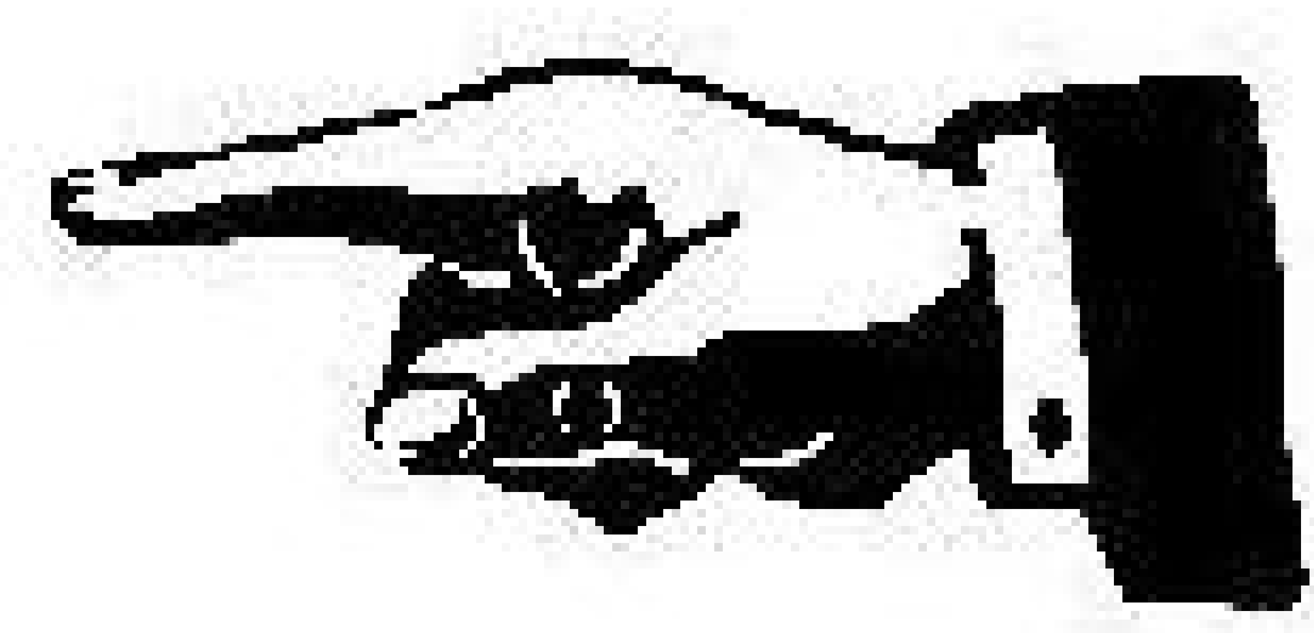
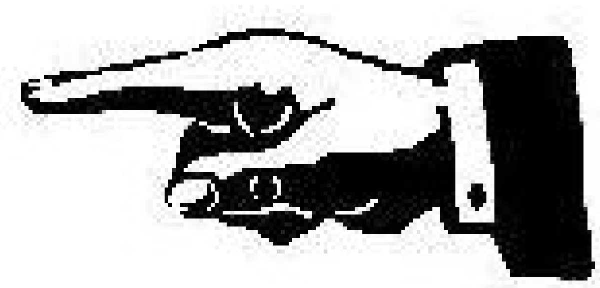
# Lesson 8: *Point to where you are going: links*



*Linked lists*

# Outline

1. **References**
2. Singly Linked List
3. Stacks and Queues
4. Doubly Linked List
5. Using Linked Lists
6. Skip Lists



# Non-Contiguous Data

- So far we have considered arrays where the data is stored in a contiguous chunk of memory
- This has the great advantage of allowing random access
- It has the disadvantage that it is expensive to add or remove data from the middle of the list or to rearrange the data
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- There are a lot of important data structures using non-contiguous memory
  - ⋆ Binary trees
  - ⋆ Graphs
- In this lecture we consider **linked-lists**
- This is a classic data structure
- However, it serves as a good introduction to much more useful data structures

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# Self-Referential Classes

- The building block for a linked list is a node class

```
struct Node<T>
{
  Node(U value, Node<U> *node): value(value), next(node) {}
  T element;
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}
```

- We create new nodes
  `Node<int> *node = new Node<int>(10, pt_to_next)`
- Note that `node` is the address of this node
- I make it a `struct` as this is a class where I want public access to the element and next
- I can make this class a private class of my linked list

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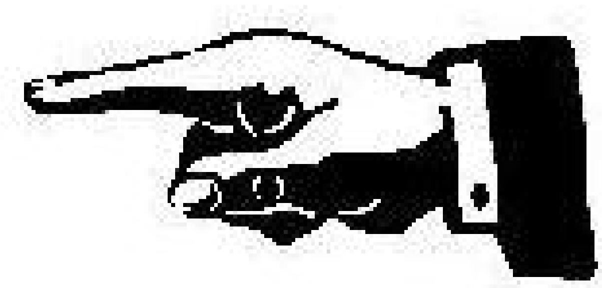
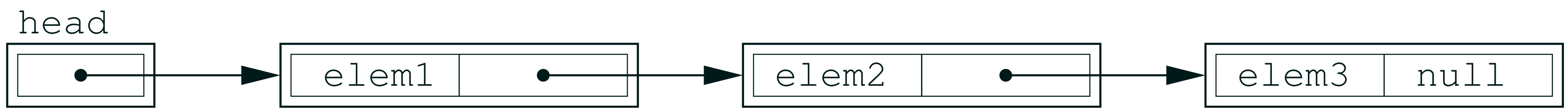


# Singly Linked List

- We can build a linked list by stringing nodes together




We don't show the "pointer" to `element`

- A singly linked list has a single "pointer" to the next element
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- We should be able to create a linked list, add elements, remove elements, see if an element exists, etc.

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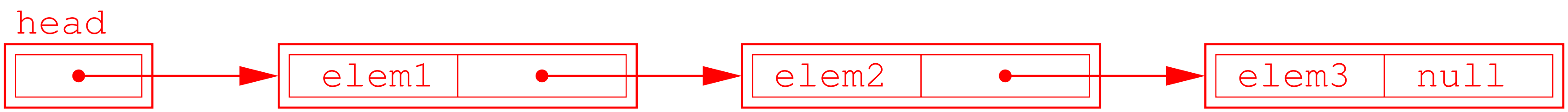


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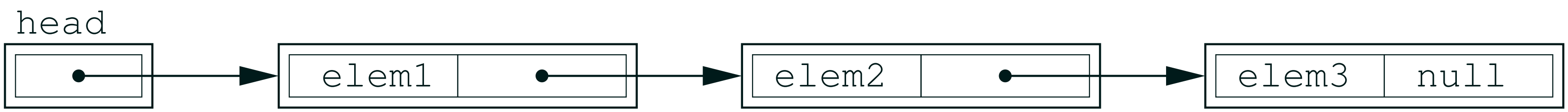


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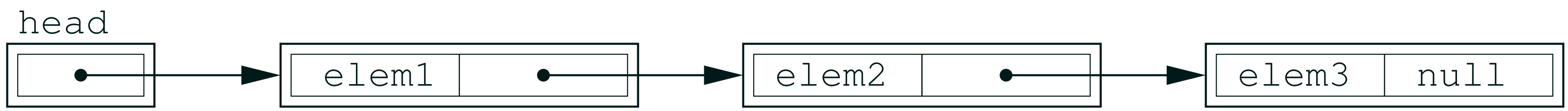


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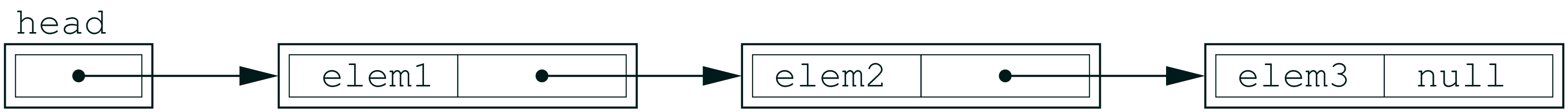


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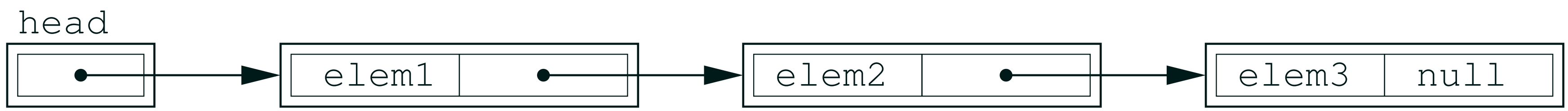


