Accepting Blame for Safe Tunneled Exceptions

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www.cs.cornell.edu/projects/genus

Exceptions

To check, or not to check, that is the question.

To check, or not to check, that is the question.

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But they are too rigid to support higher-order programming!

Checked exceptions are too rigid

A higher-order function in Java

```
<T,R> List<R> map(List<T> src, Function<T,R> f) {…}
```

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List<File> src = …;
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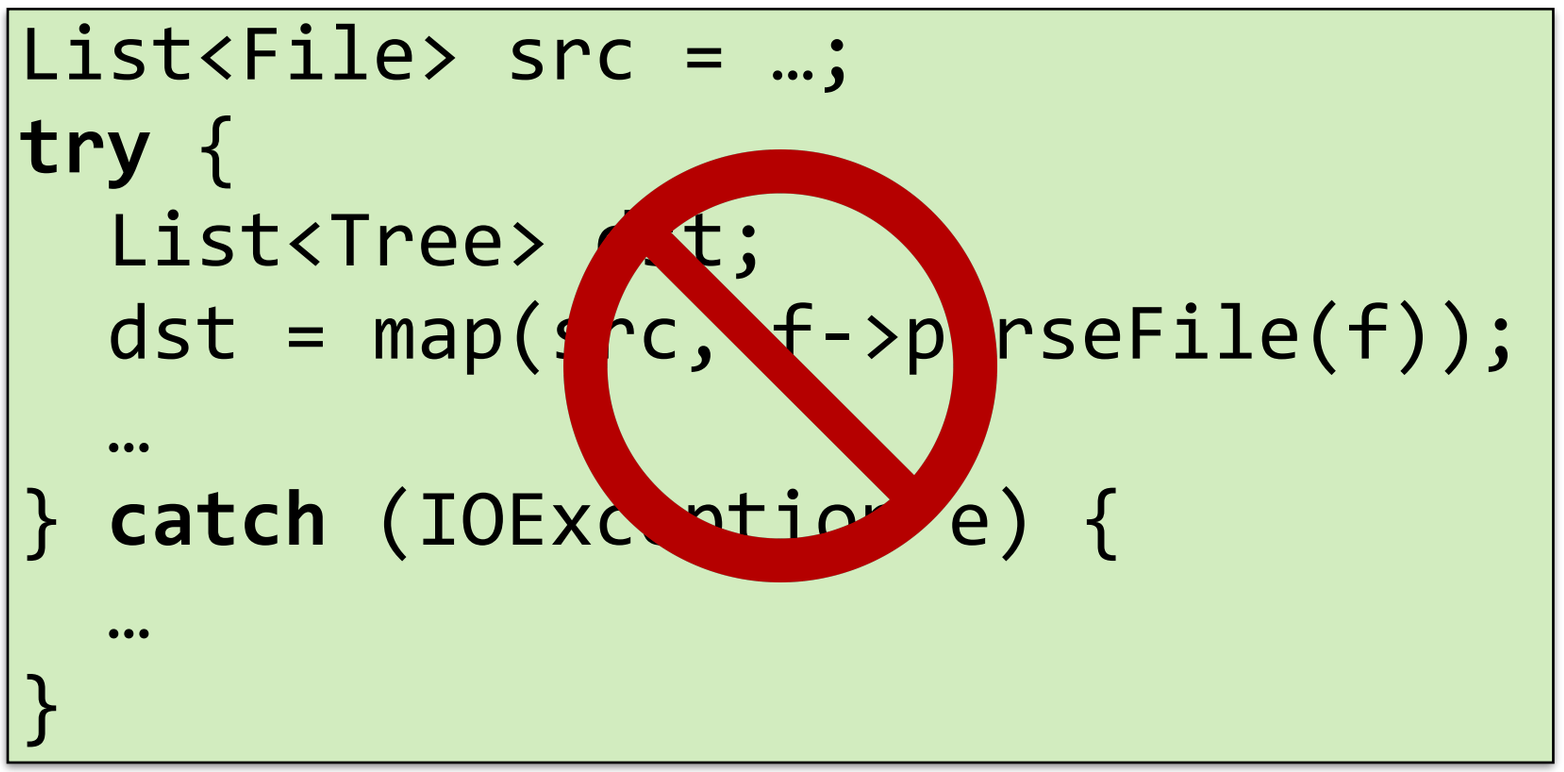

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```

javac error: Exception mismatch between `parseFile` and `Function::apply`.

```
@FunctionalInterface
interface Function<T,R> {
    R apply(T t);
}
```

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javac error: Exception mismatch between `parseFile` and `Function::apply`.

javac error: `IOException` is never thrown in `try` block.

Checked exceptions are too rigid

An unchecked wrapper class introduced in Java 8

```
class UncheckedIOException extends RuntimeException {…}
```

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exception wrapping

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} catch (UncheckedIOException u) {
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exception wrapping

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exception unwrapping

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Java

1990

2000

2010

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"More thinking is needed before we put some kind of checked exceptions mechanism in place."

—Anders Hejlsberg—

Java

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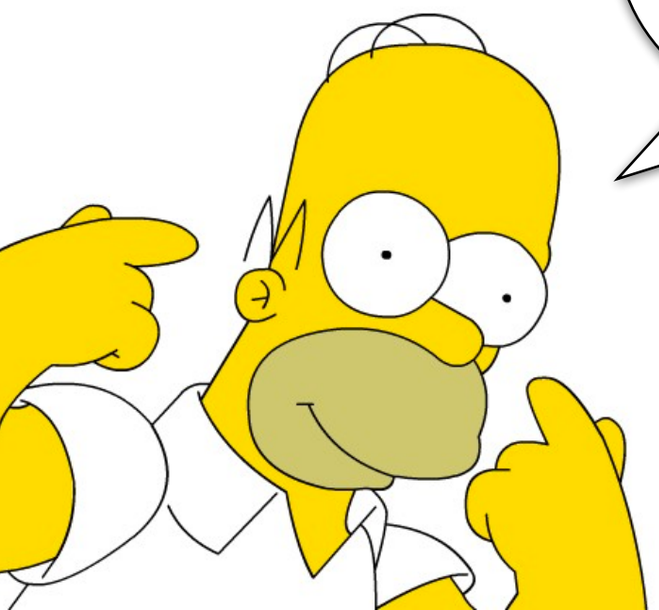

Scala

F#

Go

2010

TypeScript

Ceylon

julia

Kotlin

Accidentally caught exceptions

Accidentally caught exceptions

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<T,R> List<R> map(List<T> src, Function<T,R> f) {
  List<R> dst = new ArrayList<R>();
  for (Iterator<T> i = src.iterator();;) {
    dst.add(f.apply(i.next())); }
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  return dst;
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interface Iterator[E] {
  // The exception indicates no more element.
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The `catch` block is intended for exceptions from `i.next()`.

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`f` could be a function that throws `NoSuchElementException`.

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Accidentally caught exceptions

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Accidentally caught exceptions

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  return dst;
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`f` could be a function that throws `NoSuchElementException`.

The `catch` block is intended for exceptions from `i.next()`.

Caught by accident!

Bug: caller receives only the transformation of a list prefix

To check, or not to check:

Checked exception types

```
IOException
SQLException
ParseException
DataFormatException
…
```

Unchecked exception types

```
EmptyStackException
UncheckedIOException
NoSuchElementException
IndexOutOfBoundsException
…
```

To check, or not to check:

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To check, or not to check:

Checked exception types

`IOException`
`SQLException`
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Too rigid to work with.

Unchecked exception types

`EmptyStackException`
`UncheckedIOException`
`NoSuchElementException`
`IndexOutOfBoundsException`
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Problems remain.

To check, or not to check:

not a property of the exception type

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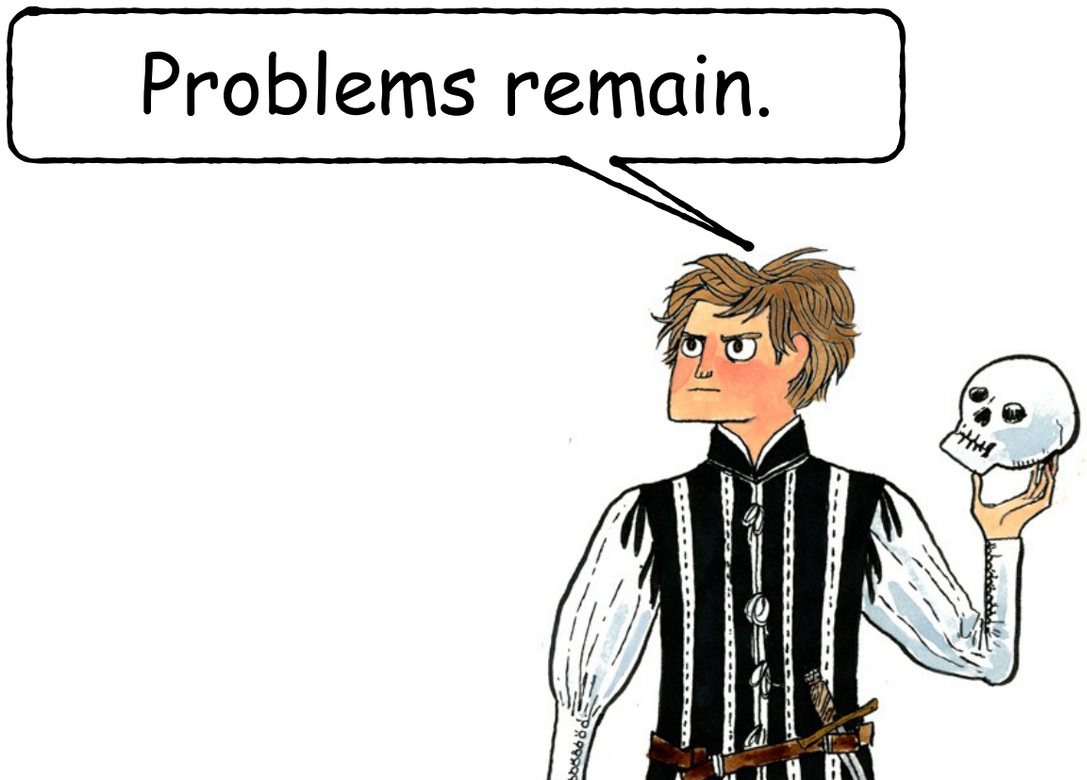

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not a property of the exception type,
but rather context-dependent.

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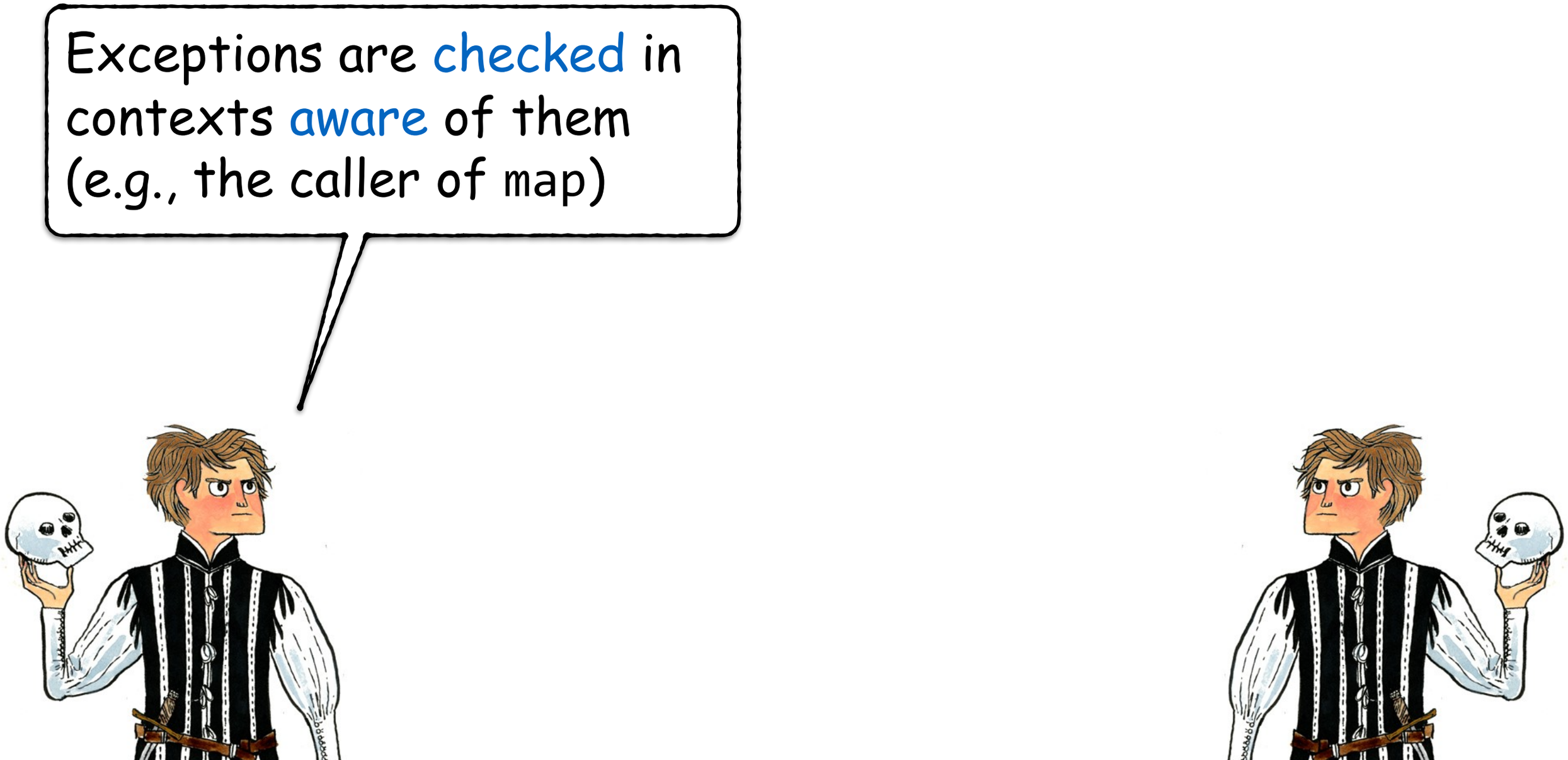

