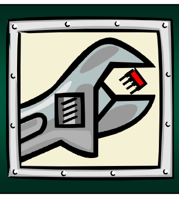
Linked List Data Structure

Part 2

1



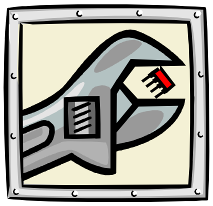
Data Structures

Return to CSC 15 and CSC 20

2

Data Structures

- Arrays and linked-lists are both examples of *data structures*
- These are different techniques of storing and organizing data
- In other words, this is *how* data is stored



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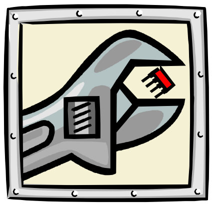
Data Structures

- Depending on *how* data is accessed, some data structures can either excel and falter
- This is true of both arrays and linked lists



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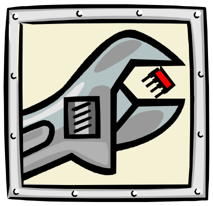
Data Structures

- We will do a quick review of arrays and linked lists
- There are more data structures than these two
- We will cover them this semester – some which have incredible in features



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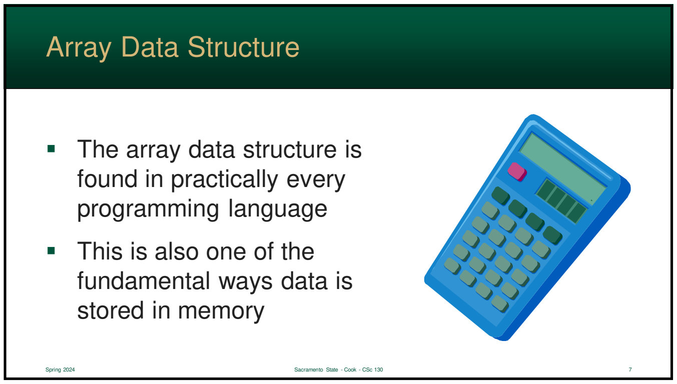
Array Data Structure

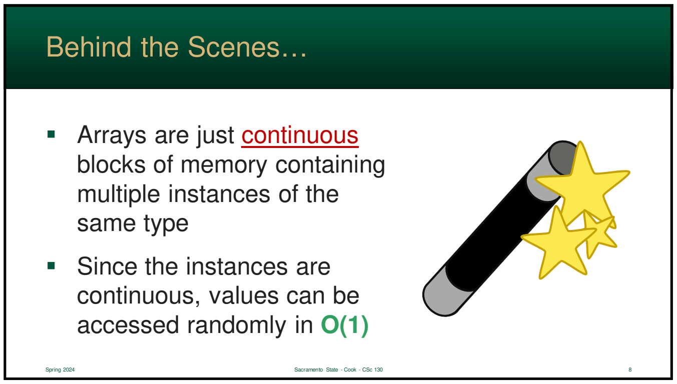
Hidden math = easy code

6



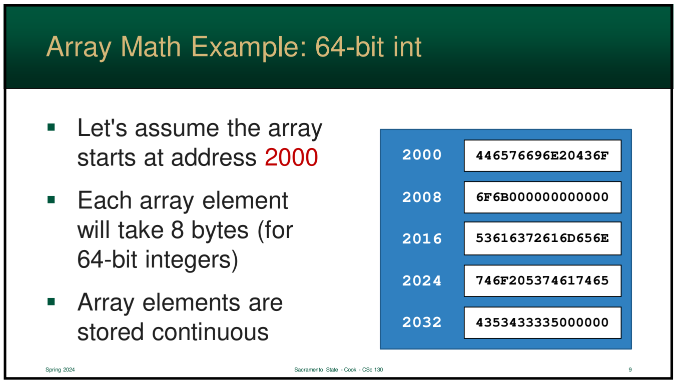
Array Data Structure

- The array data structure is found in practically every programming language
- This is also one of the fundamental ways data is stored in memory



Behind the Scenes…

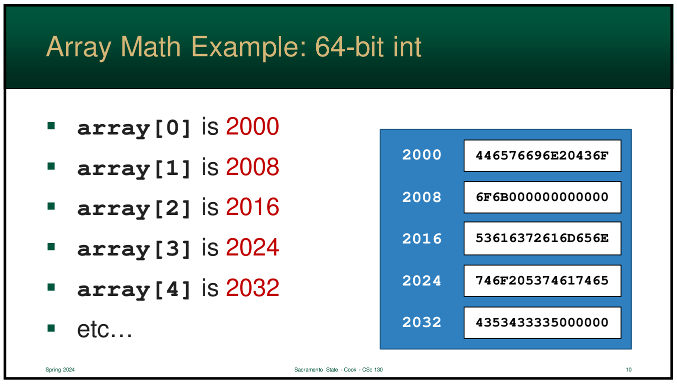
- Arrays are just continuous blocks of memory containing multiple instances of the same type
- Since the instances are continuous, values can be accessed randomly in **O(1)**



Array Math Example: 64-bit int

- Let's assume the array starts at address 2000
- Each array element will take 8 bytes (for 64-bit integers)
- Array elements are stored continuous

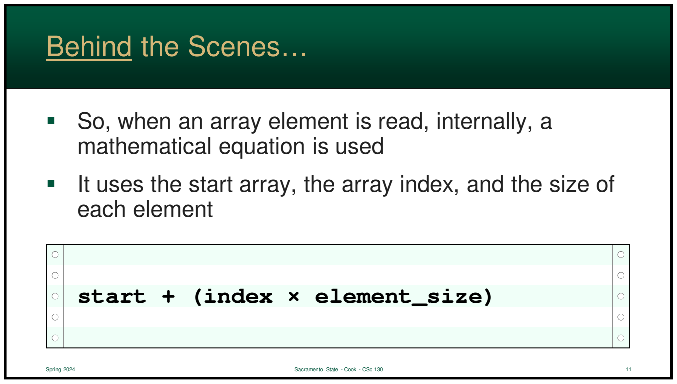
2000	446576696E20436F
2008	6F6B000000000000
2016	53616372616D656E
2024	746F205374617465
2032	4353433335000000



Array Math Example: 64-bit int

- `array[0]` is 2000
- `array[1]` is 2008
- `array[2]` is 2016
- `array[3]` is 2024
- `array[4]` is 2032
- etc…

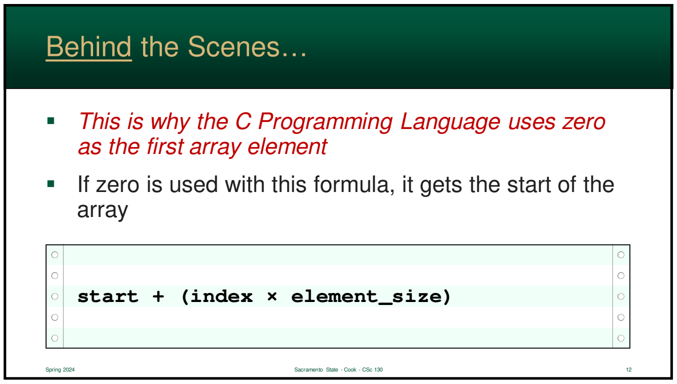
2000	446576696E20436F
2008	6F6B000000000000
2016	53616372616D656E
2024	746F205374617465
2032	4353433335000000



Behind the Scenes…

- So, when an array element is read, internally, a mathematical equation is used
- It uses the start array, the array index, and the size of each element

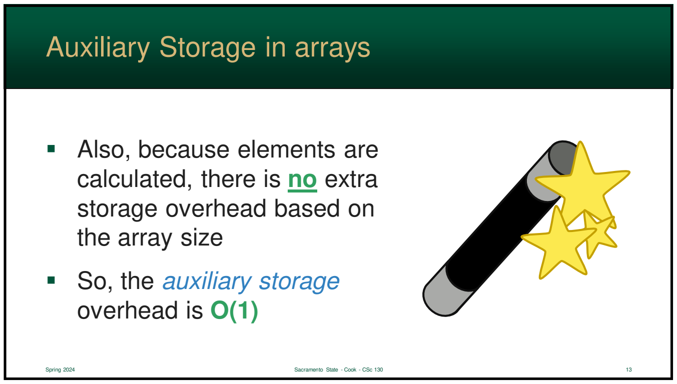
```
start + (index × element_size)
```



Behind the Scenes…

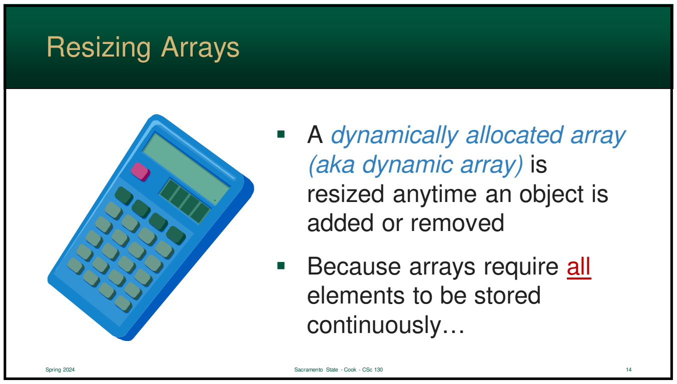
- *This is why the C Programming Language uses zero as the first array element*
- If zero is used with this formula, it gets the start of the array

```
start + (index × element_size)
```



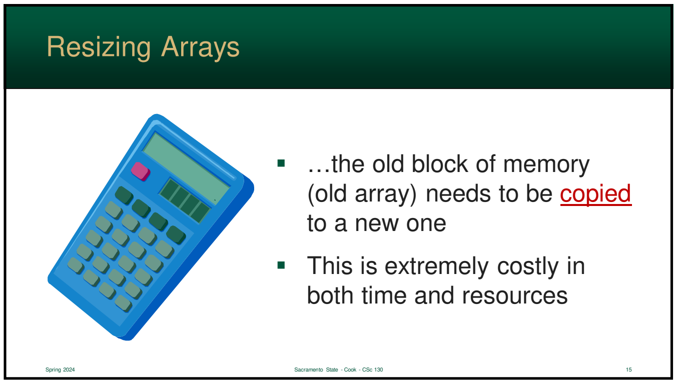
Auxiliary Storage in arrays

- Also, because elements are calculated, there is **no** extra storage overhead based on the array size
- So, the *auxiliary storage* overhead is **O(1)**



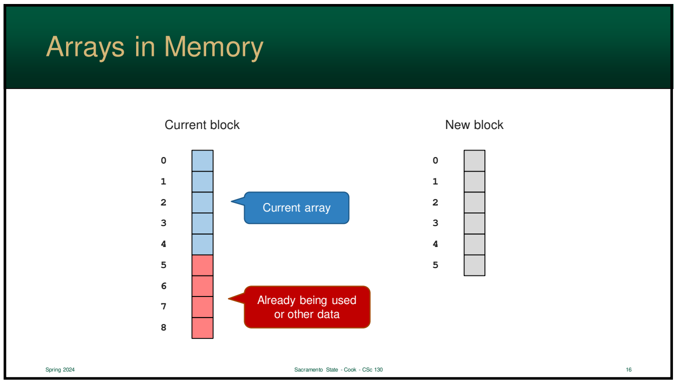
Resizing Arrays

- A *dynamically allocated array (aka dynamic array)* is resized anytime an object is added or removed
- Because arrays require all elements to be stored continuously…

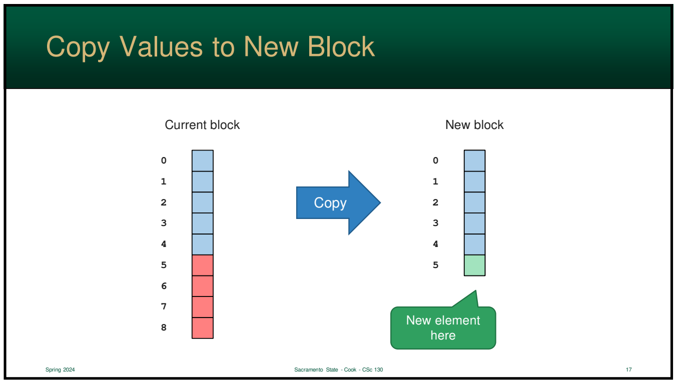


Resizing Arrays

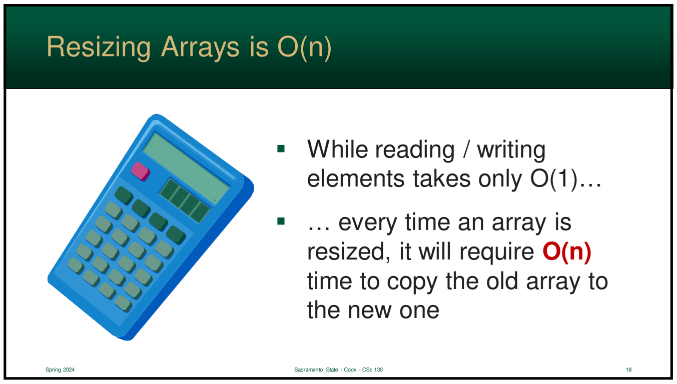
- …the old block of memory (old array) needs to be copied to a new one
- This is extremely costly in both time and resources



Arrays in Memory

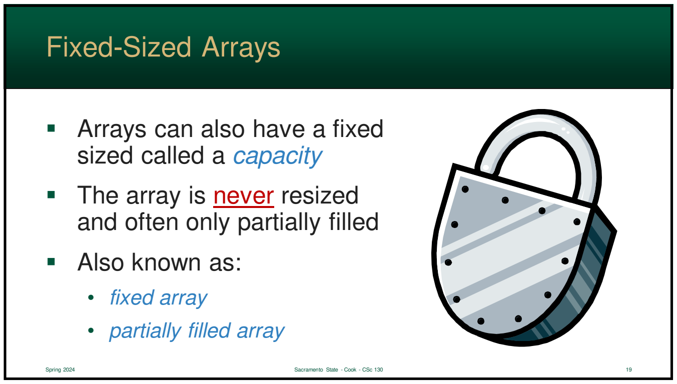


Copy Values to New Block



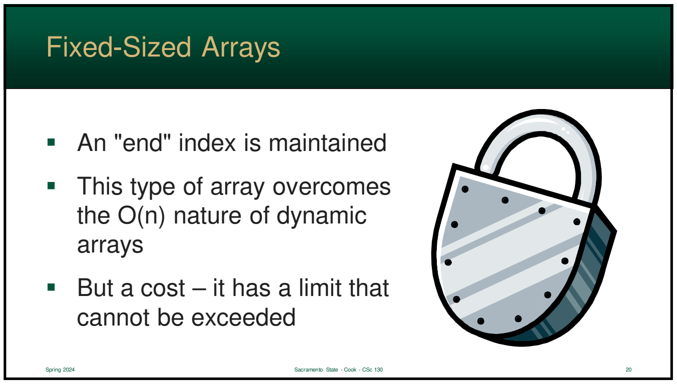
Resizing Arrays is O(n)

- While reading / writing elements takes only O(1)…
- … every time an array is resized, it will require **O(n)** time to copy the old array to the new one



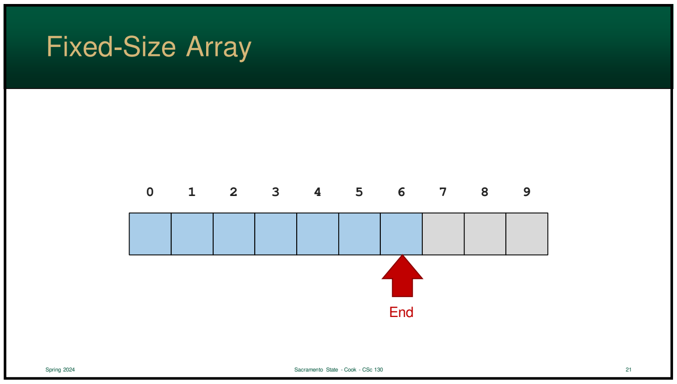
Fixed-Sized Arrays

- Arrays can also have a fixed sized called a *capacity*
- The array is never resized and often only partially filled
- Also known as:
  - *fixed array*
  - *partially filled array*

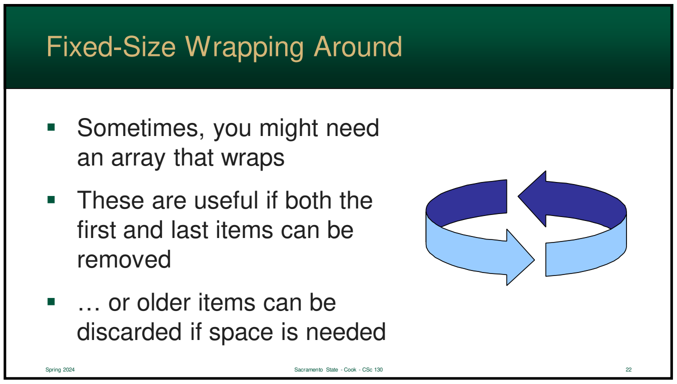


Fixed-Sized Arrays

- An "end" index is maintained
- This type of array overcomes the O(n) nature of dynamic arrays
- But a cost – it has a limit that cannot be exceeded

