Fundamental Data Structures – Part 2

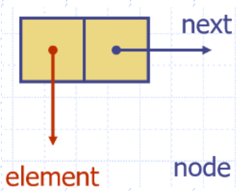
- **Circularly Linked Lists**
  - Round-Robin Scheduling
  - Designing and Implementing a Circularly Linked List
- **Equivalence Testing**
  - Equivalence Testing with Arrays
  - Equivalence Testing with Linked Lists
- **Cloning Data Structures**
  - Cloning Arrays
  - Cloning Linked Lists

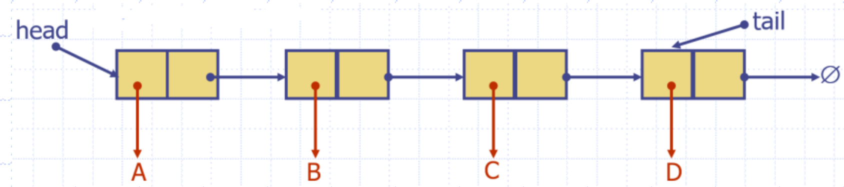
Lesson 2 Review

- **Data structures**
  - A way of organizing data
  - Leads to efficiency in insertions, deletions, searches, etc.
- **Arrays**
  - Fixed-size data structure
  - Use index to refer to array elements
  - length property
  - To add an entry into an array board at index i, we need to make room for it by shifting forward the $n - i$ entries $\boldsymbol{board}[i]$, …, $\boldsymbol{board}[n - 1]$
  - To remove the entry at index i, we need to fill the hole left by e by shifting backward the $n - i - 1$ elements $\boldsymbol{board}[i + 1]$, …, $\boldsymbol{board}[n - 1]$

Lesson 2 Review - Singly Linked List

- Data structure consisting of a sequence of nodes starting from a head node:





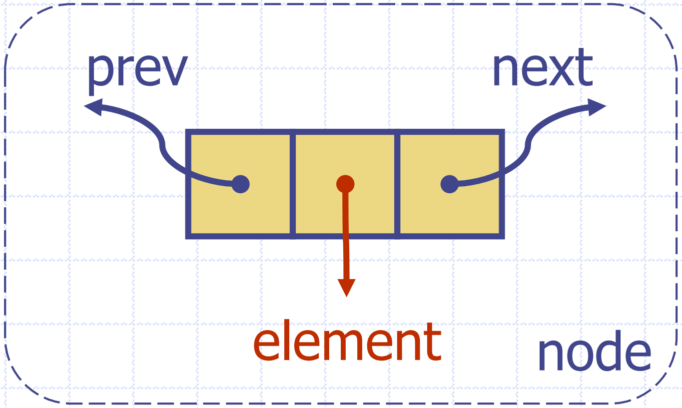
  - Each node contains the **element** (data) and a **link** to the next node
  - Self-referential **Node** class represents a node of singly linked list.
- **Insertion** of a new node **at the head - efficient**
  - Have new node point to old head node
  - Update head to point to new node
- **Inserting** a new node **at the tail - efficient**
  - Have new node point to null
  - Have old last node point to new node
  - Update tail to point to new node
- **Removing at the head - efficient**
  - Update head to point to next node in the list

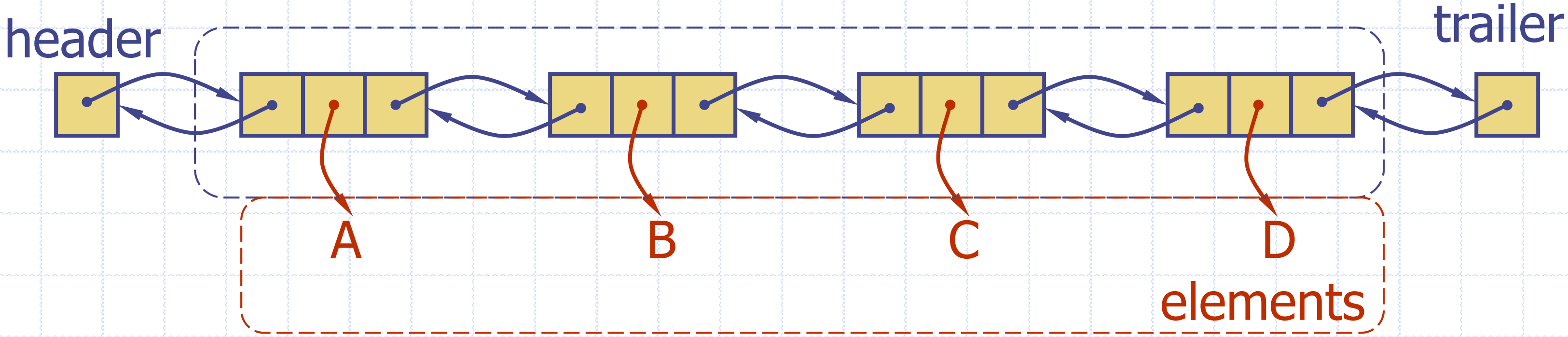
Lesson 2 Review - Singly Linked List

- **Removing at the tail** of a singly linked list
  - Need a loop to reach the last node
  - is **not efficient** - there is no constant-time way to update the tail to point to the previous node

