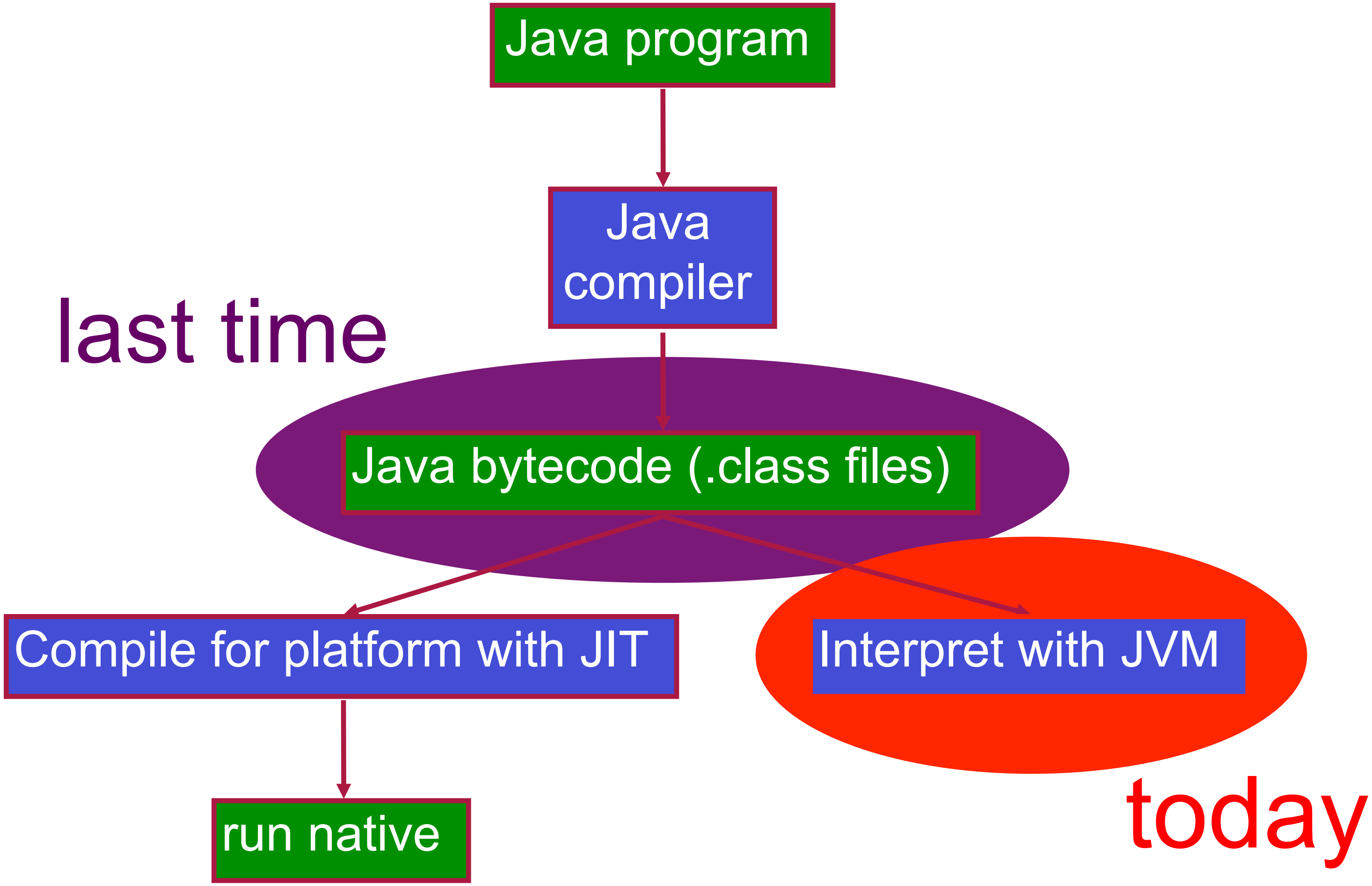
CS2112 Fall 2017

Under the Hood: The Java Virtual Machine, Part II



Java program

Java compiler

Java bytecode (.class files)

Compile for platform with JIT

run native

Interpret with JVM

last time

today

Today

- Class file format
- Class loading and initialization
- Object initialization
- Method dispatch
- Exception handling
- Java security model
  - Bytecode verification
  - Stack inspection

Instance Method Dispatch

`x.foo(...)`

- compiles to **`invokevirtual`**
- Every loaded class knows its superclass
  - name of superclass is in the constant pool
  - like a parent pointer in the class hierarchy
- bytecode evaluates arguments of **`x.foo(...)`**, pushes them on the stack
- Object **`x`** is always the first argument

Instance Method Dispatch

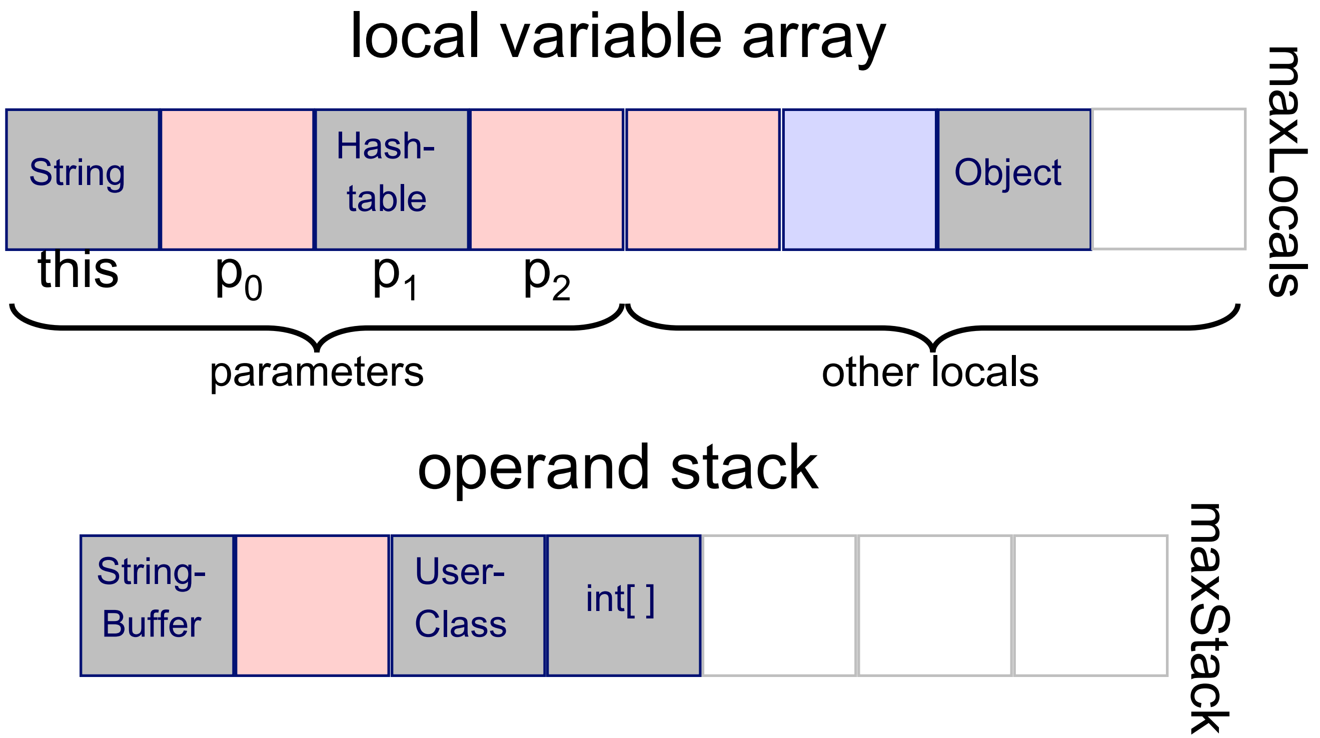
`invokevirtual foo (...)V`

- Name and type of **`foo(...)`** are arguments to **`invokevirtual`** (indices into constant pool)
- JVM retrieves them from constant pool
- Gets the dynamic (runtime) type of **`x`**
- Follows parent pointers until finds **`foo(...)V`** in one of those classes – gets bytecode from code attribute

Instance Method Dispatch

- Creates a new *stack frame* on runtime stack around arguments already there
- Allocates space in stack frame for locals and operand stack
- Prepares locals (int=0, ref=null), empty stack
- Starts executing bytecode of the method
- When returns, pops stack frame, resumes in calling method after the **`invokevirtual`** instruction

Stack Frame of a Method



local variable array

String

Hash-table

Object

this p_0 p_1 p_2

parameters

other locals

maxLocals

operand stack

String-Buffer

User-Class

int[ ]

maxStack

▨ = reference type

🟥 = integer (boolean, byte, ...)