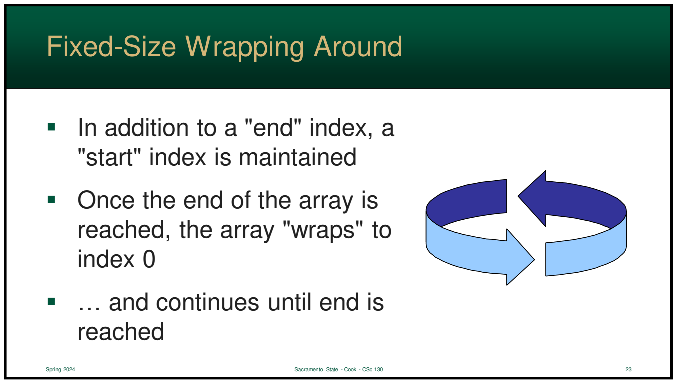


Fixed-Size Array



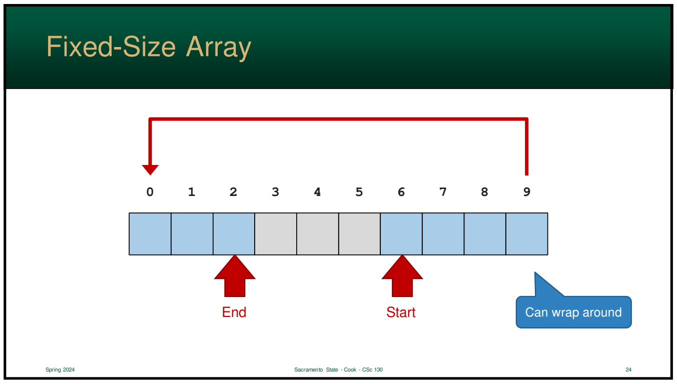
Fixed-Size Wrapping Around

- Sometimes, you might need an array that wraps
- These are useful if both the first and last items can be removed
- … or older items can be discarded if space is needed



Fixed-Size Wrapping Around

- In addition to a "end" index, a "start" index is maintained
- Once the end of the array is reached, the array "wraps" to index 0
- … and continues until end is reached



Fixed-Size Array

Linked Lists

Chain of Data

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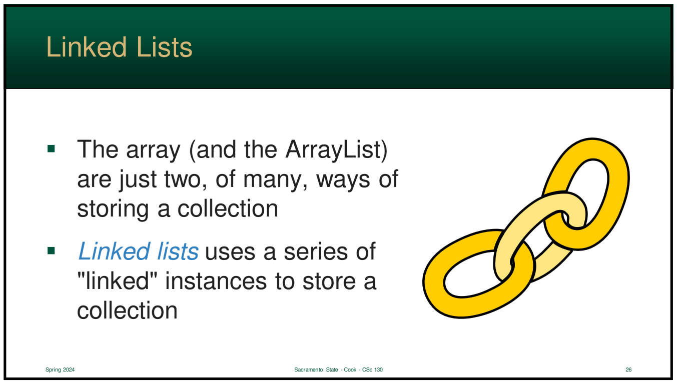

Linked Lists

- The array (and the ArrayList) are just two, of many, ways of storing a collection
- *Linked lists* uses a series of "linked" instances to store a collection

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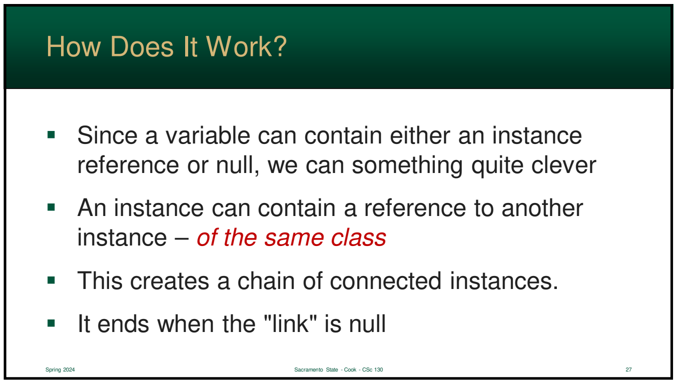

How Does It Work?

- Since a variable can contain either an instance reference or null, we can something quite clever
- An instance can contain a reference to another instance – *of the same class*
- This creates a chain of connected instances.
- It ends when the "link" is null

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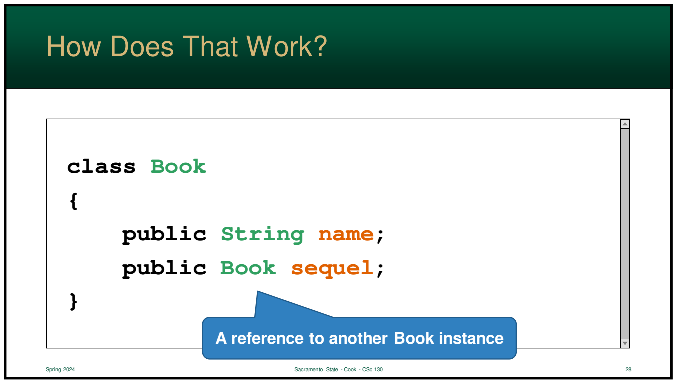

How Does That Work?

```
class Book
{
    public String name;
    public Book sequel;
}
```

A reference to another Book instance

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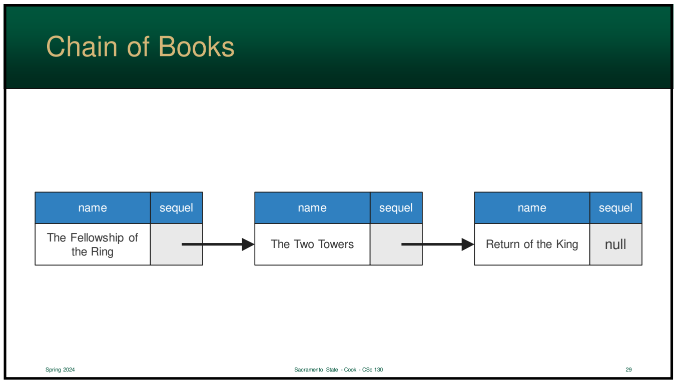

Chain of Books

name	sequel
The Fellowship of the Ring	→

name	sequel
The Two Towers	→

name	sequel
Return of the King	null

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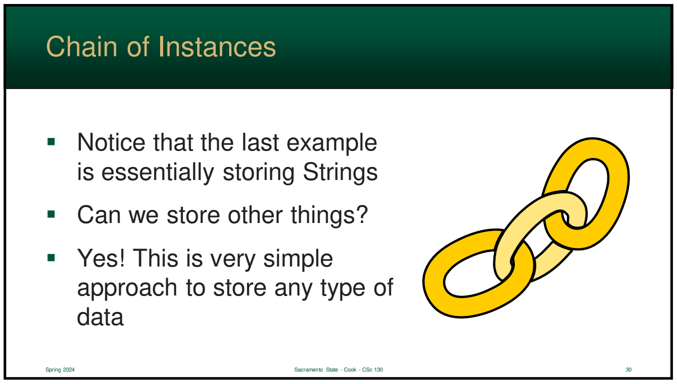

Chain of Instances

- Notice that the last example is essentially storing Strings
- Can we store other things?
- Yes! This is very simple approach to store any type of data

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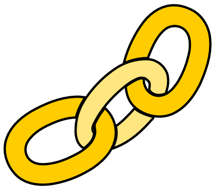
Chain of Instances

- Each link in our chain, that stores a piece of information, is called a *Node*
- The definition of a Node is extremely simple: data and a link to the next node



Generic Node Class

```
public class Node
{
     public Object data;
     public Node next;
}
```

We can make this another type

Creating a List (not well, though)

```
Node list = new Node();

list.data = "rat";
list.next = new Node();

list.next.data = "owl";
list.next.next = new Node();

list.next.next.data = "cat";
list.next.next.next = null;
```

Constructors Will Help

```
public Node(Object initData, Node initNext)
{
    this.data = initData;
    this.next = initNext;
}

public Node(Object initData)
{
    this.data = initData;
    this.next = null;
}
```

Constructors Do Help

- Constructors do help
- Though it is still a tad hard to read

```
Node list = new Node("Rat", new Node("Owl", new Node("Cat")));
```

We Could Also Do This…

```
Node rat = new Node("Rat");
Node owl = new Node("Owl");
Node cat = new Node("Cat");

rat.next = owl;
owl.next = cat;
```

Traversing a Linked List

Chain of Data

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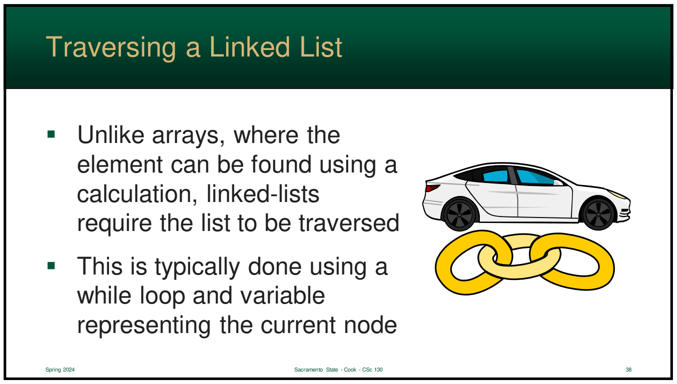

Traversing a Linked List

- Unlike arrays, where the element can be found using a calculation, linked-lists require the list to be traversed
- This is typically done using a while loop and variable representing the current node

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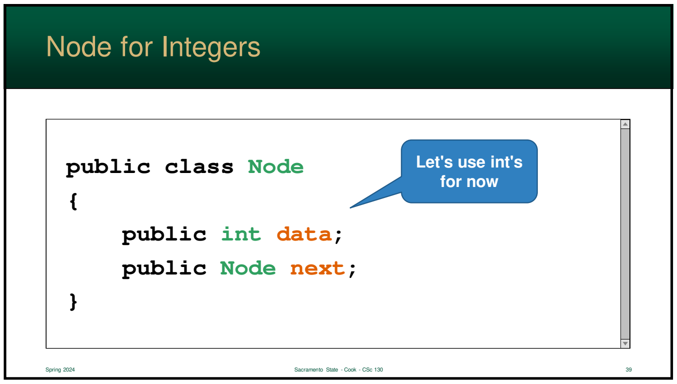

Node for Integers

```
public class Node
{
    public int data;
    public Node next;
}
```

Let's use int's for now

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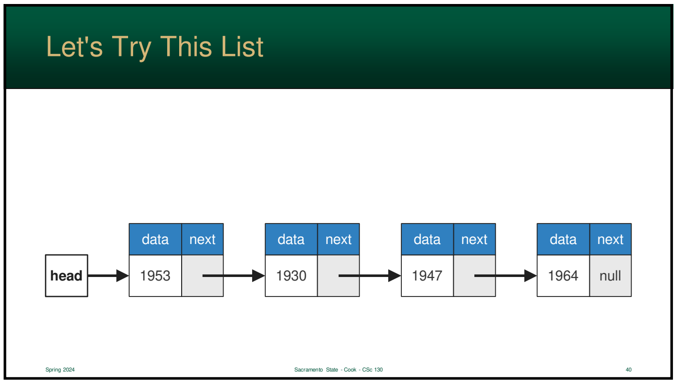

Let's Try This List

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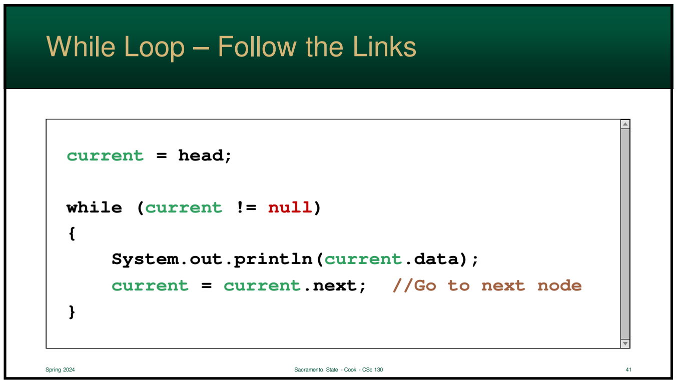

While Loop – Follow the Links

```
current = head;

while (current != null)
{
    System.out.println(current.data);
    current = current.next;   //Go to next node
}
```

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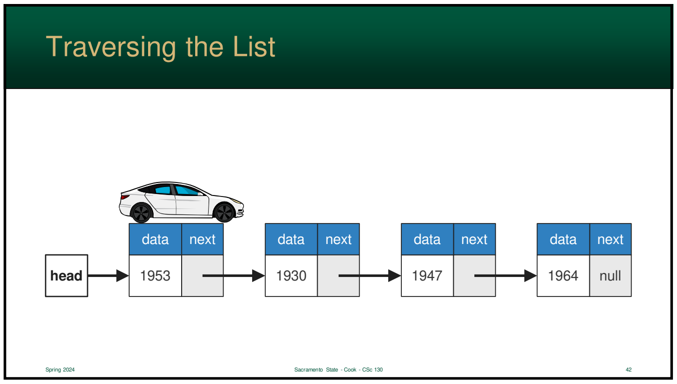

Traversing the List

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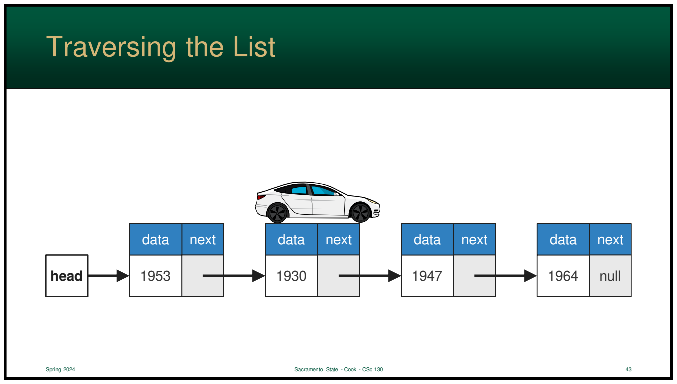

Traversing the List

head
data next 1953
data next 1930
data next 1947
data next 1964 null

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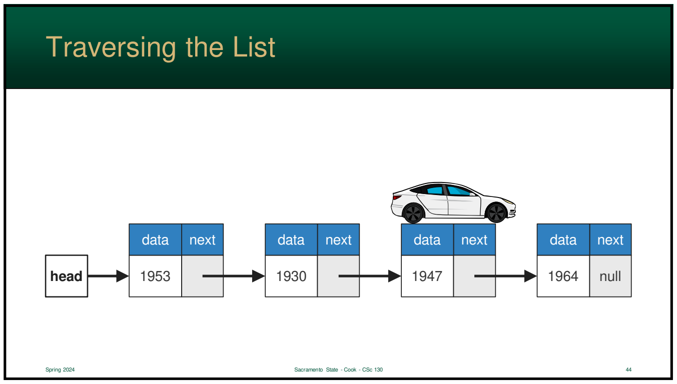
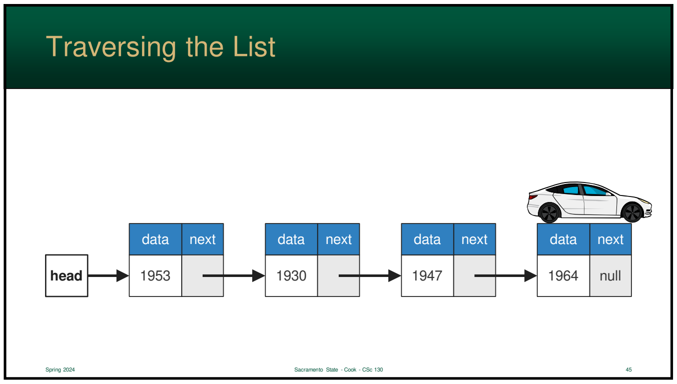


Traversing the List

head
data next 1953
data next 1930
data next 1947
data next 1964 null

44



Traversing the List

head
data next 1953
data next 1930
data next 1947
data next 1964 null

45

Adding to Linked Lists

Chain of Data

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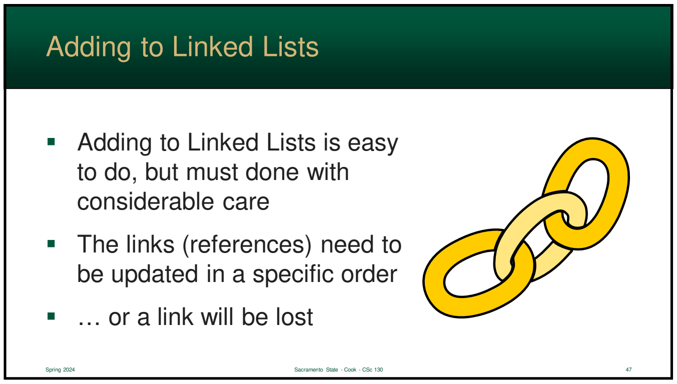

