SOEN6441: Advanced Programming Practices

Amin Ranj Bar

Design

Exception Handling

Concordia University
Engineering and Computer Science

EXCEPTION HANDLING

Exception handling: introduction

- Programs are meant to work correctly **within their specifications**.
- However, a program might be faced with unforeseen circumstances that are outside of its specifications.
- Unforeseen situations may come:
  - Externally from the environment of the program
    - When a user or software client tries to use the software outside of its specified usage characteristics.
    - When the program tries to use another piece of software and is faced with unforeseen behavior.
  - Internally from its own execution
    - When the program misbehaves due to an internal logical error and/or being in an inconsistent state.
- A robust program should be able to **handle** all kinds of circumstances, foreseen or unforeseen, whether they are coming from the exterior or are a result of its own faults.

Exception handling: error handling

- Exception handling is a mechanism that allows two separately developed program components to **communicate** when a program anomaly is encountered during the execution of the program.
- Such communication upon erroneous behavior has been long part of programming practice in the form of **error codes** and **error handling**.
- In error handling, functions set or return special **error codes** in case of malfunction and finish execution normally.
- It is then assumed that any function that might be affected will use the error code and react by **handling the error** i.e. to continue normal execution despite the error.

Exception handling: error handling

- Error handling code can create complexity in simple programs.
- There can be many different error codes, some error states can even be combinations of more than one error.
- The error code is a value to be returned. What if the functions also needs to return a value?

```
errorCodeType readFile (){
    errorCode = 0;
    open the file;
    if (theFileIsOpen) {
        determine the length of the file;
        if (gotTheFileLength) {
            allocate that much memory;
            if (gotEnoughMemory) {
                read the file into memory;
                if (readFailed) {
                    errorCode = -1;
                }
            } else {
                errorCode = -2;
            }
        } else {
            errorCode = -3;
        }
        close the file;
        if (theFileDidntClose && errorCode == 0) {
            errorCode = -4;
        } else {
            errorCode = errorCode and -4;
        }
    } else {
        errorCode = -5;
    }
    return errorCode;
}
```

Exception handling: introduction

- However, error handling introduces **confusion** as it does not enable to separate normal behavior from error-handling behavior.
- To be more structured, functions should be first programmed according to the specifications of their **normal behavior**, and clearly separate code should be provided for **abnormal cases**, i.e. cases outside of the function's specifications of normal behavior.

```
returnType readFile (){
    part of code that cannot fail;
    try {
        open the file;
        determine its size;
        allocate that much memory;
        read the file into memory;
        close the file;
    } catch (fileOpenFailed) {
        doSomething;
    } catch (sizeDeterminationFailed) {
        doSomething;
    } catch (memoryAllocationFailed) {
        doSomething;
    } catch (readFailed) {
        doSomething;
    } catch (fileCloseFailed) {
        doSomething;
    }
    other part of code that cannot fail;
}
```

Exception handling: introduction

- The first programming language to provide the early concept of exception handling was LISP in the early 1960. PL/1 later extended the concept in the early 1970s.
- An **exception** is a data structure that is generated when a special erroneous condition is met, that contains information about the nature and context of this erroneous condition.
- Exceptions are processed by an **exception handling mechanism** that only takes effect when an exception has been identified.
- The exception handling mechanism will then **take over** the normal execution mechanism until the exception is resolved.
- If the exception can be properly resolved, normal execution is resumed.
- If the exception cannot be resolved, the program execution is terminated.

Exception handling: try-throw-catch-finally

- Syntactically, handling exceptions in Java is made through of the `try-throw-catch` keyword trio, which was borrowed from C++.

- The `try` block contains a part of the code for the normal execution of the program.

- It is called a `try` block because it *tries* to execute the normal execution behavior, but where something is likely to be subject to exceptionally erroneous behavior, and we want to handle the erroneous case locally.

```
// Code for which thrown exceptions
// are not handled locally
try {
  // Code that may throw an exception
  // that may be handled locally
}
// Code for which thrown exceptions
// are not handled locally
```

Exception handling: try-throw-catch-finally

- Whenever a piece of code identifies an exceptionally wrong situation, it can create an exception and trigger the exception handling mechanism by using a `throw` statement:

```
throw new ExceptionClassName(/*PossiblySomeArguments*/);
```

- When an exception is thrown, the normal execution of the surrounding `try` block is stopped and the **exception handling mechanism takes over** the execution of the program.

- Normally, the flow of control is transferred by the exception handling mechanism to another portion of code known as a `catch` block.

- The value thrown is the argument to the `throw` operator, which must be an instance of the `Throwable` class (or in most cases of the `Exception` class) or a subclass of it.

