Classes and Objects

EECS2030 B & G: Advanced Object Oriented Programming
Fall 2025

CHEN-WEI WANG

Required: Review Tutorials on OOP in Java

Current slides are cross-referenced throughout this review tutorials on Java OOP:
https://www.eecs.yorku.ca/~jackie/teaching/tutorials/index.html#refurbished_store

Optional: Tutorial Videos to Help You Review

- **Link to Tutorial Series**:
  https://www.eecs.yorku.ca/~jackie/teaching/tutorials/index.html#java_from_scratch_w21
  - **Week 1**: **Eclipse** work environment
  - *Week 2c, 2d, 2e*: **Debugger** in Eclipse
  - **Weeks 2, 3**: Programming/Debugging **Conditionals**
  - **Weeks 4, 5**: Programming/Debugging **Arrays** and **Loops**
  - *Weeks 6, 7, 8*: **Classes** and **Objects**
- **iPad Notes**: https://www.eecs.yorku.ca/~jackie/teaching/tutorials/notes/EECS1022%20Tutorial%20on%20Java.pdf

Required: Written Notes to Review

- ***Inferring Classes/Methods from JUnit Tests***:
  https://www.eecs.yorku.ca/~jackie/teaching/lectures/2025/F/EECS2030/notes/EECS2030_F25_Inferring_Classes_from_JUnit.pdf
- ***Declaring and Manipulating Reference-Typed, Multi-Valued Attributes***: https://www.eecs.yorku.ca/~jackie/teaching/lectures/2025/F/EECS2030/notes/EECS2030_F25_Tracing_PointCollectorTester.pdf

Learning Outcomes

Understand:

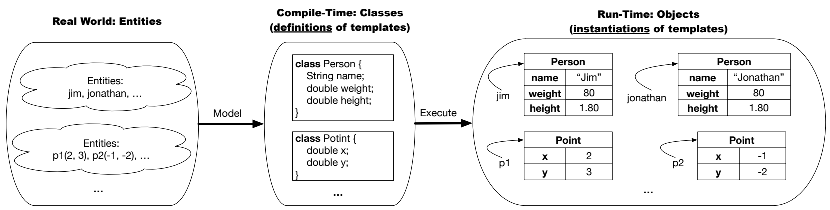
- Object Orientation
- Classes as Templates:
  - attributes, constructors, (accessor and mutator) methods
  - use of `this`
- Objects as Instances:
  - use of `new`
  - the dot notation, method invocations
  - reference aliasing
- Reference-Typed Attributes: Single-Valued vs. Multi-Valued
- Non-Static vs. Static Variables
- Helper Methods

Separation of Concerns: App/Tester vs. Model

- In EECS1022/EECS1021:
  - ***Model Component***: One or More Java Classes
    e.g., `Person` vs. `SMS`, `Student`, `CourseRecord`
  - Another Java class that "manipulates" the model class(es)
    - ***Controller*** (e.g., `BMIActivity`, `LEDController`). Effects?
      Visualized at a connected physical device (e.g., tablet, LED lightbulbs)
    - ***Tester*** (e.g., `PersonTester`, `BankTester`). Effects?
      Seen (as textual outputs) at console
      Asserting ***expected*** vs. ***actual*** Values in JUnit tests
- In Java:
  - We may define more than one *classes*.
  - Each class may contain more than one *methods*.

  Object-Oriented Programming (OOP) 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



- Study this tutorial video that walks you through the idea of *object orientation*.
- 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)

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 (1.2)

- A *template* (e.g., class `Point`) defines what's **shared** by a set of related entities (i.e., 2-D points).
  - Common *attributes* (`x`, `y`)
  - Common *behaviour* (move left, move up)
- Each template may be *instantiated* as multiple instances, each with *instance-specific* values for attributes `x` and `y`:
  - `Point` instance `p1` is located at $(3, 4)$
  - `Point` instance `p2` is located at $(-4, -3)$
- Instances of the same template may 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 (2.1)

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 (2.2)

- A *template* (e.g., class `Person`) defines what's **shared** by a set of related entities (i.e., persons).
  - Common *attributes* (`age`, `weight`, `height`)
  - Common *behaviour* (get older, lose weight, grow taller)
- Each template may be *instantiated* as multiple instances, each with *instance-specific* values for attributes `age`, `weight`, and `height`.
  - `Person` instance `jim` is 50-years old, 1.8-meters tall and 80-kg heavy
  - `Person` instance `jonathan` is 65-years old, 1.73-meters tall and 90-kg heavy
- Instances of the same template may 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 $[\frac{90}{1.73^2}]$

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 {
  private int age;
  private String nationality;
  private double weight;
  private double height;
}
```

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


Java Data Types (1)

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

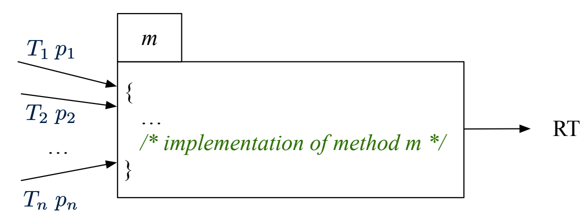
1. *Primitive Types*
   - *Integer* Type
     - `int` [set of 32-bit integers]
     - `long` [set of 64-bit integers]
   - *Floating-Point Number* Type
     - `double` [set of 64-bit FP numbers]
   - *Character* Type
     - `char` [set of single characters]
   - *Boolean* Type
     - `boolean` [set of `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!

OOP: Methods (1.1)

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



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

OOP: Methods (1.2)

- In the body of the method, you may
  - Declare new *local variables* (whose *scope* is within that method).
  - Use or change values of *attributes*.
  - Use values of *parameters*, if any.

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

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

```
public 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: Class Constructors (1.1)

- 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 (1.2)

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.
- ***Overloaded*** constructor have *distinct* lists of *parameter types*.
  - `Person(String n)`, `Person(String n, int age)` ✓
  - `Person(String n, int age)`, `Person(int age, String n)` ✓
  - `Person(String fN, int age)`, `Person(String lN, int id)` ×
- 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: Class Constructors (2.1)

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

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

  public Point(char axis, double distance) {
    if (axis == 'x') { x = distance; }
    else if (axis == 'y') { y = distance; }
    else { /* Error: invalid axis */ }
  }
}
```


OOP: Class Constructors (2.2)

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


Visualizing Objects at Runtime (1)

- To trace a program with sophisticated manipulations of objects, it's critical for you to visualize how objects are:
  - Created using *constructors*

    `Person jim = new Person(50, "British", 80, 1.8);`
  - Inquired using *accessor methods*

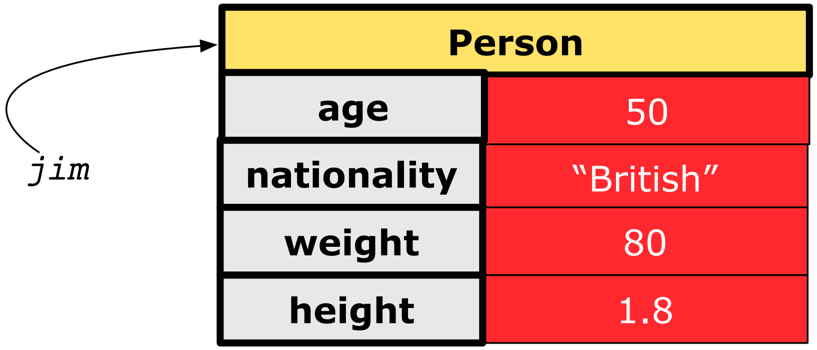
    `double bmi = jim.getBMI();`
  - Modified using *mutator methods*

    `jim.gainWeightBy(10);`
- To visualize an object:
  - Draw a rectangle box to represent *contents* of that object:
    - Title indicates the *name of class* from which the object is instantiated.
    - Left column enumerates *names of attributes* of the instantiated class.
    - Right column fills in *values* of the corresponding attributes.
  - Draw arrow(s) for *variable(s)* that store the object's *address*.

Visualizing Objects at Runtime (2.1)

After calling a *constructor* to create an object:

```
Person jim = new Person(50, "British", 80, 1.8);
```

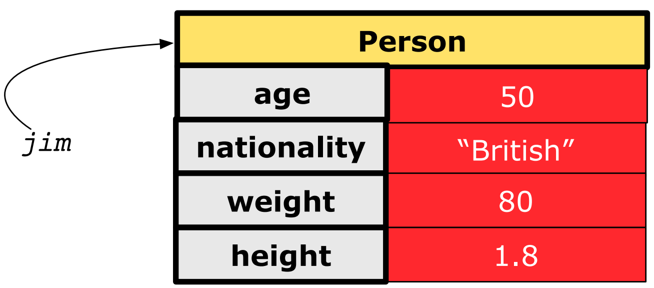


Visualizing Objects at Runtime (2.2)

After calling an *accessor* to inquire about context object `jim`:

```
double bmi = jim.getBMI();
```

- Contents of the object pointed to by `jim` remain intact.
- Retuned value $\frac{80}{(1.8)^2}$ of `jim.getBMI()` stored in variable `bmi`.



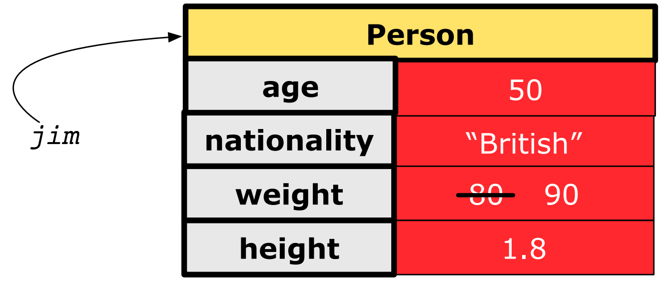
Visualizing Objects at Runtime (2.3)

After calling a *mutator* to modify the state of context object `jim`:

```
jim.gainWeightBy(10);
```

- *Contents* of the object pointed to by `jim` change.
- *Address* of the object remains unchanged.

  ⇒ `jim` points to the same object!

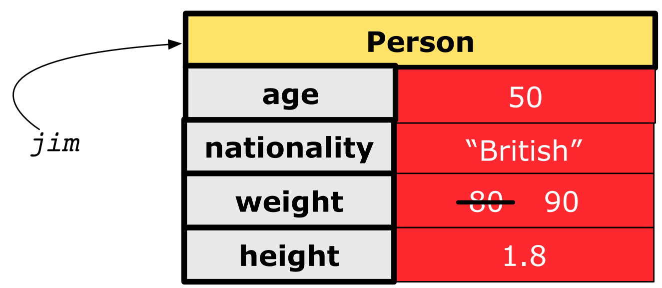


Visualizing Objects at Runtime (2.4)

After calling the same *accessor* to inquire the *modified* state of context object `jim`:

```
bmi = jim.getBMI();
```

- Contents of the object pointed to by `jim` remain intact.
- Retuned value $\frac{90}{(1.8)^2}$ of `jim.getBMI()` stored in variable `bmi`.



Object Creation (1.1)

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

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

Point	
x	2.0
y	4.0

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`.

p1

Point	
x	2.0
y	4.0

Object Creation (1.2)

```
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

Object Creation (2)

```
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.getX()+", "+p1.getY() + ")");
```

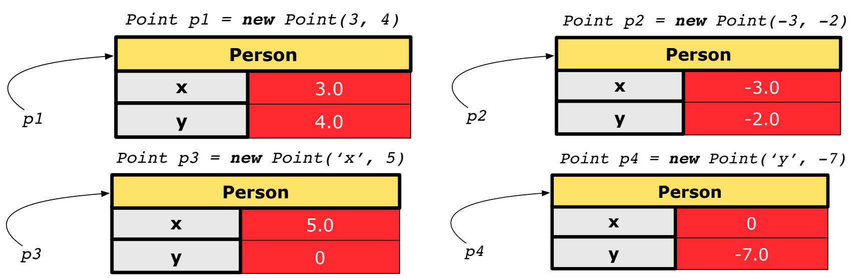
```
(2.0, 4.0)
```


OOP: Object Creation (3.1.1)

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 (3.1.2)

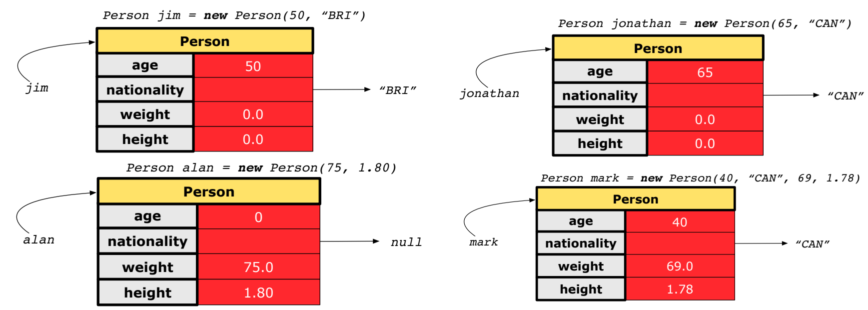


OOP: Object Creation (3.2.1)

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 (3.2.2)



OOP: Object Creation (4)

- 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: 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()`

The `this` Reference (1)

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

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

```
public class Point {
  private double x;
  private double y;
  public Point(double newX, double newY) {
    this.x = newX;
    this.y = newY;
  }
  public 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:

```
public class Point {
  private double x;
  private double y;
  public Point(double newX, double newY) {
    p1.x = newX;
    p1.y = newY;
  }
  public 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:

```
public class Point {
  private double x;
  private double y;
  public Point(double newX, double newY) {
    p2.x = newX;
    p2.y = newY;
  }
  public 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*.

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


The this Reference (6.1): Common Error

The following code fragment compiles but is problematic:

```
1  public class Person {
2    private String name;
3    private int age;
4    public Person(String name, int age) {
5      name = name;
6      age = age;
7    }
8    public void setAge(int age) {
9      age = age;
10   }
11 }
```

- Why? [variable **shadowing**]
  Target (LHS) of the assignment (L5) refers to parameter name (L4).
- Fix?

The this Reference (6.2): Common Error

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

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

OOP: Mutator Methods

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

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

```
public class Point {
  ...
  public void moveUp() {
    this.y = this.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 {
  ...
  public double getBMI() {
    double bmi = this.height / (this.weight * this.weight);
    return bmi;
  } }
```

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


OOP: Method Calls

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

See the lecture recording on tracing the above program ***here***.

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 moveUp(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)`

OOP: Reference Aliasing (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.

OOP: Reference Aliasing (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]);
```


OOP: Reference Aliasing (2.2)

Exercise: 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.getAge());
System.out.println(alan.getAge());
System.out.println(persons2[0].getAge());
persons1[0] = jim;
persons1[0].setAge(75);
System.out.println(jim.getAge());
System.out.println(alan.getAge());
System.out.println(persons2[0].getAge());
```

See the lecture recording on tracing the above program *here*.

Java Data Types (3.1)

- An *attribute* may store the reference to another object.

```
public class Person { private Person spouse; }
```

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

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

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

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

See the lecture recording on tracing the above program ***here***.

Java Data Types (3.2.1)

An attribute may be ***multi***-valued, ***reference***-typed
e.g., of type `Point[]`, storing references to `Point` objects.

```
public class PointCollector {
  private Point[] points; private int nop;/* number of points */
  public PointCollector() { this.points = new Point[100]; }
  public void addPoint(double x, double y) {
    this.points[this.nop] = new Point(x, y); this.nop++; }
  public Point[] getPointsInQuadrantI() {
    Point[] ps = new Point[this.nop];
    int count = 0; /* number of points in Quadrant I */
    for(int i = 0; i < this.nop; i++) {
      Point p = this.points[i];
      if(p.getX() > 0 && p.getY() > 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 (3.2.2)

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

See the lecture recording on tracing the above program ***here***.

Anonymous Objects (1)

- What's the difference between these two fragments of code?

```
1 double square(double x) {
2   double sqr = x * x;
3   return sqr; }
```

```
1 double square(double x) {
2   return x * x; }
```

After **L2**, the result of `x * x`:
  - LHS: it can be reused (without recalculating) via the name `sqr`.
  - RHS: it is not stored anywhere and returned right away.

- Same principles applies to objects:

```
1 Person getP(String n) {
2   Person p = new Person(n);
3   return p; }
```

```
1 Person getP(String n) {
2   return new Person(n); }
```

new Person(n) is an object whose address is not stored in a variable.
  - LHS: **L2** stores the address of this anonymous object in `p`.
  - RHS: **L2** returns the address of this anonymous object directly.