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# Implementation

- We consider a lightweight implementation
- The class will have a head, a size counter and have a `Node` as a nested class

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class MyList {
private:
  template <typename U>
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# Simple Methods

- The constructor is simple (and not strictly necessary)

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- Other simple methods are

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unsigned size() const {return noElements;}

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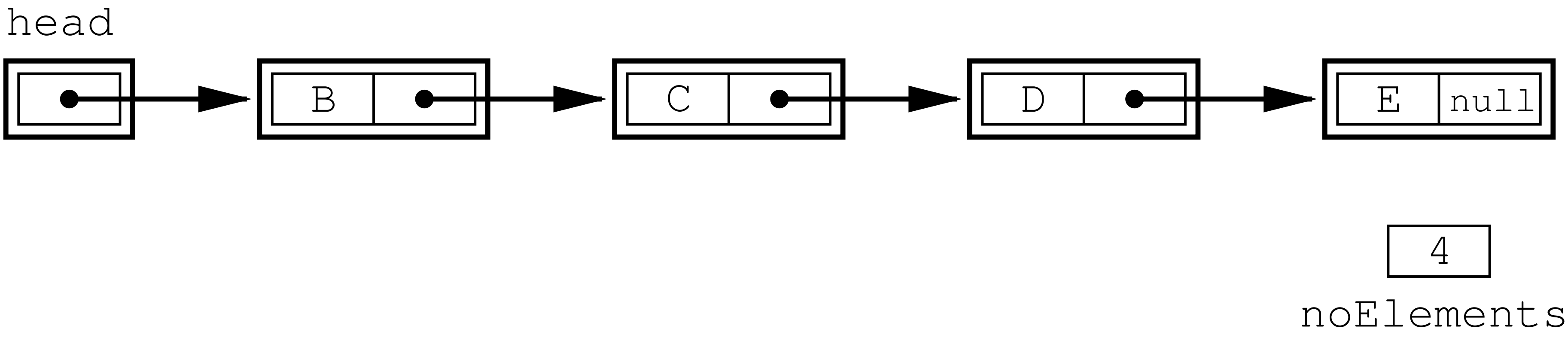

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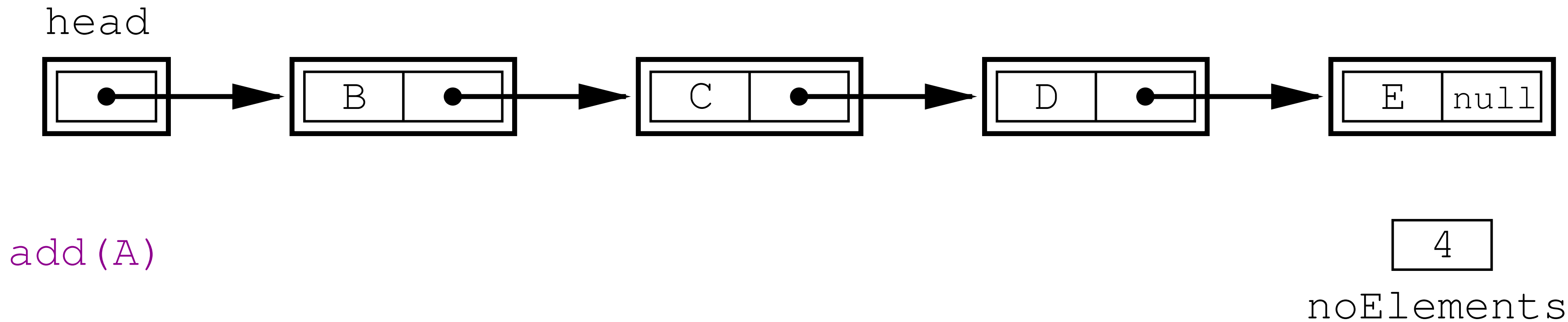

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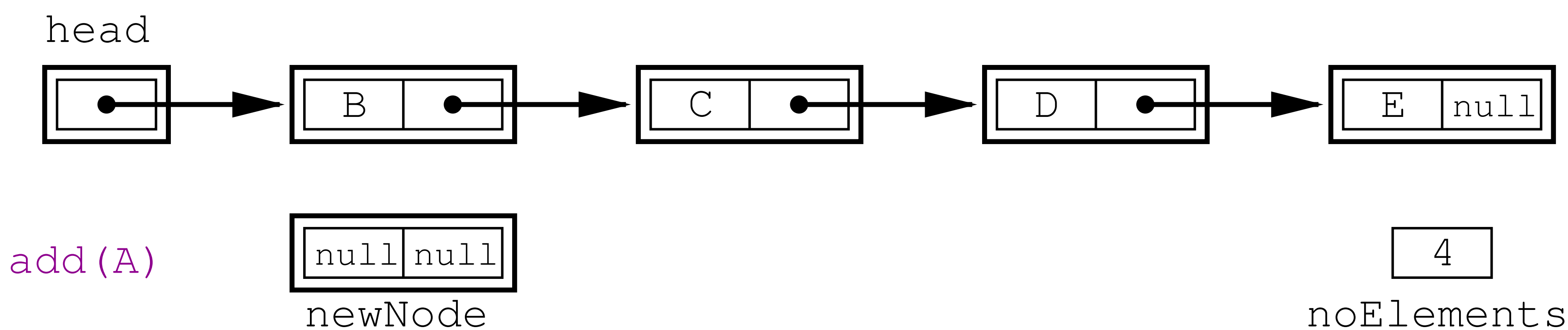

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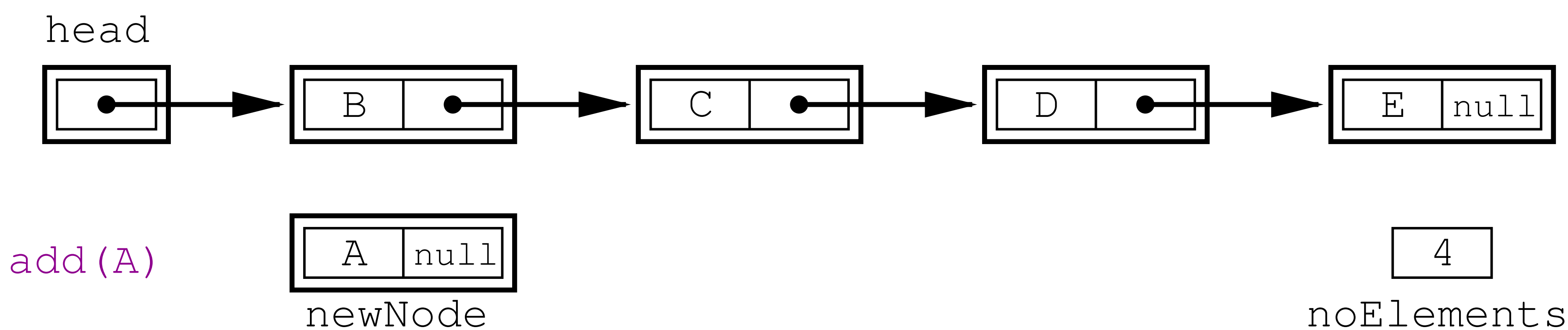

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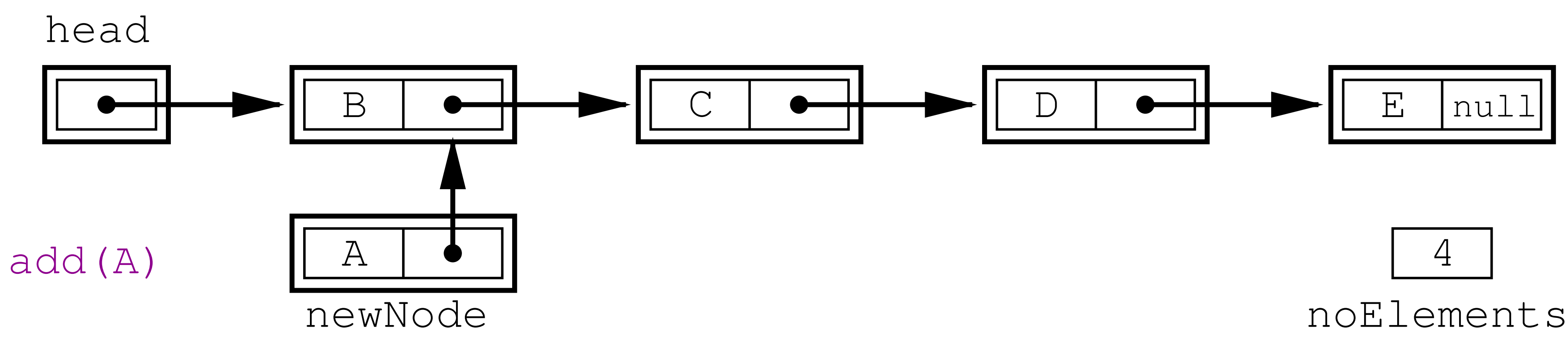