Lesson 2 Review - Doubly Linked List

- A doubly linked list can be traversed forward and backward
- Nodes store:
  - element
  - link to the previous node
  - link to the next node
- Special **trailer** and **header** nodes
- Fast insertions and deletions between nodes





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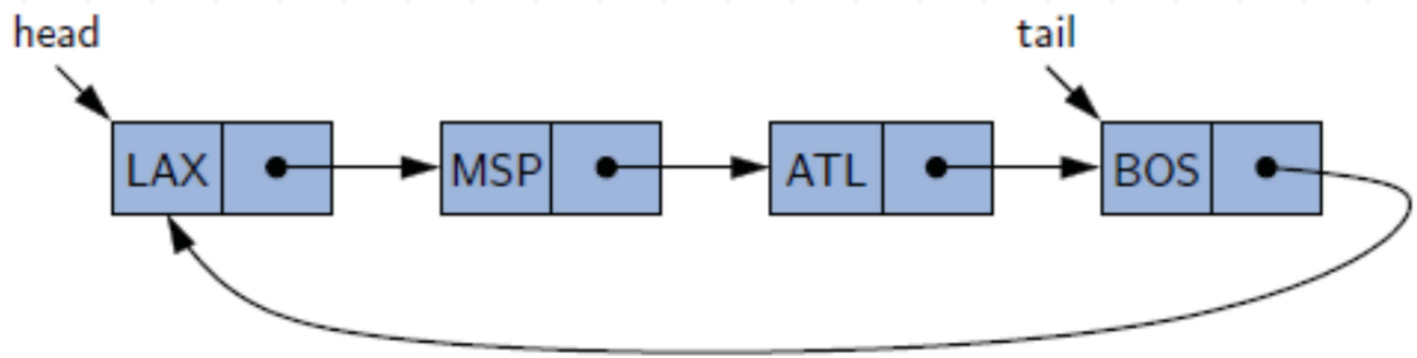
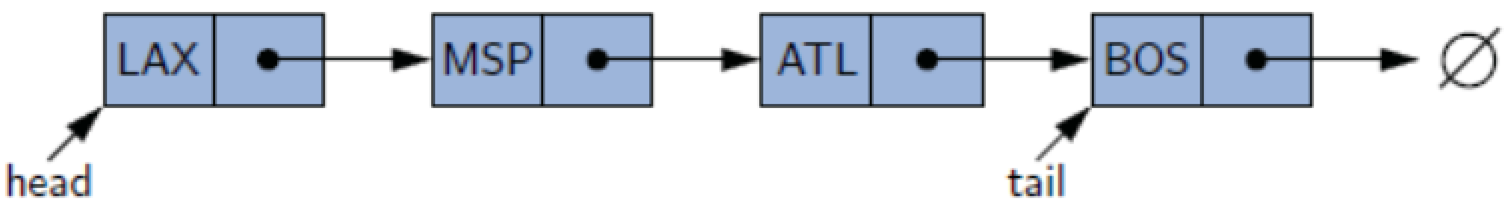
Circularly Linked Lists



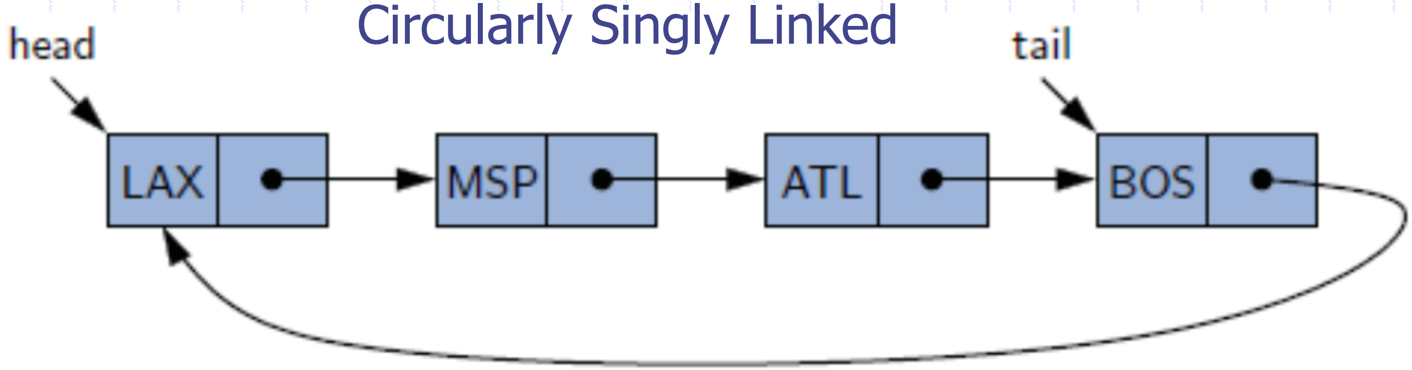
Circularly Linked List

- A circularly linked list, is essentially a singularly linked list in which the **next reference of the tail node is set to refer back to the head of the list** (rather than null)