Anonymous Objects (2.1)

Anonymous objects can also be used as *assignment sources* or *argument values*:

```
class Member {
  private Order[] orders;
  private int noo;
  /* constructor ommitted */
  public void addOrder(Order o) {
    this.orders[this.noo] = o;
    this.noo++;
  }
  public void addOrder(String n, double p, double q) {
    this.addOrder( new Order(n, p, q) );
    /* Equivalent implementation:
     * this.orders[this.noo] = new Order(n, p, q); noo ++;
     */
  }
}
```


Anonymous Objects (2.2)

One more example on using anonymous objects:

```
public class MemberTester {
  public static void main(String[] args) {
    Member m = new Member("Alan");
    Order o = new Order("Americano", 4.7, 3);
    m.addOrder(o);
    m.addOrder( new Order("Cafe Latte", 5.1, 4) );
  }
}
```


The `this` Reference (7.1): Exercise

Consider the `Person` class

```
public class Person {
  private String name;
  private Person spouse;
  public 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

```
public void marry(Person other) {
  if(this.spouse != null || other.spouse != null) {
    /* Error: both must be single */
  }
  else { this.spouse = other; other.spouse = this; }
}
```

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

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

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

```
public class Person {
  private String name;/* public accessor: name() */
  private Person spouse;/* public accessor: 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 cause *NullPointerException*!!
  - **Quesion.** Assuming that:
    - `jim` is not single. [`jim.spouse() != null`]
    - The marriage is mutual. [`jim.spouse().spouse() == jim`]

    What does `jim.spouse().spouse().name()` mean?

    Answer. `jim.name()`

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*.

See the lecture recording on helper methods *here*.

OOP: Helper (Accessor) Methods (2.1)

```
public class PersonCollector {
  private Person[] ps;
  private final int MAX = 100;/* max # of persons to store */
  private int nop; /* number of persons */
  public PersonCollector() {
    this.ps = new Person[MAX];
  }
  public void addPerson(Person p) {
    this.ps[this.nop] = p;
    this.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 (Accessor) Methods (2.2.1)

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

OOP: Helper (Accessor) Methods (2.2.2)

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


OOP: Helper (Accessor) Methods (2.3)

```
public class PersonCollector { /* Code Smell Eliminated */
  /* ps, MAX, nop, PersonCollector(), addPerson */
  private int indexOf (String n) { /* Helper Methods */
    int i = -1;
    for(int j = 0; j < nop; j ++) {
      if(ps[j].getName().equals(n)) { i = j; }
    }
    return i; /* -1 if not found; >= 0 if found. */
  }
  public boolean personExists(String n) {
    return this.indexOf (n) >= 0; }
  public void changeWeightOf(String n, double w) {
    int i = indexOf (n); if(i >= 0) { ps[i].setWeight(w); }
  }
  public 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 { /* code smells:repetitions! */
  double x; double y;

  double getDistanceFromOrigin() {
    return Math.sqrt(Math.pow(this.x - 0, 2) + Math.pow(this.y - 0, 2)); }

  double getDistancesTo(Point p1, Point p2) {
    return
      Math.sqrt(Math.pow(this.x - p1.x, 2) + Math.pow(y - p1.y, 2))
      +
      Math.sqrt(Math.pow(this.x - p2.x, 2) + Math.pow(y - p2.y, 2)); }

  double getTriDistances(Point p1, Point p2) {
    return
      Math.sqrt(Math.pow(this.x - p1.x, 2) + Math.pow(y - p1.y, 2))
      +
      Math.sqrt(Math.pow(this.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)

```
public class Point { /* Code Smell Eliminated */
  private double x; private 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)

```
public class Student {
  private String name;
  private double balance;
  public 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)

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

OOP: Helper (Mutator) Methods (4.2.2)

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


OOP: Helper (Mutator) Methods (4.3)

```java
public class Student { /* Code Smell Eliminated */
  /* name, balance, Student(String n, double b) */
  public void deposit(double val) { /* Helper Method */
    balance = balance + val;
  }
  public void withdraw(double val) { /* Helper Method */
    balance = balance - val;
  }
  public void receiveScholarship(double val) { this.deposit(val); }
  public void payLibraryOverdue(double val) { this.withdraw(val); }
  public void payCafeCoupons(double val) { this.withdraw(val) }
  public void transfer(Student other, double val) {
    this.withdraw(val);
    other.deposit(val);
  }
}
```


Static Variables (1)

```java
public class Account {
  private int id;
  private String owner;
  public int getID() { return this.id; }
  public Account(int id, String owner) {
    this.id = id;
    this.owner = owner;
  }
}
```

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

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

Static Variables (2)

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

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

- 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 `acc1` is also visible to `acc2`.

Static Variables (3)

```
public class Account {
  private static int globalCounter = 1;
  private int id; private String owner;
  public 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

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

```
public 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.getAccounts()[0] */
  steve.addAccount(acc2);
    /* mistakenly added to steve.getAccounts()[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:

```
public class Client {
  private Account[] accounts;
  private int numberOfAccounts;
  public void addAccount(Account acc) {
    accounts[this.numberOfAccounts] = acc;
    this.numberOfAccounts ++;
  }
}
```


Static Variables (5.1): Common Error

```
1 public class Bank {
2   private string branchName;
3   public String getBrachName() { return this.branchName; }
4   private static int nextAccountNumber = 0;
5   public static String getInfo() {
6     nextAccountNumber++;
7     return this.branchName + nextAccountNumber;
8   }
9 }
```

- *Non-static method cannot be referenced from a static context*
- **Line 5** declares that we *can* call the method `getInfo` without instantiating an object of the class `Bank`.
- However, in **Line 7**, the *static* method references a *non-static* attribute, for which we *must* instantiate a `Bank` object.

Static Variables (5.2): Common Error

```java
public class Bank {
   private String branchName;
   public String getBrachName() { return this.branchName; }
   private static int nextAccountNumber = 0;
   public static String getInfo() {
      nextAccountNumber++;
      return this.branchName + nextAccountNumber;
   }
}
```

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

```java
Bank.getInfo();
```

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

```java
Bank b = new Bank(); b.setBranch("Songdo IBK");
System.out.println(b.getBranchName());
```


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., `getInfo`).
2. Declare `branchName` as a *static* variable.
   - This does not make sense.
     $\because$ `branchName` should be a value specific to each `Bank` instance.

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Exceptions

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Learning Outcomes

This module is designed to help you learn about:

- Caller vs. Callee in a Method Invocation
- ***Error Handling*** via Console Message
- The ***Catch***-or-***Specify*** Requirement
- Example: To Handle or Not to Handle?
- ***Error Handling*** via Exceptions
- What to Do When an Exception is Thrown at Runtime
- More Examples on Exception Handling

Caller vs. Callee

- Within the body implementation of a method ({...}), we may call other methods.

```
1 class C1 {
2   void m1() {
3     C2 o = new C2();
4     o.m2(); /* static type of o is C2 */
5   }
6 }
```

- From **Line 4**, we say:
  - Method ***C1.m1*** (i.e., method `m1` from class `C1`) is the *caller* of method ***C2.m2***.
  - Method ***C2.m2*** is the *callee* of method ***C1.m1***.

Stack of Method Calls

- Execution of a Java project *starts* from the *`main` method* of some class (e.g., `CircleTester`, `BankApplication`).
- Each line of *method call* involves the execution of that method's *body implementation*
  - That method's body implementation may also involve *method calls*, which may in turn involve more *method calls*, and *etc.*
  - It is typical that we end up with *a chain of method calls*!
  - We visualize this chain of method calls as a *call stack*. For example:
    - `Account.withdraw` [*top* of stack; *latest* called]
    - `Bank.withdrawFrom`
    - `BankApplication.main` [*bottom* of stack; *earliest* called]
  - The closer a method is to the *top* of the call stack, the *later* its call was made.

Error Reporting via Consoles: Circles (1)

```
1 class Circle {
2   double radius;
3   Circle() { /* radius defaults to 0 */ }
4   void setRadius(double r) {
5     if (r < 0) { System.out.println("Invalid radius."); }
6     else { radius = r; }
7   }
8   double getArea() { return radius * radius * 3.14; }
9 }
```

- A negative radius is considered as an *invalid input value* to method `setRadius`.
- What if the *caller* of `Circle.setRadius` passes a negative value for `r`?
  - An error message is *printed to the console* (**Line 5**) to warn the *caller* of `setRadius`.
  - However, printing an error message to the console *does not force* the *caller* of `setRadius` to stop and handle invalid values of `r`.

Error Reporting via Consoles: Circles (2)

```
1 class CircleCalculator {
2   public static void main(String[] args) {
3     Circle c = new Circle();
4     c.setRadius(-10);
5     double area = c.getArea();
6     System.out.println("Area: " + area);
7   }
8 }
```

- **L4**: ***CircleCalculator.main*** is *caller* of ***Circle.setRadius***
- A negative radius is passed to `setRadius` in **Line 4**.
- The execution *always flows smoothly* from **Lines 4** to **Line 5**, *even when there was an error* message printed from **Line 4**.
- It is not feasible to check if there is any kind of error message printed to the console right after the execution of **Line 4**.
- **Solution:** A way to force ***CircleCalculator.main***, *caller* of ***Circle.setRadius***, to realize that things might go wrong.
  - ⇒ When things do go wrong, immediate actions are needed.

Error Reporting via Consoles: Bank (1)

```
class Account {
  int id; double balance;
  Account(int id) { this.id = id; /* balance defaults to 0 */ }
  void deposit(double a) {
    if ( a < 0 ) { System.out.println( "Invalid deposit." ); }
    else { balance += a; }
  }
  void withdraw(double a) {
    if ( a < 0 || balance - a < 0 ) {
      System.out.println( "Invalid withdraw." ); }
    else { balance -= a; }
  }
}
```

- A negative deposit or withdraw amount is *invalid*.
- When an *error* occurs, a message is *printed to the console*.
- However, printing error messages does not force the *caller* of `Account.deposit` or `Account.withdraw` to stop and handle invalid values of `a`.

Error Reporting via Consoles: Bank (2)

```
1  class Bank {
2    Account[] accounts; int numberOfAccounts;
3    Bank(int id) { ... }
4    void withdrawFrom(int id, double a) {
5      for(int i = 0; i < numberOfAccounts; i ++) {
6        if(accounts[i].id == id) {
7          accounts[i].withdraw( a );
8        }
9      } /* end for */
10   } /* end withdraw */
11 }
```

- **L7**: `Bank.withdrawFrom` is *caller* of `Account.withdraw`
- What if in **Line 7** the value of `a` is negative?
  Error message `Invalid withdraw` printed from method `Account.withdraw` to console.
- Impossible to force `Bank.withdrawFrom`, the *caller* of `Account.withdraw`, to stop and handle invalid values of `a`.

Error Reporting via Consoles: Bank (3)

```
1  class BankApplication {
2    pubic static void main(String[] args) {
3      Scanner input = new Scanner(System.in);
4      Bank b = new Bank(); Account acc1 = new Account(23);
5      b.addAccount(acc1);
6      double a = input.nextDouble();
7      b.withdrawFrom(23, a );
8      System.out.println("Transaction Completed.");
9  }
```

- There is a chain of method calls:
  - *BankApplication.main* calls **Bank.withdrawFrom**
  - **Bank.withdrawFrom** calls *Account.withdraw*.
- The actual update of balance occurs at the `Account` class.
  - What if in **Line 7** the value of `a` is negative?
    `Invalid withdraw` printed from `Bank.withdrawFrom`, originated from `Account.withdraw` to console.
  - However, impossible to stop `BankApplication.main` from continuing to execute **Line 8**, printing `Transaction Completed`.
- **Solution:** Define error checking only once and let it *propagate*.

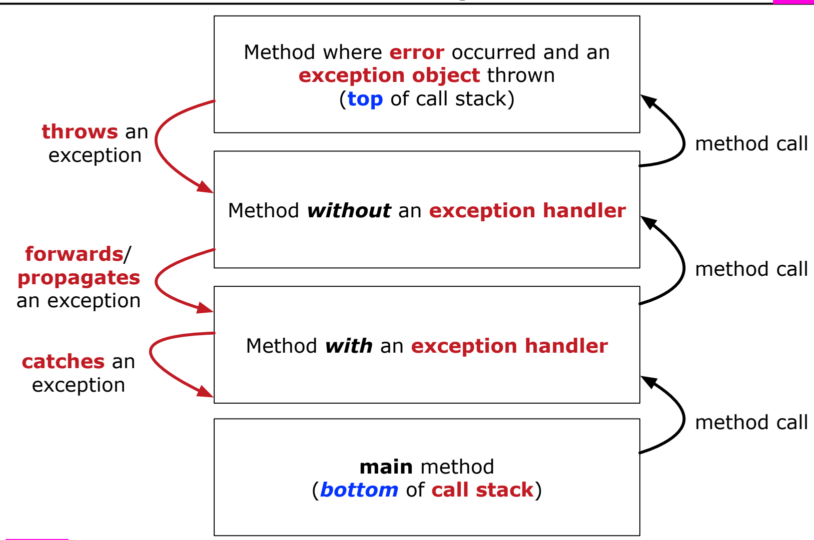
What is an Exception?

- An *exception* is an *event*, which
  - occurs during the *execution of a program*
  - *disrupts the normal flow* of the program's instructions
- When an error occurs within a method:
  - the method throws an exception:
    - first creates an *exception object*
    - then hands it over to the *runtime system*
  - the exception object contains information about the error:
    - type [e.g., `NegativeRadiusException`]
    - the state of the program when the error occurred

What to Do When an Exception Is Thrown? (1)

- After a method *throws an exception*, the *runtime system* searches the corresponding *call stack* for a method that contains a block of code to *handle* the exception.
  - This block of code is called an *exception handler*.
    - An exception handler is **appropriate** if the *type* of the *exception object thrown* matches the *type* that can be handled by the handler.
    - The exception handler chosen is said to *catch* the exception.
  - The search goes from the *top* to the *bottom* of the call stack:
    - The method in which the *error* occurred is searched first.
    - The *exception handler* is not found in the current method being searched ⇒ Search the method that calls the current method, and *etc.*
    - When an appropriate *handler* is found, the *runtime system* passes the exception to the handler.
  - The *runtime system* searches all the methods on the *call stack* without finding an **appropriate** *exception handler*
    ⇒ The program terminates and the exception object is directly "thrown" to the console!

What to Do When an Exception Is Thrown? (2)



The Catch or Specify Requirement (1)

Code (e.g., a method call) that might throw certain exceptions must be enclosed by one of the two ways:

1. **The "Catch" Solution:** A `try` statement that ***catches*** and ***handles*** the ***exception***
   (**without** propagating that exception to the method's *caller*).

```
main(...) {
  Circle c = new Circle();
  try {
    c.setRadius(-10);
  }
  catch(NegativeRaidusException e) {
    ...
  }
}
```


The Catch or Specify Requirement (2)

Code (e.g., a method call) that might throw certain exceptions must be enclosed by one of the two ways:

2. **The "Specify" Solution:** A method that specifies as part of its *header* that it may (or may not) ***throw*** the ***exception***
   (which will be thrown to the method's ***caller*** for handling).

```
class Bank {
  Account[] accounts; /* attribute */
  void withdraw (double amount)
      throws InvalidTransactionException {
    ...
    accounts[i].withdraw(amount);
    ...
  }
}
```

Example: to Handle or Not to Handle? (1.1)

Consider the following three classes:

```
class A {
  ma(int i) {
    if(i < 0) { /* Error */ }
    else { /* Do something. */ }
  } }
```

```
class B {
  mb(int i) {
    A oa = new A();
    oa.ma(i); /* Error occurs if i < 0 */
  } }
```

```
class Tester {
  public static void main(String[] args) {
    Scanner input = new Scanner(System.in);
    int i = input.nextInt();
    B ob = new B();
    ob.mb(i); /* Where can the error be handled?  */
  } }
```


Example: to Handle or Not to Handle? (1.2)

- We assume the following kind of error for negative values:

```
class NegValException extends Exception {
  NegValException(String s) { super(s); }
}
```

- The above kind of exception may be thrown by calling `A.ma`.
- We will see three kinds of possibilities of handling this exception:

  Version 1:
  Handle it in `B.mb`
  Version 2:
  Pass it from `B.mb` and handle it in `Tester.main`
  Version 3:
  Pass it from `B.mb`, then from `Tester.main`, then throw it to the console.

Example: to Handle or Not to Handle? (2.1)

Version 1: Handle the exception in `B.mb`.

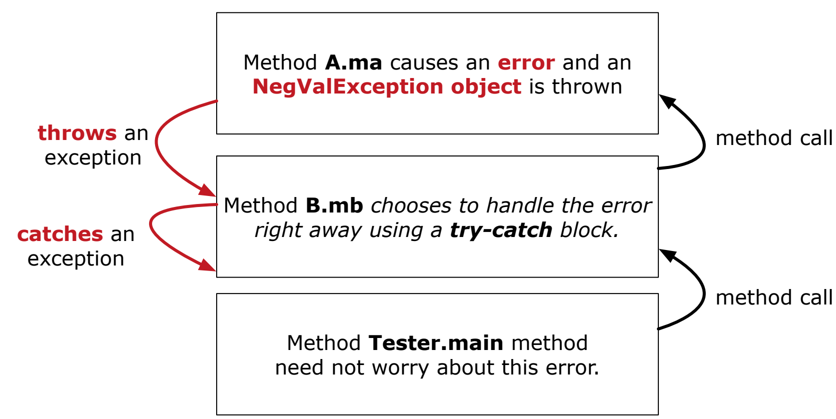
```
class A {
  ma(int i) throws NegValException {
    if(i < 0) { throw new NegValException("Error."); }
    else { /* Do something. */ }
  } }
```

```
class B {
  mb(int i) {
    A oa = new A();
    try { oa.ma(i); }
    catch(NegValException nve) { /* Do something. */ }
  } }
```

```
class Tester {
  public static void main(String[] args) {
    Scanner input = new Scanner(System.in);
    int i = input.nextInt();
    B ob = new B();
    ob.mb(i); /* Error, if any, would have been handled in B.mb.  */
  } }
```


Example: to Handle or Not to Handle? (2.2)

Version 1: Handle the exception in `B.mb`.



