Linked Lists

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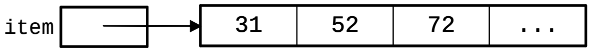
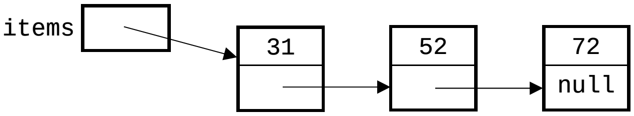
Representing a Sequence of Data

- 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
    - every item can be accessed in constant time
    - this feature of arrays is 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
  - difficult to insert/delete items at arbitrary positions
    - ex: insert 63 between 52 and 72



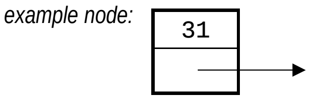
Alternative Representation: A Linked List

- Example:



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

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

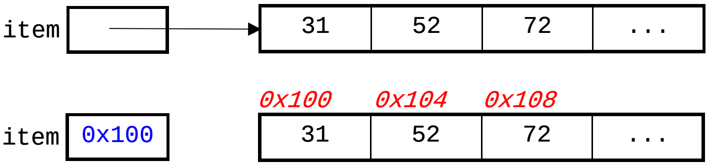


- The last node in the linked list has a link value of `null`.

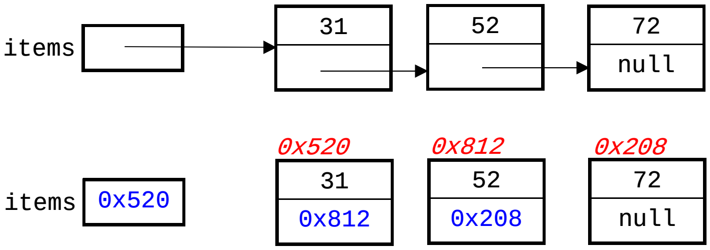
- The linked list as a whole is represented by a variable that holds a reference to the first node (e.g., `items` in the example above).

Arrays vs. Linked Lists in Memory

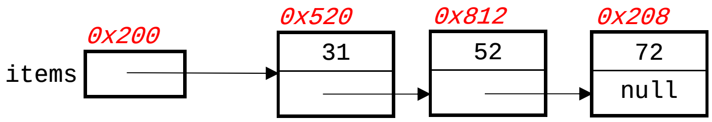
- In an array, the elements occupy consecutive memory locations:



- 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



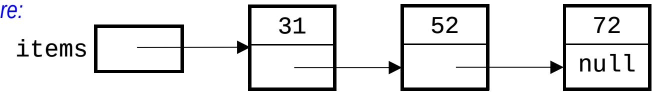
- Here's how the above linked list might actually look in memory:

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	

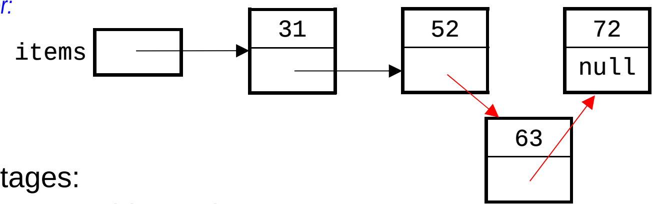
Features of Linked Lists

- They can grow without limit (provided there is enough memory).
- Easy to insert/delete an item – no need to "shift over" other items.
  - for example, to insert 63 between 52 and 72, we just modify the links as needed to accommodate the new node:

before:

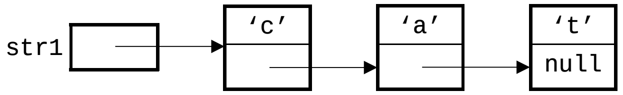


after:



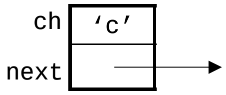
- Disadvantages:
  - they don't provide random access
    - need to "walk down" the list to access an item
  - the links take up additional memory

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 {
    private char ch;
    private StringNode next;
    …
}
```



same type as the node itself!

- The string as a whole will be represented by a variable that holds a reference to the node containing the first character.

  example:

```
StringNode str1;   // shown in the diagram above
```

- Alternative approach: use another class for the string as a whole.

