Reasoning About ADTs, Assertions and Exceptions

How to Design Your Code

- The hard way: Start hacking. When something doesn't work, hack some more

- The easier (and professional) way: Plan carefully
  - Write specs, rep invariants, abstraction functions
  - Write tests (first!), reason about code, refactor
  - Less apparent progress at first, but faster completion times, better product, less frustration, less debugging

How to Verify Your Code

- The hard way: hacking, make up some inputs
- An easier way: systematic testing
  - Black-box testing techniques (more later)
  - High white-box coverage (more later)
  - Both use JUnit framework
- Also: reasoning, complementary to testing
  - Prove that code is correct
    - Implementation satisfies specification
    - Rep invariant is preserved
  - We will write informal proofs

Uses of Reasoning

- Goal: show that code is correct
  - Verify that the implementation satisfies its specification. Hard!
    - Forward reasoning: show that if precondition holds, postcondition holds
    - Backward reasoning: compute weakest precondition, then show stated precondition <u>implies</u> the weakest precondition
    - Reasoning is an important debugging tool
  - Prove (using informal manual proofs) that rep invariant holds. This is sometimes easy, sometimes hard…

Goal: Show that Rep Invariant Is Satisfied

- Testing
  - Choose representative objects and check rep
  - Add checkRep() method that verifies representation after each method use.
  - Problem: it is often impossible to exhaustively test, therefore, we have to choose well
- Reasoning
  - Prove that all objects satisfy rep invariant
  - Sometimes easier than testing, sometimes harder
  - You should know how to use it appropriately
- Why not always leave checkRep() in code?

Ways to Make New Objects

a = constructor

b = a.producer   a’ = a.mutator   a’’ = a.observer

c = b.producer   b’ = b.mutator   b’’ = b.observer

...

Very many objects but limited number of types of operations!

Verify that Rep Invariant Is Satisfied

- We can have very many objects, but limited number of operations
- How do we prove all objects satisfy rep invariant?
  - Induction!
- Consider all ways to make a new object
  - Constructors
  - **Producers**
- All ways to modify an existing object
  - Mutators
  - Observers, **producers**.
    - Should producers, observers modify the existing object?

Benevolent Side Effects in Observers

- An implementation of observer **`IntSet.contains`**:

```
boolean contains(int x) {
   int i = data.indexOf(x);
   if (i == -1)
      return false;
   // move-to front optimization
   // speeds up repeated membership tests
   Integer y = data.elementAt(0);
   data.set(0,x);
   data.set(i,y);
   return true;
}
```

- Mutates rep (even though it does not change abstract value), must show rep invariant still holds!

Induction

- Proving facts about many objects
- Base step
  - Prove rep invariant holds on <u>exit of constructor</u>
- Inductive step
  - Assume rep invariant holds on entry of method
  - Then prove that rep invariant holds on exit
- Intuitively: there is no way to make an object, for which the rep invariant does not hold
  - Assumes no rep exposure
- Remember, our proofs are informal

The IntSet ADT

```
/** Overview: An IntSet is a mutable set
  * of integers. E.g., { x1, x2 , … xn }, {}.
  * There are no nulls and no duplicates in the set.
  */
    // effects: makes a new empty IntSet
  public IntSet()

  // modifies: this
    // effects: this_post = this_pre U { x }
  public void add(int x)

  // modifies: this
    // effects: this_post = this_pre - { x }
  public void remove(int x)

  // returns: (x in this)
  public boolean contains(int x)

  // reruns: cardinality of this
  public int size()
```

Implementation of IntSet

```
class IntSet {
    // Rep invariant:
    // data has no nulls and no duplicates
  private List<Integer> data;
  public IntSet() {
    data = new ArrayList<Integer>();
  }
  public void add(int x) {
    if (!contains(x)) data.add(x);
  }
  public void remove(int x) {
    data.remove(new Integer(x));
  }
  public boolean contains(int x) {
    return data.contains(x);
  }
}
```

Proof. IntSet Satisfies Rep Invariant

Rep invariant: data has no nulls and no duplicates

- Base case: constructor

```
public IntSet() {
    data = new ArrayList<Integer>();
}
```

Rep invariant trivially holds

- Inductive step: for each method
  - Assume rep invariant holds on entry
  - Prove rep invariant holds on exit

Inductive Step, **`contains`**

```
Rep invariant: data has no nulls and no duplicates
public boolean contains(int x) {
  return data.contains(x);
}
```

- `List.contains` does not change **`data`**, so neither does `IntSet.contains`
- Therefore, rep invariant is preserved.