Example: to Handle or Not to Handle? (3.1)

Version 2: Handle the exception in `Tester.main`.

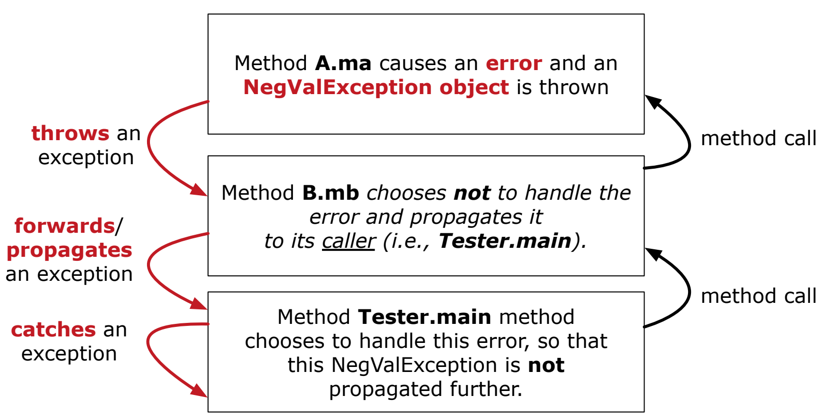
```
class A {
  ma(int i) throws NegValException {
    if(i < 0) { throw new NegValException("Error."); }
    else { /* Do something. */ }
  } }
```

```
class B {
  mb(int i) throws NegValException {
    A oa = new A();
    oa.ma(i);
  } }
```

```
class Tester {
  public static void main(String[] args) {
    Scanner input = new Scanner(System.in);
    int i = input.nextInt();
    B ob = new B();
    try { ob.mb(i); }
    catch(NegValException nve) { /* Do something. */ }
  } }
```


Example: to Handle or Not to Handle? (3.2)

Version 2: Handle the exception in `Tester.main`.



Example: to Handle or Not to Handle? (4.1)

Version 3: Handle in neither of the classes.

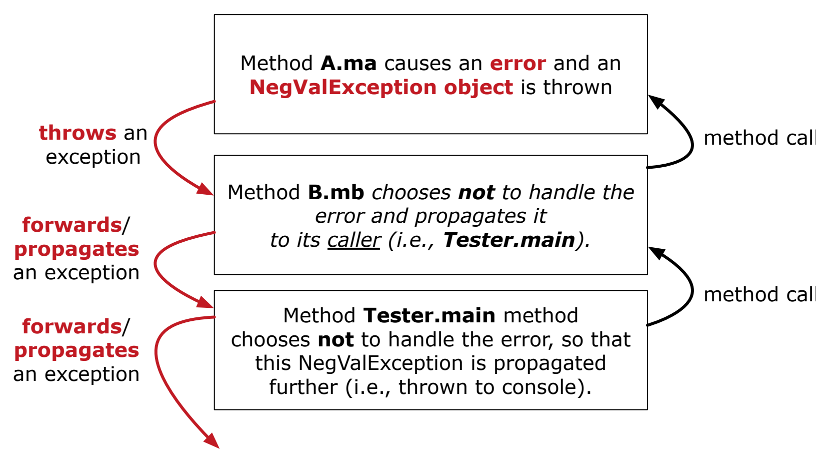
```
class A {
  ma(int i) throws NegValException {
    if(i < 0) { throw new NegValException("Error."); }
    else { /* Do something. */ }
  } }
```

```
class B {
  mb(int i) throws NegValException {
    A oa = new A();
    oa.ma(i);
  } }
```

```
class Tester {
  public static void main(String[] args) throws NegValException {
    Scanner input = new Scanner(System.in);
    int i = input.nextInt();
    B ob = new B();
    ob.mb(i);
  } }
```


Example: to Handle or Not to Handle? (4.2)

Version 3: Handle in neither of the classes.



Error Reporting via Exceptions: Circles (1)

```java
public class InvalidRadiusException extends Exception {
  public InvalidRadiusException(String s) {
    super(s);
  }
}
```

- A new kind of `Exception`: `InvalidRadiusException`
- For any method that can have this kind of error, we declare at that method's *header* that it may *throw* an `InvalidRaidusException` object.

Error Reporting via Exceptions: Circles (2)

```java
class Circle {
  double radius;
  Circle() { /* radius defaults to 0 */ }
  void setRadius(double r) throws InvalidRadiusException {
    if (r < 0) {
      throw new InvalidRadiusException("Negative radius.");
    }
    else { radius = r; }
  }
  double getArea() { return radius * radius * 3.14; }
}
```

- As part of the *header* of `setRadius`, we declare that it may *throw* an `InvalidRadiusException` object at runtime.
- Any method that calls `setRadius` will be forced to *deal with this potential error* .

Error Reporting via Exceptions: Circles (3)

```java
1  class CircleCalculator1 {
2   public static void main(String[] args) {
3    Circle c = new Circle();
4    try {
5     c.setRadius(-10);
6     double area = c.getArea();
7     System.out.println("Area: " + area);
8    }
9    catch(InvalidRadiusException e) {
10    System.out.println(e);
11   }
12  } }
```

- **Line 5** is forced to be wrapped within a *try-catch* block, since it may *throw* an `InvalidRadiusException` object.
- If an `InvalidRadiusException` object is thrown from **Line 6**, then the normal flow of execution is *interrupted* and we go to the `catch` block starting from **Line 9**.

Error Reporting via Exceptions: Circles (4)

Exercise: Extend `CircleCalculator1`: repeatedly prompt for a new radius value until a valid one is entered (i.e., the `InvalidRadiusException` does not occur).

```
Enter a radius:
-5
Radius -5.0 is invalid, try again!
Enter a radius:
-1
Radius -1.0 is invalid, try again!
Enter a radius:
5
Circle with radius 5.0 has area: 78.5
```

Error Reporting via Exceptions: Circles (5)

```
1  public class CircleCalculator2 {
2   public static void main(String[] args) {
3    Scanner input = new Scanner(System.in);
4    boolean inputRadiusIsValid = false;
5    while(!inputRadiusIsValid) {
6     System.out.println("Enter a radius:");
7     double r = input.nextDouble();
8     Circle c = new Circle();
9     try { c.setRadius(r);
10           inputRadiusIsValid = true;
11           System.out.print("Circle with radius " + r);
12           System.out.println(" has area: "+ c.getArea()); }
13    catch(InvalidRadiusException e) { print("Try again!"); }
14   } } }
```

- At **L7**, if the user's input value is:
  - Non-Negative: **L8** – **L12**. [`inputRadiusIsValid` set ***true***]
  - Negative: **L8**, **L9**, **L13**. [`inputRadiusIsValid` remains ***false***]

Error Reporting via Exceptions: Bank (1)

```
public class InvalidTransactionException extends Exception {
  public InvalidTransactionException(String s) {
    super(s);
  }
}
```

- A new kind of `Exception`: `InvalidTransactionException`
- For any method that can have this kind of error, we declare at that method's *header* that it may *throw* an `InvalidTransactionException` object.

Error Reporting via Exceptions: Bank (2)

```
class Account {
  int id; double balance;
  Account() { /* balance defaults to 0 */ }
  void withdraw(double a) throws InvalidTransactionException {
    if (a < 0 || balance - a < 0) {
      throw new InvalidTransactionException("Invalid withdraw."); }
    else { balance -= a; }
  }
}
```

- As part of the *header* of `withdraw`, we declare that it may *throw* an `InvalidTransactionException` object at runtime.
- Any method that calls `withdraw` will be forced to *deal with this potential error*.

Error Reporting via Exceptions: Bank (3)

```
class Bank {
  Account[] accounts; int numberOfAccounts;
  Account(int id) { ... }
  void withdraw(int id, double a)
     throws InvalidTransactionException {
    for(int i = 0; i < numberOfAccounts; i ++) {
      if(accounts[i].id == id) {
        accounts[i].withdraw(a);
      }
    } /* end for */ } /* end withdraw */ }
```

- As part of the *header* of `withdraw`, we declare that it may *throw* an `InvalidTransactionException` object.
- Any method that calls `withdraw` will be forced to *deal with this potential error*.
- We are *propagating* the potential error for the right party (i.e., `BankApplication`) to handle.

Error Reporting via Exceptions: Bank (4)

```
1  class BankApplication {
2   pubic static void main(String[] args) {
3     Bank b = new Bank();
4     Account acc1 = new Account(23);
5     b.addAccount(acc1);
6     Scanner input = new Scanner(System.in);
7     double a = input.nextDouble();
8     try {
9       b.withdraw(23, a);
10      System.out.println(acc1.balance); }
11    catch (InvalidTransactionException e) {
12      System.out.println(e); } } }
```

- **Lines 9** is forced to be wrapped within a *try-catch* block, since it may *throw* an `InvalidTransactionException` object.
- If an `InvalidTransactionException` object is thrown from **Line 9**, then the normal flow of execution is interrupted and we go to the `catch` block starting from **Line 11**.

More Examples (1)

```
double r = ...;
double a = ...;
try{
  Bank b = new Bank();
  b.addAccount(new Account(34));
  b.deposit(34, 100);
  b.withdraw(34, a);
  Circle c = new Circle();
  c.setRadius(r);
  System.out.println(r.getArea());
}
catch(NegativeRadiusException e) {
  System.out.println(r + " is not a valid radius value.");
  e.printStackTrace();
}
catch(InvalidTransactionException e) {
  System.out.println(r + " is not a valid transaction value.");
  e.printStackTrace();
}
```


More Example (2.1)

The `Integer` class supports a method for parsing Strings:

```
public static int parseInt(String s)
              throws NumberFormatException
```

e.g., `Integer.parseInt("23")` returns `23`

e.g., `Integer.parseInt("twenty-three")` throws a `NumberFormatException`

Write a fragment of code that prompts the user to enter a string (using `nextLine` from `Scanner`) that represents an integer.

If the user input is not a valid integer, then prompt them to enter again.

More Example (2.2)

```
Scanner input = new Scanner(System.in);
boolean validInteger = false;
while (!validInteger) {
  System.out.println("Enter an integer:");
  String userInput = input.nextLine();
  try {
    int userInteger = Integer.parseInt(userInput);
    validInteger = true;
  }
  catch(NumberFormatException e) {
    System.out.println(userInput + " is not a valid integer.");
    /* validInteger remains false */
  }
}
```

Beyond this lecture. . .

- Practice creating a new ***exception*** class upon a method throwing it in the body of implementation (e.g., `InvalidRadiusException`, `InvalidTransactionException`).
- Play with the source code:
  - `ExceptionsCircleAndBank.zip`
  - `ExceptionsToHandleOrNotToHandle.zip`

  Tip. Change input values so as to explore, in Eclipse ***debugger***, possible (***normal*** vs. ***abnormal***) ***execution paths***.

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Beyond this lecture. . .

Test-Driven Development (TDD) with JUnit

EECS2030 B & G: Advanced Object Oriented Programming
Fall 2025

CHEN-WEI WANG

Learning Outcomes

This module is designed to help you learn about:

- ***Testing*** the Solution to a Bounded Counter Problem
- Deriving ***Test Cases*** for a Bounded Variable
- Application of ***Normal*** vs. ***Disrupted*** ***Execution Flows***
- ***Intention*** of a Test: ***Exceptions*** ***Expected*** vs. ***Not Expected***
- ***Test Driven Development*** (***TDD***) via ***Regression Testing***

Motivating Example: Two Types of Errors (1)

Consider two kinds of exceptions for a counter:

```
public class ValueTooLargeException extends Exception {
  ValueTooLargeException(String s) { super(s); }
}
public class ValueTooSmallException extends Exception {
  ValueTooSmallException(String s) { super(s); }
}
```

Any thrown object instantiated from these two exception classes must be handled (***catch-or-specify*** *requirement*):

- Either ***specify*** `throws ...` in the method header/API (i.e., ***propagate*** it to the immediate **caller** in the ***call stack***)
- Or ***handle*** it in a `try-catch` block

Motivating Example: Two Types of Errors (2)

Approach 1 – *Specify*: Indicate in the method header/API that a specific exception might be thrown.

Example 1: Method that throws the exception

```
class C1 {
  void m1(int x) throws ValueTooSmallException {
    if(x < 0) {
      throw new ValueTooSmallException("val " + x);
    }
  }
}
```

Example 2: Method that calls another which throws the exception

```
class C2 {
  C1 c1;
  void m2(int x) throws ValueTooSmallException {
    c1.m1(x);
  }
}
```


A Simple Counter (1)

Consider a class for keeping track of an integer counter value:

```
public class Counter {
  public final static int MAX_VALUE = 3;
  public final static int MIN_VALUE = 0;
  private int value;
  public Counter() {
    this.value = Counter.MIN_VALUE;
  }
  public int getValue() {
    return value;
  }
  ... /* more later! */
```

- Access ***private*** attribute `value` using ***public*** accessor `getValue`.
- Two class-wide (i.e., `static`) 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 within its lower and upper bounds.

Motivating Example: Two Types of Errors (3)

Approach 2 – *Catch*: Handle the thrown exception(s) in a try-catch block.

```
class C3 {
  public static void main(String[] args) {
    Scanner input = new Scanner(System.in);
    int x = input.nextInt();
    C2 c2 = new c2();
    try {
      c2.m2(x);
    }
    catch(ValueTooSmallException e) { ... }
  }
}
```


Exceptional Scenarios

- ***Sound*** Software Engineering Practice:

  Design a ***test strategy*** even **before** code is completed.
- **Q**: Possible exceptional scenarios for such a counter?
  - An attempt to increment ***above*** the counter's upper bound.
  - An attempt to decrement ***below*** the counter's lower bound.

A Simple Counter (2)

```
/* class Counter */
 public void increment() throws ValueTooLargeException {
   if(value == Counter.MAX_VALUE) {
     throw new ValueTooLargeException("value is " + value);
   }
   else { value ++; }
 }

 public void decrement() throws ValueTooSmallException {
   if(value == Counter.MIN_VALUE) {
     throw new ValueTooSmallException("value is " + value);
   }
   else { value --; }
 }
}
```

- Change the counter value via two mutator methods.
- Changes on the counter value may ***trigger an exception***:
  - Attempt to **increment** when counter already reaches its **maximum**.
  - Attempt to **decrement** when counter already reaches its **minimum**.

Components of a Test

- Manipulate the relevant object(s).

  e.g., ***Initialize a counter object*** `c`***, then call*** `c.increment()`.

  e.g., ***Initialize a counter object*** `c`***, then call*** `c.decrement()`.
- What do you *expect to happen* ?

  e.g., ***value of counter is such that*** `Counter.MIN_VALUE + 1`

  e.g., `ValueTooSmallException` ***is thrown***
- What does your program *actually produce* ?

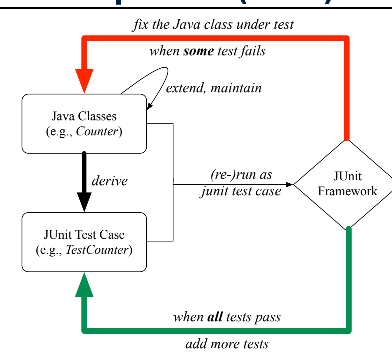
  e.g., ***call*** `c.getValue()` ***to find out.***

  e.g., ***Use a*** `try-catch` ***block to find out*** (to be discussed!).
- A test:
  - ***Passes*** if ***expected outcome*** occurs.
  - ***Fails*** if ***expected outcome*** does not occur.

Why JUnit?

- *Automate* the ***testing of correctness*** of your Java classes.
- **Derive** the list of tests. **Transform** it into a ***JUnit Test Class***.
- JUnit tests are **callers/clients** of your classes. 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 the expected exception (e.g., `ValueTooSmallException`) occurs.
    - ***Failure*** if the expected exception does ***not*** occur.
- ***Regression Testing*** : Any **change** introduced to your software *must not compromise* its established ***correctness***.

Test-Driven Development (TDD)



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

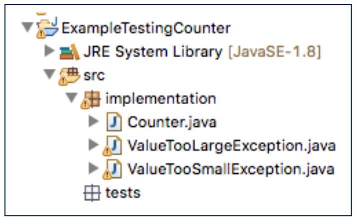
- Derive and run tests as soon as your CUD is *testable* .

  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.