Regular Singly Linked List



Circularly Singly Linked



Circularly Linked List

- In many applications data can be more naturally viewed as having a **cyclic order**, with well-defined neighboring relationships, but no fixed beginning or end.
- Examples:
  - many **multiplayer games are turn-based**, with player A taking a turn, then player B, then player C, and so on, but eventually **back to player A** again, and player B again, with the pattern repeating.
  - **city buses and subways often run on a continuous loop**, making stops in a scheduled order, but with no designated first or last stop per se.

Round-Robin Scheduling

- **Operating Systems** manage multiple processes and schedule for them CPU time.
- Most operating systems allow processes to effectively share use of the CPUs, using some form of an algorithm known as ***round-robin scheduling***.
  - A process is given a short turn to execute, known as a ***time slice***, but it is interrupted when the slice ends, even if its job is not yet complete.
  - Each active process is given its own time slice, **taking turns in a cyclic order**.
  - New processes can be added to the system, and processes that complete their work can be removed.

Round-Robin Scheduling

- A **round-robin scheduler** could be implemented with a traditional linked list, by repeatedly performing the following steps on **linked list *L*** (see Figure 3.15):
  1. process *p* = ***L*.removeFirst( )**
  2. Give a time slice to process *p*
  3. *L*.**addLast(*p*)**

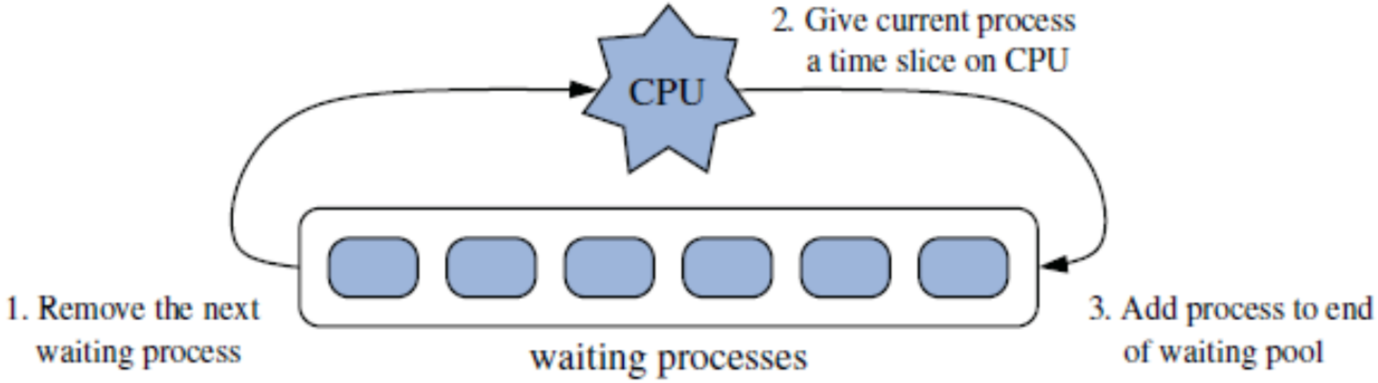


Figure 3.15: The three iterative steps for round-robin scheduling.

Designing a Circularly Linked List

- There are drawbacks to the use of a traditional linked list for implementing a round-robin scheduler.
  - inefficient to **repeatedly throw away a node** from one end of the list, only to create a new node for the same element when **reinserting it**.
  - inefficient to perform various updates to **decrement and increment the list's size** and to **unlink and relink nodes**.
- A **circularly linked list** is more efficient.
  - the **next** reference of the **tail** node is **set to refer back to the head** of the list (rather than null)

Designing a Circularly Linked List

- Add an additional update method **rotate( )**:
  - moves the first element to the end of the list (referenced by tail).
- With this new operation, round-robin scheduling can be efficiently implemented by repeatedly performing the following steps on a circularly linked list *C*:

  1. **p** = *C*.first( )

