# Programming Languages and Techniques (CIS1200)

Lecture 30

## Exceptions

Chapter 27

## Announcements (1)

- HW07: PennPals
  - Programming with Java Collections
  - Due tomorrow at 11.59pm

- Midterm 2: Friday, November 15th
  - Similar to Midterm 1
  - Content: HW 4 – 6, Chapters 11-21 (Java Arrays) and Chapter 32 (Encapsulation) of lecture notes

## Announcements (2)

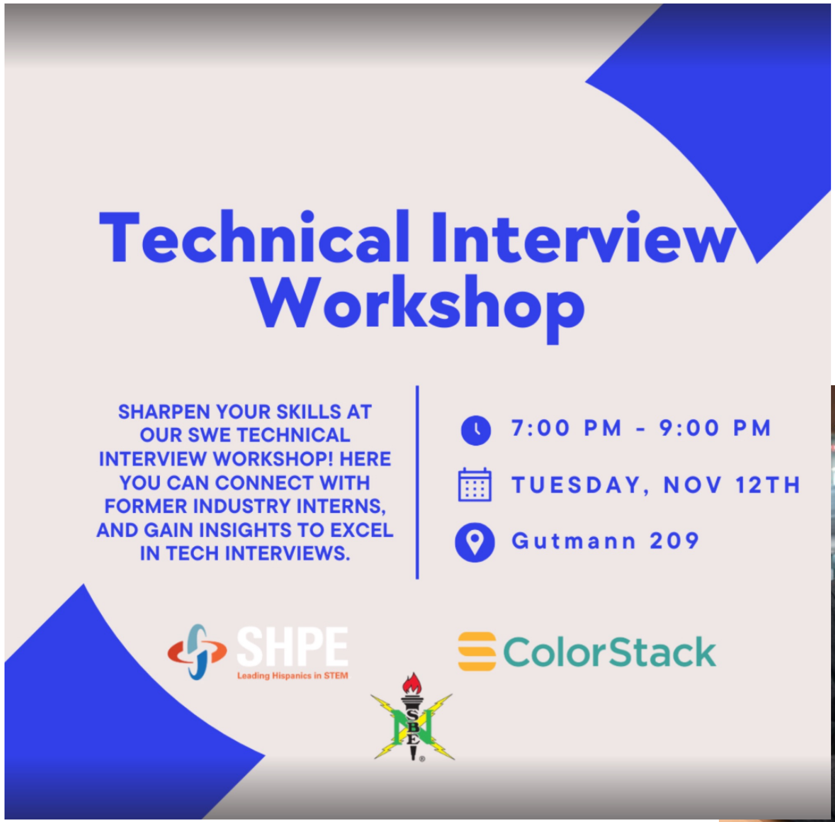
- Midterm 2: Friday, November 15
  - Coverage: up to Monday, Oct. 28 (Chapters 11-21, 32)
  - During lecture (001 @ 10.15am, 002 @ noon)
    Last names: A – Z Meyerson Hall B1
  - 60 minutes; closed book, closed notes
  - Review Material
    - old exams on the web site ("schedule" tab)
  - Review Session
    - Wednesday, 7-9pm, Towne 100 (will be recorded)

# Announcements (3)

- TA position applications are available
  - CIS 1100, 1200, 1600, 1210 (see https://tinyurl.com/2tn2t22f)
  - Other CIS and NETS classes (see https://www.cis.upenn.edu/ta-information/)
  - Accepting applications until Friday, November 22nd
  - Intro CIS TA Panel
    - Monday, November 11th from 7 to 8:30pm in Wu & Chen Auditorium

## Announcements (4)

- ColorStack technical interview workshop tomorrow from 7 to 9 in Gutmann 209



Technical Interview Workshop

SHARPEN YOUR SKILLS AT OUR SWE TECHNICAL INTERVIEW WORKSHOP! HERE YOU CAN CONNECT WITH FORMER INDUSTRY INTERNS, AND GAIN INSIGHTS TO EXCEL IN TECH INTERVIEWS.

7:00 PM - 9:00 PM

TUESDAY, NOV 12TH

Gutmann 209

SHPE Leading Hispanics in STEM

ColorStack

ColorStack
Helping Black and Latinx Computer Science students get *degreed* and *hired* nationwide.
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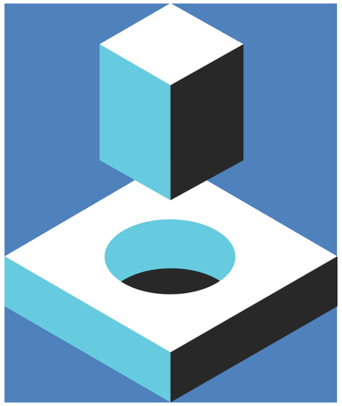
# Exceptions

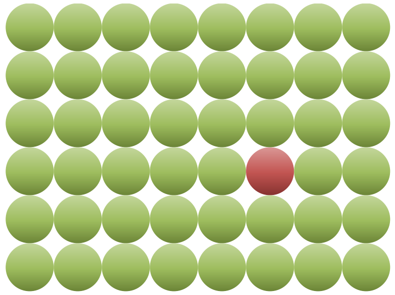
Dealing with the unexpected

# Why do methods "fail"?

- Some methods expect their arguments to satisfy conditions
  - Input to `max` must be a nonempty list, Item must be non-null, more elements must be available when calling `next`, …
- Interfaces may be imprecise
  - Some Iterators don't support the "remove" operation
- External components of a system might fail
  - Trying to open a file or resource that doesn't exist
- Resources might be exhausted
  - Program uses up all of the computer's memory or filesystem storage space



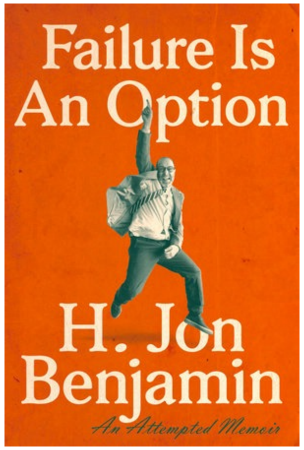
Error 404
Page Not Found!



- These are all *exceptional circumstances…*
  - How do we deal with them?

## Ways to handle failure

- Return an *error value* (or default value)
  - e.g. Math.sqrt returns NaN ("not a number") if given input < 0
  - e.g. Many Java libraries return `null`
  - e.g. file reading methods return -1 if no more input available
  - *Caller is supposed to check return value, but it's easy to forget* ☹
  - *Use with caution – easy to introduce nasty bugs!* ☹
- Return an *optional result*
  - e.g. in OCaml we used options to signal potential failure
  - *Passes responsibility to caller, who must do the proper check to extract value*
- Use *exceptions*
  - Available in both OCaml and Java
  - Any caller (not just the immediate one) can handle the exception
  - If the exception is not caught, the program terminates



# Exceptions

- A Java exception is an *object* representing an abnormal termination condition
  - Its internal state describes what went wrong
  - e.g.: NullPointerException, IllegalArgumentException, IOException
  - Can define your own exception classes
- *Throwing* an exception is an *emergency exit* from the current method
  - The exception propagates up the invocation stack until it either reaches the top of the stack, in which case the program aborts with the error, or the exception is *caught*
- *Catching* an exception lets a caller take appropriate actions to handle the abnormal circumstances
  - Java uses try / catch blocks to handle exceptions.

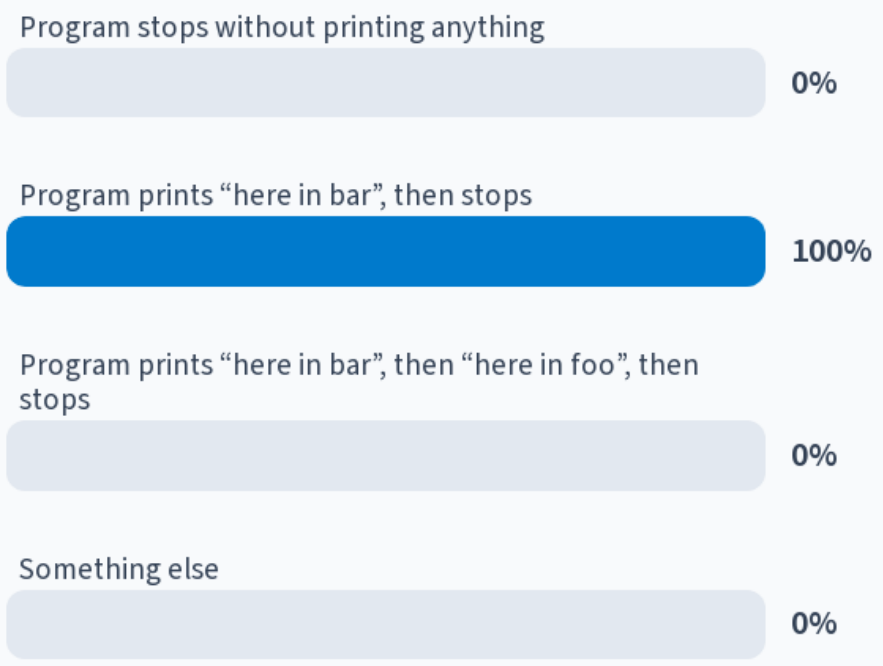
# Example from Pennstagram HW

```
private void load(String filename) {
    ImageIcon icon;

    try {
         if ((new File(filename)).exists())
                icon = new ImageIcon(filename);
         else {
                java.net.URL u = new java.net.URL(filename);
                icon = new ImageIcon(u);
              }
    } catch (Exception e) {
       // … do something about it …
    }
       …
}
```

## 30: What happens if we do (new C()).foo(). ? The program does...

✓ 1


Program stops without printing anything 0%

Program prints “here in bar”, then stops 100%

Program prints “here in bar”, then “here in foo”, then stops 0%

Something else 0%

## Simplified Example

```
class C {
  public void foo() {
    this.bar();
    System.out.println("here in foo");
  }
  public void bar() {
    this.baz();
    System.out.println("here in bar");
  }
  public void baz() {
    throw new RuntimeException();
  }
}
```

What happens if we do `(new C()).foo()` ?

1. Program stops without printing anything
2. Program prints “here in bar”, then stops
3. Program prints “here in bar”, then “here in foo”, then stops
4. Something else

Answer: 1 or 4* (*depending on whether you count stderr as "printing")

# Abstract Stack Machine

Workspace

```
(new C()).foo();
```

Stack

Heap

# Abstract Stack Machine

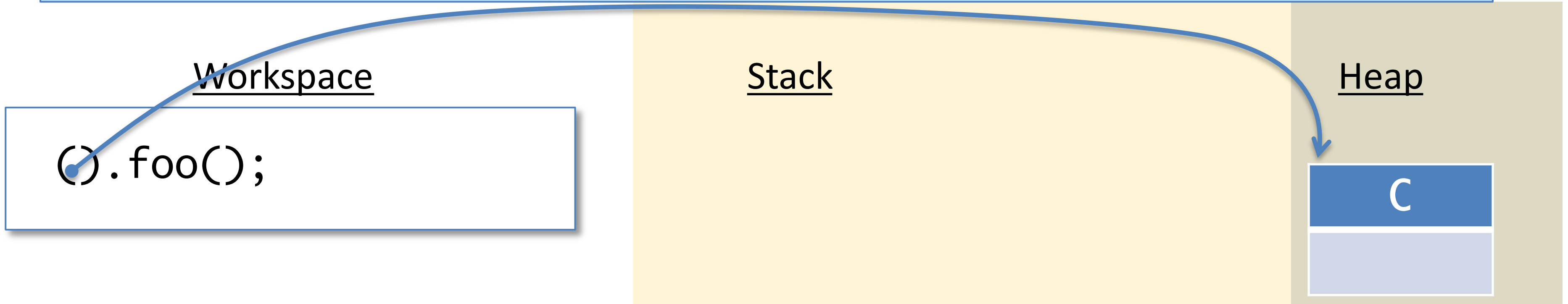
Workspace

```
(new C()).foo();
```

Stack

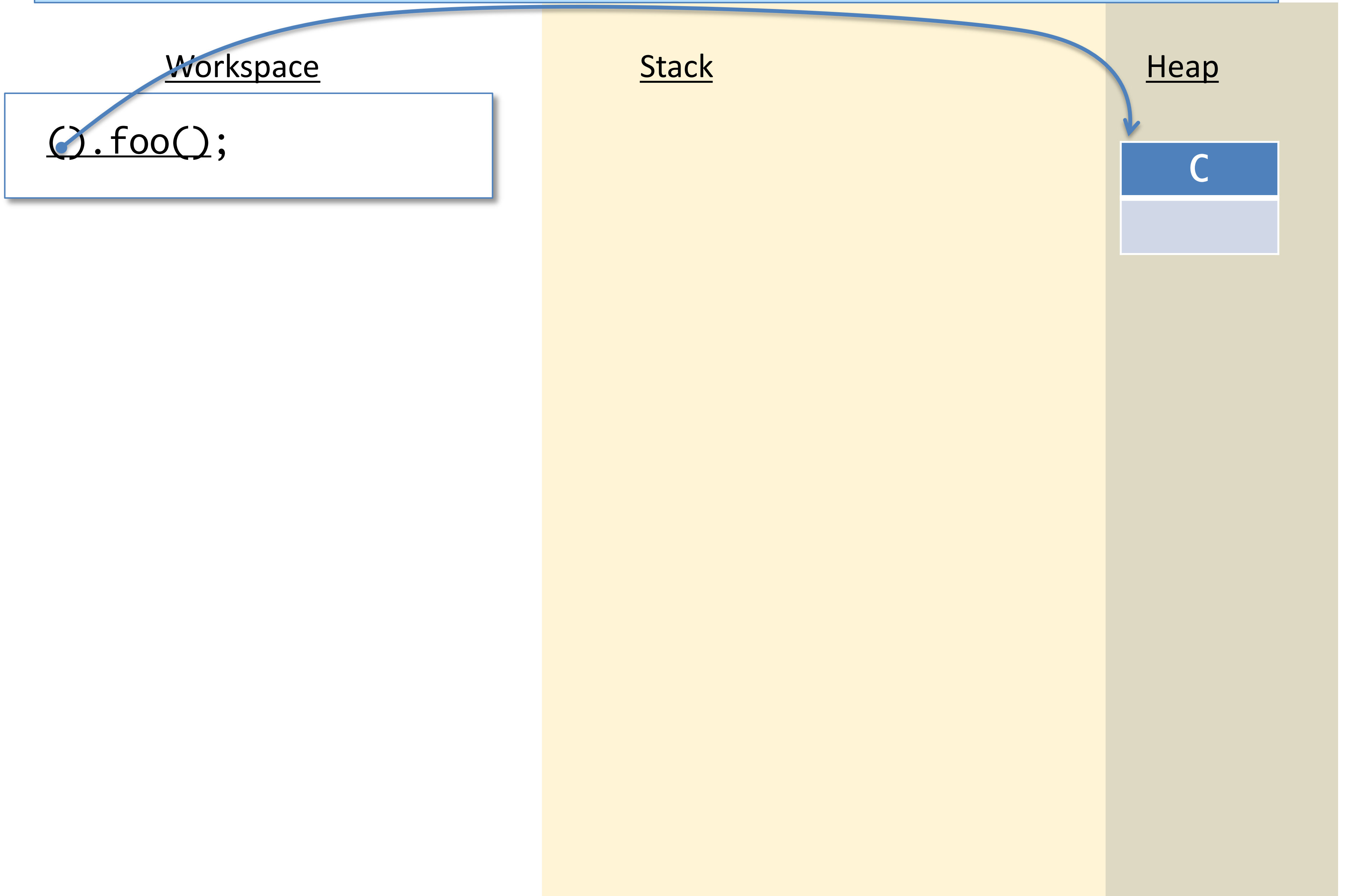
Heap

# Abstract Stack Machine



Allocate a new instance of C in the heap. (Skipping details of trivial constructor for C.)

