CSE 250
Data Structures

Dr. Eric Mikida
epmikida@buffalo.edu
208 Capen Hall

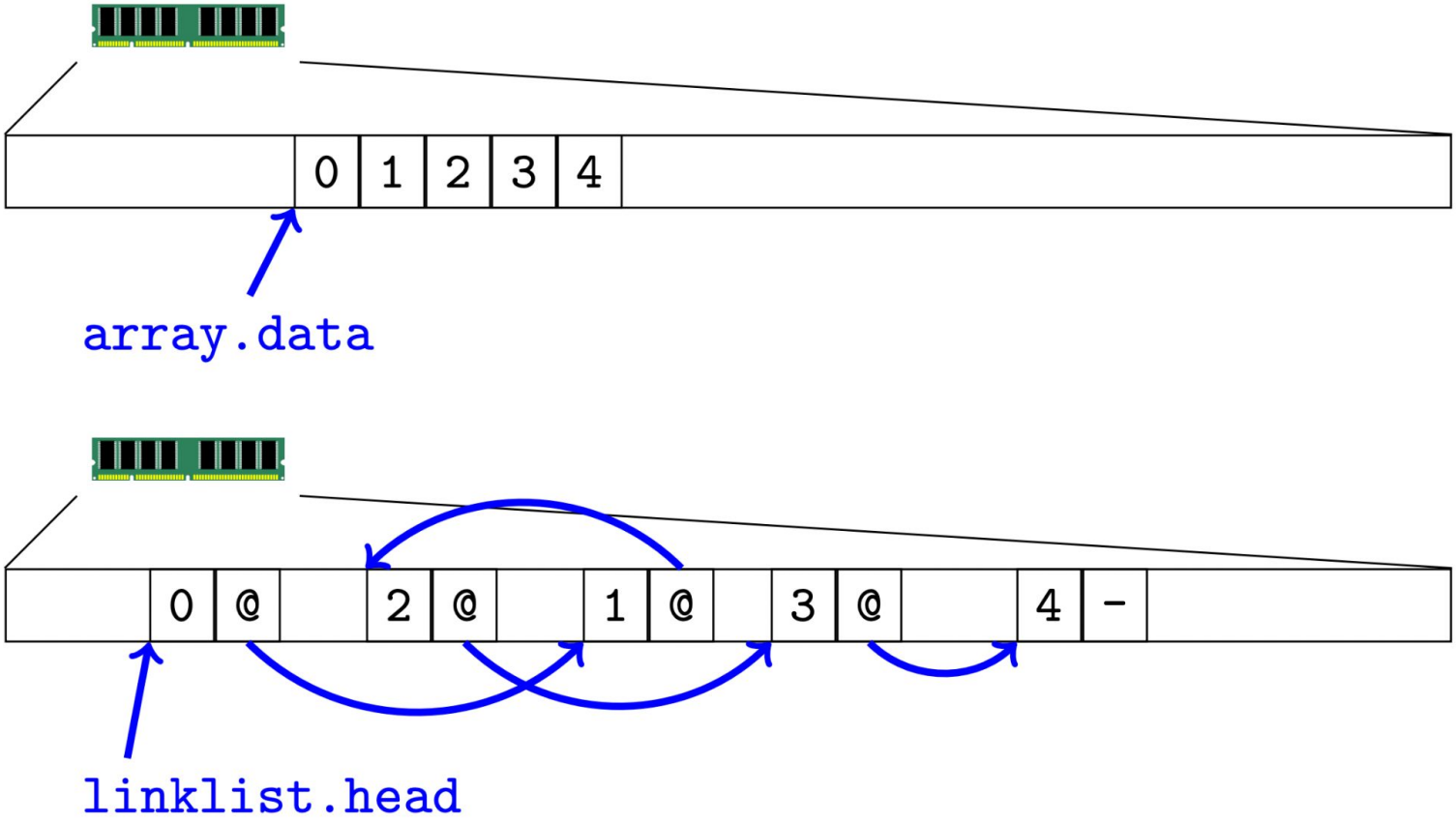
Lec 09: List ADT and Linked Lists

Announcements

- PA1 Implementation due Sunday, 9/24 @ 11:59PM
  - Continue with the same repo you've been using
- WA2 will be released after the PA1 deadline, due 9/31 @ 11:59PM
- Midterm #1 will be Monday 10/2 in class
  - **Covers:** Summations, Asymptotics, Sequences/Lists, Arrays, Linked Lists, Recursion, Bounds (Tight Upper/Lower, Unqualified vs Expected vs Amortized)

The Sequence ADT

```
1 public interface Sequence<E> {
2   public E get(idx: Int);
3   public void set(idx: Int, E value);
4   public int size();
5   public Iterator<E> iterator();
6 }
```



Arrays and Linked Lists in Memory

Sequence Runtimes (so far…)

	Array	Linked List (by index)	Linked List (by reference)
`get(...)`	$\Theta(1)$	$\Theta(idx)$ or $O(n)$	$\Theta(1)$
`set(...)`	$\Theta(1)$	$\Theta(idx)$ or $O(n)$	$\Theta(1)$
`size()`	$\Theta(1)$	$\Theta(1)$	$\Theta(1)$

The Sequence ADT

```
1 public interface Sequence<E> {
2   public E get(idx: Int);
3   public void set(idx: Int, E value);
4   public int size();
5   public Iterator<E> iterator();
6 }
```

What about adding/removing elements?

The List ADT

```
1  public interface List<E>
2      extends Sequence<E> { // Everything a sequence has, and...
3    /** Extend the sequence with a new element at the end */
4    public void add(E value);
5
6    /** Extend the sequence by inserting a new element */
7    public void add(int idx, E value);
8
9    /** Remove the element at a given index */
10   public void remove(int idx);
11 }
```