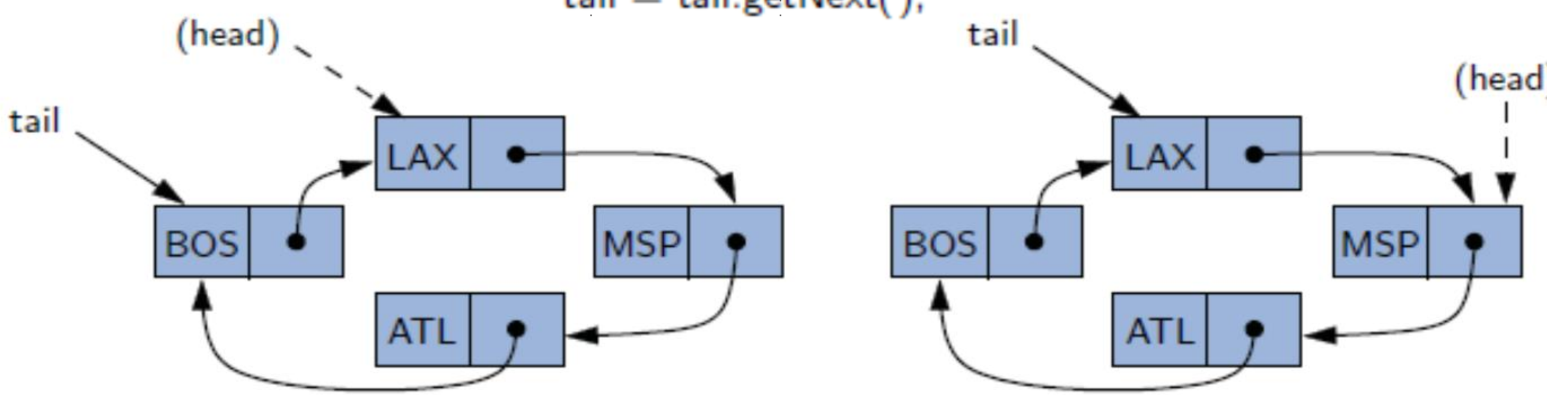
  2. Give a time slice to process **p**

  2. *C*.rotate( )
- one additional optimization - we **no longer explicitly maintain the head reference**.
- So long as we maintain **a reference to the tail**, we can **locate the head as tail.getNext( )**.

Operations on a Circularly Linked List

- Implementing the new rotate method is quite trivial.
- We do not move any nodes or elements, we simply **advance the tail reference to point to the node that follows it** (the implicit head of the list).

tail = tail.getNext( );



(a) Before the rotation (b) After the rotation

Inserting at the Head

- We can **add a new element at the front** of the list by creating a new node and linking it just *after* the tail of the list, as shown in Figure 3.18.

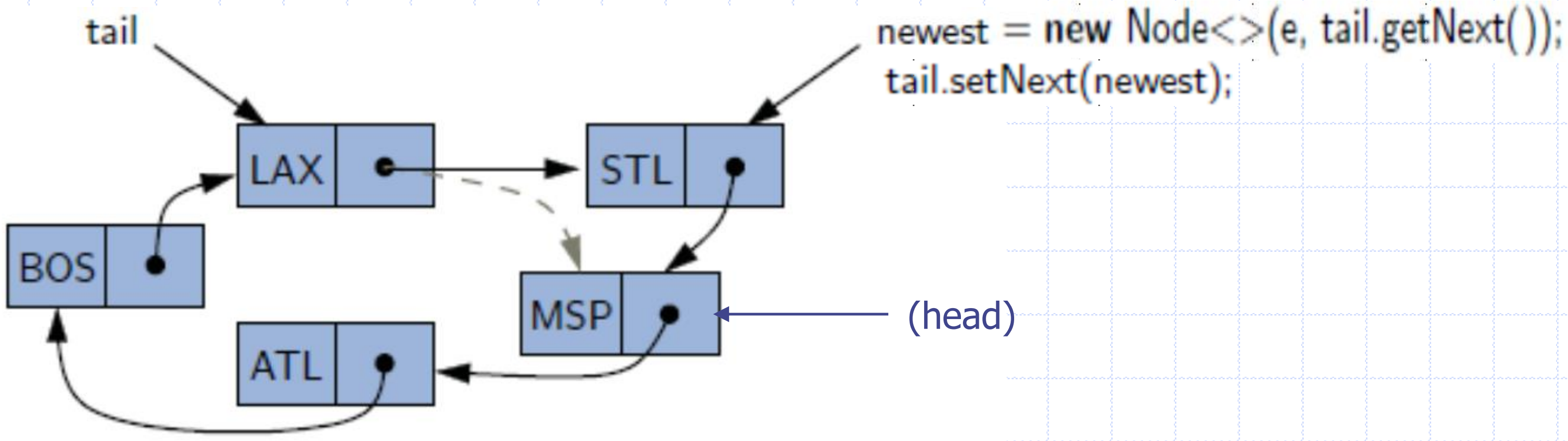
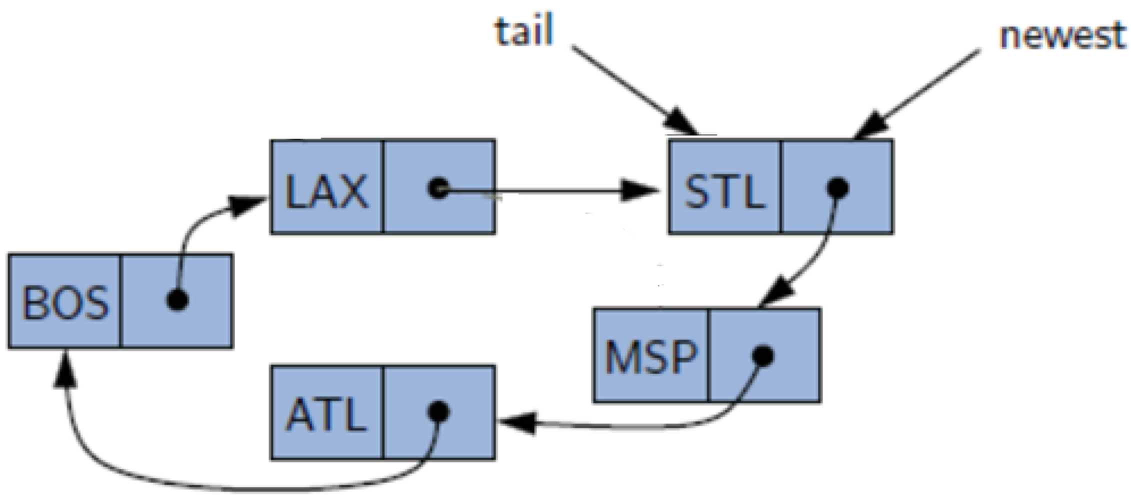