Exception handling: try-throw-catch-finally

- A `throw` statement is similar to a method call, as it receives a "parameter" (the thrown object) and "branches" to a catch block:

```
throw new ClassName("Some Descriptive String");
```

- In the above example, an object of class `ClassName` (which must be a subclass of `Exception`) is created using a `String` as its argument (which is usual for exception classes) and used as an exception object.

- The throw statement has the effect of temporarily halting the normal execution of the program and handing it over to the **exception handling mechanism**.

Exception handling: try-throw-catch-finally

- When an exception is thrown and the exception handling mechanism takes over, it tries to find a corresponding `catch` block to handle the exception.
  - A `catch` block has one and only one parameter.
  - The exception object thrown is passed to the `catch` block using a similar mechanism as for a function call's parameter passing.
  - The type of the catch block's exception object parameter determines what kind of exception a `catch` block is meant to handle.

- The execution of the `catch` block is called *catching the exception*, or *handling the exception.*

```
catch(Exception e) {
  // ExceptionHandlingCode
}
```

Exception handling: try-throw-catch-finally

- Any `catch` block is attached to one specific `try` block.
- A `catch` block is an **exception handler** that is meant to handle some exception thrown in the `try` block it is attached to.
- The type of exception it is meant to handle is specified by its parameter type.
- A `catch` block can catch any exception of the type it specifies, or any of its subtypes.
- A single `try` block can be attached to as many `catch` blocks as there are different kinds of exceptions potentially thrown in the `try` block's code.
- The exception handling mechanism goes **sequentially** over the `catch` block types and branches upon the **first one** that matches the thrown exception type.

```
try {
  // Code that potentially throws some exception(s) to be
  // handled locally in one of the following catch blocks
}
catch (ExceptionType1 e){
  // Exception handling code for ExceptionType1
}
catch (ExceptionType2 e){
  // Exception handling code for ExceptionType1
}
```

Exception handling: try-throw-catch-finally

- Frequently, some code needs to be executed whether or not an exception was thrown in the `try` block, such as releasing a resource that was allocated in the `try` block before the exception is thrown. For this, an optional `finally` block can be used.

```
try {
  // Code that potentially throws some exception(s)
  // to be handled locally in one of the following catch blocks
}
catch (ExceptionType1 e){
  // Exception handling code for ExceptionType1
}
finally {
  // Code that is executed whether or not
  // an exception was thrown in the try block
}
```

The `finally` Clause

```
try {
   statements;
}
catch(TheException ex) {
   handling ex;
}
finally {
   finalStatements;
}
```

animation

Trace a Program Execution

Suppose no exceptions in the statements

```
try {
  statements;
}
catch(TheException ex) {
  handling ex;
}
finally {
  finalStatements;
}

Next statement;
```

animation

Trace a Program Execution

```
try {
   statements;
}
catch(TheException ex) {
   handling ex;
}
finally {
   finalStatements;
}

Next statement;
```

The final block is always executed

animation

Trace a Program Execution

```
try {
  statements;
}
catch(TheException ex) {
  handling ex;
}
finally {
  finalStatements;
}

Next statement;
```

Next statement in the method is executed

animation

Trace a Program Execution

```
try {
  statement1;
  statement2;
  statement3;
}
catch(Exception1 ex) {
  handling ex;
}
finally {
  finalStatements;
}

Next statement;
```

Suppose an exception of type Exception1 is thrown in statement2

animation

Trace a Program Execution

```
try {
  statement1;
  statement2;
  statement3;
}
catch(Exception1 ex) {
  handling ex;
}
finally {
  finalStatements;
}

Next statement;
```

The exception is handled.

animation

Trace a Program Execution

```
try {
  statement1;
  statement2;
  statement3;
}
catch(Exception1 ex) {
  handling ex;
}
finally {
  finalStatements;
}

Next statement;
```

The final block is always executed.

animation

Trace a Program Execution

```
try {
  statement1;
  statement2;
  statement3;
}
catch(Exception1 ex) {
  handling ex;
}
finally {
  finalStatements;
}

Next statement;
```

The next statement in the method is now executed.

animation

Trace a Program Execution

```
try {
  statement1;
  statement2;
  statement3;
}
catch(Exception1 ex) {
  handling ex;
}
catch(Exception2 ex) {
  handling ex;
  throw ex;
}
finally {
  finalStatements;
}

Next statement;
```

