Exceptions

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Agenda

- Why exceptions?
- Syntax and informal semantics
- Semantic analysis (i.e., type checking rules)
- Operational semantics
- Code Generation for Exception

Which is the hottest city in the U.S.?

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Phoenix, Arizona

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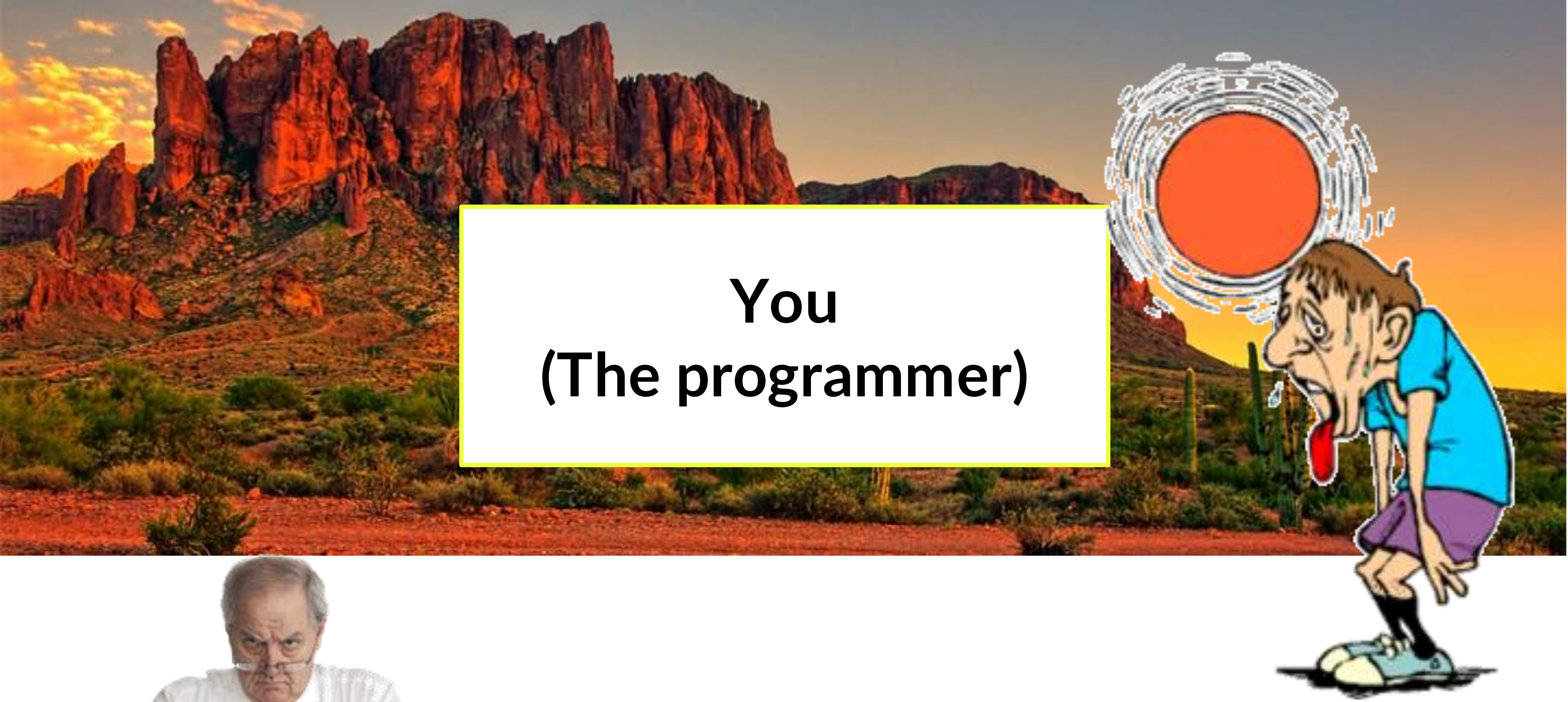
Phoenix, Arizona



You
(The programmer)

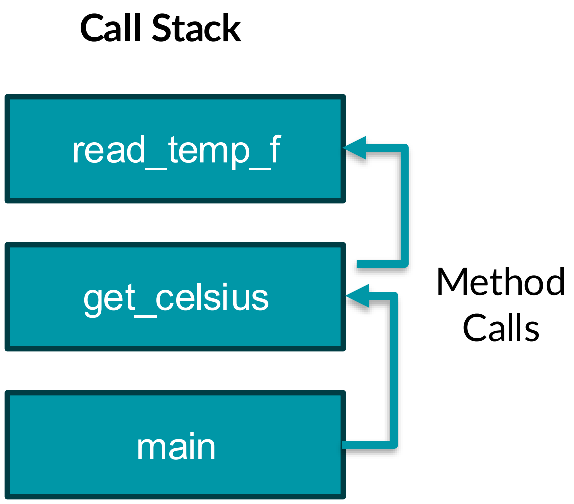
- Implement read_temp_f() to simulate reading the temperature in Phoenix, Arizona (in Fahrenheit).
- Implement get_celsius() to:
    1- First call read_temp_f() to get the temp
    2- Then convert that value to Celsius
- In main(), call get_celsius() and print the result in Celsius.