Adding to Linked Lists

- Adding to Linked Lists is easy to do, but must done with considerable care
- The links (references) need to be updated in a specific order
- … or a link will be lost

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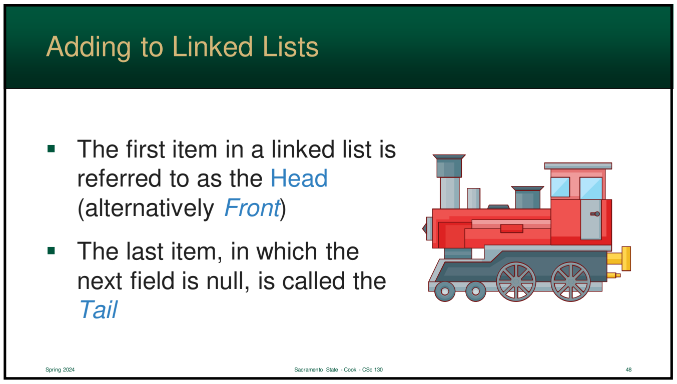

Adding to Linked Lists

- The first item in a linked list is referred to as the Head (alternatively *Front*)
- The last item, in which the next field is null, is called the *Tail*

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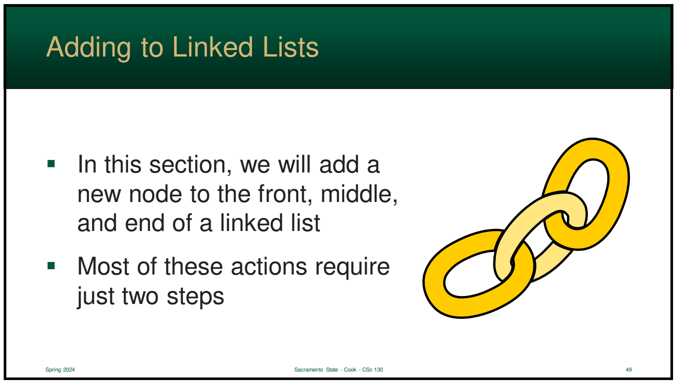

Adding to Linked Lists

- In this section, we will add a new node to the front, middle, and end of a linked list
- Most of these actions require just two steps

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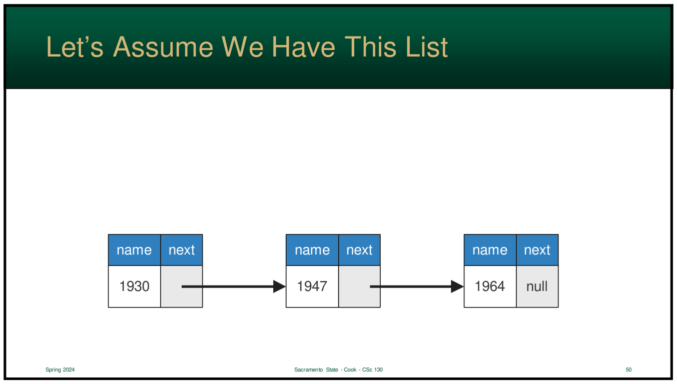

Let's Assume We Have This List

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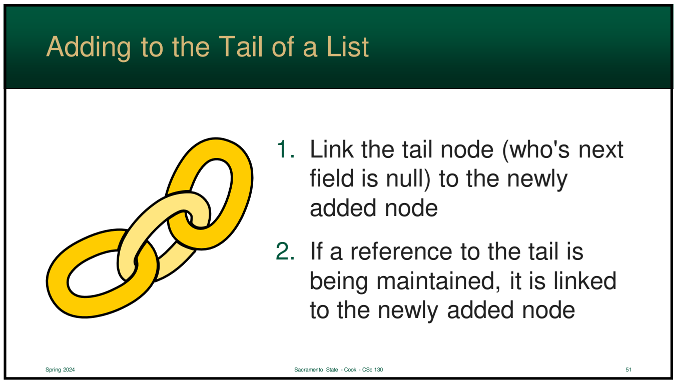

Adding to the Tail of a List

1. Link the tail node (who's next field is null) to the newly added node
2. If a reference to the tail is being maintained, it is linked to the newly added node

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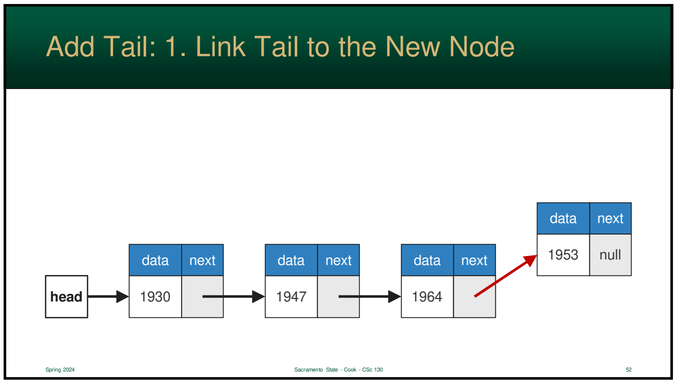

Add Tail: 1. Link Tail to the New Node

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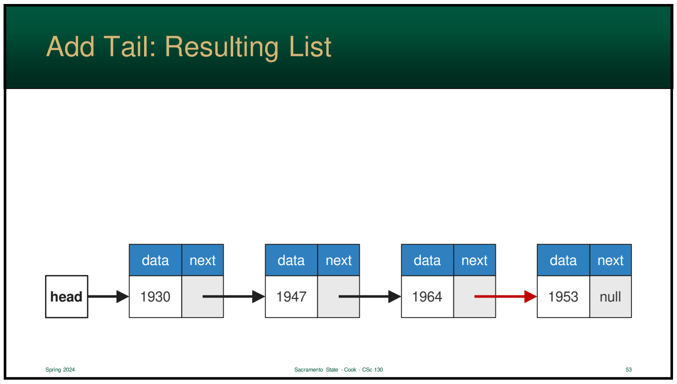

Add Tail: Resulting List

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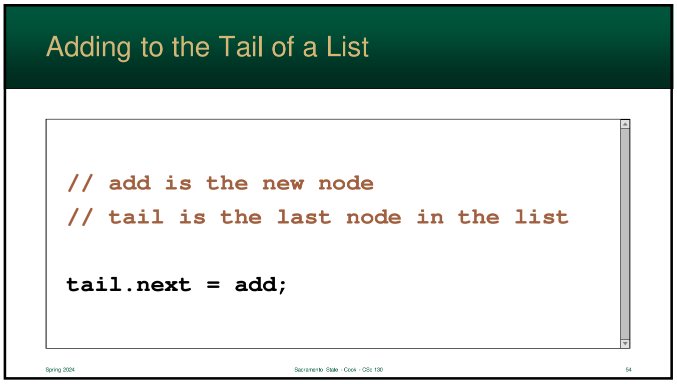

Adding to the Tail of a List

```
// add is the new node
// tail is the last node in the list

tail.next = add;
```

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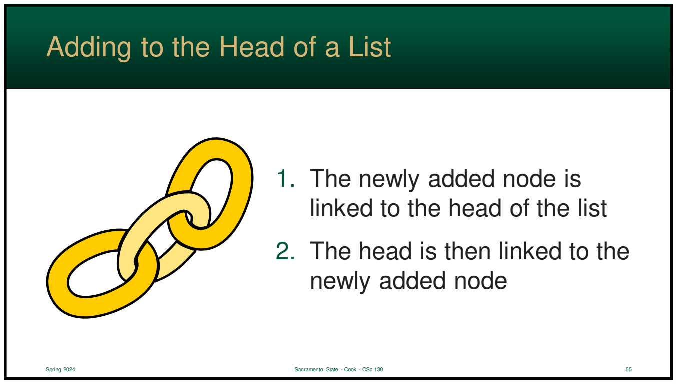

Adding to the Head of a List

1. The newly added node is linked to the head of the list
2. The head is then linked to the newly added node

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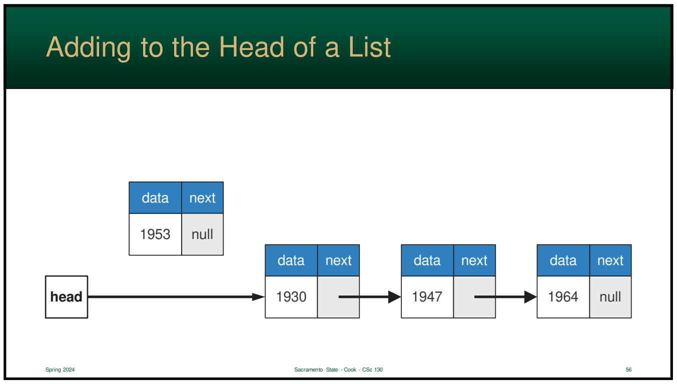

Adding to the Head of a List

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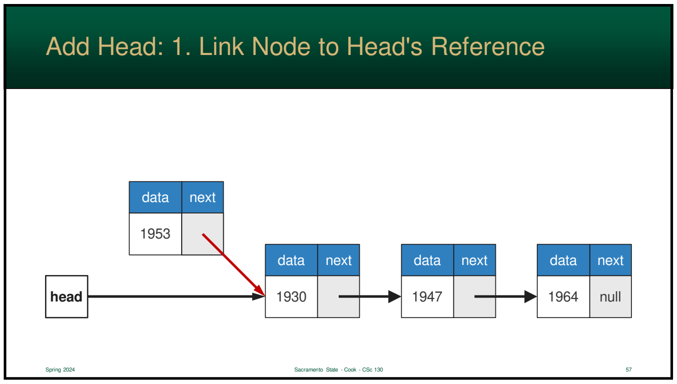

Add Head: 1. Link Node to Head's Reference

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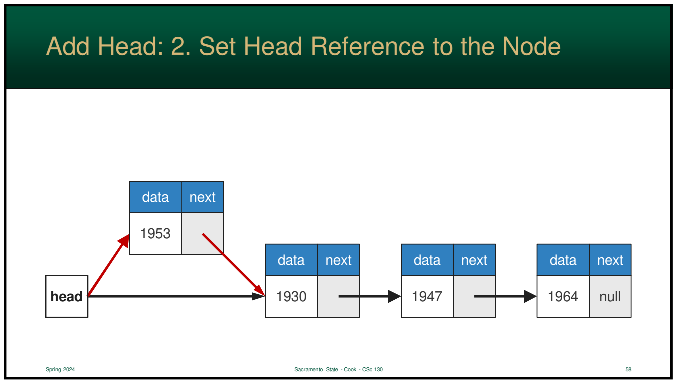

Add Head: 2. Set Head Reference to the Node

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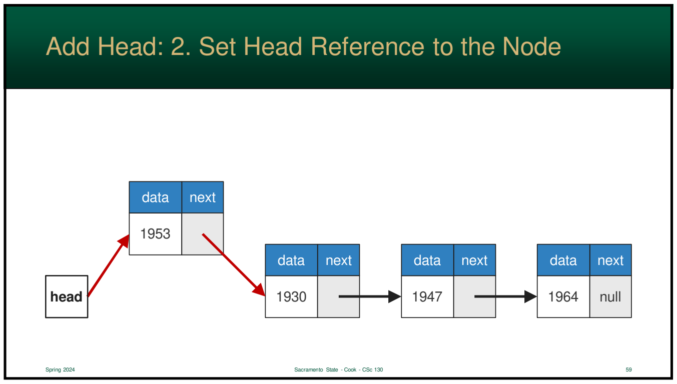

Add Head: 2. Set Head Reference to the Node

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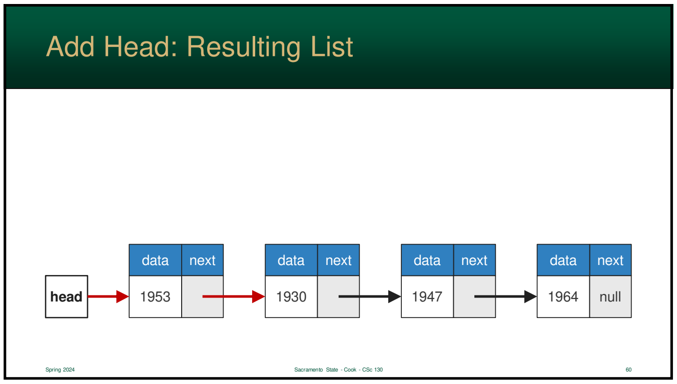

Add Head: Resulting List

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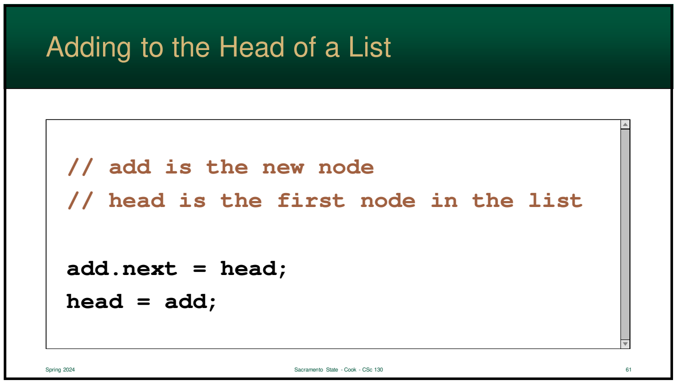

Adding to the Head of a List

```
// add is the new node
// head is the first node in the list

add.next = head;
head = add;
```

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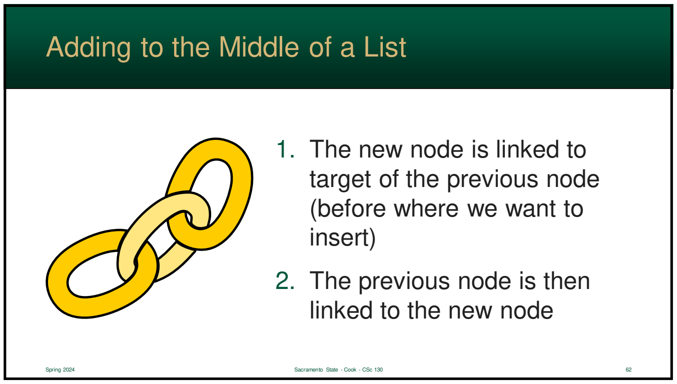

Adding to the Middle of a List

1. The new node is linked to target of the previous node (before where we want to insert)
2. The previous node is then linked to the new node

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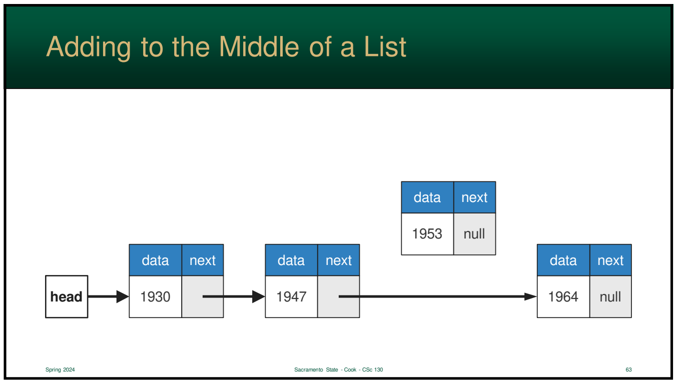

Adding to the Middle of a List

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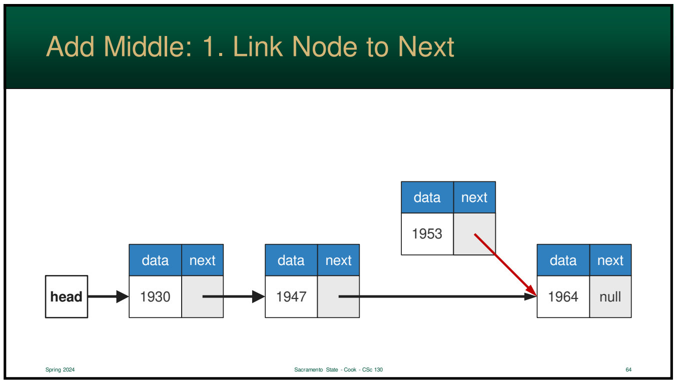

