Classes and Objects

EECS2030 B: Advanced Object Oriented Programming
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Tutorial Videos to Help You Review

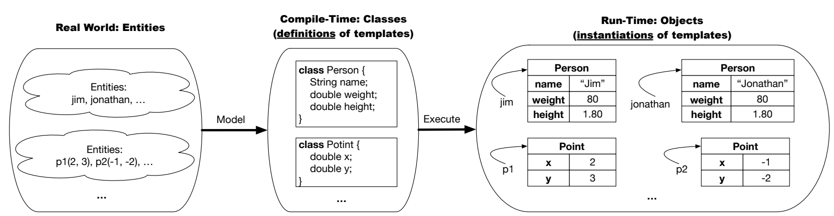
- **Link to Tutorial Series**: https://www.youtube.com/playlist?list=PL5dxAmCmjv_5NRNPG3OiWZWAqmvCjiLfG
  - **Videos 1 to 8**: Basics of Programming and **Eclipse**
  - **Videos 9 to 19**: Programming/Debugging **If-Statements**
  - **Videos 20 to 33**: Programming/Debugging **Arrays** and **Loops**
  - **Videos 34 to 38**: Basics of **Classes** and **Objects**
  - **Videos 39 to 46**: A Complete Example – `Student`, `Faculty`, `CourseRecord`, `StudentManagementSystem`
- **iPad Notes**: https://www.eecs.yorku.ca/~jackie/teaching/tutorials/notes/EECS1021%20Tutorial%20on%20Java.pdf

Separation of Concerns: App/Tester vs. Model

- In EECS1022:
  - *Model Component*: One or More Java Classes
    e.g., `Person` vs. `SMS`, `Student`, `CourseRecord`
  - Another Java class that "manipulates" the model class (by creating instances and calling methods):
    - *Controller* (e.g., `BMIActivity`, `BankActivity`). Effects? Visualized (via a GUI) at connected tablet
    - *Tester* with `main` (e.g., `PersonTester`, `BankTester`). Effects? Seen (as textual outputs) at console
- In Java:
  - We may define more than one *classes*.
  - Each class may contain more than one *methods*.

object-oriented programming in Java:
  - Use *classes* to define templates
  - Use *objects* to instantiate classes
  - At *runtime*, *create* objects and *call* methods on objects, to *simulate interactions* between real-life entities.

Object Orientation: Observe, Model, and Execute



- 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)

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

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

OO Thinking: Templates vs. Instances (1.2)

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

OO Thinking: Templates vs. Instances (2.1)

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

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

OO Thinking: Templates vs. Instances (2.2)

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

OO Thinking: Templates vs. Instances (3)

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

OOP: Classes ≈ Templates

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

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

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


OOP: Define Constructors for Creating Objects (1.1)

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

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

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

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

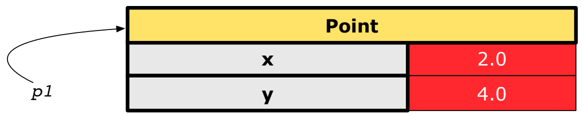
OOP: Define Constructors for Creating Objects (1.2)

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

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

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`.



OOP: Define Constructors for Creating Objects (2.1)

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

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

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

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

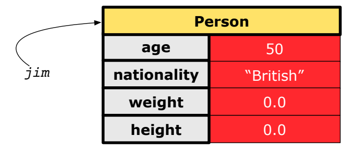

OOP: Define Constructors for Creating Objects (2.2)

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

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

Person	
age	50
nationality	"British"
weight	0.0
height	0.0

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



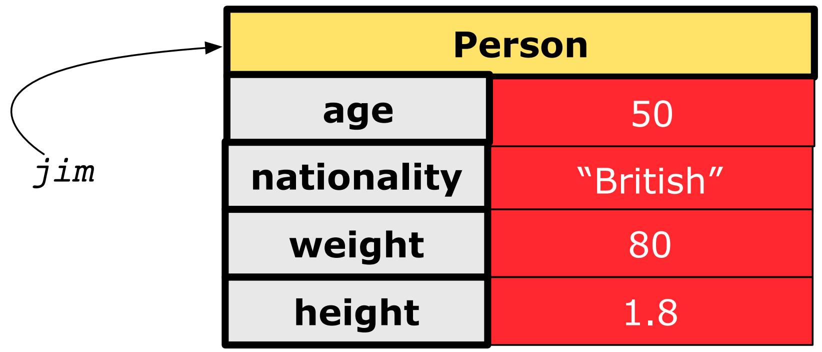
Visualizing Objects at Runtime (1)

- 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);
```

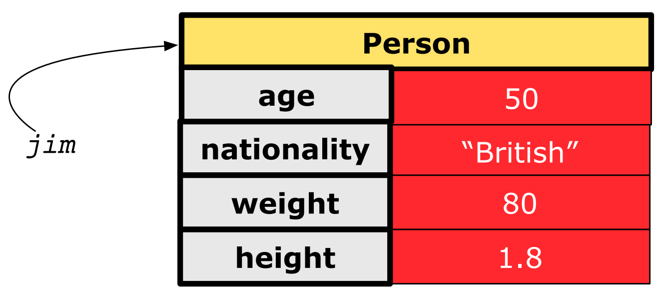


Visualizing Objects at Runtime (2.2)

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`.

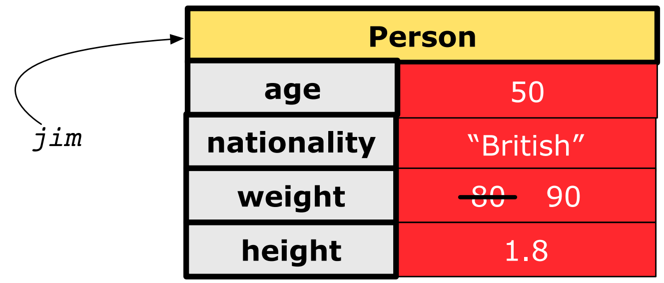


Visualizing Objects at Runtime (2.3)

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.
  $\Rightarrow$ `jim` points to the same object!

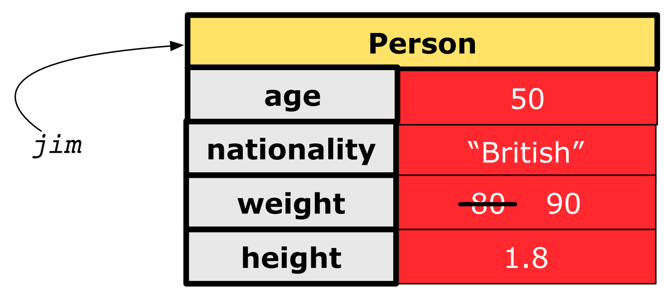


Visualizing Objects at Runtime (2.4)

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

```
bmi = p.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`.



The `this` Reference (1)

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

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

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

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

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

The `this` Reference (2)

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

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

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

The `this` Reference (3)

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

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

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

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


The `this` Reference (4)

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

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

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

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

The `this` Reference (5)

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

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


The `this` Reference (6.1): Common Error

The following code fragment compiles but is problematic:

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

Why? Fix?

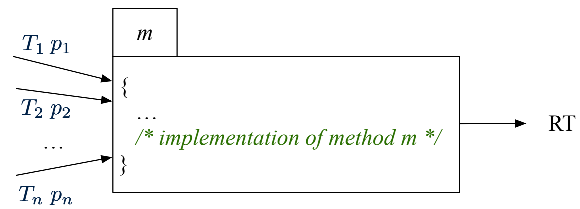
The `this` Reference (6.2): Common Error

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

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


OOP: Methods (1.1)

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



- The *header* of a method consists of: [see here]
  - 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 and use new *local variables*
    Scope of local variables is only within that method.
  - Use or change values of *attributes*.
  - Use values of *parameters*, if any.

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

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

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


OOP: Methods (2)

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

OOP: Methods (3)

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

OOP: The Dot Notation (1.1)

A binary operator:
- `LHS` stores an address (which denotes an object)
- `RHS` the name of an attribute or a method
- `LHS . RHS` means:
  Locate the context object whose address is stored in **LHS**, then apply `RHS`.
  What if `LHS` stores `null`? [`NullPointerException`]

OOP: The Dot Notation (1.2)

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

OOP: Method Calls

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

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

OOP: Class Constructors (1)

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

OOP: Class Constructors (2)

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

OOP: Class Constructors (3)

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

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

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


OOP: Class Constructors (4)

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

OOP: Object Creation (1)

```java
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:

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

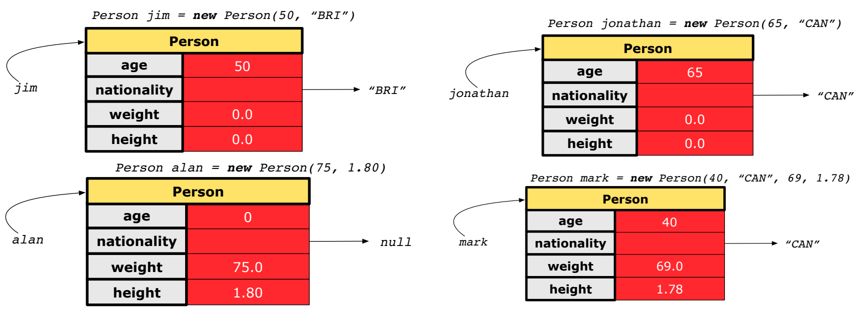
```
(2.0, 4.0)
```


OOP: Object Creation (2)

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

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

OOP: Object Creation (3)

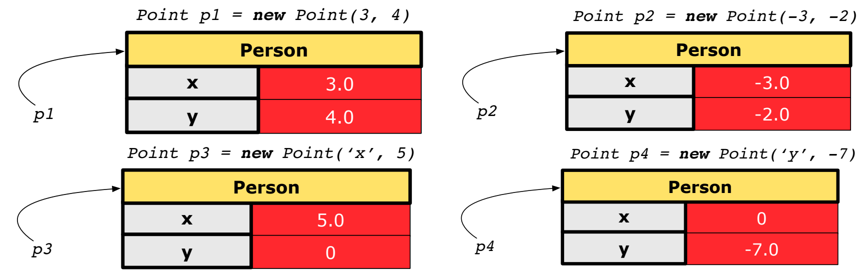


OOP: Object Creation (4)

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

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


OOP: Object Creation (5)



OOP: Object Creation (6)

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

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

OOP: Mutator Methods

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

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

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


OOP: Accessor Methods

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

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

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


OOP: Use of Mutator vs. Accessor Methods

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

OOP: Method Parameters

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

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

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

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

OOP: Object Alias (1)

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

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

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

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

OO Program Programming: Object Alias (2.1)

Problem: Consider assignments to *primitive* variables:

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


OO Program Programming: Object Alias (2.2)

Problem: Consider assignments to *reference* variables:

```
Person alan = new Person("Alan");
Person mark = new Person("Mark");
Person tom = new Person("Tom");
Person jim = new Person("Jim");
Person[] persons1 = {alan, mark, tom};
Person[] persons2 = new Person[persons1.length];
for(int i = 0; i < persons1.length; i ++) {
  persons2[i] = persons1[(i + 1) % persons1.length]; }
persons1[0].setAge(70);
System.out.println(jim.age);  /* 0 */
System.out.println(alan.age);  /* 70 */
System.out.println(persons2[0].age);  /* 0 */
persons1[0] = jim;
persons1[0].setAge(75);
System.out.println(jim.age);  /* 75 */
System.out.println(alan.age);  /* 70 */
System.out.println(persons2[0].age);  /* 0 */
```


OO Program Programming: Object Alias (3)

```
Person tom = new Person("TomCruise");
Person ethanHunt = tom;
Person spy = ethanHunt;
tom.setWeight(77);  print(tom.weight);  /* 77 */
ethanHunt.gainWeight(10);  print(tom.weight);  /* 87 */
spy.loseWeight(10);  print(tom.weight);  /* 77 */
Person prof = new Person("Jackie"); prof.setWeight(80);
spy = prof;  prof = tom;  tom = spy;
print(prof.name+" teaches 2030");/*TomCruise teaches 2030*/
print("EthanHunt is "+ethanHunt.name);/*EthanHunt is TomCruise*/
print("EthanHunt is "+spy.name);/*EthanHunt is Jackie*/
print("TomCruise is "+tom.name);/*TomCruise is Jackie*/
print("Jackie is "+prof.name);/*Jackie is TomCruise*/
```

- An *object* at runtime may have *more than one identities*. Its *address* may be stored in multiple *reference variables*.
- Calling a *method* on one of an object's identities has the *same effect* as calling the same method on any of its other identities.

Java Data Types (1)

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

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

Java Data Types (2)

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

Java Data Types (3.1)

- An attribute may store the reference to some object.

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

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

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

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

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


Java Data Types (3.2.1)

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

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

Required Reading: Point and PointCollector

Java Data Types (3.2.2)

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


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 <u>reused</u> (without recalculating) via the name `sqr`.
  - RHS: it is <u>not stored</u> 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)* denotes an object without a name reference.
  - 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 {
 Order[] orders;
 int noo;
 /* constructor ommitted */
 void addOrder(Order o) {
  orders[noo] = o;
  noo ++;
 }
 void addOrder(String n, double p, double q) {
  addOrder( new Order(n, p, q) );
  /* Equivalent implementation:
   * orders[noo] = new Order(n, p, q);
     noo ++; */
 }
}
```


Anonymous Objects (2.2)

One more example on using anonymous objects:

```
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) );
 }
}
```

Static Variables (1)

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

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

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

Static Variables (2)

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

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

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

Static Variables (3)

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

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

Static Variables (4.1): Common Error

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

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

Static Variables (4.2): Common Error

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

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


Static Variables (5.1): Common Error

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

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

Static Variables (5.2): Common Error

```
public class Bank {
  public string branchName;
  public static int nextAccountNumber = 1;
  public static void useAccountNumber() {
    System.out.println (branchName + ...);
    nextAccountNumber ++;
  }
}
```

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

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

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

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


Static Variables (5.3): Common Error

There are two possible ways to fix:

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

Non-Static Context vs. Static Context (1)

- A Recap of Rules:
  - Use of **static** variables in a **non-static** method is ***allowed***.
    e.g., `static int globalCounter` [see this slide]
  - Use if **non-static** variables in a **static** method is ***forbidden***.
    e.g., `String branchName` [see this slide]
- Principles of Judgement:
  - Using a **non-static** variable/method requires a *context object*.

```
Person jim = new Person(50, "British", 80, 1.8);
System.out.println("Jim's BMI: " + jim.getBMI());
```

  - To use a **static** variable/method, a *class name* is sufficient.

```
class Counter { static int gc = 1; /* global counter */ }
class CounterTester {
  static void main(String[] args) {
    System.out.println("Global value: " + Counter.gc);
  } }
```

  - Warning if accessing a **static** variable/method via a *context object*.

Non-Static Context vs. Static Context (2)

```
1  class MyClass {
2    int i; /* a non-static attribute */
3    static int si = 2; /* a static attribute */
4    void changeOne () { /* a non-static method */
5      i ++;
6      si ++;
7    }
8    static void changeTwo () { /* a static method */
9      i ++; /* Error: Use of non-static in static context.  */
10     si ++;
11   }
12 }
```

- Say we already created an object: `MyClass o = new MyClass()`
- **L5** & **L6** are *valid*.
  - Calling `o.changeOne()` means `o.i ++` and `o.si ++`
- **L9** is *invalid*.
  - Allowing `MyClass.changeTwo()` would allow `MyClass.i ++`.
  - But `MyClass.i ++` is *invalid* ∵ non-static `i` needs a context object

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Exceptions

EECS2030 B: Advanced Object Oriented Programming
Fall 2019

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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***.

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    Account(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`, printed from `Account.withdraw` to console.
  - However, impossible to stop `BankApplication.main` from continuing to executed **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

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*.

```
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 *signature* that it *can throw* the exception (without handling that exception).

```
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`.

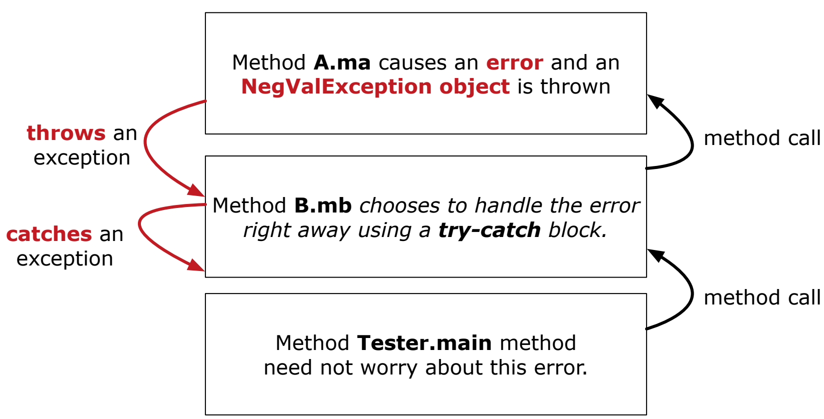
```
class A {
 ma(int i) throws NegValException {
   if(i < 0) { throw new NegValException("Error."); }
   else { /* Do something. */ }
 } }
```

```
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`.

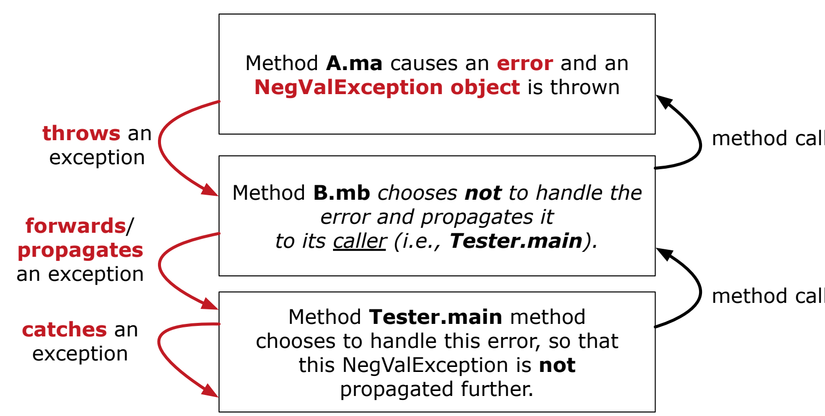
```
class A {
 ma(int i) throws NegValException {
   if(i < 0) { throw new NegValException("Error."); }
   else { /* Do something. */ }
 } }
```

```
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.

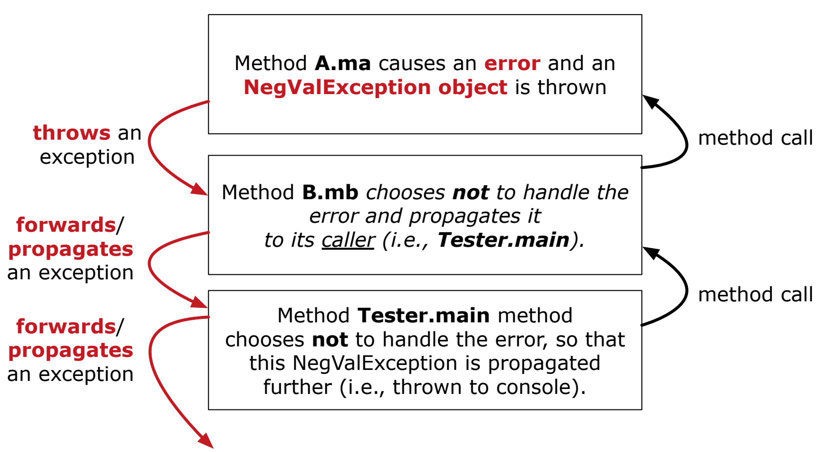
```
class A {
  ma(int i) throws NegValException {
    if(i < 0) { throw new NegValException("Error."); }
    else { /* Do something. */ }
  } }
```

```
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)

```
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 *signature* that it may *throw* an `InvalidRaidusException` object.

Error Reporting via Exceptions: Circles (2)

```
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 *signature* 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)

```
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  } }
```

- **Lines 6** 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 *signature* 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 *signature* 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 *signature* 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)

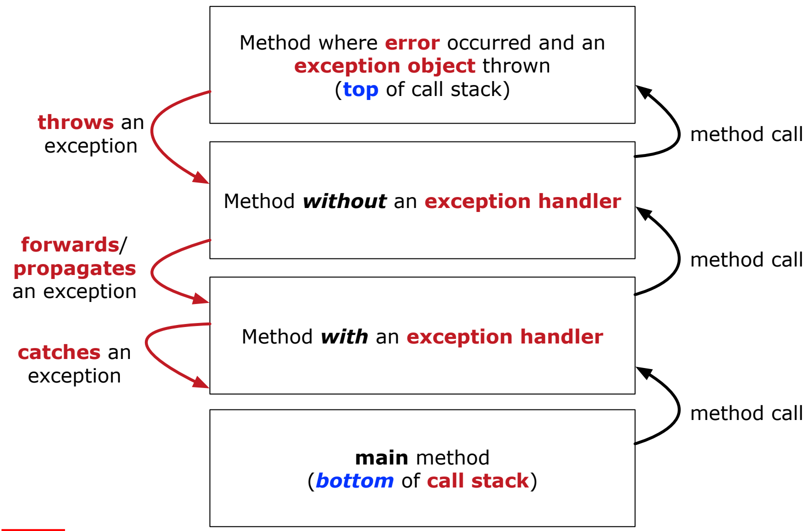
```
1  class BankApplication {
2   pubic static void main(String[] args) {
3     Bank b = new Bank();
4     Account acc1 = new Account(23);
5     b.addAccount(acc1);
6     Scanner input = new Scanner(System.in);
7     double a = input.nextDouble();
8     try {
9       b.withdraw(23, a);
10      System.out.println(acc1.balance);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

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 call this chain of method calls 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.

