Program Correctness and Efficiency

Following Koffmann and Wolfgang Chapter 2

Outline

- Categories of program errors
- Why you should catch exceptions
- The **`Exception`** hierarchy
  - Checked and unchecked exceptions
- The **`try`**-**`catch`**-**`finally`** sequence
- Throwing an exception:
  - What it means
  - How to do it

Outline (continued)

- A variety of testing strategies
- How to write testing methods
- Debugging techniques and debugger programs
- Program verification: assertions and loop invariants
- Big-O notation
  - What it is
  - How to use it to analyze an algorithm's efficiency

Program Defects and “Bugs”

- An efficient program is *worthless* if it breaks or produces a wrong answer
- Defects often appear in software after it is delivered
- Testing cannot prove the absence of defects
- It can be difficult to test a software product completely in the environment in which it is used
- *Debugging*: removing defects

Major Categories of Defects

- Syntax and other in-advance errors
- Run-time errors and exceptions
- Logic Errors

Syntax Errors

- *Syntax errors*: grammatical mistakes in a program
- The *compiler detects* syntax errors
  - You *must* correct them to compile successfully
- Some common syntax errors include:
  - Omitting or misplacing braces, parentheses, etc.
  - Misplaced end-of-comment
  - Typographical errors (in names, etc.)
  - Misplaced keywords

Semantic Errors

- <u>Semantic errors</u>: may obey grammar, but violate other rules of the language
- The *compiler detects* semantic errors
  - You *must* correct them to compile successfully
- Some common semantic errors include:
  - Performing an incorrect operation on a primitive type value
  - Invoking an instance method not defined
  - Not declaring a variable before using it
  - Providing multiple declarations of a variable
  - Failure to provide an exception handler
  - Failure to **`import`** a library routine

Run-time Errors or Exceptions

- Run-time errors
  - Occur during program execution (run-time!)
  - Occur when the JVM detects an operation that it knows to be incorrect
  - Cause the JVM to throw an exception
- Examples of run-time errors include
  - Division by zero
  - Array index out of bounds
  - Number format error
  - Null pointer exceptions

Run-time Errors or Exceptions (continued)

TABLE 2.1

Subclasses of `java.lang.RuntimeException`

Run-time Exception	Cause/Consequence
`ArithmeticException`	Integer division by zero.
`ArrayIndexOutOfBoundsException`	An attempt to access an element in an array with an index value (subscript) less than zero or greater than or equal to the array's length.
`IllegalArgumentException`	An attempt to call a method with an argument of incorrect type or inappropriate format.
`NumberFormatException`	An attempt to convert a string that is not numeric to a number (real or integer).
`NullPointerException`	An attempt to use a **`null`** reference value to access an object.
`NoSuchElementException`	An attempt to get a next token after all tokens were extracted from the string that was tokenized.

Logic Errors

- A *logic error* is programmer mistake in
  - the ***design*** of a class or method, or
  - the ***implementation*** of an algorithm
- Most logic errors
  - Are not syntax or semantic errors: get by the compiler
  - Do not cause run-time errors
  - Thus they are ***difficult to find***
- Sometimes found through testing
- Sometimes found by users

Avoiding Logic Errors

- Work from a *precise* specification
- Strive for clarity and simplicity
- Consider “corner” / extreme cases
- Have reviews / walk-throughs: *other eyes*
- Use library/published algorithms where possible
- Think through pre/post conditions, invariants
- Be organized and careful in general

The Exception Class Hierarchy

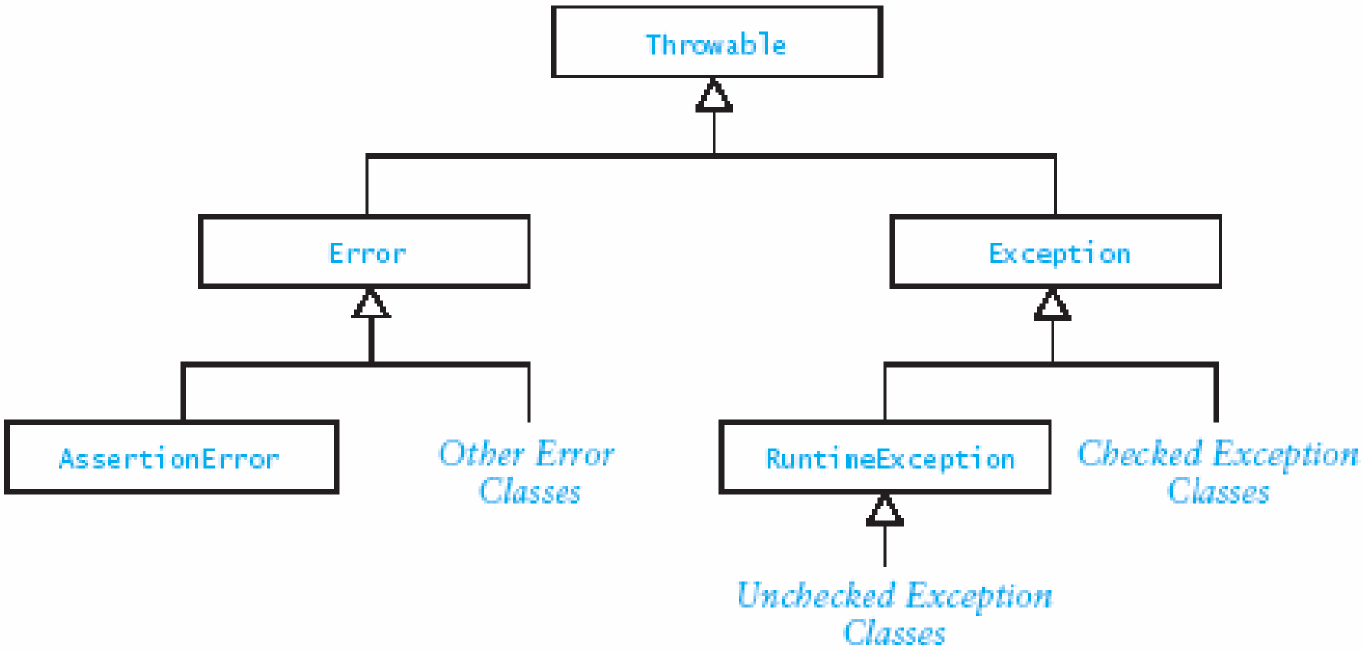
- When an exception occurs, the *first* thing that happens is a **`new`** of a Java exception object
- Different exception classes have different rules
- **`Throwable`** is the *root superclass* of the exception class hierarchy
  - **`Error`** is a subclass of **`Throwable`**
  - **`Exception`** is a subclass of **`Throwable`**
    - **`RuntimeException`** is a subclass of **`Exception`**