Lists in Other Languages

Java, Python: `List`, `list`

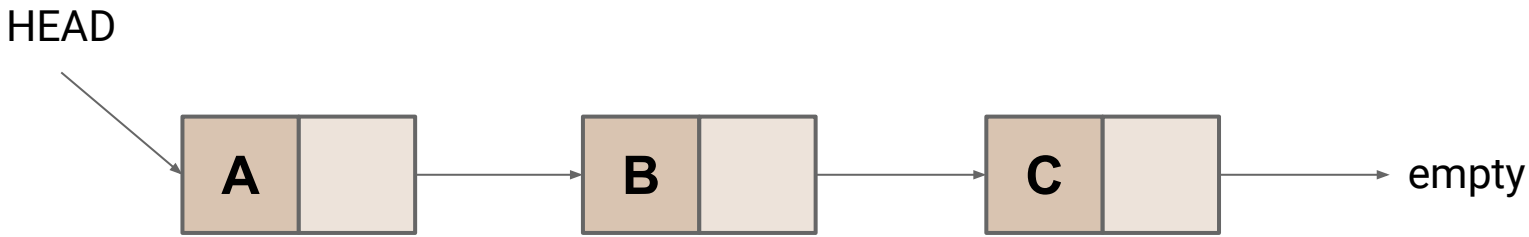
C++, Rust: `vector`, `Vec`

Scala: `Buffer`

Go: `Slice`

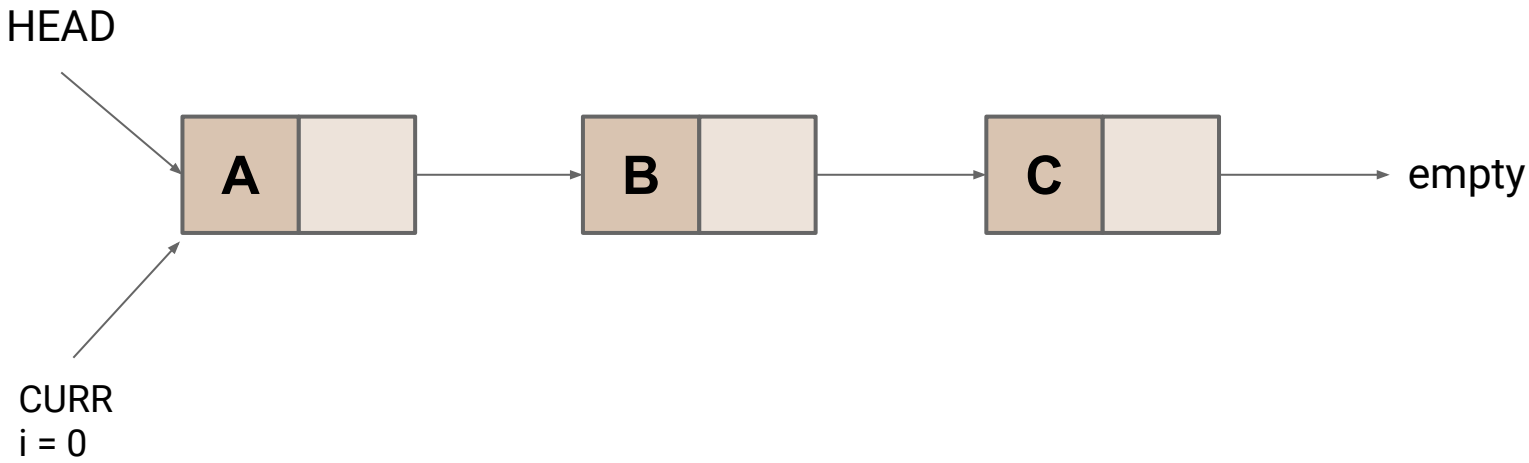
Linked Lists - `add(idx, e)`

`add(2,"D")`



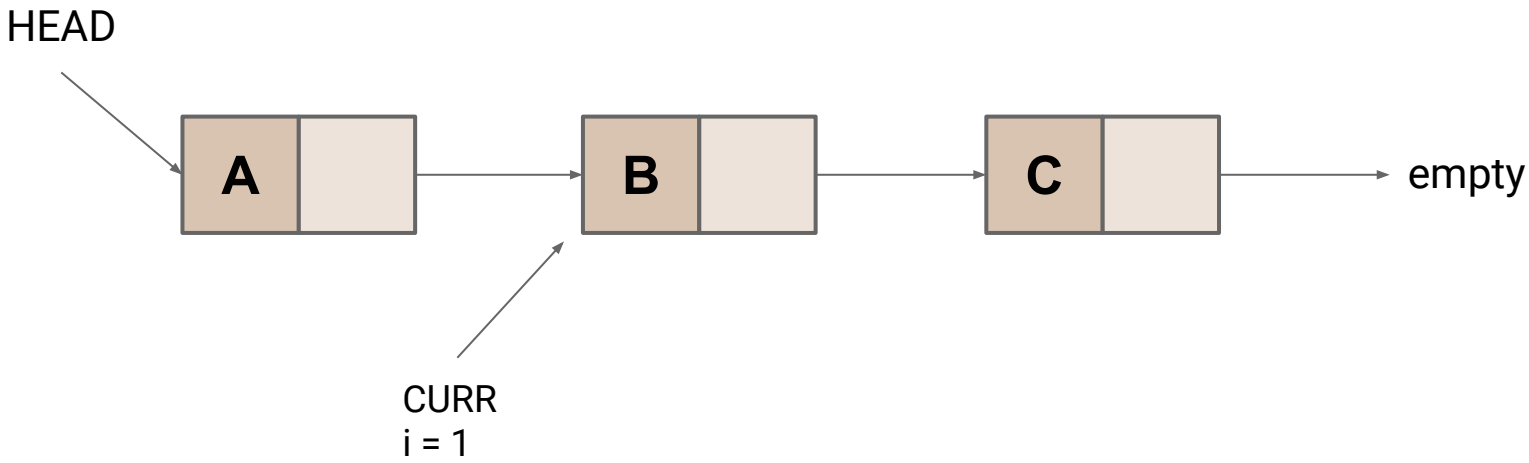
Linked Lists - add(idx, e)

add(2,"D")



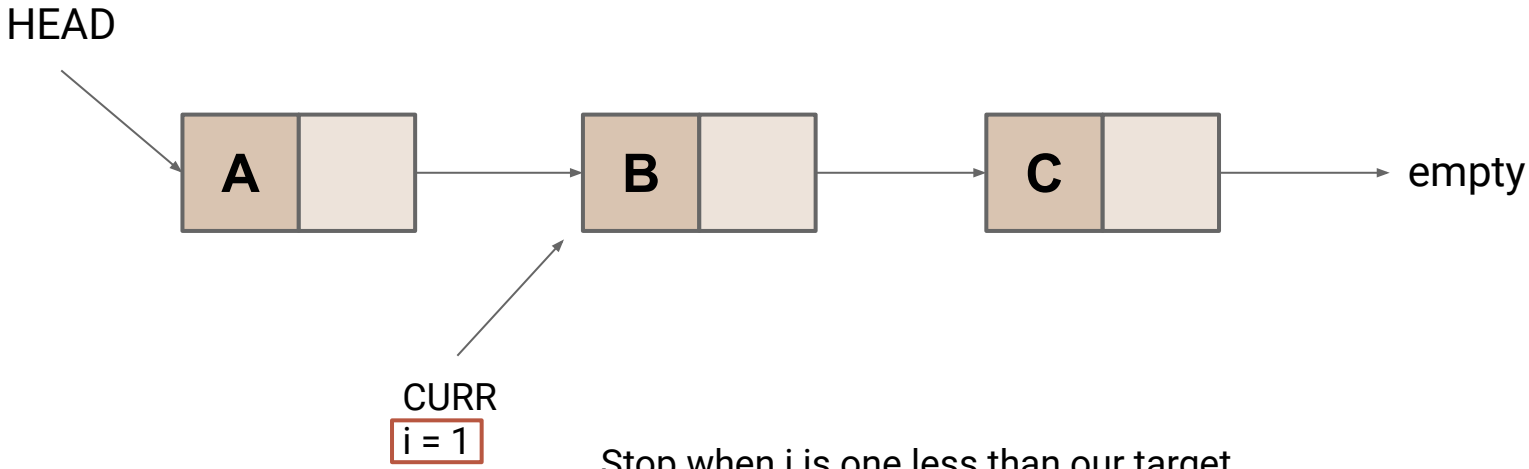
Linked Lists - add(idx, e)

add(2,"D")



Linked Lists - add(idx, e)

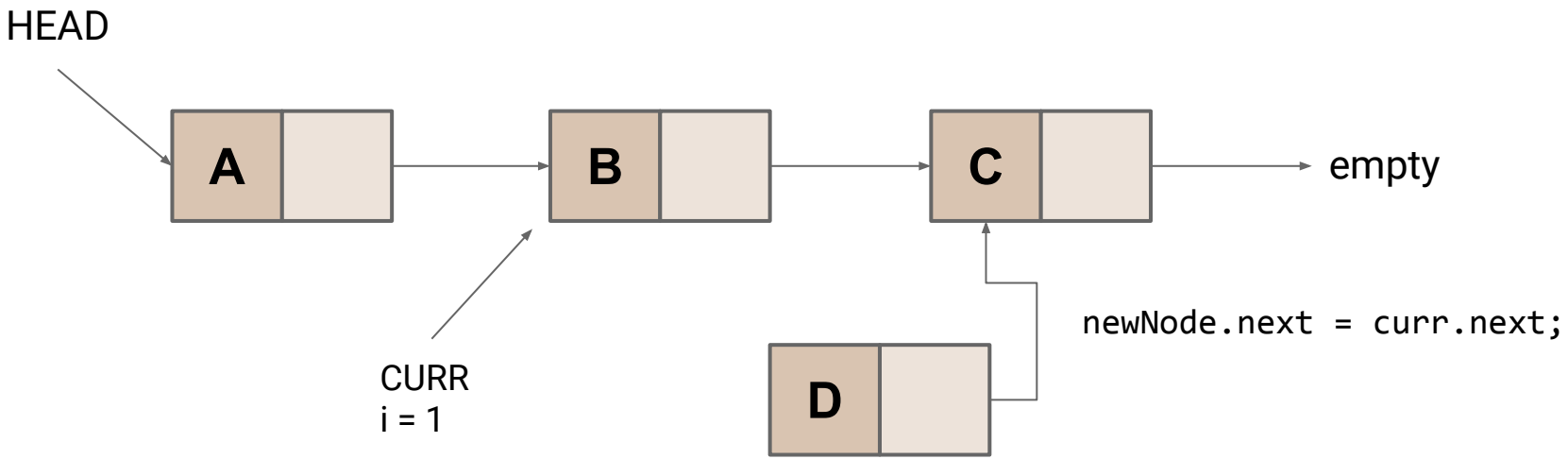
add(2, "D")



Stop when i is one less than our target

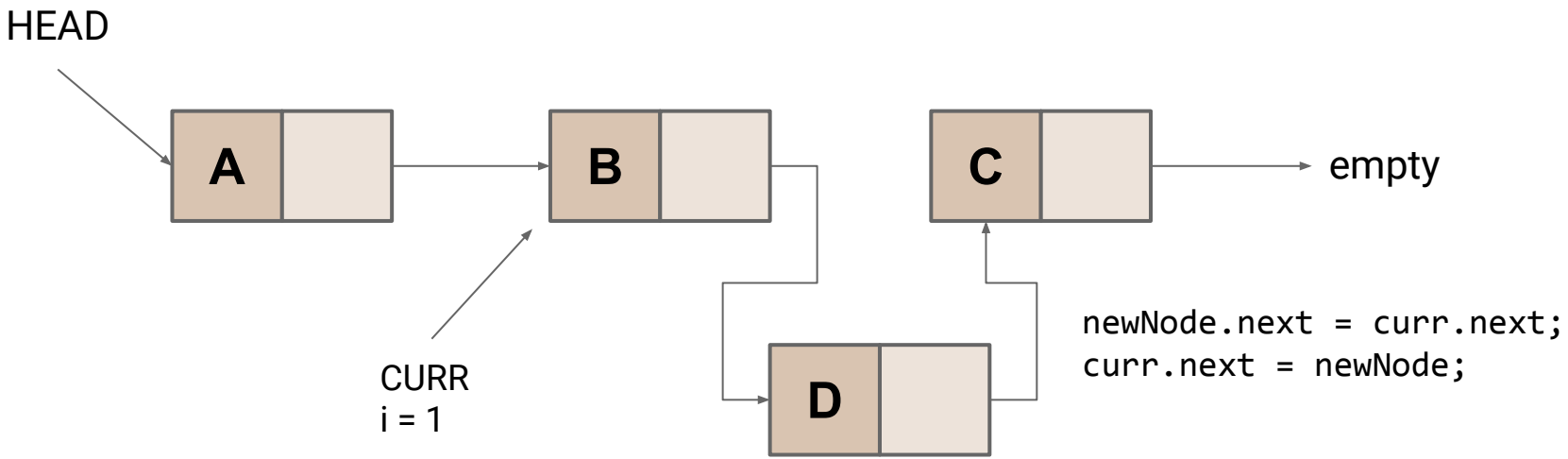
Linked Lists - add(idx, e)

```
add(2,"D")
```