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Exceptions are checked in contexts aware of them (e.g., the caller of map)

Exceptions are unchecked in contexts oblivious to them (e.g., the definition of map)

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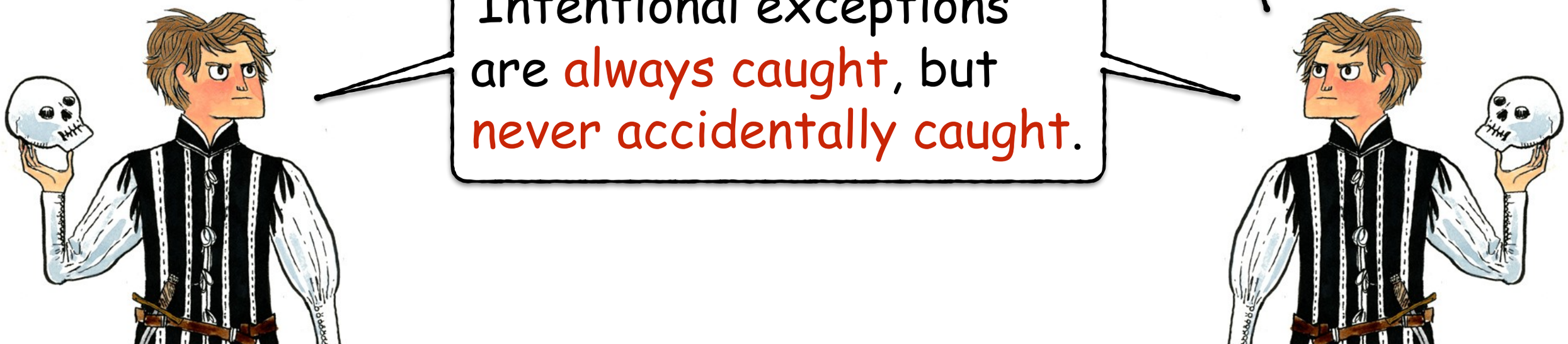
not a property of the exception type, but rather context-dependent.

Exceptions are checked in contexts aware of them (e.g., the caller of map)

Exceptions are unchecked in contexts oblivious to them (e.g., the definition of map)

Intentional exceptions are always caught, but never accidentally caught.



Genus

Genus

A variant of Java with lightweight, flexible, object-oriented generics

[Zhang et al. 2015]

Language constructs for exceptions

Inherits from Java `throw` statements, `throws` clauses, and `try`-`catch`-`finally` statements

Core ideas applicable to other languages

2 classes of exceptional events

2 classes of exceptional events

failure

violation of programmer assumptions

unusual condition

unusual, but planned-for

2 classes of exceptional events

failure

violation of programmer assumptions

- programmer mistakes
- running out of memory, etc

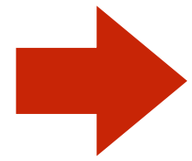
unusual condition

unusual, but planned-for

2 classes of exceptional events

failure	**violation of programmer assumptions**	- programmer mistakes - running out of memory, etc
unusual condition	**unusual, but planned-for**	such as an unusual case of an algorithm

Design goals *differ*

failure	violation of programmer assumptions	 stack trace as a debugging aid
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Design goals *differ*

failure	violation of programmer assumptions	stack trace as a debugging aid
unusual condition	unusual, but planned-for	static checking & efficiency

Design goals *differ*

failure

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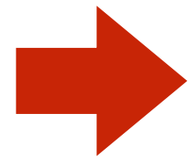

stack trace as a debugging aid

unusual condition

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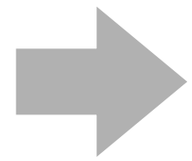