🟦 = continuation

□ = useless

Instance Method Dispatch

```
byte[] data;
void getData() {
   String x = "Hello world";
   data = x.getBytes();
}
```

```
Code(maxStack = 2, maxLocals = 2, codeLength = 12)
0: ldc "Hello world"
2: astore_1
3: aload_0 //object of which getData is a method
4: aload_1
5: invokevirtual java.lang.String.getBytes ()[B
8: putfield A.data [B
11: return
```

Exception Handling

- Each method has an *exception handler table* (possibly empty)
- Compiled from **`try/catch/finally`**
- An exception handler is just a designated block of code
- When an exception is thrown, JVM searches the exception table for an appropriate handler that is in effect
- **`finally`** clause is executed last

Exception Handling

- Finds an exception handler → empties stack, pushes exception object, executes handler
- No handler → pops runtime stack, returns exceptionally to calling routine
- `finally` clause is always executed, no matter what

Exception Table Entry

`startRange`	start of range handler is in effect
`endRange`	end of range handler is in effect
`handlerEntry`	entry point of exception handler
`catchType`	exception handled

- **`startRange`** → **`endRange`** give interval of instructions in which handler is in effect
- **`catchType`** is any subclass of **`Throwable`** (which is a superclass of **`Exception`**) -- any subclass of **`catchType`** can be handled by this handler

Example

```
Integer x = null;
Object y = new Object();

try {
    x = (Integer)y;
    System.out.println(x.intValue());
} catch (ClassCastException e) {
    System.out.println("y was not an Integer");
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} finally {
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1: astore_1
2: new java.lang.Object
5: dup
6: invokespecial java.lang.Object.<init> ()V
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11: checkcast java.lang.Integer
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86: aload 4
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Try/Catch/Finally