Add Middle: 1. Link Node to Next

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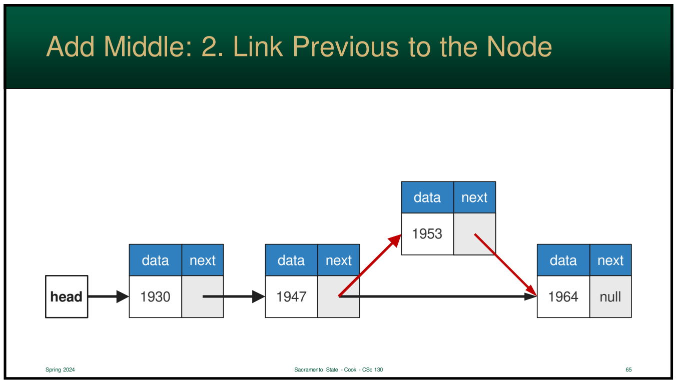
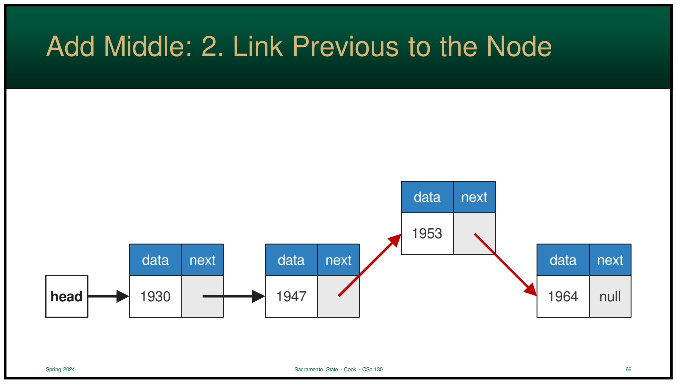


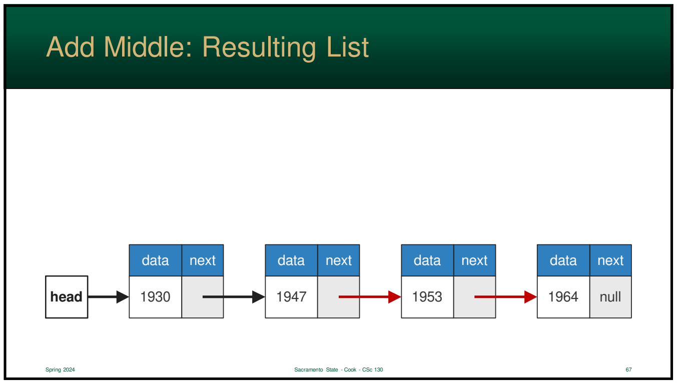
Add Middle: 2. Link Previous to the Node

65

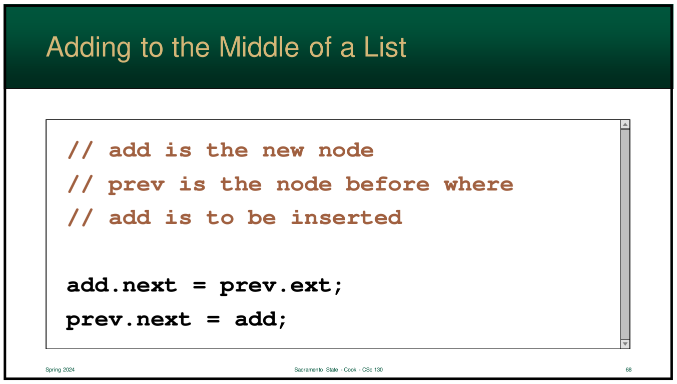


Add Middle: 2. Link Previous to the Node

66

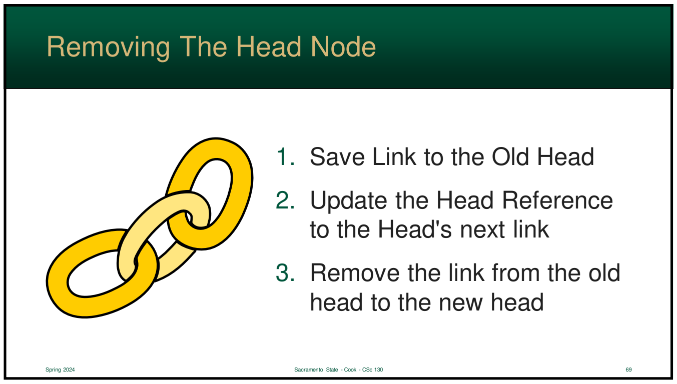


Add Middle: Resulting List



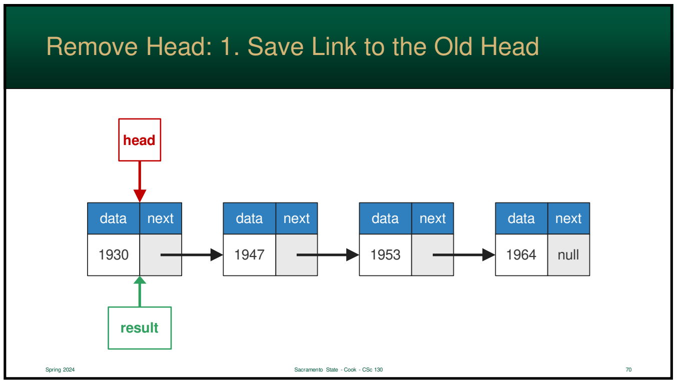
Adding to the Middle of a List

```
// add is the new node
// prev is the node before where
// add is to be inserted

add.next = prev.ext;
prev.next = add;
```

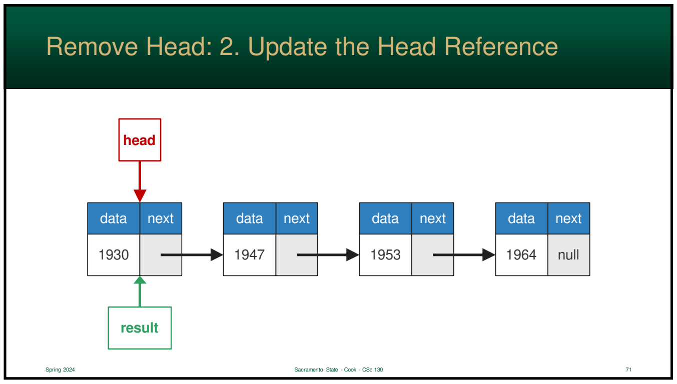


Removing The Head Node

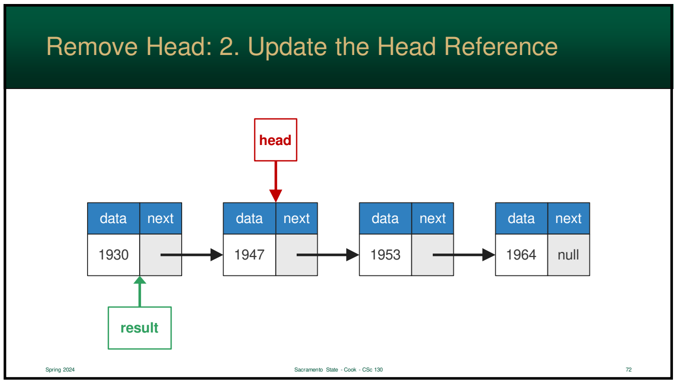
1. Save Link to the Old Head
2. Update the Head Reference to the Head's next link
3. Remove the link from the old head to the new head



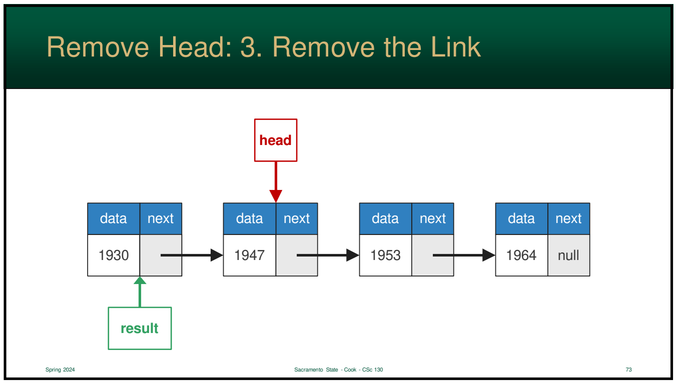
Remove Head: 1. Save Link to the Old Head



Remove Head: 2. Update the Head Reference

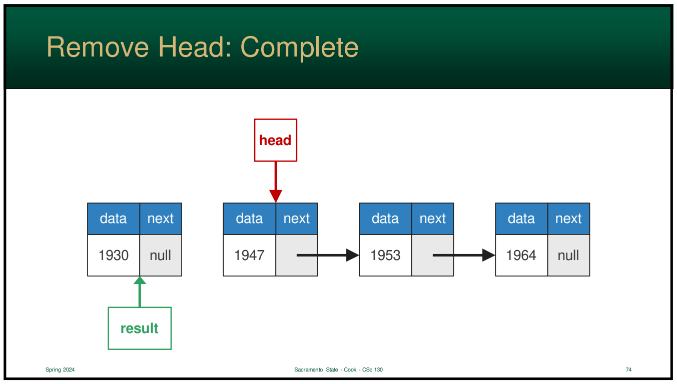


Remove Head: 2. Update the Head Reference



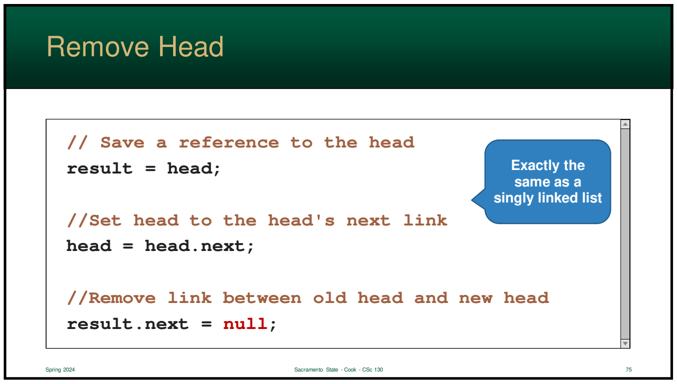
Remove Head: 3. Remove the Link

73



Remove Head: Complete

74

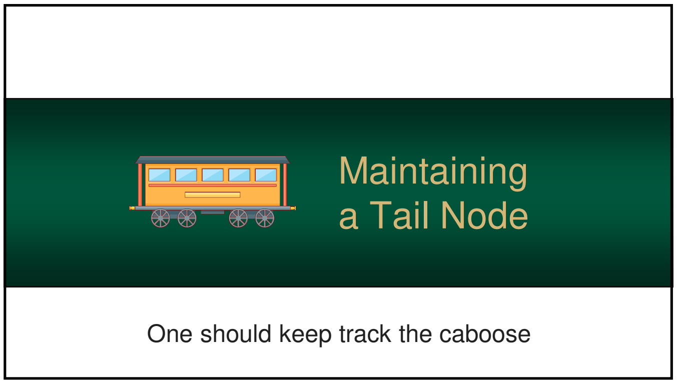


Remove Head

```
// Save a reference to the head
result = head;

//Set head to the head's next link
head = head.next;

//Remove link between old head and new head
result.next = null;
```

Exactly the same as a singly linked list

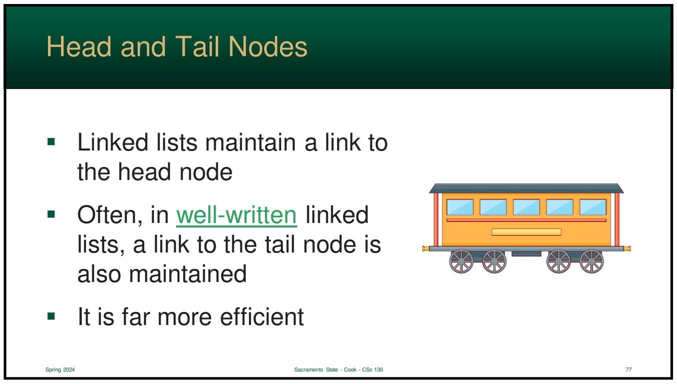
75



Maintaining a Tail Node

One should keep track the caboose

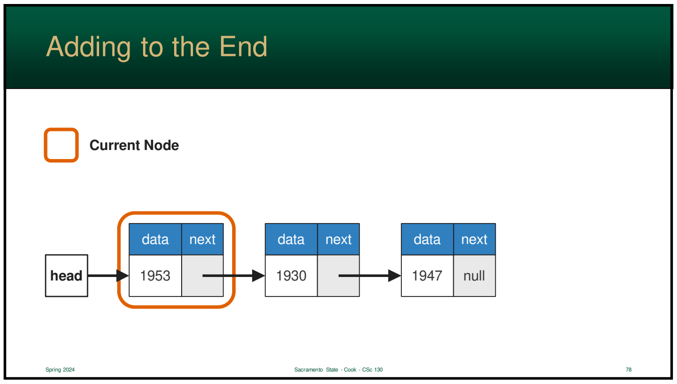
76



Head and Tail Nodes

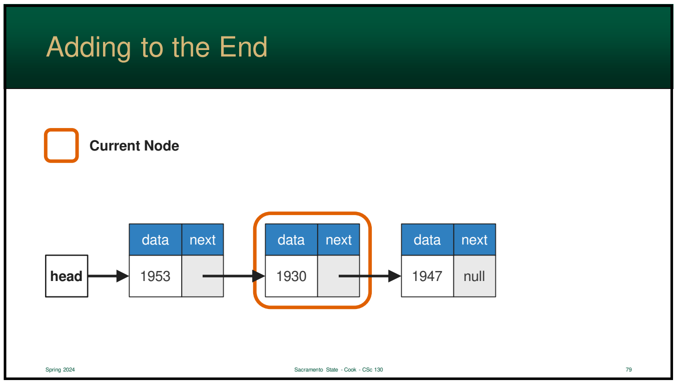
- Linked lists maintain a link to the head node
- Often, in well-written linked lists, a link to the tail node is also maintained
- It is far more efficient

77



Adding to the End

78



Adding to the End

Current Node

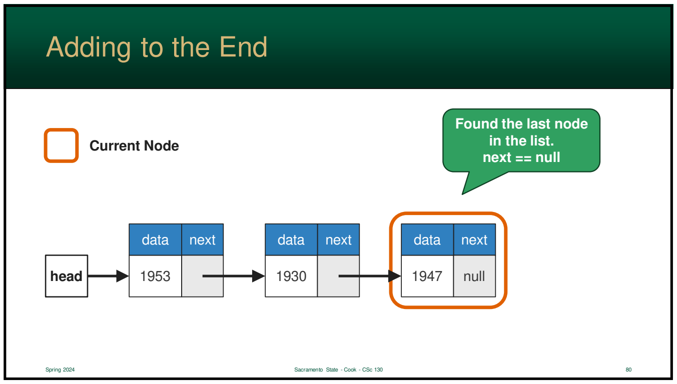
head → 1953 → 1930 → 1947

data	next
1953	

data	next
1930	

data	next
1947	null

79



Adding to the End

Current Node

Found the last node in the list. next == null

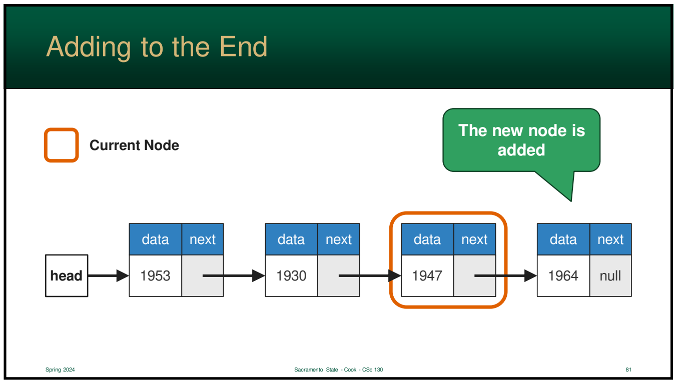
head → 1953 → 1930 → 1947

data	next
1953	

data	next
1930	

data	next
1947	null

80



Adding to the End

Current Node

The new node is added

head → 1953 → 1930 → 1947 → 1964

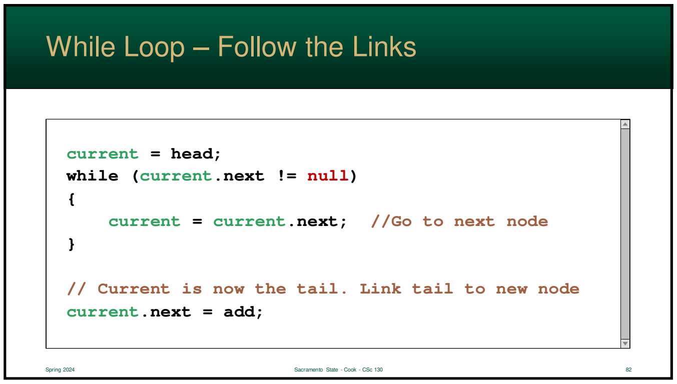
data	next
1953	

data	next
1930	

data	next
1947	

data	next
1964	null

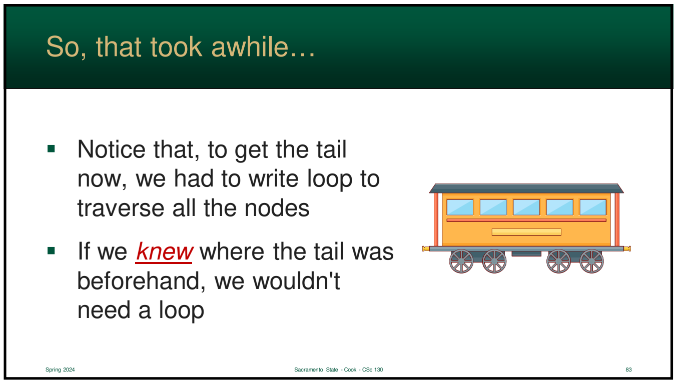
81



While Loop – Follow the Links

```
current = head;
while (current.next != null)
{
    current = current.next;  //Go to next node
}

// Current is now the tail. Link tail to new node
current.next = add;
```