static checking & efficiency

A failure event

```
// Returns: the first element.
// Precondition: the iterable is non-empty.
E first[E](Iterable[E] iterable)
{
  return iterable.iterator().next();
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The exception is impossible under the precondition.

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Indicating failure events with `fails` clauses

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// Returns: the first element.
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E first[E](Iterable[E] iterable)
    fails NoSuchElementException {
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The exception is impossible under the precondition.

Failure exceptions crash the program

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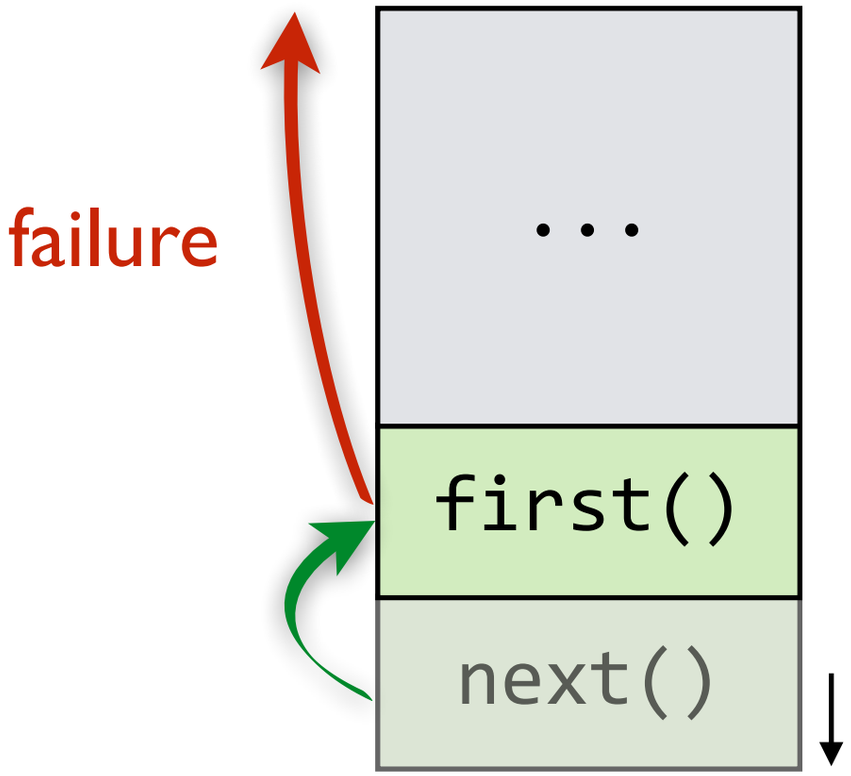

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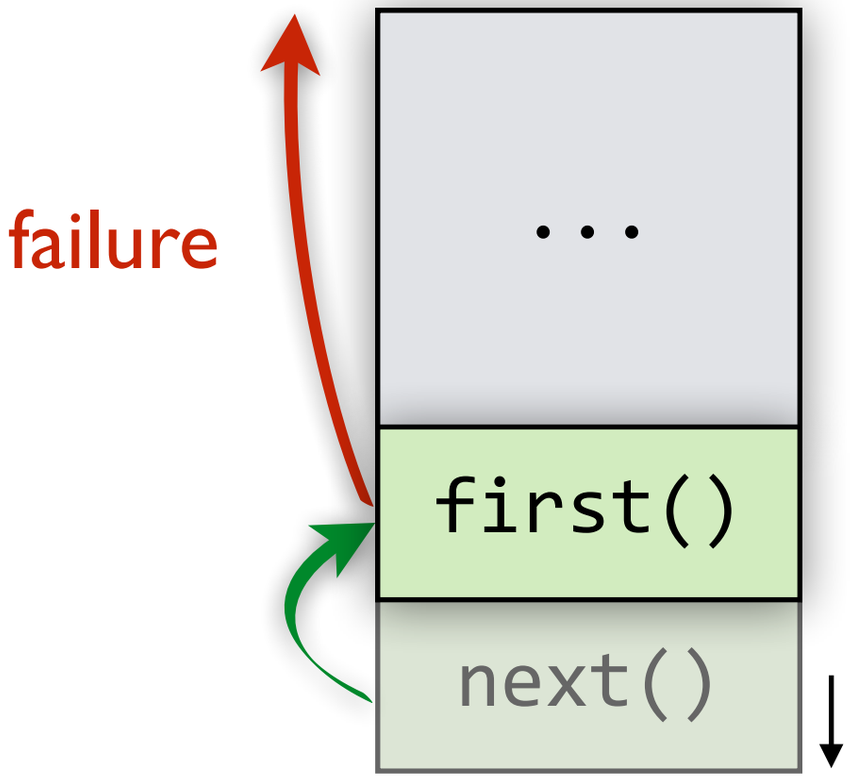

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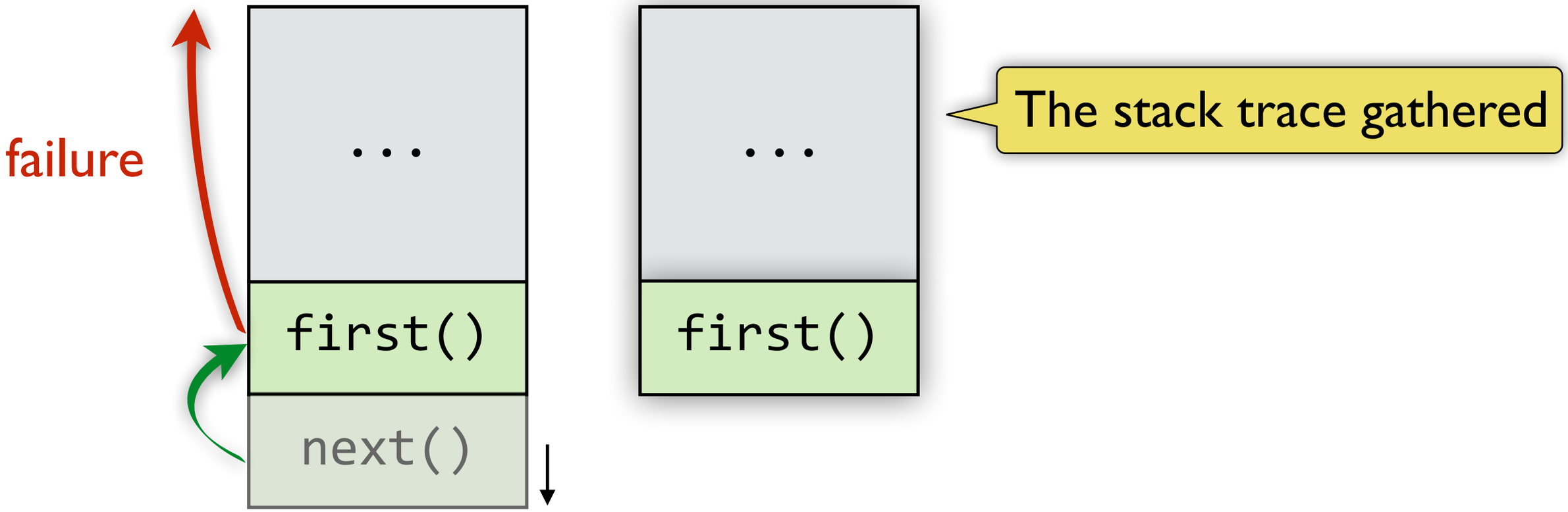

Design goals *differ*

failure

violation of programmer assumptions → stack trace as a debugging aid

unusual condition

unusual, but planned-for → **static checking & efficiency**

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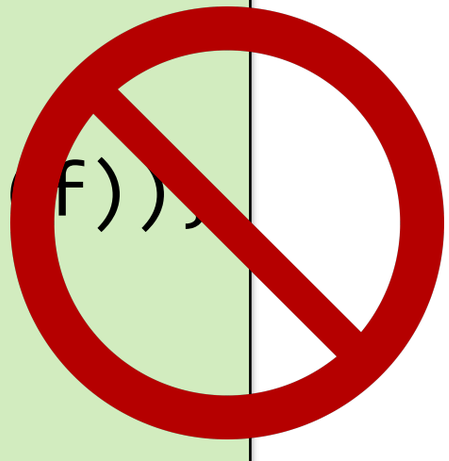
javac error: Exception mismatch between `parseFile` and `Function::apply`.



javac error: `IOException` is never thrown in `try` block.

Rewriting in Genus…

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Tunneling through higher-order functions

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List[R] map[T,R] (List[T] src, Function[T,R] f) {…}
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A method that declares an exception

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Exception mismatch is allowed.

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Tunneling through higher-order functions

A higher-order function in Genus

exception-oblivious

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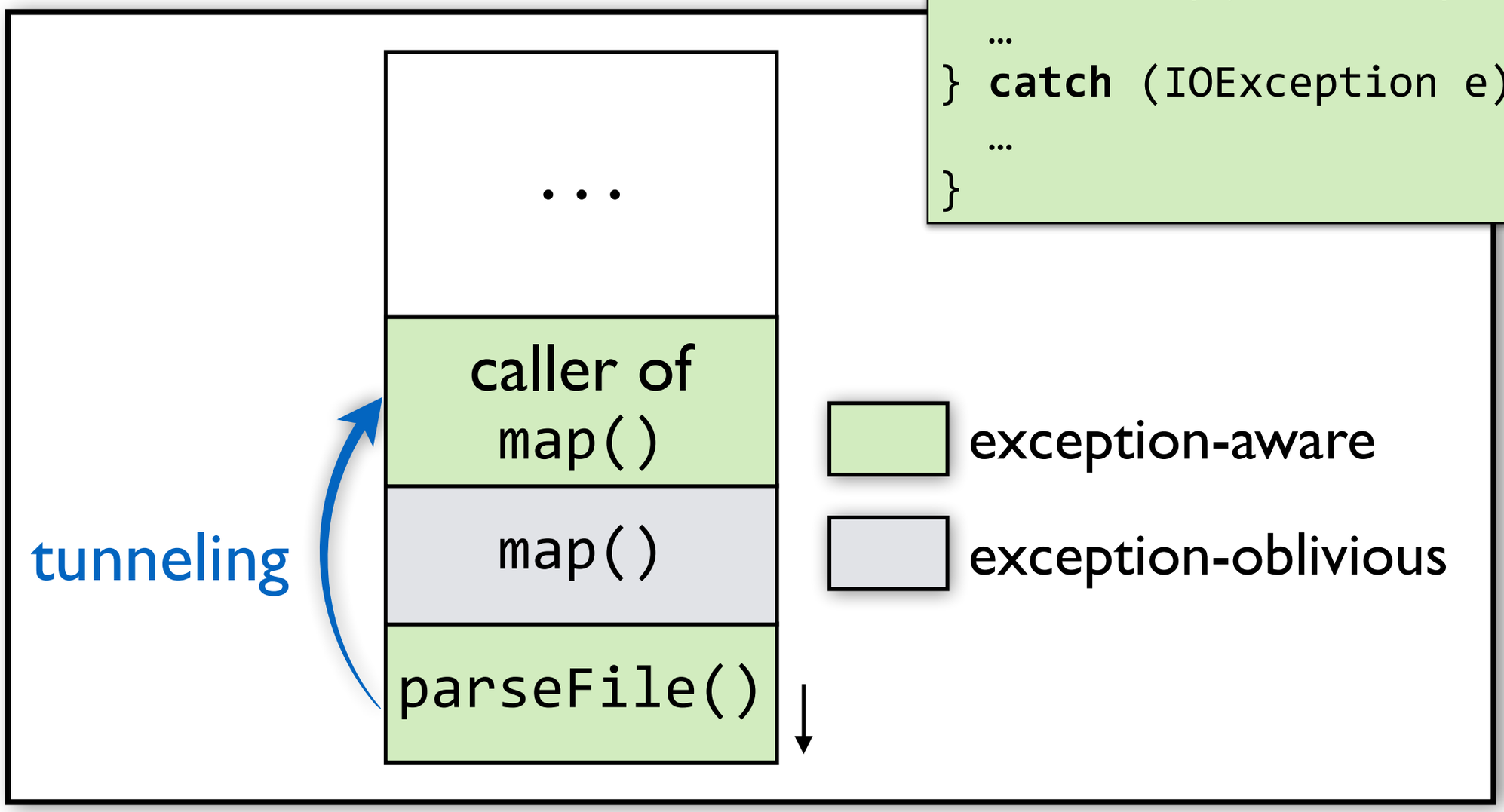

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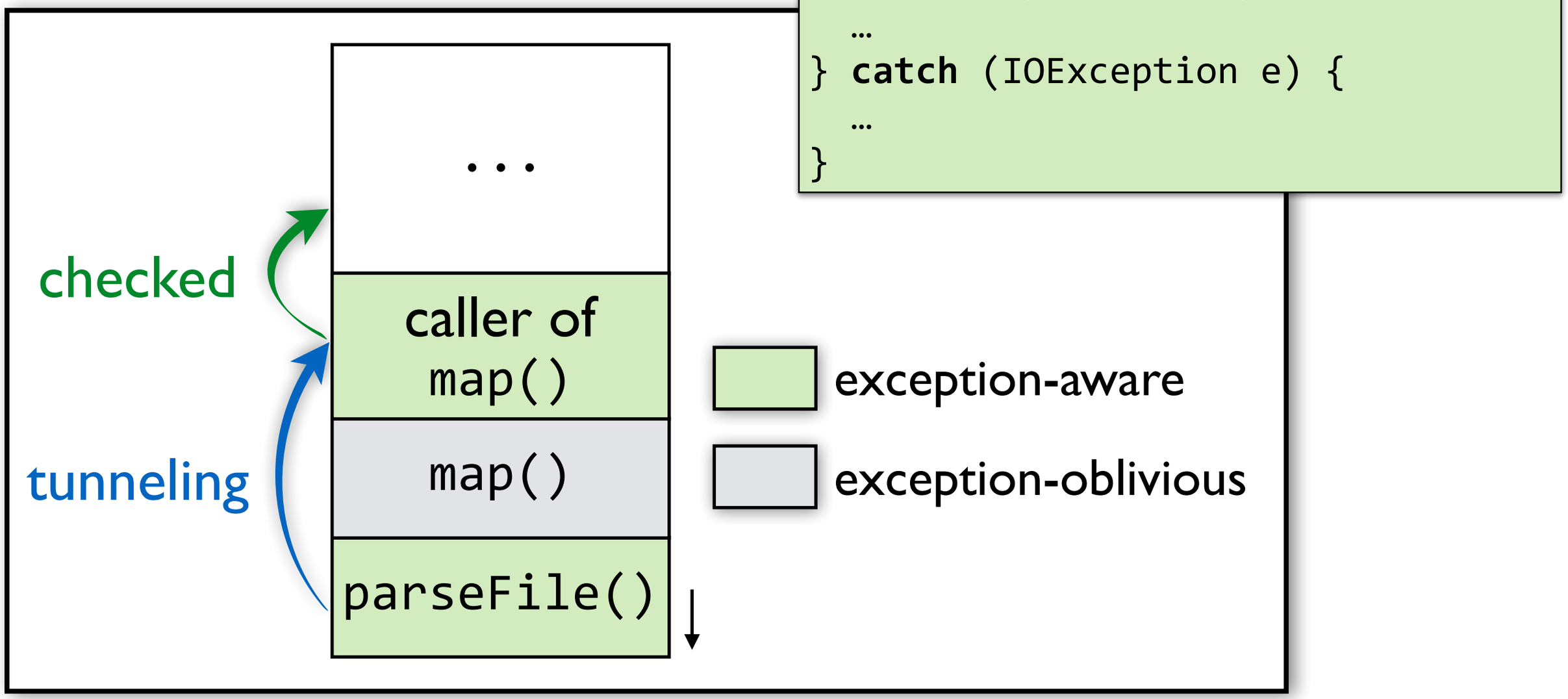

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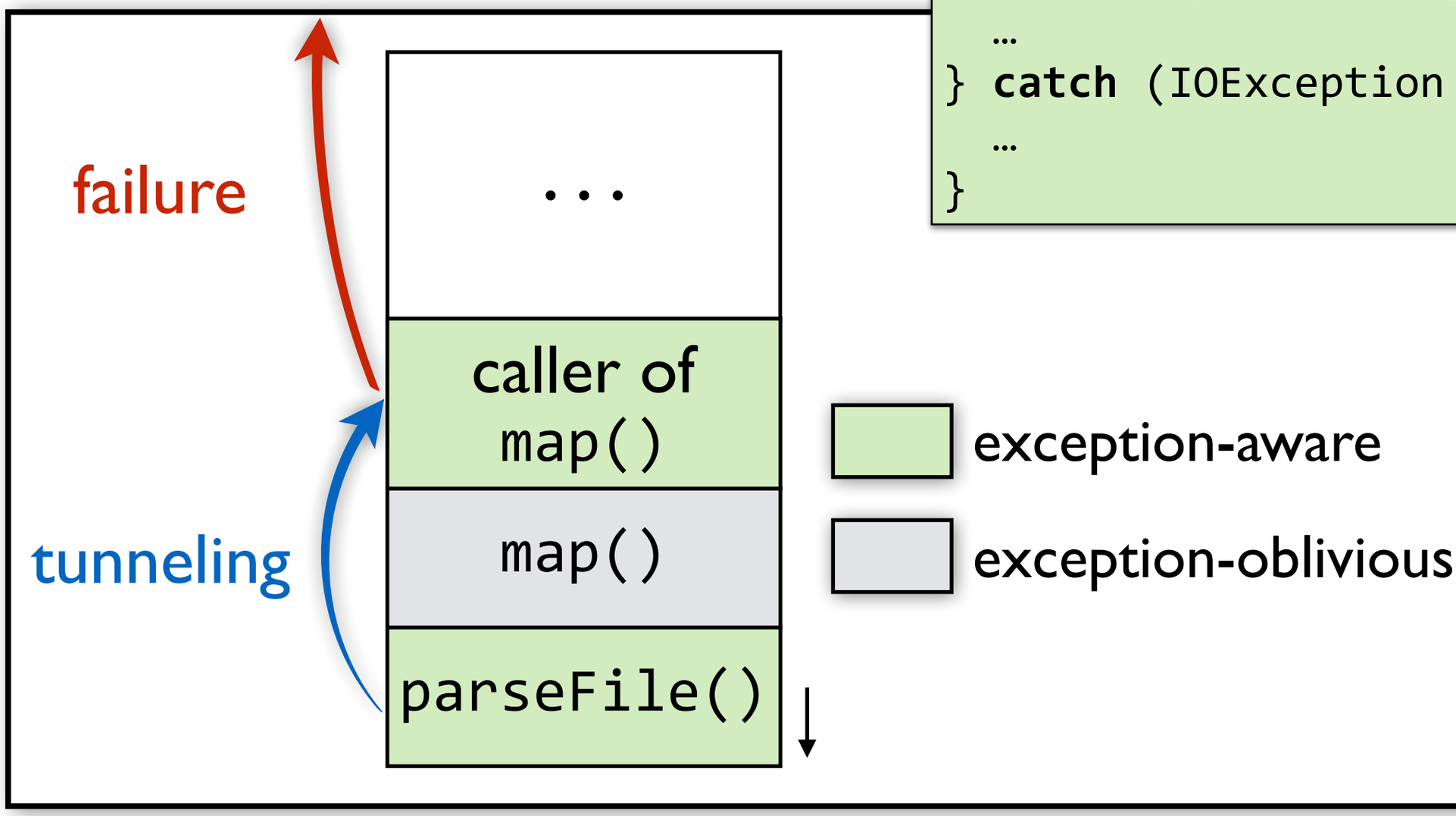

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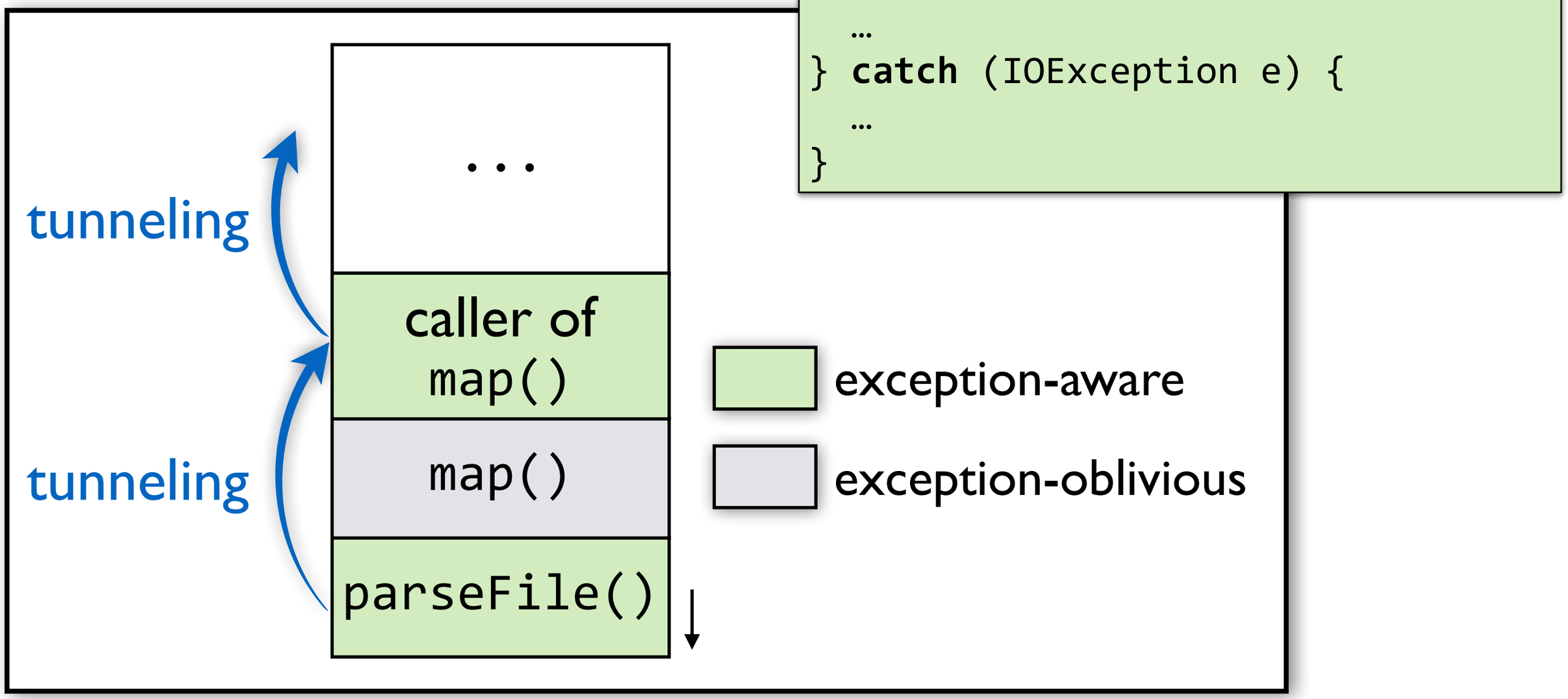

Tunneling through higher-order functions

- **Static checking** enforced in exception-aware contexts

