Advanced Topics on Classes and Objects

EECS2030 B: Advanced
Object Oriented Programming
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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 other)`
    Indicates whether some other object is "equal to" this one.
    - The default definition inherited from `Object`:

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

    e.g., Say `p1` and `p2` are of type `Point`***V1*** 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; }
}
```

```
1 PointV1 p1 = new PointV1(2, 3);
2 PointV1 p2 = new PointV1(2, 3);
3 System.out.println( p1 == p2 ); /* false */
4 System.out.println( p1.equals(p2) ); /* false */
```

- At **L4**, given that the `equals` method is not explicitly redefined/overridden in class `Point`***V1***, the <u>default version</u> inherited from class `Object` is called. Executing `p1`**`.equals`**`(p2)` boils down to (`p1` **`==`** `p2`).
- If we wish to compare contents of two `Point`***V1*** objects, need to explicitly redefine/override the `equals` method in that class.

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*
  $$x.equals(y) \land y.equals(z) \Rightarrow x.equals(z)$$

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

Equality (4.1)

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

```
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; } }
```

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

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:

```
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)

```
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`.
- `PointV2 other` at **L4** declares a variable `p` of type `PointV2`.
  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 (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 (7.1)

- ***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); /* pass */ assertSame(p2, p3); /* fail */
```

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

```
int i = 10; int j = 20; assertEquals(i, j); /* fail */
```

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

    Q: What if `equals` is not explicitly defined in *obj*1's declared type?

    A: ≈ assertSame(`obj1`, `obj2`)

```
PointV2 p4 = new PointV2(3, 4); PointV2 p5 = new PointV2(3, 4);
assertEquals(p4, p5); /* pass */
assertEquals(p1, p2); /* fail ∵ different PointV1 objects */
assertEquals(p4, p2); /* fail ∵ different types */
```

Equality in JUnit (7.2)

```
@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 in JUnit (7.3)

```
@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)

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

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

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

Defining Ordering Between Objects (1.2)

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

Defining Ordering Between Objects (2.1)

Let's now make the comparison more sophisticated:

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

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

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

Defining Ordering Between Objects (2.2)

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

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

Defining Ordering Between Objects (2.3)

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

Defining Ordering Between Objects (3)

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

- *Asymmetric* :

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

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

- *Transitive* :

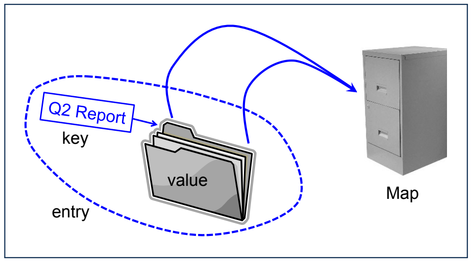
$$c1.compareTo(c2) < 0 \wedge c2.compareTo(c3) < 0 \Rightarrow c1.compareTo(c3) < 0$$
$$c1.compareTo(c2) > 0 \wedge c2.compareTo(c3) > 0 \Rightarrow c1.compareTo(c3) > 0$$

$\therefore$ 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., $0 \,..\, (a.length - 1)$]
- 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:

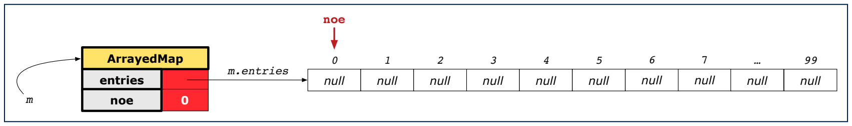
ENTRY	
(SEARCH) KEY	VALUE
1	D
25	C
3	F
14	Z
6	A
39	C
7	Q

  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()`:

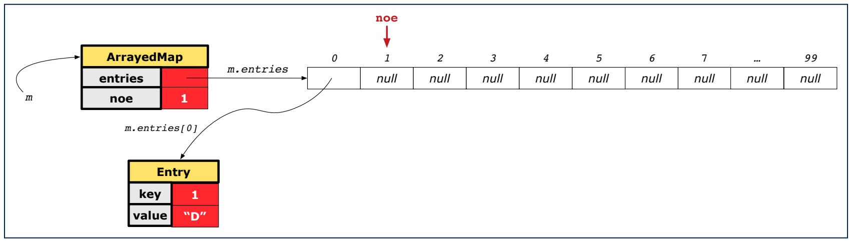
- Attribute `m.entries` initialized as an array of 100 `null` slots.
- Attribute `m.noe` is 0, meaning:
  - Current number of entries stored in the map is 0.
  - Index for storing the next new entry is 0.