```
try {p} catch (E) {q} finally {r}
```

- **`r`** is always executed, regardless of whether **`p`** and/or **`q`** halt normally or exceptionally
- If **`p`** throws an exception not caught by the catch clause, or if **`q`** throws an exception, that exception is *rethrown* upon normal termination of **`r`**

Try/Catch/Finally

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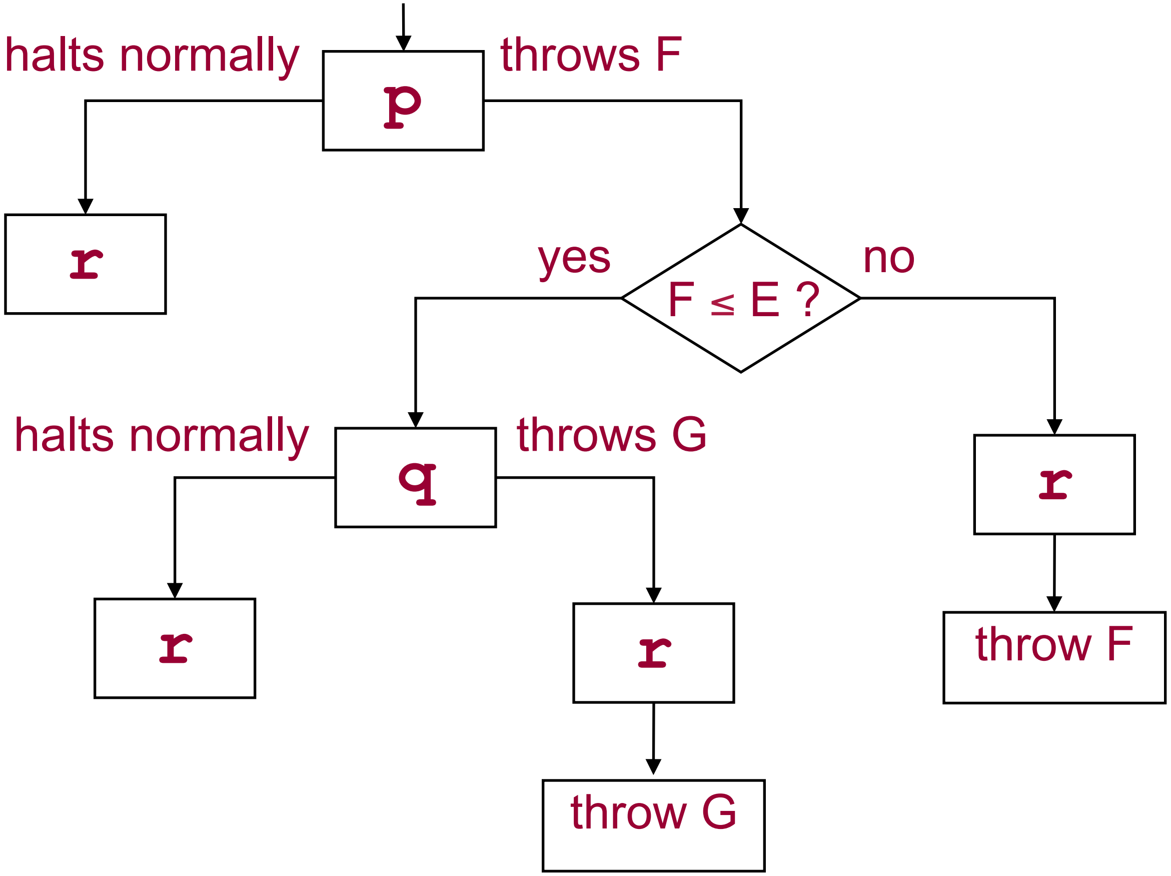


Java Security Model

- Bytecode verification
  - Type safety
  - Private/protected/package/final annotations
  - Basis for the entire security model
  - Prevents circumvention of higher-level checks
- Secure class loading
  - Guards against substitution of malicious code for standard system classes
- Stack inspection
  - Mediates access to critical resources

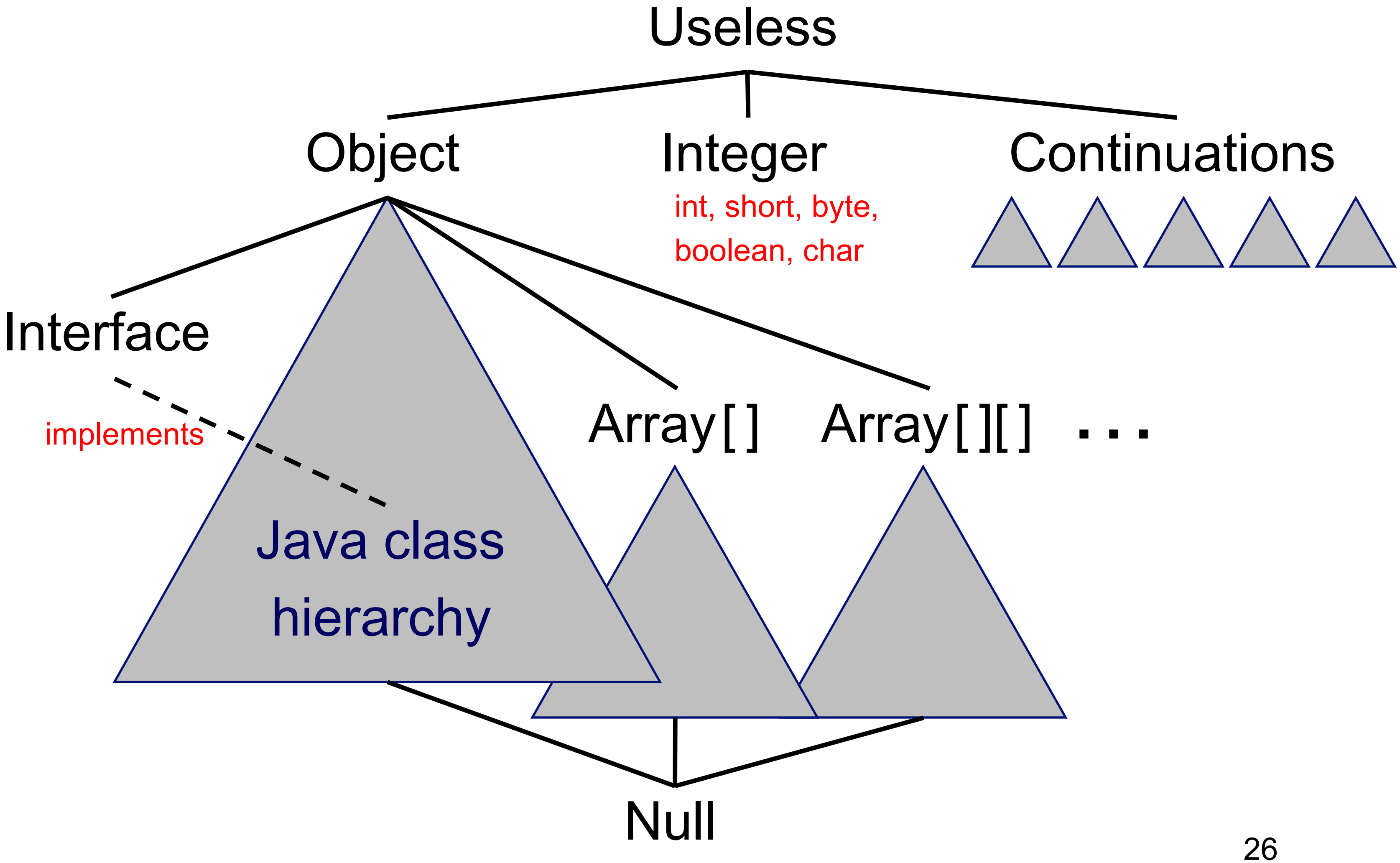
Bytecode Verification

- Performed at load time
- Enforces type safety
  - All operations are well-typed (e.g., may not confuse refs and ints)
  - Array bounds
  - Operand stack overflow, underflow
  - Consistent state over all dataflow paths
- Private/protected/package/final annotations

