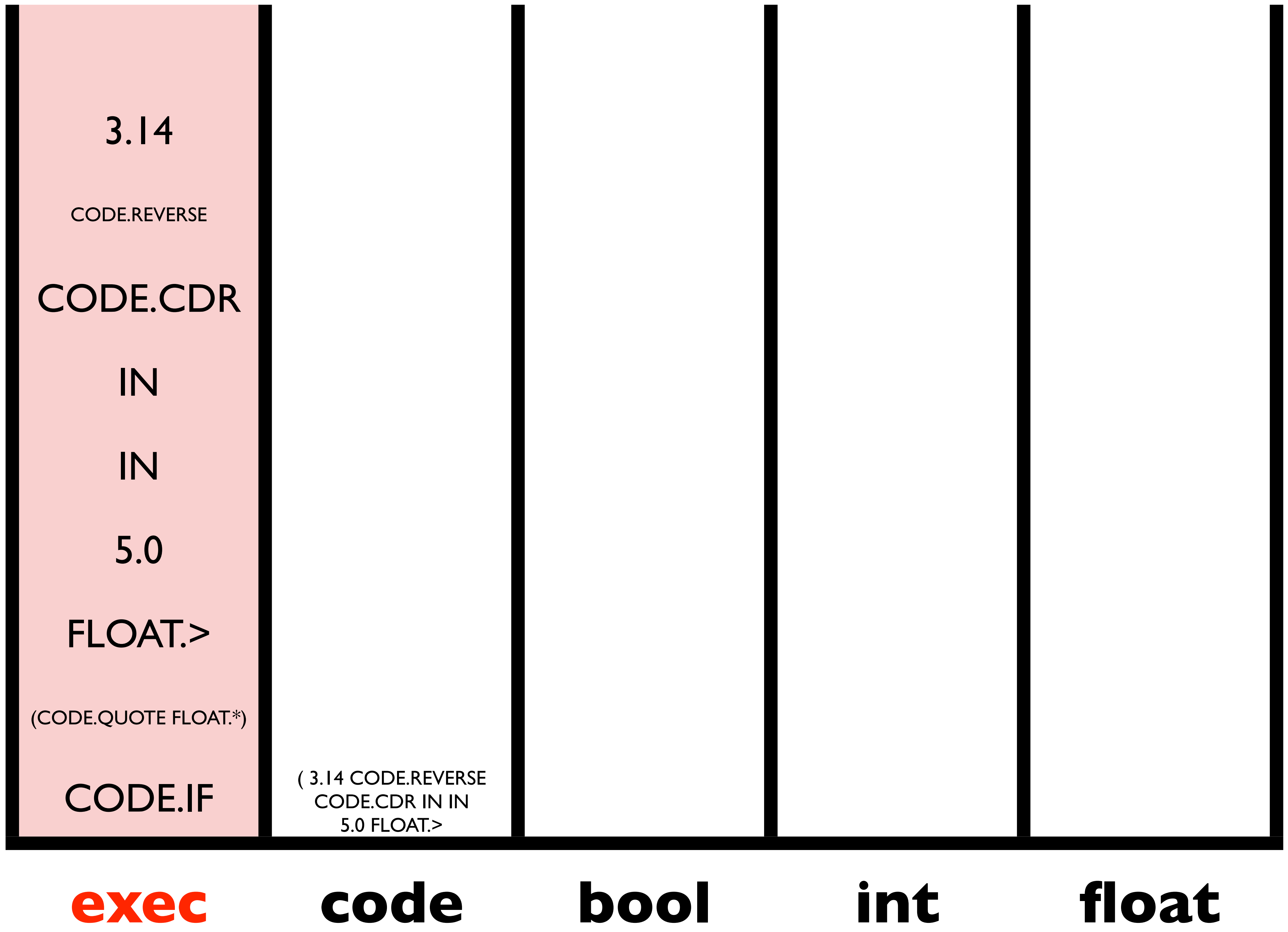
```
( 2 3 INTEGER.* 4.1 5.2 FLOAT.+
TRUE FALSE BOOLEAN.OR )
```

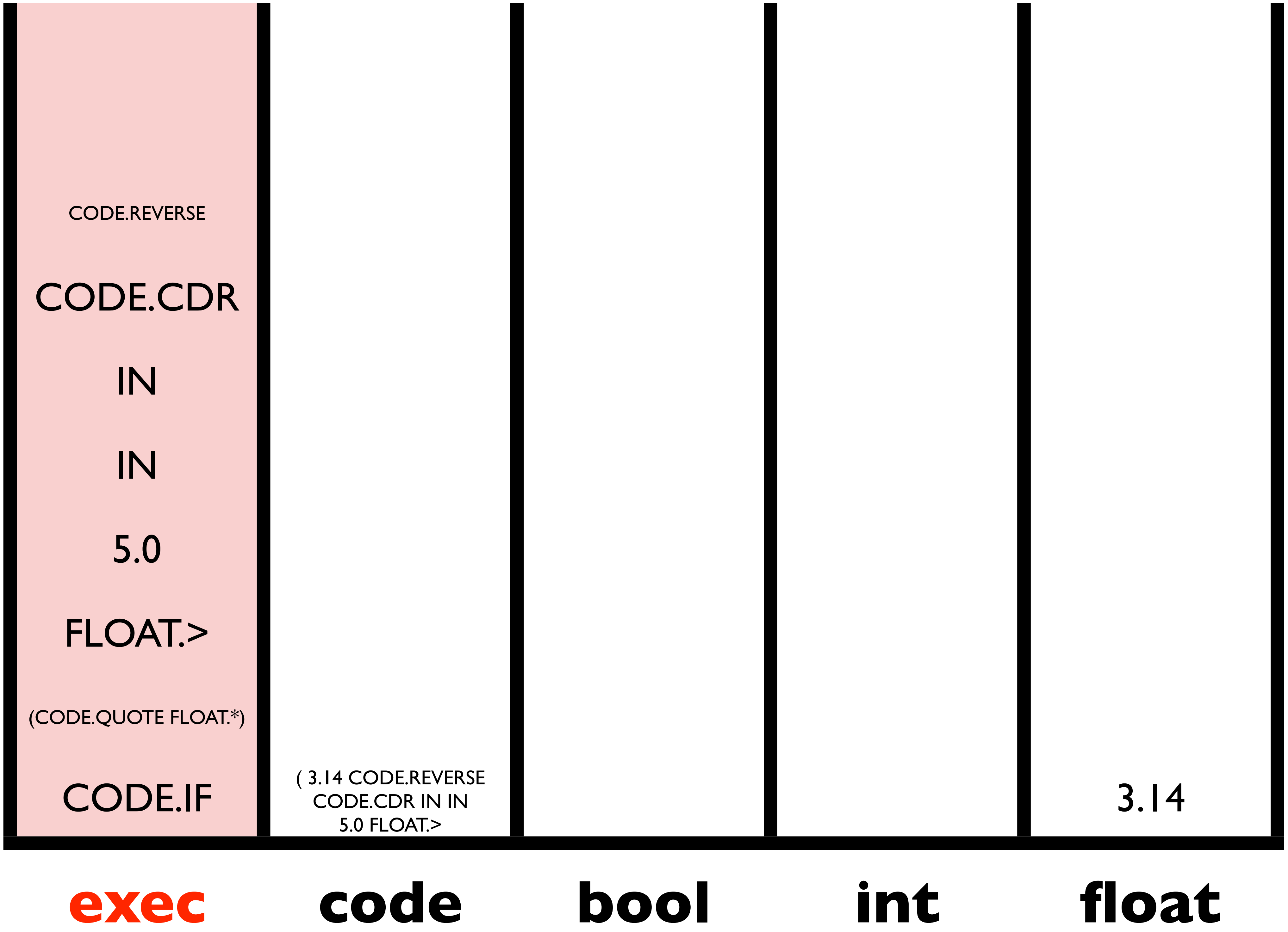
```
( 2 BOOLEAN.AND 4.1 TRUE INTEGER./ FALSE
3 5.2 BOOLEAN.OR INTEGER.* FLOAT.+ )
```

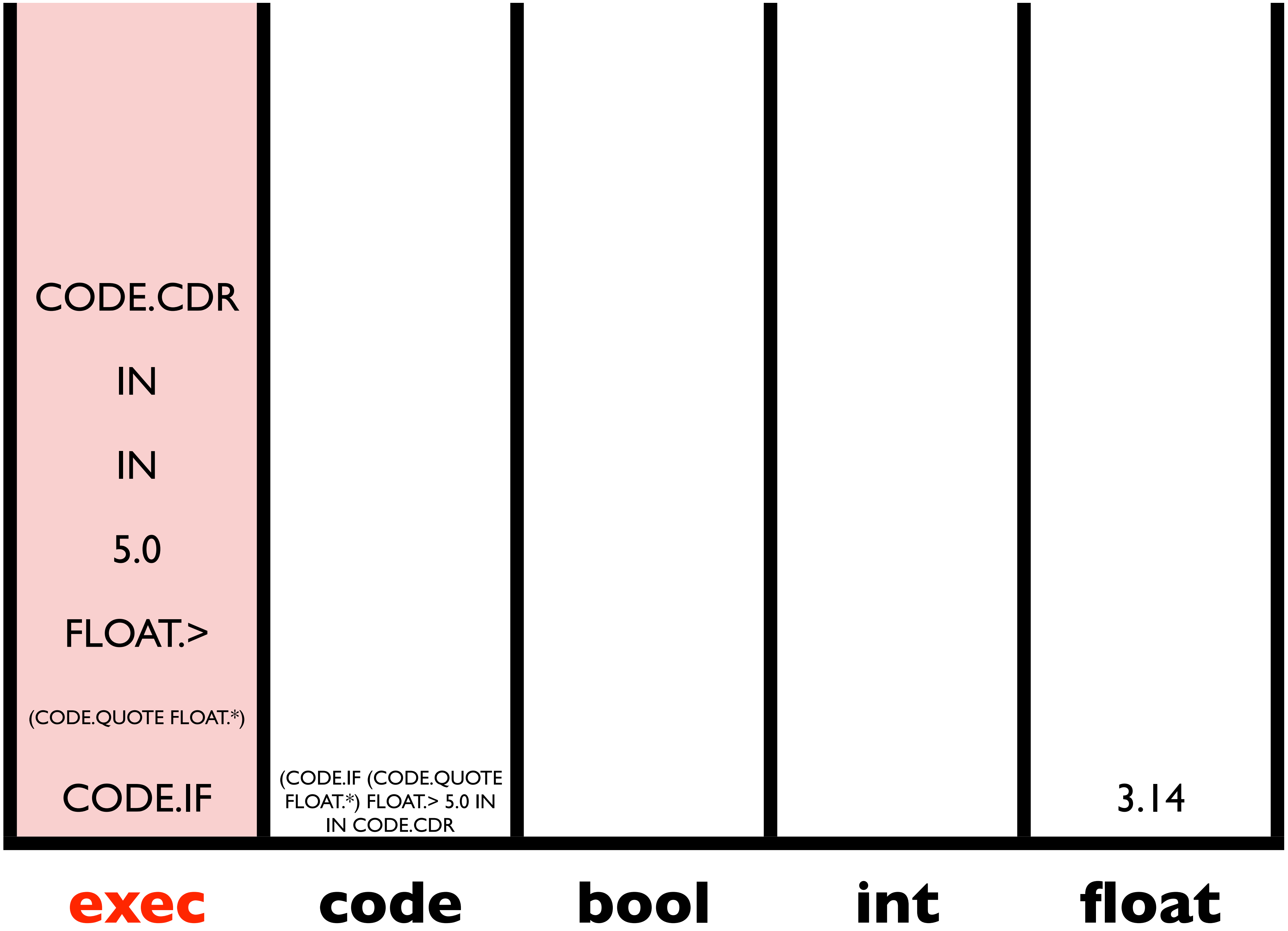
```
( 3.14 CODE.REVERSE CODE.CDR IN IN 5.0
FLOAT.> (CODE.QUOTE FLOAT.*) CODE.IF )
```