Hashing: Naive Implementation of Map (1)

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

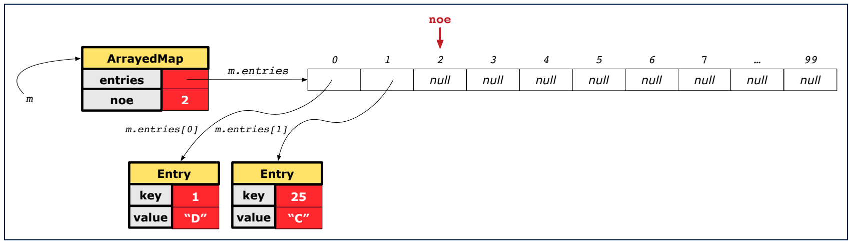
- Attribute `m.entries` has 99 `null` slots.
- Attribute `m.noe` is 1, meaning:
  - Current number of entries stored in the map is 1.
  - Index for storing the next new entry is 1.



Hashing: Naive Implementation of Map (2)

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

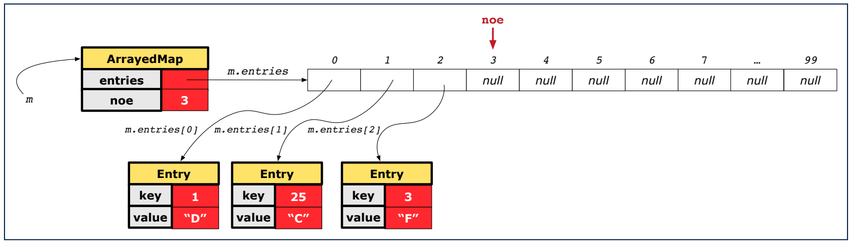
- Attribute `m.entries` has 98 `null` slots.
- Attribute `m.noe` is 2, meaning:
  - Current number of entries stored in the map is 2.
  - Index for storing the next new entry is 2.



Hashing: Naive Implementation of Map (3)

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

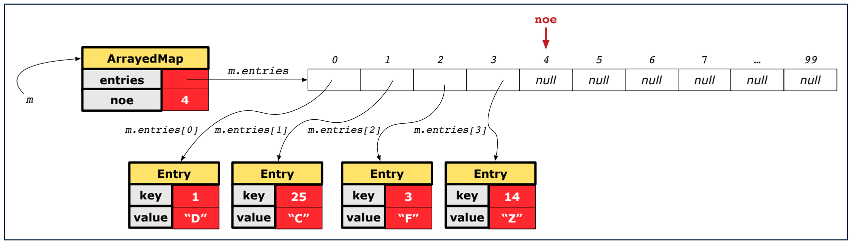
- Attribute `m.entries` has 97 `null` slots.
- Attribute `m.noe` is 3, meaning:
  - Current number of entries stored in the map is 3.
  - Index for storing the next new entry is 3.



Hashing: Naive Implementation of Map (4)

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

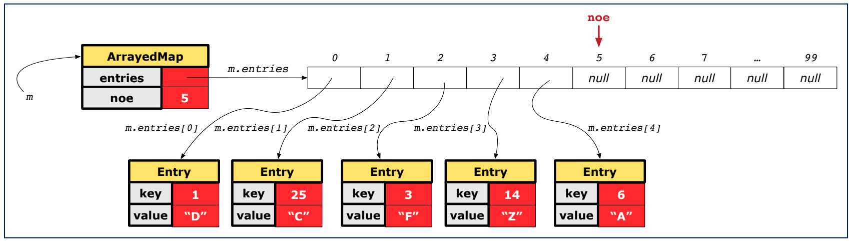
- Attribute `m.entries` has 96 `null` slots.
- Attribute `m.noe` is 4, meaning:
  - Current number of entries stored in the map is 4.
  - Index for storing the next new entry is 4.