```
public class LLString {
    StringNode first;
    …
```

(we will *not* do this for strings)

A String as a Linked List (cont.)

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

  example:

```
StringNode str2 = null;
```

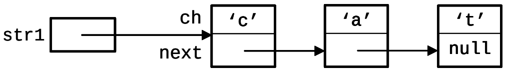
- We will use *static* methods that take the string as a parameter.
  - e.g., we will write `length(str1)` instead of `str1.length()`
  - outside the class, need the class name: `StringNode.length(str1)`
- This approach is necessary so that the methods can handle empty strings.
  - if `str1 == null`, `length(str1)` will work, but `str1.length()` will throw a `NullPointerException`
- Constructor for our `StringNode` class:

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

(see `~cscie119/examples/sequences/StringNode.java`)

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.

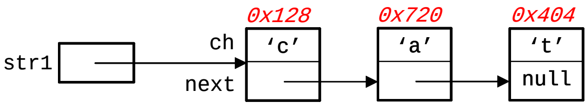


- Example: length of a string
  - length of `"cat"` = 1 + the length of `"at"`
  - length of `"at"` = 1 + the length of `"t"`
  - length of `"t"` = 1 + the length of the empty string (which = 0)
- In Java:

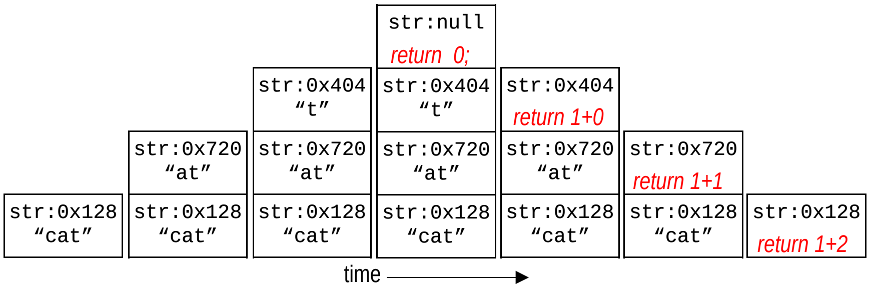
```
public static int length(StringNode str) {
    if (str == null)
        return 0;
    else
        return 1 + length(str.next);
}
```

Tracing `length()`

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



- 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*

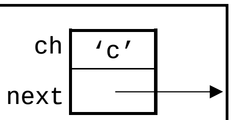
time →

Getting the Node at Position i in a Linked List

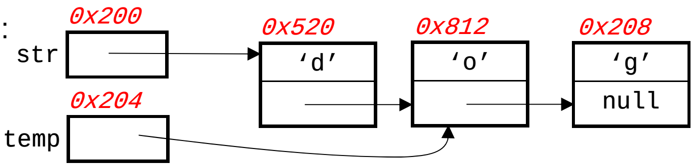
- `getNode(str, i)` – a private helper method that returns a reference to the ith node in the linked list (i == 0 for the first node)
- Recursive approach:
  node at position 2 in the linked list representing “linked”
  = node at position 1 in the linked list representing “inked”
  = node at position 0 in the linked list representing “nked”
  (return a reference to the node containing ‘n’)
- We’ll write the method together:

```
private static StringNode getNode(StringNode str, int i) {






}
```

Review of Variables



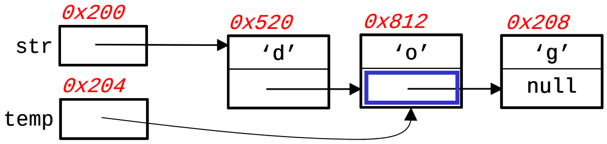
- A variable or variable expression represents both:
  - a “box” or location in memory (the *address* of the variable)
  - the contents of that “box” (the *value* of the variable)
- Practice:



```
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`		
`str.next`		

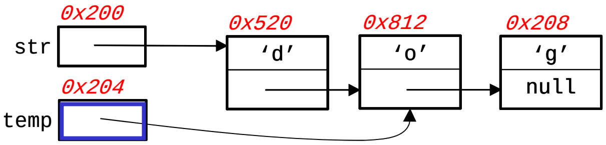
More Complicated Expressions



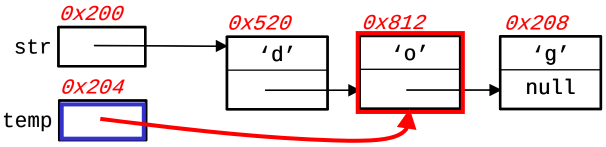
- Example: `temp.next.ch`
- Start with the start of the expression: `temp.next`
  It represents the `next` field of the node to which `temp` refers.
  - address =
  - value =
- Next, consider `temp.next.ch`
  It represents the `ch` field of the node to which `temp.next` refers.
  - address =
  - value =