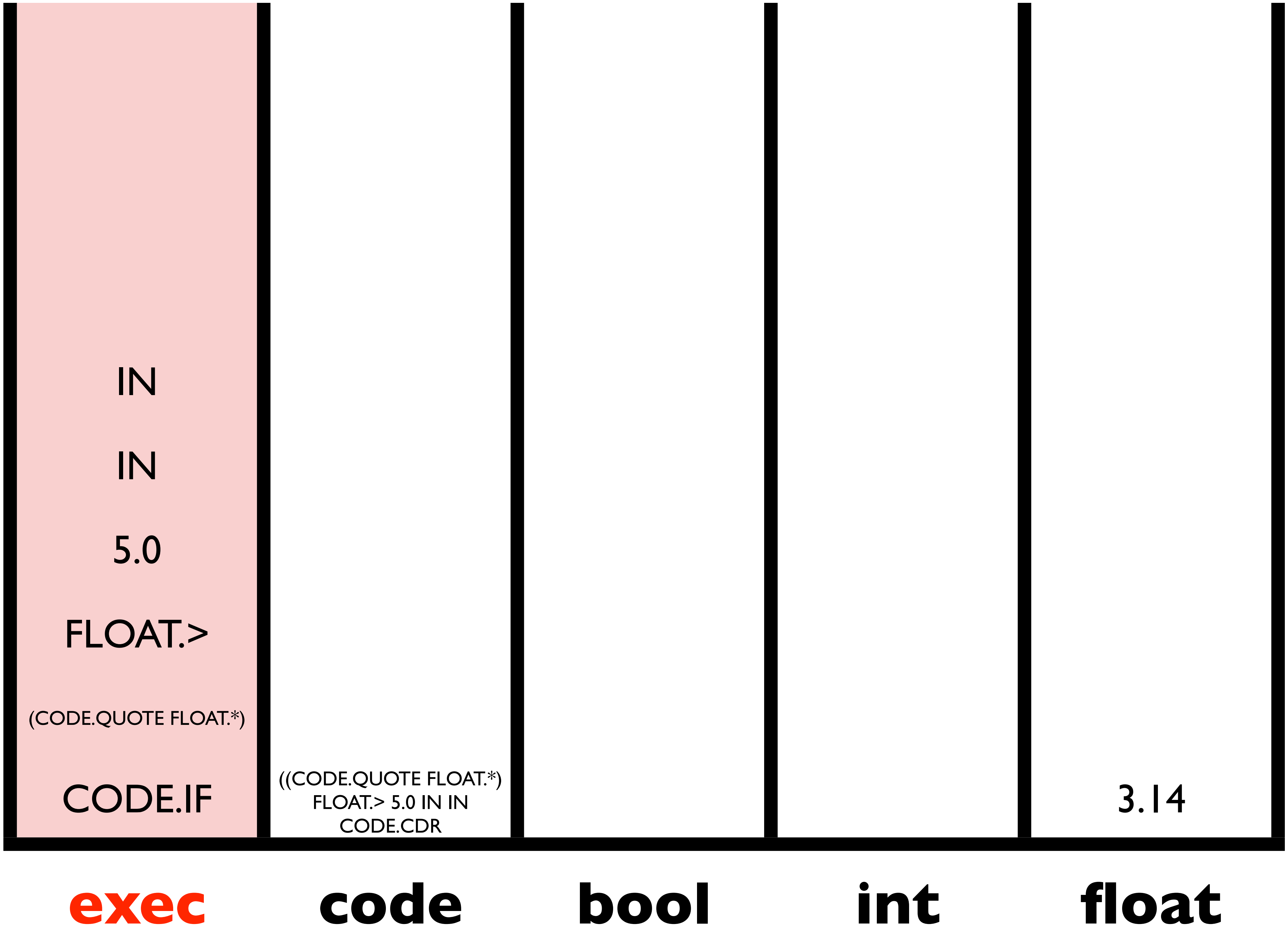
```
IN=4.0
```


(3.14 CODE.REVERSE CODE.CDR IN IN 5.0 FLOAT.>
(3.14 CODE.REVERSE CODE.CDR IN IN 5.0 FLOAT.>
exec
code
bool
int
float


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


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.>
3.14
exec
code
bool
int
float

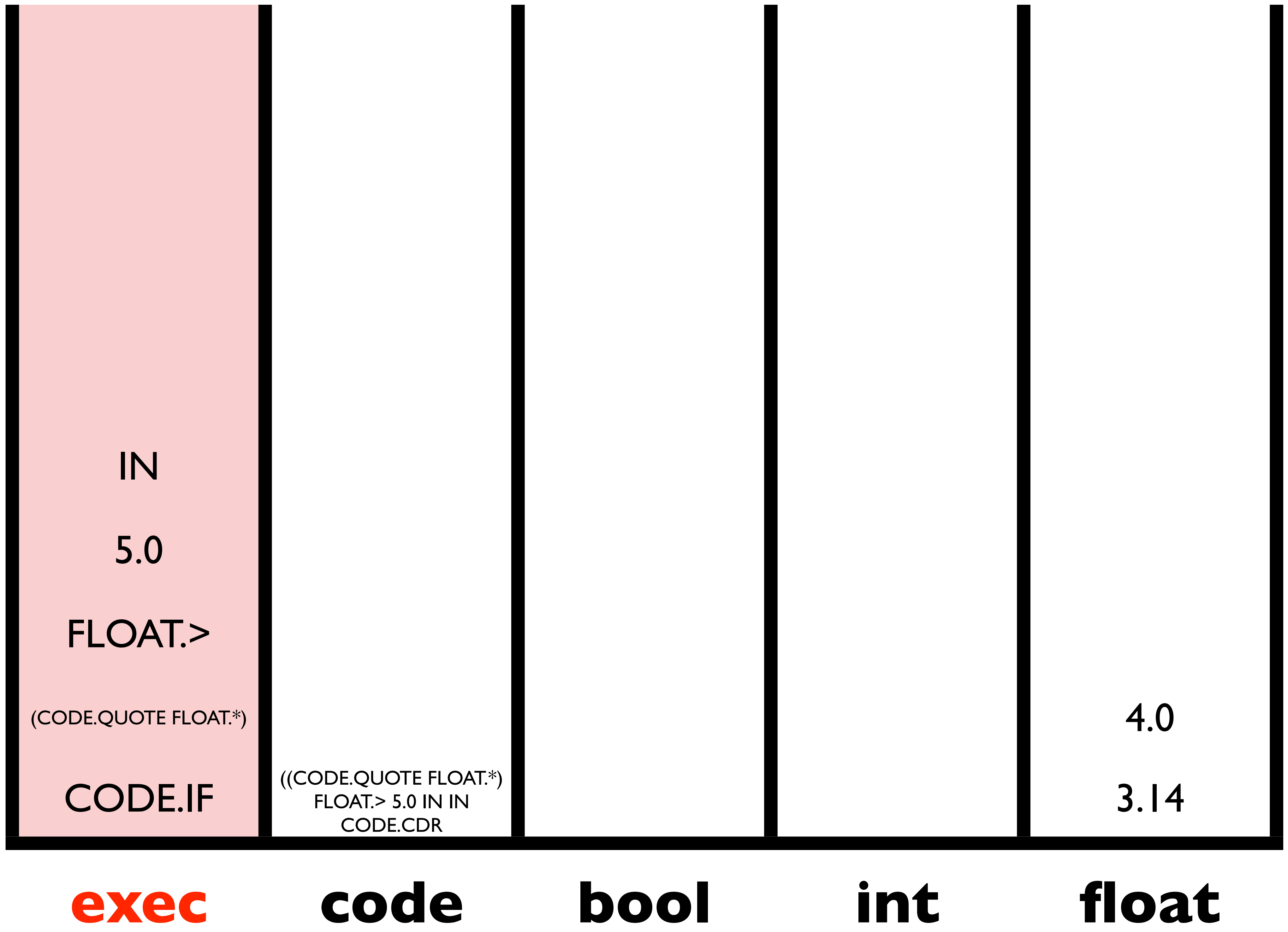

CODE.CDR
IN
IN
5.0
FLOAT.>
(CODE.QUOTE FLOAT.*)
CODE.IF
(CODE.IF (CODE.QUOTE FLOAT.*) FLOAT.> 5.0 IN IN CODE.CDR
3.14
exec
code
bool
int
float