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



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

- 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!

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 */
  }
}
```


Index (1)

Index (2)

Index (3)

Exceptions

EECS2030 B: Advanced Object Oriented Programming
Fall 2019

CHEN-WEI WANG

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***.

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    Account(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`, printed from `Account.withdraw` to console.
  - However, impossible to stop `BankApplication.main` from continuing to executed **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

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*.

```
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 *signature* that it *can throw* the exception (without handling that exception).

```
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`.

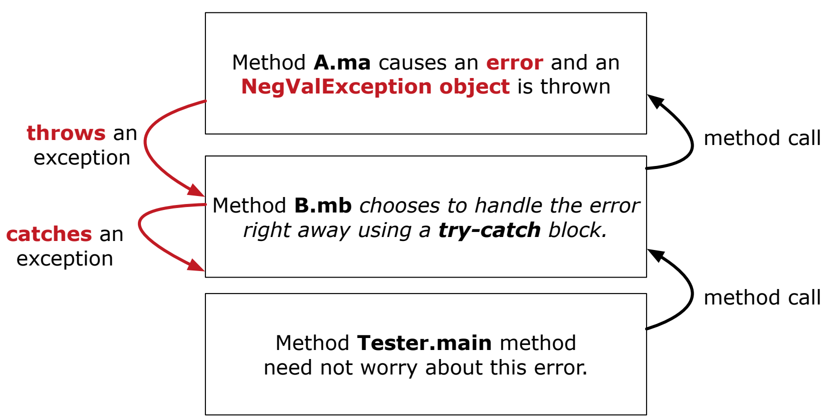
```
class A {
  ma(int i) throws NegValException {
    if(i < 0) { throw new NegValException("Error."); }
    else { /* Do something. */ }
  } }
```

```
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`.

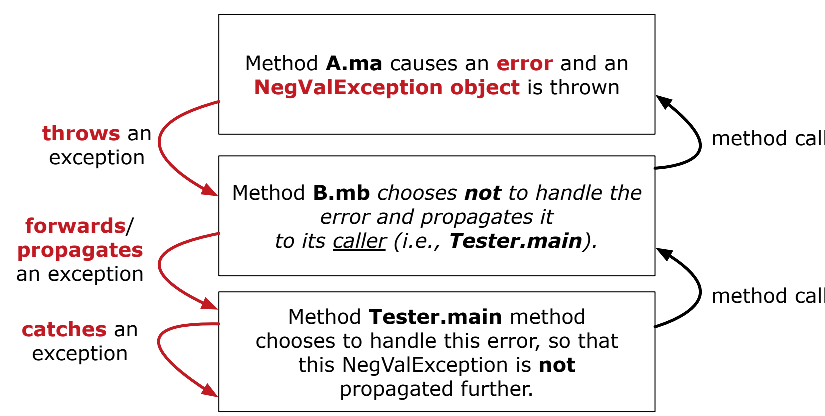
```
class A {
  ma(int i) throws NegValException {
    if(i < 0) { throw new NegValException("Error."); }
    else { /* Do something. */ }
  } }
```

```
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.

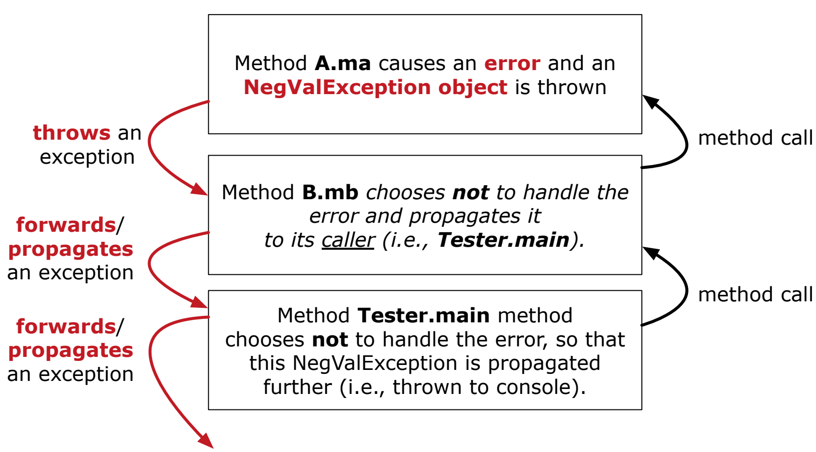
```
class A {
  ma(int i) throws NegValException {
    if(i < 0) { throw new NegValException("Error."); }
    else { /* Do something. */ }
  } }
```

```
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)

```
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 *signature* that it may *throw* an `InvalidRaidusException` object.

Error Reporting via Exceptions: Circles (2)

```
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 *signature* 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)

```
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   } }
```

- **Lines 6** 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 *signature* 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 *signature* 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 *signature* 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)

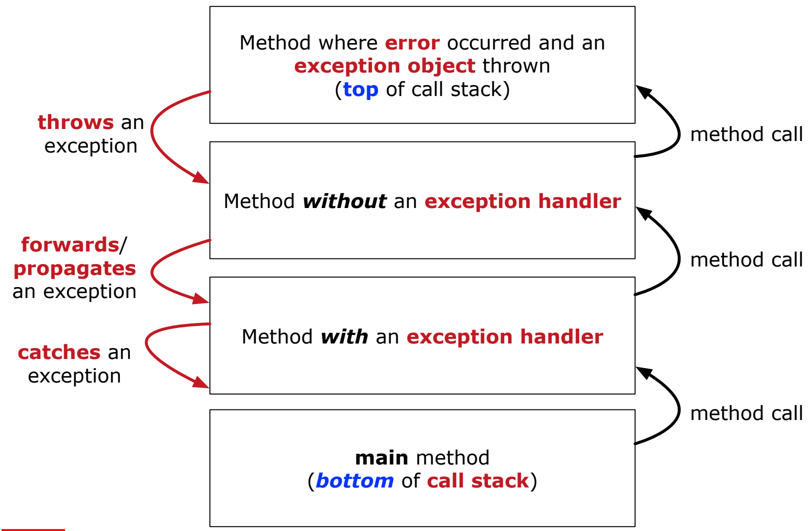
```
1  class BankApplication {
2   pubic static void main(String[] args) {
3     Bank b = new Bank();
4     Account acc1 = new Account(23);
5     b.addAccount(acc1);
6     Scanner input = new Scanner(System.in);
7     double a = input.nextDouble();
8     try {
9      b.withdraw(23, a);
10     System.out.println(acc1.balance);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

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 call this chain of method calls 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.

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



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

- 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!

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 */
  }
}
```


Index (1)

Index (2)

Index (3)

Test-Driven Development (TDD) with JUnit

EECS2030 B: Advanced Object Oriented Programming
Fall 2019

CHEN-WEI WANG

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 classes must be handled (*catch-specify requirement*):

- Either *specify* `throws ...` in the method signature (i.e., propagating it to other caller)
- Or *handle* it in a `try-catch` block

Motivating Example: Two Types of Errors (2)

Approach 1 – Specify: Indicate in the method signature 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);
  }
}
```


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) { ... }
  }
}
```

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 between its lower and upper bounds.

Exceptional Scenarios

Consider the two possible exceptional scenarios:

- 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 discuss!).
- A test:
  - ***Passes*** if expected outcome occurs.
  - ***Fails*** if expected outcome does *not* occur.
- So far, you ran tests via a tester class with the `main` method.

Testing Counter via Console V1 (1.1)

```
1  public class CounterTester1 {
2    public static void main(String[] args) {
3      Counter c = new Counter();
4      println("Init val: " + c.getValue());
5      try {
6        c.decrement();
7        println("Error: ValueTooSmallException NOT thrown.");
8      }
9      catch (ValueTooSmallException e) {
10       println("Success: ValueTooSmallException thrown.");
11     }
12   } /* end of main method */
13 } /* end of class CounterTester1 */
```

- **L3** sets `c.value` to `0`.
- At **L6**, if method `decrement` was implemented:
  - ***Correctly*** ⇒ we expect a `ValueTooSmallException`.
    ⇒ Execution jumps to **L9**, **L10 – L12**, then the program terminates.
  - ***Incorrectly*** ⇒ expected `ValueTooSmallException` *wouldn't* occur.
    ⇒ Execution continues to **L7**, **L8**, **L12**, then the program terminates.

See the equivalent, automated JUnit test `testDecFromMinValue`.

Testing Counter via Console V1 (1.2)

```
1  public class CounterTester1 {
2    public static void main(String[] args) {
3      Counter c = new Counter();
4      println("Init val: " + c.getValue());
5      try {
6        c.decrement();
7        println("Error: ValueTooSmallException NOT thrown.");
8      }
9      catch (ValueTooSmallException e) {
10       println("Success: ValueTooSmallException thrown.");
11     }
12   } /* end of main method */
13 } /* end of class CounterTester1 */
```

- Say method `decrement` is implemented ***correctly***.
- **Lines 3 – 6, 9 – 11, 12** executed, giving the Console Output:

```
Init val: 0
Success: ValueTooSmallException thrown.
```


Testing Counter via Console V1 (1.3.1)

- The real value of a *test* is:
  - Not only to confirm when your implementation is ***correct***,
  - But also to reveal errors when your implementation is ***incorrect***.
- Say now 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 --; }
  }
}
```

- Is the same console tester able to *reveal* this ***incorrect*** implementation?

Testing Counter via Console V1 (1.3.2)

```
1  public class CounterTester1 {
2    public static void main(String[] args) {
3      Counter c = new Counter();
4      println("Init val: " + c.getValue());
5      try {
6        c.decrement();
7        println("Error: ValueTooSmallException NOT thrown.");
8      }
9      catch (ValueTooSmallException e) {
10       println("Success: ValueTooSmallException thrown.");
11     }
12   } /* end of main method */
13 } /* end of class CounterTester1 */
```

- Say method `decrement` is implemented ***incorrectly***.
- **Lines 3 – 6, 7 – 8, 12** executed, giving the Console Output:

```
Init val: 0
Error: ValueTooSmallException NOT thrown.
```

Testing Counter via Console V1 (2.1)

```
1  public class CounterTester2 {
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     try {
9      c.increment();
10     println("Error: ValueTooLargeException NOT thrown.");
11    } /* end of inner try */
12    catch (ValueTooLargeException e) {
13     println("Success: ValueTooLargeException thrown.");
14    } /* end of inner catch */
15   } /* end of outer try */
16   catch (ValueTooLargeException e) {
17    println("Error: ValueTooLargeException thrown unexpectedly.");
18   } /* end of outer catch */
19  } /* end of main method */
20 } /* end of CounterTester2 class */
```

See the equivalent, automated JUnit test `testIncFromMaxValue`.

Testing Counter via Console V1 (2.2)


```
1  public class CounterTester2 {
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     try {
9      c.increment();
10     println("Error: ValueTooLargeException NOT thrown.");
11    } /* end of inner try */
12    catch (ValueTooLargeException e) {
13     println("Success: ValueTooLargeException thrown.");
14    } /* end of inner catch */
15   } /* end of outer try */
16   catch (ValueTooLargeException e) {
17    println("Error: ValueTooLargeException thrown unexpectedly.");
18   } /* end of outer catch */
19  } /* end of main method */
20 } /* end of CounterTester2 class */
```


- Say method `increment` is implemented ***correctly***.
- **Lines 3 – 9, 12 – 15, 19** executed, with Console Output:

```
Current val: 0
Current val: 3
Success: ValueTooLargeException thrown.
```


Testing Counter via Console V1 (2.3.1)


```
1  public class CounterTester2 {
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     try {
9      c.increment();
10     println("Error: ValueTooLargeException NOT thrown.");
11    } /* end of inner try */
12    catch (ValueTooLargeException e) {
13     println("Success: ValueTooLargeException thrown.");
14    } /* end of inner catch */
15   } /* end of outer try */
16   catch (ValueTooLargeException e) {
17    println("Error: ValueTooLargeException thrown unexpectedly.");
18   } /* end of outer catch */
19  } /* end of main method */
20 } /* end of CounterTester2 class */
```


- **Exercise**: Give an ***incorrect*** method `increment`, so that
- **Lines 3 – 6, 16 – 18, 19** executed, with Console Output:

```
Current val: 0
Error: ValueTooLargeException was thrown unexpectedly.
```


Testing Counter via Console V1 (2.3.2)


```
1  public class CounterTester2 {
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     try {
9      c.increment();
10     println("Error: ValueTooLargeException NOT thrown.");
11    } /* end of inner try */
12    catch (ValueTooLargeException e) {
13     println("Success: ValueTooLargeException thrown.");
14    } /* end of inner catch */
15   } /* end of outer try */
16   catch (ValueTooLargeException e) {
17    println("Error: ValueTooLargeException thrown unexpectedly.");
18   } /* end of outer catch */
19  } /* end of main method */
20 } /* end of CounterTester2 class */
```


- **Exercise**: Give an ***incorrect*** method `increment`, so that
- **Lines 3 – 11, 15, 19** executed, with Console Output:

```
Current val: 0
Current val: 3
Error: ValueTooLargeException was NOT thrown.
```

Testing Counter via Console V1 (2.3.3)

Question. Can this alternative to `ConsoleTester2` work (<u>without</u> nested `try-catch`)?

```
1  public class CounterTester2 {
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     } /* end of inner catch */
19   } /* end of main method */
20 } /* end of CounterTester2 class */
```

- 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!

Testing Counter via Console (V2)

```
import java.util.Scanner;
public class CounterTester3 {
  public static void main(String[] args) {
    Scanner input = new Scanner(System.in);
    String cmd = null; Counter c = new Counter();
    boolean userWantsToContinue = true;
    while(userWantsToContinue) {
      println("Enter \"inc\", \"dec\", or \"val\":");
      cmd = input.nextLine();
      try {
        if(cmd.equals("inc")) { c.increment() ; }
        else if(cmd.equals("dec")) { c.decrement() ; }
        else if(cmd.equals("val")) { println(c.getValue()); }
        else { userWantsToContinue = false; println("Bye!"); }
      } /* end of try */
      catch(ValueTooLargeException e){ println("Value too big!"); }
      catch(ValueTooSmallException e){ println("Value too small!"); }
    } /* end of while */
  } /* end of main method */
} /* end of class CounterTester3 */
```


Testing Counter via Console (V2): Test 1

Test Case 1: Decrement when the counter value is too small.

```
Enter "inc", "dec", or "val":
val
0
Enter "inc", "dec", or "val":
dec
Value too small!
Enter "inc", "dec", or "val":
exit
Bye!
```


Testing Counter via Console (V2): Test 2

Test Case 2: Increment when the counter value is too big.

```
Enter "inc", "dec", or "val":
inc
Enter "inc", "dec", or "val":
inc
Enter "inc", "dec", or "val":
inc
Enter "inc", "dec", or "val":
val
3
Enter "inc", "dec", or "val":
inc
Value too big!
Enter "inc", "dec", or "val":
exit
Bye!
```

Limitations of Testing from the Console

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

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

- So in total we need 8 test cases. ⇒ 6 more separate
  - `CounterTester` classes to create (like `CounterTester1`)!
  - Console interactions with `CounterTester3`!
- Problems? It is inconvenient to:
  - Run each TC by executing `main` of a `CounterTester` and comparing console outputs ***with your eyes***.
  - *Re-run* ***manually*** all TCs whenever `Counter` is changed.

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

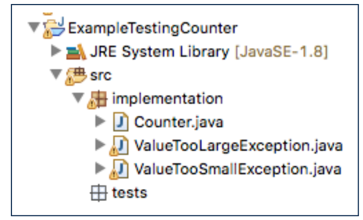
Why JUnit?

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

How to Use JUnit: Packages

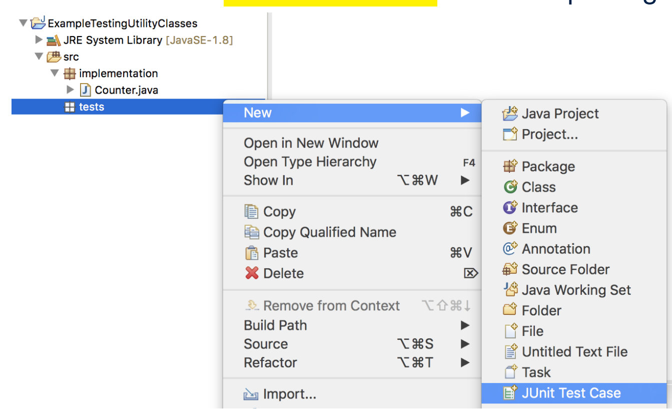
Step 1:

- 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)

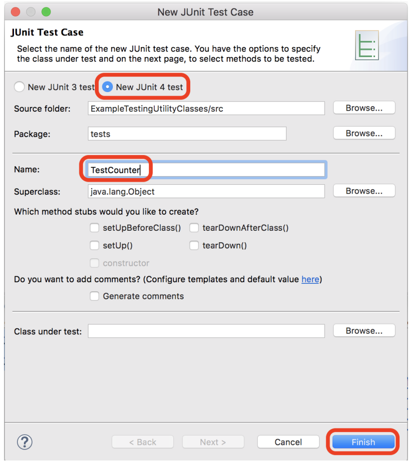
Step 2: Create a new *JUnit Test Case* in `tests` package.



Create one JUnit Test Case to test one Java class only.
⇒ If you have *n Java classes to test*, create *n JUnit test cases*.

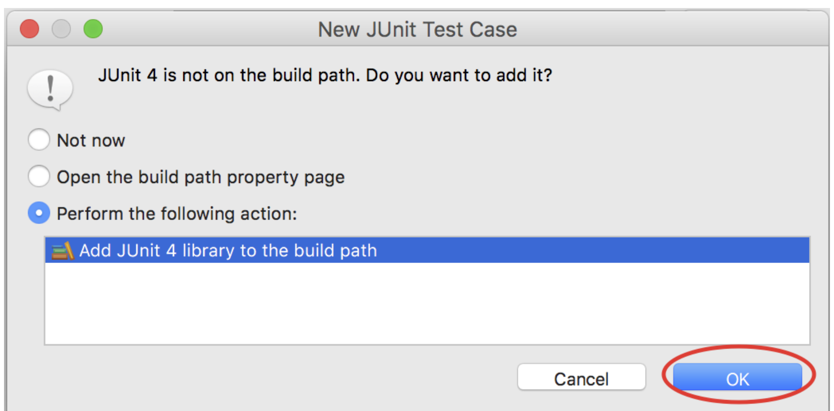
How to Use JUnit: New JUnit Test Case (2)

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

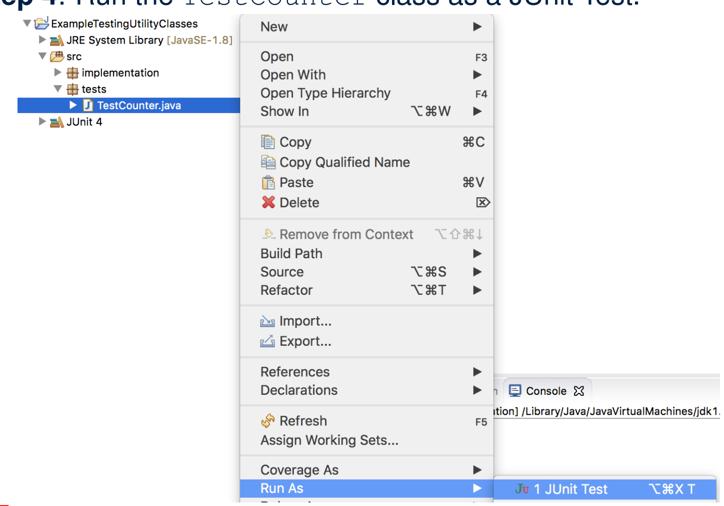
TestCounter.java

```
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".

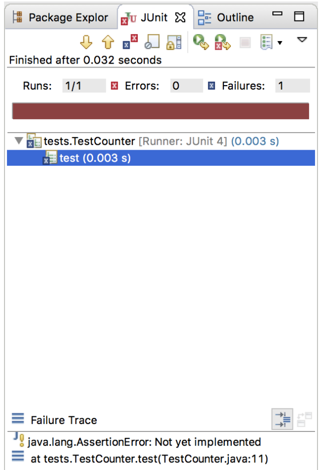
How to Use JUnit: Running Test Case

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

How to Use JUnit: Revising Test Case

TestCounter.java

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

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

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

How to Use JUnit: Re-Running Test Case

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

How to Use JUnit: Adding More Tests (1)

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

`c.getValue()`	`c.increment()`	`c.decrement()`
0	1	ValueTooSmall
1	2	0
2	3	1
3	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`).
  - Common JUnit assertion methods:
    - `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:

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

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

```
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:

```
class Circle {
  double radius;
  Circle(double radius) { this.radius = radius; }
  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);
assertTrue(36.2984, c.getArea(), 0.01);  ✓
```


How to Use JUnit: Assertion Methods

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

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

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

How to Use JUnit: Adding More Tests (2.1)

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

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

How to Use JUnit: Adding More Tests (2.2)

- Don't lose the big picture!
- JUnit test in previous slide automates this console interaction:

```
Enter "inc", "dec", or "val":
val
0
Enter "inc", "dec", or "val":
inc
Enter "inc", "dec", or "val":
val
1
Enter "inc", "dec", or "val":
exit
Bye!
```

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

How to Use JUnit: Adding More Tests (3.1)

```
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 }
```

- **Line 6** requires a try-catch block ∵ potential `ValueTooBigException`
- **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

See the equivalent, manual `ConsoleTester1`.

How to Use JUnit: Adding More Tests (3.2)

- Again, don't lose the big picture!
- JUnit test in previous slide automates `CounterTester1` and the following console interaction for `CounterTester3`:

```
Enter "inc", "dec", or "val":
val
0
Enter "inc", "dec", or "val":
dec
Value too small!
Enter "inc", "dec", or "val":
exit
Bye!
```

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

How to Use JUnit: Adding More Tests (4.1)

```
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.