```
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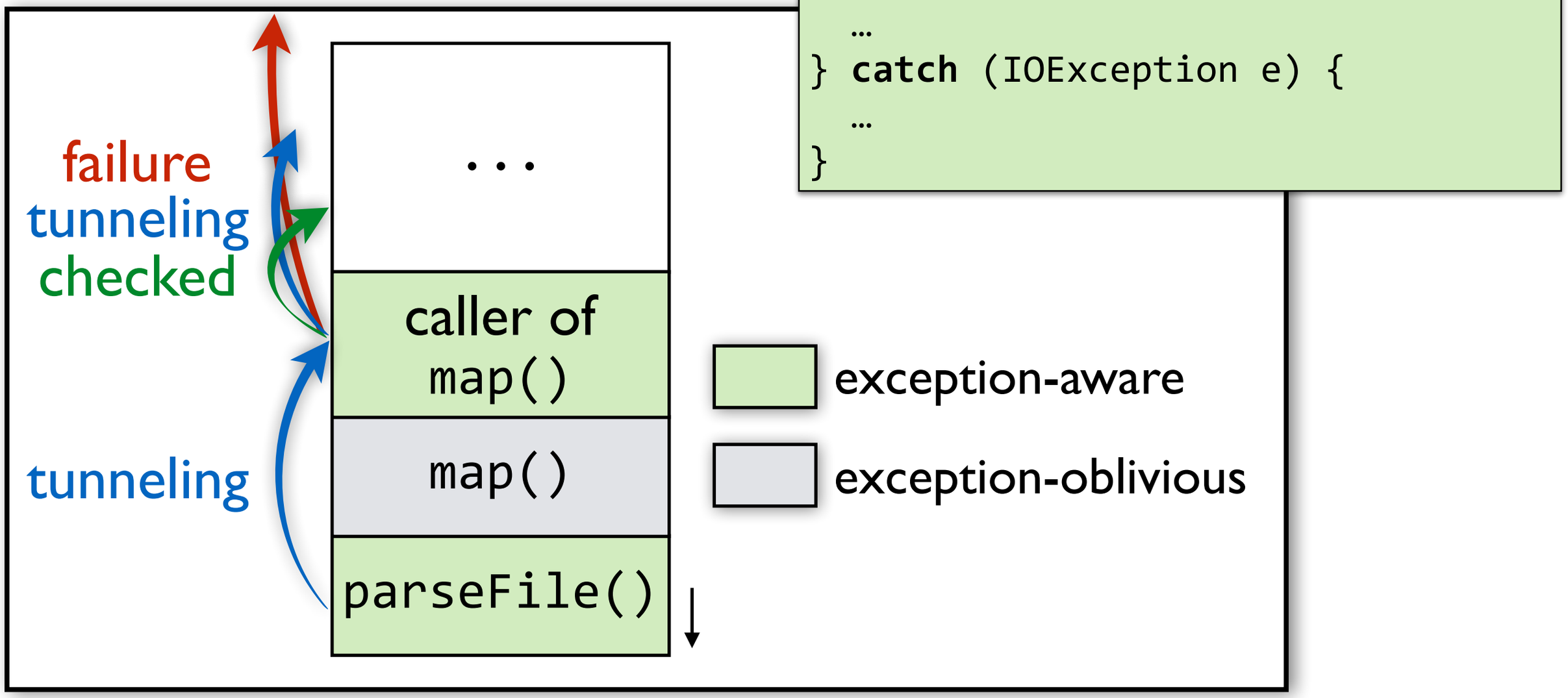
try {
  List[Tree] dst;
  dst = map(src, f->parseFile(f));
  …
} catch (IOException e) {
  …
}
```



Tunneling through higher-order functions

- **Static checking** enforced in exception-aware contexts
- **Efficient** because of no stack-trace collection

```
List[File] src = …;
try {
  List[Tree] dst;
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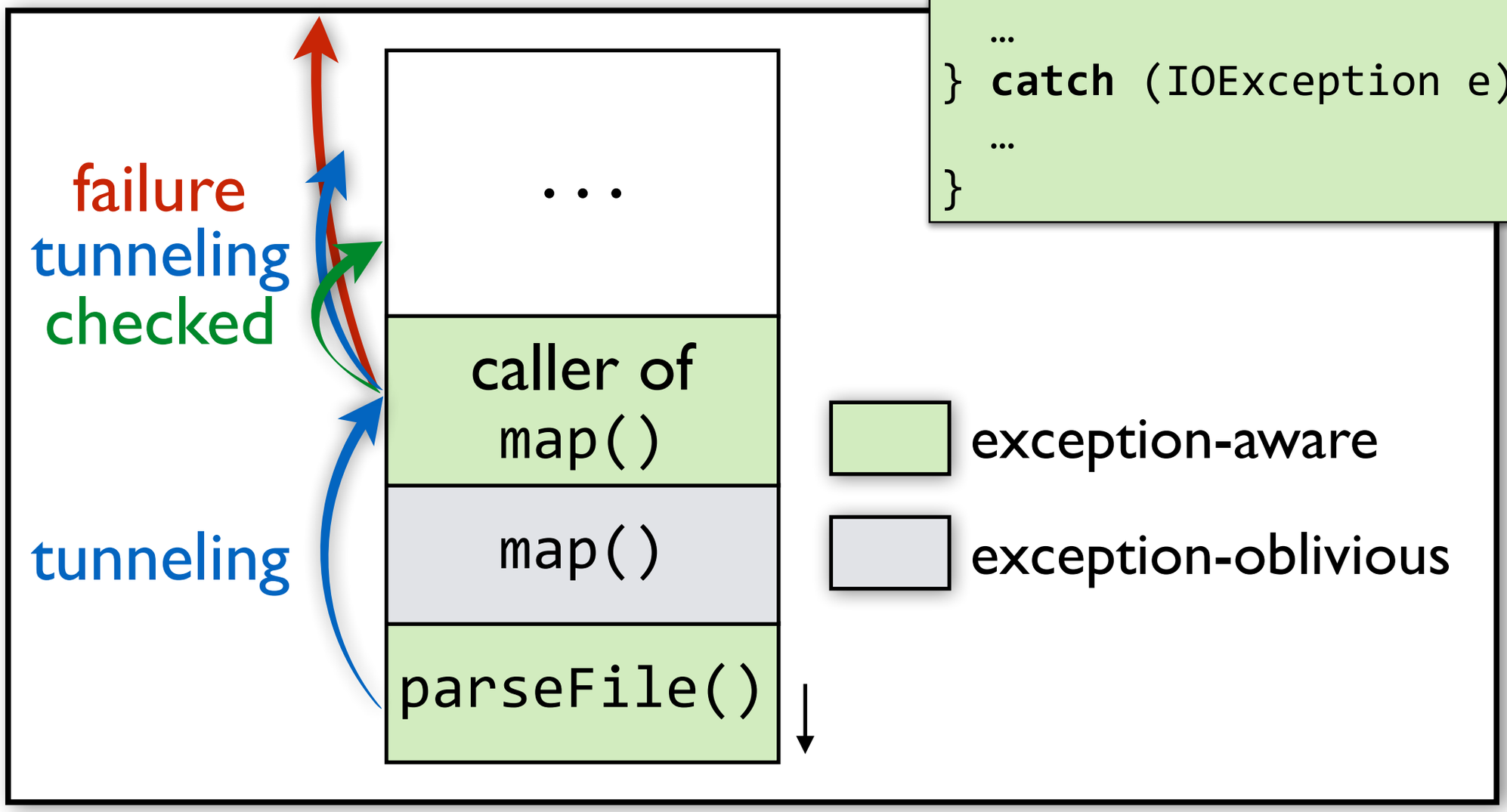
  …
} catch (IOException e) {
  …
}
```



Accidentally caught exceptions

A higher-order function in Java

```
<T,R> List<R> map(List<T> src, Function<T,R> f) {
  List<R> dst = new ArrayList<R>();
  for (Iterator<T> i = src.iterator();;) {
    try { dst.add(f.apply(i.next())); }
    catch (NoSuchElementException e) { break; }
  }
  return dst;
}
```

`f` could be a function that throws `NoSuchElementException`.

The `catch` block is intended for exceptions from `i.next()`.

Caught by accident!

Bug: caller receives only the transformation of a list prefix

The “exception capture” problem

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The `catch` block is intended for exceptions from `i.next()`.

Exception identifiers collide.

(exception identifier = exception type)

Context-awareness addresses exception capture

A higher-order function in Genus

```
List[R] map[T,R] (List[T] src, Function[T,R] f) {
  List[R] dst = new ArrayList[R]();
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Oblivious to exceptions raised by `f`.

(exception identifier = exception type + context)

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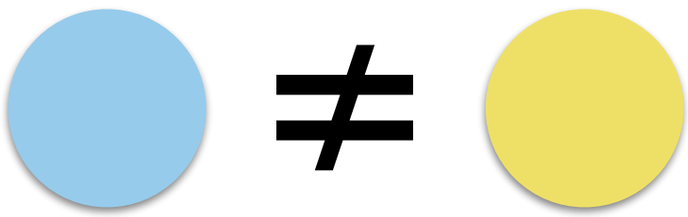

Exception identifiers differ.

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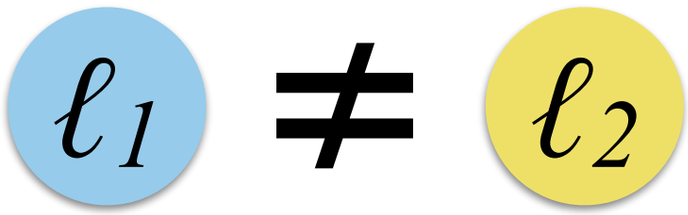

Exception identifiers differ.

(exception identifier = exception type + context)

Blame labels as a notion of context

Gradual typing

Language

type mismatch

Compiler

blame label assigned

Runtime

type-cast failure attributed to the proper context

Blame labels as a notion of context

	Language	Compiler	Runtime
Gradual typing	type mismatch	blame label assigned	type-cast failure attributed to the proper context
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Augmenting exception identifiers with implicit blame labels prevents capture

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    catch (NoSuchElementException e) { break; }
  }
  return dst;
}
```

```
void g() fails NoSuchElementException {
  … map(src, Iterator::next) …
}
```

Genus

exception mismatch → blame label assigned → exception propagated to the proper context

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ℓ_1

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  }
  return dst;
}
```

ℓ_2

```
void g() fails NoSuchElementException {
  … map(src, Iterator::next) …
}
```

ℓ_1

Genus

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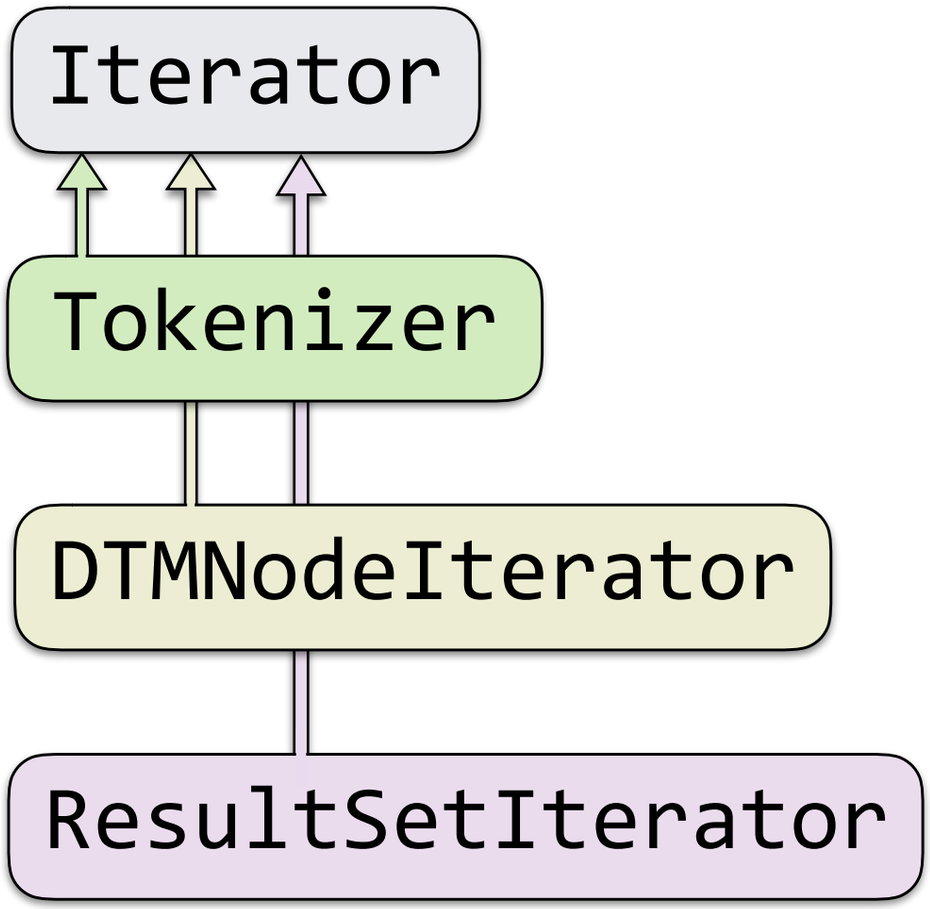
A complement to behavioral subtyping

{ Function
Iterator
Visitor
Factory
... }

Subtypes may want to throw new exceptions.