The Class Throwable

- **`Throwable`** is the superclass of all exceptions
- All exception classes inherit its methods

FIGURE 2.1

Summary of Exception Class Hierarchy



The Class Throwable (continued)

TABLE 2.2

Summary of Commonly Used Methods from the `java.lang.Throwable` Class

Method	Behavior
`String getMessage()`	Return the detail message.
`void printStackTrace()`	Print the stack trace to `System.err`.
`String toString()`	Return the name of the exception followed by the detail message.

The Exception Class Hierarchy (2)

`Throwable` is the superclass of all exception classes

- **`Error`** is for things a program *should not* catch
  - Example: **`OutOfMemoryError`**
- **`Exception`** is for things a program *might* catch
  - **`RuntimeException`** is for things the VM might throw
    - It can happen anywhere: e.g., any object access can throw NullPointerException
    - So *not required* to catch it
  - *All others* must be either:
    - Explicitly *caught* or
    - Explicitly *mentioned as thrown* by the method

Exception Hierarchy Summary

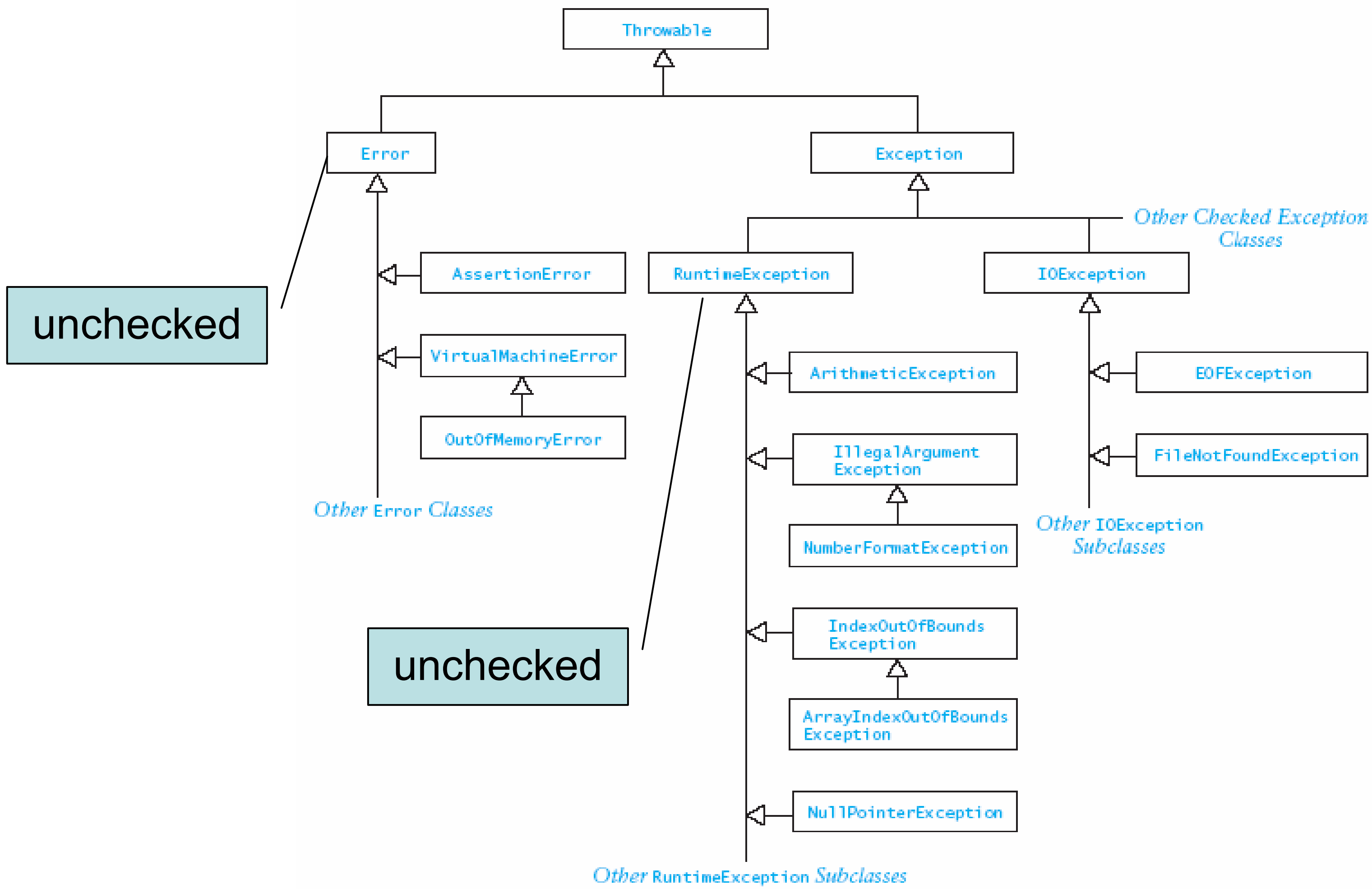
- **`Error:`** don't catch, unchecked
- **`Exception:`**
  - **`RuntimeException:`**
    - (Usually) don't catch, unchecked
  - *All others:* checked, so must
    - Catch, or
    - Mention they may be thrown