How to Use JUnit: Packages

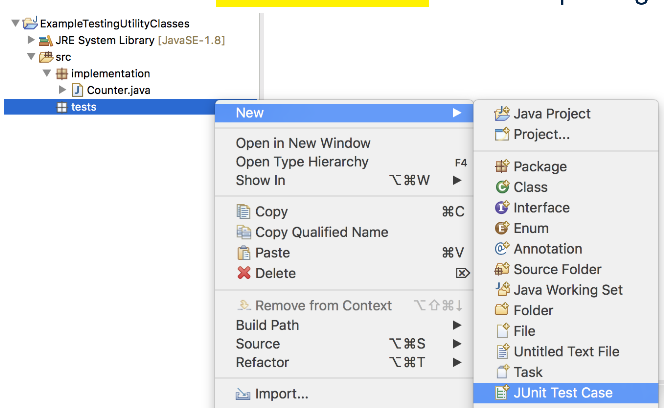
Step 1:

- In Eclipse, create a Java project `ExampleTestingCounter`
- *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.

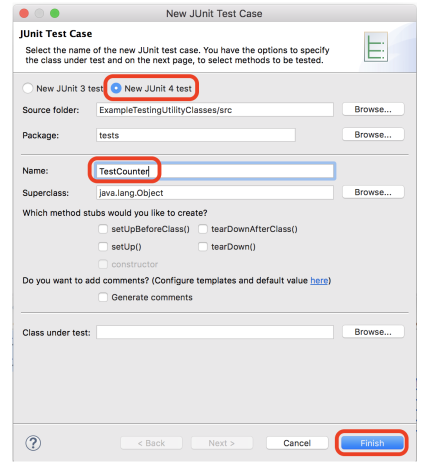


Create one JUnit Test Case to test one Java class only.

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

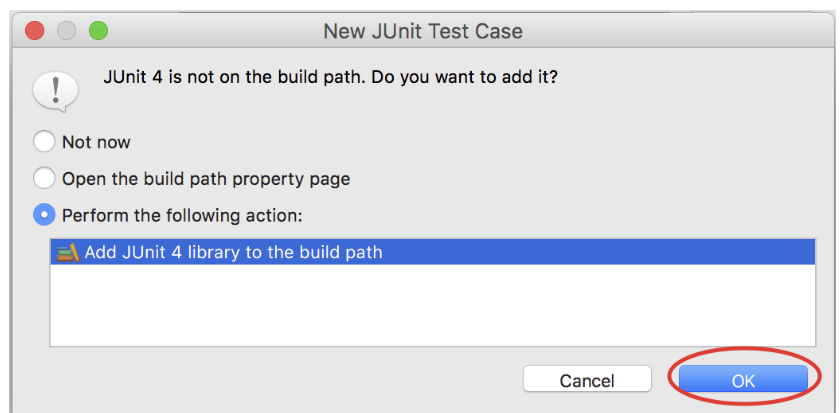
How to Use JUnit: New JUnit Test Case (2)

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

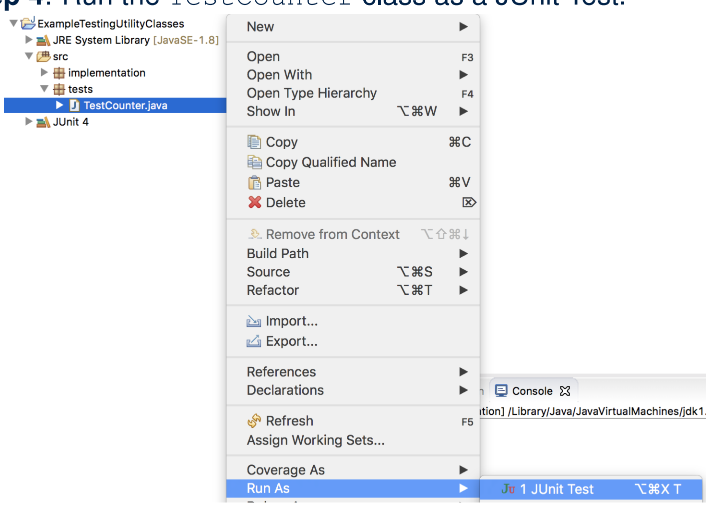
TestCounter.java

```
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”.

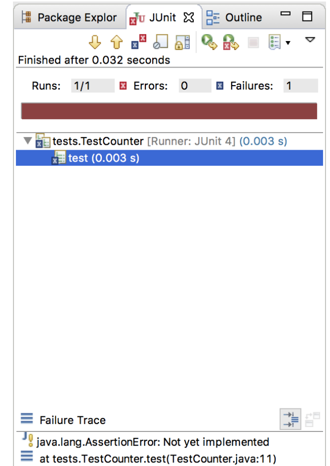
How to Use JUnit: Running Test Case

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
    - an unexpected ***exception*** (e.g., *`NullPointerException`*, *`ArrayIndexOutOfBoundException`*) 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-running 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

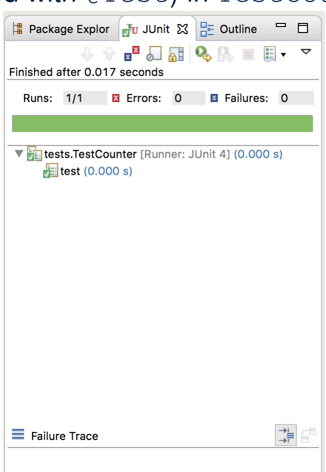
```java
package tests;
import static org.junit.Assert.*;
import org.junit.Test;
public class TestCounter {
    @Test
    public void test() {
//      fail("Not yet implemented");
    }
}
```

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: Common Assertions

- `void assertNull(Object o)`
- `void assertEquals(int expected, int actual)`
- `void assertEquals(double exp, double act, double epsilon)`
- `void assertArrayEquals(expected, actuals)`
- `void assertTrue(boolean condition)`
- `void fail(String message)`

JUnit Assertions: Examples (1)

Consider the following class:

```java
public class Point {
  private int x; private int y;
  public Point(int x, int y) { this.x = x; this.y = y; }
  public int getX() { return this.x; }
  public int getY() { return this.y; }
}
```

Then consider these assertions. Do they ***pass*** or ***fail***?

```java
Point p;
assertNull(p);  ✓
assertTrue(p == null);  ✓
assertFalse(p != null);  ✓
assertEquals(3, p.getX());  × /* NullPointerException */
p = new Point(3, 4);
assertNull(p);  ×
assertTrue(p == null);  ×
assertFalse(p != null);  ×
assertEquals(3, p.getX());  ✓
assertTrue(p.getX() == 3 && p.getY() == 4);  ✓
```

JUnit Assertions: Examples (2)

- Consider the following class:

```
public class Circle {
  private double radius;
  public Circle(double radius) { this.radius = radius; }
  public int getArea() { return 3.14 * radius * radius; }
}
```

- How do we test `c.getArea()`?
  - Mathematically: $3.4 \times 3.4 \times 3.14 = 36.2984$
  - However, base-10 numbers ***cannot*** be represented perfectly in the binary format.
  - When comparing fractional numbers, allow some *tolerance*:

$$36.2984 - \mathbf{0.01} \leq c.getArea() \leq 36.2984 + \mathbf{0.01}$$

- Then consider these assertions. Do they ***pass*** or ***fail***?

```
Circle c = new Circle(3.4);
assertEquals(36.2984, c.getArea(), 0.01);   ✓
```


More 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.

Testing Strategy

- What is the complete list of cases for testing `Counter`?

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

- Let's turn the two cases in the 1st row into two JUnit tests:
  - Test for the *green* cell *succeeds* if:
    - No failures and exceptions occur; and
    - The new counter value is `1`.
  - Tests for *red* cells *succeed* if the *expected exceptions* occur (`ValueTooSmallException` & `ValueTooLargeException`).

Testing: Correct vs. Incorrect Imp.

- The real value of a *test* is:
  - Not only to ***reaffirm*** when your implementation is ***correct***,
  - But also to ***reject*** when your implementation is ***incorrect***.
- What if the method `decrement` was implemented ***incorrectly***?

```
class Counter {
  ...
  public void decrement() throws ValueTooSmallException {
    if(value < Counter.MIN_VALUE) {
      throw new ValueTooSmallException("value is " + value);
    }
    else { value --; }
  }
}
```

- A "good" test should *reject* such an ***incorrect*** implementation.

Test Case 1: Increment from Min (1)

```
1  @Test
2  public void testIncAfterCreation() {
3    Counter c = new Counter();
4    assertEquals(Counter.MIN_VALUE, c.getValue());
5    try {
6      c.increment();
7      assertEquals(1, c.getValue());
8    }
9    catch(ValueTooLargeException e) {
10     /* Exception is not expected to be thrown. */
11     fail("ValueTooLargeException is not expected.");
12   }
13 }
```

- **L3** sets `c.value` to `0`.
- **Line 6** requires a try-catch block ∵ potential `ValueTooLargeException`
- **Lines 4, 7 11** are all assertions:
  - **Lines 4 & 7** assert that `c.getValue()` returns the expected values.
  - **Line 11**: an *assertion failure* ∵ unexpected `ValueTooLargeException`
- **Line 7** can be rewritten as `assertTrue(1 == c.getValue())`.

Test Case 1: Increment from Min (2)

```
1  @Test
2  public void testIncAfterCreation() {
3    Counter c = new Counter();
4    assertEquals(Counter.MIN_VALUE, c.getValue());
5    try {
6      c.increment();
7      assertEquals(1, c.getValue());
8    }
9    catch(ValueTooLargeException e) {
10     /* Exception is not expected to be thrown. */
11     fail("ValueTooLargeException is not expected.");
12   }
13 }
```

At **L6**, if method `decrement` is implemented:

- ***Correctly*** ⇒ a `ValueTooLargeException` does not occur.
  ⇒ Execution continues to **L7**, **L8**, **L13**, then the program <u>terminates</u>.
- ***Incorrectly*** ⇒ an unexpected `ValueTooLargeException` occurs.
  ⇒ Execution jumps to **L9**, **L10 – L11**, then the test program <u>terminates</u>.

Test Case 2: Decrement from Min (1)

```
1  @Test
2  public void testDecFromMinValue() {
3    Counter c = new Counter();
4    assertEquals(Counter.MIN_VALUE, c.getValue());
5    try {
6      c.decrement();
7      fail("ValueTooSmallException is expected.");
8    }
9    catch(ValueTooSmallException e) {
10     /* Exception is expected to be thrown. */
11   }
12 }
```

- **L3** sets `c.value` to `0`.
- **Line 6** requires a try-catch block ∵ potential `ValueTooSmallException`
- **Lines 4 & 7** are both assertions:
  - **Lines 4** asserts that `c.getValue()` returns the expected value (i.e., `Counter.MIN_VALUE`).
  - **Line 7**: an *assertion failure* ∵ expected `ValueTooSmallException` not thrown

Test Case 2: Decrement from Min (2)

```
1  @Test
2  public void testDecFromMinValue() {
3    Counter c = new Counter();
4    assertEquals(Counter.MIN_VALUE, c.getValue());
5    try {
6      c.decrement();
7      fail("ValueTooSmallException is expected.");
8    }
9    catch(ValueTooSmallException e) {
10     /* Exception is expected to be thrown. */
11   }
12 }
```

At **L6**, if method `decrement` is implemented:

- ***Correctly*** ⇒ a `ValueTooLargeException` occurs.
  ⇒ Execution jumps to **L9**, **L10 – L12**, then the program <u>terminates</u>.
- ***Incorrectly*** ⇒ expected `ValueTooLargeException` does **not** occur.
  ⇒ Execution continues to **L7**, then the test program <u>terminates</u>.

Test Case 3: Increment from Max

```java
1  @Test
2  public void testIncFromMaxValue() {
3    Counter c = new Counter();
4    try {
5      c.increment(); c.increment(); c.increment();
6    }
7    catch (ValueTooLargeException e) {
8      fail("ValueTooLargeException was thrown unexpectedly.");
9    }
10   assertEquals(Counter.MAX_VALUE, c.getValue());
11   try {
12     c.increment();
13     fail("ValueTooLargeException was NOT thrown as expected.");
14   }
15   catch (ValueTooLargeException e) {
16     /* Do nothing: ValueTooLargeException thrown as expected. */
17   }
18 }
```

- **L4 – L9**: a VTLE ***is not*** expected; **L11 – 17**: a VTLE ***is*** expected.

Exercise: Console Tester vs. JUnit Test

Q. Can this ***console tester*** work like the ***JUnit test*** `testIncFromMaxValue` does?

```java
1  public class CounterTester {
2   public static void main(String[] args) {
3     Counter c = new Counter();
4     println("Current val: " + c.getValue());
5     try {
6       c.increment(); c.increment(); c.increment();
7       println("Current val: " + c.getValue());
8     }
9     catch (ValueTooLargeException e) {
10      println("Error: ValueTooLargeException thrown unexpectedly.");
11    }
12    try {
13      c.increment();
14      println("Error: ValueTooLargeException NOT thrown.");
15    } /* end of inner try */
16    catch (ValueTooLargeException e) {
17      println("Success: ValueTooLargeException thrown.");
18    }
19  } /* end of main method */
20 } /* end of CounterTester class */
```

A. Say one of the first 3 `c.increment()` ***mistakenly*** throws `VTLE`.

- After **L10** is executed, flow of execution ***still continues*** to **L12**.
- This allows the 4th `c.increment` to be executed!

Exercise: Combining `catch` Blocks?

Q: Can we rewrite `testIncFromMaxValue` to:

```java
1  @Test
2  public void testIncFromMaxValue() {
3    Counter c = new Counter();
4    try {
5      c.increment();
6      c.increment();
7      c.increment();
8      assertEquals(Counter.MAX_VALUE, c.getValue());
9      c.increment();
10     fail("ValueTooLargeException was NOT thrown as expected.");
11   }
12   catch (ValueTooLargeException e) { }
13 }
```

No!

At **Line 12**, we would not know which line throws the VTLE:

- If it was any of the calls in **L5 – L7**, then it's ***not right***.
- If it was **L9**, then it's ***right***.

Using Loops in JUnit Test Cases

Loops can make it effective on generating test cases:

```java
@Test
public void testIncDecFromMiddleValues() {
  Counter c = new Counter();
  try {
    for(int i = Counter.MIN_VALUE; i < Counter.MAX_VALUE; i ++) {
      int currentValue = c.getValue();
      c.increment();
      assertEquals(currentValue + 1, c.getValue());
    }
    for(int i = Counter.MAX_VALUE; i > Counter.MIN_VALUE; i --) {
      int currentValue = c.getValue();
      c.decrement();
      assertEquals(currentValue - 1, c.getValue());
    }
  }
  catch(ValueTooLargeException e) {
    fail("ValueTooLargeException is thrown unexpectedly");
  }
  catch(ValueTooSmallException e) {
    fail("ValueTooSmallException is thrown unexpectedly");
  }
}
```

Exercises

1. Run all 8 tests and make sure you receive a *green* bar.
2. 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 ***error injections*** & Re-Run all 8 tests. [What happens?]

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`

Beyond this lecture. . .

Play with the source code `ExampleTestingCounter.zip`

Tip. Change input values so as to explore, in Eclipse ***debugger***, possible (***normal*** vs. ***abnormal***) ***execution paths*** .

Index (1)

Index (2)

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Object Equality

YORK UNIVERSITÉ UNIVERSITY

EECS2030 B & G: Advanced Object Oriented Programming
Fall 2025

CHEN-WEI WANG

Learning Outcomes

This module is designed to help you learn about:

- ***Call by Value***: Primitive vs. Reference Argument Values
- ***Object equality***: To ***Override*** or ***Not*** to Override
- Asserting ***Object Equality***: `assertSame` vs. `assertEquals`
- Short-Circuit Effect (SCE): `&&` vs. `||`
- Equality for Array-, Reference-Typed Attributes

Call by Value (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 to the method call.
  - Instead, argument variable **arg** is passed **indirectly**: a *copy* of the value stored in **arg** is made and passed to 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 Value: Copy of **arg**'s *stored reference/address*
    (e.g., `Point@5cb0d902`) is made and passed.

Call by Value (2.1)

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

```java
public class Point {
  private int x;
  private int y;
  public Point(int x, int y) {
    this.x = x;
    this.y = y;
  }
  public int getX() { return this.x; }
  public int getY() { return this.y; }
  public void moveVertically(int y){ this.y += y; }
  public void moveHorizontally(int x){ this.x += x; }
}
```


Call by Value (2.2.1)

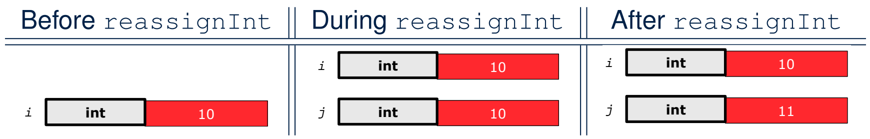
```java
public class Util {
  void reassignInt(int j) {
    j = j + 1; }
  void reassignRef(Point q) {
    Point np = new Point(6, 8);
    q = np; }
  void changeViaRef(Point q) {
    q.moveHorizontally(3);
    q.moveVertically(4); } }
```

```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 (2.2.2)



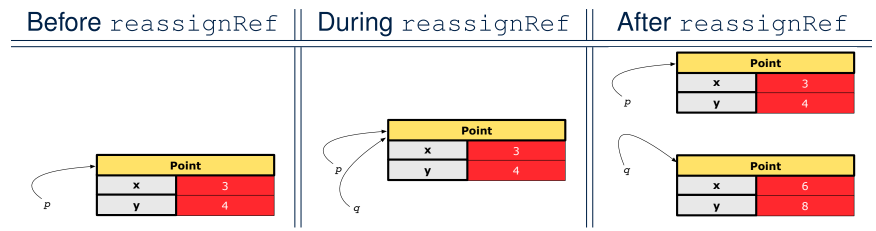
Call by Value (2.3.1)

```
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_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.getX() == 3);
9    assertTrue(p.getY() == 4);
10 }
```

- ***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 value*, 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 (2.3.2)



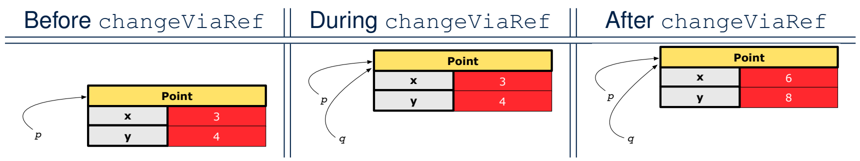
Call by Value (2.4.1)

```
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.getX() == 6);
9    assertTrue(p.getY() == 8);
10 }
```

- ***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 value*, a *copy of address* stored in `p` is made. [**Alias**: `p` and `q` store same address.]
  ⇒ `q.moveHorizontally` impacts the ***same object*** referenced by `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` values have been modified via `q`.

