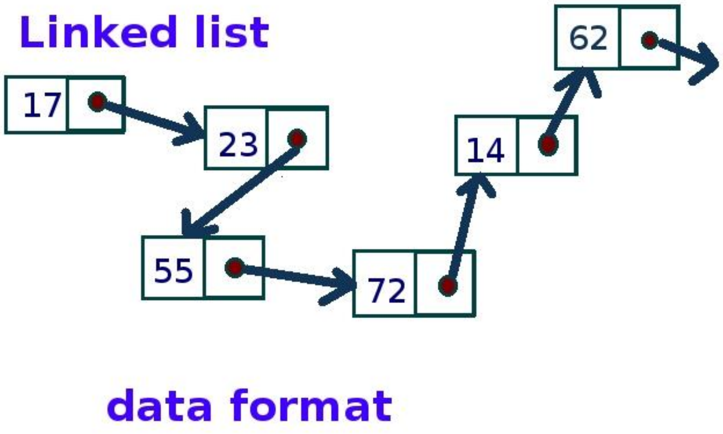


Linked Lists: An Overview

Computer Science CS112
Boston University

Christine Papadakis-Kanaris

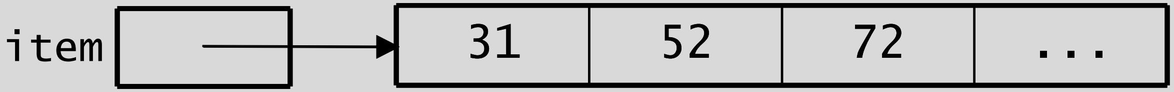
Representing a Sequence of Data

- Sequence – an ordered collection of items (position matters)
  - we will look at several types: lists, stacks, and queues

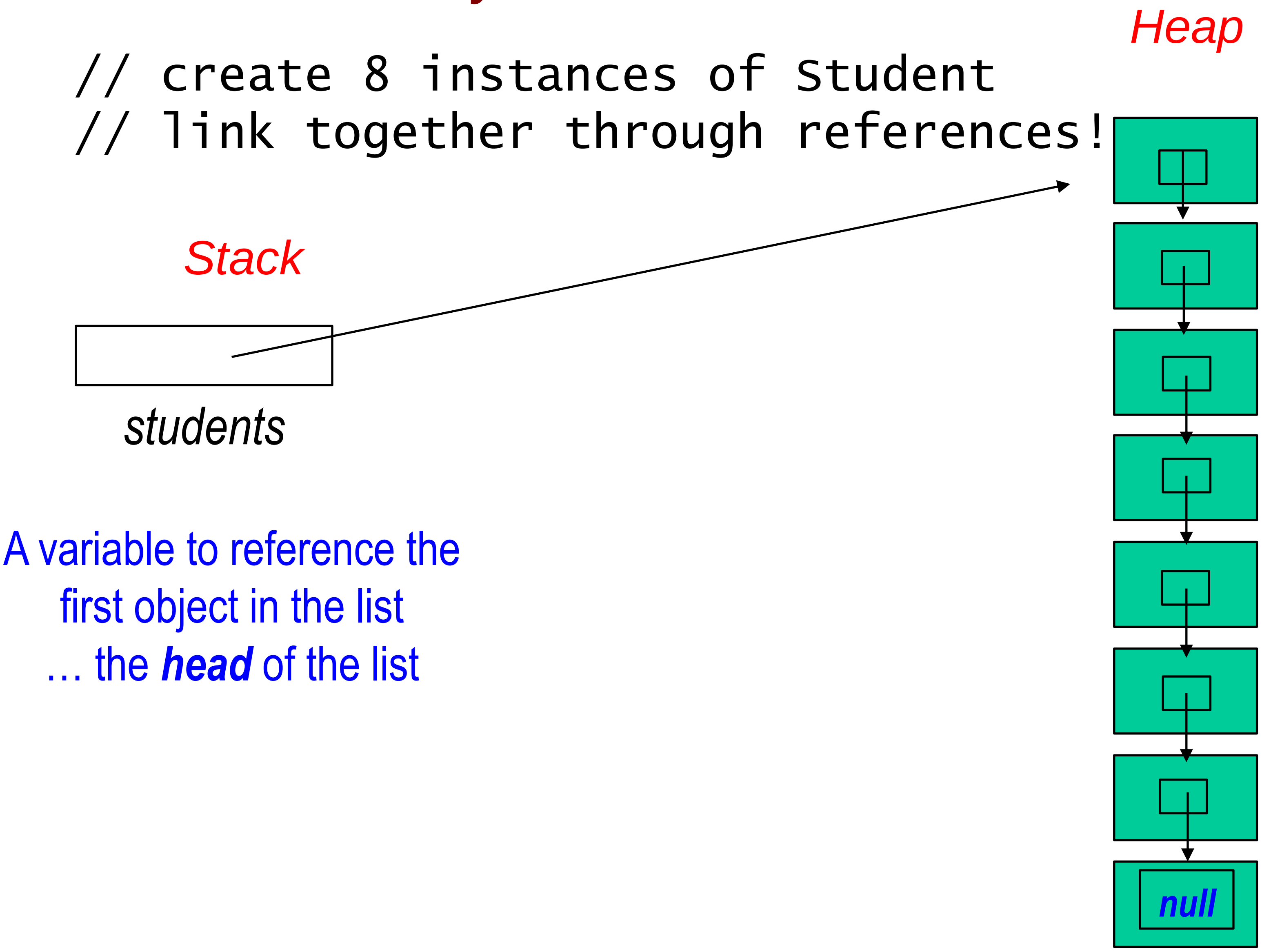
- Most common representation = an array

- Advantages of using an array:
  - easy and efficient access to *any* item in the sequence
    - `item[i]` gives you the item at position i in O(1) time
    - known as *random access*
  - very compact (but can waste space if positions are empty)

- Disadvantages of using an array:
  - have to specify an initial array size and resize it as needed
  - inserting/deleting items can require shifting other items
    - ex: insert 63 between 52 and 72



Linked List:
a dynamic Data structure

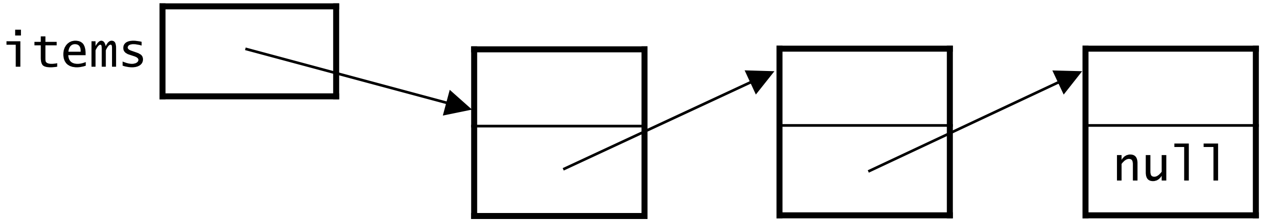


```
// create 8 instances of Student
// link together through references!
```

A variable to reference the first object in the list … the ***head*** of the list

A Linked List

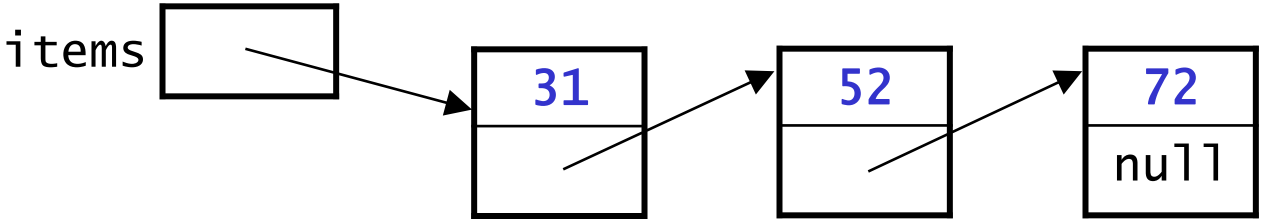
- Example:



- A linked list stores a sequence of items in separate *nodes*.

A Linked List of …

- Example:



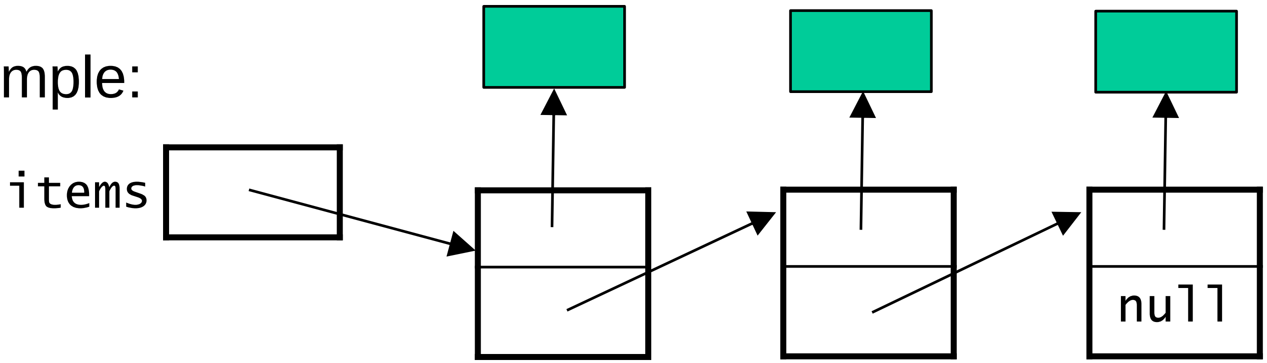
- A linked list stores a sequence of items in separate *nodes*.

- Each node contains:
  - a single *data* item

Note that the item can be a *primitive* variable or a ……………..……

A Linked List of …

- Example:



- A linked list stores a sequence of items in separate *nodes*.

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  - a single *data* item

Note that the item can be a *primitive* variable or a *reference* to an *object*!

A Linked List

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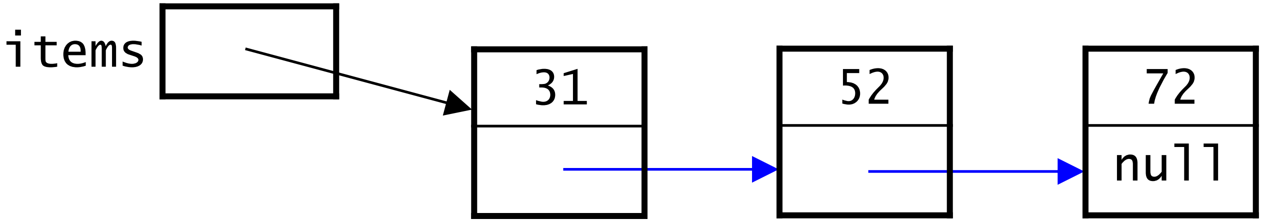
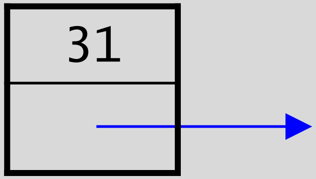


- A linked list stores a sequence of items in separate *nodes*.

- Each node contains:
  - a single *data* item
  - a "link" (i.e., a reference) to the node containing the next item

example node:



A Linked List

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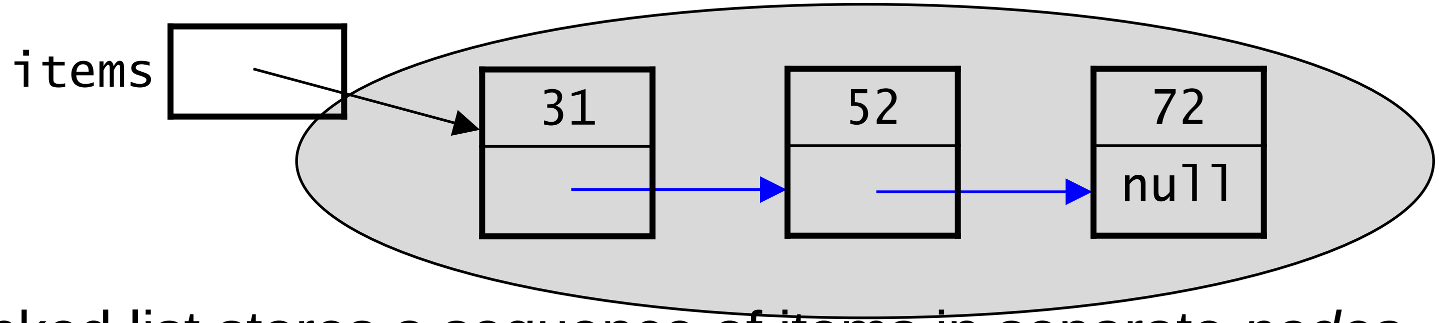

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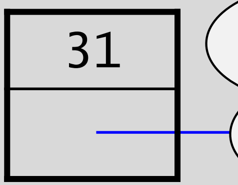
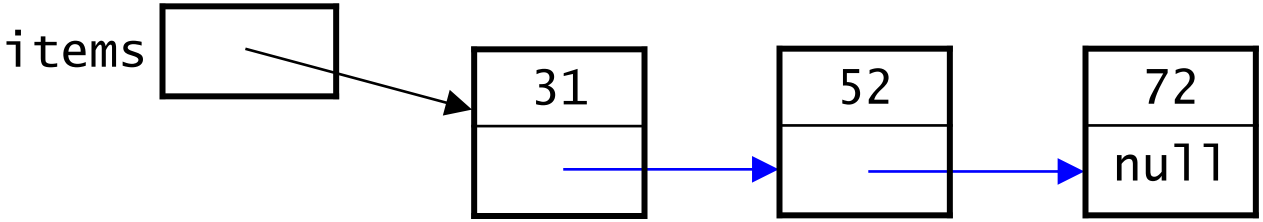


The *nodes* of the list form the sequence…

A Linked List

- Example:



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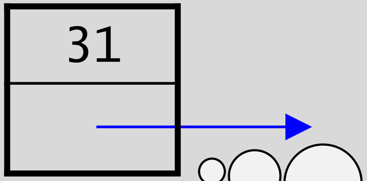
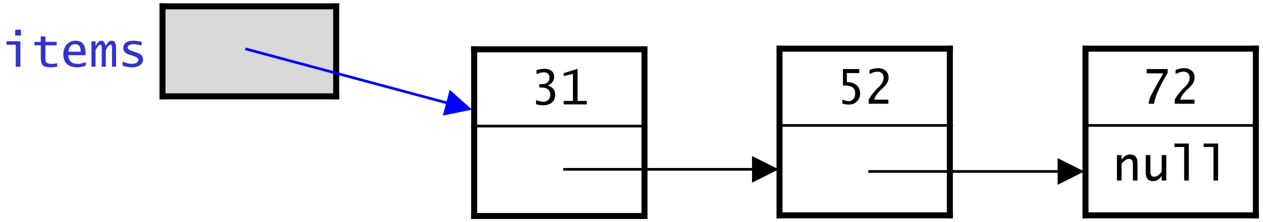


… and the *references* are the links which form the chain.