See the equivalent, manual `ConsoleTester2`.

How to Use JUnit: Adding More Tests (4.2)

- JUnit test in previous slide *automates* `CounterTester2` and the following console interaction for `CounterTester3`:

```
Enter "inc", "dec", or "val":
inc
Enter "inc", "dec", or "val":
inc
Enter "inc", "dec", or "val":
inc
Enter "inc", "dec", or "val":
val
3
Enter "inc", "dec", or "val":
inc
Value too big!
Enter "inc", "dec", or "val":
exit
Bye!
```


How to Use JUnit: Adding More Tests (4.3)

Q: Can we rewrite `testIncFromMaxValue` to:

```
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*.

How to Use JUnit: Adding More Tests (5)

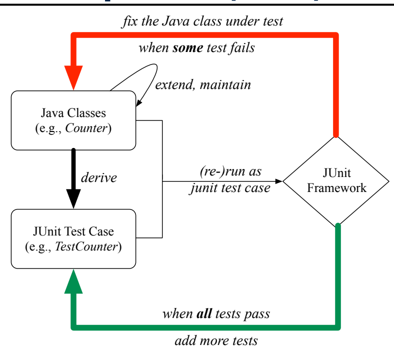
Loops can make it effective on generating test cases:

```
@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 the error injection, and re-run all 8 tests. [What happens?]

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.

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`

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Advanced Topics on Classes and Objects

EECS2030 B: Advanced Object Oriented Programming
Fall 2019

CHEN-WEI WANG

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

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 *accessor method* that every class *inherits* from the `Object` class:
  - `boolean equals(Object obj)`
    Indicates whether some other object is "equal to" this one.
    - The default definition inherited from `Object`:

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

    e.g., Say `p1` and `p2` are of type `PointV1` without the `equals` method redefined, 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)

```
class PointV1 {
  double x; double y;
  PointV1(double x, double y) { this.x = x; this.y = y; }
}
```

```
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 <u>default version</u> 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`.

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

Equality (4.1)

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

```java
class PointV2 {
  double x; double 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)`:
  - Variable `p` is declared of type `Point`***V2***
  - Variable `o` can be declared of any type (e.g., `Point`***V2***, `String`)
- We define `p` and `o` as ***equal*** if:
  - Either `p` and `o` refer to the same object;
  - Or:
    - `o` is not null.
    - `p` and `o` 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 {
  boolean equals(Object obj) {
    if(this == null) { return false; }
```

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

Equality (4.3)

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

- `Object obj` at **L2** declares a parameter `obj` of type `Object`.
- `Point`***V2*** `other` at **L4** declares a variable `p` of type `Point`***V2***.
  We call such types declared at compile time as ***static type***.
- The list of *applicable attributes/methods* that we may call on a variable depends on its ***static type***.
  e.g., We may only call the small list of methods defined in `Object` class on `obj`, which does not include `x` and `y` (specific to `Point`).
- If we are SURE that an object's "actual" type is different from its ***static type***, then we can *cast* it.
  e.g., Given that `this.getClass() == obj.getClass()`, we are sure that `obj` is also a `Point`, so we can cast it to `Point`.
- Such cast allows more attributes/methods to be called upon `(Point) obj` at **L5**.

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.

Equality in JUnit (1.1)

- ***assertSame***(obj1, obj2)
  - Passes if obj1 and obj2 are references to the same object
    ≈ ***assertTrue***(obj1 == obj2)
    ≈ ***assertFalse***(obj1 != obj2)

```
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 *obj*1's declared type
    ≈ ***assertSame***(obj1, obj2)

```
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 types of objects */
```

Case 2: If `equals` is explicitly overridden in *obj*1's declared type
≈ `obj1.equals(obj2)`

```
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.x == p2.x && p3.y == p2.y */
```


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.x == p2.x && p2.y == p2.y);
}
@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, p4); */ /* 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  class Person {
2   String firstName; String lastName; double weight; double height;
3   boolean equals(Object obj) {
4    if(this == obj) { return true; }
5    if(obj == null || this.getClass() != obj.getClass()) {
6     return false; }
7    Person other = (Person) obj;
8    return
9        this.weight == other.weight && this.height == other.height
10     && this.firstName.equals(other.firstName)
11     && this.lastName.equals(other.lastName); } }
```

Q: At **L5**, will we get `NullPointerException` if `obj` is `Null`?

A: ***No*** ∵ Short-Circuit Effect of `||`

`obj` is `null`, then `obj == null` evaluates to ***true***

⇒ no need to evaluate the RHS

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

Equality (6.2)

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

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

Q: At **L5**, if swapping the order of two operands of disjunction:

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

Will we get `NullPointerException` if `obj` is `Null`?

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

Equality (6.3)

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

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

L10 & L11 call `equals` method defined in the `String` class.

When defining `equals` method for your own class, *reuse* `equals` methods defined in other classes wherever possible.

Equality (6.4)

Person collectors are equal if containing equal lists of persons.

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

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

```
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.persons[0] == pc2.persons[0]);
  assertTrue(pc1.persons[0].equals(pc2.persons[0]));
  assertTrue(pc1.equals(pc2));

  pc1.addPerson(p3); pc2.addPerson(p4);
  assertTrue(pc1.persons[1] == pc2.persons[1]);
  assertTrue(pc1.persons[1].equals(pc2.persons[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.persons[2] == pc2.persons[2]);
  assertFalse(pc1.persons[2].equals(pc2.persons[2]));
  assertFalse(pc1.equals(pc2));
}
```


Why Ordering Between Objects? (1)

Each employee has their numerical id and salary.

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

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

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

  e.g., ⟨*alan*, *tom*, *mark*⟩
- *Solution*:
  - Define ***ordering*** of `Employee` objects.

    [`Comparable` interface, `compareTo` method]
  - Use the library method `Arrays.sort`.

Why Ordering Between Objects? (2)

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

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

L8 triggers a ***java.lang.ClassCastException***:
Employee cannot be cast to java.lang.Comparable

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

Defining Ordering Between Objects (1.1)

- Say `ces` is an array of `CEmployee1` (`CEmployee1[] ces`), calling `Arrays.sort(ces)` re-arranges `ces`, so that:

  `ces[0]` ≤ `ces[1]` ≤ ... ≤ `ces[ces.length - 1]`

  (each a `CEmployee1` *object*)
- Given two `CEmployee1` objects `ce1` and `ce2`:
  - `ce1.compareTo(ce2) > 0` [`ce1` "is greater than" `ce2`]
  - `ce1.compareTo(ce2) == 0` [`ce1` "is equal to" `ce2`]
  - `ce1.compareTo(ce2) < 0` [`ce1` "is smaller than" `ce2`]

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

Defining Ordering Between Objects (1.2)

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


Defining Ordering Between Objects (2.1)

Let's now make the comparison more sophisticated:

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

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


Defining Ordering Between Objects (2.2)

Alternatively, we can express the equivalent logic in a slightly more compact way.

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

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

Defining Ordering Between Objects (2.3)

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

Defining Ordering Between Objects (3)

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

- *Asymmetric*:

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

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

- *Transitive*:

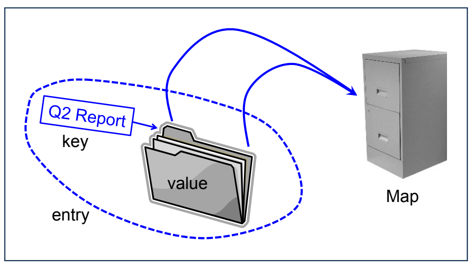
$$c1.compareTo(c2) < 0 \wedge c2.compareTo(c3) < 0 \Rightarrow c1.compareTo(c3) < 0$$
$$c1.compareTo(c2) > 0 \wedge c2.compareTo(c3) > 0 \Rightarrow c1.compareTo(c3) > 0$$

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

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

Hashing: What is a Map?

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



Entry	
(Search) Key	Value
1	D
25	C
3	F
14	Z
6	A
39	C
7	Q

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

Hashing: Arrays are Maps

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

Hashing: Naive Implementation of Map

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

Entry	
(Search) Key	Value
1	D
25	C
3	F
14	Z
6	A
39	C
7	Q

Let's just assume that the maximum map capacity is 100.

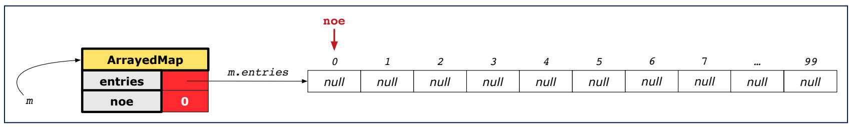
- **Naive Solution**:

Let's understand the expected runtime structures before seeing the Java code!

Hashing: Naive Implementation of Map (0)

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

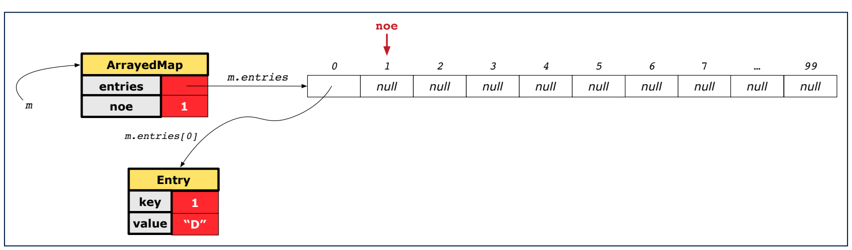
- Attribute `m.entries` initialized as an array of 100 `null` slots.
- Attribute `m.noe` is 0, meaning:
  - Current number of entries stored in the map is 0.
  - Index for storing the next new entry is 0.



Hashing: Naive Implementation of Map (1)

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

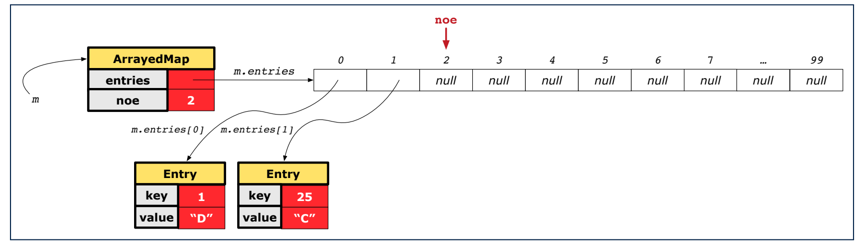
- Attribute `m.entries` has 99 `null` slots.
- Attribute `m.noe` is 1, meaning:
  - Current number of entries stored in the map is 1.
  - Index for storing the next new entry is 1.



Hashing: Naive Implementation of Map (2)

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

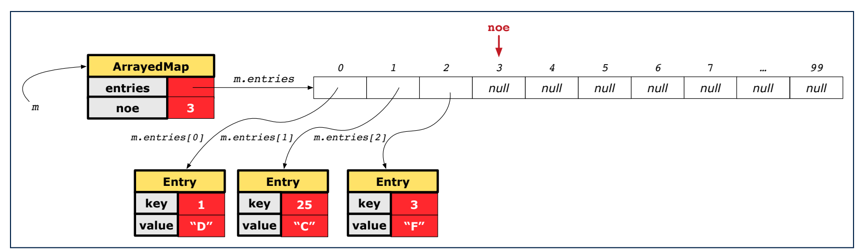
- Attribute `m.entries` has 98 `null` slots.
- Attribute `m.noe` is 2, meaning:
  - Current number of entries stored in the map is 2.
  - Index for storing the next new entry is 2.



Hashing: Naive Implementation of Map (3)

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

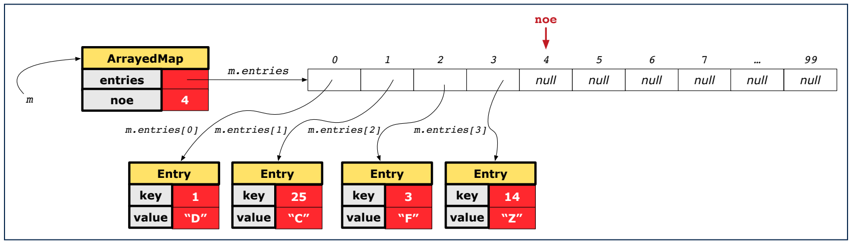
- Attribute `m.entries` has 97 `null` slots.
- Attribute `m.noe` is 3, meaning:
  - Current number of entries stored in the map is 3.
  - Index for storing the next new entry is 3.



Hashing: Naive Implementation of Map (4)

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

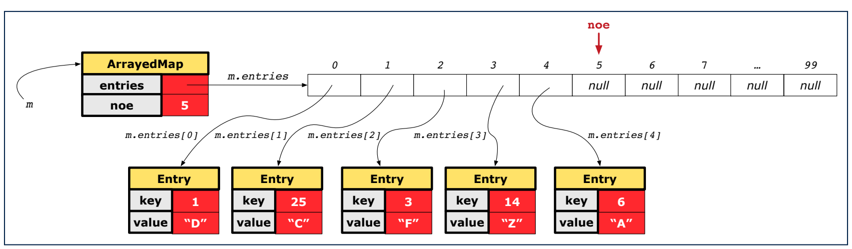
- Attribute `m.entries` has 96 `null` slots.
- Attribute `m.noe` is 4, meaning:
  - Current number of entries stored in the map is 4.
  - Index for storing the next new entry is 4.



Hashing: Naive Implementation of Map (5)

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

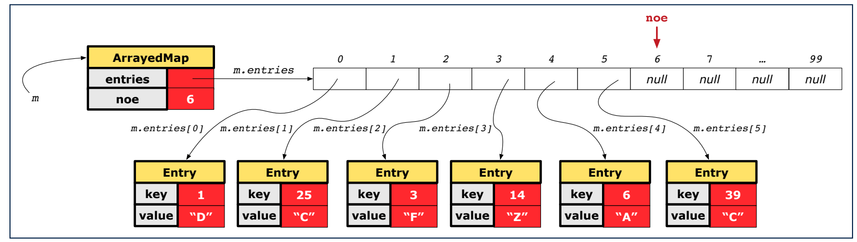
- Attribute `m.entries` has 95 `null` slots.
- Attribute `m.noe` is 5, meaning:
  - Current number of entries stored in the map is 5.
  - Index for storing the next new entry is 5.



Hashing: Naive Implementation of Map (6)

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

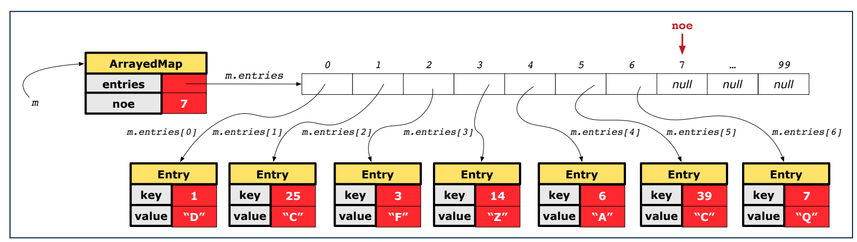
- Attribute `m.entries` has 94 `null` slots.
- Attribute `m.noe` is 6, meaning:
  - Current number of entries stored in the map is 6.
  - Index for storing the next new entry is 6.



Hashing: Naive Implementation of Map (7)

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

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



Hashing: Naive Implementation of Map (8.1)

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

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


Hashing: Naive Implementation of Map (8.2)

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

Required Reading: Point and PointCollector

Hashing: Naive Implementation of Map (8.3)

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


Hashing: Naive Implementation of Map (8.4)

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

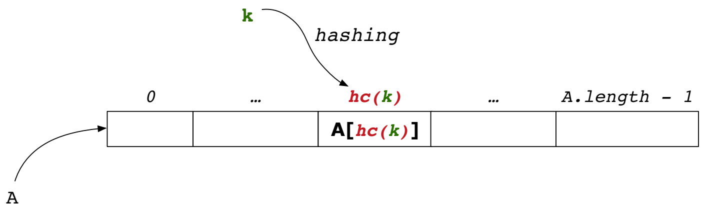
Say `entries` is: {(1, D), (25, C), (3, F), (14, Z), (6, A), (39, C), (7, Q), null, . . .}

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

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

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

Hashing: Hash Table (1)

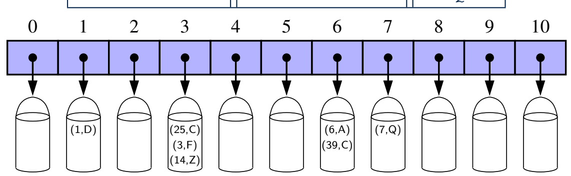


- Given a (numerical or non-numerical) search key ***k***:
  - Apply a function ***hc*** so that ***hc(k)*** returns an integer.
    - We call ***hc(k)*** the *hash code* of key ***k***.
    - Value of ***hc(k)*** denotes a ***valid index*** of some array `A`.
  - Rather than searching through array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

Hashing: Hash Table as a Bucket Array (2.1)

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

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

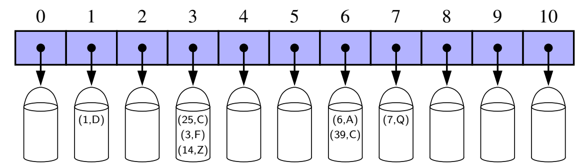


- **Collision**: unequal keys have same hash code (e.g., 25, 3, 14)
  ⇒ Unavoidable as number of entries ↑, but a *good* hash function should have sizes of the buckets uniformly distributed.

Hashing: Hash Table as a Bucket Array (2.2)

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

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



- **Collision**: unequal keys have same hash code (e.g., 25, 3, 14)
  ⇒ When there are *multiple entries* in the *same bucket*, we distinguish between them using their ***unequal*** keys.

Hashing: Contract of Hash Function

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

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

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

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

  Different hash codes must be generated from unequal keys.
- What if $\neg k1.equals(k2)$?
  - $hc(k1) == hc(k2)$ [collision e.g., 25 and 3]
  - $hc(k1) \neq hc(k2)$ [no collision e.g., 25 and 1]
- What if $hc(k1) == hc(k2)$?
  - $\neg k1.equals(k2)$ [collision e.g., 25 and 3]
  - $k1.equals(k2)$ [sound hash function]

inconsistent `hashCode` and `equals`

Hashing: Defining Hash Function in Java (1)

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

```
1  public class IntegerKey {
2    private int k;
3    public IntegerKey(int k) { this.k = k; }
4    @Override
5    public int hashCode() { return k % 11; }
6    @Override
7    public boolean equals(Object obj) {
8      if(this == obj) { return true; }
9      if(obj == null) { return false; }
10     if(this.getClass() != obj.getClass()) { return false; }
11     IntegerKey other = (IntegerKey) obj;
12     return this.k == other.k;
13 } }
```

Q: Can we replace **L12** by `return this.hashCode() == other.hashCode()`?

A: *No* ∵ When collision happens, keys with same hash code (i.e., in the same bucket) cannot be distinguished.

Hashing: Defining Hash Function in Java (2)

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

  IntegerKey ik39_1 = new IntegerKey(39); /* 39 % 11 == 6 */
  IntegerKey ik39_2 = new IntegerKey(39);
  IntegerKey ik6 = new IntegerKey(6); /* 6 % 11 == 6 */

  assertTrue(ik39_1.hashCode() == 6);
  assertTrue(ik39_2.hashCode() == 6);
  assertTrue(ik6.hashCode() == 6);

  assertTrue(ik39_1.hashCode() == ik39_2.hashCode());
  assertTrue(ik39_1.equals(ik39_2));

  assertTrue(ik39_1.hashCode() == ik6.hashCode());
  assertFalse(ik39_1.equals(ik6));
}
```


Hashing: Using Hash Table in Java

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


Hashing: Defining Hash Function in Java (3)

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

Hashing: Defining Hash Function in Java (4.1.1)

Caveat: Always make sure that the `hashCode` and `equals` are redefined/overridden to work together consistently.

e.g., Consider an alternative version of the `IntegerKey` class:

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


Hashing: Defining Hash Function in Java (4.1.2)

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

- ***Problem***?
  - Default implementation of `hashCode()` from the `Object` class: Objects with *distinct* addresses have *distinct* hash code values.
  - Violation of the Contract of `hashCode()`:
    $$hc(k1) \neq hc(k2) \Rightarrow \neg k1.equals(k2)$$
- What about `equal` objects with different addresses?

Hashing: Defining Hash Function in Java (4.2)

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

L3, 4, 10, 11: Default version of `hashCode`, inherited from `Object`, returns a *distinct* integer for every new object, despite its contents. [***Fix***: Override `hashCode` of your classes!]