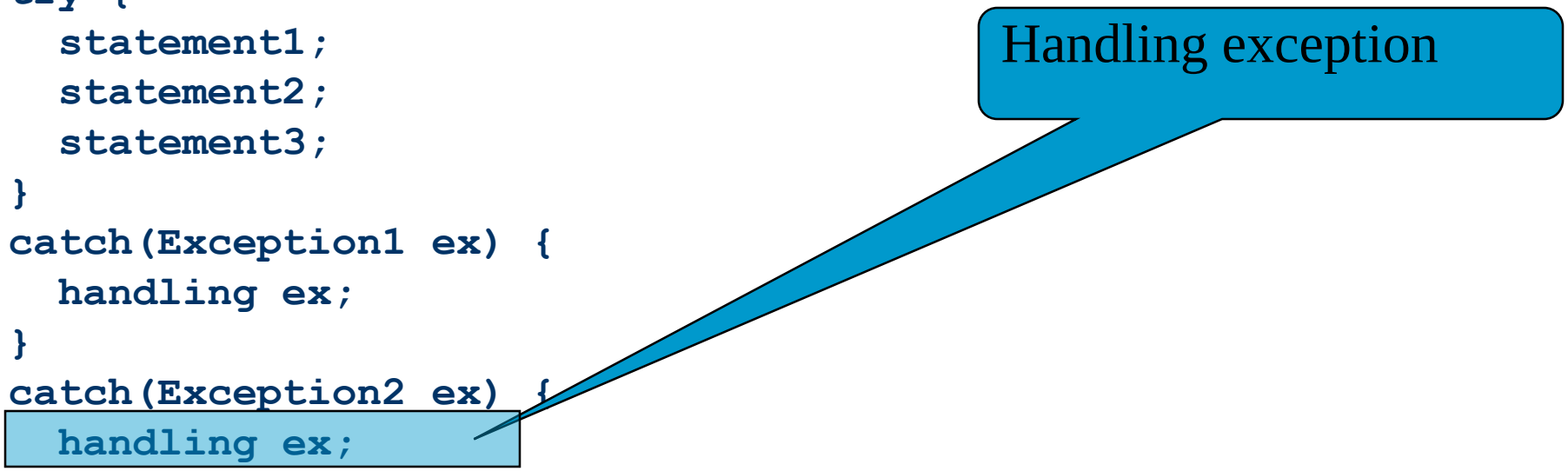
statement2 throws an exception of type Exception2.

animation

Trace a Program Execution

```
try {
  statement1;
  statement2;
  statement3;
}
catch(Exception1 ex) {
  handling ex;
}
catch(Exception2 ex) {
  handling ex;
  throw ex;
}
finally {
  finalStatements;
}

Next statement;
```