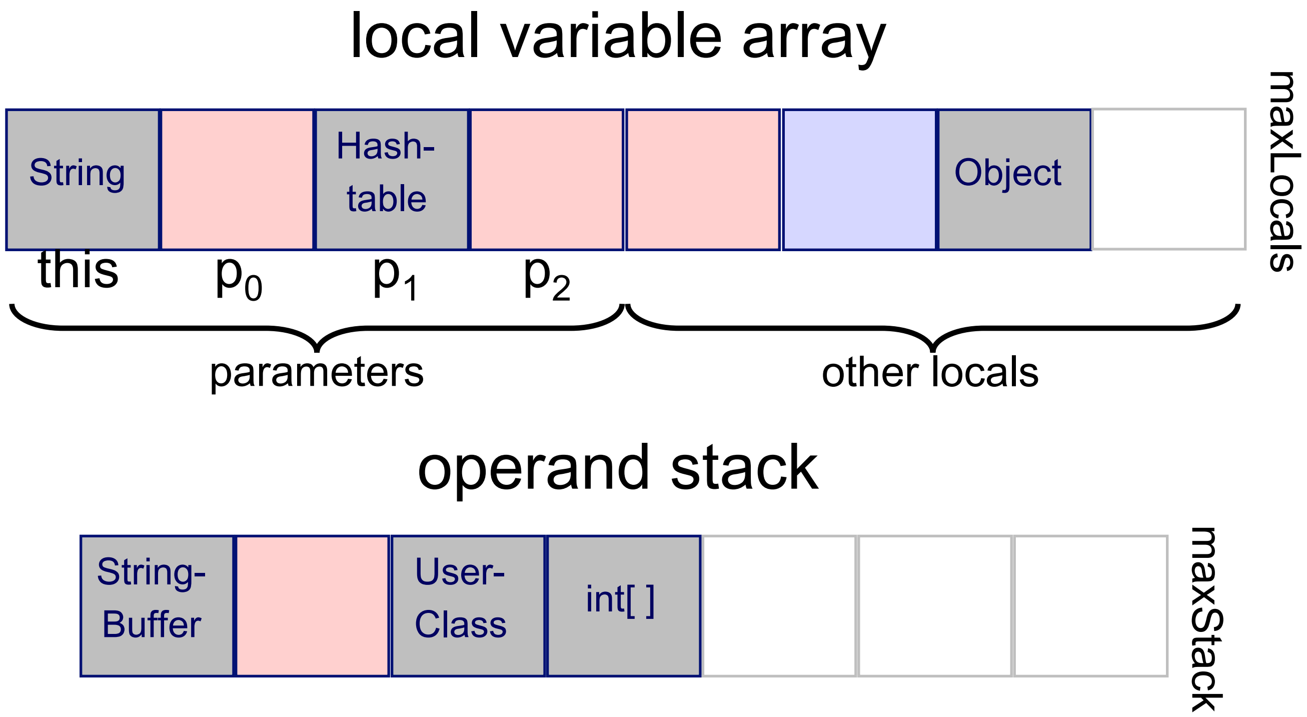
Bytecode Verification

- A form of *dataflow analysis* or *abstract interpretation* performed at load time
- Annotate the program with information about the execution state at each point
- Guarantees that values are used correctly

Types in the JVM



Typing of Java Bytecode



local variable array

String | | Hash-table | | | | Object |

this p_0 p_1 p_2

parameters

other locals

maxLocals

operand stack

String-Buffer | | User-Class | int[ ] | | |

maxStack

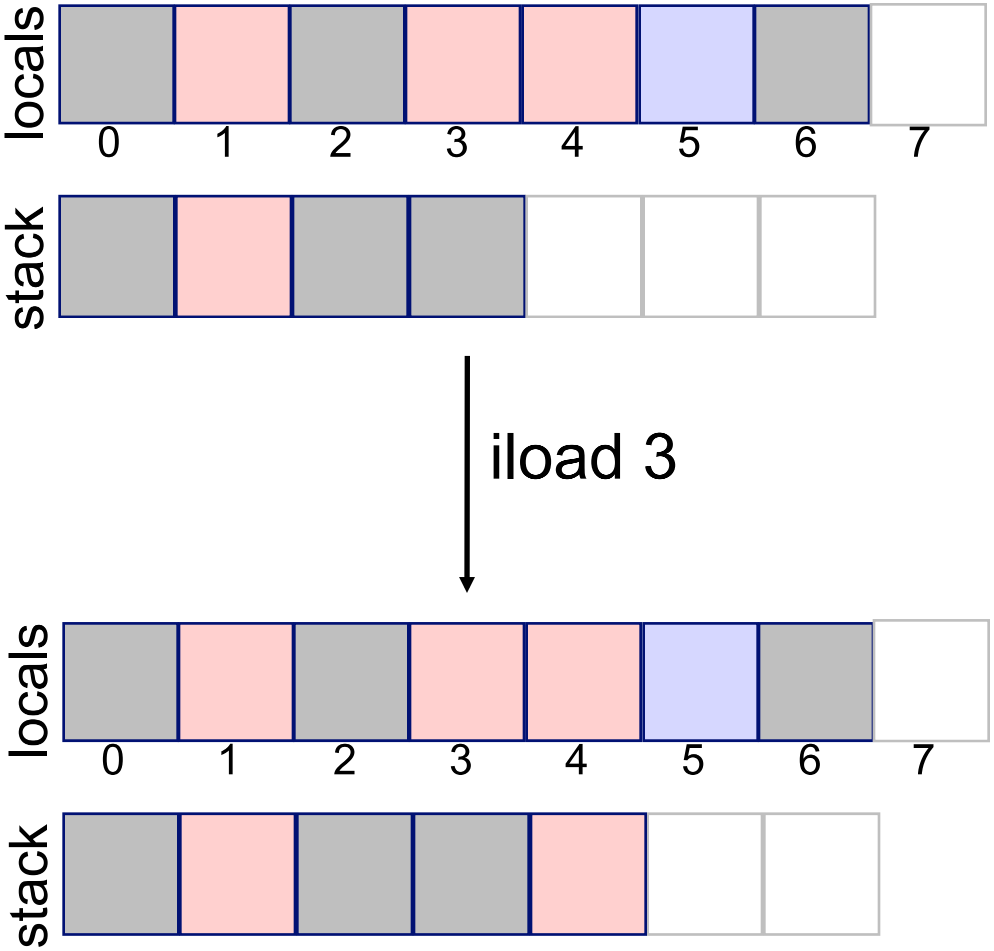
▨ = reference type

🟥 = integer

🟦 = continuation

⬜ = useless

Example



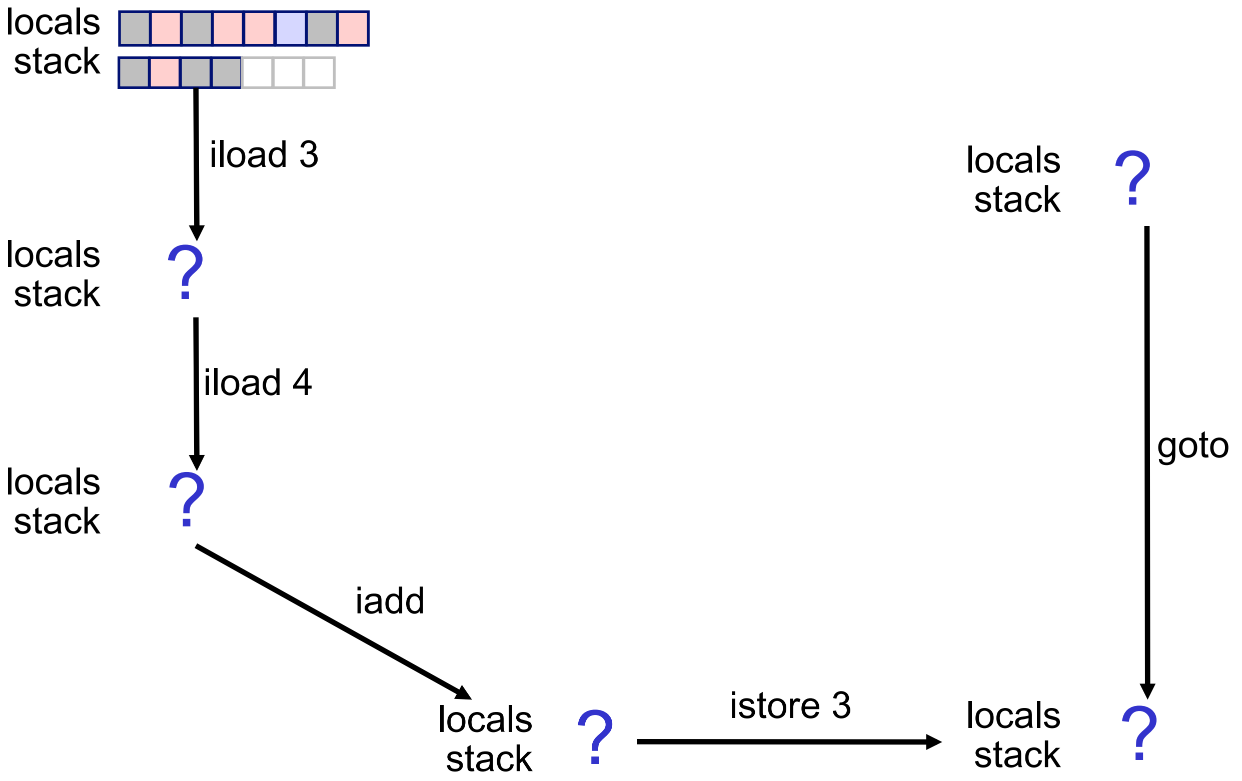
Preconditions for safe execution:

- local 3 is an integer
- stack is not full

Effect:

- push integer in local 3 on stack

Example



locals
stack

iload 3

locals
stack
?

iload 4

locals
stack
?

iadd

locals
stack
?

istore 3

locals
stack
?

goto

locals
stack
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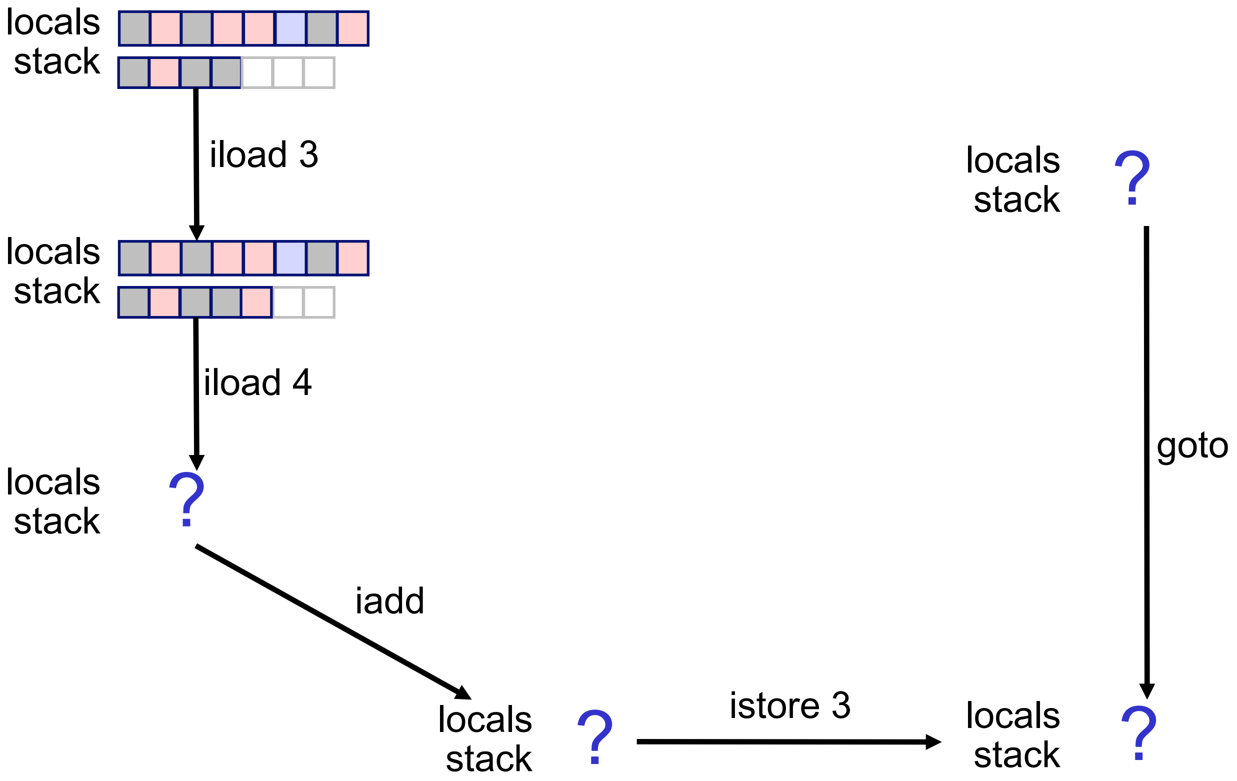
Example


locals
stack
iload 3
locals