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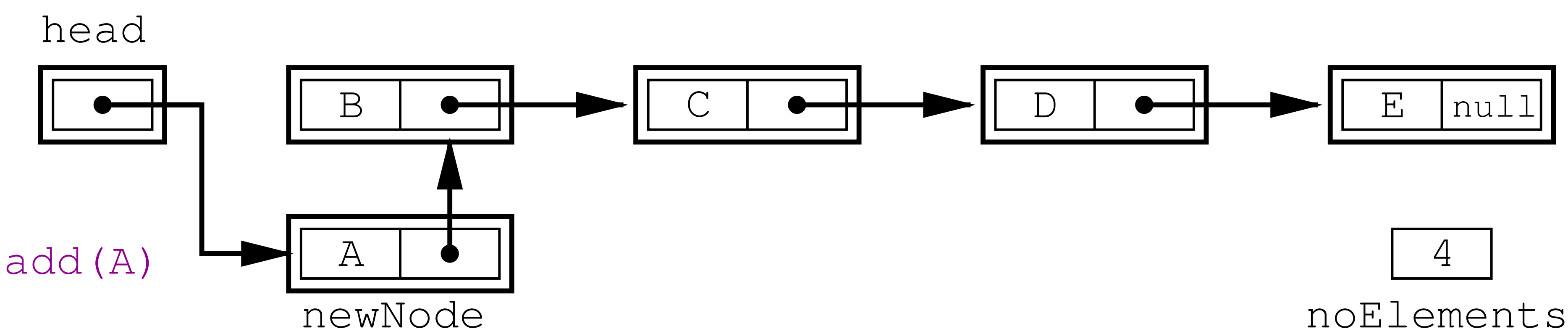

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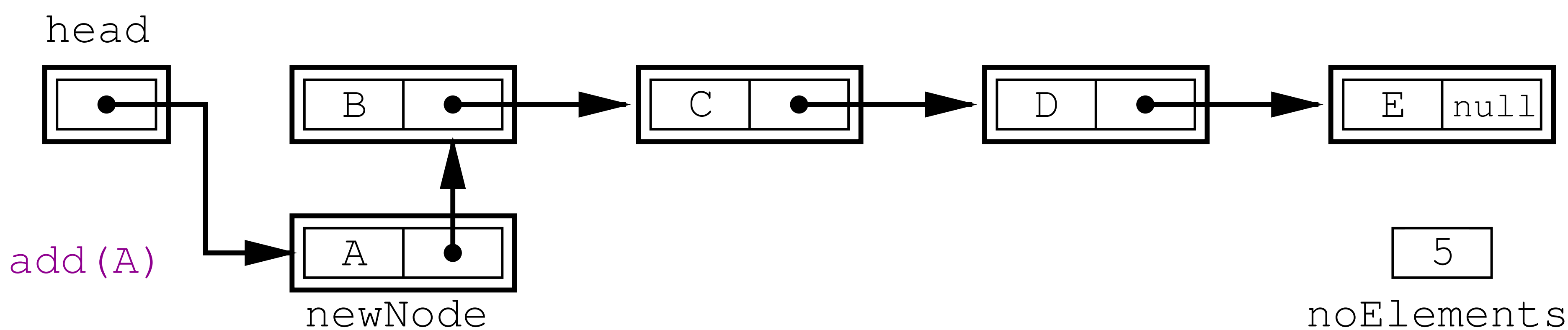

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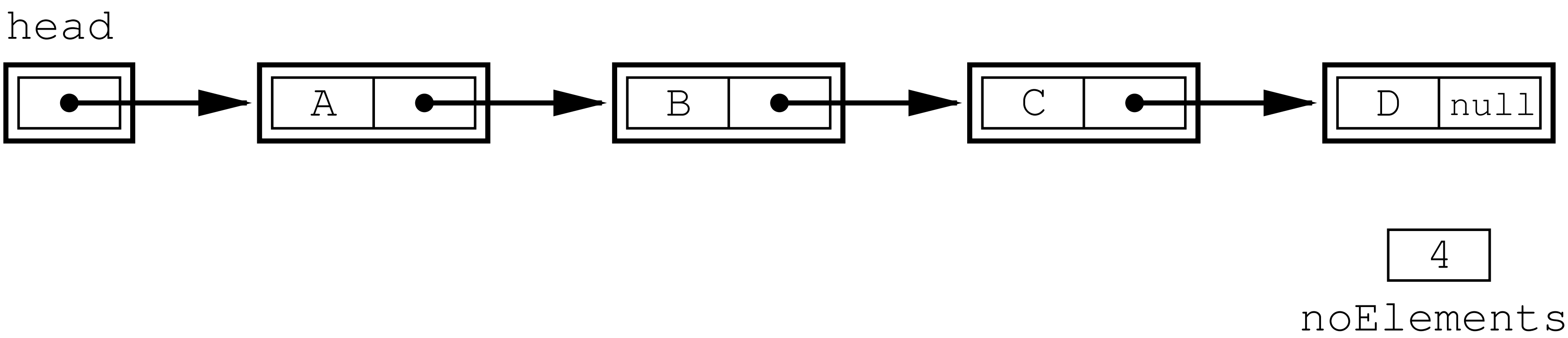

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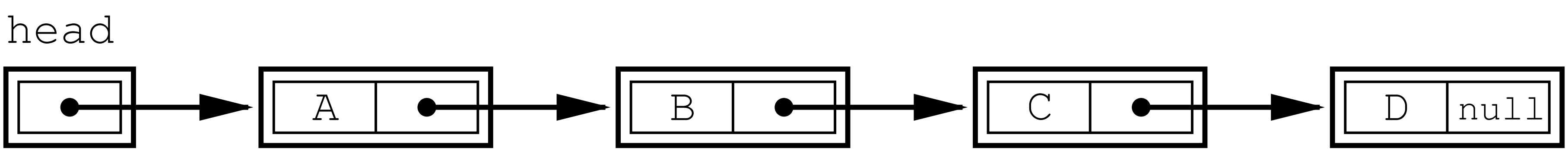


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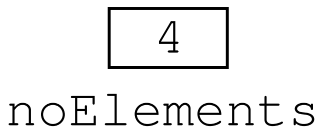

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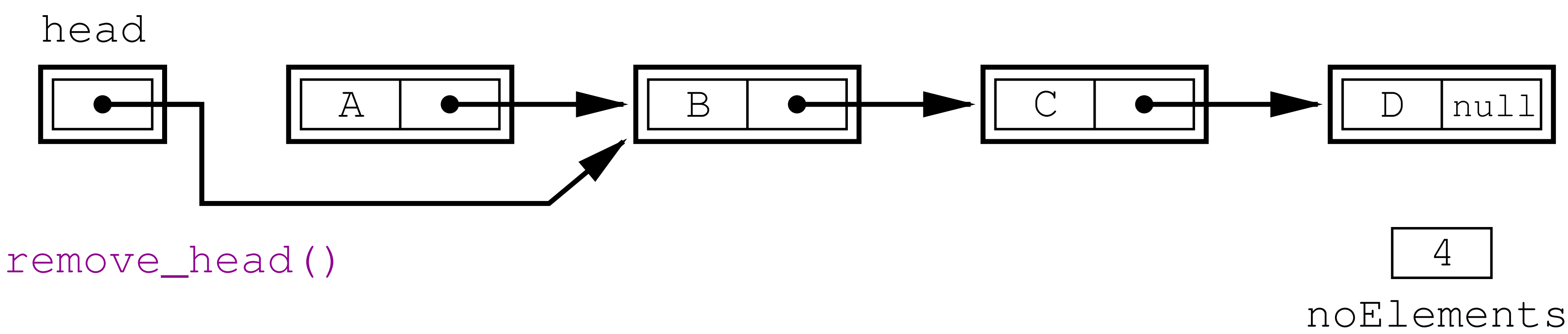