Linked Lists - add(idx, e)

```
add(2,"D")
```



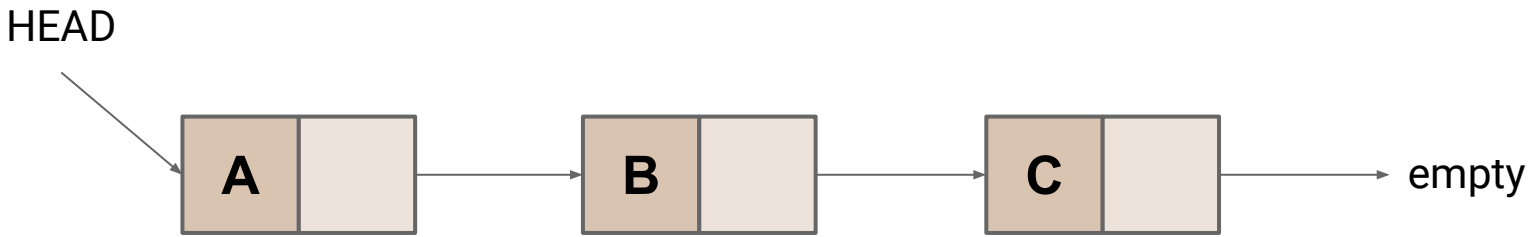
Linked Lists - `add(idx, e)`

1. Find node before **`idx`**: ***O*(*n*)**
2. Allocate a new node and assign its value: ***O*(1)**
3. Set the new nodes **`next`** reference: ***O*(1)**
4. Update the node before **`idx`**'s **`next`** reference: ***O*(1)**

Total: *O*(*n*)

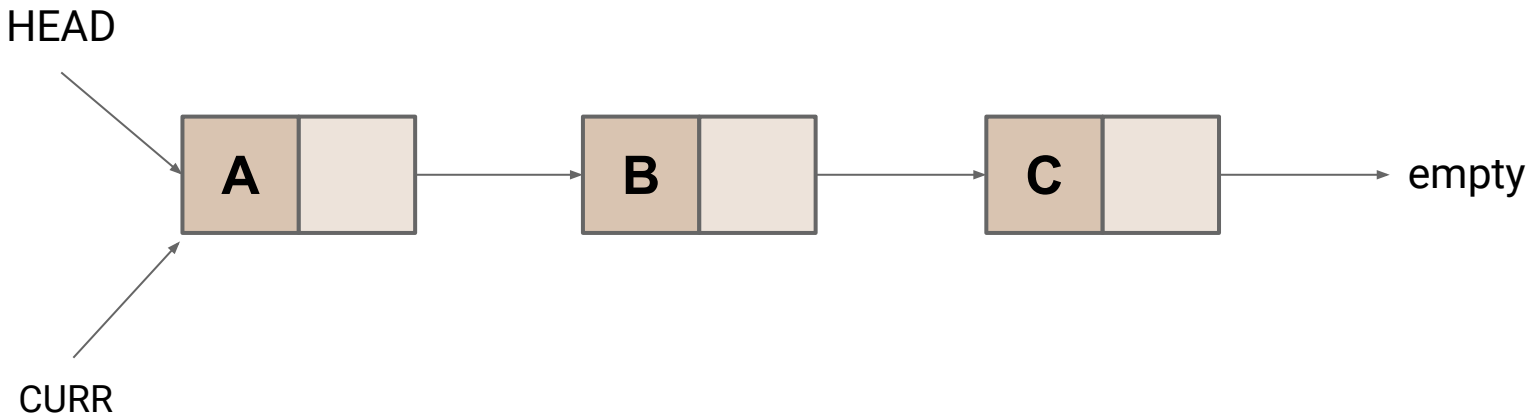
Linked Lists - add(e)

add("Z")

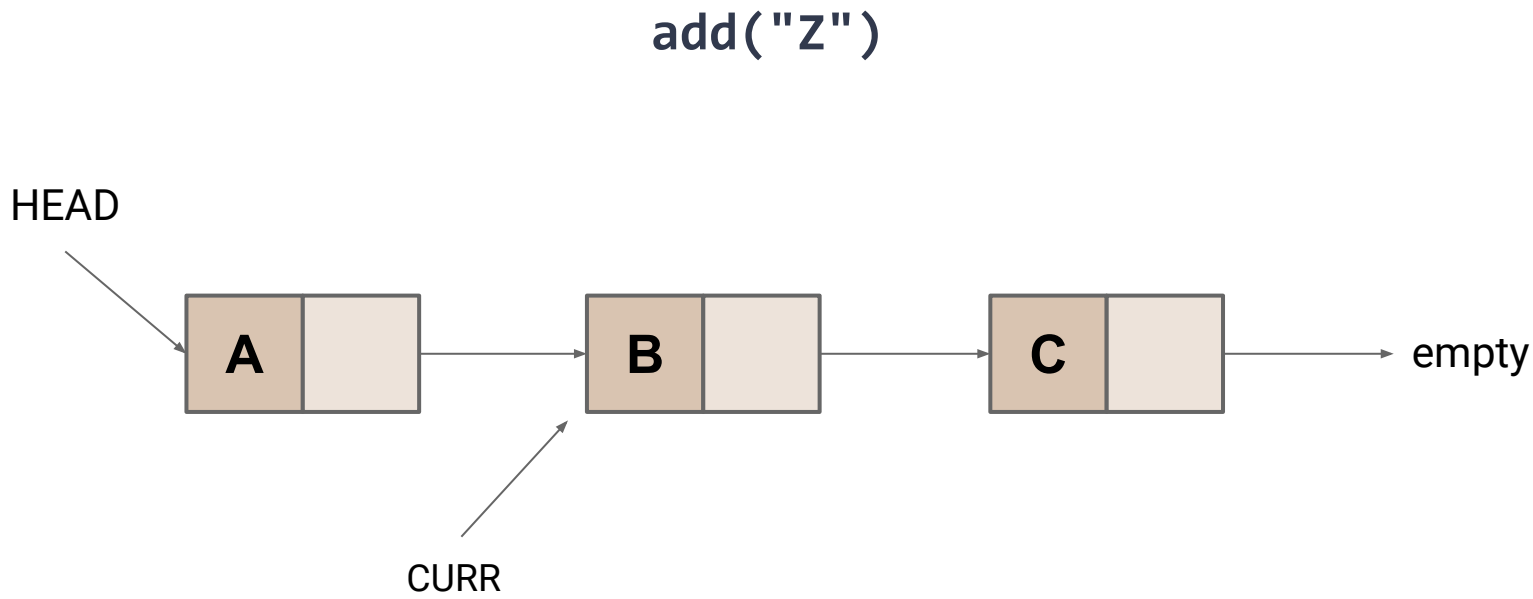


Linked Lists - add(e)

add("Z")

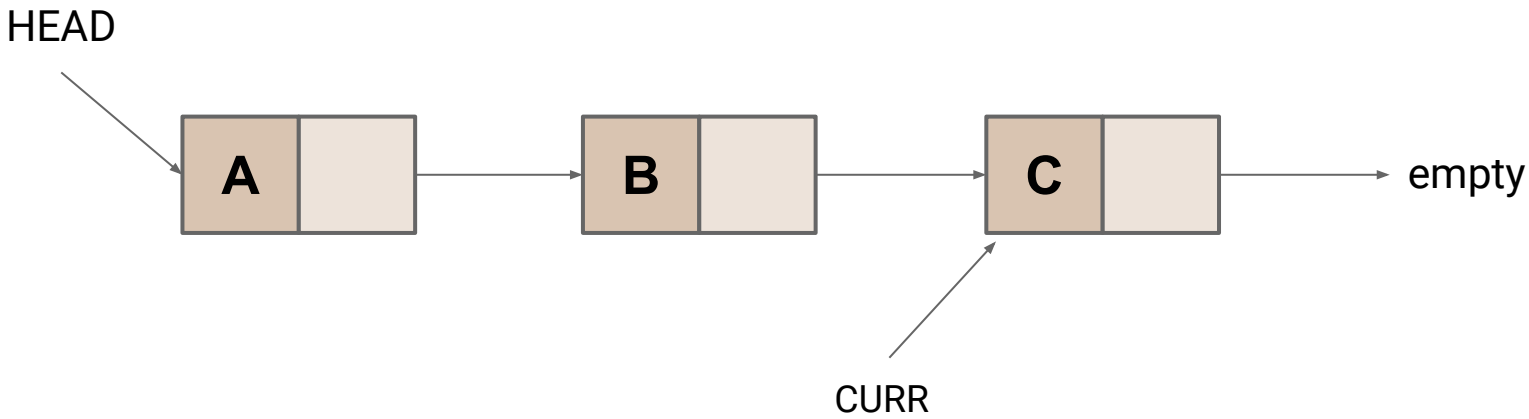


Linked Lists - add(e)

