Documenting, Using, and Testing Utility Classes

Readings: Chapter 2 of the Course Notes

EECS2030: Advanced Object Oriented Programming
Fall 2017

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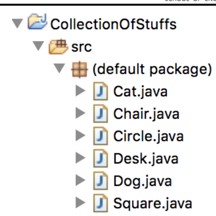
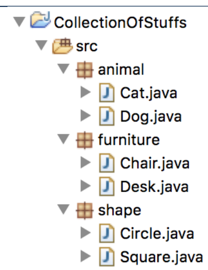
Structure of Project: Packages and Classes

A Java *project* may store a list of Java *classes*.

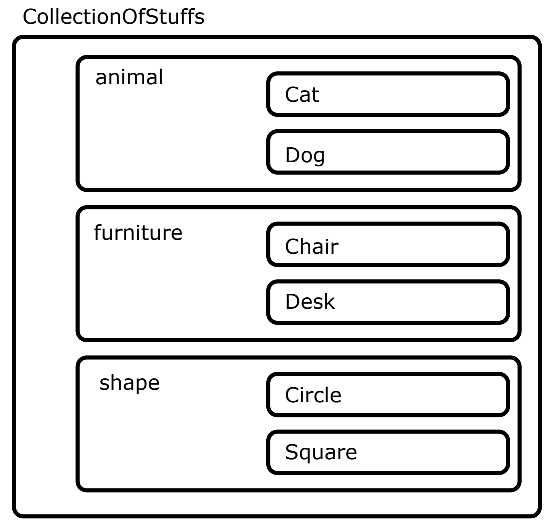


You may group each list of related classes into a *package*.



To see project structure in Eclipse: `Package Explorer` view.

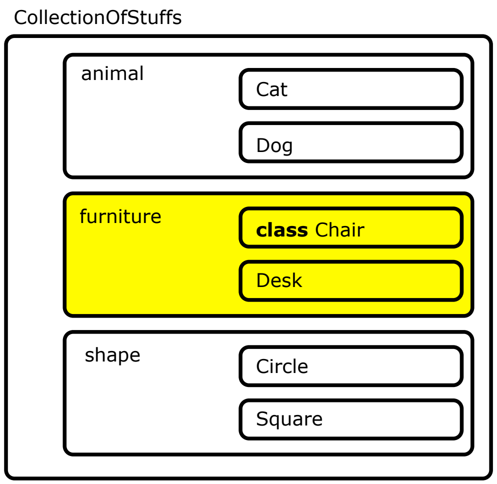
Visibility: Project, Packages, Classes



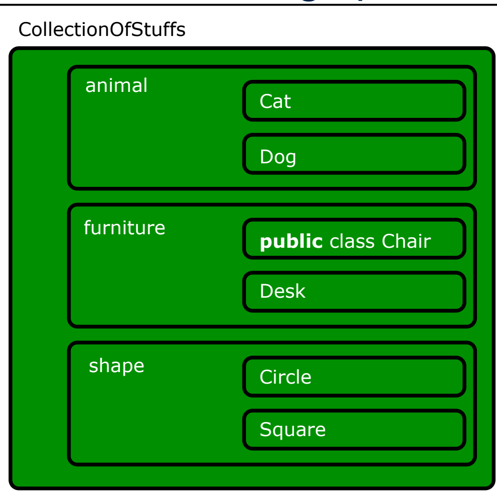
Visibility of Classes

- Only one modifier for declaring visibility of classes: *public*.
- Use of ***private*** is forbidden for declaring a class.
  e.g., `private class Chair` is **not** allowed!!
- **Visibility** of a class may be declared using a modifier, indicating that it is accessible:
  1. Across classes within its resident package [no modifier]
     e.g., Declare `class Chair { ... }`
  2. Across packages [*public*]
     e.g., Declare `public class Chair { ... }`
- Consider class `Chair` in: Resident package `furniture`; Resident project `CollectionOfStuffs`.

Visibility of Classes: Across All Classes Within the Resident Package (no modifier)



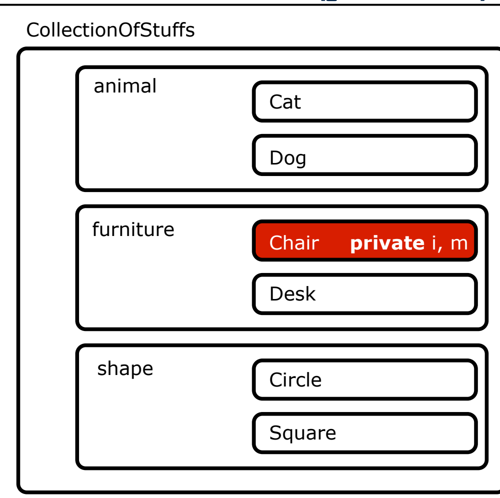
Visibility of Classes: Across All Classes Within the Resident Package (no modifier)



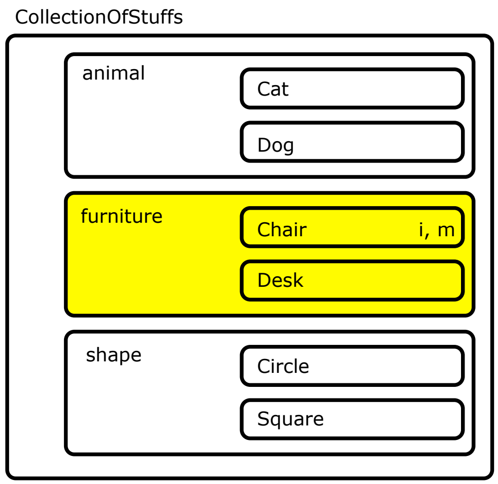
Visibility of Attributes/Methods: Using Modifiers to Define Scopes

- Two modifiers for declaring visibility of attributes/methods: *public* and *private*
- **Visibility** of an attribute or a method may be declared using a modifier, indicating that it is accessible:
  1. Within its resident class (*most* restrictive) [*private*]
     e.g., Declare attribute `private static int i;`
     e.g., Declare method `private static void m(){};`
  2. Across classes within its resident package [no modifier]
     e.g., Declare attribute `static int i;`
     e.g., Declare method `static void m(){};`
  3. Across packages (*least* restrictive) [*public*]
     e.g., Declare attribute `public static int i;`
     e.g., Declare method `public static void m(){};`
- Consider `i` and `m` in: Resident class `Chair`; Resident package `furniture`; Resident project `CollectionOfStuffs`.

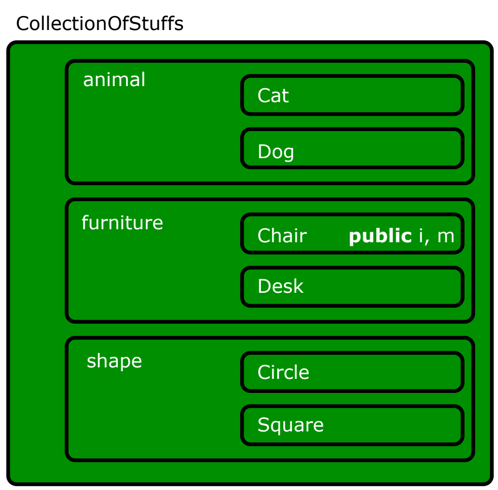
Visibility of Attr./Meth.: Across All Methods Within the Resident Class (`private`)



Visibility of Attr./Meth.: Across All Classes Within the Resident Package (no modifier)



Visibility of Attr./Meth.: Across All Packages Within the Resident Project (`public`)



Structure of Utility Classes

- *Utility classes* are a special kind of classes, where:
  - All *attributes* (i.e., stored data) are declared as *static*.
  - All *methods* (i.e., stored operations) are declared as *static*.
- For now, understand all these *static* attributes and methods collectively make their resident utility class a **single** (i.e., one that cannot be duplicated) machine, upon which you may:
  - Access the value of a data item. [attribute]
  - Compute and return a value. [accessor]
  - Computer and change the data (without returning). [mutator]
- We will later discuss non-static attributes and methods.

To see class structure in Eclipse: `Outline` view.

Structure of Utility Classes: Example (1.1)

```
1  public class CircleUtilities {
2    private static final int RADIUS_TO_DIAMETER = 2;
3    static int radius = 10;
4    public static final int PI = 3;
5    static int getDiameter() {
6      int diameter = radius * RADIUS_TO_DIAMETER;
7      return diameter;
8    }
9    static int getDiameter(int radius) { return radius * RADIUS_TO_DIAMETER; }
10   static void setRadius(int newRadius) { radius = newRadius; }
11   public static int getCircumference(int radius) { return getDiameter(radius) * PI; }
12   public static int getCircumference1() { return getDiameter() * PI; }
13   private static int getCircumference2() { return getCircumference(radius); }
14 }
```

Three independent groups of modifiers in the above utility class:

1. Access :*private* (**L2**, **L13**), *public* (**L4**, **L11**, **L12**), and no access modifier (**L3**, **L5**, **L9**, **L10**).
2. Uniqueness :*static* (all attributes and methods) and non-static (not in a utility class)
3. Assignable :*final* (**L2**, **L4**) means it is a constant value and can never be assigned, and non-final attributes are variables.

Structure of Utility Classes: Example (1.2)

```java
1  public class CircleUtilities {
2    private static final int RADIUS_TO_DIAMETER = 2;
3    static int radius = 10;
4    public static final int PI = 3;
5    static int getDiameter() {
6      int diameter = radius * RADIUS_TO_DIAMETER;
7      return diameter;
8    }
9    static int getDiameter(int radius) { return radius * RADIUS_TO_DIAMETER; }
10   static void setRadius(int newRadius) { radius = newRadius; }
11   public static int getCircumference(int radius) { return getDiameter(radius) * PI; }
12   public static int getCircumference1() { return getDiameter() * PI; }
13   private static int getCircumference2() { return getCircumference(radius); }
14 }
```

Each utility class contains a list of attributes and methods:

1. **L2 – L4**: Three attributes `RADIUS_TO_DIAMETER`, `radius`, `PI`
   - Each of these attributes has an initial value (2, 10, and 3).
   - Only the value of `radius` (non-final) may be changed.
2. **L5 – L13**: Six methods:
   - 1 **Mutator** (with the return type `void`): `setRadius(int newRadius)`
   - 5 **Accessors** (with an explicit `return` statement): e.g., `getDiameter()`, `getCircumference(int radius)`

Structure of Utility Classes: Example (1.3)


```java
1  public class CircleUtilities {
2    private static final int RADIUS_TO_DIAMETER = 2;
3    static int radius = 10;
4    public static final int PI = 3;
5    static int getDiameter() {
6      int diameter = radius * RADIUS_TO_DIAMETER;
7      return diameter;
8    }
9    static int getDiameter(int radius) { return radius * RADIUS_TO_DIAMETER; }
10   static void setRadius(int newRadius) { radius = newRadius; }
11   public static int getCircumference(int radius) { return getDiameter(radius) * PI; }
12   public static int getCircumference1() { return getDiameter() * PI; }
13   private static int getCircumference2() { return getCircumference(radius); }
14 }
```


Each method has a (possibly empty) list of *parameters* (i.e., inputs) and their types:

- e.g., `getDiameter` (**L5**) has no parameters (i.e., it takes no inputs for its computation)
- e.g., `setRadius` (**L10**) has one parameter (i.e., `newRadius` of type `int`)

We talk about *parameters* in the context of method declarations.

Structure of Utility Classes: Example (1.4)


```java
1  public class CircleUtilities {
2    private static final int RADIUS_TO_DIAMETER = 2;
3    static int radius = 10;
4    public static final int PI = 3;
5    static int getDiameter() {
6      int diameter = radius * RADIUS_TO_DIAMETER;
7      return diameter;
8    }
9    static int getDiameter(int radius) { return radius * RADIUS_TO_DIAMETER; }
10   static void setRadius(int newRadius) { radius = newRadius; }
11   public static int getCircumference(int radius) { return getDiameter(radius) * PI; }
12   public static int getCircumference1() { return getDiameter() * PI; }
13   private static int getCircumference2() { return getCircumference(radius); }
14 }
```


When the name of a method parameter clashes with the name of an attribute (**L9**):

- Any mention about that name (e.g., `radius`) refers to the parameter, not the attribute anymore.
- To refer to the attribute, write: `Utilities.radius`
- If you know what you're doing, that's fine; otherwise, use a different name (e.g., **L10**) to avoid unintended errors.

Structure of Utility Classes: Example (1.5)


```java
1  public class CircleUtilities {
2    private static final int RADIUS_TO_DIAMETER = 2;
3    static int radius = 10;
4    public static final int PI = 3;
5    static int getDiameter() {
6      int diameter = radius * RADIUS_TO_DIAMETER;
7      return diameter;
8    }
9    static int getDiameter(int radius) { return radius * RADIUS_TO_DIAMETER; }
10   static void setRadius(int newRadius) { radius = newRadius; }
11   public static int getCircumference(int radius) { return getDiameter(radius) * PI; }
12   public static int getCircumference1() { return getDiameter() * PI; }
13   private static int getCircumference2() { return getCircumference(radius); }
14 }
```


The body (i.e., what's written between { and }) of a method (accessor or mutator) may:

1. Declare local variables (e.g., **L6**) to store intermediate computation results.
   The scope of these local variables is only within that method.
2. Perform assignments to change values of either local variables (**L6**) or attributes (**L10**).

Structure of Utility Classes: Example (1.6)

```
1  public class CircleUtilities {
2    private static final int RADIUS_TO_DIAMETER = 2;
3    static int radius = 10;
4    public static final int PI = 3;
5    static int getDiameter() {
6      int diameter = radius * RADIUS_TO_DIAMETER;
7      return diameter;
8    }
9    static int getDiameter(int radius) { return radius * RADIUS_TO_DIAMETER; }
10   static void setRadius(int newRadius) { radius = newRadius; }
11   public static int getCircumference(int radius) { return getDiameter(radius) * PI; }
12   public static int getCircumference1() { return getDiameter() * PI; }
13   private static int getCircumference2() { return getCircumference(radius); }
14 }
```

A method body may *call* another method (i.e., *reuse* code):

3. Call a utility accessor and use (e.g., store, print, return) its return value: **L11** and **L13**.
   - **L11**: Since we are in the same class, we do not need to write `CircleUtilities.getDiameter(radius)`
   - **L11**: `getDiameter(radius)` passes method *parameter* `radius` as an *argument* value to method `getDiameter(...)`
   - **L11**: It is equivalent to write (without reusing any code): `return radius * RADIUS_TO_DIAMETER * PI`

Structure of Utility Classes: Exercise

```
1  public class CircleUtilities {
2    private static final int RADIUS_TO_DIAMETER = 2;
3    static int radius = 10;
4    public static final int PI = 3;
5    static int getDiameter() {
6      int diameter = radius * RADIUS_TO_DIAMETER;
7      return diameter;
8    }
9    static int getDiameter(int radius) { return radius * RADIUS_TO_DIAMETER; }
10   static void setRadius(int newRadius) { radius = newRadius; }
11   public static int getCircumference(int radius) { return getDiameter(radius) * PI; }
12   public static int getCircumference1() { return getDiameter() * PI; }
13   private static int getCircumference2() { return getCircumference(radius); }
14 }
```

Is the body of method `getCircumference1` equivalent to the body of method `getCircumference2`? Why or why not?

Structure of Utility Classes: Example (1.7)

```
1  public class CircleUtilities {
2    private static final int RADIUS_TO_DIAMETER = 2;
3    static int radius = 10;
4    public static final int PI = 3;
5    static int getDiameter() {
6      int diameter = radius * RADIUS_TO_DIAMETER;
7      return diameter;
8    }
9    static int getDiameter(int radius) { return radius * RADIUS_TO_DIAMETER; }
10   static void setRadius(int newRadius) { radius = newRadius; }
11   public static int getCircumference(int radius) { return getDiameter(radius) * PI; }
12   public static int getCircumference1() { return getDiameter() * PI; }
13   private static int getCircumference2() { return getCircumference(radius); }
14 }
```

A method body may *call* another method (i.e., *reuse* code):

4. Call a utility mutator to change some data.

We will see an example about this later.

Visualizing a Utility Class

All *static* attributes and methods collectively make their resident utility class a **single** (i.e., one that cannot be duplicated) machine, which contains:

- Current values of attributes
- Definitions of methods (i.e., how computation is to be executed)

CircleUtilities	
RADIUS_TO_DIAMETER	2
radius	10
PI	3
getDiameter()	int diameter = radius * RADIUS_TO_DIAMETER; return diameter;
setRadius(int newRadius)	radius = newRadius;
getCircumference(int radius)	return getDiameter(radius) * PI;
getCircumference1()	return getDiameter() * PI;
getCircumference2()	return getCircumference(radius);

Using a Utility Class (1)

- We can either access a static attribute or call a static method in a utility class using its name.
- e.g., the method call `CircleUtilities.setRadius(40)` passes the value `40` as *argument*, which is used to instantiate every occurrence of the method *parameter* `newRadius` in method `setRadius` by `40`.

```
void setRadius(int newRadius 40) {
  radius = newRadius 40;
}
```

- Consequently, the effect of this method call is to change the current value of `CircleUtilities.radius` to `40`.

Entry Point of Execution: the "main" Method

The *main* method is treated by Java as the *starting point* of executing your program.

```
public class CircleUtilitiesApplication {
  public static void main(String[] args) {
    /* Your programming solution is defined here. */
  }
}
```

The execution starts with the first line in the *main* method, proceed line by line, from top to bottom, until there are no more lines to execute, then it *terminates*.

Using a Utility Class (2.1)

```
public class CircileUtilitesApplication {
 public static void main(String[] args) {
  System.out.println("Initial radius of CU: " + CircleUtilities.radius);
  int d1 = CircleUtilities.getDiameter();
  System.out.println("d1 is: " + d1);
  System.out.println("c1 is: " + CircleUtilities.getCircumference1());
  System.out.println("======");
  System.out.println("d2 is: " + CircleUtilities.getDiameter(20));
  System.out.println("c2 is: " + CircleUtilities.getCircumference(20));
  System.out.println("======");
  System.out.println("Change the radius of CU to 30...");
  CircleUtilities.setRadius(30);
  System.out.println("======");
  d1 = CircleUtilities.getDiameter();
  System.out.println("d1 is: " + d1);
  System.out.println("c1 is: " + CircleUtilities.getCircumference1());
  System.out.println("======");
  System.out.println("d2 is: " + CircleUtilities.getDiameter(20));
  System.out.println("c2 is: " + CircleUtilities.getCircumference(20));
}
}
```

Executing it, what will be output to the console?

Using a Utility Class (2.2)

```
Initial radius of CU: 10
d1 is: 20
c1 is: 60
======
d2 is: 40
c2 is: 120
======
Change the radius of CU to 30...
======
d1 is: 60
c1 is: 180
======
d2 is: 40
c2 is: 120
```

Using a Utility Class: Client vs. Supplier (1)

- A *supplier* implements/provides a service (e.g., microwave).
- A *client* uses a service provided by some supplier.
  - The client must follow certain instructions to obtain the service (e.g., supplier **assumes** that client powers on, closes door, and heats something that is not explosive).
  - If instructions are followed, the client would **expect** that the service does what is required (e.g., a lunch box is heated).
  - The client does not care how the supplier implements it.
- What then are the *benefits* and *obligations* os the two parties?

	benefits	*obligations*
CLIENT	obtain a service	follow instructions
SUPPLIER	give instructions	provide a service

- There is a *contract* between two parties, violated if:
  - The instructions are not followed. [Client's fault]
  - Instructions followed, but service not satisfactory. [Supplier's fault]

Using a Utility Class: Client vs. Supplier (2)

```
class CUtil {
  static int PI = 3;
  static int getArea(int r) {
    /* Assume: r positive */
    return r * r * 3;
  }
}
```

```
1 class CUtilApp {
2   public static void main(...) {
3     int radius = ???;
4     println(CUtil.getArea(radius));
5   } }
```

- Method call **CircleUtilities.getArea(radius)**, inside class **CircleUtilitiesApp**, suggests a ***client-supplier relation***.
  - **Client**: resident class of the static method call [`CUtilApp`]
  - **Supplier**: context class of the static method [`CUtil`]
- What if the value of ??? at **L3** of `CUtilApp` is `-10`?

```
300
```

- What's wrong with this?
  - Client `CUtil` mistakenly gives illegal circle with radius `-10`.
  - Supplier `CUtil` should have reported a *contract violation*!

Using a Utility Class: Client vs. Supplier (3)

- *Method Precondition* : supplier's assumed circumstances, under which the client can expect a satisfactory service.
  - Precondition of `int divide(int x, int y)`? [`y != 0`]
  - Precondition of `int getArea(int r)`? [`r > 0`]
- When **supplier** is requested to provide service with *preconditions* ***not*** satisfied, *contract is violated* by **client**.
- *Precondition Violations* ≈ `IllegalArgumentException`.
  Use `if-elseif` statements to determine if a violation occurs.

```
class CUtil {
  static int PI = 3;
  static int getArea(int r) throws IllegalArgumentException {
    if(r < 0) {
      throw new IllegalArgumentException("Circle radius " + r + "is not positive.");
    }
    else {
      return r * r * PI;
    }
  }
}
```


Documenting Your Class using Javadoc (1)

There are three types of comments in Java:

- `//` [line comment]
- `/* */` [block comment]
  - These two types of comments are only for you as a **supplier** to document interworking of your code.
  - They are hidden from **clients** of your software.
- `/** */` [block documentation]
  - This type of comments is for **clients** to learn about how to use of your software.

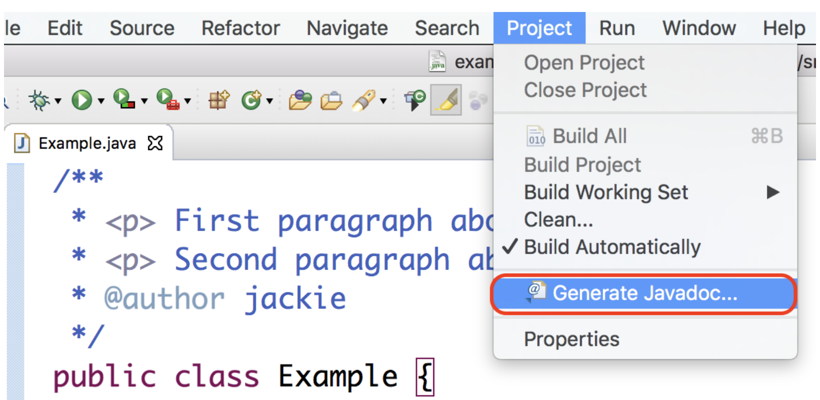
Documenting Classes using Javadoc (2.1)

```java
/**
 * <p> First paragraph about this class.
 * <p> Second paragraph about this class.
 * @author jackie
 */
public class Example {
  /** <p> Summary about attribute 'i'
   * <p> More details about 'i'
   */
  public static int i;
  /**
   * <p> Summary about accesor method 'am' with two parameters.
   * <p> More details about 'am'.
   * @return Always false for some reason.
   * @param s Documentation about the first parameter
   * @param d Documentation about the second parameter
   */
  public static boolean am (String s, double d) { return false; }
  /**
   * <p> Summary about mutator method 'mm' with no parameters.
   * <p> More details about 'mm'.
   */
  public static void mm () { /* code omitted */ }
}
```

- Use *@return* only for mutator methods (i.e., returning non-`void`).
- Use *@param* for each input parameter.

Documenting Classes using Javadoc (2.2)

Generate an HTML documentation using the Javadoc tool supported by Eclipse:



Exercises

- Implement a utility class named `Counter`, where
  - There is a static integer counter `i` whose initial value is `5`.
  - There is a static constant maximum `MAX` of value `10` for counter `i`.
  - There is a static constant minimum `MIN` of value `10` for counter `i`.
  - Your implementation should be such that the counter value can never fall out of the range $[5, 10]$.
  - There is a mutator method `incrementBy` which takes an integer input parameter `j`, and increments the counter `i` value by `j` if possible (i.e., it would not go above `MAX`).
  - There is a mutator method `decrementBy` which takes an integer input parameter `j`, and decrements the counter `i` value by `j` if possible (i.e., it would not go below `MIN`).
  - There is an accessor method `isPositive` which takes an integer input parameter `j`, and returns `true` if `j` is positive, or returns `false` if otherwise.
- Properly document your `Counter` class using Javadoc and generate the HTML documentation using Eclipse.

Index (1)

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Unit and Regression Testing using JUnit

EECS2030: Advanced Object Oriented Programming
Fall 2017

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A Simple Counter (1)

Consider a *utility class* (where attributes and methods are **static**) for keeping track of an integer counter value:

```
public class Counter {
  public final static int MAX_COUNTER_VALUE = 3;
  public final static int MIN_COUNTER_VALUE = 0;
  public static int value = MIN_COUNTER_VALUE;
  ... /* more code later! */
```

- When attempting to access the **static** attribute `value` ***outside*** the `Counter` class, write `Counter.value`.
- Two constants (i.e., `final`) for lower and upper bounds of the counter value.
- Initialize the counter value to its lower bound.
- ***Requirement*** :
  The counter value must be between its lower and upper bounds.

Encode Precondition Violation as `IllegalArgumentException`

Consider two possible scenarios of *Precondition Violations* (i.e., scenarios of throwing `IllegalArgumentException`):

- When the counter value is attempted (but not yet) to be updated **above** its upper bound.
- When the counter value is attempted (but not yet) to be updated **below** its upper bound.

A Simple Counter (2)

```
public static void increment() {
  if( value == Counter.MAX_COUNTER_VALUE ) {
    /* Precondition Violation */
    throw new IllegalArgumentException("Too large to increment");
  }
  else { value ++; }
}
public static void decrement() {
  if( value == Counter.MIN_COUNTER_VALUE ) {
    /* Precondition Violation */
    throw new IllegalArgumentException("Too small to decrement");
  }
  else { value --; }
}
```

- Change the counter value via two mutator methods.
- Changes on the counter value may ***violate a precondition***:
  - Attempt to **increment** when counter value reaches its **maximum**.
  - Attempt to **decrement** when counter value reaches its **minimum**.

Testing the Counter Class from Console: Test Case 1

Consider a class for testing the `Counter` class:

```
public class CounterTester1 {
  public static void main(String[] args) {
    System.out.println("Init val: " + Counter.value);
    System.out.println("Attempt to decrement:");
    /* Right before calling the decrement mutator,
     * Counter.value is 0 and too small to be decremented.
     */
    Counter.decrement();
  }
}
```

Executing it as Java Application gives this Console Output:

```
Init val: 0
Attempt to decrement:
Exception in thread "main"
  java.lang.IllegalArgumentException: Too small to decrement
```


Testing the Counter Class from Console: Test Case 2

Consider **another** class for testing the `Counter` class:

```
public class CounterTester2 {
  public static void main(String[] args) {
    Counter.increment(); Counter.increment(); Counter.increment();
    System.out.println("Current val: " + Counter.value);
    System.out.println("Attempt to increment:");
    /* Right before calling the increment mutator,
     * Counter.value is 3 and too large to be incremented.
     */
    Counter.increment();
  }
}
```

Executing it as Java Application gives this Console Output:

```
Current val: 3
Attempt to increment:
Exception in thread "main"
  java.lang.IllegalArgumentException: Too large to increment
```


Limitations of Testing from the Console

- Do **Test Cases** 1 & 2 suffice to test `Counter`'s *correctness*?
  - Is it plausible to claim that the implementation of `Counter` is *correct* because it passes the two test cases?
- What other test cases can you think of?

`Counter.value`	`Counter.increment()`	`Counter.decrement()`
0	1	`ValueTooSmall`
1	2	0
2	3	1
3	`ValueTooBig`	2

- So in total we need 8 test cases.
  ⇒ 6 more separate `CounterTester` classes to create!
- Problems? It is inconvenient to:
  - Run each TC by executing `main` of a `CounterTester` and comparing console outputs ***with your eyes***.
  - Re-run ***manually*** all TCs whenever `Counter` is changed.

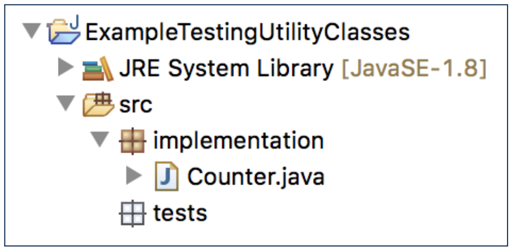
    Principle: Any **change** introduced to your software *must not compromise* its established **correctness**.

Why JUnit?

- *Automate* the ***testing of correctness*** of your Java classes.
- Once you derive the list of tests, translate it into a JUnit test case, which is just a Java class that you can execute upon.
- JUnit tests are *helpful clients* of your classes, where each test may:
  - Either attempt to use a method in a ***legal*** way (i.e., ***satisfying*** its precondition), and report:
    - ***Success*** if the result is as expected
    - ***Failure*** if the result is ***not*** as expected
  - Or attempt to use a method in an ***illegal*** way (i.e., ***not satisfying*** its precondition), and report:
    - ***Success*** if precondition violation (i.e., `IllegalArgumentException`) occurs.
    - ***Failure*** if precondition violation (i.e., `IllegalArgumentException`) does ***not*** occur.

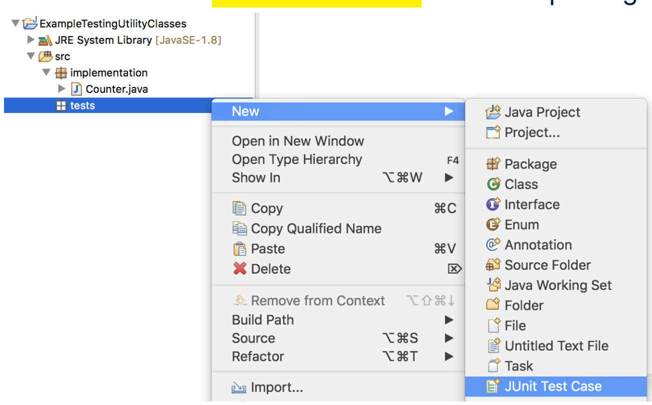
How to Use JUnit: Packages

Step 1:
- In Eclipse, create a Java project `ExampleTestingUtilityClasses`
- *Separation of concerns* :
  - Group classes for ***implementation*** (i.e., `Counter`) into package `implementation`.
  - Group classes classes for ***testing*** (to be created) into package `tests`.



How to Use JUnit: New JUnit Test Case (1)

Step 2: Create a new *JUnit Test Case* in `tests` package.

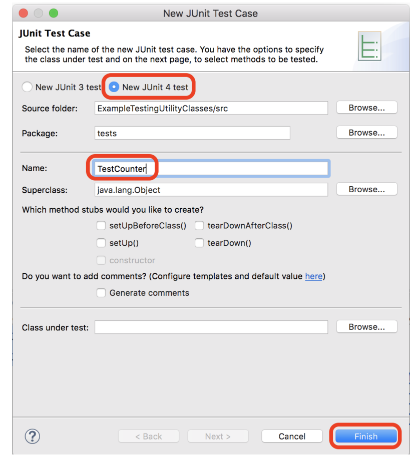


Create one JUnit Test Case to test one Java class only.

⇒ If you have *n Java classes to test*, create *n JUnit test cases*.

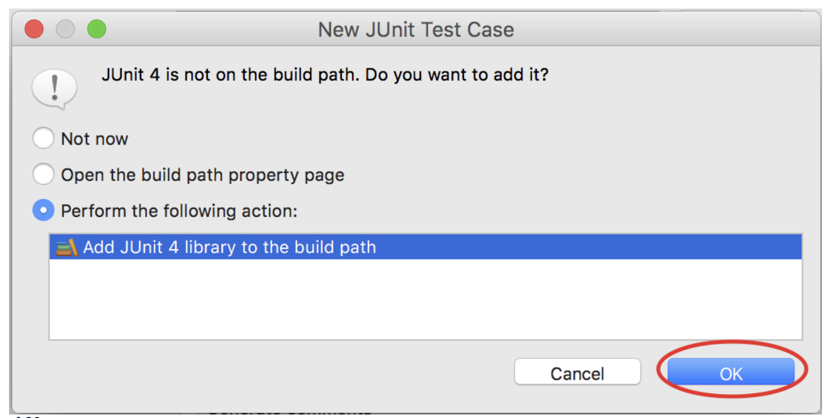
How to Use JUnit: New JUnit Test Case (2)

Step 3: Select the version of JUnit (JUnit 4); Enter the name of test case (`TestCounter`); Finish creating the new test case.



How to Use JUnit: Adding JUnit Library

Upon creating the very first test case, you will be prompted to add the JUnit library to your project's build path.



How to Use JUnit: Generated Test Case

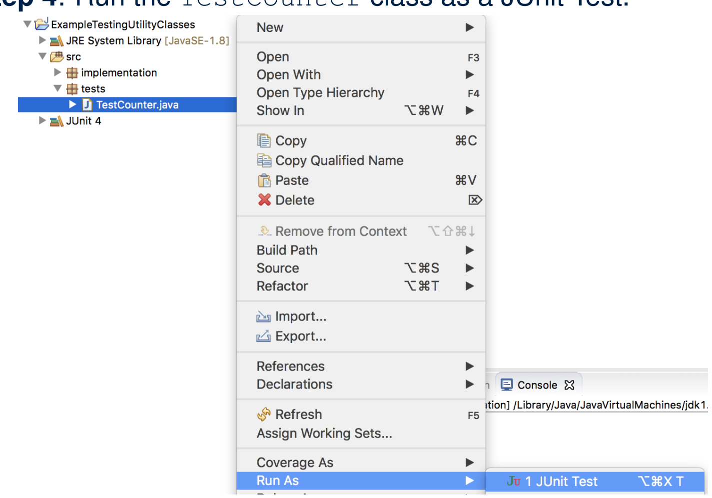
TestCounter.java

```java
1 package tests;
2 import static org.junit.Assert.*;
3 import org.junit.Test;
4 public class TestCounter {
5     @Test
6     public void test() {
7         fail("Not yet implemented");
8     }
9 }
```

- **Lines 6 – 8**: `test` is just an ***ordinary mutator method*** that has a one-line implementation body.
- **Line 5** is critical: Prepend the tag `@Test` verbatim, requiring that ***the method is to be treated as a JUnit test***.
  ⇒ When `TestCounter` is run as a JUnit Test Case, only ***those methods prepended by the `@Test` tags*** will be run and reported.
- **Line 7**: By default, we deliberately fail the test with a message "Not yet implemented".

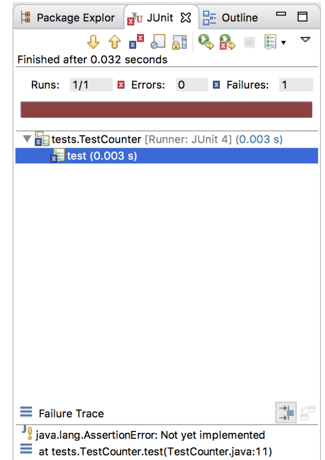
How to Use JUnit: Running Test Case

Step 4: Run the `TestCounter` class as a JUnit Test.



How to Use JUnit: Generating Test Report

A *report* is generated after running all tests (i.e., methods prepended with `@Test`) in `TestCounter`.



How to Use JUnit: Interpreting Test Report

- A ***test*** is a method prepended with the `@Test` tag.
- The result of running a test is considered:
  - ***Failure*** if either
    - an assertion failure (e.g., caused by `fail`, `assertTrue`, `assertEquals`) occurs; or
    - an *unexpected* exception (e.g., `NullPointerException`, `ArrayIndexOutOfBoundException`) is thrown.
  - ***Success*** if neither assertion failures nor *unexpected* exceptions occur.
- After running all tests:
  - A *green* bar means that ***all*** tests succeed.
    ⇒ Keep challenging yourself if *more tests* may be added.
  - A *red* bar means that ***at least one*** test fails.
    ⇒ Keep fixing the class under test and re-runing all tests, until you receive a *green* bar.
- **Question**: What is the easiest way to making `test` a *success*?
  Answer: Delete the call `fail("Not yet implemented")`.

How to Use JUnit: Revising Test Case

TestCounter.java

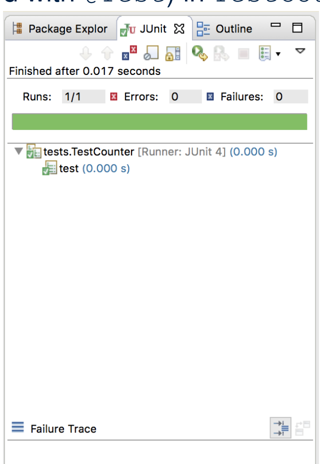
```java
package tests;
import static org.junit.Assert.*;
import org.junit.Test;
public class TestCounter {
    @Test
    public void test() {
//      fail("Not yet implemented");
    }
}
```

Now, the body of `test` simply does nothing.
⇒ Neither assertion failures nor exceptions will occur.
⇒ The execution of `test` will be considered as a *success*.

∵ There is currently only one test in `TestCounter`.
∴ We will receive a *green* bar!
Caution: `test` which passes at the moment is **not useful** at all!

How to Use JUnit: Re-Running Test Case

A new report is generated after re-running all tests (i.e., methods prepended with `@Test`) in `TestCounter`.



How to Use JUnit: Adding More Tests (1)

- Recall the complete list of cases for testing `Counter`:

`c.getValue()`	`c.increment()`	`c.decrement()`
0	1	`ValueTooSmall`
1	2	0
2	3	1
3	`ValueTooBig`	2

- Let's turn the two cases in the 1st row into two JUnit tests:
  - Test for left cell *succeeds* if:
    - No failures and exceptions occur; and
    - The new counter value is `1`.
  - Test for right cell *succeeds* if the *expected precondition violation* occurs (`IllegalArgumentException` is thrown).
- Common JUnit assertion methods (complete list in next slide):
  - `void assertNull(Object o)`
  - `void assertEquals(expected, actual)`
  - `void assertTrue(boolean condition)`
  - `void fail(String message)`

How to Use JUnit: Assertion Methods

method name / parameters	description
`assertTrue(`***test***`)` `assertTrue("`***message***`",` ***test***`)`	Causes this test method to fail if the given `boolean` test is not `true`.
`assertFalse(`***test***`)` `assertFalse("`***message***`",` ***test***`)`	Causes this test method to fail if the given `boolean` test is not `false`.
`assertEquals(`***expectedValue***`,` ***value***`)` `assertEquals("`***message***`",` ***expectedValue***`,` ***value***`)`	Causes this test method to fail if the given two values are not equal to each other. (For objects, it uses the `equals` method to compare them.) The first of the two values is considered to be the result that you expect; the second is the actual result produced by the class under test.
`assertNotEquals(`***value1***`,` ***value2***`)` `assertNotEquals("`***message***`",` ***value1***`,` ***value2***`)`	Causes this test method to fail if the given two values *are* equal to each other. (For objects, it uses the `equals` method to compare them.)
`assertNull(`***value***`)` `assertNull("`***message***`",` ***value***`)`	Causes this test method to fail if the given value is not `null`.
`assertNotNull(`***value***`)` `assertNotNull("`***message***`",` ***value***`)`	Causes this test method to fail if the given value *is* `null`.

`assertSame(`***expectedValue***`,` ***value***`)`
`assertSame("`***message***`",` ***expectedValue***`,` ***value***`)`
`assertNotSame(`***value1***`,` ***value2***`)`
`assertNotSame("`***message***`",` ***value1***`,` ***value2***`)`
	Identical to `assertEquals` and `assertNotEquals` respectively, except that for objects, it uses the `==` operator rather than the `equals` method to compare them. (The difference is that two objects that have the same state might be `equals` to each other, but not `==` to each other. An object is only `==` to itself.)

`fail()` `fail("`***message***`")`	Causes this test method to fail.

How to Use JUnit: Adding More Tests (2.1)

```
1  @Test
2  public void testIncAfterCreation() {
3    /* Assert that initial value of counter is correct. */
4    assertEquals(Counter.MIN_COUNTER_VALUE, Counter.value);
5    /* Attempt to increment the counter value,
6     * which is expected to succeed.
7     */
8    Counter.increment();
9    /* Assert that the updated counter value is correct. */
10   assertEquals(1, Counter.value);
11 }
```

- **L4**: Alternatively, you can write:

```
assertTrue(Counter.MIN_COUNTER_VALUE == Counter.value);
```

- **L10**: Alternatively, you can write:

```
assertTrue(1 == Counter.value);
```


How to Use JUnit: Adding More Tests (2.2)

- Don't lose the big picture!
- The JUnit test in the previous slide automates the following console tester which requires interaction with the external user:

```
public class CounterTester1 {
  public static void main(String[] args) {
    System.out.println("Init val: " + Counter.value);
    System.out.println("Attempt to decrement:");
    /* Right before calling the decrement mutator,
     * Counter.value is 0 and too small to be decremented.
     */
    Counter.decrement();
  }
}
```

- ***Automation** is exactly rationale behind using JUnit!*

How to Use JUnit: Adding More Tests (3.1)

```
1  @Test
2  public void testDecAfterCreation() {
3    assertTrue(Counter.MIN_COUNTER_VALUE == Counter.value);
4    try {
5      Counter.decrement();
6      /* Reaching this line means
7       * IllegalArgumentException not thrown! */
8      fail("Expected Precondition Violation Did Not Occur!");
9    }
10   catch(IllegalArgumentException e) {
11     /* Precondition Violated Occurred as Expected. */
12   } }
```

- **Lines 4 & 10**: We need a try-catch block because of **Line 5**.
  - Method `decrement` from class `Counter` is expected to throw the `IllegalArgumentException` because of a *precondition violation* .
- **Lines 3 & 8** are both assertions:
  - **Lines 3** asserts that `Counter.value` returns the expected value (`Counter.MIN_COUNTER_VALUE`).
  - **Line 8**: an assertion failure
    ∵ expected `IllegalArgumentException` not thrown

How to Use JUnit: Adding More Tests (3.2)

- Again, don't lose the big picture!
- The JUnit test in the previous slide automates the following console tester which requires interaction with the external user:

```
public class CounterTester2 {
  public static void main(String[] args) {
    Counter.increment(); Counter.increment(); Counter.increment();
    System.out.println("Current val: " + Counter.value);
    System.out.println("Attempt to increment:");
    /* Right before calling the increment mutator,
     * Counter.value is 3 and too large to be incremented.
     */
    Counter.increment();
  }
}
```

- Again, ***automation** is exactly rationale behind using JUnit!*

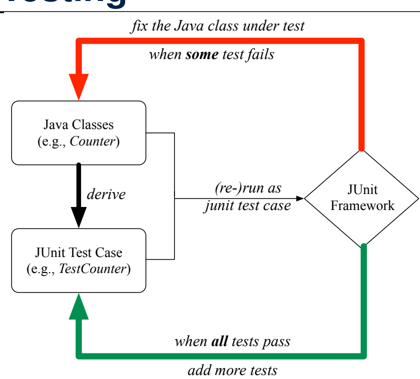
Exercises

1. Convert the rest of the cells into JUnit tests:

`c.getValue()`	`c.increment()`	`c.decrement()`
0	1	`ValueTooSmall`
1	2	0
2	3	1
3	`ValueTooBig`	2

2. Run all 8 tests and make sure you receive a *green* bar.
3. Now, introduction an error to the implementation: Change the line `value ++` in `Counter.increment` to `--`.
   - Re-run all 8 tests and you should receive a *red* bar. [Why?]
   - Undo the error injection, and re-run all 8 tests. [What happens?]