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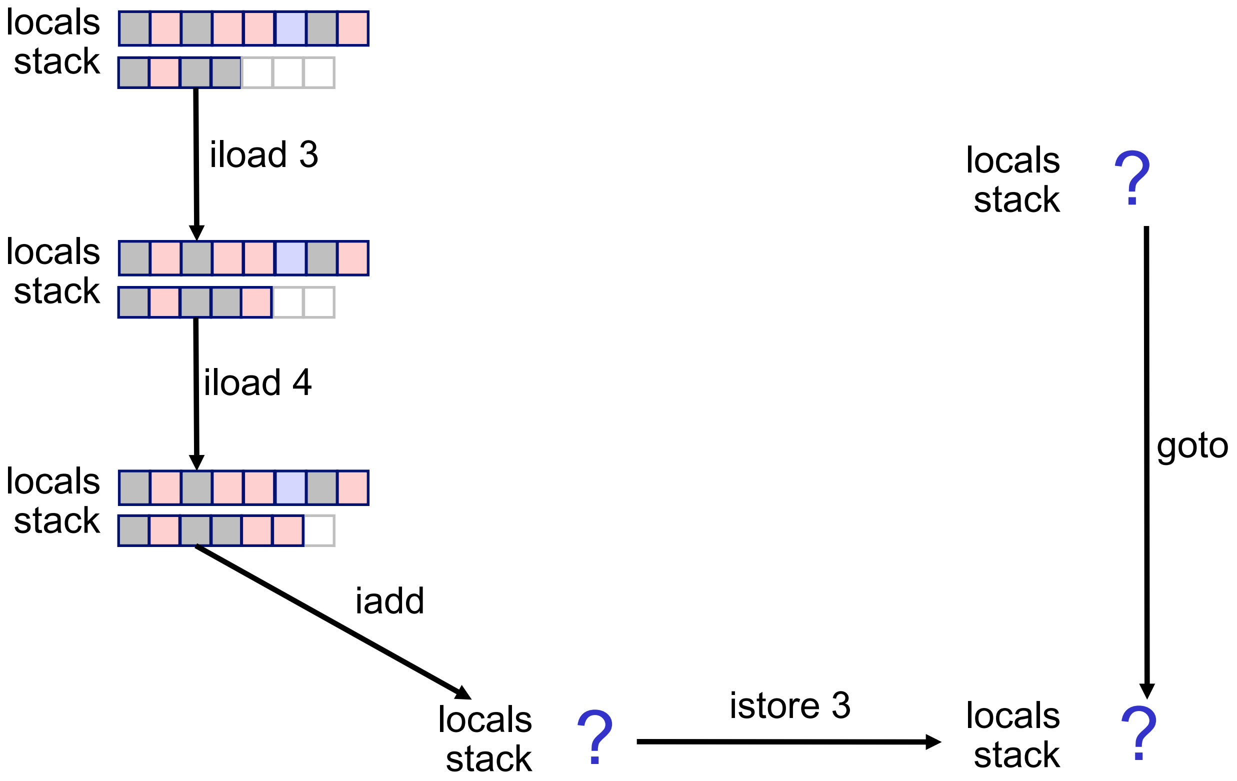
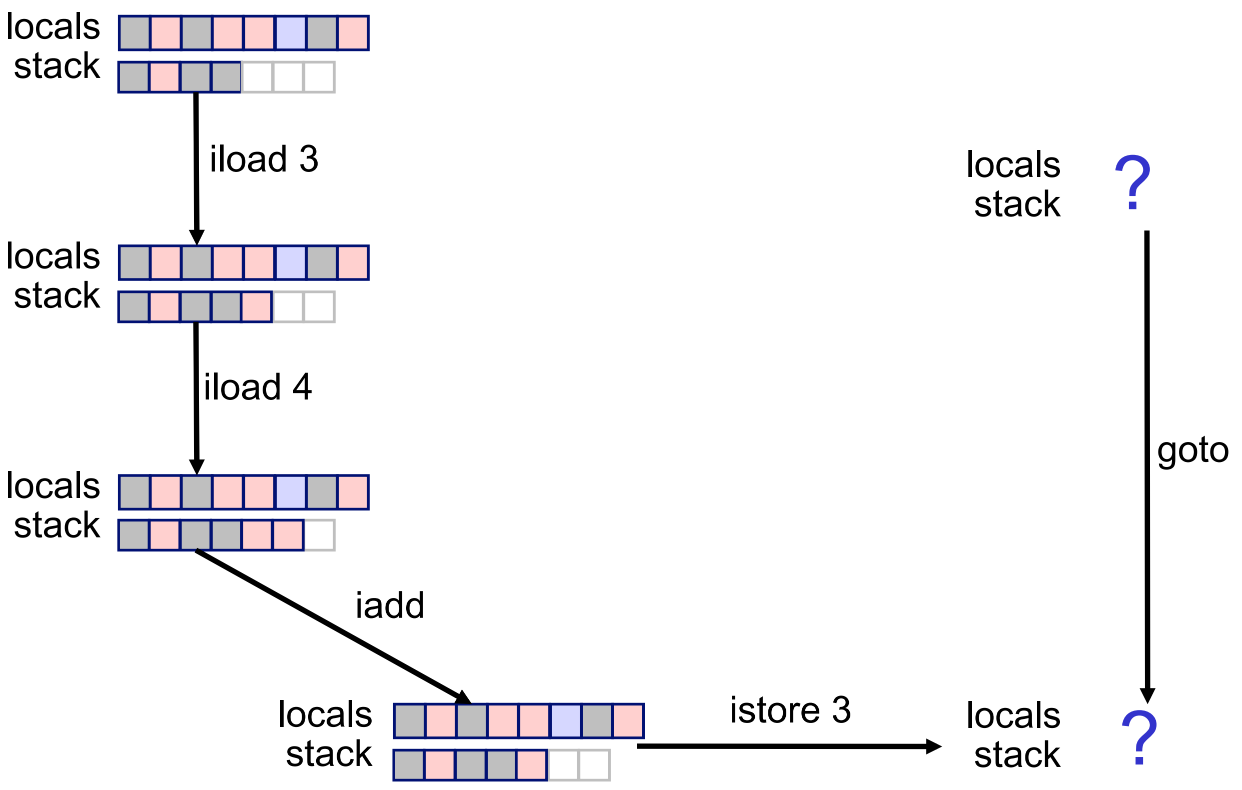
iload 4
locals
stack
?
iadd
locals
stack
?
istore 3
locals
stack
?
goto
locals
stack
?

Example


locals
stack
iload 3
locals
stack
iload 4
locals
stack
iadd
locals
stack
?
istore 3
locals
stack
?
locals
stack
?
goto

Example



locals
stack

iload 3

locals
stack

iload 4

locals
stack

iadd

locals
stack

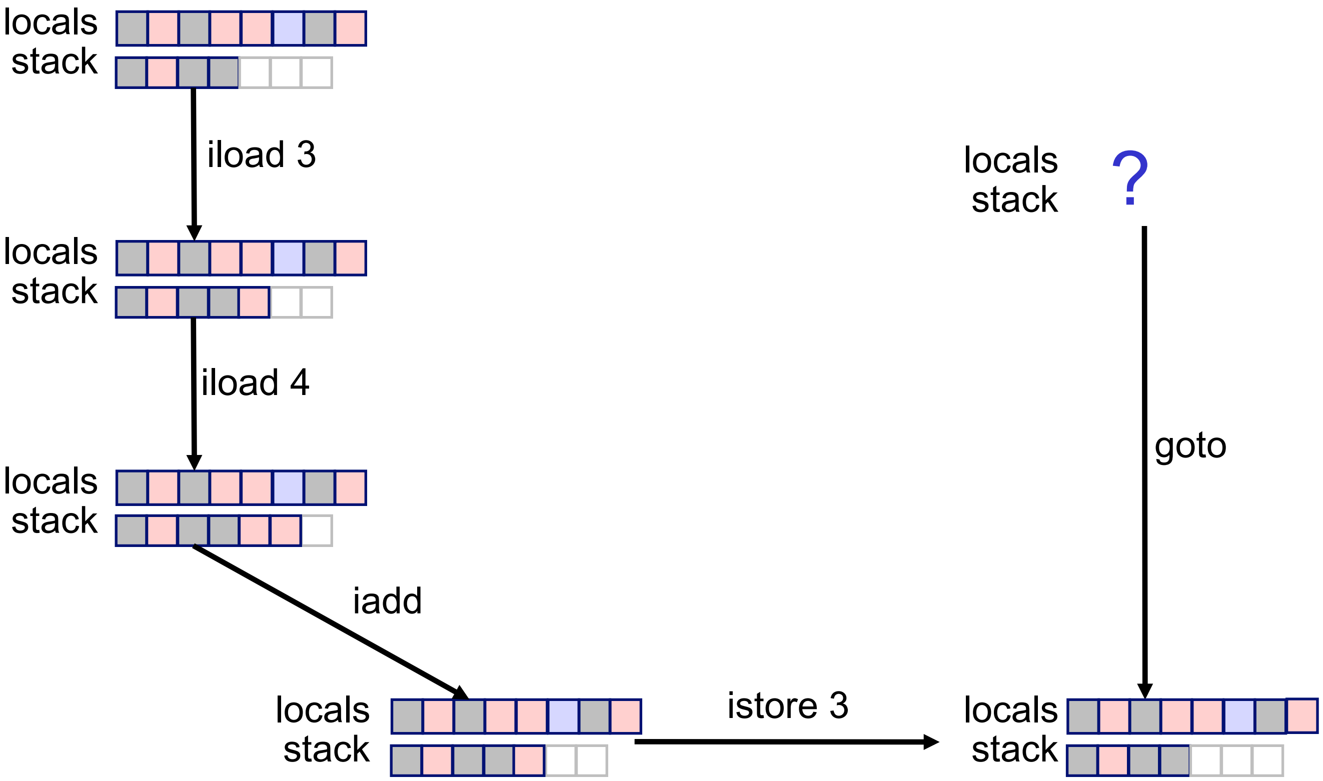
istore 3

locals
stack
?

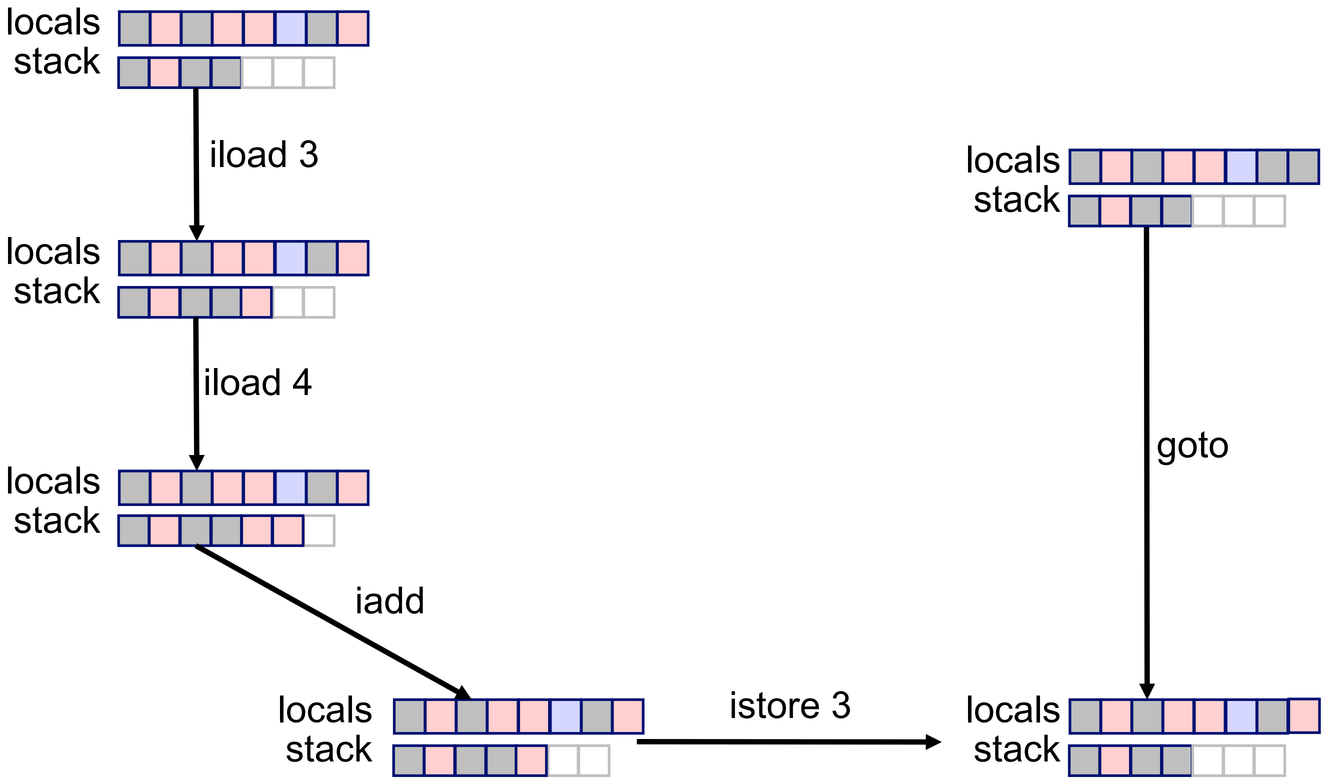
goto

locals
stack
?

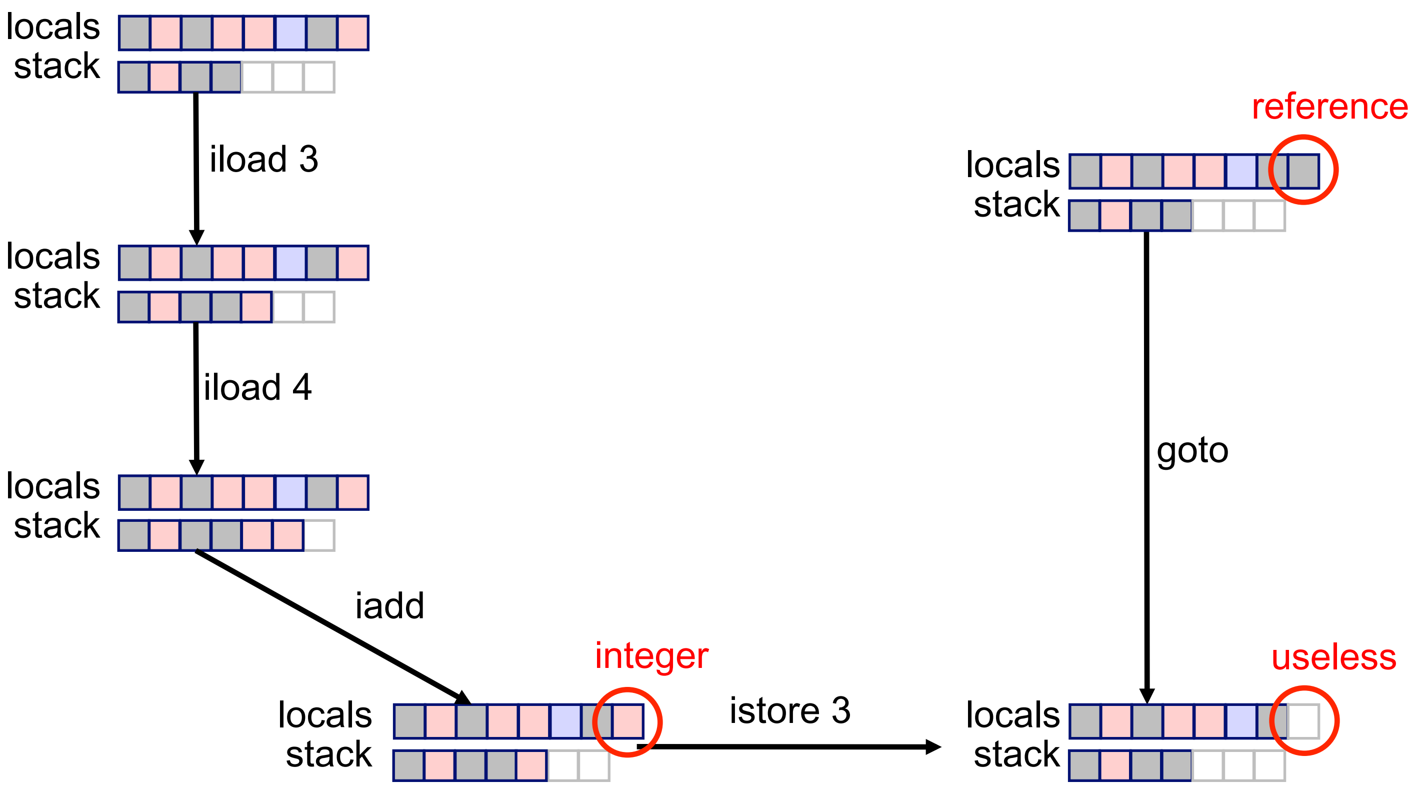
Example


locals
stack
iload 3
locals
stack
iload 4
locals
stack
iadd
locals
stack
istore 3
locals
stack
locals
stack
?
goto

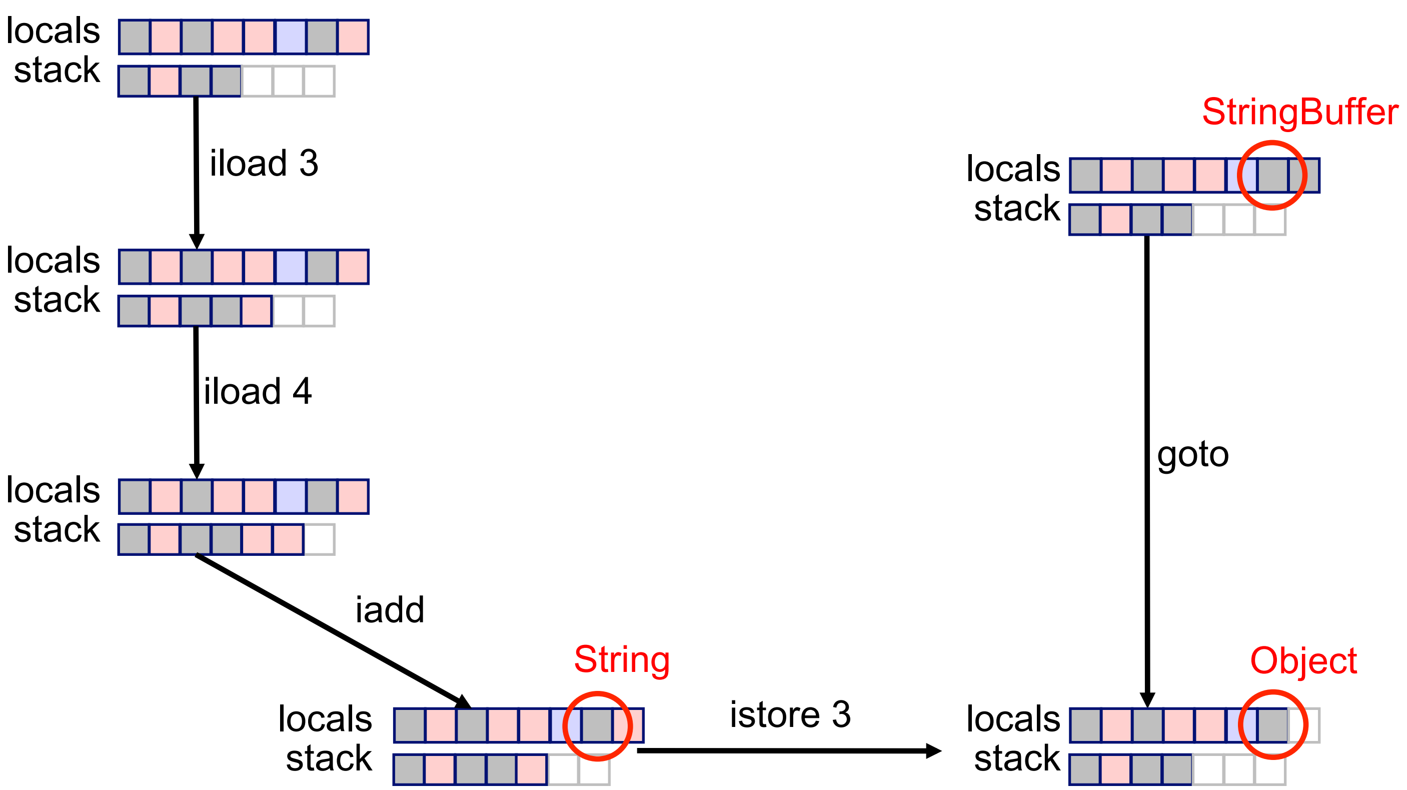
Example


locals
stack
iload 3
locals
stack
iload 4
locals
stack
iadd
locals
stack
istore 3
locals
stack
locals
stack
goto

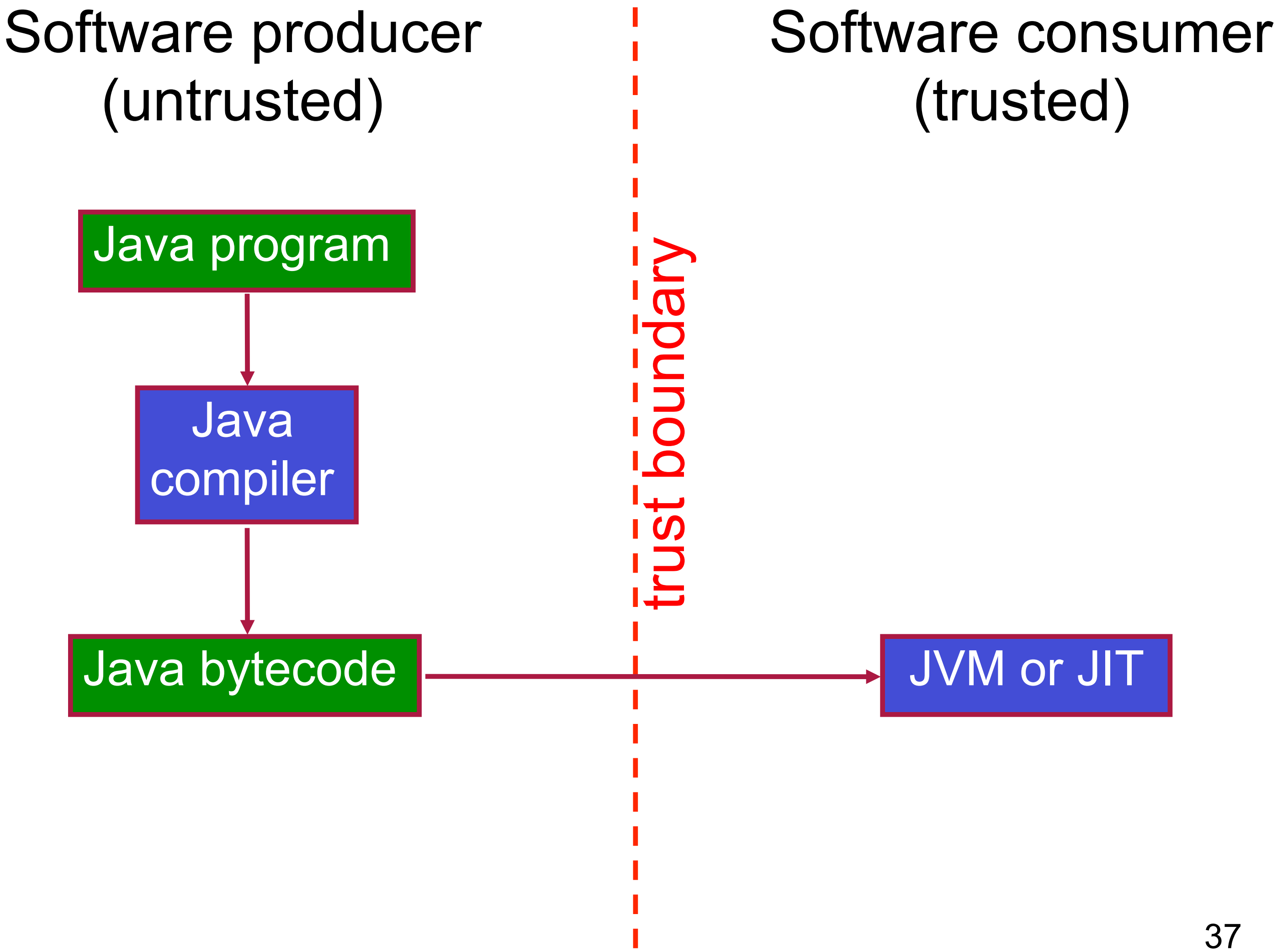
Example


locals
stack
iload 3
locals
stack
iload 4
locals
stack
iadd
integer
locals
stack
istore 3
reference
locals
stack
goto
useless
locals
stack

Example


locals