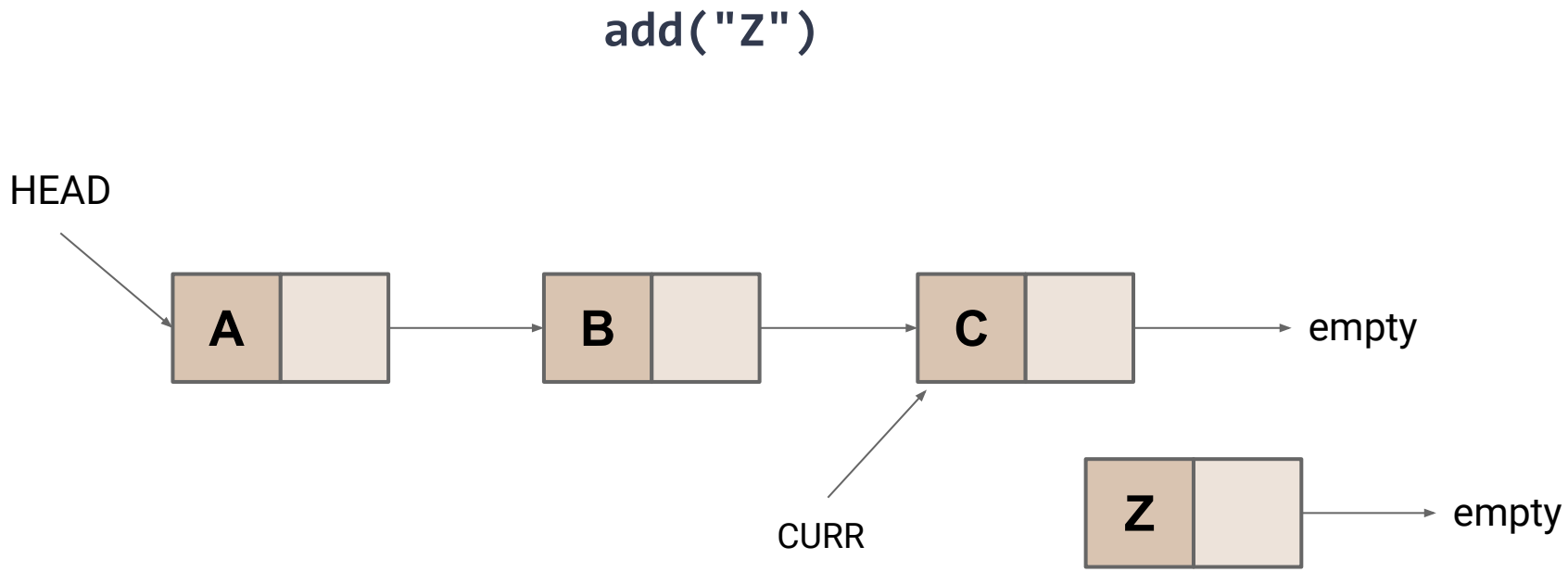


Linked Lists - add(e)

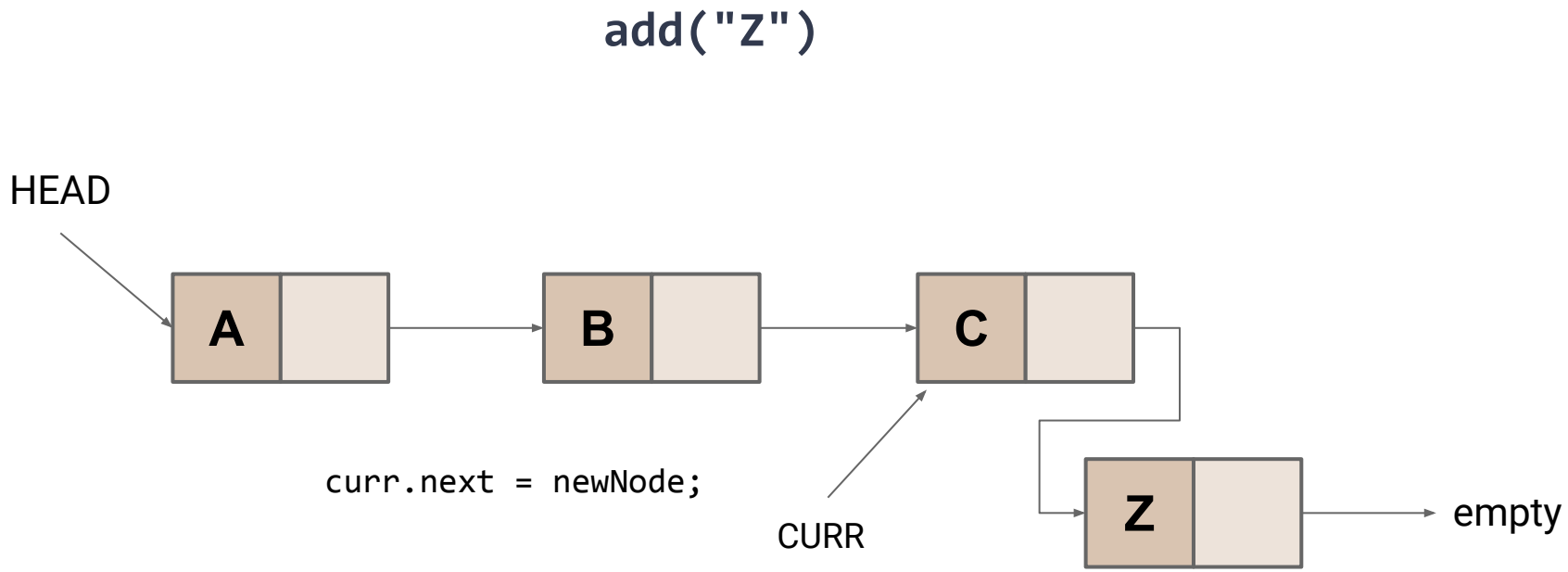
add("Z")



Linked Lists - add(e)



Linked Lists - add(e)