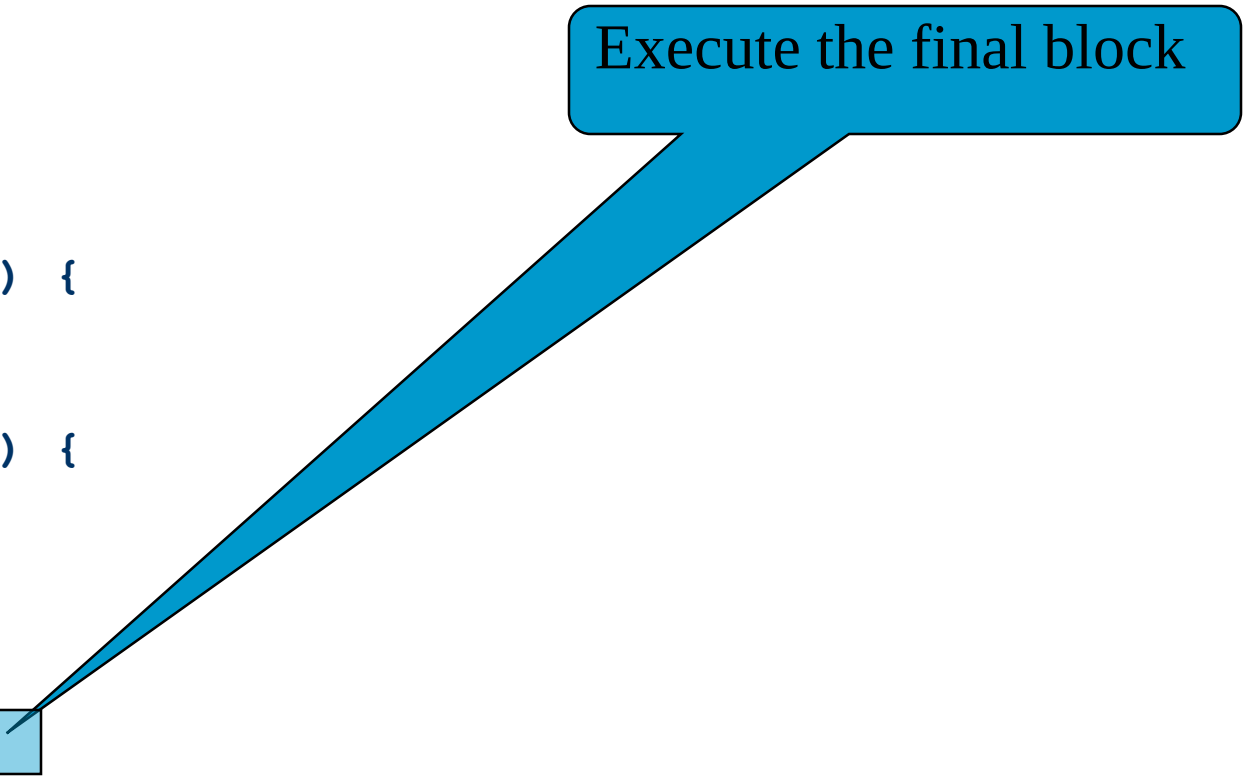


animation

Trace a Program Execution

```
try {
  statement1;
  statement2;
  statement3;
}
catch(Exception1 ex) {
  handling ex;
}
catch(Exception2 ex) {
  handling ex;
  throw ex;
}
finally {
  finalStatements;
}

Next statement;
```



animation

Trace a Program Execution

```
try {
  statement1;
  statement2;
  statement3;
}
catch(Exception1 ex) {
  handling ex;
}
catch(Exception2 ex) {
  handling ex;
  throw ex;
}
finally {
  finalStatements;
}

Next statement;
```

Rethrow the exception and control is transferred to the caller

Exception handling: try-with-resources

- Java SE 7.0 introduced the **try-with-resources block**, which allows to declare an object as a resource managed during the execution of a `try` block

```
try (BufferedReader br = new BufferedReader(new FileReader(fileName))) {
  String s = br.readLine();
}
```

- where a class implementing the `java.lang.AutoCloseable` interface is opened as the `try` is declared, and will be automatically closed regardless of whether the `try` will complete normally or abruptly.

Exception handling: try-throw-catch-finally

- When a try block is executed, three things can happen:

1. **No exception is thrown in the try block**
   - The code in the try block is executed to the end of the block.
   - The catch blocks are skipped.
   - The finally block is executed.
   - The execution continues with the code placed after the finally block.
2. **An exception is thrown in the try block and caught in a catch block**
   - The rest of the code in the try block is skipped.
   - Control is transferred to a following catch block.
   - The thrown object is passed to the catch block using parameter passing.
   - The code in the catch block is executed.
   - The finally block is executed.
   - Normal execution resumes using the code that follows the finally block.

Exception handling: try-throw-catch-finally

- When a try block is executed, three things can happen:

3. **An exception is thrown in the try block and there is no corresponding catch block to handle the exception**
   - The rest of the code in the try block is skipped.
   - As there is no suitable local catch block, the exception cannot be handled locally in the function.
   - The finally block is executed.
   - The function throws the exception to its calling function.
   - The calling function either catches the exception using a catch block, or itself throws the exception.
   - If all functions fail to catch the exception, it will eventually be thrown all the way to the main function.
   - If the main function cannot catch the exception, the program ends, itself throwing the exception.

Exception handling: stack unwinding

- Once the exception handling mechanism takes control as a `throw` statement is executed, control moves from the `throw` statement to the first `catch` statement that can handle the thrown type.
- Once the control goes to the `catch` handler, a process known as **stack unwinding** is used to **release all the local variables** that were used between the execution site where the exception was thrown and the execution site where the exception is caught.
- The physical deallocation of released objects is eventually done by the garbage collector.
- However, other kinds of allocated resources are not managed by the garbage collector.
- If, for example a file is opened, then the read/write operation fails by throwing an exception, the file resource release must appropriately be managed.

```
BufferedWriter file = new BufferedWriter(new FileWriter("DummyOutput.txt"));
file.write(pd.dummyName + ", " + pd.age);
// never closed if write() throws an exception!
// solution is to catch here, or else the file resource is leaked.
file.close();
```

Exceptions: handle or declare rule

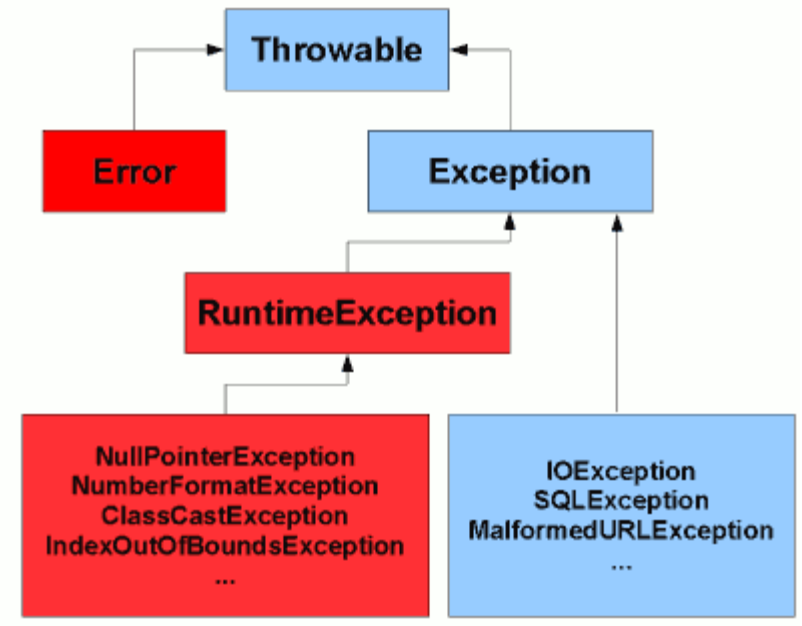
- Exception specifications: `throws` clause

```
public void readFile(String file) throws FileNotFoundException
```