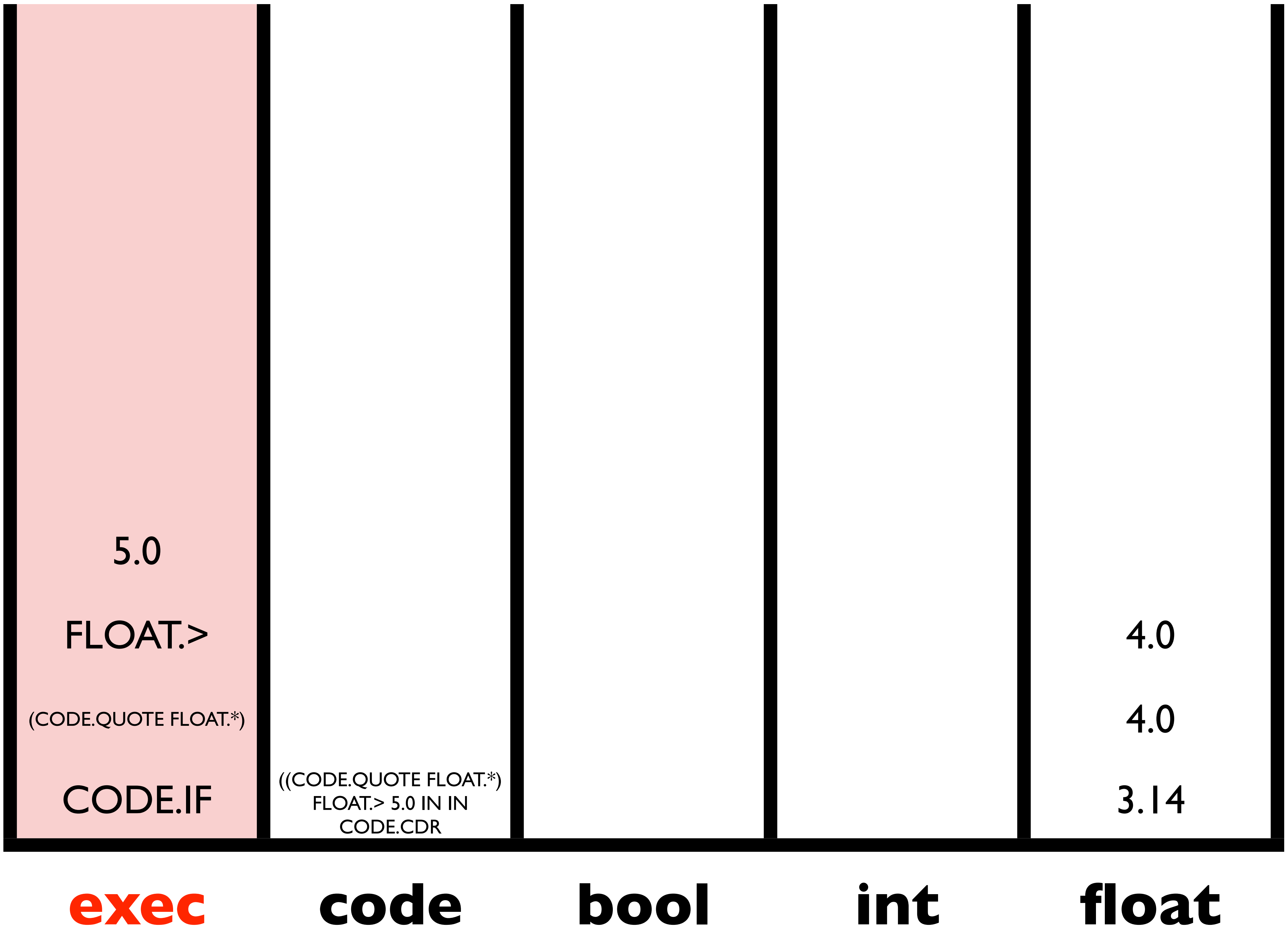


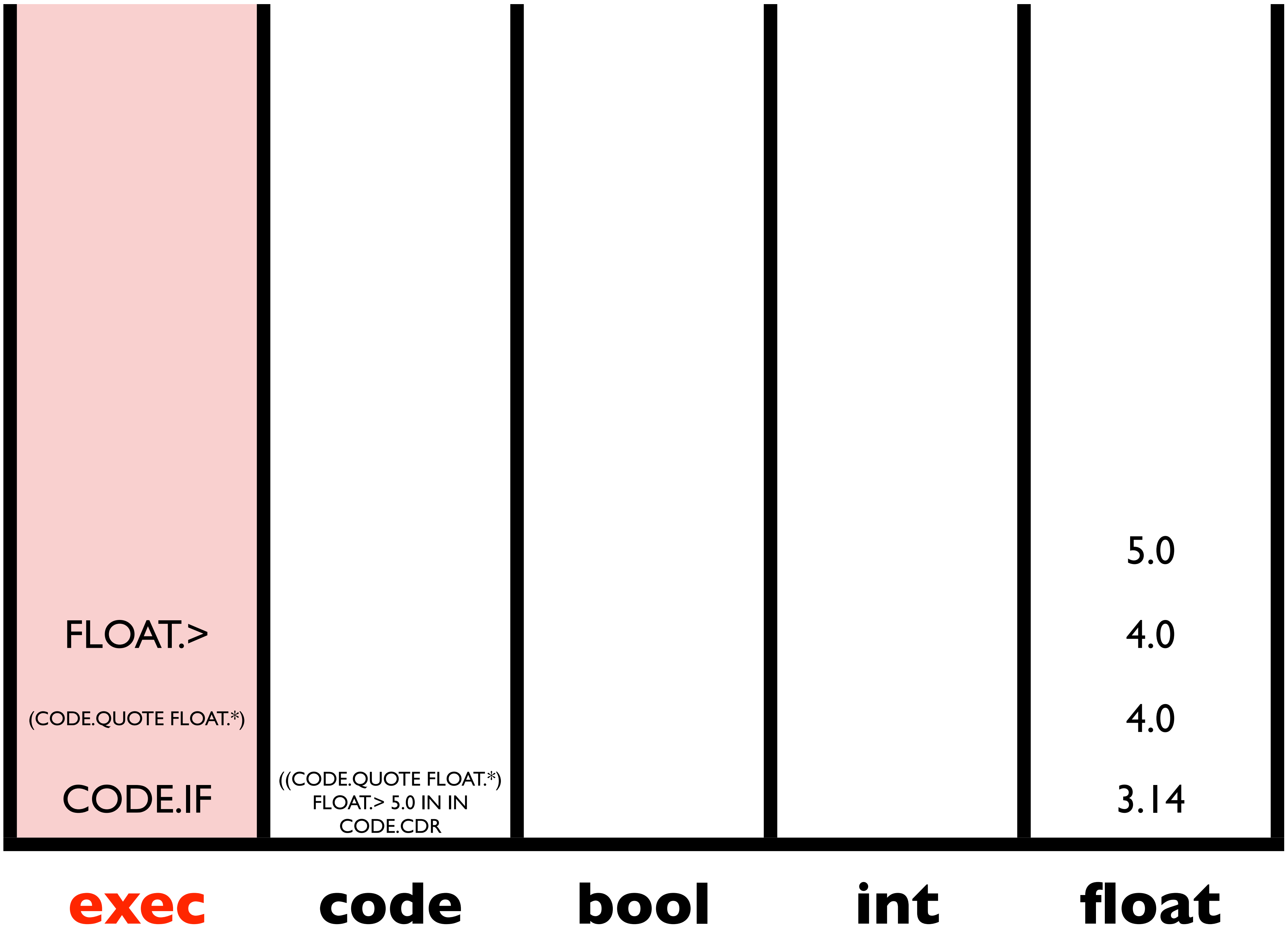
```
exec:
IN
IN
5.0
FLOAT.>
(CODE.QUOTE FLOAT.*)
CODE.IF

code:
((CODE.QUOTE FLOAT.*)
FLOAT.> 5.0 IN IN
CODE.CDR

float:
3.14
```

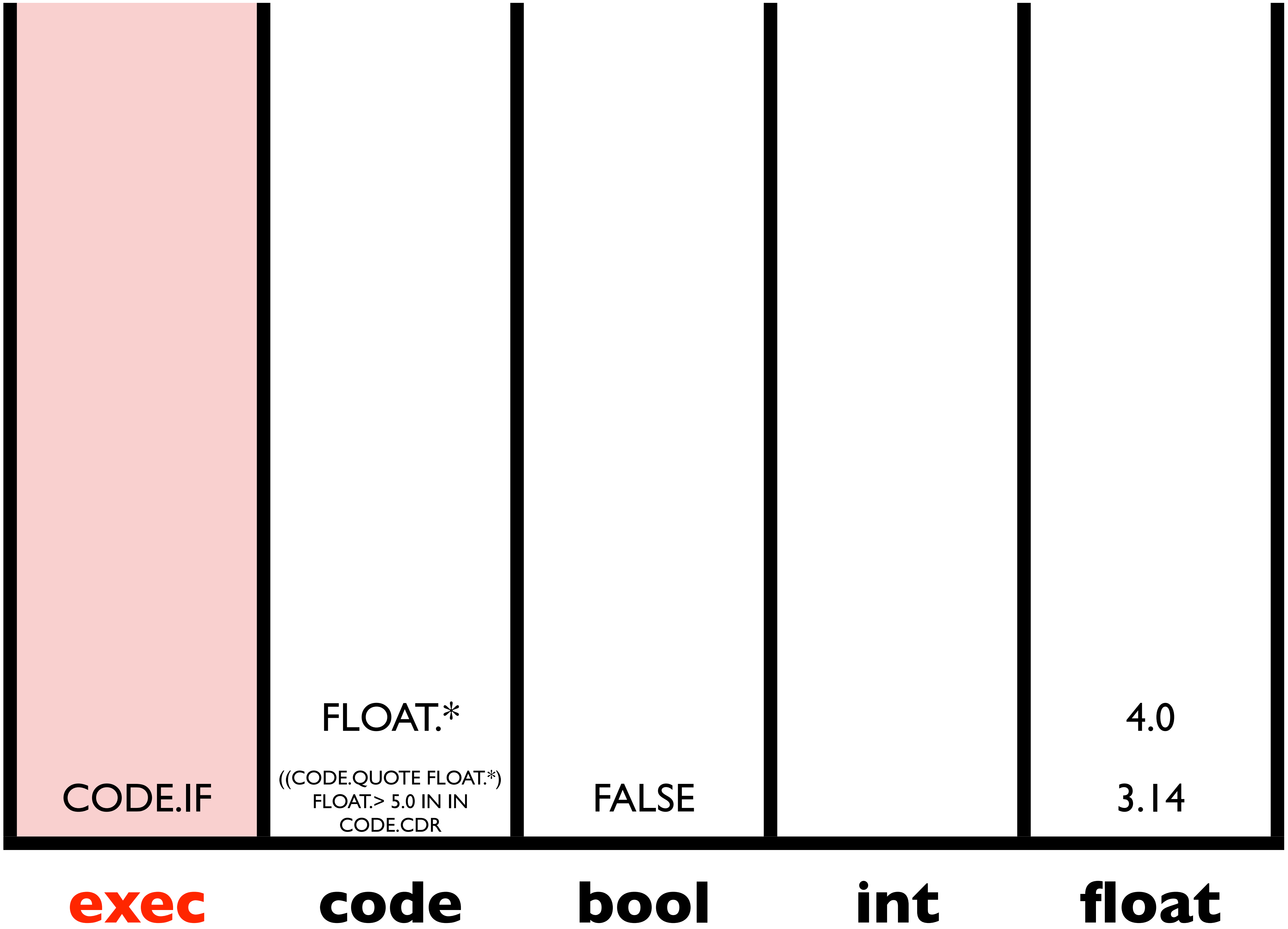

IN
5.0
FLOAT.>
(CODE.QUOTE FLOAT.*)
CODE.IF
((CODE.QUOTE FLOAT.*) FLOAT.> 5.0 IN IN CODE.CDR
4.0
3.14
exec
code
bool
int
float

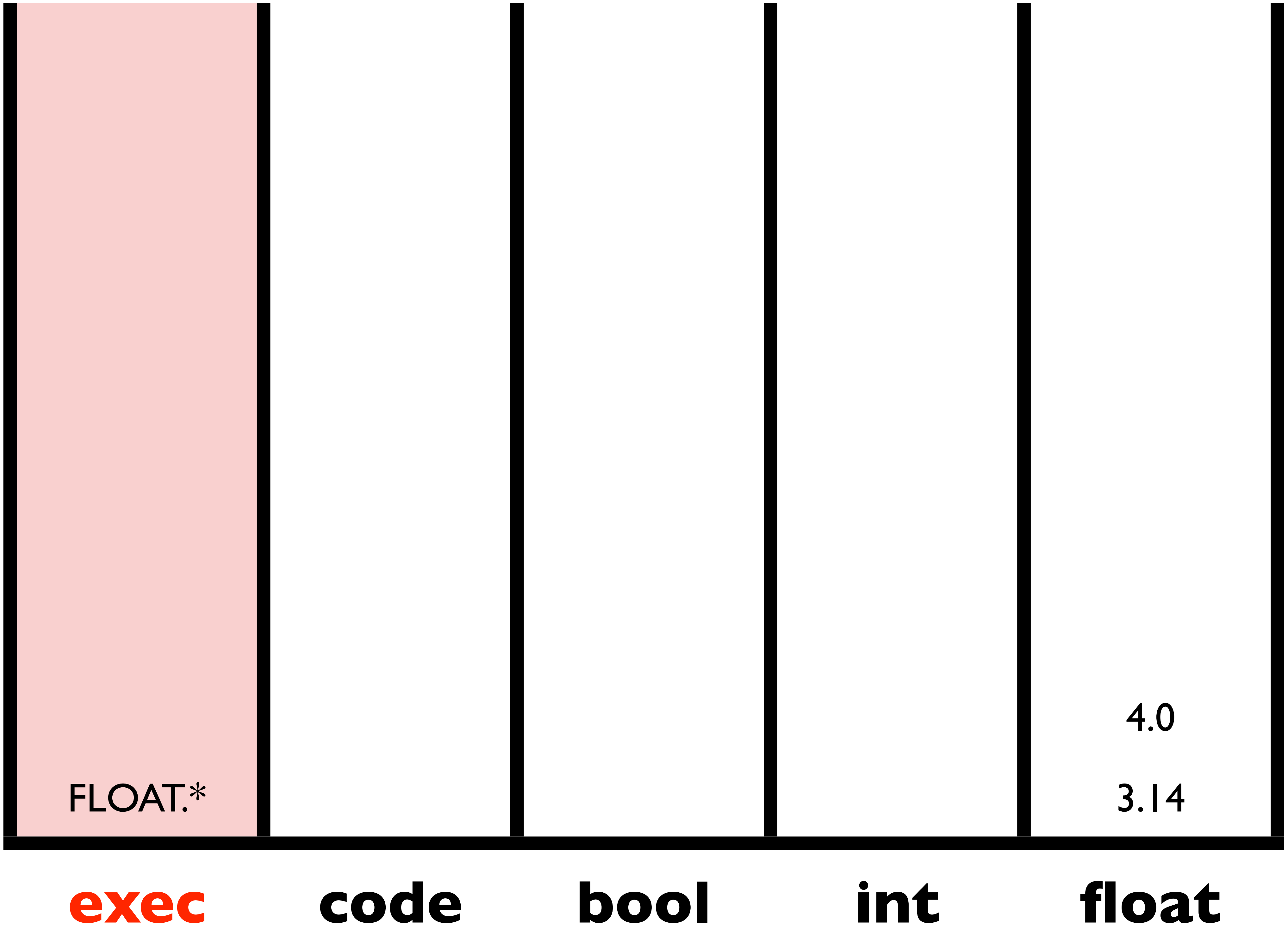

5.0
FLOAT.>
(CODE.QUOTE FLOAT.*)
CODE.IF
((CODE.QUOTE FLOAT.*) FLOAT.> 5.0 IN IN CODE.CDR
4.0
4.0
3.14
exec
code
bool
int
float