Dereferencing a Reference

- 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`

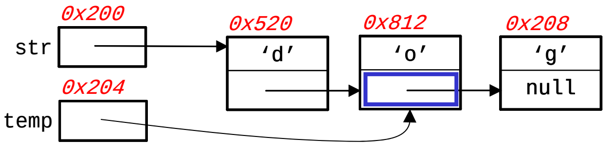


- Dereference: **`temp`**`.next.ch`

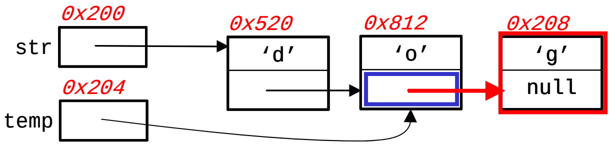


Dereferencing a Reference (cont.)

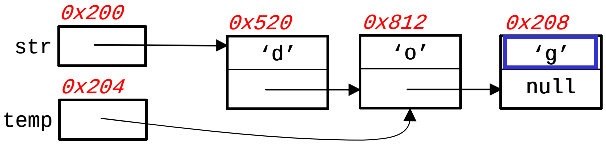
- Get the `next` field: `temp.next.ch`



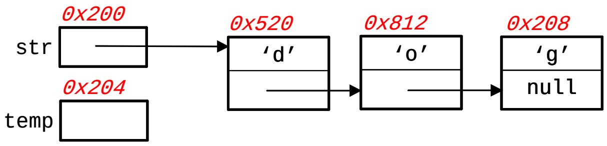
- Dereference: `temp.next.ch`



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



More Complicated Expressions (cont.)



- Here’s another example: `str.next.next`
  - address = ?
  - value = ?

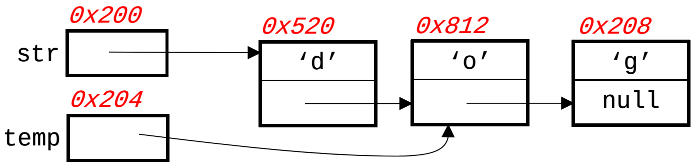
Assignments Involving References

- An assignment of the form

  `var1 = var2;`

  takes the *value* of `var2` and copies it into the location in memory given by the *address* of `var1`.

- Practice:

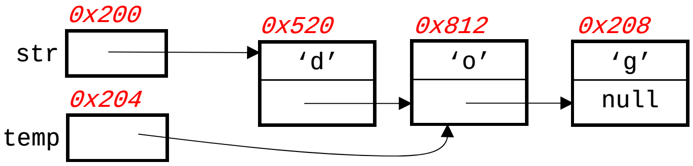


- What happens if we do the following?
  1) `str.next = temp.next;`

  2) `temp = temp.next;`

Assignments Involving References (cont.)

- Beginning with the original diagram, if `temp` didn't already refer to the `'o'` node, what assignment would we need to perform to make it refer to that node?



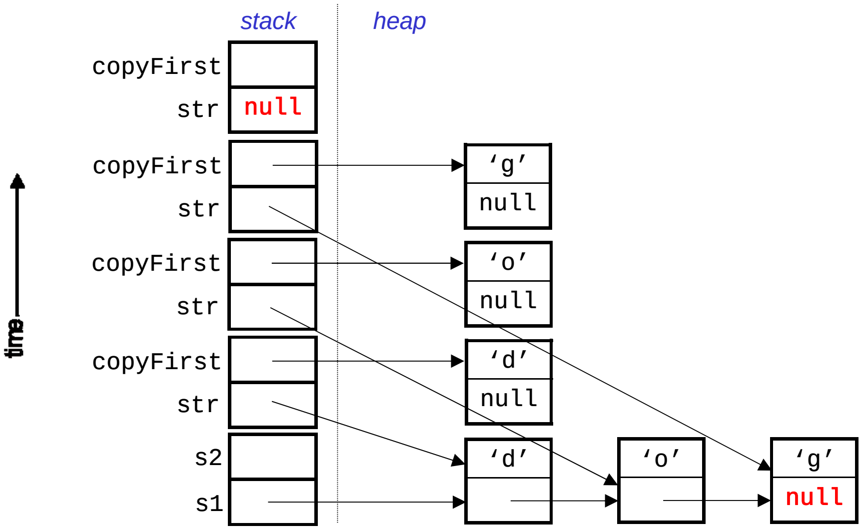
Creating a Copy of a Linked List

- `copy(str)` – create a copy of `str` and return a reference to it
- Recursive approach:
  - base case: if `str` is empty, return `null`
  - else: copy the first character
    make a recursive call to copy the rest

```
public static StringNode copy(StringNode str) {
    if (str == null)         // base case
        return null;

    // create the first node of the copy, copying the
    // first character into it
    StringNode copyFirst = new StringNode(str.ch, null);

    // make a recursive call to get a copy the rest and
    // store the result in the first node's next field
    copyFirst.next = copy(str.next);

    return copyFirst;
}
```