What is the first thing you should do?

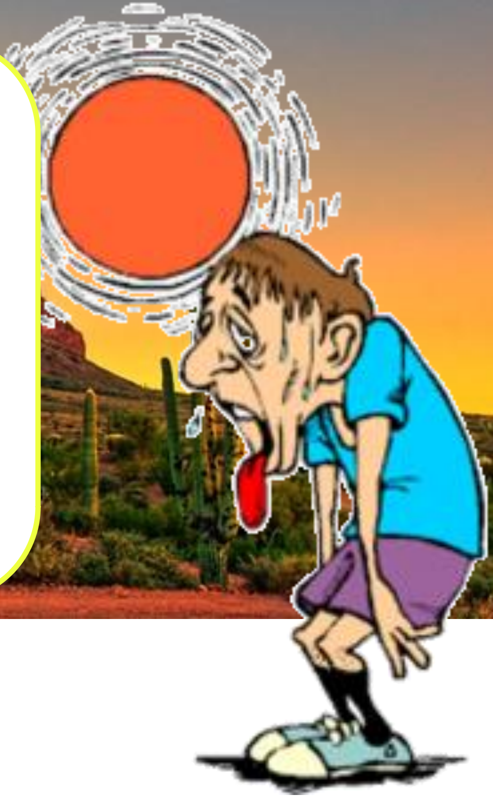
Cool down!

- Implement read_temp_f() to simulate reading the temperature in Phoenix, Arizona (in Fahrenheit).
- Implement get_celsius() to:
  1- First call read_temp_f() to get the temp
  2- Then convert that value to Celsius
- In main(), call get_celsius() and print the result in Celsius.

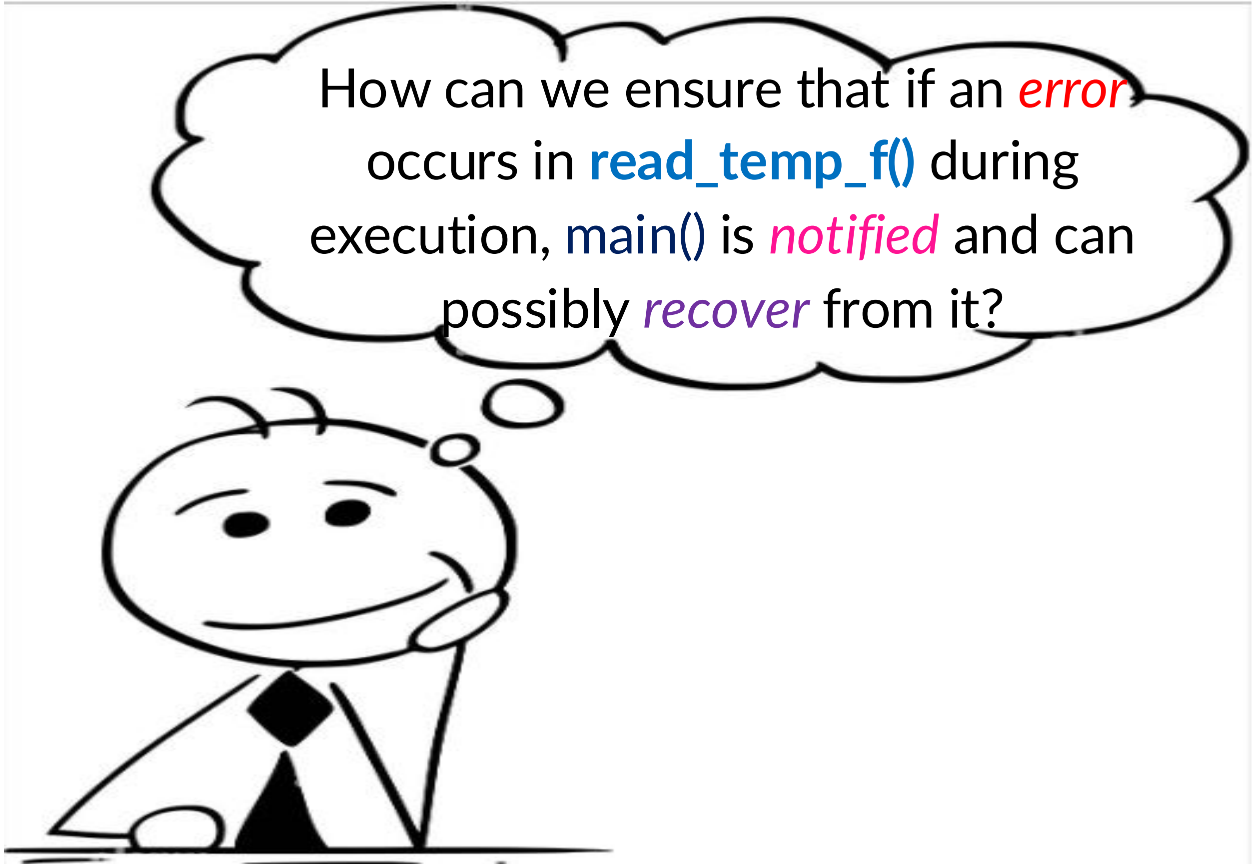
```c
// read_temp_f: reads temperature from a sensor
float read_temp_f() {
    float temperature = /* get temp from sensor*/;
    return temperature;
}

// get_celsius: converts Celsius to Fahrenheit, needs valid temperature
int get_celsius() {
    float celsius = read_temp_f();
    int fahrenheit = (int)(celsius * 9.0f / 5.0f + 32.0f);
    return fahrenheit;
}

// main: gets Fahrenheit temperature or prints error
int main() {
    int result = get_celsius();
        printf("Temperature: %d°F\n", result);
}
```