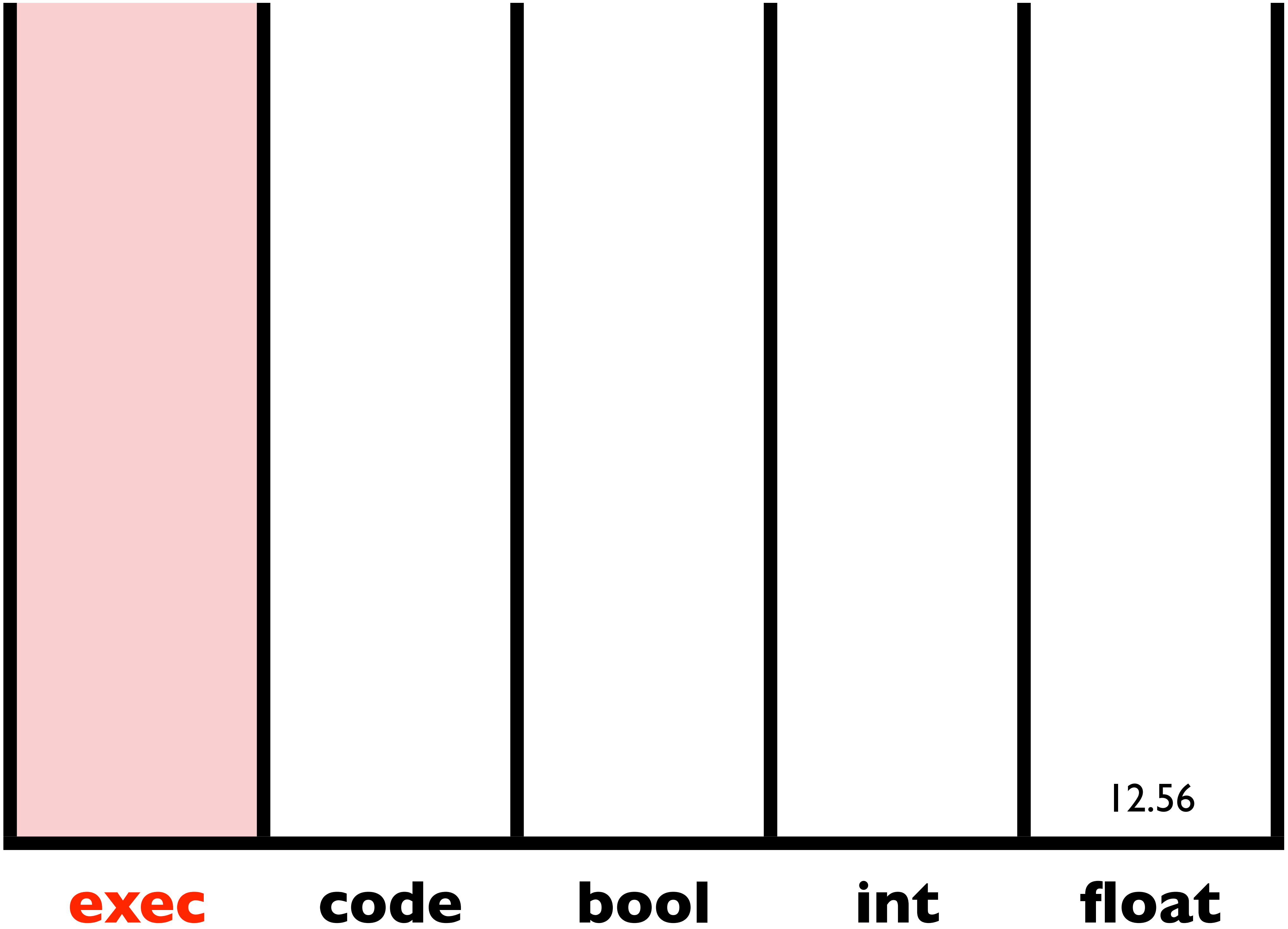

FLOAT.>
(CODE.QUOTE FLOAT.*)
CODE.IF
((CODE.QUOTE FLOAT.*) FLOAT.> 5.0 IN IN CODE.CDR
5.0
4.0
4.0
3.14
exec
code
bool
int
float

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

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

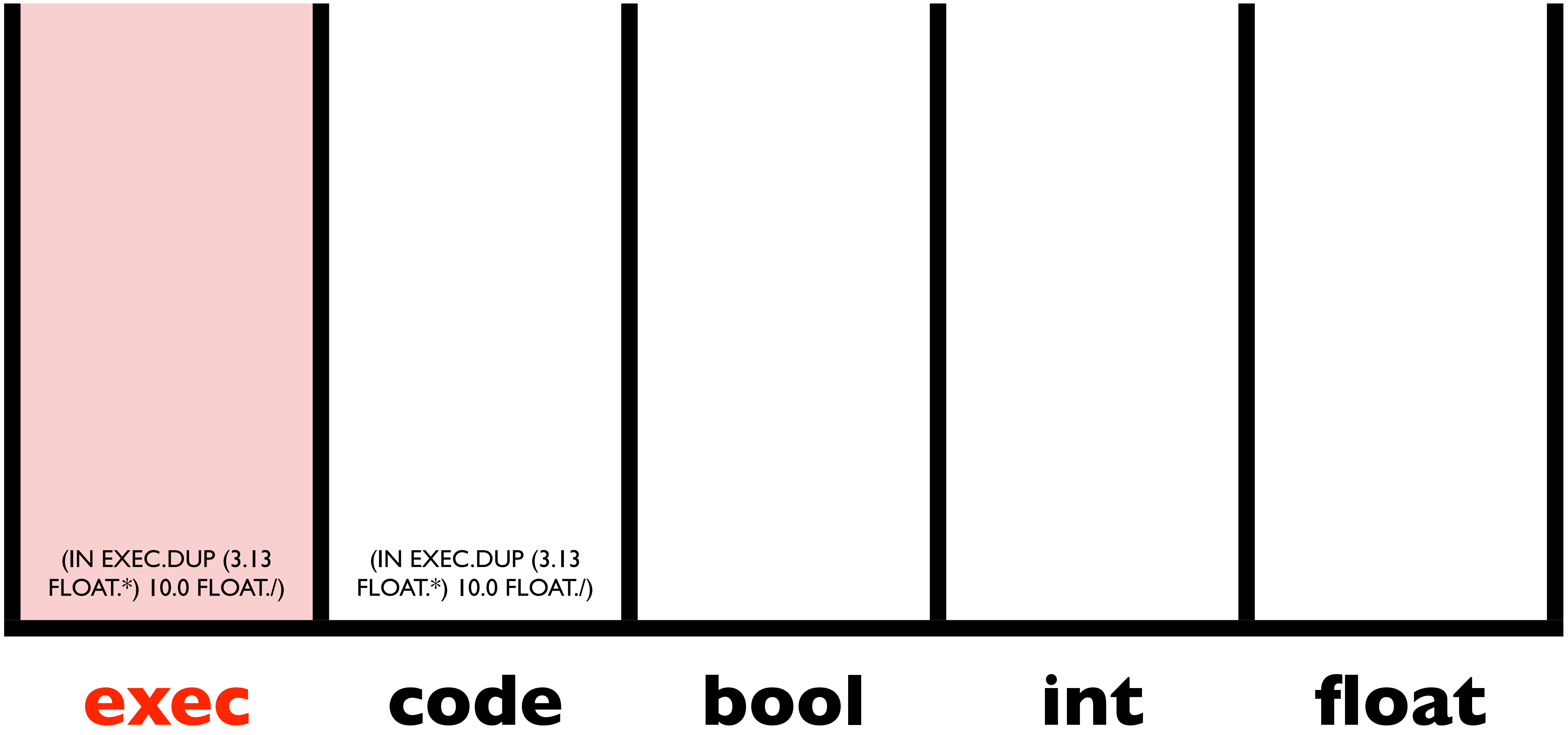

CODE.IF
FLOAT.*
((CODE.QUOTE FLOAT.*) FLOAT.> 5.0 IN IN CODE.CDR
FALSE
4.0
3.14
exec
code
bool
int
float