Checked and Unchecked Exceptions

- Checked exceptions
  - Normally not due to programmer error
  - Generally beyond the control of the programmer
  - Examples: **`IOException`**, **`FileNotFoundException`**
- Unchecked exception may result from
  - Programmer error
  - Serious external condition that is unrecoverable

Checked and Unchecked Exceptions (2)

FIGURE 2.2
Exception Hierarchy Showing Selected Checked and Unchecked Exceptions



Some Common Unchecked Exceptions

- **`ArithmeticException`**
  - Division by zero, etc.
- **`ArrayIndexOutOfBoundsException`**
- **`NumberFormatException`**
  - Converting a "bad" string to a number
- **`NullPointerException`**
- **`NoSuchElementException`**
  - No more tokens available

Catching and Handling Exceptions

- When an exception is thrown, the normal sequence of execution is interrupted
- Default behavior,i.e., no handler
  - Program stops
  - JVM displays an error message
- The programmer may provide a *handler*
  - Enclose statements in a **`try`** block
  - Process the exception in a **`catch`** block

Example Handler

```
InputStream in = null;
try {
  in = new FileInputStream(args[0]);
  ...
} catch (FileNotFoundException e) {
  System.out.printf(
      “File not found: %s%n”, name);
} catch (Throwable e) {
  System.err.println("Exception!");
  e.printStackTrace(System.err);
} finally {
  if (in != null) in.close();
}
```

Uncaught Exceptions

- Uncaught exception exits VM with a *stack trace*
- The stack trace shows
  - The sequence of method calls
  - Starts with throwing method
  - Ends at **`main`**

FIGURE 2.3

Example of a Stack Trace for an Uncaught Exception

The **`try-catch`** Sequence

- Avoiding uncaught exceptions
  - Write a **`try-catch`** to handle the exception
  - Point: prevent ugly program termination!
    - Unpleasant for user
    - Worse, may leave things messed up / “broken”

- **`catch`** block is skipped if no exception thrown within the **`try`** block

Handling Exceptions to *Recover* from Errors

- Exceptions provide the opportunity to
  - *Report* errors
  - *Recover* from errors
- *User* errors common, and *should be recoverable*
- Most closely enclosing handler that *matches* is the one that executes
  - A handler matches if its class includes what's thrown
- Compiler displays an error message if it encounters an unreachable **`catch`** clause

The **`finally`** block

- On exception, a **`try`** is abandoned
- Sometimes more actions *<u>must</u>* be taken
  - Example: Close an output file
- Code in a **`finally`** block is *<u>always</u>* executed
  - After the **`try`** finishes normally, or
  - After a **`catch`** clause completes
- **`finally`** is *optional*

Example of **finally** block

```
try {
  InputStream ins = ...;
  ... ins.read(); ...

} catch (EOFException e) {
  System.err.println("Unexpected EOF");
  e.printStackTrace();
  System.exit(17);

} finally {
  if (ins != null) ins.close();

}
```

Throwing Exceptions

- Lower-level method can *pass exception through*
  - Can be caught and handled by a higher-level method
  - *Mark* lower-level method
    - Say it may throw a checked exception
    - Mark by **`throws`** clause in the header
  - May throw the exception in the lower-level method
    - Use a **`throw`** statement
- Particularly useful if calling module already has a handler for this exception type

Throwing Exceptions (2)

- Use a **`throw`** statement when you detect an error
- Further execution stops immediately:
  - Goes to closest suitable handler
  - May be a number of level of calls earlier
  - Does execute any **`finally`** blocks in the middle

Example of Throwing an Exception

```
/** adds a new entry or changes an old one
 * @param name the name to create/update
 * @param number the (new) number
 * @return the previous number, a String
 * @throws IllegalArgumentException if the number
 * is not in phone number format
 */
public String addOrChangeEntry(
    String name, String number) {
  if (!isPhoneNumberFormat(number)) {
    throw new IllegalArgumentException(
      “Invalid phone number: “ + number);
  }
  ...
}
```