stack
iload 3
locals
stack
iload 4
locals
stack
iadd
String
locals
stack
istore 3
StringBuffer
locals
stack
goto
Object
locals
stack

Mobile Code



Software producer
(untrusted)

Software consumer
(trusted)

Java program

Java compiler

Java bytecode

trust boundary

JVM or JIT

Mobile Code

Problem: mobile code is not trustworthy!

- We often have *trusted* and *untrusted* code running together in the same virtual machine
  - e.g., applets downloaded off the net and running in our browser
- Do not want untrusted code to perform critical operations (file I/O, net I/O, class loading, security management,...)
- *How do we prevent this?*

Mobile Code

Early approach: *signed applets*

- Not so great
  - everything is either trusted or untrusted, nothing in between
  - a signature can only *verify* an already existing relationship of trust, it cannot *create* trust
- Would like to allow untrusted code to interact with trusted code
  - just monitor its activity somehow

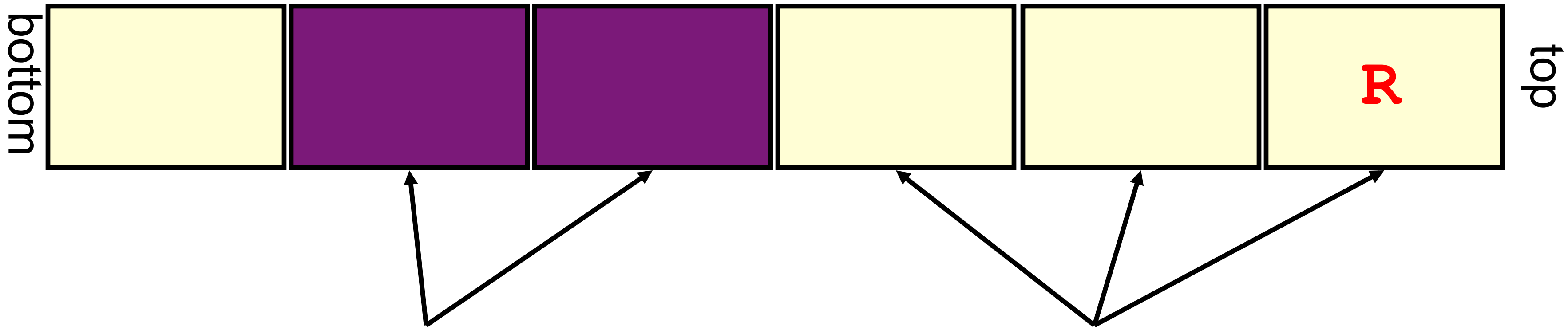
Mobile Code

Q) Why not just let trusted (system) code do anything it wants, even in the presence of untrusted code?