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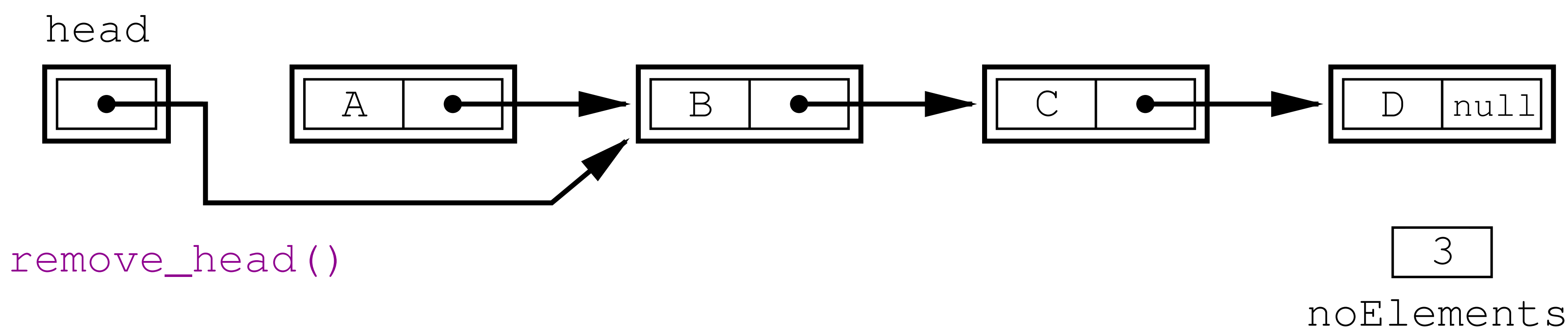

# Other Methods

- We can easily implement many other methods
  - `get(int i)`—return $i^{th}$ item in list
  - `remove(T obj)`-remove `obj` from list
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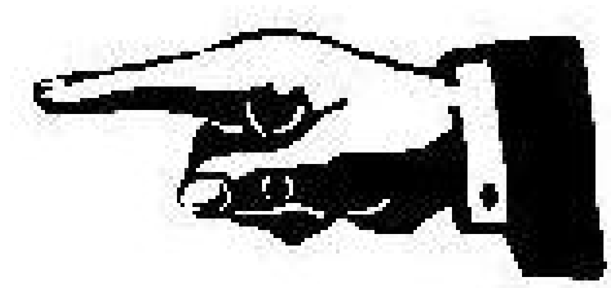

# Stack

- It is easy to implement a stack using a linked list

```
template <typename T>
class Stack<E>
{
  private Mylist<T> list = new mylist<T>();

  boolean push(E obj) {list.add(obj);}

  E top() {return list.get_head();} // throw exception

  E pop() {
    T tmp = list.get_head();
    list.remove_head();
    return tmp;
  }

  boolean empty() {return list.empty();}
}
```

# Complexity of Stack

- All operations of the stack is constant time, i.e. $O(1)$
- This is the same time complexity as an array implementation
- Memory requirement is approximately $2 \times n$ reference and $n$ objects—same as worst case for an array
- However, hidden cost of creating and destroying `Node` objects
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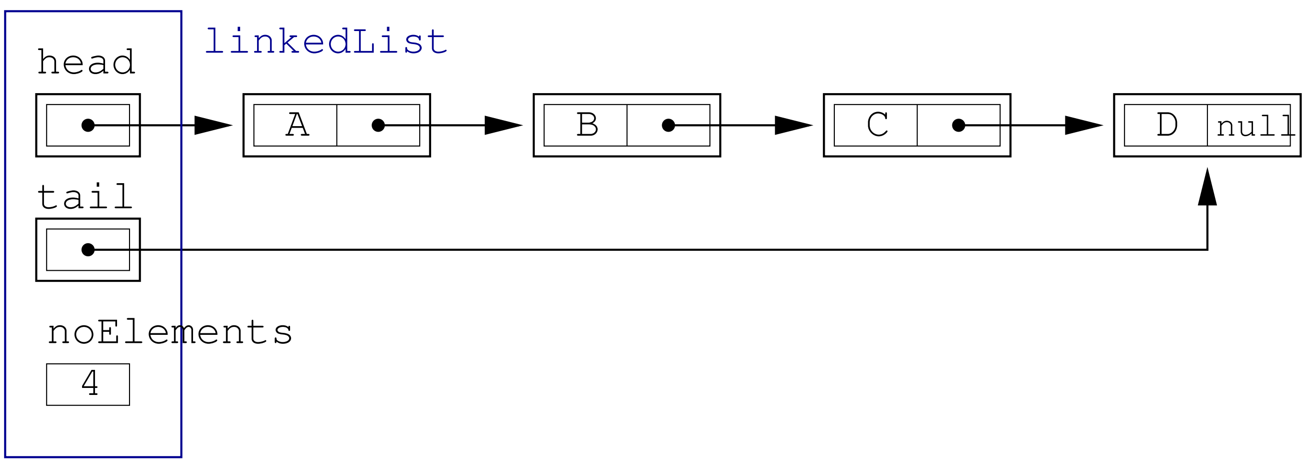
- Thus our linked list isn't the right data structure to implement a queue
- However, we could include a pointer to the end of the queue



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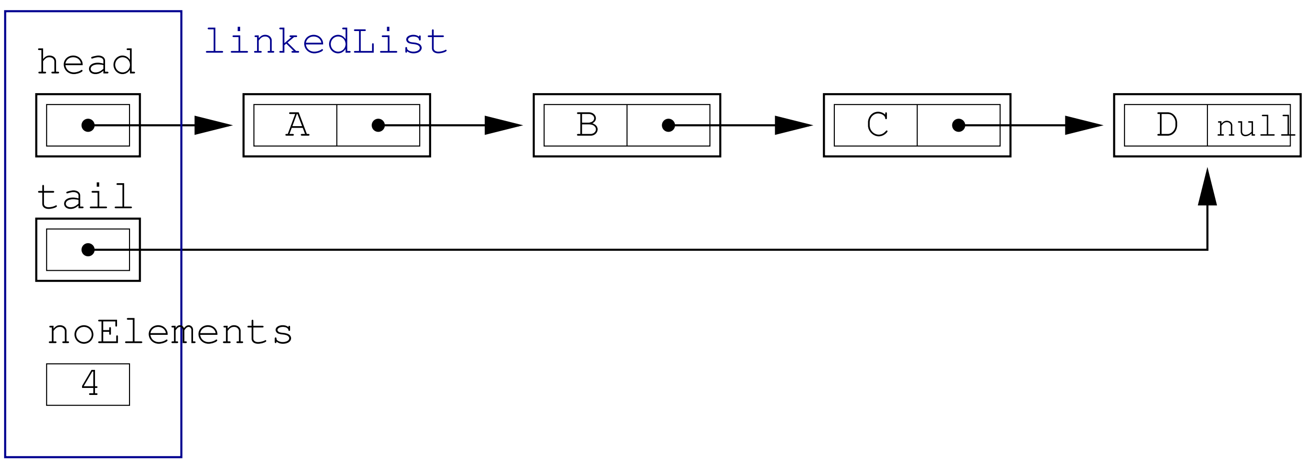