A Linked List

- Example:



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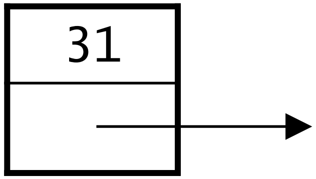
example node:

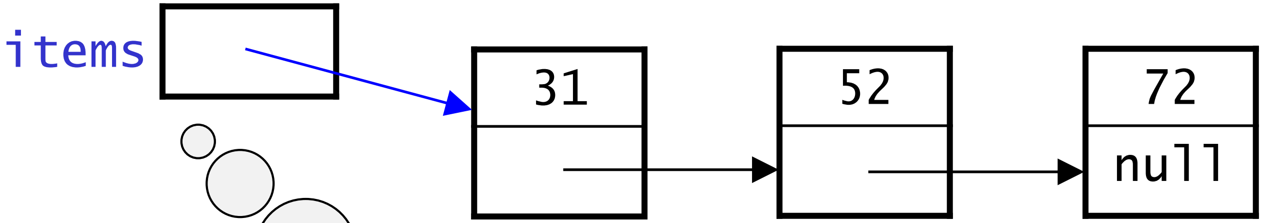


- The last node in the linked list has a link value of `null`.

- The linked list as a whole is represented by a variable that holds a reference to the first node (e.g., `items` in the example above).

A Linked List

- Example:



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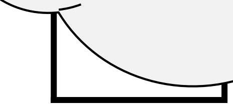
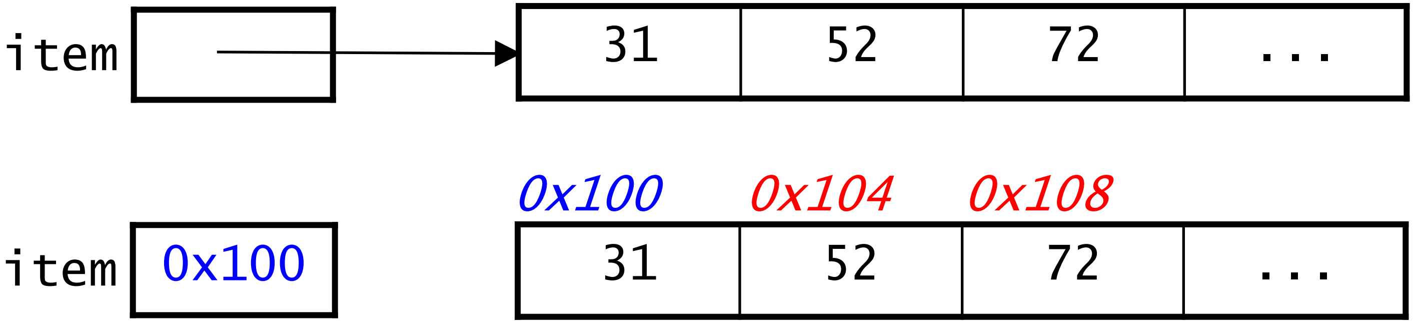


Can be referred to as the *head* or the variable that *references* the “*head of the list*”.

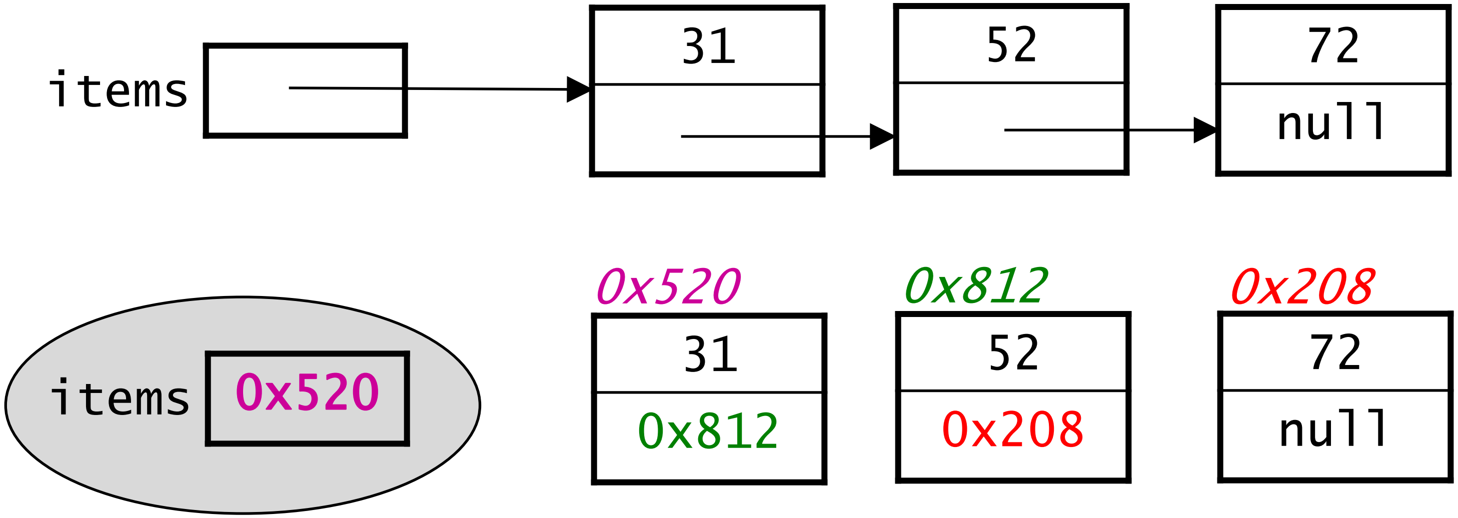
- The last node in the linked list has a link value of `null`.
- The linked list as a whole is represented by a variable that holds a reference to the first node (e.g., `items` in the example above).

Arrays vs. Linked Lists in Memory

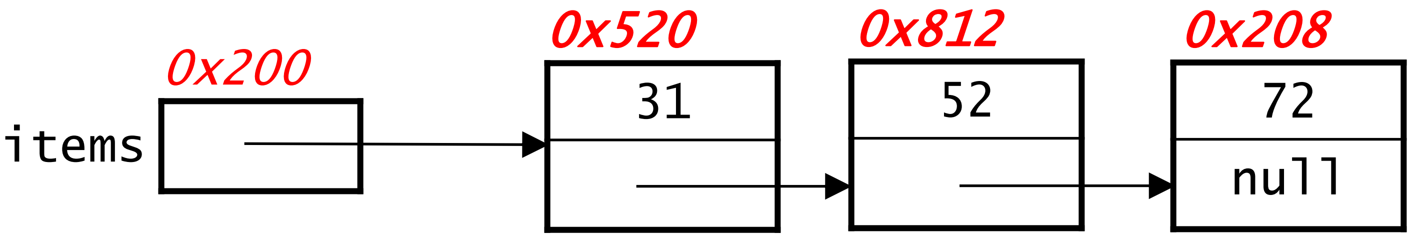
- In an array, the elements occupy consecutive memory locations:



- In a linked list, each node is a *distinct object* on the heap. The nodes do *not* have to be next to each other in memory. That's why we need the links to get from one node to the next.



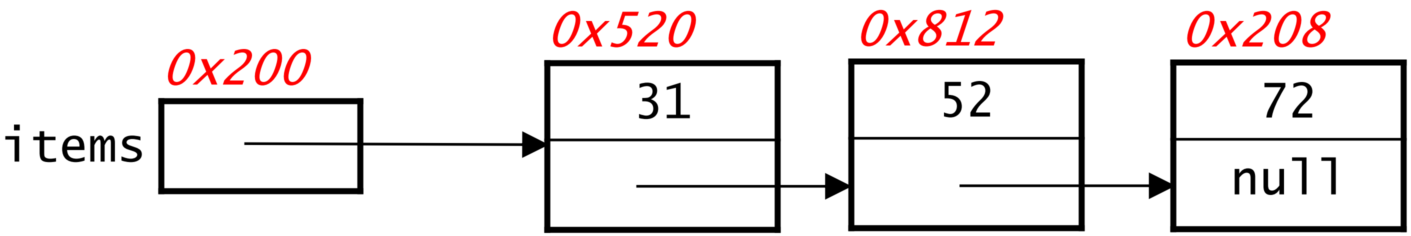
Linked Lists in Memory



- Here's how the above linked list might actually look in memory:

0x200	0x520	← *the variable* `items`
0x204		
0x208	72	*the last node*
0x212	null	
0x216		
...	...	
0x520	31	*the first node*
0x524	0x812	
0x528		
...	...	
0x812	52	*the second node*
0x816	0x208	

Linked Lists in Memory



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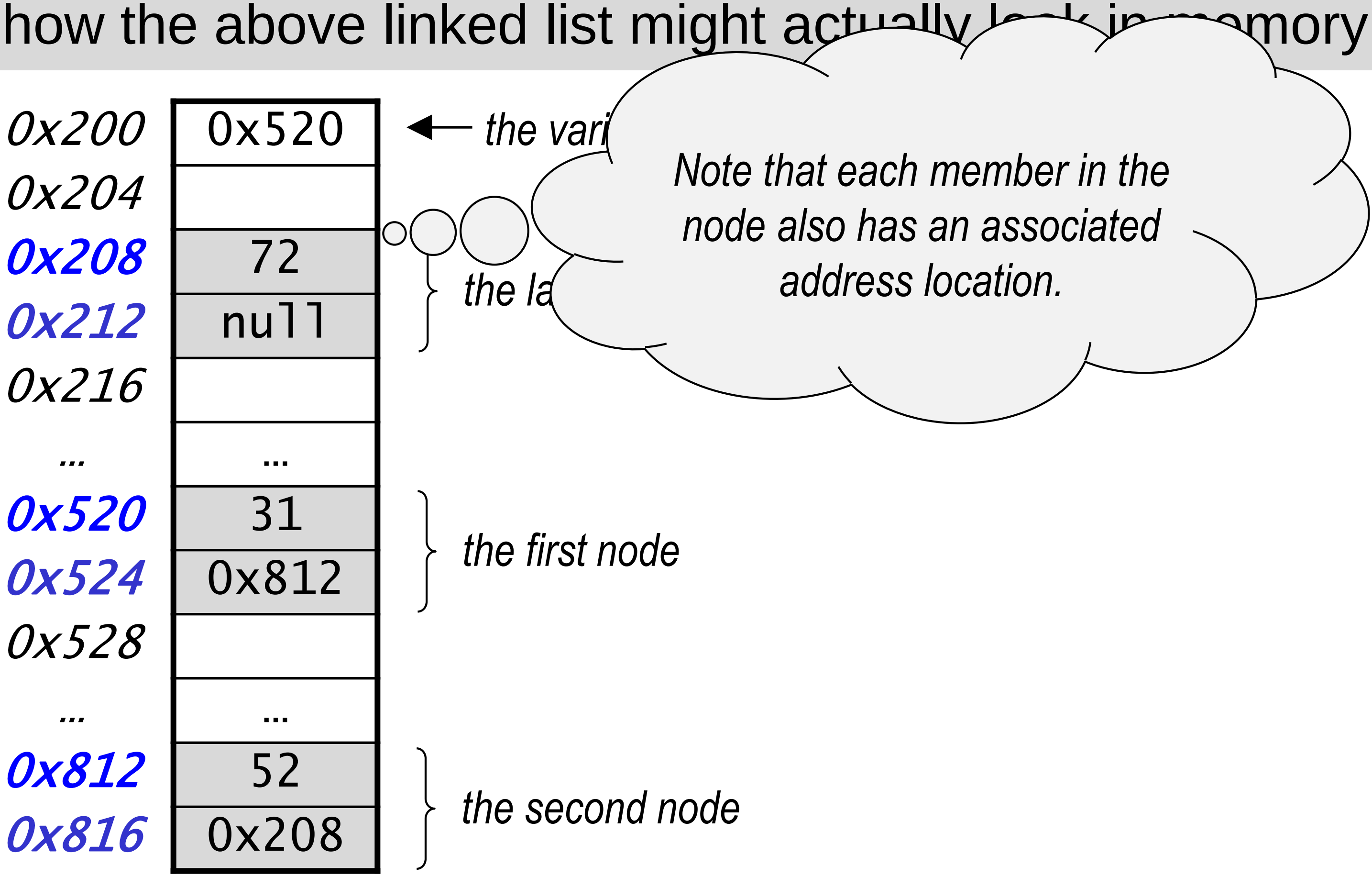

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0x216	
…	…
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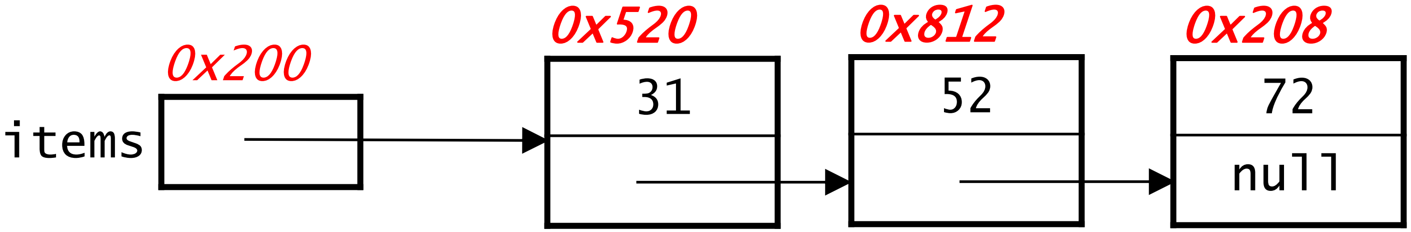
Note that each member in the node also has an associated address location.