  - This `throws` clause signifies that the function `readFile` can only throw exceptions of type `FileNotFoundException`.
  - This informs any function calling `readFile` that it may throw this specific kind of exception, and that it will not handle it internally.
  - It forces any calling function to either catch this exception, or itself declare that it may throw it using its own `throws` clause.
  - A method can throw any subclass of the exception type mentioned in its `throws` clause.
  - The `throws` clause is a very useful annotation for the programmer when programing with exceptions.
  - Any function that contains code that may throw exceptions either needs to make the call to the throwing function in a `try` block and catch the exception, or itself have a `throws` clause that specifies that it may throw.
  - This is referred to as the "***handle or declare rule***".

Checked and unchecked exceptions

- The handle or declare rule applies only to **checked exceptions**, which are of the Exception type that are not of the RunTimeException type.



- An `Error` is a subclass of `Throwable` that indicates serious problems that a reasonable application should not try to catch. Most such errors are abnormal conditions.
- `RuntimeException` is the superclass of those exceptions that can be thrown during the normal operation of the Java Virtual Machine.

Custom exception classes

- Any instance of the `Throwable` class can be thrown as an exception.
- Custom exception classes can be derived from the standard `Exception` class.
- The only particularity of this class is that it offers a members function `getMessage()` to return a `String` that allows the programmer to store a descriptive message on the nature of the circumstances that led to the error.
- This string is passed to the constructor upon creation of the exception.

```
public class HardwareException extends Exception {
  public
    HardwareException() {
      exc_time = getTime();
    }
    String getTime() {
      DateFormat format = new SimpleDateFormat("yyyy-MM-dd HH:mm:ss");
      return format.format(new Date());
    }
    String exc_time;
}
```

```
public class ActuatorException extends HardwareException {
  public
    ActuatorException(HardwareState new_s) {
      super();
      hw_state = new_s;
    }
    String toString() {
      return this.exc_time+":"+this.getClass()+":"+this.hw_state.name();
    }
    HardwareState hw_state;
}
```

```
public class StuckValveException extends ActuatorException {
  public
    StuckValveException(HardwareState new_s) {
      super(new_s);
  }
}
```

Custom exception classes

- An exception class can be made to store any other useful information, e.g. the time where the exception was thrown.
- The `getMessage()` function of the `Exception` class can also be overridden to provide information otherwise than assuming the programmer to provide a `String` upon construction.
- As for any other class, one can also override the `toString()` function to enable output to console, files, or other streams.