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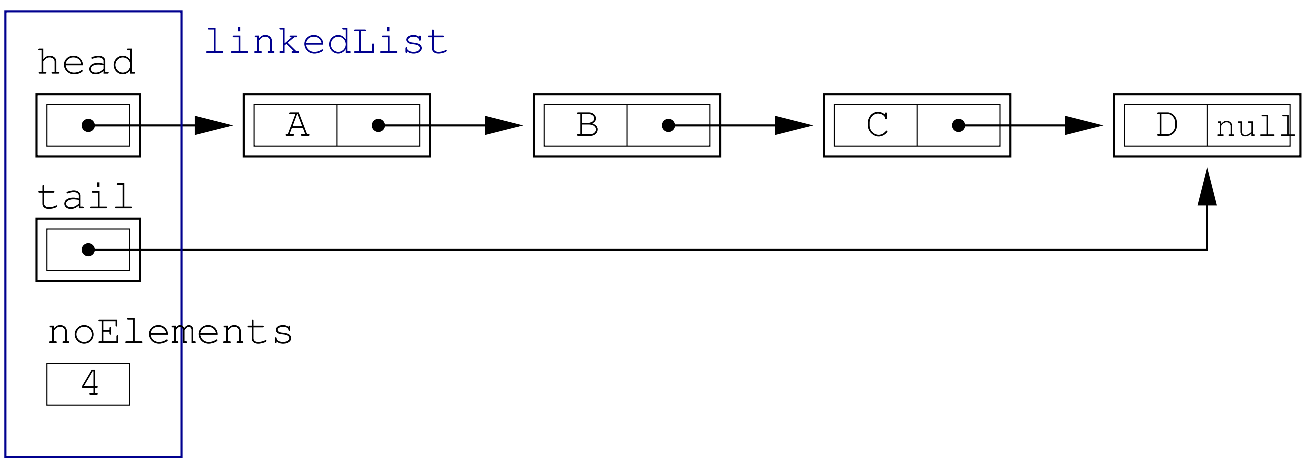

# Implementing a Queue

- We can then add elements to the tail in constant time
- We can the implement a queue in $O(1)$ time by
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- I leave the implementation details as an exercise for you
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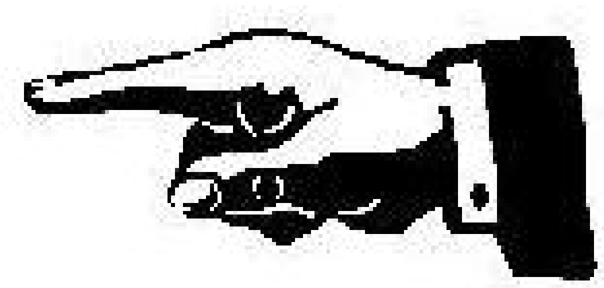
- We can the implement a queue in $O(1)$ time by
  - `enqueue`ing at the back
  - `dequeue`ing at the head
- I leave the implementation details as an exercise for you
- Note that although adding an element to the tail is constant time, removing an element from the tail is $O(n)$ as we have to find the new tail

# Outline

1. References
2. Singly Linked List
3. Stacks and Queues
4. **Doubly Linked List**
5. Using Linked Lists
6. Skip Lists



# Doubly linked list

- In a more powerful linked list we would like to navigate the list in either direction
- To achieve this it uses a doubly-linked lists with elements to next and previous

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  T element;
  Node<T> *next;
  Node<T> *previous;
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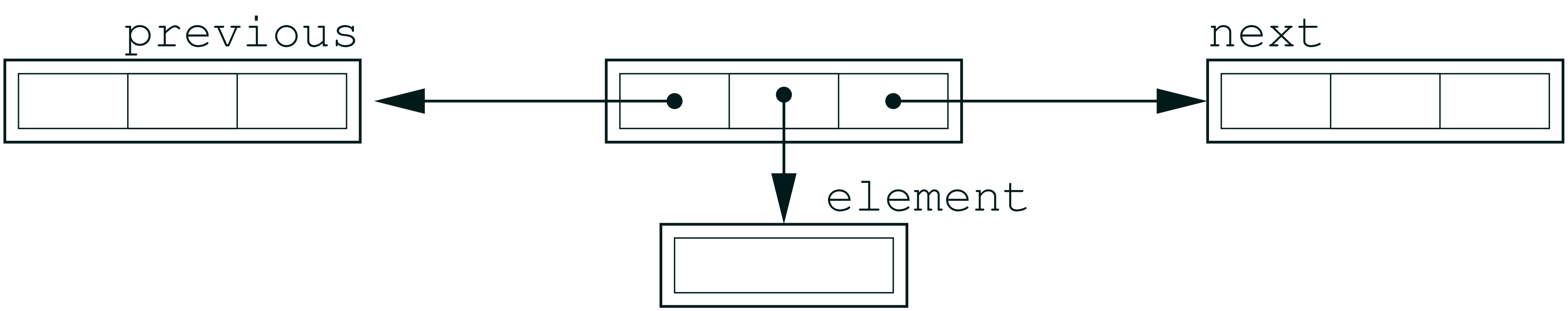

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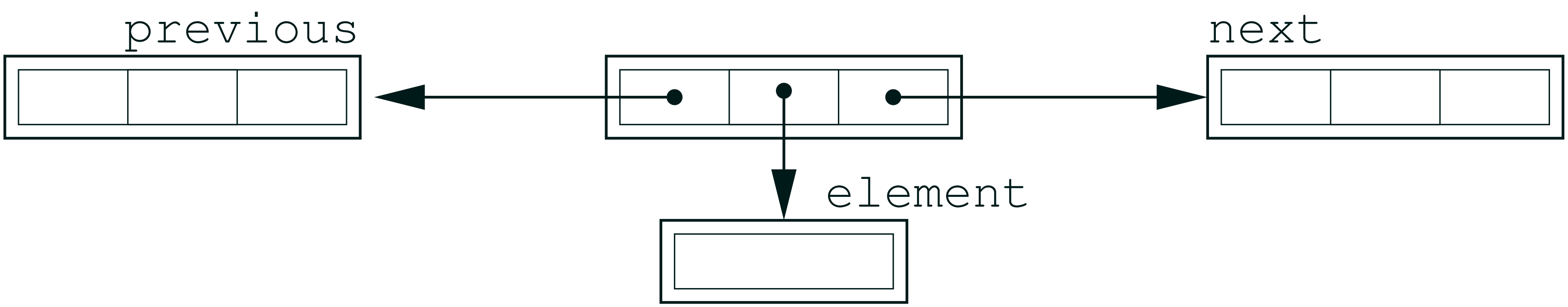

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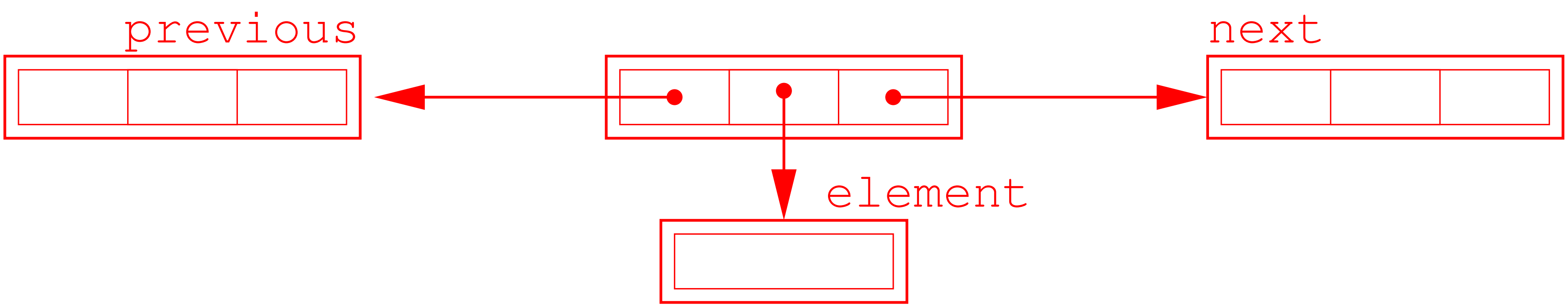

# Dummy Node

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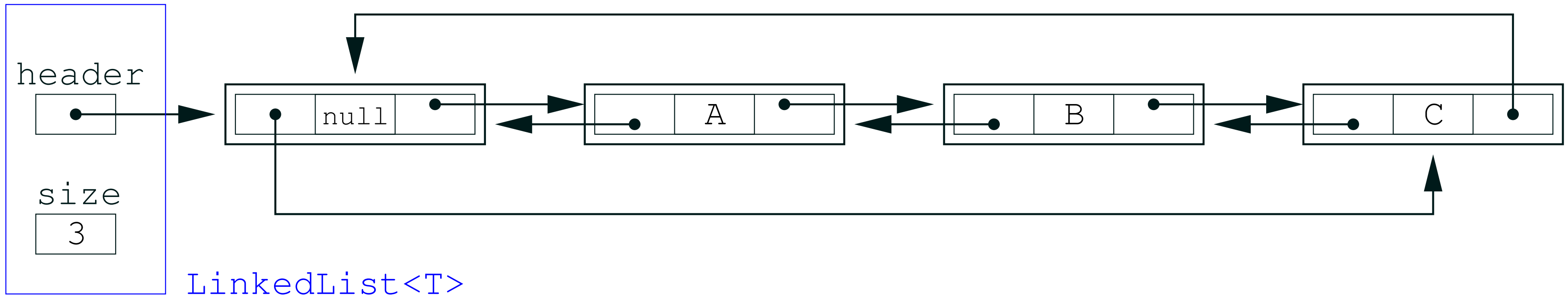