Regression Testing



Maintain a collection of tests which define the *correctness* of your Java class under development (CUD):

- Derive and run tests as soon as your CUD is *testable* .
  i.e., A Java class is testable when defined with method signatures.
- *Red* bar reported: Fix the class under test (CUT) until *green* bar.
- *Green* bar reported: Add more tests and Fix CUT when necessary.

Resources

- Official Site of JUnit 4:
  `http://junit.org/junit4/`
- API of JUnit assertions:
  `http://junit.sourceforge.net/javadoc/org/junit/Assert.html`
- Another JUnit Tutorial example:
  `https://courses.cs.washington.edu/courses/cse143/11wi/eclipse-tutorial/junit.shtml`

Index (1)

Index (2)

Classes and Objects

Readings: Chapters 3 – 4 of the Course Notes

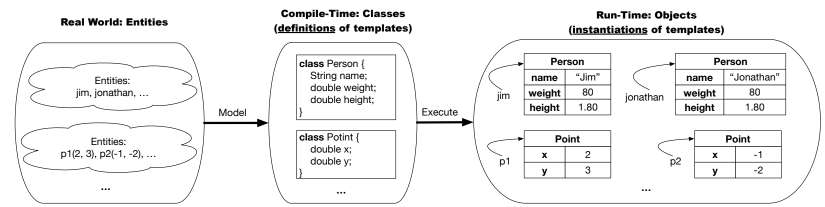
EECS2030: Advanced Object Oriented Programming
Fall 2017

CHEN-WEI WANG

Separation of Concerns: App vs. Model

- So far we have developed:
  Supplier: A single utility class.
  Client: A class with its `main` method using the utility methods.
- In Java:
  - We may define more than one (non-utility) *classes*
  - Each class may contain more than one *methods*
- *object-oriented programming* in Java:
  - Use *classes* to define templates
  - Use *objects* to instantiate classes
  - At *runtime*, *create* objects and *call* methods on objects, to *simulate interactions* between real-life entities.

Object Orientation: Observe, Model, and Execute



- We *observe* how real-world *entities* behave.
- We *model* the common *attributes* and *behaviour* of a set of entities in a single *class*.
- We *execute* the program by creating *instances* of classes, which interact in a way analogous to that of real-world *entities*.

Object-Oriented Programming (OOP)

- In real life, lots of *entities* exist and interact with each other.
  e.g., *People* gain/lose weight, marry/divorce, or get older.
  e.g., *Cars* move from one point to another.
  e.g., *Clients* initiate transactions with banks.
- Entities:
  - Possess *attributes*;
  - Exhibit *bebaviour*; and
  - Interact with each other.
- Goals: Solve problems *programmatically* by
  - *Classifying* entities of interest
    Entities in the same class share *common* attributes and bebaviour.
  - *Manipulating* data that represent these entities
    Each entity is represented by *specific* values.

OO Thinking: Templates vs. Instances (1.1)

A person is a being, such as a human, that has certain attributes and behaviour constituting personhood: a person ages and grows on their heights and weights.

- A template called `Person` defines the common
  - *attributes* (e.g., `age`, `weight`, `height`) [≈ nouns]
  - *behaviour* (e.g., get older, gain weight) [≈ verbs]

OO Thinking: Templates vs. Instances (1.2)

- Persons share these common *attributes* and *behaviour*.
  - Each person possesses an age, a weight, and a height.
  - Each person's age, weight, and height might be *distinct*
    e.g., `jim` is 50-years old, 1.8-meters tall and 80-kg heavy
    e.g., `jonathan` is 65-years old, 1.73-meters tall and 90-kg heavy
- Each person, depending on the *specific values* of their attributes, might exhibit *distinct* behaviour:
  - When `jim` gets older, he becomes 51
  - When `jonathan` gets older, he becomes 66.
  - `jim`'s BMI is based on his own height and weight [$\frac{80}{1.8^2}$]
  - `jonathan`'s BMI is based on his own height and weight [$\frac{90}{1.73^2}$]

OO Thinking: Templates vs. Instances (2.1)

Points on a two-dimensional plane are identified by their signed distances from the X- and Y-axises. A point may move arbitrarily towards any direction on the plane. Given two points, we are often interested in knowing the distance between them.

- A template called `Point` defines the common
  - *attributes* (e.g., `x`, `y`) [≈ nouns]
  - *behaviour* (e.g., move up, get distance from) [≈ verbs]

OO Thinking: Templates vs. Instances (2.2)

- Points share these common *attributes* and *behaviour*.
  - Each point possesses an x-coordinate and a y-coordinate.
  - Each point's location might be *distinct*
    e.g., `p1` is located at $(3, 4)$
    e.g., `p2` is located at $(-4, -3)$
- Each point, depending on the *specific values* of their attributes (i.e., locations), might exhibit *distinct* behaviour:
  - When `p1` moves up for 1 unit, it will end up being at $(3, 5)$
  - When `p2` moves up for 1 unit, it will end up being at $(-4, -2)$
  - Then, `p1`'s distance from origin: [$\sqrt{3^2 + 5^2}$]
  - Then, `p2`'s distance from origin: [$\sqrt{(-4)^2 + (-2)^2}$]

OO Thinking: Templates vs. Instances (3)

- A *template* defines what's **shared** by a set of related entities.
  - Common *attributes* (`age` in `Person`, `x` in `Point`)
  - Common *behaviour* (get older for `Person`, move up for `Point`)
- Each template may be *instantiated* into multiple instances.
  - `Person` instances: `jim` and `jonathan`
  - `Point` instances: `p1` and `p2`
- Each *instance* may have *specific values* for the attributes.
  - Each `Person` instance has an age:
    `jim` is 50-years old, `jonathan` is 65-years old
  - Each `Point` instance has a location:
    `p1` is at $(3, 4)$, `p2` is at $(-3, -4)$
- Therefore, instances of the same template may exhibit *distinct behaviour*.
  - Each `Person` instance can get older: `jim` getting older from 50 to 51; `jonathan` getting older from 65 to 66.
  - Each `Point` instance can move up: `p1` moving up from $(3, 3)$ results in $(3, 4)$; `p1` moving up from $(-3, -4)$ results in $(-3, -3)$.

OOP: Classes ≈ Templates

In Java, you use a *class* to define a *template* that enumerates *attributes* that are common to a set of *entities* of interest.

```
public class Person {
  int age;
  String nationality;
  double weight;
  double height;
}
```

```
public class Point {
  double x;
  double y;
}
```


OOP: Define Constructors for Creating Objects (1.1)

- Within class `Point`, you define *constructors*, specifying how instances of the `Point` template may be created.

```
public class Point {
  ... /* attributes: x, y */
  Point(double newX, double newY) {
    x = newX;
    y = newY; } }
```

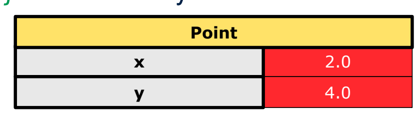
- In the corresponding tester class, each *call* to the `Point` constructor creates an instance of the `Point` template.

```
public class PersonTester {
  public static void main(String[] args) {
    Point p1 = new Point(2, 4);
    println(p1.x + " " + p1.y);
    Point p2 = new Point(-4, -3);
    println(p2.x + " " + p2.y); } }
```

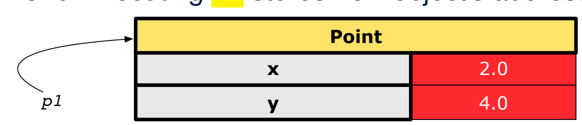

OOP: Define Constructors for Creating Objects (1.2)

```
Point p1 = new Point(2, 4);
```

1. **RHS (Source) of Assignment**: `new Point(2, 4)` creates a new *Point object* in memory.



2. **LHS (Target) of Assignment**: `Point p1` declares a *variable* that is meant to store the *address* of *some Point object*.
3. **Assignment**: Executing `=` stores new object's address in `p1`.



The `this` Reference (1)

- Each *class* may be instantiated to multiple *objects* at runtime.

```
class Point {
  double x; double y;
  void moveUp(double units) { y += units; }
}
```

- Each time when we call a method of some class, using the dot notation, there is a specific *target*/*context* object.

```
1 Point p1 = new Point(2, 3);
2 Point p2 = new Point(4, 6);
3 p1.moveUp(3.5);
4 p2.moveUp(4.7);
```

  - `p1` and `p2` are called the *call targets* or *context objects*.
  - **Lines 3 and 4** apply the same definition of the `moveUp` method.
  - But how does Java distinguish the change to `p1.y` versus the change to `p2.y`?

The `this` Reference (2)

- In the *method* definition, each *attribute* has an *implicit* `this` which refers to the *context object* in a call to that method.

```
class Point {
  double x;
  double y;
  Point(double newX, double newY) {
    this.x = newX;
    this.y = newY;
  }
  void moveUp(double units) {
    this.y = this.y + units;
  }
}
```

- Each time when the *class* definition is used to create a new `Point` *object*, the `this` reference is substituted by the name of the new object.

The `this` Reference (3)

- After we create `p1` as an instance of `Point`

```
Point p1 = new Point(2, 3);
```

- When invoking `p1.moveUp(3.5)`, a version of `moveUp` that is specific to `p1` will be used:

```
class Point {
  double x;
  double y;
  Point(double newX, double newY) {
    p1.x = newX;
    p1.y = newY;
  }
  void moveUp(double units) {
    p1.y = p1.y + units;
  }
}
```


The `this` Reference (4)

- After we create `p2` as an instance of `Point`

```
Point p2 = new Point(4, 6);
```

- When invoking `p2.moveUp(4.7)`, a version of `moveUp` that is specific to `p2` will be used:

```
class Point {
  double x;
  double y;
  Point(double newX, double newY) {
    p2.x = newX;
    p2.y = newY;
  }
  void moveUp(double units) {
    p2.y = p2.y + units;
  }
}
```

The `this` Reference (5)

The `this` reference can be used to *disambiguate* when the names of *input parameters* clash with the names of *class attributes*.

```
class Point {
  double x;
  double y;
  Point(double x, double y) {
    this.x = x;
    this.y = y;
  }
  void setX(double x) {
    this.x = x;
  }
  void setY(double y) {
    this.y = y;
  }
}
```


The `this` Reference (6.1): Common Error

The following code fragment compiles but is problematic:

```
class Person {
  String name;
  int age;
  Person(String name, int age) {
    name = name;
    age = age;
  }
  void setAge(int age) {
    age = age;
  }
}
```

Why? Fix?

The `this` Reference (6.2): Common Error

Always remember to use `this` when *input parameter* names clash with *class attribute* names.

```
class Person {
  String name;
  int age;
  Person(String name, int age) {
    this.name = name;
    this.age = age;
  }
  void setAge(int age) {
    this.age = age;
  }
}
```


OOP: Define Constructors for Creating Objects (2.1)

- Within class `Person`, you define *constructors*, specifying how instances of the `Person` template may be created.

```
public class Person {
  ... /* attributes: age, nationality, weight, height */
  Person(int newAge, String newNationality) {
    age = newAge;
    nationality = newNationality; } }
```

- In the corresponding tester class, each *call* to the `Person` constructor creates an instance of the `Person` template.

```
public class PersonTester {
  public static void main(String[] args) {
    Person jim = new Person(50, "British");
    println(jim.nationlaity + " " + jim.age);
    Person jonathan = new Person(60, "Canadian");
    println(jonathan.nationlaity + " " + jonathan.age); } }
```

OOP: Define Constructors for Creating Objects (2.2)

```
Person jim = new Person(50, "British");
```

1. **RHS (Source) of Assignment**: `new Person(50, "British")` creates a new *Person object* in memory.

Person	
age	50
nationality	"British"
weight	0.0
height	0.0

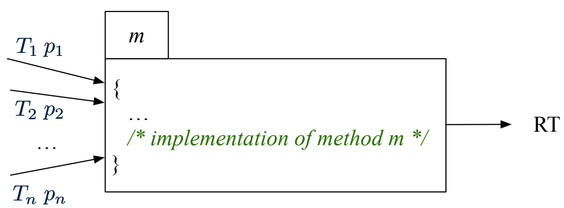
2. **LHS (Target) of Assignment**: `Point jim` declares a *variable* that is meant to store the *address* of *some Person object*.
3. **Assignment**: Executing `=` stores new object's address in `jim`.

jim →

Person	
age	50
nationality	"British"
weight	0.0
height	0.0

OOP: Methods (1.1)

- A *method* is a named block of code, *reusable* via its name.



- The *Signature* of a method consists of:
  - Return type [*RT* (which can be `void`)]
  - Name of method [*m*]
  - Zero or more *parameter names* [$p_1, p_2, \dots, p_n$]
  - The corresponding *parameter types* [$T_1, T_2, \dots, T_n$]
- A call to method *m* has the form: $m(a_1, a_2, \dots, a_n)$
  Types of *argument values* $a_1, a_2, \dots, a_n$ must match the the corresponding parameter types $T_1, T_2, \dots, T_n$.

OOP: Methods (1.2)

- In the body of the method, you may
  - Declare and use new *local variables*
    Scope of local variables is only within that method.
  - Use or change values of *attributes*.
  - Use values of *parameters*, if any.

```
class Person {
  String nationality;
  void changeNationality(String newNationality) {
    nationality = newNationality; } }
```

- *Call* a *method*, with a *context object*, by passing *arguments*.

```
class PersonTester {
  public static void main(String[] args) {
    Person jim = new Person(50, "British");
    Person jonathan = new Person(60, "Canadian");
    jim.changeNationality("Korean");
    jonathan.changeNationality("Korean"); } }
```


OOP: Methods (2)

- Each *class* `C` defines a list of methods.
  - A *method* `m` is a named block of code.
- We *reuse* the code of method `m` by calling it on an *object* `obj` of class `C`.
  For each *method call* `obj.m(...)`:
  - `obj` is the *context object* of type `C`
  - `m` is a method defined in class `C`
  - We intend to apply the *code effect of method* `m` to object `obj`.
    e.g., `jim.getOlder()` vs. `jonathan.getOlder()`
    e.g., `p1.moveUp(3)` vs. `p2.moveUp(3)`
- All objects of class `C` share *the same definition* of method `m`.
- However:
  ∵ Each object may have *distinct attribute values*.
  ∴ Applying *the same definition* of method `m` has *distinct effects*.

OOP: Methods (3)

1. *Constructor*
   - Same name as the class. No return type. *Initializes* attributes.
   - Called with the **new** keyword.
   - e.g., `Person jim = new Person(50, "British");`
2. *Mutator*
   - *Changes* (re-assigns) attributes
   - `void` return type
   - Cannot be used when a value is expected
   - e.g., `double h = jim.setHeight(78.5)` is illegal!
3. *Accessor*
   - *Uses* attributes for computations (without changing their values)
   - Any return type other than `void`
   - An explicit *`return` statement* (typically at the end of the method) returns the computation result to where the method is being used.
     e.g., `double bmi = jim.getBMI();`
     e.g., `println(p1.getDistanceFromOrigin());`

OOP: The Dot Notation (1)

- A binary operator:
  - **LHS** an object
  - **RHS** an attribute or a method
- Given a *variable* of some *reference type* that is **not** `null`:
  - We use a dot to retrieve any of its *attributes*.
    Analogous to 's in English
    e.g., `jim.nationality` means `jim`'s nationality
  - We use a dot to invoke any of its *mutator methods*, in order to *change* values of its attributes.
    e.g., `jim.changeNationality("CAN")` changes the `nationality` attribute of `jim`
  - We use a dot to invoke any of its *accessor methods*, in order to *use* the result of some computation on its attribute values.
    e.g., `jim.getBMI()` computes and returns the BMI calculated based on `jim`'s weight and height
  - Return value of an *accessor method* must be stored in a variable.
    e.g., `double jimBMI = jim.getBMI()`

OOP: The Dot Notation (2)

- **LHS** of dot *can be more complicated than a variable*:
  - It can be a *path* that brings you to an object

```
class Person {
  String name;
  Person spouse;
}
```

  - Say we have `Person jim = new Person("Jim Davies")`
  - Inquire about `jim`'s name? [`jim.name`]
  - Inquire about `jim`'s spouse's name? [`jim.spouse.name`]
  - But what if `jim` is single (i.e., `jim.spouse == null`)?
    Calling `jim.spouse.name` will trigger *NullPointerException*!!
  - Assuming that:
    - `jim` is not single. [`jim.spouse != null`]
    - The marriage is mutual. [`jim.spouse.spouse != null`]

    What does `jim.spouse.spouse.name` mean? [`jim.name`]

OOP: Method Calls

```
1 Point p1 = new Point(3, 4);
2 Point p2 = new Point(-6, -8);
3 System.out.println(p1.getDistanceFromOrigin());
4 System.out.println(p2.getDistanceFromOrigin());
5 p1.moveUp(2);
6 p2.moveUp(2);
7 System.out.println(p1.getDistanceFromOrigin());
8 System.out.println(p2.getDistanceFromOrigin());
```

- **Lines 1 and 2** create two different instances of `Point`
- **Lines 3 and 4:** invoking the same accessor method on two different instances returns *distinct* values
- **Lines 5 and 6:** invoking the same mutator method on two different instances results in *independent* changes
- **Lines 3 and 7:** invoking the same accessor method on the same instance *may* return *distinct* values, why? **Line 5**

OOP: Class Constructors (1)

- The purpose of defining a *class* is to be able to create *instances* out of it.
- To *instantiate* a class, we use one of its *constructors*.
- A constructor
  - declares input *parameters*
  - uses input parameters to *initialize* *some or all* of its *attributes*

OOP: Class Constructors (2)

```
public class Person {
  int age;
  String nationality;
  double weight;
  double height;
  Person(int initAge, String initNat) {
    age = initAge;
    nationality = initNat;
  }
  Person (double initW, double initH) {
    weight = initW;
    height = initH;
  }
  Person(int initAge, String initNat,
         double initW, double initH) {
    ... /* initialize all attributes using the parameters */
  }
}
```


OOP: Class Constructors (3)

```
public class Point {
  double x;
  double y;

  Point(double initX, double initY) {
    x = initX;
    y = initY;
  }

  Point(char axis, double distance) {
    if (axis == 'x') { x = distance; }
    else if (axis == 'y') { y = distance; }
    else { System.out.println("Error: invalid axis.") }
  }
}
```


OOP: Class Constructors (4)

- For each *class*, you may define *one or more* *constructors*:
  - *Names* of all constructors must match the class name.
  - *No return types* need to be specified for constructors.
  - Each constructor must have a *distinct* list of *input parameter types*.
  - Each *parameter* that is used to initialize an attribute must have a *matching type*.
  - The *body* of each constructor specifies how *some or all* *attributes* may be *initialized*.

OOP: Object Creation (1)

```
Point p1 = new Point(2, 4);
System.out.println(p1);
```

```
Point@677327b6
```

By default, the address stored in `p1` gets printed.

Instead, print out attributes separately:

```
System.out.println("(" + p1.x + ", " + p1.y + ")");
```

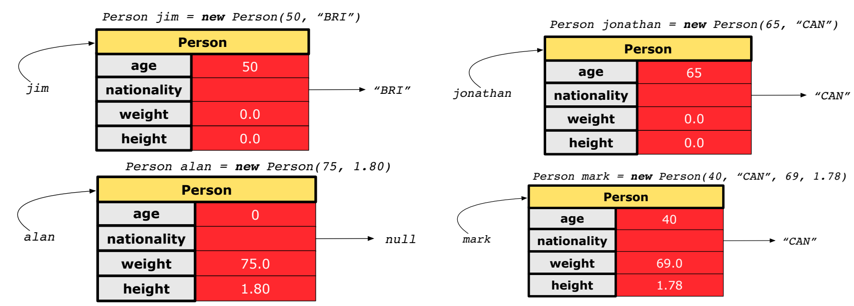
```
(2.0, 4.0)
```


OOP: Object Creation (2)

A constructor may only *initialize* some attributes and leave others *uninitialized*.

```
public class PersonTester {
  public static void main(String[] args) {
    /* initialize age and nationality only */
    Person jim = new Person(50, "BRI");
    /* initialize age and nationality only */
    Person jonathan = new Person(65, "CAN");
    /* initialize weight and height only */
    Person alan = new Person(75, 1.80);
    /* initialize all attributes of a person */
    Person mark = new Person(40, "CAN", 69, 1.78);
  }
}
```


OOP: Object Creation (3)

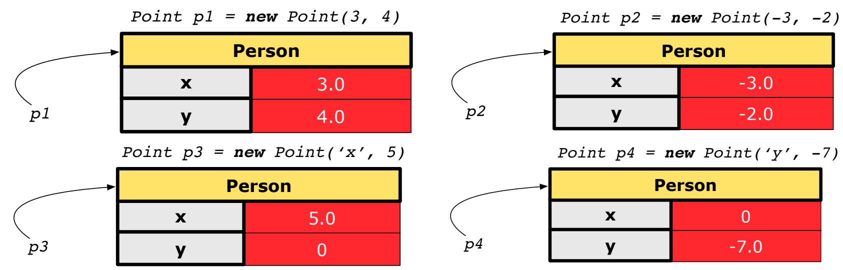


OOP: Object Creation (4)

A constructor may only *initialize* some attributes and leave others *uninitialized*.

```
public class PointTester {
  public static void main(String[] args) {
    Point p1 = new Point(3, 4);
    Point p2 = new Point(-3 -2);
    Point p3 = new Point('x', 5);
    Point p4 = new Point('y', -7);
  }
}
```

OOP: Object Creation (5)



OOP: Object Creation (6)

- When using the constructor, pass *valid* *argument values*:
  - The type of each argument value must match the corresponding parameter type.
  - e.g., `Person(50, "BRI")` matches `Person(int initAge, String initNationality)`
  - e.g., `Point(3, 4)` matches `Point(double initX, double initY)`
- When creating an instance, *uninitialized* attributes implicitly get assigned the *default values*.
  - Set *uninitialized* attributes properly later using **mutator** methods

```
Person jim = new Person(50, "British");
jim.setWeight(85);
jim.setHeight(1.81);
```


OOP: Mutator Methods

- These methods *change* values of attributes.
- We call such methods *mutators* (with `void` return type).

```
public class Person {
  ...
  void gainWeight(double units) {
    weight = weight + units;
  }
}
```

```
public class Point {
  ...
  void moveUp() {
    y = y + 1;
  }
}
```


OOP: Accessor Methods

- These methods *return* the result of computation based on attribute values.
- We call such methods *accessors* (with non-`void` return type).

```
public class Person {
  ...
  double getBMI() {
    double bmi = height / (weight * weight);
    return bmi;
  }
}
```

```
public class Point {
  ...
  double getDistanceFromOrigin() {
    double dist = Math.sqrt(x*x + y*y);
    return dist;
  }
}
```

OOP: Use of Mutator vs. Accessor Methods

- Calls to *mutator methods* *cannot* be used as values.
  - e.g., `System.out.println(jim.setWeight(78.5));` ×
  - e.g., `double w = jim.setWeight(78.5);` ×
  - e.g., `jim.setWeight(78.5);` ✓
- Calls to *accessor methods* *should* be used as values.
  - e.g., `jim.getBMI();` ×
  - e.g., `System.out.println(jim.getBMI());` ✓
  - e.g., `double w = jim.getBMI();` ✓

OOP: Method Parameters

- **Principle 1:** A *constructor* needs an *input parameter* for every attribute that you wish to initialize.

  e.g., `Person(double w, double h)` vs. `Person(String fName, String lName)`
- **Principle 2:** A *mutator* method needs an *input parameter* for every attribute that you wish to modify.

  e.g., In `Point`, `void moveToXAxis()` vs. `void moveUpBy(double unit)`
- **Principle 3:** An *accessor method* needs *input parameters* if the attributes alone are not sufficient for the intended computation to complete.

  e.g., In `Point`, `double getDistFromOrigin()` vs. `double getDistFrom(Point other)`

The `this` Reference (7.1): Exercise

Consider the `Person` class

```
class Person {
  String name;
  Person spouse;
  Person(String name) {
    this.name = name;
  }
}
```

How do you implement a mutator method `marry` which marries the current `Person` object to an input `Person` object?

The `this` Reference (7.2): Exercise

```
void marry(Person other) {
  if(this.spouse != null || other.spouse != null) {
    System.out.println("Error: both must be single.");
  }
  else { this.spouse = other; other.spouse = this; }
}
```

When we call `jim.marry(elsa)`: `this` is substituted by the call target `jim`, and `other` is substituted by the argument `elsa`.

```
void marry(Person other) {
  ...
    jim.spouse = elsa;
    elsa.spouse = jim;
  }
}
```

Java Data Types (1)

A (data) type denotes a set of related *runtime values*.

1. *Primitive Types*
   - *Integer* Type
     - `int` [set of 32-bit integers]
     - `long` [set of 64-bit integers]
   - *Floating-Point Number* Type
     - `double` [set of 64-bit FP numbers]
   - *Character* Type
     - `char` [set of single characters]
   - *Boolean* Type
     - `boolean` [set of `true` and `false`]
2. *Reference Type* : *Complex Type with Attributes and Methods*
   - *String* [set of references to character sequences]
   - *Person* [set of references to Person objects]
   - *Point* [set of references to Point objects]
   - *Scanner* [set of references to Scanner objects]

Java Data Types (2)

- A variable that is declared with a *type* but *uninitialized* is implicitly assigned with its *default value*.
  - **Primitive Type**
    - `int i;` [*0* is implicitly assigned to `i`]
    - `double d;` [*0.0* is implicitly assigned to `d`]
    - `boolean b;` [*false* is implicitly assigned to `b`]
  - **Reference Type**
    - `String s;` [*null* is implicitly assigned to `s`]
    - `Person jim;` [*null* is implicitly assigned to `jim`]
    - `Point p1;` [*null* is implicitly assigned to `p1`]
    - `Scanner input;` [*null* is implicitly assigned to `input`]
- You *can* use a primitive variable that is *uninitialized*.
  Make sure the *default value* is what you want!
- Calling a method on a *uninitialized* reference variable crashes your program. [*NullPointerException*]
  Always initialize reference variables!

Java Data Types (3.1)

- An attribute may be of type *ArrayList*, storing references to other objects.

```
class Person { Person spouse; }
```

- Methods may take as *parameters* references to other objects.

```
class Person {
  void marry(Person other) { ... } }
```

- *Return values* from methods may be references to other objects.

```
class Point {
  void moveUpBy(int i) { y = y + i; }
  Point movedUpBy(int i) {
    Point np = new Point(x, y);
    np.moveUp(i);
    return np;
  }
}
```


Java Data Types (3.2.1)

An attribute may be of type *ArrayList<Point>*, storing references to `Point` objects.

```
1  class PointCollector {
2   ArrayList<Point> points;
3   PointCollector() { points = new ArrayList<>(); }
4   void addPoint(Point p) {
5    points.add (p); }
6   void addPoint(double x, double y) {
7    points.add (new Point(x, y)); }
8   ArrayList<Point> getPointsInQuadrantI() {
9    ArrayList<Point> q1Points = new ArrayList<>();
10   for(int i = 0; i < points.size(); i ++) {
11    Point p = points.get(i);
12    if(p.x > 0 && p.y > 0) { q1Points.add (p); } }
13   return q1Points;
14  } }
```

L8 & L9 may be replaced by:

```
for(Point p : points) { q1Points.add(p); }
```

Java Data Types (3.2.2)

```
class PointCollectorTester {
 public static void main(String[] args) {
   PointCollector pc = new PointCollector();
   System.out.println(pc.points.size());  /* 0 */
   pc.addPoint(3, 4);
   System.out.println(pc.points.size());  /* 1 */
   pc.addPoint(-3, 4);
   System.out.println(pc.points.size());  /* 2 */
   pc.addPoint(-3, -4);
   System.out.println(pc.points.size());  /* 3 */
   pc.addPoint(3, -4);
   System.out.println(pc.points.size());  /* 4 */
   ArrayList<Point> ps = pc.getPointsInQuadrantI();
   System.out.println(ps.length);  /* 1 */
   System.out.println("(" + ps[0].x + ", " + ps[0].y + ")");
   /* (3, 4) */
 }
}
```


Java Data Types (3.3.1)

An attribute may be of type `Point[]`, storing references to `Point` objects.

```
class PointCollector {
 Point[] points; int nop; /* number of points */
 PointCollector() { points = new Point[100]; }
 void addPoint(double x, double y) {
  points[nop] = new Point(x, y); nop++; }
 Point[] getPointsInQuadrantI() {
  Point[] ps = new Point[nop];
  int count = 0; /* number of points in Quadrant I */
  for(int i = 0; i < nop; i ++) {
   Point p = points[i];
   if(p.x > 0 && p.y > 0) { ps[count] = p; count ++; } }
  Point[] q1Points = new Point[count];
  /* ps contains null if count < nop */
  for(int i = 0; i < count; i ++) { q1Points[i] = ps[i] }
  return q1Points ;
 } }
```

Required Reading: Point and PointCollector

Java Data Types (3.3.2)

```
class PointCollectorTester {
 public static void main(String[] args) {
   PointCollector pc = new PointCollector();
   System.out.println(pc.nop);  /* 0 */
   pc.addPoint(3, 4);
   System.out.println(pc.nop);  /* 1 */
   pc.addPoint(-3, 4);
   System.out.println(pc.nop);  /* 2 */
   pc.addPoint(-3, -4);
   System.out.println(pc.nop);  /* 3 */
   pc.addPoint(3, -4);
   System.out.println(pc.nop);  /* 4 */
   Point[] ps = pc.getPointsInQuadrantI();
   System.out.println(ps.length);  /* 1 */
   System.out.println("(" + ps[0].x + ", " + ps[0].y + ")");
   /* (3, 4) */
 }
}
```


OOP: Object Alias (1)

```
1 int i = 3;
2 int j = i;  System.out.println(i == j);  /* true */
3 int k = 3;  System.out.println(k == i && k == j);  /* true */
```

- **Line 2** copies the number stored in `i` to `j`.
- After **Line 4**, `i`, `j`, `k` refer to three separate integer placeholder, which happen to store the same value `3`.

```
1 Point p1 = new Point(2, 3);
2 Point p2 = p1;  System.out.println(p1 == p2);  /* true */
3 Point p3 = new Point(2, 3);
4 Systme.out.println(p3 == p1 || p3 == p2);  /* false */
5 Systme.out.println(p3.x == p1.x && p3.y == p1.y);  /* true */
6 Systme.out.println(p3.x == p2.x && p3.y == p2.y);  /* true */
```

- **Line 2** copies the *address* stored in `p1` to `p2`.
- Both `p1` and `p2` refer to the same object in memory!
- `p3`, whose *contents* are same as `p1` and `p2`, refer to a different object in memory.

OO Program Programming: Object Alias (2.1)

Problem: Consider assignments to *primitive* variables:

```
int i1 = 1;
int i2 = 2;
int i3 = 3;
int[] numbers1 = {i1, i2, i3};
int[] numbers2 = new int[numbers1.length];
for(int i = 0; i < numbers1.length; i ++) {
  numbers2[i] = numbers1[i];
}
numbers1[0] = 4;
System.out.println(numbers1[0]);
System.out.println(numbers2[0]);
```


OO Program Programming: Object Alias (2.2)

Problem: Consider assignments to *reference* variables:

```
Person alan = new Person("Alan");
Person mark = new Person("Mark");
Person tom = new Person("Tom");
Person jim = new Person("Jim");
Person[] persons1 = {alan, mark, tom};
Person[] persons2 = new Person[persons1.length];
for(int i = 0; i < persons1.length; i ++) {
  persons2[i] = persons1[i]; }
persons1[0].setAge(70);
System.out.println(jim.age);
System.out.println(alan.age);
System.out.println(persons2[0].age);
persons1[0] = jim;
persons1[0].setAge(75);
System.out.println(jim.age);
System.out.println(alan.age);
System.out.println(persons2[0].age);
```


Call by Value vs. Call by Reference (1)

- Consider the general form of a call to some ***mutator method*** `m`, with ***context object*** `co` and **argument value** `arg`:

  `co.m (arg)`

  - Argument variable **arg** is ***not*** passed directly for the method call.
  - Instead, argument variable **arg** is passed ***indirectly***: a *copy* of the value stored in **arg** is made and passed for the method call.
- What can be the type of variable **arg**? [Primitive or Reference]
  - **arg** is primitive type (e.g., `int`, `char`, `boolean`, *etc.*):
    Call by Value : Copy of **arg**'s *stored value* (e.g., `2`, `'j'`, `true`) is made and passed.
  - **arg** is reference type (e.g., `String`, `Point`, `Person`, *etc.*):
    Call by Reference : Copy of **arg**'s *stored reference/address* (e.g., `Point@5cb0d902`) is made and passed.

Call by Value vs. Call by Reference (2.1)

For illustration, let's assume the following variant of the `Point` class:

```
class Point {
  int x;
  int y;
  Point(int x, int y) {
    this.x = x;
    this.y = y;
  }
  void moveVertically(int y){
    this.y += y;
  }
  void moveHorizontally(int x){
    this.x += x;
  }
}
```

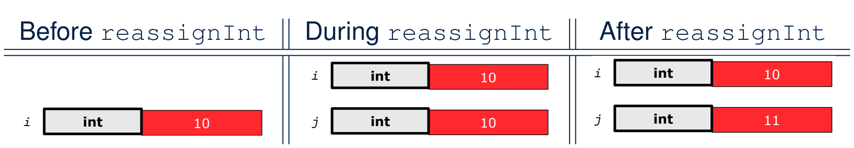
Call by Value vs. Call by Reference (2.2.1)

```java
public class Util {
  void reassignInt(int j) {
    j = j + 1; }
  void reassignRef(Point q) {
    Point np = new Point(6, 8);
    q = np; }
  void changeViaRef(Point q) {
    q.moveHorizontally(3);
    q.moveVertically(4); } }
```

```java
1 @Test
2 public void testCallByVal() {
3   Util u = new Util();
4   int i = 10;
5   assertTrue(i == 10);
6   u.reassignInt(i);
7   assertTrue(i == 10);
8 }
```

- ***Before*** the mutator call at **L6**, *primitive* variable `i` stores `10`.
- **When** executing the mutator call at **L6**, due to *call by value*, a copy of variable `i` is made.
  ⇒ The assignment `i = i + 1` is only effective on this copy, not the original variable `i` itself.
- ∴ ***After*** the mutator call at **L6**, variable `i` still stores `10`.

Call by Value vs. Call by Reference (2.2.2)



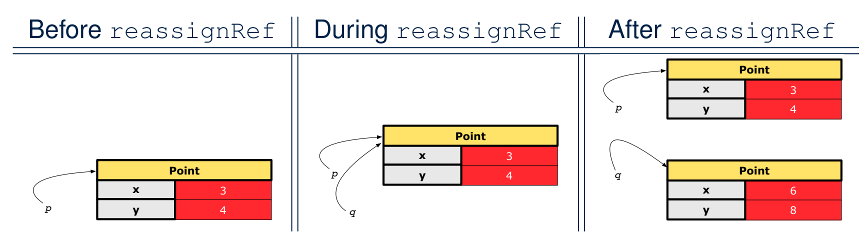
Call by Value vs. Call by Reference (2.3.1)

```java
public class Util {
  void reassignInt(int j) {
    j = j + 1; }
  void reassignRef(Point q) {
    Point np = new Point(6, 8);
    q = np; }
  void changeViaRef(Point q) {
    q.moveHorizontally(3);
    q.moveVertically(4); } }
```

```java
1 @Test
2 public void testCallByRef_1() {
3   Util u = new Util();
4   Point p = new Point(3, 4);
5   Point refOfPBefore = p;
6   u.reassignRef(p);
7   assertTrue(p==refOfPBefore);
8   assertTrue(p.x==3 && p.y==4);
9 }
```

- ***Before*** the mutator call at **L6**, *reference* variable `p` stores the *address* of some `Point` object (whose `x` is `3` and `y` is `4`).
- **When** executing the mutator call at **L6**, due to *call by reference*, a *copy of address* stored in `p` is made.
  ⇒ The assignment `p = np` is only effective on this copy, not the original variable `p` itself.
- ∴ ***After*** the mutator call at **L6**, variable `p` still stores the original address (i.e., same as `refOfPBefore`).

Call by Value vs. Call by Reference (2.3.2)



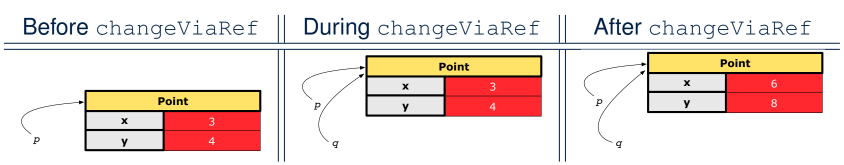
Call by Value vs. Call by Reference (2.4.1)

```
public class Util {
  void reassignInt(int j) {
    j = j + 1; }
  void reassignRef(Point q) {
    Point np = new Point(6, 8);
    q = np; }
  void changeViaRef(Point q) {
    q.moveHorizontally(3);
    q.moveVertically(4); } }
```

```
1 @Test
2 public void testCallByRef_2() {
3   Util u = new Util();
4   Point p = new Point(3, 4);
5   Point refOfPBefore = p;
6   u.changeViaRef(p);
7   assertTrue(p==refOfPBefore);
8   assertTrue(p.x==6 && p.y==8);
9 }
```

- ***Before*** the mutator call at **L6**, *reference* variable `p` stores the *address* of some `Point` object (whose `x` is `3` and `y` is `4`).
- **When** executing the mutator call at **L6**, due to *call by reference*, a *copy of address* stored in `p` is made. [**Alias**: `p` and `q` store same address.]
  ⇒ Calls to `q.moveHorizontally` and `q.moveVertically` are effective on both `p` and `q`.
- ∴ ***After*** the mutator call at **L6**, variable `p` still stores the original address (i.e., same as `refOfPBefore`), but its `x` and `y` have been modified via `q`.

Call by Value vs. Call by Reference (2.4.2)



Aggregation vs. Composition: Terminology

Container object: an object that contains others.

Containee object: an object that is contained within another.

- e.g., Each course has a faculty member as its instructor.
  - ***Container***: `Course` ***Containee***: `Faculty`.
- e.g., Each student is registered in a list of courses; Each faculty member teaches a list of courses.
  - ***Container***: `Student`, `Faculty` ***Containees***: `Course`.

    e.g., `eecs2030` taken by `jim` (student) and taught by `tom` (faculty).

    ⇒ ***Containees*** **may** be *shared* by different classes of ***containers***.

    e.g., When EECS2030 is finished, `jim` and `jackie` still exist!

    ⇒ ***Containees*** **may** exist *independently* without their ***containers***.
- e.g., In a file system, each directory contains a list of files.
  - ***Container***: `Directory` ***Containees***: `File`.

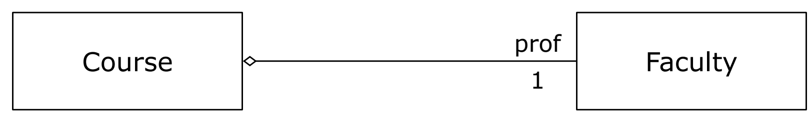
    e.g., Each file has exactly one parent directory.

    ⇒ A ***containee*** **may** be *owned* by only one ***container***.

    e.g., Deleting a directory also deletes the files it contains.

    ⇒ ***Containees*** **may** *co-exist* with their ***containers***.