Linked Lists in Memory



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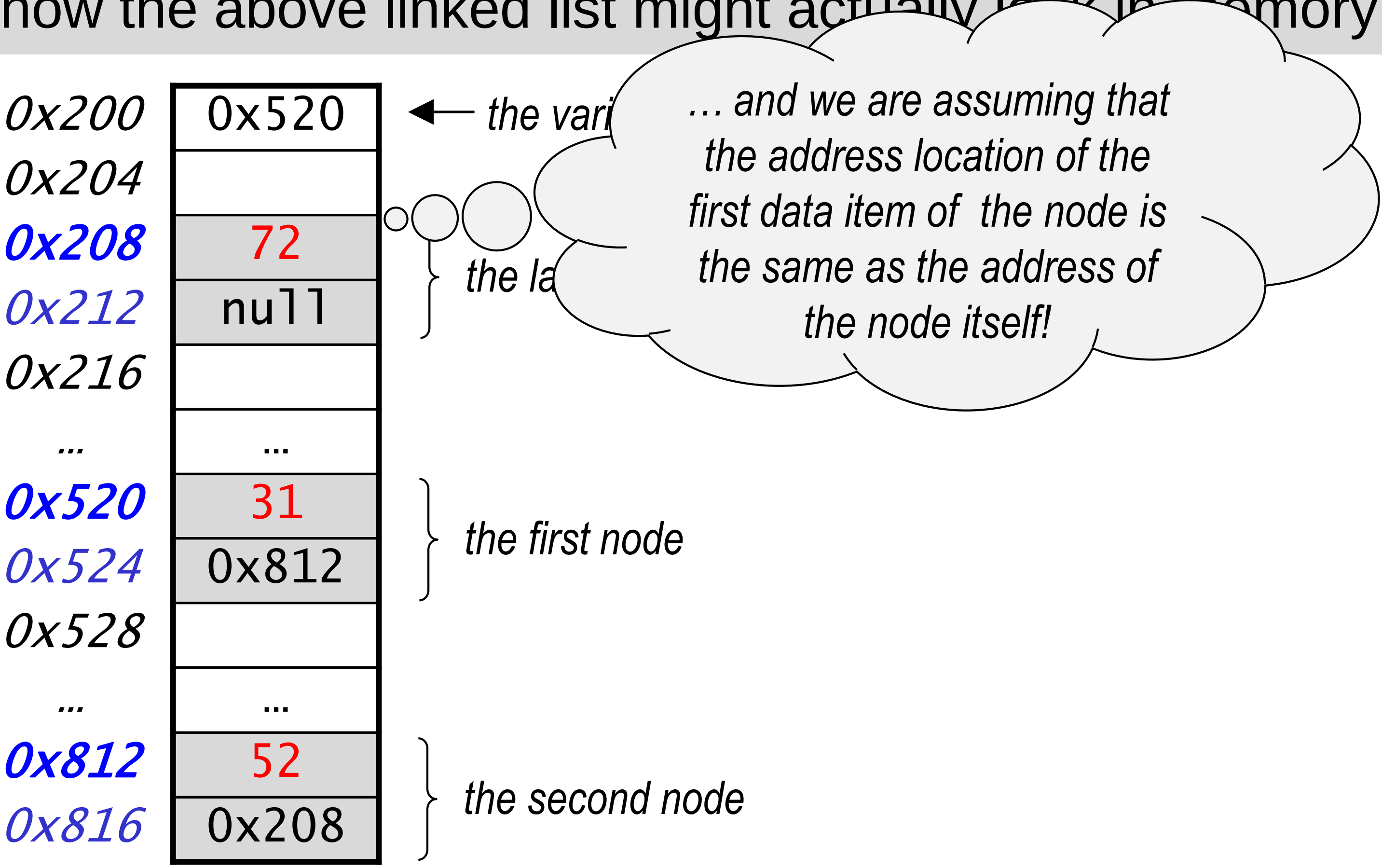

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the vari

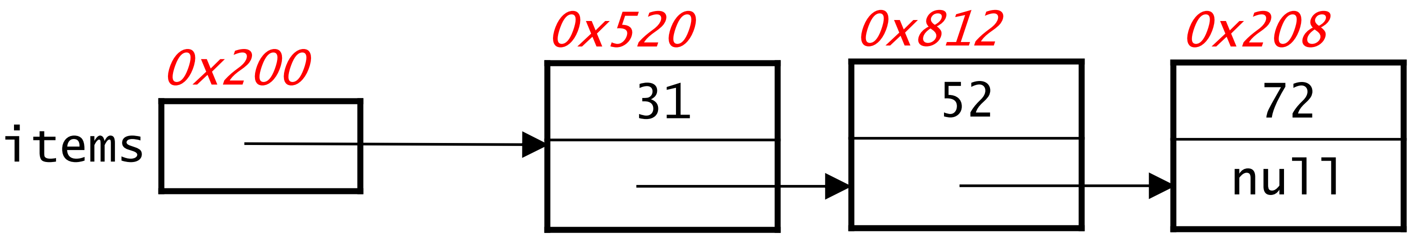
the la

the first node

the second node

… and we are assuming that the address location of the first data item of the node is the same as the address of the node itself!

Linked Lists in Memory



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0x816	0x208

the vari

the la

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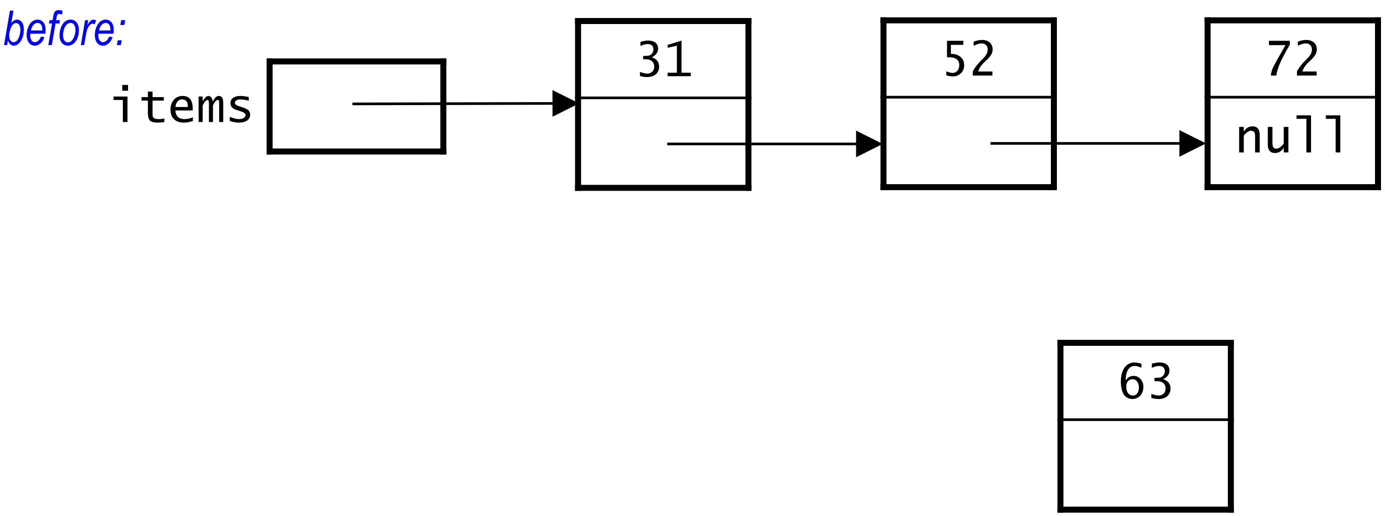
the second node

Since the data item is an integer, we assume the address location of the next member is 4 bytes away.

Features of Linked Lists

- They can grow without limit (provided there is enough memory).
- To insert an item there is no need to "shift over" other items.
    - for example, to insert 63 between nodes 52 and 72:



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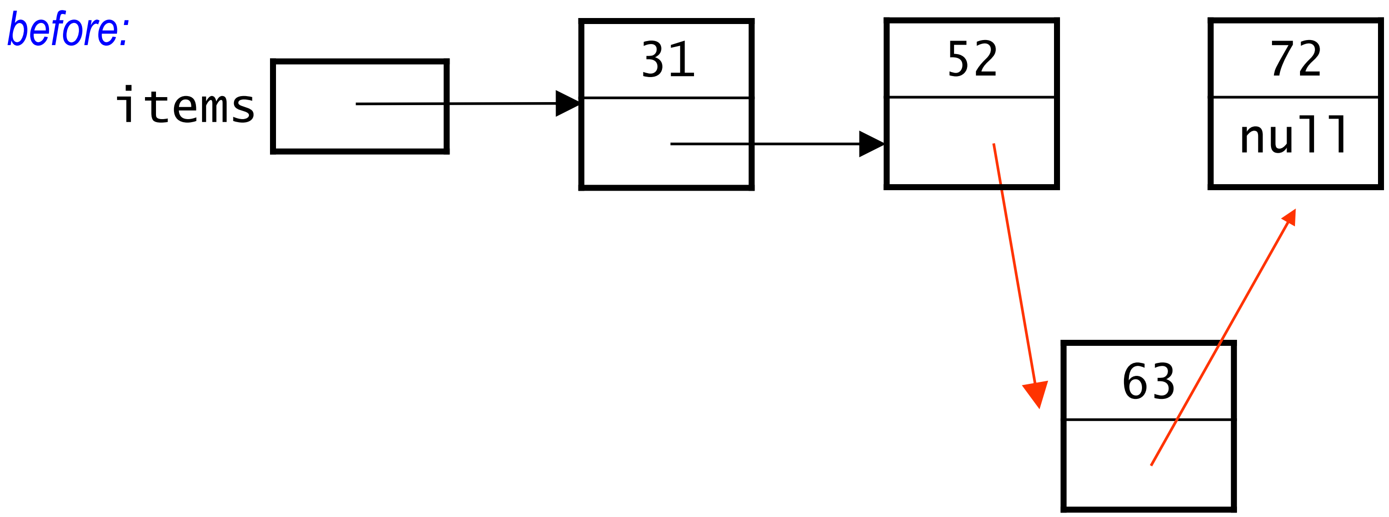

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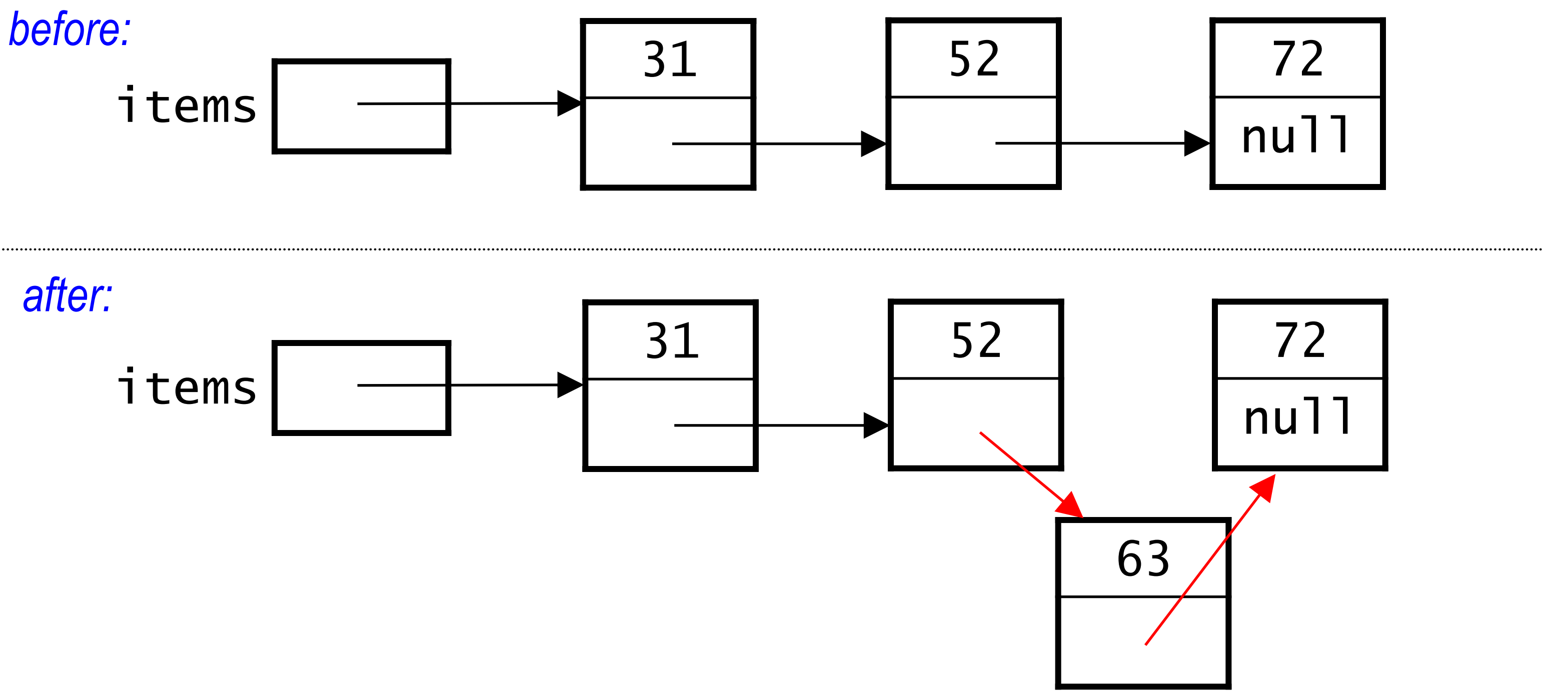