# Abstract Stack Machine

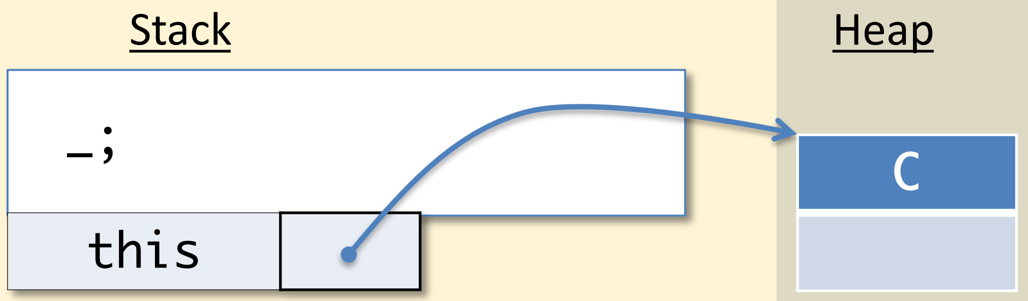


```
().foo();
```

# Abstract Stack Machine

Workspace

```
this.bar();
System.out.println(
  “here in foo”);
```

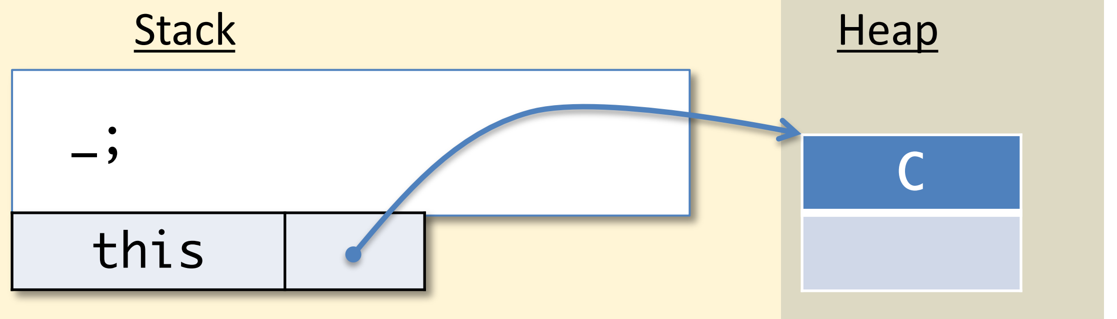


Save a copy of the current workspace in the stack, leaving a “hole”, written _, where we are going to return to. Also save the `this` pointer, followed by arguments (in this case none) onto the stack. Use the dynamic class to look up the method body from the class table.

# Abstract Stack Machine

Workspace

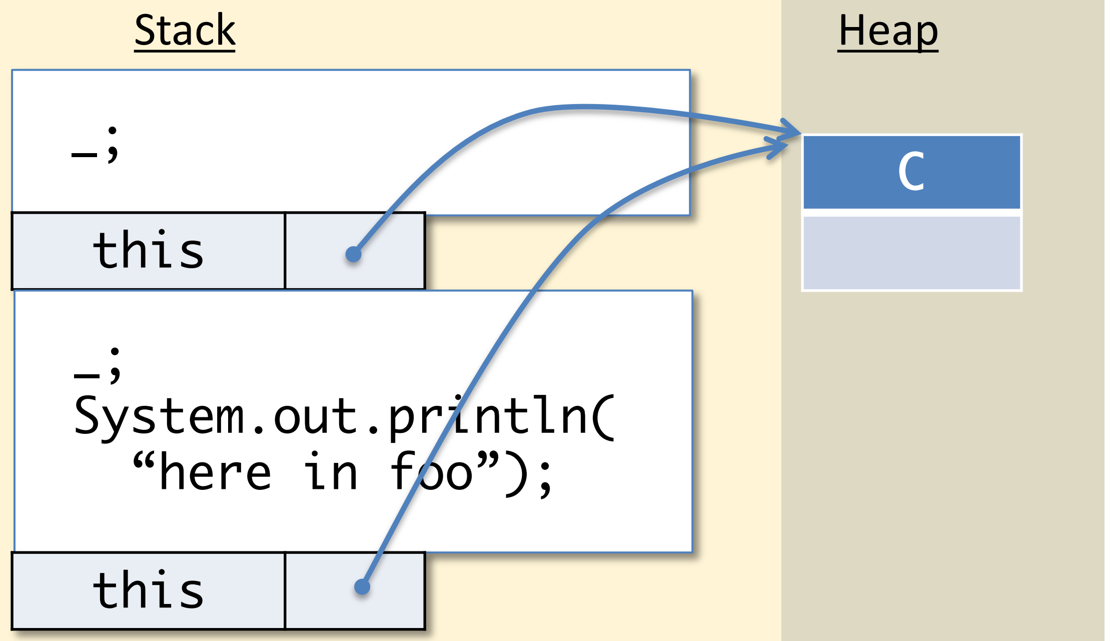
```
this.bar();
System.out.println(
  “here in foo”);
```



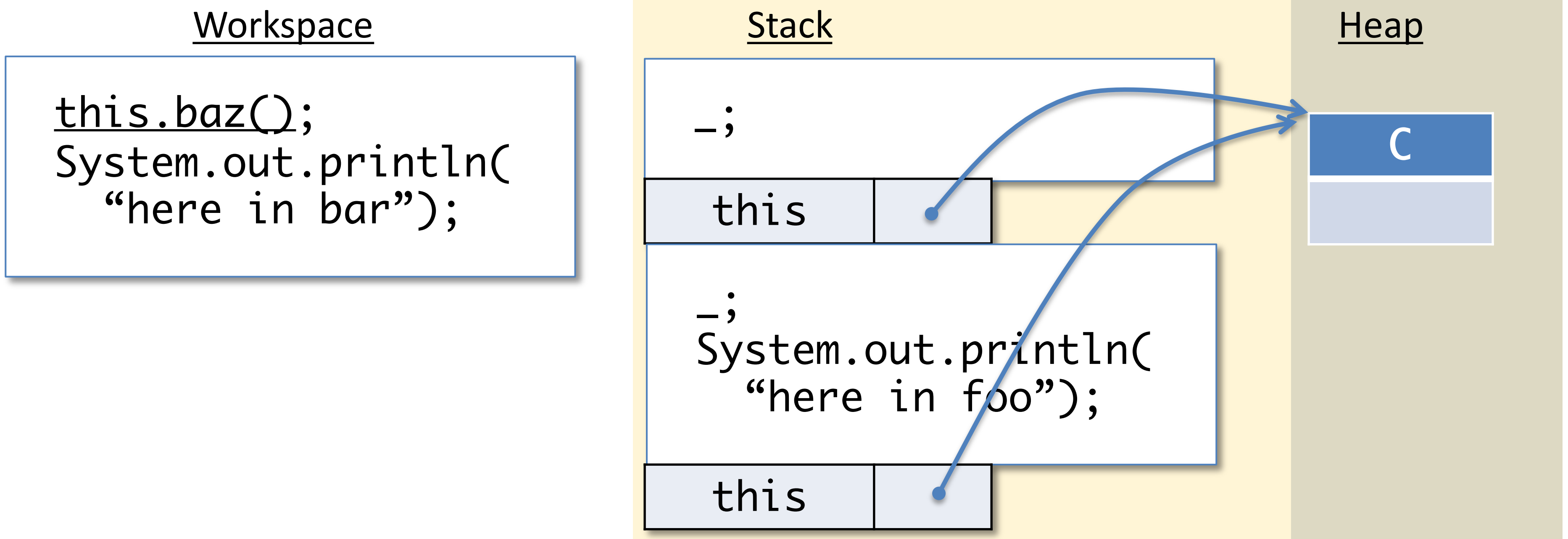
# Abstract Stack Machine

Workspace

```
this.baz();
System.out.println(
  “here in bar”);
```



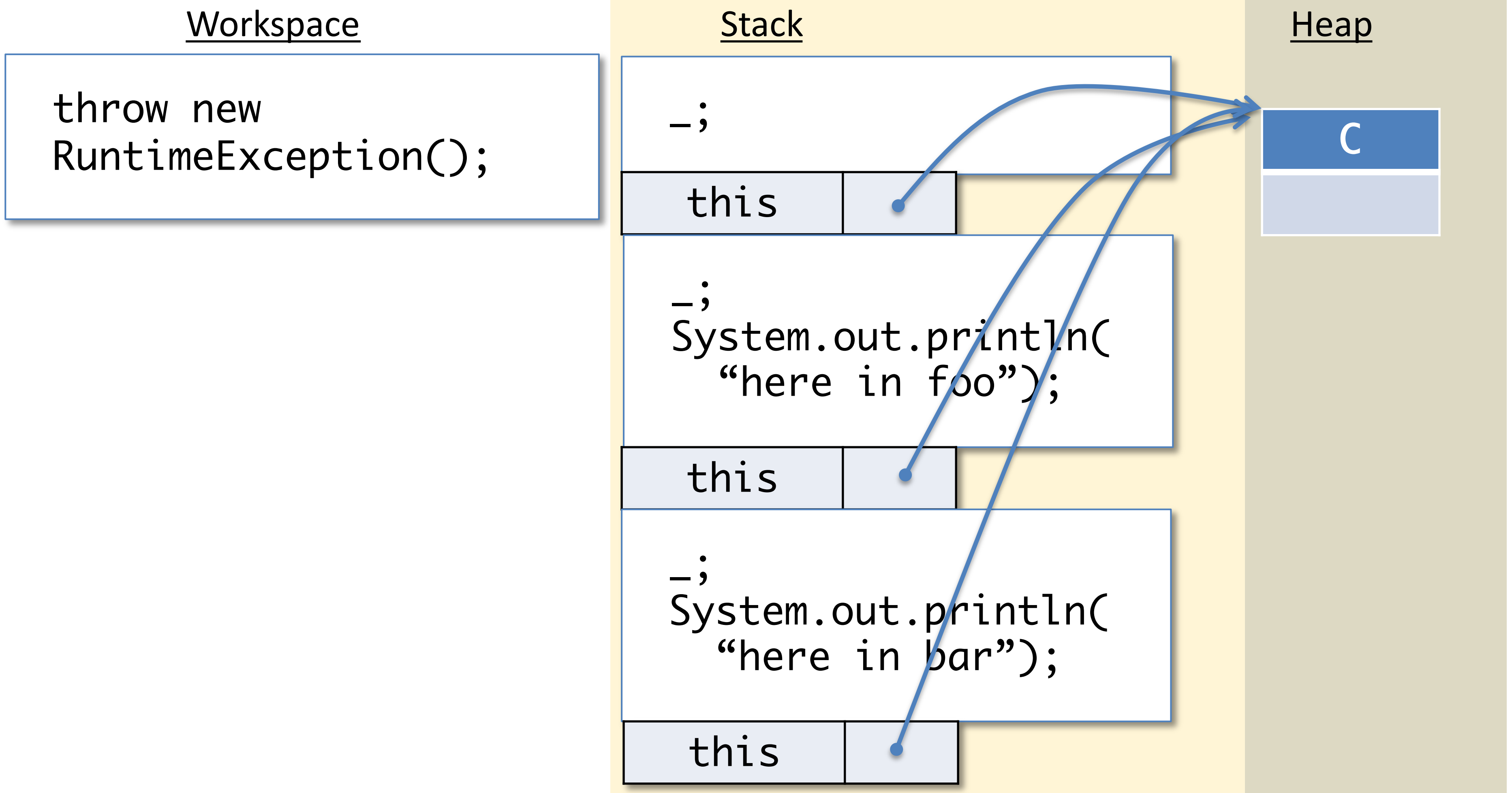
# Abstract Stack Machine



```
this.baz();
System.out.println(
  “here in bar”);
```

```
_;
System.out.println(
  “here in foo”);
```

# Abstract Stack Machine



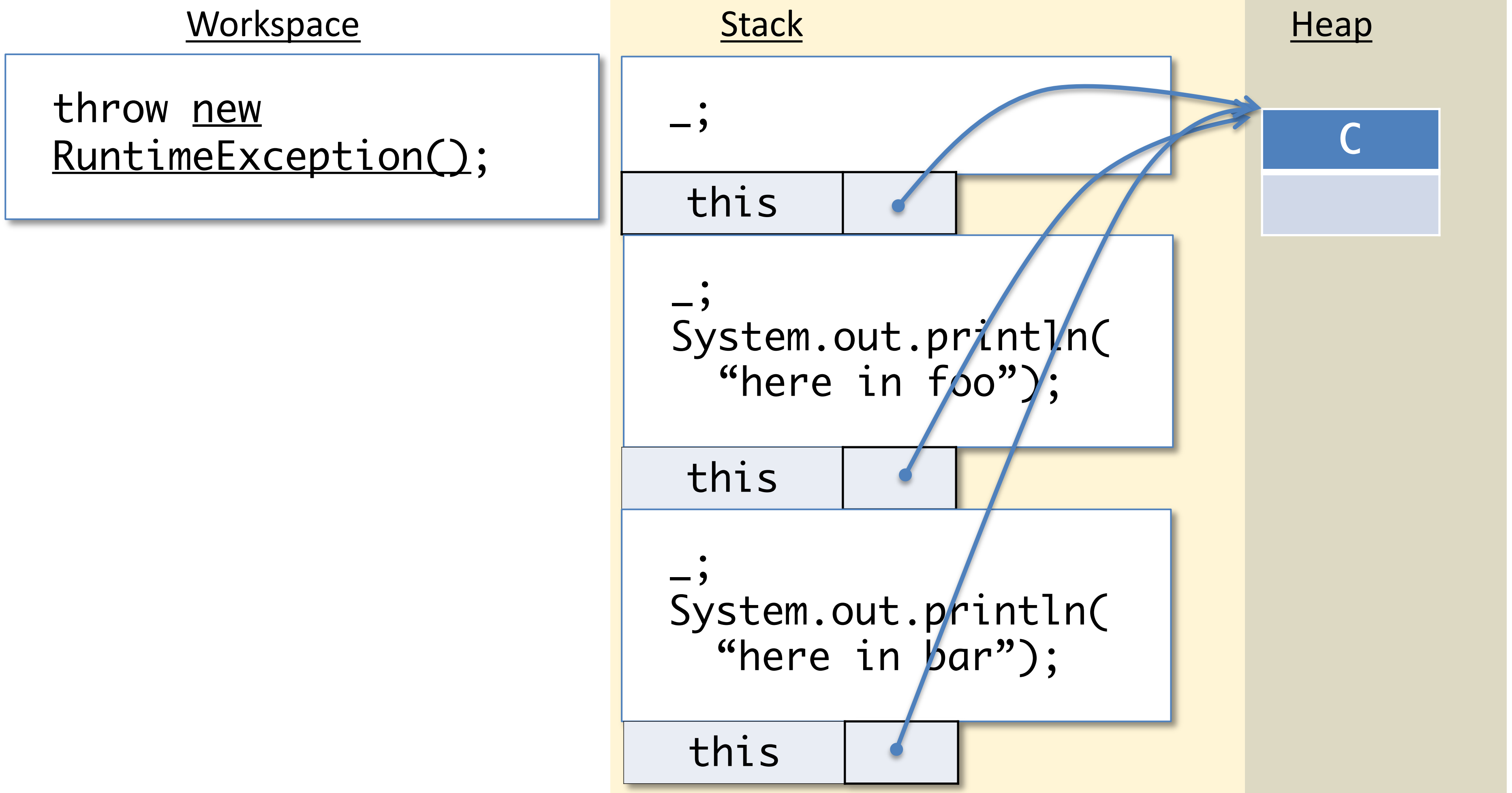
```
throw new
RuntimeException();
```

```
_;
```

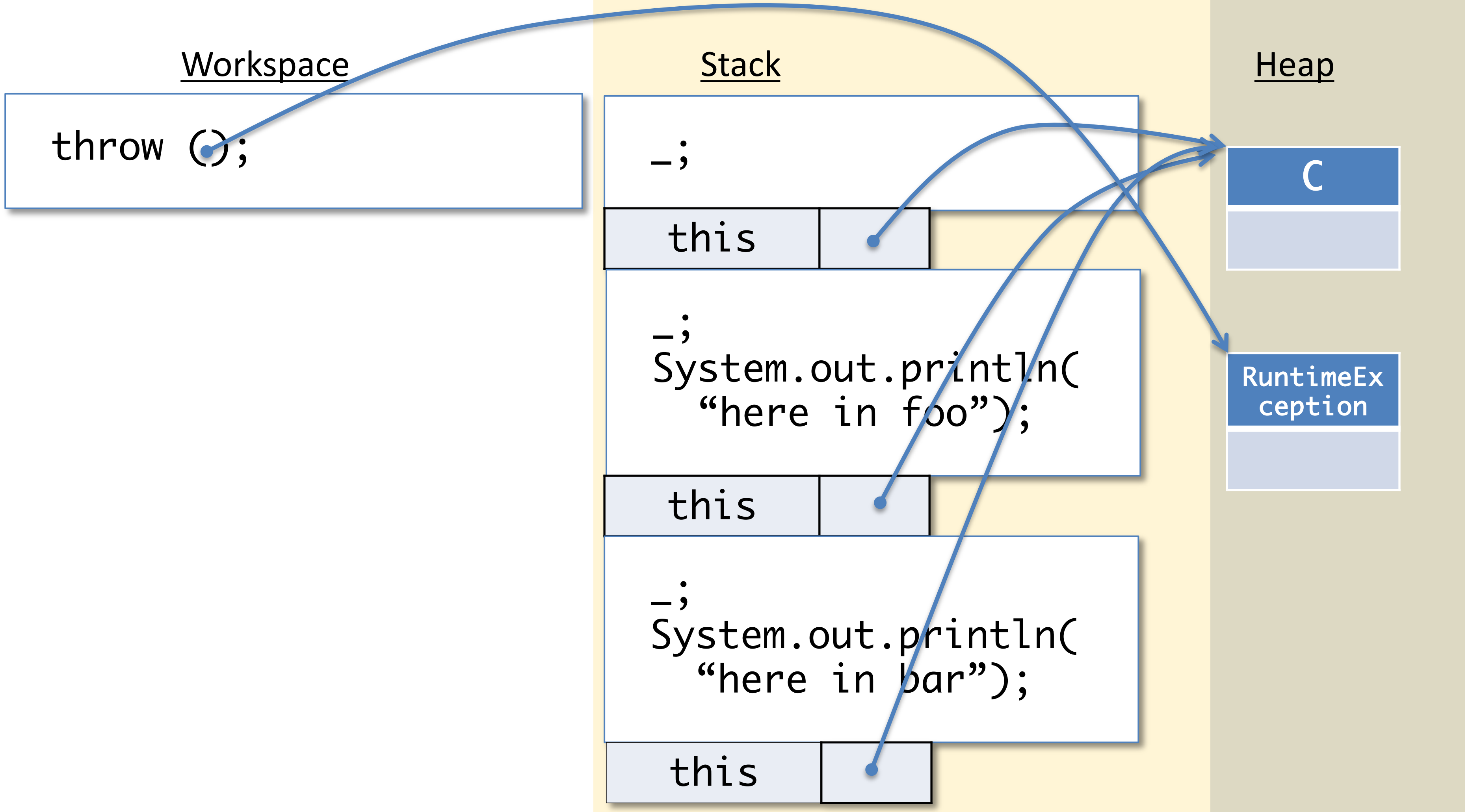
```
_;
System.out.println(
  "here in foo");
```

```
_;
System.out.println(
  "here in bar");
```