Aggregation: Independent Containees Shared by Containers (1.1)




```
class Course {
  String title;
  Faculty prof;
  Course(String title) {
    this.title = title;
  }
  void setProf(Faculty prof) {
    this.prof = prof;
  }
  Faculty getProf() {
    return this.prof;
  }
}
```

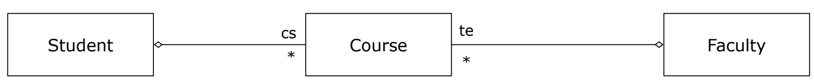
```
class Faculty {
  String name;
  Faculty(String name) {
    this.name = name;
  }
  void setName(String name) {
    this.name = name;
  }
  String getName() {
    return this.name;
  }
}
```

Aggregation: Independent Containees Shared by Containers (1.2)

```
@Test
public void testAggregation1() {
  Course eecs2030 = new Course("Advanced OOP");
  Course eecs3311 = new Course("Software Design");
  Faculty prof = new Faculty("Jackie");
  eecs2030.setProf(prof);
  eecs3311.setProf(prof);
  assertTrue(eecs2030.getProf() == eecs3311.getProf());
  /* aliasing */
  prof.setName("Jeff");
  assertTrue(eecs2030.getProf() == eecs3311.getProf());
  assertTrue(eecs2030.getProf().getName().equals("Jeff"));

  Faculty prof2 = new Faculty("Jonathan");
  eecs3311.setProf(prof2);
  assertTrue(eecs2030.getProf() != eecs3311.getProf());
  assertTrue(eecs2030.getProf().getName().equals("Jeff"));
  assertTrue(eecs3311.getProf().getName().equals("Jonathan"));
}
```


Aggregation: Independent Containees Shared by Containers (2.1)




```
class Student {
  String id; ArrayList<Course> cs; /* courses */
  Student(String id) { this.id = id; cs = new ArrayList<>(); }
  void addCourse(Course c) { cs.add(c); }
  ArrayList<Course> getCS() { return cs; }
}
```

```
class Course { String title; }
```

```
class Faculty {
  String name; ArrayList<Course> te; /* teaching */
  Faculty(String name) { this.name = name; te = new ArrayList<>(); }
  void addTeaching(Course c) { te.add(c); }
  ArrayList<Course> getTE() { return te; }
}
```

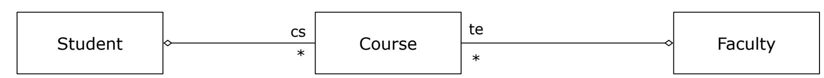

Aggregation: Independent Containees Shared by Containers (2.2)

```
@Test
public void testAggregation2() {
  Faculty p = new Faculty("Jackie");
  Student s = new Student("Jim");
  Course eecs2030 = new Course("Advanced OOP");
  Course eecs3311 = new Course("Software Design");
  eecs2030.setProf(p);
  eecs3311.setProf(p);
  p.addTeaching(eecs2030);
  p.addTeaching(eecs3311);
  s.addCourse(eecs2030);
  s.addCourse(eecs3311);

  assertTrue(eecs2030.getProf() == s.getCS().get(0).getProf());
  assertTrue(s.getCS().get(0).getProf() == s.getCS().get(1).getProf());
  assertTrue(eecs3311 == s.getCS().get(1));
  assertTrue(s.getCS().get(1) == p.getTE().get(1));
}
```


OOP: The Dot Notation (3.1)

In real life, the relationships among classes are sophisticated.




```
class Student {
  String id;
  ArrayList<Course> cs;
}
```

```
class Course {
  String title;
  Faculty prof;
}
```

```
class Faculty {
  String name;
  ArrayList<Course> te;
}
```

Aggregation links between classes constrain how you can *navigate* among these classes.

e.g., In the context of class `Student`:

- Writing **`cs`** denotes the list of registered courses.
- Writing **`cs[i]`** (where `i` is a valid index) navigates to the class `Course`, which changes the context to class `Course`.

OOP: The Dot Notation (3.2)

```
class Student {
  String id;
  ArrayList<Course> cs;
}
```

```
class Course {
  String title;
  Faculty prof;
}
```

```
class Faculty {
  String name;
  ArrayList<Course> te;
}
```

```
class Student {
  ... /* attributes */
  /* Get the student's id */
  String getID() { return this.id; }
  /* Get the title of the ith course */
  String getCourseTitle(int i) {
    return this.cs.get(i).title;
  }
  /* Get the instructor's name of the ith course */
  String getInstructorName(int i) {
    return this.cs.get(i).prof.name;
  }
}
```


OOP: The Dot Notation (3.3)

```
class Student {
  String id;
  ArrayList<Course> cs;
}
```

```
class Course {
  String title;
  Faculty prof;
}
```

```
class Faculty {
  String name;
  ArrayList<Course> te;
}
```

```
class Course {
  ... /* attributes */
  /* Get the course's title */
  String getTitle() { return this.title; }
  /* Get the instructor's name */
  String getInstructorName() {
    return this.prof.name;
  }
  /* Get title of ith teaching course of the instructor */
  String getCourseTitleOfInstructor(int i) {
    return this.prof.te.get(i).title;
  }
}
```


OOP: The Dot Notation (3.4)

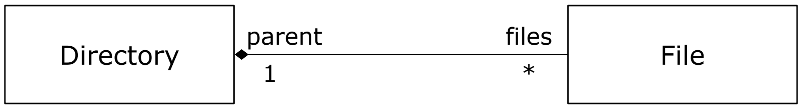
```
class Student {
  String id;
  ArrayList<Course> cs;
}
```

```
class Course {
  String title;
  Faculty prof;
}
```

```
class Faculty {
  String name;
  ArrayList<Course> te;
}
```

```
class Faculty {
  ... /* attributes */
  /* Get the instructor's name */
  String getName() {
    return this.name;
  }
  /* Get the title of ith teaching course */
  String getCourseTitle(int i) {
    return this.te.get(i).title;
  }
}
```


Composition: Dependent Containees Owned by Containers (1.1)

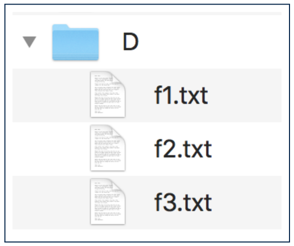


Assumption: Files are not shared among directories.

```
class File {
  String name;
  File(String name) {
    this.name = name;
  }
}
```

```
class Directory {
  String name;
  File[] files;
  int nof; /* num of files */
  Directory(String name) {
    this.name = name;
    files = new File[100];
  }
  void addFile(String fileName) {
    files[nof] = new File(fileName);
    nof ++;
  }
}
```

Composition: Dependent Containees Owned by Containers (1.2.1)

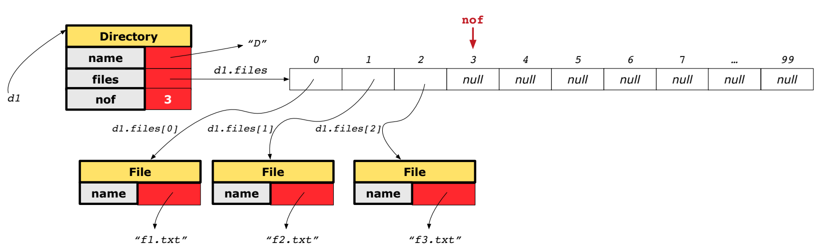



```
1 @Test
2 public void testComposition() {
3   Directory d1 = new Directory("D");
4   d1.addFile("f1.txt");
5   d1.addFile("f2.txt");
6   d1.addFile("f3.txt");
7   assertTrue(
8     d1.files[0].name.equals("f1.txt"));
9 }
```

- **L4**: a 1st `File` object is created and ***owned exclusively*** by `d1`. No other directories are sharing this `File` object with `d1`.
- **L5**: a 2nd `File` object is created and ***owned exclusively*** by `d1`. No other directories are sharing this `File` object with `d1`.
- **L6**: a 3rd `File` object is created and ***owned exclusively*** by `d1`.

Composition: Dependent Containees Owned by Containers (1.2.2)

Right before test method `testComposition` terminates:



Composition: Dependent Containees Owned by Containers (1.3)

Problem: How do you implement a *copy instructor* for the `Directory` class?

```
class Directory {
  Directory(Directory other) {
    /* ?? */
  }
}
```

Hints:

- The implementation should be consistent with the effect of copying and pasting a directory.
- Separate copies of files are created.

Composition: Dependent Containees Owned by Containers (1.4.1)

Version 1: *Shallow Copy* by copying all attributes using =.

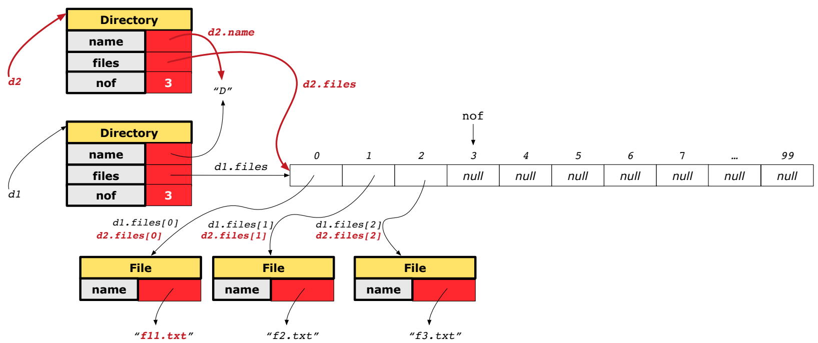
```
class Directory {
  Directory(Directory other) {
    /* value copying for primitive type */
    nof = other.nof;
    /* address copying for reference type */
    name = other.name; files = other.files; } }
```

Is a shallow copy satisfactory to support composition?
i.e., Does it still forbid sharing to occur? [***NO***]

```
@Test
void testShallowCopyConstructor() {
  Directory d1 = new Directory("D");
  d1.addFile("f1.txt"); d1.addFile("f2.txt"); d1.addFile("f3.txt");
  Directory d2 = new Directory(d1);
  assertTrue(d1.files == d2.files); /* violation of composition */
  d2.files[0].changeName("f11.txt");
  assertFalse(d1.files[0].name.equals("f1.txt")); }
```

Composition: Dependent Containees Owned by Containers (1.4.2)

Right before test method `testShallowCopyConstructor` terminates:



Composition: Dependent Containees Owned by Containers (1.5.1)

Version 2: a *Deep Copy*

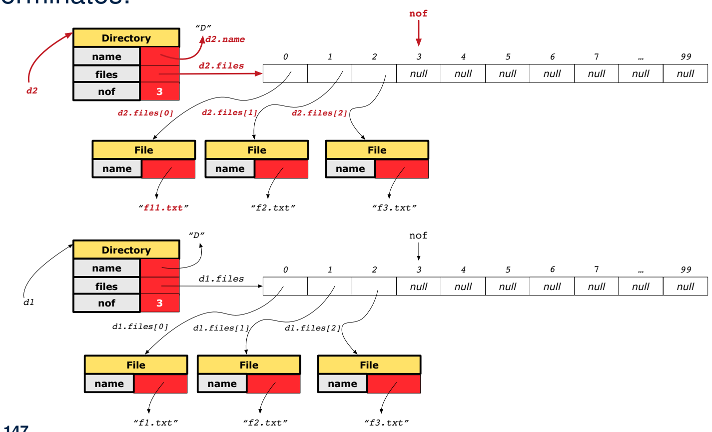
```
class File {
  File(File other) {
    this.name =
      new String(other.name);
  }
}
```

```
class Directory {
  Directory(String name) {
    this.name = new String(name);
    files = new File[100]; }
  Directory(Directory other) {
    this (other.name);
    for(int i = 0; i < nof; i ++) {
      File src = other.files[i];
      File nf = new File(src);
      this.addFile(nf); } } }
```

```
@Test
void testDeepCopyConstructor() {
  Directory d1 = new Directory("D");
  d1.addFile("f1.txt"); d1.addFile("f2.txt"); d1.addFile("f3.txt");
  Directory d2 = new Directory(d1);
  assertTrue(d1.files != d2.files); /* composition preserved */
  d2.files[0].changeName("f11.txt");
  assertTrue(d1.files[0].name.equals("f1.txt")); }
```


Composition: Dependent Containees Owned by Containers (1.5.2)

Right before test method `testDeepCopyConstructor` terminates:



Composition: Dependent Containees Owned by Containers (1.6)

Exercise: Implement the accessor in class `Directory`

```
class Directory {
  File[] files;
  int nof;
  File[] getFiles() {
    /* Your Task */
  }
}
```

so that it ***preserves composition***, i.e., does not allow references of files to be shared.

Aggregation vs. Composition (1)

Terminology:

- **Container** object: an object that contains others.
- **Containee** object: an object that is contained within another.

Aggregation :

- Containees (e.g., `Course`) may be *shared* among containers (e.g., `Student`, `Faculty`).
- Containees *exist independently* without their containers.
- When a container is destroyed, its containees still exist.

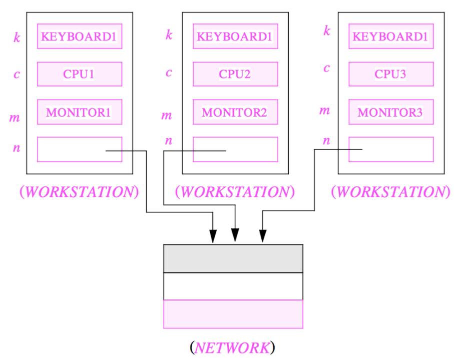
Composition :

- Containers (e.g, `Directory`, `Department`) *own* exclusive access to their containees (e.g., `File`, `Faculty`).
- Containees cannot exist without their containers.
- Destroying a container destroys its containeees *cascadingly*.

Aggregation vs. Composition (2)

Aggregations and *Compositions* may exist at the same time!
e.g., Consider a workstation:

- Each workstation owns CPU, monitor, keyword. [***compositions***]
- All workstations share the same network. [***aggregations***]



OOP: Equality (1)

```
Point p1 = new Point(2, 3);
Point p2 = new Point(2, 3);
boolean sameLoc = ( p1 == p2 );
System.out.println("p1 and p2 same location?" + sameLoc);
```

```
p1 and p2 same location?  false
```


OOP: Equality (2)

- Recall that
  - A *primitive* variable stores a primitive *value*
    e.g., `double d1 = 7.5; double d2 = 7.5;`
  - A *reference* variable stores the *address* to some object (rather than storing the object itself)
    e.g., `Point p1 = new Point(2, 3)` assigns to `p1` the address of the new `Point` object
    e.g., `Point p2 = new Point(2, 3)` assigns to `p2` the address of *another* new `Point` object
- The binary operator `==` may be applied to compare:
  - *Primitive* variables: their *contents* are compared
    e.g., `d1 == d2` evaluates to *true*
  - *Reference* variables: the *addresses* they store are compared (**rather than** comparing contents of the objects they refer to)
    e.g., `p1 == p2` evaluates to *false* because `p1` and `p2` are addresses of *different* objects, even if their contents are *identical*.

OOP: Equality (3)

- Implicitly:
  - Every class is a *child/sub* class of the `Object` class.
  - The `Object` class is the *parent/super* class of every class.
- There are two useful *accessor methods* that every class *inherits* from the `Object` class:
  - `boolean equals(Object other)`
    Indicates whether some other object is "equal to" this one.
    - The default definition inherited from `Object`:

```
boolean equals(Object other) {
  return (this == other); }
```

  - `String toString()`
    Returns a string representation of the object.
- Very often when you define new classes, you want to *redefine* / *override* the inherited definitions of `equals` and `toString`.

OOP: Contract of `equals`

Given that reference variables `x`, `y`, `z` are not `null`:

- $$\neg\, x.equals(null)$$
- *Reflexive*:
  $$x.equals(x)$$
- *Symmetric*
  $$x.equals(y) \iff y.equals(x)$$
- *Transitive*
  $$x.equals(y) \wedge y.equals(z) \Rightarrow x.equals(z)$$

API of `equals`   Inappropriate Def. of `equals` using `hashCode`

OOP: Equality (4.1)

- How do we compare *contents* rather than addresses?
- Define the *accessor method* `equals`, e.g.,

```
class Point {
  double x; double y;
  boolean equals (Object obj) {
    if(this == obj) { return true; }
    if(obj == null) { return false; }
    if(this.getClass() != obj.getClass()) { return false; }
    Point other = (Point) obj;
    return this.x == other.x && this.y == other.y; } }
```

```
class PointTester {
  String s = "(2, 3)";
  Point p1 = new Point(2, 3); Point p2 = new Point(2, 3);
  System.out.println(p1. equals (p1));  /* true */
  System.out.println(p1.equals(null));  /* false */
  System.out.println(p1.equals(s));  /* false */
  System.out.println(p1 == p2);  /* false */
  System.out.println(p1. equals (p2));  /* true */ }
```


OOP: Equality (4.2)

- When making a method call `p.equals(o)`:
  - Variable `p` is of type `Point`
  - Variable `o` can be any type
- We define `p` and `o` as ***equal*** if:
  - Either `p` and `o` refer to the same object;
  - Or:
    - `o` is not null.
    - `p` and `o` are of the same type.
    - The `x` and `y` coordinates are the same.
- **Q**: In the `equals` method of `Point`, why is there no such a line:

```
class Point {
  boolean equals (Object obj) {
    if(this == null) { return false; }
```

A: If `this` is `null`, a `NullPointerException` would have occurred and prevent the body of `equals` from being executed.

OOP: Equality (4.3)

```
1 class Point {
2  boolean equals (Object obj) {
3   ...
4   Point other = (Point) obj;
5   return this.x == other.x && this.y == other.y; } }
```

- `Object obj` at **L2** declares a parameter `obj` of type `Object`.
- `Point p` at **L4** declares a variable `p` of type `Point`.
  We call such types declared at compile time as ***static type***.
- The list of applicable methods that we may call on a variable depends on its ***static type***.
  e.g., We may only call the small list of methods defined in `Object` class on `obj`, which does not include `x` and `y` (specific to `Point`).
- If we are SURE that an object's "actual" type is different from its ***static type***, then we can *cast* it.
  e.g., Given that `this.getClass() == obj.getClass()`, we are sure that `obj` is also a `Point`, so we can cast it to `Point`.
- Such cast allows more attributes/methods to be called upon `(Point) obj` at **L5**.

OOP: Equality (5.1)

Exercise: Persons are *equal* if names and measures are equal.

```
1 class Person {
2  String firstName; String lastName; double weight; double height;
3  boolean equals (Object obj) {
4   if(this == obj) { return true }
5   if(obj == null || this.getClass() != obj.getClass()) {
6    return false; }
7   Person other = (Person) obj;
8   return
9      this.weight == other.weight && this.height == other.height
10    && this.firstName. equals (other.firstName)
11    && this.lastName. equals (other.lastName) } }
```

Q: At **L5**, will we get `NullPointerException` if `obj` is `Null`?
A: ***No*** ∵ Short-Circuit Effect of `||`
`obj` is `null`, then `obj == null` evaluates to ***true***
⇒ no need to evaluate the RHS

The left operand `obj == null` acts as a *guard constraint* for the right operand `this.getClass() != obj.getClass()`.

OOP: Equality (5.2)

Exercise: Persons are *equal* if names and measures are equal.

```
1 class Person {
2  String firstName; String lastName; double weight; double height;
3  boolean equals (Object obj) {
4   if(this == obj) { return true }
5   if(obj == null || this.getClass() != obj.getClass()) {
6    return false; }
7   Person other = (Person) obj;
8   return
9      this.weight == other.weight && this.height == other.height
10    && this.firstName. equals (other.firstName)
11    && this.lastName. equals (other.lastName) } }
```

Q: At **L5**, if swapping the order of two operands of disjunction:
`this.getClass() != obj.getClass() || obj == null`
Will we get `NullPointerException` if `obj` is `Null`?
A: ***Yes*** ∵ Evaluation of operands is from left to right.

OOP: Equality (5.3)

Exercise: Persons are *equal* if names and measures are equal.

```
1 class Person {
2  String firstName; String lastName; double weight; double height;
3  boolean equals (Object obj) {
4   if(this == obj) { return true }
5   if(obj == null || this.getClass() != obj.getClass()) {
6    return false; }
7   Person other = (Person) obj;
8   return
9      this.weight == other.weight && this.height == other.height
10    && this.firstName. equals (other.firstName)
11    && this.lastName. equals (other.lastName) } }
```

L10 & L11 call `equals` method defined in the `String` class.
When defining `equals` method for your own class, *reuse* `equals` methods defined in other classes wherever possible.

OOP: Equality (6)

Two notions of *equality* for variables of *reference* types:

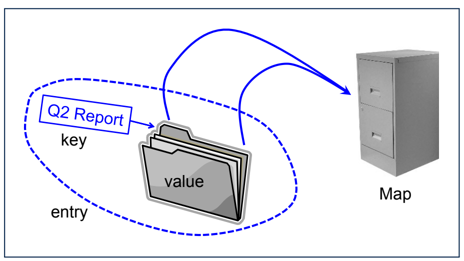
- *Reference Equality* : use == to compare *addresses*
- *Object Equality* : define `equals` method to compare *contents*

```
Point p1 = new Point(3, 4);
Point p2 = new Point(3, 4);
Point p3 = new Point(4, 5);
System.out.println(p1 == p1);   /* true */
System.out.println(p1.equals(p1));   /* true */
System.out.println(p1 == p2);   /* false */
System.out.println(p1.equals(p2));   /* true */
System.out.println(p2 == p3);   /* false */
System.out.println(p2.equals(p3));   /* false */
```

- Being *reference*-equal implies being *object*-equal
- Being *object*-equal does *not* imply being *reference*-equal

Hashing: What is a Map?

- A *map* (a.k.a. table or dictionary) stores a collection of *entries*.



ENTRY	
(SEARCH) KEY	VALUE
1	D
25	C
3	F
14	Z
6	A
39	C
7	Q

- Each *entry* is a pair: a *value* and its *(search) key*.
- Each *search key* :
  - *Uniquely* identifies an object in the map
  - Should be used to *efficiently* retrieve the associated value
- Search keys must be *unique* (i.e., do not contain duplicates).

Hashing: Arrays are Maps

- Each array *entry* is a pair: an object and its *numerical* index.
  e.g., say `String[] a = {"A", "B", "C"}`, how many entries?
  3 entries: `(0, "A")`, `(1, "B")`, `(2, "C")`
- *Search keys* are the set of numerical index values.
- The set of index values are *unique* [e.g., $0 .. (a.length - 1)$]
- Given a *valid* index value *i*, we can
  - *Uniquely* determines where the object is [$(i+1)^{th}$ item]
  - *Efficiently* retrieves that object [`a[i]` ≈ fast memory access]
- Maps in general may have *non-numerical* key values:
  - Student ID [student record]
  - Social Security Number [resident record]
  - Passport Number [citizen record]
  - Residential Address [household record]
  - Media Access Control (MAC) Address [PC/Laptop record]
  - Web URL [web page]

  ...

Hashing: Naive Implementation of Map

- **Problem**: Support the construction of this simple map:

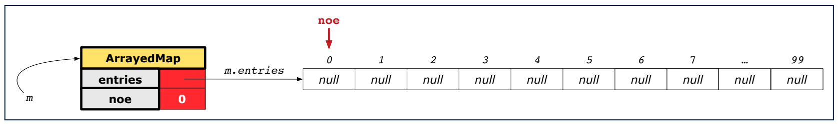
ENTRY	
(SEARCH) KEY	VALUE
1	D
25	C
3	F
14	Z
6	A
39	C
7	Q

  Let's just assume that the maximum map capacity is 100.
- **Naive Solution**:
  Let's understand the expected runtime structures before seeing the Java code!

Hashing: Naive Implementation of Map (0)

After executing `ArrayedMap m = new ArrayedMap()`:

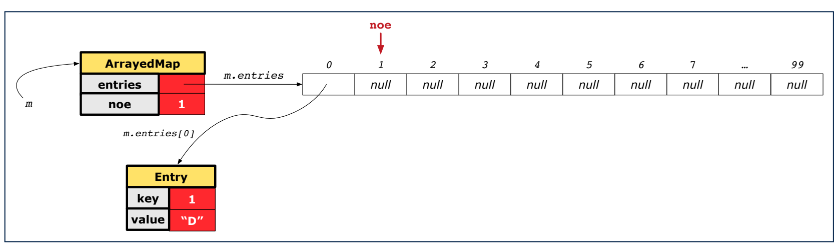
- Attribute `m.entries` initialized as an array of 100 `null` slots.
- Attribute `m.noe` is 0, meaning:
  - Current number of entries stored in the map is 0.
  - Index for storing the next new entry is 0.



Hashing: Naive Implementation of Map (1)

After executing `m.put(new Entry(1, "D"))`:

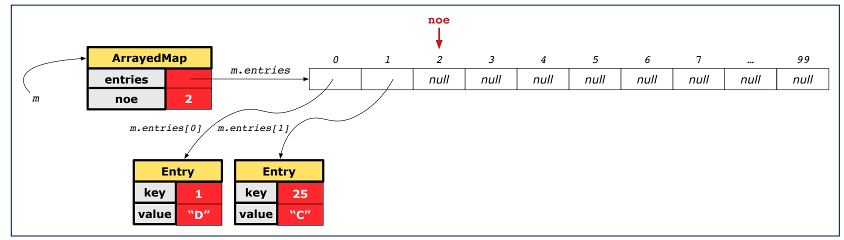
- Attribute `m.entries` has 99 `null` slots.
- Attribute `m.noe` is 1, meaning:
  - Current number of entries stored in the map is 1.
  - Index for storing the next new entry is 1.



Hashing: Naive Implementation of Map (2)

After executing `m.put(new Entry(25, "C"))`:

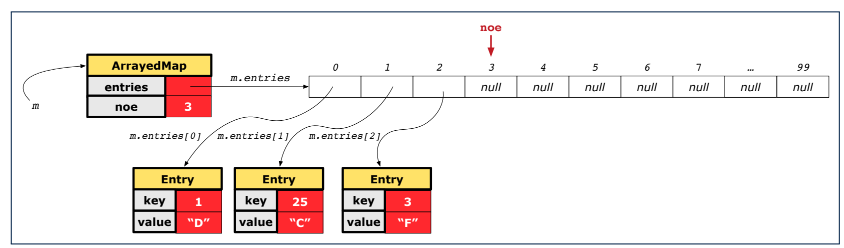
- Attribute `m.entries` has 98 `null` slots.
- Attribute `m.noe` is 2, meaning:
  - Current number of entries stored in the map is 2.
  - Index for storing the next new entry is 2.



Hashing: Naive Implementation of Map (3)

After executing `m.put(new Entry(3, "F"))`:

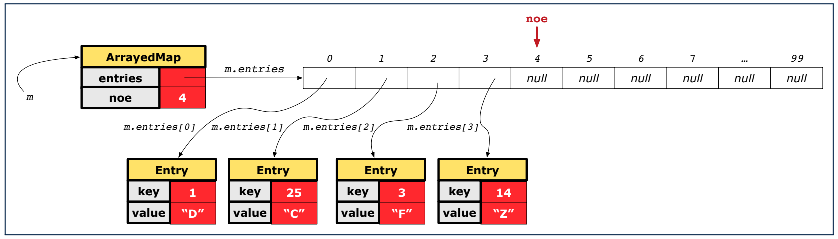
- Attribute `m.entries` has 97 `null` slots.
- Attribute `m.noe` is 3, meaning:
  - Current number of entries stored in the map is 3.
  - Index for storing the next new entry is 3.



Hashing: Naive Implementation of Map (4)

After executing `m.put(new Entry(14, "Z"))`:

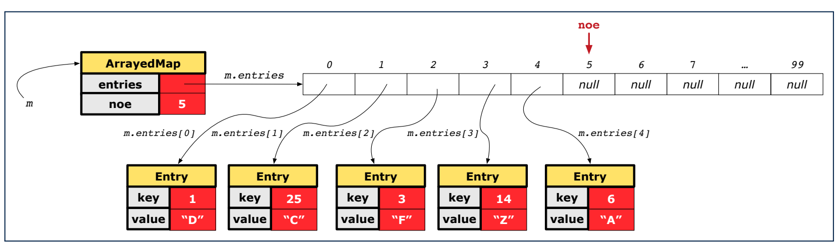
- Attribute `m.entries` has 96 `null` slots.
- Attribute `m.noe` is 4, meaning:
  - Current number of entries stored in the map is 4.
  - Index for storing the next new entry is 4.



Hashing: Naive Implementation of Map (5)

After executing `m.put(new Entry(6, "A"))`:

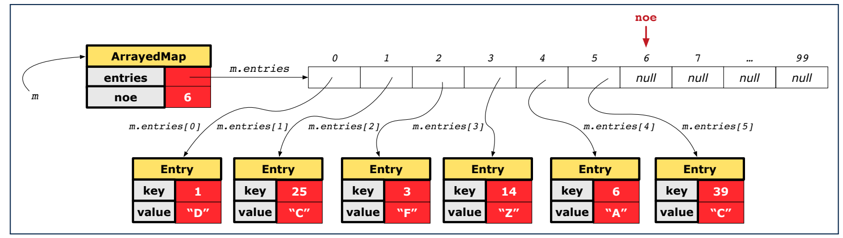
- Attribute `m.entries` has 95 `null` slots.
- Attribute `m.noe` is 5, meaning:
  - Current number of entries stored in the map is 5.
  - Index for storing the next new entry is 5.



Hashing: Naive Implementation of Map (6)

After executing `m.put(new Entry(39, "C"))`:

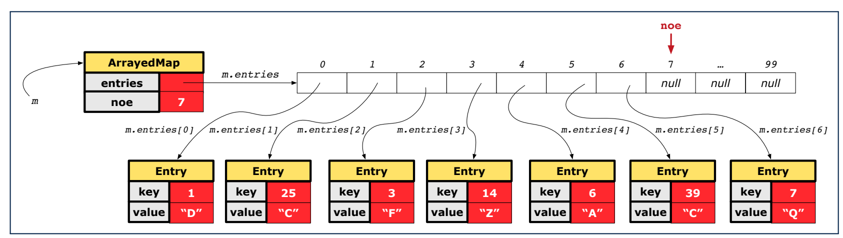
- Attribute `m.entries` has 94 `null` slots.
- Attribute `m.noe` is 6, meaning:
  - Current number of entries stored in the map is 6.
  - Index for storing the next new entry is 6.



Hashing: Naive Implementation of Map (7)

After executing `m.put(new Entry(7, "Q"))`:

- Attribute `m.entries` has 93 `null` slots.
- Attribute `m.noe` is 7, meaning:
  - Current number of entries stored in the map is 7.
  - Index for storing the next new entry is 7.



Hashing: Naive Implementation of Map (8.1)

```
public class Entry {
  private int key;
  private String value;

  public Entry(int key, String value) {
    this.key = key;
    this.value = value;
  }
  /* Getters and Setters for key and value */
}
```


Hashing: Naive Implementation of Map (8.2)

```
public class ArrayedMap {
  private final int MAX_CAPCAITY = 100;
  private Entry[] entries;
  private int noe; /* number of entries */
  public ArrayedMap() {
    entries = new Entry[MAX_CAPCAITY];
    noe = 0;
  }
  public int size() {
    return noe;
  }
  public void put(int key, String value) {
    Entry e = new Entry(key, value);
    entries[noe] = e;
    noe ++;
  }
```

Required Reading: Point and PointCollector

Hashing: Naive Implementation of Map (8.3)

```
@Test
public void testArrayedMap() {
  ArrayedMap m = new ArrayedMap();
  assertTrue(m.size() == 0);
  m.put(1, "D");
  m.put(25, "C");
  m.put(3, "F");
  m.put(14, "Z");
  m.put(6, "A");
  m.put(39, "C");
  m.put(7, "Q");
  assertTrue(m.size() == 7);
  /* inquiries of existing key */
  assertTrue(m.get(1).equals("D"));
  assertTrue(m.get(7).equals("Q"));
  /* inquiry of non-existing key */
  assertTrue(m.get(31) == null);
}
```


Hashing: Naive Implementation of Map (8.4)

```
public class ArrayedMap {
  private final int MAX_CAPCAITY = 100;
  public String getValue (int key) {
    for(int i = 0; i < noe; i ++) {
      Entry e = entries[i];
      int k = e.getKey();
      if(k == key) { return e.getValue(); }
    }
    return null;
  }
```

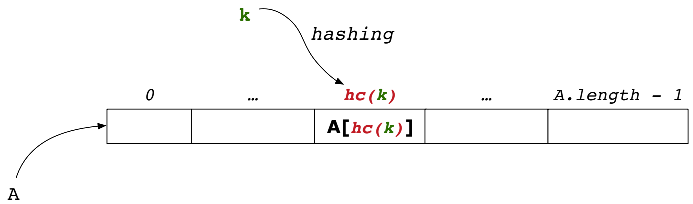
Say `entries` is: {(1, D), (25, C), (3, F), (14, Z), (6, A), (39, C), (7, Q), null, ...}

- How efficient is `m.get(1)`? [1 iteration]
- How efficient is `m.get(7)`? [7 iterations]
- If `m` is full, worst case of `m.get(k)`? [100 iterations]
- If `m` with 10^6 entries, worst case of `m.get(k)`? [10^6 iterations]

  ⇒ `get`'s worst-case performance is *linear* on size of `m.entries`!

A much *faster* (and ***correct***) solution is possible!

Hashing: Hash Table (1)

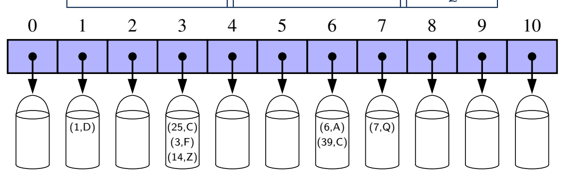


- Given a (numerical or non-numerical) search key ***k***:
  - Apply a function ***hc*** so that ***hc(k)*** returns an integer.
    - We call ***hc(k)*** the *hash code* of key ***k***.
    - Value of ***hc(k)*** denotes a ***valid index*** of some array `A`.
  - Rather than searching through array `A`, go directly to `A[` ***hc(k)*** `]` to get the associated value.
- Both computations are fast:
  - Converting ***k*** to ***hc(k)***
  - Indexing into `A[` ***hc(k)*** `]`

Hashing: Hash Table as a Bucket Array (2)

For illustration, assume `A.length` is 10 and $hc(k) = k\%11$.

$hc(k) = k\%11$	(SEARCH) KEY	VALUE
1	1	D
3	25	C
3	3	F
3	14	Z
6	6	A
6	39	C
7	7	Q



- **Collision**: unequal keys have same hash code (e.g., 25, 3, 14)
  ⇒ Unavoidable as number of entries ↑, but a *good* hash function should have sizes of the buckets uniformly distributed.

Hashing: Contract of Hash Function

- Principle of defining a hash function ***hc***:

$$k1.equals(k2) \Rightarrow hc(k1) == hc(k2)$$

  Equal keys always have the same hash code.
- Equivalently, according to contrapositive:

$$hc(k1) \neq hc(k2) \Rightarrow \neg k1.equals(k2)$$

  Different hash codes must be generated from unequal keys.

inconsistent `hashCode` and `equals`

Hashing: Defining Hash Function in Java (1)

The `Object` class (common super class of all classes) has the method for redefining the hash function for your own class:

```
public class IntegerKey {
  private int k;
  public IntegerKey(int k) { this.k = k; }
  @Override
  public int hashCode() { return k % 11; }
  @Override
  public boolean equals(Object obj) {
    if(this == obj) { return true; }
    if(obj == null) { return false; }
    if(this.getClass() != obj.getClass()) { return false; }
    IntegerKey other = (IntegerKey) obj;
    return this.k == other.k;
  } }
```

Q: Can we define `equals` as `return this.hashCode == other.hashCode()`? [*No* ∵ Collision; see contract of `equals`]

Hashing: Defining Hash Function in Java (2)

```
@Test
public void testCustomizedHashFunction() {
  IntegerKey ik1 = new IntegerKey(1);
  /* 1 % 11 == 1 */
  assertTrue(ik1.hashCode() == 1);

  IntegerKey ik39_1 = new IntegerKey(39);
  /* 39 % 11 == 3 */
  assertTrue(ik39_1.hashCode() == 6);

  IntegerKey ik39_2 = new IntegerKey(39);
  assertTrue(ik39_1.equals(ik39_2));
  assertTrue(ik39_1.hashCode() == ik39_2.hashCode());
}
```


Hashing: Using Hash Table in Java

```
@Test
public void testHashTable() {
  Hashtable<IntegerKey, String> table = new Hashtable<>();
  IntegerKey k1 = new IntegerKey(39);
  IntegerKey k2 = new IntegerKey(39);
  assertTrue(k1.equals(k2));
  assertTrue(k1.hashCode() == k2.hashCode());
  table.put(k1, "D");
  assertTrue(table.get(k2).equals("D"));
}
```


Hashing: Defining Hash Function in Java (3)

- When you are given instructions as to how the `hashCode` method of a class should be defined, override it manually.
- Otherwise, use Eclipse to generate the `equals` and `hashCode` methods for you.
  - Right click on the class.
  - Select `Source`.
  - Select `Generate hashCode() and equals()`.
  - Select the relevant attributes that will be used to compute the hash value.

Hashing: Defining Hash Function in Java (4.1)

Caveat: Always make sure that the `hashCode` and `equals` are redefined/overridden to work together consistently.
e.g., Consider an alternative version of the `IntegerKey` class:

```
public class IntegerKey {
  private int k;
  public IntegerKey(int k) { this.k = k; }
  /* hashCode() inherited from Object NOT overridden. */
  @Override
  public boolean equals(Object obj) {
    if(this == obj) { return true; }
    if(obj == null) { return false; }
    if(this.getClass() != obj.getClass()) { return false; }
    IntegerKey other = (IntegerKey) obj;
    return this.k == other.k;
  } }
```

Problem? [**Hint**: Contract of `hashCode()`]

Hashing: Defining Hash Function in Java (4.2)

```
1  @Test
2  public void testDefaultHashFunction() {
3    IntegerKey ik39_1 = new IntegerKey(39);
4    IntegerKey ik39_2 = new IntegerKey(39);
5    assertTrue(ik39_1.equals(ik39_2));
6    assertTrue(ik39_1.hashCode() != ik39_2.hashCode()); }
7  @Test
8  public void testHashTable() {
9    Hashtable<IntegerKey, String> table = new Hashtable<>();
10   IntegerKey k1 = new IntegerKey(39);
11   IntegerKey k2 = new IntegerKey(39);
12   assertTrue(k1.equals(k2));
13   assertTrue(k1.hashCode() != k2.hashCode());
14   table.put(k1, "D");
15   assertTrue(table.get(k2) == null); }
```

L3, 4, 11, 12: Default version of `hashCode`, inherited from `Object`, returns a *distinct* integer for every new object, *despite its contents*. [***Fix***: Override `hashCode` of your classes!]

Why Ordering Between Objects? (1)

Each employee has their numerical id and salary.

e.g., (*alan*, 2, 4500.34), (*mark*, 3, 3450.67), (*tom*, 1, 3450.67)

- ***Problem***: To facilitate an annual review on their statuses, we want to arrange them so that ones with smaller id's come before ones with larger id's.s

  e.g., $\langle$*tom*, *alan*, *mark*$\rangle$
- Even better, arrange them so that ones with larger salaries come first; only compare id's for employees with equal salaries.

  e.g., $\langle$*alan*, *tom*, *mark*$\rangle$
- *Solution*:
  - Define ***ordering*** of `Employee` objects. [`Comparable` interface, `compareTo` method]
  - Use the library method `Arrays.sort`.

Why Ordering Between Objects? (2)

```
class Employee {
  int id; double salary;
  Employee(int id) { this.id = id; }
  void setSalary(double salary) { this.salary = salary; } }
```

```
1  @Test
2  public void testUncomparableEmployees() {
3    Employee alan = new Employee(2);
4    Employee mark = new Employee(3);
5    Employee tom = new Employee(1);
6    Employee[] es = {alan, mark, tom};
7    Arrays.sort(es);
8    Employee[] expected = {tom, alan, mark};
9    assertArrayEquals(expected, es); }
```

L8 triggers a ***java.lang.ClassCastException***:

Employee cannot be cast to java.lang.Comparable

∵ `Arrays.sort` expects an array whose element type defines a precise ***ordering*** of its instances/objects.

Defining Ordering Between Objects (1.1)

```
class CEmployee1 implements Comparable<CEmployee1> {
  ... /* attributes, constructor, mutator similar to Employee */
  @Override
  public int compareTo(CEmployee1 e) { return this.id - e.id; }
}
```

- Given two `CEmployee1` objects `ce1` and `ce2`:
  - `ce1.compareTo(ce2) > 0` [`ce1` "is greater than" `ce2`]
  - `ce1.compareTo(ce2) == 0` [`ce1` "is equal to" `ce2`]
  - `ce1.compareTo(ce2) < 0` [`ce1` "is smaller than" `ce2`]
- Say `ces` is an array of `CEmployee1` (`CEmployee1[] ces`), calling `Arrays.sort(ces)` re-arranges `ces`, so that:

$$\underbrace{\texttt{ces[0]}}_{\texttt{CEmployee1}\ \textit{object}} \leq \underbrace{\texttt{ces[1]}}_{\texttt{CEmployee1}\ \textit{object}} \leq \ldots \leq \underbrace{\texttt{ces[ces.length - 1]}}_{\texttt{CEmployee1}\ \textit{object}}$$

Defining Ordering Between Objects (1.2)

```
@Test
public void testComparableEmployees_1() {
  /*
   * CEmployee1 implements the Comparable interface.
   * Method compareTo compares id's only.
   */
  CEmployee1 alan = new CEmployee1(2);
  CEmployee1 mark = new CEmployee1(3);
  CEmployee1 tom = new CEmployee1(1);
  alan.setSalary(4500.34);
  mark.setSalary(3450.67);
  tom.setSalary(3450.67);
  CEmployee1[] es = {alan, mark, tom};
  /* When comparing employees,
   * their salaries are irrelevant.
   */
  Arrays.sort(es);
  CEmployee1[] expected = {tom, alan, mark};
  assertArrayEquals(expected, es);
}
```


Defining Ordering Between Objects (2.1)

Let's now make the comparison more sophisticated:

- Employees with higher salaries come before those with lower salaries.
- When two employees have same salary, whoever with lower id comes first.

```
1 class CEmployee2 implements Comparable<CEmployee2> {
2   ... /* attributes, constructor, mutator similar to Employee */
3   @Override
4   public int compareTo(CEmployee2 other) {
5     int salaryDiff = Double.compare(this.salary, other.salary);
6     int idDiff = this.id - other.id;
7     if(salaryDiff != 0) { return - salaryDiff; }
8     else { return idDiff; } } }
```

- **L5**: `Double.compare(d1, d2)` returns
  - (`d1 < d2`), 0 (`d1 == d2`), or + (`d1 > d2`).
- **L7**: Why inverting the sign of `salaryDiff`?
  - *this.salary* > *other.salary* ⇒ `Double.compare`(*this.salary*, *other.salary*) > 0
  - But we should consider employee with *higher* salary as "smaller".
    ∵ We want that employee to come *before* the other one!