Features of Linked Lists

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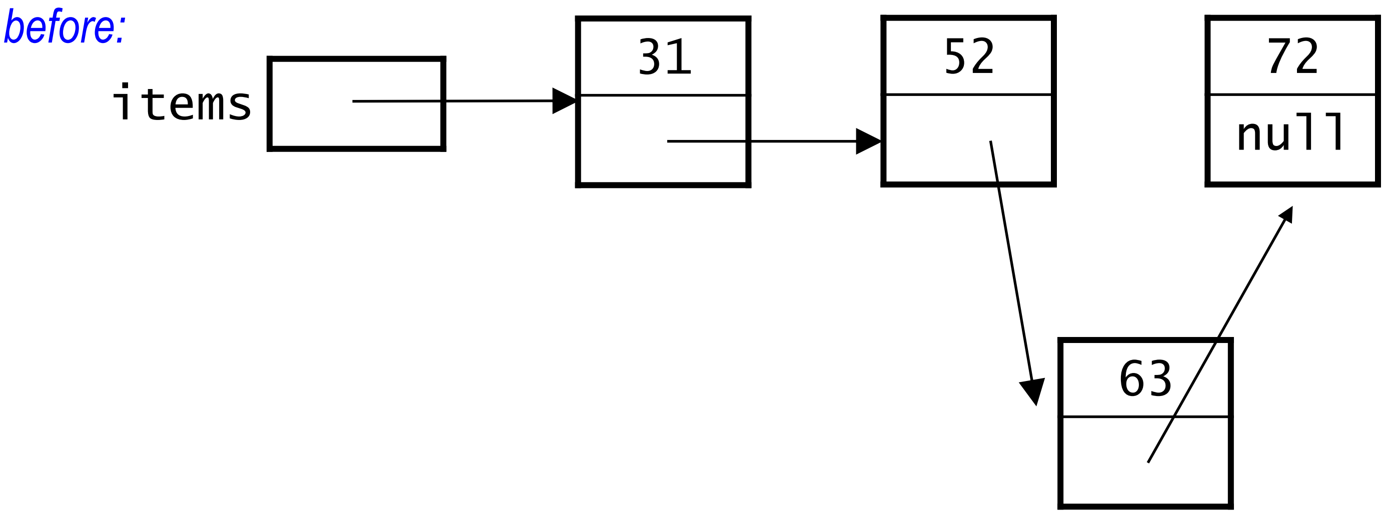
- To delete an item – also no need to "shift over" other items.
  - for example, to delete node 52:



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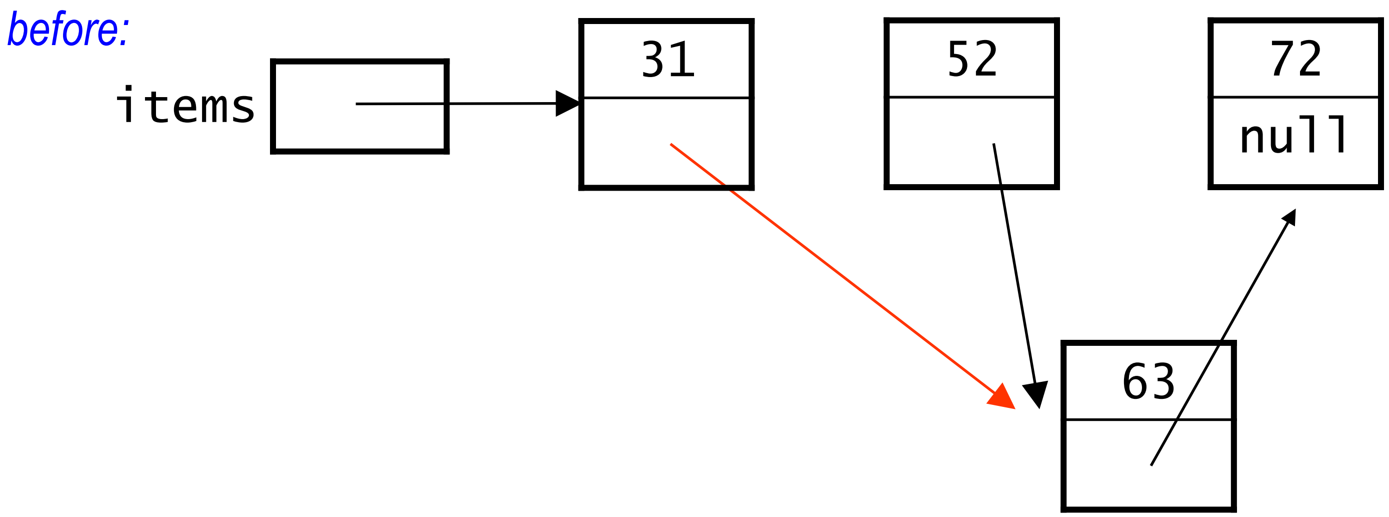

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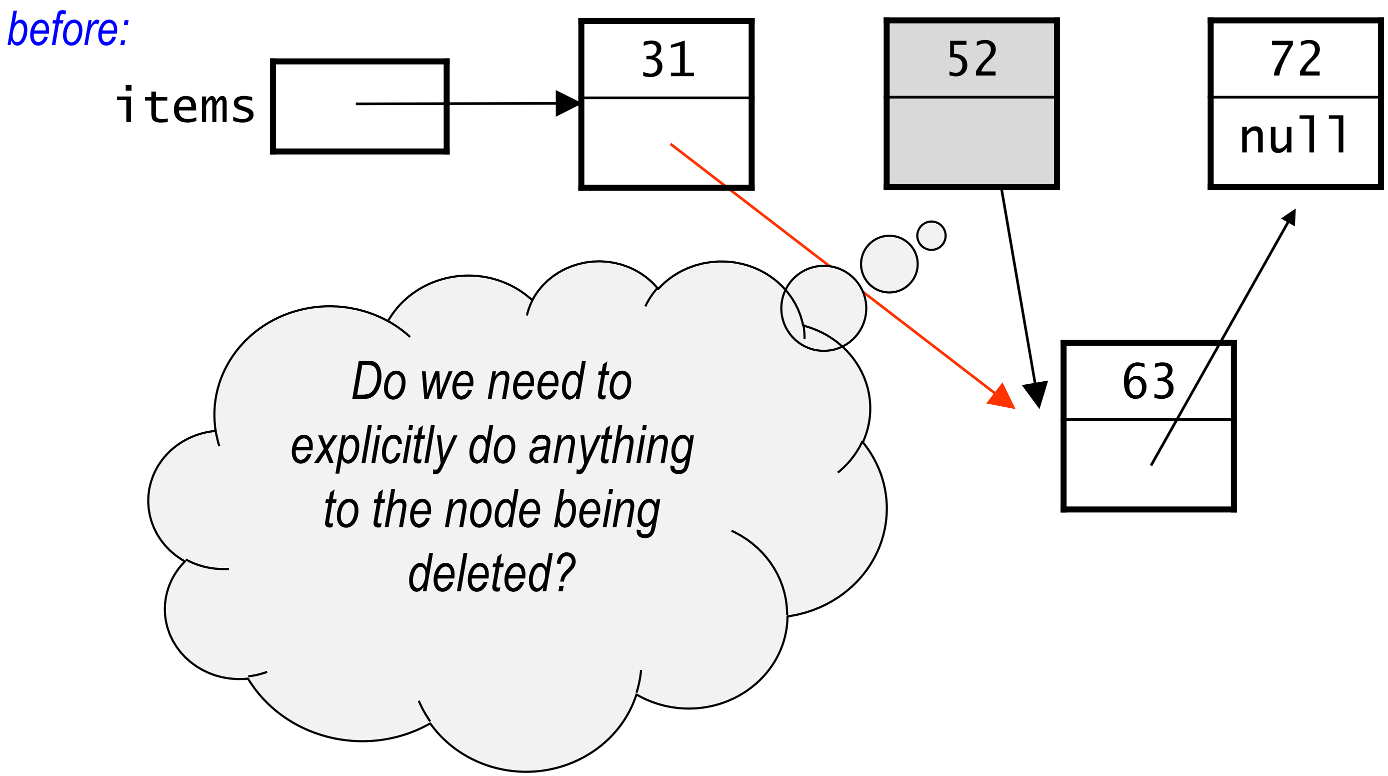

Do we need to explicitly do anything to the node being deleted?

Features of Linked Lists

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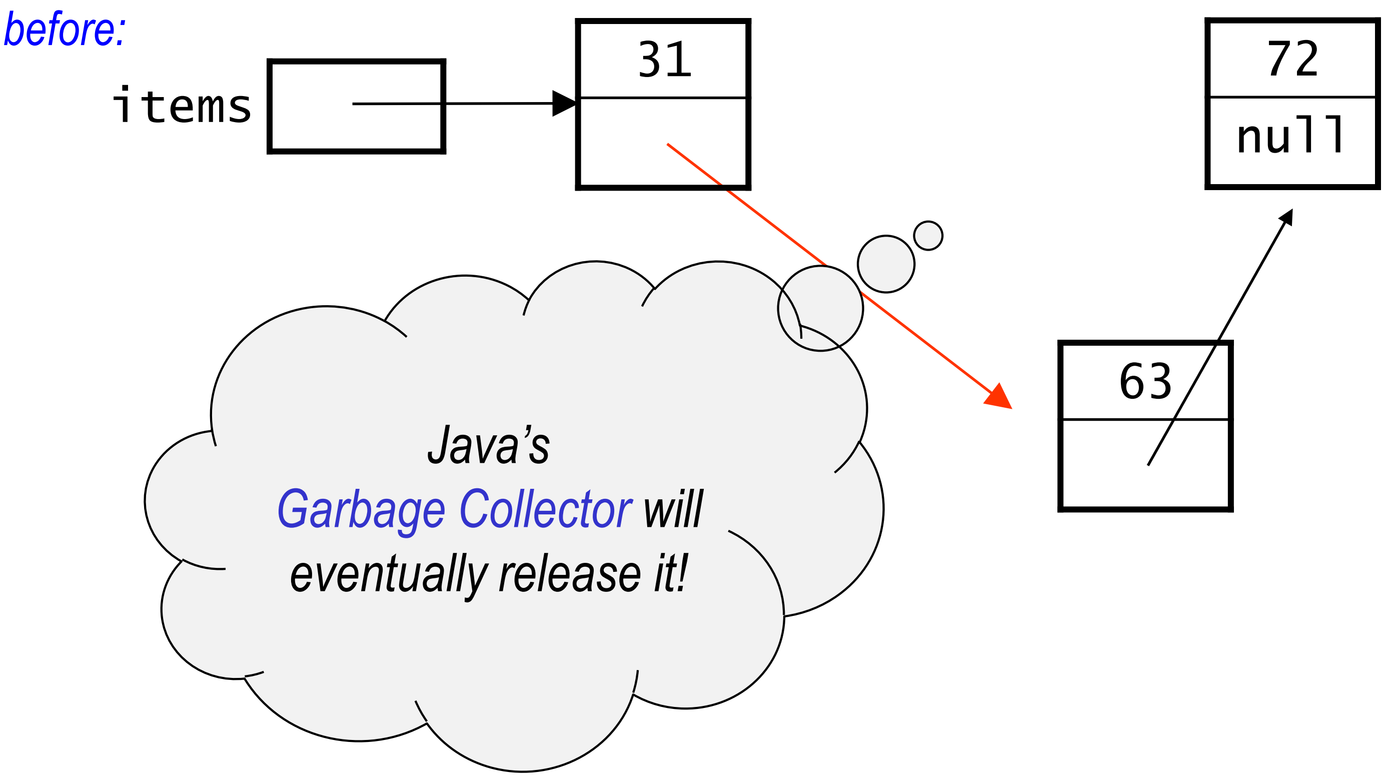


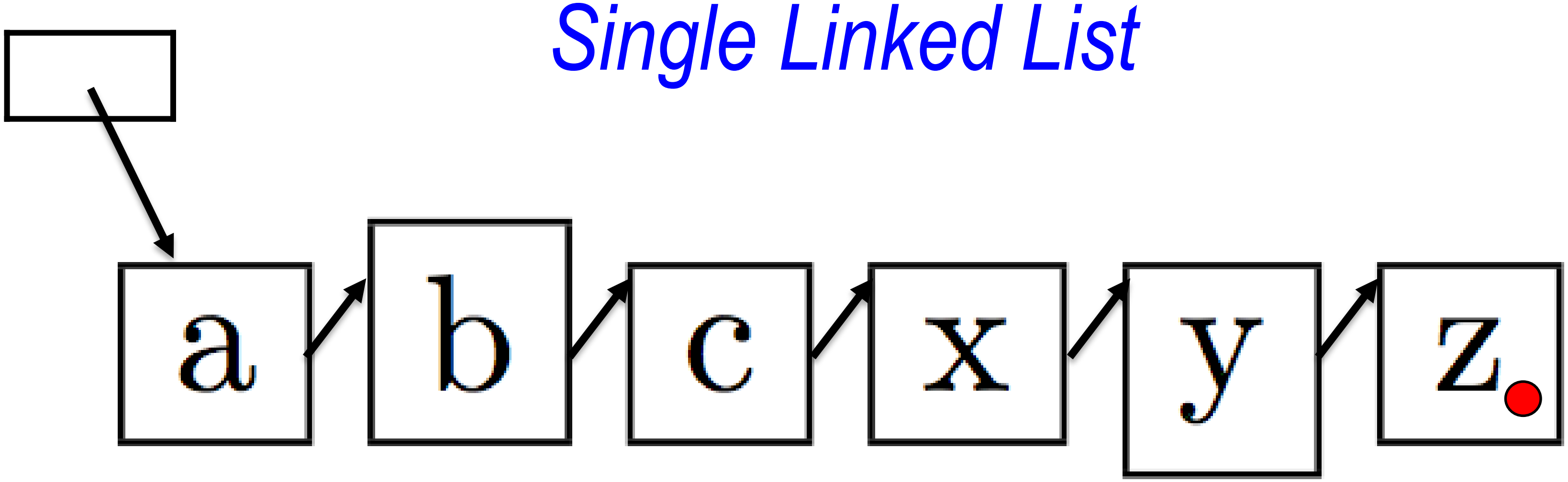
Features of Linked Lists

- Disadvantages:
  - they don't provide random access
    - need to "walk down" or *traverse* the list to access an item
  - the links take up additional memory

Case Study

- A linked list class to represent a string as a linked list of characters.