A) Because untrusted code calls system code to do stuff (file I/O, etc.) – system code could be operating on behalf of untrusted code

Runtime Stack

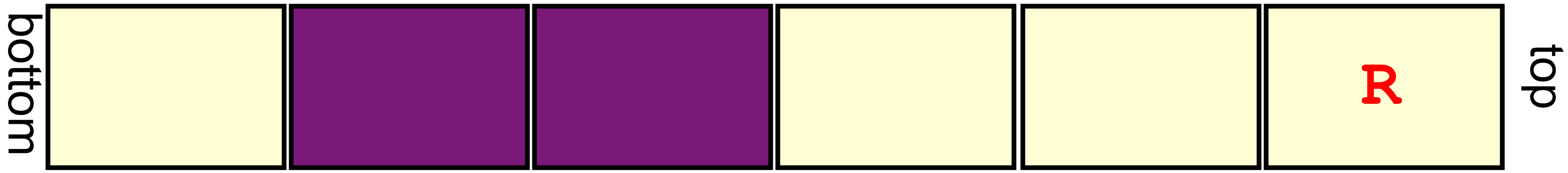
some restricted operation (e.g. write to disk)



stack frames of applet methods (untrusted)

stack frames of system methods (trusted)

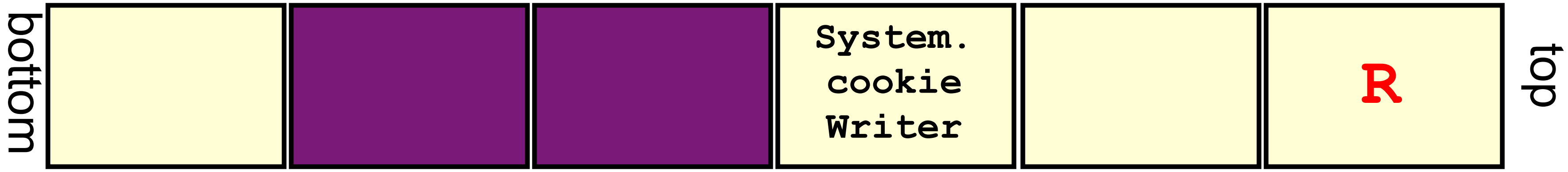
Runtime Stack



Maybe we want to disallow it

- the malicious applet may be trying to erase our disk
- it's calling system code to do that

Runtime Stack



bottom

System. cookie Writer

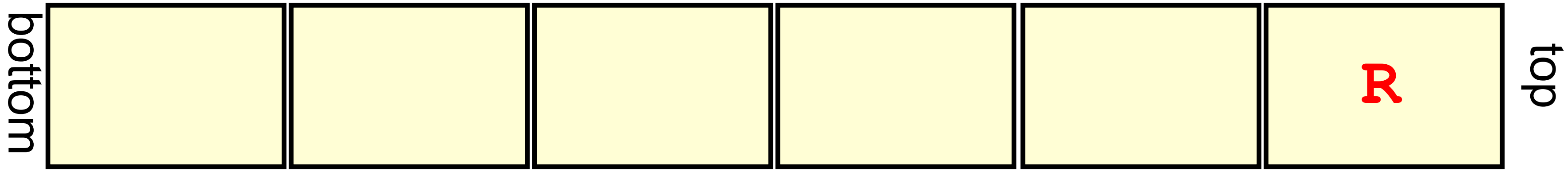
R

top

Or, maybe we want to allow it

- it may just want to write a cookie
- it called **`System.cookieWriter`**
- **`System.cookieWriter`** knows it's ok

Runtime Stack



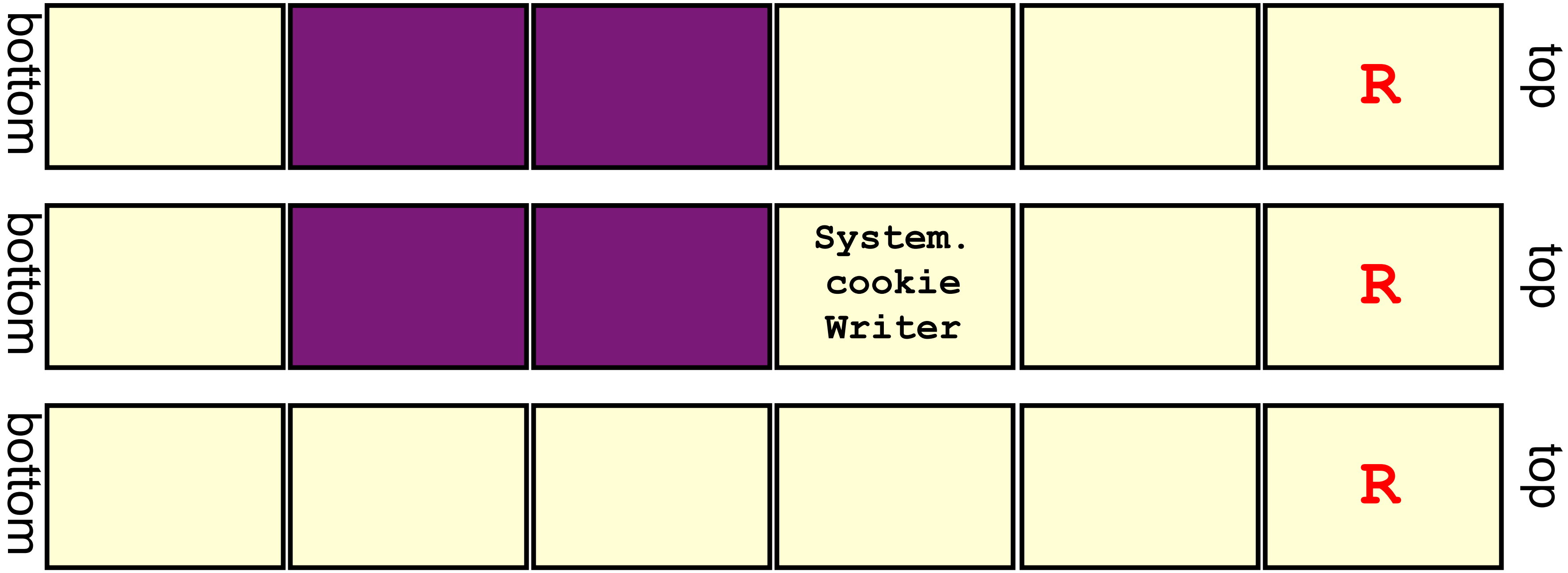
bottom

R

top

Maybe we want to allow it for another reason

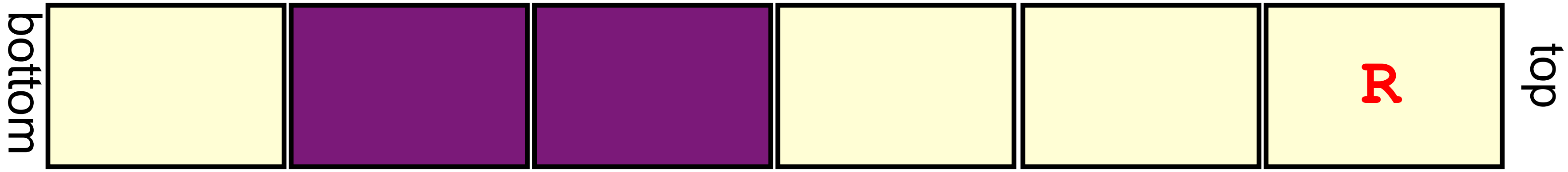
- all running methods are trusted



Q) How do we tell the difference between these scenarios?

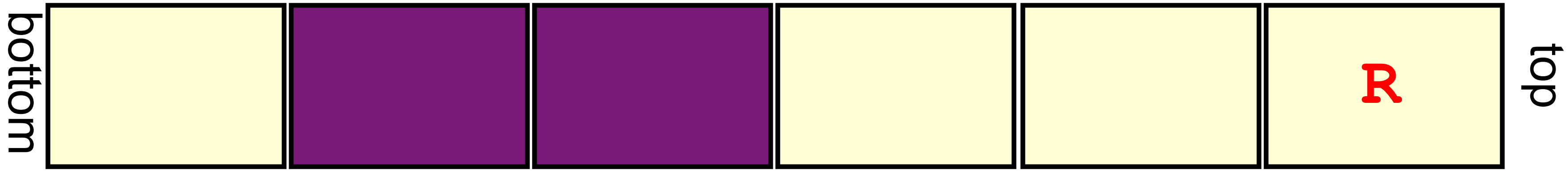