- Why do we even need to check `contains`?

`contains` with Benevolent Side Effects

- An implementation of observer **`IntSet.contains`**:

```
boolean contains(int x) {
   int i = data.indexOf(x);
   if (i == -1)
      return false;
   // move-to front optimization
   // speeds up repeated membership tests
   Integer y = data.elementAt(0);
   data.set(0,x);
   data.set(i,y);
   return true;
}
```

- We swapped elements of **`data`** at positions **`i`** and **`0`**. If there were no duplicates and no nulls on entry, there are no duplicates and no nulls on exit

Inductive Step, `remove`

Rep invariant: data has no nulls and no duplicates

```
public void remove(int x) {
  data.remove(new Integer(x));
}
```

- **`ArrayList.remove`** has two behaviors
  - Removes an element
  - If there were no duplicates on entry, remove can’t change that.
  - Only addition can violate rep invariant
  - Therefore, rep invariant is preserved

Inductive Step, **add**

Rep invariant: data has no nulls and no duplicates

```
public void add(int x) {
  if (!contains(x))
    data.add(x);
}
```

- Case 1: **x** in **data**$_{pre}$
  - **data** is unchanged, thus rep invariant is preserved
- Case 2: **x** is not in **data**$_{pre}$
  - New element is not null (ints can't be null) or a duplicate, thus rep invariant holds at exit
  - Uses autoboxing

Inductive Step, **add**

- How does `contains` determine that an object is already in array?
  - JavaDocs says:
    - Returns true if this list contains the specified element. More formally, returns true if and only if this list contains at least one element e such that (o==null ? e==null : o.equals(e)).
  - Notice that it uses equals() for contained type
  - Integer overrides equals()

Reasoning About Rep Invariant

- Inductive step must consider all possible changes to the rep
  - Including representation exposure!
  - If the proof does not account for representation exposure, then it is invalid!

  - Exposure of immutable rep is OK.
  - Exposure of mutable rep is not!

Problem: Willy Wazoo's IntStack

- Help Willy implement an **`IntStack`** with an **`IntMap`**

```
class WillysIntStack implements IntStack {
  private IntMap theRep;
  int size;
  …
```

- Write a rep invariant and abstraction function

IntMap Overview

The Overview:

```
/** An IntMap is a mapping from integers to integers.
* It implements a subset of the functionality of
Map<int,int>.
* All operations are exactly as specified in the
documentation for Map.
*
* IntMap can be thought of as a set of key-value pairs:
*
* @specfield pairs = { <k1, v1>, <k2, v2>, <k3, v3>,
... }
*/
```

IntMap Description

```
class IntMap {
      IntMap() {…}
```

/** Associates specified `value` with specified `key` in pairs. */

```
  bool put(int key, int value) {…}
```

/** Removes the mapping for `key` from pairs if it is present. */

```
  void remove(int key) {…}
```

/** Returns true if pairs contains a mapping for the specified `key`. */

```
 bool containsKey(int key) {…}
```

/** Returns the value to which specified key is mapped, or 0 if this map contains no mapping for the key. */

```
  int get(int key) {…}
}
```

Review Problem: Willy's **`IntStack`**

```
class IntStack {
   // Rep invariant: |theRep| = size
   // and theRep.keySet = {i | 1 ≤ i ≤ size}
   private IntMap theRep = new IntMap();
   private int size = 0;

   public void push(int val) {
      size = size+1;
      theRep.put(size,val);
   }

   public int pop() {
      int val = theRep.get(size);
      theRep.remove(size);
      size = size-1;
      return val;
   }
```

Willy’s IntStack

AF: Willy’s IntStack is a LIFO collection consisting of a map
between positions and data:
Map <1, data1>, <2, Data2> … <size, data_size> -> stack data1, data2…data_size

Rep invariant: size of theRep == size
Data is only accessed at size position.