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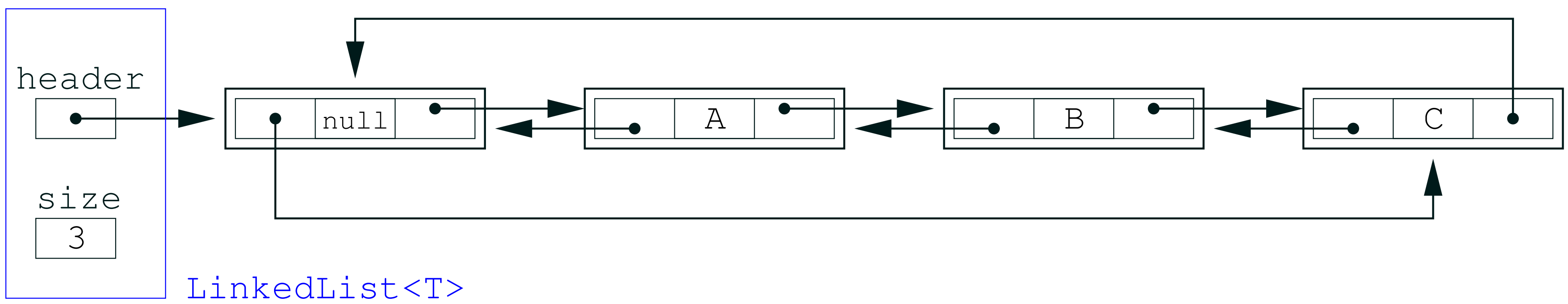


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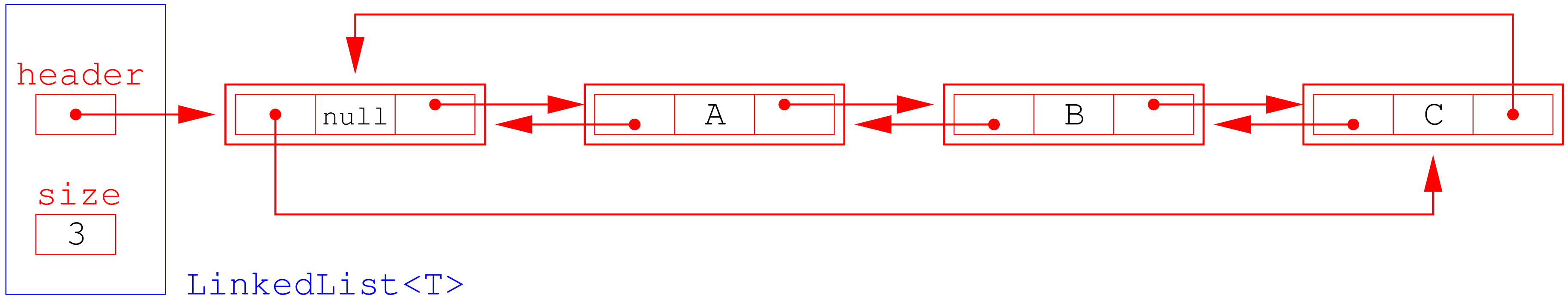


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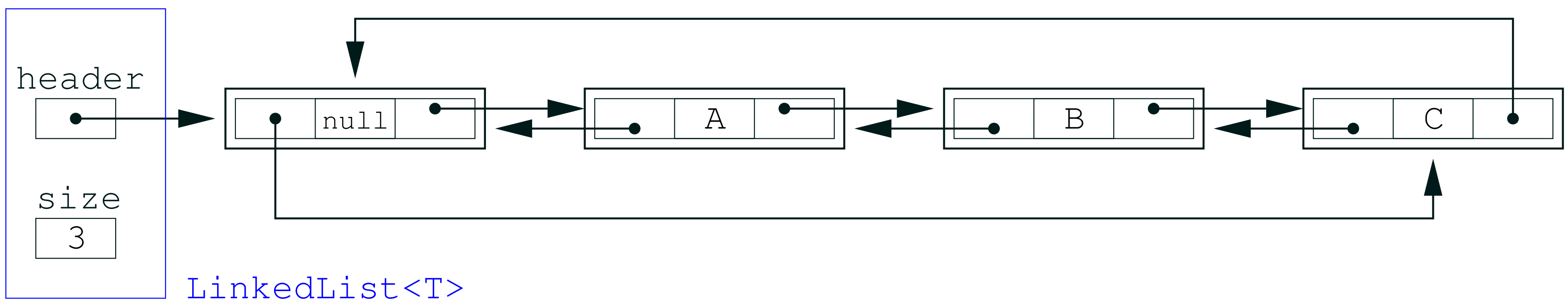


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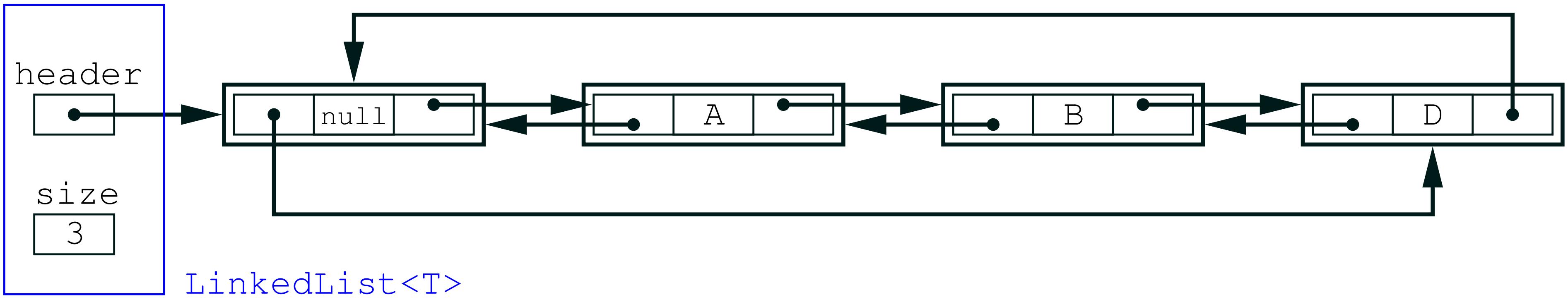

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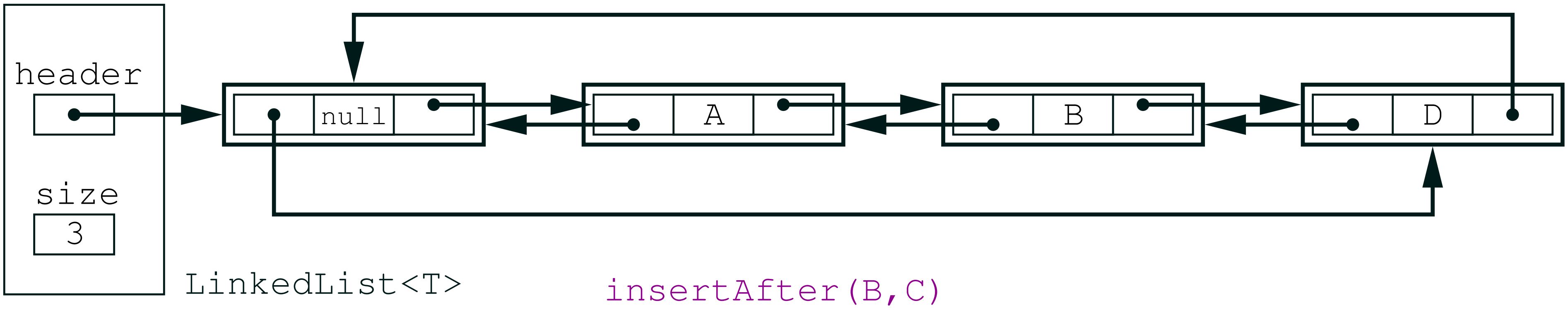