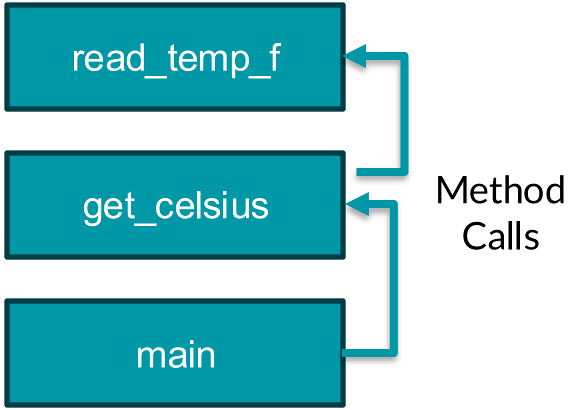


- ❑ The temperature read from sensors in read_temp_f may be faulty and raise Error_In_Sensor.
- ❑ **Make sure to handle sensor failure gracefully in main().**



Main Challenge





Option1: Error Return Codes

- Select special error codes in read_temp_f() and get_celsius()
- When an error happens, the *callee* returns the code to the *caller*
- The *caller* promises to check the error return

and either:
  - Correct the error, or
  - Pass it on to its own caller.
- Very common in C and C++ programming
- Example:
  - malloc() (memory allocation)
    - Returns NULL if memory cannot be allocated.
    - Have you ever checked the return value of malloc() when using it?

```c
// read_temp_f: reads temperature from a sensor
float read_temp_f() {
    float temperature = /* get temp from sensor*/;
    if (Error_In_Sensor) {
        return ???; // Error code
    }
    return temperature;
}

// get_celsius: converts Celsius to Fahrenheit, needs valid temperature
int get_celsius() {
    float celsius = read_temp_f();
    if (???) { // read_temp_f failed
        return ???;         // get_celsius own error code
    }
    int fahrenheit = (int)(celsius * 9.0f / 5.0f + 32.0f);
    return fahrenheit;
}

// main: gets Fahrenheit temperature or prints error
int main() {
    int result = get_celsius();
    if (???) {
        printf("Error reading temperature!\n");
    } else {
        printf("Temperature: %d°F\n", result);
    }
}
```

We need to choose error return codes that are distinguishable from normal values

Which is the hottest city in the U.S.?

Phoenix, Arizona

```c
// read_temp_f: reads temperature from a sensor
float read_temp_f() {
    float temperature = /* get temp from sensor*/;
    if (Error_In_Sensor) {
        return -1.0f; // Error code
    }
    return temperature;
}

// get_celsius: converts Celsius to Fahrenheit, needs valid temperature
int get_celsius() {
    float celsius = read_temp_f();
    if (celsius < 0.0f) { // read_temp_f failed
        return -20;        // get_celsius own error code
    }
    int fahrenheit = (int)(celsius * 9.0f / 5.0f + 32.0f);
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// main: gets Fahrenheit temperature or prints error
int main() {
    int result = get_celsius();
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```

Different error conventions

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    } else {
        printf("Temperature: %d°F\n", result);
    }
}
```

Manual error checking in callers

```c
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        printf("Temperature: %d°F\n", result);
    }
}
```

Callers need to remember the codes

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// main: gets Fahrenheit temperature or prints error
int main() {
    int result = get_celsius();
    if (result==-20{
        printf("Error reading temperature!\n");
    } else {
        printf("Temperature: %d°F\n", result);
    }
}
```

Manual error checking everywhere

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// read_temp_f: reads temperature from a sensor
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```

Silent errors if a check is forgotten

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    }
}
```

Much Extra Code and Messy!

- ❑ Extend the code to work in Alaska as well.