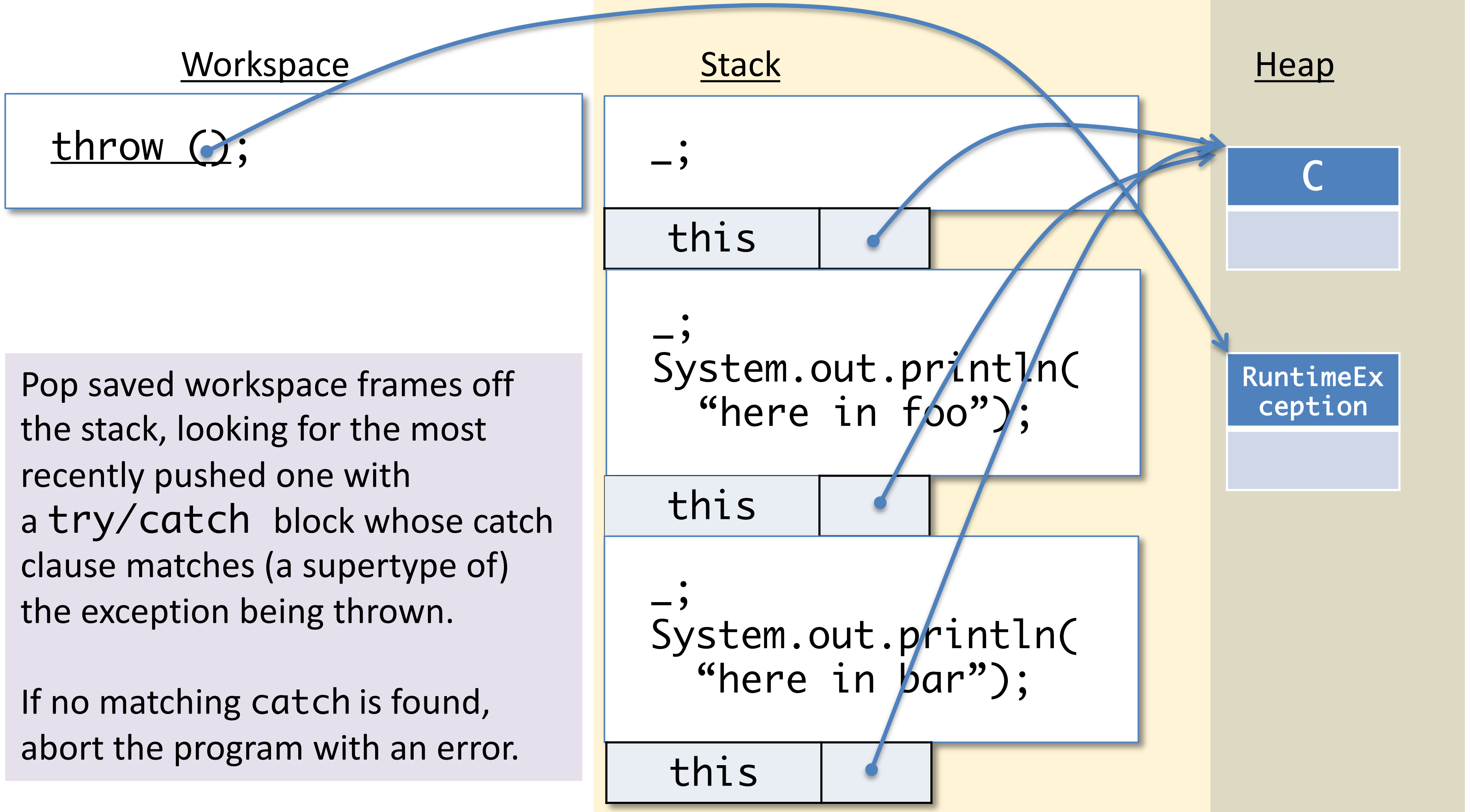
# Abstract Stack Machine



# Abstract Stack Machine



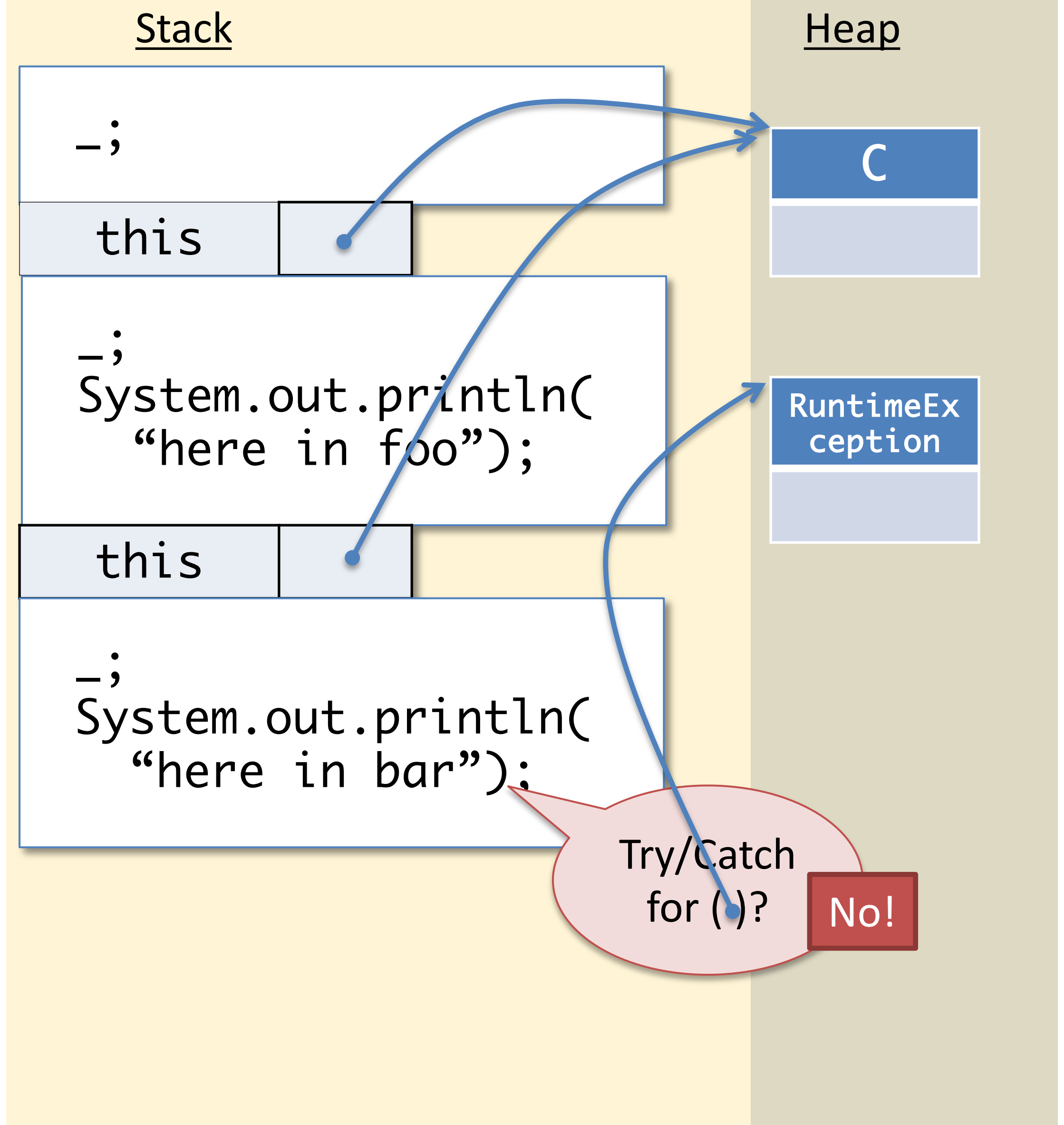
# Abstract Stack Machine



Pop saved workspace frames off the stack, looking for the most recently pushed one with a `try/catch` block whose catch clause matches (a supertype of) the exception being thrown.

If no matching `catch` is found, abort the program with an error.

# Abstract Stack Machine



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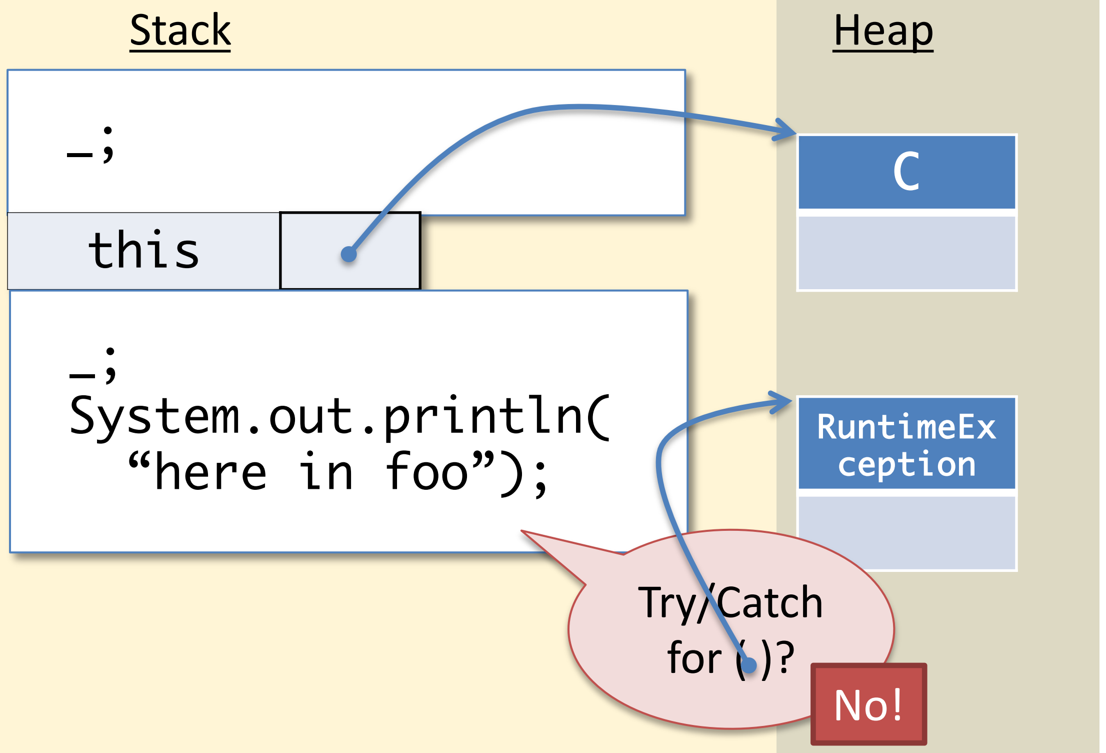
# Abstract Stack Machine



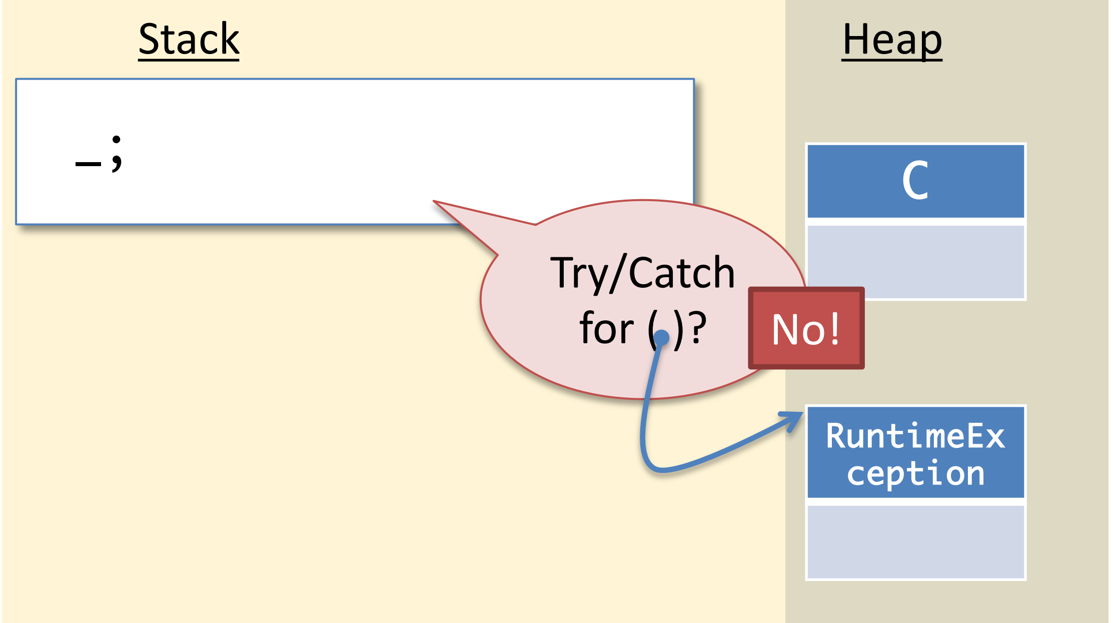
Discard the current workspace.

Then, pop saved workspace frames off the stack, looking for the most recently pushed one that contains a `try/catch` block whose catch clause declares (a supertype of) the exception being thrown.

If no matching catch is found, abort the program with an error.

# Abstract Stack Machine

Workspace



Discard the current workspace.

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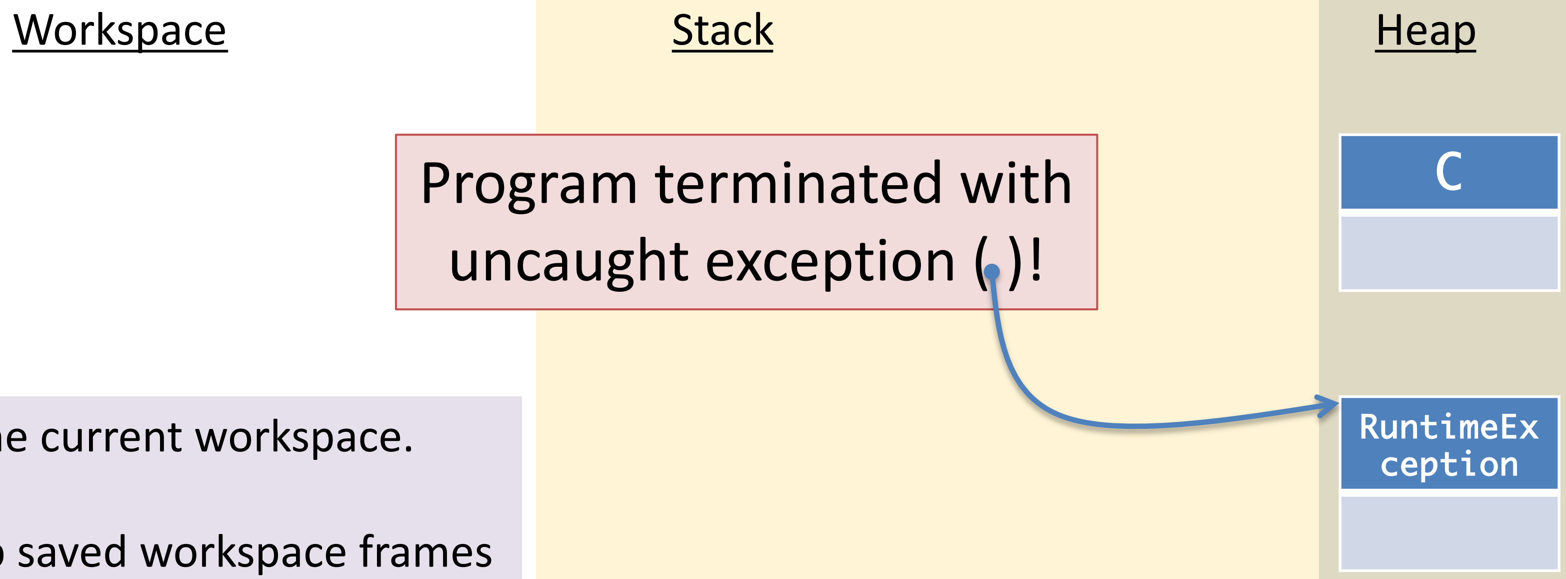
If no matching catch is found, abort the program with an error.