Defining Ordering Between Objects (2.2)

Alternatively, we can use extra `if` statements to express the logic more clearly.

```
class CEmployee2 implements Comparable<CEmployee2> {
  ... /* attributes, constructor, mutator similar to Employee */
  @Override
  public int compareTo(CEmployee2 other) {
    if(this.salary > other.salary) {
      return -1;
    }
    else if (this.salary < other.salary) {
      return 1;
    }
    else { /* equal salaries */
      return this.id - other.id;
    }
}
```


Defining Ordering Between Objects (2.3)

```
@Test
public void testComparableEmployees_2() {
  /*
   * CEmployee2 implements the Comparable interface.
   * Method compareTo first compares salaries, then
   * compares id's for employees with equal salaries.
   */
  CEmployee2 alan = new CEmployee2(2);
  CEmployee2 mark = new CEmployee2(3);
  CEmployee2 tom = new CEmployee2(1);
  alan.setSalary(4500.34);
  mark.setSalary(3450.67);
  tom.setSalary(3450.67);
  CEmployee2[] es = {alan, mark, tom};
  Arrays.sort(es);
  CEmployee2[] expected = {alan, tom, mark};
  assertArrayEquals(expected, es);
}
```

Defining Ordering Between Objects (3)

When you have your class `C` implement the interface `Comparable<C>`, you should design the `compareTo` method, such that given objects `c1`, `c2`, `c3` of type `C`:

- *Asymmetric* :

$$\neg(c1.compareTo(c2) < 0 \land c2.compareTo(c1) < 0)$$
$$\neg(c1.compareTo(c2) > 0 \land c2.compareTo(c1) > 0)$$

$\therefore$ We don't have $c1 < c2$ and $c2 < c1$ at the same time!

- *Transitive* :

$$c1.compareTo(c2) < 0 \land c2.compareTo(c3) < 0 \Rightarrow c1.compareTo(c3) < 0$$
$$c1.compareTo(c2) > 0 \land c2.compareTo(c3) > 0 \Rightarrow c1.compareTo(c3) > 0$$

$\therefore$ We have $c1 < c2 \land c2 < c3 \Rightarrow c1 < c3$

Q. How would you define the `compareTo` method for the `Player` class of a rock-paper-scissor game? [**Hint**: Transitivity]

Static Variables (1)

```
class Account {
  int id;
  String owner;
  Account(int id, String owner) {
    this.id = id;
    this.owner = owner;
  }
}
```

```
class AccountTester {
  Account acc1 = new Account(1, "Jim");
  Account acc2 = new Account(2, "Jeremy");
  System.out.println(acc1.id != acc2.id);
}
```

But, managing the unique id's *manually* is *error-prone* !

Static Variables (2)

```
class Account {
  static int globalCounter = 1;
  int id; String owner;
  Account(String owner) {
    this.id = globalCounter ; globalCounter ++;
    this.owner = owner; } }
```

```
class AccountTester {
  Account acc1 = new Account("Jim");
  Account acc2 = new Account("Jeremy");
  System.out.println(acc1.id != acc2.id); }
```

- Each instance of a class (e.g., `acc1`, `acc2`) has a *local* copy of each attribute or instance variable (e.g., `id`).
  - Changing `acc1.id` does not affect `acc2.id`.
- A ***static*** variable (e.g., `globalCounter`) belongs to the class.
  - All instances of the class share a *single* copy of the ***static*** variable.
  - Change to `globalCounter` via `c1` is also visible to `c2`.

Static Variables (3)

```
class Account {
  static int globalCounter = 1;
  int id; String owner;
  Account(String owner) {
    this.id = globalCounter ;
    globalCounter ++;
    this.owner = owner;
  } }
```

- *Static* variable `globalCounter` is not instance-specific like *instance* variable (i.e., attribute) `id` is.
- To access a *static* variable:
  - ***No*** context object is needed.
  - Use of the class name suffices, e.g., `Account.globalCounter`.
- Each time `Account`'s constructor is called to create a new instance, the increment effect is *visible to all existing objects* of `Account`.

Static Variables (4.1): Common Error

```
class Client {
  Account[] accounts;
  static int numberOfAccounts = 0;
  void addAccount(Account acc) {
    accounts[numberOfAccounts] = acc;
    numberOfAccounts ++;
  } }
```

```
class ClientTester {
  Client bill = new Client("Bill");
  Client steve = new Client("Steve");
  Account acc1 = new Account();
  Account acc2 = new Account();
  bill.addAccount(acc1);
    /* correctly added to bill.accounts[0] */
  steve.addAccount(acc2);
    /* mistakenly added to steve.accounts[1]! */
}
```


Static Variables (4.2): Common Error

- Attribute `numberOfAccounts` should **not** be declared as `static` as its value should be specific to the client object.
- If it were declared as `static`, then every time the `addAccount` method is called, although on different objects, the increment effect of `numberOfAccounts` will be visible to all `Client` objects.
- Here is the correct version:

```
class Client {
  Account[] accounts;
  int numberOfAccounts = 0;
  void addAccount(Account acc) {
    accounts[numberOfAccounts] = acc;
    numberOfAccounts ++;
  }
}
```


Static Variables (5.1): Common Error

```
1 public class Bank {
2    public string branchName;
3    public static int nextAccountNumber = 1;
4    public static void useAccountNumber() {
5       System.out.println (branchName + ...);
6       nextAccountNumber ++;
7    }
8 }
```

- *Non-static method cannot be referenced from a static context*
- **Line 4** declares that we *can* call the method `userAccountNumber` without instantiating an object of the class `Bank`.
- However, in **Lined 5**, the *static* method references a *non-static* attribute, for which we *must* instantiate a `Bank` object.

Static Variables (5.2): Common Error

```
1 public class Bank {
2    public string branchName;
3    public static int nextAccountNumber = 1;
4    public static void useAccountNumber() {
5       System.out.println (branchName + ...);
6       nextAccountNumber ++;
7    }
8 }
```

- To call `useAccountNumber()`, no instances of `Bank` are required:

```
Bank.useAccountNumber();
```

- *Contradictorily*, to access `branchName`, a *context object* is required:

```
Bank b1 = new Bank(); b1.setBranch("Songdo IBK");
System.out.println(b1.branchName);
```

Static Variables (5.3): Common Error

There are two possible ways to fix:

1. Remove all uses of *non-static* variables (i.e., `branchName`) in the *static* method (i.e., `useAccountNumber`).
2. Declare `branchName` as a *static* variable.
   - This does not make sense.
     ∵ `branchName` should be a value specific to each `Bank` instance.

OOP: Helper (Accessor) Methods (2.1)

```
class PersonCollector {
  Person[] ps;
  final int MAX = 100; /* max # of persons to be stored */
  int nop; /* number of persons */
  PersonCollector() {
    ps = new Person[MAX];
  }
  void addPerson(Person p) {
    ps[nop] = p;
    nop++;
  }
  /* Tasks:
   * 1. An accessor: boolean personExists(String n)
   * 2. A mutator: void changeWeightOf(String n, double w)
   * 3. A mutator: void changeHeightOf(String n, double h)
   */
}
```


OOP: Helper Methods (1)

- After you complete and test your program, feeling confident that it is *correct*, you may find that there are lots of *repetitions*.
- When similar fragments of code appear in your program, we say that your code "*smells*"!
- We may eliminate *repetitions* of your code by:
  - *Factoring out* recurring code fragments into a new method.
  - This new method is called a *helper method*:
    - You can replace every occurrence of the recurring code fragment by a *call* to this helper method, with appropriate argument values.
    - That is, we *reuse* the body implementation, rather than repeating it over and over again, of this helper method via calls to it.
- This process is called *refactoring* of your code:

  Modify the code structure **without** compromising *correctness*.

OOP: Helper (Accessor) Methods (2.2.1)

```
class PersonCollector {
  /* ps, MAX, nop, PersonCollector(), addPerson */
  boolean personExists(String n) {
    boolean found = false;
    for(int i = 0; i < nop; i ++) {
      if(ps[i].name.equals(n)) { found = true; } }
    return found;
  }
  void changeWeightOf(String n, double w) {
    for(int i = 0; i < nop; i ++) {
      if(ps[i].name.equals(n)) { ps[i].setWeight(w); } }
  }
  void changeHeightOf(String n, double h) {
    for(int i = 0; i < nop; i ++) {
      if(ps[i].name.equals(n)) { ps[i].setHeight(h); } }
  }
}
```

OOP: Helper (Accessor) Methods (2.2.2)

```
class PersonCollector { /* code smells: repetitions! */
  /* ps, MAX, nop, PersonCollector(), addPerson */
  boolean personExists(String n) {
    boolean found = false;
    for(int i = 0; i < nop; i ++) {
      if(ps[i].name.equals(n)) { found = true; } }
    return found;
  }
  void changeWeightOf(String n, double w) {
    for(int i = 0; i < nop; i ++) {
      if(ps[i].name.equals(n)) { ps[i].setWeight(w); } }
  }
  void changeHeightOf(String n, double h) {
    for(int i = 0; i < nop; i ++) {
      if(ps[i].name.equals(n)) { ps[i].setHeight(h); } }
  }
}
```


OOP: Helper (Accessor) Methods (2.3)

```
class PersonCollector { /* Eliminate code smell. */
  /* ps, MAX, nop, PersonCollector(), addPerson */
  int indexOf(String n) { /* Helper Methods */
    int i = -1;
    for(int j = 0; j < nop; j ++) {
      if(ps[j].name.equals(n)) { i = j; }
    }
    return i; /* -1 if not found; >= 0 if found. */
  }
  boolean personExists(String n) { return indexOf(n) >= 0; }
  void changeWeightOf(String n, double w) {
    int i = indexOf(n); if(i >= 0) { ps[i].setWeight(w); }
  }
  void changeHeightOf(String n, double h) {
    int i = indexOf(n); if(i >= 0) { ps[i].setHeight(h); }
  }
}
```


OOP: Helper (Accessor) Methods (3.1)

Problems:

- A `Point` class with `x` and `y` coordinate values.
- Accessor `double getDistanceFromOrigin()`.
  `p.getDistanceFromOrigin()` returns the distance between `p` and `(0, 0)`.
- Accessor `double getDistancesTo(Point p1, Point p2)`.
  `p.getDistancesTo(p1, p2)` returns the sum of distances between `p` and `p1`, and between `p` and `p2`.
- Accessor `double getTriDistances(Point p1, Point p2)`.
  `p.getDistancesTo(p1, p2)` returns the sum of distances between `p` and `p1`, between `p` and `p2`, and between `p1` and `p2`.

OOP: Helper (Accessor) Methods (3.2)

```
class Point {
  double x; double y;
  double getDistanceFromOrigin() {
    return Math.sqrt(Math.pow(x - 0, 2) + Math.pow(y - 0, 2)); }
  double getDistancesTo(Point p1, Point p2) {
    return
    Math.sqrt(Math.pow(x - p1.x, 2) + Math.pow(y - p1.y, 2))
    +
    Math.sqrt(Math.pow(x - p2.x, 2), Math.pow(y - p2.y, 2)); }
  double getTriDistances(Point p1, Point p2) {
    return
    Math.sqrt(Math.pow(x - p1.x, 2) + Math.pow(y - p1.y, 2))
    +
    Math.sqrt(Math.pow(x - p2.x, 2) + Math.pow(y - p2.y, 2))
    +
    Math.sqrt(Math.pow(p1.x - p2.x, 2)
              +
              Math.pow(p1.y - p2.y, 2));
  } }
```

OOP: Helper (Accessor) Methods (3.3)

- The code pattern

  `Math.sqrt(Math.pow(... - ..., 2) + Math.pow(... - ..., 2))`

  is written down explicitly every time we need to use it.
- Create a *helper method* out of it, with the right *parameter* and *return* types:

```
double getDistanceFrom(double otherX, double otherY) {
   return
    Math.sqrt(Math.pow(ohterX - this.x, 2)
    +
    Math.pow(otherY - this.y, 2));
}
```


OOP: Helper (Accessor) Methods (3.4)

```
class Point {
  double x; double y;
  double getDistanceFrom(double otherX, double otherY) {
    return Math.sqrt(Math.pow(ohterX - this.x, 2) +
           Math.pow(otherY - this.y, 2));
  }
  double getDistanceFromOrigin() {
    return this.getDistanceFrom(0, 0);
  }
  double getDistancesTo(Point p1, Point p2) {
    return this.getDistanceFrom(p1.x, p1.y) +
           this.getDistanceFrom(p2.x, p2.y);
  }
  double getTriDistances(Point p1, Point p2) {
    return this.getDistanceFrom(p1.x, p1.y) +
           this.getDistanceFrom(p2.x, p2.y) +
           p1.getDistanceFrom(p2.x, p2.y)
  } }
```


OOP: Helper (Mutator) Methods (4.1)

```
class Student {
  String name;
  double balance;
  Student(String n, double b) {
    name = n;
    balance = b;
  }

  /* Tasks:
   * 1. A mutator void receiveScholarship(double val)
   * 2. A mutator void payLibraryOverdue(double val)
   * 3. A mutator void payCafeCoupons(double val)
   * 4. A mutator void transfer(Student other, double val)
   */
}
```


OOP: Helper (Mutator) Methods (4.2.1)

```
class Student {
  /* name, balance, Student(String n, double b) */
  void receiveScholarship(double val) {
    balance = balance + val;
  }
  void payLibraryOverdue(double val) {
    balance = balance - val;
  }
  void payCafeCoupons(double val) {
    balance = balance - val;
  }
  void transfer(Student other, double val) {
    balance = balance - val;
    other.balance = other.balance + val;
  }
}
```

OOP: Helper (Mutator) Methods (4.2.2)

```
class Student { /* code smells: repetitions! */
  /* name, balance, Student(String n, double b) */
  void receiveScholarship(double val) {
    balance = balance + val;
  }
  void payLibraryOverdue(double val) {
    balance = balance - val;
  }
  void payCafeCoupons(double val) {
    balance = balance - val;
  }
  void transfer(Student other, double val) {
    balance = balance - val;
    balance = other.balance + val;
  }
}
```


OOP: Helper (Mutator) Methods (4.3)

```
class Student { /* Eliminate code smell. */
  /* name, balance, Student(String n, double b) */
  void deposit (double val) { /* Helper Method */
    balance = balance + val;
  }
  void withdraw (double val) { /* Helper Method */
    balance = balance - val;
  }
  void receiveScholarship(double val) { this. deposit (val); }
  void payLibraryOverdue(double val) { this. withdraw (val); }
  void payCafeCoupons(double val) { this. withdraw (val) }
  void transfer(Student other, double val) {
    this. withdraw (val);
    other. deposit (val);
  }
}
```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Asymptotic Analysis of Algorithms

EECS2030: Advanced Object Oriented Programming
Fall 2017

CHEN-WEI WANG

Algorithm and Data Structure

- A *data structure* is:
  - A systematic way to store and organize data in order to facilitate *access* and *modifications*
  - Never suitable for all purposes: it is important to know its *strengths* and *limitations*
- A *well-specified* *computational problem* precisely describes the desired *input/output relationship*.
  - **Input:** A sequence of n numbers $\langle a_1, a_2, \ldots, a_n \rangle$
  - **Output:** A permutation (reordering) $\langle a'_1, a'_2, \ldots, a'_n \rangle$ of the input sequence such that $a'_1 \leq a'_2 \leq \ldots \leq a'_n$
  - An *instance* of the problem: $\langle 3, 1, 2, 5, 4 \rangle$
- An *algorithm* is:
  - A solution to a well-specified *computational problem*
  - A *sequence of computational steps* that takes value(s) as *input* and produces value(s) as *output*
- Steps in an *algorithm* manipulate well-chosen *data structure(s)*.

Measuring "Goodness" of an Algorithm

1. *Correctness* :
   - Does the algorithm produce the expected output?
   - Use JUnit to ensure this.
2. Efficiency:
   - *Time Complexity*: processor time required to complete
   - *Space Complexity*: memory space required to store data

Correctness is always the priority.

How about efficiency? Is time or space more of a concern?

Measuring Efficiency of an Algorithm

- *Time* is more of a concern than is *storage*.
- Solutions that are meant to be run on a computer should run *as fast as possible*.
- Particularly, we are interested in how *running time* depends on two *input factors*:
  1. size
     e.g., sorting an array of 10 elements vs. 1m elements
  2. structure
     e.g., sorting an already-sorted array vs. a hardly-sorted array
- *How do you determine the running time of an algorithm?*
  1. Measure time via *experiments*
  2. Characterize time as a *mathematical function* of the input size

Measure Running Time via Experiments

- Once the algorithm is implemented in Java:
  - Execute the program on *test inputs* of various *sizes* and *structures*.
  - For each test, record the *elapsed time* of the execution.

```
long startTime = System.currentTimeMillis();
/* run the algorithm */
long endTime = System.currenctTimeMillis();
long elapsed = endTime - startTime;
```

  - *Visualize* the result of each test.
- To make *sound statistical claims* about the algorithm's *running time*, the set of input tests must be "reasonably" *complete*.

Example Experiment

- *Computational Problem*:
  - **Input**: A character *c* and an integer *n*
  - **Output**: A string consisting of *n* repetitions of character *c*
    e.g., Given input `'*'` and `15`, output `***************`.
- *Algorithm 1* using *String* Concatenations:

```
public static String repeat1(char c, int n) {
  String answer = "";
  for (int i = 0; i < n; i ++) { answer += c; }
  return answer; }
```

- *Algorithm 2* using *StringBuilder* `append`'s:

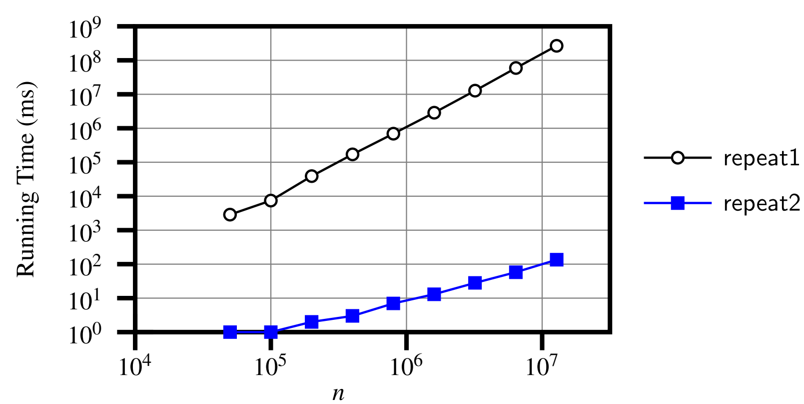
```
public static String repeat2(char c, int n) {
  StringBuilder sb = new StringBuilder();
  for (int i = 0; i < n; i ++) { sb.append(c); }
  return sb.toString(); }
```


Example Experiment: Detailed Statistics

n	`repeat1` (in ms)	`repeat2` (in ms)
50,000	2,884	1
100,000	7,437	1
200,000	39,158	2
400,000	170,173	3
800,000	690,836	7
1,600,000	2,847,968	13
3,200,000	12,809,631	28
6,400,000	59,594,275	58
12,800,000	265,696,421 (≈ 3 days)	135

- As *input size* is doubled, *rates of increase* for both algorithms are *linear*:
  - *Running time* of `repeat1` increases by ≈ 5 times.
  - *Running time* of `repeat2` increases by ≈ 2 times.

Example Experiment: Visualization



Experimental Analysis: Challenges

1. An algorithm must be *fully implemented* (i.e., translated into valid Java syntax) in order study its runtime behaviour *experimentally*.
   - What if our purpose is to *choose among alternative* data structures or algorithms to implement?
   - Can there be a *higher-level analysis* to determine that one algorithm or data structure is *superior* than others?
2. Comparison of multiple algorithms is only *meaningful* when experiments are conducted under the same environment of:
   - *Hardware*: CPU, running processes
   - *Software*: OS, JVM version
3. Experiments can be done only on *a limited set of test inputs*.
   - What if "*important*" inputs were not included in the experiments?

Moving Beyond Experimental Analysis

- A better approach to analyzing the *efficiency* (e.g., *running times*) of algorithms should be one that:
  - Allows us to calculate the *relative efficiency* (rather than absolute elapsed time) of algorithms in a ways that is *independent of* the hardware and software environment.
  - Can be applied using a *high-level description* of the algorithm (without fully implementing it).
  - Considers *all* possible inputs.
- We will learn a better approach that contains 3 ingredients:
  1. Counting *primitive operations*
  2. Approximating running time as *a function of input size*
  3. Focusing on the *worst-case* input (requiring the most running time)

Counting Primitive Operations

- A *primitive operation* corresponds to a low-level instruction with a *constant execution time*.
  - Assignment [e.g., `x = 5;`]
  - Indexing into an array [e.g., `a[i]`]
  - Arithmetic, relational, logical op. [e.g., `a + b`, `z > w`, `b1 && b2`]
  - Accessing a field of an object [e.g., `acc.balance`]
  - Returning from a method [e.g., `return result;`]
  - Why is a method call is in general *not* a primitive operation?
- The *number of primitive operations* required by an algorithm should be *proportional* to its *actual running time* on a specific environment: $RT = \Sigma_{i=1}^{N} t(i)$ [N = # of PO's]
  - Say c is the *absolute* time of executing a *primitive operation* on a specific computer platform.
  - $RT = \Sigma_{i=1}^{N} t(i) = c \times N \approx N$

  ⇒ *approximate* *# of primitive operations* that its steps contain.

Example: Counting Primitive Operations

```
1 findMax (int[] a, int n) {
2   currentMax = a[0];
3   for (int i = 1; i < n; ) {
4     if (a[i] > currentMax) {
5       currentMax = a[i]; }
6     i ++ }
7   return currentMax; }
```

# of times `i < n` in **Line 3** is executed? [n]

# of times the loop body (**Line 4** to **Line 6**) is executed? [$n-1$]

- **Line 2**: 2 [1 indexing + 1 assignment]
- **Line 3**: $n+1$ [1 assignment + n comparisons]
- **Line 4**: $(n-1)\cdot 2$ [1 indexing + 1 comparison]
- **Line 5**: $(n-1)\cdot 2$ [1 indexing + 1 assignment]
- **Line 6**: $(n-1)\cdot 2$ [1 addition + 1 assignment]
- **Line 7**: 1 [1 return]
- **Total # of Primitive Operations**: 7n - 2

Example: Approx. # of Primitive Operations

- Given # of primitive operations counted precisely as $7n^1 - 2$, we view it as

$$7 \cdot n - 2 \cdot n^0$$

- We say
  - n is the ***highest power***
  - 7 and 2 are the ***multiplicative constants***
  - 2 is the ***lower term***
- When approximating a function (considering that input size may be very large):
  - **Only** the ***highest power*** matters.
  - ***multiplicative constants*** and ***lower terms*** can be dropped.

  $\Rightarrow$ $7n - 2$ is approximately n

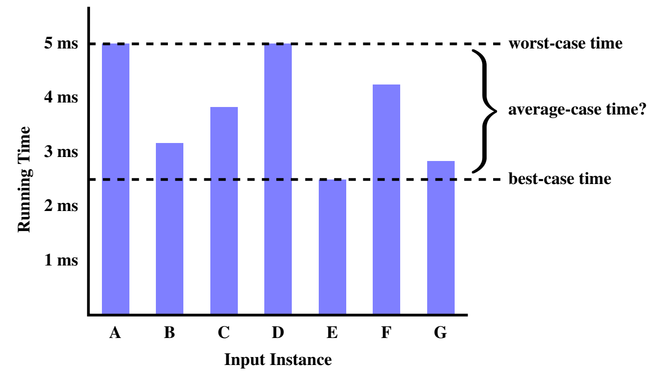
  Exercise: Consider $7n + 2n \cdot log\ n + 3n^2$:
  - ***highest power***? [n^2]
  - ***multiplicative constants***? [7, 2, 3]
  - ***lower terms***? [$7n + 2n \cdot log\ n$]

Approximating Running Time as a Function of Input Size

Given the *high-level description* of an algorithm, we associate it with a function f, such that $f(n)$ returns the *number of primitive operations* that are performed on an *input of size n*.

- $f(n) = 5$ [constant]
- $f(n) = log_2 n$ [logarithmic]
- $f(n) = 4 \cdot n$ [linear]
- $f(n) = n^2$ [quadratic]
- $f(n) = n^3$ [cubic]
- $f(n) = 2^n$ [exponential]

Focusing on the Worst-Case Input



- *Average-case* analysis calculates the *expected running times* based on the probability distribution of input values.
- *worst-case* analysis or *best-case* analysis?

What is Asymptotic Analysis?

Asymptotic analysis

- Is a method of describing *behaviour in the limit*:
  - How the *running time* of the algorithm under analysis changes as the *input size* changes without bound
  - e.g., contrast $RT_1(n) = n$ with $RT_2(n) = n^2$
- Allows us to compare the *relative* performance of alternative algorithms:
  - For large enough inputs, the *multiplicative constants* and *lower-order* terms of an exact running time can be disregarded.
  - e.g., $RT_1(n) = 3n^2 + 7n + 18$ and $RT_1(n) = 100n^2 + 3n - 100$ are considered **equally efficient**, *asymptotically*.
  - e.g., $RT_1(n) = n^3 + 7n + 18$ is considered **less efficient** than $RT_1(n) = 100n^2 + 100n + 2000$, *asymptotically*.

Three Notions of Asymptotic Bounds

We may consider three kinds of *asymptotic bounds* for the *running time* of an algorithm:

- Asymptotic **upper** bound [O]
- Asymptotic lower bound [Ω]
- Asymptotic tight bound [Θ]

Asymptotic Upper Bound: Definition

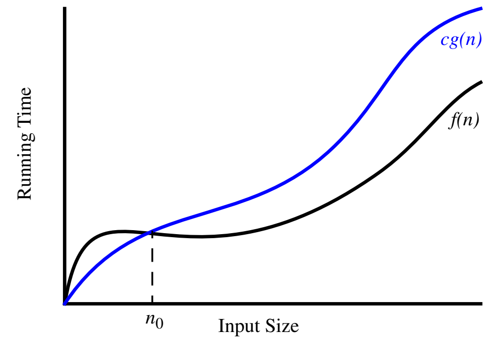
- Let $f(n)$ and $g(n)$ be functions mapping positive integers (input size) to positive real numbers (running time).
  - $f(n)$ characterizes the running time of some algorithm.
  - $O(g(n))$ denotes *a collection of* functions.
- $O(g(n))$ consists of *all* functions that can be upper bounded by $g(n)$, starting at some point, using some constant factor.
- $f(n) \in O(g(n))$ if there are:
  - A real *constant* $c > 0$
  - An integer *constant* $n_0 \geq 1$

  such that:

$$f(n) \leq c \cdot g(n) \quad \text{for } n \geq n_0$$

- For each member function $f(n)$ in $O(g(n))$, we say that:
  - $f(n) \in O(g(n))$ [f(n) is a member of "big-Oh of g(n)"]
  - $f(n)$ **is** $O(g(n))$ [f(n) is "big-Oh of g(n)"]
  - $f(n)$ **is order of** $g(n)$

Asymptotic Upper Bound: Visualization



From n_0, $f(n)$ is upper bounded by $c \cdot g(n)$, so $f(n)$ is $O(g(n))$.

Asymptotic Upper Bound: Example (1)

Prove: The function $8n + 5$ is $O(n)$.
Strategy: Choose a real constant $c > 0$ and an integer constant $n_0 \geq 1$, such that for every integer $n \geq n_0$:

$$8n + 5 \leq c \cdot n$$

Can we choose $c = 9$? What should the corresponding n_0 be?

n	8n + 5	9n
1	13	9
2	21	18
3	29	27
4	37	36
5	45	45
6	53	54

...

Therefore, we prove it by choosing $c = 9$ and $n_0 = 5$.
We may also prove it by choosing $c = 13$ and $n_0 = 1$. Why?

Asymptotic Upper Bound: Example (2)

Prove: The function $f(n) = 5n^4 + 3n^3 + 2n^2 + 4n + 1$ is $O(n^4)$.

Strategy: Choose a real constant $c > 0$ and an integer constant $n_0 \geq 1$, such that for every integer $n \geq n_0$:

$$5n^4 + 3n^3 + 2n^2 + 4n + 1 \leq c \cdot n^4$$

$f(1) = 5 + 3 + 2 + 4 + 1 = 15$

Choose $c = 15$ and $n_0 = 1$!

Asymptotic Upper Bound: Proposition (1)

If $f(n)$ is a polynomial of degree d, i.e.,

$$f(n) = a_0 \cdot n^0 + a_1 \cdot n^1 + \cdots + a_d \cdot n^d$$

and $a_0, a_1, \ldots, a_d$ are integers (i.e., negative, zero, or positive), then $f(n)$ is $O(n^d)$.

Proof:

1. We know that for $n \geq 1$: $\quad n^0 \leq n^1 \leq n^2 \leq \cdots \leq n^d$
2. By choosing $c = |a_0| + |a_1| + \cdots + |a_d|$:

   $$a_0 \cdot n^0 + a_1 \cdot n^1 + \cdots + a_d \cdot n^d \leq |a_0| \cdot n^d + |a_1| \cdot n^d + \cdots + |a_d| \cdot n^d$$

3. By choosing $n_0 = 1$:

   $$a_0 \cdot 1^0 + a_1 \cdot 1^1 + \cdots + a_d \cdot 1^d \leq |a_0| \cdot 1^d + |a_1| \cdot 1^d + \cdots + |a_d| \cdot 1^d$$

   That is, we prove by choosing

   $$\begin{aligned} c &= |a_0| + |a_1| + \cdots + |a_d| \\ n_0 &= 1 \end{aligned}$$

Asymptotic Upper Bound: Proposition (2)

$$O(n^0) \subset O(n^1) \subset O(n^2) \subset \ldots$$

If a function $f(n)$ is *upper bounded* by another function $g(n)$ of degree d, $d \geq 0$, then $f(n)$ is also upper bounded by all other functions of a *strictly higher degree* (i.e., $d + 1$, $d + 2$, *etc.*).

Asymptotic Upper Bound: More Examples

- $5n^2 + 3n \cdot logn + 2n + 5$ is $O(n^2)$ $\quad [c = 15,\ n_0 = 1]$
- $20n^3 + 10n \cdot logn + 5$ is $O(n^3)$ $\quad [c = 35,\ n_0 = 1]$
- $3 \cdot logn + 2$ is $O(logn)$ $\quad [c = 5,\ n_0 = 2]$
  - Why can't n_0 be 1?
  - Choosing $n_0 = 1$ means $\Rightarrow f(\boxed{1})$ ***is*** upper-bounded by $c \cdot log\boxed{1}$:
    - We have $f(\boxed{1}) = 3 \cdot log1 + 2$, which is 2.
    - We have $c \cdot log\boxed{1}$, which is 0.

    $\Rightarrow f(\boxed{1})$ ***is not*** upper-bounded by $c \cdot log\boxed{1}$ $\quad$ [Contradiction!]
- 2^{n+2} is $O(2^n)$ $\quad [c = 4,\ n_0 = 1]$
- $2n + 100 \cdot logn$ is $O(n)$ $\quad [c = 102,\ n_0 = 1]$

Using Asymptotic Upper Bound Accurately

- Use the big-Oh notation to characterize a function (of an algorithm's running time) *as closely as possible*.

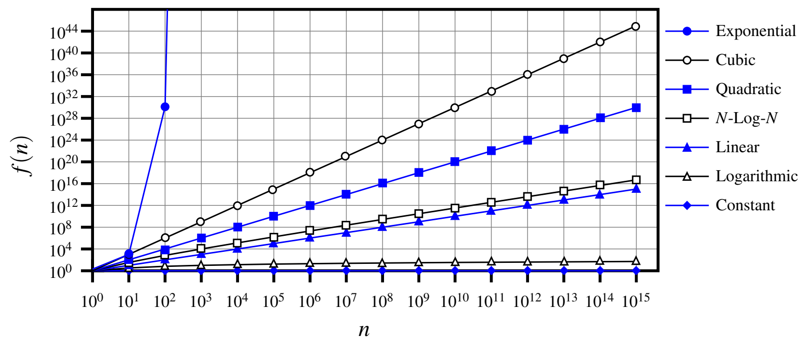
  For example, say $f(n) = 4n^3 + 3n^2 + 5$:
  - Recall: $O(n^3) \subset O(n^4) \subset O(n^5) \subset \ldots$
  - It is the *most accurate* to say that $f(n)$ is $O(n^3)$.
  - It is also true, but not very useful, to say that $f(n)$ is $O(n^4)$ and that $f(n)$ is $O(n^5)$.
- Do not include *constant factors* and *lower-order terms* in the big-Oh notation.

  For example, say $f(n) = 2n^2$ is $O(n^2)$, do not say $f(n)$ is $O(4n^2 + 6n + 9)$.

Classes of Functions

upper bound	class	cost
$O(1)$	constant	*cheapest*
$O(log(n))$	logarithmic	
$O(n)$	linear	
$O(n \cdot log(n))$	"n-log-n"	
$O(n^2)$	quadratic	
$O(n^3)$	cubic	
$O(n^k), k \geq 1$	polynomial	
$O(a^n), a > 1$	exponential	*most expensive*

Rates of Growth: Comparison



Upper Bound of Algorithm: Example (1)

```
maxOf (int x, int y) {
  int max = x;
  if (y > x) {
    max = y;
  }
  return max;
}
```

- \# of primitive operations: 4

  2 assignments + 1 comparison + 1 return = 4
- Therefore, the running time is $O(1)$.
- That is, this is a *constant-time* algorithm.

Upper Bound of Algorithm: Example (2)

```
findMax (int[] a, int n) {
  currentMax = a[0];
  for (int i = 1; i < n; ) {
    if (a[i] > currentMax) {
      currentMax = a[i]; }
    i ++ }
  return currentMax; }
```

- From last lecture, we calculated that the # of primitive operations is $7n - 2$.
- Therefore, the running time is $O(n)$.
- That is, this is a *linear-time* algorithm.

Upper Bound of Algorithm: Example (3)

```
1 containsDuplicate (int[] a, int n) {
2   for (int i = 0; i < n; ) {
3     for (int j = 0; j < n; ) {
4       if (i != j && a[i] == a[j]) {
5         return true; }
6       j ++; }
7     i ++; }
8   return false; }
```

- Worst case is when we reach Line 8.
- # of primitive operations $\approx c_1 + n \cdot n \cdot c_2$, where c_1 and c_2 are some constants.
- Therefore, the running time is $O(n^2)$.
- That is, this is a *quadratic* algorithm.

Upper Bound of Algorithm: Example (4)

```
sumMaxAndCrossProducts (int[] a, int n) {
  int max = a[0];
  for(int i = 1; i < n;) {
    if (a[i] > max) { max = a[i]; }
  }
  int sum = max;
  for (int j = 0; j < n; j ++) {
    for (int k = 0; k < n; k ++) {
      sum += a[j] * a[k]; } }
  return sum; }
```

- # of primitive operations $\approx (c_1 \cdot n + c_2) + (c_3 \cdot n \cdot n + c_4)$, where c_1, c_2, c_3, and c_4 are some constants.
- Therefore, the running time is $O(n + n^2) = O(n^2)$.
- That is, this is a *quadratic* algorithm.

Upper Bound of Algorithm: Example (5)

```
triangularSum (int[] a, int n) {
  int sum = 0;
  for (int i = 0; i < n; i ++) {
    for (int j = i; j < n; j ++) {
      sum += a[j]; } }
  return sum; }
```

- # of primitive operations $\approx n + (n-1) + \cdots + 2 + 1 = \frac{n \cdot (n+1)}{2}$
- Therefore, the running time is $O(\frac{n^2+n}{2}) = O(n^2)$.
- That is, this is a *quadratic* algorithm.

Index (1)

Index (2)

Index (3)

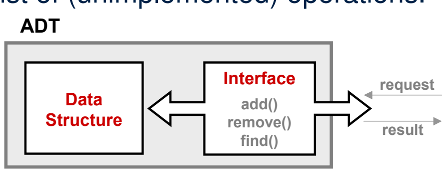
ADTs, Arrays, and Linked-Lists

EECS2030: Advanced Object Oriented Programming
Fall 2017

CHEN-WEI WANG

Abstract Data Types (ADTs)

- Given a problem, you are required to filter out *irrelevant* details.
- The result is an *abstract data type (ADT)*, whose *interface* consists of a list of (unimplemented) operations.



- *Supplier*'s *Obligations*:
  - Implement all operations
  - Choose the "right" data structure (DS)
- *Client*'s *Benefits*:
  - Correct output
  - Efficient performance
- The internal details of an *implemented ADT* should be **hidden**.

Standard ADTs

- *Standard* ADTs are *reusable components* that have been adopted in solving many real-world problems.

  e.g., Stacks, Queues, Lists, Tables, Trees, Graphs
- You will be required to:
  - *Implement* standard ADTs
  - *Design* algorithms that make use of standard ADTs
- For each standard ADT, you are required to know:
  - The list of supported operations (i.e., *interface*)
  - Time (and sometimes space) *complexity* of each operation
- In this lecture, we learn about two *basic data structures*:
  - arrays
  - linked lists

Basic Data Structure: Arrays

- An array is a sequence of indexed elements.
- *Size* of an array is **fixed** at the time of its construction.
- Supported *operations* on an array:
  - *Accessing*: e.g., `int max = a[0];`

    Time Complexity: *O(1)* [constant operation]
  - *Updating*: e.g., `a[i] = a[i + 1];`

    Time Complexity: *O(1)* [constant operation]
  - *Inserting/Removing*:

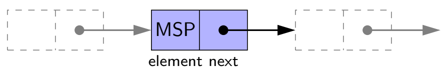
```
insertAt(String[] a, int n, String e, int i)
  String[] result = new String[n + 1];
  for(int j = 0; j < i; j ++){ result[i] = a[i]; }
  result[i] = e;
  for(int j = i + 1; j < n; j ++){ result[j] = a[j - 1]; }
  return result;
```

Time Complexity: *O(n)* [linear operation]

Basic Data Structure: Singly-Linked Lists

- We know that *arrays* perform:
  - *well* in indexing
  - *badly* in inserting and deleting
- We now introduce an alternative data structure to arrays.
- A *linked list* is a series of connected *nodes* that collectively form a *linear sequence*.
- Each node in a *singly-linked* list has:
  - A *reference* to an *element of the sequence*
  - A *reference* to the *next node* in the list

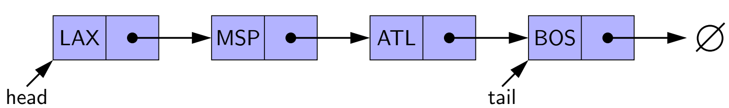
  Contrast this *relative* positioning with the *absolute* indexing of arrays.



- The *last element* in a *singly-linked* list is different from others. How so? Its reference to the next node is simply `null`.

Singly-Linked List: How to Keep Track?

- Due to its "chained" structure, we can use a singly-linked list to *dynamically* store as many elements as we desire.
  - By creating a *new node* and setting the relevant *references*.
  - e.g., inserting an element to the beginning/middle/end of a list
  - e.g., deleting an element from the list requires a similar procedure
- *Contrary to the case of arrays*, we simply *cannot* keep track of all nodes in a lined list *directly* by indexing the *next* references.
- Instead, we only store a reference to the *head* (i.e., *first node*), and find other parts of the list *indirectly*.



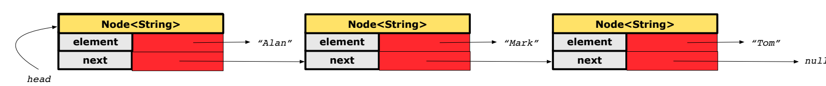
- **Exercise**: Given the *head* reference of a singly-linked list:
  - Count the number of nodes currently in the list [Running Time?]
  - Find the reference to its *tail* (i.e., last element) [Running Time?]