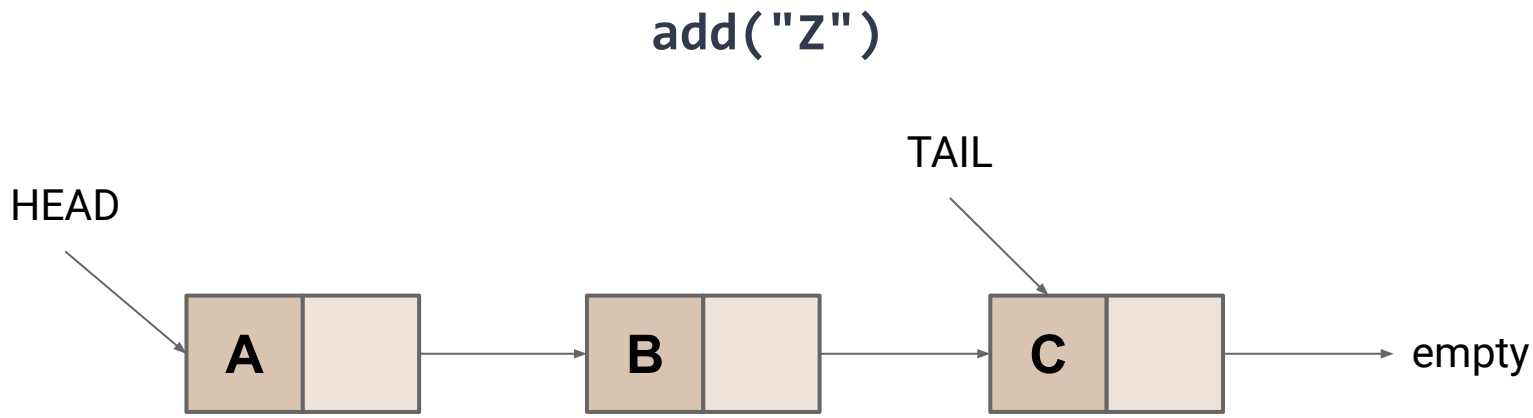


Linked Lists - `add(e)`

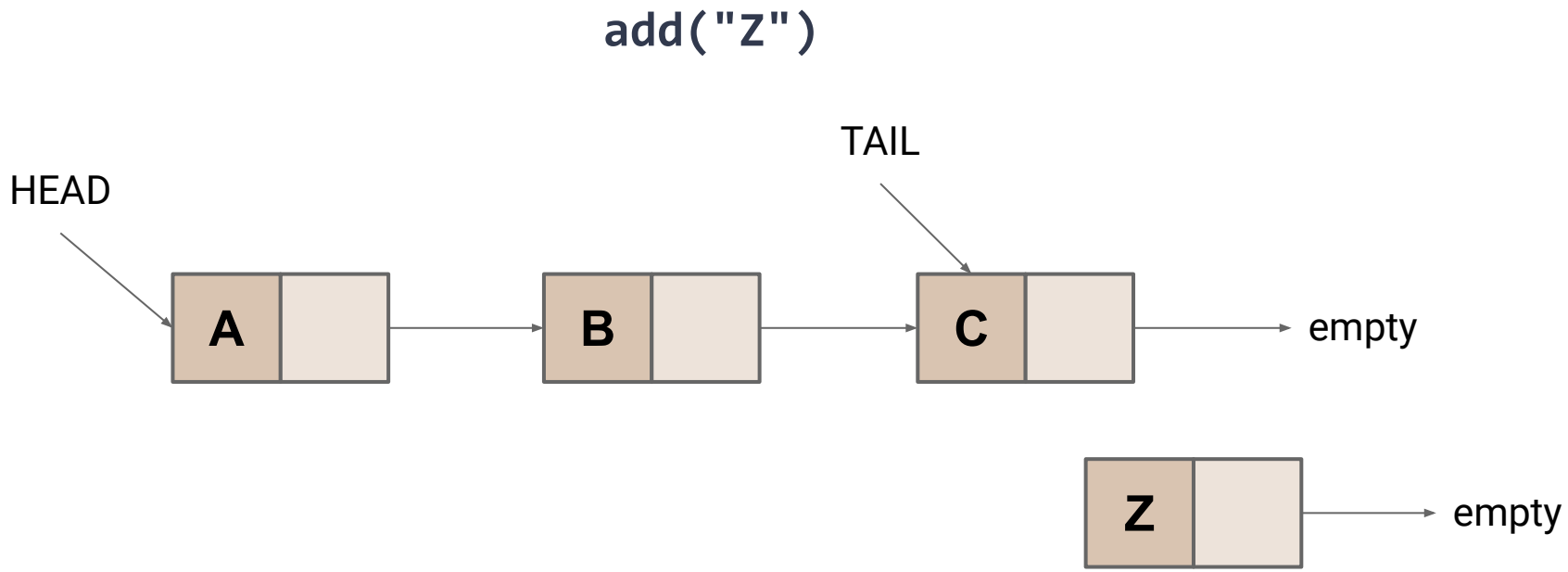
1. Find last node: ***O*(*n*)**
2. Allocate a new node and assign its value: ***O*(1)**
3. Update the last nodes **`next`** reference: ***O*(1)**

Total: *O*(*n*)

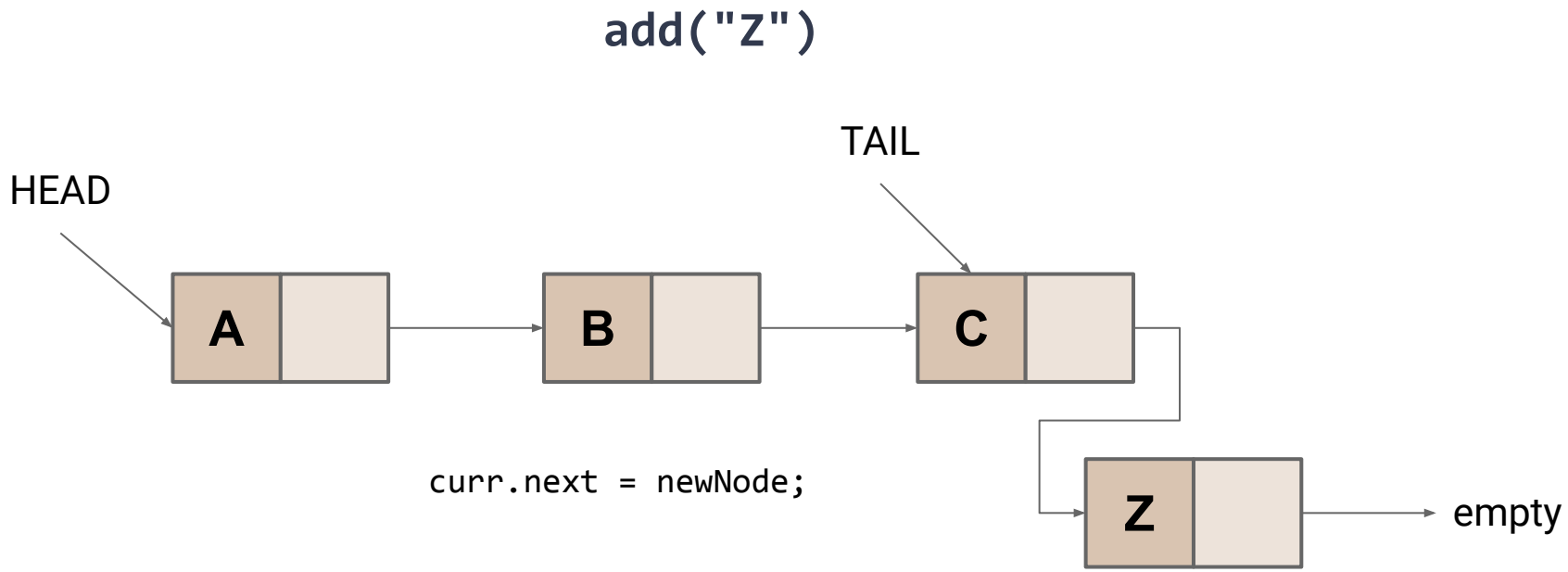
Linked Lists (w/ref to tail) - add(e)



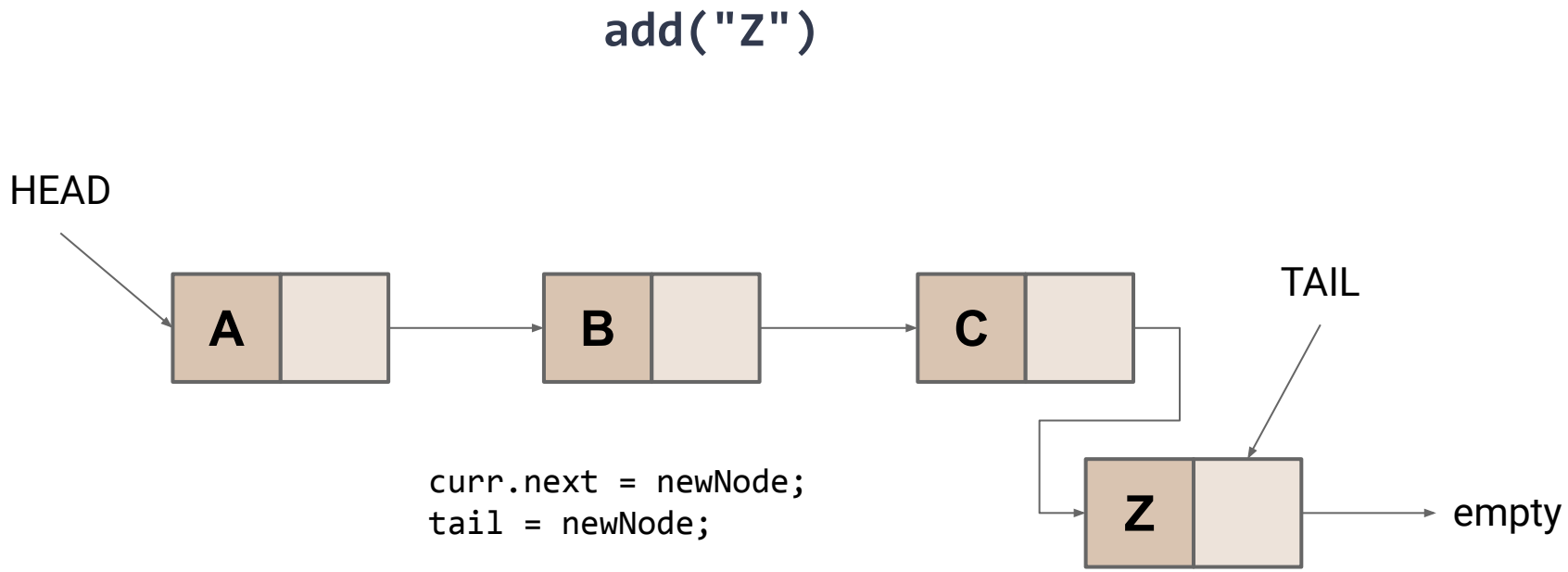
Linked Lists (w/ref to tail) - add(e)



Linked Lists (w/ref to tail) - add(e)



Linked Lists (w/ref to tail) - add(e)