Fig. 3.18

Inserting at the Tail

- To implement the addLast method, we can rely on the use of a call to addFirst and then immediately advance the tail reference so that **the newest node becomes the last.**

```
addFirst(e);
tail = tail.getNext( );
```

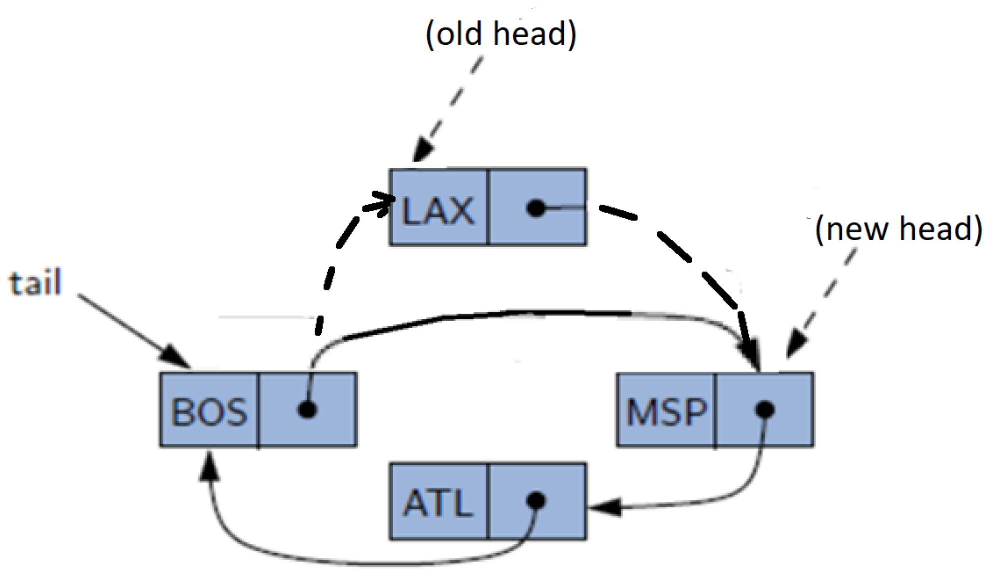


Java Methods

```
// update methods
public void rotate( ) {              // rotate the first element to the back of the list
  if (tail != null)                        // if empty, do nothing
    tail = tail.getNext( );                // the old head becomes the new tail
}
public void addFirst(E e) {                // adds element e to the front of the list
  if (size == 0) {
    tail = new Node<>(e, null);
    tail.setNext(tail);                    // link to itself circularly
  } else {
    Node<E> newest = new Node<>(e, tail.getNext( ));
    tail.setNext(newest);
  }
  size++;
}
public void addLast(E e) {                 // adds element e to the end of the list
  addFirst(e);                             // insert new element at front of list
  tail = tail.getNext( );                  // now new element becomes the tail
}
```