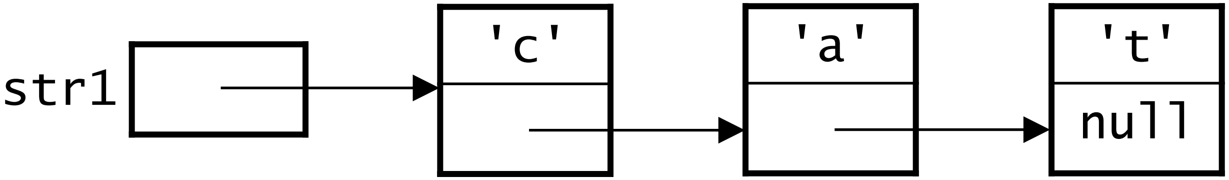
Single Linked List



head of the list

Example:

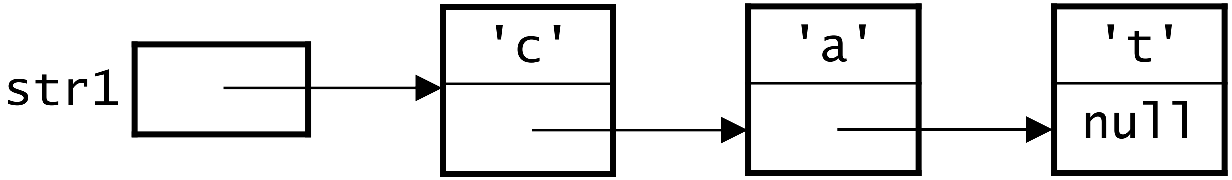
A String as a Linked List of Characters



- Each node in the linked list represents one character.

Example:

A String as a Linked List of Characters



- Each node in the linked list represents one character.

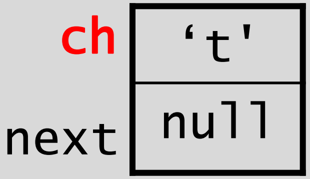
- Java class for this type of node:

```
public class StringNode {
    // data member for ch
    // data member for next


    // constructor to initialize the members



    ...
}
```



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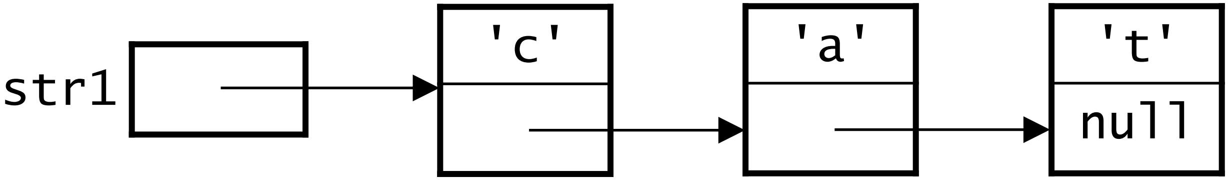

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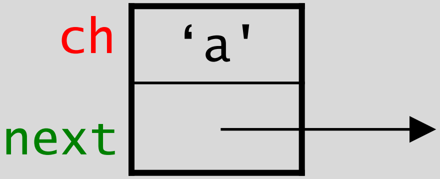


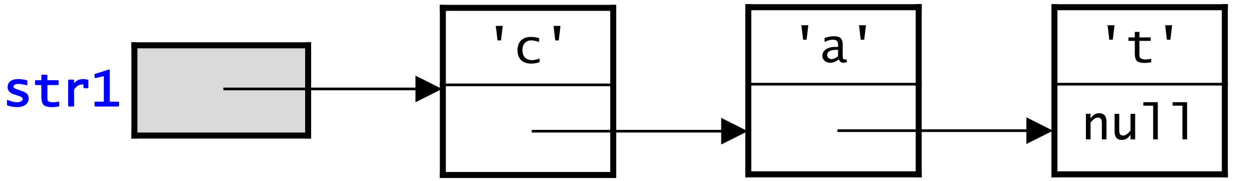
```
public class StringNode {
    private char ch;
    private StringNode next;

    public StringNode(char c, StringNode n) {
        this.ch = c;
        this.next = n;
    }
    ...
}
```

same type as the node itself!

Example:

A String as a Linked List of Characters



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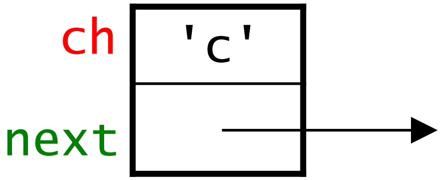
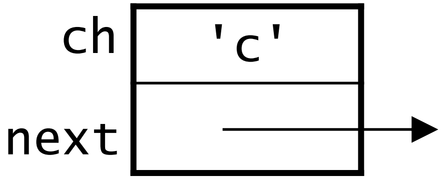


- The string as a whole is represented by a variable that holds a reference to the node for the first character (e.g., `str1` above).

Review of Variables



- A variable or variable expression represents both:
  - a "box" or location in memory (the *address* of the variable)
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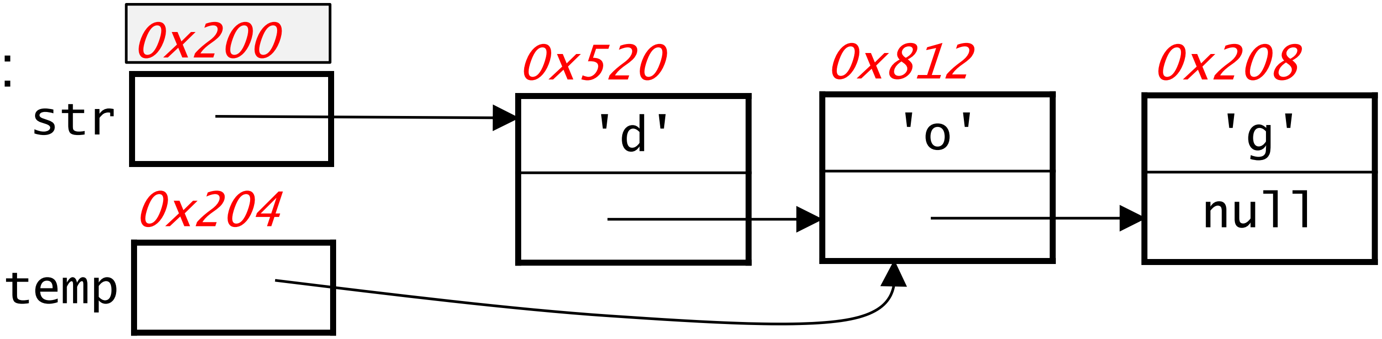
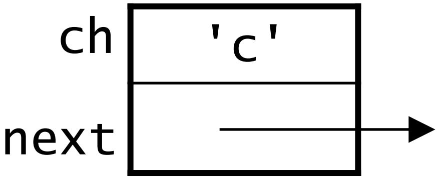
- Practice:



```
StringNode str;   // points to the first node
StringNode temp;  // points to the second node
```

Review of Variables



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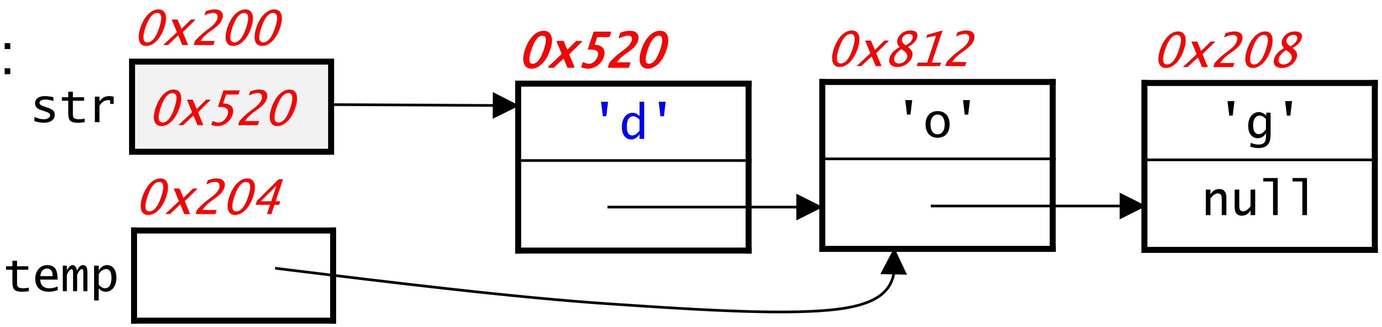

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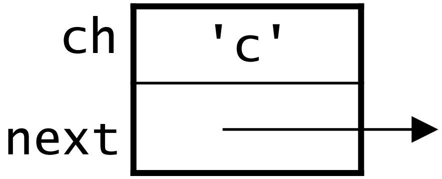

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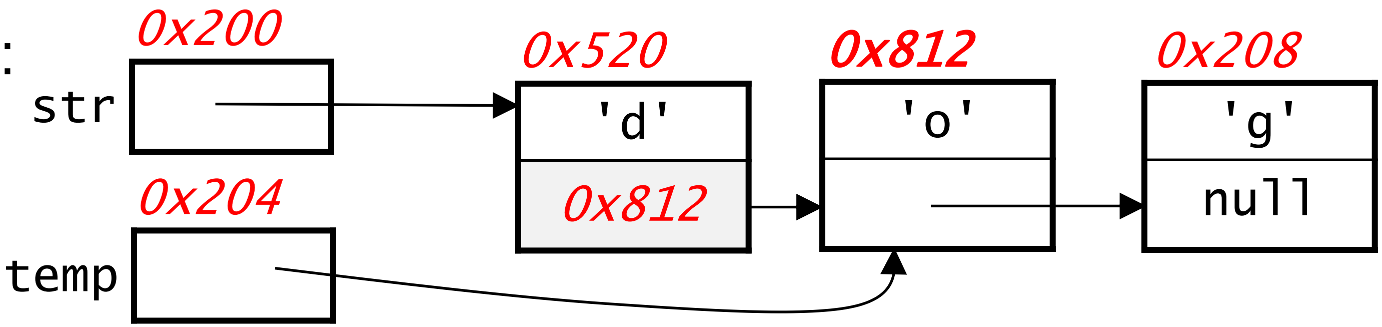

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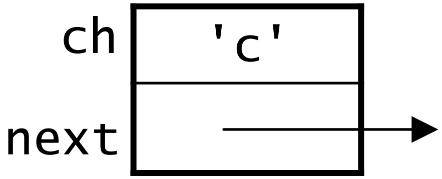

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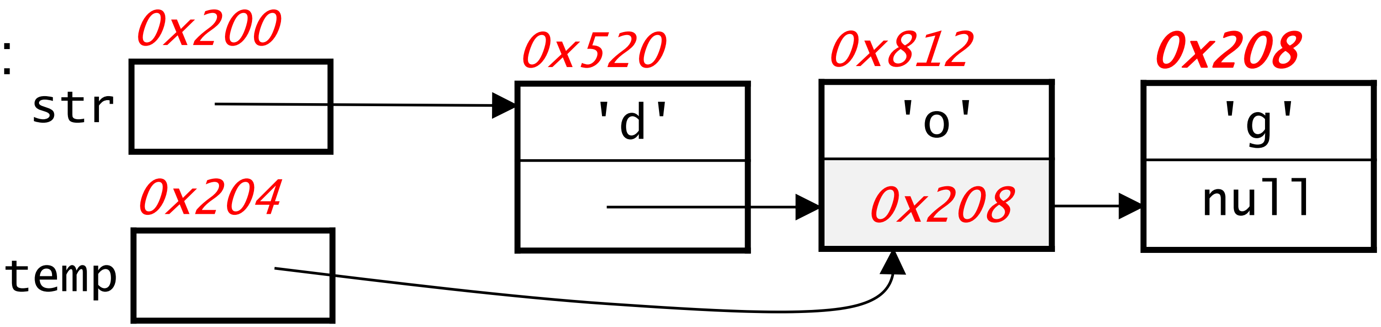

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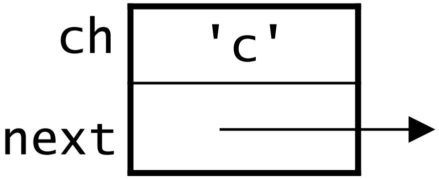

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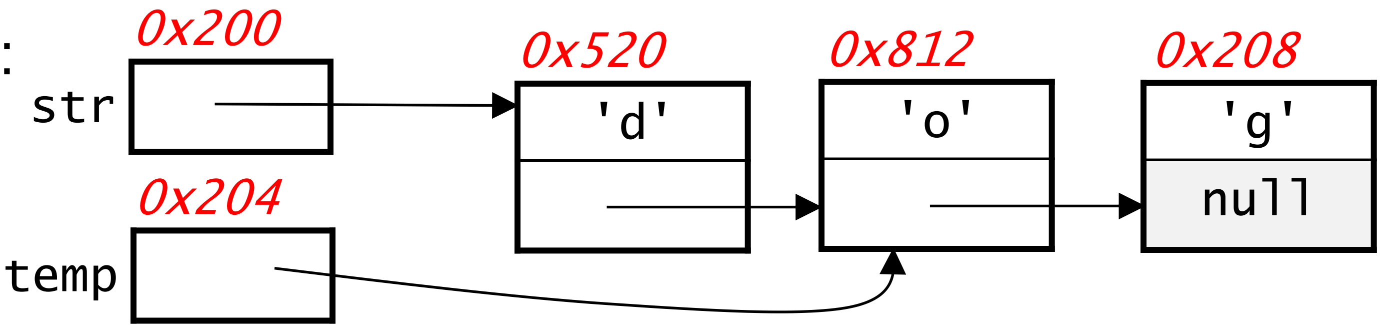