Hashing: Naive Implementation of Map (5)

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

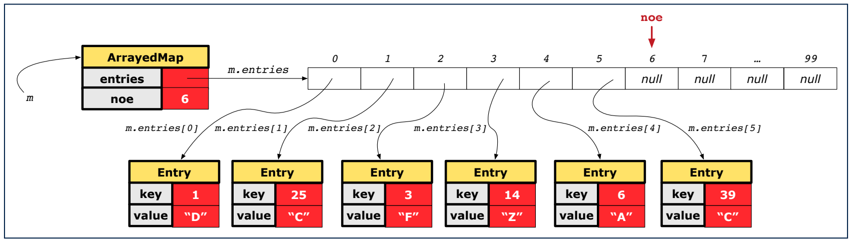
- Attribute `m.entries` has 95 `null` slots.
- Attribute `m.noe` is 5, meaning:
  - Current number of entries stored in the map is 5.
  - Index for storing the next new entry is 5.



Hashing: Naive Implementation of Map (6)

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

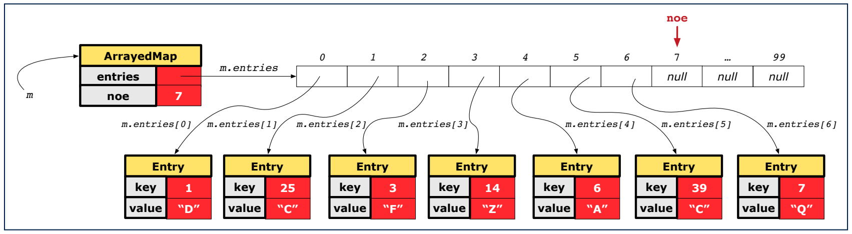
- Attribute `m.entries` has 94 `null` slots.
- Attribute `m.noe` is 6, meaning:
  - Current number of entries stored in the map is 6.
  - Index for storing the next new entry is 6.



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;
  }
```

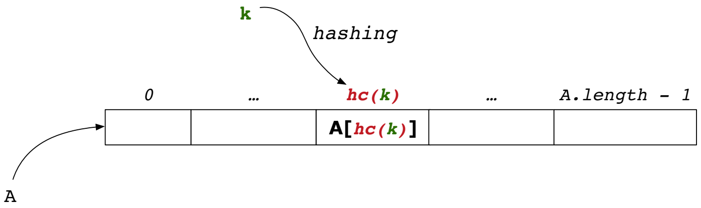
Say `entries` is: {(1, D), (25, C), (3, F), (14, Z), (6, A), (39, C), (7, Q), null, . . .}

- 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)

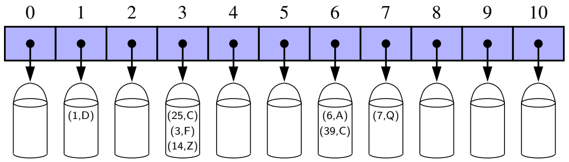


- Given a (numerical or non-numerical) search key ***k***:
  - Apply a function **hc** so that ***hc(k)*** returns an integer.
    - We call ***hc(k)*** the *hash code* of key ***k***.
    - Value of ***hc(k)*** denotes a ***valid index*** of some array `A`.
  - Rather than searching through array `A`, 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

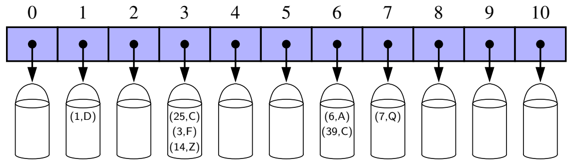


- **Collision**: unequal keys have same hash code (e.g., 25, 3, 14)
  ⇒ Unavoidable as number of entries ↑, but a *good* hash function should have sizes of the buckets uniformly distributed.

Hashing: Hash Table as a Bucket Array (2.2)

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

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



- **Collision**: unequal keys have same hash code (e.g., 25, 3, 14)
  ⇒ 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!]

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