A complement to behavioral subtyping



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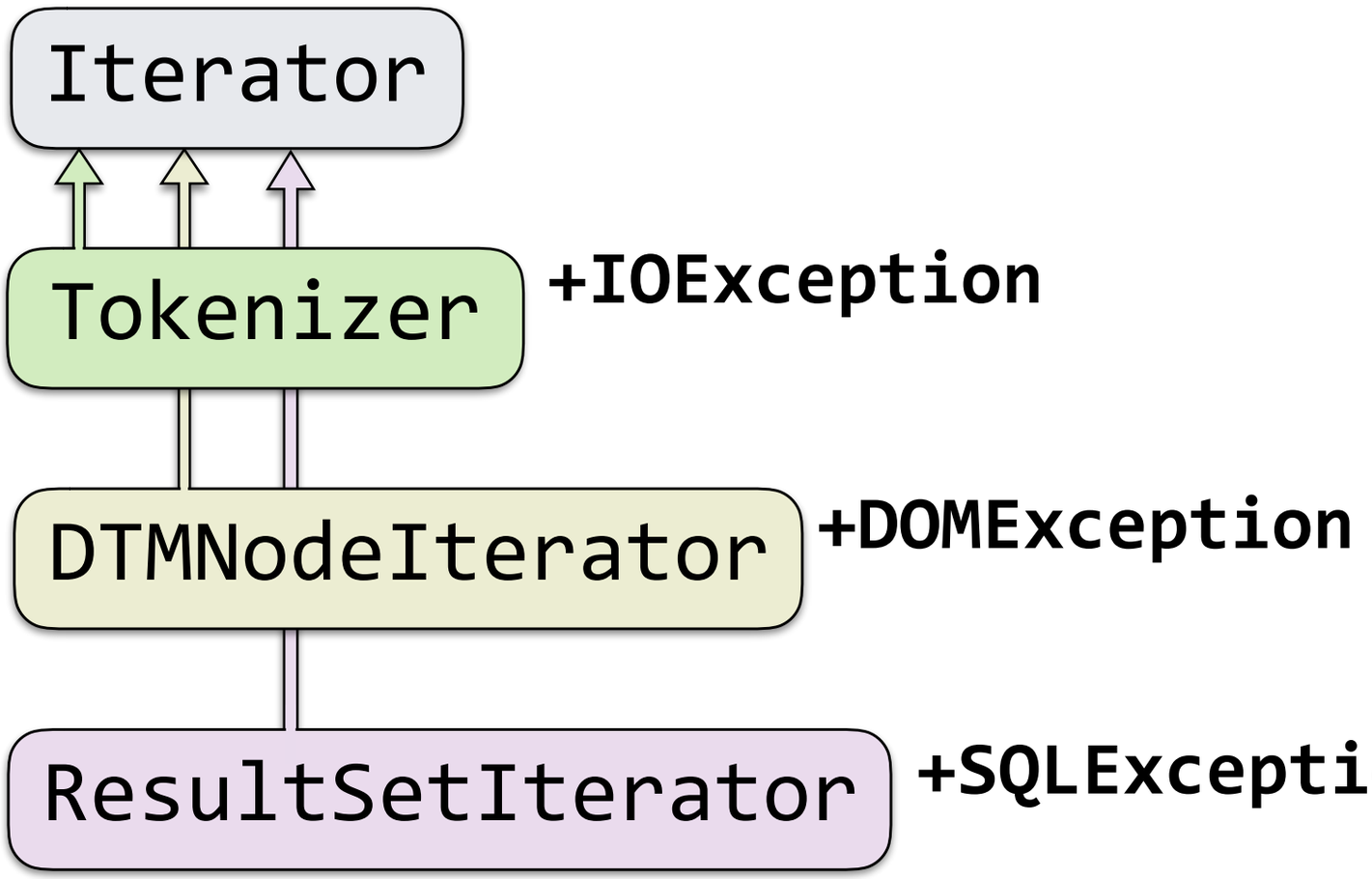

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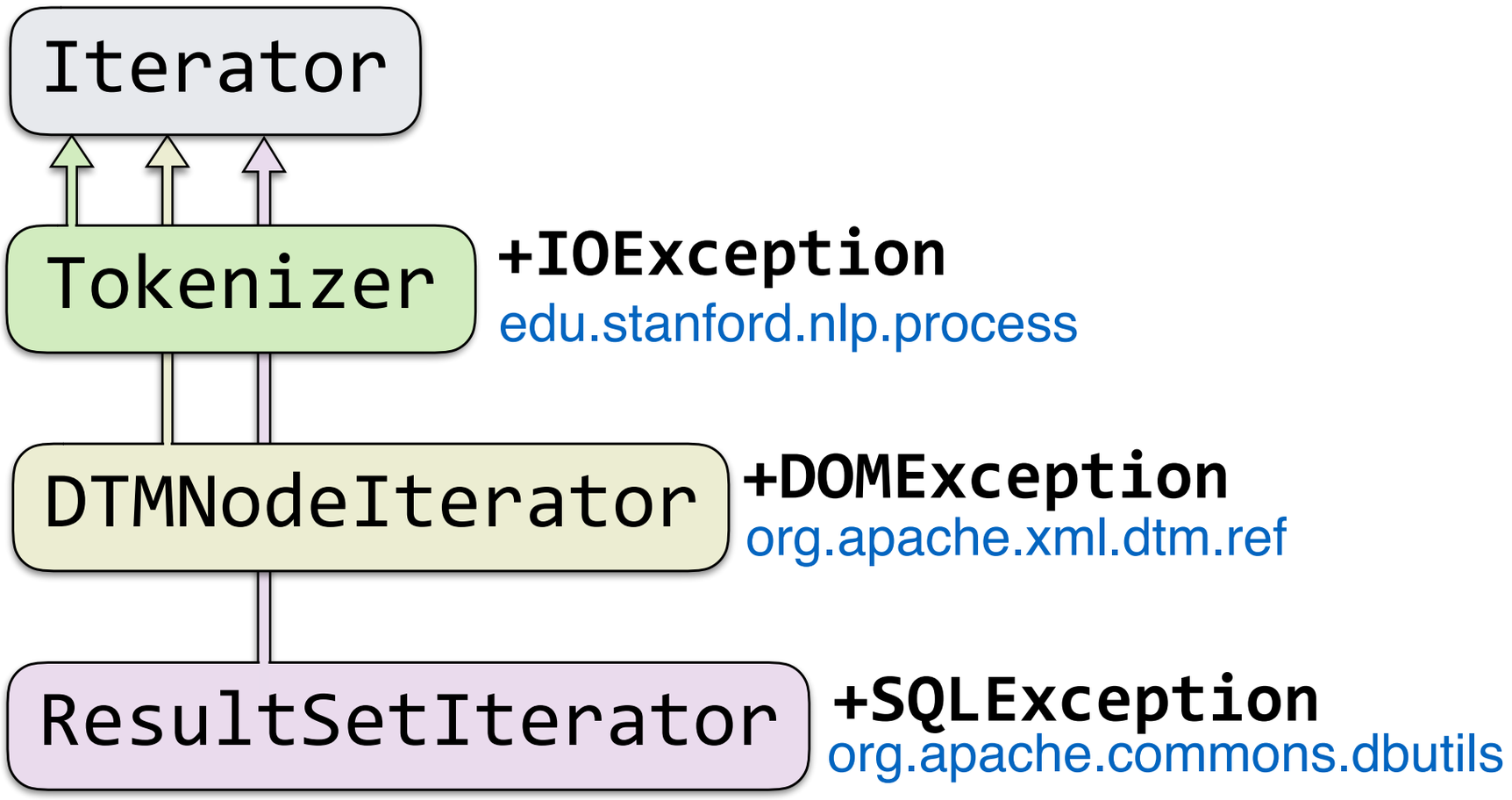

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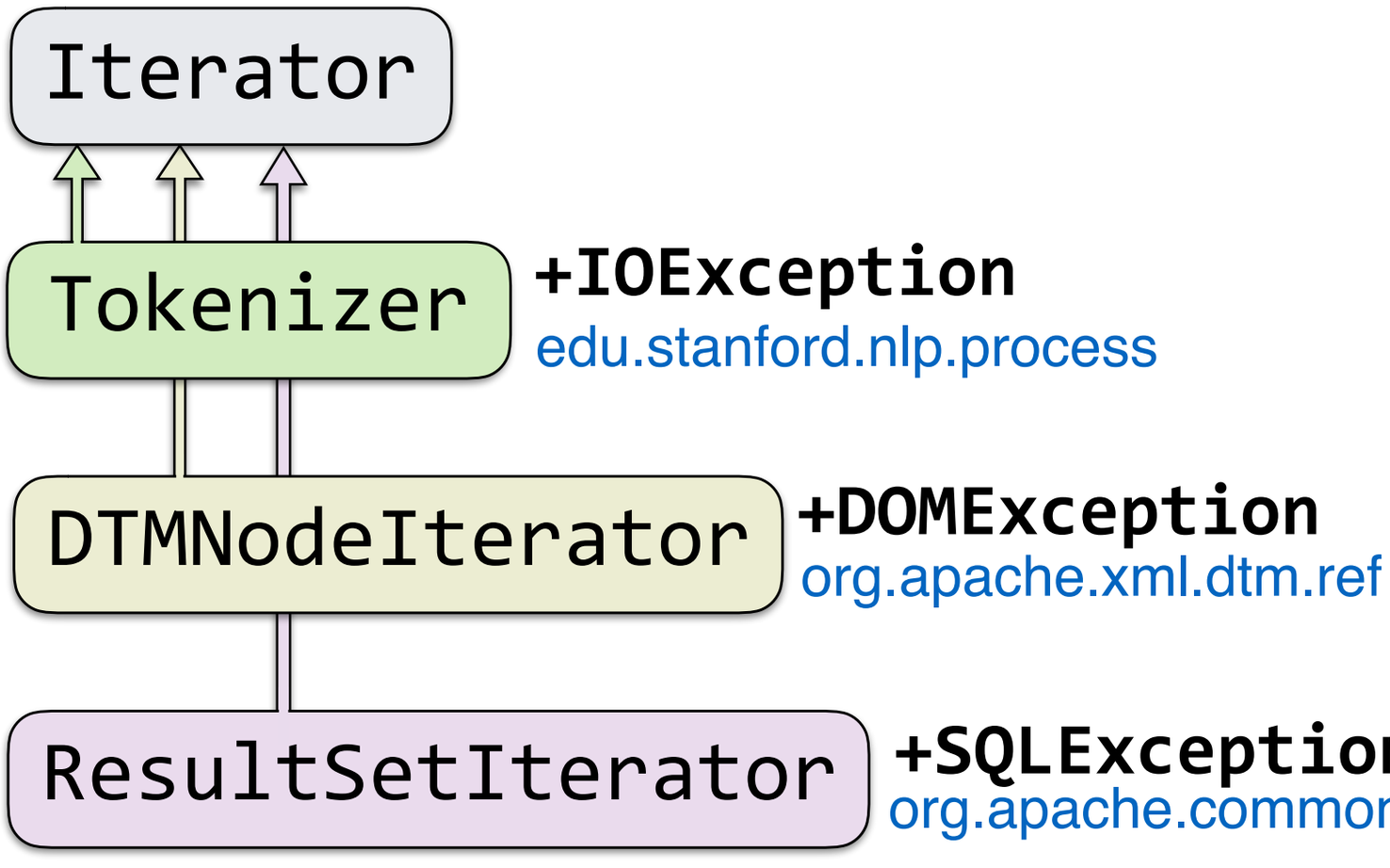

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Behavioral subtyping: subtypes cannot add new exceptions.

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Behavioral subtyping: subtypes cannot add new exceptions, **unless the supertype is weak.**

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Indicates mismatch is allowed

```
weak interface Factory[T] { T make(); }
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```
class ConnectionFactory
implements Factory[Connection] {
  Connection make() throws SQLException {…}
}
```

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class ConnectionFactory
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```

An exception mismatch

```
Factory[Connection] f =
  new ConnectionFactory();
try { Connection conn = f.make(); … }
catch (SQLException e) {…}
```

{ Function, Iterator, Visitor, Factory, ... }

Subtypes may want to throw new exceptions, **but the extra exceptions are checked.**

Behavioral subtyping: subtypes cannot add new exceptions, **unless the supertype is weak.**

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An exception mismatch

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Accounts for the mismatch

Behavioral subtyping: subtypes cannot add new exceptions, **unless the supertype is weak.**

{ Function Iterator Visitor Factory ... }

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A mismatch analysis

Infers mismatch inherent in weak-ly typed local variables.

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assignment to f induces a constraint

$$\texttt{Factory[Connection]}\langle \texttt{make} : \texttt{SQLException} \rangle \leq \texttt{Factory[Connection]}\langle \ell \rangle$$