Another Example of Throwing an Exception

```
public void accessLocalFile (String askingUser)
    throws CertificateException {
  ...
  if (user's secure socket certificate bad) {
    throw new CertificateException(reason);
  }
  ...
}
```

Programming Style

- You can always avoid handling exceptions:
  - *Declare* that they are thrown, or
  - *Throw* them and let them be handled farther back
- <u>*But:*</u> usually best to handle instead of passing
- <u>*Guidelines:*</u>

1. If recoverable here, handle here
2. If checked exception likely to be caught higher up
   Declare that it can occur using a **`throws`** clause
3. Don't use **`throws`** with *unchecked* exceptions
   Use an **`@throws`** javadoc comment when helpful

Programming Style (2)

Don't do this!

```
try {...} catch (Throwable e) { }
```

- Omits arbitrary patches of code
  - Can leave things in "broken" state
- No warning to user
- Leads to hidden, difficult to detect, defects

Handling Exceptions in Phone Dir Example

- In **`loadData`**:
  - **`FileNotFoundException`** from **`FileReader`** constructor
  - **`IOException`** from **`readLine`**
- In **`PDConsoleUI`**:
  - **`InputMismatchException`** from **`nextInt`**
- In **`addOrChangeEntry`**:
  - **`IllegalArgumentException`** for empty **`String`**

Testing Programs

- A program with
  - No syntax/semantic errors, and
  - No run-time errors,
  - May still contain ***logic errors***
- “Best” case is logic error that ***always executes***
  - Otherwise, hard to find!
- Worst case is logic error in code ***rarely run***

Goal of testing: Test every part of the code, on “good” and “bad”/”hard” cases

Structured Walkthroughs

- Most logic errors:
  - Come from the <u>design phase</u>
  - Result from an <u>incorrect algorithm</u>
- Logic errors sometimes come from typos that do not cause syntax, semantic, or run-time errors
  - Famous FORTRAN: **`DO 10 I = 1.100`**
  - Common C: **`if (i = 3) ...`**
- One way to test: hand-trace algorithm

  <u>before</u> implementing!
- Thus: **Structured Walkthroughs**

Structured Walkthroughs (2)

The Designer:

- Explains the algorithm to other team members
- Simulate its execution with them looking on

The Team:

- Verifies that it works
- Verifies that it handles all cases

Walkthroughs are helpful, but do not replace **testing!**

Testing Defined

- **Testing:**
  - Exercising a program under controlled conditions
  - Verifying the results
- *Purpose:* detect program defects after
  - All syntax/semantic errors removed
  - Program compiles
- No amount of testing can *guarantee* the absence of defects in sufficiently complex programs

Levels of Testing

- **Unit testing:** checking the smallest testable piece
  - A method or class
- **Integration testing:**
  - The interactions among units
- **System testing:** testing the program in context
- **Acceptance testing:** system testing intended to show that the program meets its functional requirements

Some Types of Testing

- **Black-box testing:**
  - Tests item based *only* on its interfaces and functional requirements
  - Assumes no knowledge of internals
- **White-box testing:**
  - Tests *with* knowledge of internal structure

Preparing to Test

- Develop **test plan** *early*, in the design phase
  - How to test the software
  - When to do the tests
  - Who will do the testing
  - What test data to use
- Early test plan allows testing ***during*** design & coding
- Good programmer practices ***defensive programming***
  - Includes code to detect unexpected or invalid data

Testing Tips for Program Systems

- Program systems contain collections of classes, each with several methods
- A method specification should document
  - Input parameters
  - Expected results
- Carefully document (with javadoc, etc.):
  - Each method parameter
  - Each class attribute (instance and static variable)
  - *As you write the code!*

Testing Tips for Program Systems (2)

Trace execution by displaying method name as you enter a method:

```
public static final boolean TRACING = true;
...
public int computeWeight (...) {
  if (TRACING) {
    trace.printf("Entering computeWeight");
  }
  ...
}
```

Testing Tips for Program Systems (3)

Display values of all input parameters on entry:

```
public int computeWeight (float volume,
                          float density) {
  if (TRACING) {
    trace.printf(“Entering computeWeight“);
    trace.printf(“volume = %f, “, volume);
    trace.printf(“density = %f%n“, density);
  }
  ...
}
```

Testing Tips for Program Systems (4)

- **Display values** of any class attributes (instance and static variables) accessed by the method
- **Display values** of all method outputs at point of return from a method

- **Plan for testing** *as you write* each module,
  - Not after the fact!

Developing Test Data

- **Specify test data** during analysis and design
  - For each level of testing: unit, integration, and system
- **Black-box** testing: unit inputs $\Rightarrow$ outputs
  - Check all *expected* inputs
  - Check *unanticipated* data
- **White-box** testing: exercise all code paths
  - Different tests to make each if test (etc.) true and false
  - Called *coverage*

Developing Test Data (2)

- Helpful to do **both** black- and white-box testing
- **Black-box** tests can be developed *early* since they have to do with the unit *specification*
- **White-box** tests are developed with detailed design or implementation: *need code structure*

Testing Boundary Conditions

- Exercise *all paths* for
  - Hand-tracing in a structured walkthrough
  - Performing white-box testing
- Must check special cases:

  boundary conditions
- Examples:
  - Loop executes 0 times, 1 time, all the way to the end
  - Item not found

Who does the testing?