# Abstract Stack Machine



Program terminated with uncaught exception ( )!

Discard the current workspace.

Then, pop saved workspace frames off the stack, looking for the most recently pushed one that contains a `try/catch` block whose catch clause declares (a supertype of) the exception being thrown.

If no matching catch is found, abort the program with an error.

## Catching the Exception

```
class C {
  public void foo() {
    this.bar();
    System.out.println("here in foo");
  }
  public void bar() {
    try {
      this.baz();
    } catch (Exception e) { System.out.println("caught"); }
    System.out.println("here in bar");
  }
  public void baz() {
    throw new RuntimeException();
  }
}
```

*Now* what happens if we do `(new C()).foo();`?

# Abstract Stack Machine

Workspace

```
(new C()).foo();
```

Stack

Heap

# Abstract Stack Machine

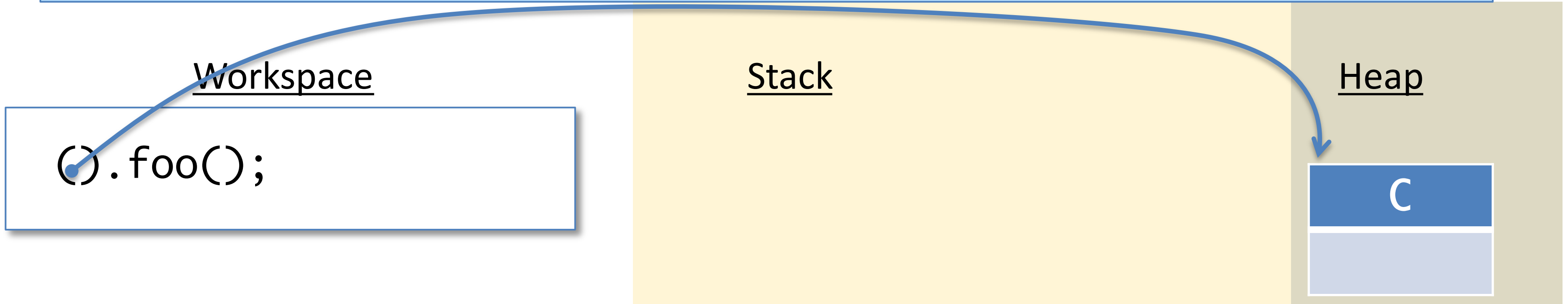
Workspace

```
(new C()).foo();
```

Stack

Heap

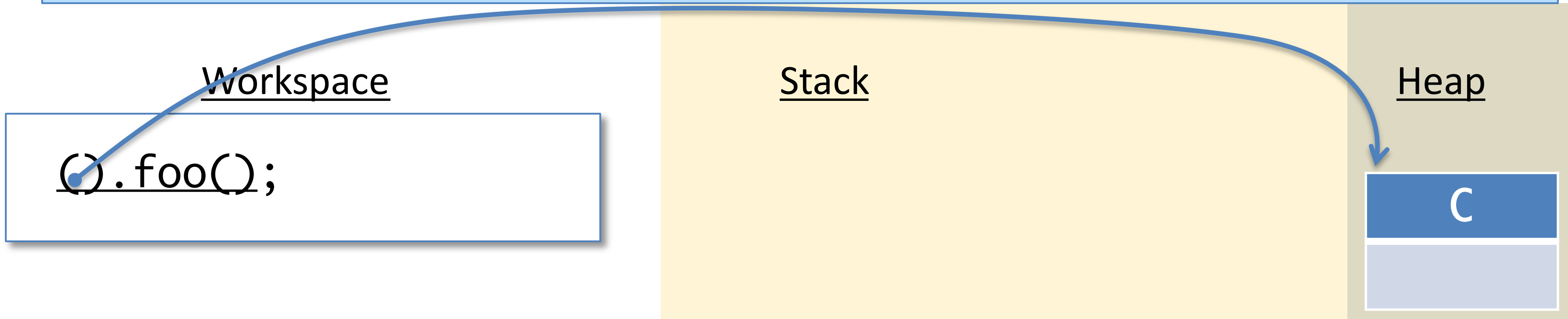
# Abstract Stack Machine



```
( ).foo();
```

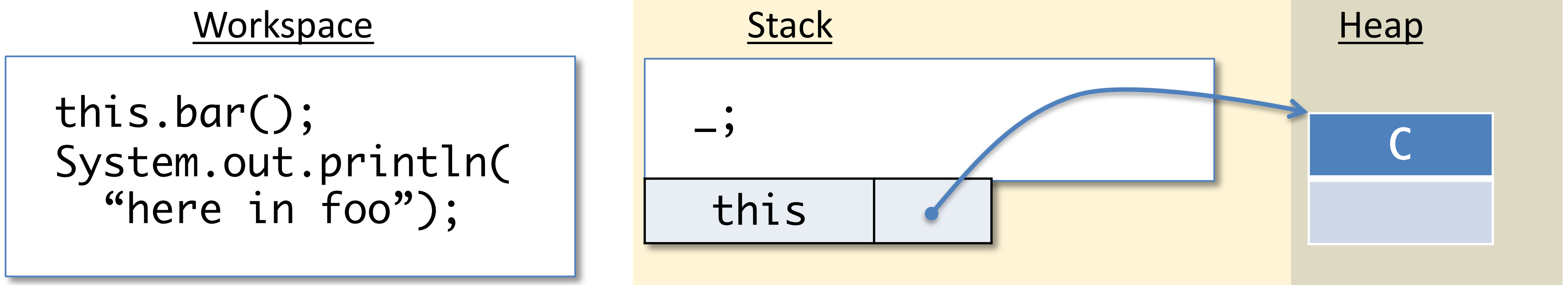
Allocate a new instance of C in the heap.

# Abstract Stack Machine



```
().foo();
```

# Abstract Stack Machine



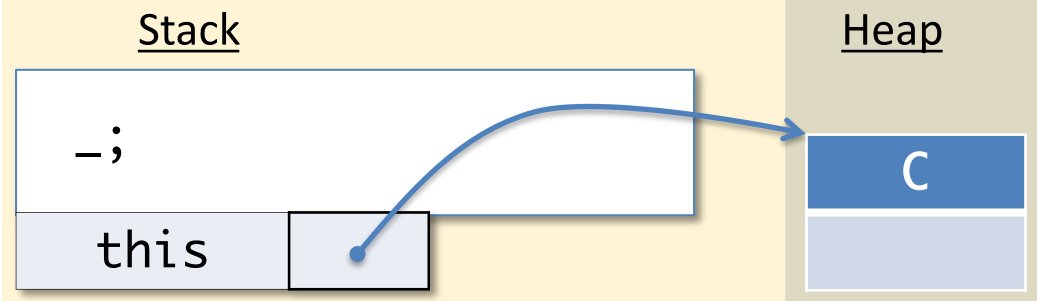
```
this.bar();
System.out.println(
  “here in foo”);
```

Save a copy of the current workspace in the stack, leaving a “hole”, written _, where we return to. Push the `this` pointer, followed by arguments (in this case none) onto the stack.

# Abstract Stack Machine

Workspace

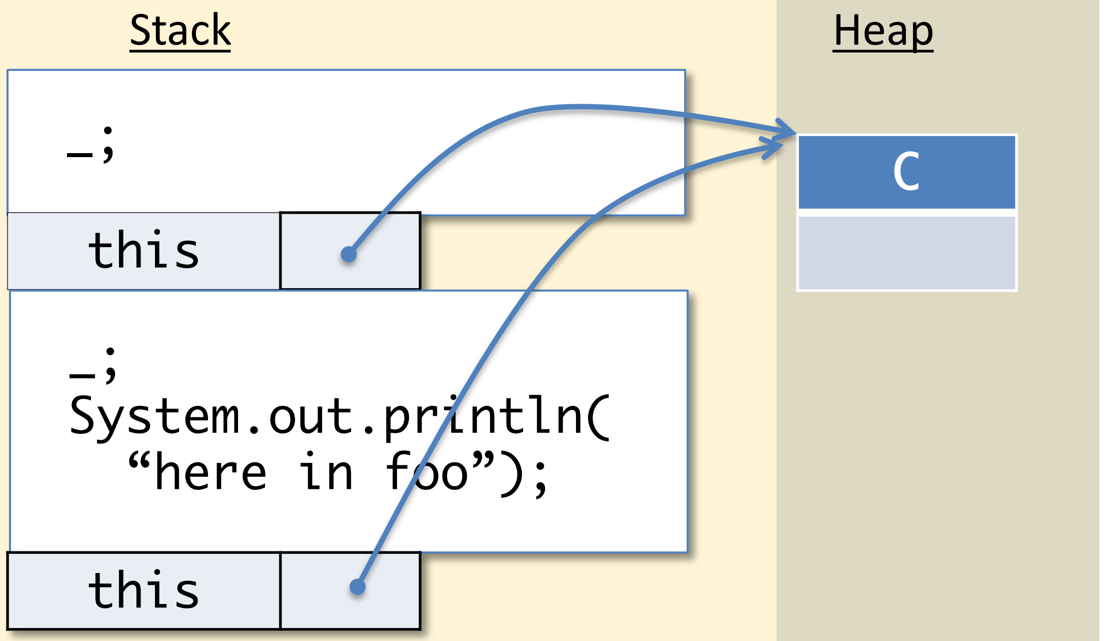
```
this.bar();
System.out.println(
  “here in foo”);
```



# Abstract Stack Machine

Workspace

```
try {
   baz();
} catch (Exception e)
{ System.out.println
  (“caught”); }
System.out.println(
  “here in bar”);
```



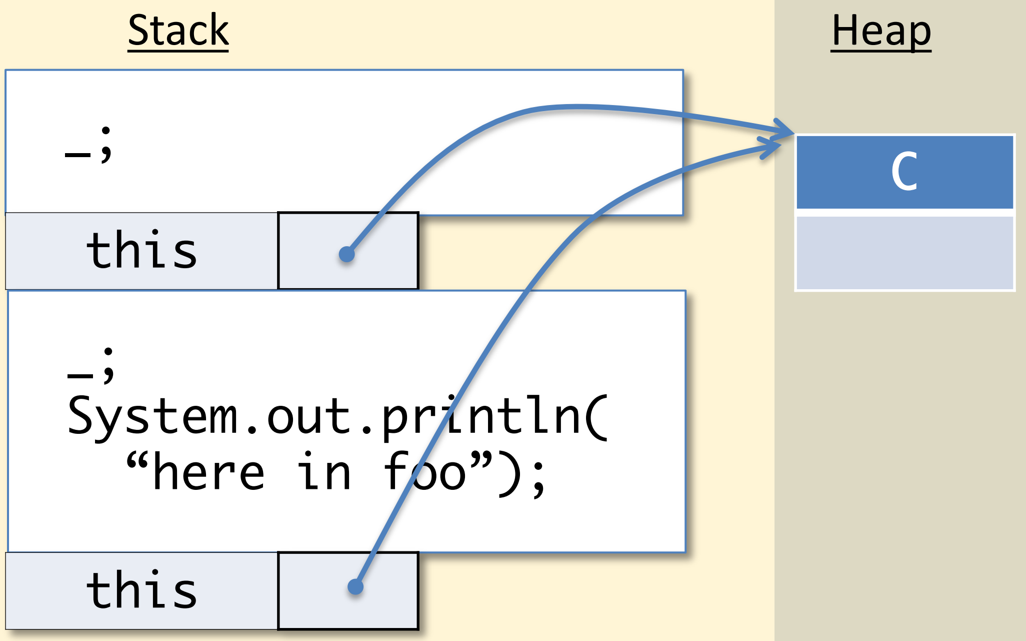
# Abstract Stack Machine

Workspace

```
try {
    baz();
} catch (Exception e)
{ System.out.println
    ("caught"); }
System.out.println(
    "here in bar");
```

Stack

Heap



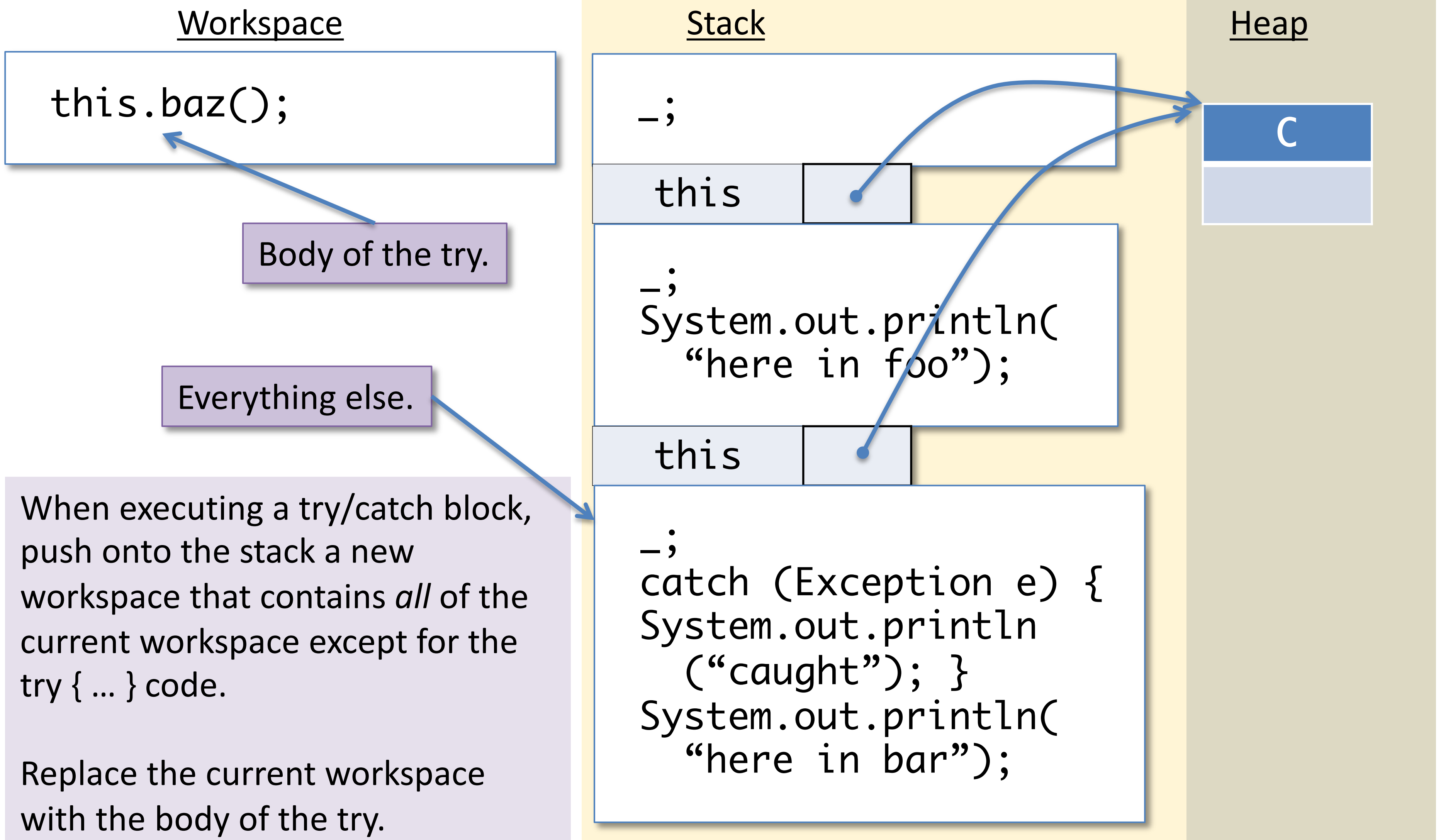
```
_;
```

```
_;
System.out.println(
    "here in foo");
```

When executing a try/catch block, push onto the stack a new workspace that contains *all* of the current workspace except for the try { … } code.

Replace the current workspace with the body of the try.