Singly-Linked List: Java Implementation

```
public class Node {
  private String element;
  private Node next;
  public Node(String e, Node n) { element = e; next = n; }
  public String getElement() { return element; }
  public void setElement(String e) { element = e; }
  public Node getNext() { return next; }
  public void setNext(Node n) { next = n; }
}
```

```
public class SinglyLinkedList {
  private Node head = null;
  public void addFirst(String e) { ... }
  public void removeLast() { ... }
  public void addAt(int i, String e) { ... }
}
```


Singly-Linked List: A Running Example



Approach 1

```
Node tom = new Node("Tom", null);
Node mark = new Node("Mark", tom);
Node alan = new Node("Alan", mark);
```

Approach 2

```
Node alan = new Node("Alan", null);
Node mark = new Node("Mark", null);
Node tom = new Node("Tom", null);
alan.setNext(mark);
mark.setNext(tom);
```

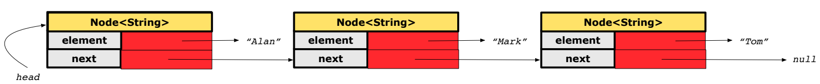
Singly-Linked List: Counting # of Nodes (1)

- Assume we are in the context of class `SinglyLinkedList`.

```
1  int getSize() {
2    int size = 0;
3    Node current = head;
4    while (current != null) {
5      /* exit when current == null */
6      current = current.getNext();
7      size ++;
8    }
9    return size;
10 }
```

- When does the *while loop* (Line 4) terminate? `current` is null
- Only the *last node* has a null *next* reference.
- RT of `getSize` *O(n)* [linear operation]
- **Contrast**: RT of `a.length` is *O(1)* [constant]

Singly-Linked List: Counting # of Nodes (2)




```
int getSize() {
  int size = 0;
  Node current = head;
  while (current != null) { /* exit when current == null */
    current = current.getNext();
    size ++;
  }
  return size;
}
```

`current`	`current != null`	Beginning of Iteration	`size`
Alan	*true*	1	1
Mark	*true*	2	2
Tom	*true*	3	*3*
`null`	*false*	–	–

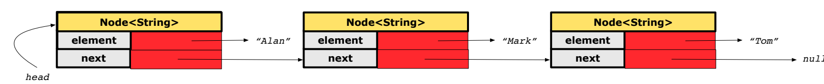
Singly-Linked List: Finding the Tail (1)

- Assume we are in the context of class `SinglyLinkedList`.

```
1  Node getTail() {
2    Node current = head;
3    Node tail = null;
4    while (current != null) {
5      /* exit when current == null */
6      tail = current;
7      current = current.getNext();
8    }
9    return tail;
10 }
```

- When does the *while loop* (Line 4) terminate? `current` is null
- Only the *last node* has a null *next* reference.
- RT of `getTail` is *O(n)* [linear operation]
- **Contrast**: RT of `a[a.length - 1]` is *O(1)* [constant]

Singly-Linked List: Finding the Tail (2)



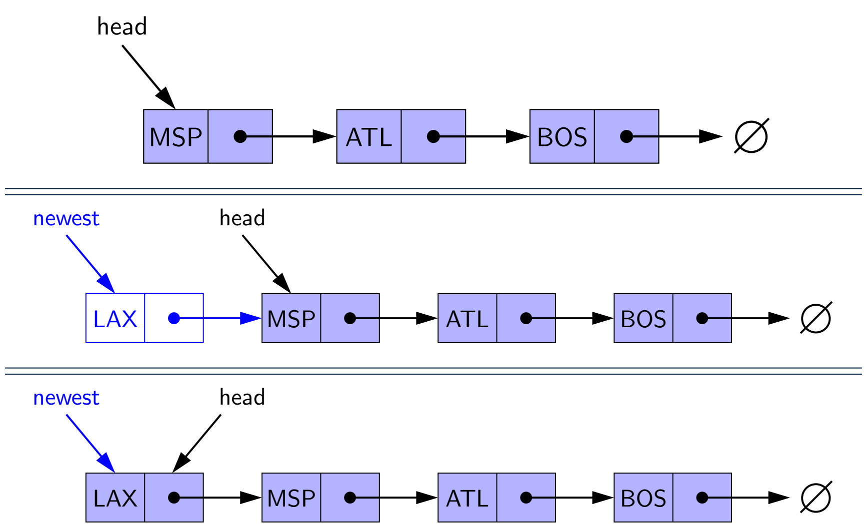

```
Node getTail() {
  Node current = head;
  Node tail = null;
  while (current != null) { /* exit when current == null */
    tail = current;
    current = current.getNext();
  }
  return tail;
}
```

`current`	`current != null`	Beginning of Iteration	`tail`
Alan	*true*	1	Alan
Mark	*true*	2	Mark
Tom	*true*	3	*Tom*
`null`	*false*	–	–

Singly-Linked List: Can We Do Better?

- It is frequently needed to
  - access the *tail* of list [e.g., a new customer joins service queue]
  - query about its *size* [e.g., is the service queue full?]
- How can we improve the *running time* of these two operations?
- We may trade *space* for *time*.
- In addition to *head*, we also declare:
  - A variable *tail* that points to the end of the list
  - A variable *size* that keeps tracks of the number of nodes in list
  - Running time of these operations are both $O(1)$!
- Nonetheless, we cannot declare variables to store references to *nodes in-between* the head and tail. Why?
  - At the *time of declarations*, we simply do not know how many nodes there will be at *runtime*.

Singly-Linked List: Inserting to the Front (1)



Singly-Linked List: Inserting to the Front (2)

- Assume we are in the context of class `SinglyLinkedList`.

```
void addFirst (String e) {
  head = new Node(e, head);
  if (size == 0) {
    tail = head;
  }
  size ++;
}
```

- Remember that RT of accessing *head* or *tail* is $O(1)$
- RT of `addFirst` is *O(1)* [constant operation]
- **Contrast**: RT of inserting into an array is *O(n)* [linear]

Your Homework

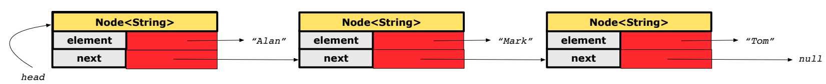
- Complete the Java *implementations* and *running time analysis* for `removeFirst()`, `addLast(E e)`.
- **Question:** *The `removeLast()` method may not be completed in the same way as is `addLast(String e)`. Why?*

Singly-Linked List: Accessing the Middle (1)

- Assume we are in the context of class `SinglyLinkedList`.

```
Node getNodeAt (int i) {
  if (i < 0 || i >= size) {
    throw IllegalArgumentException("Invalid Index");
  }
  else {
    int index = 0;
    Node current = head;
    while (index < i) {  /* exit when index == i */
      index ++;
      /* current is set to node at index i
       * last iteration: index incremented from i - 1 to i
       */
      current = current.getNext();
    }
    return current;
  }
}
```


Singly-Linked List: Accessing the Middle (2)




```
Node getNodeAt (int i) {
  if (i < 0 || i >= size) { /* print error */ }
  else {
    int index = 0;
    Node current = head;
    while (index < i) { /* exit when index == i */
      index ++;
      current = current.getNext();
    }
    return current;
  }
}
```

Let's now consider `list.getNodeAt(2)`:

`current`	`index`	`index < 2`	Beginning of Iteration
Alan	0	*true*	1
Mark	1	*true*	2
Tom	2	*false*	–

Singly-Linked List: Accessing the Middle (3)

- What is the *worst case* of the index `i` for `getNodeAt(i)`?
- Worst case: `list.getNodeAt(list.size - 1)`
- RT of `getNodeAt` is $O(n)$ [linear operation]
- **Contrast**: RT of accessing an array element is $O(1)$ [constant]

Singly-Linked List: Inserting to the Middle (1)

- Assume we are in the context of class `SinglyLinkedList`.

```
void addAt (int i, String e) {
  if (i < 0 || i >= size) {
    throw IllegalArgumentException("Invalid Index.");
  }
  else {
    if (i == 0) {
      addFirst(e);
    }
    else {
      Node nodeBefore = getNodeAt(i - 1);
      newNode = new Node(e, nodeBefore.getNext());
      nodeBefore.setNext(newNode);
      size ++;
    }
  }
}
```

Singly-Linked List: Inserting to the Middle (2)

- A call to `addAt(i, e)` may end up executing:
  - Line 3 (throw exception) [$O(1)$]
  - Line 7 (addFirst) [$O(1)$]
  - Lines 10 (getNodeAt) [$O(n)$]
  - Lines 11 – 13 (setting references) [$O(1)$]
- What is the *worst case* of the index `i` for `addAt(i, e)`?
- Worst case: `list.addAt(list.getSize() - 1, e)`
- RT of `addAt` is $O(n)$ [linear operation]
- **Contrast**: RT of inserting into an array is $O(n)$ [linear]
- On the other hand, for arrays, when given the *index* to an element, the RT of inserting an element is always $O(n)$!

Singly-Linked List: Removing from the End

- Assume we are in the context of class `SinglyLinkedList`.

```
void removeLast () {
  if (size == 0) {
    System.err.println("Empty List.");
  }
  else if (size == 1) {
    removeFirst();
  }
  else {
    Node secondLastNode = getNodeAt(size - 2);
    secondLastNode.setNext(null);
    tail = secondLastNode;
    size --;
  }
}
```

Running time? $O(n)$

Singly-Linked List: Exercises

Consider the following two linked-list operations, where a *reference node* is given as an input parameter:

- `void insertAfter(Node n, String e)`
  - Steps?
    - *Create a new node* `nn`.
    - *Set* `nn`*'s next to* `n`*'s next.*
    - *Set* `n`*'s next to* `nn`.
  - Running time? [$O(1)$]
- `void insertBefore(Node n, String e)`
  - Steps?
    - *Iterate from the* `head`*, until* `current.next == n`.
    - *Create a new node* `nn`.
    - *Set* `nn`*'s next to* `current`*'s next (which is* `n`*).*
    - *Set* `current`*'s next to* `nn`.
  - Running time? [$O(n)$]

Your Homework

- Complete the Java *implementation* and *running time analysis* for `removeAt(int i)`.

Arrays vs. Singly-Linked Lists

<table>
<tr><th colspan="2">Data Structure / Operation</th><th>Array</th><th>Singly-Linked List</th></tr>
<tr><td colspan="2">get size</td><td colspan="2" rowspan="2">O(1)</td></tr>
<tr><td colspan="2">get first/last element</td></tr>
<tr><td colspan="2">get element at index i</td><td rowspan="2">O(1)</td><td rowspan="2">O(n)</td></tr>
<tr><td colspan="2">remove last element</td></tr>
<tr><td colspan="2">add/remove first element, add last element</td><td rowspan="3">O(n)</td><td>O(1)</td></tr>
<tr><td rowspan="2">add/remove i^{th} element</td><td>given reference to $(i-1)^{th}$ element</td><td>O(1)</td></tr>
<tr><td>not given</td><td>O(n)</td></tr>
</table>

Index (1)

Index (2)

Stacks and Queues

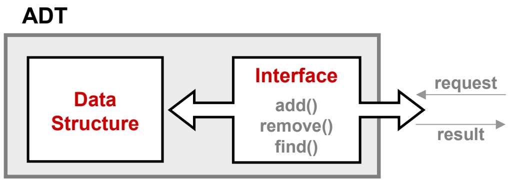
EECS2030: Advanced
Object Oriented Programming
Fall 2017

CHEN-WEI WANG

What is a Stack?

- A *stack* is a collection of objects.
- Objects in a *stack* are inserted and removed according to the *last-in, first-out (LIFO)* principle.
  - *Cannot* access *arbitrary* elements of a stack
  - *Can* only access or remove the *most-recently inserted* element

The Stack ADT



- *Accessors*
  - ***top***
  - ***size***
  - ***isEmpty***
- *Mutators*
  - ***push***
  - ***pop***

Stack: Illustration

OPERATION	RETURN VALUE	STACK CONTENTS
–	–	∅
isEmpty	*true*	∅
push(5)	–	5
push(3)	–	3 5
push(1)	–	1 3 5
size	3	1 3 5
top	1	1 3 5
pop	1	3 5
pop	3	5
pop	5	∅

Implementing Stack ADT: Array (1)

```
public class ArrayedStack {
  private static final int MAX_CAPACITY = 1000;
  private String[] data;
  private int t; /* top index */
  public ArrayedStack() {
    data = new String[MAX_CAPACITY];
    t = -1; }
  public int size() { return (t + 1); }
  public boolean isEmpty() { return (t == -1); }
  public String top() {
    if (isEmpty()) { /* Error: Empty Stack. */ }
    else { return data[t]; } }
  public void push(String e) {
    if (size() == MAX_CAPACITY) { /* Error: Stack Full. */ }
    else { t ++; data[t] = e; } }
  public String pop() {
    String result;
    if (isEmpty()) { /* Error: Empty Stack */ }
    else { result = data[t]; data[t] = null; t --; }
    return result; }
}
```


Implementing Stack ADT: Array (2)

```
@Test
public void testArrayedStack() {
  ArrayedStack s = new ArrayedStack();
  assertTrue(s.size() == 0 && s.isEmpty());
  try { String top = s.top();
        fail("Empty stack should have caused an exception."); }
  catch(IllegalArgumentException e) { }
  s.push("Alan");
  s.push("Mark");
  s.push("Tom");
  assertTrue(s.size() == 3 && !s.isEmpty());
  assertEquals("Tom", s.top());
  String oldTop = s.pop();
  assertEquals("Tom", oldTop);
  String newTop = s.top();
  assertEquals("Mark", newTop);
  oldTop = s.pop();
  assertEquals("Mark", oldTop);
  newTop = s.top();
  assertEquals("Alan", newTop);
}
```


Implementing Stack ADT: Array (3)

Running Times of *Array*-Based *Stack* Operations?

ArrayedStack Method	Running Time
size	O(1)
isEmpty	O(1)
top	O(1)
push	O(1)
pop	O(1)

Q: What if the preset capacity turns out to be insufficient?

A: $O(n)$ time to grow the array size and copy existing contents!

Implementing Stack ADT: Singly-Linked List (1)

```
public class LinkedStack {
  private SinglyLinkedList list; /* assumed: head, tail, size */
  ...
}
```

Question:

Stack Method	Singly-Linked List Method	
	Strategy 1	Strategy 2
size	list.size	
isEmpty	list.isEmpty	
top	list.first	list.last
push	list.addFirst	list.addLast
pop	list.removeFirst	list.removeLast

Which *implementation strategy* should be chosen? Either?

Implementing Stack ADT: Singly-Linked List (2)

- If the *front of list* is treated as the *top of stack*, then:
  - All stack operations remain $O(1)$.
  - *No resizing* is necessary!
- If the *back of list* is treated as the *top of stack*, then:
  - Still *no resizing* is necessary!
  - The pop operation (via removeLast) takes $O(n)$!

Application (1): Reversing an Array

```
public static void reverse(String[] a) {
  ArrayedStack buffer = new ArrayedStack();
  for (int i = 0; i < a.length; i ++) {
    buffer.push(a[i]);
  }
  for (int i = 0; i < a.length; i ++) {
    a[i] = buffer.pop();
  }
}
```

```
@Test
public void testReverseViaStack() {
  String[] names = {"Alan", "Mark", "Tom"};
  String[] reverseOfNames = {"Tom", "Mark", "Alan"};
  StackUtilities.reverse(names);
  assertArrayEquals(reverseOfNames, names);
}
```


Application (2): Matching Delimiters

- **Problem**

  Opening delimiters: `(`, `[`, `{`

  Closing delimiters: `)`, `]`, `}`

  e.g., *Correct:* "()(())([()])"

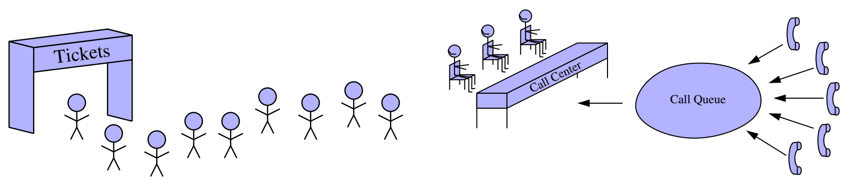
  e.g., *Incorrect:*
  - "([])" [mismatched opening and closing]
  - "{{]" [more openings than closings]
  - "{}]" [more closings than openings]
- Can we simply say $s.equals(reverseOf(s)) \Rightarrow isMatched(s)$?
  - e.g., "[()]" is matched, and its reverse are equal.
  - ***NO***! e.g., "([])[()]" matched, but different from its reverse.
- **Sketch of Solution**
  - When a new *opening* delimiter is found, *push* it to the *stack*.
  - When a new *closing* delimiter is found:
    - If it matches the *top* of the *stack*, then *pop* off the stack.
    - Otherwise, an error is found!
  - Finishing reading the input, an empty *stack* means a success!

Application (2): Matching Delimiters in Java

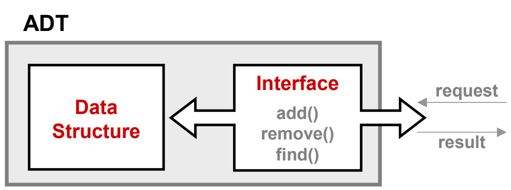
```
public static boolean isMatched(String expression) {
  final String open = "([{";
  final String close = ")]}";
  ArrayedStack openings = new ArrayedStack();
  for (int i = 0; i < expression.length(); i ++) {
    String c = Character.toString(expression.charAt(i));
    if(open.indexOf(c) != -1) { openings.push(c); }
    else if (close.indexOf(c) != -1) {
      if( openings.isEmpty() ) { return false; /* e.g., {}) */ }
      else {
        if (open.indexOf( openings.top() ) == close.indexOf(c)) {
          openings.pop(); }
        else { return false; /* e.g., (] */ }
      }
    }
  }
  return openings.isEmpty(); /* e.g., {{ */
}
```

What is a Queue?

- A *queue* is a collection of objects.
- Objects in a *queue* are inserted and removed according to the *first-in, first-out (FIFO)* principle.
  - Each new element joins at the *back* of the queue.
  - *Cannot* access *arbitrary* elements of a queue
  - *Can* only access or remove the *front* of queue: *least-recently (or longest) inserted* element



The Queue ADT



- *Accessors*
  - ***first*** [compare: ***top*** of stack]
  - ***size***
  - ***isEmpty***
- *Mutators*
  - ***enqueue*** [compare: ***push*** of stack]
  - ***dequeue*** [compare: ***pop*** of stack]

Queue: Illustration

Operation	Return Value	Queue Contents
–	–	∅
isEmpty	*true*	∅
enqueue(5)	–	(5)
enqueue(3)	–	(5, 3)
enqueue(1)	–	(5, 3, 1)
size	3	(5, 3, 1)
dequeue	5	(3, 1)
dequeue	3	1
dequeue	1	∅

Implementing Queue ADT: Array (1)

```
public class ArrayedQueue {
  private static final int MAX_CAPACITY = 1000;
  private String[] data;
  private int r; /* rear index */
  public ArrayedQueue() { data = new String[MAX_CAPACITY]; r = -1;}
  public int size() { return (r + 1); }
  public boolean isEmpty() { return (r == -1); }
  public String first() {
    if (isEmpty()) { /* Error: Empty Queue */ }
    else { return data[0]; } }
  public void enqueue(String e) {
    if (size() == MAX_CAPACITY) { /* Error: Queue Full. */ }
    else { r ++; data[r] = e; } }
  public String dequeue() {
    String result;
    if (isEmpty()) { /* Error: Empty Queue. */ }
    else {
      result = data[0];
      for (int i = 0; i < r; i ++) { data[i] = data[i + 1]; }
      r --; }
    return result; }
}
```

Implementing Queue ADT: Array (2)

```java
@Test
public void testArrayedQueue() {
  ArrayedQueue q = new ArrayedQueue();
  assertTrue(q.size() == 0 && q.isEmpty());
  try { String first = q.first();
        fail("Empty queue should have caused an exception."); }
  catch(IllegalArgumentException e) { }
  q.enqueue("Alan");
  q.enqueue("Mark");
  q.enqueue("Tom");
  assertTrue(q.size() == 3 && !q.isEmpty());
  assertEquals("Alan", q.first());
  String oldFirst = q.dequeue();
  assertEquals("Alan", oldFirst);
  String newFirst = q.first();
  assertEquals("Mark", newFirst);
  oldFirst = q.dequeue();
  assertEquals("Mark", oldFirst);
  newFirst = q.first();
  assertEquals("Tom", newFirst);
}
```


Implementing Queue ADT: Array (3)

Running Times of *Array*-Based *Queue* Operations?

***ArrayQueue* Method**	**Running Time**
size	O(1)
isEmpty	O(1)
first	O(1)
enqueue	O(1)
dequeue	$O(n)$

Q: What if the preset capacity turns out to be insufficient?

A: $O(n)$ time to grow the array size and copy existing contents!

Implementing Queue ADT: Singly-Linked List (1)

```java
public class LinkedQueue {
  private SinglyLinkedList list; /* assumed: head, tail, size */
  ...
}
```

Question:

Queue Method	**Singly-Linked List Method** Strategy 1	Strategy 2
size	list.size	
isEmpty	list.isEmpty	
first	list.first	list.last
enqueue	list.addLast	list.addFirst
dequeue	list.removeFirst	list.removeLast

Which *implementation strategy* should be chosen? Either?

Implementing Queue ADT: Singly-Linked List (2)

- If the *front of list* is treated as the *first of queue*, then:
  - All queue operations remain $O(1)$.
  - *No resizing* is necessary!
- If the *back of list* is treated as the *first of queue*, then:
  - Still *no resizing* is necessary!
  - The dequeue operation (via removeLast) takes $O(n)$!

Index (1)

Index (2)

Recursion

EECS2030: Advanced Object Oriented Programming
Fall 2017

CHEN-WEI WANG

Recursion: Principle

- *Recursion* is useful in expressing solutions to problems that can be *recursively* defined:
  - ***Base* Cases:** Small problem instances immediately solvable.
  - ***Recursive* Cases:**
    - Large problem instances *not immediately solvable*.
    - Solve by reusing *solution(s) to strictly smaller problem instances*.
- Similar idea learnt in high school: [*mathematical induction*]
- Recursion can be easily expressed programmatically in Java:
  - In the body of a method m, there might be *a call or calls to m itself*.
  - Each such self-call is said to be a *recursive call*.
  - Inside the execution of $m(i)$, a recursive call $m(j)$ must be that $j < i$.

```
m (i) {
  ...
  m (j);/* recursive call with strictly smaller value */
  ...
}
```


Recursion: Factorial (1)

- Recall the formal definition of calculating the n factorial:

$$n! = \begin{cases} 1 & \text{if } n = 0 \\ n \cdot (n-1) \cdot (n-2) \cdot \dots \cdot 3 \cdot 2 \cdot 1 & \text{if } n \geq 1 \end{cases}$$

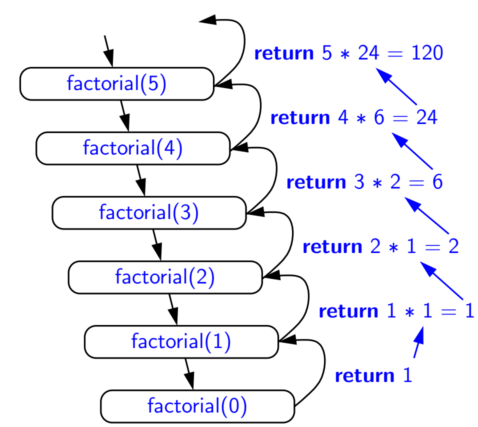
- How do you define the same problem *recursively*?

$$n! = \begin{cases} 1 & \text{if } n = 0 \\ n \cdot (n-1)! & \text{if } n \geq 1 \end{cases}$$

- To solve $n!$, we combine n and the solution to (n - 1)!.

```
int factorial (int n) {
  int result;
  if(n == 0) { /* base case */ result = 1; }
  else { /* recursive case */
    result = n * factorial (n - 1);
  }
  return result;
}
```


Recursion: Factorial (2)



Recursion: Factorial (3)

- When running *factorial(5)*, a *recursive call factorial(4)* is made. Call to *factorial(5)* suspended until *factorial(4)* returns a value.
- When running *factorial(4)*, a *recursive call factorial(3)* is made. Call to *factorial(4)* suspended until *factorial(3)* returns a value.

  ...
- *factorial(0)* returns 1 back to *suspended call factorial(1)*.
- *factorial(1)* receives 1 from *factorial(0)*, multiplies 1 to it, and returns 1 back to the *suspended call factorial(2)*.
- *factorial(2)* receives 1 from *factorial(1)*, multiplies 2 to it, and returns 2 back to the *suspended call factorial(3)*.
- *factorial(3)* receives 2 from *factorial(1)*, multiplies 3 to it, and returns 6 back to the *suspended call factorial(4)*.
- *factorial(4)* receives 6 from *factorial(3)*, multiplies 4 to it, and returns 24 back to the *suspended call factorial(5)*.
- *factorial(5)* receives 24 from *factorial(4)*, multiplies 5 to it, and returns 120 as the result.

Recursion: Factorial (4)

- When the execution of a method (e.g., *factorial(5)*) leads to a nested method call (e.g., *factorial(4)*):
  - The execution of the current method (i.e., *factorial(5)*) is *suspended*, and a structure known as an *activation record* or *activation frame* is created to store information about the progress of that method (e.g., values of parameters and local variables).
  - The nested methods (e.g., *factorial(4)*) may call other nested methods (*factorial(3)*).
  - When all nested methods complete, the activation frame of the *latest suspended* method is re-activated, then continue its execution.
- What kind of data structure does this activation-suspension process correspond to? [LIFO Stack]

Tracing Recursion using a Stack

- When a method is called, it is ***activated*** (and becomes *active*) and *pushed* onto the stack.
- When the body of a method makes a (helper) method call, that (helper) method is ***activated*** (and becomes *active*) and *pushed* onto the stack.

  ⇒ The stack contains activation records of all *active* methods.
  - *Top* of stack denotes the current point of execution.
  - Remaining parts of stack are (temporarily) ***suspended***.
- When entire body of a method is executed, stack is *popped*.

  ⇒ The current point of execution is returned to the new *top* of stack (which was ***suspended*** and just became ***active***).
- Execution terminates when the stack becomes *empty*.

Recursion: Fibonacci (1)

Recall the formal definition of calculating the n_{th} number in a Fibonacci series (denoted as F_n), which is already itself recursive:

$$F_n = \begin{cases} 1 & \text{if } n = 1 \\ 1 & \text{if } n = 2 \\ F_{n-1} + F_{n-2} & \text{if } n > 2 \end{cases}$$

```
int fib (int n) {
  int result;
  if(n == 1) { /* base case */ result = 1; }
  else if(n == 2) { /* base case */ result = 1; }
  else { /* recursive case */
    result = fib (n - 1) + fib (n - 2);
  }
  return result;
}
```

Recursion: Fibonacci (2)

```
  fib(5)
= {fib(5) = fib(4) + fib(3); push(fib(5)); suspended: ⟨fib(5)⟩; active: fib(4)}
  fib(4) + fib(3)
= {fib(4) = fib(3) + fib(2); suspended: ⟨fib(4), fib(5)⟩; active: fib(3)}
  ( fib(3) + fib(2) ) + fib(3)
= {fib(3) = fib(2) + fib(1); suspended: ⟨fib(3), fib(4), fib(5)⟩; active: fib(2)}
  (( fib(2) + fib(1) ) + fib(2)) + fib(3)
= {fib(2) returns 1; suspended: ⟨fib(3), fib(4), fib(5)⟩; active: fib(1)}
  (( 1 + fib(1) ) + fib(2)) + fib(3)
= {fib(1) returns 1; suspended: ⟨fib(3), fib(4), fib(5)⟩; active: fib(3)}
  (( 1 + 1 ) + fib(2)) + fib(3)
= {fib(3) returns 1 + 1; pop(); suspended: ⟨fib(4), fib(5)⟩; active: fib(2)}
  (2 + fib(2) ) + fib(3)
= {fib(2) returns 1; suspended: ⟨fib(4), fib(5)⟩; active: fib(4)}
  (2 + 1) + fib(3)
= {fib(4) returns 2 + 1; pop(); suspended: ⟨fib(5)⟩; active: fib(3)}
  3 + fib(3)
= {fib(3) = fib(2) + fib(1); suspended: ⟨fib(3),fib(5)⟩; active: fib(2)}
  3 + ( fib(2) + fib(1))
= {fib(2) returns 1; suspended: ⟨fib(3), fib(5)⟩; active: fib(1)}
  3 + (1 + fib(1) )
= {fib(1) returns 1; suspended: ⟨fib(3), fib(5)⟩; active: fib(3)}
  3 + (1 + 1)
= {fib(3) returns 1 + 1; pop() ; suspended: ⟨fib(5)⟩; active: fib(5)}
  3 + 2
= {fib(5) returns 3 + 2; suspended: ⟨⟩}
  5
```


Java Library: String

```java
public class StringTester {
  public static void main(String[] args) {
    String s = "abcd";
    System.out.println(s.isEmpty()); /* false */
    /* Characters in index range [0, 0) */
    String t0 = s.substring(0, 0);
    System.out.println(t0); /* "" */
    /* Characters in index range [0, 4) */
    String t1 = s.substring(0, 4);
    System.out.println(t1); /* "abcd" */
    /* Characters in index range [1, 3) */
    String t2 = s.substring(1, 3);
    System.out.println(t2); /* "bc" */
    String t3 = s.substring(0, 2) + s.substring(2, 4);
    System.out.println(s.equals(t3)); /* true */
    for(int i = 0; i < s.length(); i ++) {
      System.out.print(s.charAt(i));
    }
    System.out.println();
  }
}
```


Recursion: Palindrome (1)

Problem: A palindrome is a word that reads the same forwards and backwards. Write a method that takes a string and determines whether or not it is a palindrome.

```java
System.out.println(isPalindrome(""));  true
System.out.println(isPalindrome("a"));  true
System.out.println(isPalindrome("madam"));  true
System.out.println(isPalindrome("racecar"));  true
System.out.println(isPalindrome("man"));  false
```

Base Case 1: Empty string ⟶ Return *true* immediately.

Base Case 2: String of length 1 ⟶ Return *true* immediately.

Recursive Case: String of length ≥ 2 ⟶

- 1st and last characters match, **and**
- *the rest (i.e., middle) of the string is a palindrome*.

Recursion: Palindrome (2)

```java
boolean isPalindrome (String word) {
  if(word.length() == 0 || word.length() == 1) {
    /* base case */
    return true;
  }
  else {
    /* recursive case */
    char firstChar = word.charAt(0);
    char lastChar = word.charAt(word.length() - 1);
    String middle = word.substring(1, word.length() - 1);
    return
        firstChar == lastChar
        /* See the API of java.lang.String.substring. */
        && isPalindrome (middle);
  }
}
```

Recursion: Reverse of String (1)

Problem: The reverse of a string is written backwards. Write a method that takes a string and returns its reverse.

```
System.out.println(reverseOf(""));  /* "" */
System.out.println(reverseOf("a"));  "a"
System.out.println(reverseOf("ab"));  "ba"
System.out.println(reverseOf("abc"));  "cba"
System.out.println(reverseof("abcd"));  "dcba"
```

Base Case 1: Empty string ⟶ Return *empty string*.

Base Case 2: String of length 1 ⟶ Return *that string*.

Recursive Case: String of length ≥ 2 ⟶

1) Head of string (i.e., first character)
2) Reverse of the tail of string (i.e., all but the first character)

Return the concatenation of **1)** and **2)**.

Recursion: Reverse of a String (2)

```
String reverseOf (String s) {
  if(s.isEmpty()) { /* base case 1 */
    return "";
  }
  else if(s.length() == 1) { /* base case 2 */
    return s;
  }
  else { /* recursive case */
    String tail = s.substring(1, s.length());
    String reverseOfTail = reverseOf (tail);
    char head = s.charAt(0);
    return reverseOfTail + head;
  }
}
```


Recursion: Number of Occurrences (1)

Problem: Write a method that takes a string `s` and a character `c`, then count the number of occurrences of `c` in `s`.

```
System.out.println(occurrencesOf("", 'a'));  /* 0 */
System.out.println(occurrencesOf("a", 'a'));  /* 1 */
System.out.println(occurrencesOf("b", 'a'));  /* 0 */
System.out.println(occurrencesOf("baaba", 'a'));  /* 3 */
System.out.println(occurrencesOf("baaba", 'b'));  /* 2 */
System.out.println(occurrencesOf("baaba", 'c'));  /* 0 */
```

Base Case: Empty string ⟶ Return *0*.

Recursive Case: String of length ≥ 1 ⟶

1) Head of `s` (i.e., first character)
2) Number of occurrences of `c` in the tail of `s` (i.e., all but the first character)

If head is equal to `c`, return 1 + **2)**.
If head is not equal to `c`, return 0 + **2)**.

Recursion: Number of Occurrences (2)

```
int occurrencesOf (String s, char c) {
  if(s.isEmpty()) {
    /* Base Case */
    return 0;
  }
  else {
    /* Recursive Case */
    char head = s.charAt(0);
    String tail = s.substring(1, s.length());
    if(head == c) {
      return 1 + occurrencesOf (tail, c);
    }
    else {
      return 0 + occurrencesOf (tail, c);
    }
  }
}
```

Recursion: All Positive (1)

Problem: Determine if an array of integers are all positive.

```
System.out.println(allPositive({}));  /* true */
System.out.println(allPositive({1, 2, 3, 4, 5}));  /* true */
System.out.println(allPositive({1, 2, -3, 4, 5}));  /* false */
```

Base Case: Empty array ⟶ Return *true* immediately.
The base case is *true* ∵ we can *not* find a counter-example (i.e., a number *not* positive) from an empty array.
Recursive Case: Non-Empty array ⟶

- 1st element positive, **and**
- *the rest of the array* *is all positive* .

Exercise: Write a method `boolean somePostive(int[] a)` which *recursively* returns *true* if there is some positive number in `a`, and *false* if there are no positive numbers in `a`.
Hint: What to return in the base case of an empty array? [*false*]
∵ No witness (i.e., a positive number) from an empty array

Making Recursive Calls on an Array

- Recursive calls denote solutions to *smaller* sub-problems.
- *Naively*, explicitly create a new, smaller array:

```
void m(int[] a) {
  int[] subArray = new int[a.length - 1];
  for(int i = 1; i < a.length; i ++) { subArray[0] = a[i - 1]; }
  m(subArray) }
```

- For *efficiency*, we pass the same array *by reference* and specify the *range of indices* to be considered:

```
void m(int[] a, int from, int to) {
  if(from == to) { /* base case */ }
  else { m(a, from + 1, to) } }
```

  - `m(a, 0, a.length - 1)` [Initial call; entire array]
  - `m(a, 1, a.length - 1)` [1st r.c. on array of size *a.length* – 1]
  - `m(a, 2, a.length - 1)` [2nd r.c. on array of size *a.length* – 2]
  - ...
  - `m(a, a.length-1, a.length-1)` [Last r.c. on array of size 1]

Recursion: All Positive (2)

```
boolean allPositive(int[] a) {
  return allPositiveHelper (a, 0, a.length - 1);
}

boolean allPositiveHelper (int[] a, int from, int to) {
  if (from > to) { /* base case 1: empty range */
    return true;
  }
  else if(from == to) { /* base case 2: range of one element */
    return a[from] > 0;
  }
  else { /* recursive case */
    return a[from] > 0 && allPositiveHelper (a, from + 1, to);
  }
}
```


Recursion: Is an Array Sorted? (1)

Problem: Determine if an array of integers are sorted in a non-descending order.

```
System.out.println(isSorted({}));  true

System.out.println(isSorted({1, 2, 2, 3, 4}));  true

System.out.println(isSorted({1, 2, 2, 1, 3}));  false
```

Base Case: Empty array ⟶ Return *true* immediately.
The base case is *true* ∵ we can *not* find a counter-example (i.e., a pair of adjacent numbers that are *not* sorted in a non-descending order) from an empty array.
Recursive Case: Non-Empty array ⟶

- 1st and 2nd elements are sorted in a non-descending order, **and**
- *the rest of the array*, starting from the 2nd element, *are sorted in a non-descending positive* .

Recursion: Is an Array Sorted? (2)

```
boolean isSorted(int[] a) {
  return isSortedHelper(a, 0, a.length - 1);
}

boolean isSortedHelper(int[] a, int from, int to) {
  if (from > to) { /* base case 1: empty range */
    return true;
  }
  else if(from == to) { /* base case 2: range of one element */
    return true;
  }
  else {
    return a[from] <= a[from + 1]
      && isSortedHelper(a, from + 1, to);
  }
}
```


Recursion: Sorting an Array (1)

Problem: Sort an array into a non-descending order, using the *selection-sort* strategy.

Base Case: Arrays of size 0 or 1 ⟶ Completed immediately.

Recursive Case: Non-Empty array `a` ⟶

Run an iteration from indices $i = 0$ to $a.length - 1$.
In each iteration:

- In index range $[i, a.length - 1]$, *recursively* compute the *minimum* element $\boxed{e}$.
- Swap $\boxed{a[i]}$ and $\boxed{e}$ if $e < a[i]$.

Recursion: Sorting an Array (2)

```
public static int getMinIndex (int[] a, int from, int to) {
  if(from == to) { return from; }
  else {
    int minIndexOfTail = getMinIndex(a, from + 1, to);
    if(a[from] < a[minIndexOfTail]) { return from; }
    else { return minIndexOfTail; }
  }
}
public static void selectionSort(int[] a) {
  if(a.length == 0 || a.length == 1) { /* sorted, do nothing */ }
  else {
    for(int i = 0; i < a.length; i ++) {
      int minIndex = getMinIndex (a, i, a.length - 1);
      /* swap a[i] and a[minIndex] */
      int temp = a[i];
      a[i] = a[minIndex];
      a[minIndex] = temp;
    }
  }
}
```


Recursion: Binary Search (1)

- **Searching Problem**

  Input: A number a and a *sorted* list of n numbers $\langle a_1, a_2, \ldots, a_n \rangle$ such that $a'_1 \leq a'_2 \leq \ldots \leq a'_n$

  Output: Whether or not a exists in the input list

- **An Efficient Recursive Solution**

  Base Case: Empty list ⟶ *False*.

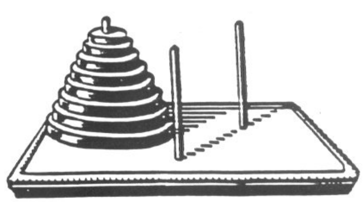
  Recursive Case: List of size ≥ 1 ⟶

  - *Compare* the *middle* element against a.
    - All elements to the left of *middle* are $\leq a$
    - All elements to the right of *middle* are $\geq a$
  - If the *middle* element *is* equal to a ⟶ *True*.
  - If the *middle* element *is not* equal to a:
    - If $a <$ *middle*, recursively find a on the left half.
    - If $a >$ *middle*, recursively find a on the right half.

Recursion: Binary Search (2)

```java
boolean binarySearch(int[] sorted, int key) {
  return binarySearchHelper(sorted, 0, sorted.length - 1, key);
}
boolean binarySearchHelper(int[] sorted, int from, int to, int key) {
  if (from > to) { /* base case 1: empty range */
    return false; }
  else if(from == to) { /* base case 2: range of one element */
    return sorted[from] == key; }
  else {
    int middle = (from + to) / 2;
    int middleValue = sorted[middle];
    if(key < middleValue) {
      return binarySearchHelper(sorted, from, middle - 1, key);
    }
    else if (key > middleValue) {
      return binarySearchHelper(sorted, middle + 1, to, key);
    }
    else  { return true; }
  }
}
```


Tower of Hanoi: Specification



- *Given*: A tower of 8 disks, initially stacked in decreasing size on one of 3 pegs
- *Rules*:
  - Move only one disk at a time
  - Never move a larger disk onto a smaller one
- *Problem*: Transfer the entire tower to one of the other pegs.

Tower of Hanoi: Strategy

- Generalize the problem by considering *n* disks.
- Introduce appropriate notation:
  - T_n denotes the *minimum* number of moves required to to transfer *n* disks from one to another under the rules.
- General patterns are easier to perceive when the extreme or base cases are well understood.
  - Look at small cases first:
    - $T_1 = 1$
    - $T_2 = 3$
    - How about T_3? Does it help us perceive the general case of n?

Tower of Hanoi: A General Solution Pattern

A possible (yet to be proved as *optimal*) solution requires 3 steps:

1. Transfer the *n - 1* smallest disks to a different peg.
2. Move the largest to the remaining free peg.
3. Transfer the *n - 1* disks back onto the largest disk.

How many moves are required from the above 3 steps?

$$(2 \times T_{n-1}) + 1$$

However, we have only proved that the # moves required by this solution are *sufficient*:

$$T_n \leq (2 \times T_{n-1}) + 1$$

But are the above steps all *necessary*? Can you justify?

$$T_n \geq (2 \times T_{n-1}) + 1$$

Tower of Hanoi: Recurrence Relation for T_n

We end up with the following recurrence relation that allows us to compute T_n for any n we like:

$$\begin{aligned} T_0 &= 0 \\ T_n &= (2 \times T_{n-1}) + 1 \quad \text{for } n > 0 \end{aligned}$$

However, the above relation only gives us *indirect* information:

To calculate T_n, first calculate T_{n-1}, which requires the calculation of T_{n-2}, and so on.

Instead, we need a *closed-form solution* to the above recurrence relation, which allows us to *directly* calculate the value of T_n.

Tower of Hanoi: A Hypothesized Closed Form Solution to T_n

$$\begin{aligned} T_0 & & &= 0 \\ T_1 &= 2 \times T_0 + 1 &&= 1 \\ T_2 &= 2 \times T_1 + 1 &&= 3 \\ T_3 &= 2 \times T_2 + 1 &&= 7 \\ T_4 &= 2 \times T_3 + 1 &&= 15 \\ T_5 &= 2 \times T_4 + 1 &&= 31 \\ T_6 &= 2 \times T_5 + 1 &&= 63 \\ \ldots \end{aligned}$$

Guess:

$$T_n = 2^n - 1 \qquad \text{for } n \geq 0$$

Prove by *mathematical induction*.

Tower of Hanoi: Prove by Mathematical Induction

Basis:

$$T_0 = 2^0 - 1 = 0$$

Induction:

Assume that

$$T_{n-1} = 2^{n-1} - 1$$

then

$$\begin{aligned} & T_n \\ = & \{\texttt{Recurrence relation for } T_n\} \\ & (2 \times T_{n-1}) + 1 \\ = & \{\texttt{Inductive assumption}\} \\ & (2 \times (2^{n-1} - 1)) + 1 \\ = & \{\texttt{Arithmetic}\} \\ & 2^n - 1 \end{aligned}$$

Revisiting the Tower of Hanoi

Given: A tower of 8 disks, initially stacked in decreasing size on one of 3 pegs.

This shall require

$$T_8 = 2^8 - 1 = 255$$

moves to complete.