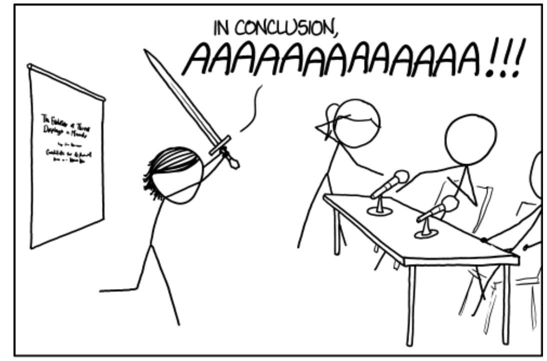
Possible problem: doesn’t check for empty stack on pop.

Review Problem: Willy's **`IntStack`**

- Base case
  - Prove rep invariant holds on exit of constructor
- Inductive step
  - Prove that if rep invariant holds on entry of method, it holds on exit of method
  - **`push`**
  - **`pop`**

- For brevity, ignore popping an empty stack

Practice Defensive Programming



THE BEST THESIS DEFENSE IS A GOOD THESIS OFFENSE.

- Check
  - Precondition
  - Postcondition
  - Rep invariant
  - Other properties we know must hold
    - Loop invariants
- Check statically via reasoning
  - "Statically" means before execution
  - Works in simpler cases can be difficult in general
    - Motivates us to simplify and/or decompose our code!

Practice Defensive Programming

- Check dynamically via assertions
    - At run time

```
assert index >= 0;
assert coeffs.length-1 == degree : "Bad rep"
assert coeffs[degree] != 0 : "Bad rep"
```

- Write assertions, as you write code
- Not to be confused with JUnit method such as assertEquals!

Assertions

- **java** runs with assertions disabled (default)
  - Submitty run Java with assertions disabled
- **java –ea** runs Java with assertions enabled
- For Eclipse, see http://stackoverflow.com/questions/5509082/eclipse-enable-assertions
- Always enable assertions during development. Turn off in rare circumstances

If assertion fails, program exits:
Exception in thread "main" java.lang.AssertionError
at Main.main(Main.java:34)

```
assert (index >= 0) && (index < names.length);
```

When NOT to Use Assertions

- Useless:

```
x = y+1;
assert x == y+1;
```

- When there are side effects

```
assert list.remove(x);
```

// Better:

```
boolean found = list.remove(x);
assert found;
```

Check Assertions

Check to see if assertions are enabled

```
boolean assertEnabled;
int flag = 0;
assert ( (flag=1) == 1 );
if (flag == 1) assertEnabled = true;
else assertEnabled = false;
```

Cleaner method

```
boolean assertsEnabled = false;
// Intentional side-effect!!!
// If assertions not enabled, nothing happens
assert assertsEnabled = true;
// Now assertsEnabled is set to the correct value
```

Failure

Some causes of failure

1. Misuse of your code
    - Precondition violation
2. Errors in your code
    - Bugs, rep exposure, many more
3. Unpredictable external problems
    - Out of memory
    - Missing file
    - Memory corruption
    - Connection failure
    - Etc.

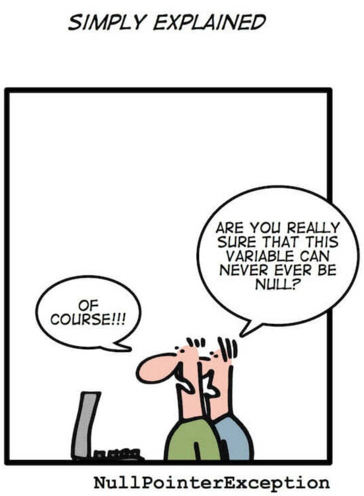
What to Do When Something Goes Wrong?