Call by Value (2.4.2)



Equality (1)

- 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 <u>another</u> new `Point` object
- The binary operator `==` may be applied to compare:
  - *Primitive* variables: their ***values*** are compared
    e.g., `d1 == d2` evaluates to <u>**true**</u>
  - *Reference* variables: the ***addresses*** they store are compared (<u>**rather than**</u> comparing contents of the objects they refer to)
    e.g., `p1 == p2` evaluates to <u>**false**</u> because `p1` and `p2` are addresses of <u>different</u> objects, even if their contents are <u>identical</u>.

Equality (2.1)

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

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

    e.g., Say `p1` and `p2` are of type <u>`Point`***V1***</u> in which the `equals` method is <u>not</u> ***redefined/overridden***, then `p1.equals(p2)` boils down to (`p1 == p2`).
  - Very often when you define new classes, you want to *redefine* / *override* the inherited definition of `equals`.

Equality (2.2): Common Error

```
int i = 10;
int j = 12;
boolean sameValue = i.equals(j);
```

Compilation Error

The `equals` method is only applicable to reference types.

Fix

Write `i == j` instead.

Equality (3)

```java
public class PointV1 {
  private int x; private int y;
  public PointV1(int x, int y) { this.x = x; this.y = y; }
}
```

```java
String s = "(2, 3)";
PointV1 p1 = new PointV1(2, 3);
PointV1 p2 = new PointV1(2, 3);
PointV1 p3 = new PointV1(4, 6);
System.out.println(p1 == p2);  /* false */
System.out.println(p2 == p3);  /* false */
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.equals(p2));  /* false */
System.out.println(p2.equals(p3));  /* false */
```

- The `equals` method is not explicitly redefined/overridden in class `PointV1` ⇒ The default version inherited from class **`Object`** is called.
  e.g., Executing `p1.equals(null)` boils down to (`p1 == null`).
- To compare contents of `PointV1` objects, ***redefine/override*** `equals`.

Equality (4.1)

To compare ***contents*** rather than addresses, override `equals`.

```java
public class PointV2 {
  private int x; private int y;
  public boolean equals (Object obj) {
    if(this == obj) { return true; }
    if(obj == null) { return false; }
    if(this.getClass() != obj.getClass()) { return false; }
    PointV2 other = (PointV2) obj;
    return this.x == other.x && this.y == other.y;
  }
}
```

```java
String s = "(2, 3)";
PointV2 p1 = new PointV2(2, 3);
PointV2 p2 = new PointV2(2, 3);
PointV2 p3 = new PointV2(4, 6);
System.out.println(p1 == p2);  /* false */
System.out.println(p2 == p3);  /* false */
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.equals(p2));  /* true */
System.out.println(p2.equals(p3));  /* false */
```


Equality (4.2)

- When making a method call `p.equals(o)`:
  - Say variable `p` is declared of type `PointV2`
  - Variable `o` can be declared of any type (e.g., `PointV2`, `String`)
- We define `p` and `o` as ***equal*** if:
  - Either `p` and `o` refer to the same object;
  - Or:
    - `o` does **not** store the **`null`** address.
    - `p` and `o` at runtime point to objects 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:

```java
class PointV2 {
  public boolean equals(Object obj) {
    if(this == null) { return false; }
```

A: If `this` was `null`, a ***`NullPointerException`*** would have occurred, preventing the body of `equals` from being executed.

Equality (4.3)

```java
1 public class PointV2 {
2  public boolean equals(Object obj) {
3    ...
4    if(this.getClass() != obj.getClass()) { return false; }
5    PointV2 other = (PointV2) obj;
6    return this.x == other.x && this.y == other.y;
7  }
8 }
```

- `Object obj` at **L2** declares a parameter `obj` of type `Object`.
- `PointV2 other` at **L5** declares a variable `p` of type `PointV2`.
  We call such types declared at **compile time** as ***static type***.
- *Applicable attributes/methods* callable upon 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 `PointV2`).
- If we are **certain** 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 `PointV2`.
- The ***cast*** `(PointV2) obj` creates an **alias** of `obj`, upon which (or upon its alias such as `other`) more methods can be invoked.

Equality (5)

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

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

```
PointV2 p1 = new PointV2(3, 4);
PointV2 p2 = new PointV2(3, 4);
PointV2 p3 = new PointV2(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.

Requirements 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`

Equality in JUnit (1.1)

- ***assertSame***(`exp1`, `exp2`)
  - Passes if `exp1` and `exp2` are references to the same object
    ≈ ***assertTrue***(`exp1 == exp2`)
    ≈ ***assertFalse***(`exp1 != exp2`)

```
PointV1 p1 = new PointV1(3, 4);
PointV1 p2 = new PointV1(3, 4);
PointV1 p3 = p1;
assertSame(p1, p3);  ✓
assertSame(p2, p3);  ×
```

- ***assertEquals***(`exp1`, `exp2`)
  - ≈ `exp1 == exp2` if `exp1` and `exp2` are **primitive** type

```
int i = 10;
int j = 20;
assertEquals(i, j);  ×
```


Equality in JUnit (1.2)

- ***assertEquals***(`exp1`, `exp2`)
  - ≈ `exp1`.**equals**(`exp2`) if `exp1` and `exp2` are ***reference*** type

    Case 1: If `equals` is ***not*** explicitly overridden in `exp1`'s dynamic type
    ≈ ***assertSame***(`exp1`, `exp2`)

```
PointV1 p1 = new PointV1(3, 4);
PointV1 p2 = new PointV1(3, 4);
PointV2 p3 = new PointV2(3, 4);
assertEquals(p1, p2);  × /* ∵ different PointV1 objects */
assertEquals(p2, p3);  × /* ∵ different object addresses */
```

Case 2: If `equals` is explicitly ***overridden*** in `exp1`'s dynamic type
≈ `exp1.`***`equals`***`(exp2)`

```
PointV1 p1 = new PointV1(3, 4);
PointV1 p2 = new PointV1(3, 4);
PointV2 p3 = new PointV2(3, 4);
assertEquals(p1, p2);  × /* ≈ p1.equals(p2) ≈ p1 == p2 */
assertEquals(p2, p3);  × /* ≈ p2.equals(p3) ≈ p2 == p3 */
assertEquals(p3, p2);  × /* ≈ p3.equals(p2) ≈ p3.getClass()==p2.getClass() */
```

Equality in JUnit (2)

```
@Test
public void testEqualityOfPointV1() {
  PointV1 p1 = new PointV1(3, 4); PointV1 p2 = new PointV1(3, 4);
  assertFalse(p1 == p2); assertFalse(p2 == p1);
  /* assertSame(p1, p2); assertSame(p2, p1); */ /* both fail */
  assertFalse(p1.equals(p2)); assertFalse(p2.equals(p1));
  assertTrue(p1.getX() == p2.getX() && p1.getY() == p2.getY());
}
@Test
public void testEqualityOfPointV2() {
  PointV2 p3 = new PointV2(3, 4); PointV2 p4 = new PointV2(3, 4);
  assertFalse(p3 == p4); assertFalse(p4 == p3);
  /* assertSame(p3, p4); assertSame(p4, p3); */ /* both fail */
  assertTrue(p3.equals(p4)); assertTrue(p4.equals(p3));
  assertEquals(p3, p4); assertEquals(p4, p3);
}
@Test
public void testEqualityOfPointV1andPointv2() {
  PointV1 p1 = new PointV1(3, 4); PointV2 p2 = new PointV2(3, 4);
  /* These two assertions do not compile because p1 and p2 are of different types. */
  /* assertFalse(p1 == p2); assertFalse(p2 == p1); */
  /* assertSame can take objects of different types and fail. */
  /* assertSame(p1, p2); */ /* compiles, but fails */
  /* assertSame(p2, p1); */ /* compiles, but fails */
  /* version of equals from Object is called */
  assertFalse(p1.equals(p2));
  /* version of equals from PointP2 is called */
  assertFalse(p2.equals(p1));
}
```


Equality (6.1)

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

```
1  public class Person {
2    private String firstName; private String lastName;
3    private double weight; private double height;
4    public boolean equals(Object obj) {
5      if(this == obj) { return true; }
6      if(obj == null || this.getClass() != obj.getClass()) { return false; }
7      Person other = (Person) obj;
8      return
9           this.weight == other.weight
10       && this.height == other.height
11       && this.firstName.equals(other.firstName)
12       && this.lastName.equals(other.lastName);
13   }
14 }
```

Q: At **L6**, will we get a ***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()`.

Equality (6.2)

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

```
1  public class Person {
2    private String firstName; private String lastName;
3    private double weight; private double height;
4    public boolean equals(Object obj) {
5      if(this == obj) { return true; }
6      if(obj == null || this.getClass() != obj.getClass()) { return false; }
7      Person other = (Person) obj;
8      return
9           this.weight == other.weight
10       && this.height == other.height
11       && this.firstName.equals(other.firstName)
12       && this.lastName.equals(other.lastName);
13   }
14 }
```

Q: At **L6**, if swapping the order of two operands of disjunction:

`this.getClass() != obj.getClass() || obj == null`

Will we get a ***NullPointerException*** if `obj` is `null`?

A: ***Yes*** ∵ Evaluation of operands is from left to right.

Equality (6.3)

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

```
1  public class Person {
2    private String firstName; private String lastName;
3    private double weight; private double height;
4    public boolean equals(Object obj) {
5      if(this == obj) { return true; }
6      if(obj == null || this.getClass() != obj.getClass()) { return false; }
7      Person other = (Person) obj;
8      return
9           this.weight == other.weight
10       && this.height == other.height
11       && this.firstName.equals(other.firstName)
12       && this.lastName.equals(other.lastName);
13   }
14 }
```

Q: At **L11 & L12**, where is the `equals` method defined?

A: The `equals` method ***overridden*** in the `String` class.

When implementing the `equals` method for your own class, ***reuse*** the `equals` methods ***overridden*** in other classes wherever possible.

Equality (6.4)

Person collectors are equal if containing equal lists of persons.

```
class PersonCollector {
 private Person[] persons;
 private int nop; /* number of persons */
 public PersonCollector() { ... }
 public void addPerson(Person p) { ... }
 public int getNop() { return this.nop; }
 public Person[] getPersons() { ... }
}
```

Redefine/Override the `equals` method in `PersonCollector`.

```
public boolean equals(Object obj) {
 if(this == obj) { return true; }
 if(obj == null || this.getClass() != obj.getClass()) { return false; }
 PersonCollector other = (PersonCollector) obj;
 boolean equal = false;
 if(this.nop == other.nop) {
  equal = true;
  for(int i = 0; equal && i < this.nop; i ++) {
   equal = this.persons[i].equals(other.persons[i]);
  }
 }
 return equal;
}
```


Equality in JUnit (3)

```
@Test
public void testPersonCollector() {
 Person p1 = new Person("A", "a", 180, 1.8);
 Person p2 = new Person("A", "a", 180, 1.8);
 Person p3 = new Person("B", "b", 200, 2.1);
 Person p4 = p3;
 assertFalse(p1 == p2); assertTrue(p1.equals(p2));
 assertTrue(p3 == p4); assertTrue(p3.equals(p4));
 PersonCollector pc1 = new PersonCollector();
 PersonCollector pc2 = new PersonCollector();
 assertFalse(pc1 == pc2); assertTrue(pc1.equals(pc2));
 pc1.addPerson(p1);
 assertFalse(pc1.equals(pc2));
 pc2.addPerson(p2);
 assertFalse(pc1.getPersons()[0] == pc2.getPersons()[0]);
 assertTrue(pc1.getPersons()[0].equals(pc2.getPersons()[0]));
 assertTrue(pc1.equals(pc2));
 pc1.addPerson(p3);
 pc2.addPerson(p4);
 assertTrue(pc1.getPersons()[1] == pc2.getPersons()[1]);
 assertTrue(pc1.getPersons()[1].equals(pc2.getPersons()[1]));
 assertTrue(pc1.equals(pc2));
 pc1.addPerson(new Person("A", "a", 175, 1.75));
 pc2.addPerson(new Person("A", "a", 165, 1.55));
 assertFalse(pc1.getPersons()[2] == pc2.getPersons()[2]);
 assertFalse(pc1.getPersons()[2].equals(pc2.getPersons()[2]));
 assertFalse(pc1.equals(pc2));
}
```


Beyond this lecture...

- Play with the source code `ExampleEqualityPointsPersons.zip`

  Tip. Use the debugger to step into executing the various versions of `equals` method.
- Go back to your Review Tutorial: Extend the `Product`, `Entry`, and `RefurbishedStore` classes by ***overridden*** versions of the `equals` method.

Index (1)

Index (2)

Inheritance

YORK UNIVERSITÉ UNIVERSITY

EECS2030 B & G: Advanced Object Oriented Programming
Fall 2025

CHEN-WEI WANG

Index (3)

Learning Outcomes

This module is designed to help you learn about:

- Alternative designs to **inheritance**
- Using **inheritance** for code reuse
- ***Static Types***, Expectations, ***Dynamic Types***
- *Polymorphism*
  (variable assignments, method arguments & return values)
- *Dynamic Binding*
- ***Type Casting***

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.

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

```java
public class ResidentStudent {
  private String name;
  private Course[] courses; private int noc;
  private double premiumRate; /* assume a mutator for this */
  public ResidentStudent (String name) {
    this.name = name;
    this.courses = new Course[10];
  }
  public void register(Course c) {
    this.courses[this.noc] = c;
    this.noc ++;
  }
  public double getTuition() {
    double tuition = 0;
    for(int i = 0; i < this.noc; i ++) {
      tuition += this.courses[i].fee;
    }
    return tuition * this. premiumRate;
  }
}
```


No Inheritance: `NonResidentStudent` Class

```java
public class NonResidentStudent {
  private String name;
  private Course[] courses; private int noc;
  private double discountRate; /* assume a mutator for this */
  public NonResidentStudent (String name) {
    this.name = name;
    this.courses = new Course[10];
  }
  public void register(Course c) {
    this.courses[this.noc] = c;
    this.noc ++;
  }
  public double getTuition() {
    double tuition = 0;
    for(int i = 0; i < this.noc; i ++) {
      tuition += this.courses[i].fee;
    }
    return tuition * this. discountRate;
  }
}
```

No Inheritance: Testing Student Classes

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

```
public class StudentTester {
  public 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?
  Hint. Maintenance of code
- 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***.
  - This violates the so-called ***single-choice design principle***.

No Inheritance: Maintainability of Code (1)

What if the way for registering a course changes?

e.g.,

```
public void register(Course c) throws TooManyCoursesException {
  if (this.noc >= MAX_ALLOWANCE) {
    throw new TooManyCoursesException("Too many courses");
  }
  else {
    this.courses[this.noc] = c;
    this.noc ++;
  }
}
```

Changes needed for `register` method in ***both*** student classes!

No Inheritance: Maintainability of Code (2)

What if the way for calculating the base tuition changes?

e.g.,

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

Changes needed for `getTuition` method in ***both*** student classes!