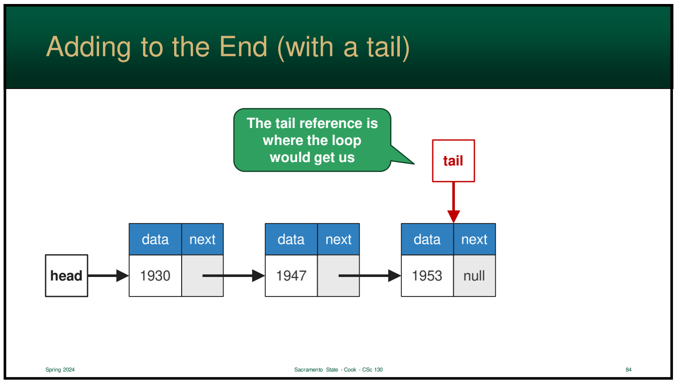
82



So, that took awhile…

- Notice that, to get the tail now, we had to write loop to traverse all the nodes
- If we *knew* where the tail was beforehand, we wouldn't need a loop

83



Adding to the End (with a tail)

The tail reference is where the loop would get us

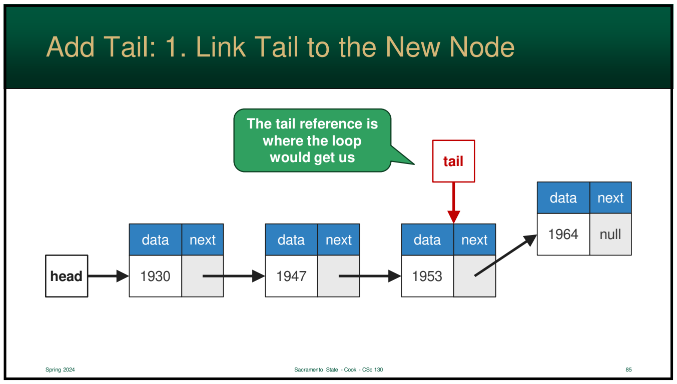
head → 1930 → 1947 → 1953

data	next
1930	

data	next
1947	

data	next
1953	null

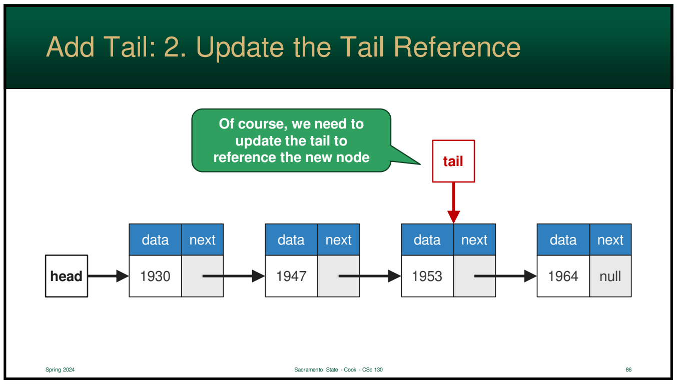
84



Add Tail: 1. Link Tail to the New Node

The tail reference is where the loop would get us

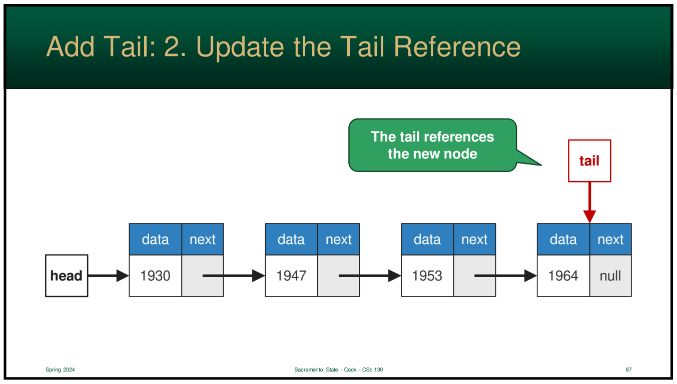
85



Add Tail: 2. Update the Tail Reference

Of course, we need to update the tail to reference the new node

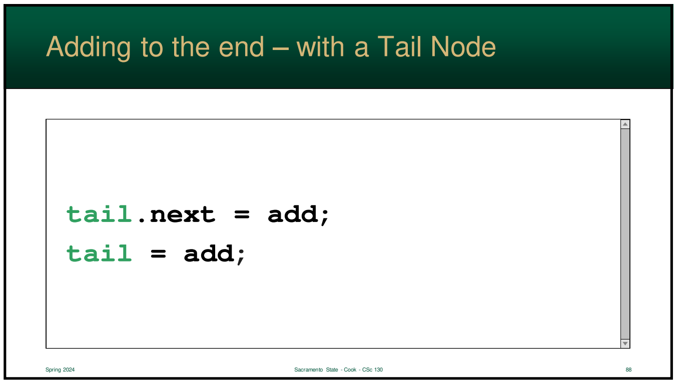
86



Add Tail: 2. Update the Tail Reference

The tail references the new node

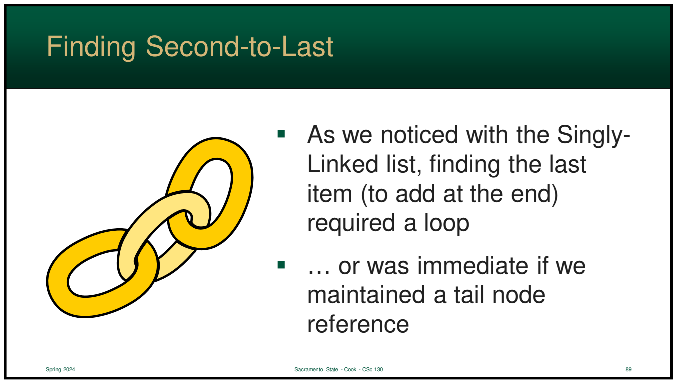
87



Adding to the end – with a Tail Node

```
tail.next = add;
tail = add;
```

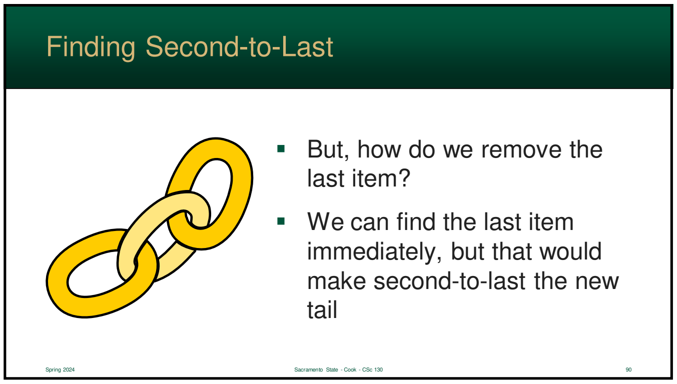
88



Finding Second-to-Last

- As we noticed with the Singly-Linked list, finding the last item (to add at the end) required a loop
- … or was immediate if we maintained a tail node reference

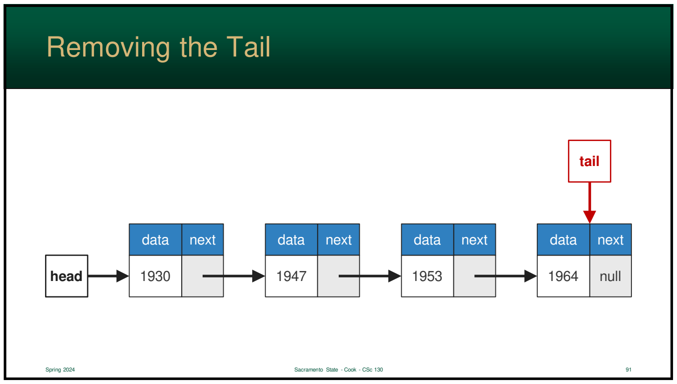
89



Finding Second-to-Last

- But, how do we remove the last item?
- We can find the last item immediately, but that would make second-to-last the new tail

90

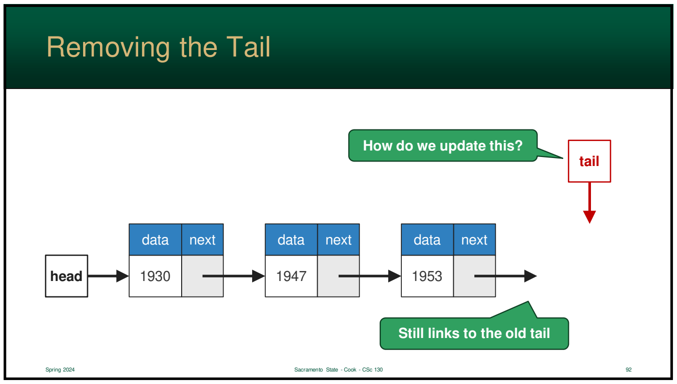


Removing the Tail

tail

head → data 1930 next → data 1947 next → data 1953 next → data 1964 next null

91



Removing the Tail

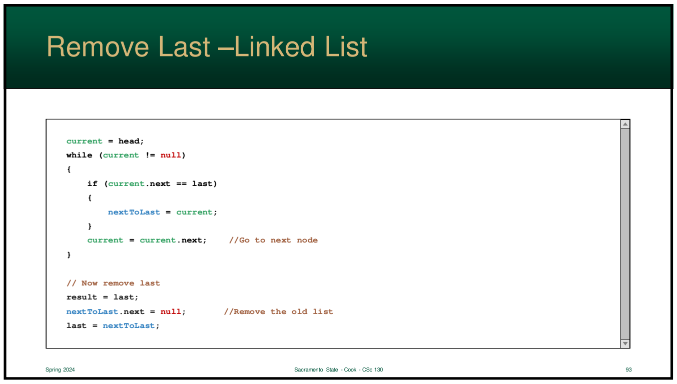
How do we update this?

tail

head → data 1930 next → data 1947 next → data 1953 next →

Still links to the old tail

92



Remove Last –Linked List

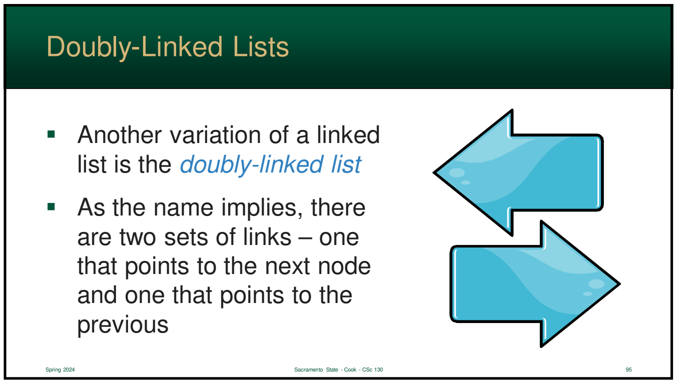
```
current = head;
while (current != null)
{
    if (current.next == last)
    {
        nextToLast = current;
    }
    current = current.next;    //Go to next node
}

// Now remove last
result = last;
nextToLast.next = null;       //Remove the old list
last = nextToLast;
```

93

Doubly-Linked Lists

Two Way Streets

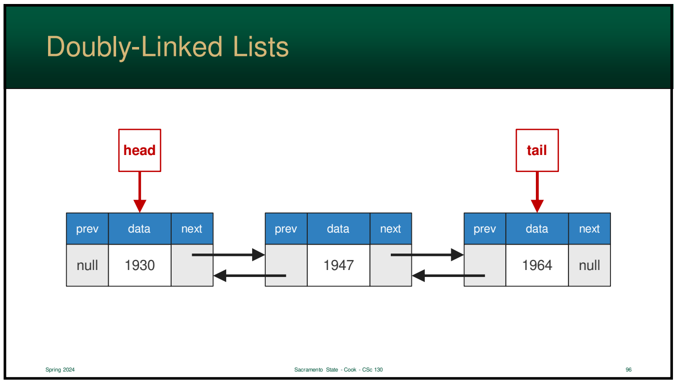
94



Doubly-Linked Lists

- Another variation of a linked list is the *doubly-linked list*
- As the name implies, there are two sets of links – one that points to the next node and one that points to the previous

95



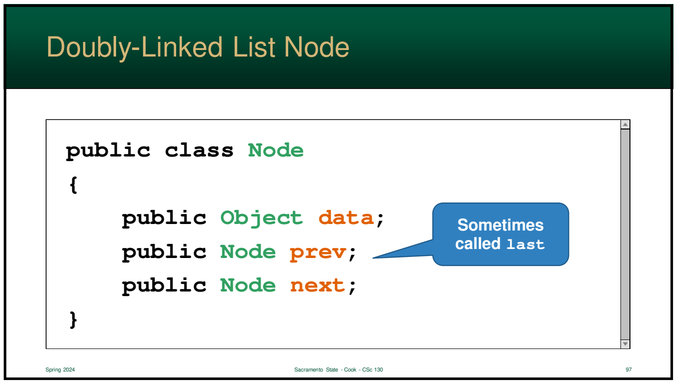
Doubly-Linked Lists

head

tail

prev null data 1930 next ⇄ prev data 1947 next ⇄ prev data 1964 next null

96



Doubly-Linked List Node

```
public class Node
{
    public Object data;
    public Node prev;
    public Node next;
}
```

Sometimes called `last`

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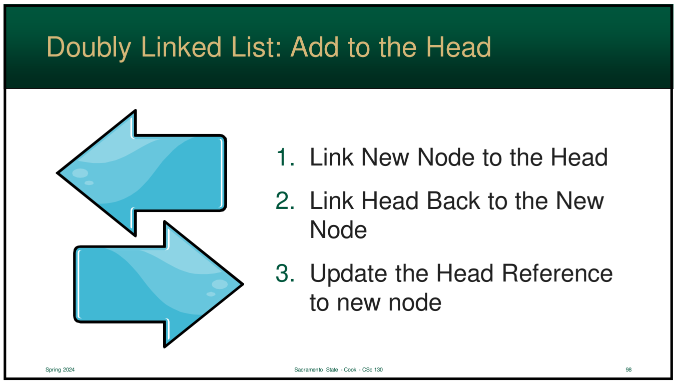
97



Doubly Linked List: Add to the Head

1. Link New Node to the Head
2. Link Head Back to the New Node
3. Update the Head Reference to new node

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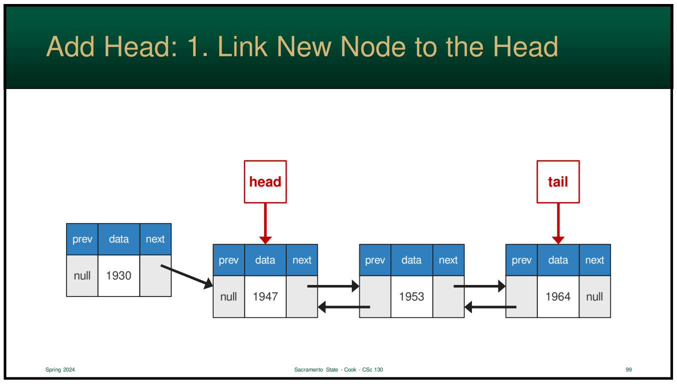
98



Add Head: 1. Link New Node to the Head

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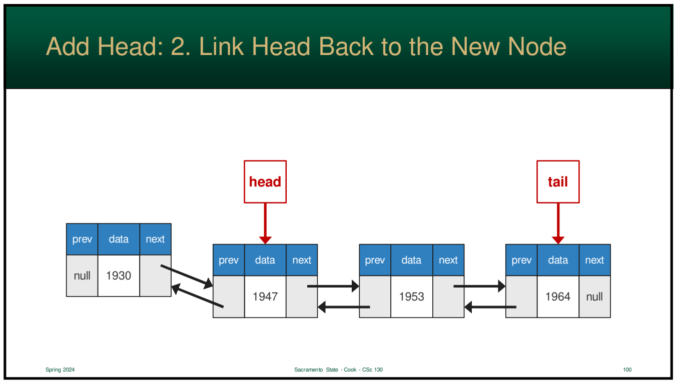
99