# Abstract Stack Machine



```
this.baz();
```

```
_;
```

```
_;
System.out.println(
  “here in foo”);
```

```
_;
catch (Exception e) {
System.out.println
  (“caught”); }
System.out.println(
  “here in bar”);
```

When executing a try/catch block, push onto the stack a new workspace that contains *all* of the current workspace except for the try { … } code.

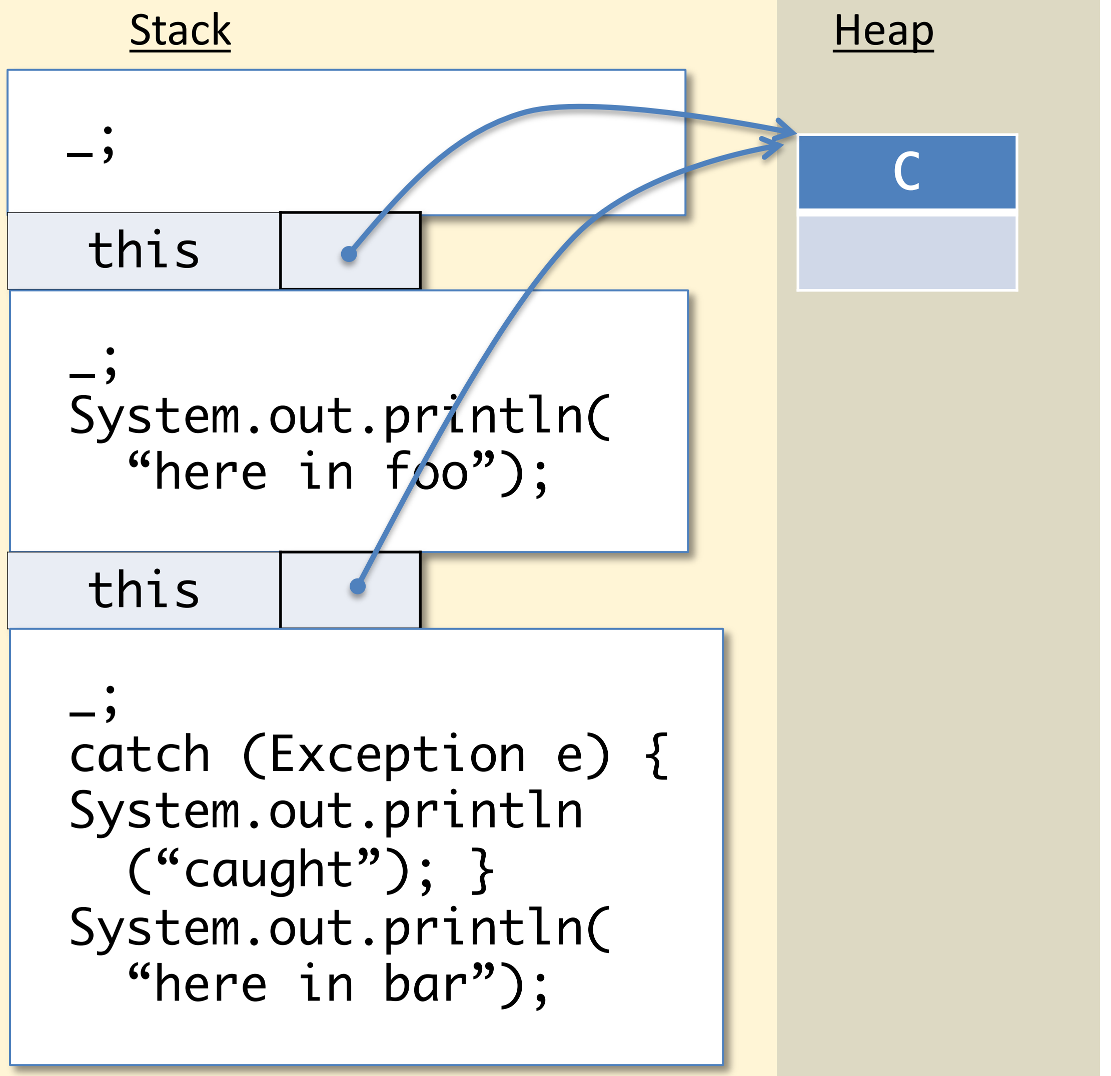
Replace the current workspace with the body of the try.

# Abstract Stack Machine

Workspace

```
this.baz();
```

Continue executing as normal.



```
_;
```

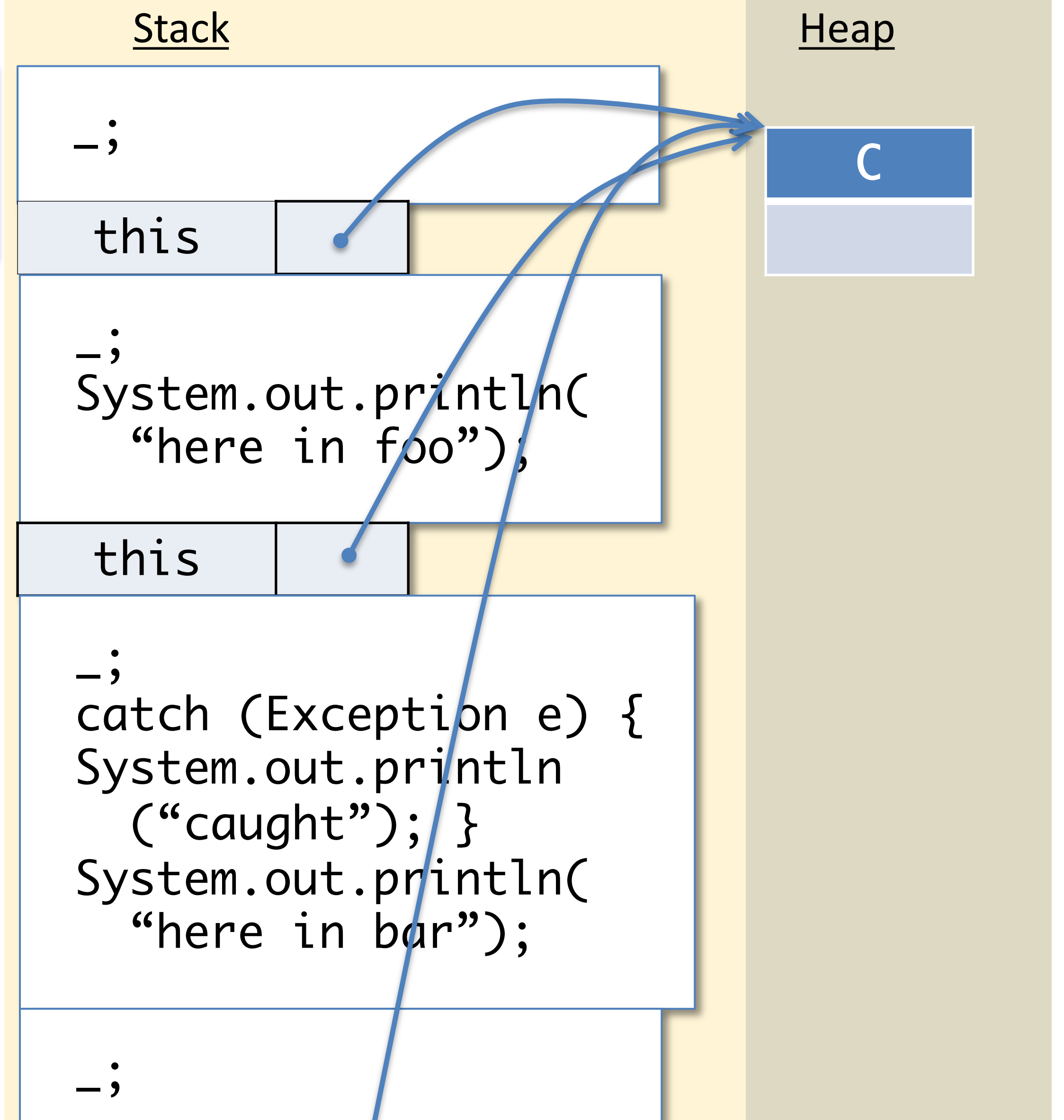
```
_;
System.out.println(
  “here in foo”);
```

```
_;
catch (Exception e) {
System.out.println
  (“caught”); }
System.out.println(
  “here in bar”);
```

# Abstract Stack Machine

Workspace

```
throw new
RuntimeException();
```



```
_;
```

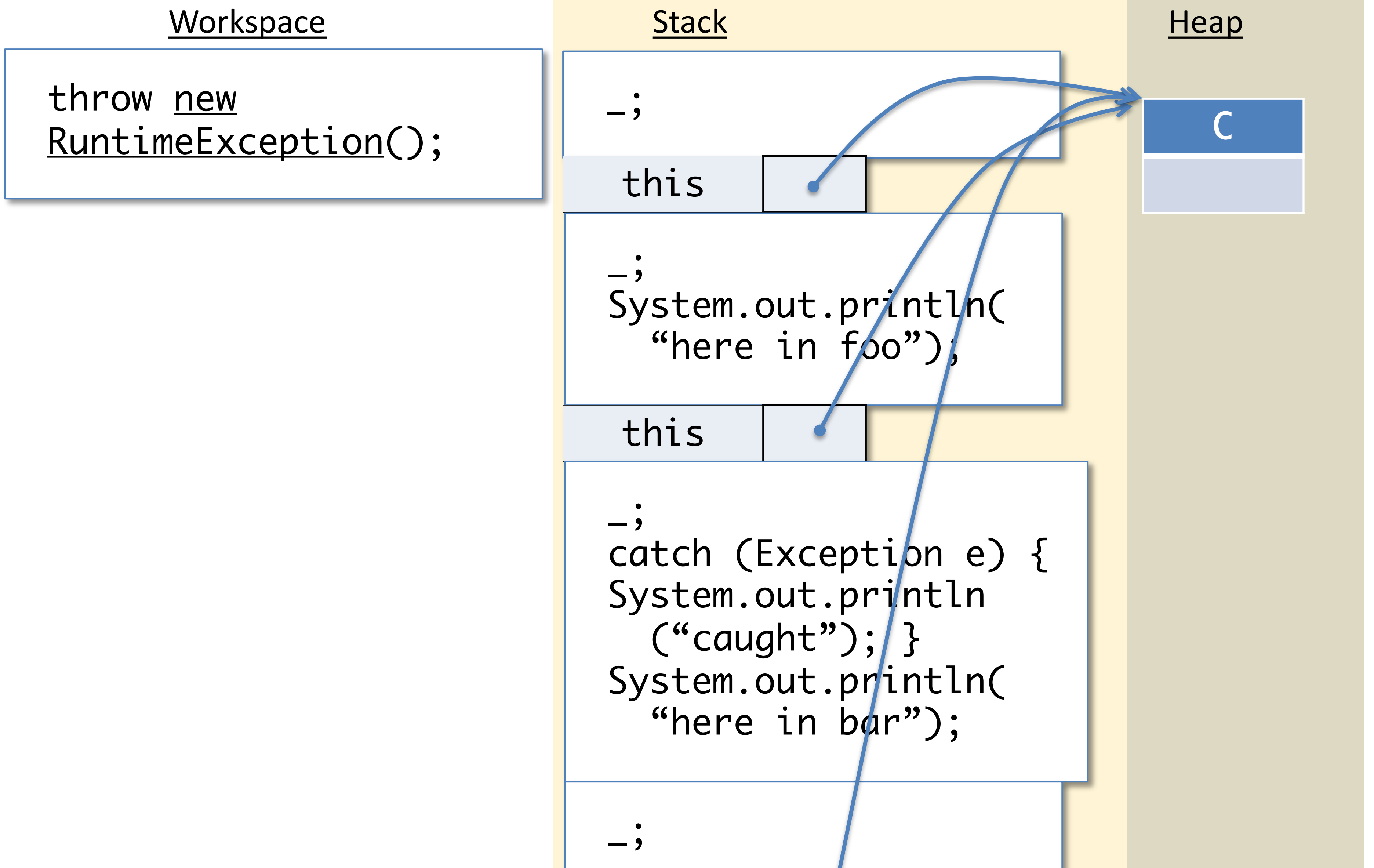
```
_;
System.out.println(
  “here in foo”);
```

```
_;
catch (Exception e) {
System.out.println
  (“caught”); }
System.out.println(
  “here in bar”);
```

```
_;
```

The top of the stack is off the bottom of the page… ☺

# Abstract Stack Machine



```
throw new
RuntimeException();
```

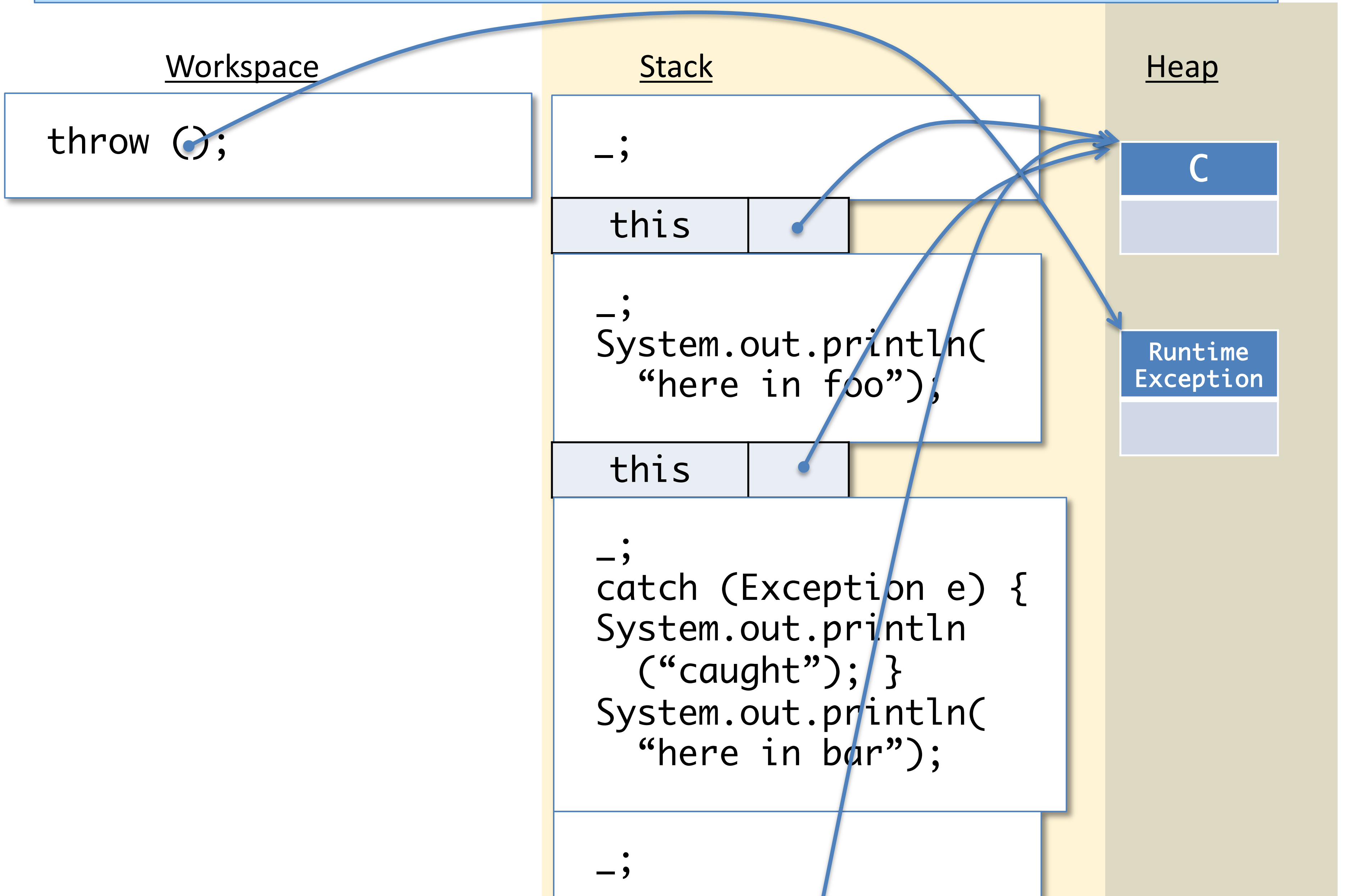
```
_;
```

```
_;
System.out.println(
  "here in foo");
```