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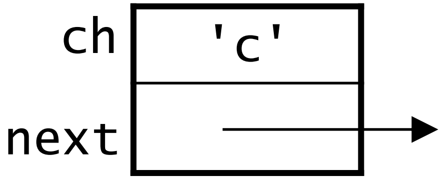

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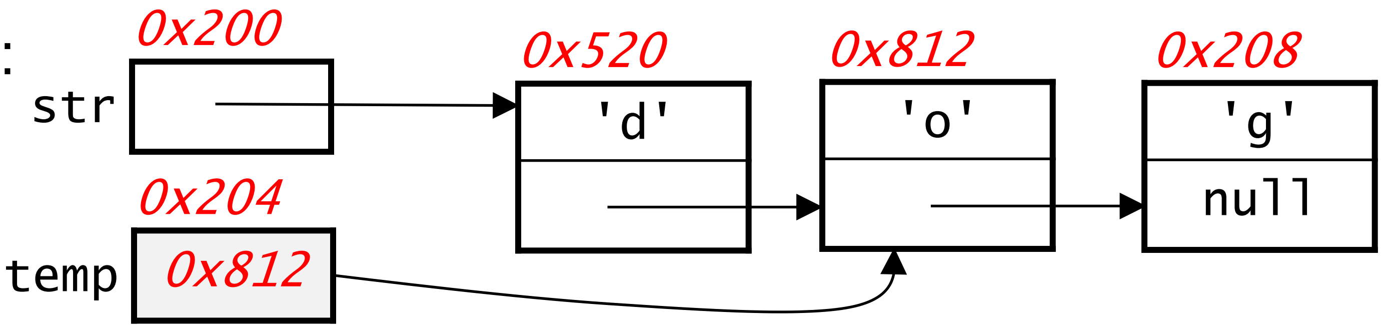
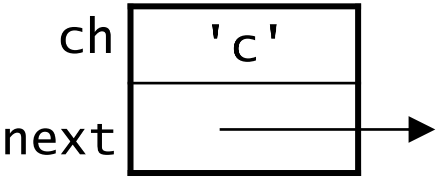
  - a "box" or location in memory (the *address* of the variable)
  - the contents of that "box" (the *value* of the variable)

- Practice:



```
StringNode str;    // points to the first node
StringNode temp;   // points to the second node
```

Review of Variables



- A variable or variable expression represents both:
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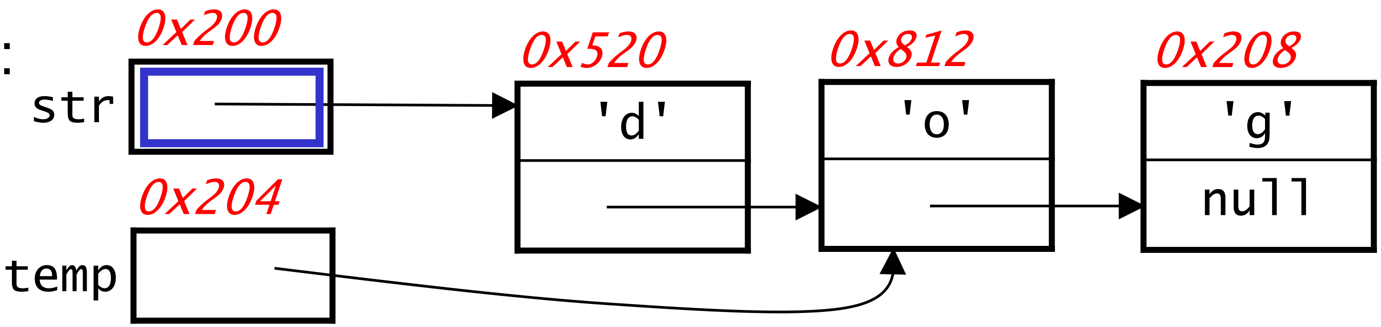
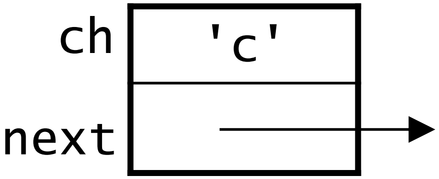
- Practice:



```
StringNode str;   // points to the first node
StringNode temp;  // points to the second node
```

expression	*address*	*value*
`str`	**0x200**	**0x520 (reference to the 'd' node)**
`str.ch`		
`str.next`		

Review of Variables



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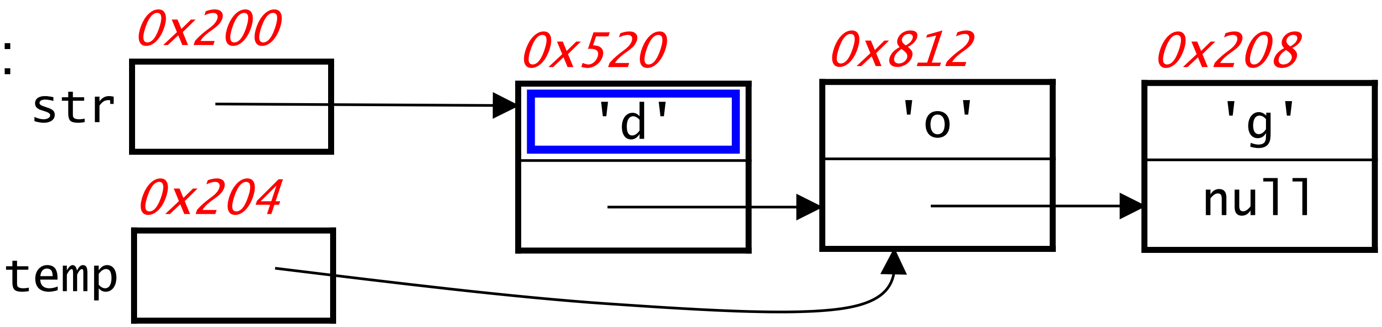
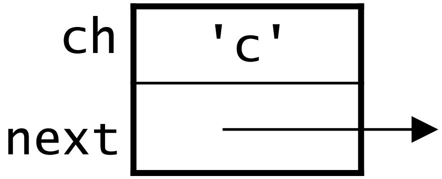


```
StringNode str;   // points to the first node
StringNode temp;  // points to the second node
```

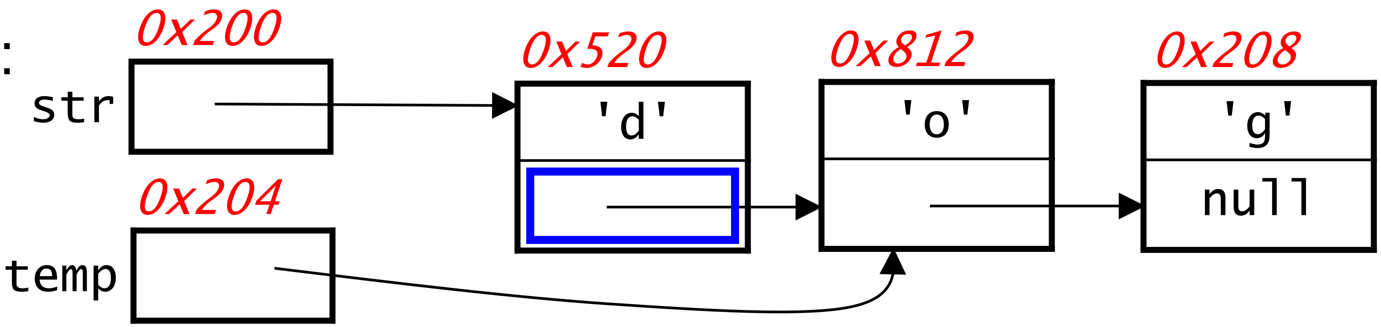
expression	*address*	*value*
`str`	0x200	0x520 (reference to the 'd' node)
`str.ch`	0x520	'd'
`str.next`		

Review of Variables



- A variable or variable expression represents both:
  - a "box" or location in memory (the *address* of the variable)
  - the contents of that "box" (the *value* of the variable)

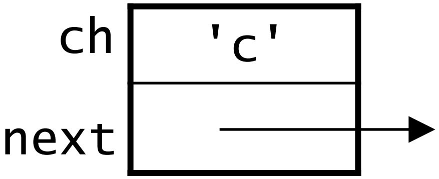
- Practice:



```
StringNode str;   // points to the first node
StringNode temp;  // points to the second node
```

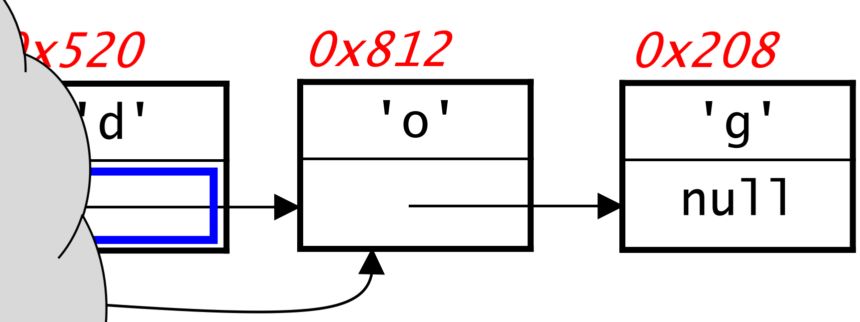
expression	*address*	*value*
`str`	0x200	0x520 (reference to the 'd' node)
`str.ch`	0x520	'd'
`str.next`	**0x522**	**0x812 (reference to the 'o' node)**

Review of Variables



- A variable or variable expression represents both:
  - a "box" or location in memory (the *address* of the variable)
  - the contents of that "box" (the *value* of the variable)

- Practice:

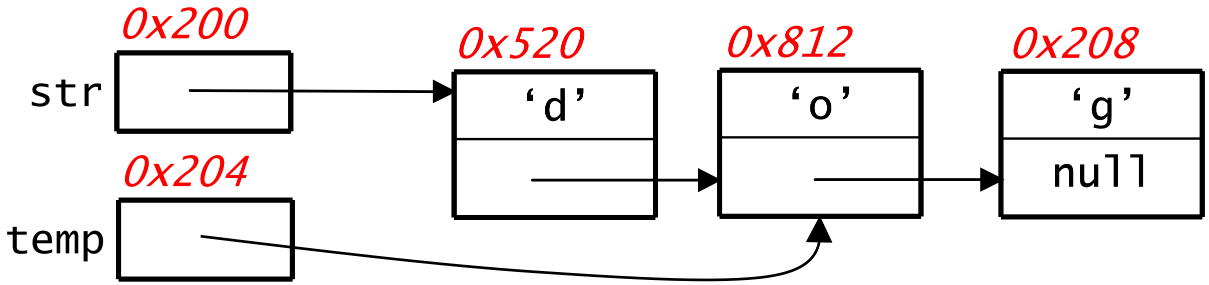


Note the use of the dot operator.

```
nts to the first node
oints to the second node
```

express	ess	*value*
str	0x200	0x520 (reference to the 'd' node)
str.ch	0x520	'd'
str.next	0x522	0x812 (reference to the 'o' node)

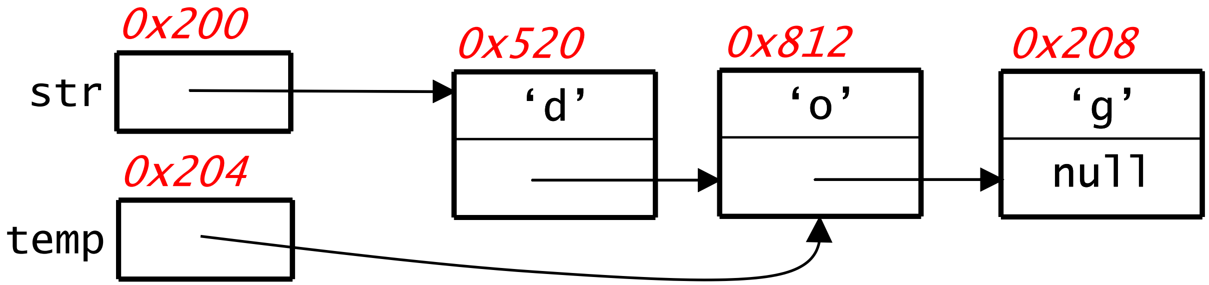
More Complicated Expressions



- Example: `temp.next.ch`

Understanding the dot operator

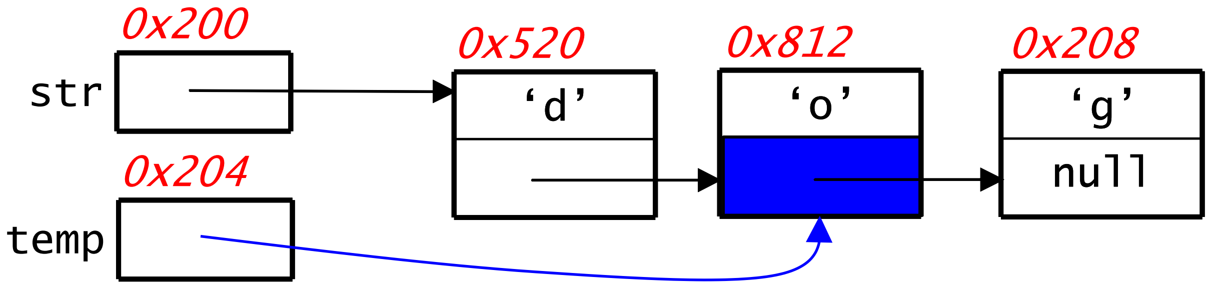
More Complicated Expressions



- Example: `temp.next.ch`

- `System.out.println( temp );` *0x812*

More Complicated Expressions



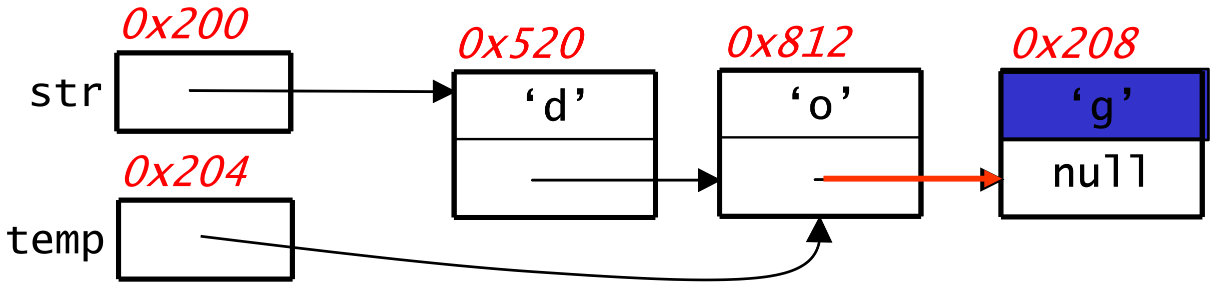
- Example: `temp.next.ch`

- `System.out.println( temp );` *0x812*

- `System.out.println( temp.next );` *0x208*

Says…
follow the reference.
Go to the address location stored in variable temp and access the next field of that object.