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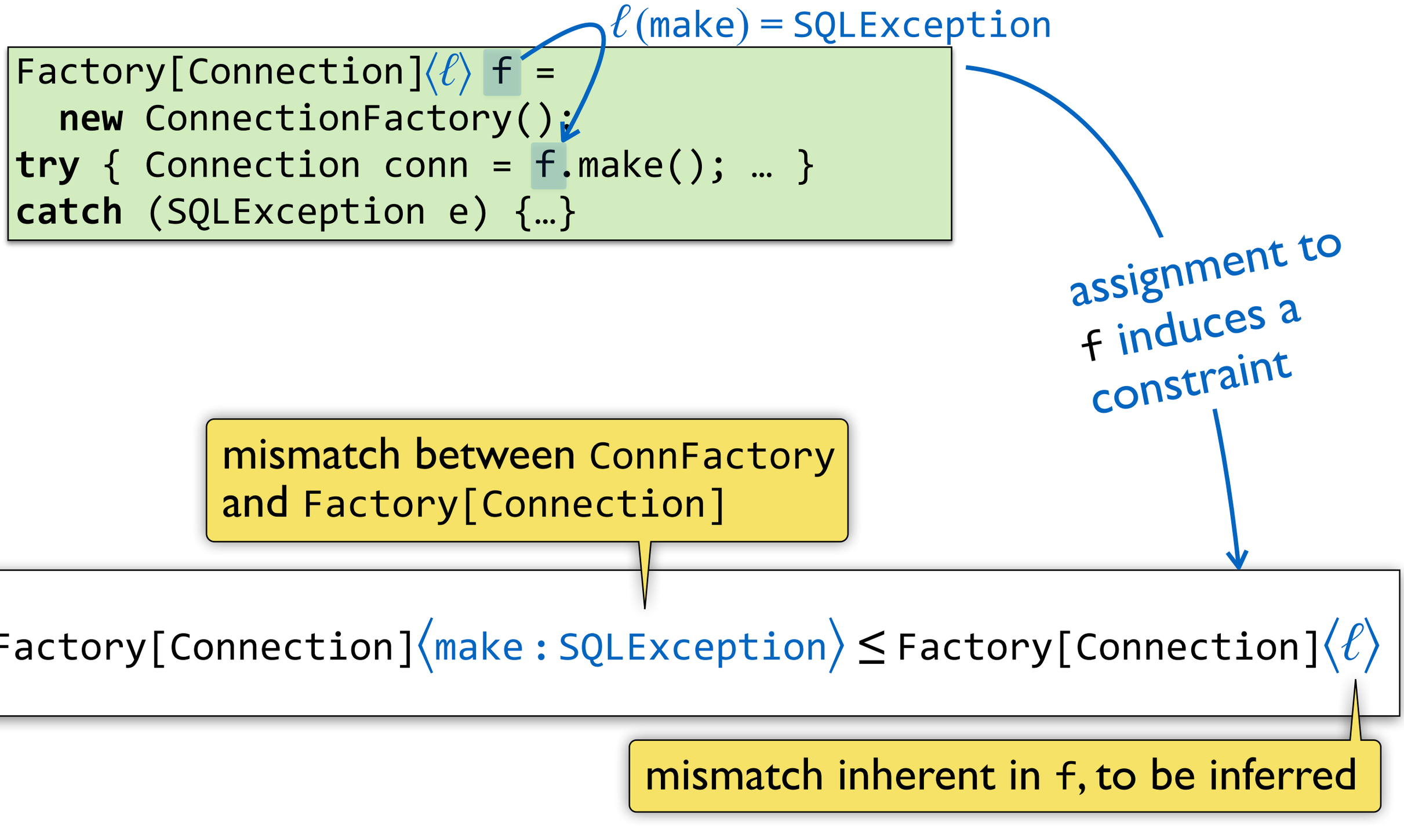
assignment to `f` induces a constraint

$$\texttt{Factory[Connection]}\langle \texttt{make} : \texttt{SQLException} \rangle \leq \texttt{Factory[Connection]}\langle \ell \rangle$$

mismatch inherent in `f`, to be inferred

A mismatch analysis

Infers mismatch inherent in `weak`-ly typed local variables.



Preventing mismatches from escaping

Blame labels are scoped

⇒ Mismatches cannot escape their scopes

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```
class ObjectPool[T] {
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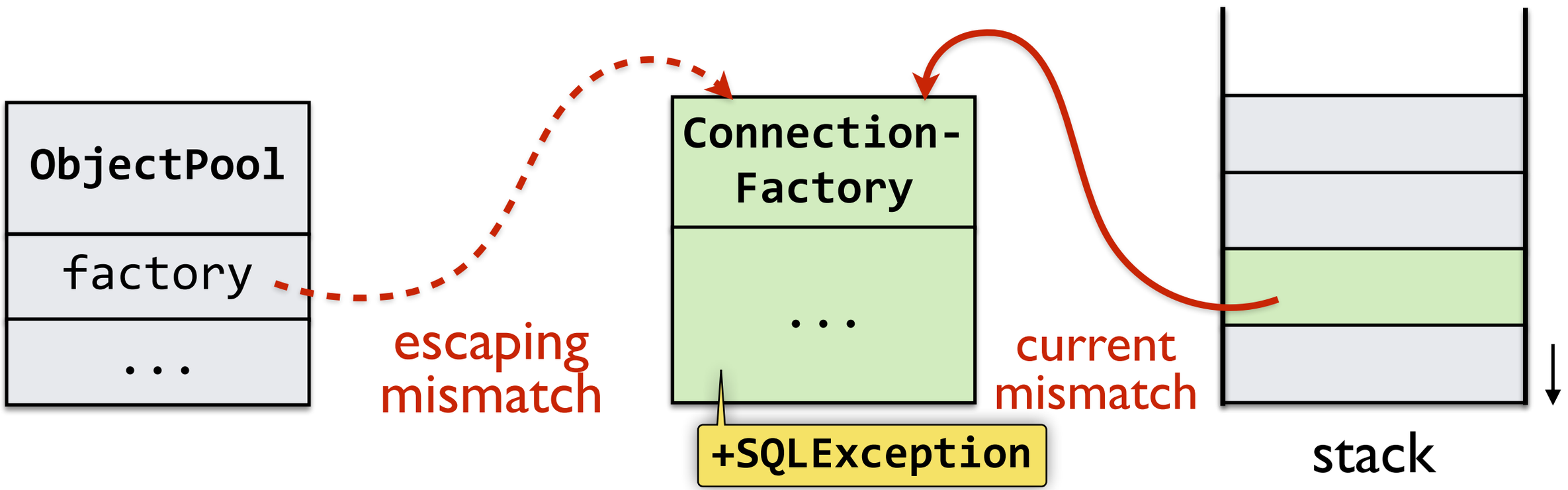

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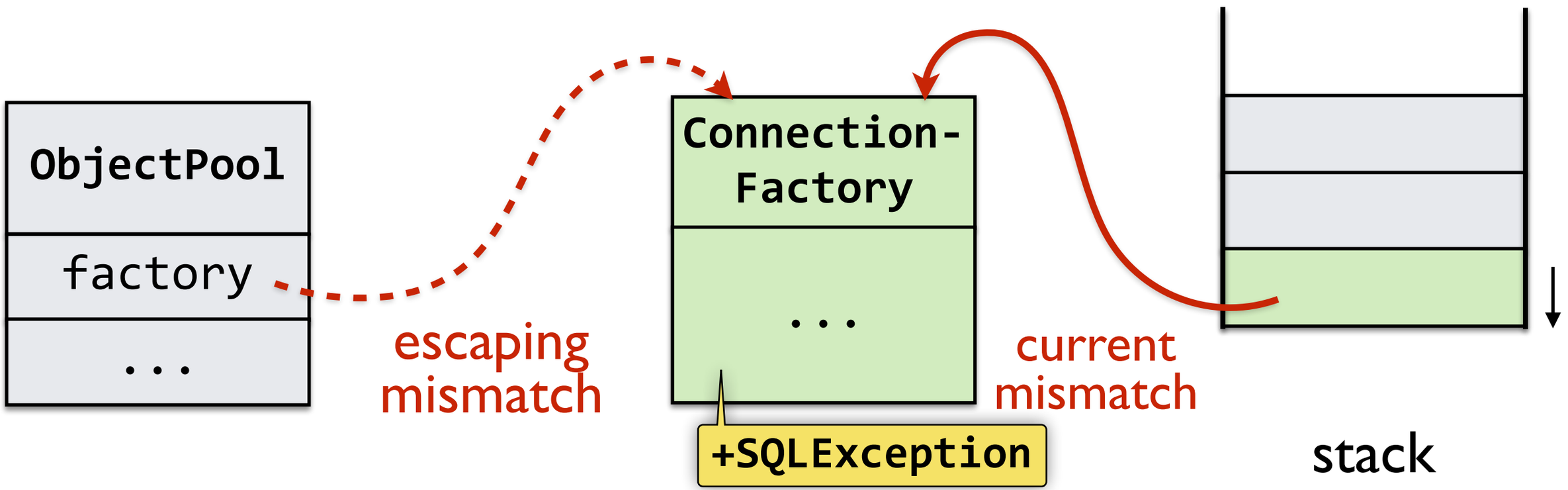

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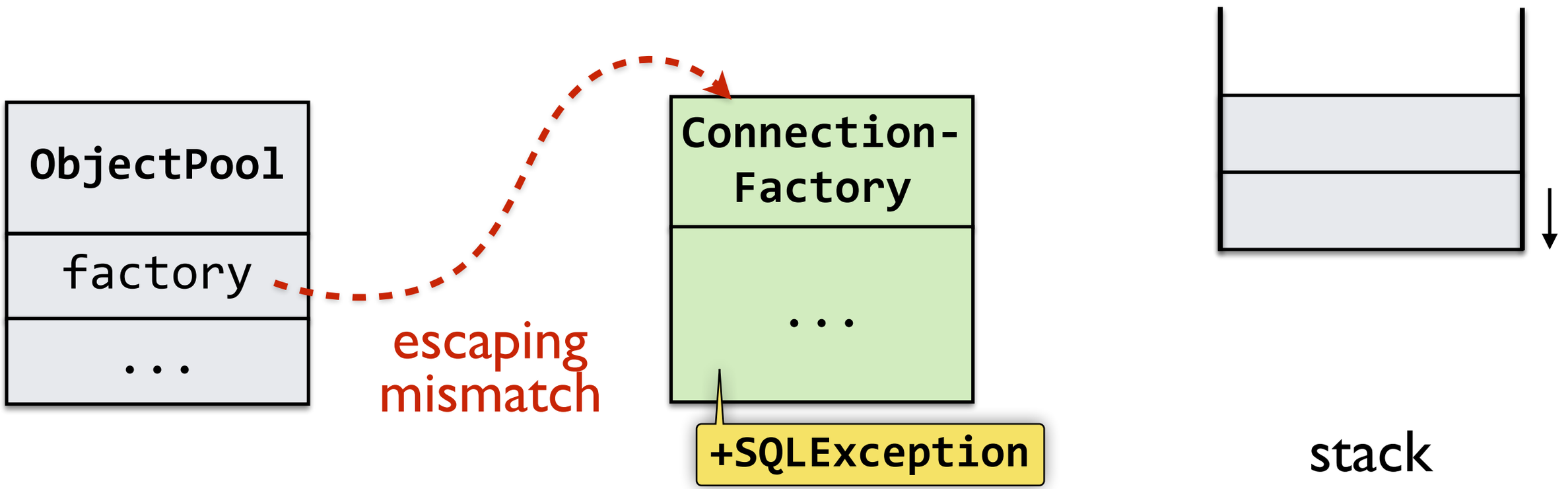

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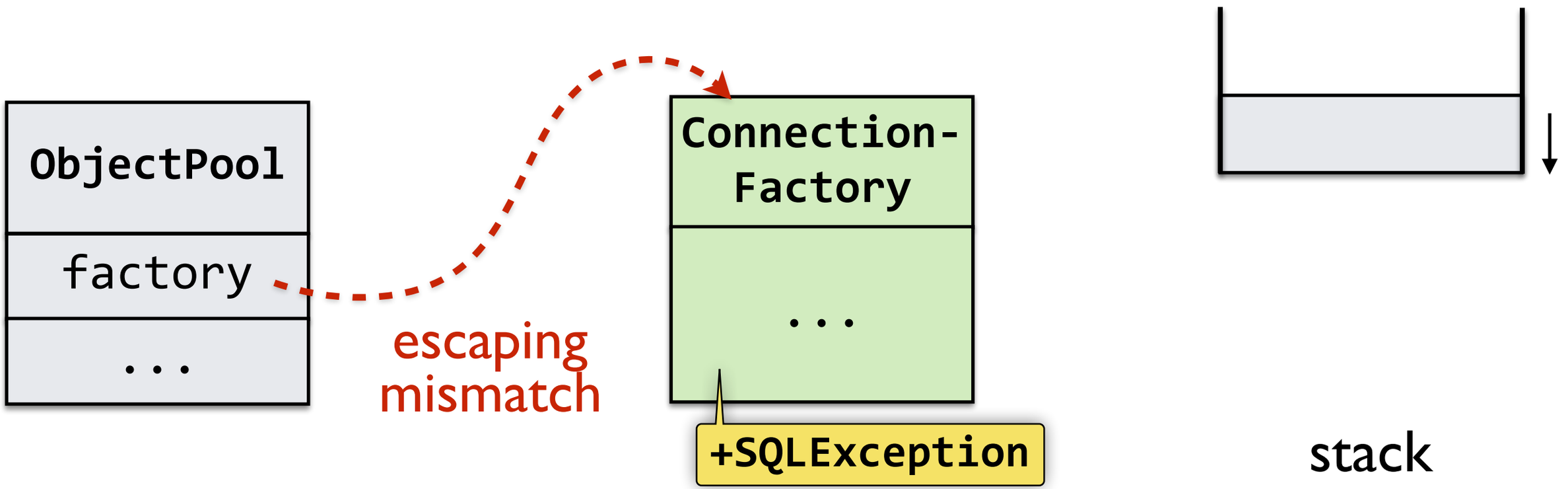

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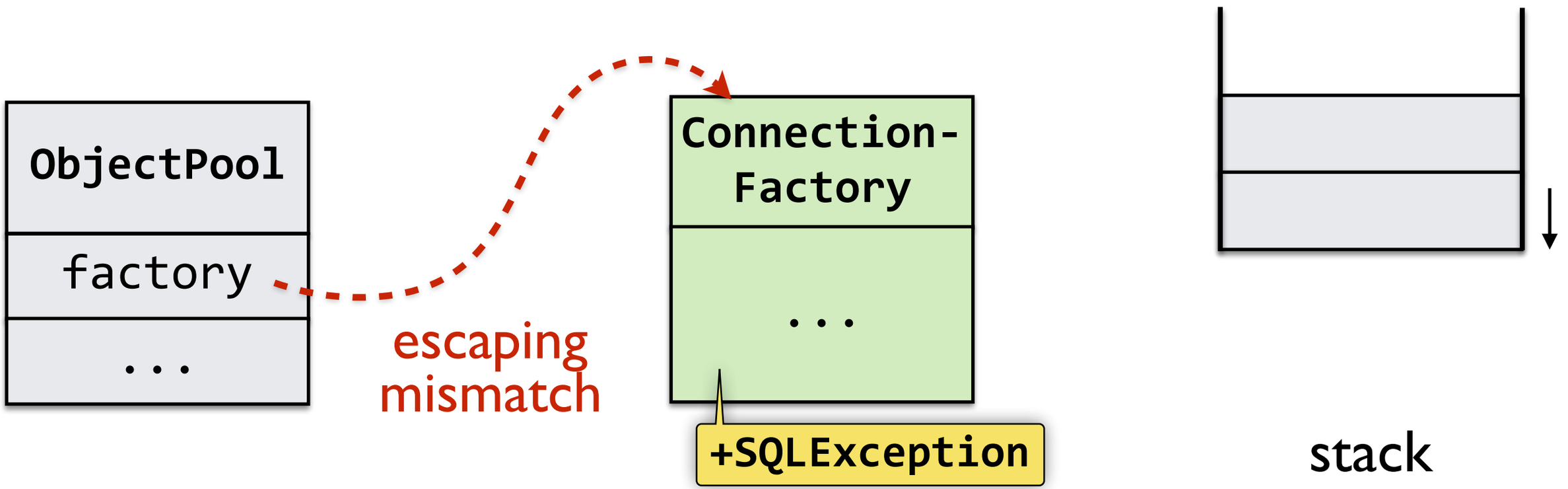