Tower of Hanoi in Java (1)

```
void towerOfHanoi(String[] disks) {
  tohHelper(disks, 0, disks.length - 1, 1, 3);
}
void tohHelper(String[] disks, int from, int to, int p1, int p2) {
  if(from > to) { }
  else if(from == to) {
    print("move " + disks[to] + " from " + p1 + " to " + p2);
  }
  else {
    int intermediate = 6 - p1 - p2;
    tohHelper(disks, from, to - 1, p1, intermediate);
    print("move " + disks[to] + " from " + p1 + " to " + p2);
    tohHelper(disks, from, to - 1, intermediate, p2);
  }
}
```

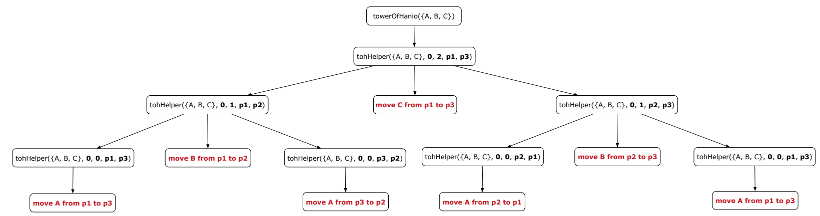
- `tohHelper(disks, from, to, p1, p2)` moves disks $\{disks[from], disks[from+1], \ldots, disks[to]\}$ from peg $p1$ to peg $p2$.
- Peg id's are 1, 2, and 3 ⇒ The intermediate one is $6 - p1 - p2$.

Tower of Hanoi in Java (2)

Say ds (disks) is $\{A, B, C\}$, where $A < B < C$.

$tohH(ds, \underbrace{0, 2}_{\{A,B,C\}}, p1, p3) =$
- $tohH(ds, \underbrace{0, 1}_{\{A,B\}}, p1, p2) =$
  - $tohH(ds, \underbrace{0, 0}_{\{A\}}, p1, p3) =$ { `Move A: p1 to p3`
  - `Move B: p1 to p2`
  - $tohH(ds, \underbrace{0, 0}_{\{A\}}, p3, p2) =$ { `Move A: p3 to p2`
- `Move C: p1 to p3`
- $tohH(ds, \underbrace{0, 1}_{\{A,B\}}, p2, p3) =$
  - $tohH(ds, \underbrace{0, 0}_{\{A\}}, p2, p1) =$ { `Move A: p2 to p1`
  - `Move B: p2 to p3`
  - $tohH(ds, \underbrace{0, 0}_{\{A\}}, p1, p3) =$ { `Move A: p1 to p3`

Tower of Hanoi in Java (3)



Recursive Methods: Correctness Proofs

```
1 boolean allPositive(int[] a) { return allPosH (a, 0, a.length - 1); }
2 boolean allPosH (int[] a, int from, int to) {
3   if (from > to) { return true; }
4   else if(from == to) { return a[from] > 0; }
5   else { return a[from] > 0 && allPosH (a, from + 1, to); } }
```

- Via mathematical induction, prove that `allPosH` is correct:
  Base Cases
  - In an empty array, there is no non-positive number ∴ result is ***true***. **[L3]**
  - In an array of size 1, the only one elements determines the result. **[L4]**

  Inductive Cases
  - **Inductive Hypothesis**: `allPosH(a, from + 1, to)` returns ***true*** if a[from + 1], a[from + 2], . . . , a[to] are all positive; ***false*** otherwise.
  - `allPosH(a, from, to)` should return ***true*** if: **1)** a[from] is positive; and **2)** a[from + 1], a[from + 2], . . . , a[to] are all positive.
  - By *I.H.*, result is $a[from] > 0 \land$ `allPosH(a, from + 1, to)`. **[L5]**
- `allPositive(a)` is correct by invoking `allPosH(a, 0, a.length - 1)`, examining the entire array. **[L1]**

Beyond this lecture . . .

- Notes on Recursion:
  `http://www.eecs.yorku.ca/~jackie/teaching/lectures/2017/F/EECS2030/slides/EECS2030_F17_Notes_Recursion.pdf`
- API for `String`:
  `https://docs.oracle.com/javase/8/docs/api/java/lang/String.html`
- Fantastic resources for sharpening your recursive skills for the exam:
  `http://codingbat.com/java/Recursion-1`
  `http://codingbat.com/java/Recursion-2`
- The *best* approach to learning about recursion is via a functional programming language:
  Haskell Tutorial: `https://www.haskell.org/tutorial/`

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Binary Trees

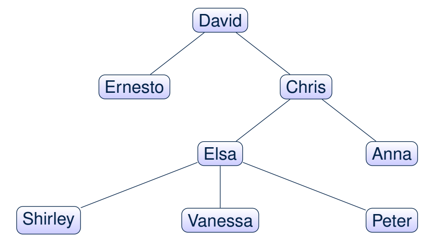
EECS2030: Advanced Object Oriented Programming
Fall 2017

CHEN-WEI WANG

General Trees

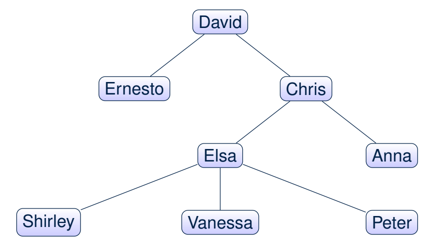
- A *linear* data structure is a sequence, where stored objects can be related via the "*before*" and "*after*" relationships.
  e.g., arrays, singly-linked lists, and doubly-linked lists
- A *tree* is a *non-linear* collection of nodes.
  - Each node stores some data object.
  - Nodes stored in a *tree* is organized in a *non-linear* manner.
  - In a *tree*, the relationships between stored objects are *hierarchical*: some objects are "*above*" others, and some are "*below*" others.
- The main terminology for the *tree* data structure comes from that of family trees: parents, siblings, children, ancestors, descendants.

General Trees: Terminology (1)



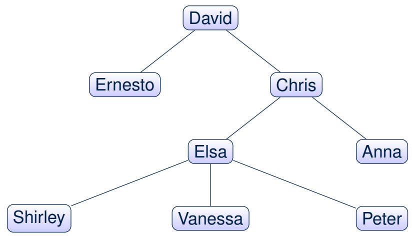
- *root of tree*: top element of the tree
  e.g., *root* of the above family tree: David
- *parent of node v*: node immediately above and connected to *v*
  e.g., *parent* of Vanessa: Elsa
- *children of node v*: nodes immediately below and connected to *v*
  e.g., *children* of Elsa: Shirley, Vanessa, and Peter
  e.g., *children* of Ernesto: ∅

General Trees: Terminology (2)



- *ancestors of node v*: *v* + *v*'s parent + *v*'s grand parent + ...
  e.g., *ancestors* of Vanessa: *Vanessa*, Elsa, Chris, and David
  e.g., *ancestors* of David: David
- *descendants of node v*: *v* + *v*'s children + *v*'s grand children + ...
  e.g., *descendants* of Vanessa: Vanessa
  e.g., *descendants* of David: the entire family tree

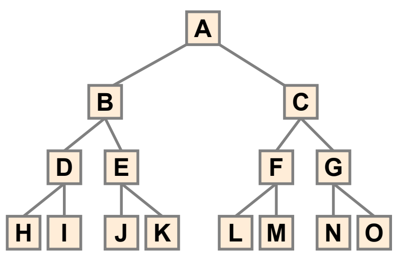
General Trees: Terminology (3)



- *siblings of node v* : nodes whose parents are the same as *v*'s
  e.g., *siblings* of Vanessa: Shirley and Peter
- *subtree rooted at v* : a tree formed by all descendant of *v*
- *external nodes (leaves)* : nodes that have no children
  e.g., *leaves* of the above tree: Ernesto, Anna, Shirley, Vanessa, Peter
- *internal nodes* : nodes that has at least one children
  e.g., *non-leaves* of the above tree: David, Chris, Elsa

Exercise: Identifying Subtrees

How many subtrees are there?

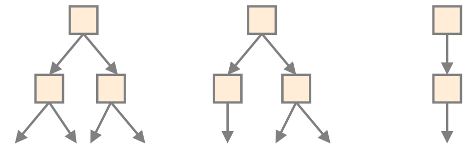


15 subtrees [i.e., subtrees rooted at each node]

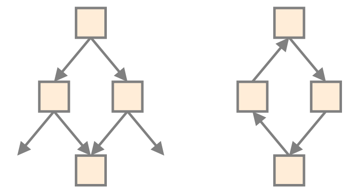
Size of Subtree	Roots of Subtrees
1	H, I, J, K, L, M, N, O
3	D, E, F, G
7	B, C
15	A

General Tree: Important Characteristics

There is a *single unique path* along the edges from the *root* to any particular node.



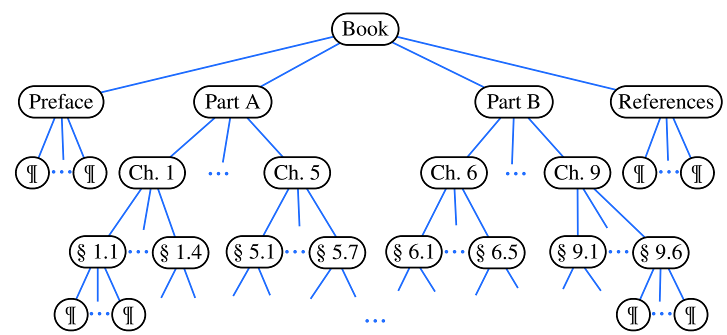
legal tree organization



illegal tree organization (nontrees)

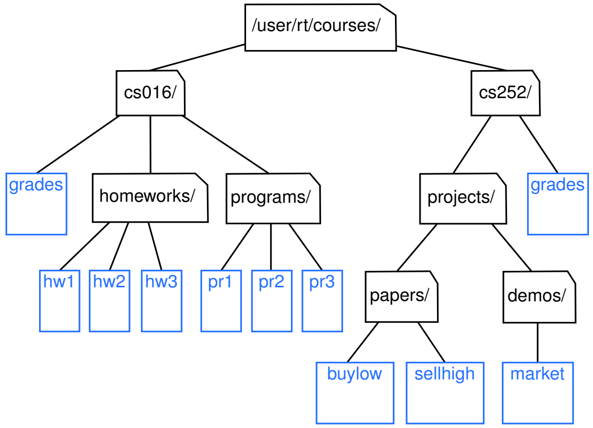
General Trees: Ordered Trees

A tree is *ordered* if there is a meaningful *linear* order among the *children* of each node.



General Trees: Unordered Trees

A tree is **unordered** if the order among the *children* of each node does not matter.



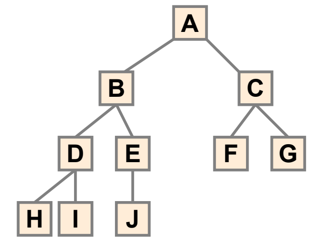
Binary Trees

- A **binary tree** is an *ordered* tree which satisfies the following properties:
  1. Each node has *at most two* children.
  2. Each child node is labeled as either a *left child* or a *right child*.
  3. A *left child* precedes a *right child* in the order of children of a node.

Binary Trees: Terminology (1)

For an *internal* node n:

- Subtree rooted at its *left child* is called *left subtree*.
  n has no left child ⇒ n's left subtree is **empty**
- Subtree rooted at its *right child* is called *right subtree*.
  n has no right child ⇒ n's right subtree is **empty**



A's *left subtree* is rooted at B and *right subtree* rooted at C.
H's *left subtree* and *right subtree* are both empty.

Binary Trees: Recursive Definition

A *binary* tree is either:

- An *empty* tree; or
- A *nonempty* tree with a root node r that
  - has a *left binary subtree* rooted at its left child
  - has a *right binary subtree* rooted at its right child

⇒ To solve problems *recursively* on a binary tree rooted at r:

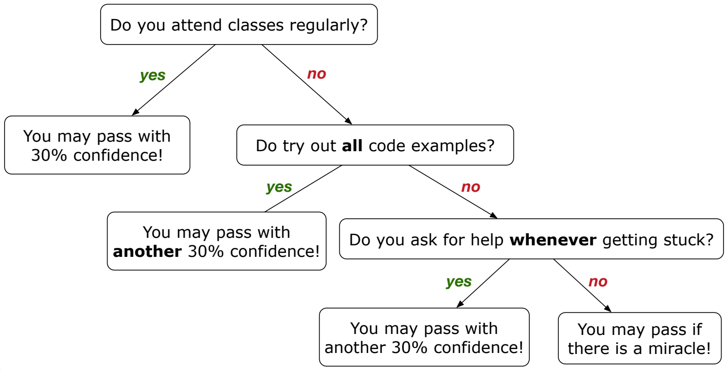
- Do something with root r.
- Recur on r's ***left subtree***. [strictly smaller problem]
- Recur on r's ***right subtree***. [strictly smaller problem]

Similar to how we *recur on* ***subarrays*** (by passing the `from` and `to` indices), we *recur on* ***subtrees*** by passing their roots (i.e., the current root's left child and right child).

Binary Trees: Application (1)

A *decision tree* is a binary tree used to to express the decision-making process:

- Each *internal node* has two children (yes and no).
- Each *external node* represents a decision.

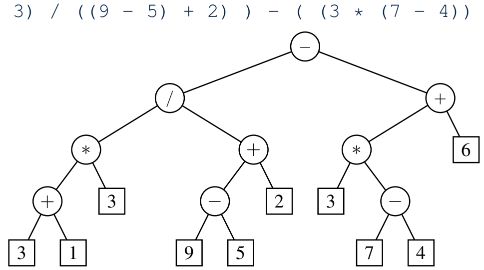


Binary Trees: Application (2)

An *arithmetic expression* can be represented using a binary tree:

- Each *internal node* denotes an operator (unary or binary).
- Each *external node* denotes an operand (i.e., a number).
  e.g., Use a binary tree to represent the arithmetic expression

```
( ((3 + 1) * 3) / ((9 − 5) + 2) ) − ( (3 * (7 − 4)) + 6 )
```



- To print, or to evaluate, the expression that is represented by a binary tree, certain *traversal* over the entire tree is required.

Tree Traversal Algorithms: Definition

- A *traversal* of a tree T is a systematic way of visiting **all** the nodes of T.
- The visit of each node may be associated with an action: e.g.,
  - print the node element
  - determine if the node element satisfies certain property
  - accumulate the node element value to some global counter

Tree Traversal Algorithms: Common Types

- **Inorder**: Visit left subtree, then parent, then right subtree.

```
inorder (r): if(r != null) {/*subtree with root r is not empty*/
  inorder (r's left child)
  visit and act on the subtree rooted at r
  inorder (r's right child) }
```

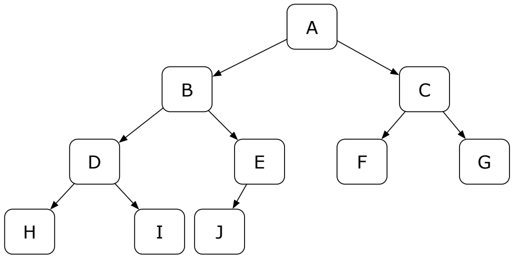
- **Preorder**: Visit parent, then left subtree, then right subtree.

```
preorder (r): if(r != null) {/*subtree with root r is not empty*/
  visit and act on the subtree rooted at r
  preorder (r's left child)
  preorder (r's right child) }
```

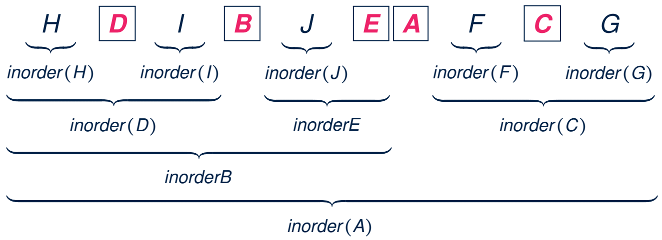
- **Postorder**: Visit left subtree, then right subtree, then parent.

```
postorder (r): if(r != null) {/*subtree with root r is not empty*/
  postorder (r's left child)
  postorder (r's right child)
  visit and act on the subtree rooted at r }
```

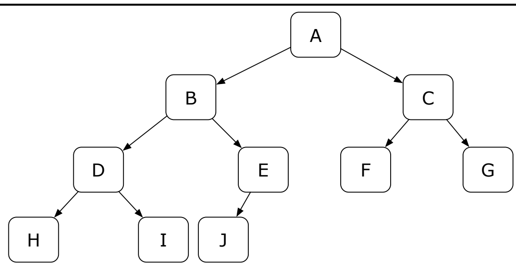
Tree Traversal: Inorder



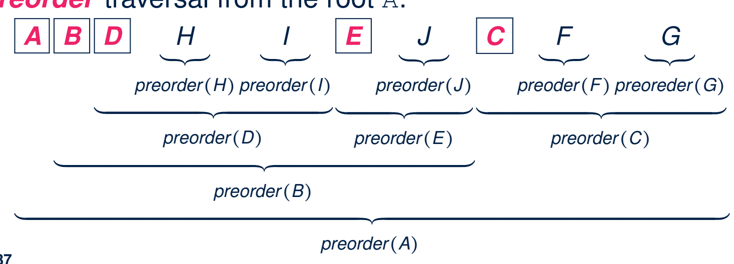
inorder traversal from the root `A`:



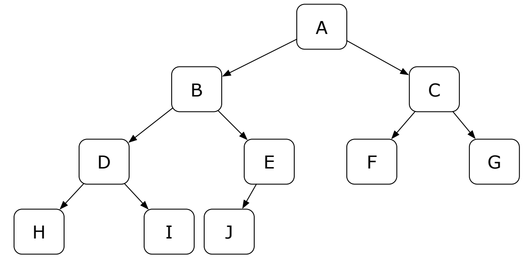
Tree Traversal: Preorder



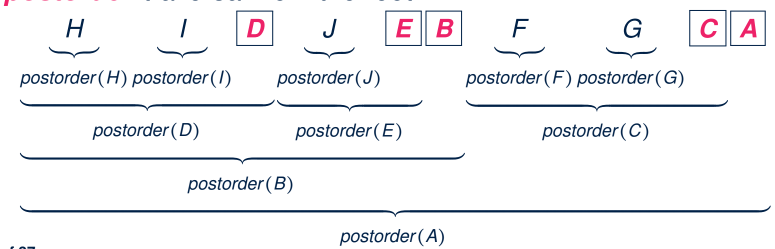
preorder traversal from the root `A`:



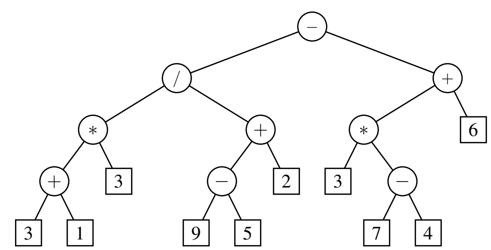
Tree Traversal: Postorder



postorder traversal from the root `A`:



Tree Traversal: Exercises



- ***inorder*** traversal from the root:
  `3+1*3/9-5+2-3*7-4+6`
- ***preorder*** traversal from the root:
  `-/*+313+-952+*3-746`
- ***postorder*** traversal from the root:
  `31+3*95-2+/374-*6+-`

Binary Tree in Java: Linked Node

```
public class BTNode {
  private String element;
  private BTNode left;
  private BTNode right;

  BTNode(String element) {
    this.element = element;
  }

  public String getElement() { return element; }
  public BTNode getLeft() { return left; }
  public BTNode getRight() { return right; }

  public void setElement(String element) { this.element = element; }
  public void setLeft(BTNode left) { this.left = left; }
  public void setRight(BTNode right) { this.right = right; }
}
```


Binary Tree in Java: Root Note

```
public class BinaryTree {
  private BTNode root;

  public BinaryTree() {
   /* Initialize an empty binary tree with root being null. */
  }

  public void setRoot(BTNode root) {
    this.root = root;
  }

  ...
}
```

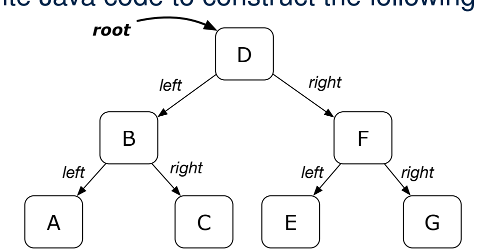

Binary Tree in Java: Adding Nodes (1)

```
public class BinaryTree {
  private BTNode root;
  public void addToLeft(BTNode n, String element) {
    if(n.getLeft() != null) {
      throw new IllegalArgumentException("Left is already there");
    }
    n.setLeft(new BTNode(element));
  }
  public void addToRight(BTNode n, String element) {
    if(n.getRight() != null) {
      throw new IllegalArgumentException("Right is already there");
    }
    n.setRight(new BTNode(element));
  }
}
```

- The way we implement the `add` methods is ***not*** recursive.
- These two `add` methods assume that the caller calls them by *passing references* of the ***parent nodes***.

Binary Tree in Java: Adding Nodes (2)

Exercise: Write Java code to construct the following binary tree:




```
BinaryTree bt = new BinaryTree(); /* empty binary tree */
BTNode root = new BTNode("D"); /* node disconnected from BT */
bt.setRoot(root); /* node connected to BT */
bt.addToLeft(root, "B");
bt.addToRight(root, "F");
bt.addToLeft(root.getLeft(), "A");
bt.addToRight(root.getLeft(), "C");
bt.addToLeft(root.getRight(), "E");
bt.addToRight(root.getRight(), "G");
```

Binary Tree in Java: Counting Size (1)

Size of a tree rooted at *r* is 1 (counting *r* itself) plus the size of *r*'s left subtree and plus the size of *r*'s right subtree.

```
public class BinaryTree {
  private BTNode root;
  public int size() { return sizeHelper(root); }
  private int sizeHelper(BTNode root) {
    if(root == null) {
      return 0;
    }
    else {
      return
          1
        + sizeHelper(root.getLeft())
        + sizeHelper(root.getRight());
    }
  }
}
```


Binary Tree in Java: Counting Size (2)

```
@Test
public void testBTSize() {
  BinaryTree bt = new BinaryTree();
  assertEquals(0, bt.size());

  BTNode root = new BTNode("D");
  bt.setRoot(root);
  assertEquals(1, bt.size());

  bt.addToLeft(root, "B");
  bt.addToRight(root, "F");
  bt.addToLeft(root.getLeft(), "A");
  bt.addToRight(root.getLeft(), "C");
  bt.addToLeft(root.getRight(), "E");
  bt.addToRight(root.getRight(), "G");
  assertEquals(7, bt.size());
}
```


Binary Tree in Java: Membership (1)

An element *e* exists in a tree rooted at *r* if either *r* contains *e*, or *r*'s left subtree contains *e*, or *r*'s right subtree contains *e*.

```
public class BinaryTree {
  private BTNode root;

  public boolean has(String e) { return hasHelper(root, e); }
  private boolean hasHelper(BTNode root, String e) {
    if(root == null) {
      return false;
    }
    else {
      return
           root.getElement().equals(e)
        || hasHelper(root.getLeft(), e)
        || hasHelper(root.getRight(), e);
    }
  }
}
```


Binary Tree in Java: Membership (2)

```
@Test
public void testBTMembership() {
  BinaryTree bt = new BinaryTree();
  assertFalse(bt.has("D"));
  BTNode root = new BTNode("D");
  bt.setRoot(root);
  assertTrue(bt.has("D"));
  assertFalse(bt.has("A"));
  bt.addToLeft(root, "B");
  bt.addToRight(root, "F");
  bt.addToLeft(root.getLeft(), "A");
  bt.addToRight(root.getLeft(), "C");
  bt.addToLeft(root.getRight(), "E");
  bt.addToRight(root.getRight(), "G");
  assertTrue(bt.has("A")); assertTrue(bt.has("B"));
  assertTrue(bt.has("C")); assertTrue(bt.has("D"));
  assertTrue(bt.has("E")); assertTrue(bt.has("F"));
  assertTrue(bt.has("G"));
  assertFalse(bt.has("H"));
  assertFalse(bt.has("I"));
}
```

Binary Tree in Java: Inorder Traversal (1)

```
public class BinaryTree {
  private BTNode root;

  public ArrayList<String> inorder() {
    ArrayList<String> list = new ArrayList<>();
    inorderHelper(root, list);
    return list;
  }
  private void inorderHelper(BTNode root, ArrayList<String> list) {
    if(root != null) {
      inorderHelper(root.getLeft(), list);
      list.add(root.getElement());
      inorderHelper(root.getRight(), list);
    }
  }
}
```


Binary Tree in Java: Inorder Traversal (2)

```
@Test
public void testBT_inorder() {
  BinaryTree bt = new BinaryTree();
  BTNode root = new BTNode("D");
  bt.setRoot(root);
  bt.addToLeft(root, "B");
  bt.addToRight(root, "F");
  bt.addToLeft(root.getLeft(), "A");
  bt.addToRight(root.getLeft(), "C");
  bt.addToLeft(root.getRight(), "E");
  bt.addToRight(root.getRight(), "G");
  ArrayList<String> list = bt.inroder();
  assertEquals(list.get(0), "A");
  assertEquals(list.get(1), "B");
  assertEquals(list.get(2), "C");
  assertEquals(list.get(3), "D");
  assertEquals(list.get(4), "E");
  assertEquals(list.get(5), "F");
  assertEquals(list.get(6), "G");
}
```


Binary Tree in Java: Preorder Traversal (1)

```
public class BinaryTree {
  private BTNode root;

  public ArrayList<String> preorder() {
    ArrayList<String> list = new ArrayList<>();
    preorderHelper(root, list);
    return list;
  }
  private void preorderHelper(BTNode root, ArrayList<String> list) {
    if(root != null) {
      list.add(root.getElement());
      preorderHelper(root.getLeft(), list);
      preorderHelper(root.getRight(), list);
    }
  }
}
```


Binary Tree in Java: Preorder Traversal (2)

```
@Test
public void testBT_inorder() {
  BinaryTree bt = new BinaryTree();
  BTNode root = new BTNode("D");
  bt.setRoot(root);
  bt.addToLeft(root, "B");
  bt.addToRight(root, "F");
  bt.addToLeft(root.getLeft(), "A");
  bt.addToRight(root.getLeft(), "C");
  bt.addToLeft(root.getRight(), "E");
  bt.addToRight(root.getRight(), "G");
  ArrayList<String> list = bt.preorder();
  assertEquals(list.get(0), "D");
  assertEquals(list.get(1), "B");
  assertEquals(list.get(2), "A");
  assertEquals(list.get(3), "C");
  assertEquals(list.get(4), "F");
  assertEquals(list.get(5), "E");
  assertEquals(list.get(6), "G");
}
```

Binary Tree in Java: Postorder Traversal (1)

```
public class BinaryTree {
  private BTNode root;

  public ArrayList<String> preorder() {
    ArrayList<String> list = new ArrayList<>();
    postorderHelper(root, list);
    return list;
  }
  private void postorderHelper(BTNode root, ArrayList<String> list) {
    if(root != null) {
      list.add(root.getElement());
      postorderHelper(root.getLeft(), list);
      postorderHelper(root.getRight(), list);
    }
  }
}
```


Binary Tree in Java: Postorder Traversal (2)

```
@Test
public void testBT_inorder() {
  BinaryTree bt = new BinaryTree();
  BTNode root = new BTNode("D");
  bt.setRoot(root);
  bt.addToLeft(root, "B");
  bt.addToRight(root, "F");
  bt.addToLeft(root.getLeft(), "A");
  bt.addToRight(root.getLeft(), "C");
  bt.addToLeft(root.getRight(), "E");
  bt.addToRight(root.getRight(), "G");
  ArrayList<String> list = bt.postorder();
  assertEquals(list.get(0), "A");
  assertEquals(list.get(1), "C");
  assertEquals(list.get(2), "B");
  assertEquals(list.get(3), "E");
  assertEquals(list.get(4), "G");
  assertEquals(list.get(5), "F");
  assertEquals(list.get(6), "D");
}
```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Inheritance

EECS2030: Advanced
Object Oriented Programming
Fall 2017

CHEN-WEI WANG

Why Inheritance: A Motivating Example

Problem: A *student management system* stores data about students. There are two kinds of university students: *resident* students and *non-resident* students. Both kinds of students have a *name* and a list of *registered courses*. Both kinds of students are restricted to *register* for no more than 10 courses. When *calculating the tuition* for a student, a base amount is first determined from the list of courses they are currently registered (each course has an associated fee). For a non-resident student, there is a *discount rate* applied to the base amount to waive the fee for on-campus accommodation. For a resident student, there is a *premium rate* applied to the base amount to account for the fee for on-campus accommodation and meals.

Tasks: Write Java classes that satisfy the above problem statement. At runtime, each type of student must be able to register a course and calculate their tuition fee.

No Inheritance: ResidentStudent Class

```
class ResidentStudent {
  String name;
  Course[] registeredCourses;
  int numberOfCourses;
  double premiumRate; /* there's a mutator method for this */
  ResidentStudent (String name) {
    this.name = name;
    registeredCourses = new Course[10];
  }
  void register(Course c) {
    registeredCourses[numberOfCourses] = c;
    numberOfCourses ++;
  }
  double getTuition() {
    double tuition = 0;
    for(int i = 0; i < numberOfCourses; i ++) {
      tuition += registeredCourses[i].fee;
    }
    return tuition * premiumRate;
  }
}
```


No Inheritance: NonResidentStudent Class

```
class NonResidentStudent {
  String name;
  Course[] registeredCourses;
  int numberOfCourses;
  double discountRate; /* there's a mutator method for this */
  NonResidentStudent (String name) {
    this.name = name;
    registeredCourses = new Course[10];
  }
  void register(Course c) {
    registeredCourses[numberOfCourses] = c;
    numberOfCourses ++;
  }
  double getTuition() {
    double tuition = 0;
    for(int i = 0; i < numberOfCourses; i ++) {
      tuition += registeredCourses[i].fee;
    }
    return tuition * discountRate;
  }
}
```

No Inheritance: Testing Student Classes

```
class Course {
 String title;
 double fee;
 Course(String title, double fee) {
  this.title = title; this.fee = fee; } }
```

```
class StudentTester {
 static void main(String[] args) {
  Course c1 = new Course("EECS2030", 500.00); /* title and fee */
  Course c2 = new Course("EECS3311", 500.00); /* title and fee */
  ResidentStudent jim = new ResidentStudent("J. Davis");
  jim.setPremiumRate(1.25);
  jim.register(c1); jim.register(c2);
  NonResidentStudent jeremy = new NonResidentStudent("J. Gibbons");
  jeremy.setDiscountRate(0.75);
  jeremy.register(c1); jeremy.register(c2);
  System.out.println("Jim pays " + jim.getTuition());
  System.out.println("Jeremy pays " + jeremy.getTuition());
 }
}
```


No Inheritance: Issues with the Student Classes

- Implementations for the two student classes seem to work. But can you see any potential problems with it?
- The code of the two student classes share a lot in common.
- *Duplicates of code make it hard to maintain your software!*
- This means that when there is a change of policy on the common part, we need modify *more than one places*.

No Inheritance: Maintainability of Code (1)

What if the way for registering a course changes?

e.g.,

```
void register(Course c) {
 if (numberOfCourses >= MAX_ALLOWANCE) {
  throw new IllegalArgumentException("Maximum allowance reached.");
 }
 else {
  registeredCourses[numberOfCourses] = c;
  numberOfCourses ++;
 }
}
```

We need to change the `register` method in *both* student classes!

No Inheritance: Maintainability of Code (2)

What if the way for calculating the base tuition changes?

e.g.,

```
double getTuition() {
 double tuition = 0;
 for(int i = 0; i < numberOfCourses; i ++) {
  tuition += registeredCourses[i].fee;
 }
 /* ... can be premiumRate or discountRate */
 return tuition * inflationRate * ...;
}
```

We need to change the `getTuition` method in *both* student classes.

No Inheritance: A Collection of Various Kinds of Students

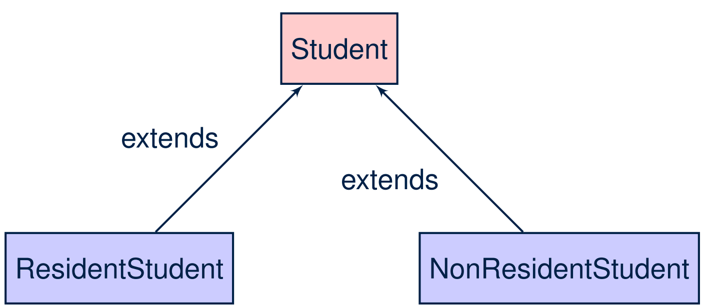
How do you define a class `StudentManagementSystem` that contains a list of *resident* and *non-resident* students?

```
class StudentManagementSystem {
  ResidentStudent[] rss;
  NonResidentStudent[] nrss;
  int nors; /* number of resident students */
  int nonrs; /* number of non-resident students */
  void addRS (ResidentStudent rs){ rss[nors]=rs; nors++; }
  void addNRS (NonResidentStudent nrs){ nrss[nonrs]=nrs; nonrs++; }
  void registerAll (Course c) {
    for(int i = 0; i < nors; i ++) { rss[i].register(c); }
    for(int i = 0; i < nonrs; i ++) { nrss[i].register(c); }
  } }
```

But what if we later on introduce *more kinds of students*?

Very *inconvenient* to handle each list of students *separately*!

Inheritance Architecture



Inheritance: The `Student` Parent/Super Class

```
class Student {
  String name;
  Course[] registeredCourses;
  int numberOfCourses;
  Student (String name) {
    this.name = name;
    registeredCourses = new Course[10];
  }
  void register(Course c) {
    registeredCourses[numberOfCourses] = c;
    numberOfCourses ++;
  }
  double getTuition() {
    double tuition = 0;
    for(int i = 0; i < numberOfCourses; i ++) {
      tuition += registeredCourses[i].fee;
    }
    return tuition; /* base amount only */
  }
}
```


Inheritance: The `ResidentStudent` Child/Sub Class

```
1 class ResidentStudent extends Student {
2   double premiumRate; /* there's a mutator method for this */
3   ResidentStudent (String name) { super(name); }
4   /* register method is inherited */
5   double getTuition() {
6     double base = super.getTuition();
7     return base * premiumRate;
8   }
9 }
```

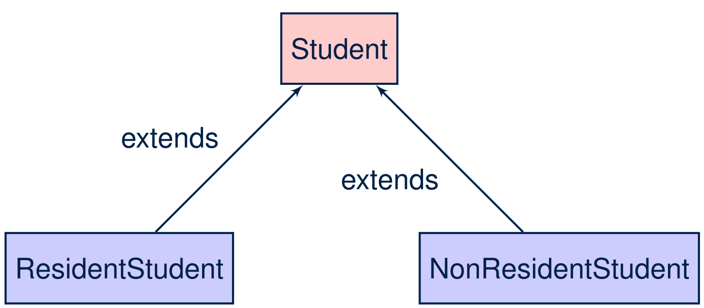
- **L1** declares that `ResidentStudent` inherits all attributes and methods (except constructors) from `Student`.
- There is no need to repeat the `register` method
- Use of *super* in **L4** is as if calling `Student(name)`
- Use of *super* in **L8** returns what `getTuition()` in `Student` returns.
- Use *super* to refer to attributes/methods defined in the super class: `super.name`, `super.register(c)`.

Inheritance: The `NonResidentStudent` Child/Sub Class

```
1 class NonResidentStudent extends Student {
2   double discountRate; /* there's a mutator method for this */
3   NonResidentStudent (String name) { super(name); }
4   /* register method is inherited */
5   double getTuition() {
6     double base = super.getTuition();
7     return base * discountRate;
8   }
9 }
```

- **L1** declares that `NonResidentStudent` inherits all attributes and methods (except constructors) from `Student`.
- There is no need to repeat the `register` method
- Use of *super* in **L4** is as if calling `Student(name)`
- Use of *super* in **L8** returns what `getTuition()` in `Student` returns.
- Use *super* to refer to attributes/methods defined in the super class: `super.name`, `super.register(c)`.

Inheritance Architecture Revisited



- The class that defines the common attributes and methods is called the *parent* or *super* class.
- Each "extended" class is called a *child* or *sub* class.

Visualizing Parent/Child Objects (1)

- A child class inherits ***all*** attributes from its parent class.

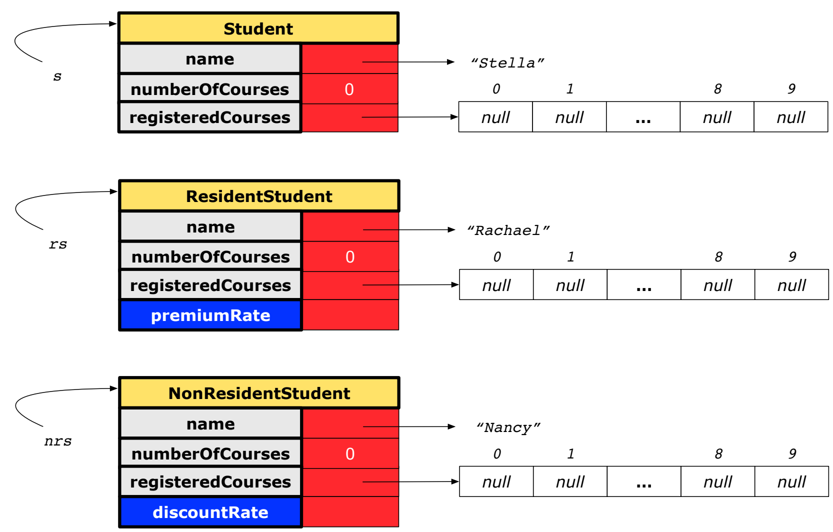
  ⇒ A child instance has ***at least as many*** attributes as an instance of its parent class.

  Consider the following instantiations:

```
Student s = new Student("Stella");
ResidentStudent rs = new ResidentStudent("Rachael");
NonResidentStudent nrs = new NonResidentStudent("Nancy");
```

- How will these initial objects look like?

Visualizing Parent/Child Objects (2)

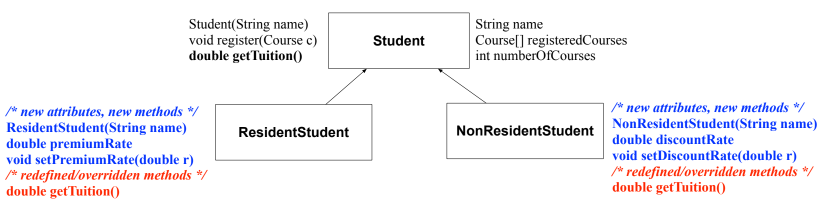


Using Inheritance for Code Reuse

Inheritance in Java allows you to:

- Define *common attributes and methods* in a separate class.
  e.g., the `Student` class
- Define an "extended" version of the class which:
  - *inherits* definitions of all attributes and methods
    e.g., `name`, `registeredCourses`, `numberOfCourses`
    e.g., `register`
    e.g., base amount calculation in `getTuition`
    This means code reuse and elimination of code duplicates!
  - *defines* **new** attributes and methods if necessary
    e.g., `setPremiumRate` for `ResidentStudent`
    e.g., `setDiscountRate` for `NonResidentStudent`
  - *redefines*/*overrides* methods if necessary
    e.g., compounded tuition for `ResidentStudent`
    e.g., discounted tuition for `NonResidentStudent`

Inheritance Architecture Revisited




```
Student s = new Student("Stella");
ResidentStudent rs = new ResidentStudent("Rachael");
NonResidentStudent nrs = new NonResidentStudent("Nancy");
```

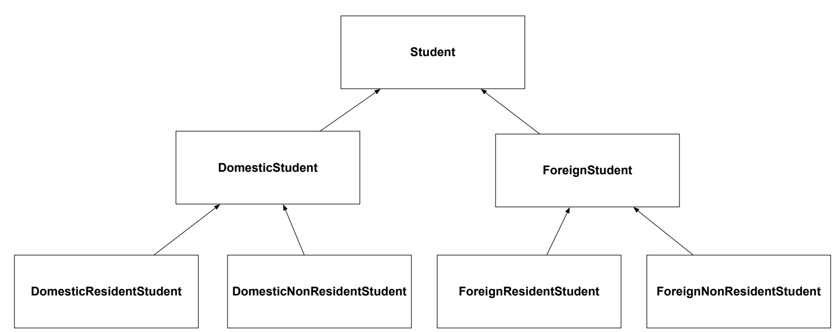
<table>
<tr><th></th><th>name</th><th>rcs</th><th>noc</th><th>reg</th><th>getT</th><th>pr</th><th>setPR</th><th>dr</th><th>setDR</th></tr>
<tr><td>s.</td><td colspan="5">✓</td><td colspan="4">×</td></tr>
<tr><td>rs.</td><td colspan="5">✓</td><td colspan="2">✓</td><td colspan="2">×</td></tr>
<tr><td>nrs.</td><td colspan="5">✓</td><td colspan="2">×</td><td colspan="2">✓</td></tr>
</table>

Testing the Two Student Sub-Classes

```
class StudentTester {
  static void main(String[] args) {
    Course c1 = new Course("EECS2030", 500.00); /* title and fee */
    Course c2 = new Course("EECS3311", 500.00); /* title and fee */
    ResidentStudent jim = new ResidentStudent("J. Davis");
    jim.setPremiumRate(1.25);
    jim.register(c1); jim.register(c2);
    NonResidentStudent jeremy = new NonResidentStudent("J. Gibbons");
    jeremy.setDiscountRate(0.75);
    jeremy.register(c1); jeremy.register(c2);
    System.out.println("Jim pays " + jim.getTuition());
    System.out.println("Jeremy pays " + jeremy.getTuition());
  }
}
```

- The software can be used in exactly the same way as before (because we did not modify *method signatures*).
- But now the internal structure of code has been made *maintainable* using *inheritance*.