- Fail friendly, fail early to prevent harm

- Goal 1: Give information
  - To the programmer, to the client code

- Goal 2: Prevent harm
  - Abort: inform a human, cleanup, log error, etc.
  - Retry: problem might be temporary
    - E.g. file busy
    - Not always possible, be cautious
  - Skip subcomputation: permit rest of program to continue
    - Warn user this is happening
  - Fix the problem (usually infeasible)
    - Can be dangerous

Preconditions vs. Exceptions



- A precondition tells client not to misuse your code
  - Adding preconditions weakens the spec
- A precondition ducks the problem
  - Behavior of your code when precondition is violated is unspecified!
  - Does not help clients violating precondition of your code
- Removing a precondition requires specifying the new behavior.
  - Strengthens the spec
  - Example: specify that an exception is thrown
  - Exceptions specify behavior when some constraint is violated
  - It's almost always better to specify behavior rather than leave it unspecified

Which One Is Better?

```
Choice 1:
// modifies: this
// effects: removes element at index from this
// throws: IndexOutOfBoundsException if index < 0 ||
//         index >= this.size
public void remove(int index) {
  if (index >= size() || index < 0)
      throw new IndexOutOfBoundsException("Info…");
  else
      // remove element at index from collection
}
Choice 2:
// requires: 0 <= index < this.size
// modifies: this
// effects: removes element at index from this
public void remove(int index) {
  // no check, remove element at index
}
```

Preconditions vs. Exceptions

- In certain cases, a precondition is the right choice
  - When checking would be expensive. E.g., array is sorted
  - In private methods
- Whenever possible, <u>remove preconditions</u> from public methods and specify behavior
  - Often, this entails throwing an Exception
  - Stronger spec, easier to use by client

Square Root, With Precondition and Assertions

```
// requires: x >= 0
// returns: approximation to square root of x
public double sqrt(double x) {
  assert x >= 0 : "Input must be >=0";
  double result;
  … // compute result

  return result;
}
```

Better: Square root, Specified for All Inputs

```
// throws: IllegalArgumentException if x < 0
// returns: approximation to square root of x
public double sqrt(double x)
       throws IllegalArgumentException {
  double result;
  if (x < 0)
    throw new IllegalArgumentException("…");
  … // compute result
  return result;
}
```

Better: Square root, Specified for All Inputs

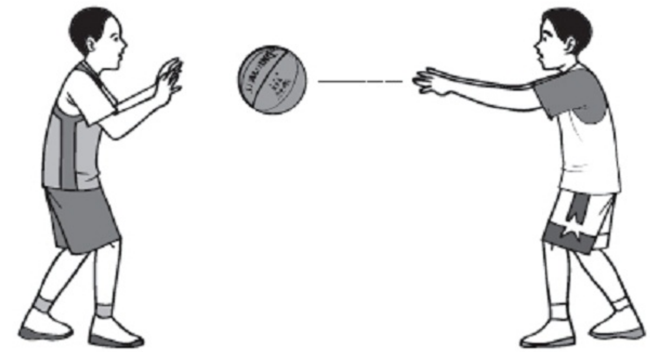
Client code:

```
try {
  y = sqrt(-1);
} catch (IllegalArgumentException e) {
  e.printStackTrace(); // or take same other action
}
```

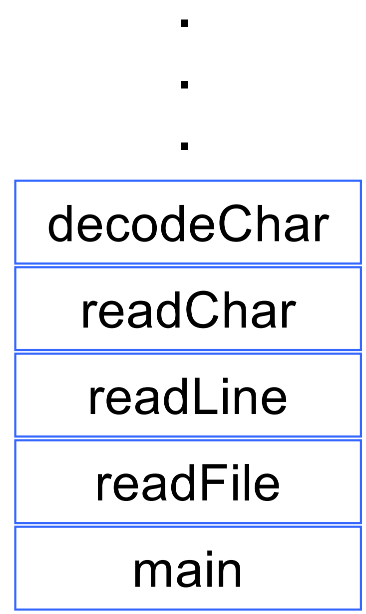
Exception is handled by **`catch`** block associated with nearest dynamically enclosing **`try`**

Top-level handler: print stack trace, terminate program

Throwing and Catching



- Java maintains a call stack of methods that are currently executing
- When an exception is thrown, control transfers to the nearest method with a matching **`catch`** block
  - If none found, top-level handler
- Exceptions allow non-local error handling
  - A method far down the call stack can handle a deep error!