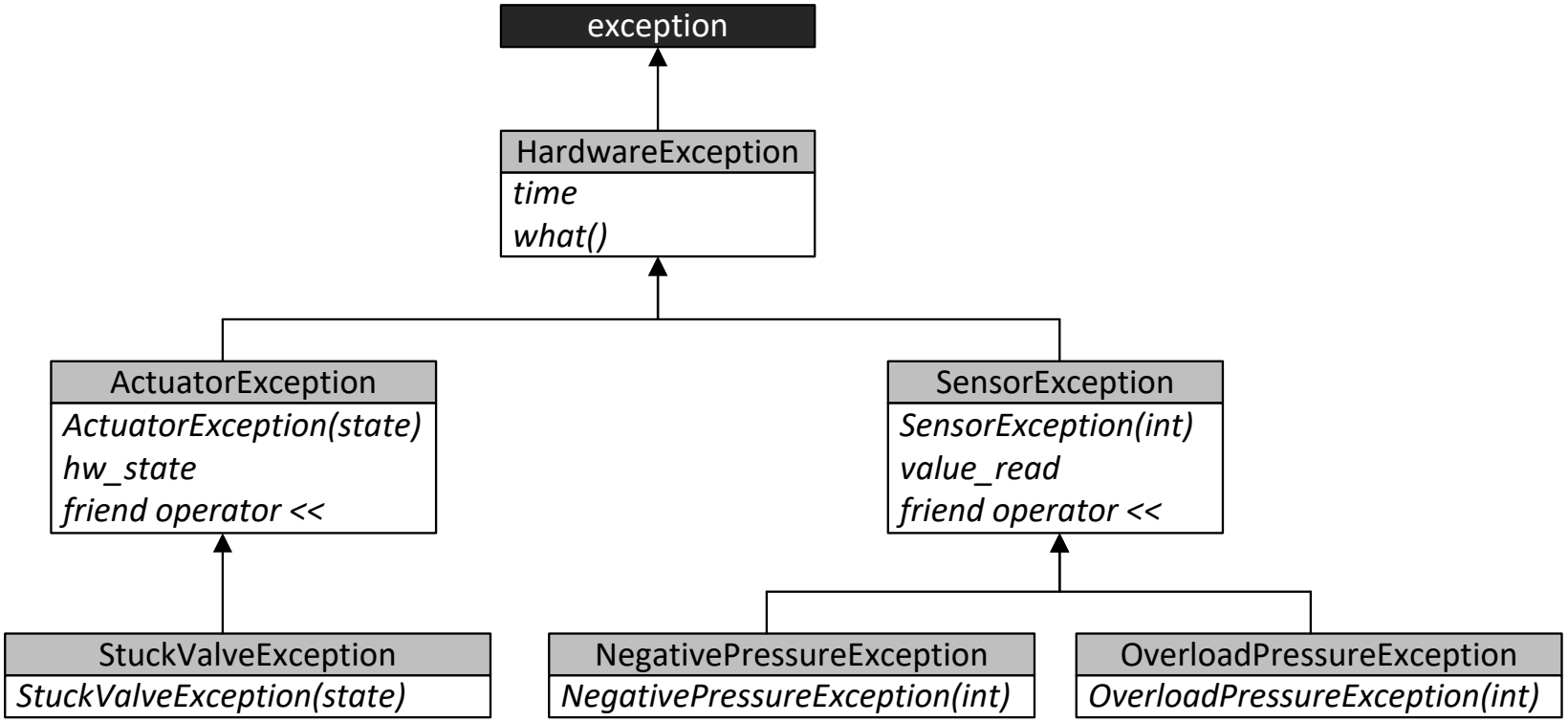
```
public class SensorException extends HardwareException {
  public
    String toString() {
      return this.exc_time+":"+this.getClass()+":"+valueRead;
    }
    SensorException(int new_v) {
      super();
      valueRead = new_v;
    }
    int valueRead;
}
```

```
public class HardwareException extends Exception {
  public
    HardwareException() {
      exc_time = getTime();
    }
    String getTime() {
      DateFormat format = new SimpleDateFormat("yyyy-MM-dd HH:mm:ss");
      return format.format(new Date());
    }
    String exc_time;
}
```

```
public class OverloadPressureException extends SensorException {
  public
    OverloadPressureException(int new_v) {
      super(new_v);
    }
}
```

```
public class NegativePressureException extends SensorException {
  public
    NegativePressureException(int new_v) {
      super(new_v);
    }
}
```