Java Methods – removal at the head

```
public E removeFirst( ) {                  // removes and returns the first element
  if (isEmpty( )) return null;             // nothing to remove
  Node<E> head = tail.getNext( );
  if (head == tail) tail = null;           // must be the only node left
  else tail.setNext(head.getNext( ));      // removes "head" from the list
  size−−;
  return head.getElement( );
}
```



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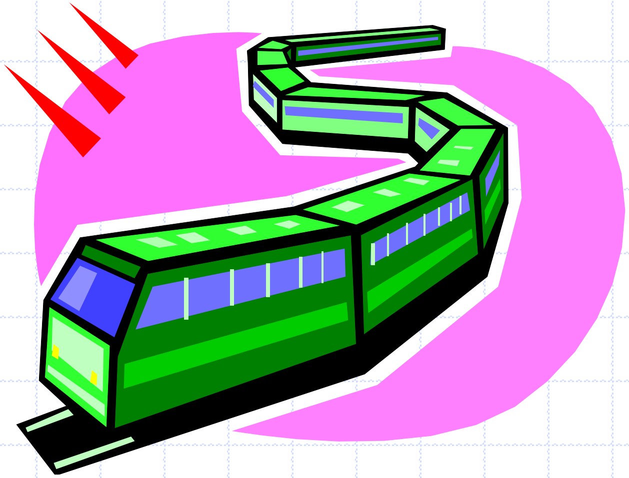
Equivalence Testing



Equivalence Testing

- When working with reference types, there are many different notions of **what it means for one expression to be equal to another**.
- At the lowest level, if a and b are reference variables, then expression **a == b tests whether a and b refer to the same object** (or if both are set to the null value).
- However, for many types there is a higher-level notion of two variables being considered “equivalent” even if they do not actually refer to the same instance of the class.
- For example, we typically want to consider **two String instances to be equivalent to each other if they represent the identical sequence of characters**.

Equivalence Testing

- To support a broader notion of equivalence, all object types support a method named **equals**.
- Users of reference types should rely on the syntax **a.equals(b)**, unless they have a specific need to test the more narrow notion of identity.
- The **equals method is formally defined in the Object class**, which serves as a superclass for all reference types, but **that implementation reverts to returning the value of expression a == b**.
- Defining a more meaningful notion of equivalence requires knowledge about a class and its representation.

Equivalence Testing

- The consistency of Java's libraries depends upon the **equals** method defining what is known as an ***equivalence relation*** in mathematics, satisfying the following properties:
  - Treatment of null: For any nonnull reference variable x, the call **x.equals(null)** should return false (that is, nothing equals null except null).
  - Reflexivity: For any nonnull reference variable x, the call **x.equals(x)** should return true (that is, an object should equal itself).
  - Symmetry: For any nonnull reference variables x and y, the calls **x.equals(y)** and **y.equals(x)** should return the same value.
  - Transitivity: For any nonnull reference variables x, y, and z, if both calls **x.equals(y)** and **y.equals(z)** return true, then call **x.equals(z)** must return true as well.

Equivalence Testing with Arrays

- The following provides a summary of the treatment of equivalence for arrays, assuming that variables a and b refer to array objects:
  - **a == b**: Tests if a and b refer to the same underlying array instance.
  - **a.equals(b)**: Interestingly, this is identical to a == b.
    - Arrays are not a true class type and do not override the **Object.equals** method.

Equivalence Testing with Arrays

- **Arrays.equals(a,b)**: This provides a more intuitive notion of equivalence, returning true if the arrays have the same length and **all pairs of corresponding elements are "equal" to each other**.
  - More specifically, if the array elements are primitives, then it uses the standard **==** to compare values.
  - If elements of the arrays are a reference type, then it makes pairwise comparisons **a[k].equals(b[k])** in evaluating the equivalence.

Equivalence Testing with Arrays

- For most applications, the **Arrays.equals** behavior captures the appropriate notion of equivalence.
- However, there is an additional complication when using multidimensional arrays.
  - The fact that two-dimensional arrays in Java are really one-dimensional arrays nested inside a common one-dimensional array raises an interesting issue with respect to how we think about ***compound objects***, which are objects—like a two-dimensional array—that are made up of other objects.
  - In particular, it brings up the question of where a compound object begins and ends.

Multidimensional Arrays

Java Multidimensional Array (2d

programiz.com/java-programming/multidimensional-array

As mentioned, each component of array `a` is an array in itself, and length of each rows is also different.