Multi-Level Inheritance Architecture



Root of the Java Class Hierarchy

- Implicitly:
  - Every class is a *child/sub* class of the `Object` class.
  - The `Object` class is the *parent/super* class of every class.
- There are two useful *accessor methods* that every class *inherits* from the `Object` class:
  - `boolean equals(Object other)`
    Indicates whether some other object is "equal to" this one.
    - The default definition inherited from `Object`:

```
boolean equals(Object other) {
 return (this == other); }
```

  - `String toString()`
    Returns a string representation of the object.
- Very often when you define new classes, you want to *redefine* / *override* the inherited definitions of `equals` and `toString`.

Behaviour of the Inherited `equals` Method (1)

Problem: Define `equals` method for the `Rectangle` class

```
class Rectangle{
 double width; double length;
 double getArea() { return width * length; } }
```

and the `RectangleCollector` class

```
class RectangleCollector{
 Rectangle[] rectangles;
 final int MAX = 100;
 int nor; /* number of rectangles */
 RectangleCollector() { rectangles = new Rectangle[ MAX ]; }
 addRectangle(Rectangle c) { rectangles[ nor ] = c; nor++; }
}
```

Two rectangles are *equal* if their areas are *equal*.

Two rectangle collectors are *equal* if rectangles they contain are *equal* .

Behaviour of the Inherited `equals` Method (2)

```
1  class RectangleCollectorTester {
2   Rectangle r1 = new Rectangle(3, 6);
3   Rectangle r2 = new Rectangle(2, 9);
4   System.out.println(r1 == r2);  /* false */
5   System.out.println(r1.equals(r2));  /* false */
6   RectangleCollector rc1 = new RectangleCollector();
7   rc1.addRectangle(r1);
8   RectangleCollector rc2 = new RectangleCollector();
9   rc2.addRectangle(r2);
10  System.out.println(rc1 == rc2);  /* false */
11  System.out.println(rc1.equals(rc2));  /* false */
12 }
```

- Lines 5 and 11 return *false* because we have not **explicitly** redefined/overridden the `equals` method inherited from the `Object` class (which compares addressed by default).
- We need to *redefine* / *override* the inherited `equals` method in both `Rectangle` and `RectangleCollector`.

Behaviour of the Inherited `equals` Method (3)

Two rectangles are equal if their areas are equal:

```
class Rectangle{
 double width;
 double length;
 getArea() { ... }
 boolean equals(Object obj) {
  if(this == obj) {
   return true;
  }
  if(obj == null || this.getClass() != obj.getClass()) {
   return false;
  }
  Rectangle other = (Rectangle) obj;
  return getArea() == other.getArea();
 }
}
```

Behaviour of the Inherited `equals` Method (4)

Rectangle collectors are equal if rectangles collected are equal:

```
class RectangleCollector{
 /* rectangles, RectangleCollector(), nor, addRectangle */
 boolean equals (Object obj) {
  if(this == obj) {
   return true;
  }
  if(obj == null || this.getClass() != obj.getClass()) {
   return false;
  }
  RectangleCollector other = (RectangleCollector) obj;
  boolean soFarEqual = this.nor == other.nor;
  for(int i = 0; soFarEqual && i < this.nor; i ++) {
   soFarEqual =
     this.rectangles[i]. equals (other.rectangles[i]);
  }
  return soFarEqual;
 }
}
```


Behaviour of the Inherited `equals` Method (5)

Now that we have *redefined* / *overridden* the `equals` method, inherited from the `Object` class, in both `Rectangle` and `RectangleCollector`, the test results shall be different!

```
class RectangleCollectorTester {
 Rectangle r1 = new Rectangle(3, 6);
 Rectangle r2 = new Rectangle(2, 9);
 System.out.println(r1 == r2);  /* false */
 System.out.println(r1.equals(r2));  /* true */
 RectangleCollector rc1 = new RectangleCollector();
 rc1.addRectangle(r1);
 RectangleCollector rc2 = new RectangleCollector();
 rc2.addRectangle(r2);
 System.out.println(rc1 == rc2);  /* false */
 System.out.println(rc1.equals(rc2));  /* true */
}
```


Behaviour of Inherited `toString` Method (1)

```
Point p1 = new Point(2, 4);
System.out.println(p1);
```

```
Point@677327b6
```

- Implicitly, the `toString` method is called inside the `println` method.
- By default, the address stored in `p1` gets printed.
- We need to *redefine* / *override* the `toString` method, inherited from the `Object` class, in the `Point` class.

Behaviour of Inherited `toString` Method (2)

```
class Point {
 double x;
 double y;
 public String toString() {
  return "(" + this.x + ", " + this.y + ")";
 }
}
```

After redefining/overriding the `toString` method:

```
Point p1 = new Point(2, 4);
System.out.println(p1);
```

```
(2, 4)
```

Behaviour of Inherited `toString` Method (3)

Exercise: Override the `toString` method for the `Rectangle` and `RectangleCollector` classes.

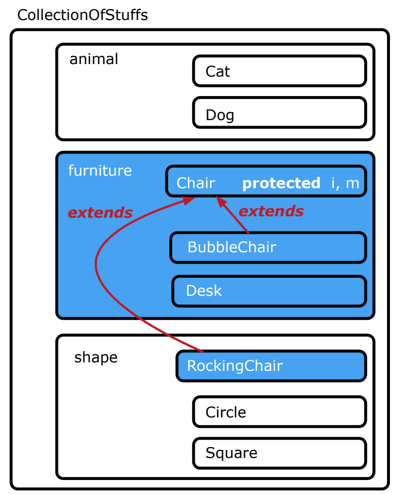
Exercise: Override the `equals` and `toString` methods for the `ResidentStudent` and `NonResidentStudent` classes.

Use of the `protected` Modifier

- ***`private`*** attributes are not inherited to subclasses.
- package-level attributes (i.e., with **no modifier**) and project-level attributes (i.e., ***`public`***) are inherited.
- What if we want attributes to be:
  - *visible* to sub-classes outside the current package, but still
  - *invisible* to other non-sub-classes outside the current package?

  Use `protected`!

Visibility of Attr./Meth.: Across All Methods Same Package and Sub-Classes (`protected`)



Visibility of Attributes/Methods

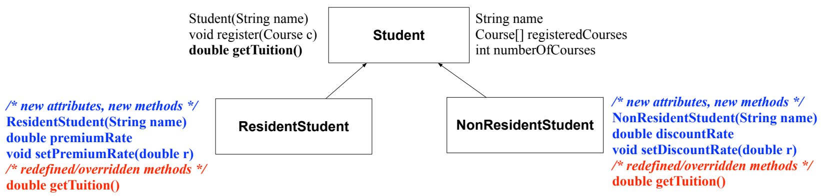
modifier \ scope	CLASS	PACKAGE	SUBCLASS (same pkg)	SUBCLASS (different pkg)	PROJECT
`public`	(green)	(green)	(green)	(green)	(green)
`protected`	(green)	(green)	(green)	(green)	(red)
no modifier	(green)	(green)	(green)	(red)	(red)
`private`	(green)	(red)	(red)	(red)	(red)

For the rest of this lecture, for simplicity, we assume that:

All relevant descendant classes are in the same package.

⇒ Attributes with **no modifiers** (package-level visibility) suffice.

Inheritance Architecture Revisited




```
Student s = new Student("Stella");
ResidentStudent rs = new ResidentStudent("Rachael");
NonResidentStudent nrs = new NonResidentStudent("Nancy");
```

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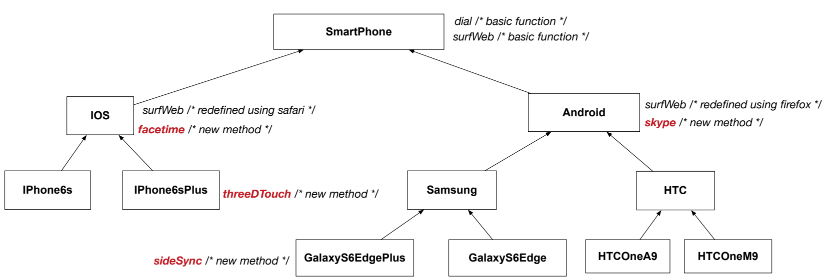
</table>

Multi-Level Inheritance Hierarchy: Smart Phones



Polymorphism: Intuition (1)

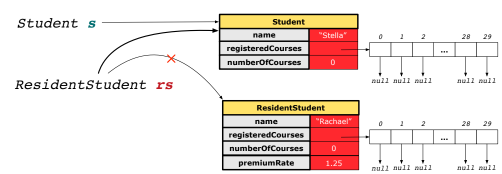
```
1 Student s = new Student("Stella");
2 ResidentStudent rs = new ResidentStudent("Rachael");
3 rs.setPremiumRate(1.25);
4 s = rs; /* Is this valid? */
5 rs = s; /* Is this valid? */
```

- Which one of **L4** and **L5** is *valid*? Which one is *invalid*?
- **Hints**:
  - **L1**: What *kind* of address can **s** store? [`Student`]
    ∴ The context object **s** is *expected* to be used as:
    - `s.register(eecs2030)` and `s.getTuition()`
  - **L2**: What *kind* of address can **rs** store? [`ResidentStudent`]
    ∴ The context object **rs** is *expected* to be used as:
    - `rs.register(eecs2030)` and `rs.getTuition()`
    - `rs.setPremiumRate(1.50)` [increase premium rate]

Polymorphism: Intuition (2)

```
1 Student s = new Student("Stella");
2 ResidentStudent rs = new ResidentStudent("Rachael");
3 rs.setPremiumRate(1.25);
4 s = rs; /* Is this valid? */
5 rs = s; /* Is this valid? */
```

- **rs** = **s** (**L5**) should be *invalid*:

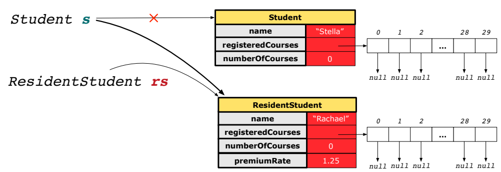


- Since **rs** is declared of type `ResidentStudent`, a subsequent call `rs.setPremiumRate(1.50)` can be expected.
- **rs** is now pointing to a `Student` object.
- Then, what would happen to `rs.setPremiumRate(1.50)`?
  CRASH ∵ `rs.premiumRate` is *undefined*!!

Polymorphism: Intuition (3)

```
1 Student s = new Student("Stella");
2 ResidentStudent rs = new ResidentStudent("Rachael");
3 rs.setPremiumRate(1.25);
4 s = rs; /* Is this valid? */
5 rs = s; /* Is this valid? */
```

- **s** = **rs** (**L4**) should be *valid*:



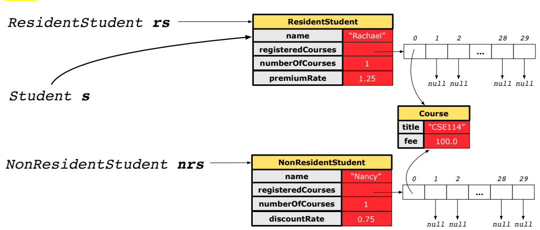
- Since **s** is declared of type `Student`, a subsequent call `s.setPremiumRate(1.50)` is *never* expected.
- **s** is now pointing to a `ResidentStudent` object.
- Then, what would happen to `s.getTuition()`?

  OK ∵ `s.premiumRate` is just *never used*!!

Dynamic Binding: Intuition (1)

```
1 Course eecs2030 = new Course("EECS2030", 100.0);
2 Student s;
3 ResidentStudent rs = new ResidentStudent("Rachael");
4 NonResidentStudent nrs = new NonResidentStudent("Nancy");
5 rs.setPremiumRate(1.25); rs.register(eecs2030);
6 nrs.setDiscountRate(0.75); nrs.register(eecs2030);
7 s = rs;  System.out.println( s .getTuition());/* output: 125.0 */
8 s = nrs;  System.out.println( s .getTuition());/* output: 75.0 */
```

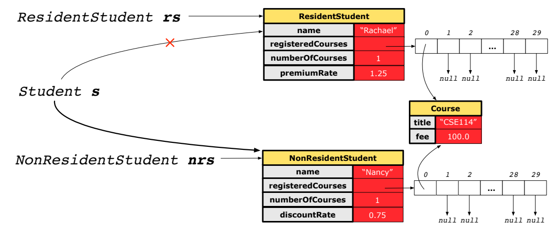
After `s = rs` (**L7**), `s` points to a `ResidentStudent` object.
⇒ Calling `s.getTuition()` applies the `premiumRate`.



Dynamic Binding: Intuition (2)

```
1 Course eecs2030 = new Course("EECS2030", 100.0);
2 Student s;
3 ResidentStudent rs = new ResidentStudent("Rachael");
4 NonResidentStudent nrs = new NonResidentStudent("Nancy");
5 rs.setPremiumRate(1.25); rs.register(eecs2030);
6 nrs.setDiscountRate(0.75); nrs.register(eecs2030);
7 s = rs;  System.out.println( s .getTuition()); /* output: 125.0 */
8 s = nrs;  System.out.println( s .getTuition()); /* output: 75.0 */
```

After `s = nrs` (**L8**), `s` points to a `NonResidentStudent` object.
⇒ Calling `s.getTuition()` applies the `discountRate`.



Inheritance Forms a Type Hierarchy

- A (data) *type* denotes a set of related *runtime values*.
  - Every *class* can be used as a type: the set of runtime *objects*.
- Use of *inheritance* creates a *hierarchy* of classes:
  - (Implicit) Root of the hierarchy is `Object`.
  - Each `extends` declaration corresponds to an upward arrow.
  - The `extends` relationship is *transitive*: when `A` extends `B` and `B` extends C, we say `A` *indirectly* extends `C`.
    e.g., Every class implicitly `extends` the `Object` class.
- *Ancestor* vs. *Descendant* classes:
  - The *ancestor classes* of a class `A` are: `A` itself and all classes that `A` directly, or indirectly, extends.
    - `A` inherits all code (attributes and methods) from its *ancestor classes*.
      ∴ `A`'s instances have a ***wider range of expected usages*** (i.e., attributes and methods) than instances of its *ancestor* classes.
  - The *descendant classes* of a class `A` are: `A` itself and all classes that directly, or indirectly, extends `A`.
    - Code defined in `A` is inherited to all its *descendant classes*.

Inheritance Accumulates Code for Reuse

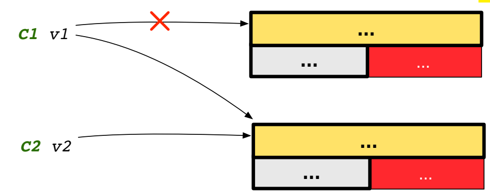
- The *lower* a class is in the type hierarchy, the *more code* it accumulates from its *ancestor classes*:
  - A *descendant class* inherits all code from its *ancestor classes*.
  - A *descendant class* may also:
    - Declare new attributes
    - Define new methods
    - *Redefine* / *Override* inherited methods
- Consequently:
  - When being used as *context objects*, instances of a class' *descendant classes* have a ***wider range of expected usages*** (i.e., attributes and methods).
  - When expecting an object of a particular class, we may *substitute* it with an object of any of its *descendant classes*.
  - e.g., When expecting a `Student` object, we may substitute it with either a `ResidentStudent` or a `NonResidentStudent` object.
  - **Justification**: A *descendant class* contains *at least as many* methods as defined in its *ancestor classes* (but not vice versa!).

Reference Variable: Static Type

- A reference variable's *static type* is what we declare it to be.
  - `Student jim` declares `jim`'s ST as `Student`.
  - `SmartPhone myPhone` declares `myPhone`'s ST as `SmartPhone`.
  - The *static type* of a reference variable *never changes*.
- For a reference variable *v*, its *static type* *C* defines the *expected usages of v as a context object*.
- A method call `v.m(...)` is ***compilable*** if ***m*** is defined in *C*.
  - e.g., After declaring `Student jim`, we
    - **may** call `register` and `getTuition` on `jim`
    - **may *not*** call `setPremiumRate` (specific to a resident student) or `setDiscountRate` (specific to a non-resident student) on `jim`
  - e.g., After declaring `SmartPhone myPhone`, we
    - **may** call `dial` and `surfWeb` on `myPhone`
    - **may *not*** call `facetime` (specific to an IOS phone) or `skype` (specific to an Android phone) on `myPhone`

Substitutions via Assignments

- By declaring ***C1*** `v1`, *reference variable* `v1` will store the *address* of an object "of class `C1`" at runtime.
- By declaring ***C2*** `v2`, *reference variable* `v2` will store the *address* of an object "of class `C2`" at runtime.
- Assignment `v1 = v2` *copies address* stored in `v2` into `v1`.
  - `v1` will instead point to wherever `v2` is pointing to. [*object alias*]



- In such assignment `v1 = v2`, we say that we *substitute* an object of (*static*) type `C1` by an object of (*static*) type `C2`.
- *Substitutions* are subject to *rules*!

Rules of Substitution

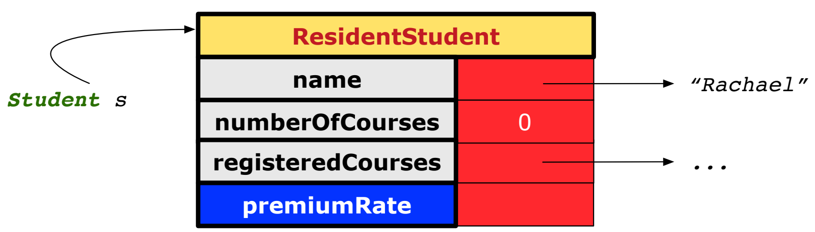
1. When expecting an object of ***static type*** `A`, it is *safe* to *substitute* it with an object whose ***static type*** is any of the *descendant class* of `A` (including `A`).
   - ∵ Each *descendant class* of `A` is guaranteed to contain code for all (non-private) attributes and methods that are defined in `A`.
   - ∴ All attributes and methods defined in `A` are *guaranteed to be available* in the new substitute.
   - e.g., When expecting an `IOS` phone, you *can* substitute it with either an `IPhone6s` or `IPhone6sPlus`.
2. When expecting an object of ***static type*** `A`, it is *unsafe* to *substitute* it with an object whose ***static type*** is any of the *ancestor classes of `A`'s parent* (excluding `A`).
   - ∵ Class `A` may have defined new methods that do not exist in any of its *parent's ancestor classes*.
   - e.g., When expecting `IOS` phone, *unsafe* to substitute it with a `SmartPhone` ∵ `facetime` not supported in `Android` phone.

Reference Variable: Dynamic Type

A *reference variable*'s *dynamic type* is the type of object that it is currently pointing to at runtime.

- The *dynamic type* of a reference variable *may change* whenever we *re-assign* that variable to a different object.
- There are two ways to re-assigning a reference variable.

Visualizing Static Type vs. Dynamic Type



- Each segmented box denotes a *runtime* object.
- Arrow denotes a variable (e.g., `s`) storing the object's address.
  Usually, when the context is clear, we leave the variable's ***static type*** implicit (***Student***).
- Title of box indicates type of runtime object, which denotes the ***dynamic type*** of the variable (***ResidentStudent***).

Reference Variable: Changing Dynamic Type (1)

Re-assigning a reference variable to a newly-created object:

- Substitution Principle : the new object's class must be a *descendant class* of the reference variable's *static type*.
- e.g., `Student jim = new ResidentStudent(...)` changes the *dynamic type* of `jim` to `ResidentStudent`.
- e.g., `Student jim = new NonResidentStudent(...)` changes the *dynamic type* of `jim` to `NonResidentStudent`.
- e.g., `ResidentStudent jim = new Student(...)` is illegal because `Studnet` is **not** a *descendant class* of the *static type* of `jim` (i.e., `ResidentStudent`).

Reference Variable: Changing Dynamic Type (2)

Re-assigning a reference variable `v` to an existing object that is referenced by another variable `other` (i.e., `v = other`):

- Substitution Principle : the static type of `other` must be a *descendant class* of `v`'s *static type*.
- e.g., Say we declare

```
Student jim = new Student(...);
ResidentStudent rs = new ResidentStudnet(...);
NonResidentStudnet nrs = new NonResidentStudent(...);
```

- `rs = jim` ×
- `nrs = jim` ×
- `jim = rs` ✓
  changes the *dynamic type* of `jim` to the dynamic type of `rs`
- `jim = nrs` ✓
  changes the *dynamic type* of `jim` to the dynamic type of `nrs`

Polymorphism and Dynamic Binding (1)

- *Polymorphism*: An object variable may have *"multiple possible shapes"* (i.e., allowable *dynamic types*).
  - Consequently, there are *multiple possible versions* of each method that may be called.
    - e.g., A ***Student*** variable may have the *dynamic type* of ***Student***, ***ResidentStudent***, or ***NonResidentStudent***,
    - This means that there are three possible versions of the `getTuition()` that may be called.
- *Dynamic binding*: When a method `m` is called on an object variable, the version of `m` corresponding to its *"current shape"* (i.e., one defined in the *dynamic type* of *m*) will be called.

```
Student jim = new ResidentStudent(...);
jim.getTuition();  /* version in ResidentStudent */
jim = new NonResidentStudent(...);
jim.getTuition();  /* version in NonResidentStudent */
```


Polymorphism and Dynamic Binding (2.1)

```
class Student {...}
class ResidentStudent extends Student {...}
class NonResidentStudent extends Student {...}
```

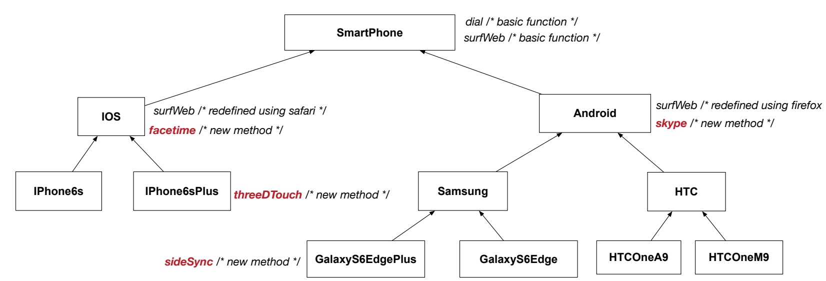
```
class StudentTester1 {
 public static void main(String[] args) {
  Student jim = new Student("J. Davis");
  ResidentStudent rs = new ResidentStudent("J. Davis");
  jim = rs;  /* legal */
  rs = jim;  /* illegal */

  NonResidentStudnet nrs = new NonResidentStudent("J. Davis");
  jim = nrs;  /* legal */
  nrs = jim;  /* illegal */
 }
}
```


Polymorphism and Dynamic Binding (2.2)

```
class Student {...}
class ResidentStudent extends Student {...}
class NonResidentStudent extends Student {...}
```

```
class StudentTester2 {
 public static void main(String[] args) {
  Course eecs2030 = new Course("EECS2030", 500.0);
  Student jim = new Student("J. Davis");
  ResidentStudent rs = new ResidentStudent("J. Davis");
  rs.setPremiumRate(1.5);
  jim = rs;
  System.out.println( jim.getTuition() );  /* 750.0 */
  NonResidentStudnet nrs = new NonResidentStudent("J. Davis");
  nrs.setDiscountRate(0.5);
  jim = nrs;
  System.out.println( jim.getTuition() );  /* 250.0 */
 }
}
```


Polymorphism and Dynamic Binding (3.1)



Polymorphism and Dynamic Binding (3.2)

```java
class SmartPhoneTest1 {
  public static void main(String[] args) {
    SmartPhone myPhone;
    IOS ip = new IPhone6sPlus();
    Samsung ss = new GalaxyS6Edge();
    myPhone = ip;  /* legal */
    myPhone = ss;  /* legal */

    IOS presentForHeeyeon;
    presentForHeeyeon = ip;  /* legal */
    presentForHeeyeon = ss;  /* illegal */
  }
}
```


Polymorphism and Dynamic Binding (3.3)

```java
class SmartPhoneTest2 {
  public static void main(String[] args) {
    SmartPhone myPhone;
    IOS ip = new IPhone6sPlus();
    myPhone = ip;
    myPhone. surfWeb (); /* version of surfWeb in IPhone6sPlus */

    Samsung ss = new GalaxyS6Edge();
    myPhone = ss;
    myPhone. surfWeb (); /* version of surfWeb in GalaxyS6Edge */
  }
}
```


Reference Type Casting: Motivation (1)

```java
1 Student jim = new ResidentStudent("J. Davis");
2 ResidentStudent rs = jim;
3 rs.setPremiumRate(1.5);
```

- **L1** is *legal*: `ResidentStudent` is a **descendant class** of the ***static type*** of `jim` (i.e., `Student`).
- **L2** is *illegal*: `jim`'s ***ST*** (i.e., `Student`) is ***not*** a **descendant class** of `rs`'s ***ST*** (i.e., `ResidentStudent`).
- Java compiler is *unable to infer* that `jim`'s ***dynamic type*** in **L2** is `ResidentStudent`!
- Force the Java compiler to believe so via a cast in **L2**:
  `ResidentStudent rs = (ResidentStudent) jim;`

  ⇒ Now it compiles ∵ `jim`'s temporary ***ST*** (`ResidentStudent`) is a **descendant** of `rs`' ***ST*** (`ResidentStudent`).
- *dynamic binding* : After the *cast* , **L3** will execute the correct version of `setPremiumRate`.

Reference Type Casting: Motivation (2)

```java
1 SmartPhone aPhone = new IPhone6sPlus();
2 IOS forHeeyeon = aPhone;
3 forHeeyeon.facetime();
```

- **L1** is *legal*: `IPhone6sPlus` is a **descendant class** of the ***static type*** of `aPhone` (i.e., `SmartPhone`).
- **L2** is *illegal*: `aPhone`'s ***ST*** (i.e., `SmartPhone`) is ***not*** a **descendant class** of `forHeeyeon`'s ***ST*** (i.e., `IOS`).
- Java compiler is *unable to infer* that `aPhone`'s ***dynamic type*** in **L2** is `IPhone6sPlus`!
- Force Java compiler to believe so via a *cast* in **L2**:
  `IOS forHeeyeon = (IPhone6sPlus) aPhone;`

  ⇒ Now it compiles ∵ `aPhone`'s temporary ***ST*** (`IPhone6sPlus`) is a **descendant** of `forHeeyeon`' ***ST*** (`IOS`).
- *dynamic binding* : After the *cast* , **L3** will execute the correct version of `facetime`.

Type Cast: Named or Anonymous

LASSONDE

Named Cast: Use intermediate variable to store the cast result.

```
SmartPhone aPhone = new IPhone6sPlus();
IOS forHeeyeon = (IPhone6sPlus) aPhone;
forHeeyeon.facetime();
```

Anonymous Cast: Use the cast result directly.

```
SmartPhone aPhone = new IPhone6sPlus();
((IPhone6sPlus) aPhone).facetime();
```

Common Mistake:

```
1 SmartPhone aPhone = new IPhone6sPlus();
2 (IPhone6sPlus) aPhone.facetime();
```

L2 ≡ `(IPhone6sPlus) (aPhone.facetime())`: Call, then cast.

⇒ This does **not** compile ∵ `facetime()` is **not** declared in the *static type* of `aPhone` (`SmartPhone`).

Notes on Type Cast (1)

LASSONDE

- Given variable **v** of ***static type*** ST_v, it is *compilable* to cast **v** to *C*, as long as *C* is an **ancestor** or **descendant** of ST_v.
- Without cast, we can **only** call methods defined in ST_v on v.
- Casting v to *C* **temporarily** changes the ***ST*** of v from ST_v to *C*.

  ⇒ All methods that are defined in *C* can be called.

```
Android myPhone = new GalaxyS6EdgePlus();
/* can call methods declared in Android on myPhone
 * dial, surfweb, skype ✓ sideSync × */
SmartPhone sp = (SmartPhone) myPhone;
/* Compiles OK ∵ SmartPhone is an ancestor class of Android
 * expectations on sp narrowed to methods in SmartPhone
 * sp.dial, sp.surfweb ✓ sp.skype, sp.sideSync × */
GalaxyS6EdgePlus ga = (GalaxyS6EdgePlus) myPhone;
/* Compiles OK ∵ GalaxyS6EdgePlus is a descendant class of Android
 * expectations on ga widened to methods in GalaxyS6EdgePlus
 * ga.dial, ga.surfweb, ga.skype, ga.sideSync ✓ */
```


Reference Type Casting: Danger (1)

LASSONDE

```
1 Student jim = new NonResidentStudent("J. Davis");
2 ResidentStudent rs = (ResidentStudent) jim;
3 rs.setPremiumRate(1.5);
```

- **L1** is *legal*: `NonResidentStudent` is a **descendant** of the static type of `jim` (`Student`).
- **L2** is *legal* (where the cast type is `ResidentStudent`):
  - cast type is **descendant** of `jim`'s ST (`Student`).
  - cast type is **descendant** of `rs`'s ST (`ResidentStudent`).
- **L3** is *legal* ∵ `setPremiumRate` is in `rs`' ***ST*** `ResidentStudent`.
- Java compiler is *unable to infer* that `jim`'s *dynamic type* in **L2** is actually `NonResidentStudent`.
- Executing **L2** will result in a *`ClassCastException`*.

  ∵ Attribute `premiumRate` (expected from a ***ResidentStudent***) is *undefined* on the ***NonResidentStudent*** object being cast.

Reference Type Casting: Danger (2)

LASSONDE

```
1 SmartPhone aPhone = new GalaxyS6EdgePlus();
2 IPhone6sPlus forHeeyeon = (IPhone6sPlus) aPhone;
3 forHeeyeon.threeDTouch();
```

- **L1** is *legal*: `GalaxyS6EdgePlus` is a **descendant** of the static type of `aPhone` (`SmartPhone`).
- **L2** is *legal* (where the cast type is `Iphone6sPlus`):
  - cast type is **descendant** of `aPhone`'s ST (`SmartPhone`).
  - cast type is **descendant** of `forHeeyeon`'s ST (`IPhone6sPlus`).
- **L3** is *legal* ∵ `threeDTouch` is in `forHeeyeon`' ***ST*** `IPhone6sPlus`.
- Java compiler is *unable to infer* that `aPhone`'s *dynamic type* in **L2** is actually `NonResidentStudent`.
- Executing **L2** will result in a *`ClassCastException`*.

  ∵ Methods `facetime`, `threeDTouch` (expected from an ***IPhone6sPlus***) is *undefined* on the ***GalaxyS6EdgePlus*** object being cast.

Notes on Type Cast (2.1)

Given a variable *v* of static type ST_v and dynamic type DT_v:

- `(C) v` is *compilable* if `C` is ST_v's **ancestor** or **descendant**.
- Casting `v` to `C`'s ***ancestor***/***descendant*** ***narrows***/***widens*** expectations.
- However, being *compilable* does not guarantee ***runtime-error-free***!

```
1 SmartPhone myPhone = new Samsung();
2 /* ST of myPhone is SmartPhone; DT of myPhone is Samsung */
3 GalaxyS6EdgePlus ga = (GalaxyS6EdgePlus) myPhone;
4 /* Compiles OK ∵ GalaxyS6EdgePlus is a descendant class of SmartPhone
5  * can now call methods declared in GalaxyS6EdgePlus on ga
6  * ga.dial, ga.surfweb, ga.skype, ga.sideSync ✓ */
```

- Type cast in **L3** is *compilable*.
- Executing **L3** will cause `ClassCastException`.

L3: `myPhone`'s *DT* `Samsung` cannot meet expectations of the temporary *ST* `GalaxyS6EdgePlus` (e.g., `sideSync`).

Notes on Type Cast (2.2)

Given a variable *v* of static type ST_v and dynamic type DT_v:

- `(C) v` is *compilable* if `C` is ST_v's **ancestor** or **descendant**.
- Casting `v` to `C`'s ***ancestor***/***descendant*** ***narrows***/***widens*** expectations.
- However, being *compilable* does not guarantee ***runtime-error-free***!

```
1 SmartPhone myPhone = new Samsung();
2 /* ST of myPhone is SmartPhone; DT of myPhone is Samsung */
3 IPhone6sPlus ip = (IPhone6sPlus) myPhone;
4 /* Compiles OK ∵ IPhone6sPlus is a descendant class of SmartPhone
5  * can now call methods declared in IPhone6sPlus on ip
6  * ip.dial, ip.surfweb, ip.facetime, ip.threeDTouch ✓ */
```

- Type cast in **L3** is *compilable*.
- Executing **L3** will cause `ClassCastException`.

L3: `myPhone`'s *DT* `Samsung` cannot meet expectations of the temporary *ST* `IPhone6sPlus` (e.g., `threeDTouch`).

Notes on Type Cast (2.3)

A cast `(C) v` is *compilable* and ***runtime-error-free*** if *C* is located along the **ancestor path** of DT_v.

e.g., Given ***SmartPhone*** myPhone = new ***Samsung***();

- Cast `myPhone` to a class along the path between ***SmartPhone*** and ***Samsung***.
- Casting `myPhone` to a class with more expectations than ***Samsung*** (e.g., `GalaxyS6EdgePlus`) will cause `ClassCastException`.
- Casting `myPhone` to a class irrelevant to ***Samsung*** (e.g., `IPhone6sPlus`) will cause `ClassCastException`.

Compilable Cast vs. Exception-Free Cast

```
class A { }
class B extends A { }
class C extends B { }
class D extends A { }
```

```
1 B b = new C();
2 D d = (D) b;
```

- After **L1**:
  - ***ST*** of `b` is `B`
  - ***DT*** of `b` is `C`
- Does **L2** compile? [NO]

  ∵ cast type `D` is neither an ancestor nor a descendant of `b`'s ***ST*** `B`
- Would `D d = (D) ((A) b)` fix **L2**? [YES]

  ∵ cast type `D` is an ancestor of `b`'s cast, temporary ***ST*** `A`
- `ClassCastException` when executing this fixed **L2**? [YES]

  ∵ cast type `D` is not an ancestor of `b`'s ***DT*** `C`

Reference Type Casting: Runtime Check (1)

```
1 Student jim = new NonResidentStudent("J. Davis");
2 if (jim instanceof ResidentStudent ) {
3   ResidentStudent rs = ( ResidentStudent ) jim;
4   rs.setPremiumRate(1.5);
5 }
```

- **L1** is *legal*: `NonResidentStudent` is a **descendant class** of the ***static type*** of `jim` (i.e., `Student`).
- **L2** checks if `jim`'s *dynamic type* is `ResidentStudent`.

  FALSE ∵ `jim`'s *dynamic type* is `NonResidentStudent`!
- **L3** is *legal*: `jim`'s cast type (i.e., `ResidentStudent`) is a **descendant class** of `rs`'s ***static type*** (i.e., `ResidentStudent`).
- **L3** will not be executed at runtime, hence no `ClassCastException`, thanks to the check in **L2**!

Reference Type Casting: Runtime Check (2)

```
1 SmartPhone aPhone = new GalaxyS6EdgePlus();
2 if (aPhone instanceof IPhone6sPlus ) {
3   IOS forHeeyeon = ( IPhone6sPlus ) aPhone;
4   forHeeyeon.facetime();
5 }
```

- **L1** is *legal*: `GalaxyS6EdgePlus` is a **descendant class** of the static type of `aPhone` (i.e., `SmartPhone`).
- **L2** checks if `aPhone`'s *dynamic type* is `IPhone6sPlus`.

  FALSE ∵ `aPhone`'s *dynamic type* is `GalaxyS6EdgePlus`!
- **L3** is *legal*: `aPhone`'s cast type (i.e., `IPhone6sPlus`) is a **descendant class** of `forHeeyeon`'s ***static type*** (i.e., `IOS`).
- **L3** will not be executed at runtime, hence no `ClassCastException`, thanks to the check in **L2**!

Notes on the `instanceof` Operator (1)

Given a reference variable `v` and a class `C`, you write

`v instanceof C`

to check if the ***dynamic type*** of `v`, at the moment of being checked, is a **descendant class** of `C`.

```
SmartPhone myPhone = new GalaxyS6Edge();
println(myPhone instanceof Android);
/* true ∵ GalaxyS6Edge is a descendant of Android */}
println(myPhone instanceof Samsung);
/* true ∵ GalaxyS6Edge is a descendant of Samsung */}
println(myPhone instanceof GalaxyS6Edge);
/* true ∵ GalaxyS6Edge is a descendant of GalaxyS6Edge */}
println(myPhone instanceof IOS);
/* false ∵ GalaxyS6Edge is not a descendant of IOS */}
println(myPhone instanceof IPhone6sPlus);
/* false ∵ GalaxyS6Edge is not a descendant of IPhone6sPlus */}
```


Notes on the `instanceof` Operator (2)

Given a reference variable `v` and a class `C`, `v instanceof C` checks if the ***dynamic type*** of `v`, at the moment of being checked, is a `descendant class` of `C`.

```
1  SmartPhone myPhone = new Samsung();
2  /* ST of myPhone is SmartPhone; DT of myPhone is Samsung */
3  if(myPhone instanceof Samsung) {
4    Samsung samsung = (Samsung) myPhone;
5  }
6  if(myPhone instanceof GalaxyS6EdgePlus) {
7    GalaxyS6EdgePlus galaxy = (GalaxyS6EdgePlus) myPhone;
8  }
9  if(myphone instanceof HTC) {
10   HTC htc = (HTC) myPhone;
11 }
```

- **L3** evaluates to *true*. [*safe* to cast]
- **L6** and **L9** evaluate to *false*. [*unsafe* to cast]

  This prevents **L7** and **L10**, causing `ClassCastException` if executed, from being executed.

Static Type and Polymorphism (1.1)

```
class SmartPhone {
  void dial() { ... }
}
class IOS extends SmartPhone {
  void facetime() { ... }
}
class IPhone6sPlus extends IOS {
  void threeDTouch() { ... }
}
```

```
SmartPhone sp = new IPhone6sPlus();   ✓
sp.dial();   ✓
sp.facetime();   ×
sp.threeDTouch();   ×
```

Static type of *sp* is `SmartPhone`

⇒ can only call methods defined in `SmartPhone` on *sp*

Static Type and Polymorphism (1.2)

```
class SmartPhone {
  void dial() { ... }
}
class IOS extends SmartPhone {
  void facetime() { ... }
}
class IPhone6sPlus extends IOS {
  void threeDTouch() { ... }
}
```

```
IOS ip = new IPhone6sPlus();   ✓
ip.dial();   ✓
ip.facetime();   ✓
ip.threeDTouch();   ×
```

Static type of *ip* is `IOS`

⇒ can only call methods defined in `IOS` on *ip*

Static Type and Polymorphism (1.3)

```
class SmartPhone {
  void dial() { ... }
}
class IOS extends SmartPhone {
  void facetime() { ... }
}
class IPhone6sPlus extends IOS {
  void threeDTouch() { ... }
}
```

```
IPhone6sPlus ip6sp = new IPhone6sPlus();   ✓
ip6sp.dial();   ✓
ip6sp.facetime();   ✓
ip6sp.threeDTouch();   ✓
```

Static type of *ip6sp* is `IPhone6sPlus`

⇒ can call all methods defined in `IPhone6sPlus` on *ip6sp*

Static Type and Polymorphism (1.4)

```
class SmartPhone {
  void dial() { ... }
}
class IOS extends SmartPhone {
  void facetime() { ... }
}
class IPhone6sPlus extends IOS {
  void threeDTouch() { ... }
}
```

```
1 SmartPhone sp = new IPhone6sPlus();   ✓
2 ((IPhone6sPlus) sp).dial();   ✓
3 ((IPhone6sPlus) sp).facetime();   ✓
4 ((IPhone6sPlus) sp).threeDTouch();   ✓
```

L4 is equivalent to the following two lines:

```
IPhone6sPlus ip6sp = (IPhone6sPlus) sp;
ip6sp.threeDTouch();
```

Static Type and Polymorphism (2)

Given a reference variable declaration

```
C v;
```

- *Static type* of reference variable *v* is class *C*
- A method call `v.m` is valid if *m* is a method **defined** in class ***C***.
- Despite the *dynamic type* of *v*, you are only allowed to call methods that are defined in the *static type* `C` on *v*.
- If you are certain that *v*'s *dynamic type* can be expected **more** than its *static type*, then you may use an `insanceof` check and a cast.

```
Course eecs2030 = new Course("EECS2030", 500.0);
Student s = new ResidentStudent("Jim");
s.register(eecs2030);
if(s instanceof ResidentStudent) {
  ((ResidentStudent) s).setPremiumRate(1.75);
  System.out.println(((ResidentStudent) s).getTuition());
}
```


Polymorphism: Method Call Arguments (1)

```
1 class StudentManagementSystem {
2   Student [] ss; /* ss[i] has static type Student */ int c;
3   void addRS(ResidentStudent rs) { ss[c] = rs; c ++; }
4   void addNRS(NonResidentStudent nrs) { ss[c] = nrs; c++; }
5   void addStudent(Student s) { ss[c] = s; c++; } }
```

- **L3**: `ss[c] = rs` is valid. ∵ RHS's ST `ResidentStudent` is a *descendant class* of LHS's ST `Student`.
- Say we have a `StudentManagementSystem` object `sms`:
  - Method call `sms.addRS(o)` attempts the following assignment, which replaces parameter `rs` by a copy of argument `o`:

    ```
    rs = o;
    ```

  - Whether this argument passing is valid depends on `o`'s *static type*.
- In the signature of a method `m`, if the type of a parameter is class `C`, then we may call method `m` by passing objects whose *static types* are `C`'s *descendants*.