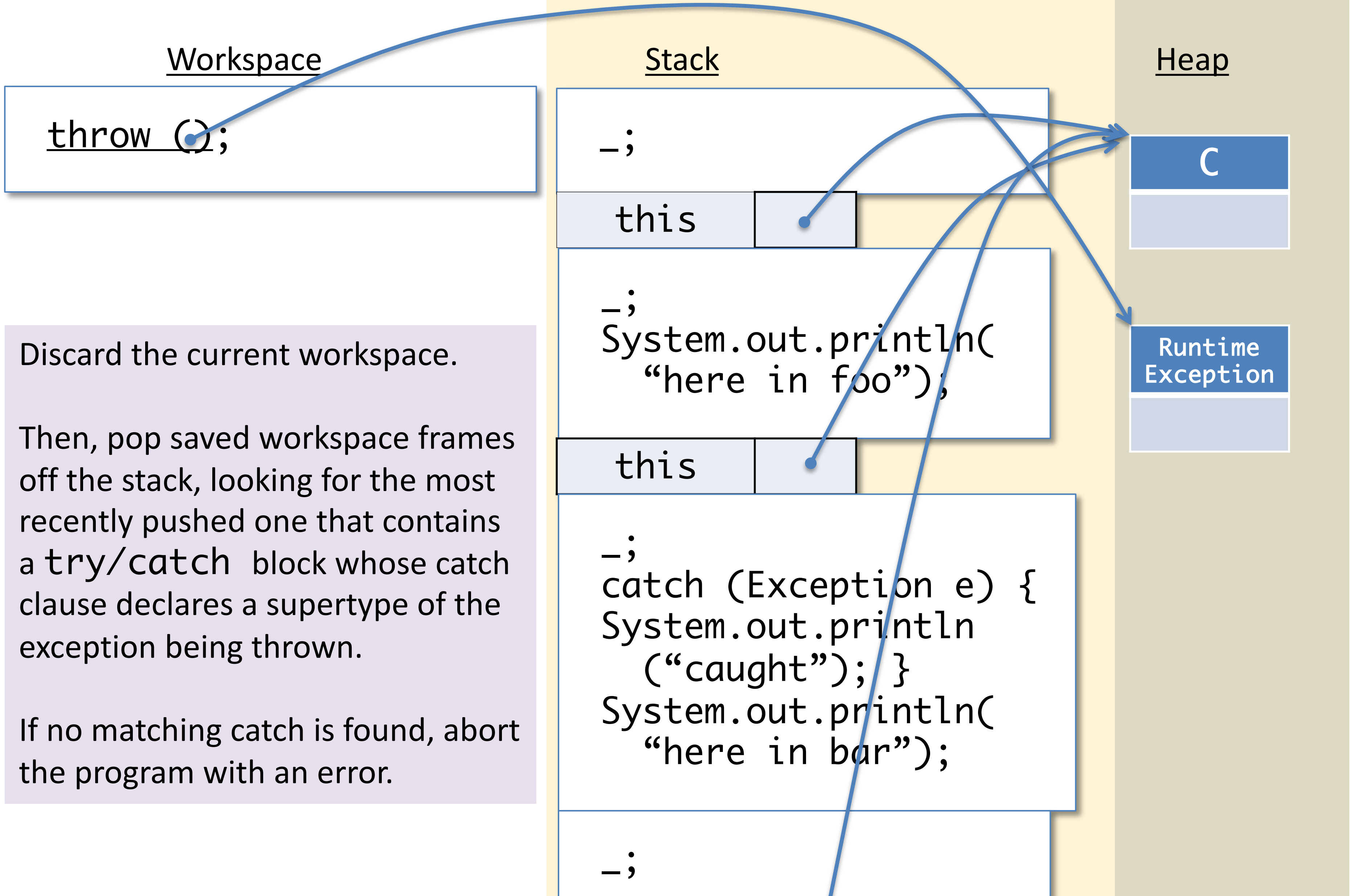
```
_;
catch (Exception e) {
System.out.println
  ("caught"); }
System.out.println(
  "here in bar");
```

```
_;
```

# Abstract Stack Machine



# Abstract Stack Machine



```
throw ( );
```

```
_;
```

```
_;
System.out.println(
  “here in foo”);
```

```
_;
catch (Exception e) {
System.out.println
  (“caught”); }
System.out.println(
  “here in bar”);
```

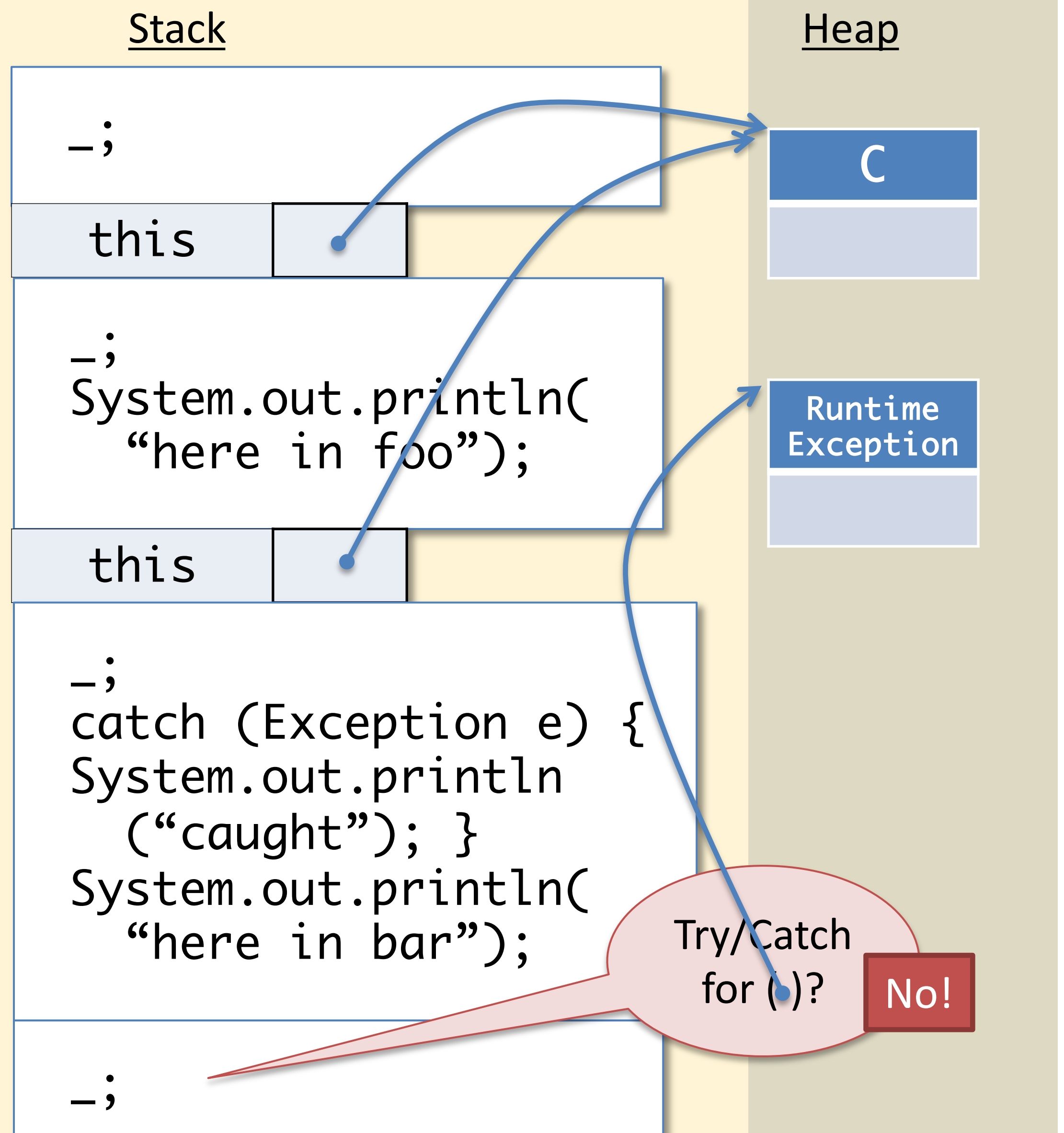
```
_;
```

Discard the current workspace.

Then, pop saved workspace frames off the stack, looking for the most recently pushed one that contains a `try/catch` block whose catch clause declares a supertype of the exception being thrown.

If no matching catch is found, abort the program with an error.

# Abstract Stack Machine



Discard the current workspace.

Then, pop saved workspace frames off the stack, looking for the most recently pushed one that contains a `try/catch` block whose catch clause declares a supertype of the exception being thrown.

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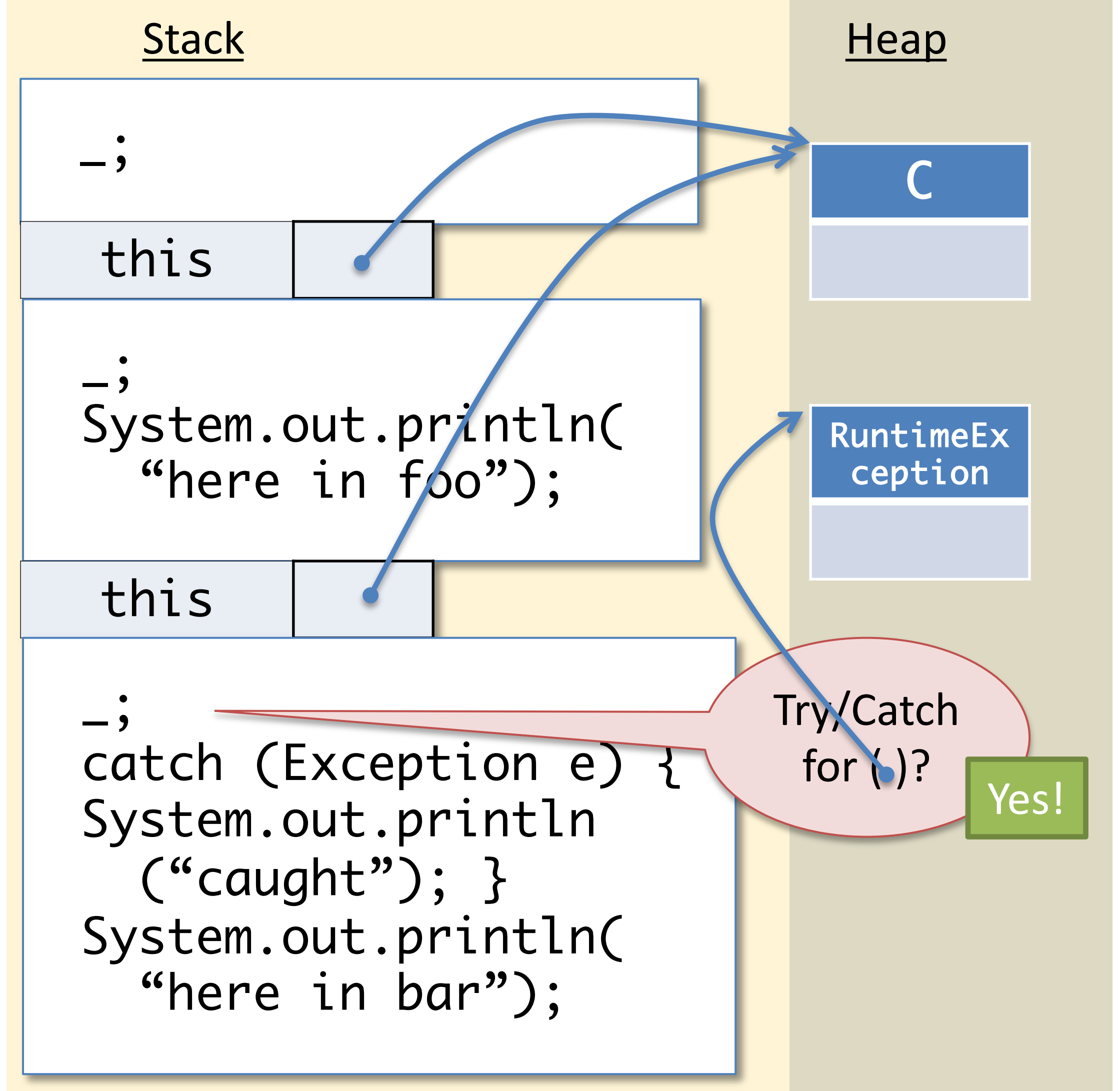
# Abstract Stack Machine



When a matching catch block is found, add a new binding to the stack for the exception variable declared in the catch. Then replace the workspace with catch body and the rest of the saved workspace.

Continue executing as usual.

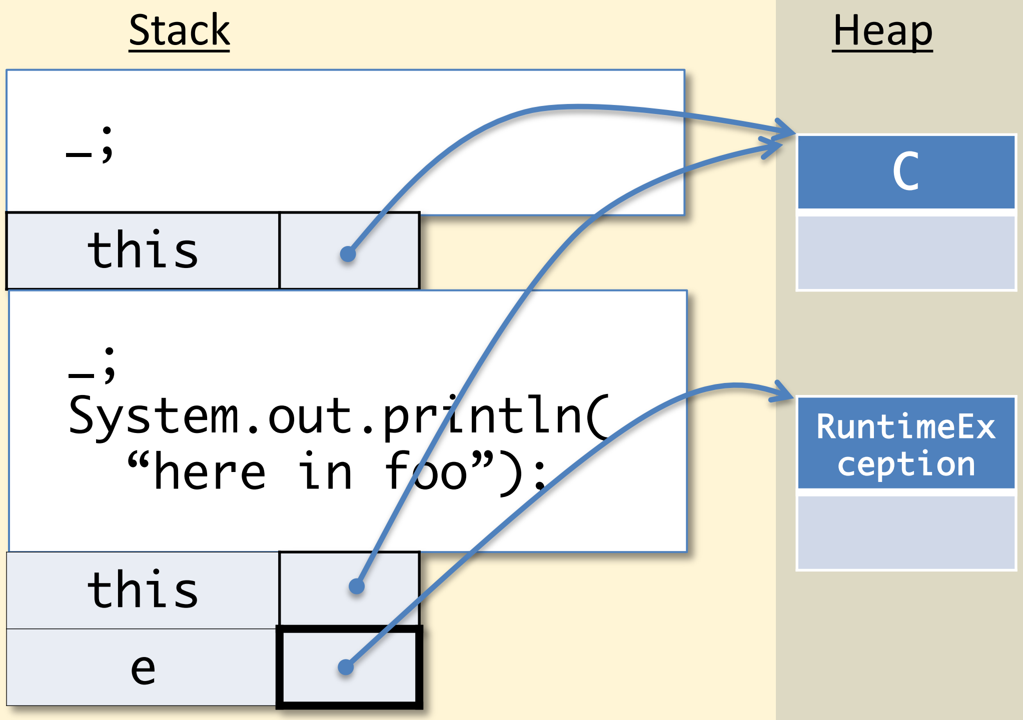
# Abstract Stack Machine

Workspace

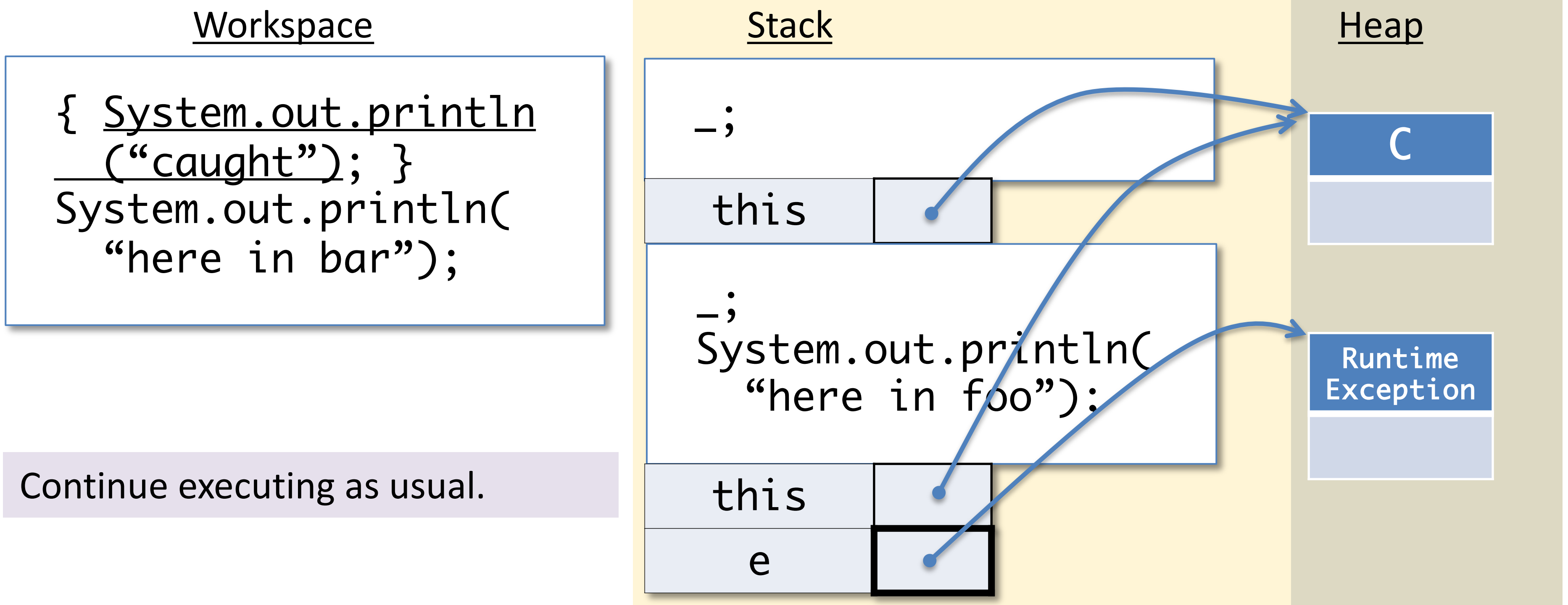
```
{ System.out.println
  ("caught"); }
System.out.println(
  "here in bar");
```

When a matching catch block is found, add a new binding to the stack for the exception variable declared in the catch.  Then replace the workspace with catch body and the rest of the saved workspace.

