Reasoning About ADTs, Assertions and Exceptions

Some Material Thanks to Michael Ernst, University of Washington

Connecting Implementation to Specification

- Representation invariant: Object → boolean
  - Indicates whether data representation is well-formed. Only well-formed representations are meaningful
  - Defines the set of valid values
- Abstraction function: Object → abstract value
  - What the data representation really means
    - E.g., array [2, 3, -1] represents $-x^2 + 3x + 2$
  - How the data structure is to be interpreted

IntMap Specification

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 Specification

interface 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);

}

IntStack Specification

```
/**
* An IntStack represents a stack (LIFO) of ints.
* It implements a subset of the functionality of Stack<int>.
* All operations are exactly as specified in the documentation
* for Stack.
*
* IntStack can be thought of as an ordered list of ints:
*
* @specfield stack = [a_0, a_1, a_2, ..., a_k]
*/
```

IntStack Specification

```
interface IntStack {
/** Pushes an item onto the top of this stack.
* If stack_pre = [a_0, a_1, a_2, ..., a_(k-1), a_k]
* then stack_post = [a_0, a_1, a_2, ..., a_(k-1), a_k, val].
*/
   void push(int val);
/**
* Removes the int at the top of this stack and returns that int.
* If stack_pre = [a_0, a_1, a_2, ..., a_(k-1), a_k]
* then stack_post = [a_0, a_1, a_2, ..., a_(k-1)]
* and the return value is a_k.
*/
   int pop();
}
```

Outline of Today's Class

- Static reasoning about ADTs
  - Proving that rep invariant holds

- Dynamic "reasoning": assertions

- 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)
  - 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 implies the weakest precondition
    - Reasoning is an important debugging tool
  - Today: prove (using informal manual proofs) that rep invariant holds. This is sometimes easy, sometimes hard…

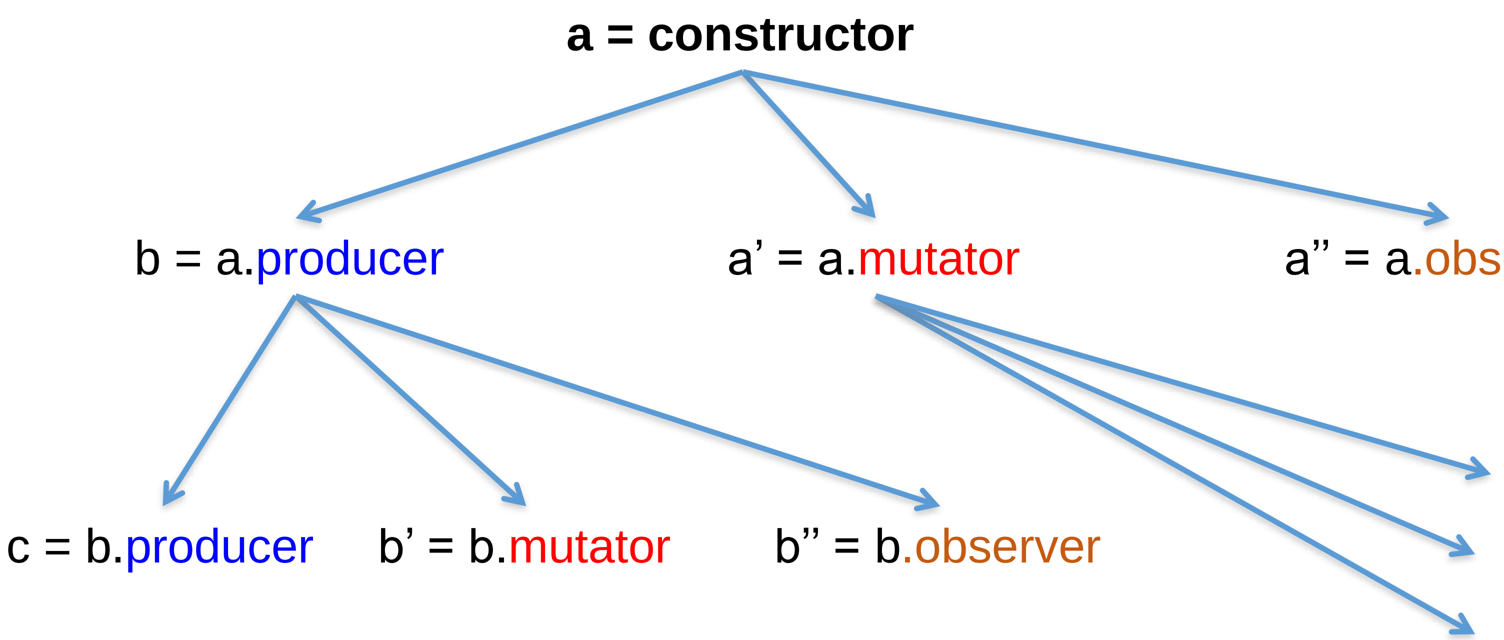
Goal: Show that Rep Invariant Is Satisfied

- Testing
  - Choose representative objects and check rep
  - Problem: it is often impossible to exhaustively test, therefore, we have to chose 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?