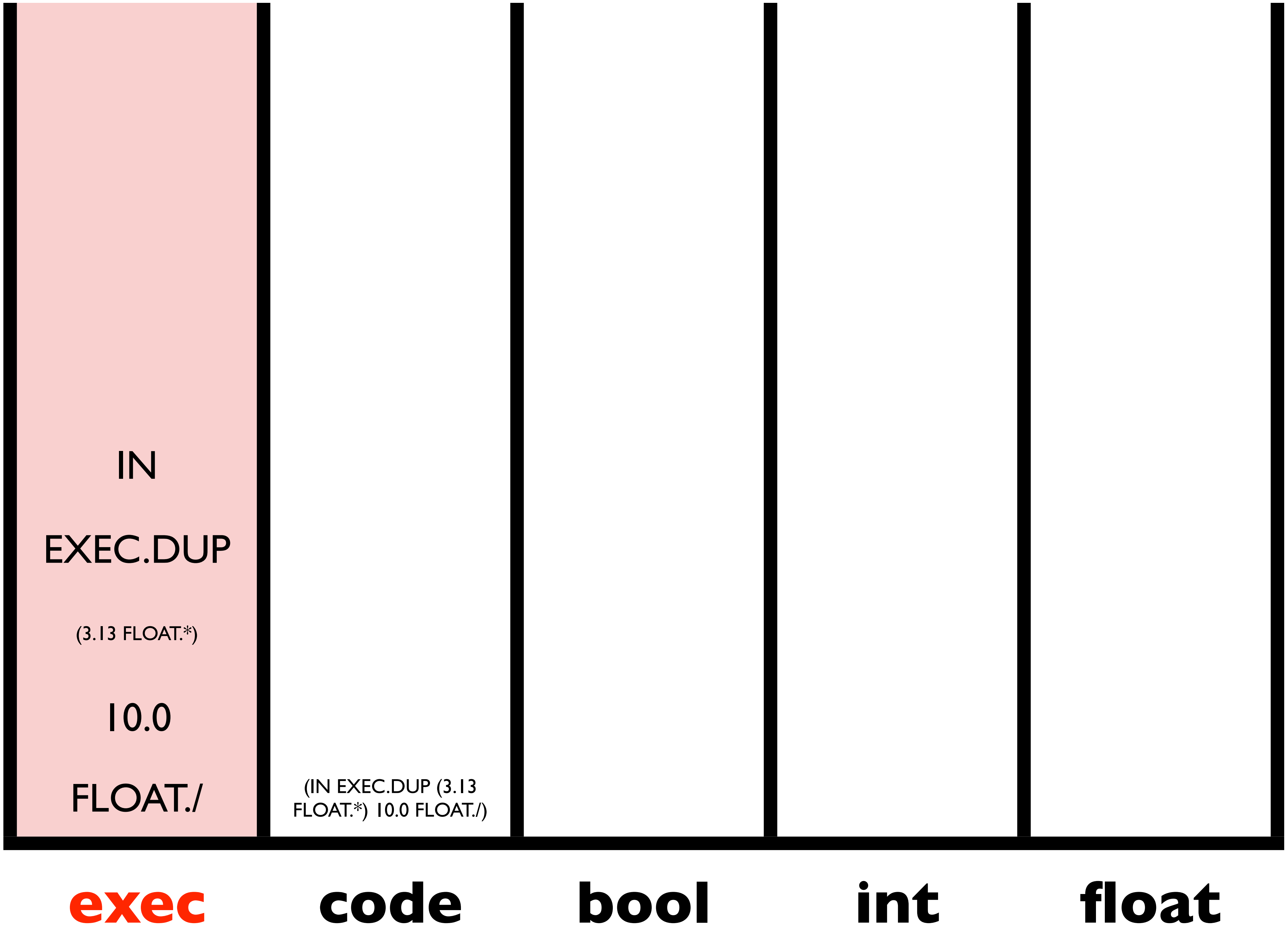

FLOAT.*
4.0
3.14
exec
code
bool
int
float


12.56
exec
code
bool
int
float

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

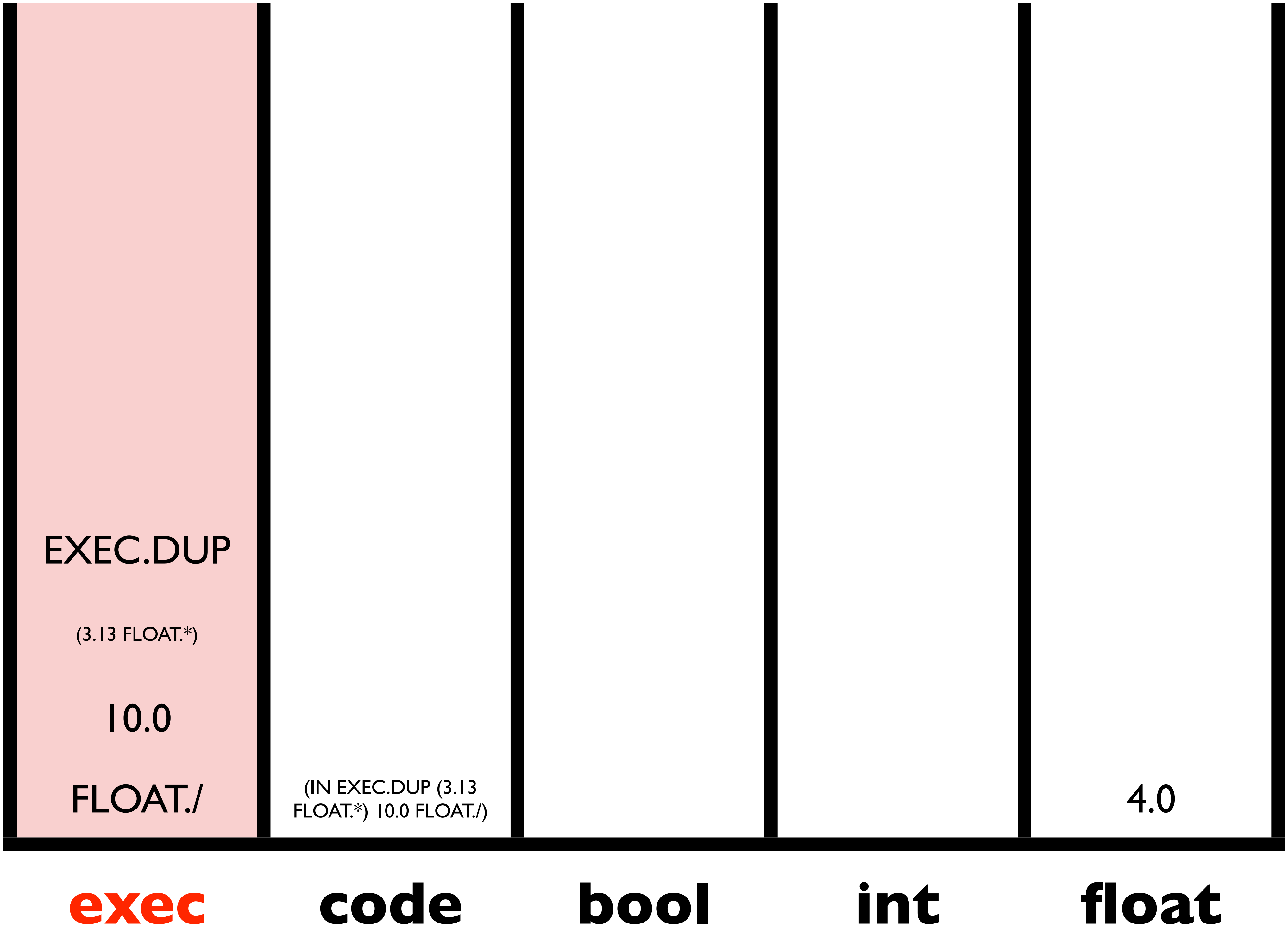
```
IN=4.0
```

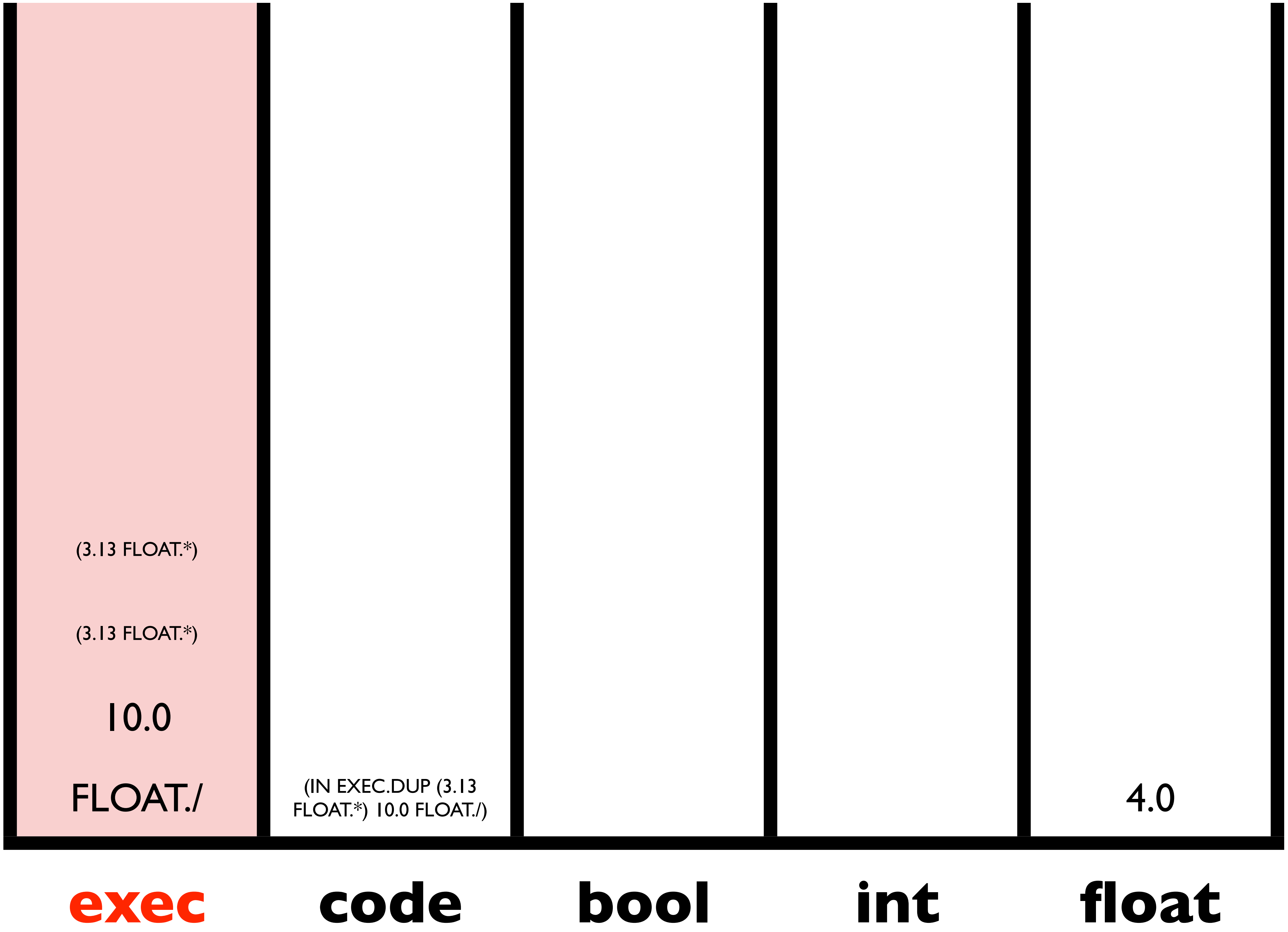

(IN EXEC.DUP (3.13 FLOAT.*) 10.0 FLOAT./)
(IN EXEC.DUP (3.13 FLOAT.*) 10.0 FLOAT./)
exec
code
bool
int
float