More Complicated Expressions



- Example: `temp.next.ch`

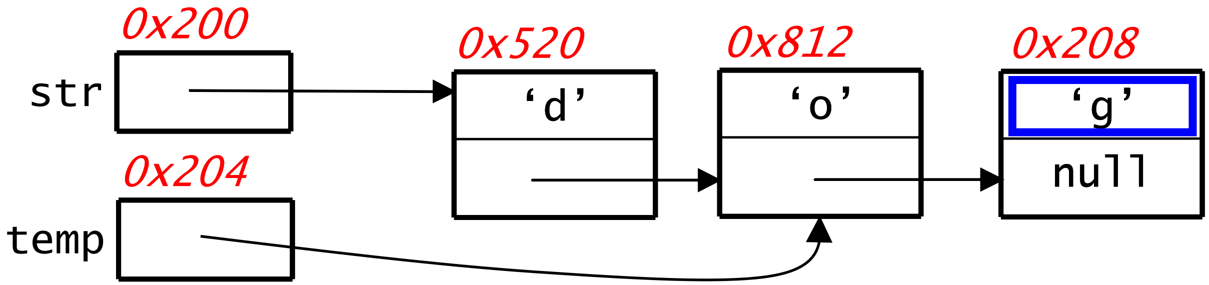
- `System.out.println( temp );` 0x812

- `System.out.println( temp.next );` 0x208

- `System.out.println( temp.next.ch );` 'g'

follow the reference

More Complicated Expressions



- Example: `temp.next.ch`

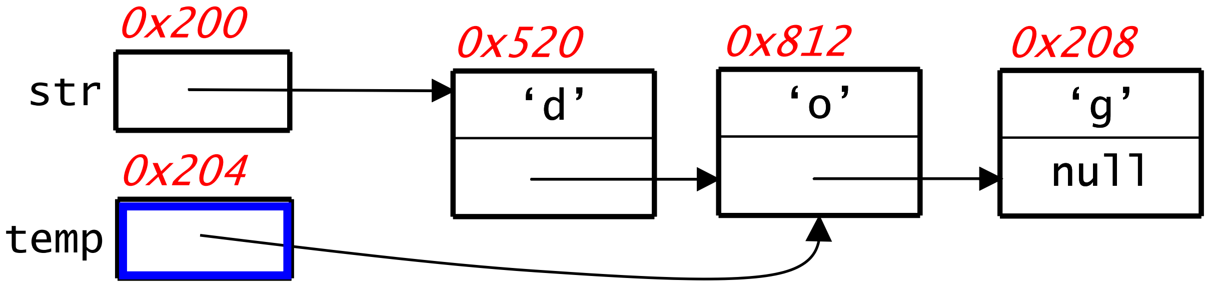
- Start with the beginning of the expression: `temp.next`
  It represents the `next` field of the node to which `temp` refers.
  - address = `0x814`
  - value = `0x208` (reference to the `'g'` node)

- Next, consider `temp.next.ch`
  It represents the `ch` field of the node to which `temp.next` refers.
  - address = **`0x208`**
  - value = **`'g'`**

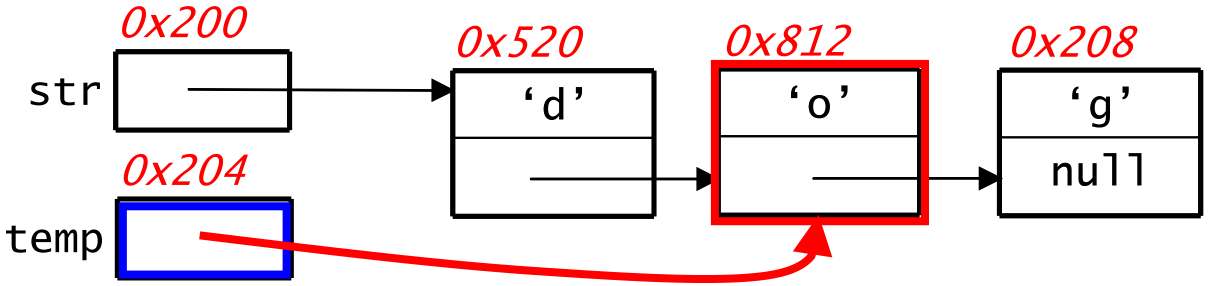
Dereferencing a Reference:

another look

- Each dot causes us to *dereference* the reference represented by the expression preceding the dot.
- Consider again `temp.next.ch`
- Start with temp: `temp.next.ch`



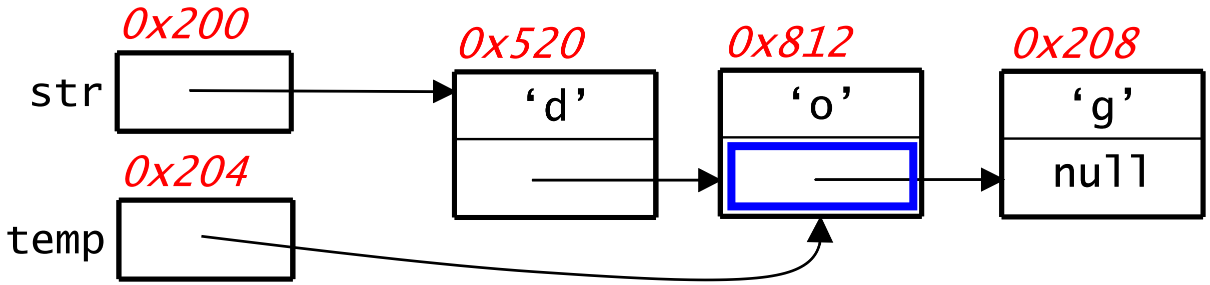
- Dereference: `temp.next.ch`



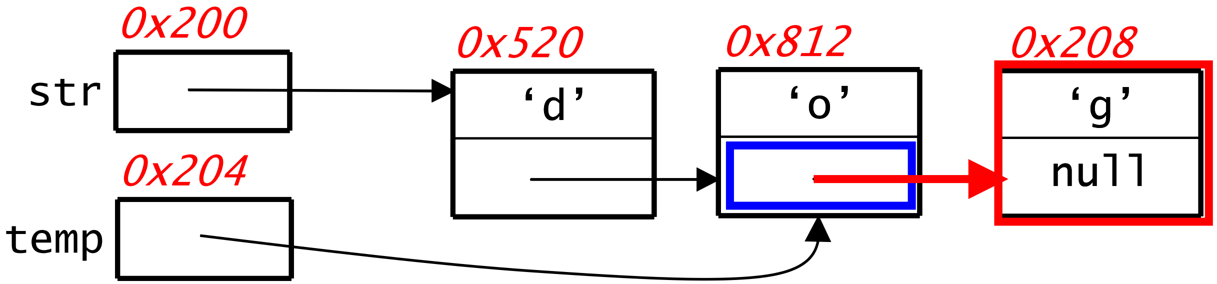
Dereferencing a Reference:

another look

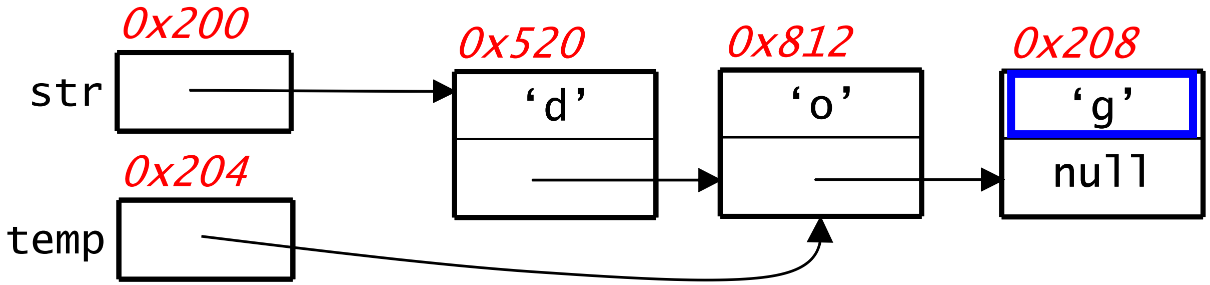
- Get the `next` field: `temp.next.ch`



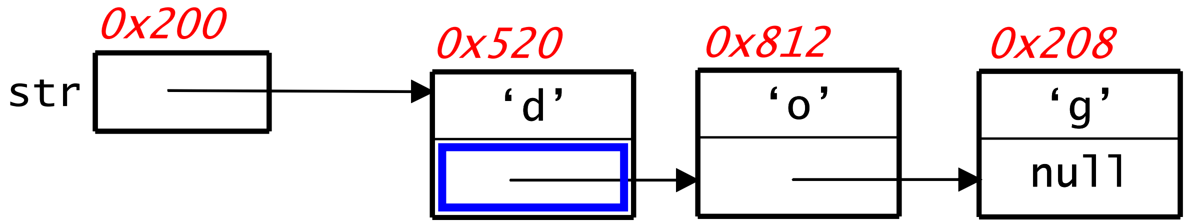
- Dereference: `temp.next.ch`



- Get the `ch` field: `temp.next.ch`



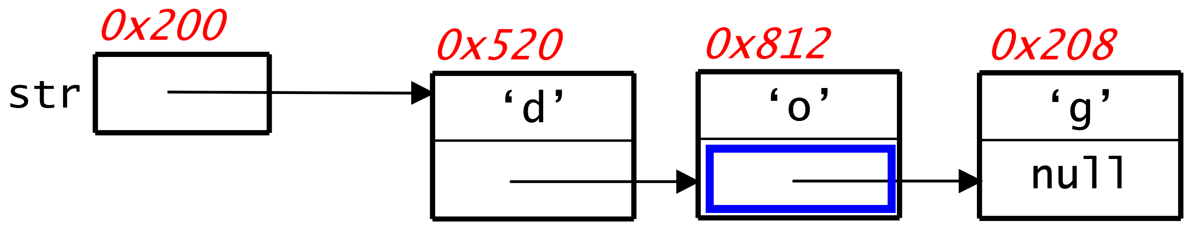
What are the address and value of `str.next.next`?



- `str.next` is the `next` field in the node to which `str` refers
  - it holds a *reference* to the `'o'` node

	address	value
A.	0x522	0x812
B.	0x812	'o'
C.	0x814	0x208
D.	0x208	'g'
E.	0x210	null

What are the address and value of `str.next.next`?



- `str.next` is the `next` field in the node to which `str` refers
  - it holds a reference to the `'o'` node
- thus, `str.next.next` is the `next` field in the `'o'` node
  - it holds a reference to the `'g'` node

	address	value
A.	`0x522`	`0x812`
B.	`0x812`	`'o'`
C.	**`0x814`**	**`0x208`**
D.	`0x208`	`'g'`
E.	`0x210`	`null`

Review of Assignment Statements

- An assignment of the form

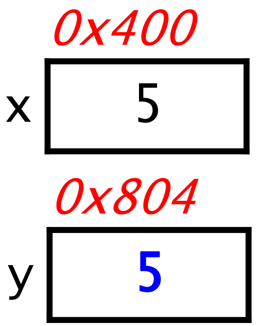
```
var1 = var2;
```

  - takes the *value* of `var2`
  - copies it into the box (*memory cell*) at the *address* of `var1`

In other words, it takes the value in `var2` *and copies it into* `var1`

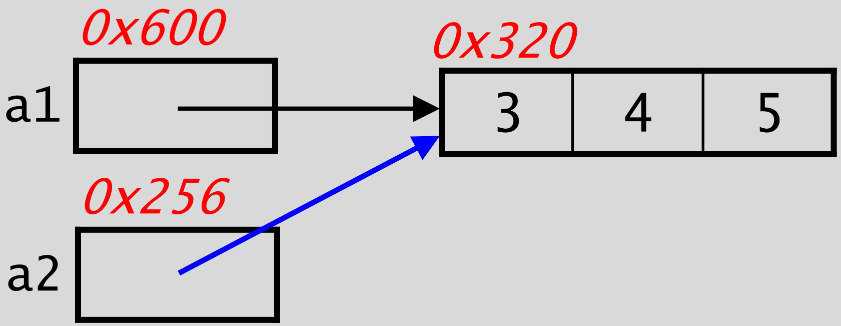
- Example involving integers:

```
int x = 5;
int y = x;
        5
```



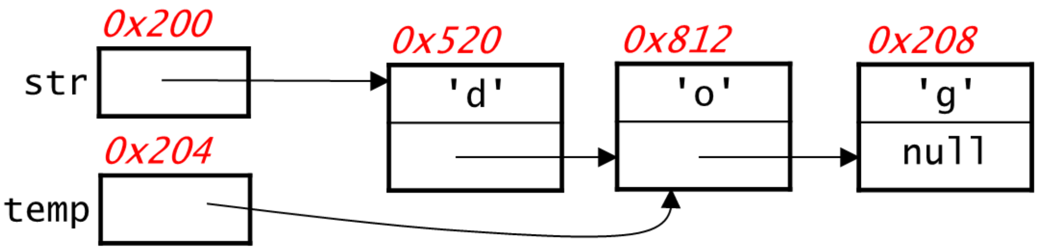
- Example involving references:

```
int[] a1 = {3, 4, 5};
int[] a2 = a1;
           0x320
```



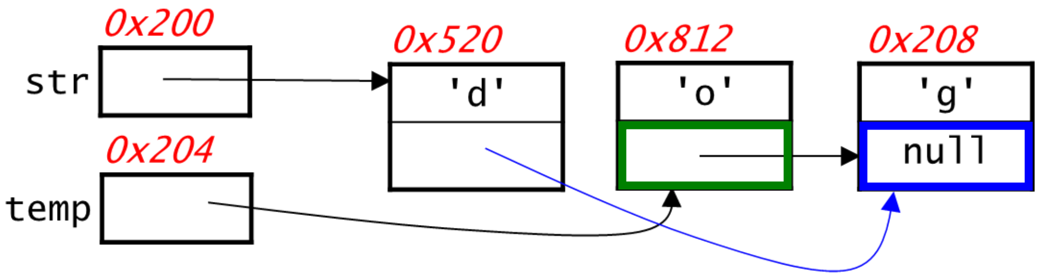
What About These Assignments?