Tracing `copy()`: part I

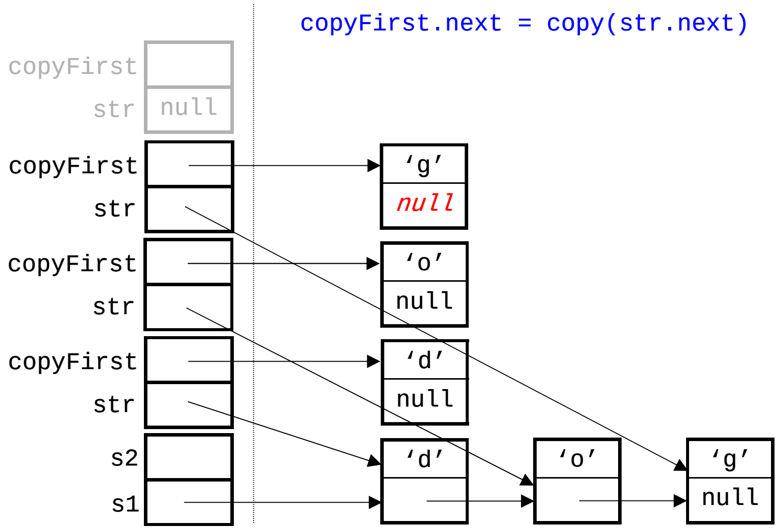
- Example: `StringNode s2 = StringNode.copy(s1);`
- The stack grows as a series of recursive calls are made:



Tracing `copy()`: part II

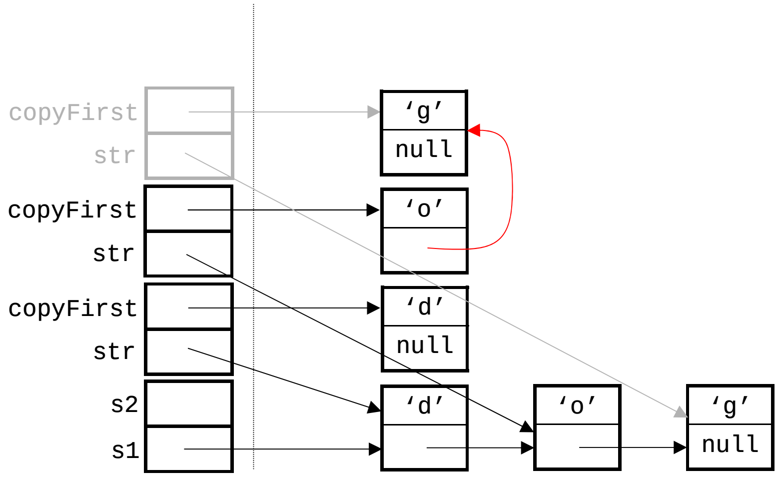
- The base case is reached, so the final recursive call returns `null`.
- This return value is stored in the `next` field of the `'g'` node:

`copyFirst.next = copy(str.next)`



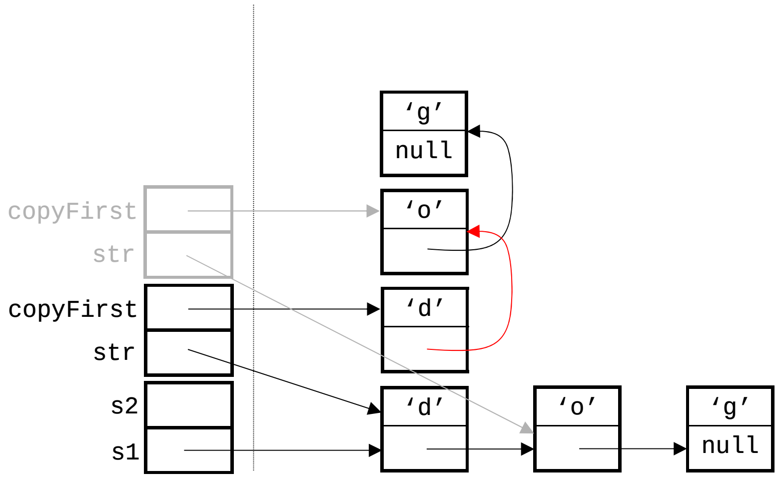
Tracing `copy()`: part III

- The recursive call that created the `'g'` node now completes, returning a reference to the `'g'` node.
- This return value is stored in the `next` field of the `'o'` node:



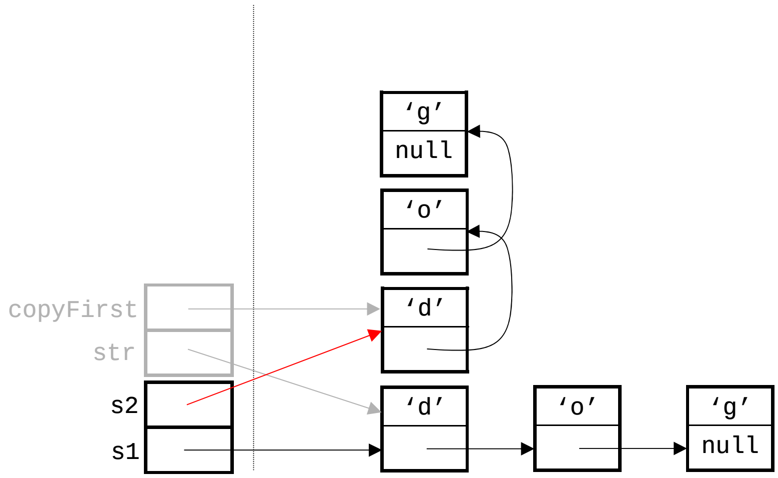
Tracing `copy()`: part IV

- The recursive call that created the `'o'` node now completes, returning a reference to the `'o'` node.
- This return value is stored in the `next` field of the `'d'` node:



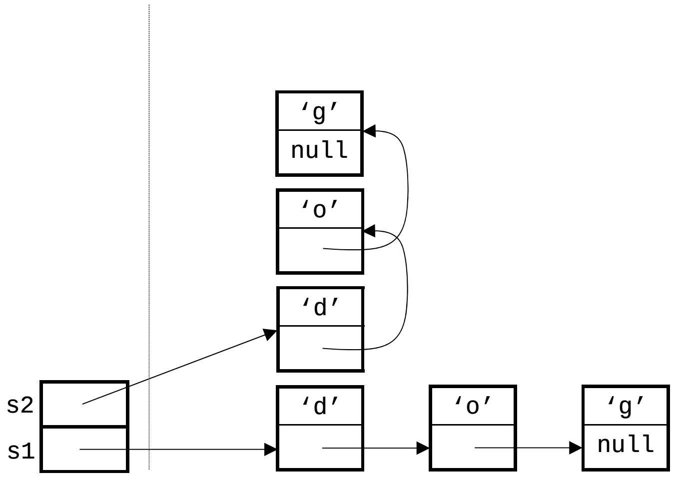
Tracing `copy()`: part V

- The original call (which created the `'d'` node) now completes, returning a reference to the `'d'` node.
- This return value is stored in `s2`:



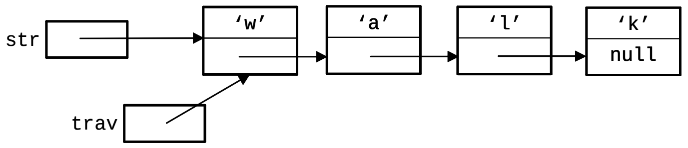
Tracing `copy()`: Final Result

- `StringNode s2 = StringNode.copy(s1);`
- `s2` now holds a reference to a linked list that is a copy of the linked list to which `s1` holds a reference.



Using Iteration to Traverse a Linked List

- Many tasks require us to traverse or “walk down” a linked list.
- We’ve already seen methods that use recursion to do this.
- It can also be done using iteration (for loops, while loops, etc.).
- We make use of a variable (call it `trav`) that keeps track of where we are in the linked list.