- Normally testing is done by
  - The programmer
  - Team members who did not code the module
  - Final users of the product
- Programmers often blind to their own oversights
- Companies may have quality assurance groups
- **Extreme programming:** programmers paired
  - One writes the <u>*code*</u>
  - The other writes the <u>*tests*</u>

Stubs for Testing

- Hard to test a method or class that interacts with other methods or classes
- A ***stub*** stands in for a method not yet available
- The stub:
  - Has the same header as the method it replaces
  - Body only displays a message that it was called
- Sometimes you need to *synthesize* a reasonable facsimile of a result, for the caller to continue

Drivers

A **driver program**:

- Declares necessary instances and variables
- Provides values for method inputs
- Calls the method
- Displays values of method outputs

- A **`main`** method in a class can serve as a driver to test the class's methods

Regression Testing

- Once code has passed all initial tests, it is important to *continue to test regularly*
- Environment and other changes $\Rightarrow$ "*software rot*"
- A **regression test** is designed to:
  - Catch any "regression" or decay in the software
  - Insure old functionality works in face of enhancement
  - Alert earlier to any issues arising from other changes
- Regression testing eased by a *testing framework*

Using a Testing Framework

Testing framework: software that facilitates:

- *Writing* test cases
- *Organizing* the test cases into test suites
- *Running* the test suites
- *Reporting* the results

JUnit

- A Java testing framework
- Open-source product
- Can be used stand-alone or with an IDE
- Available from **`junit.org`**

JUnit Example

```
import junit.framework.*;
public class TestDirectoryEntry
    extends TestCase {
  private DirectoryEntry tom;
  private DirectoryEntry dick;
  private DirectoryEntry tom2;

  public void setUp () {
    tom  = new DirectoryEntry(“Tom” , “...”);
    dick = new DirectoryEntry(“Dick”, “...”);
    tom2 = new DirectoryEntry(“Tom” , “...”);
  }
```

JUnit Example (2)

```
public void testTomCreate () {
  assertEquals(tom.getName()  , “Tom”);
  assertEquals(tom.getNumber(), “...”);
}

public void testTomEqualsDick () {
  assertFalse(tom.equals(dick));
  assertFalse(dick.equals(tom));
}
```

JUnit Example (3)

```
public void testTomEqualsTom () {
  assertTrue(tom.equals(tom));
  assertTrue(tom.equals(tom2));
  assertTrue(tom2.equals(tom));
}

public void testSetNumber () {
  dick.setNumber(tom.getNumber());
  assertEquals(tom.getNumber(),dick.getNumber());
}
```

Integration Testing

- Larger components: *collection of classes*
- Done with smaller collection, then larger ones
- Drive with ***use cases:*** scenarios with
  - Sample user inputs
  - Expected outputs
  - Can be challenging to automate

Debugging a Program

Debugging: the major activity during the testing phase

- *Testing* determines that there *is* an error
- *Debugging* determines the *cause*
- Debugging is like detective work: logical deduction
  - *Inspect all program output* carefully
  - *Insert additional output statements* to find out more
  - *Use breakpoints* to examine world ...
    at *carefully* selected points

Using a Debugger

- **Debuggers** often are included with IDEs
- Debugger supports *incremental* program execution
- *Single-step execution* provides increments as small as one program statement (or even one instruction)
- *Breakpoints* traverse larger portions of code at once
- Details depend on the specfic IDE

Key to debugging: Think first! Think a lot!

- Also: try to split possible error sources *in half* with each investigation

Reasoning about Programs: Assertions and Loop Invariants

- **Assertions:**
  - *Logical statements* about program state
  - Claimed to be *true*
  - At a particular *point in the program*
  - Written as a *comment*, OR use **`assert`** statement
- *Preconditions* and *postconditions* are assertions
- *Loop invariants* are also assertions

Reasoning about Programs: Loop Invariants

A **loop invariant**:

- Helps prove that a loop meets it specification
- Is true *before* loop begins
- Is true *at the beginning of each iteration*
- Is true just *after loop exit*

Example: Sorting an array of n elements

Sorted(i): Array elements j, for $0 \le j < i$, are sorted

Beginning: Sorted(0) is (trivially) true

Middle: We insure initial portion sorted as we increase i

End: Sorted(n): All elements $0 \le j < n$ are sorted

Efficiency of Algorithms

Question: How can we characterize the performance of an *algorithm* ...

- Without regard to a *specific computer?*
- Without regard to a *specific language?*
- Over a wide *range of inputs?*

Desire: Function that describes *execution time* in terms of *input size*

- Other measures might be memory needed, etc.

The “Order” of Performance: (Big) O

- Basic idea:
  1. Ignore constant factor: computer and language implementation details affect that: go for fundamental rate of increase with problem size.
  2. Consider fastest growing term: Eventually, for large problems, it will dominate.
- Value: Compares fundamental performance difference of algorithms
- Caveat: For smaller problems, big-O worse performer may actually do better

$T(n) = O(f(n))$

- $T(n)$ = time for algorithm on input size n
- $f(n)$ = a simpler function that grows at about the same rate

- Example: $T(n) = 3n^2+5n-17 = O(n^2)$
  - $f(n)$ has faster growing term
  - no extra leading constant in $f(n)$