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 for the method call.
  - Instead, argument variable **arg** is passed ***indirectly***: a *copy* of the value stored in **arg** is made and passed for the method call.
- What can be the type of variable **arg**? [Primitive or Reference]
  - **arg** is primitive type (e.g., `int`, `char`, `boolean`, *etc.*):
    Call by Value: Copy of **arg**'s *stored value*
    (e.g., `2`, `'j'`, `true`) is made and passed.
  - **arg** is reference type (e.g., `String`, `Point`, `Person`, *etc.*):
    Call by 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:

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

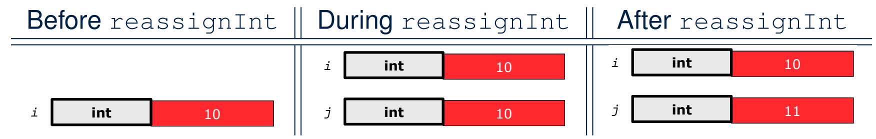

Call by Value (2.2.1)

```
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 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)



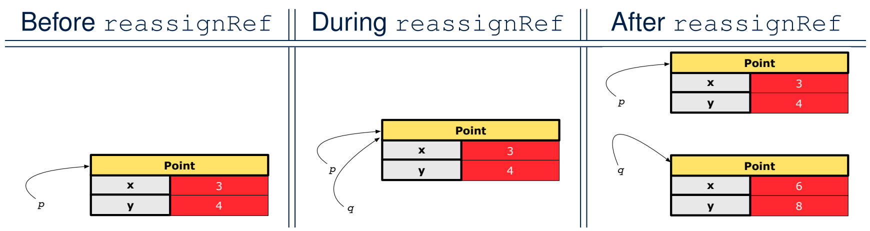
Call by Value (2.3.1)

```
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.x==3 && p.y==4);
9 }
```

- ***Before*** the mutator call at **L6**, *reference* variable `p` stores the *address* of some `Point` object (whose `x` is `3` and `y` is `4`).
- **When** executing the mutator call at **L6**, due to *call by 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)



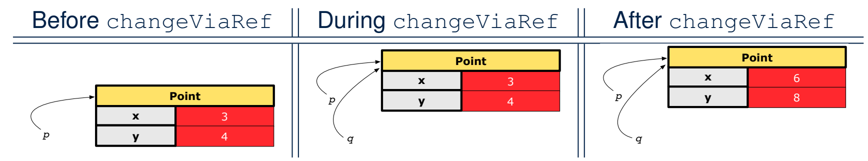
Call by Value (2.4.1)

```
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.x==6 && p.y==8);
9 }
```

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

Call by Value (2.4.2)



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Using Java Collections

EECS2030 B: Advanced
Object Oriented Programming
Fall 2019

CHEN-WEI WANG

Learning Outcomes

Understand:

- Method Header
- Parameters vs. Arguments
- Self-Exploration of Java API

Application Programming Interface (API)

- Each time before you start solving a problem:
  - As a ***beginner***, crucial to implement **everything** by yourself.
  - As you get more ***experienced***, first check to see if it is already solved by one of the library classes or methods.

    Rule of the Thumb: DO NOT REINVENT THE WHEEL!
- An *Application Programming Interface (API)* is a collection of *programming facilities* for *reuse* and building your applications.
- Java API contains a library of *classes* (e.g., `Math`, `ArrayList`, `HashMap`) and *methods* (e.g., `sqrt`, `add`, `remove`):

  https://docs.oracle.com/javase/8/docs/api/
- To use a library class, put a corresponding `import` statement:

```
import java.util.ArrayList;
class MyClass {
  ArrayList<String> myList;
  ... /* call methods on myList */
}
```


Classes vs. Methods

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

  e.g., As a user of the `sqrt` method (from the `Math` class):
  - Implementation code of `sqrt` is *hidden* from you.
  - You only need to know how to *call* it in order to use it.
  - A *non-static method* must be called using a context object.

    e.g., Illegal to call `ArrayList.add("Suyeon")`. Instead:

```
ArrayList<String> list = new ArrayList<String>();
list.add("Suyeon")
```

  - A *static method* can be called using the name of its class.

    e.g., By calling `Math.sqrt(1.44)`, you are essentially *reusing* a block of code, *hidden* from you, that will be executed and calculate the square root of the input value you supply (i.e., `1.44`).
- A *class* contains a collection of *related* methods.

  e.g., The `Math` *class* supports *methods* related to more advanced mathematical computations beyond the simple arithmetical operations we have seen so far (i.e., `+`, `-`, `*`, `/`, and `%`).

Parameters vs. Arguments

- *Parameters* of a *method* are its *input variables* that you read from the API page.

  e.g., `double pow(double a, double b)` has:
  - two parameters `a` and `b`, both of type `double`
  - one output/return value of type `double`
- *Arguments* of a *method* are the specific *input values* that you supply/pass in order to use it.

  e.g., To use the `pow` method to calculate 3.4^5, we call it by writing `Math.pow(3.4, 5)`.
- *Argument values* must conform to the corresponding *parameter types*.

  e.g., `Math.pow("three point four", "5")` is an invalid call!

Header of a Method

Header of a *method* informs users of the *intended usage*:
- *Name* of method
- List of *inputs* (a.k.a. *parameters*) and their types
- Type of the *output* (a.k.a. *return type*)
  - Methods with the `void` return type are mutators.
  - Methods with non-`void` return types are accessors.

e.g. In Java API, the **Method Summary** section lists *headers* and descriptions of methods.

Example Method Headers: ArrayList Class

An ArrayList acts like a "resizable" array (indices start with 0).

int	size() Returns the number of elements in this list.
boolean	add(E e) Appends the specified element to the end of this list.
void	add(int index, E element) Inserts the specified element at the specified position in this list.
boolean	contains(Object o) Returns true if this list contains the specified element.
E	remove(int index) Removes the element at the specified position in this list.
boolean	remove(Object o) Removes the first occurrence of the specified element from this list, if it is present.
int	indexOf(Object o) Returns the index of the first occurrence of the specified element in this list, or -1 if this list does not contain the element.
E	get(int index) Returns the element at the specified position in this list.

Generic Parameters: ArrayList Class (1)

- Consider the API of `ArrayList`:

```
1 class ArrayList<E> {
2   boolean add(E e)
3   E remove(int index)
4   E get(int index)
5 }
```

  - **L1** ***declares*** a generic parameter `E`, denoting the type of values stored in the array list.
  - All other occurrences of `E` at **L2**, **L3**, and **L4** refer to whatever `E` is ***instantiated*** by some caller.
- A caller of `ArrayList` may ***instantiate*** `E` to any known class:

```
ArrayList<String> list1 = new ArrayList<String>();
ArrayList<Point> list2 = new ArrayList<Point>();
```

Generic Parameters: ArrayList Class (2)

A caller of `ArrayList` may ***instantiate*** `E` to any known class:

```
1 ArrayList<String> list1 = new ArrayList<String>();
2 ArrayList<Point> list2 = new ArrayList<Point>();
```

- **L1** instantiate `E` to `String`, as if the following class was declared:

```
class ArrayList {
  boolean add(String e)
  String remove(int index)
  String get(int index)
}
```

- **L2** instantiate `E` to `Point`, as if the following class was declared:

```
class ArrayList {
  boolean add(Point e)
  Point remove(int index)
  Point get(int index)
}
```


Case Study: Using an ArrayList

```
import java.util.ArrayList;
public class ArrayListTester {
  public static void main(String[] args) {
    ArrayList<String> list = new ArrayList<String>();
    println(list.size());
    println(list.contains("A"));
    println(list.indexOf("A"));
    list.add("A");
    list.add("B");
    println(list.contains("A")); println(list.contains("B")); println(list.contains("C"));
    println(list.indexOf("A")); println(list.indexOf("B")); println(list.indexOf("C"));
    list.add(1, "C");
    println(list.contains("A")); println(list.contains("B")); println(list.contains("C"));
    println(list.indexOf("A")); println(list.indexOf("B")); println(list.indexOf("C"));
    list.remove("C");
    println(list.contains("A")); println(list.contains("B")); println(list.contains("C"));
    println(list.indexOf("A")); println(list.indexOf("B")); println(list.indexOf("C"));

    for(int i = 0; i < list.size(); i ++) {
      println(list.get(i));
    }
  }
}
```


Example Method Headers: HashTable Class

A HashTable acts like a two-column table of (searchable) keys and values.

`int`	`size()` Returns the number of keys in this hashtable.
`boolean`	`containsKey(Object key)` Tests if the specified object is a key in this hashtable.
`boolean`	`containsValue(Object value)` Returns true if this hashtable maps one or more keys to this value.
`V`	`get(Object key)` Returns the value to which the specified key is mapped, or `null` if this map contains no mapping for the key.
`V`	`put(K key, V value)` Maps the specified key to the specified `value` in this hashtable.
`V`	`remove(Object key)` Removes the key (and its corresponding value) from this hashtable.

Generic Parameters: Hashtable Class (1)

- Consider the API of `Hashtable`:

```
1 class Hashtable<K, V> {
2   V put(K key, V value)
3   V get(Object key)
4 }
```

  - **L1** ***declares*** two generic parameters `K` and `V`, denoting types of keys and values stored in the hash table.
  - All other occurrences of `K` and `V` at **L2**, **L3**, and **L4** refer to whatever `K` and `V` are ***instantiated*** by some caller.

- A caller of `ArrayList` may ***instantiate*** `E` to any known class:

```
1 Hashtable<String, Integer> t1 = new Hashtable<String, Integer>();
2 Hashtable<Integer, String> t2 = new Hashtable<Integer, String>();
```

Generic Parameters: Hashtable Class (2)

A caller of `Hashtable` may ***instantiate*** `K` and `V` to any known classes:

```
1 Hashtable<String, Integer> t1 = new Hashtable<String, Integer>();
2 Hashtable<Integer, String> t2 = new Hashtable<Integer, String>();
```

- **L1** instantiate `K` and `V` to, respectively, `String` and `Integer`, as if the following class was declared:

```
class Hashtable {
  Integer put(String key, Integer value)
  Integer get(Object key)
}
```

- **L2** instantiate `K` and `V` to, respectively, `Integer` and `String`, as if the following class was declared:

```
class Hashtable {
  String put(Integer key, String value)
  String get(Object key)
}
```


Case Study: Using a HashTable

```
import java.util.Hashtable;
public class HashTableTester {
  public static void main(String[] args) {
    Hashtable<String, String> grades = new Hashtable<String, String>();
    System.out.println("Size of table: " + grades.size());
    System.out.println("Key Alan exists: " + grades.containsKey("Alan"));
    System.out.println("Value B+ exists: " + grades.containsValue("B+"));
    grades.put("Alan", "A");
    grades.put("Mark", "B+");
    grades.put("Tom", "C");
    System.out.println("Size of table: " + grades.size());
    System.out.println("Key Alan exists: " + grades.containsKey("Alan"));
    System.out.println("Key Mark exists: " + grades.containsKey("Mark"));
    System.out.println("Key Tom exists: " + grades.containsKey("Tom"));
    System.out.println("Key Simon exists: " + grades.containsKey("Simon"));
    System.out.println("Value A exists: " + grades.containsValue("A"));
    System.out.println("Value B+ exists: " + grades.containsValue("B+"));
    System.out.println("Value C exists: " + grades.containsValue("C"));
    System.out.println("Value A+ exists: " + grades.containsValue("A+"));
    System.out.println("Value of existing key Alan: " + grades.get("Alan"));
    System.out.println("Value of existing key Mark: " + grades.get("Mark"));
    System.out.println("Value of existing key Tom: " + grades.get("Tom"));
    System.out.println("Value of non-existing key Simon: " + grades.get("Simon"));
    grades.put("Mark", "F");
    System.out.println("Value of existing key Mark: " + grades.get("Mark"));
    grades.remove("Alan");
    System.out.println("Key Alan exists: " + grades.containsKey("Alan"));
    System.out.println("Value of non-existing key Alan: " + grades.get("Alan"));
  }
}
```


Tutorial Videos

- Use of `ArrayList`:

  https://www.youtube.com/watch?v=SJjZM2DKA3M&index=2&list=PL5dxAmCmjv_4rOxjfTfIxNp42vO8SnT8n
- Use of `HashMap`:

  https://www.youtube.com/watch?v=_PV7dP5aIMg&list=PL5dxAmCmjv_4rOxjfTfIxNp42vO8SnT8n&index=3
- iPad Notes:

  https://www.eecs.yorku.ca/~jackie/teaching/tutorials/notes/Tutorial%20on%20Java%20Collections.pdf

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Recursion

EECS2030 B: Advanced Object Oriented Programming
Fall 2019

CHEN-WEI WANG

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.

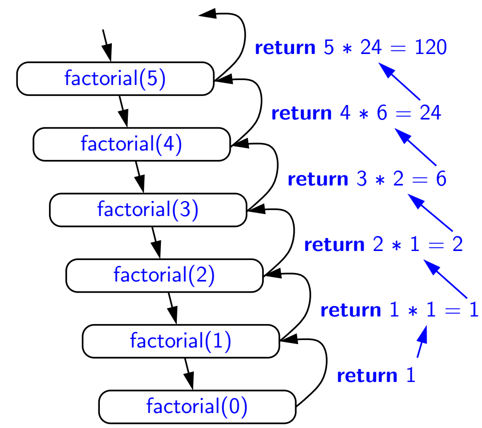
- Recursive Calls on Non-Smaller Problem Instances.

```
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 (1)

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

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

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


Recursion: Fibonacci (2)

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


Java Library: String

```
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.

```
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)

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


Recursion: Reverse of String (1)

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

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

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

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

Recursive Case: String of length ≥ 2 ⟶

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

Return the concatenation of **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[0] = a[i - 1]; }
    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 positive*.

Recursion: Is an Array Sorted? (2)

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

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


Recursive Methods: Correctness Proofs

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

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

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

Recursion: Binary Search (1)

- **Searching Problem**

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

  Output: Whether or not *a* exists in the input list

- **An Efficient Recursive Solution**

  Base Case: Empty list $\longrightarrow$ *False*.

  Recursive Case: List of size $\geq 1 \longrightarrow$

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

Recursion: Binary Search (2)

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


Running Time: Binary Search (1)

We use *T(n)* to denote the running time function of a binary search, where *n* is the size of the input array.

$$\begin{cases} T(0) = 1 \\ T(1) = 1 \\ T(n) = T(\frac{n}{2}) + 1 \quad \text{where } n \geq 2 \end{cases}$$

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

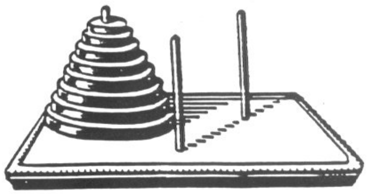
Running Time: Binary Search (2)

Without loss of generality, assume $n = 2^i$ for some non-negative *i*.

$$\begin{aligned} T(n) &= T(\tfrac{n}{2}) + 1 \\ &= \underbrace{(T(\frac{n}{4}) + 1)}_{T(\frac{n}{2})} + \underbrace{1}_{1 \text{ time}} \\ &= \underbrace{((T(\frac{n}{8}) + 1) + 1)}_{T(\frac{n}{4})} + \underbrace{1) + 1}_{2 \text{ times}} \\ &= \ldots \\ &= (\,((\underbrace{\quad 1 \quad}_{T(\frac{n}{2^{\log n}}) = T(1)}) + \underbrace{1)\ \ldots\ ) + 1}_{\log n \text{ times}} \end{aligned}$$

$\therefore T(n)$ is $O(\log n)$

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: A Recursive Solution

The general, recursive solution requires 3 steps:

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

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);
  }
}
```

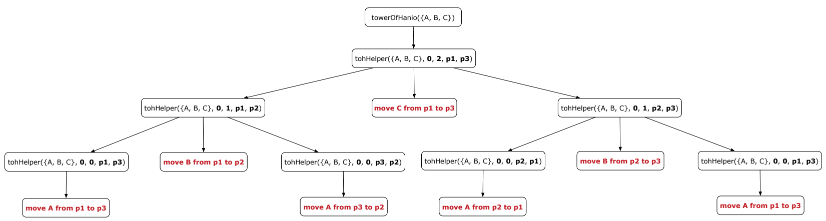
- `tohHelper(disks, from, to, ori, des)` moves disks $\{disks[from], disks[from+1], \dots, disks[to]\}$ from peg *ori* to peg *des*.
- Peg id's are 1, 2, and 3 ⇒ The intermediate one is 6 − *ori* − *des*.

Tower of Hanoi in Java (2)

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

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

Tower of Hanoi in Java (3)



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 different peg.
  2. Move the largest to the remaining free peg.
  3. Transfer the *n - 1* 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:

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

- 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)

$$\begin{aligned} T(n) &= 2 \times T(n-1) + 1 \\ &= 2 \times \underbrace{(2 \times T(n-2) + 1)}_{T(n-1)} + 1 \\ &= 2 \times (2 \times \underbrace{(2 \times T(n-3) + 1)}_{T(n-2)} + 1) + 1 \\ &= \dots \\ &= 2 \times (2 \times (2 \times \underbrace{(\dots \times \overbrace{(2 \times T(1) + 1)}^{T(2)} + \dots)}_{T(n-3)} + 1) + 1) + 1 \\ &= 2^{n-1} + (n-1) \end{aligned}$$

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

Recursion: Merge Sort

- **Sorting Problem**

  Input: A list of n numbers $\langle a_1, a_2, \dots, a_n \rangle$

  Output: A permutation (reordering) $\langle a'_1, a'_2, \dots, a'_n \rangle$ of the input list such that $a'_1 \le a'_2 \le \dots \le a'_n$
- **Recursive Solution**

  Base Case 1: Empty list $\longrightarrow$ Automatically sorted.

  Base Case 2: List of size 1 $\longrightarrow$ Automatically sorted.

  Recursive Case: List of size ≥ 2 $\longrightarrow$
  - Split the list into two (unsorted) halves: *L* and *R*;
  - **Recursively** sort *L* and *R*: *sortedL* and *sortedR*;
  - Return the *merge* of *sortedL* and *sortedR*.

Recursion: Merge Sort in Java (1)