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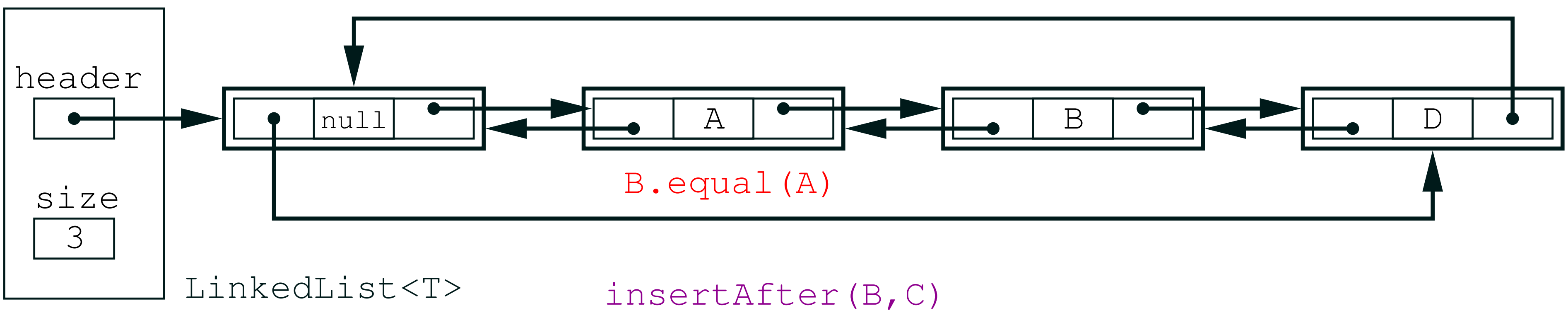

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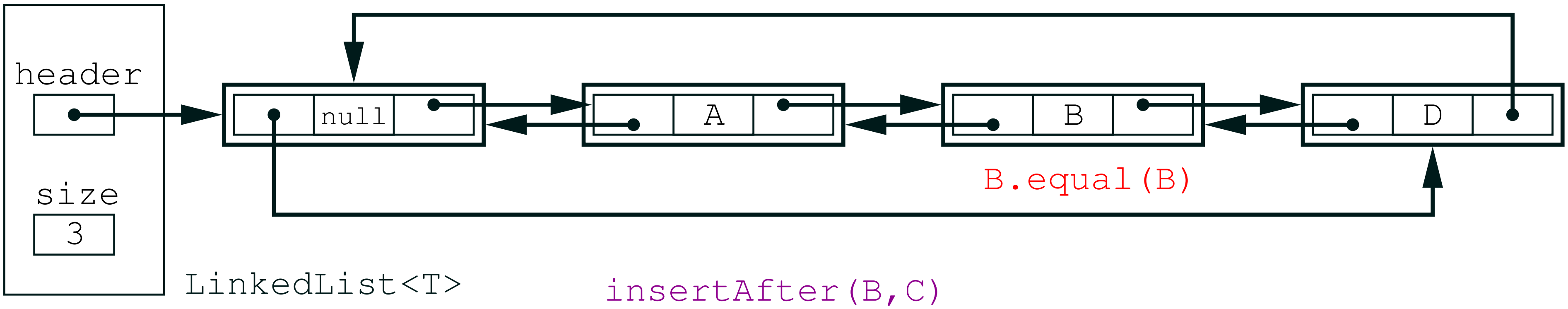

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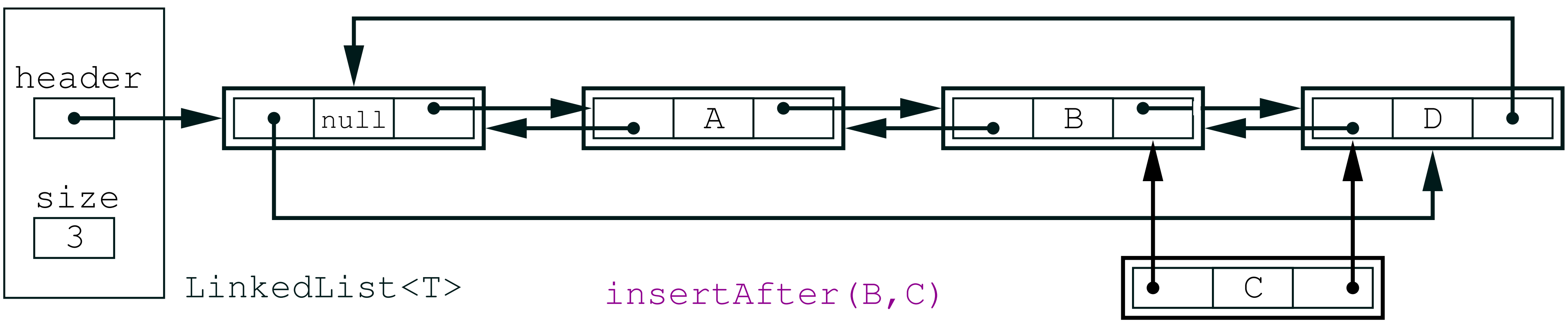

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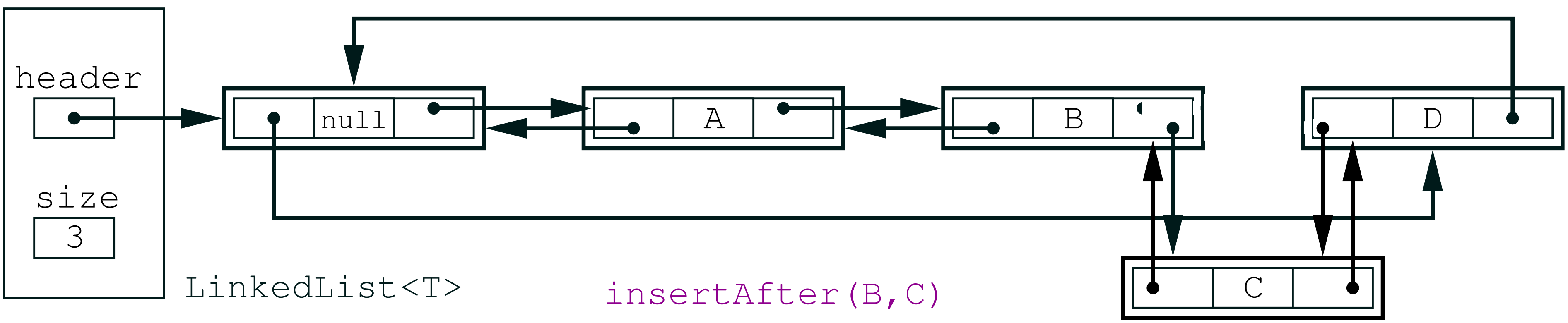

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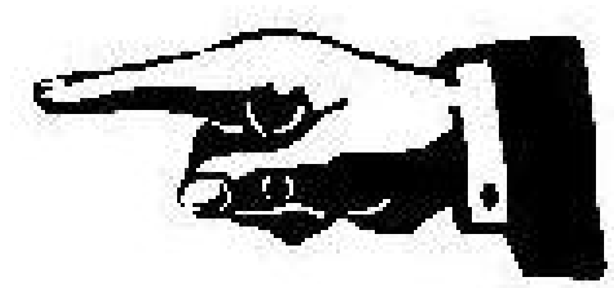

# When To Use Linked Lists

- It is difficult to think of applications where linked lists are the best data structure

- lists—variable length arrays are usually better

- queues—linked list OK, but circular arrays are probably better

- sorted lists—binary trees much better

- linked lists have efficient insertion and deletion but it is difficult to think of an application where this matters

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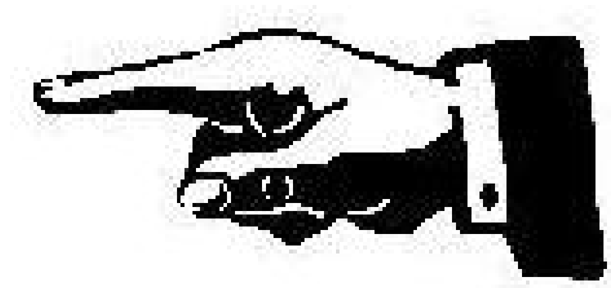