Add Head: 2. Link Head Back to the New Node

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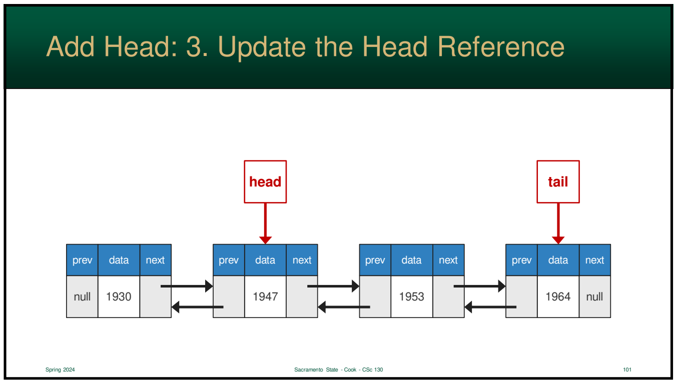
100



Add Head: 3. Update the Head Reference

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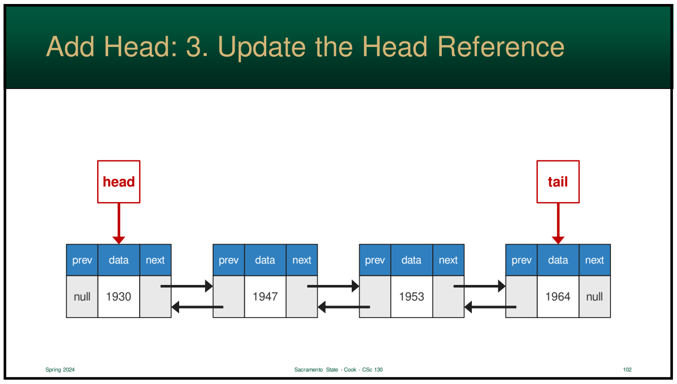
101



Add Head: 3. Update the Head Reference

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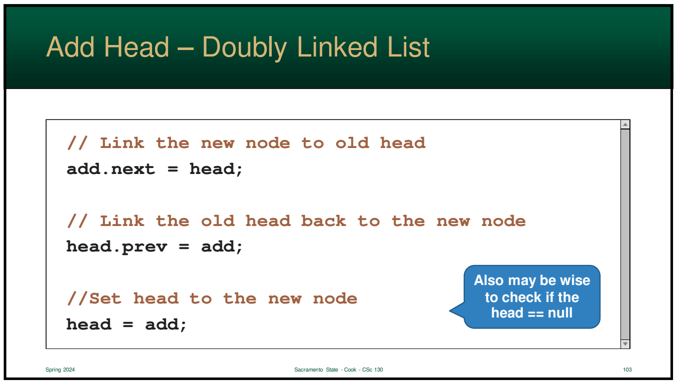
102



Add Head – Doubly Linked List

```
// Link the new node to old head
add.next = head;

// Link the old head back to the new node
head.prev = add;

//Set head to the new node
head = add;
```

Also may be wise to check if the head == null

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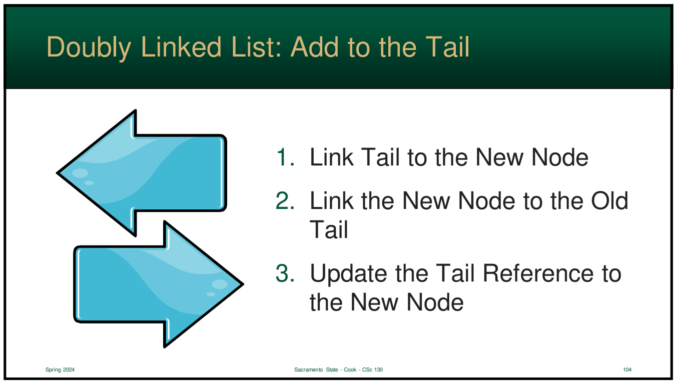
103



Doubly Linked List: Add to the Tail

1. Link Tail to the New Node
2. Link the New Node to the Old Tail
3. Update the Tail Reference to the New Node

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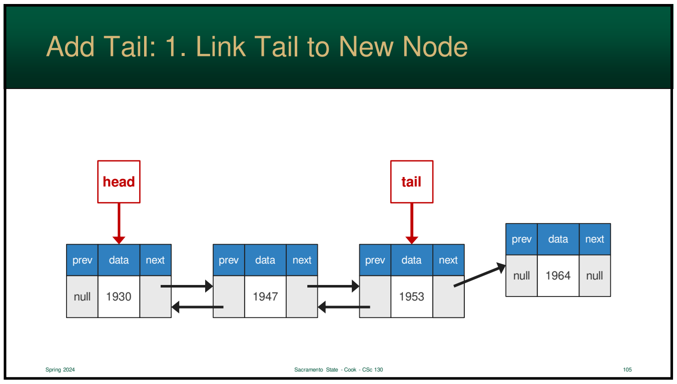
104



Add Tail: 1. Link Tail to New Node

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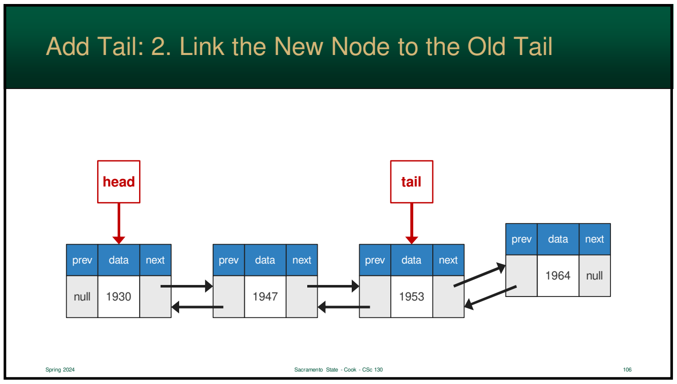
105



Add Tail: 2. Link the New Node to the Old Tail

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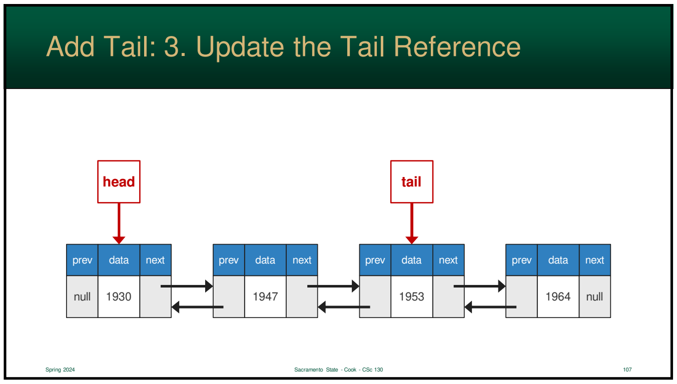
106



Add Tail: 3. Update the Tail Reference

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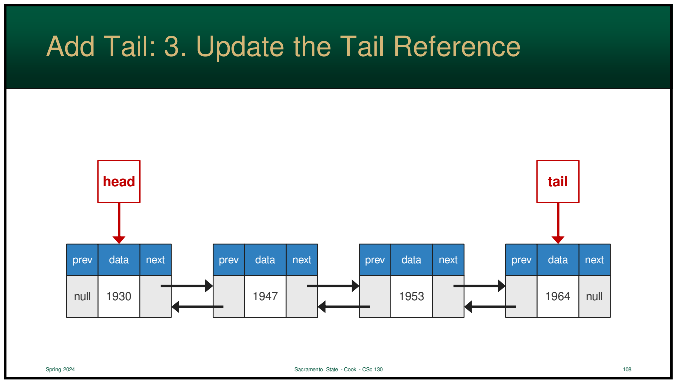
107



Add Tail: 3. Update the Tail Reference

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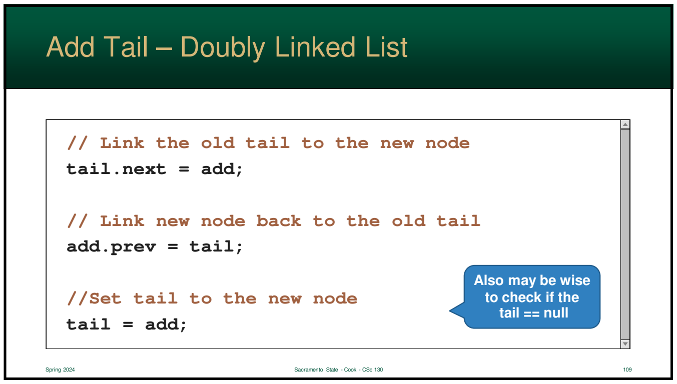
108



Add Tail – Doubly Linked List

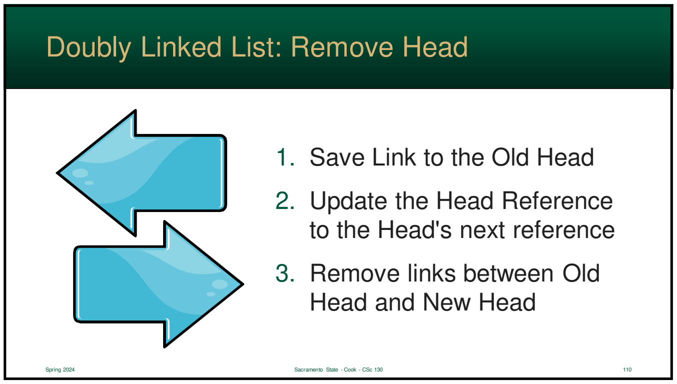
```
// Link the old tail to the new node
tail.next = add;

// Link new node back to the old tail
add.prev = tail;

//Set tail to the new node
tail = add;
```

Also may be wise to check if the tail == null

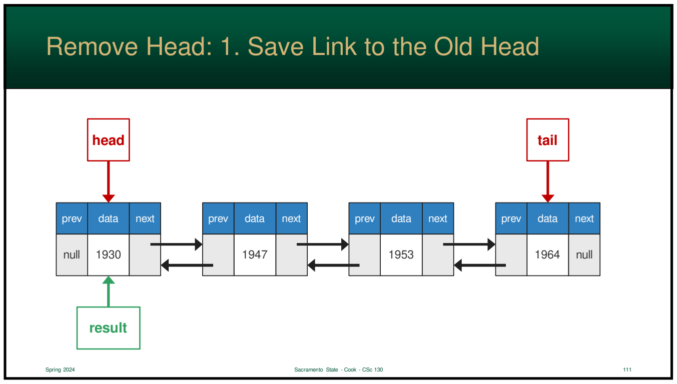
109



Doubly Linked List: Remove Head

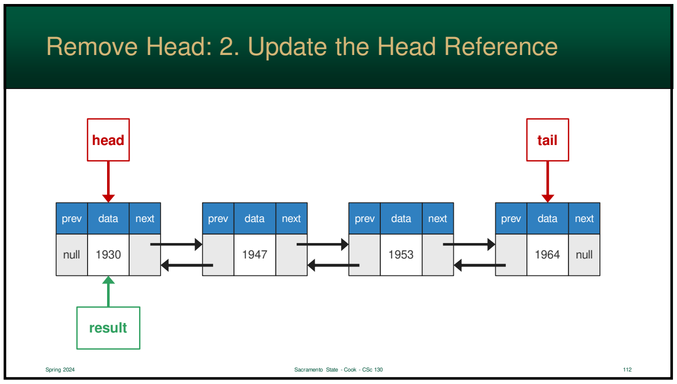
1. Save Link to the Old Head
2. Update the Head Reference to the Head's next reference
3. Remove links between Old Head and New Head

110



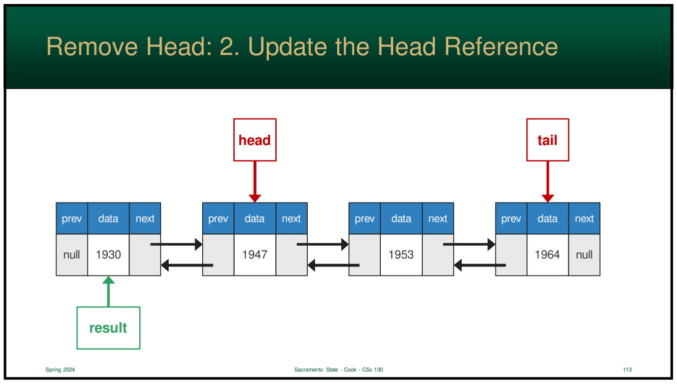
Remove Head: 1. Save Link to the Old Head

111



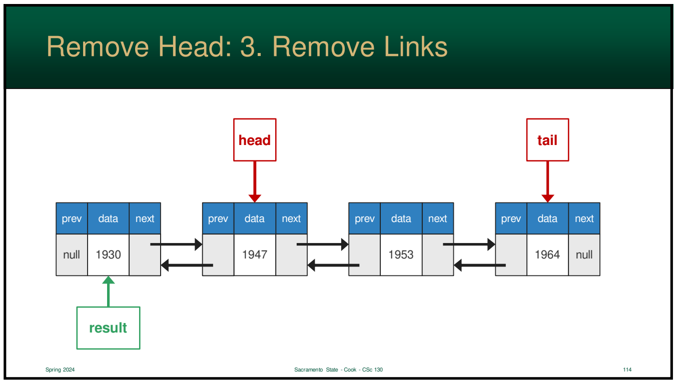
Remove Head: 2. Update the Head Reference

112



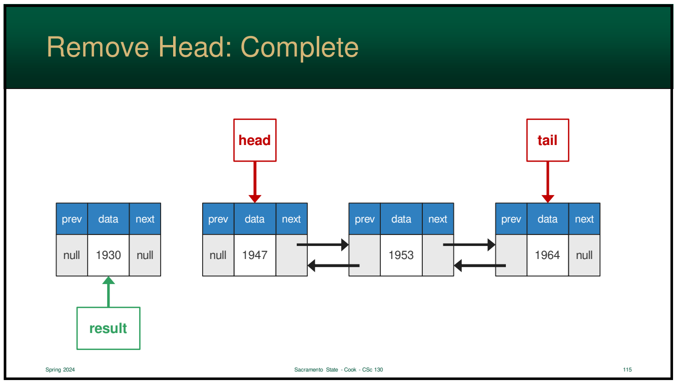
Remove Head: 2. Update the Head Reference

113



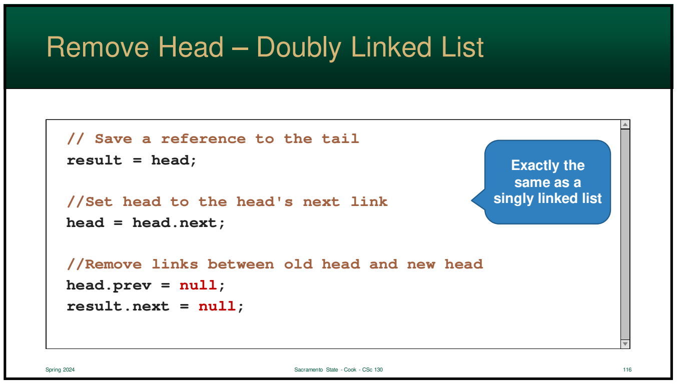
Remove Head: 3. Remove Links

114



Remove Head: Complete

115



Remove Head – Doubly Linked List

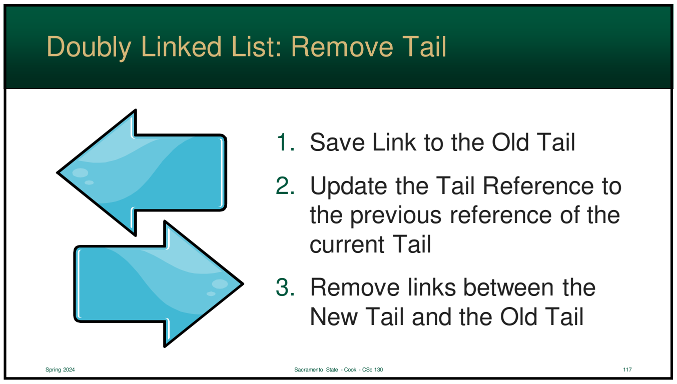
```
// Save a reference to the tail
result = head;

//Set head to the head's next link
head = head.next;

//Remove links between old head and new head
head.prev = null;
result.next = null;
```