The **`finally`** Block

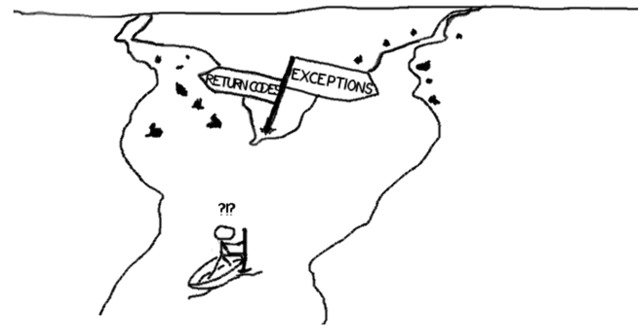
- **`finally`** is always executed
  - No matter whether exception is thrown or not
- Useful for clean-up code

```
FileWriter out = null;
try {
  out = new FileWriter(…);
  … write to out; may throw IOException
} finally {
   if (out != null) {
    out.close();
  }
}
```

Propagating an Exception up the Call Chain

```
// throws: IllegalArgumentException if no real
//         solution exists
// returns: x such that ax^2 + bx + c = 0
double solveQuad(double a, double b, double c)
         throws IllegalArgumentException {
  …
  // exception thrown by sqrt is declared,
  // no need to catch it here
  return (-b + sqrt(b*b - 4*a*c))/(2*a);
}
```

Informing the Client of a Problem



- Special value
  - **`null` – `Map.get(x)`**
  - **`-1` – `List.indexOf(x)`**
  - **`NaN` – `sqrt`** of negative number
- Problems with using special value
  - Hard to distinguish from real values
  - Hard to propagate up call stack
  - Error-prone: programmer forgets to check result? The value is illegal and will cause problems later
  - Ugly
- Exceptions are often a better solution

Exceptions vs. Special Values

- Why exceptions?
  - Handling special values is verbose

```
if(doSomething() == val1) {
   if(doSomethingElse() == val2)    {
      if(doSomethingElseAgain() == val3)  {
          // etc.
      }
      else  {
         // react to failure of doSomethingElseAgain
      }
   }
   else   {
      // react to failure of doSomethingElse
   }
}
else {
   // react to failure of doSomething
}
```

vs.

```
try {
   doSomething() ;
   doSomethingElse() ;
   doSomethingElseAgain() ;
}
catch(SomethingException e1) {
   // react to failure of doSomething
}
catch(SomethingElseException e2) {
   // react to failure of doSomethingElse
}
catch(SomethingElseAgainException e3) {
   // react to failure of doSomethingElseAgain
}
```

Exceptions vs. Special Values

- Return codes can cause problems when ignored.
  - Method returns null reference; reference is used later in program.
- Exceptions are typed.
  - So are special values, but a method can throw multiple types of exception
  - Methods can only return one type
- Java.lang.Math returns NaN for many standard math functions
  - NaNs are "sticky"
  - SomeType o = add(a, div(b, c)) ;
  - May be difficult to know where NaN arose
- General Rule of Thumb:
  - Throw when something should **not** happen
  - Return a special value when something unusual but generally expected can happen and client code can react to it.
    - Many (not all) java.lang.Math methods return NaN
    - Some post Java 7 methods throw ArithmeticException

Two Distinct Uses of Exceptions

- (External) failures (e.g., device failure)
  - Unexpected by your code
  - Usually unrecoverable. If condition is left unchecked, exception propagates up the stack
- Special results
  - Expected by your code
  - Always check and handle locally.
    - Maybe take special action and continue computing
    - May throw a module-level exception, e.g.
      - In `solveQuad`, catch an `ArithmeticException` and throw a `NoRealSolutionException`.