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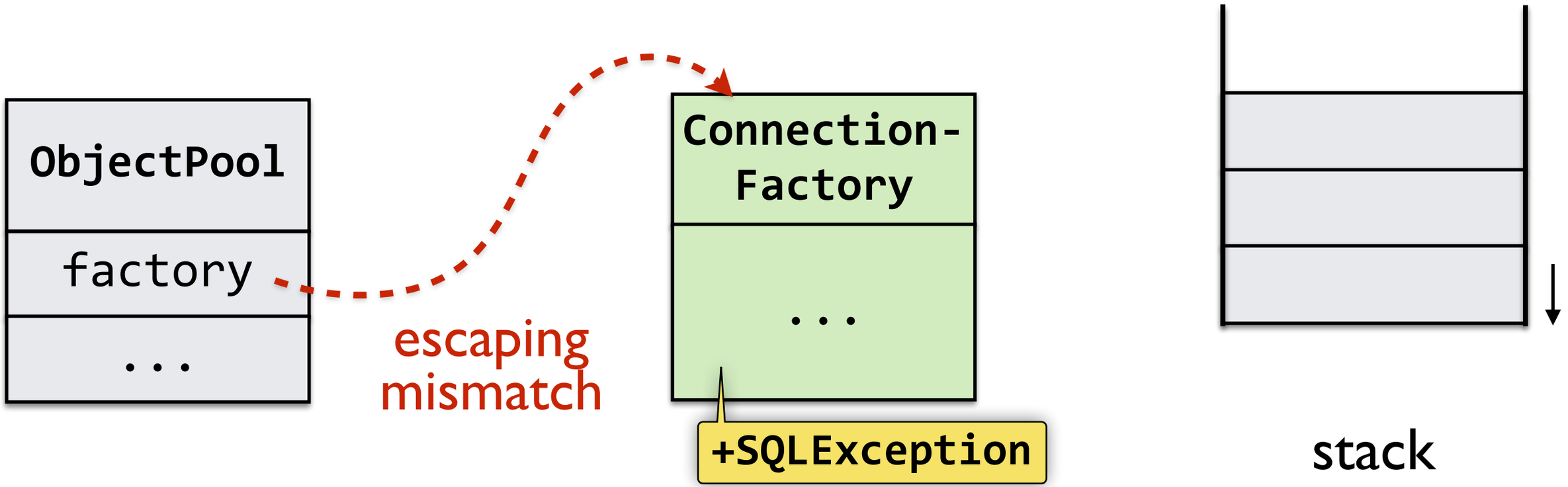

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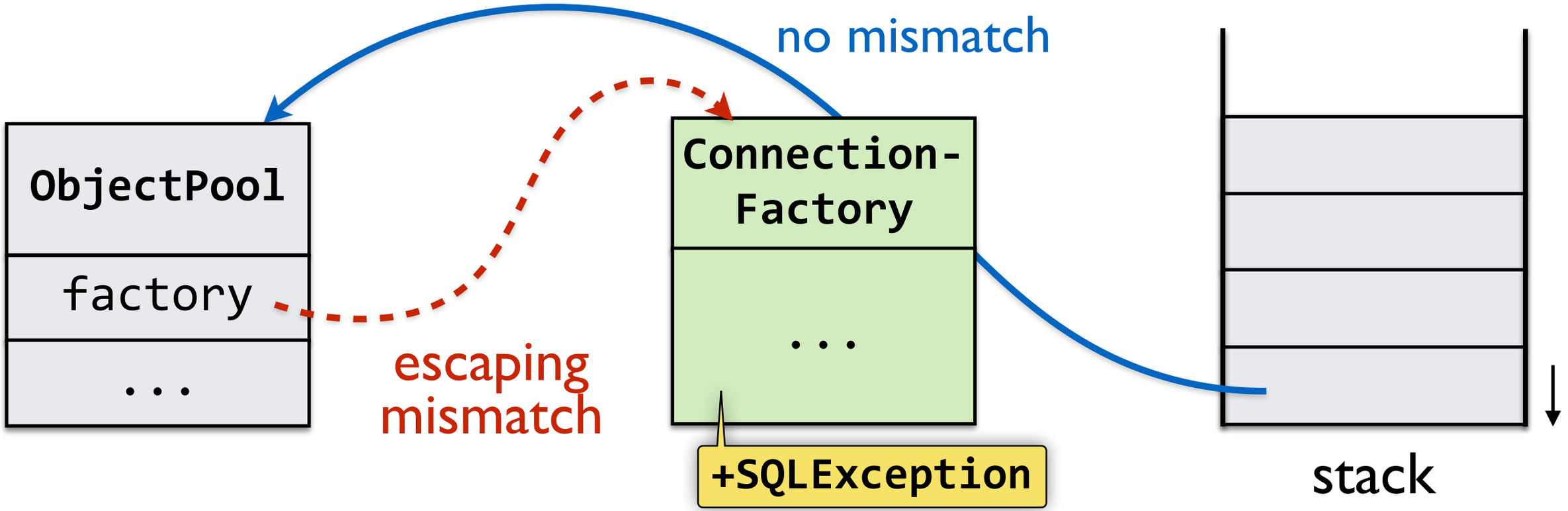

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class ObjectPool[T] {
  ObjectPool(Factory[T]⟨ℓ⟩ f) { factory = f; }
  Factory[T] factory;
  …
  T borrow() { … factory.make() … }
}
```

assignment to `iter` induces a constraint

Argument `f` can have arbitrary mismatch.

$$\forall \ell.\ \texttt{Factory[T]}\langle \ell \rangle \leq \texttt{Factory[T]}\langle \bot \rangle$$

Field `factory` does not allow mismatch.

Preventing mismatches from escaping

Blame labels are scoped

⇒ Mismatches cannot escape their scopes

A warning is issued.

```
class ObjectPool[T] {
  ObjectPool(Factory[T]⟨ℓ⟩ f) { factory = f; }
  Factory[T] factory;
  …
  T borrow() { … factory.make() … }
}
```

constraint unsatisfiable

assignment to `iter` induces a constraint

Argument `f` can have arbitrary mismatch.

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Field `factory` does not allow mismatch.

Use @exact to indicate no mismatch

Blame labels are scoped

⇒ Mismatches cannot escape their scopes

```
class ObjectPool[T] {
  ObjectPool(@exact Factory[T] f) { factory = f; }
  Factory[T] factory;
  …
  T borrow() { … factory.make() … }
}
```

assignment to `iter` induces a constraint

`@exact` indicates no mismatch.

$$\texttt{Factory[T]}\langle\bot\rangle \leq \texttt{Factory[T]}\langle\bot\rangle$$

Field `factory` does not allow mismatch.

Use generics to indicate polymorphic mismatch

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```
constraint Factory[T] {
  static T make();
}
```

Use generics to indicate polymorphic mismatch

```
constraint Factory[T] {
  static T make();
}
```

```
class ObjectPool[T]
    where Factory[T] {
  T borrow()
    { … f.make() … }
  …
}
```

Use generics to indicate polymorphic mismatch

```
constraint Factory[T] {
  static T make();
}
```

```
model ConnectionFactory
for Factory[Connection] {
  Connection make()
    throws SQLException { … }
}
```

```
class ObjectPool[T]
    where Factory[T] {
  T borrow()
    { … f.make() … }
  …
}
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```
// Using code
try {
  ObjectPool[Connection] pool =
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} catch (SQLException e) { … }
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The model is inferred, and is part of the type.

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// Using code
try {
  ObjectPool[Connection] pool =
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  Connection c = pool.borrow();
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```

SQLException is tracked precisely.

Object Pool pattern in Java

```
interface Factory<T> {
  T make() throws Exception;
}
```

```
class ConnectionFactory
implements Factory<Connection> {
  Connection make()
    throws SQLException { … }
}
```

```
class ObjectPool<T> {
  Factory<T> f;
  T borrow() throws Exception
    { … f.make() … }
  …
}
```

```
// Using code
try {
  ObjectPool<Connection> pool =
    new ObjectPool<Connection>(cf);
  Connection c = pool.borrow();
  …
} catch (Exception e) { … }
```

Object Pool pattern in Java

A simplification of the `apache.commons.pool` package

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  T borrow() throws Exception
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  …
}
```

Catching "`Exception`" raises the risk of exception capture.

```
// Using code
try {
  ObjectPool<Connection> pool =
    new ObjectPool<Connection>(cf);
  Connection c = pool.borrow();
  …
} catch (Exception e) { … }
```

Using code is littered with the overly general "`Exception`" type.

Formalizing the language

- An extension of the simply typed λ-calculus
  Models exception tunneling and mismatch analysis.

- A translation from surface syntax into a kernel calculus

- **Theorem** *Well-typed programs handle their exceptions.*

Implementing the language

- An extension of the base Genus compiler [Zhang et al.'15]
  ~6,000 LoC

- A translation from Genus to Java

Key challenge:

(a) preventing exception capture (by reifying blame labels)

(b) … without slowing down normal control flow

Experience: safer and cleaner code

Porting the Java Collections Framework

(All general-purpose implementations)

- Static checking found "unreachable" `catch` blocks
- Prevents **exception capture** bugs

Porting exception-tunneling code

- Examples come from various sources:

  `javac` compiler, Apache Commons, etc.

- Restores static checking
- Eliminates ~200 (out of ~1,000) LoC in a `javac` visitor

Performance evaluation

1. Does reifying blame labels slow down normal-case code?

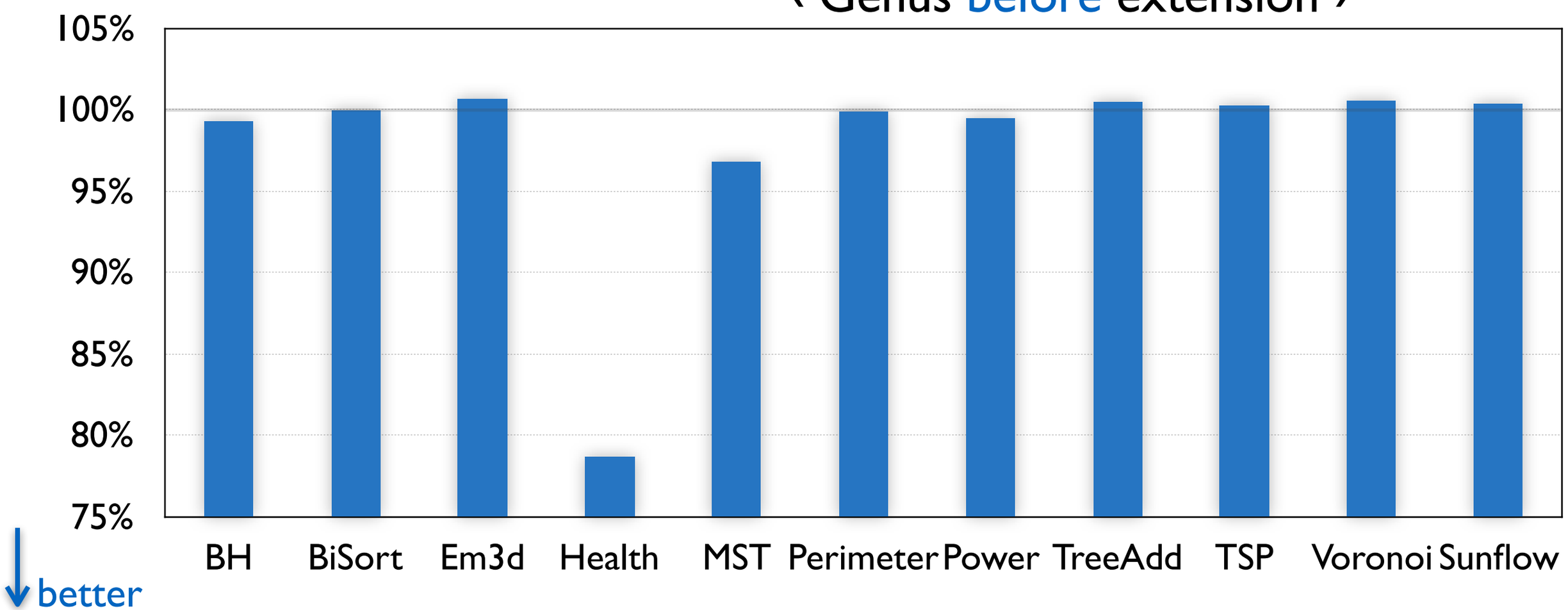
2. What speedup is achieved for exception-heavy code by not gathering a stack trace?