Exactly the same as a singly linked list

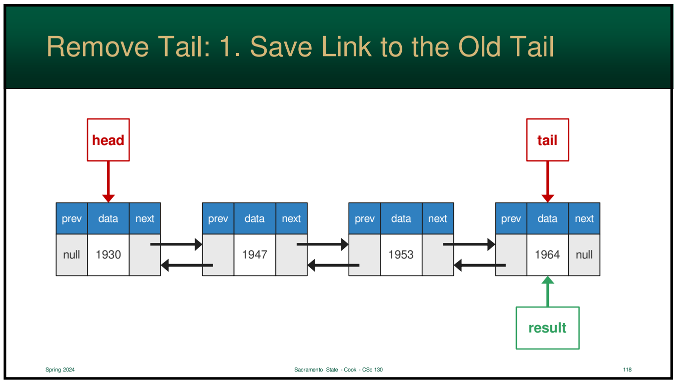
116



Doubly Linked List: Remove Tail

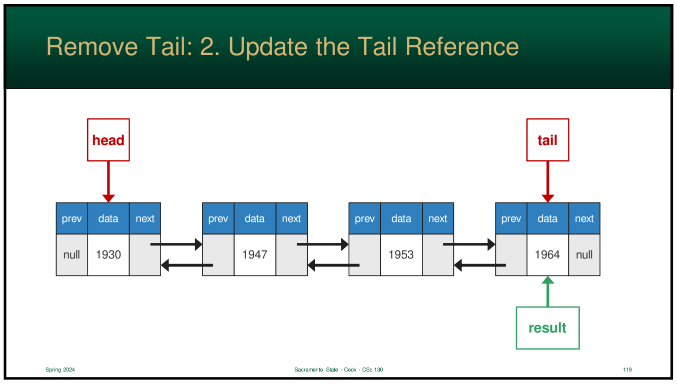
1. Save Link to the Old Tail
2. Update the Tail Reference to the previous reference of the current Tail
3. Remove links between the New Tail and the Old Tail

117



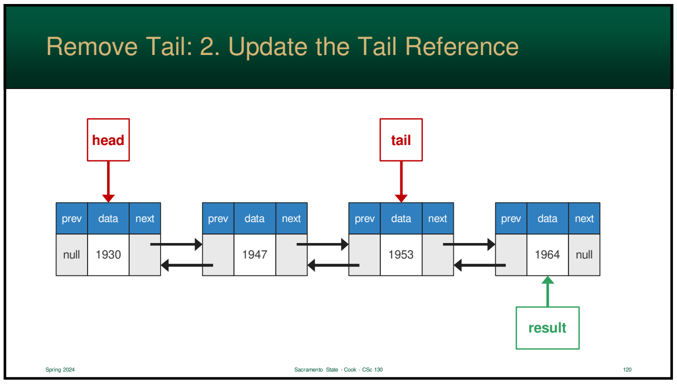
Remove Tail: 1. Save Link to the Old Tail

118



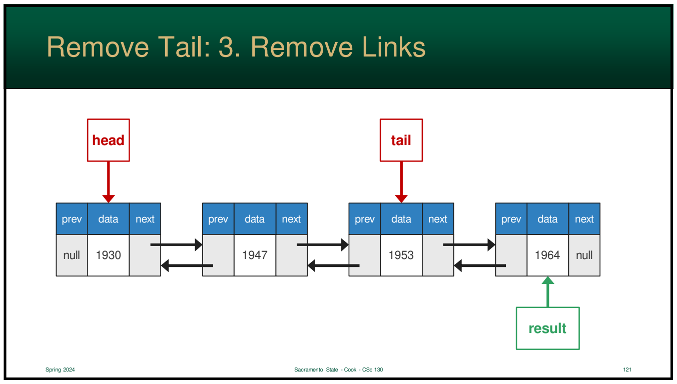
Remove Tail: 2. Update the Tail Reference

119



Remove Tail: 2. Update the Tail Reference

120



Remove Tail: 3. Remove Links

head

tail

prev	data	next
null	1930	

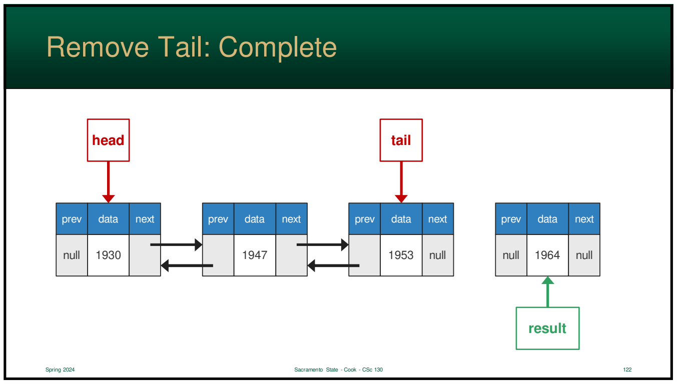
prev	data	next
	1947	

prev	data	next
	1953	

prev	data	next
	1964	null

result

121



Remove Tail: Complete

head

tail

prev	data	next
null	1930	

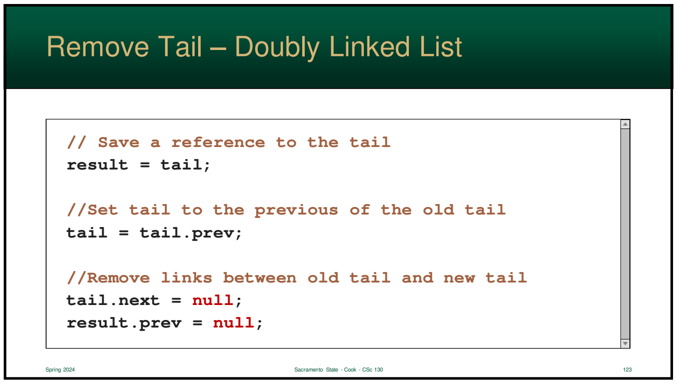
prev	data	next
	1947	

prev	data	next
	1953	null

prev	data	next
null	1964	null

result

122



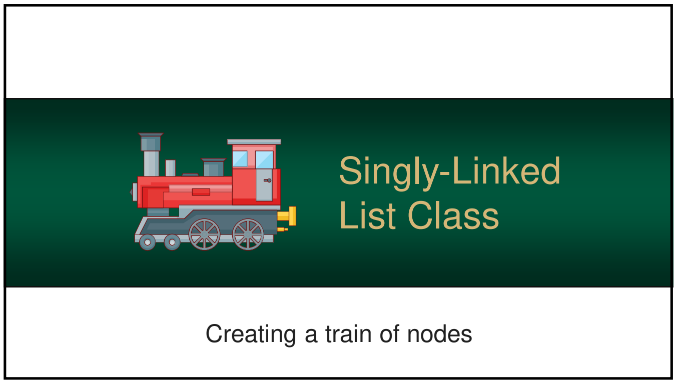
Remove Tail – Doubly Linked List

```
// Save a reference to the tail
result = tail;

//Set tail to the previous of the old tail
tail = tail.prev;

//Remove links between old tail and new tail
tail.next = null;
result.prev = null;
```

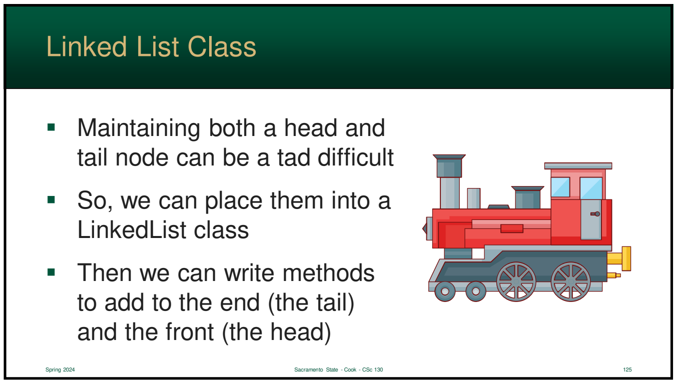
123



Singly-Linked List Class

Creating a train of nodes

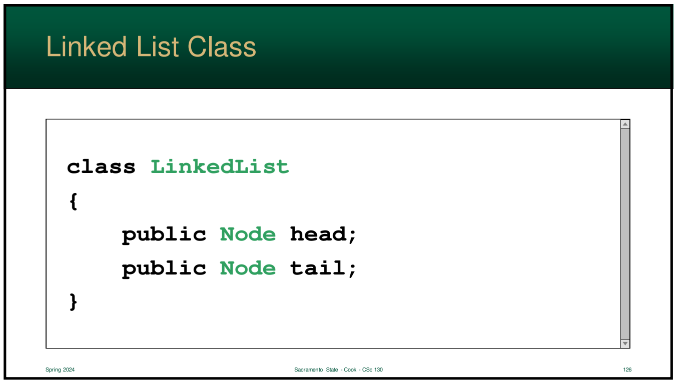
124



Linked List Class

- Maintaining both a head and tail node can be a tad difficult
- So, we can place them into a LinkedList class
- Then we can write methods to add to the end (the tail) and the front (the head)

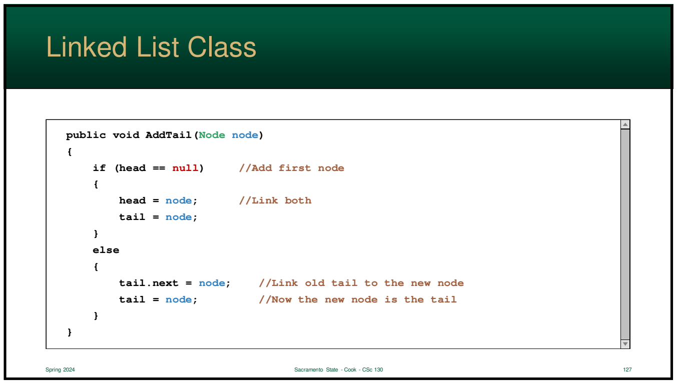
125



Linked List Class

```
class LinkedList
{
    public Node head;
    public Node tail;
}
```

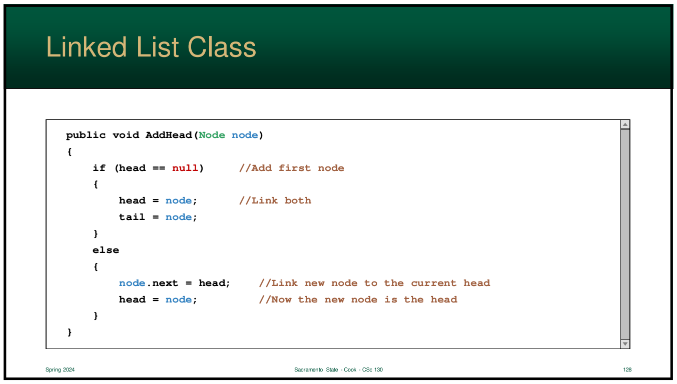
126



Linked List Class

```
public void AddTail(Node node)
{
    if (head == null)     //Add first node
    {
        head = node;      //Link both
        tail = node;
    }
    else
    {
        tail.next = node;    //Link old tail to the new node
        tail = node;         //Now the new node is the tail
    }
}
```

127



Linked List Class

```
public void AddHead(Node node)
{
    if (head == null)     //Add first node
    {
        head = node;      //Link both
        tail = node;
    }
    else
    {
        node.next = head;    //Link new node to the current head
        head = node;         //Now the new node is the head
    }
}
```

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Linked List Class

- Now that we have compensated for the head/tail being null, we can also a method to remove the head
- But there are more cases that need to be considered

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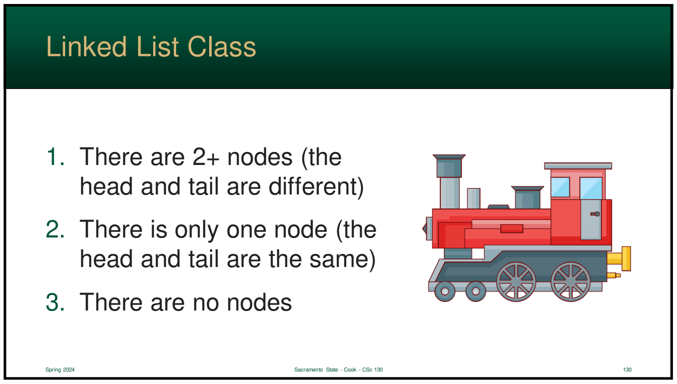
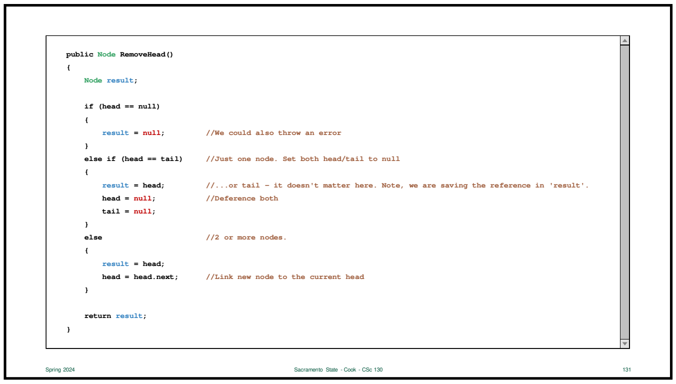


Linked List Class

1. There are 2+ nodes (the head and tail are different)
2. There is only one node (the head and tail are the same)
3. There are no nodes

130



```
public Node RemoveHead()
{
    Node result;

    if (head == null)
    {
        result = null;         //We could also throw an error
    }
    else if (head == tail)     //Just one node. Set both head/tail to null
    {
        result = head;         //...or tail – it doesn't matter here. Note, we are saving the reference in 'result'.
        head = null;           //Deference both
        tail = null;
    }
    else                       //2 or more nodes.
    {
        result = head;
        head = head.next;      //Link new node to the current head
    }

    return result;
}
```

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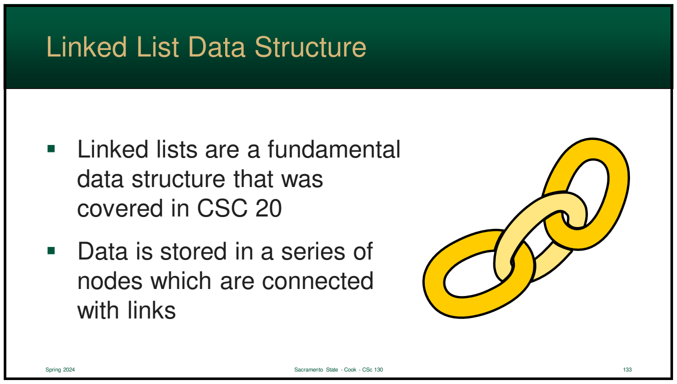
Linked List Big-O

How Good Is This?

132



Linked List Data Structure

- Linked lists are a fundamental data structure that was covered in CSC 20
- Data is stored in a series of nodes which are connected with links

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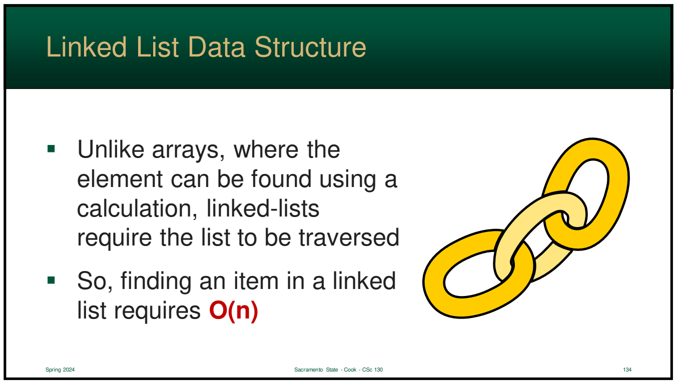
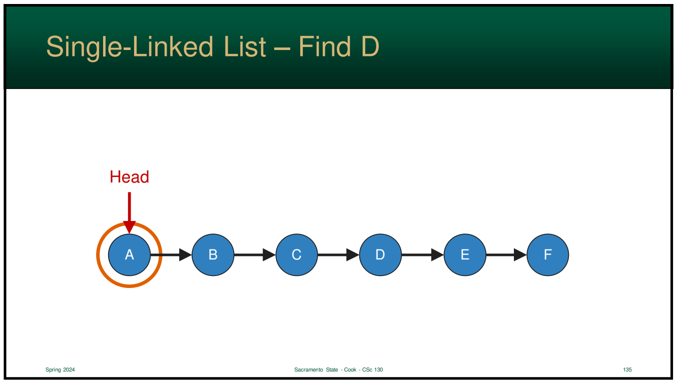


Linked List Data Structure

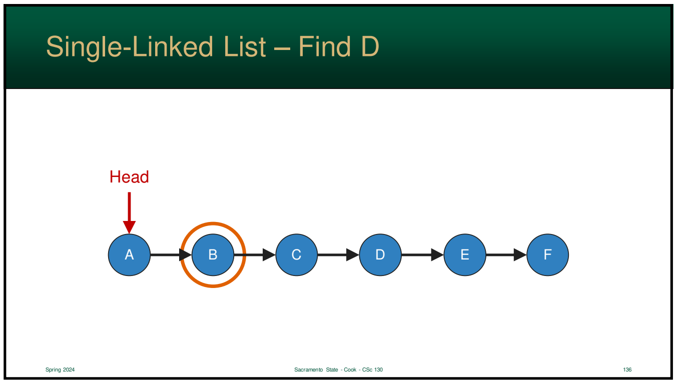
- Unlike arrays, where the element can be found using a calculation, linked-lists require the list to be traversed
- So, finding an item in a linked list requires **O(n)**