Verify that Rep Invariant Is Satisfied

- We have infinitely 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**.
    - Why do we include these?

Ways to Make New Objects



...

Infinitely many objects but limited number of types of operations!

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 infinitely many objects
- Base step
  - Prove rep invariant holds on exit of constructor
- 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
- 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
  - 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

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

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;
   }
```

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

- Check
  - Precondition
  - Postcondition
  - Rep invariant
  - Other properties we know must hold
- Check statically via reasoning
  - “Statically” means before execution
  - Works in simpler cases (the examples we saw), can be difficult in general
    - Motivates us to simplify and/or decompose our code!

Practice Defensive Programming

- Check dynamically via assertions
  - What do we mean by “dynamically”?
    - 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
  - Aside: not to be confused with JUnit method such as assertEquals!

Assertions

- **java** runs with assertions disabled (default)
- **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;
```

- How can you test at runtime whether assertions are enabled?

Outline of Today's Class

- Static reasoning about ADTs
  - Proving rep invariants
- Dynamic reasoning: assertions
- Exceptions
  - Basics
  - Uses of exceptions

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

Which one is it?

A) Failure of a subcomponent

B) Division by zero

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
  - Skip subcomputation: permit rest of program to continue
  - Fix the problem (usually infeasible)
    - Can be dangerous

Preconditions vs. Exceptions

- A precondition prohibits misuse of your code
  - Adding a 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 the precondition requires specifying the 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, usually used in local context
- Whenever possible, remove preconditions from public methods and specify behavior
  - Usually, 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
  assert(Math.abs(result*result – x) < .0001);
  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:

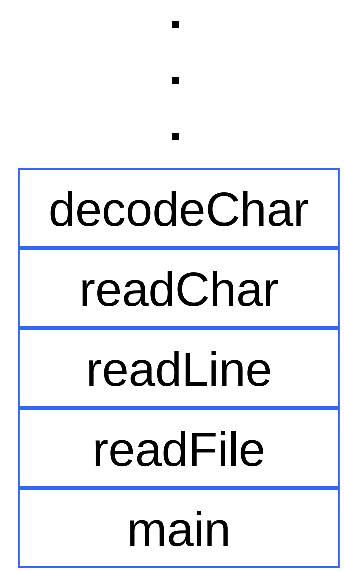
```
try {
  y = sqrt(-1);
} catch (IllegalArgumentException e) {
  e.printStackTrace(); // or take same other
}
```

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
- Better solution: exceptions

Two Distinct Uses of Exceptions

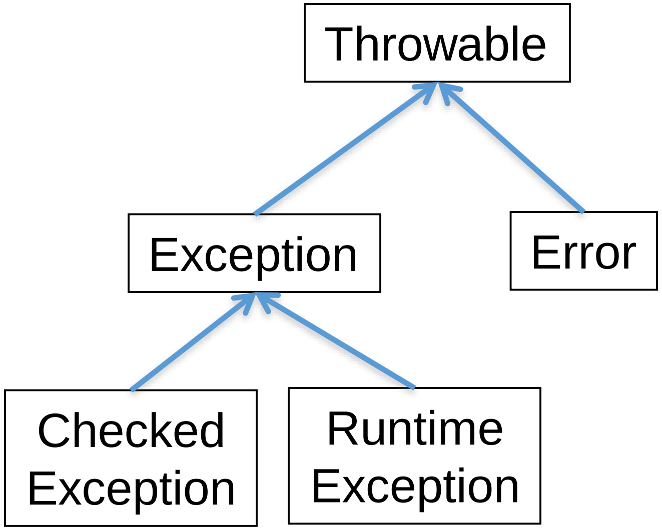
- (External) failures (e.g., file not found)
  - Unexpected by your code
  - Usually unrecoverable. If condition is left unchecked, exception propagates up the stack
- Special results
  - Expected by your code
  - Unknowable for the client of your code
  - Always check and handle locally. Take special action and continue computing