- *Identify the two boxes.*
- *Determine the value in the box specified by the right-hand side.*
- *Copy that value into the box specified by the left-hand side.*



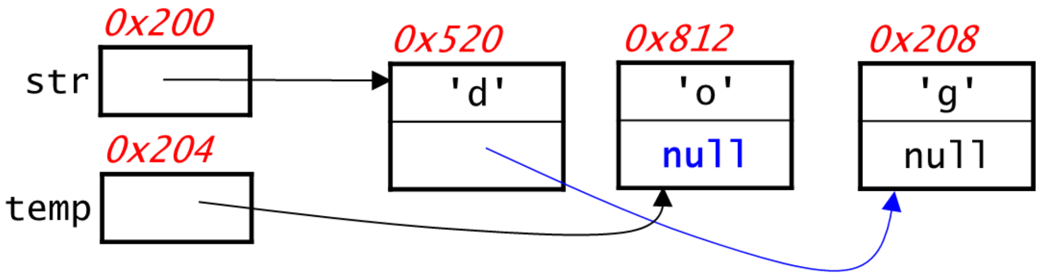
```
1)  str.next = temp.next;
```

0x208 (a reference to the 'g' node)



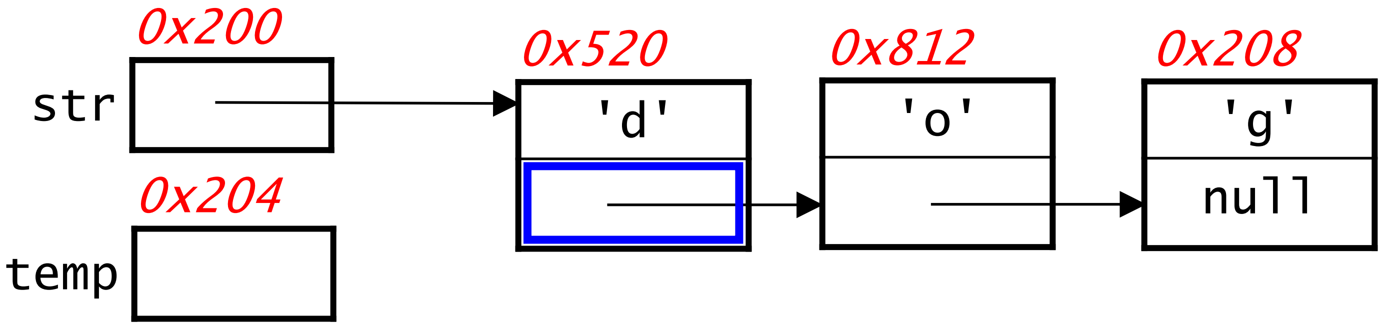
```
2)  temp.next = temp.next.next;
```

null



Writing an Appropriate Assignment

- What assignment is needed to make variable `temp` reference the node containing the character 'o‘ ?



  - find the reference to the `'o'` node:
  - determine the expression to accesses the reference:
    `str.next`
  - write the assignment:
    `temp = str.next;`

Example:
A String as a Linked List of Characters

- An empty string will be represented by a null value.

  example:

  ```
  StringNode str2 = null;
  ```

- We will use *static* methods that take the string as a parameter.
  - e.g., we will write `length(str1)` instead of `str1.length()`
  - outside the class, call the methods using the class name:

    ```
    StringNode.length(str1)
    ```

- Using static methods allows the methods to handle empty strings.
  - if `str1 == null`:
    - `length(str1)` will work
    - `str1.length()` will throw a `NullPointerException`

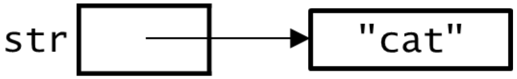
A Linked List Is a Recursive Data Structure!

- Recursive definition of a linked list: a linked list is either
  a) empty or
  b) a single node, followed by a linked list

- Viewing linked lists in this way allows us to write recursive methods that operate on linked lists.

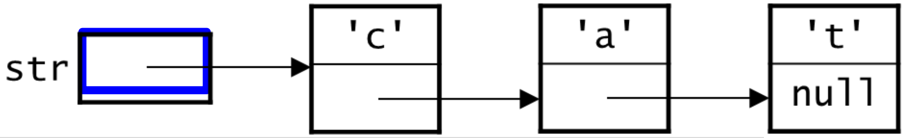
Recursively Finding the Length of a String

- For a built-in Java `String` object:



```
public static int length(String str) {
    if (str == null || str.equals("")) {
        return 0;
    } else {
        int lenRest = length(str.substring(1));
        return 1 + lenRest;
    }
}
```

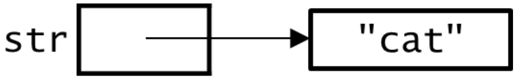
- **For a linked-list string:**



```
public static int length(StringNode str) {
    if (???) {
        return 0;
    } else {
        int lenRest = length(???);
        return 1 + lenRest;
    }
}
```

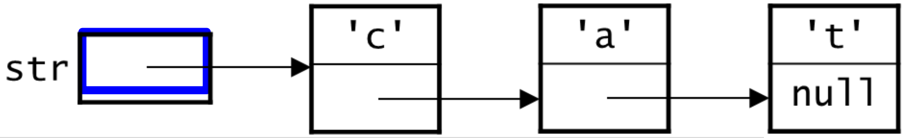
Recursively Finding the Length of a String

- For a built-in Java `String` object:



```
public static int length(String str) {
    if (str == null || str.equals("")) {
        return 0;
    } else {
        int lenRest = length(str.substring(1));
        return 1 + lenRest;
    }
}
```

- For a linked-list string:



```
public static int length(StringNode str) {
    if (str == null) {
        return 0;
    } else {
        int lenRest = length(???);
        return 1 + lenRest;
    }
}
```

Recursively Finding the Length of a String

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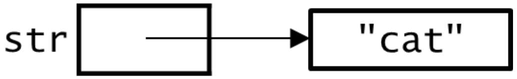
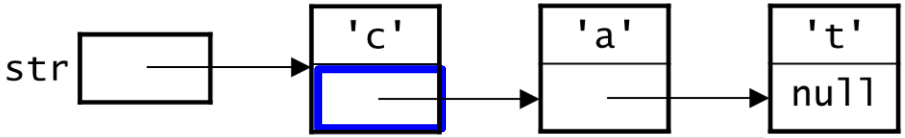


```
public static int length(String str) {
    if (str == null || str.equals("")) {
        return 0;
    } else {
        int lenRest = length(str.substring(1));
        return 1 + lenRest;
    }
}
```

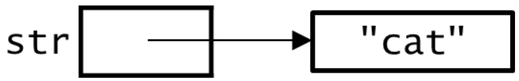
- For a linked-list string:



```
public static int length(StringNode str) {
    if (str == null) {
        return 0;
    } else {
        int lenRest = length(???);
        return 1 + lenRest;
    }
}
```

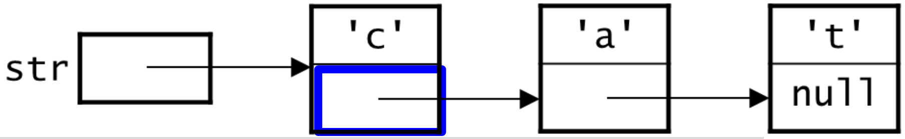
Recursively Finding the Length of a String

- For a built-in Java `String` object:



```
public static int length(String str) {
    if (str == null || str.equals("")) {
        return 0;
    } else {
        int lenRest = length(str.substring(1));
        return 1 + lenRest;
    }
}
```

- For a linked-list string:



```
public static int length(StringNode str) {
    if (str == null) {
        return 0;
    } else {
        int lenRest = length(str.next);
        return 1 + lenRest;
    }
}
```

Recursively Finding the Length of a String

An Alternative Version of the Method

- Original version:

```
public static int length(StringNode str) {
    if (str == null || str == null) {
        return 0;
    } else {
        int lenRest = length(str.next);
        return 1 + lenRest;
    }
}
```

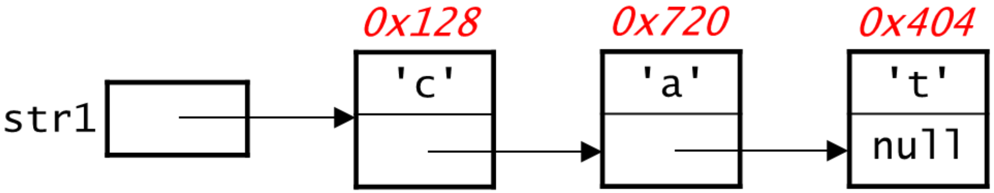
- Version without a variable for the result of the recursive call:

```
public static int length(StringNode str) {
    if (str == null) {
        return 0;
    } else {
        return 1 + length(str.next);
    }
}
```

Tracing length():

the recursive method

```
public static int length(StringNode str) {
    if (str == null) {
        return 0;
    } else {
        return 1 + length(str.next);
    }
}
```



0x128 0x720 0x404

str1

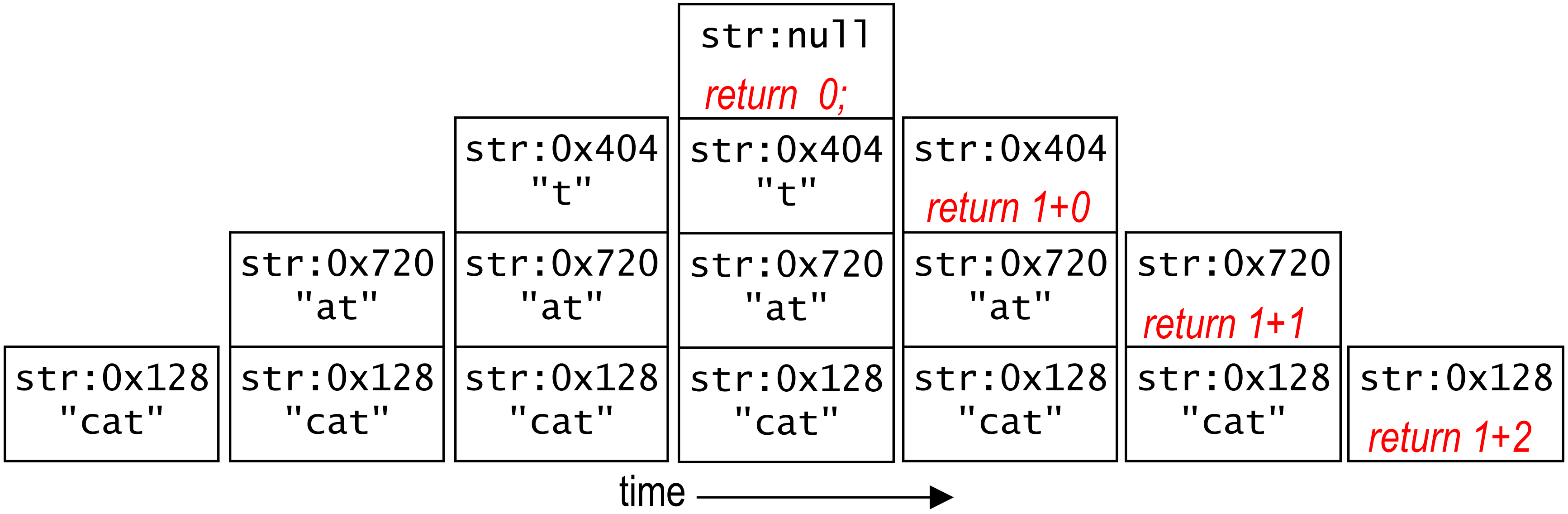
'c'

'a'

't'

null

- Example: `StringNode.length(str1)`



str:0x128
"cat"

str:0x720
"at"

str:0x128
"cat"

str:0x404
"t"

str:0x720
"at"

str:0x128
"cat"

str:null
return 0;

str:0x404
"t"

str:0x720
"at"

str:0x128
"cat"

str:0x404
return 1+0

str:0x720
"at"

str:0x128
"cat"

str:0x720
return 1+1

str:0x128
"cat"

str:0x128
return 1+2

time