Java Exceptions: Checked vs. Unchecked Exceptions

- Checked exceptions
  - Anything that is a subclass of `java.lang.Exception`
    - Except for `RuntimeException`
- Unchecked Exceptions
  - Subclasses of `java.lang.RuntimeException` and `Error`
- Calls throwing checked exceptions need to be enclosed in a `try{}` block or handled in a level above in the caller of the method.
  - In that case the current method must declare that it throws the exceptions so that the callers can make appropriate arrangements to handle the exception.

Java Exceptions: Checked vs. Unchecked Exceptions

- Checked exceptions are checked at compile time.
  - The method must either handle the exception or it must specify the exception using throws keyword.

```
// compile error – FileReader, etc. throw IOException
// IOException is a checked exception
// compiler gives unhandled exception error
class Main {
    public static void main(String[] args) {
        FileReader file = new FileReader("C:\\test\\a.txt");
        BufferedReader fileInput = new BufferedReader(file);

        // Print first 3 lines of file "C:\test\a.txt"
        for (int counter = 0; counter < 3; counter++)
            System.out.println(fileInput.readLine());

        fileInput.close();
    }
}
```

Java Exceptions: Checked vs. Unchecked Exceptions

- Checked are checked at compile time.
  - The method must either handle the exception or it must specify the exception using throws keyword.
  - Compiler checks that the exception is being handled

```
class Main {
    public static void main(String[] args) throws IOException {
        FileReader file = new FileReader("C:\\test\\a.txt");
        BufferedReader fileInput = new BufferedReader(file);

        // Print first 3 lines of file "C:\test\a.txt"
        for (int counter = 0; counter < 3; counter++)
            System.out.println(fileInput.readLine());

        fileInput.close();
    }
}
```

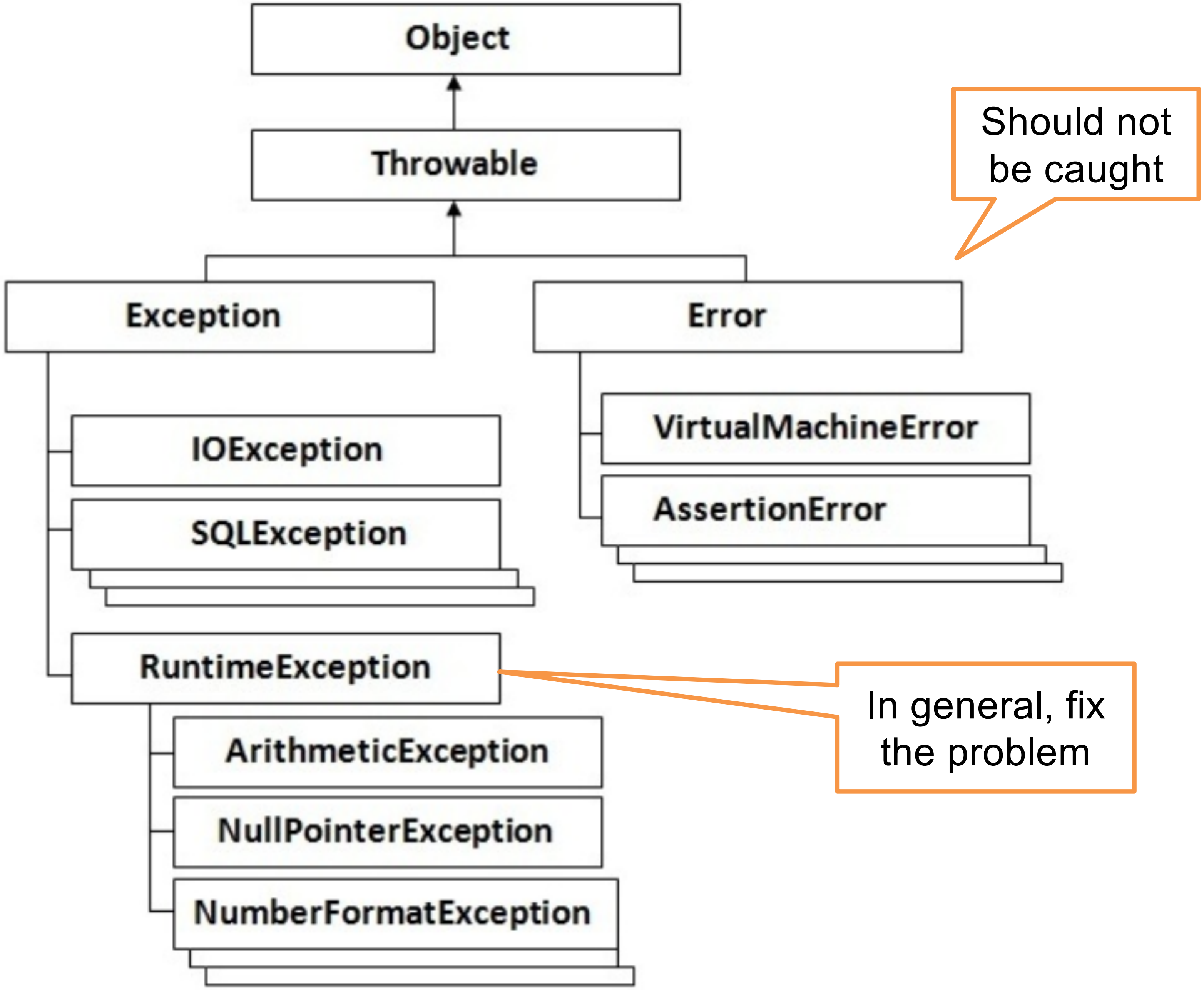
Java Exceptions: Checked vs. Unchecked Exceptions