New Challenge!

```c
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float read_temp_f() {
    float temperature = /* get temp from sensor*/;
    if (Error_In_Sensor) {
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    }
}
```

Error codes can now be *legitimate temperatures*!

```
// read_temp_f: reads temperature from a sensor
float read_temp_f() {
    float temperature = /* get temp from sensor*/;
    if (Error_In_Sensor) {
        return std::numeric_limits<float>::min(); // Error code
    }
    return temperature;
}

// get_celsius: converts Celsius to Fahrenheit, needs valid temperature
int get_celsius() {
    float celsius = read_temp_f();
    if (celsius == std::numeric_limits<float>::min()) { // read_temp_f failed
        return std::numeric_limits<int>::min(); // get_celsius own error code
    }
    int fahrenheit = (int)(celsius * 9.0f / 5.0f + 32.0f);
    return fahrenheit;
}

// main: gets Fahrenheit temperature or prints error
int main() {
    int result = get_celsius();
    if (result == std::numeric_limits<int>::min(); ) {
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Error codes can now be *legitimate temperatures*!

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Error codes can now be *legitimate temperatures*!

Hard to change or extend

Option1: Error Return Codes

- **Problems?**
  - It might be hard to select a value as an error code

    e.g., double sum (double num1, double num2)

    How can we handle this?
  - Different error codes, hard to remember, and extend
  - It is easy to forget to check the error return codes
  - Much extra code, messy…

Option2: Exceptions

Option2: Exceptions

- Exceptions are a language mechanism designed to allow:
    - Deferral of error handling to a *caller*
    - Without (explicit) *error codes* 
    - And without (explicit) error return code checking

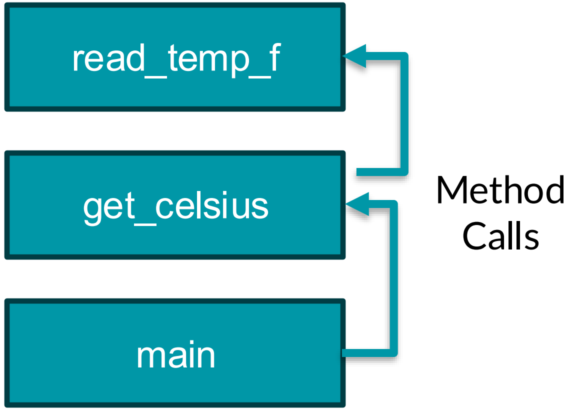
```cpp
#include <cstdio>
#include <stdexcept>

float bar() {
    float temperature = /* get temp from sensor*/;
    if (Error_In_Sensor) {
        throw std::runtime_error("Error in bar()");
    }
    return 42.0f;
}

int foo() {
    float val = bar();
    return (int)(val + 1);
}

int main() {
    try {
        int result = foo();
        printf("Result: %d\n", result);
    } catch (const std::runtime_error& e) {
        printf("Caught error: %s\n", e.what());
    }
}
```

Less Extra Code



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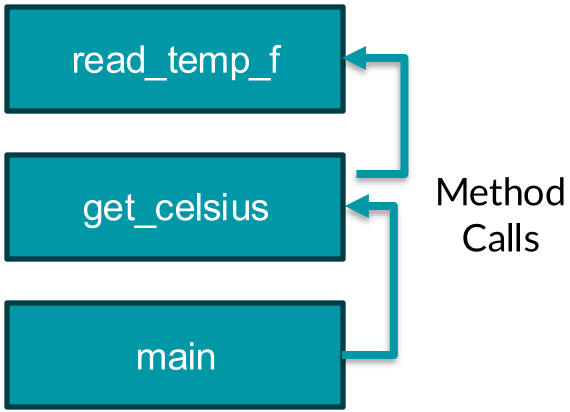

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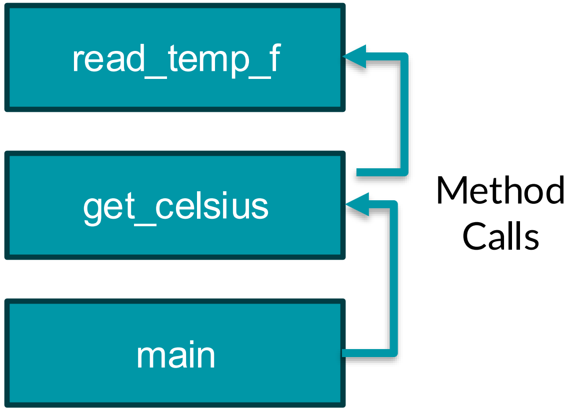

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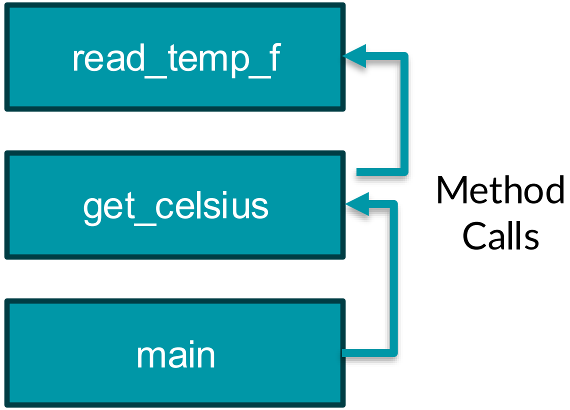
```