	Column 1	Column 2	Column 3	Column 4
Row 1	1 a[0][0]	2 a[0][1]	3 a[0][2]	
Row 2	4 a[1][0]	5 a[1][1]	6 a[1][2]	9 a[1][3]
Row 3	7 a[2][0]			

Let's write a program to prove it.

```
class MultidimensionalArray {
    public static void main(String[] args) {

        int[][] a = {
                {1, 2, 3},
                {4, 5, 6, 9},
                {7},
        };

        System.out.println("Length of row 1: " + a[0].length);
        System.out.println("Length of row 2: " + a[1].length);
        System.out.println("Length of row 3: " + a[2].length);
    }
}
```


https://www.programiz.com/java-programming/multidimensional-array

Equivalence Testing with Arrays

- To support the more natural notion of multidimensional arrays being equal if they have equal contents, the class provides an additional method:
- **Arrays.deepEquals(a,b)**: Identical to Arrays.equals(a,b) except when the elements of a and b are themselves arrays, in which case it calls Arrays.deepEquals(a[k],b[k]) for corresponding entries, rather than a[k].equals(b[k]).

Equivalence Testing Linked Lists

- Using a definition very similar to the treatment of arrays by the java.util.Arrays.equals method, we consider **two lists to be equivalent if they have the same length and contents that are element-by-element equivalent**.
- We can evaluate such equivalence by **simultaneously traversing two lists, verifying that x.equals(y) for each pair of corresponding elements x and y**.

Equivalence Testing Linked Lists

- The implementation of the SinglyLinkedList.equals method is given in Code Fragment 3.19.

```
public boolean equals(Object o) {
  if (o == null) return false;
  if (getClass( ) != o.getClass( )) return false;
  SinglyLinkedList other = (SinglyLinkedList) o;        // use nonparameterized type
  if (size != other.size) return false;
  Node walkA = head;                                    // traverse the primary list
  Node walkB = other.head;                              // traverse the secondary list
  while (walkA != null) {
    if (!walkA.getElement( ).equals(walkB.getElement( ))) return false; //mismatch
    walkA = walkA.getNext( );
    walkB = walkB.getNext( );
  }
  return true;    // if we reach this, everything matched successfully
}
```

Code Fragment 3.19: Implementation of the SinglyLinkedList.equals method.

Cloning Data Structures

- The universal **Object** superclass defines a method named **clone**, which can be used to produce what is known as a ***shallow copy*** of an object.
- This uses the standard assignment semantics to **assign the value of each field of the new object equal to the corresponding field of the existing object that is being copied**.
- The reason this is known as a shallow copy is because if the field is a reference type, then an initialization of the form **duplicate.field = original.field** causes the field of the new object to refer to the same underlying instance as the field of the original object.

Cloning Data Structures

- A shallow copy is not always appropriate for all classes, and therefore, **Java intentionally disables use of the clone( )** method by declaring it as **protected**, and by having it throw a CloneNotSupportedException when called.
- The author of a class must explicitly **declare support for cloning by formally declaring that the class implements the Cloneable interface**, and by declaring a public version of the clone( ) method.
- That public method can simply call the protected one to do the field-by-field assignment that results in a shallow copy, if appropriate.
- However, for many classes, **the class may choose to implement a deeper version of cloning**, in which some of the referenced objects are themselves cloned.

Cloning Arrays

- Although arrays support some special syntaxes such as a[k] and a.length, it is important to remember that they are objects, and that array variables are reference variables.
- This has important consequences. As a first example, consider the following code:

```
int[ ] data = {2, 3, 5, 7, 11, 13, 17, 19};
int[ ] backup;
backup = data; // warning; not a copy
```

- The assignment of variable backup to data does not create any new array; it simply **creates a new alias for the same array**, as portrayed in Figure 3.23

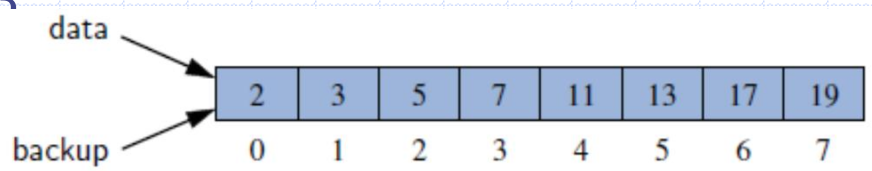


Figure 3.23: The result of the command backup = data for **int** arrays.

Cloning Arrays

- Instead, if we want to make a copy of the array, data, and assign a reference to the new array to variable, backup, we should write:

  backup = data.clone( );
- The clone method, when executed on an array, initializes each cell of the new array to the value that is stored in the corresponding cell of the original array.
- This results in an independent array, as shown in Figure 3.24.
- If we subsequently make an assignment such as data[4] = 23 in this configuration, the backup array is unaffected.

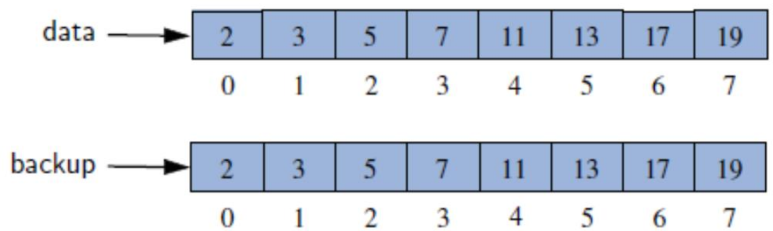


Figure 3.24: The result of the command backup = data.clone( ) for **int** arrays.