```
/* Assumption:  L and R are both already sorted.  */
private List<Integer> merge(List<Integer> L, List<Integer> R) {
  List<Integer> merge = new ArrayList<>();
  if(L.isEmpty() || R.isEmpty()) { merge.addAll(L); merge.addAll(R); }
  else {
    int i = 0;
    int j = 0;
    while(i < L.size() && j < R.size()) {
      if( L.get(i) <= R.get(j) ) { merge.add(L.get(i)); i ++; }
      else { merge.add(R.get(j)); j ++; }
    }
    /* If i >= L.size(), then this for loop is skipped. */
    for(int k = i; k < L.size(); k ++) { merge.add(L.get(k)); }
    /* If j >= R.size(), then this for loop is skipped. */
    for(int k = j; k < R.size(); k ++) { merge.add(R.get(k)); }
  }
  return merge;
}
```

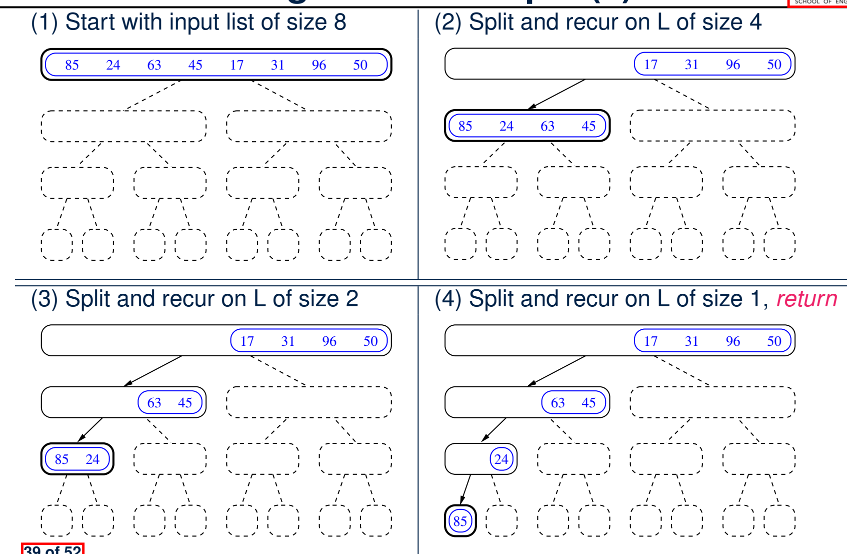
RT(merge)? [O(n)]

Recursion: Merge Sort in Java (2)

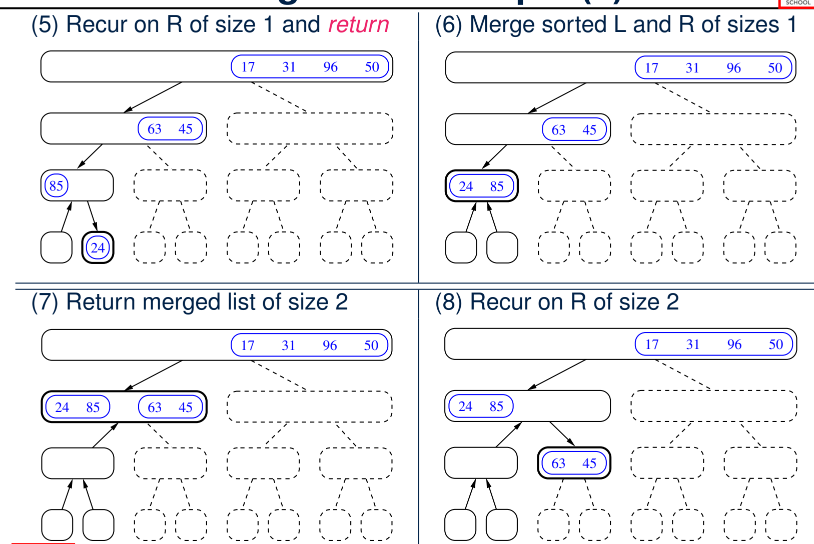
```
public List<Integer> sort (List<Integer> list) {
  List<Integer> sortedList;
  if(list.size() == 0) { sortedList = new ArrayList<>(); }
  else if(list.size() == 1) {
    sortedList = new ArrayList<>();
    sortedList.add(list.get(0));
  }
  else {
    int middle = list.size() / 2;
    List<Integer> left = list.subList(0, middle);
    List<Integer> right = list.subList(middle, list.size());
    List<Integer> sortedLeft = sort (left);
    List<Integer> sortedRight = sort (right);
    sortedList = merge (sortedLeft, sortedRight);
  }
  return sortedList;
}
```

$$RT(sort) = \underbrace{RT(merge)}_{O(n)} \times \underbrace{\texttt{\# splits until size 0 or 1}}_{O(\log n)}$$

Recursion: Merge Sort Example (1)

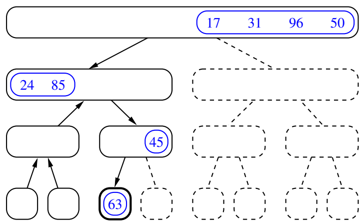


Recursion: Merge Sort Example (2)

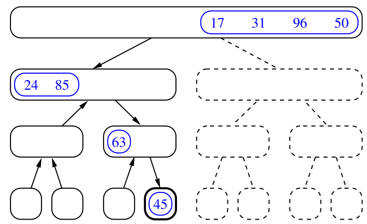


Recursion: Merge Sort Example (3)

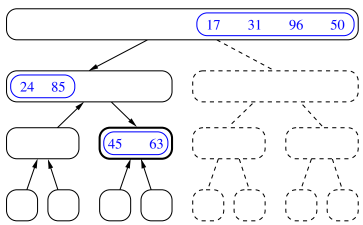
(9) Split and recur on L of size 1, *return*



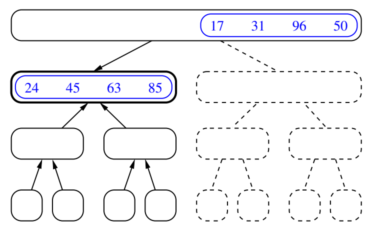
(10) Recur on R of size 1, *return*



(11) Merge sorted L and R of sizes 1, *return*

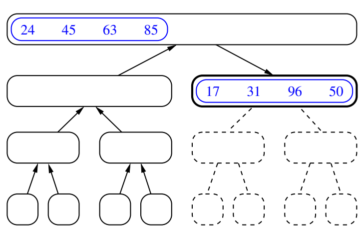


(12) Merge sorted L and R of sizes 2

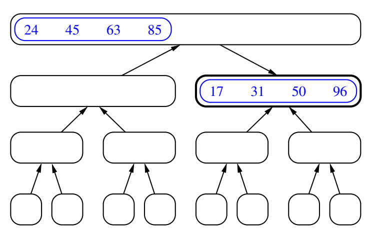


Recursion: Merge Sort Example (4)

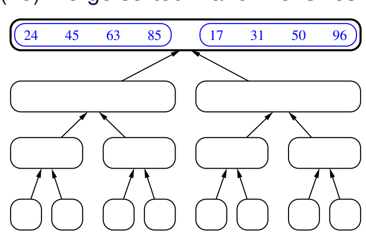
(13) Recur on R of size 4



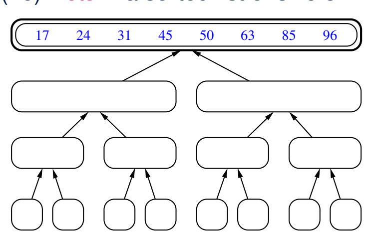
(14) *Return* a sorted list of size 4



(15) Merge sorted L and R of sizes 4

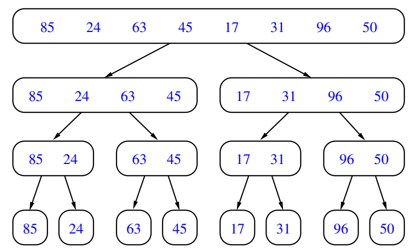


(16) *Return* a sorted list of size 8

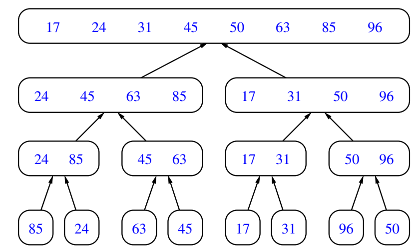


Recursion: Merge Sort Example (5)

(1) Recursion trees of *unsorted* lists



(2) Recursion trees of *sorted* lists



Recursion: Merge Sort Running Time (1)

Base Case 1: Empty list ⟶ Automatically sorted. [O(1)]

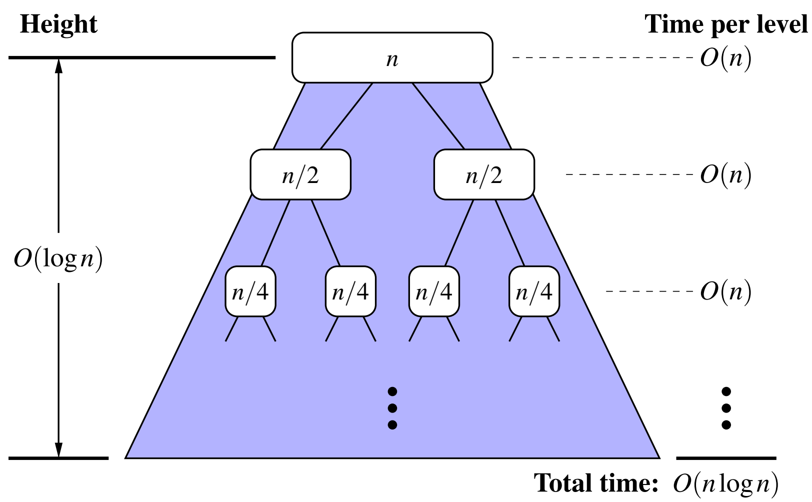
Base Case 2: List of size 1 ⟶ Automatically sorted. [O(1)]

Recursive Case: List of size ≥ 2 ⟶

- Split the list into two (unsorted) halves: *L* and *R*; [O(1)]
- **Recursively** sort *L* and *R*: *sortedL* and *sortedR*;
  How many times to split until *L* and *R* have size 0 or 1? [*O(log n)*]
- Return the *merge* of *sortedL* and *sortedR*. [*O(n)*]

```
  RT
= (RT each RC)                     × (# RCs)
= (RT merging sortedL and sortedR) × (# splits until bases)
= n · log n
```

Recursion: Merge Sort Running Time (2)



Recursion: Merge Sort Running Time (3)

We use *T(n)* to denote the running time function of a merge sort, where *n* is the size of the input list.

$$\begin{cases} T(0) = 1 \\ T(1) = 1 \\ T(n) = 2 \cdot T(\frac{n}{2}) + n \quad \texttt{where} \quad n \geq 2 \end{cases}$$

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

Recursion: Merge Sort Running Time (4)

Without loss of generality, assume $n = 2^i$ for some non-negative i.

$$\begin{aligned}
T(n) &= 2 \times T(\tfrac{n}{2}) + n \\
&= \underbrace{2 \times (2}_{\texttt{2 terms}} \times T(\tfrac{n}{4}) + \underbrace{\frac{n}{2}) + n}_{\texttt{2 terms}} \\
&= \underbrace{2 \times (2 \times (2}_{\texttt{3 terms}} \times T(\tfrac{n}{8}) + \underbrace{\frac{n}{4}) + \frac{n}{2}) + n}_{\texttt{3 terms}} \\
&= \dots \\
&= \underbrace{2 \times (2 \times (2 \times \dots \times (2}_{logn\ \texttt{terms}} \times T(\tfrac{n}{2^{logn}}) + \underbrace{\frac{n}{2^{logn-1}}) + \dots + \frac{n}{4}) + \frac{n}{2}) + n}_{logn\ \texttt{terms}} \\
&= 2^{logn} + \underbrace{(2 \cdot \frac{n}{2} + 2^2 \cdot \frac{n}{4} + \dots + 2^{logn-1} \cdot \frac{n}{2^{logn-1}} + n)}_{logn\ \texttt{terms}}
\end{aligned}$$

$\therefore T(n)$ is $O(n \cdot log\ n)$

Beyond this lecture . . .

- Notes on Recursion:
  `http://www.eecs.yorku.ca/~jackie/teaching/lectures/2019/F/EECS2030/slides/EECS2030_F19_Notes_Recursion.pdf`
- API for `String`:
  `https://docs.oracle.com/javase/8/docs/api/java/lang/String.html`
- Fantastic resources for sharpening your recursive skills for the exam:
  `http://codingbat.com/java/Recursion-1`
  `http://codingbat.com/java/Recursion-2`
- The *best* approach to learning about recursion is via a functional programming language:
  Haskell Tutorial: `https://www.haskell.org/tutorial/`

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Aggregation and Composition

EECS2030 B: Advanced Object Oriented Programming
Fall 2019

CHEN-WEI WANG

Aggregation vs. Composition: Terminology

Container object: an object that contains others.

Containee object: an object that is contained within another.

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

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

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

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

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

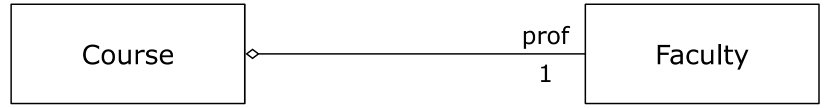
    e.g., Each file has exactly one parent directory.

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

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

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

Aggregation: Independent Containees Shared by Containers (1.1)




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

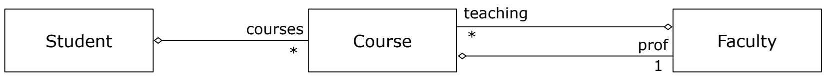
```java
class Faculty {
  String name;
  Faculty(String name) {
    this.name = name;
  }
  void setName(String name) {
    this.name = name;
  }
  String getName() {
    return this.name;
  }
}
```


Aggregation: Independent Containees Shared by Containers (1.2)

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

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

Aggregation: Independent Containees Shared by Containers (2.1)




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

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

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

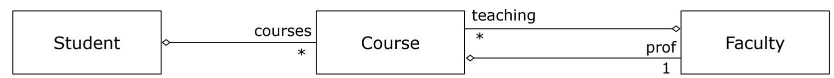

Aggregation: Independent Containees Shared by Containers (2.2)

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

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


The Dot Notation (3.1)

In real life, the relationships among classes are sophisticated.




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

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

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

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

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

The Dot Notation (3.2)

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

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

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

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

The Dot Notation (3.3)

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

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

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

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


The Dot Notation (3.4)

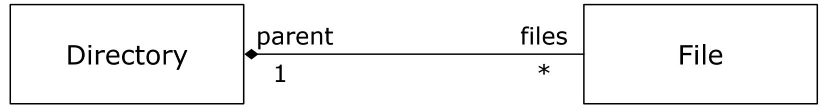
```
class Student {
  String id;
  ArrayList<Course> cs;
}
```

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

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

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


Composition: Dependent Containees Owned by Containers (1.1)

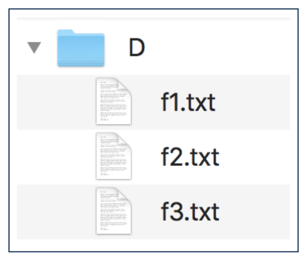


Assumption: Files are not shared among directories.

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

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


Composition: Dependent Containees Owned by Containers (1.2.1)

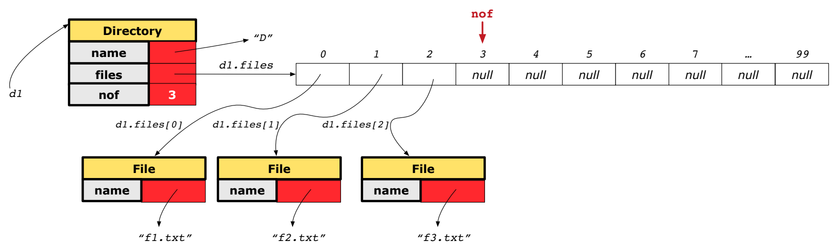



```
1 @Test
2 public void testComposition() {
3   Directory d1 = new Directory("D");
4   d1.addFile("f1.txt");
5   d1.addFile("f2.txt");
6   d1.addFile("f3.txt");
7   assertTrue(
8     d1.files[0].name.equals("f1.txt"));
9 }
```

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

Composition: Dependent Containees Owned by Containers (1.2.2)

Right before test method `testComposition` terminates:



Composition: Dependent Containees Owned by Containers (1.3)

Problem: Implement a *copy constructor* for `Directory`.

A ***copy constructor*** is a constructor which initializes attributes from the argument object `other`.

```
class Directory {
  Directory(Directory other) {
    /* Initialize attributes via attributes of 'other'. */
  }
}
```

Hints:

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

Composition: Dependent Containees Owned by Containers (1.4.1)

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

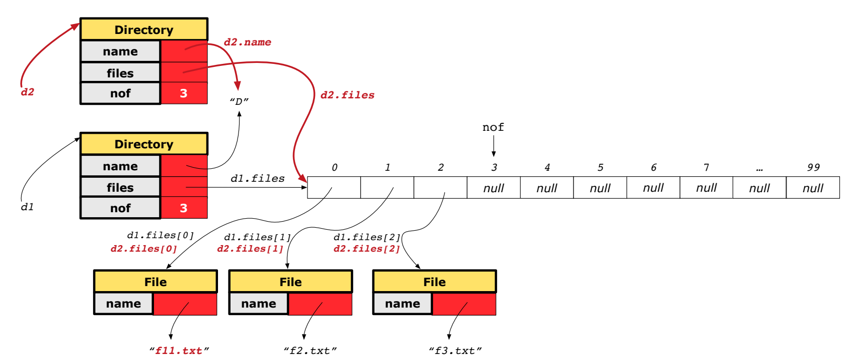
```
class Directory {
 Directory(Directory other) {
   /* value copying for primitive type */
   nof = other.nof;
   /* address copying for reference type */
   name = other.name; files = other.files; } }
```

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

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


Composition: Dependent Containees Owned by Containers (1.4.2)

Right before test method `testShallowCopyConstructor` terminates:



Composition: Dependent Containees Owned by Containers (1.5.1)

Version 2: a *Deep Copy*

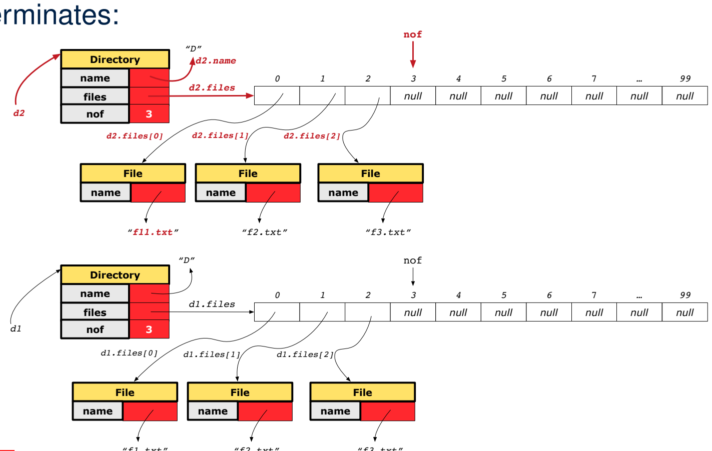
```
class File {
  File(File other) {
    this.name =
      new String(other.name);
  }
}
```

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

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


Composition: Dependent Containees Owned by Containers (1.5.2)

Right before test method `testDeepCopyConstructor` terminates:



Composition: Dependent Containees Owned by Containers (1.5.3)

Q: Composition Violated?

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

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

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


Composition: Dependent Containees Owned by Containers (1.6)

Exercise: Implement the accessor in class `Directory`

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

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

Aggregation vs. Composition (1)

Terminology:

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

Aggregation :

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

Composition :

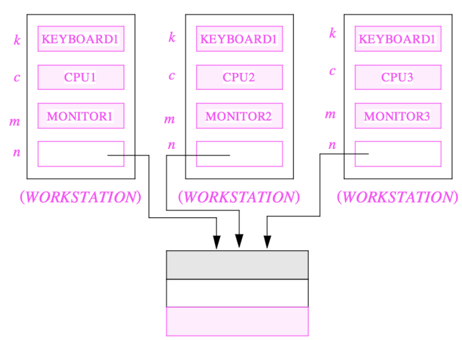
- Containers (e.g, `Directory`, `Department`) *own* exclusive access to their containees (e.g., `File`, `Faculty`).
- Containees cannot exist without their containers.
- Destroying a container destroys its containeees *cascadingly*.

Aggregation vs. Composition (2)

Aggregations and *Compositions* may exist at the same time!

e.g., Consider a workstation:

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



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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.

Inheritance

EECS2030 B: Advanced Object Oriented Programming
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YORK UNIVERSITÉ UNIVERSITY

No Inheritance: `ResidentStudent` Class

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

No Inheritance: `NonResidentStudent` Class

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


No Inheritance: Testing Student Classes

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

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


No Inheritance: Issues with the Student Classes

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

No Inheritance: Maintainability of Code (1)

What if the way for registering a course changes?

e.g.,

```
void register(Course c) {
  if (numberOfCourses >= MAX_ALLOWANCE) {
    throw new IllegalArgumentException("Too many courses");
  }
  else {
    registeredCourses[numberOfCourses] = c;
    numberOfCourses ++;
  }
}
```

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

No Inheritance: Maintainability of Code (2)

What if the way for calculating the base tuition changes?

e.g.,

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

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

No Inheritance: A Collection of Various Kinds of Students

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

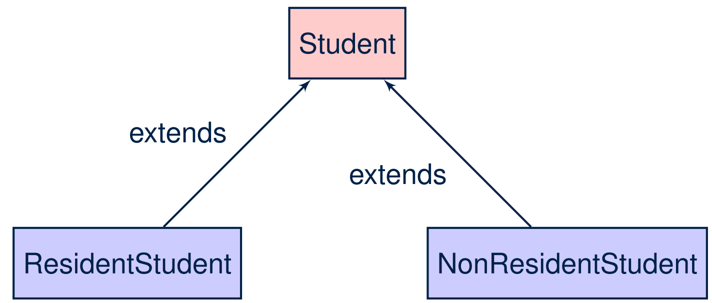
```
class StudentManagementSystem {
  ResidentStudent[] rss;
  NonResidentStudent[] nrss;
  int nors; /* number of resident students */
  int nonrs; /* number of non-resident students */
  void addRS(ResidentStudent rs){ rss[nors]=rs; nors++; }
  void addNRS(NonResidentStudent nrs){ nrss[nonrs]=nrs;nonrs++;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

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

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

a polymorphic collection of students

Inheritance Architecture



Inheritance: The `Student` Parent/Super Class

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

Inheritance: The `ResidentStudent` Child/Sub Class

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

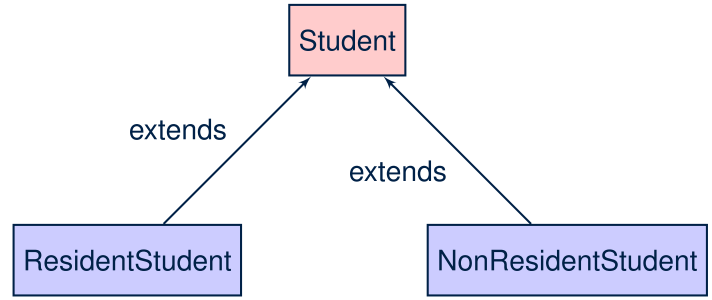
- **L1** declares that `ResidentStudent` inherits all attributes and methods (except constructors) from `Student`.
- There is no need to repeat the `register` method
- Use of *super* in **L4** is as if calling `Student(name)`
- Use of *super* in **L8** returns what `getTuition()` in `Student` returns.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

Inheritance: The `NonResidentStudent` Child/Sub Class

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

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

Inheritance Architecture Revisited



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

Using Inheritance for Code Reuse

Inheritance in Java allows you to:

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

Visualizing Parent/Child Objects (1)

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

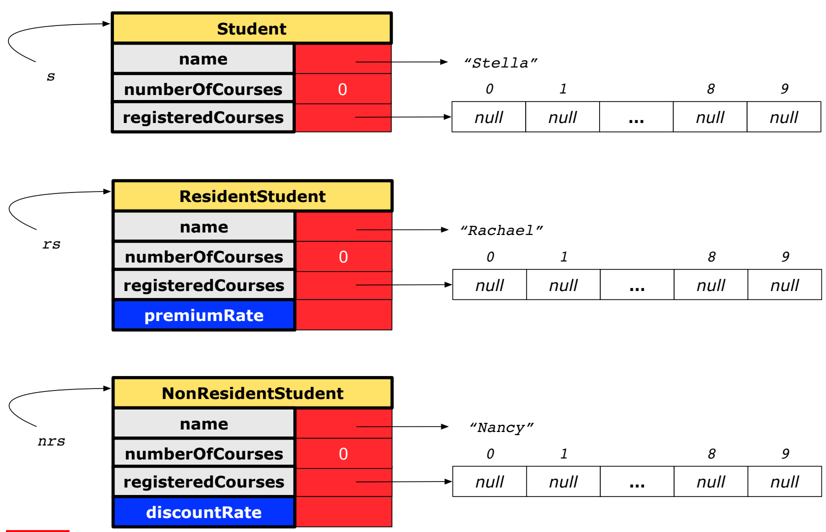
  ⇒ A child instance has ***at least as many*** attributes as an instance of its parent class.