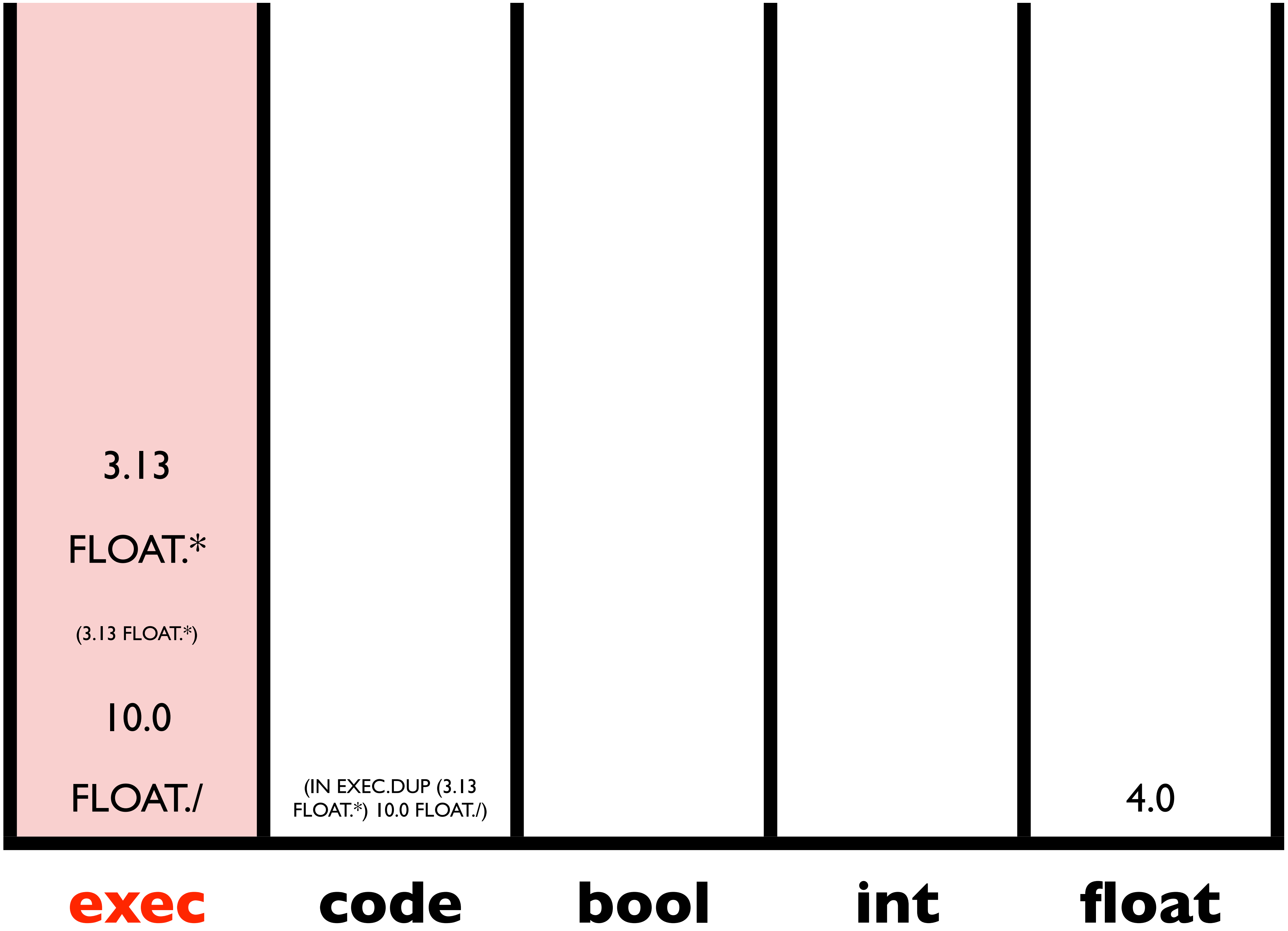


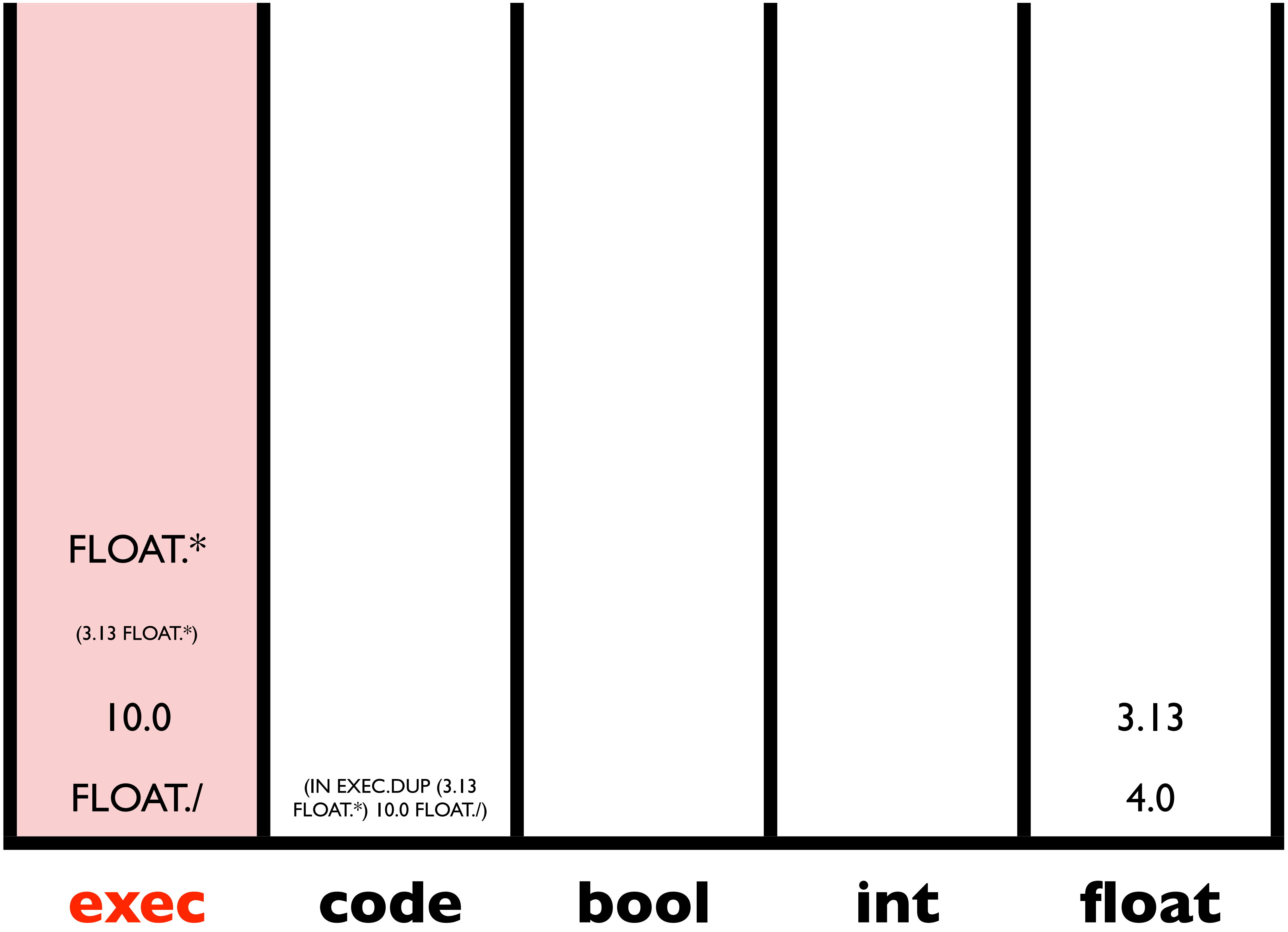
```
IN
EXEC.DUP
(3.13 FLOAT.*)
10.0
FLOAT./
```

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

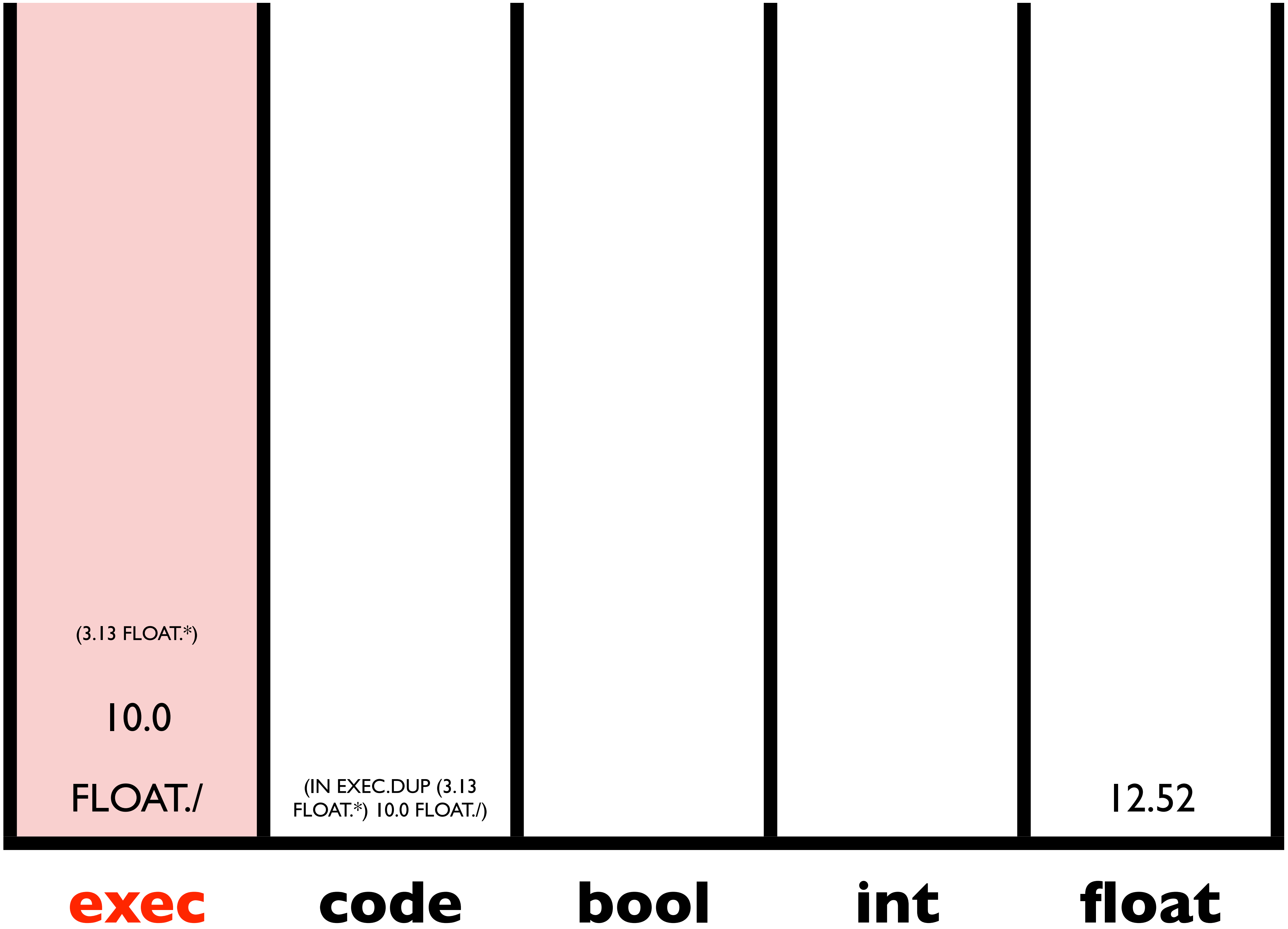

EXEC.DUP
(3.13 FLOAT.*)
10.0
FLOAT./
(IN EXEC.DUP (3.13 FLOAT.*) 10.0 FLOAT./)
4.0
exec
code
bool
int
float