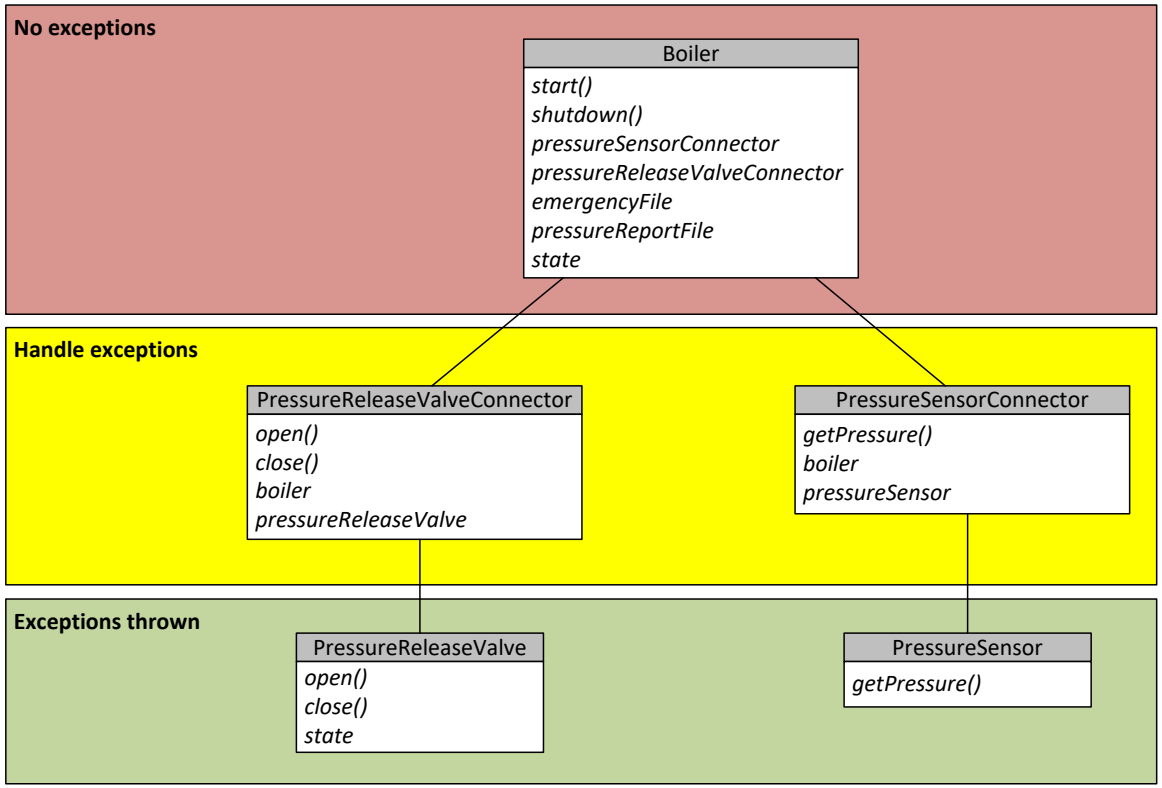
Custom exception classes



Exception handling: example

- Industrial boiler controlled by software.
- Connected to a pressure sensor and a pressure release valve.
- Keeps the pressure within an acceptable range.
- If the sensor is misbehaving, it shuts down the boiler by opening the valve.
- If the valve is stuck, it calls an emergency.

- Keeps a log of the pressure readings, as well as another log for operational events.
- Hardware drivers can throw exceptions.
- For security, the boiler controller should be shielded from those exceptions.
- Thus, an exception handling layer is added.



Exception handling: example

```
public class Boiler {
  public
    Boiler() {
      emergencyFile = new FileWriterWrapper("EmergencyFile.txt");
      emergencyFile.write("STARTING BOILER CONTROLLER\r\n");
      pressureReportFile = new FileWriterWrapper("pressureReportFile.txt");
      pressureReportFile.write("STARTING BOILER CONTROLLER\r\n");
      ps = new PressureSensorConnector(new PressureSensor(), this);
      prv = new PressureReleaseValveConnector(new PressureReleaseValve(
          HardwareState.stuck), this);
      boilerState = BoilerState.safe;
    }
    void shutdown() {
      emergencyFile.write("Engaging shutdown procedure.\r\n");
      prv.open();
      emergencyFile.write("BOILER CONTROLLER SHUT DOWN\r\n");
      emergencyFile.close();
      pressureReportFile.write("BOILER CONTROLLER SHUT DOWN\r\n");
      pressureReportFile.close();
    }
    void start() {
      while (boilerState == BoilerState.safe) {
        try {
          Thread.sleep(1000);
        }
        catch (InterruptedException e) {
        }
        System.out.println(ps.getPressure());
      }
    }
    PressureSensorConnector ps;
    PressureReleaseValveConnector prv;
    BoilerState boilerState;
    FileWriterWrapper emergencyFile;
    FileWriterWrapper pressureReportFile
}
```

- `Boiler`: connected to a temperature sensor and pressure release valve.
- Reports pressure readings in `pressureReportFile`.
- Reports erroneous behaviors in `EmergencyFile`.
- Repeatedly reads the pressure.
- No exception handling here.
- Could there be?

```
public enum ActuatorState {
  opened, closed }

public enum BoilerState {
  safe, unsafe, critical }

public enum HardwareState {
  operational, stuck }
```

```
public class BoilerDriver {
  public
    static void main(String[] args) {
      Boiler b = new Boiler();
      b.start();
    }
}
```

Exception handling: example

```
public class FileWriterWrapper {
  public
    FileWriterWrapper(String new_file) {
      try {
        file = new BufferedWriter(new FileWriter(new_file));
      } catch (IOException e) {
        System.out.println("WARNING: file cannot be opened");
      }
    }

    void close() {
      try {
        file.close();
      }
      catch (IOException e) {
        System.out.println("WARNING: file cannot be closed");
      }
    }

    void write(String new_string) {
      try {
        file.write(new_string);
      }
      catch (IOException e) {
        System.out.println("WARNING: file cannot be written");
      }
    }

  private BufferedWriter file;
}
```

- The `FileWriterWrapper` class is created to isolate the file handling exceptions.
- Any exception thrown while opening, writing or closing a file are kept local to this class and thus do not reach the `Boiler` class
- This simplifies the code of the `Boiler` class.