T(n) = O(f(n)) Defined

1. $\exists n_0$ and
2. $\exists c$ such that

If $n > n_0$ then $c \cdot f(n) \geq T(n)$

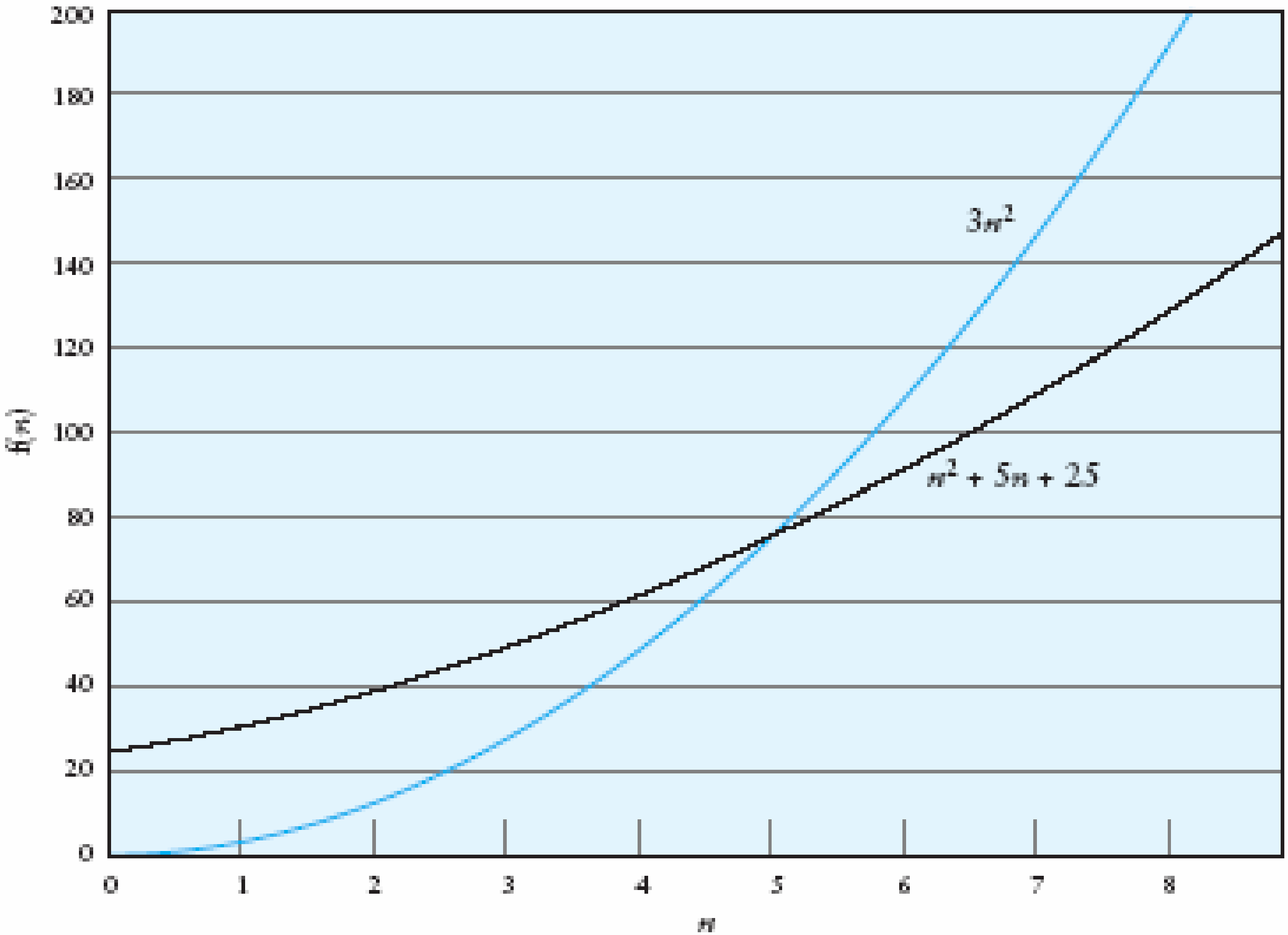
Example: $T(n) = 3n^2+5n-17$

Pick $c = 4$, say; need $4n_0^2 > 3n_0^2+5n_0-17$

$n_0^2 > 5n_0-17$, for which $n_0 = 5$ will do.