Normal **execution STOPS**

Less Extra Code



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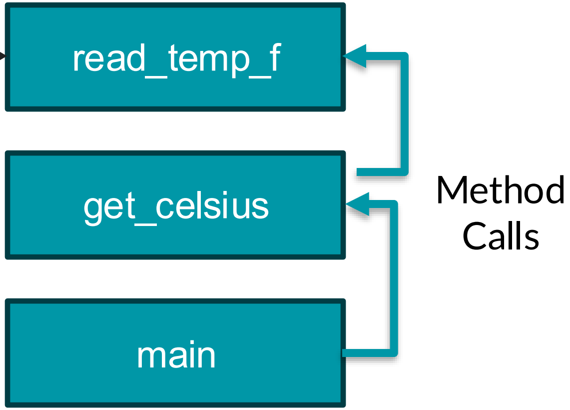
Less Extra Code

The runtime system looks for a catch



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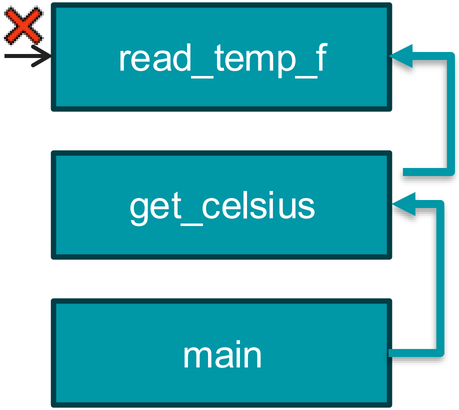

Method Calls

```
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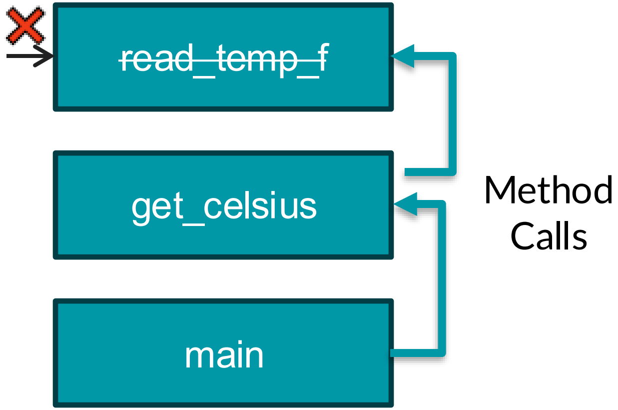

Unwind: Read_temp_f() does not catch the exception, so Read_temp_f() 's execution is abandoned — variables in Read_temp_f() are destroyed, memory is cleaned up, and it "pops off" the call stack.

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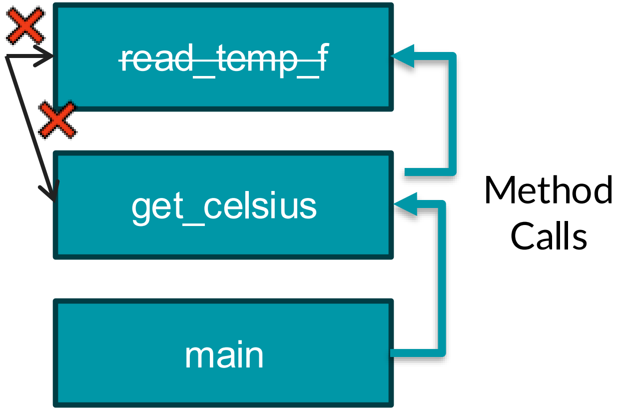
    }
}
```

Normal **execution STOPS**

Less Extra Code

The runtime system looks for a catch



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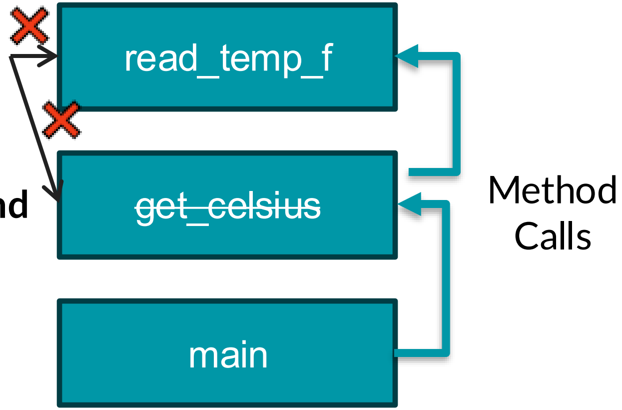
Normal **execution STOPS**

Less Extra Code

The runtime system looks for a catch

Unwind



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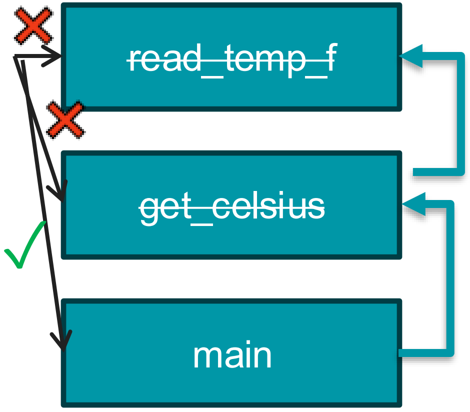
Normal **execution STOPS**