Java Exceptions: Checked vs. Unchecked Exceptions

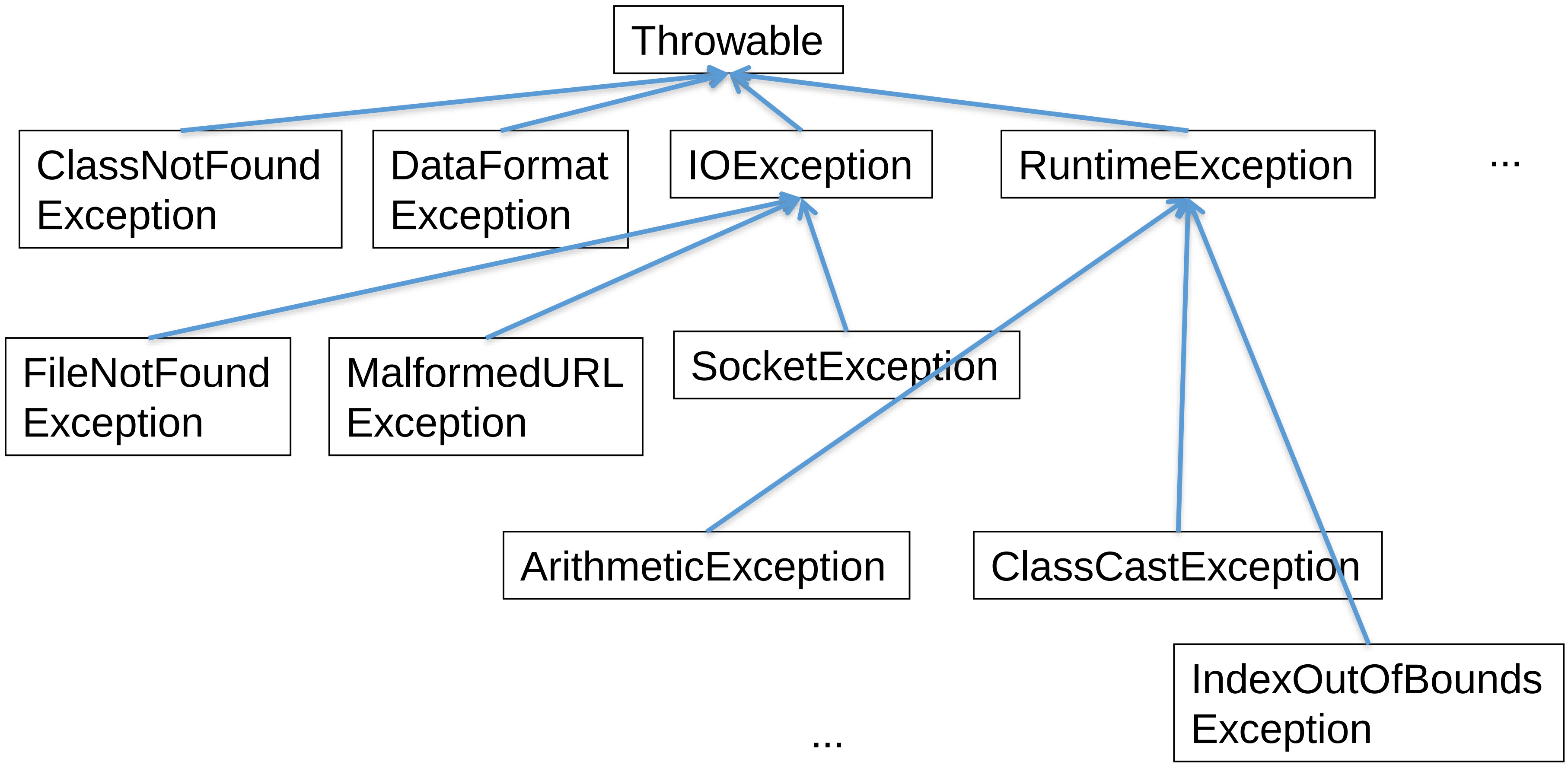
- Checked exceptions
  - Anything that is a subclass of java.lang.Exception
    - Except for RuntimeException
- Unchecked Exceptions
  - subclasses of java.lang.RuntimeException
- Calls throwing checked exceptions need to be enclosed in a try{} block or handled in a level above in the caller of the method.
  - 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. 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



Java Exception Hierarchy (Part of)



Don’t Ignore Exceptions

- An empty catch block is poor style!
  - Often done to hide an error or get 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
  - Want program to fail as early as possible

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

Avoid too many checked 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
- Java sometimes uses null as special value