(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



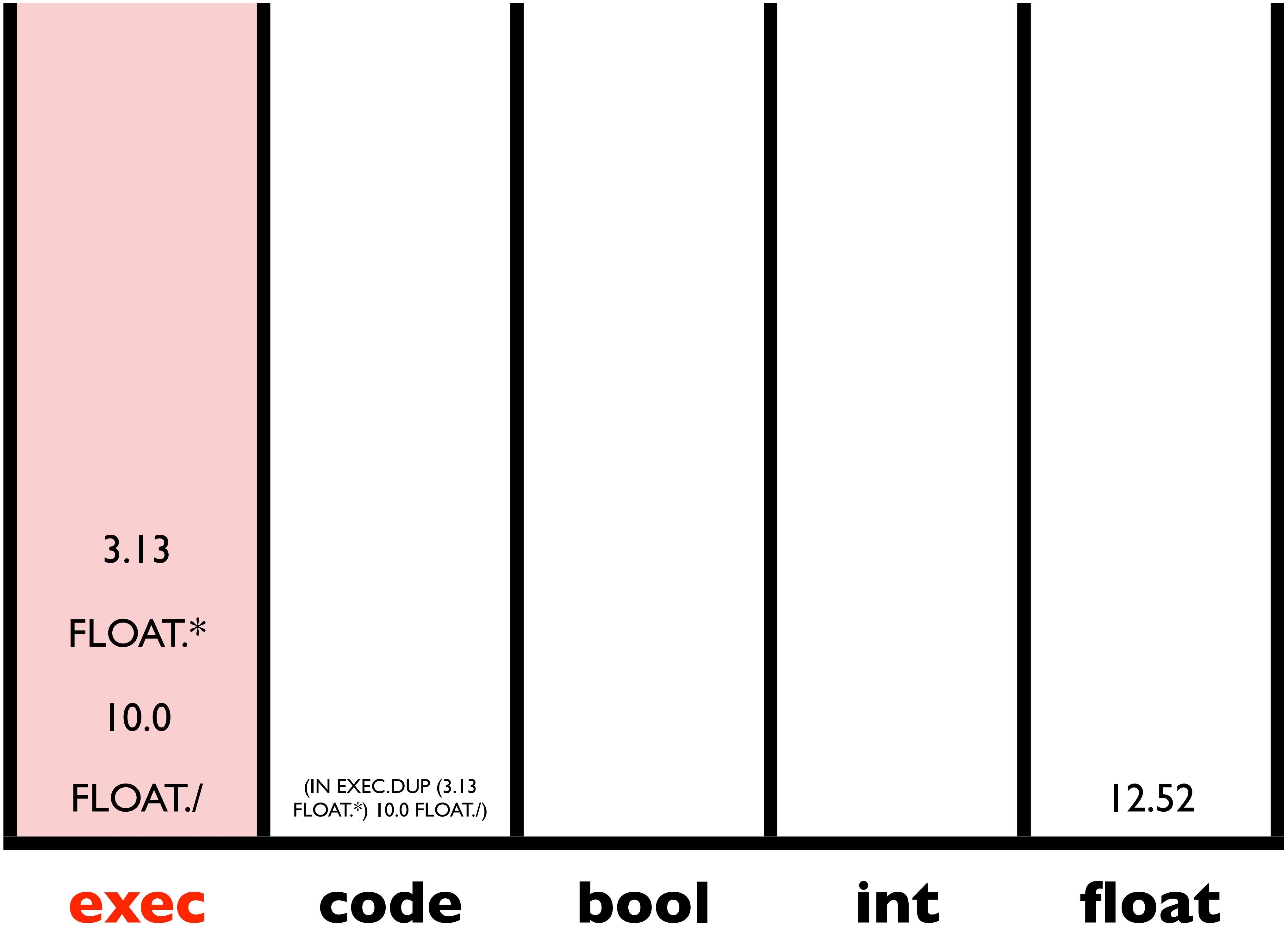
exec	code	bool	int	float
FLOAT.*				
(3.13 FLOAT.*)				
10.0				3.13
FLOAT./	(IN EXEC.DUP (3.13 FLOAT.*) 10.0 FLOAT./)			4.0



```
(3.13 FLOAT.*)
10.0
FLOAT./
```

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

```
12.52
```

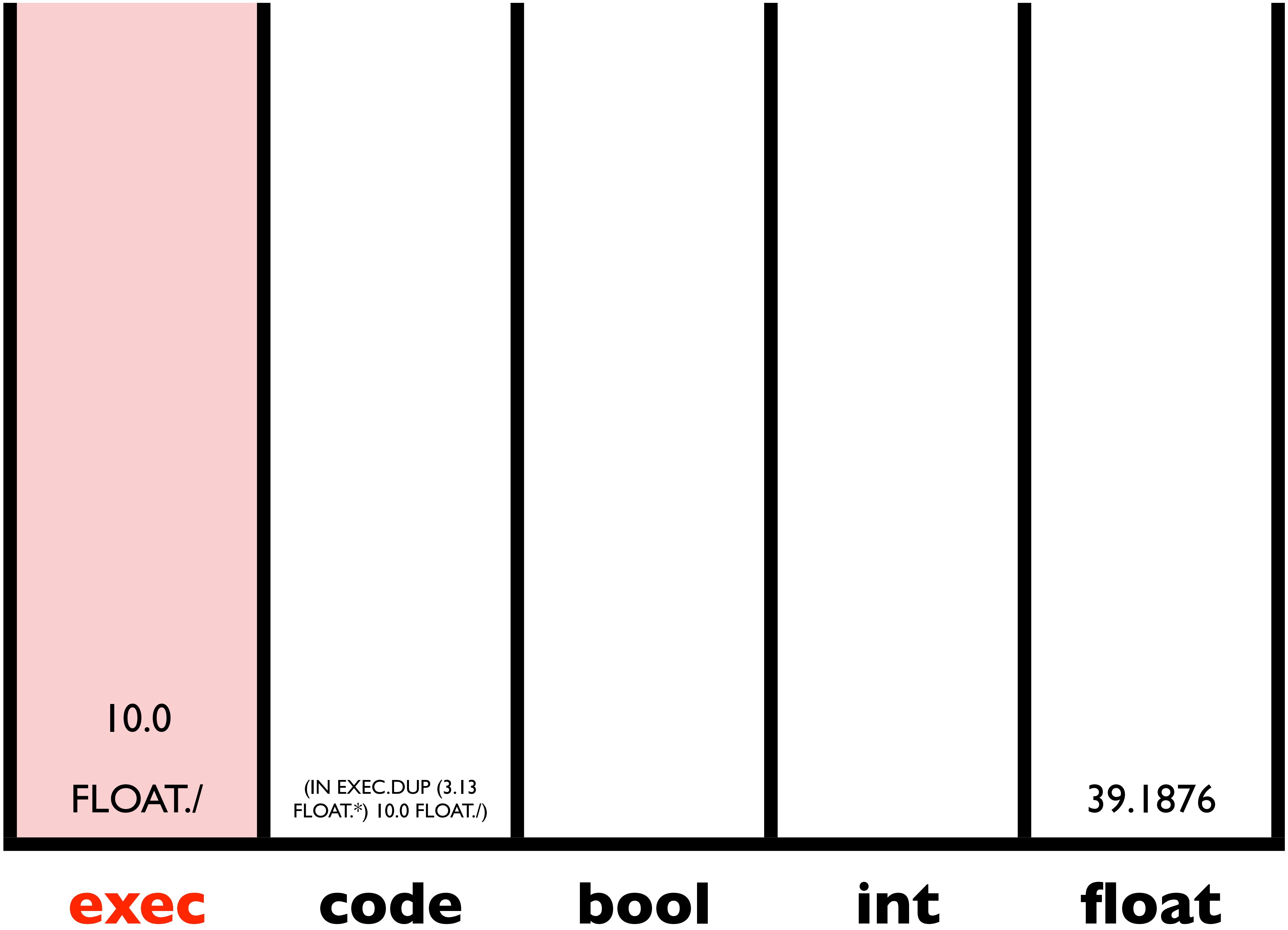


```
3.13
FLOAT.*
10.0
FLOAT./
```

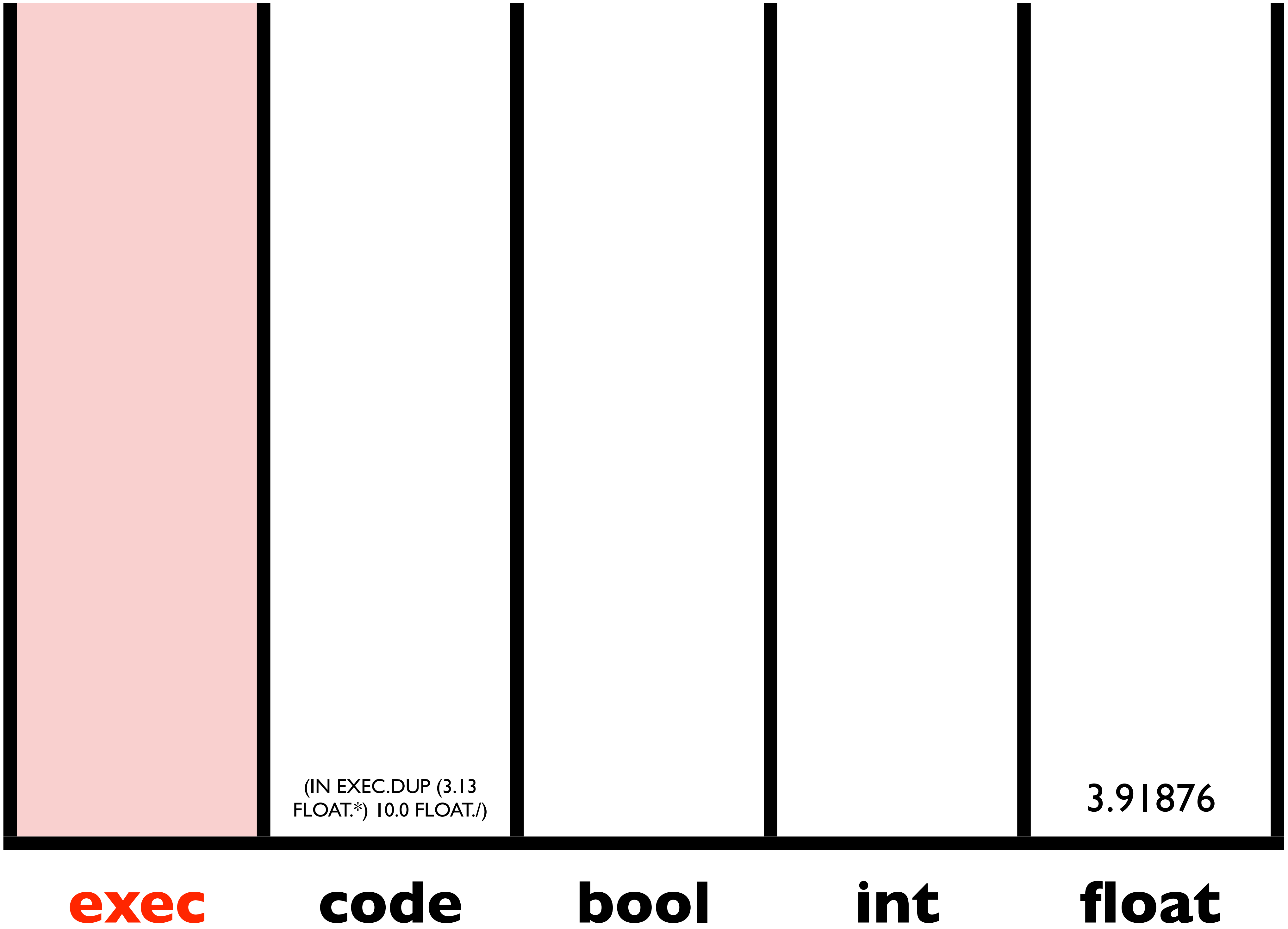
```
(IN EXEC.DUP (3.13
FLOAT.*) 10.0 FLOAT./)
```

```
12.52
```

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


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

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



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

Auto-simplification

```
Loop:
    Make it randomly simpler
    If it’s as good or better: keep it
    Otherwise: revert
```

Modularity in Software

- Pervasive and widely acknowledged to be essential
- Modules may be functions, procedures, methods, classes, data structures, interfaces, etc.
- Modularity measures include coupling, cohesion, encapsulation, composability, etc.