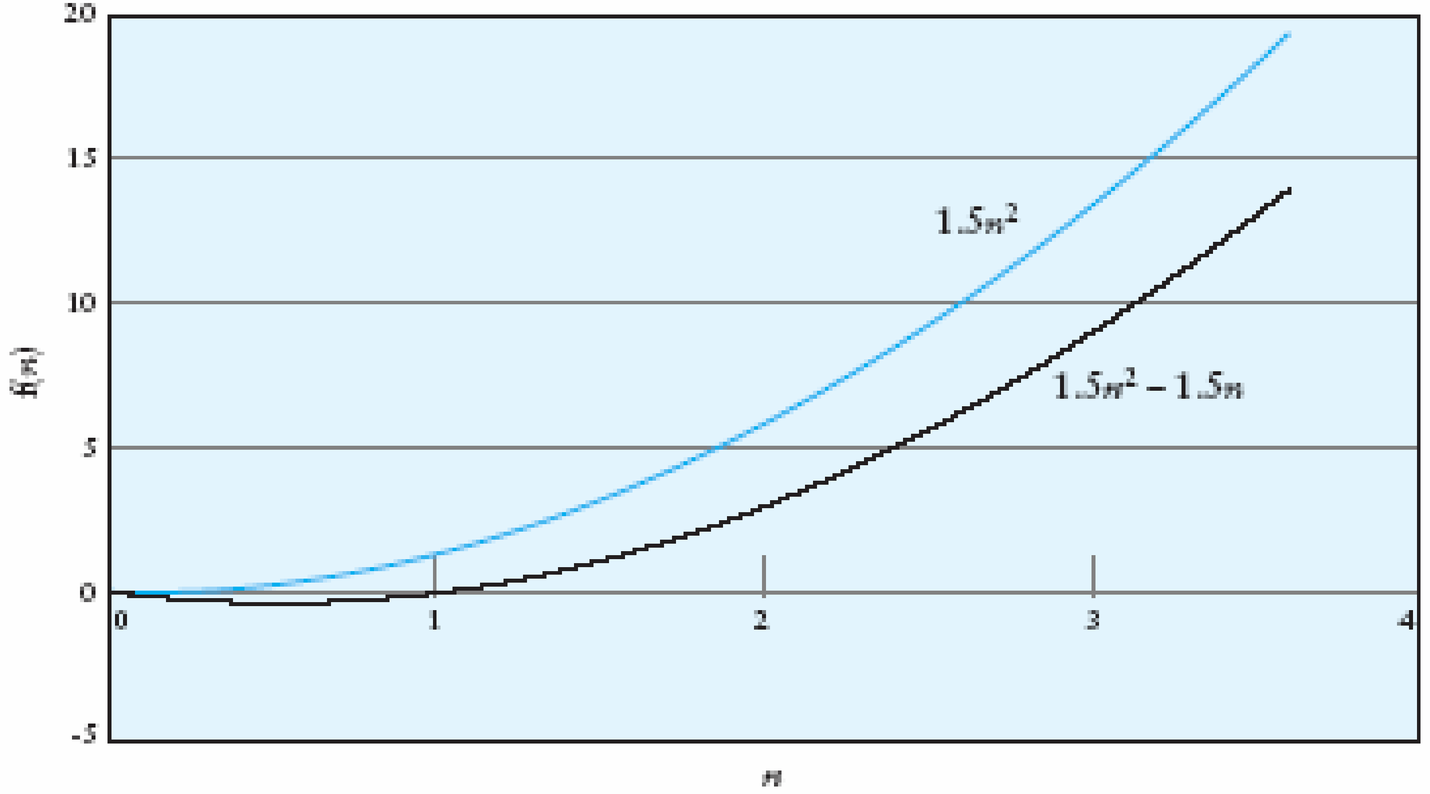
Efficiency of Algorithms (continued)

FIGURE 2.12
$3n^2$ vs. $n^2 + 5n + 25$



Efficiency of Algorithms (continued)

FIGURE 2.13
$1.5n^2$ versus $1.5n^2 - 1.5n$



Efficiency of Algorithms (continued)

TABLE 2.5

Symbols Used in Quantifying Software Performance

$T(n)$	The time that a method or program takes as a function of the number of inputs, n. We may not be able to exactly measure or determine this.
$f(n)$	Any function of n. Generally $f(n)$ will represent a simpler function than $T(n)$, for example, n^2 rather than $1.5n^2 - 1.5n$.
$O(f(n))$	Order of magnitude. $O(f(n))$ is the set of functions that grow no faster than $f(n)$. We say that $T(n) = O(f(n))$ to indicate that the growth of $T(n)$ is bounded by the growth of $f(n)$.

Efficiency of Algorithms (continued)