  Consider the following instantiations:

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

- How will these initial objects look like?

Visualizing Parent/Child Objects (2)

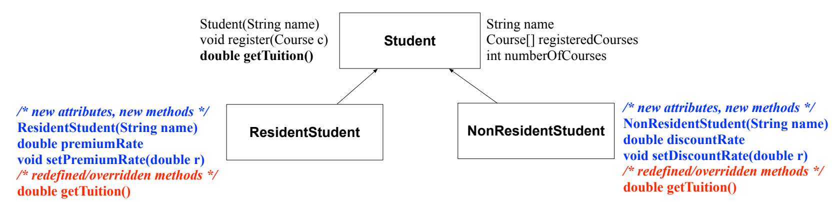


Testing the Two Student Sub-Classes

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

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

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)

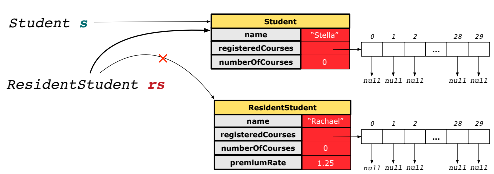
```
1 Student s = new Student("Stella");
2 ResidentStudent rs = new ResidentStudent("Rachael");
3 rs.setPremiumRate(1.25);
4 s = rs; /* Is this valid? */
5 rs = s; /* Is this valid? */
```

- 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*:

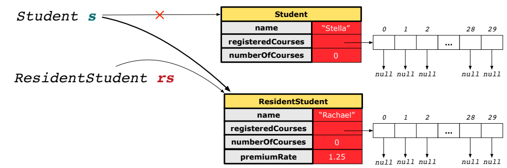


- Since *rs* is declared of type `ResidentStudent`, a subsequent call `rs.setPremiumRate(1.50)` can be expected.
- *rs* is now pointing to a `Student` object.
- Then, what would happen to `rs.setPremiumRate(1.50)`?
  CRASH ∵ `rs.premiumRate` is *undefined*!!

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*:

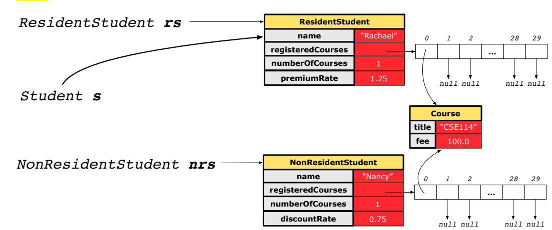


- Since *s* is declared of type `Student`, a subsequent call `s.setPremiumRate(1.50)` is *never* expected.
- *s* is now pointing to a `ResidentStudent` object.
- Then, what would happen to `s.getTuition()`?
  OK ∵ `s.premiumRate` is *never directly used*!!

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

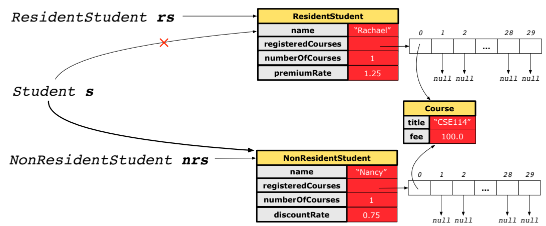
After `s = rs` (**L7**), `s` points to a `ResidentStudent` object.
⇒ Calling `s.getTuition()` applies the `premiumRate`.



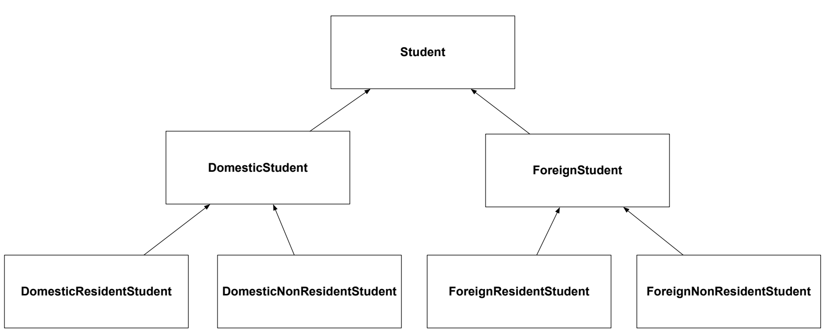
Dynamic Binding: Intuition (2)

```
1 Course eecs2030 = new Course("EECS2030", 100.0);
2 Student s;
3 ResidentStudent rs = new ResidentStudent("Rachael");
4 NonResidentStudent nrs = new NonResidentStudent("Nancy");
5 rs.setPremiumRate(1.25); rs.register(eecs2030);
6 nrs.setDiscountRate(0.75); nrs.register(eecs2030);
7 s = rs; System.out.println( s .getTuition()); /* output: 125.0 */
8 s = nrs; System.out.println( s .getTuition()); /* output: 75.0 */
```

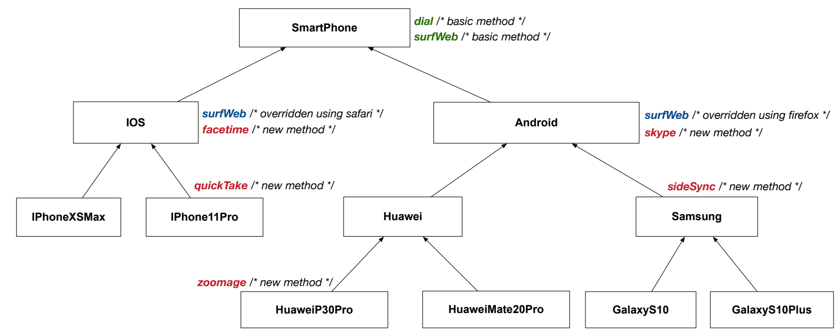
After `s = nrs` (**L8**), `s` points to a `NonResidentStudent` object.
⇒ Calling `s.getTuition()` applies the `discountRate`.



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

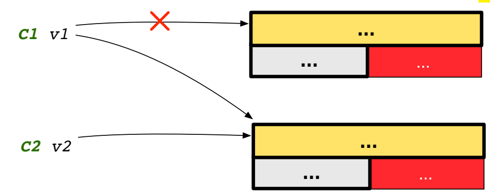
- The *lower* a class is in the type hierarchy, the *more code* it accumulates from its *ancestor classes*:
  - A *descendant class* inherits all code from its *ancestor classes*.
  - A *descendant class* may also:
    - Declare new attributes
    - Define new methods
    - *Redefine* / *Override* inherited 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).
  - When expecting 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 `IPhone11Pro` 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* *C* defines the *expected usages of v as a context object*.
- A method call `v.m(...)` is ***compilable*** if ***m*** is defined in *C*.
  - e.g., After declaring `Student jim`, we
    - **may** call `register` and `getTuition` on `jim`
    - **may *not*** call `setPremiumRate` (specific to a resident student) or `setDiscountRate` (specific to a non-resident student) on `jim`
  - e.g., After declaring `SmartPhone myPhone`, we
    - **may** call `dial` and `surfWeb` on `myPhone`
    - **may *not*** call `facetime` (specific to an IOS phone) or `skype` (specific to an Android phone) on `myPhone`

Substitutions via Assignments

- By declaring ***C1*** `v1`, *reference variable* `v1` will store the *address* of an object "of class `C1`" at runtime.
- By declaring ***C2*** `v2`, *reference variable* `v2` will store the *address* of an object "of class `C2`" at runtime.
- Assignment `v1 = v2` *copies address* stored in `v2` into `v1`.
  - `v1` will instead point to wherever `v2` is pointing to. [*object alias*]



- In such assignment `v1 = v2`, we say that we *substitute* an object of (*static*) type `C1` by an object of (*static*) type `C2`.
- *Substitutions* are subject to *rules*!

Rules of Substitution

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

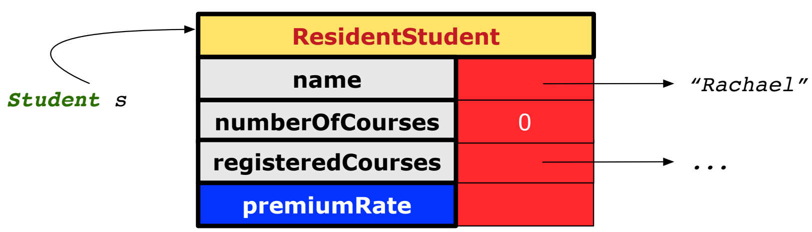
- It is *safe* to *substitute* it with an object whose ***static type*** is any of the *descendant class* of `A` (including `A`).
  - ∵ Each *descendant class* of `A`, being the new substitute, is guaranteed to contain all (non-private) attributes/methods defined in `A`.
  - e.g., When expecting an `IOS` phone, you *can* substitute it with either an `IPhoneXSMax` or `IPhone11Pro`.
- 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 `HuaweiP30Pro` ∵ `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 {...}
```

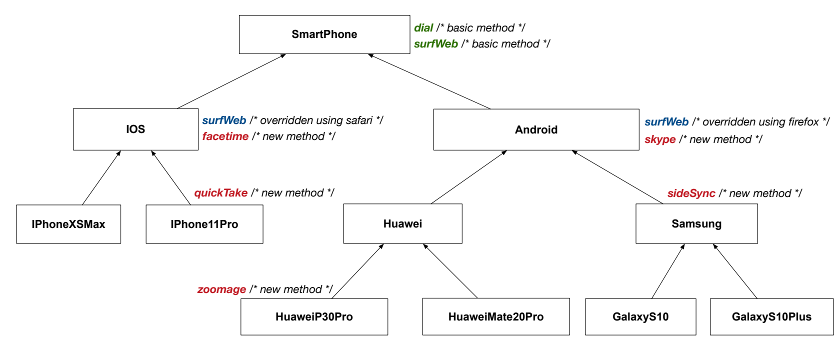
```
class StudentTester1 {
  public static void main(String[] args) {
    Student jim = new Student("J. Davis");
    ResidentStudent rs = new ResidentStudent("J. Davis");
    jim = rs; /* legal */
    rs = jim; /* illegal */

    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 IPhoneXSMax();
    Samsung ss = new GalaxyS10Plus();
    myPhone = ip;  /* legal */
    myPhone = ss;  /* legal */

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


Polymorphism and Dynamic Binding (3.3)

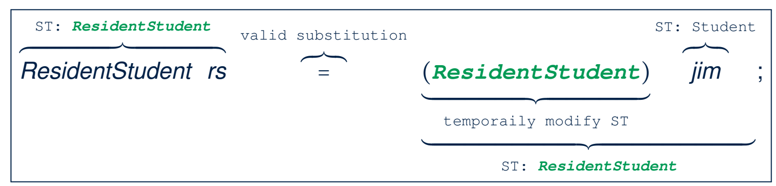
```
class SmartPhoneTest2 {
  public static void main(String[] args) {
    SmartPhone myPhone;
    IOS ip = new IPhone11Pro();
    myPhone = ip;
    myPhone.surfWeb();  /* version of surfWeb in IPhone11Pro */

    Samsung ss = new GalaxyS10();
    myPhone = ss;
    myPhone.surfWeb();  /* version of surfWeb in GalaxyS10 */
  }
}
```


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` on the **RHS of =** temporarily modifies `jim`'s ***ST*** to `ResidentStudent`.
  - Alias `rs` of ***ST*** `ResidentStudent` is then created via an assignment.
- *dynamic binding* : After the *cast* , **L3** will execute the correct version of `setPremiumRate`.

Reference Type Casting: Motivation (1.2)



- Variable `rs` is declared of ***static type*** (***ST***) `ResidentStudent`.
- Variable `jim` is declared of ***ST*** `Student`.
- The cast expression `(ResidentStudent) jim` *temporarily* modifies `jim`'s ***ST*** to `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 IPhone11Pro();
2 IOS forHeeyeon = aPhone;
3 forHeeyeon.facetime();
```

- **L1** is *legal*: `IPhone11Pro` is a **descendant class** of the ***static type*** of `aPhone` (i.e., `SmartPhone`).
- **L2** is *illegal*: `aPhone`'s ***ST*** (i.e., `SmartPhone`) is ***not*** a **descendant class** of `forHeeyeon`'s ***ST*** (i.e., `IOS`).
  Java compiler is *unable to infer* that `aPhone`'s ***dynamic type*** in **L2** is `IPhone11Pro`!
- Force Java compiler to believe so via a *cast* in **L2**:
  `IOS forHeeyeon = (IPhone11Pro) aPhone;`
  - The cast `(IPhone11Pro) aPhone` on the **RHS of =** temporarily modifies `aPhone`'s ***ST*** to `IPhone11Pro`.
  - Alias `forHeeyeon` of ***ST*** `IOS` is then created via an assignment.
- *dynamic binding*: After the *cast*, **L3** will execute the correct version of `facetime`.

Reference Type Casting: Motivation (2.2)

```
ST: IOS                  valid substitution                ST: SmartPhone
IOS forHeeyeon                   =           (IPhone11Pro)   aPhone        ;
                                             temporaily modify ST
                                                        ST: IPhone11Pro
```

- Variable `forHeeyeon` is declared of ***static type*** (***ST***) `IOS`.
- Variable `aPhone` is declared of ***ST*** `SmartPhone`.
- The cast expression `(IPhone11Pro) aPhone` *temporarily* modifies `aPhone`'s ***ST*** to `IPhone11Pro`.
  ⇒ Such a cast makes the assignment valid.
  ∵ RHS's ***ST*** (`IPhone11Pro`) is a descendant of LHS's ***ST*** (`IOS`).
  ⇒ The assignment creates an alias `forHeeyeon` with ***ST*** `IOS`.
- **No** new object is created.
  Only an *alias* `forHeeyeon` with a different ***ST*** (`IOS`) 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 IPhone11Pro();
IOS forHeeyeon = (IPhone11Pro) aPhone;
forHeeyeon.facetime();
```

Anonymous Cast: Use the cast result directly.

```
SmartPhone aPhone = new IPhone11Pro();
((IPhone11Pro) aPhone).facetime();
```

Common Mistake:

```
1 SmartPhone aPhone = new IPhone11Pro();
2 (IPhone11Pro) aPhone.facetime();
```

L2 ≡ `(IPhone11Pro) (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 **temporarily** changes the ***ST*** of v from ST_v to C.
  ⇒ All methods that are defined in C can be called.

```
Android myPhone = new GalaxyS10Plus();
/* 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  × */
GalaxyS10Plus ga = (GalaxyS10Plus) myPhone;
/* Compiles OK ∵ GalaxyS10Plus is a descendant class of Android
 * expectations on ga widened to methods in GalaxyS10Plus
 * 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 GalaxyS10Plus();
2 IPhone11Pro forHeeyeon = (IPhone11Pro) aPhone;
3 forHeeyeon.quickTake();
```

- **L1** is *legal*: `GalaxyS10Plus` 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 (`IPhone11Pro`).
- **L3** is *legal* ∵ `quickTake` is in `forHeeyeon`' ***ST*** `IPhone11Pro`.
- Java compiler is *unable to infer* that `aPhone`'s *dynamic type* in **L2** is actually `NonResidentStudent`.
- Executing **L2** will result in a *`ClassCastException`*.
  ∵ Methods `facetime`, `quickTake` (expected from an ***IPhone11Pro***) is *undefined* on the ***GalaxyS10Plus*** 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 GalaxyS10Plus ga = (GalaxyS10Plus) myPhone;
4 /* Compiles OK ∵ GalaxyS10Plus is a descendant class of SmartPhone
5  * can now call methods declared in GalaxyS10Plus 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* `GalaxyS10Plus` (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 IPhone11Pro ip = (IPhone11Pro) myPhone;
4 /* Compiles OK ∵ IPhone11Pro is a descendant class of SmartPhone
5  * can now call methods declared in IPhone11Pro 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* `IPhone11Pro` (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., `GalaxyS10Plus`) will cause `ClassCastException`.
- Casting `myPhone` to a class irrelevant to its ***DT Samsung*** (e.g., `HuaweiMate20Pro`) will cause `ClassCastException`.

Required Reading: Static Types, Dynamic Types, Casts

https://www.eecs.yorku.ca/~jackie/teaching/lectures/2019/F/EECS2030/notes/EECS2030_F19_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 *dynamic type* is `ResidentStudent`.

  FALSE ∵ `jim`'s *dynamic type* is `NonResidentStudent`!
- **L3** is *legal*: `jim`'s cast type (i.e., `ResidentStudent`) is a **descendant class** of `rs`'s ***static type*** (i.e., `ResidentStudent`).
- **L3** will not be executed at runtime, hence no `ClassCastException`, thanks to the check in **L2**!

Reference Type Casting: Runtime Check (2)

```
1 SmartPhone aPhone = new GalaxyS10Plus();
2 if (aPhone instanceof IPhone11Pro) {
3   IOS forHeeyeon = (IPhone11Pro) aPhone;
4   forHeeyeon.facetime();
5 }
```

- **L1** is *legal*: `GalaxyS10Plus` is a **descendant class** of the static type of `aPhone` (i.e., `SmartPhone`).
- **L2** checks if `aPhone`'s *dynamic type* is `IPhone11Pro`.

  FALSE ∵ `aPhone`'s *dynamic type* is `GalaxyS10Plus`!
- **L3** is *legal*: `aPhone`'s cast type (i.e., `IPhone11Pro`) 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 GalaxyS10);
/* false ∵ Samsung is not a descendant of GalaxyS10 */
println(myPhone instanceof IOS);
/* false ∵ Samsung is not a descendant of IOS */
println(myPhone instanceof IPhone11Pro);
/* false ∵ Samsung is not a descendant of IPhone11Pro */
```

⇒ ***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 GalaxyS10Plus) {
7    GalaxyS10Plus galaxy = (GalaxyS10Plus) myPhone;
8  }
9  if(myphone instanceof HuaweiMate20Pro) {
10   Huawei hw = (HuaweiMate20Pro) myPhone;
11 }
```

- **L3** evaluates to *true*. [*safe* to cast]
- **L6** and **L9** evaluate to *false*. [*unsafe* to cast]

  This prevents **L7** and **L10**, causing `ClassCastException` if executed, from being executed.