Less Extra Code

The runtime system looks for a catch



Method Calls

```cpp
#include <cstdio>
#include <stdexcept>

float bar() {
    float temperature = /* get temp from sensor*/;
    if (Error_In_Sensor) {
        throw std::runtime_error("Error in bar()");
    }
    return 42.0f;
}

int foo() {
    float val = bar();
    return (int)(val + 1);
}

int main() {
    try {
        int result = foo();
        printf("Result: %d\n", result);
    } catch (const std::runtime_error& e) {
        printf("Caught error: %s\n", e.what());
    }
}
```

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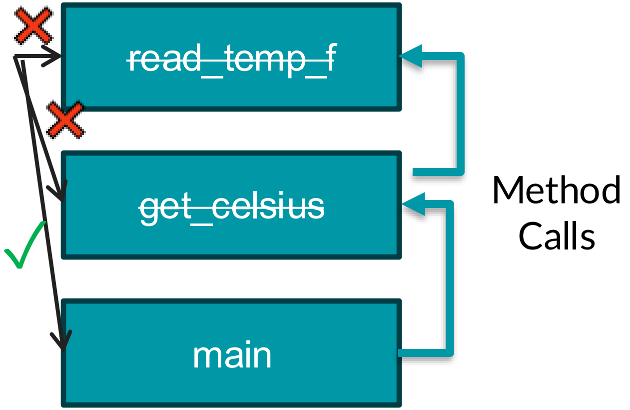

Control jumps here

Adding Exceptions to Cool

- We extend the language of expressions:

  $$e :: throw\ e \mid try\ e\ catch\ x{:}T \ \Longrightarrow e_2$$

- (Informal) semantics of $throw\ e$
  - Signals an exception
  - *Interrupts* the current evaluation and *searches* for an exception handler up the activation tree
  - The value of e is an exception parameter and can be used to communicate details about the exception

Typing Exceptions (1)

- We must extend the Cool typing judgment

$$O, M, C \vdash e : T$$

  - Type T refers to the normal return value!
- We'll start with the rule for try:
  - Parameter "x" is bound in the catch expression – try is like a conditional

$$\frac{O, M, C \vdash e : T_1 \qquad O[T/x], M, C \vdash e' : T_2}{O, M, C \vdash \text{try } e \text{ catch } x : T \Rightarrow e' : T_1 \sqcup T_2}$$

Typing Exceptions (2)

- What is the type of “throw e” ?
- The type of an expression:
  - Is a description of the possible return values, and
  - Is used to decide in what contexts we can use the expression

“throw” does not return to its immediate context but directly to the exception handler!

- The same “throw e” is valid in any context:

  if throw e then (throw e) + 1 else (throw e).foo()

As if “throw e” has *any type*!

Typing Exceptions(3)

$$\frac{O, M, C \vdash e : T_1}{O, M, C \vdash \text{throw } e : T_2}$$

- As long as “e” is well typed, “throw e” is well typed with any type needed in the context.
  - T_2 is unbound!

- This is convenient because we want to be able to signal errors from any context

Tired?

Operational Semantics of Exceptions

- Several ways to model the behavior of exceptions
- A generalized value is
  - Either a normal termination value, or
  - An exception with a parameter value

    g ::= Norm(v) | Exc(v)
- Thus given a generalized value we can:
  - Tell if it is normal or exceptional return, and
  - Extract the return value or the exception parameter

Operational Semantics of Exceptions (1)

- The existing rules change to use Norm(v) :

$$\frac{\begin{array}{c} so, E, S \vdash e_1 : Norm(Int(n_1)), S_1 \\ so, E, S_1 \vdash e_2 : Norm(Int(n_2)), S_2 \end{array}}{so, E, S \vdash e_1 + e_2 : Norm(Int(n_1 + n_2)), S_2}$$

$$\frac{\begin{array}{c} E(id) = l_{id} \\ S(l_{id}) = v \end{array}}{so, E, S \vdash id : Norm(v), S}$$

$$\frac{}{so, E, S \vdash self : Norm(so), S}$$

Operational Semantics of Exceptions (2)

- "throw" returns exceptionally:

$$\frac{so, E, S \vdash e : v, S_1}{so, E, S \vdash \text{throw } e : \text{Exc}(v), S_1}$$

- The rule above *is not well formed*! Why?

Operational Semantics of Exceptions (2)

- "throw" returns exceptionally:

$$\frac{so, E, S \vdash e : v, S_1}{so, E, S \vdash \text{throw } e : Exc(v), S_1}$$

- The rule above *is not well formed*! Why? We want:

$$\frac{so, E, S \vdash e : Norm(v), S_1}{so, E, S \vdash \text{throw } e : Exc(v), S_1}$$

Operational Semantics of Exceptions (3)

- "throw e" always returns exceptionally:

$$\frac{so, E\,,\,S \vdash e : Norm(v), S_1}{so, E, S \vdash \text{throw } e : Exc(v), S_1}$$

- What if the evaluation of e itself throws an exception?
  - Informally: "throw (1 + (throw 2))" is like "throw 2"
  - Formally:

$$\frac{so, E\,,\,S \vdash e : Exc(v), S_1}{so, E, S \vdash \text{throw } e : Exc(v), S_1}$$

Operational Semantics of Exceptions (4)