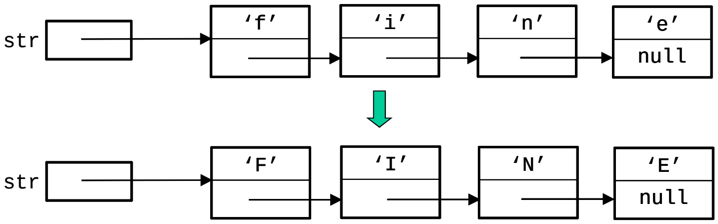


- Template for traversing an entire linked list:

```
StringNode trav = str;    // start with the first node
while (trav != null) {
    // usually do something here
    trav = trav.next;    // move trav down one node
}
```

Example of Iterative Traversal

- `toUpperCase(str)`: converting `str` to all upper-case letters

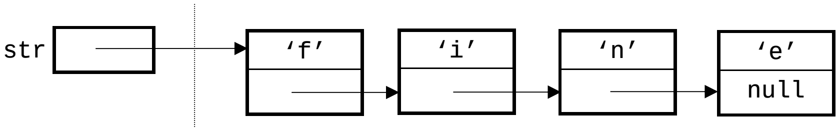


- Java method:

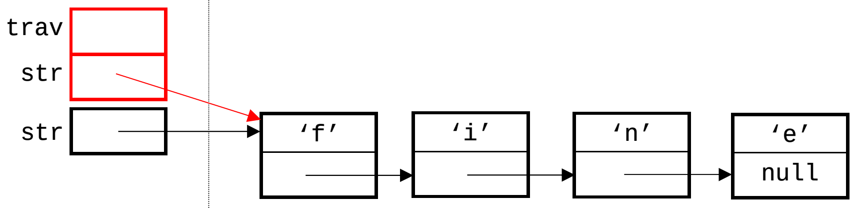
```
public static void toUpperCase(StringNode str) {
     StringNode trav = str;
     while (trav != null) {
          trav.ch = Character.toUpperCase(trav.ch);
          trav = trav.next;
     }
}
```

(makes use of the `toUpperCase()` method from Java's built-in `Character` class)

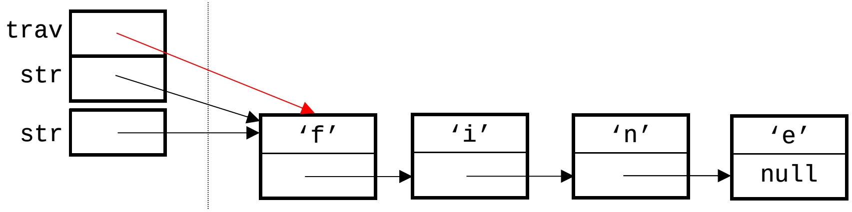
Tracing `toUpperCase()`: Part I



Calling `StringNode.toUpperCase(str)` adds a stack frame to the stack:

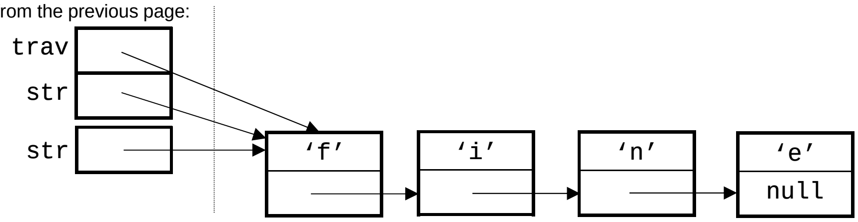


`StringNode trav = str;`



Tracing `toUpperCase()`: Part II

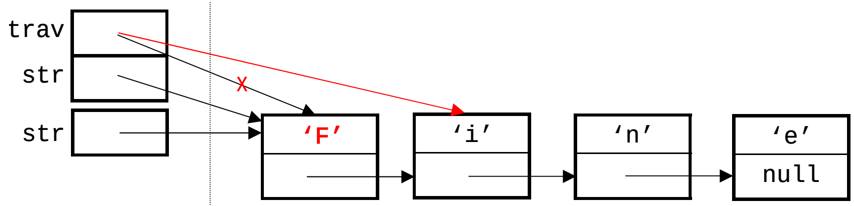
from the previous page:



we enter the `while` loop:

```
    while (trav != null) {
        trav.ch = Character.toUpperCase(trav.ch);
        trav = trav.next;
    }
```

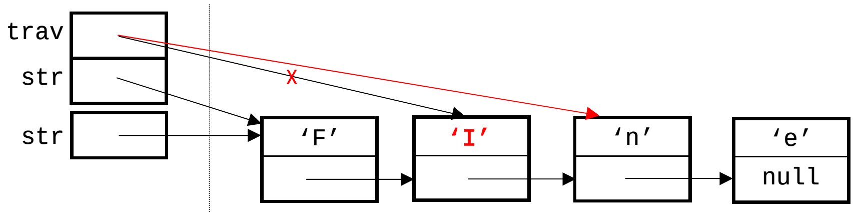
results of the first pass through the loop:



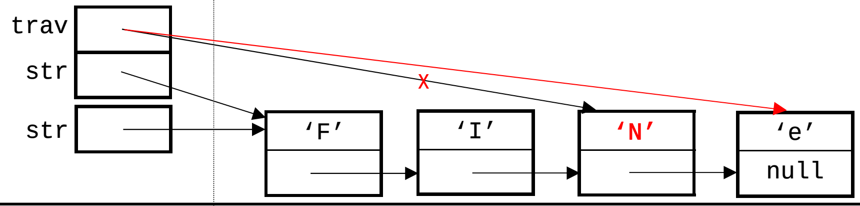
Tracing `toUpperCase()`: Part III

```
    while (trav != null) {
        trav.ch = Character.toUpperCase(trav.ch);
        trav = trav.next;
    }
```

results of the second pass through the loop:



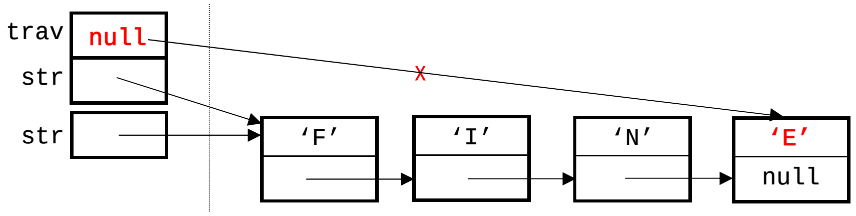
results of the third pass:



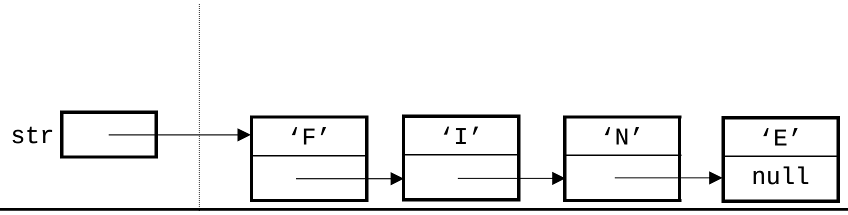
Tracing `toUpperCase()`: Part IV

```
while (trav != null) {
     trav.ch = Character.toUpperCase(trav.ch);
     trav = trav.next;
}
```

results of the fourth pass through the loop:

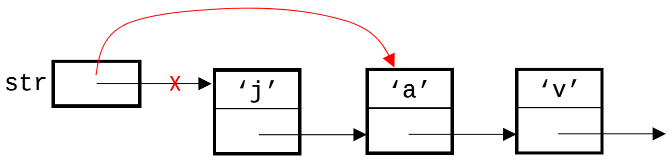


and now `trav == null`, so we break out of the loop and return:

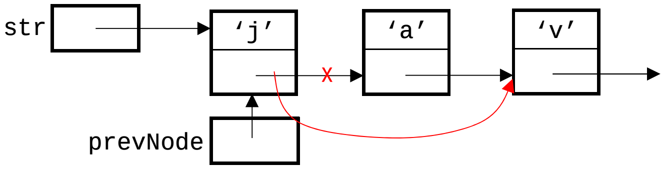


Deleting the Item at Position i

- Two cases:
  1) `i == 0`: delete the first node by doing
     `str = str.next;`



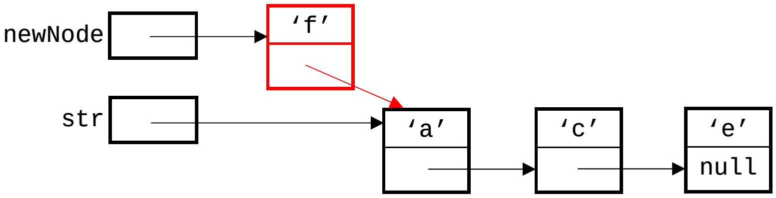
  2) `i > 0`: first obtain a reference to the *previous* node
     (example for i == 1*)*



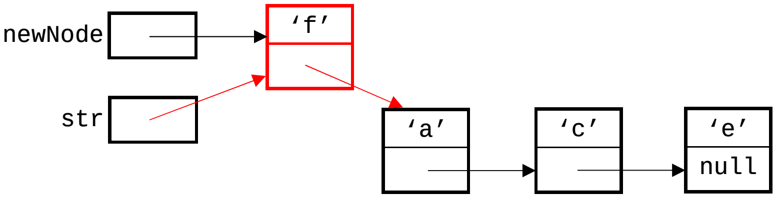
What line of code will perform the deletion?