134



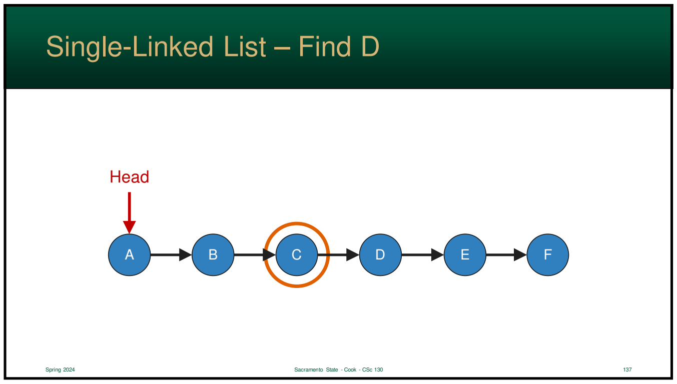
Single-Linked List – Find D

135



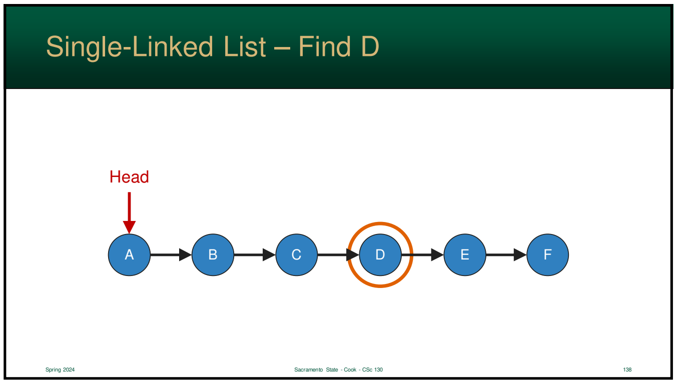
Single-Linked List – Find D

136



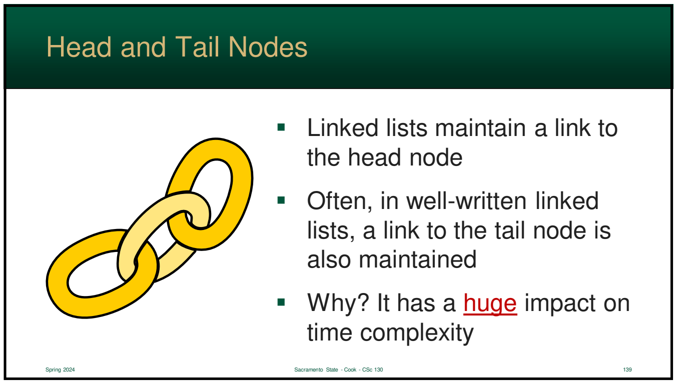
Single-Linked List – Find D

137



Single-Linked List – Find D

138



Head and Tail Nodes

- Linked lists maintain a link to the head node
- Often, in well-written linked lists, a link to the tail node is also maintained
- Why? It has a huge impact on time complexity

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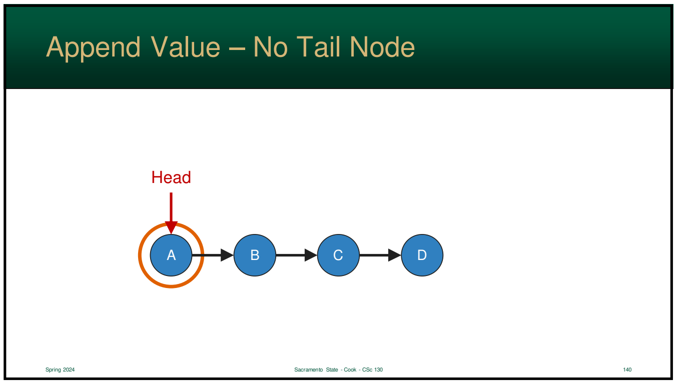

Append Value – No Tail Node

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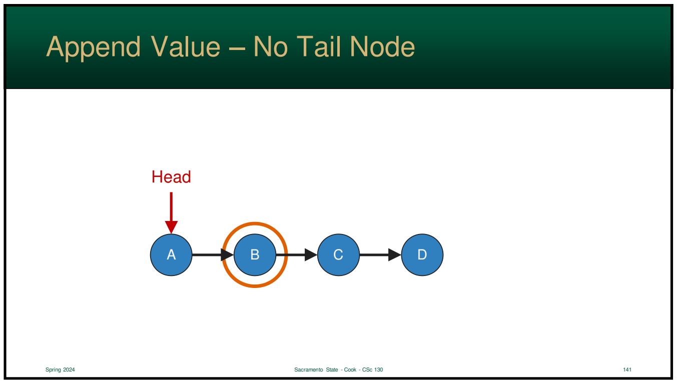
140



Append Value – No Tail Node

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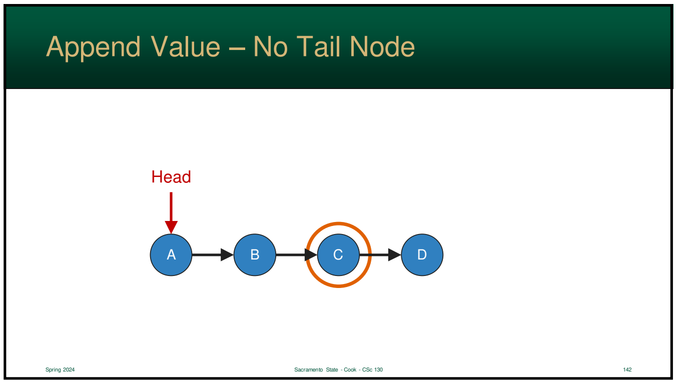
141



Append Value – No Tail Node

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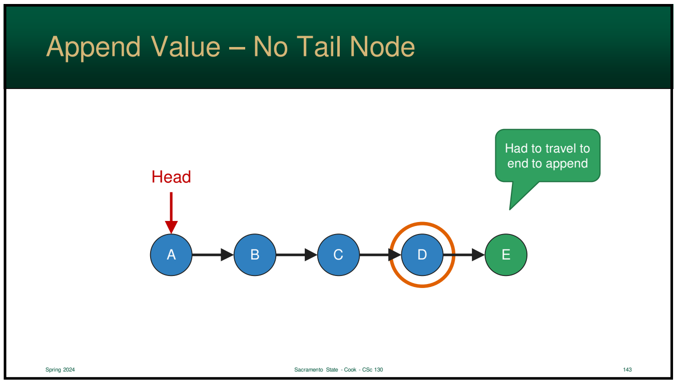
142



Append Value – No Tail Node

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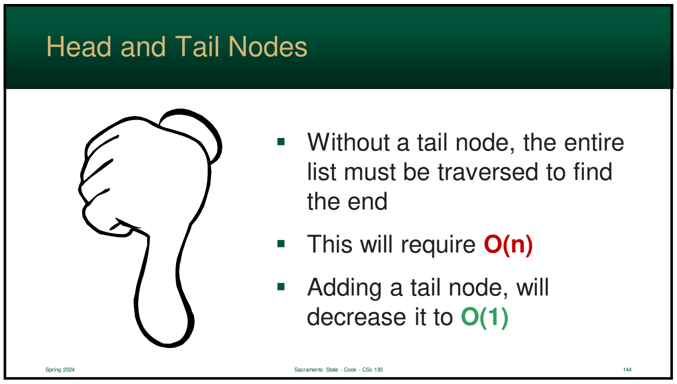
143



Head and Tail Nodes

- Without a tail node, the entire list must be traversed to find the end
- This will require **O(n)**
- Adding a tail node, will decrease it to **O(1)**

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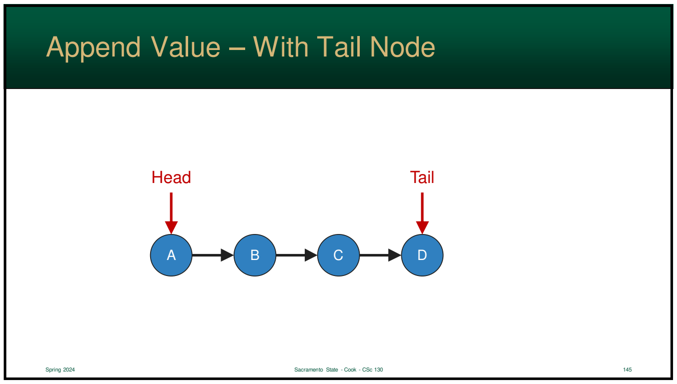

Append Value – With Tail Node

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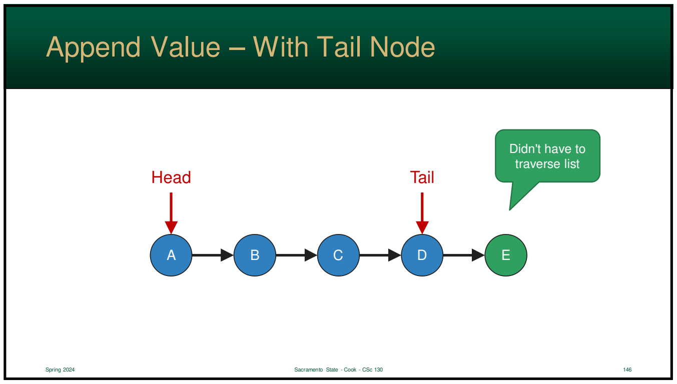
145



Append Value – With Tail Node

Didn't have to traverse list

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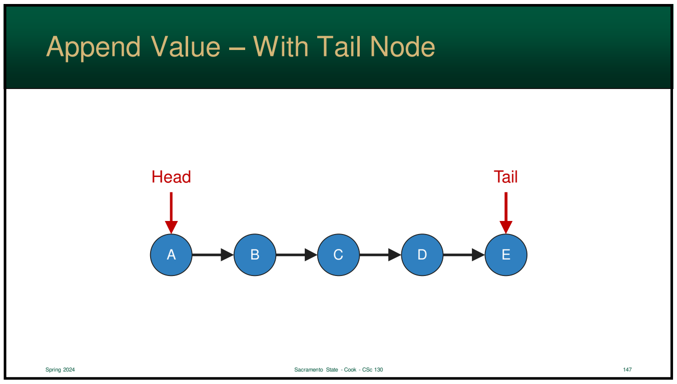

Append Value – With Tail Node

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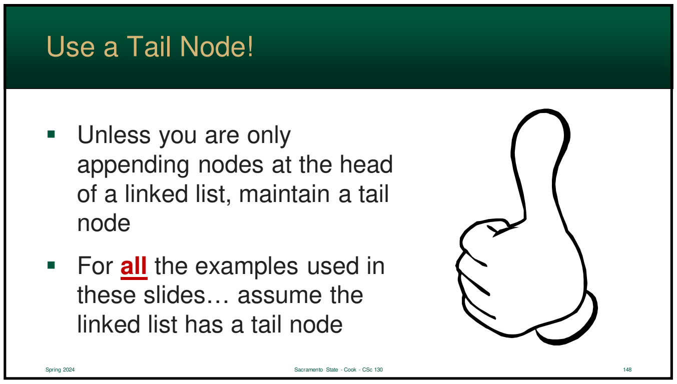
147



Use a Tail Node!

- Unless you are only appending nodes at the head of a linked list, maintain a tail node
- For **all** the examples used in these slides… assume the linked list has a tail node

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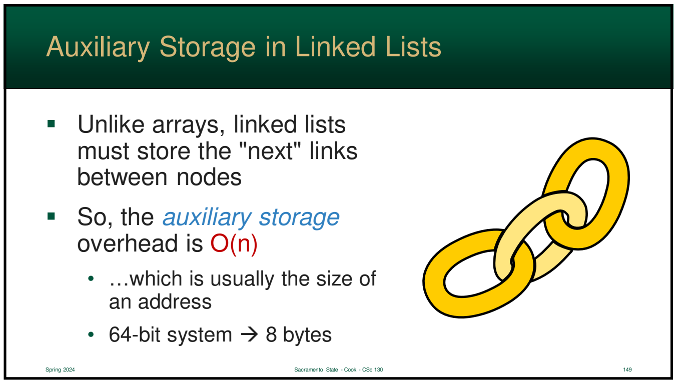

Auxiliary Storage in Linked Lists

- Unlike arrays, linked lists must store the "next" links between nodes
- So, the *auxiliary storage* overhead is O(n)
  - …which is usually the size of an address
  - 64-bit system → 8 bytes

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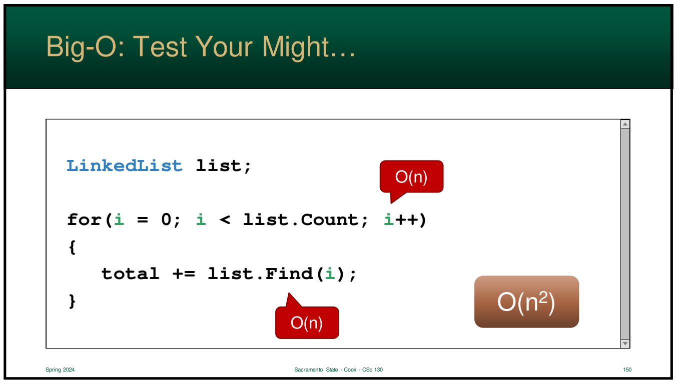

Big-O: Test Your Might…

```
LinkedList list;

for(i = 0; i < list.Count; i++)
{
   total += list.Find(i);
}
```

O(n)

O(n)

O(n^2)

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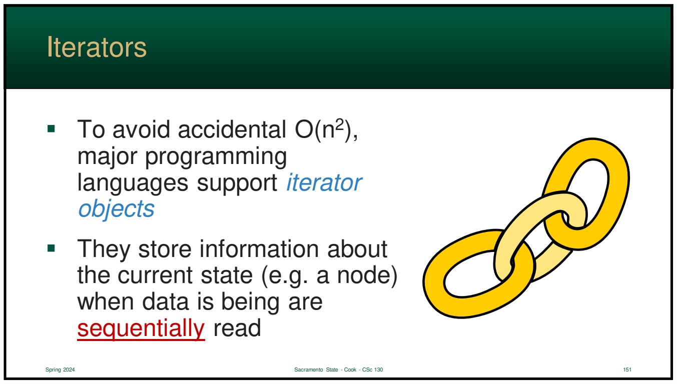

Iterators

- To avoid accidental $O(n^2)$, major programming languages support *iterator objects*
- They store information about the current state (e.g. a node) when data is being are sequentially read

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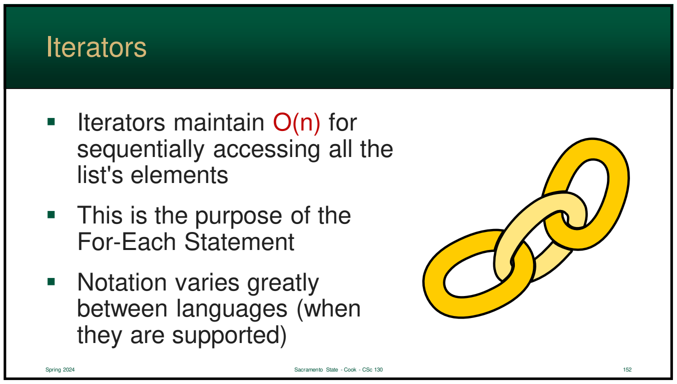

Iterators

- Iterators maintain O(n) for sequentially accessing all the list's elements
- This is the purpose of the For-Each Statement
- Notation varies greatly between languages (when they are supported)

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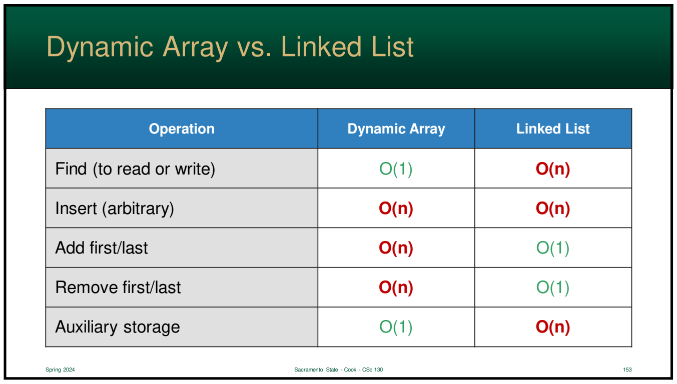

Dynamic Array vs. Linked List

Operation	Dynamic Array	Linked List
Find (to read or write)	O(1)	**O(n)**
Insert (arbitrary)	**O(n)**	**O(n)**
Add first/last	**O(n)**	O(1)
Remove first/last	**O(n)**	O(1)
Auxiliary storage	O(1)	**O(n)**

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