Cloning Arrays

- There are more considerations when copying an array that stores reference types rather than primitive types.
- The clone( ) method produces a ***shallow copy*** of the array, producing a new array whose **cells refer to the same objects referenced by the first array**.
- For example, if the variable *contacts* refers to an array of hypothetical *Person* instances, the result of the command:

guests = contacts.clone( ) produces a shallow copy, as portrayed in Figure 3.25.

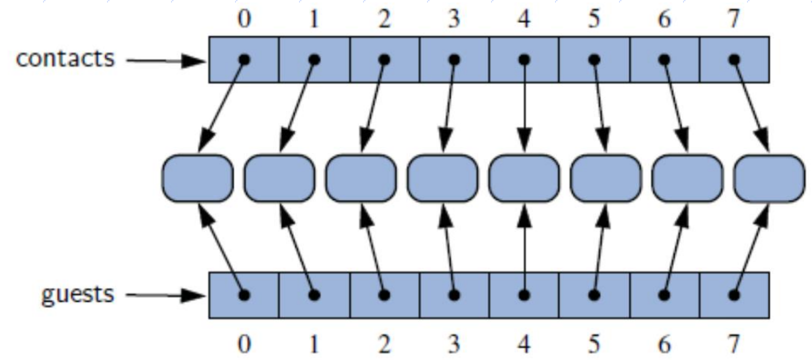


Figure 3.25: A shallow copy of an array of objects, resulting from the command guests = contacts.clone( ).

Cloning Arrays

- A ***deep copy*** of the contact list can be created by **iteratively cloning the individual elements**, as follows, but only if the Person class is declared as Cloneable.

```
Person[ ] guests = new Person[contacts.length];
for (int k=0; k < contacts.length; k++)
  guests[k] = (Person) contacts[k].clone( ); // returns Object type
```

- Because a two-dimensional array is really a one-dimensional array storing other one-dimensional arrays, the same distinction between a shallow and deep copy exists.
- Unfortunately, the java.util.Arrays class does not provide any "deepClone" method.

Cloning Arrays

- However, we can **implement our own method by cloning the individual rows of an array**, as shown in Code Fragment 3.20, for a two-dimensional array of integers.

```
public static int[ ][ ] deepClone(int[ ][ ] original)
{
    int[ ][ ] backup = new int[original.length][ ]; // create top-level array of arrays
    for (int k=0; k < original.length; k++)
        backup[k] = original[k].clone( ); // copy row k
    return backup;
}
```

Code Fragment 3.20: A method for creating a deep copy of a two-dimensional array of integers.

Cloning Linked Lists

- Let’s add support for cloning instances of the SinglyLinkedList class from previous lecture.
- The first step to making a class cloneable in Java is declaring that it implements the **Cloneable** interface.
- Therefore, we adjust the first line of the class definition to appear as follows:

```java
public class SinglyLinkedList<E> implements Cloneable {
```

- The remaining task is implementing a public version of the clone() method of the class, which we present in Code Fragment 3.21.

Cloning Linked Lists

```
public SinglyLinkedList<E> clone() throws CloneNotSupportedException {
  // always use inherited Object.clone() to create the initial copy
  SinglyLinkedList<E> other = (SinglyLinkedList<E>) super.clone(); // safe cast
  if (size > 0) {                          // we need independent chain of nodes
    other.head = new Node<>(head.getElement(), null);
    Node<E> walk = head.getNext();         // walk through remainder of original list
    Node<E> otherTail = other.head;        // remember most recently created node
    while (walk != null) {                 // make a new node storing same element
      Node<E> newest = new Node<>(walk.getElement(), null);
      otherTail.setNext(newest);           // link previous node to this one
      otherTail = newest;
      walk = walk.getNext();
    }
      other.tail = otherTail;
  }
  return other;
}
```

Code Fragment 3.21: Implementation of the SinglyLinkedList.clone method.

Cloning Linked Lists

- By convention, that method should begin by creating a new instance using a call to **super.clone( )**, which in our case invokes the method from the Object class (line 3).
- Because the inherited version returns an Object, we perform a narrowing cast to type **SinglyLinkedList<E>**.
- At this point in the execution, the other list has been created as a **shallow copy of the original**.
- Since our list class has two fields, *size* and *head*, the following
- assignments have been made:
  - other.size = this.size;
  - other.head = this.head;
- We create a new head node at line 5 of the code, and then perform a walk through the remainder of the original list (lines 8–13) while creating and linking new nodes for the new list.