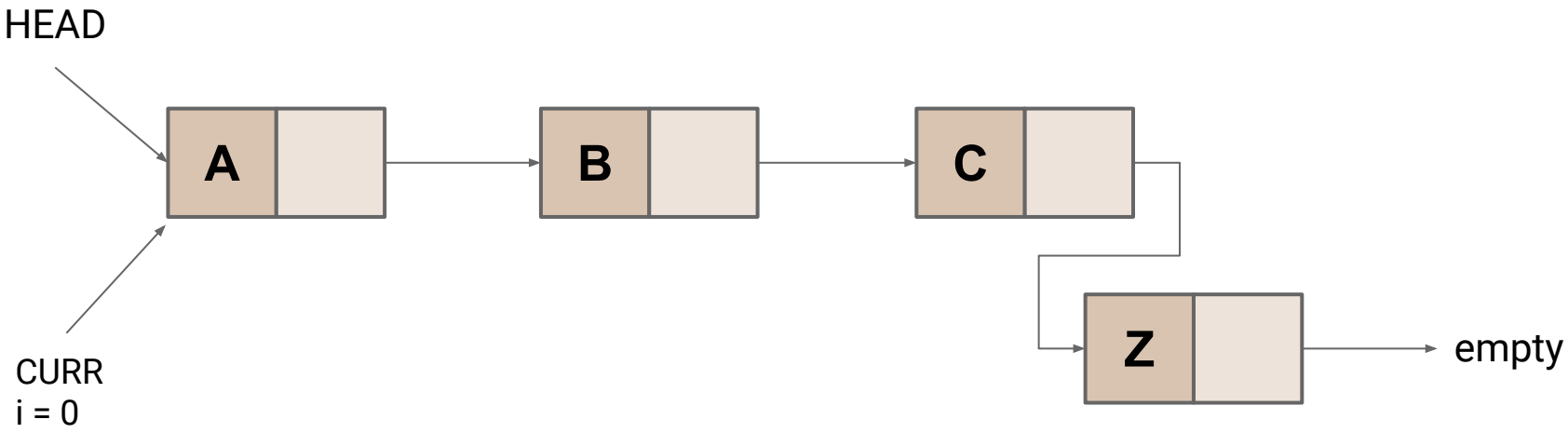
Linked Lists (w/ref to tail) - add(e)

1. Find last node: ***O*(1)**
2. Allocate a new node and assign its value: ***O*(1)**
3. Update the last nodes **`next`** reference: ***O*(1)**

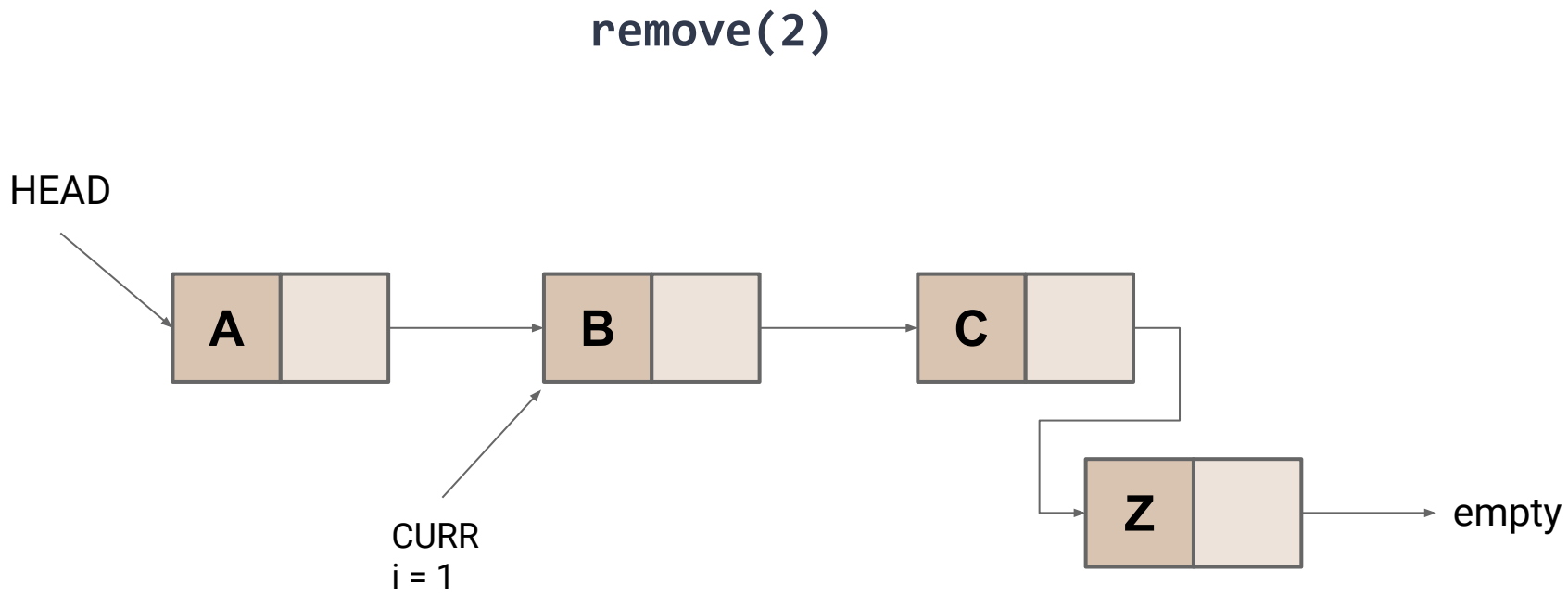
Total: *O*(1)

Linked Lists - `remove(idx)`

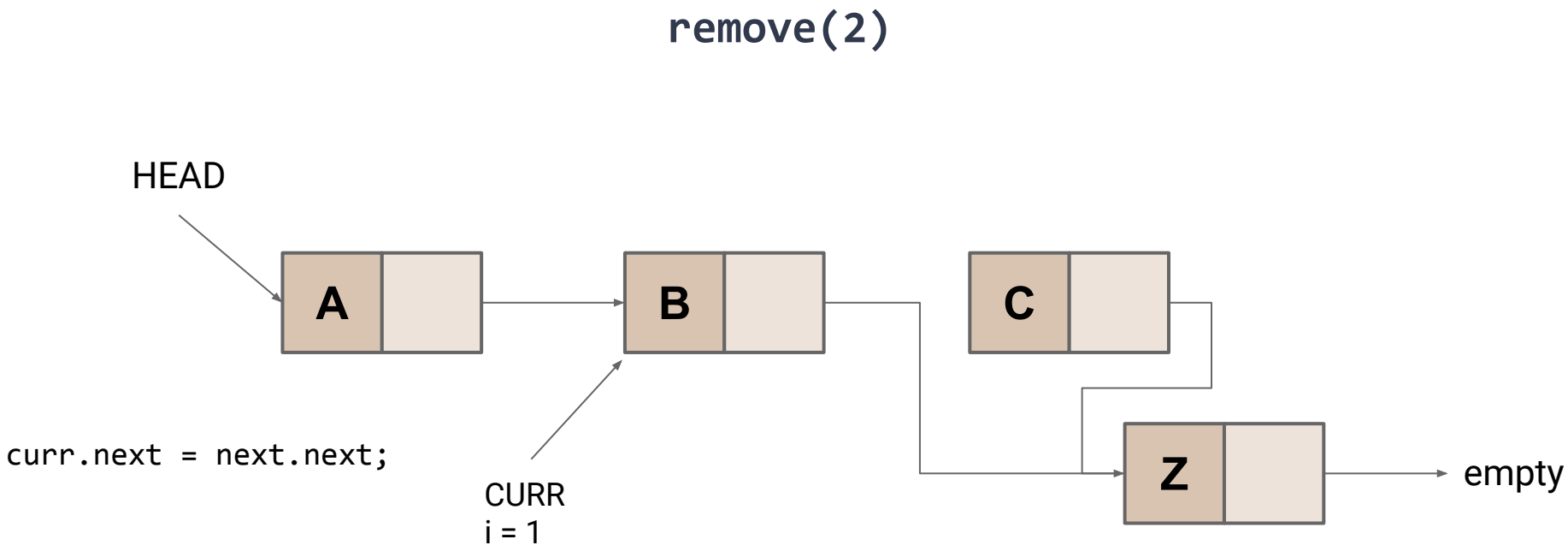
`remove(2)`



Linked Lists - `remove(idx)`



Linked Lists - `remove(idx)`



Linked Lists - `remove(idx)`

1. Find node before **`idx`**: ***O*(*n*)**
2. Update the node before **`idx`**'s **`next`** reference: ***O*(1)**
3. Allow the old node to be reclaimed: ***O*(1)**

Total: *O*(*n*)

Linked Lists

What is the expensive part of all of these operations?

Linked Lists

What is the expensive part of all of these operations?

Iterating to the correct index

Enumeration Example

```
1  int sumList(List<Integer> list){
2    int rslt = 0;
3    for(int i = 0; i < list.length; i++){
4      int temp = list.get(i);
5      rslt += temp;
6    }
7    return rslt;
8  }
```

What is the complexity of this code?

Enumeration Example

```
1  int sumList(List<Integer> list){
2    Θ(1)
3    for(int i = 0; i < list.length; i++){
4      int temp = list.get(i);
5      Θ(1)
6    }
7    Θ(1)
8  }
```

What is the complexity of this code?

Enumeration Example

```
1  int sumList(List<Integer> list){
2    Θ(1)
3    for(int i = 0; i < list.length; i++){
4      int temp = list.get(i);
5      Θ(1)
6    }
7    Θ(1)
8  }
```

What is the complexity of this code?

Enumeration Example

```
1  int sumList(List<Integer> list){
2    Θ(1)
3    for(int i = 0; i < list.length; i++){
4      Θ(n)
5      Θ(1)
6    }
7    Θ(1)
8  }
```

What is the complexity of this code?

Enumeration Example

```
1  int sumList(List<Integer> list){
2    Θ(1)
3    Θ(n^2)
4    Θ(1)
5  }
```

What is the complexity of this code? $\Theta(n^2)$

Enumeration Example

```
1  int sumList(List<Integer> list){
2    Θ(1)
3    Θ(n^2)
4    Θ(1)
5  }
```

What is the complexity of this code? $\Theta(n^2)$

Why is it so expensive?