Inserting an Item at Position i

- Case 1: `i == 0` (insertion at the front of the list):
- What line of code will *create* the new node?

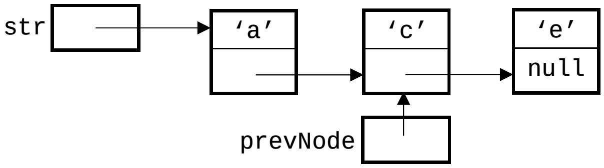


- What line of code will *insert* the new node?

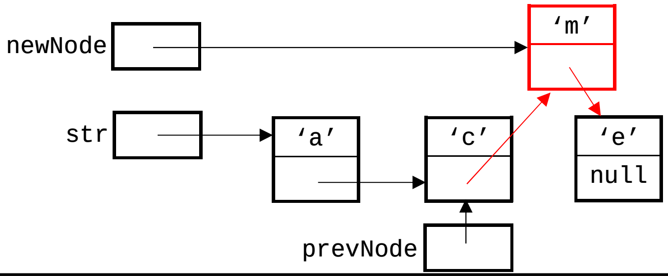


Inserting an Item at Position i (cont.)

- Case 2: `i > 0`: insert *before* the character currently in posn `i`
- First obtain a reference to the node at position `i-1`:
  (example for i == 2)



- What lines of code will insert the character `‘m’`?



Returning a Reference to the First Node

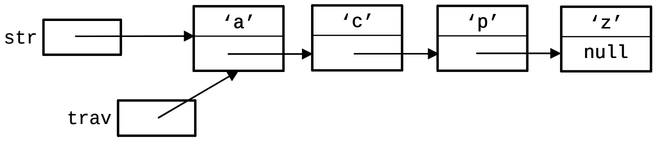
- Both `deleteChar()` and `insertChar()` return a reference to the first node in the linked list. For example:

```
private static StringNode deleteChar(StringNode str, int i) {
    …
    if (i == 0)                 // case 1
        str = str.next;
    else {                      // case 2
        StringNode prevNode = getNode(str, i-1);
        if (prevNode != null && prevNode.next != null)
            prevNode.next = prevNode.next.next;
        …
    }
    return str;
}
```

- They do so because the first node may change.
- Invoke as follows:
```
str = StringNode.deleteChar(str, i);
str = StringNode.insertChar(str, i, ch);
```
- If the first node changes, `str` will point to the new first node.

Using a “Trailing Reference” During Traversal

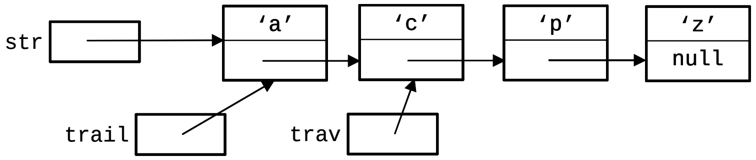
- When traversing a linked list, using a single `trav` reference isn’t always good enough.
- Ex: insert `ch = ‘n’` at the right place in this *sorted* linked list:



- Traverse the list to find the right position:
```
StringNode trav = str;
while (trav != null && trav.ch < ch)
    trav = trav.next;
```
- When we exit the loop, where will `trav` point? Can we insert `‘n’`?
- The following changed version doesn’t work either. Why not?
```
StringNode trav = str;
while (trav != null && trav.next.ch < ch)
    trav = trav.next;
```

Using a “Trailing Reference” (cont.)

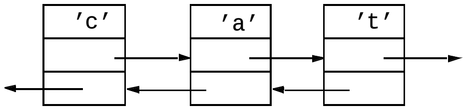
- To get around the problem seen on the previous page, we traverse the list using two different references:
  - `trav`, which we use as before
  - `trail`, which stays one node behind `trav`



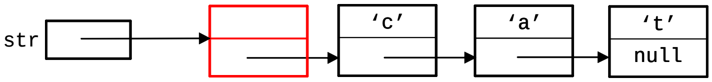
```
StringNode trav = str;
StringNode trail = null;
while (trav != null && trav.ch < ch) {
    trail = trav;
    trav = trav.next;
}
// if trail == null, insert at the front of the list
// else insert after the node to which trail refers
```

Other Variants of Linked Lists

- Doubly linked list



  - add a `prev` reference to each node -- refers to the previous node
  - allows us to “back up” from a given node
- Linked list with a dummy node at the front:



  - the dummy node doesn’t contain a data item
  - it eliminates the need for special cases to handle insertion and deletion at the front of the list
    - more on this in the next set of notes