No Inheritance: A Collection of Various Kinds of Students

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

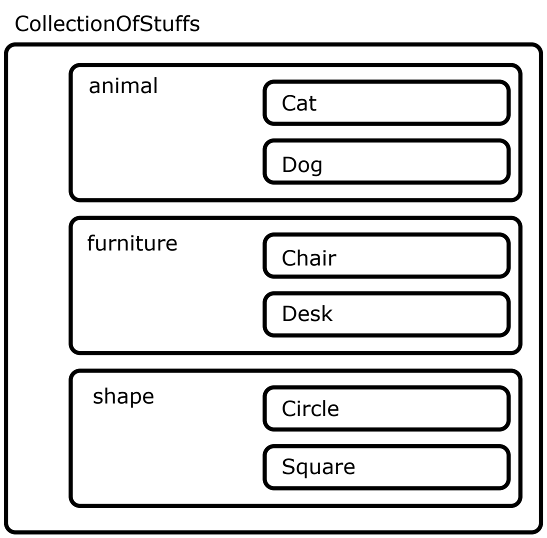
```
public class StudentManagementSystem {
  private ResidentStudent[] rss;
  private NonResidentStudent[] nrss;
  private int nors; /* number of resident students */
  private int nonrs; /* number of non-resident students */
  public void addRS(ResidentStudent rs){ rss[nors]=rs; nors++; }
  public void addNRS(NonResidentStudent nrs){ nrss[nonrs]=nrs;nonrs++; }
  public 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***!

a polymorphic collection of students

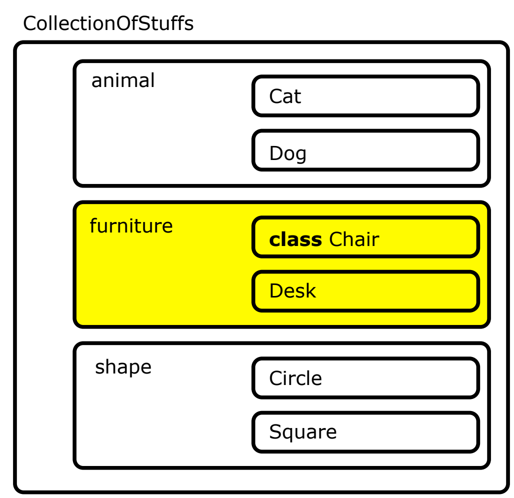
Visibility: Project, Packages, Classes



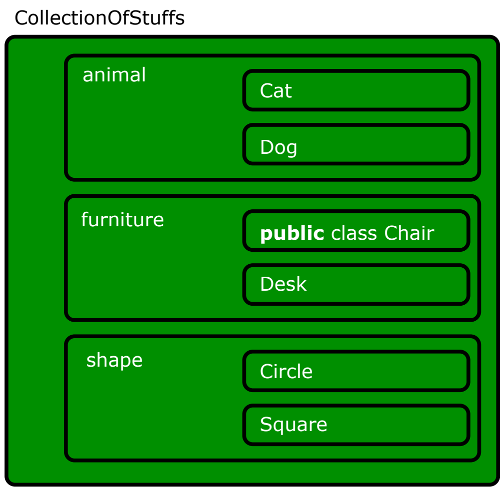
Visibility of Classes

- 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 residing package [no modifier]
     e.g., Declare **class** Chair { ... }
  2. Across packages [***public***]
     e.g., Declare ***public*** **class** Chair { ... }
- Consider class `Chair` which resides in:
  - package `furniture`
  - project `CollectionOfStuffs`

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



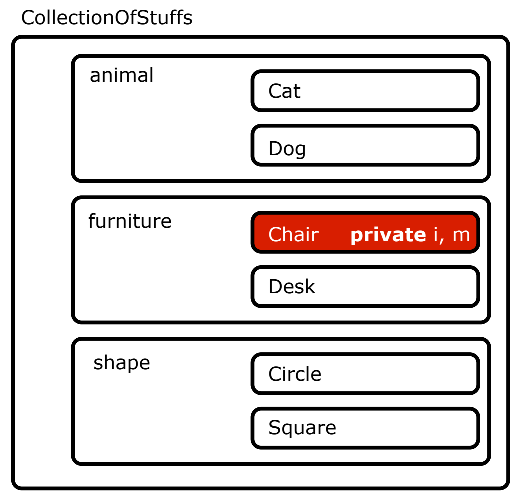
Visibility of Classes: Across All Classes Within the Resident Package (no modifier)



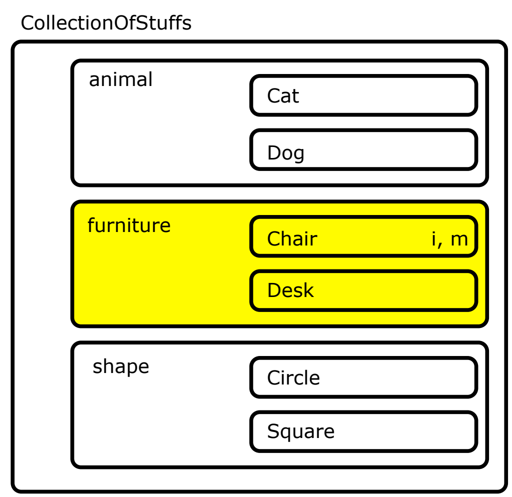
Visibility of Attributes/Methods: Using Modifiers to Define Scopes

- 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 residing class (***most*** restrictive) [***private***]
     e.g., Declare attribute `private int i;`
     e.g., Declare method `private void m(){};`
  2. Across classes within its residing package [no modifier]
     e.g., Declare attribute `int i;`
     e.g., Declare method `void m(){};`
  3. Across packages (***least*** restrictive) [***public***]
     e.g., Declare attribute `public int i;`
     e.g., Declare method `public void m(){};`
- Consider attributes `i` and `m` residing in:
  Class `Chair`; Package `furniture`; Project `CollectionOfStuffs`.

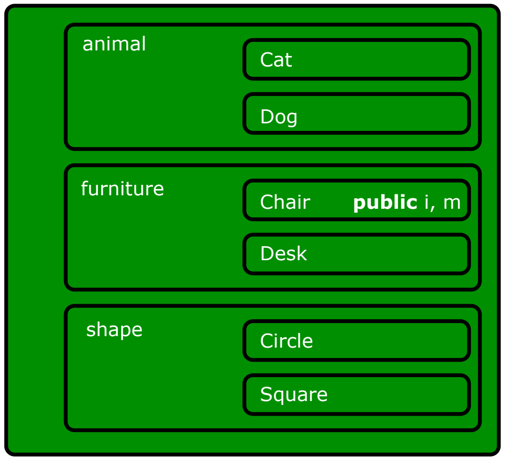
Visibility of Attr./Meth.: Across All Methods Within the Resident Class (private)



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`)

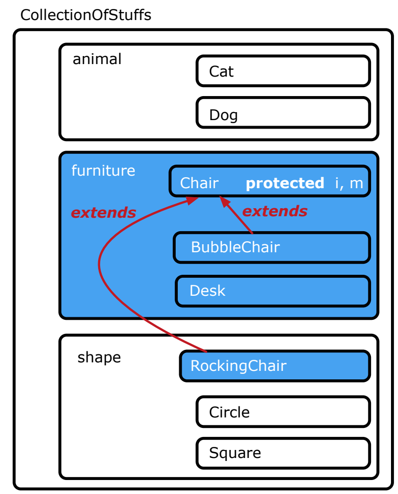


Use of the `protected` Modifier

- ***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

scope / modifier	CLASS	PACKAGE	SUBCLASS (same pkg)	SUBCLASS (different pkg)	NON-SUBCLASS (across Project)
`public`					
`protected`					
no modifier					
`private`					

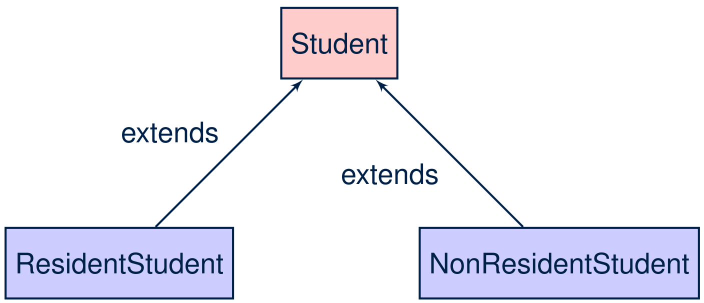
For the rest of this lecture, for simplicity, we assume that:

All relevant parent/child classes are in the same package .

⇒ Attributes with **no modifiers** (***package***-level visibility) suffice.

⇒ Methods with **no modifiers** (***package***-level visibility) suffice.

Inheritance Architecture



Inheritance: The `Student` Parent/Super Class

```
class Student {
  String name;
  Course[] courses; int noc;
  Student (String name) {
    this.name = name;
    this.courses = new Course[10];
  }
  void register(Course c) {
    this.courses[this.noc] = c;
    this.noc ++;
  }
  double getTuition() {
    double tuition = 0;
    for(int i = 0; i < this.noc; i ++) {
      tuition += this.courses[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 }
```

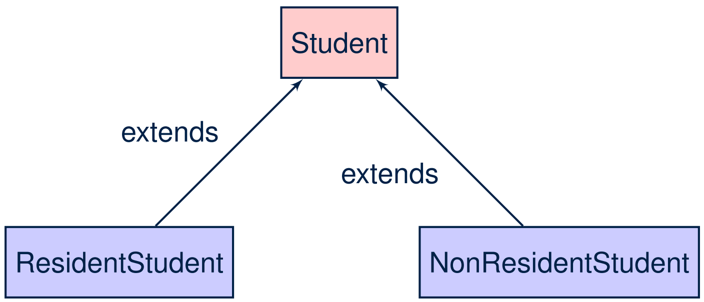
- **L1** declares that `ResidentStudent` inherits all attributes and methods (except constructors) from `Student`.
- There is no need to repeat the `register` method
- Use of *super* in **L3** is as if calling `Student(name)`
- Use of *super* in **L6** returns what `getTuition()` in `Student` returns.
- 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 **L3** is as if calling `Student(name)`
- Use of *super* in **L6** 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.

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`, `courses`, `noc`
    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`

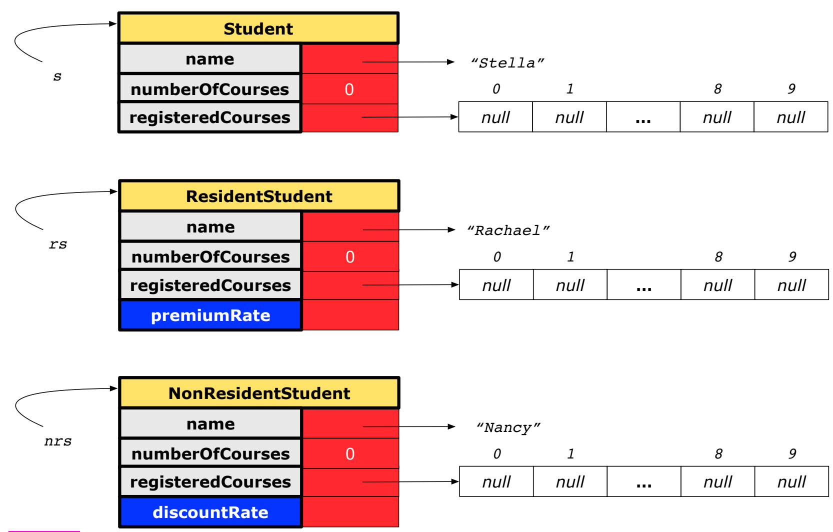
Visualizing Parent/Child Objects (1)

- A child class inherits ***all*** non-private 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)

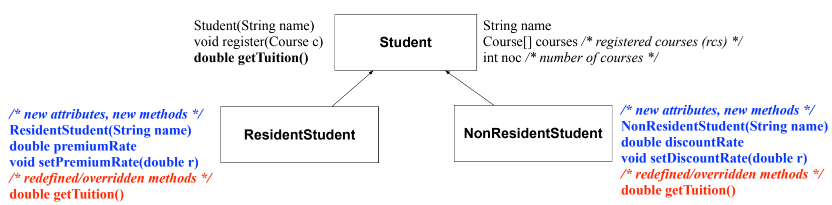


Testing the Two Student Sub-Classes

```
public class StudentTester {
  public 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 the exact same way as before (because we did not modify ***method headers***).
- But now the internal structure of code has been made ***maintainable*** using *inheritance*.

Inheritance Architecture: Static Types & Expectations




```
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>

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`]

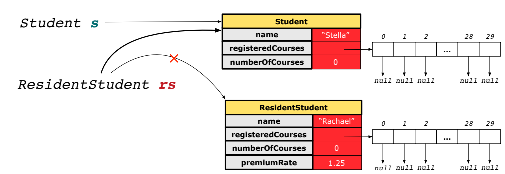
    ∴ The context object ***s*** is *expected* to be used as:
    - `s.register(eecs2030)` and `s.getTuition()`
  - **L2**: What *kind* of address can ***rs*** store? [`ResidentStudent`]

    ∴ 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*:



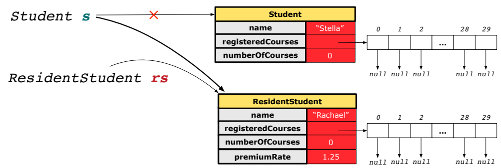
- Since ***rs*** is declared of type `ResidentStudent`, a subsequent call `rs.setPremiumRate(1.50)` can be expected.
- ***rs*** is now pointing to a `Student` object.
- Then, what would happen to `rs.setPremiumRate(1.50)`?

  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*:



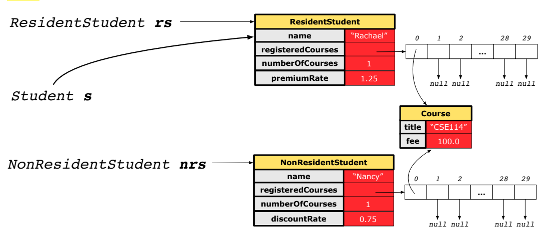
- Since *s* is declared of type `Student`, a subsequent call *`s.setPremiumRate(1.50)`* is *never* expected.
- *s* is now pointing to a `ResidentStudent` object.
- Then, what would happen to *`s.getTuition()`*?

  OK ∵ *s*`.premiumRate` is *never directly 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()); /* 125.0 */
8 s = nrs; System.out.println( s .getTuition()); /* 75.0 */
```

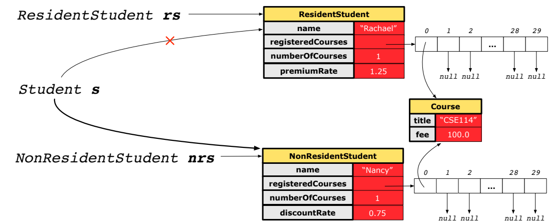
After `s = rs` (**L7**), `s` points to a `ResidentStudent` object.
⇒ Calling `s.getTuition()` applies the `premiumRate`.



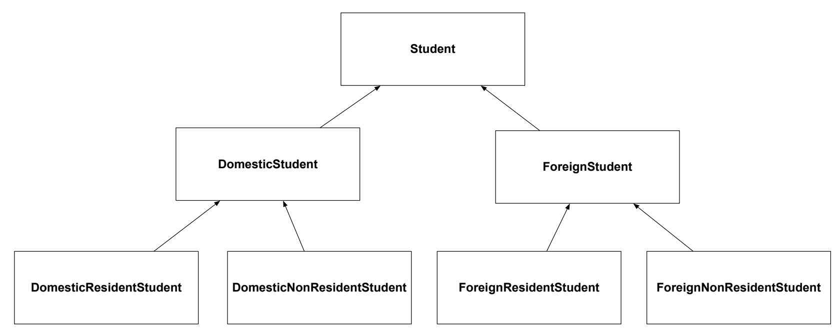
Dynamic Binding: Intuition (2)

```
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()); /* 125.0 */
8 s = nrs; System.out.println( s .getTuition()); /* 75.0 */
```

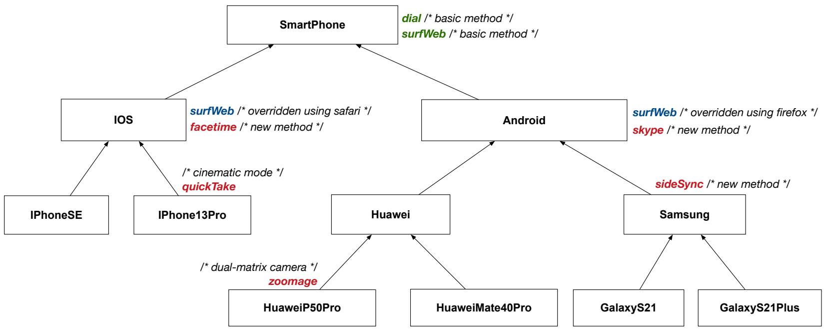
After `s = nrs` (**L8**), `s` points to a `NonResidentStudent` object.
⇒ Calling `s.getTuition()` applies the `discountRate`.