TABLE 2.6

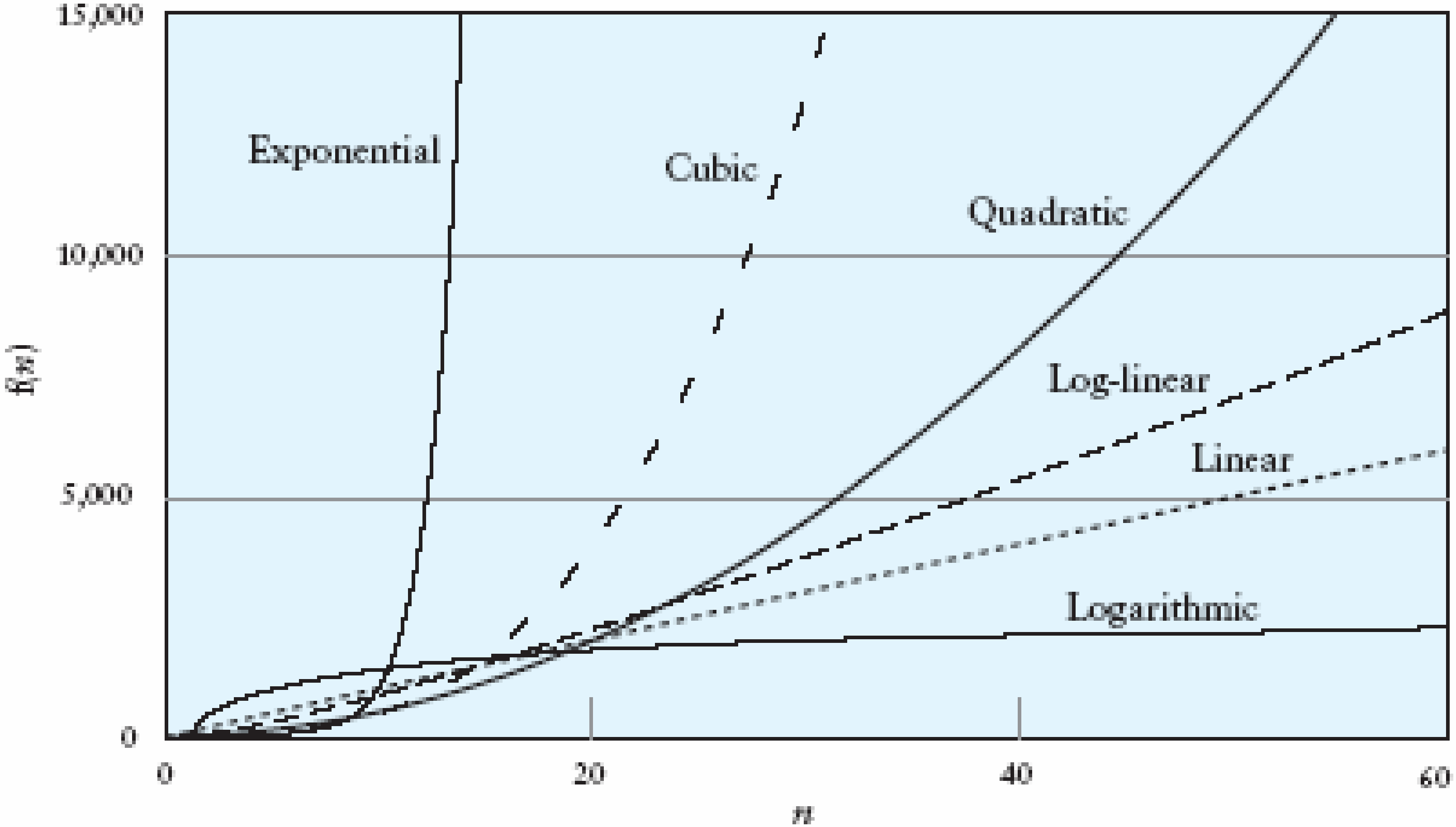
Common Growth Rates

Big-O	Name
$O(1)$	Constant
$O(\log n)$	Logarithmic
$O(n)$	Linear
$O(n \log n)$	Log-linear
$O(n^2)$	Quadratic
$O(n^3)$	Cubic
$O(2^n)$	Exponential
$O(n!)$	Factorial

Efficiency of Algorithms (continued)

FIGURE 2.14

Different Growth Rates



Efficiency Examples

```
public static int find (int[]x, int val) {
  for (int i = 0; i < x.length; i++) {
    if (x[i] == val)
      return i;
  }
  return -1;  // not found
}
```

Letting n be **`x.length`**:

Average iterations if *found* = (1+...+n)/n = (n+1)/2 = O(n)

Iterations if *not found* = n = O(n)

Hence this is called *linear search*.

Efficiency Examples (2)

```
public static boolean allDifferent (
    int[] x, int[] y) {
  for (int i = 0; i < x.length; i++) {
    if (find(y, x[i]) != -1)
      return false;
  }
  return true;  // no x element found in y
}
```

Letting m be **`x.length`** and n be **`y.length`**:

Time if all different = O(m·n) = m · cost of search(n)

Efficiency Examples (3)

```
public static boolean unique (int[] x) {
  for (int i = 0; i < x.length; i++) {
    for (int j = 0; j < x.length; j++ {
      if (i != j && x[i] == x[j])
        return false;
    }
  }
  return true;  // no duplicates in x
}
```

Letting n be **`x.length`**:

Time if unique = n^2 iterations = $O(n^2)$

Efficiency Examples (4)

```
public static boolean unique (int[] x) {
  for (int i = 0; i < x.length; i++) {
    for (int j = i+1; j < x.length; j++ {
      if (i != j && x[i] == x[j])
        return false;
    }
  }
  return true;  // no duplicates in x
}
```

Letting n be **`x.length`**:

Time if unique = (n-1)+(n-2)+...+2+1 iterations =
n(n-1)/2 iterations = $O(n^2)$ *still* ... only factor of 2 better

Efficiency Examples (5)

```
for (int i = 1; i < n; i *= 2) {
  do something with x[i]
}
```

Sequence is 1, 2, 4, 8, ..., ~n.

Number of iterations = $\log_2 n$ = log n.

Computer scientists generally use base 2 for log, since that matches with number of *bits*, etc.

Also $O(\log_b n) = O(\log_2 n)$ since chane of base just multiples by a constant: $\log_2 n = \log_b n / \log_b 2$

Chessboard Puzzle

Payment scheme #1: \$1 on first square, \$2 on second, \$3 on third, ..., \$64 on 64^{th}.

Payment scheme #2: 1¢ on first square, 2¢ on second, 4¢ on third, 8¢ on fourth, etc.

Which is best?

Chessboard Puzzle Analyzed

Payment scheme #1: Total = \$1+\$2+\$3+...+\$64 = \$64×65/2 = \$1755

Payment scheme #2: 1¢+2¢+4¢+...+2^{63}¢ = 2^{64}-1¢ = \$184.467440737 *trillion*

Many cryptographic schemes require $O(2^n)$ work to break a key of length n bits. A key of length n=40 is perhaps breakable, but one with n=100 is not.