Static Type and Polymorphism (1.1)

```
class SmartPhone {
  void dial() { ... }
}
class IOS extends SmartPhone {
  void facetime() { ... }
}
class IPhone11Pro extends IOS {
  void quickTake() { ... }
}
```

```
SmartPhone sp = new IPhone11Pro();   ✓
sp.dial();   ✓
sp.facetime();   ×
sp.quickTake();   ×
```

Static type of *sp* is `SmartPhone`

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

Static Type and Polymorphism (1.2)

```
class SmartPhone {
  void dial() { ... }
}
class IOS extends SmartPhone {
  void facetime() { ... }
}
class IPhone11Pro extends IOS {
  void quickTake() { ... }
}
```

```
IOS ip = new IPhone11Pro();   ✓
ip.dial();   ✓
ip.facetime();   ✓
ip.quickTake();   ×
```

Static type of *ip* is `IOS`

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

Static Type and Polymorphism (1.3)

```
class SmartPhone {
  void dial() { ... }
}
class IOS extends SmartPhone {
  void facetime() { ... }
}
class IPhone11Pro extends IOS {
  void quickTake() { ... }
}
```

```
IPhone11Pro ip6sp = new IPhone11Pro();   ✓
ip6sp.dial();   ✓
ip6sp.facetime();   ✓
ip6sp.quickTake();   ✓
```

Static type of *ip6sp* is `IPhone11Pro`

⇒ can call all methods defined in `IPhone11Pro` on *ip6sp*

Static Type and Polymorphism (1.4)

```
class SmartPhone {
  void dial() { ... }
}
class IOS extends SmartPhone {
  void facetime() { ... }
}
class IPhone11Pro extends IOS {
  void quickTake() { ... }
}
```

```
1 SmartPhone sp = new IPhone11Pro();   ✓
2 ((IPhone11Pro) sp).dial();   ✓
3 ((IPhone11Pro) sp).facetime();   ✓
4 ((IPhone11Pro) sp).quickTake();   ✓
```

L4 is equivalent to the following two lines:

```
IPhone11Pro ip6sp = (IPhone11Pro) sp;
ip6sp.quickTake();
```


Static Type and Polymorphism (2)

Given a reference variable declaration

```
C v;
```

- *Static type* of reference variable *v* is class *C*
- A method call `v.m` is valid if *m* is a method **defined** in class ***C***.
- Despite the *dynamic type* of *v*, you are only allowed to call methods that are defined in the *static type* `C` on *v*.
- If you are certain that *v*'s *dynamic type* can be expected **more** than its *static type*, then you may use an `insanceof` check and a cast.

```
Course eecs2030 = new Course("EECS2030", 500.0);
Student s = new ResidentStudent("Jim");
s.register(eecs2030);
if(s instanceof ResidentStudent) {
  ((ResidentStudent) s).setPremiumRate(1.75);
  System.out.println(((ResidentStudent) s).getTuition());
}
```

Polymorphism: Method Call Arguments (1)

```
1 class StudentManagementSystem {
2   Student [] ss; /* ss[i] has static type Student */ int c;
3   void addRS(ResidentStudent rs) { ss[c] = rs; c ++; }
4   void addNRS(NonResidentStudent nrs) { ss[c] = nrs; c++; }
5   void addStudent(Student s) { ss[c] = s; c++; } }
```

- **L3**: `ss[c] = rs` is valid. ∵ RHS's ST `ResidentStudent` is a *descendant class* of LHS's ST `Student`.
- Say we have a `StudentManagementSystem` object `sms`:
  - `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 Call Arguments (2.1)

In the `StudentManagementSystemTester`:

```
Student s1 = new Student();
Student s2 = new ResidentStudent();
Student s3 = new NonResidentStudent();
ResidentStudent rs = new ResidentStudent();
NonResidentStudent nrs = new NonResidentStudent();
StudentManagementSystem sms = new StudentManagementSystem();
sms.addRS(s1);   ×
sms.addRS(s2);   ×
sms.addRS(s3);   ×
sms.addRS(rs);   ✓
sms.addRS(nrs);   ×
sms.addStudent(s1);   ✓
sms.addStudent(s2);   ✓
sms.addStudent(s3);   ✓
sms.addStudent(rs);   ✓
sms.addStudent(nrs);   ✓
```


Polymorphism: Method Call Arguments (2.2)

In the `StudentManagementSystemTester`:

```
1 Student s = new Student("Stella");
2 /* s' ST: Student; s' DT: Student */
3 StudentManagementSystem sms = new StudentManagementSystem();
4 sms.addRS(s); ×
```

- **L4** ***compiles*** with a cast: `sms.addRS((ResidentStudent) s)`
  - *Valid* cast ∵ `(ResidentStudent)` is a descendant of `s`' ***ST***.
  - *Valid* call ∵ `s`' temporary ***ST*** (`ResidentStudent`) is now a descendant class of `addRS`'s parameter `rs`' ***ST*** (`ResidentStudent`).
- But, there will be a `ClassCastException` at runtime!
  ∵ `s`' ***DT*** (`Student`) is **not** a descendant of `ResidentStudent`.
- We should have written:

  ```
  if(s instanceof ResidentStudent) {
    sms.addRS((ResidentStudent) s);
  }
  ```

  The **`instanceof`** expression will evaluate to *false*, meaning it is *unsafe* to cast, thus preventing `ClassCastException`.

Polymorphism: Method Call Arguments (2.3)

In the `StudentManagementSystemTester`:

```
1 Student s = new NonResidentStudent("Nancy");
2 /* s' ST: Student; s' DT: NonResidentStudent */
3 StudentManagementSystem sms = new StudentManagementSystem();
4 sms.addRS(s); ×
```

- **L4** ***compiles*** with a cast: `sms.addRS((ResidentStudent) s)`
  - *Valid* cast ∵ `(ResidentStudent)` is a descendant of `s`' ***ST***.
  - *Valid* call ∵ `s`' temporary ***ST*** (`ResidentStudent`) is now a descendant class of `addRS`'s parameter `rs`' ***ST*** (`ResidentStudent`).
- But, there will be a `ClassCastException` at runtime!
  ∵ `s`' ***DT*** (`NonResidentStudent`) **not** descendant of `ResidentStudent`.
- We should have written:

  ```
  if(s instanceof ResidentStudent) {
    sms.addRS((ResidentStudent) s);
  }
  ```

  The **`instanceof`** expression will evaluate to *false*, meaning it is *unsafe* to cast, thus preventing `ClassCastException`.

Polymorphism: Method Call Arguments (2.4)

In the `StudentManagementSystemTester`:

```
1 Student s = new ResidentStudent("Rachael");
2 /* s' ST: Student; s' DT: ResidentStudent */
3 StudentManagementSystem sms = new StudentManagementSystem();
4 sms.addRS(s); ×
```

- **L4 *compiles*** with a cast: `sms.addRS((ResidentStudent) s)`
  - *Valid* cast ∵ `(ResidentStudent)` is a descendant of `s`' ***ST***.
  - *Valid* call ∵ `s`' temporary ***ST*** (`ResidentStudent`) is now a descendant class of `addRS`'s parameter `rs`' ***ST*** (`ResidentStudent`).
- And, there will be **no** `ClassCastException` at runtime!
  ∵ `s`' ***DT*** (`ResidentStudent`) is descendant of `ResidentStudent`.
- We should have written:

```
if(s instanceof ResidentStudent) {
  sms.addRS((ResidentStudent) s);
}
```

The **`instanceof`** expression will evaluate to *true*, meaning it is *safe* to cast.

Polymorphism: Method Call Arguments (2.5)

In the `StudentManagementSystemTester`:

```
1 NonResidentStudent nrs = new NonResidentStudent();
2 /* ST: NonResidentStudent; DT: NonResidentStudent */
3 StudentManagementSystem sms = new StudentManagementSystem();
4 sms.addRS(nrs); ×
```

Will **L4** with a cast compile? `sms.addRS( (ResidentStudent) nrs)`

NO ∵ `(ResidentStudent)` is ***not*** a descendant of `nrs`'s ***ST*** (`NonResidentStudent`).

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)
    }
  }
}
```

a collection of students without inheritance

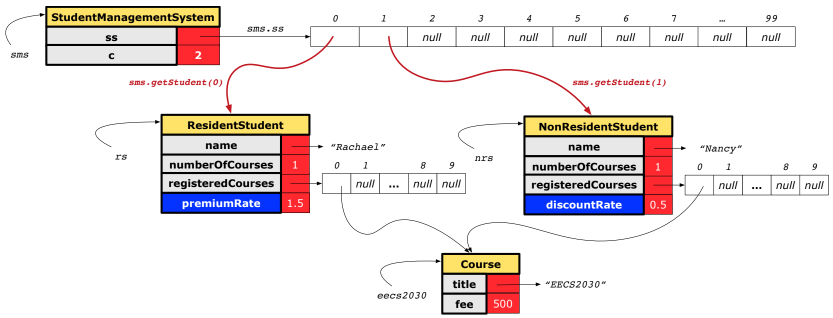
Polymorphism and Dynamic Binding: A Polymorphic Collection of Students (1)

```
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 Values (1)

```
1  class StudentManagementSystem {
2    Student[] ss; int c;
3    void addStudent(Student s) { ss[c] = s; c++; }
4    Student getStudent(int i) {
5      Student s = null;
6      if(i < 0 || i >= c) {
7        throw new IllegalArgumentException("Invalid index.");
8      }
9      else {
10       s = ss[i];
11     }
12     return s;
13 } }
```

L4: `Student` is ***static type*** of `getStudent`'s return value.
L10: `ss[i]`'s ST (`Student`) is **descendant** of `s`' ST (`Student`).
Question: What can be the ***dynamic type*** of `s` after **L10**?
Answer: All descendant classes of `Student`.

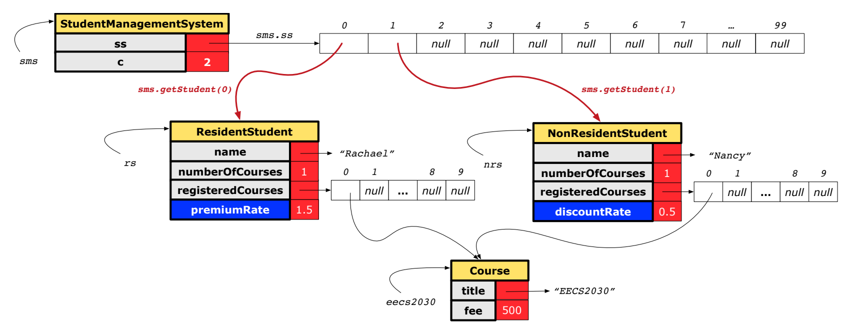
Polymorphism: Return Values (2)

```
Course eecs2030 = new Course("EECS2030", 500);
ResidentStudent rs = new ResidentStudent("Rachael");
rs.setPremiumRate(1.5); rs.register(eecs2030);
NonResidentStudent nrs = new NonResidentStudent("Nancy");
nrs.setDiscountRate(0.5); nrs.register(eecs2030);
StudentManagementSystem sms = new StudentManagementSystem();
sms.addStudent(rs); sms.addStudent(nrs);
Student s = sms.getStudent(0) ; /* dynamic type of s? */
                static return type: Student
print(s instanceof Student && s instanceof ResidentStudent);/*true*/
print(s instanceof NonResidentStudent); /* false */
print( s.getTuition() );/*Version in ResidentStudent called:750*/
ResidentStudent rs2 = sms.getStudent(0); ×
s = sms.getStudent(1) ; /* dynamic type of s? */
                static return type: Student
print(s instanceof Student && s instanceof NonResidentStudent);/*true*/
print(s instanceof ResidentStudent); /* false */
print( s.getTuition() );/*Version in NonResidentStudent called:250*/
NonResidentStudent nrs2 = sms.getStudent(1); ×
```


Polymorphism: Return Values (3)

At runtime, attribute `sms.ss` is a *polymorphic* array:

- ***Static type*** of each item is as declared: ***Student***
- ***Dynamic type*** of each item is a **descendant** of ***Student***: ***ResidentStudent***, ***NonResidentStudent***



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).

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`.

Summary: Type Checking Rules

CODE	CONDITION TO BE TYPE CORRECT
`x = y`	Is `y`'s ***ST*** a **descendant** of `x`'s ***ST***?
`x.m(y)`	Is method `m` defined in `x`'s ***ST***? Is `y`'s ***ST*** a **descendant** of `m`'s parameter's ***ST***?
`z = x.m(y)`	Is method `m` defined in `x`'s ***ST***? Is `y`'s ***ST*** a **descendant** of `m`'s parameter's ***ST***? Is ***ST*** of `m`'s return value a **descendant** of `z`'s ***ST***?
`(C) y`	Is `C` an **ancestor** or a **descendant** of `y`'s ***ST***?
`x = (C) y`	Is `C` an **ancestor** or a **descendant** of `y`'s ***ST***? Is `C` a **descendant** of `x`'s ***ST***?
`x.m((C) y)`	Is `C` an **ancestor** or a **descendant** of `y`'s ***ST***? Is method `m` defined in `x`'s ***ST***? Is `C` a **descendant** of `m`'s parameter's ***ST***?

Even if `(C) y` compiles OK, there will be a runtime `ClassCastException` if `C` is not an **ancestor** of `y`'s ***DT***!

Overriding and Dynamic Binding (1)

`Object` is the common parent/super class of every class.

- Every class inherits the *default version* of `equals`
- Say a reference variable *v* has ***dynamic type*** *D*:
  - **Case 1** *D overrides* `equals`

    ⇒ *`v.equals(...)`* invokes the *overridden version* in *D*
  - **Case 2** *D* does *not override* `equals`

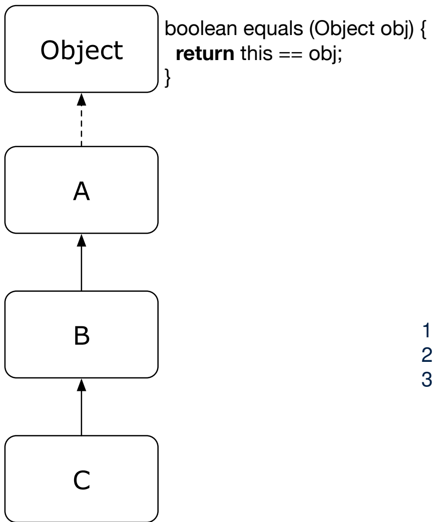
    Case 2.1 At least one ancestor classes of *D override* `equals`

    ⇒ *`v.equals(...)`* invokes the *overridden version* in the ***closest ancestor class***

    Case 2.2 No ancestor classes of *D override* `equals`

    ⇒ *`v.equals(...)`* invokes *default version* inherited from `Object`.
- Same principle applies to the `toString` method, and all overridden methods in general.

Overriding and Dynamic Binding (2.1)

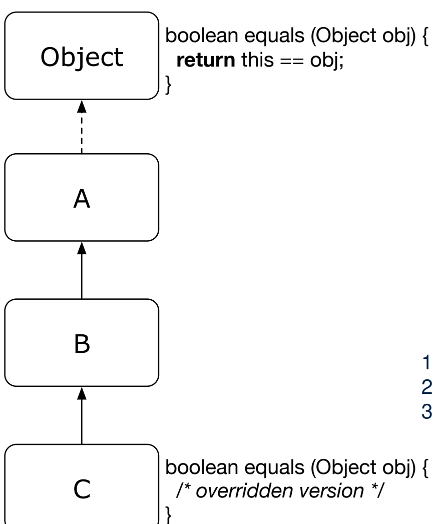



```
class A {
  /*equals not overridden*/
}
class B extends A {
  /*equals not overridden*/
}
class C extends B {
  /*equals not overridden*/
}
```

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

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

Overriding and Dynamic Binding (2.2)

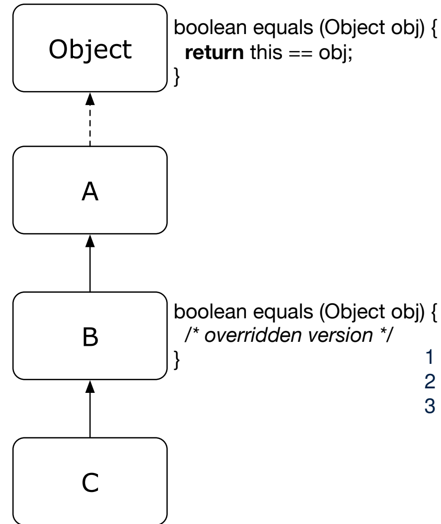



```
class A {
  /*equals not overridden*/
}
class B extends A {
  /*equals not overridden*/
}
class C extends B {
  boolean equals(Object obj) {
    /* overridden version */
  }
}
```

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

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

Overriding and Dynamic Binding (2.3)




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

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

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

Behaviour of Inherited `toString` Method (1)

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

```
Point@677327b6
```

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

Behaviour of Inherited `toString` Method (2)

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

After redefining/overriding the `toString` method:

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

```
(2, 4)
```


Behaviour of Inherited `toString` Method (3)

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

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Abstract Classes and Interfaces

EECS2030 B: Advanced Object Oriented Programming
Fall 2019

CHEN-WEI WANG

Abstract Class (1)

Problem: A polygon may be either a triangle or a rectangle. Given a polygon, we may either
- ***Grow*** its shape by incrementing the size of each of its sides;
- Compute and return its ***perimeter***; or
- Compute and return its ***area***.

- For a rectangle with *length* and *width*, its area is *length* × *width*.
- For a triangle with sides *a*, *b*, and *c*, its area, according to Heron's formula, is

$$\sqrt{s(s-a)(s-b)(s-c)}$$

where

$$s = \frac{a+b+c}{2}$$

- How would you solve this problem in Java, while *minimizing code duplicates* ?

Abstract Class (2)

```java
public abstract class Polygon {
  double[] sides;
  Polygon(double[] sides) { this.sides = sides; }
  void grow() {
    for(int i = 0; i < sides.length; i ++) { sides[i] ++; }
  }
  double getPerimeter() {
    double perimeter = 0;
    for(int i = 0; i < sides.length; i ++) {
      perimeter += sides[i];
    }
    return perimeter;
  }
  abstract double getArea();
}
```

- Method `getArea` not implemented and shown *signature* only.
- ∴ `Polygon` cannot be used as a *dynamic type*
- Writing `new Polygon(...)` is forbidden!

Abstract Class (3)

```
public class Rectangle extends Polygon {
  Rectangle(double length, double width) {
    super(new double[4]);
    sides[0] = length; sides[1] = width;
    sides[2] = length; sides[3] = width;
  }
  double getArea() { return sides[0] * sides[1]; }
}
```

- Method `getPerimeter` is inherited from the super-class `Polygon`.
- Method `getArea` is implemented in the sub-class `Rectangle`.
- ∴ `Rectangle` can be used as a *dynamic type*
- Writing `Polygon p = new Rectangle(3, 4)` allowed!

Abstract Class (4)

```
public class Triangle extends Polygon {
  Triangle(double side1, double side2, double side3) {
    super(new double[3]);
    sides[0] = side1; sides[1] = side2; sides[2] = side3;
  }
  double getArea() {
    /* Heron's formula */
    double s = getPerimeter() * 0.5;
    double area = Math.sqrt(
      s * (s - sides[0]) * (s - sides[1]) * (s - sides[2]));
    return area;
  }
}
```

- Method `getPerimeter` is inherited from `Polygon`.
- Method `getArea` is implemented in the sub-class `Triangle`.
- ∴ `Triangle` can be used as a *dynamic type*
- Writing `Polygon p = new Triangle(3, 4, 5)` allowed!

Abstract Class (5)

```
1  public class PolygonCollector {
2    Polygon[] polygons;
3    int numberOfPolygons;
4    PolygonCollector() { polygons = new Polygon[10]; }
5    void addPolygon(Polygon p) {
6      polygons[numberOfPolygons] = p; numberOfPolygons ++;
7    }
8    void growAll() {
9      for(int i = 0; i < numberOfPolygons; i ++) {
10       polygons[i].grow();
11     }
12   }
13 }
```

- **Polymorphism**: **Line 5** may accept as argument any object whose *static type* is `Polygon` or any of its sub-classes.
- **Dynamic Binding**: **Line 10** calls the version of `grow` inherited to the *dynamic type* of `polygons[i]`.

Abstract Class (6)

```
1  public class PolygonConstructor {
2    Polygon getPolygon(double[] sides) {
3      Polygon p = null;
4      if(sides.length == 3) {
5        p = new Triangle(sides[0], sides[1], sides[2]);
6      }
7      else if(sides.length == 4) {
8        p = new Rectangle(sides[0], sides[1]);
9      }
10     return p;
11   }
12   void grow(Polygon p) { p.grow(); }
13 }
```

- **Polymorphism**:
  - **Line 2** may accept as return value any object whose *static type* is `Polygon` or any of its sub-classes.
  - **Line 5** returns an object whose *dynamic type* is `Triangle`; **Line 8** returns an object whose *dynamic type* is `Rectangle`.

Abstract Class (7.1)

```
public class PolygonTester {
 public static void main(String[] args) {
  Polygon p;
  p = new Rectangle(3, 4); /* polymorphism */
  System.out.println(p.getPerimeter()); /* 14.0 */
  System.out.println(p.getArea()); /* 12.0 */
  p = new Triangle(3, 4, 5); /* polymorphism */
  System.out.println(p.getPerimeter()); /* 12.0 */
  System.out.println(p.getArea()); /* 6.0 */

  PolygonCollector col = new PolygonCollector();
  col.addPolygon(new Rectangle(3, 4)); /* polymorphism */
  col.addPolygon(new Triangle(3, 4, 5)); /* polymorphism */
  System.out.println(col.polygons[0].getPerimeter()); /* 14.0 */
  System.out.println(col.polygons[1].getPerimeter()); /* 12.0 */
  col.growAll();
  System.out.println(col.polygons[0].getPerimeter()); /* 18.0 */
  System.out.println(col.polygons[1].getPerimeter()); /* 15.0 */
```


Abstract Class (7.2)

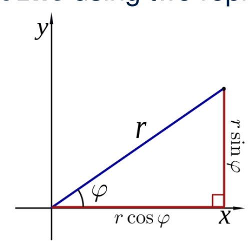
```
  PolygonConstructor con = new PolygonConstructor();
  double[] recSides = {3, 4, 3, 4};  p = con.getPolygon(recSides);
  System.out.println(p instanceof Polygon);  ✓
  System.out.println(p instanceof Rectangle);  ✓
  System.out.println(p instanceof Triangle);  ×
  System.out.println(p.getPerimeter()); /* 14.0 */
  System.out.println(p.getArea()); /* 12.0 */
  con.grow(p);
  System.out.println(p.getPerimeter()); /* 18.0 */
  System.out.println(p.getArea()); /* 20.0 */
  double[] triSides = {3, 4, 5};  p = con.getPolygon(triSides);
  System.out.println(p instanceof Polygon);  ✓
  System.out.println(p instanceof Rectangle);  ×
  System.out.println(p instanceof Triangle);  ✓
  System.out.println(p.getPerimeter()); /* 12.0 */
  System.out.println(p.getArea()); /* 6.0 */
  con.grow(p);
  System.out.println(p.getPerimeter()); /* 15.0 */
  System.out.println(p.getArea()); /* 9.921 */
 } }
```


Abstract Class (8)

- An *abstract class*:
  - Typically has **at least one** method with no implementation body
  - May define common implementations inherited to **sub-classes**.
- Recommended to use an *abstract class* as the ***static type*** of:
  - A *variable*
    e.g., `Polygon p`
  - A *method parameter*
    e.g., `void grow(Polygon p)`
  - A *method return value*
    e.g., `Polygon getPolygon(double[] sides)`
- It is forbidden to use an *abstract class* as a ***dynamic type***
  e.g., `Polygon p = new Polygon(...)` is not allowed!
- Instead, create objects whose ***dynamic types*** are descendant classes of the *abstract class* ⇒ Exploit *dynamic binding*!
  e.g., `Polygon p = con.getPolygon(recSides)`
  This is is as if we did `Polygon p = new Rectangle(...)`

Interface (1.1)

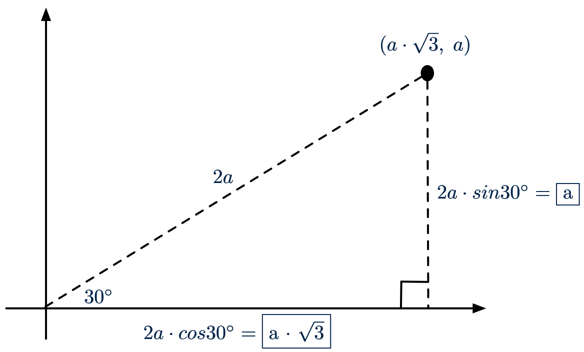
- We may implement `Point` using two representation systems:



  - The *Cartesian system* stores the *absolute* positions of `x` and `y`.
  - The *Polar system* stores the *relative* position: the angle (in radian) `phi` and distance `r` from the origin (0.0).
- As far as users of a `Point` object `p` is concerned, being able to call `p.getX()` and `getY()` is what matters.
- How `p.getX()` and `p.getY()` are internally computed, depending on the *dynamic type* of `p`, do not matter to users.