Multi-Level Inheritance Architecture



Multi-Level Inheritance Hierarchy: Smart Phones



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

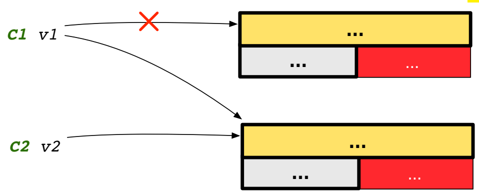
- The ***lower*** a class is in the type hierarchy, the ***more code*** it accumulates from its ***ancestor classes***:
  - A ***descendant class*** inherits all code from its ***ancestor classes***.
  - A ***descendant class*** may also:
    - Declare new attributes
    - Define new methods
    - *Redefine* / *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).
  - Given a ***reference variable***, expected to store the address of an object of a particular class, we may *substitute* it with (*re-assign* it to) an object of any of its ***descendant classes***.
  - e.g., When expecting a `SmartPhone` object, we may substitute it with either a `IPhone13Pro` or a `Samsung` object.
  - **Justification**: A ***descendant class*** contains *at least as many* methods as defined in its ***ancestor classes*** (but not vice versa!).

Static Types Determine Expectations

- 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* $\boxed{C}$ defines the *expected usages of v as a context object*.
- A method call `v.m(...)` is ***compilable*** if ***m*** is defined in $\boxed{C}$.
  - 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

When expecting an object of ***static type*** A:

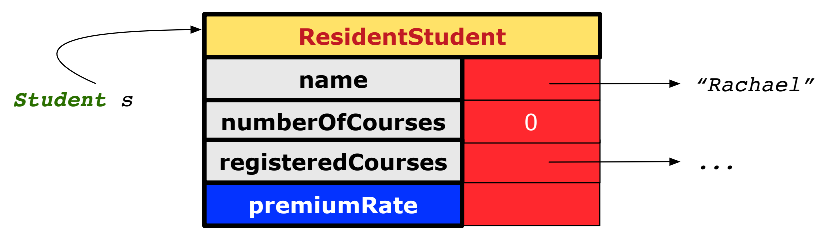
- It is ***safe*** to *substitute* it with an object whose ***static type*** is any of the *descendant class* of A (including A).
  - ∵ Each *descendant class* of A, being the new substitute, is guaranteed to contain all (non-private) attributes/methods defined in A.
  - e.g., When expecting an IOS phone, you ***can*** substitute it with either an IPhoneSE or IPhone13Pro.
- 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.
- It is also ***unsafe*** to *substitute* it with an object whose ***static type*** is neither an ancestor nor a descendant of A.
  - e.g., When expecting IOS phone, ***unsafe*** to substitute it with a HuaweiP50Pro ∵ 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., `jim = new NonResidentStudent(...)` changes the ***dynamic type*** of `jim` to `NonResidentStudent`.
- e.g., `ResidentStudent jeremy = new Student(...)` is illegal because `Studnet` is **not** a *descendant class* of the ***static type*** of `jeremy` (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(...);
```

  - `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`
  - `rs = jim` ×
  - `nrs = jim` ×

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 {...}
```

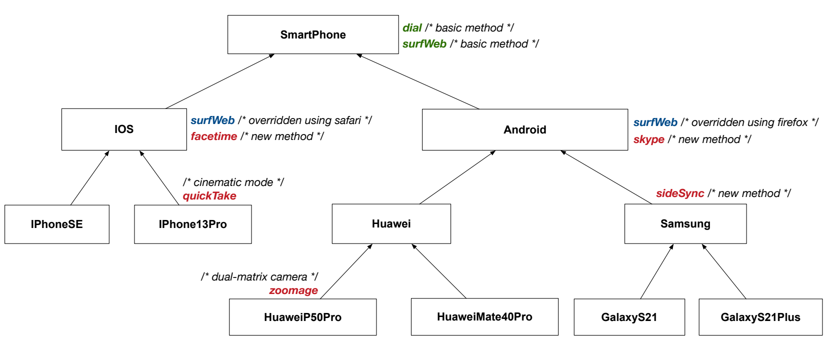
```
class StudentTester1 {
  public static void main(String[] args) {
    Student jim = new Student("J. Davis");
    ResidentStudent rs = new ResidentStudent("J. Davis");
    jim = rs;  /* legal */
    rs = jim;  /* illegal */

    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)

```
class SmartPhoneTest1 {
  public static void main(String[] args) {
    SmartPhone myPhone;
    IOS ip = new IPhoneSE();
    Samsung ss = new GalaxyS21Plus();
    myPhone = ip;  /* legal */
    myPhone = ss;  /* legal */

    IOS presentForHeeyeon;
    presentForHeeyeon = ip;  /* legal */
    presentForHeeyeon = ss;  /* illegal */
  }
}
```


Polymorphism and Dynamic Binding (3.3)

```
class SmartPhoneTest2 {
  public static void main(String[] args) {
    SmartPhone myPhone;
    IOS ip = new IPhone13Pro();
    myPhone = ip;
    myPhone. surfWeb ();  /* version of surfWeb in IPhone13Pro */

    Samsung ss = new GalaxyS21();
    myPhone = ss;
    myPhone. surfWeb ();  /* version of surfWeb in GalaxyS21 */
  }
}
```

Reference Type Casting: Motivation (1.1)

```
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;`
  - The cast (***ResidentStudent***) jim creates for `jim` ***a temporary alias*** whose ***ST*** corresponds to the ***cast type*** (***ResidentStudent***).
  - Alias `rs` of ***ST*** **`ResidentStudent`** is then created via an assignment. **Note**. `jim`'s ***ST*** always remains **`Student`**.
- *dynamic binding* : After the *cast* , **L3** will execute the correct version of `setPremiumRate` (∵ ***DT*** of `rs` is ***`ResidentStudent`***).

Reference Type Casting: Motivation (1.2)

$$\overbrace{ResidentStudent\ \ rs}^{\texttt{ST: ResidentStudent}}\ \overbrace{=}^{\texttt{valid substitution}}\ \underbrace{(\texttt{ResidentStudent})\ \ \overbrace{jim}^{\texttt{ST: Student}}}_{\texttt{an alias whose ST is ResidentStudent}}\ ;$$

- Variable `rs` is declared of ***static type*** (***ST***) `ResidentStudent`.
- Variable `jim` is declared of ***ST*** `Student`.
- The cast (***ResidentStudent***) jim creates for `jim` a **temporary alias**, whose ***ST*** corresponds to the ***cast type*** (`ResidentStudent`).

  ⇒ Such a cast makes the assignment valid.

  ∵ RHS's ***ST*** (`ResidentStudent`) is a descendant of LHS's ***ST*** (`ResidentStudent`).

  ⇒ The assignment creates an alias `rs` with ***ST*** `ResidentStudent`.
- **No** new object is created.

  Only an ***alias*** `rs` with a different ***ST*** (`ResidentStudent`) is created.
- After the assignment, `jim`'s ***ST*** **remains** `Student`.

Reference Type Casting: Motivation (2.1)

```
1 SmartPhone aPhone = new IPhone13Pro();
2 IPhone13Pro forHeeyeon = aPhone;
3 forHeeyeon.facetime(1.5);
```

- **L1** is *legal*: `IPhone13Pro` 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., `IPhone13Pro`).

  Java compiler is *unable to infer* that `aPhone`'s ***dynamic type*** in **L2** is `IPhone13Pro`!
- Force the Java compiler to believe so via a cast in **L2**:

  `IPhone13Pro forHeeyeon = (IPhone13Pro) aPhone;`
  - The cast (***IPhone13Pro***) aPhone creates for `aPhone` ***a temporary alias*** whose ***ST*** corresponds to the ***cast type*** (***IPhone13Pro***).
  - Alias `forHeeyeon` of ***ST*** **`IPhone13Pro`** is then created via an assignment. **Note**. `aPhone`'s ***ST*** always remains **`SmartPhone`**.
- *dynamic binding* : After the *cast* , **L3** will execute the correct version of `facetime` (∵ ***DT*** of `forHeeyeon` is ***`IPhone13Pro`***).

Reference Type Casting: Motivation (2.2)

$$\overbrace{IPhone13Pro\ \ forHeeyeon}^{\texttt{ST: IPhone13Pro}}\ \overbrace{=}^{\texttt{valid substitution}}\ \underbrace{(\texttt{IPhone13Pro})\ \ \overbrace{aPhone}^{\texttt{ST: SmartPhone}}}_{\texttt{an alias whose ST is IPhone13Pro}}\ ;$$

- Variable `forHeeyeon` is declared of ***static type*** (***ST***) `IPhone13Pro`.
- Variable `aPhone` is declared of ***ST*** `SmartPhone`.
- The cast (***IPhone13Pro***) aPhone creates for `aPhone` a **temporary alias**, whose ***ST*** corresponds to the ***cast type*** (`IPhone13Pro`).

  ⇒ Such a cast makes the assignment valid.

  ∵ RHS's ***ST*** (`IPhone13Pro`) is a descendant of LHS's ***ST*** (`IPhone13Pro`).

  ⇒ The assignment creates an alias `forHeeyeon` with ***ST*** `IPhone13Pro`.
- **No** new object is created.

  Only an ***alias*** `forHeeyeon` with a different ***ST*** (`IPhone13Pro`) is created.
- After the assignment, `aPhone`'s ***ST*** **remains** `SmartPhone`.

Type Cast: Named or Anonymous

Named Cast: Use intermediate variable to store the cast result.

```
SmartPhone aPhone = new IPhone13Pro();
IOS forHeeyeon = (IPhone13Pro) aPhone;
forHeeyeon.facetime();
```

Anonymous Cast: Use the cast result directly.

```
SmartPhone aPhone = new IPhone13Pro();
((IPhone13Pro) aPhone).facetime();
```

Common Mistake:

```
1 SmartPhone aPhone = new IPhone13Pro();
2 (IPhone13Pro) aPhone.facetime();
```

L2 ≡ `(IPhone13Pro) (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)

- 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* creates for v an alias with ***ST*** *C*.

  ⇒ All methods that are defined in *C* can be called.

```
Android myPhone = new GalaxyS21Plus();
/* 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 × */
GalaxyS21Plus ga = (GalaxyS21Plus) myPhone;
/* Compiles OK ∵ GalaxyS21Plus is a descendant class of Android
 * expectations on ga widened to methods in GalaxyS21Plus
 * ga.dial, ga.surfweb, ga.skype, ga.sideSync ✓ */
```


Reference Type Casting: Danger (1)

```
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)

```
1 SmartPhone aPhone = new GalaxyS21Plus();
2 IPhone13Pro forHeeyeon = (IPhone13Pro) aPhone;
3 forHeeyeon.quickTake();
```

- **L1** is *legal*: `GalaxyS21Plus` 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 (`IPhone13Pro`).
- **L3** is *legal* ∵ `quickTake` is in `forHeeyeon`' ***ST*** `IPhone13Pro`.
- Java compiler is *unable to infer* that `aPhone`'s *dynamic type* in **L2** is actually `GalaxyS21Plus`.
- Executing **L2** will result in a *`ClassCastException`*.

  ∵ Methods `facetime`, `quickTake` (expected from an ***IPhone13Pro***) is *undefined* on the ***GalaxyS21Plus*** 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 GalaxyS21Plus ga = (GalaxyS21Plus) myPhone;
4 /* Compiles OK ∵ GalaxyS21Plus is a descendant class of SmartPhone
5  * can now call methods declared in GalaxyS21Plus 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* `GalaxyS21Plus` (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 IPhone13Pro ip = (IPhone13Pro) myPhone;
4 /* Compiles OK ∵ IPhone13Pro is a descendant class of SmartPhone
5  * can now call methods declared in IPhone13Pro on ip
6  * ip.dial, ip.surfweb, ip.facetime, ip.quickTake ✓ */
```

- Type cast in **L3** is *compilable*.
- Executing **L3** will cause *`ClassCastException`*.

  L3: `myPhone`'s *DT* `Samsung` cannot meet expectations of the temporary *ST* `IPhone13Pro` (e.g., `quickTake`).

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 ***Android*** myPhone = new ***Samsung***();

- Cast `myPhone` to a class along the **ancestor path** of its ***DT Samsung***.
- Casting `myPhone` to a class with more expectations than its ***DT Samsung*** (e.g., `GalaxyS21Plus`) will cause `ClassCastException`.
- Casting `myPhone` to a class irrelevant to its ***DT Samsung*** (e.g., `HuaweiMate40Pro`) will cause `ClassCastException`.

Required Reading: Static Types, Dynamic Types, Casts

https://www.eecs.yorku.ca/~jackie/teaching/lectures/2025/F/EECS2030/notes/EECS2030_F25_Notes_Static_Types_Cast.pdf

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 ***DT*** is a descendant of `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 ***ST*** (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 GalaxyS21Plus();
2 if (aPhone instanceof IPhone13Pro ) {
3   IOS forHeeyeon = ( IPhone13Pro ) aPhone;
4   forHeeyeon.facetime();
5 }
```

- **L1** is *legal*: `GalaxyS21Plus` is a **descendant class** of the static type of `aPhone` (i.e., `SmartPhone`).
- **L2** checks if `aPhone`'s ***DT*** is a descendant of `IPhone13Pro`.
  FALSE ∵ `aPhone`'s *dynamic type* is `GalaxyS21Plus`!
- **L3** is *legal*: `aPhone`'s cast type (i.e., `IPhone13Pro`) 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` (so that `(C) v` is safe).

```
SmartPhone myPhone = new Samsung();
println(myPhone instanceof Android);
/* true ∵ Samsung is a descendant of Android */
println(myPhone instanceof Samsung);
/* true ∵ Samsung is a descendant of Samsung */
println(myPhone instanceof GalaxyS21);
/* false ∵ Samsung is not a descendant of GalaxyS21 */
println(myPhone instanceof IOS);
/* false ∵ Samsung is not a descendant of IOS */
println(myPhone instanceof IPhone13Pro);
/* false ∵ Samsung is not a descendant of IPhone13Pro */
```

⇒ ***Samsung*** is the most specific type which `myPhone` can be **safely** cast to.

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 GalaxyS21Plus) {
7    GalaxyS21Plus galaxy = (GalaxyS21Plus) myPhone;
8  }
9  if(myphone instanceof HuaweiMate40Pro) {
10   Huawei hw = (HuaweiMate40Pro) 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 Types, Casts, Polymorphism (1.1)

```
class SmartPhone {
  void dial() { ... }
}
class IOS extends SmartPhone {
  void facetime() { ... }
}
class IPhone13Pro extends IOS {
  void quickTake() { ... }
}
```

```
SmartPhone sp = new IPhone13Pro();   ✓
sp.dial();   ✓
sp.facetime();   ×
sp.quickTake();   ×
```

Static type of *sp* is `SmartPhone`

⇒ can only call methods defined in `SmartPhone` on *sp*

Static Types, Casts, Polymorphism (1.2)

```
class SmartPhone {
  void dial() { ... }
}
class IOS extends SmartPhone {
  void facetime() { ... }
}
class IPhone13Pro extends IOS {
  void quickTake() { ... }
}
```

```
IOS ip = new IPhone13Pro();   ✓
ip.dial();   ✓
ip.facetime();   ✓
ip.quickTake();   ×
```

Static type of *ip* is `IOS`

⇒ can only call methods defined in `IOS` on *ip*

Static Types, Casts, Polymorphism (1.3)

```
class SmartPhone {
  void dial() { ... }
}
class IOS extends SmartPhone {
  void facetime() { ... }
}
class IPhone13Pro extends IOS {
  void quickTake() { ... }
}
```

```
IPhone13Pro ip6sp = new IPhone13Pro();   ✓
ip6sp.dial();   ✓
ip6sp.facetime();   ✓
ip6sp.quickTake();   ✓
```

Static type of *ip6sp* is `IPhone13Pro`

⇒ can call all methods defined in `IPhone13Pro` on *ip6sp*

Static Types, Casts, Polymorphism (1.4)

```
class SmartPhone {
  void dial() { ... }
}
class IOS extends SmartPhone {
  void facetime() { ... }
}
class IPhone13Pro extends IOS {
  void quickTake() { ... }
}
```

```
1 SmartPhone sp = new IPhone13Pro();  ✓
2 ( (IPhone13Pro) sp).dial();  ✓
3 ( (IPhone13Pro) sp).facetime();  ✓
4 ( (IPhone13Pro) sp).quickTake();  ✓
```

L4 is equivalent to the following two lines:

```
IPhone13Pro ip6sp = (IPhone13Pro) sp;
ip6sp.quickTake();
```


Static Types, Casts, 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 Parameters (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`:
  - `sms.addRS(o)` attempts the following assignment (recall call by value), 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 Parameters (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 Parameters (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 Parameters (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 Parameters (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 Parameters (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`).

Why Inheritance: A Polymorphic Collection 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)
    }
  }
}
```

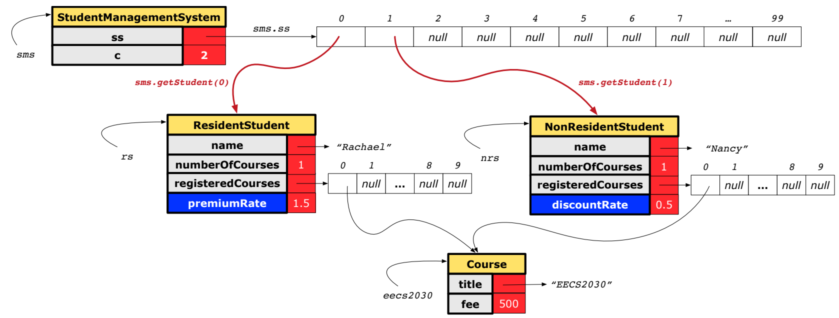

Polymorphism and Dynamic Binding: A Polymorphic Collection of Students (1)

```
ResidentStudent rs = new ResidentStudent("Rachael");
rs.setPremiumRate(1.5);
NonResidentStudent nrs = new NonResidentStudent("Nancy");
nrs.setDiscountRate(0.5);
StudentManagementSystem sms = new StudentManagementSystem();
sms.addStudent( rs ); /* polymorphism */
sms.addStudent( nrs ); /* 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() );
}
```


Polymorphism and Dynamic Binding: A Polymorphic Collection of Students (2)

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***



Polymorphism: Return Types (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 InvalidStudentIndexException("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`.