- Unchecked exceptions are not checked at compile time.
  - Exceptions under `Error` and `RuntimeException` classes are unchecked exceptions, everything else under throwable is checked.
  - In C++, all exceptions are unchecked
  - Checked exceptions are preferred
    - Compiler checks that exception will be handled
  - `Error` class exception should be used for serious problems.

Java Exceptions: Checked vs. Unchecked Exceptions

- Checked exceptions. For special results
  - Library: must declare in signature
  - Client: must either catch or declare in signature
  - It is guaranteed there is a dynamically enclosing catch
- Unchecked exceptions. For failures
  - Library: no need to declare
  - Client: no need to catch
  - `RuntimeException` and `Error`
  - Often indicates a code problem, i.e. a bug
- From the JavaDoc documentation:

  *If a client can reasonably be expected to recover from an exception, make it a **checked** exception. If a client cannot do anything to recover from the exception, make it an **unchecked** exception*


Object
Throwable
Exception
Error
Should not be caught
IOException
SQLException
VirtualMachineError
AssertionError
RuntimeException
In general, fix the problem
ArithmeticException
NullPointerException
NumberFormatException

Don't Ignore Exceptions

- An empty catch block is poor style!
  - Often done to hide an error or get program to compile

```
try {
   readFile(filename);
} catch (IOException e) {} // do nothing on error
```

- At a minimum, print the exception

```
 }catch (IOException e) {
    e.printStackTrace();
  }
```

Exceptions, review

- Use an exception when
  - Checking the condition is feasible
  - Used in a broad or unpredictable context

- Use a precondition when
  - Checking would be prohibitive
    - E.g., requiring that a list is sorted
  - Used in a narrow context in which calls can be checked

Exceptions, review

- Avoid preconditions because
  - Caller may violate precondition
  - Program can fail in an uninformative or dangerous way
    - Program should fail as early as possible
  - Stronger preconditions -> Weaker specifications

- Use checked exceptions most of the time
- Handle exceptions <u>sooner rather than later</u>

Checked vs. Unchecked exceptions

- Unchecked exceptions are better if clients will usually write code that ensures the exception will not happen
  - The exception reflects completely unanticipated failures
- Otherwise, use a checked exception
  - Must be caught and handled – prevents program defects
  - Checked exceptions should be locally caught and handled
  - Checked exceptions that propagate long distance are bad design
  - If not caught, generates a program termination
- Java sometimes uses null or NaN as special value