Performance with normal-case code

Benchmarks: JOlden & SunFlow (from DaCapo, ~21,000 LoC)

- 2.4% speedup across benchmarks
- Less than 0.5% slowdown in the worse case

Ratio of running times $\left(\frac{\text{Genus after extension}}{\text{Genus before extension}}\right)$

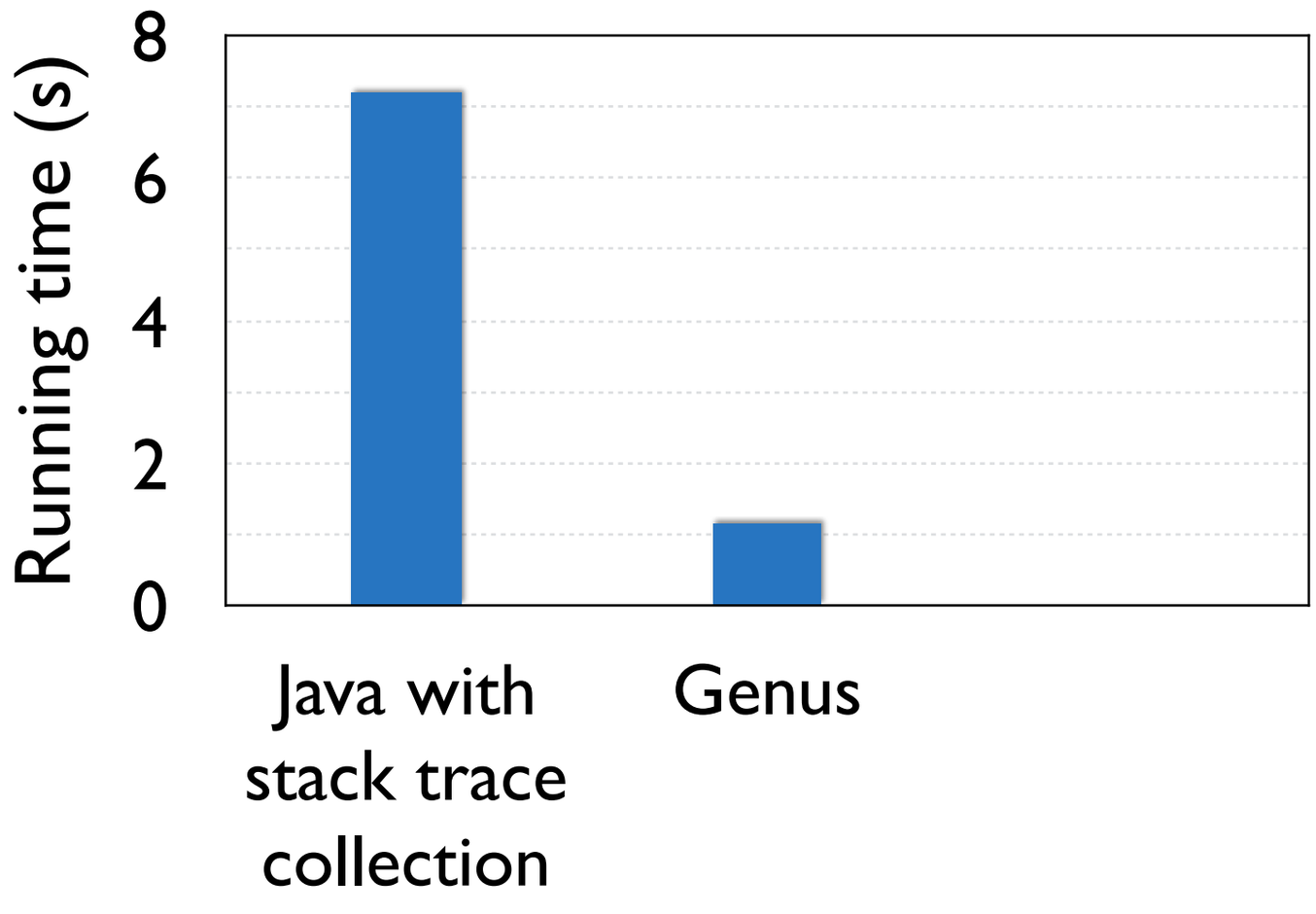


Performance with exception-heavy code

Benchmark: EasyIO (a text parsing package)

~6,200,000 exceptions raised per run

6× speedup by not collecting stack traces



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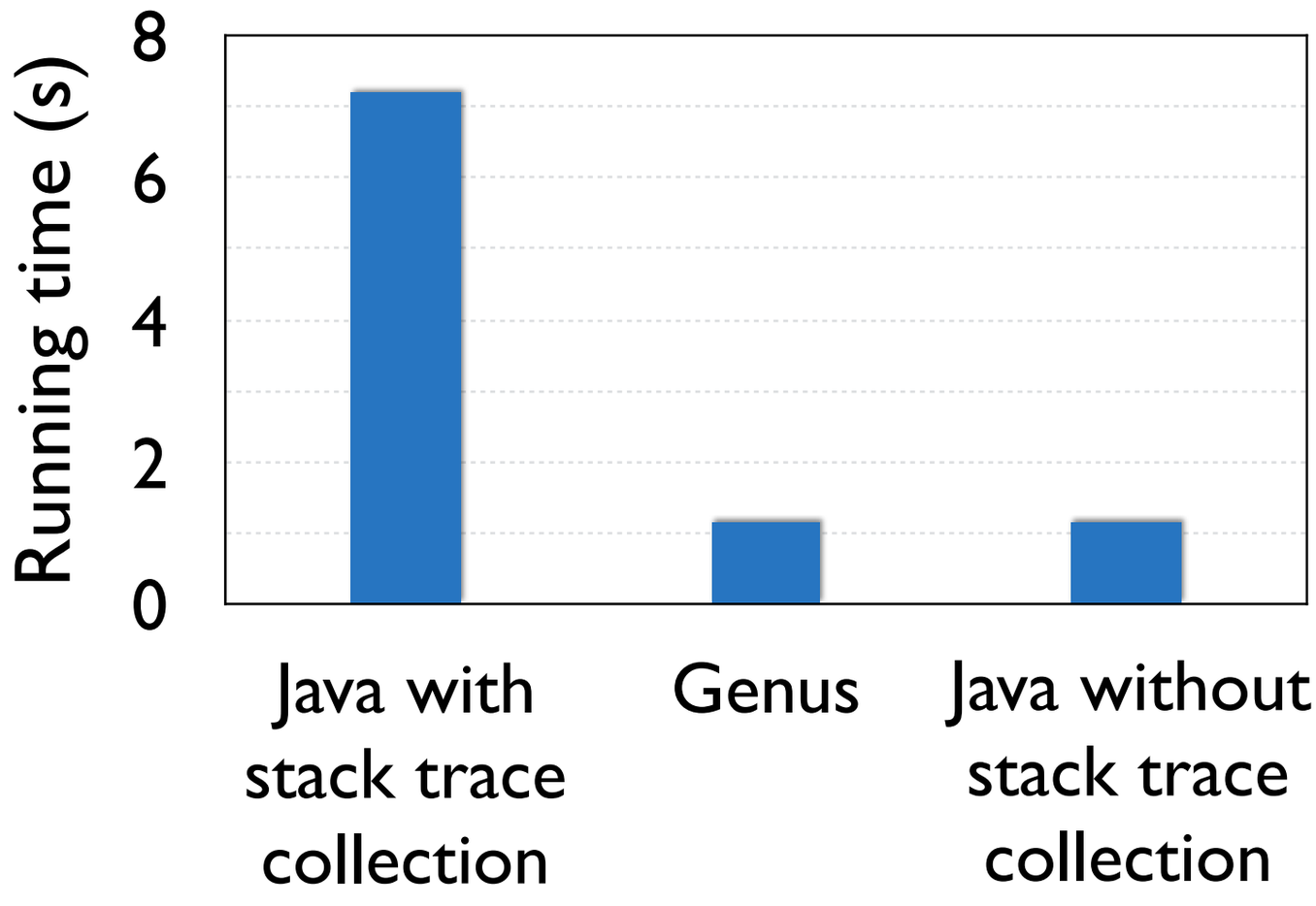

Related work

Exception Analysis	SML [Fähndrich, Foster, Aiken, & Cu '98]
	OCaml [Leroy & Pessaux '00]
	Java [Robillard and Murphy '03]
	Java [Bravenboer & Smaragdakis '09]
	Others
Exception Polymorphism	Java [van Dooren & Steegmans '05]
	Scala [Rytz, Odersky, & Haller '12]
	Koka [Leijen '14]
	Swift 2 [Apple Inc. '15]

Blame Tracking	Higher-order contracts [Findler & Felleisen '02]
	Blame Calculus [Wadler & Findler '09]
Type Inference	Gradual type inference [Rastogi, Chaudhuri, & Hosmer '12]
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- **Trade-off** between performance and precision
- **Global reasoning** does not help code understanding

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- **Trade-off** between performance and precision
- **Global reasoning** does not help code understanding

- Notional burden
- Exception capture

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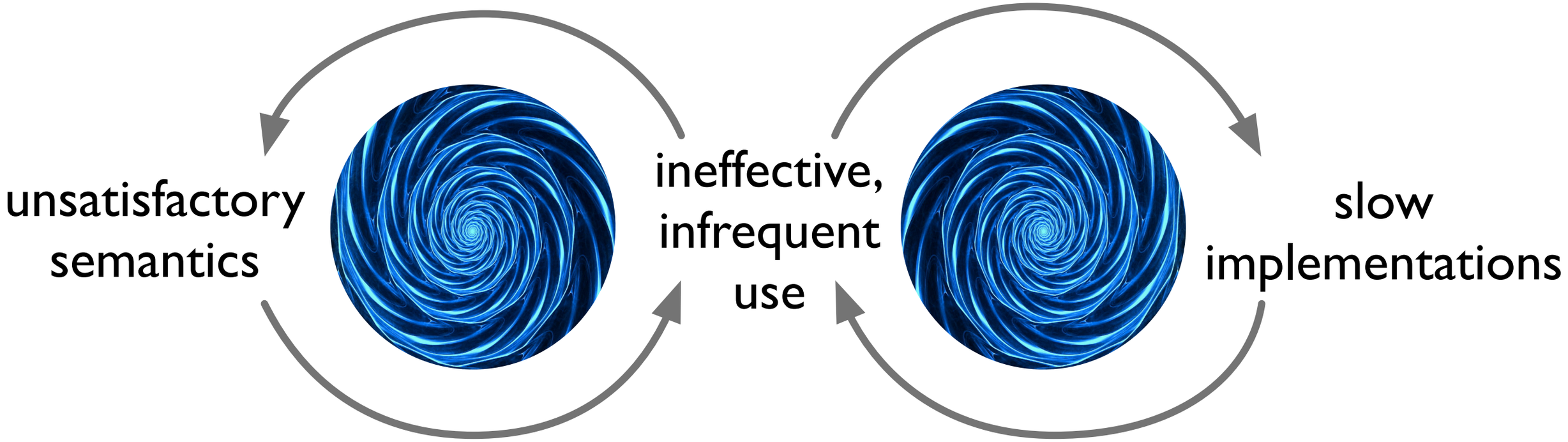
Breaking vicious cycles in language design



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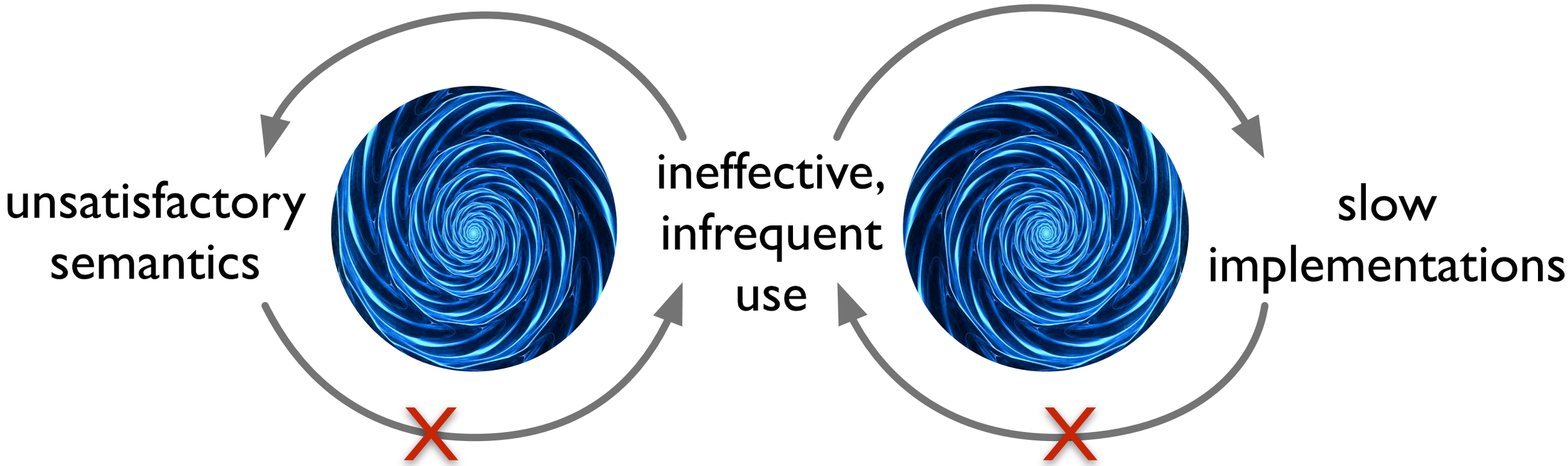

A safe, flexible, and efficient approach to exceptions

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www.cs.cornell.edu/projects/genus

Yizhou Zhang*
Guido Salvaneschi†
Quinn Beightol*
Barbara Liskov‡
Andrew Myers*

**Cornell* †*TU Darmstadt* ‡*MIT*

Exception-based desugaring of foreach loops

```
for (E e : c) {
  print(e);
}
```

Java's desugaring

```
Iterator<E> it = c.iterator();
while (it.hasNext()) {
  E e = it.next();
  print(e);
}
```

Genus' desugaring

```
Iterator[E] it = c.iterator();
while (true) {
  E e;
  try { e = it.next(); }
  catch (NoSuchElementException stop) { break; }
  print(e);
}
```