Exception handling: example

```
public class PressureSensorConnector {
  private
    PressureSensor ps;
    Boiler b;
  public
    PressureSensorConnector(PressureSensor new_ps, Boiler new_b) {
      ps = new_ps;
      b = new_b;
    }
    int getPressure() {
      int pressure = 999;
      try {
        pressure = ps.getPressure();
        b.pressureReportFile.write(pressure+"@"+getTime()+"\r\n");
      }
      catch (SensorException e) {
        b.emergencyFile.write(e.toString() + "\r\n");
        b.boilerState = BoilerState.unsafe;
        b.shutdown();
      }
      return pressure;
    }
    String getTime() {
      DateFormat format = new SimpleDateFormat("yyyy-MM-dd HH:mm:ss");
      return format.format(new Date());
    }
}
```

- `PressureSensor`: hardware component that reads temperature. If out of range, throw exception.
- Connected to the boiler using a `PressureSensorConnector` that reports pressure readings and catches and reports the exceptions thrown by the sensor.
- Exceptions thrown by the sensors do not reach the `Boiler` class.

```
public class PressureSensor {
  public
    PressureSensor() {
      randomGenerator = new Random();
    }
    int getPressure() throws NegativePressureException,
      OverloadPressureException {
      int pressure = randomGenerator.nextInt(105) - 1;
      if (pressure < 0) {
        throw new NegativePressureException(pressure);
      }
      if (pressure > 100) {
        throw new OverloadPressureException(pressure);
      }
      return pressure;
    }
    Random randomGenerator;
}
```

Exception handling: example

```
public class PressureReleaseValveConnector {
  private
    PressureReleaseValve prv;
    Boiler b;
  public
    PressureReleaseValveConnector(PressureReleaseValve new_prv, Boiler new_b) {
      prv = new_prv;
      b = new_b;
    }
    void close() {
      try {
        prv.close();
      }
      catch (StuckValveException e) {
        b.emergencyFile.write(e.toString());
      }
    }
    void open() {
      try {
        prv.open();
      }
      catch (StuckValveException e) {
        b.boilerState = BoilerState.critical;
        b.emergencyFile.write(e.toString() + "\r\n"
        b.emergencyFile.write("Evacuation!!\r\n");
      }
    }
}
```

- `PressureReleaseValveConnector` reports pressure readings to the Boiler while catching and reporting the exceptions thrown by the sensor.

- `PressureReleaseValve`: hardware component that opens/closes the boiler's container. If the valve is stuck throw an exception. If the valve is stuck closed, put the boiler in critical state.

```
public class PressureReleaseValve {
  public
    PressureReleaseValve(HardwareState new_s) {
      hw_state = new_s;
      act_state = ActuatorState.closed;
      randomGenerator = new Random();
    }
    void close() throws StuckValveException {
      if (randomGenerator.nextInt(100) <= 2) {
        hw_state = HardwareState.stuck;
      }
      if (hw_state == HardwareState.stuck && act_state == ActuatorState.opened) {
        throw new StuckValveException(hw_state);
      }
    }
    void open() throws StuckValveException {
      if (randomGenerator.nextInt(100) <= 2) {
        hw_state = HardwareState.stuck;
      }
      if (hw_state == HardwareState.stuck && act_state == ActuatorState.closed) {
        throw new StuckValveException(hw_state);
      }
    }
  private
    ActuatorState act_state;
    HardwareState hw_state;
    Random randomGenerator;
}
```

Exception handling: significance

- Does the exception handling mechanism solve our error handling problems?
  - No, it is only a mechanism.

- Does the exception handling mechanism provide a radically new way of dealing with errors?
  - No, it simply provides a formal and explicit way of applying the standard techniques.

- The exception handling mechanism

1. Makes it easier to adhere to good programming practices.
2. Gives error handling a more regular style.
3. Makes error handling code more readable.
4. Makes error handling code more amenable to tools.

[Bjarne Stroustrup]

Exceptions: overhead

- The exception mechanism has a very minimal performance cost if no exception is thrown.
- If an exception is thrown, the cost of the stack traversal and unwinding is roughly comparable to the cost of a function call.
- Additional data structures are required to track the call stack after a try block is entered, and additional instructions are required to unwind the stack if an exception is thrown.
- However, in most scenarios, the cost in performance and memory footprint is not significant.
- The adverse effect of exceptions on performance is likely to be significant only on very memory-constrained systems, or in performance-critical loops where an error is likely to occur regularly and the code to handle it is tightly coupled to the code that reports it.

Exceptions: overhead

- The real cost of exception handling is in the difficulty of designing exception-safe code.
  - Constructors that throw exceptions are problematic: if a constructor fails, the object is not created, which makes it hard to recover from. This is even more problematic with class hierarchies, which require a sequence of constructors to succeed in order for an object to be fully constructed. In Java, an object is either successfully fully constructed or it does not exist.
  - Garbage collection definitely helps making things more easy for stack unwinding.
  - Additional design considerations may be needed in order to contain exceptions inside a certain scope.

References

- Oracle Corporation. The Java Tutorials: Exceptions.
- Oracle Corporation. The Java Tutorials: The try-with-resources Statement.
- Oracle Corporation. The Java Tutorials: Advantages of Exceptions.
- Java.net. Mala Gupta. Using Throws and Throw Statements in Java.