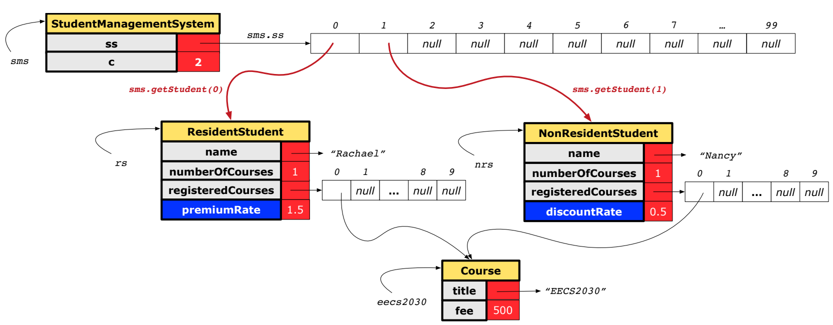
Polymorphism: Return Types (2)

```
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 Types (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***



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***!

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); }
```

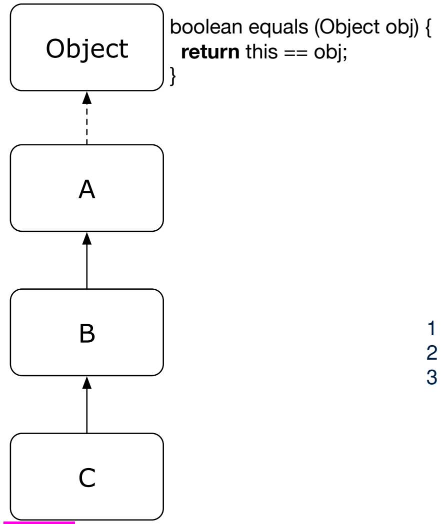
  - `String toString()`
    Returns a string representation of the object.
- Very often when you define new classes, you want to *redefine* / *override* the inherited definitions of `equals` and `toString`.

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)

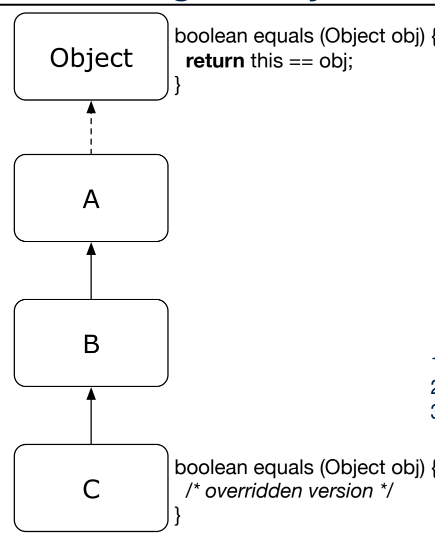



```
class A {
  /*equals not overridden*/
}
class B extends A {
  /*equals not overridden*/
}
class C extends B {
  /*equals not overridden*/
}
```

```
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)

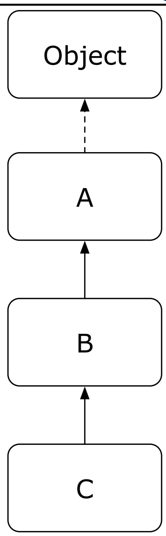



```
class A {
  /*equals not overridden*/
}
class B extends A {
  /*equals not overridden*/
}
class C extends B {
  boolean equals(Object obj) {
    /* overridden version */
  }
}
```

```
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)



boolean equals (Object obj) {
  return this == obj;
}

boolean equals (Object obj) {
  / overridden version */*
}

```java
class A {
  /*equals not overridden*/
}
class B extends A {
  boolean equals(Object obj) {
    /* overridden version */
  }
}
class C extends B {
  /*equals not overridden*/
}
```

```java
1 Object c1 = new C();
2 Object c2 = new C();
3 println(c1.equals(c2));
```

L3 calls which version of `equals`? [`B`]

Behaviour of Inherited `toString` Method (1)

```java
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)

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

After redefining/overriding the `toString` method:

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

```
(2, 4)
```


Behaviour of Inherited `toString` Method (3)

Exercise: Override the `equals` and `toString` methods for the `ResidentStudent` and `NonResidentStudent` classes.

Beyond this lecture...

- Implement the ***inheritance hierarchy*** of **Students** and reproduce all lecture examples.
- Implement the ***inheritance hierarchy*** of **Smart Phones** and reproduce all lecture examples.
  Hints. Pay attention to:
  - *Valid*? *Compiles*?
  - *ClassCastException*?
- Study the `ExampleTypeCasts` example: draw the ***inheritance hierarchy*** and experiment with the various substitutions and casts.

Index (1)

Index (2)

Index (3)

Index (4)

Index (5)

Index (6)

Index (7)

Index (8)

Index (9)

Index (10)

Index (11)

Recursion

EECS2030 B & G: Advanced Object Oriented Programming
Fall 2025

CHEN-WEI WANG

YORK UNIVERSITÉ UNIVERSITY

Learning Outcomes

This module is designed to help you learn about:

1. How to solve problems ***recursively***
2. Example ***recursions*** on string and arrays
3. Some more advanced example (if time permitted)

Beyond this lecture . . .

- 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/`

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:

```
m (i) {
  if(i == ...) { /* base case: do something directly */ }
  else {
    m (j);/* recursive call with strictly smaller value */
  }
}
```

  - 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 $j < i$.

Tracing Method Calls via 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: 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;
}
```


Common Errors of Recursive Methods

- Missing Base Case(s).

```
int factorial (int n) {
  return n * factorial (n - 1);
}
```

Base case(s) are meant as points of stopping growing the runtime stack.

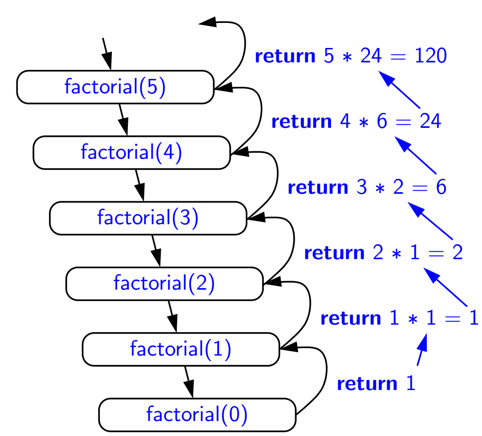
- Recursive Calls on Non-Smaller Problem Instances.

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

Recursive calls on ***strictly smaller*** problem instances are meant for moving gradually towards the base case(s).

- In both cases, a `StackOverflowException` will be thrown.

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]

Recursion: Fibonacci Sequence (1)

- Can you identify the pattern of a Fibonacci sequence?

$$F = 1, 1, 2, 3, 5, 8, 13, 21, 34, 55, 89, \ldots$$

- Here is the formal, ***recursive*** definition of calculating the n_{th} number in a Fibonacci sequence (denoted as F_n):

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

```
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 Sequence (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.

```java
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 **2)** and **1)**.

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);
    }
  }
}
```


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) {
  if(a.length == 0) { /* base case */ }
  else if(a.length == 1) { /* base case */ }
  else {
    int[] sub = new int[a.length - 1];
    for(int i = 1; i < a.length; i ++) { sub[i - 1] = a[i]; }
    m(sub) } }
```

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

```
void m(int[] a, int from, int to) {
  if(from > to) { /* base case */ }
  else 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, a.length-1, a.length-1)` [Last r.c. on array of size 1]

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

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.

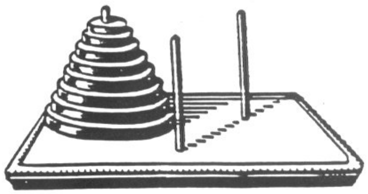
```
System.out.println(isSorted({}));  true

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 order* .

Recursion: Is an Array Sorted? (2)

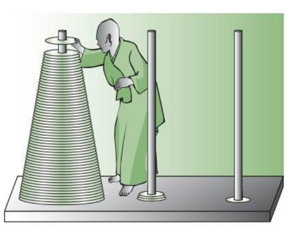
```
boolean isSorted(int[] a) {
  return isSortedHelper (a, 0, a.length - 1);
}

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);
  }
}
```

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: Lengend



*Brahmins at a temple in Benares, India have been carrying out movement of "Sacred Tower of Brahma", consisting of **sixty-four** golden disks, according to the same rules as in the Tower of Hanoi game, and that the completion of the tower would lead to the end of the world.*

Tower of Hanoi: A Recursive Solution

The general, a recursive solution requires 3 steps:

1. Transfer the **n - 1** **smallest** disks to a ***second*** peg.
2. Move the **largest** peg to the ***third*** peg (free of disks).
3. Transfer the **n - 1** **smallest** disks back onto the **largest** disk.

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 ori, int des){
  if(from > to) { }
  else if(from == to) {
    print("move " + disks[to] + " from " + ori + " to " + des);
  }
  else {
    int intermediate = 6 - ori - des;
    tohHelper(disks, from, to - 1, ori, intermediate);
    print("move " + disks[to] + " from " + ori + " to " + des);
    tohHelper(disks, from, to - 1, intermediate, des);
  }
}
```

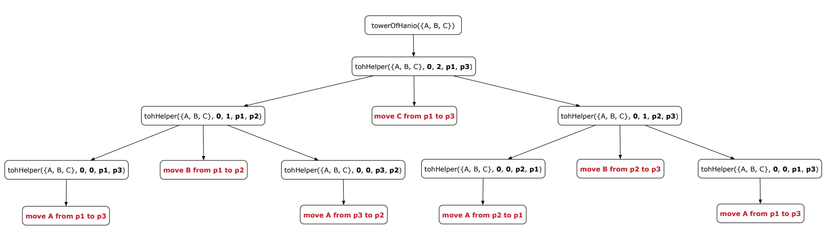
- `tohHelper(disks, from, to, ori, des)` moves disks $\{disks[from], disks[from+1], \ldots, disks[to]\}$ from peg *ori* to peg *des*.
- Peg id's are 1, 2, and 3 ⇒ The intermediate one is 6 − *ori* − *des*.

Tower of Hanoi in Java (2)

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

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

Tower of Hanoi in Java (3)



Running Time: Tower of Hanoi (1)

- Generalize the problem by considering **n** disks.
- Let ***T(n)*** denote the number of moves required to to transfer **n** disks from one to another under the rules.
- Recall the general solution pattern:
  1. Transfer the **n - 1** **smallest** disks to a ***second*** peg.
  2. Move the **largest** peg to the ***third*** peg (free of disks).
  3. Transfer the **n - 1** **smallest** disks back onto the **largest** disk.
- We end up with the following recurrence relation that allows us to compute ***T(n)*** for any **n** we like:

$$
\begin{cases} T(1) &= 1 \\ T(n) &= 2 \cdot T(n-1) + 1 \quad \text{where } n > 0 \end{cases}
$$

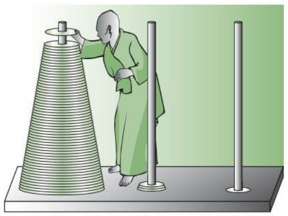
- To solve this recurrence relation, we study the pattern of ***T(n)*** and observe how it reaches the ***base case(s)***.

Running Time: Tower of Hanoi (2)

$$
\begin{aligned}
T(n) &= \underbrace{2}_{1 \text{ term}} \times T(n-1) + \underbrace{1}_{1 \text{ term}} \\
&= \underbrace{2 \times (2}_{2 \text{ terms}} \times T(n-2) + \underbrace{1) + 1}_{2 \text{ terms}} \\
&= \underbrace{2 \times (2 \times (2}_{3 \text{ terms}} \times T(n-3) + \underbrace{1) + 1) + 1}_{3 \text{ terms}} \\
&= \ldots \\
&= \underbrace{2 \times (2 \times (2 \times (\cdots \times (2 \times}_{n-1 \text{ terms}} \overbrace{T(1)}^{T(n-(n-1))} \underbrace{+ 1) + \ldots) + 1) + 1) + 1}_{n-1 \text{ terms}} \\
&= 2^{n-1} + (n-1)
\end{aligned}
$$

$\therefore$ ***T(n)*** is ***O(2^n)***

Tower of Hanoi: Lengend



Brahmins at a temple in Benares, India have been carrying out movement of "Sacred Tower of Brahma", consisting of ***sixty-four*** *golden disks, according to the same rules as in the Tower of Hanoi game, and that the completion of the tower would lead to the end of the world.*

Say one disk can be moved in one second.

Q. How long does it take to finish moving 64 disks ($n = 64$)?

A. 2^{64} seconds $\approx$ 585 billion years (>> 5 billion centries)!

Beyond this lecture ...

- Recursions on Arrays: Lab Exercise from EECS2030-F19
- Notes on Recursion:
  http://www.eecs.yorku.ca/~jackie/teaching/lectures/2025/F/EECS2030/notes/EECS2030_F25_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/

Index (1)

Index (2)

Index (3)

Wrap-Up

EECS2030 B & G: Advanced Object Oriented Programming
Fall 2025

CHEN-WEI WANG

What You Learned (1)

- ***Procedural Programming in Java***
  - Exceptions
  - Recursion (thinking, implementation, tracing)
- ***Data Structures***
  - Arrays

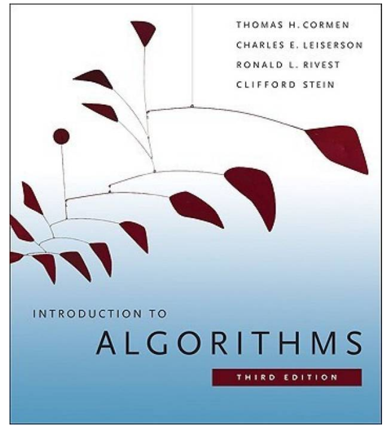
What You Learned (2)

- ***Object-Oriented Programming in Java***
  - classes, attributes, objects, reference data types
  - methods: constructors, accessors, mutators, helpers
  - dot notation, context objects
  - aliasing
  - inheritance:
    - code reuse, single-choice principle, cohesion
    - expectations
    - rules of substitutions
    - static vs. dynamic types
    - polymorphism, dynamic binding
    - polymorphic method parameters
    - polymorphic collections
    - polymorphic method return types
    - compilable casts, `ClassCastException`, `instanceof` checks
    - method overriding and dynamic binding: e.g., `equals`

What You Learned (3)

- ***Integrated Development Environment (IDE): Eclipse***
  - Break Point and Debugger
  - Unit Testing using JUnit
  - Test Driven Development (TDD), Regression Testing

Beyond this course. . . (1)



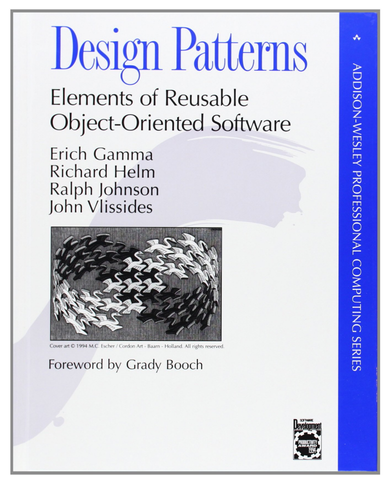
- *Introduction to Algorithms (3rd Ed.)* by Cormen, *etc.*
- DS by DS, Algo. by Algo.:
  - *Understand* math analysis
  - *Read* pseudo code
  - ***Translate*** into Java code
  - ***Write and pass*** JUnit tests

Optional Topics

`https://www.eecs.yorku.ca/~jackie/teaching/lectures/index.html#EECS2030_F21`

- ***Generics*** [Week 10 & 11]

Beyond this course. . . (2)



- *Design Patterns: Elements of Reusable Object-Oriented Software* by Gamma, *etc.*
- Pattern by Pattern:
  - ***Understand*** the problem
  - ***Read*** the solution (not in Java)
  - ***Translate*** into Java code
  - ***Write and pass*** JUnit tests

Wish You All the Best

- What you have learned will be **assumed** in `EECS2101`.
- Logic is your friend: Learn/Review `EECS1019/EECS1090`.
- Do **not** abandon Java during the break!!
- Feel free to get in touch and let me know how you're doing :D