- All existing rules are changed to propagate the exception:

$$\frac{so, E, S \vdash e_1 : Exc(v), S_1}{so, E, S \vdash e_1 + e_2 : Exc(v), S_1}$$

  - Note: the evaluation of e_2 is skipped
- What if the evaluation of e itself throws an exception?

$$\frac{\begin{array}{c} so, E, S \vdash e_1 : Norm(Int(n_1)), S_1 \\ so, E, S_1 \vdash e_2 : Exc(v), S_2 \end{array}}{so, E, S \vdash e_1 + e_2 : Exc(v), S_2}$$

Operational Semantics of Exceptions (5)

- The rules for "try" expressions:
  - – Multiple rules (just like for a conditional)

$$\frac{so, E, S \vdash e : Norm(v), S_1}{so, E, S \vdash try\ e\ catch\ x : T \Rightarrow e' : Norm(v), S_1}$$

- What if e terminates exceptionally?
  - We must check whether it terminates with an exception parameter of type T or not.

Operational Semantics of Exceptions (6)

- If e does not throw the expected exception

$$\frac{\begin{array}{c}\text{so}, E, S \vdash e : ??????????\\ v = X(\ldots)\\ \text{Not }(??????????)\end{array}}{\text{so}, E, S \vdash \text{try } e \text{ catch } x : T \Rightarrow e' : \text{Exc}(v), S_1}$$

- If e does throw the expected exception

$$\frac{\begin{array}{c}\text{so}, E, S \vdash e : \text{Exc}(v), S_1\\ v = X(\ldots)\\ X \leq T\\ L_{new} = ??????????\\ \text{So}, ?????????? \vdash e' : g, S_2\end{array}}{\text{so}, E, S \vdash \text{try } e \text{ catch } x : T \Rightarrow e' : g, S_2}$$

Operational Semantics of Exceptions (7)

- If e does not throw the expected exception

$$\frac{\begin{array}{c}\text{so, E, S} \vdash \text{e : Exc(v), S}_1 \\ \text{v = X(...)} \\ \text{not (X} \leq \text{T)}\end{array}}{\text{so, E, S} \vdash \text{try e catch x : T} \Rightarrow \text{e}' \text{ : Exc(v), S}_1}$$

- If e does throw the expected exception

$$\frac{\begin{array}{c}\text{so, E, S} \vdash \text{e : Exc(v), S}_1 \\ \text{v = X(...)} \\ \text{X} \leq \text{T} \\ \text{l}_{\text{new}} = \text{newloc(S}_1\text{)} \\ \text{so, E[l}_{\text{new}}\text{/x] , S}_1\text{[v/l}_{\text{new}}\text{]} \vdash \text{e}' \text{ : g, S}_2\end{array}}{\text{so, E, S} \vdash \text{try e catch x : T} \Rightarrow \text{e}' \text{ : g, S}_2}$$

Operational Semantics of Exceptions: Notes

- Our semantics is precise
- But is not very clean
    - It has two or more versions of each original rule
- It is not a good recipe for implementation
    - It models exceptions as “compiler-inserted propagation of error return codes”
    - There are much better ways of implementing exceptions

Code Generation for Exceptions

- One method is suggested by the operational semantics
- Simple to implement
- But not very good
  - We pay a cost at each call/return (i.e., often)
  - Even though exceptions are rare (i.e., exceptional)
- A good engineering principle:
  - Don’t pay often for something that you use rarely!
    - What is Amdahl’s Law?
- – Optimize the common case!

Code Generation for Exceptions: C

- **No built-in exception handling**
- **Manual / Low-Level with setjmp/longjmp**
- Achieved using:

```
#include <setjmp.h>
jmp_buf env;
if (setjmp(env) == 0) {
    // do some risky job in which longjmp(env, 1); // Throw
} else {
    // Catch block
}
...
```

Code Generation for Exceptions: C

- How it works
  - setjmp() saves stack/context
  - longjmp() jumps back to saved point
- Disadvantages
  - No automatic cleanup of stack variables
  - Programmer must manually manage control flow
  - Prone to bugs, no type safety
  - Unsafe
  - No error types or hierarchy

Exceptions in Java

- *"An exception is an **event** that occurs during the **execution** of a program that **disrupts** the **normal flow** of instructions." (oracle)*
- Exception = Exceptional Event

```
public class X {
  public static void main(String[] args) {
    String str = null;
    printLen(str);
  }
  public static int printLen(String str){
    System.out.println(str.length());
  }
}
```

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2.    public static void main(String[] args) {
3.      String str = null;
4.      printLen(str);
5.    }
6.    public static int printLen(String str){
7.      System.out.println(str.length());
8.    }
9.  }
```

This code compiles without any errors

```
Exception in thread "main" java.lang.NullPointerException
at NullPointerExample.main(NullPointerExample.java:4)
```

In runtime

Exceptions in Java

- *"An exception is an event that occurs during the* ***execution*** *of a program that* ***disrupts*** *the* ***normal flow*** *of instructions." (oracle)*
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- **Are all Exceptional Events bad?**
    - No! Example?