Continue executing as usual.



# Abstract Stack Machine

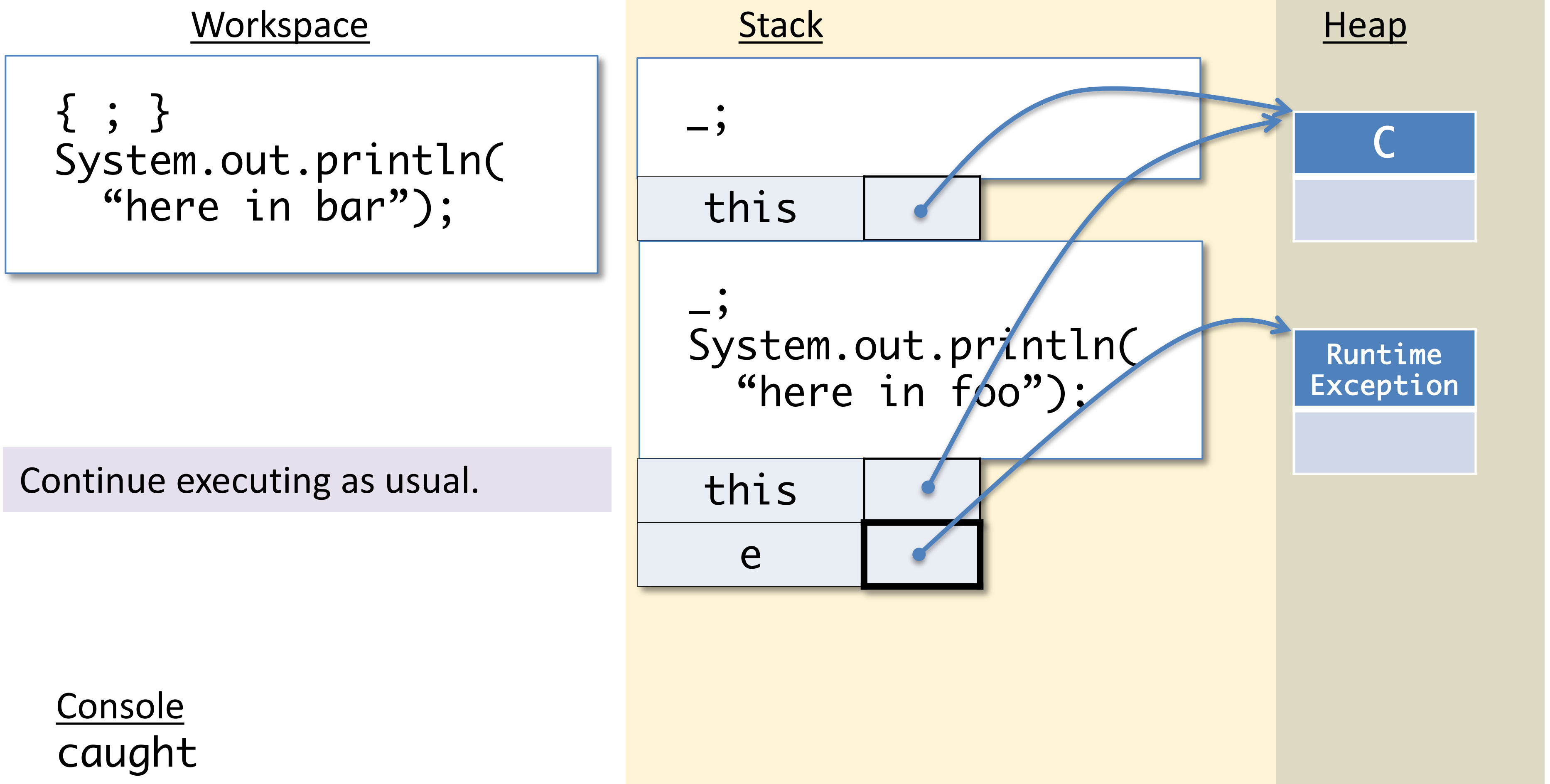


```
{ System.out.println
  ("caught"); }
System.out.println(
  "here in bar");
```

```
System.out.println(
  "here in foo");
```

Continue executing as usual.

# Abstract Stack Machine



```
{ ; }
System.out.println(
  “here in bar”);
```

Continue executing as usual.

```
caught
```

# Abstract Stack Machine

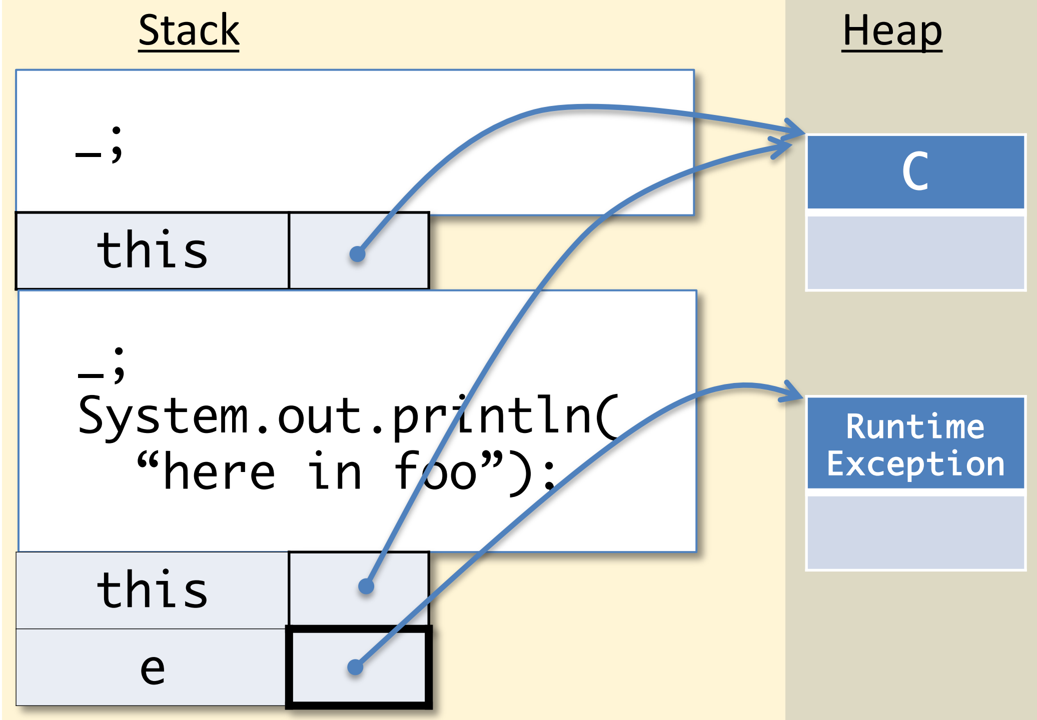
Workspace

```
{ ; }
System.out.println(
  "here in bar");
```

We're sweeping a few details about lexical scoping of variables under the rug – the scope of e is just the body of the catch, so when that is done, e must be popped from the stack too.

Console

```
caught
```



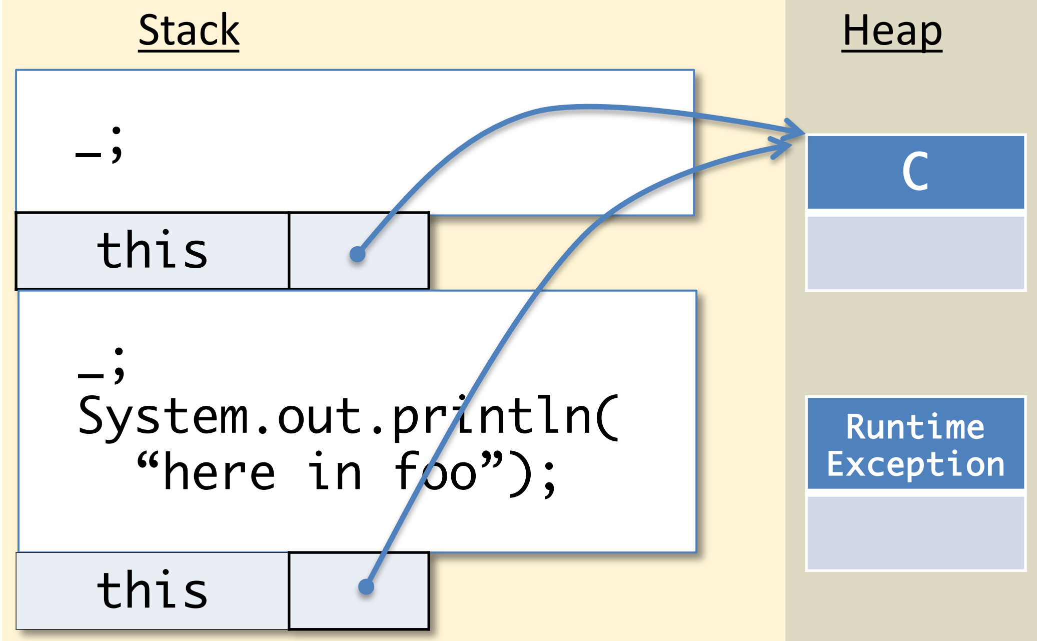
# Abstract Stack Machine

Workspace

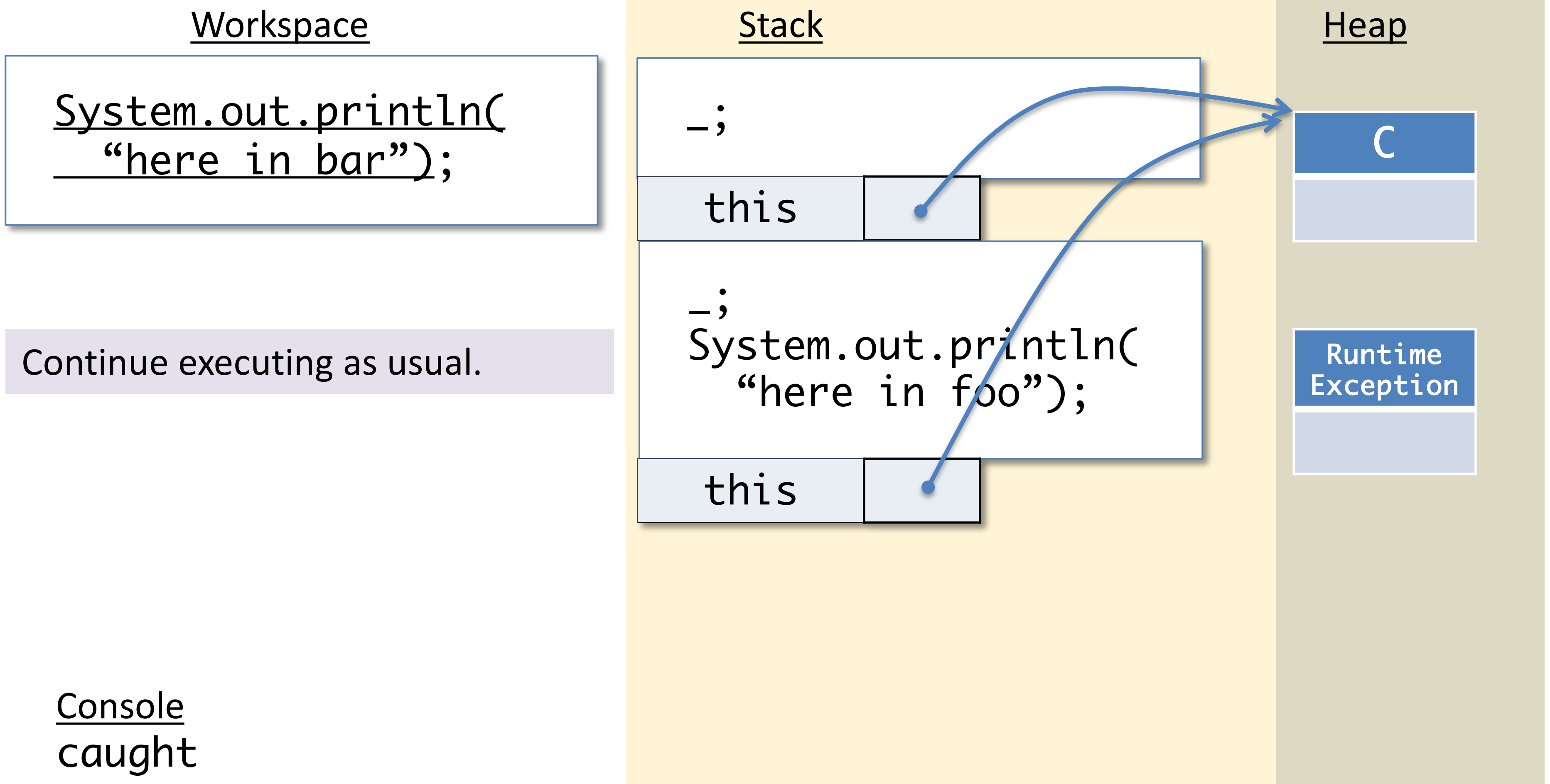
```
System.out.println(
  "here in bar");
```

Continue executing as usual.

Console
caught



# Abstract Stack Machine



```
System.out.println(
  "here in bar");
```

```
_;
System.out.println(
  "here in foo");
```

Continue executing as usual.

# Abstract Stack Machine

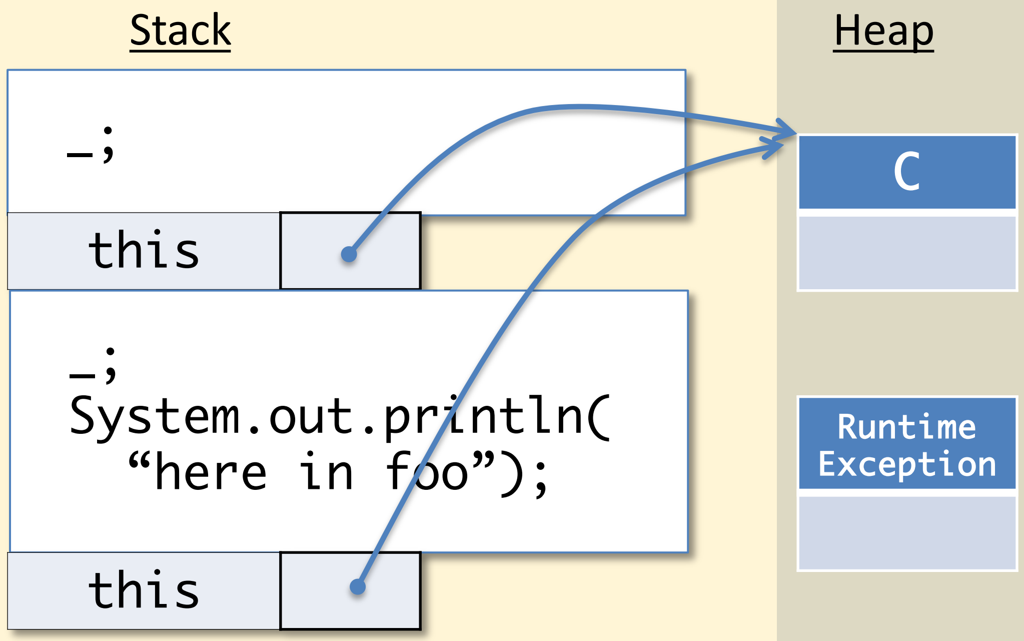
Workspace

```
;
```

Pop the stack when the workspace is done, returning to the saved workspace just after the _ mark.