Interface (1.2)

Recall: $sin30° = \frac{1}{2}$ and $cos30° = \frac{1}{2} \cdot \sqrt{3}$



We consider the same point represented differently as:

- $r = 2a$, $\psi = 30°$ [polar system]
- $x = 2a \cdot cos30° = a \cdot \sqrt{3}$, $y = 2a \cdot sin30° = a$ [cartesian system]

Interface (2)

```
interface Point {
      double getX();
      double getY();
}
```

- An interface `Point` defines how users may access a point: either get its *x* coordinate or its *y* coordinate.
- Methods `getX` and `getY` similar to `getArea` in `Polygon`, have no implementations, but *signatures* only.
- ∴ `Point` cannot be used as a *dynamic type*
- Writing `new Point(...)` is forbidden!

Interface (3)

```
public class CartesianPoint implements Point {
  double x;
  double y;
  CartesianPoint(double x, double y) {
    this.x = x;
    this.y = y;
  }
  public double getX() { return x; }
  public double getY() { return y; }
}
```

- `CartesianPoint` is a possible implementation of `Point`.
- Attributes `x` and `y` declared according to the *Cartesian system*
- All method from the interface `Point` are implemented in the sub-class `CartesianPoint`.
- ∴ `CartesianPoint` can be used as a *dynamic type*
- `Point p = new CartesianPoint(3, 4)` allowed!

Interface (4)

```
public class PolarPoint implements Point {
  double phi;
  double r;
  public PolarPoint(double r, double phi) {
    this.r = r;
    this.phi = phi;
  }
  public double getX() { return Math.cos(phi) * r; }
  public double getY() { return Math.sin(phi) * r; }
}
```

- `PolarPoint` is a possible implementation of `Point`.
- Attributes `phi` and `r` declared according to the *Polar system*
- All method from the interface `Point` are implemented in the sub-class `PolarPoint`.
- ∴ `PolarPoint` can be used as a *dynamic type*
- `Point p = new PolarPoint(3,` $\frac{\pi}{6}$`)` allowed! [$360° = 2\pi$]

Interface (5)

```
1  public class PointTester {
2   public static void main(String[] args) {
3     double A = 5;
4     double X = A * Math.sqrt(3);
5     double Y = A;
6     Point p;
7     p = new CartisianPoint(X, Y); /* polymorphism */
8     print("(" + p.getX() + ", " + p.getY() + ")"); /* dyn. bin. */
9     p = new PolarPoint(2 * A, Math.toRadians(30)); /* polymorphism */
10    print("(" + p.getX() + ", " + p.getY() + ")"); /* dyn. bin. */
11  }
12 }
```

- **Lines 7 and 9** illustrate *polymorphism*, how?
- **Lines 8 and 10** illustrate *dynamic binding*, how?

Interface (6)

- An *interface*:
  - Has **all** its methods with no implementation bodies.
  - Leaves complete freedom to its ***implementors***.
- Recommended to use an *interface* as the ***static type*** of:
  - A *variable*
    e.g., `Point p`
  - A *method parameter*
    e.g., `void moveUp(Point p)`
  - A *method return value*
    e.g., `Point getPoint(double v1, double v2, boolean isCartesian)`
- It is forbidden to use an *interface* as a ***dynamic type***
  e.g., `Point p = new Point(...)` is not allowed!
- Instead, create objects whose ***dynamic types*** are descendant classes of the *interface* ⇒ Exploit *dynamic binding*!

Abstract Classes vs. Interfaces: When to Use Which?

- Use *interfaces* when:
  - There is a *common set of functionalities* that can be implemented via *a variety of strategies*.
    e.g., Interface `Point` declares signatures of `getX()` and `getY()`.
  - Each descendant class represents a different implementation strategy for the same set of functionalities.
  - `CartesianPoint` and `PolarPoinnt` represent different strategies for supporting `getX()` and `getY()`.
- Use *abstract classes* when:
  - *Some (not all) implementations can be shared* by descendants, and *some (not all) implementations cannot be shared*.
    e.g., Abstract class `Polygon`:
    - Defines implementation of `getPerimeter`, to be shared by `Rectangle` and `Triangle`.
    - Declares signature of `getArea`, to be implemented by `Rectangle` and `Triangle`.

Index (1)

Index (2)

Algorithm and Data Structure

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

Asymptotic Analysis of Algorithms

YORK UNIVERSITÉ UNIVERSITY

EECS2030 B: Advanced Object Oriented Programming
Fall 2019

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Measuring "Goodness" of an Algorithm

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

Correctness is always the priority.

How about efficiency? Is <u>time</u> or <u>space</u> more of a concern?

Measuring Efficiency of an Algorithm

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

Measure Running Time via Experiments

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

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

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

Example Experiment

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

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

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

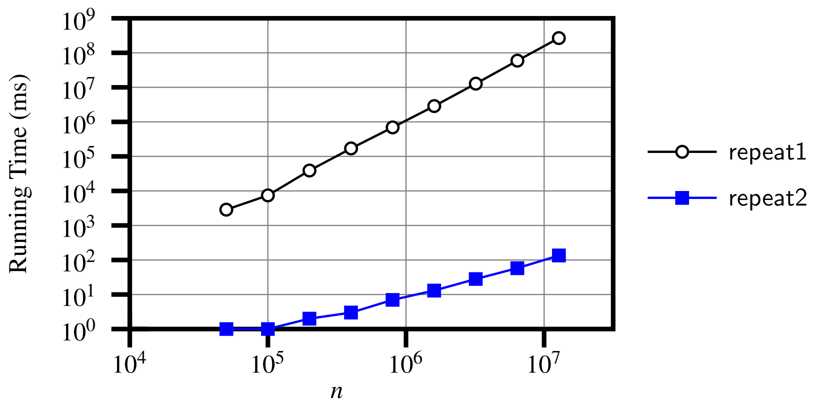
```
public static String repeat2(char c, int n) {
  StringBuilder sb = new StringBuilder();
  for (int i = 0; i < n; i ++) { sb.append(c); }
  return sb.toString(); }
```


Example Experiment: Detailed Statistics

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

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

Example Experiment: Visualization



Experimental Analysis: Challenges

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

Moving Beyond Experimental Analysis

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

Counting Primitive Operations

A *primitive operation* corresponds to a low-level instruction with a *constant execution time*.

- Assignment [e.g., `x = 5;`]
- Indexing into an array [e.g., `a[i]`]
- Arithmetic, relational, logical op. [e.g., `a + b`, `z > w`, `b1 && b2`]
- Accessing an attribute of an object [e.g., `acc.balance`]
- Returning from a method [e.g., `return result;`]

Q: Why is a method call in general *not* a primitive operation?
A: It may be a call to:

- a "*cheap*" method (e.g., printing `Hello World`), or
- an "*expensive*" method (e.g., sorting an array of integers)

Example: Counting Primitive Operations

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

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

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

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

From Absolute RT to Relative RT

- Each *primitive operation* (PO) takes approximately the same, constant amount of time to execute. [say t]
- The *number of primitive operations* required by an algorithm should be *proportional* to its *actual running time* on a specific environment.

  e.g., `findMax (int[] a, int n)` has $7n - 2$ POs

  $$RT = (7n - 2) \cdot t$$

  Say two algorithms with RT $(7n - 2) \cdot t$ and RT $(10n + 3) \cdot t$.

  ⇒ It suffices to compare their *relative* running time:

  $7n - 2$ vs. $10n + 3$.
- To determine the *time efficiency* of an algorithm, we only focus on their *number of POs*.

Example: Approx. # of Primitive Operations

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

  $$7 \cdot n^1 - 2 \cdot n^0$$
- We say
  - n is the ***highest power***
  - 7 and 2 are the ***multiplicative constants***
  - 2 is the ***lower term***
- When approximating a function (considering that input size may be very large):
  - **Only** the ***highest power*** matters.
  - ***multiplicative constants*** and ***lower terms*** can be dropped.

  ⇒ $7n - 2$ is approximately n

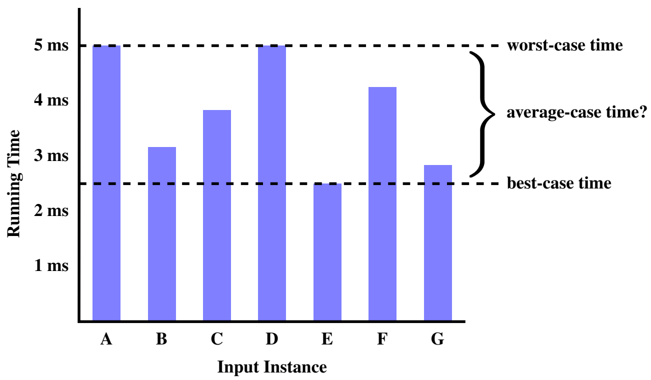
  Exercise: Consider $7n + 2n \cdot log\ n + 3n^2$:
  - ***highest power***? [n^2]
  - ***multiplicative constants***? [7, 2, 3]
  - ***lower terms***? [$7n + 2n \cdot log\ n$]

Approximating Running Time as a Function of Input Size

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

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

Focusing on the Worst-Case Input



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

What is Asymptotic Analysis?

Asymptotic analysis

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

Three Notions of Asymptotic Bounds

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

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

Asymptotic Upper Bound: Definition

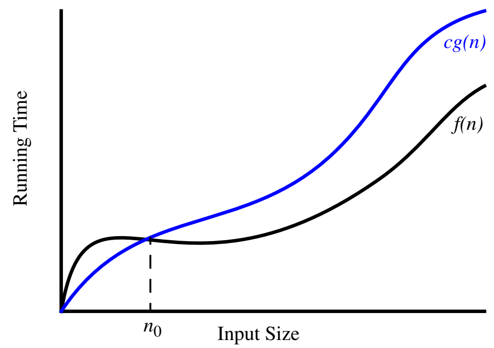
- Let $f(n)$ and $g(n)$ be functions mapping positive integers (input size) to positive real numbers (running time).
  - $f(n)$ characterizes the running time of some algorithm.
  - $O(g(n))$ denotes *a collection of* functions.
- $O(g(n))$ consists of *all* functions that can be upper bounded by $g(n)$,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

  such that:

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

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

Asymptotic Upper Bound: Visualization



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

Asymptotic Upper Bound: Example (1)

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

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

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

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

...

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

Asymptotic Upper Bound: Example (2)

Prove: The function $f(n) = 5n^4 + 3n^3 + 2n^2 + 4n + 1$ is $O(n^4)$.
Strategy: Choose a real constant $c > 0$ and an integer constant $n_0 \geq 1$, such that for every integer $n \geq n_0$:

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

$f(1) = 5 + 3 + 2 + 4 + 1 = 15$
Choose $c = 15$ and $n_0 = 1$!

Asymptotic Upper Bound: Proposition (1)

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

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

and $a_0, a_1, \ldots, a_d$ are integers, then $f(n)$ *is* $O(n^d)$.

- We prove by choosing

$$c = |a_0| + |a_1| + \cdots + |a_d|$$
$$n_0 = 1$$

- We know that for $n \geq 1$: $n^0 \leq n^1 \leq n^2 \leq \cdots \leq n^d$
- Upper-bound effect: $n_0 = 1$? $[f(1) \leq (|a_0| + |a_1| + \cdots + |a_d|) \cdot 1^d]$

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

- Upper-bound effect holds? $[f(n) \leq (|a_0| + |a_1| + \cdots + |a_d|) \cdot n^d]$

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

Asymptotic Upper Bound: Proposition (2)

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

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

e.g., Family of $O(n)$ contains:

$n^0, 2n^0, 3n^0, \ldots$ [functions with degree 0]
$n, 2n, 3n, \ldots$ [functions with degree 1]

e.g., Family of $O(n^2)$ contains:

$n^0, 2n^0, 3n^0, \ldots$ [functions with degree 0]
$n, 2n, 3n, \ldots$ [functions with degree 1]
$n^2, 2n^2, 3n^2, \ldots$ [functions with degree 2]

Asymptotic Upper Bound: More Examples

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

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

Using Asymptotic Upper Bound Accurately

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

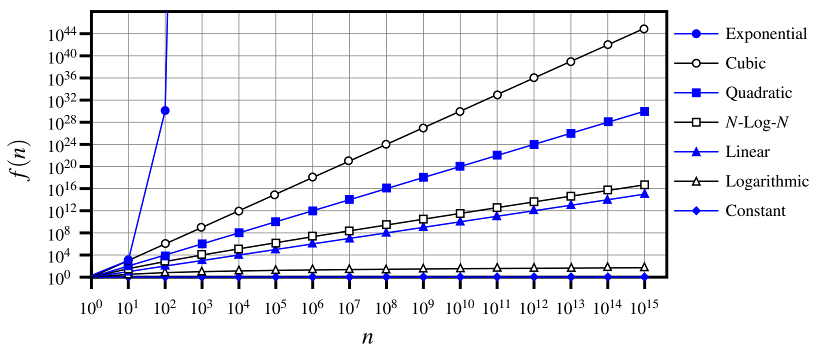
  For example, say $f(n) = 4n^3 + 3n^2 + 5$:
  - Recall: $O(n^3) \subset O(n^4) \subset O(n^5) \subset \ldots$
  - It is *most accurate* to say that $f(n)$ is $O(n^3)$.
  - It is ***true***, but not very useful, to say that $f(n)$ is $O(n^4)$ and that $f(n)$ is $O(n^5)$.
  - It is ***false*** to say that $f(n)$ is $O(n^2)$, $O(n)$, or $O(1)$.
- Do not include *constant factors* and *lower-order terms* in the big-Oh notation.

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

Classes of Functions

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

Rates of Growth: Comparison



Upper Bound of Algorithm: Example (1)

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

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

Upper Bound of Algorithm: Example (2)

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

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

Upper Bound of Algorithm: Example (3)

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

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

Upper Bound of Algorithm: Example (4)

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

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

Upper Bound of Algorithm: Example (5)

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

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

Basic Data Structure: Arrays

- An array is a sequence of indexed elements.
- *Size* of an array is **fixed** at the time of its construction.
- Supported *operations* on an array:
  - *Accessing*: e.g., `int max = a[0];`
    Time Complexity: *O(1)* [constant operation]
  - *Updating*: e.g., `a[i] = a[i + 1];`
    Time Complexity: *O(1)* [constant operation]
  - *Inserting/Removing*:

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

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

Array Case Study: Comparing Two Sorting Strategies

- Problem:
  Input: An array a of n numbers $\langle a_1, a_2, \ldots, a_n \rangle$
  Output: A permutation (reordering) $\langle a'_1, a'_2, \ldots, a'_n \rangle$ of the input sequence such that $a'_1 \leq a'_2 \leq \ldots \leq a'_n$
- We propose two *alternative implementation strategies* for solving this problem.
- At the end, we want to know which one to choose, based on *time complexity*.

Sorting: Strategy 1 – Selection Sort

- Maintain a (initially empty) *sorted portion* of array *a*.
- From left to right in array *a*, select and insert *the minimum element* to the end of this sorted portion, so it remains sorted.

```
1 selectionSort(int[] a, int n)
2   for (int i = 0; i <= (n - 2); i ++)
3     int minIndex = i;
4     for (int j = i; j <= (n - 1); j ++)
5       if (a[j] < a[minIndex]) { minIndex = j; }
6     int temp = a[i];
7     a[i] = a[minIndex];
8     a[minIndex] = temp;
```

- How many times does the body of *for loop* (Line 4) run?
- Running time? [$O(n^2)$]

$$\underbrace{n}_{\texttt{find \{a[0], ..., a[n-1]\}}} + \underbrace{(n-1)}_{\texttt{find \{a[1], ..., a[n-1]\}}} + \cdots + \underbrace{2}_{\texttt{find \{a[n - 2], a[a[n - 1]]\}}}$$

- So selection sort is a *quadratic-time algorithm*.

Sorting: Strategy 2 – Insertion Sort

- Maintain a (initially empty) *sorted portion* of array *a*.
- From left to right in array *a*, insert *one element at a time* into the "right" spot in this sorted portion, so it remains sorted.

```
1 insertionSort(int[] a, int n)
2   for (int i = 1; i < n; i ++)
3     int current = a[i];
4     int j = i;
5     while (j > 0 && a[j - 1] > current)
6       a[j] = a[j - 1];
7       j --;
8     a[j] = current;
```

- *while loop* (L5) exits when? `j <= 0` or `a[j - 1] <= current`
- Running time? [$O(n^2)$]

$$O(\underbrace{1}_{\texttt{insert into \{a[0]\}}} + \underbrace{2}_{\texttt{insert into \{a[0], a[1]\}}} + \cdots + \underbrace{(n-1)}_{\texttt{insert into \{a[0], ..., a[n-2]\}}})$$

- So insertion sort is a *quadratic-time algorithm*.

Sorting: Alternative Implementations?

- In the Java implementations for *selection* sort and *insertion* sort, we maintain the "sorted portion" from the *left* end.
  - For *selection* sort, we select the *minimum* element from the "unsorted portion" and insert it to the *end* in the "sorted portion".
- For *insertion* sort, we choose the *left-most* element from the "unsorted portion" and insert it at the "*right spot*" in the "sorted portion".
- **Question:** Can we modify the Java implementations, so that the "sorted portion" is maintained and grown from the *right* end instead?

Comparing Insertion & Selection Sorts

- *Asymptotically*, running times of selection sort and insertion sort are both $O(n^2)$.
- We will later see that there exist better algorithms that can perform better than quadratic: $O(n \cdot logn)$.

Index (1)

Index (2)

Index (3)

Wrap-Up

EECS2030 B: Advanced
Object Oriented Programming
Fall 2019

CHEN-WEI WANG

What You Learned (1)

- *Procedural Programming in Java*
  - Exceptions
  - Recursion (implementation, running time, correctness)
- *Data Structures*
  - Arrays
  - Maps and Hash Tables

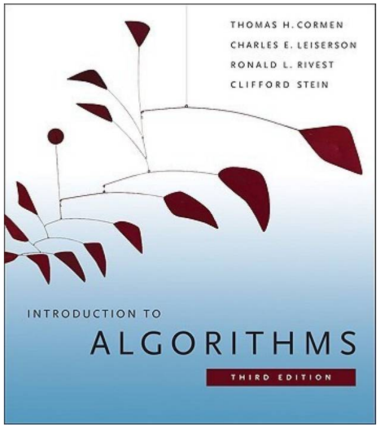
What You Learned (2)

- *Object-Oriented Programming in Java*
  - classes, attributes, encapsulation, objects, reference data types
  - methods: constructors, accessors, mutators, helper
  - dot notation, context objects
  - aliasing
  - inheritance:
    - code reuse
    - expectations
    - static vs. dynamic types
    - rules of substitutions
    - casts and `instanceof` checks
    - polymorphism and method arguments/return values
    - method overriding and dynamic binding: e.g., `equals`
    - abstract classes vs. interfaces

What You Learned (3)

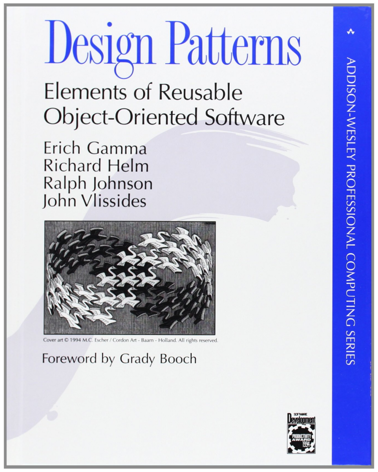
- *Integrated Development Environment (IDE) for Java: Eclipse*
  - Break Point and Debugger
  - Unit Testing using JUnit

Beyond this course. . . (1)



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

Beyond this course. . . (2)



- *Design Patterns: Elements of Reusable Object-Oriented Software* by Gamma, *etc.*
- 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 `EECS2011`.
- 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
- Exam Review Sessions:

1pm to 3pm	Monday	December 9
12pm to 2pm	Tuesday	December 10
1pm to 3pm	Thursday	December 12

Course Evaluation

Compliments or Complaints on my teaching?

`http://courseevaluations.yorku.ca/`