```
try {
    FileReader reader = new FileReader("config.txt");
} catch (FileNotFoundException e) {
    // File doesn't exist? Create a new one with defaults
    createDefaultConfigFile();
}
```

Exceptions in Java

- *“An exception is an event that occurs during the* ***execution*** *of a program that* ***disrupts*** *the* ***normal flow*** *of instructions.” (oracle)*
- **Are all Exceptional Events bad?**
  - No! Example?

```
@Test
void testExceptionThrown() {
    assertThrows(IllegalArgumentException.class, () -> {
        someMethodThatShouldThrow();
    });
}
```

Exceptions

- Do you know of any other ***runtime semantic constraint violations*** in Java?

  - Division by zero → ArithmeticException
  - Array index out of bounds → ArrayIndexOutOfBoundsException
  - Stack overflow due to infinite recursion → StackOverflowError
  - Out of memory → OutOfMemoryError

  …

Exceptions in Java

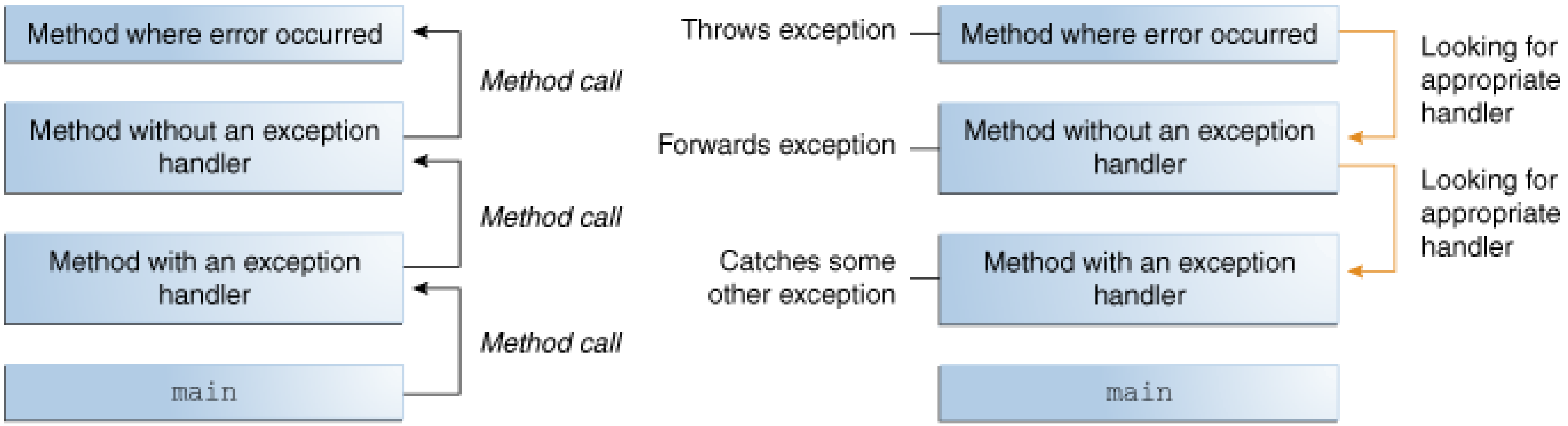
- **Exceptional Events**
  - **Language-Defined Exceptions**
    - Resource Exhaustion (disk full, out of memory, etc.)
    - Invalid Input (e.g., bad method parameters)
    - Runtime Errors (e.g., null pointer dereference)
  - **Custom Exceptions**
    - Must be explicitly thrown
    - Example in Java:

```
throw new InvalidAgeException("Age must be 18 or older.");
```

Exceptions in Java

- **Checked Exceptions**
  - Verified by compiler at compile time.
  - Must be caught or declared with throws.
  - Caused by external issues (files, database, network).
  - Examples: IOException, SQLException, FileNotFoundException
- **Unchecked Exceptions**
  - Not checked by compiler.
  - Caused by programming errors (bugs).
  - *No requirement to catch or declare.*
  - Examples: NullPointerException, ArrayIndexOutOfBoundsException, IllegalArgumentException

Exception Handling in Java



Zero-Cost (Table-Based) Exception Handling

- The Java compiler (javac) generates exception tables in the class bytecode
- Tables map code regions to catch blocks for specific exception types
- During normal execution, the JVM ignores the tables → no overhead
- When an exception is thrown, the JVM:
  - Uses the table to find the correct catch block
  - Unwinds the stack
  - Executes any associated finally blocks
- Ensures structured, type-safe, and efficient error handling
- Called “zero-cost” because there’s no performance impact unless an exception occurs

Exception Handling in Java

- How it works (at runtime):
  - JVM uses precomputed exception tables
  - If throw happens:
    - JVM searches table for *matching handler*
    - Skips over intermediate frames
    - Unwinds stack
    - Transfers control to catch

Code Generation for Exceptions: Java

```java
// try-catch
try { } catch (Exception e) { }

// try-catch-finally
try { } catch (Exception e) { } finally { }

// try-finally (no catch)
try { } finally { }

// throw
throw new IllegalArgumentException("Bad input");

// throws (in method signature)
public void myMethod() throws IOException { }
```