Stack

Heap



```
_;
```

```
_;
System.out.println(
  “here in foo”);
```

Console

```
caught
here in bar
```

# Abstract Stack Machine

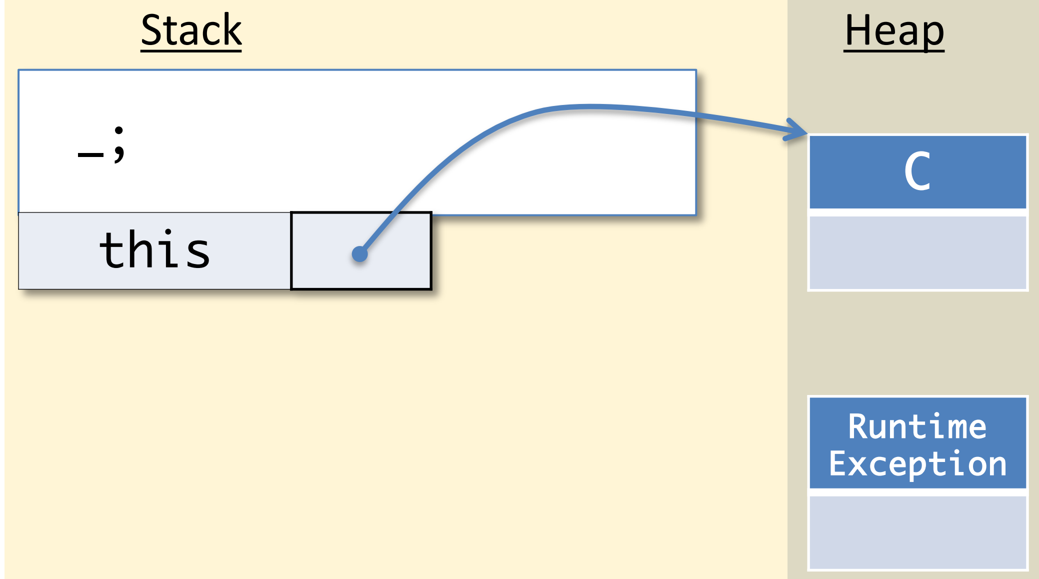
Workspace

```
System.out.println(
  “here in foo”);
```

Continue executing as usual.

Console

```
caught
here in bar
```



# Abstract Stack Machine

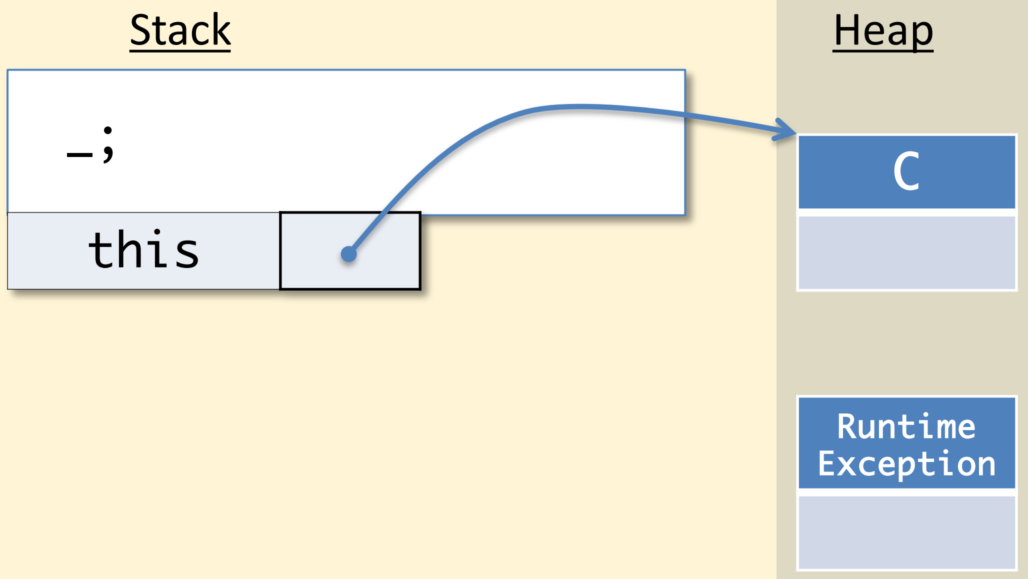
Workspace

```
System.out.println(
   "here in foo");
```

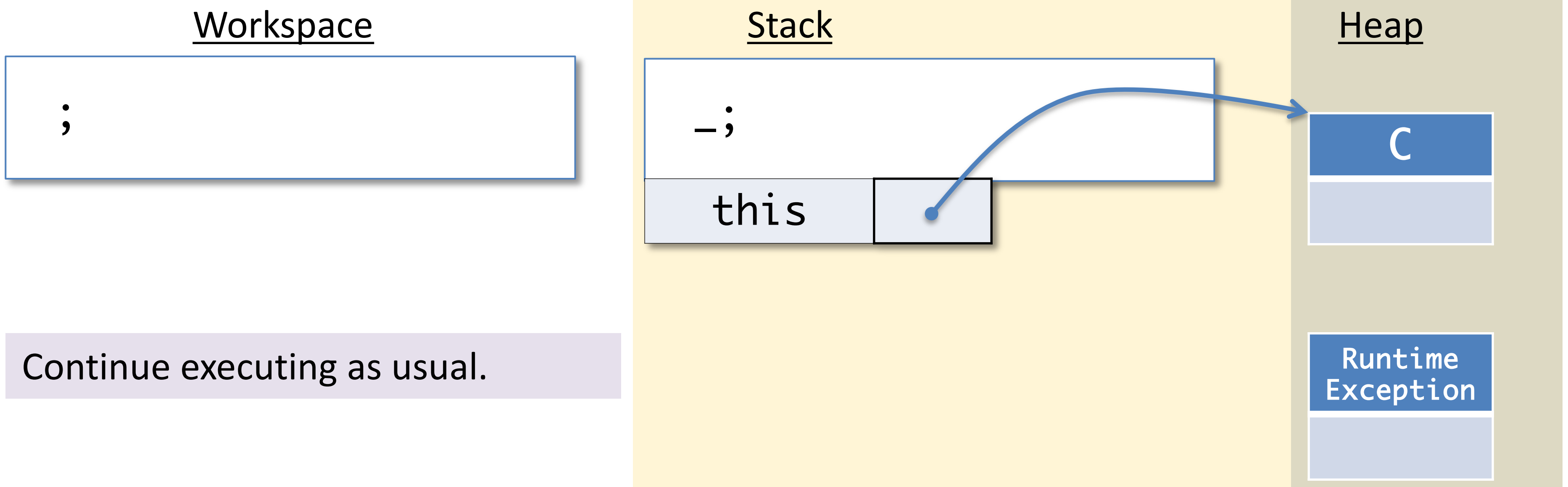
Continue executing as usual.

Console

```
caught
here in bar
```



# Abstract Stack Machine



Continue executing as usual.

Console

```
caught
here in bar
here in foo
```

# Abstract Stack Machine

Workspace

Program terminated normally.

Stack

Heap

C

Runtime Exception

Console

```
caught
here in bar
here in foo
```

# When No Exception is Thrown

If no exception is thrown while executing the body of a try {…} block, evaluation *skips* the corresponding catch block.

- i.e. if you ever reach a workspace where “catch” is the statement to run, just skip it:

Workspace

```
catch
(RuntimeException e)
{ System.out.println
  (“caught”); }
System.out.println(
  “here in bar”);
```

→

Workspace

```
System.out.println(
  “here in bar”);
```

## Catching Exceptions

There can be more than one "catch" clause associated with a given "try"

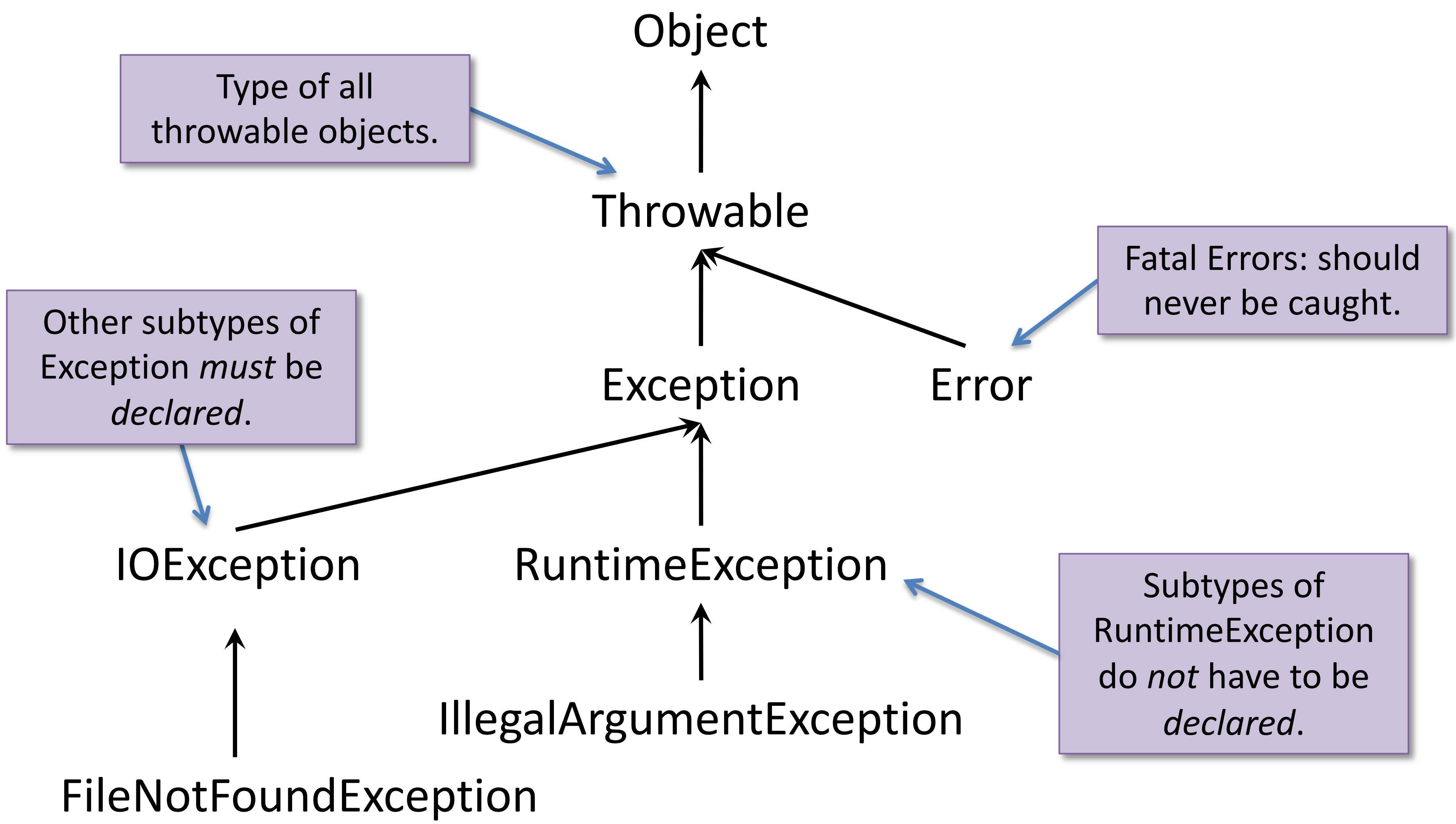
- Matched in order, according to the *dynamic* class of the exception thrown
- Helps refine error handling

```
try {
      …    // do something with the IO library
} catch (FileNotFoundException e) {
      …    // handle an absent file
} catch (IOException e) {
      …    // handle other kinds of IO errors.
}
```

- Good style: be as specific as possible about the exceptions you're handling.
  - Avoid `catch (Exception e) {…}` it's usually too generic!

## Informative Exception Handling

# Exception Class Hierarchy


Object
Throwable
Exception
Error
IOException
RuntimeException
IllegalArgumentException
FileNotFoundException
Type of all throwable objects.
Fatal Errors: should never be caught.
Other subtypes of Exception *must* be *declared*.
Subtypes of RuntimeException do *not* have to be *declared*.

# Checked (Declared) Exceptions

- Exceptions that are subtypes of `Exception` but not `RuntimeException` are called *checked* or *declared*.
- A method that might throw a checked exception must declare it using a "throws" clause in the method type.
- Such a method might raise a checked exception either by
  - directly throwing such an exception…

```
public void maybeDoIt (String file) throws AnException{
      if (…) throw new AnException(); //directly throw
      …
```

  - …or by calling another method that might itself throw a checked exception

```
public void doSomeIO (String file) throws IOException {
      Reader r = new FileReader(file);  // might throw
      …
```

# Unchecked (Undeclared) Exceptions

- Subclasses of RuntimeException *do not* need to be declared via “throws”
  - even if the method does not explicitly handle them.
- Many “pervasive” types of errors cause RuntimeExceptions
  - NullPointerException
  - IndexOutOfBoundsException
  - IllegalArgumentException

```
public void mightFail (String file) {
      if (file.equals(“dictionary.txt”) {
         // file could be null!
      …
```

- The original intent was that such exceptions represent disastrous conditions from which it was impossible to sensibly recover…

## 30: Which methods need a "throws" clause? (Note: *IllegalArgumentException* is a subtype of *RuntimeException*. *IOException* is not.)

0

| | |
|---|---|
| all of them | 0% |
| none of them | 0% |
| m and n | 0% |
| n only | 0% |
| n, r, and s | 0% |
| n, q, and s | 0% |
| m, p, and s | 0% |
| something else | 0% |

# Checked vs. Unchecked Exceptions

Which methods need a "throws" clause?

*Note: IllegalArgumentException is a subtype of RuntimeException.*

*IOException is not.*

1) all of them
2) none of them
3) m and n
4) n only
5) n, r, and s
6) n, q, and s
7) m, p, and s
8) something else

```
public class ExceptionQuiz {
    public void m(Object x) {
      if (x == null)
          throw new IllegalArgumentException();
    }
    public void n(Object y) {
      if (y == null) throw new IOException();
    }
    public void p() {
      m(null);
    }
    public void q() {
      n(null);
    }
    public void r() {
      try { n(null); } catch (IOException e) {}
    }
    public void s() {
      n(new Object());
    }
}
```

Answer:
n, q and s should say throws IOException

# Declared vs. Undeclared?

- Tradeoffs in the software design process:
- *Declared*: better documentation
  - forces callers to either deal with the exception or pass responsibility to their callers
- *Undeclared*: fewer static guarantees (compiler can help less)
  - but lighter weight and easier to refactor code
- In practice: test-driven development encourages “fail early/fail often” model of design and lots of refactoring, so “undeclared” exceptions are prevalent in real code.

- A reasonable compromise:
  - Use declared exceptions for libraries, where the documentation and usage enforcement are critical
  - Use undeclared exceptions in client code to facilitate more flexible development

# Finally

```
try {
   ...
} catch (Exn1 e1) {
   ...
} catch (Exn2 e2) {
   ...
} finally {
   ...
}
```

- A `finally` clause of a try/catch/finally statement *always* gets run, regardless of whether there is no exception, a propagated exception, or a caught exception.

# Using Finally

`finally` is often used for releasing resources held/created by a `try` block:

```
public void doSomeIO (String file) {
  FileReader r = null;
  try {
    r = new FileReader(file);
    … // do some IO
  } catch (FileNotFoundException e) {
    … // handle the absent file
  } catch (IOException e) {
    … // handle other IO problems
  } finally {
    if (r != null) {    // don’t forget null check!
      try { r.close(); } catch (IOException e) {…}
    }
  }
}
```

## 30: What happens if we do (new C()).foo(); ? The program prints...

0

“finally"

0%

“caught” then “here in bar” then “here in foo” then “finally"

0%

“finally” then “caught” then “here in foo"

0%

“caught” then “finally” then “here in bar” then “here in foo"

0%

# Using Finally

```
class C {
      public void foo() {
        this.bar();
        System.out.println("here in foo");
      }
      public void bar() {
        try {
          this.baz();
        } catch (Exception e) {
            System.out.println("caught");
        } finally { System.out.println("finally"); }
        System.out.println("here in bar");
      }
      public void baz() {
        throw new RuntimeException();
      }
    }
```

What happens if we do `(new C()).foo()` ?

Answer: 4

1. Program prints only "finally"
2. Program prints "here in bar", then "here in foo", then "finally"
3. Program prints "finally", then "caught", then "here in foo"
4. Program prints "caught", then "finally", then "here in bar", then "here in foo"

# Good Style for Exceptions

- In Java, exceptions should be used to capture *exceptional circumstances*
  - Try/catch/throw incur performance costs and complicate reasoning about the program, don't use them when better solutions exist
- *Re-use existing exception types* when they are meaningful to the situation
  - e.g. use NoSuchElementException when implementing a container
- Define your own subclasses of Exception if doing so can convey useful information to possible callers that can handle the exception.

# Good Style for Exceptions

- It is often sensible to catch one exception and re-throw a different (more meaningful) kind of exception.
  - e.g. when implementing the `next` method of `WordScanner` (in upcoming lectures), we will catch `IOException` and throw `NoSuchElementException`.

- Catch exceptions as near to the source of failure as makes sense
  - i.e., where you have the information to deal with the exception

- Catch exceptions with as much precision as you can

```
BAD:      try {…} catch (Exception e) {…}
BETTER:   try {…} catch (IOException e) {…}
```