Polymorphism: Method Call Arguments (2.1)

In the `StudentManagementSystemTester`:

```
Student s1 = new Student();
Student s2 = new ResidentStudent();
Student s3 = new NonResidentStudent();
ResidentStudent rs = new ResidentStudent();
NonResidentStudent nrs = new NonResidentStudent();
StudentManagementSystem sms = new StudentManagementSystem();
sms.addRS(s1);  ×
sms.addRS(s2);  ×
sms.addRS(s3);  ×
sms.addRS(rs);  ✓
sms.addRS(nrs);  ×
sms.addStudent(s1);  ✓
sms.addStudent(s2);  ✓
sms.addStudent(s3);  ✓
sms.addStudent(rs);  ✓
sms.addStudent(nrs);  ✓
```


Polymorphism: Method Call Arguments (2.2)

In the `StudentManagementSystemTester`:

```
1 Student s = new Student("Stella");
2 /* s' ST: Student; s' DT: Student */
3 StudentManagementSystem sms = new StudentManagementSystem();
4 sms.addRS(s); ×
```

- **L4** ***compiles*** with a cast: `sms.addRS((ResidentStudent) s)`
  - *Valid* cast ∵ `(ResidentStudent)` is a descendant of `s`' ***ST***.
  - *Valid* call ∵ `s`' temporary ***ST*** (`ResidentStudent`) is now a descendant class of `addRS`'s parameter `rs`' ***ST*** (`ResidentStudent`).
- But, there will be a `ClassCastException` at runtime! ∵ `s`' ***DT*** (`Student`) is **not** a descendant of `ResidentStudent`.
- We should have written:

  ```
  if(s instanceof ResidentStudent) {
    sms.addRS((ResidentStudent) s);
  }
  ```

  The **`instanceof`** expression will evaluate to *false*, meaning it is *unsafe* to cast, thus preventing `ClassCastException`.

Polymorphism: Method Call Arguments (2.3)

In the `StudentManagementSystemTester`:

```
1 Student s = new NonResidentStudent("Nancy");
2 /* s' ST: Student; s' DT: NonResidentStudent */
3 StudentManagementSystem sms = new StudentManagementSystem();
4 sms.addRS(s); ×
```

- **L4** ***compiles*** with a cast: `sms.addRS((ResidentStudent) s)`
  - *Valid* cast ∵ `(ResidentStudent)` is a descendant of s' ***ST***.
  - *Valid* call ∵ s' temporary ***ST*** (`ResidentStudent`) is now a descendant class of `addRS`'s parameter `rs`' ***ST*** (`ResidentStudent`).
- But, there will be a `ClassCastException` at runtime!
  ∵ s' ***DT*** (`NonResidentStudent`) **not** descendant of `ResidentStudent`.
- We should have written:

```
if(s instanceof ResidentStudent) {
  sms.addRS((ResidentStudent) s);
}
```

The **`instanceof`** expression will evaluate to *false*, meaning it is *unsafe* to cast, thus preventing `ClassCastException`.

Polymorphism: Method Call Arguments (2.4)

In the `StudentManagementSystemTester`:

```
1 Student s = new ResidentStudent("Rachael");
2 /* s' ST: Student; s' DT: ResidentStudent */
3 StudentManagementSystem sms = new StudentManagementSystem();
4 sms.addRS(s); ×
```

- **L4** ***compiles*** with a cast: `sms.addRS((ResidentStudent) s)`
  - *Valid* cast ∵ `(ResidentStudent)` is a descendant of s' ***ST***.
  - *Valid* call ∵ s' temporary ***ST*** (`ResidentStudent`) is now a descendant class of `addRS`'s parameter `rs`' ***ST*** (`ResidentStudent`).
- And, there will be **no** `ClassCastException` at runtime!
  ∵ s' ***DT*** (`ResidentStudent`) is descendant of `ResidentStudent`.
- We should have written:

```
if(s instanceof ResidentStudent) {
  sms.addRS((ResidentStudent) s);
}
```

The **`instanceof`** expression will evaluate to *true*, meaning it is *safe* to cast.

Polymorphism: Method Call Arguments (2.5)

In the `StudentManagementSystemTester`:

```
1 NonResidentStudent nrs = new NonResidentStudent();
2 /* ST: NonResidentStudent; DT: NonResidentStudent */
3 StudentManagementSystem sms = new StudentManagementSystem();
4 sms.addRS(nrs); ×
```

Will **L4** with a cast compile?

`sms.addRS( (ResidentStudent) nrs)`

NO ∵ `(ResidentStudent)` is ***not*** a descendant of `nrs`'s ***ST*** (`NonResidentStudent`).

Polymorphism: Return Values (1)

```
1  class StudentManagementSystem {
2   Student[] ss; int c;
3   void addStudent(Student s) { ss[c] = s; c++; }
4   Student getStudent(int i) {
5    Student s = null;
6    if(i < 0 || i >= c) {
7     throw new IllegalArgumentException("Invalid index.");
8    }
9    else {
10    s = ss[i];
11   }
12   return s;
13 } }
```

L4: `Student` is ***static type*** of `getStudent`'s return value.
L10: `ss[i]`'s ST (`Student`) is **descendant** of `s`' ST (`Student`).
Question: What can be the ***dynamic type*** of `s` after **L10**?
Answer: All descendant classes of `Student`.

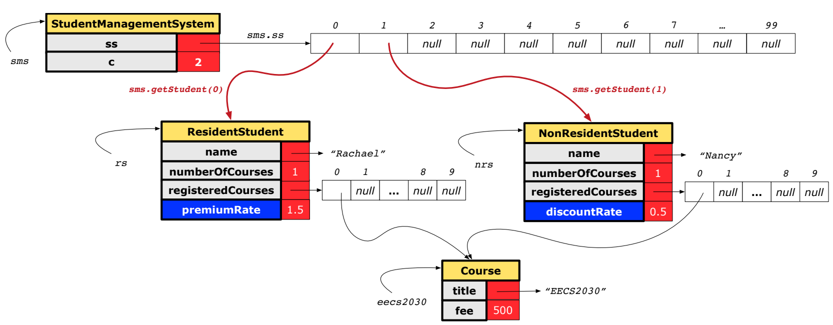
Polymorphism: Return Values (2)

```
Course eecs2030 = new Course("EECS2030", 500);
ResidentStudent rs = new ResidentStudent("Rachael");
rs.setPremiumRate(1.5); rs.register(eecs2030);
NonResidentStudent nrs = new NonResidentStudent("Nancy");
nrs.setDiscountRate(0.5); nrs.register(eecs2030);
StudentManagementSystem sms = new StudentManagementSystem();
sms.addStudent(rs); sms.addStudent(nrs);
Student s =   sms.getStudent(0)   ; /* dynamic type of s? */
              static return type: Student
print(s instanceof Student && s instanceof ResidentStudent);/*true*/
print(s instanceof NonResidentStudent);  /* false */
print( s.getTuition() );/*Version in ResidentStudent called:750*/
ResidentStudent rs2 = sms.getStudent(0);   ×
s =   sms.getStudent(1)   ;  /* dynamic type of s? */
      static return type: Student
print(s instanceof Student && s instanceof NonResidentStudent);/*true*/
print(s instanceof ResidentStudent);  /* false */
print( s.getTuition() );/*Version in NonResidentStudent called:250*/
NonResidentStudent nrs2 = sms.getStudent(1); ×
```


Polymorphism: Return Values (3)

At runtime, attribute `sms.ss` is a *polymorphic* array:

- ***Static type*** of each item is as declared: ***Student***
- ***Dynamic type*** of each item is a **descendant** of ***Student***: ***ResidentStudent***, ***NonResidentStudent***



Why Inheritance: A Collection of Various Kinds of Students

How do you define a class `StudentManagementSystem` that contains a list of *resident* and *non-resident* students?

```
class StudentManagementSystem {
  Student[] students;
  int numOfStudents;

  void addStudent(Student s) {
    students[numOfStudents] = s;
    numOfStudents ++;
  }

  void registerAll (Course c) {
    for(int i = 0; i < numberOfStudents; i ++) {
      students[i].register(c)
    }
  }
}
```


Polymorphism and Dynamic Binding: A Collection of Various Kinds of Students

```
class StudentManagementSystemTester {
  static void main(String[] args) {
    ResidentStudent jim = new ResidentStudent("J. Davis");
    NonResidentStudent jeremy =
      new NonResidentStudent("J. Davis");
    StudentManagementSystem sms =
      new StudentManagementSystem();
    sms.addStudent( jim ); /* polymorphism */
    sms.addStudent( jeremy ); /* polymorphism */
    Course eecs2030 = new Course("EECS2030", 500.0);
    sms.registerAll(eecs2030);
    for(int i = 0; i < sms.numberOfStudents; i ++) {
      /* Dynamic Binding:
       * Right version of getTuition will be called */
      System.out.println(sms.students[i]. getTuition() );
    }
  }
}
```

Static Type vs. Dynamic Type: When to consider which?

- *Whether or not Java code compiles* depends only on the ***static types*** of relevant variables.
  - ∵ Inferring the ***dynamic type*** statically is an *undecidable* problem that is inherently impossible to solve.
- *The behaviour of Java code being executed at runtime* (e.g., which version of method is called due to dynamic binding, whether or not a `ClassCastException` will occur, *etc.*) depends on the ***dynamic types*** of relevant variables.
  - ⇒ Best practice is to visualize how objects are created (by drawing boxes) and variables are re-assigned (by drawing arrows).

Summary: Type Checking Rules

CODE	CONDITION TO BE TYPE CORRECT
`x = y`	Is `y`'s ***ST*** a **descendant** of `x`'s ***ST***?
`x.m(y)`	Is method `m` defined in `x`'s ***ST***? Is `y`'s ***ST*** a **descendant** of `m`'s parameter's ***ST***?
`z = x.m(y)`	Is method `m` defined in `x`'s ***ST***? Is `y`'s ***ST*** a **descendant** of `m`'s parameter's ***ST***? Is ***ST*** of `m`'s return value a **descendant** of `z`'s ***ST***?
`(C) y`	Is `C` an **ancestor** or a **descendant** of `y`'s ***ST***?
`x = (C) y`	Is `C` an **ancestor** or a **descendant** of `y`'s ***ST***? Is `C` a **descendant** of `x`'s ***ST***?
`x.m((C) y)`	Is `C` an **ancestor** or a **descendant** of `y`'s ***ST***? Is method `m` defined in `x`'s ***ST***? Is `C` a **descendant** of `m`'s parameter's ***ST***?

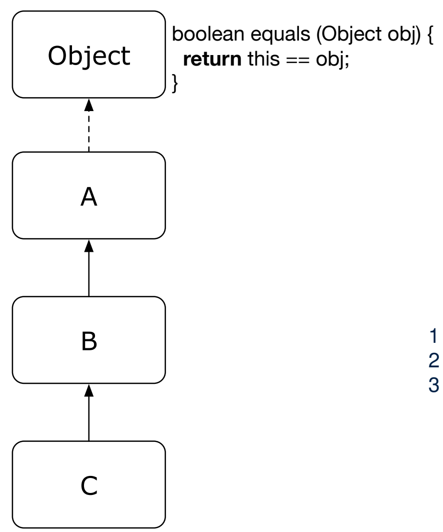
Even if `(C) y` compiles OK, there will be a runtime `ClassCastException` if `C` is not an **ancestor** of `y`'s ***DT***!

Overriding and Dynamic Binding (1)

`Object` is the common parent/super class of every class.

- Every class inherits the *default version* of `equals`
- Say a reference variable *v* has ***dynamic type*** *D*:
  - **Case 1** *D overrides* `equals`
    ⇒ *`v.equals(...)`* invokes the *overridden version* in *D*
  - **Case 2** *D* does *not override* `equals`
    Case 2.1 At least one ancestor classes of *D override* `equals`
    ⇒ *`v.equals(...)`* invokes the *overridden version* in the ***closest ancestor class***
    Case 2.2 No ancestor classes of *D override* `equals`
    ⇒ *`v.equals(...)`* invokes *default version* inherited from `Object`.
- Same principle applies to the `toString` method, and all overridden methods in general.

Overriding and Dynamic Binding (2.1)

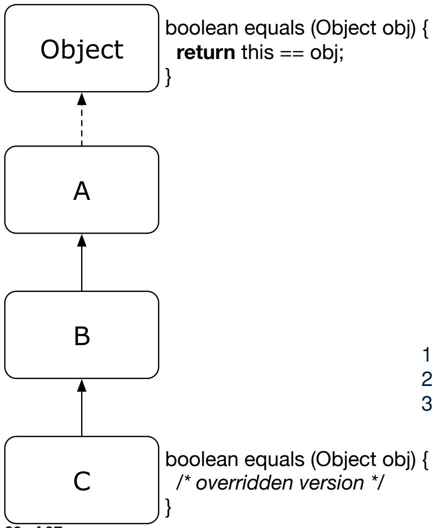



```
class A {
  /*equals not overridden*/
}
class B extends A {
  /*equals not overridden*/
}
class C extends B {
  /*equals not overridden*/
}
```

```
1 Object c1 = new C();
2 Object c2 = new C();
3 println(c1.equals(c2));
```

L3 calls which version of `equals`? [`Object`]

Overriding and Dynamic Binding (2.2)

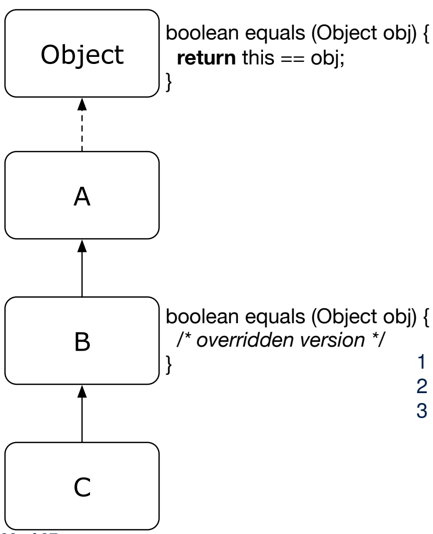



```
class A {
  /*equals not overridden*/
}
class B extends A {
  /*equals not overridden*/
}
class C extends B {
  boolean equals(Object obj) {
    /* overridden version */
  }
}
```

```
1 Object c1 = new C();
2 Object c2 = new C();
3 println(c1.equals(c2));
```

L3 calls which version of `equals`? [C]

Overriding and Dynamic Binding (2.3)




```
class A {
  /*equals not overridden*/
}
class B extends A {
  boolean equals(Object obj) {
    /* overridden version */
  }
}
class C extends B {
  /*equals not overridden*/
}
```

```
1 Object c1 = new C();
2 Object c2 = new C();
3 println(c1.equals(c2));
```

L3 calls which version of `equals`? [B]

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Abstract Classes and Interfaces

EECS2030: Advanced Object Oriented Programming
Fall 2017

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Abstract Class (1)

Problem: A polygon may be either a triangle or a rectangle. Given a polygon, we may either

- Grow its shape by incrementing the size of each of its sides;
- Compute and return its perimeter; or
- Compute and return its area.

- For a rectangle with *length* and *width*, its area is $length \times width$.
- For a triangle with sides a, b, and c, its area, according to Heron's formula, is

$$\sqrt{s(s-a)(s-b)(s-c)}$$

where

$$s = \frac{a+b+c}{2}$$

- How would you solve this problem in Java, while minimizing code duplicates?

Abstract Class (2)

```
public abstract class Polygon {
  double[] sides;
  Polygon(double[] sides) { this.sides = sides; }
  void grow() {
    for(int i = 0; i < sides.length; i ++) {
      sides[i] ++;
    }
  }
  double getPerimeter() {
    double perimeter = 0;
    for(int i = 0; i < sides.length; i ++) { perimeter += sides[i];}
    return perimeter;
  }
  abstract double getArea();
}
```

- Method `getArea` not implemented and shown *signature* only.
- ∴ `Polygon` cannot be used as a *dynamic type*
- Writing `new Polygon(...)` is forbidden!

Abstract Class (3)

```
public class Rectangle extends Polygon {
  Rectangle(double length, double width) {
    super(new double[4]);
    sides[0] = length; sides[1] = width;
    sides[2] = length; sides[3] = width;
  }
  double getArea() { return sides[0] * sides[1]; }
}
```

- Method `getPerimeter` is inherited from the super-class `Polygon`.
- Method `getArea` is implemented in the sub-class `Rectangle`.
- ∴ `Rectangle` can be used as a *dynamic type*
- Writing `Polygon p = new Rectangle(3, 4)` allowed!

Abstract Class (4)

```
public class Triangle extends Polygon {
  Triangle(double side1, double side2, double side3) {
    super(new double[3]);
    sides[0] = side1; sides[1] = side2; sides[2] = side3;
  }
  double getArea() {
    /* Heron's formula */
    double s = getPerimeter() * 0.5;
    double area = Math.sqrt(
      s * (s - sides[0]) * (s - sides[1]) * (s - sides[2]));
    return area;
  }
}
```

- Method `getPerimeter` is inherited from `Polygon`.
- Method `getArea` is implemented in the sub-class `Triangle`.
- ∴ `Triangle` can be used as a *dynamic type*
- Writing `Polygon p = new Triangle(3, 4, 5)` allowed!

Abstract Class (5)

```
1  public class PolygonCollector {
2    Polygon[] polygons;
3    int numberOfPolygons;
4    PolygonCollector() { polygons = new Polygon[10]; }
5    void addPolygon(Polygon p) {
6      polygons[numberOfPolygons] = p; numberOfPolygons ++;
7    }
8    void growAll() {
9      for(int i = 0; i < numberOfPolygons; i ++) {
10       polygons[i].grow();
11     }
12   }
13 }
```

- **Polymorphism**: **Line 5** may accept as argument any object whose *static type* is `Polygon` or any of its sub-classes.
- **Dynamic Binding**: **Line 10** calls the version of `grow` inherited to the *dynamic type* of `polygons[i]`.

Abstract Class (6)

```
1  public class PolygonConstructor {
2    Polygon getPolygon(double[] sides) {
3      Polygon p = null;
4      if(sides.length == 3) {
5        p = new Triangle(sides[0], sides[1], sides[2]);
6      }
7      else if(sides.length == 4) {
8        p = new Rectangle(sides[0], sides[1]);
9      }
10     return p;
11   }
12   void grow(Polygon p) { p.grow(); }
13 }
```

- **Polymorphism**:
  - **Line 2** may accept as return value any object whose *static type* is `Polygon` or any of its sub-classes.
  - **Line 5** returns an object whose *dynamic type* is `Triangle`; **Line 8** returns an object whose *dynamic type* is `Rectangle`.

Abstract Class (7.1)

```
public class PolygonTester {
  public static void main(String[] args) {
    Polygon p;
    p = new Rectangle(3, 4); /* polymorphism */
    System.out.println(p.getPerimeter()); /* 14.0 */
    System.out.println(p.getArea()); /* 12.0 */
    p = new Triangle(3, 4, 5); /* polymorphism */
    System.out.println(p.getPerimeter()); /* 12.0 */
    System.out.println(p.getArea()); /* 6.0 */

    PolygonCollector col = new PolygonCollector();
    col.addPolygon(new Rectangle(3, 4)); /* polymorphism */
    col.addPolygon(new Triangle(3, 4, 5)); /* polymorphism */
    System.out.println(col.polygons[0].getPerimeter()); /* 14.0 */
    System.out.println(col.polygons[1].getPerimeter()); /* 12.0 */
    col.growAll();
    System.out.println(col.polygons[0].getPerimeter()); /* 18.0 */
    System.out.println(col.polygons[1].getPerimeter()); /* 15.0 */
```

Abstract Class (7.2)

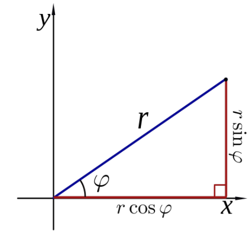
```
PolygonConstructor con = new PolygonConstructor();
double[] recSides = {3, 4, 3, 4};  p = con.getPolygon(recSides);
System.out.println(p instanceof Polygon);  ✓
System.out.println(p instanceof Rectangle);  ✓
System.out.println(p instanceof Triangle);  ×
System.out.println(p.getPerimeter()); /* 14.0 */
System.out.println(p.getArea()); /* 12.0 */
con.grow(p);
System.out.println(p.getPerimeter()); /* 18.0 */
System.out.println(p.getArea()); /* 20.0 */
double[] triSides = {3, 4, 5};  p = con.getPolygon(triSides);
System.out.println(p instanceof Polygon);  ✓
System.out.println(p instanceof Rectangle);  ×
System.out.println(p instanceof Triangle);  ✓
System.out.println(p.getPerimeter()); /* 12.0 */
System.out.println(p.getArea()); /* 6.0 */
con.grow(p);
System.out.println(p.getPerimeter()); /* 15.0 */
System.out.println(p.getArea()); /* 9.921 */
} }
```


Abstract Class (8)

- An *abstract class*:
  - Typically has **at least one** method with no implementation body
  - May define common implementations inherited to **sub-classes**.
- Recommended to use an *abstract class* as the ***static type*** of:
  - A *variable*
    e.g., `Polygon p`
  - A *method parameter*
    e.g., `void grow(Polygon p)`
  - A *method return value*
    e.g., `Polygon getPolygon(double[] sides)`
- It is forbidden to use an *abstract class* as a ***dynamic type***
  e.g., `Polygon p = new Polygon(...)` is not allowed!
- Instead, create objects whose ***dynamic types*** are descendant classes of the *abstract class* ⇒ Exploit *dynamic binding*!
  e.g., `Polygon p = con.getPolygon(recSides)`
  This is is as if we did `Polygon p = new Rectangle(...)`

Interface (1.1)

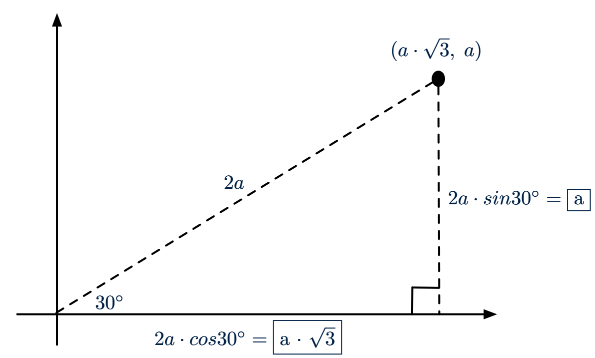
- We may implement `Point` using two representation systems:



  - The *Cartesian system* stores the *absolute* positions of `x` and `y`.
  - The *Polar system* stores the *relative* position: the angle (in radian) `phi` and distance `r` from the origin (0.0).
- As far as users of a `Point` object `p` is concerned, being able to call `p.getX()` and `getY()` is what matters.
- How `p.getX()` and `p.getY()` are internally computed, depending on the *dynamic type* of `p`, do not matter to users.

Interface (1.2)

Recall: $sin 30° = \frac{1}{2}$ and $cos 30° = \frac{1}{2} \cdot \sqrt{3}$



We consider the same point represented differently as:

- $r = 2a$, $\psi = 30°$ [polar system]
- $x = 2a \cdot cos30° = a \cdot \sqrt{3}$, $y = 2a \cdot sin30° = a$ [cartesian system]

Interface (2)

```
interface Point {
      double getX();
      double getY();
}
```

- An interface `Point` defines how users may access a point: either get its *x* coordinate or its *y* coordinate.
- Methods `getX` and `getY` similar to `getArea` in `Polygon`, have no implementations, but *signatures* only.
- ∴ `Point` cannot be used as a *dynamic type*
- Writing `new Point(...)` is forbidden!

Interface (3)

```
public class CartesianPoint implements Point {
  double x;
  double y;
  CartesianPoint(double x, double y) {
    this.x = x;
    this.y = y;
  }
  public double getX() { return x; }
  public double getY() { return y; }
}
```

- `CartesianPoint` is a possible implementation of `Point`.
- Attributes `x` and `y` declared according to the *Cartesian system*
- All method from the interface `Point` are implemented in the sub-class `CartesianPoint`.
- ∴ `CartesianPoint` can be used as a *dynamic type*
- `Point p = new CartesianPoint(3, 4)` allowed!

Interface (4)

```
public class PolarPoint implements Point {
  double phi;
  double r;
  public PolarPoint(double r, double phi) {
    this.r = r;
    this.phi = phi;
  }
  public double getX() { return Math.cos(phi) * r; }
  public double getY() { return Math.sin(phi) * r; }
}
```

- `PolarPoint` is a possible implementation of `Point`.
- Attributes `phi` and `r` declared according to the *Polar system*
- All method from the interface `Point` are implemented in the sub-class `PolarPoint`.
- ∴ `PolarPoint` can be used as a *dynamic type*
- `Point p = new PolarPoint(3,` $\frac{\pi}{6}$`)` allowed! [$360° = 2\pi$]

Interface (5)

```
1  public class PointTester {
2    public static void main(String[] args) {
3      double A = 5;
4      double X = A * Math.sqrt(3);
5      double Y = A;
6      Point p;
7      p = new CartisianPoint(X, Y); /* polymorphism */
8      print("(" + p. getX() + ", " + p. getY() + ")"); /* dyn. bin. */
9      p = new PolarPoint(2 * A, Math.toRadians(30)); /* polymorphism */
10     print("(" + p. getX() + ", " + p. getY() + ")"); /* dyn. bin. */
11   }
12 }
```

- **Lines 7 and 9** illustrate *polymorphism*, how?
- **Lines 8 and 10** illustrate *dynamic binding*, how?

Interface (6)

- An *interface* :
  - Has **all** its methods with no implementation bodies.
  - Leaves complete freedom to its ***implementors***.
- Recommended to use an *interface* as the ***static type*** of:
  - A *variable*
    e.g., `Point p`
  - A *method parameter*
    e.g., `void moveUp(Point p)`
  - A *method return value*
    e.g., `Point getPoint(double v1, double v2, boolean isCartesian)`
- It is forbidden to use an *interface* as a ***dynamic type***
  e.g., `Point p = new Point(...)` is not allowed!
- Instead, create objects whose ***dynamic types*** are descendant classes of the *interface* ⇒ Exploit *dynamic binding* !

Abstract Classes vs. Interfaces: When to Use Which?

- Use *interfaces* when:
  - There is a *common set of functionalities* that can be implemented via *a variety of strategies*.
    e.g., Interface `Point` declares signatures of `getX()` and `getY()`.
  - Each descendant class represents a different implementation strategy for the same set of functionalities.
  - `CartesianPoint` and `PolarPoinnt` represent different strategies for supporting `getX()` and `getY()`.
- Use *abstract classes* when:
  - *Some (not all) implementations can be shared* by descendants, and *some (not all) implementations cannot be shared*.
    e.g., Abstract class `Polygon`:
    - Defines implementation of `getPerimeter`, to be shared by `Rectangle` and `Triangle`.
    - Declares signature of `getArea`, to be implemented by `Rectangle` and `Triangle`.

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Generics in Java

EECS2030: Advanced Object Oriented Programming
Fall 2017

CHEN-WEI WANG

Motivating Example: A Book of Objects

```
class Book {
  String[] names;
  Object[] records;
  /* add a name-record pair to the book */
  void add (String name, Object record) { ... }
  /* return the record associated with a given name */
  Object get (String name) { ... } }
```

Question: Which line has a type error?

```
1 Date birthday; String phoneNumber;
2 Book b; boolean isWednesday;
3 b = new Book();
4 phoneNumber = "416-67-1010";
5 b.add ("Suyeon", phoneNumber);
6 birthday = new Date(1975, 4, 10);
7 b.add ("Yuna", birthday);
8 isWednesday = b.get("Yuna").getDay() == 4;
```


Motivating Example: Observations (1)

- In the `Book` class:
  - By declaring the attribute

    ```
    Object[] records
    ```

    We meant that each book instance may store any object whose *static type* is a *descendant class* of `Object`.
  - Accordingly, from the return type of the `get` method, we only know that the returned record is an `Object`, but not certain about its *dynamic type* (e.g., `Date`, `String`, *etc.*).
    ∴ a record retrieved from the book, e.g., `b.get("Yuna")`, may only be called upon methods in its *static type* (i.e,. `Object`).
- In the tester code of the `Book` class:
  - In **Line 1**, the *static types* of variables `birthday` (i.e., `Date`) and `phoneNumber` (i.e., `String`) are *descendant classes* of `Object`.
  - So, **Line 5** and **Line 7** compile.

Motivating Example: Observations (2)

Due to *polymorphism*, the *dynamic types* of stored objects (e.g., `phoneNumber` and `birthday`) need not be the same.

- Methods supported in the *dynamic types* (e.g., method `getDay` of class `Date`) may be new methods not inherited from `Object`.
- This is why **Line 8** would fail to compile, and may be fixed using an explicit *cast*:

  ```
  isWednesday = ((Date) b.get("Yuna")).getDay() == 4;
  ```

- But what if the *dynamic type* of the returned object is not a `Date`?

  ```
  isWednesday = ((Date) b.get("Suyeon")).getDay() == 4;
  ```

- To avoid such a `ClassCastException` at runtime, we need to check its *dynamic type* before performing a cast:

  ```
  if (b.get("Suyeon") instanceof Date) {
    isWednesday = ((Date) b.get("Suyeon")).getDay() == 4;
  }
  ```

Motivating Example: Observations (2.1)

- It seems: combining `instanceof` *check* and *type cast* works.
- Can you see any potential problem(s)?
- **Hints:** What happens when you have a large number of records of distinct *dynamic types* stored in the book (e.g., `Date`, `String`, `Person`, `Account`, *etc.*)?

Motivating Example: Observations (2.2)

Imagine that the tester code (or an application) stores 100 different record objects into the book.

- All of these records are of *static type* `Object`, but of distinct *dynamic types*.

```
Object rec1 = new C1(); b.add(..., rec1);
Object rec2 = new C2(); b.add(..., rec2);
...
Object rec100 = new C100(); b.add(..., rec100);
```

  where classes *C1* to *C100* are *descendant classes* of `Object`.
- **Every time** you retrieve a record from the book, you need to check "exhaustively" on its *dynamic type* before calling some method(s).

```
Object rec = b.get("Jim");
if (rec instanceof C1) { ((C1) rec).m1; }
...
else if (rec instanceof C100) { ((C100) rec).m100; }
```

- Writing out this list multiple times is tedious and error-prone!

Motivating Example: Observations (3)

We need a solution that:

- Saves us from explicit `instanceof` checks and type casts
- Eliminates the occurrences of `ClassCastException`

As a sketch, this is how the solution looks like:

- When the user declares a `Book` object `b`, they must *commit to the kind of record that* `b` *stores at runtime*.
  e.g., `b` stores either `Date` objects only or `String` objects only, but ***not a mix***.
- When attempting to store a new record object `rec` into `b`, what if `rec`'s *static type* is not a **descendant class** of the type of book that the user previously commits to?
  ⇒ A *compilation error*
- When attempting to retrieve a record object from `b`, there is *no longer a need to check and cast*.
  ∵ ***Static types*** of all records in `b` are guaranteed to be the same.

Parameters

- In mathematics:
  - The same *function* is applied with different *argument values*.
    e.g., `2 + 3`, `1 + 1`, `10 + 101`, *etc.*
  - We *generalize* these instance applications into a definition.
    e.g., $+ : (\mathbb{Z} \times \mathbb{Z}) \rightarrow \mathbb{Z}$ is a function that takes two integer *parameters* and returns an integer.
- In Java programming:
  - We want to call a *method*, with different *argument values*, to achieve a similar goal.
    e.g., `acc.deposit(100)`, `acc.deposit(23)`, *etc.*
  - We generalize these possible method calls into a definition.
    e.g., In class `Account`, a method `void deposit(int amount)` takes one integer *parameter*.
- When you design a mathematical function or a Java method, always consider the list of *parameters*, each of which representing a set of possible *argument values*.

Java Generics: Design of a Generic Book

```
class Book<E> {
  String[] names;
  E[] records;
  /* add a name-record pair to the book */
  void add (String name, E record) { ... }
  /* return the record associated with a given name */
  E get (String name) { ... } }
```

Question: Which line has a type error?

```
1 Date birthday; String phoneNumber;
2 Book<Date> b; boolean isWednesday;
3 b = new Book<Date>();
4 phoneNumber = "416-67-1010";
5 b.add ("Suyeon", phoneNumber);
6 birthday = new Date(1975, 4, 10);
7 b.add ("Yuna", birthday);
8 isWednesday = b.get("Yuna").getDay() == 4;
```


Java Generics: Observations

- In class `Book`:
  - At the class level, we *parameterize the type of records* that an instance of book may store: `class Book<E>` where *E* is the name of a type parameter, which should be *instantiated* when the user declares an instance of `Book`.
  - Every occurrence of `Object` (the most general type of records) is replaced by *E*.
  - As soon as *E* at the class level is committed to some known type (e.g., `Date`, `String`, *etc.*), every occurrence of *E* will be replaced by that type.
- In the tester code of `Book`:
  - In **Line 2**, we commit that the book `b` will store `Date` objects only.
  - **Line 5** now fails to compile. [`String` is not a `Date`]
  - **Line 7** still compiles.
  - **Line 8** does *not need* any instance check and type cast, and does *not cause* any `ClassCastException`.

    ∵ Only `Date` objects were allowed to be stored.

Bad Example of using Generics

Has the following client made an appropriate choice?

```
Book<Object> book
```

NO!!!!!!!!!!!!!!!!!!!!!!!

- It allows **all** kinds of objects to be stored.

  ∵ All classes are descendants of ***Object***.
- We can expect **very little** from an object retrieved from this book.

  ∵ The ***static type*** of `book`'s items are ***Object***, root of the class hierarchy, has the *minimum* amount of features available for use.

  ∵ Exhaustive list of casts are unavoidable.

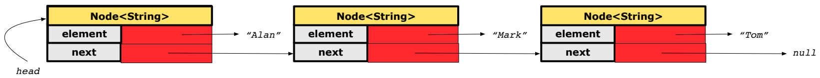
  [***bad*** for extensibility and maintainability]

Generic Classes: Singly-Linked List (1)

```
public class Node< E > {
  private E element;
  private Node< E > next;
  public Node( E e, Node< E > n) { element = e; next = n; }
  public E getElement() { return element; }
  public Node< E > getNext() { return next; }
  public void setNext(Node< E > n) { next = n; }
  public void setElement( E e) { element = e; }
}
```

```
public class SinglyLinkedList< E > {
  private Node< E > head;
  private Node< E > tail;
  private int size = null;
  public void addFirst( E e) { ... }
  Node< E > getNodeAt (int i) { ... }
  ...
}
```

Generic Classes: Singly-Linked List (2)



Approach 1

```java
Node<String> tom = new Node<>("Tom", null);
Node<String> mark = new Node<>("Mark", tom);
Node<String> alan = new Node<>("Alan", mark);
```

Approach 2

```java
Node<String> alan = new Node<>("Alan", null);
Node<String> mark = new Node<>("Mark", null);
Node<String> tom = new Node<>("Tom", null);
alan.setNext(mark);
mark.setNext(tom);
```


Generic Classes: Singly-Linked List (3)

Assume we are in the context of class `SinglyLinkedList`.

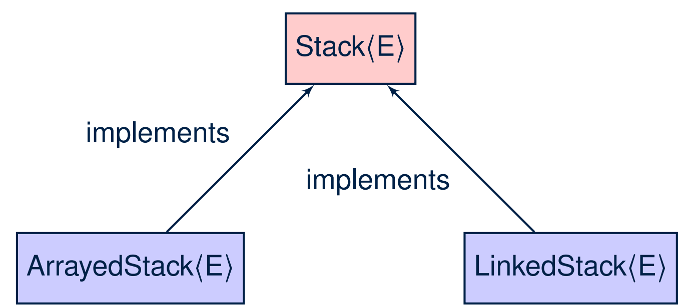
```java
void addFirst (E e) {
  head = new Node<E>(e, head);
  if (size == 0) { tail = head; }
  size ++;
}
```

```java
Node<E> getNodeAt (int i) {
  if (i < 0 || i >= size) {
   throw new IllegalArgumentException("Invalid Index"); }
  else {
    int index = 0;
    Node<E> current = head;
    while (index < i) {
      index ++; current = current.getNext();
    }
    return current;
  }
}
```


Generic Stack: Interface

```java
public interface Stack< E > {
  public int size();
  public boolean isEmpty();
  public E top();
  public void push( E e);
  public E pop();
}
```


Generic Stack: Architecture



Generic Stack: Array Implementation

```
public class ArrayedStack< E > implements Stack< E > {
  private static final int MAX_CAPACITY = 1000;
  private E [] data;
  private int t; /* top index */
  public ArrayedStack() {
    data = ( E []) new Object[MAX_CAPACITY];
    t = -1; }
  public int size() { return (t + 1); }
  public boolean isEmpty() { return (t == -1); }
  public E top() {
    if (isEmpty()) { /* Error: Empty Stack. */ }
    else { return data[t]; } }
  public void push( E e) {
    if (size() == MAX_CAPACITY) { /* Error: Stack Full. */ }
    else { t ++; data[t] = e; } }
  public E pop() {
    E result;
    if (isEmpty()) { /* Error: Empty Stack */ }
    else { result = data[t]; data[t] = null; t --; }
    return result; }
}
```


Generic Stack: SLL Implementation

```
public class LinkedStack< E > implements Stack< E > {
  private SinglyLinkedList< E > data;
  public LinkedStack() {
    data = new SinglyLinkedList< E >();
  }
  public int size() { return data.size(); }
  public boolean isEmpty() { return size() == 0; }
  public E top() {
    if (isEmpty()) { /* Error: Empty Stack. */ }
    else { return data.getFirst(); } }
  public void push( E e) {
    data.addFirst(e); }
  public E pop() {
    E result;
    if (isEmpty()) { /* Error: Empty Stack */ }
    else { result = top(); data.removeFirst(); }
    return result; }
}
```


Generic Stack: Testing Both Implementations

```
@Test
public void testPolymorphicStacks() {
  Stack<String> s = new ArrayedStack<>();
  s. push ("Alan"); /* dynamic binding */
  s. push ("Mark"); /* dynamic binding */
  s. push ("Tom"); /* dynamic binding */
  assertTrue(s.size() == 3 && !s.isEmpty());
  assertEquals("Tom", s. top ());

  s = new LinkedStack<>();
  s. push ("Alan"); /* dynamic binding */
  s. push ("Mark"); /* dynamic binding */
  s. push ("Tom"); /* dynamic binding */
  assertTrue(s.size() == 3 && !s.isEmpty());
  assertEquals("Tom", s. top ());
}
```


Beyond this lecture ...

- Study `https://docs.oracle.com/javase/tutorial/java/generics/index.html` for further details on Java generics.

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Wrap-Up

YORK UNIVERSITÉ UNIVERSITY

EECS2030: Advanced Object Oriented Programming
Fall 2017

CHEN-WEI WANG

What You Learned (1)

- *Procedural Programming in Java*
  - Utilities classes
  - Recursion (implementation, running time, correctness)
- *Data Structures*
  - Arrays
  - Maps and Hash Tables
  - Singly-Linked Lists
  - Stacks and Queues
  - Binary Trees

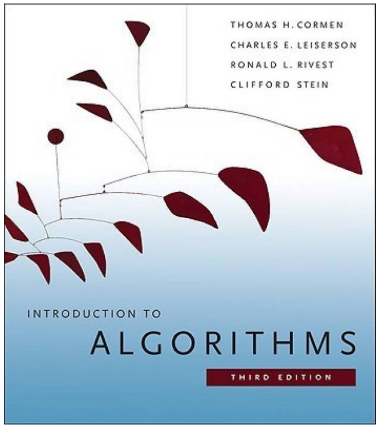
What You Learned (2)

- *Object-Oriented Programming in Java*
  - classes, attributes, encapsulation, objects, reference data types
  - methods: constructors, accessors, mutators, helper
  - dot notation, context objects
  - aliasing
  - inheritance:
    - code reuse
    - expectations
    - static vs. dynamic types
    - rules of substitutions
    - casts and `instanceof` checks
    - polymorphism and method arguments/return values
    - method overriding and dynamic binding: e.g., `equals`
    - abstract classes vs. interfaces
    - generics (vs. collection of `Object`)
  - keywords: `private`, `this`, `protected`, `static`, `extends`, `super`, `abstract`, `implements`

What You Learned (3)

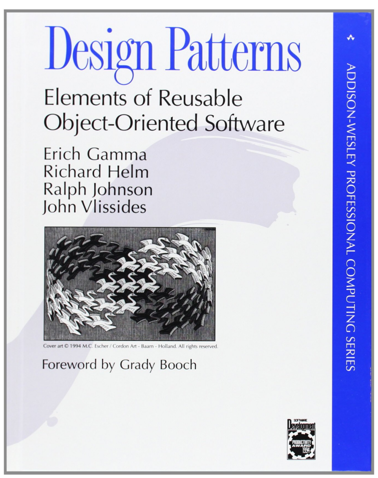
- *Integrated Development Environment (IDE) for Java: Eclipse*
  - Break Point and Debugger
  - Unit Testing using JUnit

Beyond this course. . . (1)



- *Introduction to Algorithms (3rd Ed.)* by Cormen, *etc.*
- DS by DS, Algo. by Algo.:
  - *Understand* math analysis
  - *Read* pseudo code
  - *Translate* into Java code
  - *Write and pass* JUnit tests

Beyond this course. . . (2)



- *Design Patterns: Elements of Reusable Object-Oriented Software* by Gamma, *etc.*
- Patter by Pattern:
  - *Understand* the problem
  - *Read* the solution (not in Java)
  - *Translate* into Java code
  - *Write and pass* JUnit tests

Beyond this course. . . (3)

Visit my lectures on *EECS3311 Software Design*:

`http://www.eecs.yorku.ca/~jackie/teaching/lectures/index.html#EECS3311_F17`

- Design by Contracts
- Design Patterns
- Program Verification

Wish You All the Best

- What you have learned will be **assumed** in `EECS2011`.
- Logic is your friend: Learn/Review `EECS1019/EECS1090`.
- Do **not** abandon Java during the break!!
- As ever, feel free to get in touch and let me know how you're doing :D