Enumeration Example

```
1  int sumList(List<Integer> list){
2    Θ(1)
3    Θ(n^2)
4    Θ(1)
5  }
```

What is the complexity of this code? $\Theta(n^2)$

Why is it so expensive? **We start from index 0 every time!**

Enumeration Example #2

```
1  int sumLinkedList(LinkedList<Integer> list){
2    int rslt = 0;
3    Optional<LinkedListNode> n = Optional.ofNullable(list.headNode);
4    while (n.isPresent()){
5      int temp = n.get().value;
6      rslt += temp;
7      n = n.get().next;
8    }
9    return rslt;
10 }
```

Enumeration Example #2

```
1  int sumLinkedList(LinkedList<Integer> list){
2    int rslt = 0;
3    Optional<LinkedListNode> n = Optional.ofNullable(list.headNode);
4    while (n.isPresent()){
5      int temp = n.get().value;
6      rslt += temp;
7      n = n.get().next;
8    }
9    return rslt;
10 }
```

Now this is all constant time

Enumeration Example #2

```
1  int sumLinkedList(LinkedList<Integer> list){
2    Θ(1)
3    while (n.isPresent()){
4      Θ(1)
5    }
6    Θ(1)
7  }
```

Enumeration Example #2

```
1  int sumLinkedList(LinkedList<Integer> list){
2    Θ(1)
3    Θ(n)
4    Θ(1)
5  }
```

Total complexity: $\Theta(n)$

Enumeration

Problem:

- This code is specialized for `LinkedList`
- It will not work for other types of `List` (ie `ArrayList`)

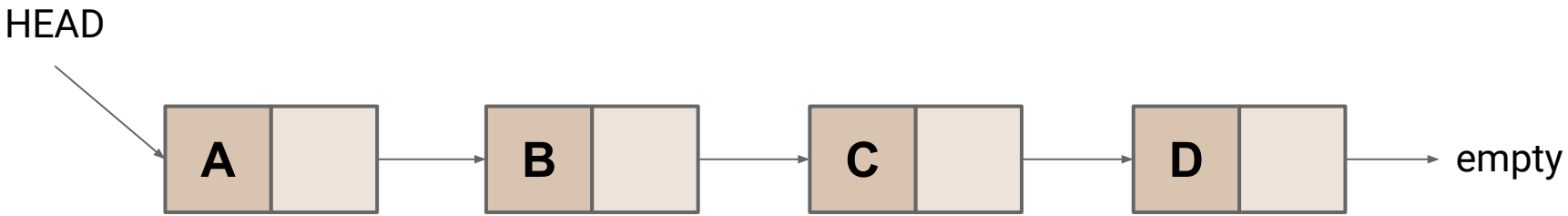
How can we get code that is both fast and general?

- Must be able to represent a reference to the `idx`'th element of a `List`

ListIterator

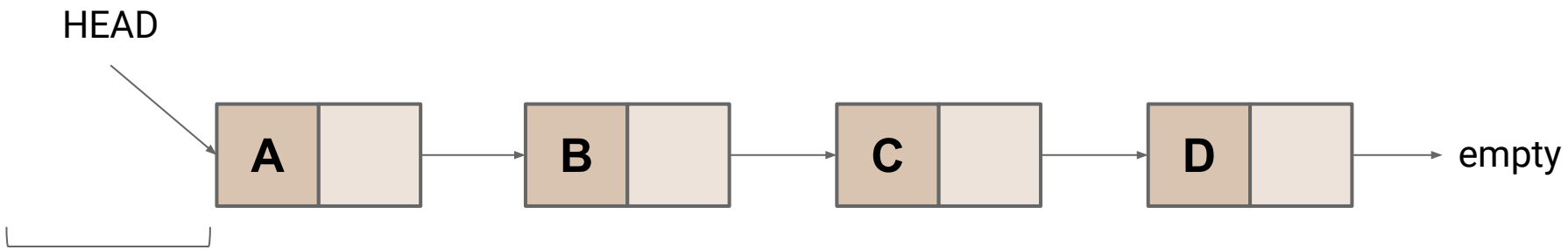
```
1  public interface ListIterator<E> {
2    public boolean hasNext();
3    public E next();
4    public void add(E value);
5    public void set(E value);
6    public void remove();
7  }
```

Linked List Iterator



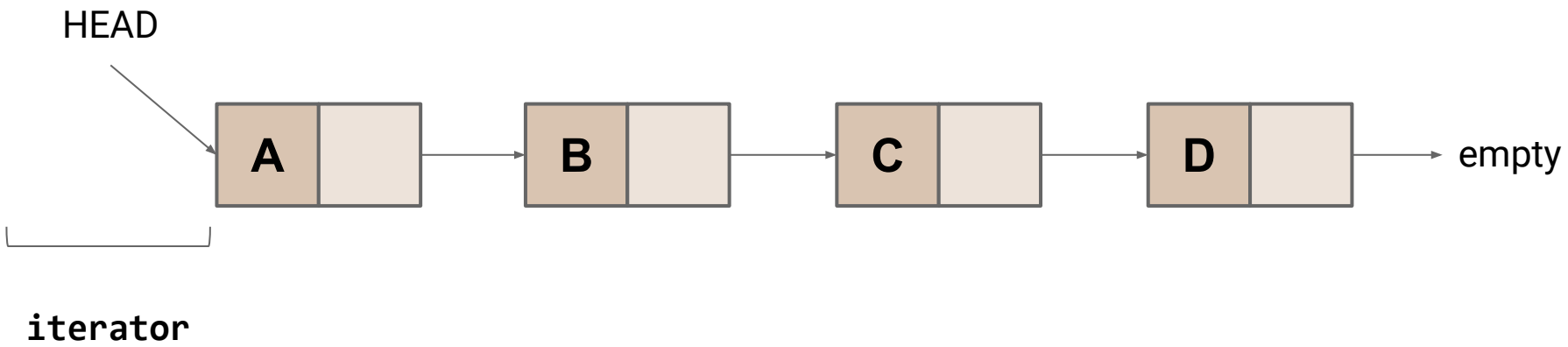
Linked List Iterator

```
iterator = list.iterator()
```