A) *Stack inspection!*

Stack Inspection

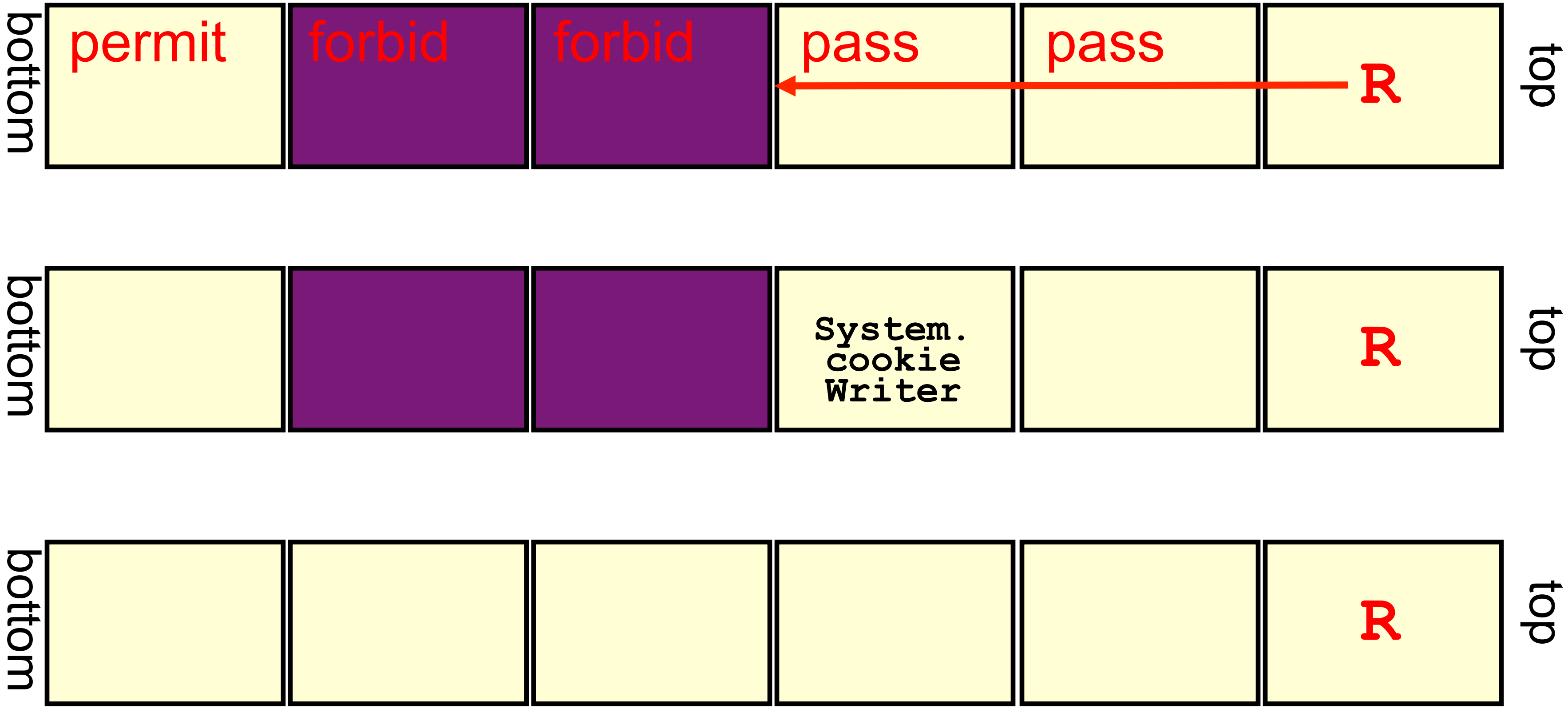


- An invocation of a trusted method, when calling another method, may either:
  - *permit* R on the stack above it
  - *forbid* R on the stack above it
  - *pass* permission from below (be transparent)
- An instantiation of an untrusted method must *forbid* R above it

Stack Inspection



- When about to execute R, look down through the stack until we see either
  - a system method permitting R -- do it
  - a system method forbidding R -- don't do it
  - an untrusted method -- don't do it
- If we get all the way to the bottom, do it (IE, Sun JDK) or don't do it (Netscape)



bottom

permit

forbid

forbid

pass

pass

R

top

bottom

System.
cookie
Writer

R

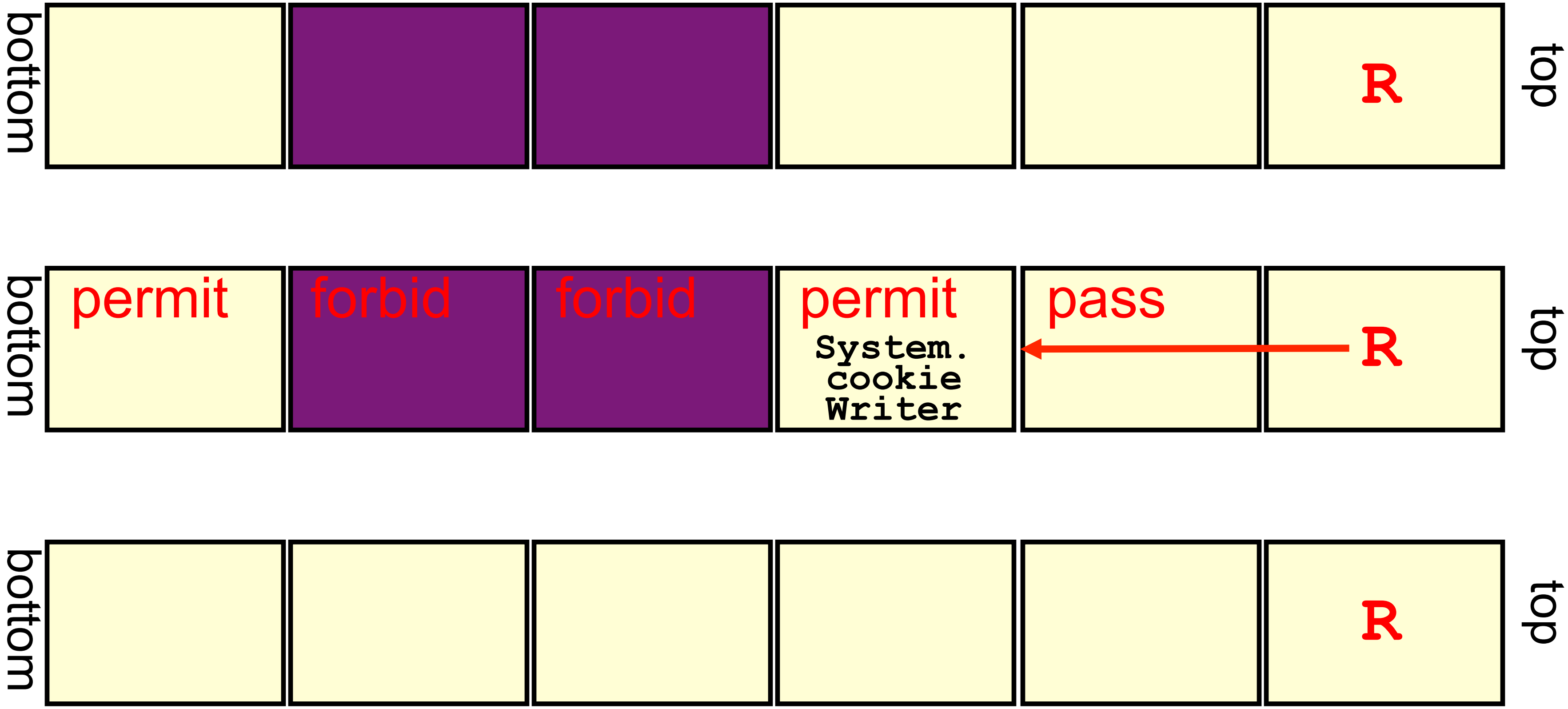
top

bottom

R

top

Case A: R is not executed

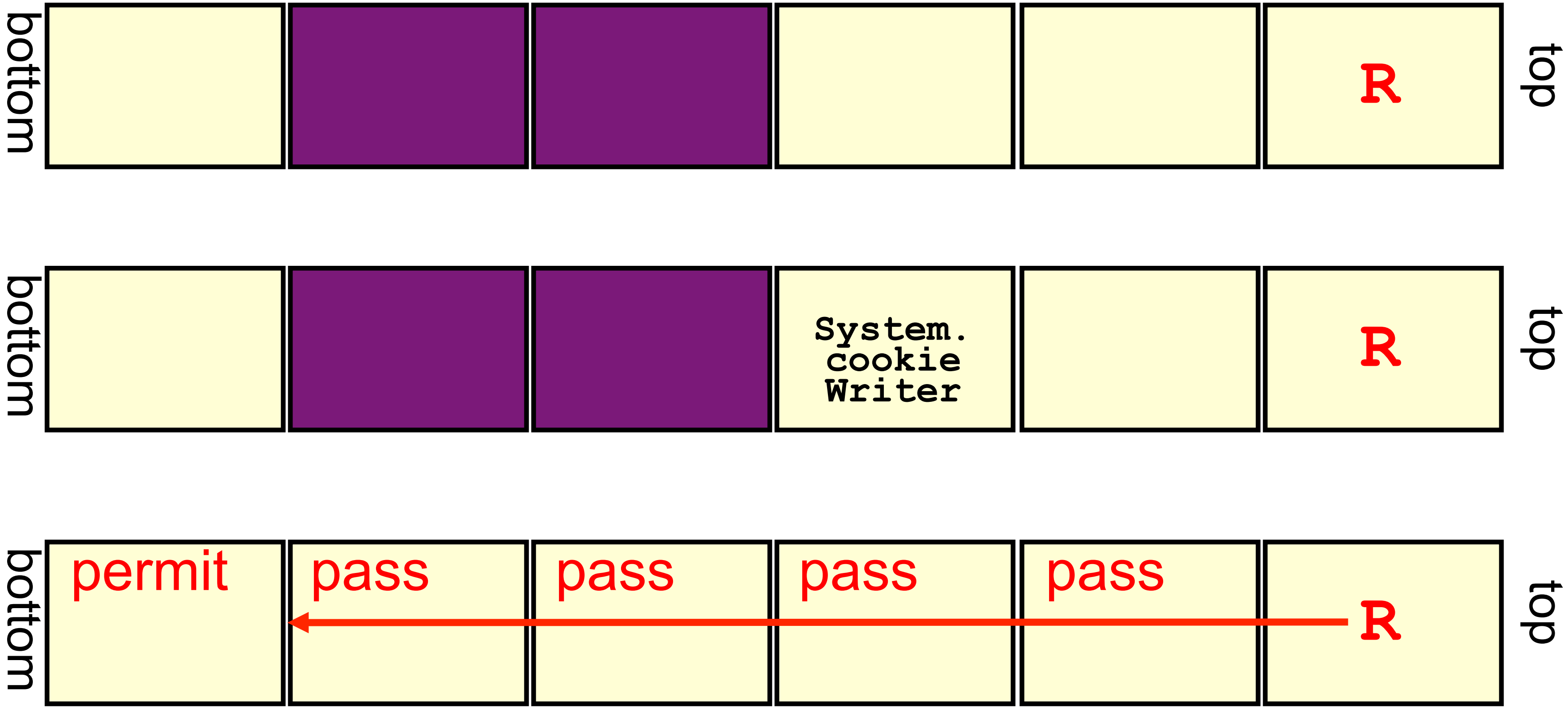


bottom R top

bottom permit forbid forbid permit System. cookie Writer pass R top

bottom R top

Case B: R is executed



Case C: R is executed

Conclusion

Java and the Java Virtual Machine:

Lots of interesting ideas!