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

Structure via GP (2)

- Specialize GP techniques to **indirectly** support human programming language abstractions
- Constrain genetic change, or repair after genetic change, to satisfy abstraction syntax
- 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
- **Push**

Tags

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

Calculator Execution Architecture

Lexicase Selection

- Each parent is selected by filtering the entire population, one one case at a time (in random order), keeping only the elite at each stage
- Useful for "modal" problems, which require qualitatively different responses to different inputs
- Useful for "uncompromising" problems, in which solutions must be optimal on each case
- All comparisons are "within case," so may be useful whenever cases are non-comparable

Lexicase Selection

Initialize:

Candidates = the entire population

Cases = a list of all of the test cases in random order

Loop:

Candidates = the subset of **Candidates** with exactly the best performance of any current candidate for the first case in **Cases**

If **Candidates** or **Cases** contains just a single element then return a randomly selected individual from **Candidates**

Otherwise remove the first case from **Cases** and go to **Loop**

Finite Algebras

$\mathbf{A}_1$ $*$	0	1	2
0	2	1	2
1	1	0	0
2	0	0	1

$\mathbf{A}_2$ $*$	0	1	2
0	2	0	2
1	1	0	2
2	1	2	1

A1 Mal'cev Term

Selection	Successes	CE	MBF
Tournament Size 2	35	532,000	0.75
Tournament Size 3	43	420,000	0.70
Tournament Size 4	31	440,000	0.75
Tournament Size 5	22	616,000	0.77
Tournament Size 6	25	750,000	0.90
Tournament Size 7	23	403,000	0.92
Tournament Size 8	26	464,000	0.94
Tournament Size 9	21	550,000	1.06
Lexicase	94	90,000	0.05

A2 Mal'cev Term

Selection	Successes	CE	MBF
Tournament Size 3	7	3,780,000	1.50
Tournament Size 4	5	3,648,000	1.50
Tournament Size 5	8	2,052,000	1.51
Tournament Size 6	9	1,921,000	1.45
Tournament Size 7	3	4,131,000	1.59
Tournament Size 8	9	990,000	1.64
Tournament Size 9	10	1,356,000	1.60
Lexicase	75	208,000	0.25

The *Digital Multiplier* Problem

- Evolve a digital circuit to multiply two binary numbers
- *n*-bit digital multiplier: 2 x *n* bits → 2*n* bits
- Multiple outputs
- Scalable
- Recommended as a GP benchmark problem (McDermott, et al 2012, White et al 2013)

3-bit Digital Multiplier

Boolean Stack	and, or, xor, invert_first_then_and, dup, swap, rot
Input / Output	in0, ..., in2n, out0, ..., out2n

Selection	**Successes**	**MBF**
Tournament Size 7	0	0.24
Lexicase	100	0

Factorial

Boolean Stack	and, dup, eq, frominteger, not, or, pop, rot, swap
Integer Stack	add, div, dup, eq, fromBoolean, greaterThan, lessThan, mod, mult, pop, rot, sub, swap
Exec Stack	dup, eq, if , noop, pop, rot, swap, when, k, s, y
Input	in
Constants	0, 1

Selection	**Successes**	**MBF**
Tournament Size 7	0	74,545
Lexicase	61	28,980

Calculator Test Cases

Keys pressed => number, error flag

- Digit entry tests
- Digit entry pair tests
- Double digit float entry tests
- Single digit math tests
- Single digit incomplete math tests
- Single digit chained math tests
- Division by zero tests

Digit Entry Tests

- :zero => 0.0, false
- :one => 1.0, false
- :two => 2.0, false
- :three => 3.0, false
- ...

Digit Entry Pair Tests

- :zero :zero => 0.0, false
- :zero :one => 1.0, false
- :two :three => 23.0, false
- :nine :nine => 99.0, false
- ...

Float Entry Tests

- :zero :point :nine => 0.9, false
- :zero :point :two => 0.2 false
- :seven :point :nine => 7.9, false
- :three :point :two => 3.2, false
- ...

Single Digit Math Tests

- :zero :plus :nine :equals => 9.0, false
- :three :times :four :equals => 12.0, false
- :three :minus :nine :equals => -6.0, false
- :three :divided-by :four :equals => 0.75, false
- ...

Incomplete Math Tests

- :three :plus :four => 4.0, false
- :seven :plus => 7.0, false
- ...

Chained Math Tests

- :three :plus :nine :minus :five :equals
  => 7.0, false
- :three :times :two :divided-by :eight :equals
  => 0.75, false
- :three :divided-by :nine :minus :five :equals
  => -4.6666665, false
- ...

Division by Zero Tests

- :zero :divided-by :zero :equals => 0.0, true
- :seven :divided-by :zero :equals => 0.0, true
- :three :divided-by :zero :equals => 0.0, true
- ...

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

ULTRA

Uniform Variation

- All genetic material that a child inherits should be ≈ likely to be mutated
- Parts of both parents should be ≈ likely to appear in children (at least if they are ≈ in size), and to appear in a range of combinations
- Should be applicable to genomes of varying size and structure

Why Uniformity?

- No hiding from mutation
- All parts of parents subject to variation and recombination
- Biological genetic variation, while not fully uniform, has uniformity properties that prevent some of the problems we see in GP; e.g. just having more genes doesn't generally "protect" genes any of them

Prior Work

- Point mutations or "uniform crossovers" that replace/swap nodes but only in restricted ways; cannot change structure, has depth biases (McKay et al, 1995; Page et al, 1998; Poli and Langdon, 1998; Poli and Page, 2000; Semenkin and Semenkina, 2012)
- Uniform mutation via size-based numbers of tree replacements; depth biases, little demonstrated benefit (McKay et al, 1995; Van Belle and Ackley, 2002)

ULTRA

- Achieve uniformity by treating genomes as linear sequences, even if they are hierarchically structured
- Repair after transform to ensure structural validity

The ULTRA Operator

- Uniform Linear Transformation with Repair and Alternation
- Linearize 2 parents, treating "(" and ")" as ordinary tokens
- Start at the beginning of one parent and copy tokens to the child, switching parents stochastically (according to the *alternation rate*, and subject to an *alignment deviation*)
- Post-process with uniform mutation (according to a *mutation rate*) and repair

Parents:

```
( a b ( c ( d ) ) e ( f g ) )
( 1 ( 2 ( 3 4 ) 5 ) 6 )
```

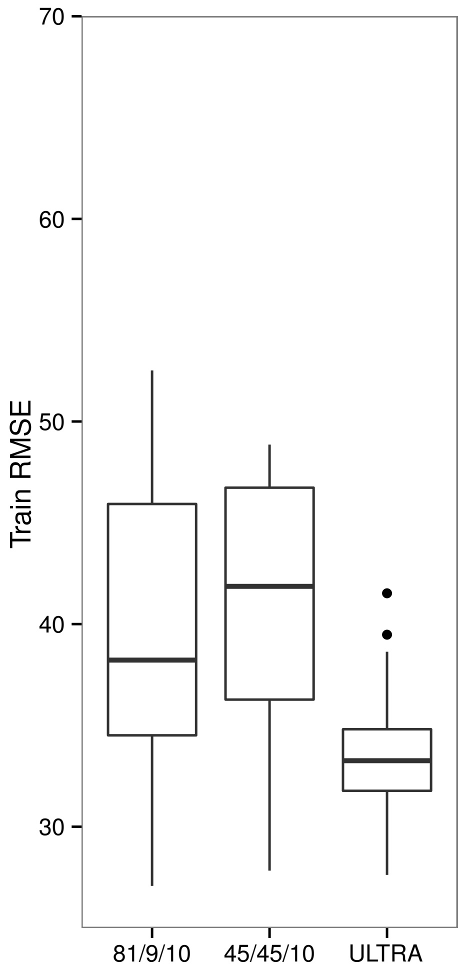
Result of alternation:

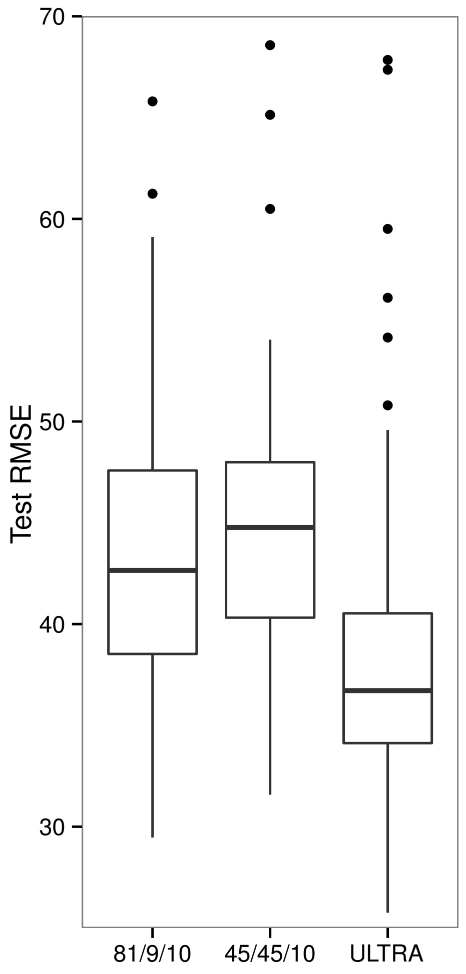
```
( a b 2 ( 3 4 d ) ) 6 )
```

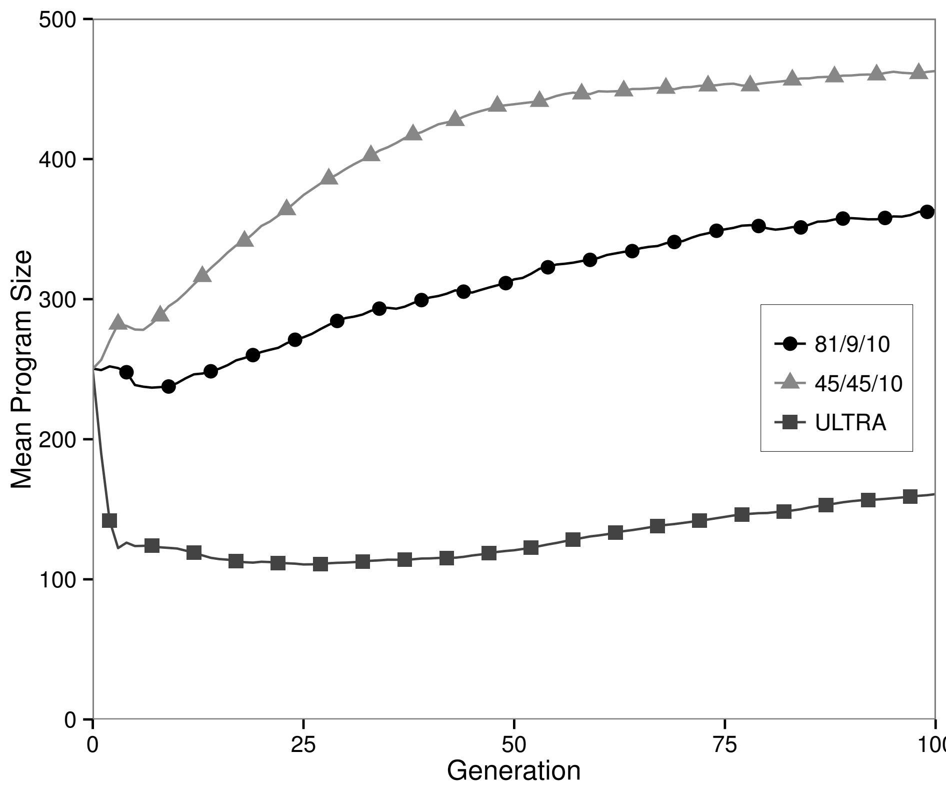
Result of repair:

```
( a ( b 2 ( 3 4 d ) ) 6 )
```

ULTRA on the bioavailability problem







- Bowling
- wc
- generative tests
- multiple metrics on each test (e.g. Levenshtein distance)