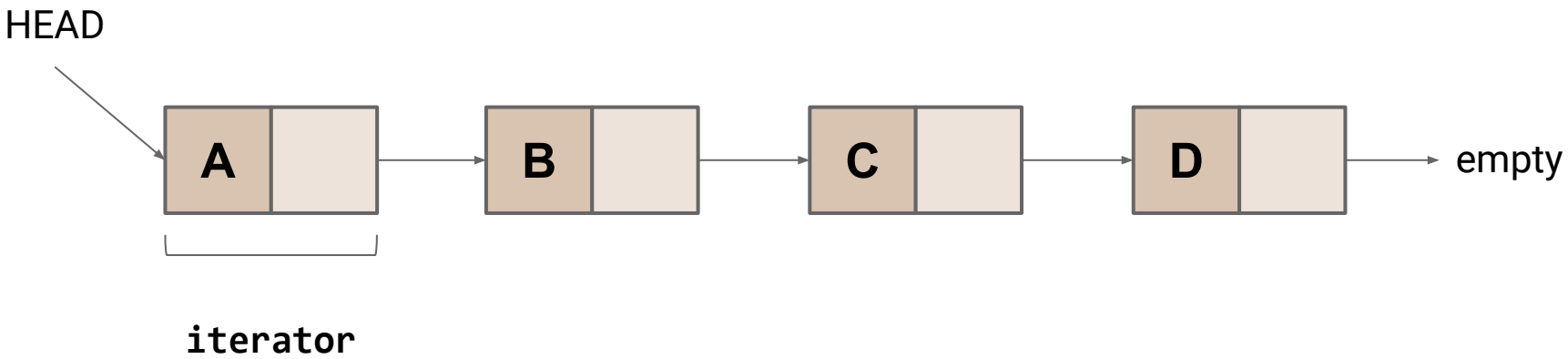
Linked List Iterator

`iterator.hasNext() → true`



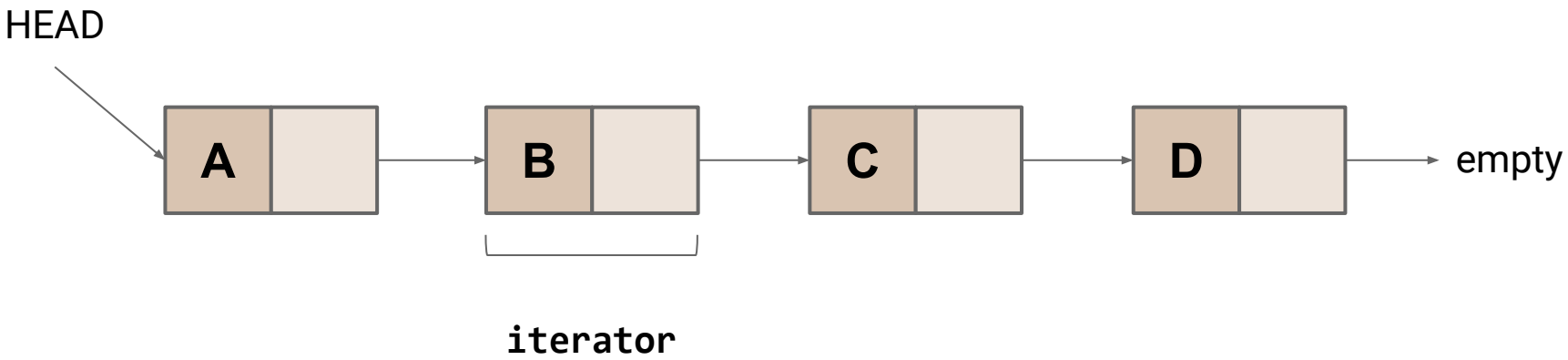
Linked List Iterator

`iterator.next() → A`



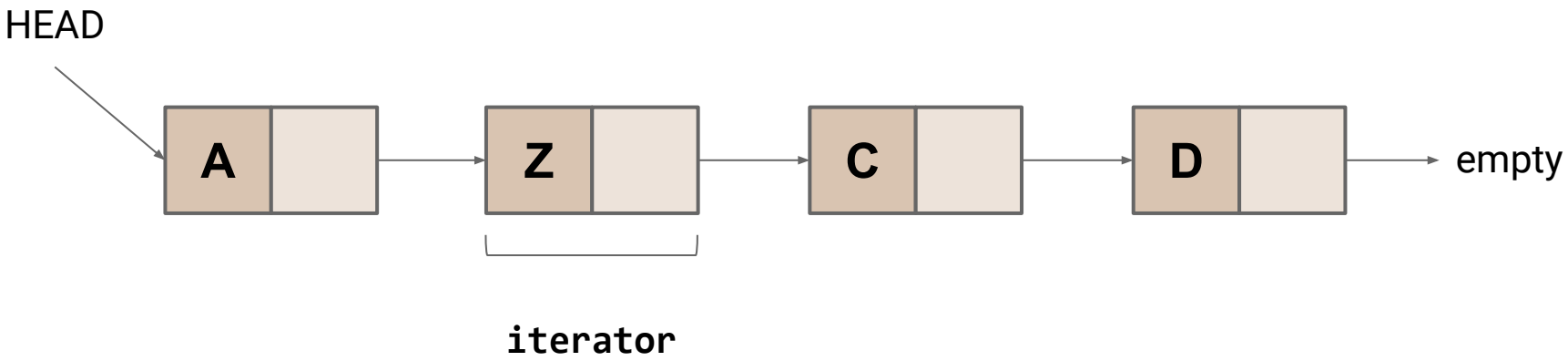
Linked List Iterator

`iterator.next() → B`



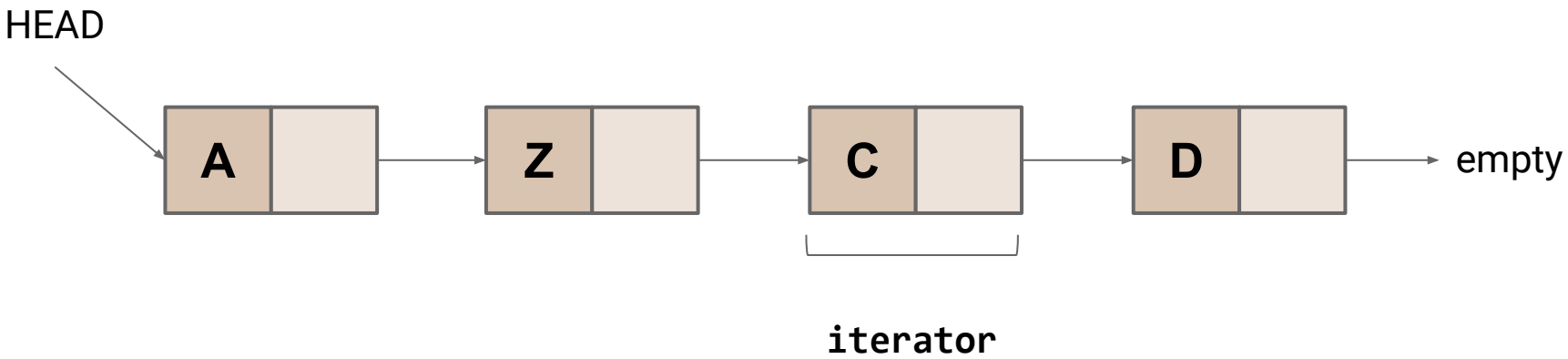
Linked List Iterator

```
iterator.set(Z)
```



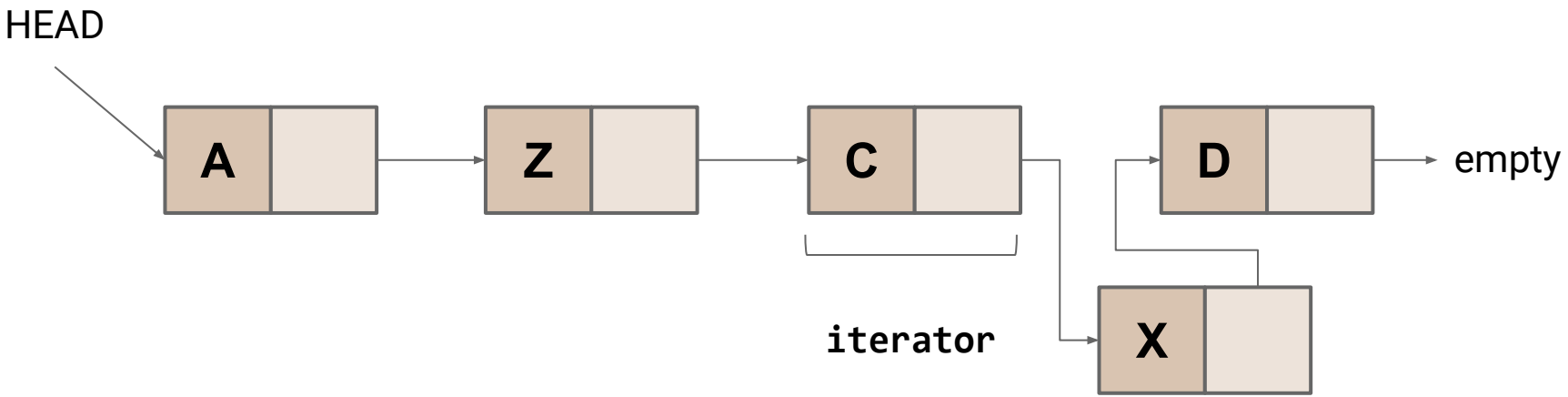
Linked List Iterator

`iterator.next()` → `C`



Linked List Iterator

`iterator.add(X)`



Linked List Iterator

```
1 public class LinkedListIterator<E>
2   extends ListIterator<E> {
3   LinkedList<E> list;
4   Optional<LinkedListNode<E>> before = Optional.empty();
5   Optional<LinkedListNode<E>> after = Optional.of(list.head);
6   /* ... */
7 }
```

Linked List Iterator

`boolean hasNext()`

If **`after.isPresent()`**, return true — $O(1)$

`T next()`

If **`after.isPresent()`**, advance **`before`** and **`after`**, and return the value of **`before`** — $O(1)$

`void set(T value)`

Update **`before.value`** — $O(1)$

Linked List Iterator

`void add(T value)`

Create a new node, update it's **`next`** and **`before.next`** ***O*(1)**

`void remove(T value)`

Set **`before.next`** to **`after.next`** and update **`after`** ***O*(1)**

Enumeration using ListIterator

```
1 public void int sumUpList(List<Integer> list) {
2   int total = 0;
3   ListIterator<Integer> iterator = list.iterator();
4   while(iterator.hasNext()) {
5     int value = iterator.next();
6     total += value;
7   }
8   return total;
9 }
```

Enumeration using ListIterator

```
1  public void int sumUpList(List<Integer> list) {
2    int total = 0;
3    ListIterator<Integer> iterator = list.iterator();
4    while(iterator.hasNext()) {
5      int value = iterator.next();
6      total += value;
7    }
8    return total;
9  }
```

Generalized to work with any kind of list!

Enumeration using ListIterator

```
1  public void int sumUpList(List<Integer> list) {
2    int total = 0;
3    ListIterator<Integer> iterator = list.iterator();
4    while(iterator.hasNext()) {
5      int value = iterator.next();
6      total += value;
7    }
8    return total;
9  }
```

Loop body only contains $\Theta(1)$ operations

Enumeration using ListIterator

```
1  public void int sumUpList(List<Integer> list) {
2    int total = 0;
3    ListIterator<Integer> iterator = list.iterator();
4    while(iterator.hasNext()) {
5      int value = iterator.next();
6      total += value;
7    }
8    return total;
9  }
```

Total Complexity: $\Theta(n)$

ArrayLists

Question: How can we implement **`add(e)`** on an **`ArrayList`**?

ArrayLists

Question: How can we implement **`add(e)`** on an **`ArrayList`**?

Problem: Arrays have a fixed size!

ArrayLists - Attempt #1

1. Allocate a new array of size $N + 1$ $O(1)$
2. Copy all N elements to the new array $O(n)$
3. Insert the new item at position N $O(1)$

Total: $O(n)$

ArrayLists - Attempt #1

1. Allocate a new array of size $N + 1$ $O(1)$
2. Copy all N elements to the new array $O(n)$
3. Insert the new item at position N $O(1)$

Total: $O(n)$

Can we do better? next class…