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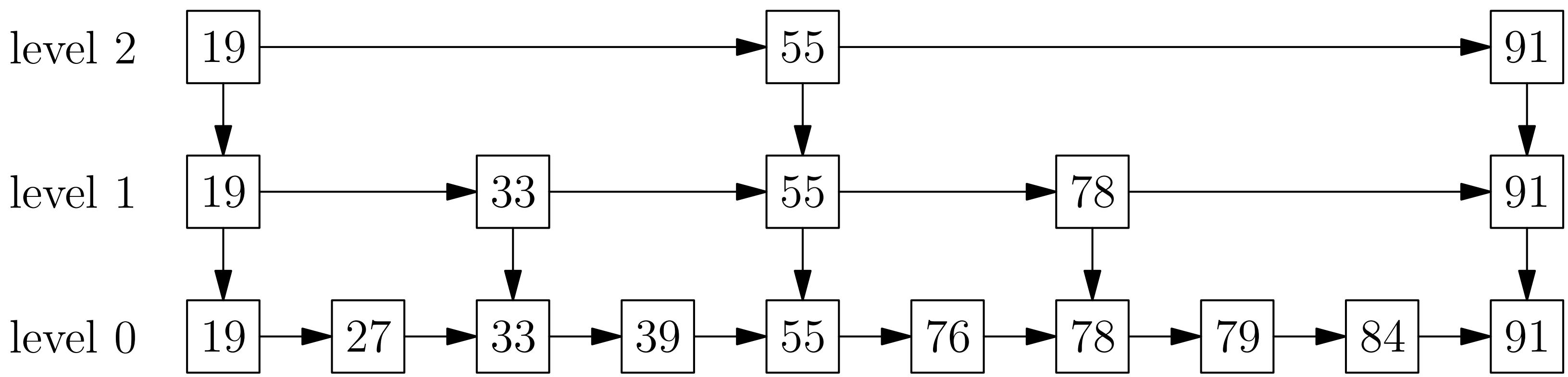

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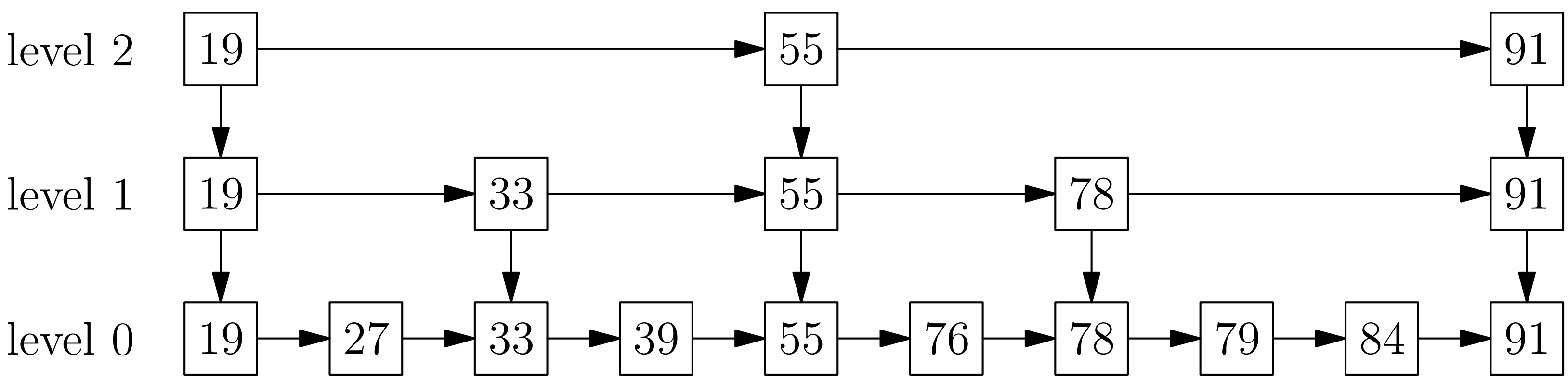

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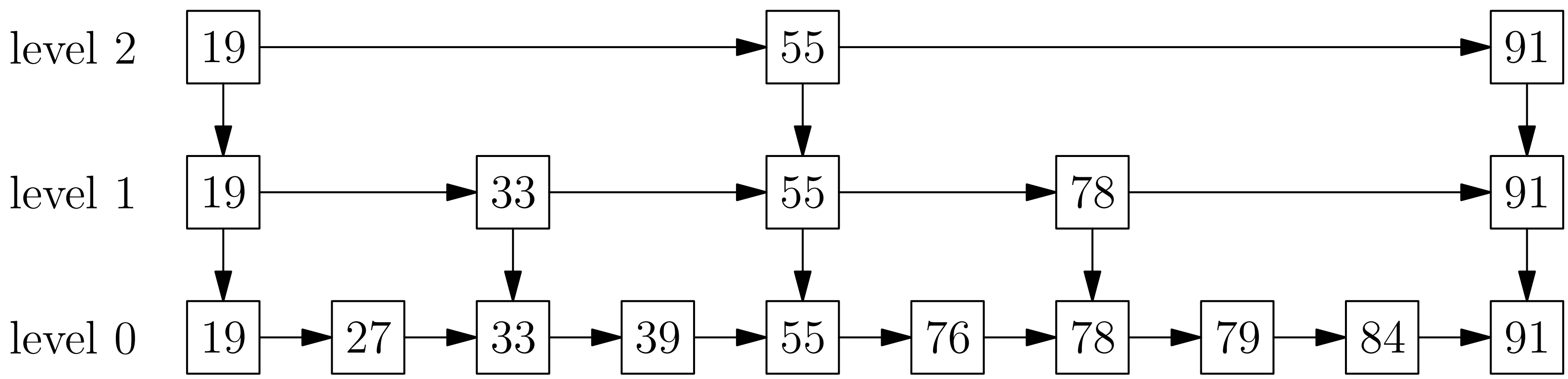

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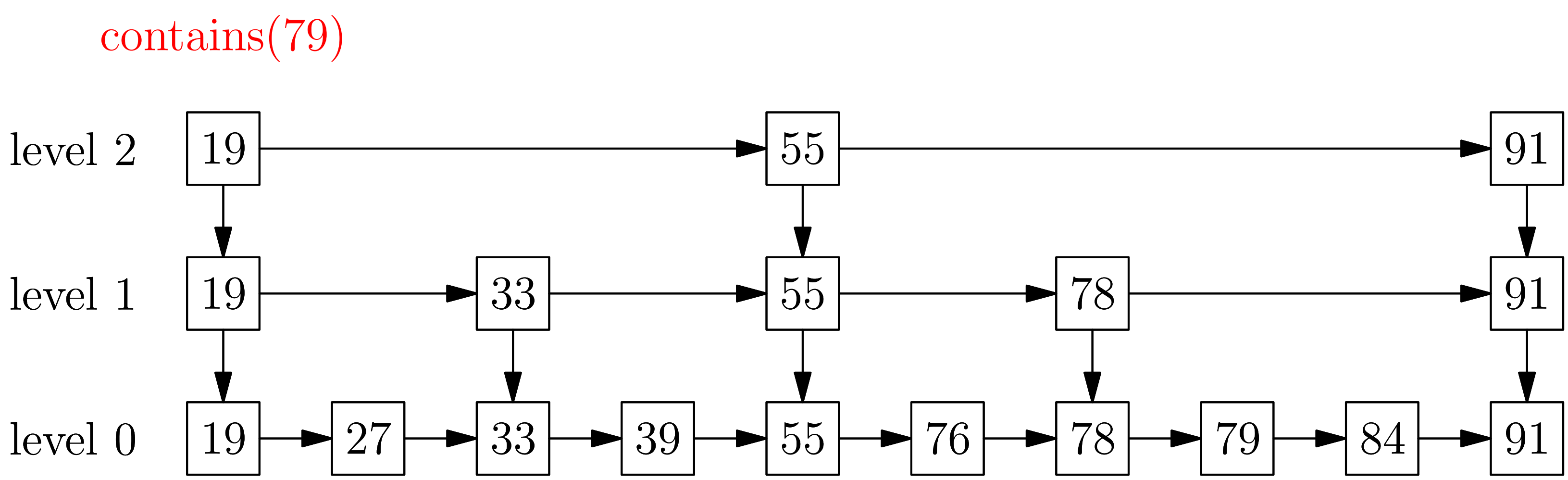

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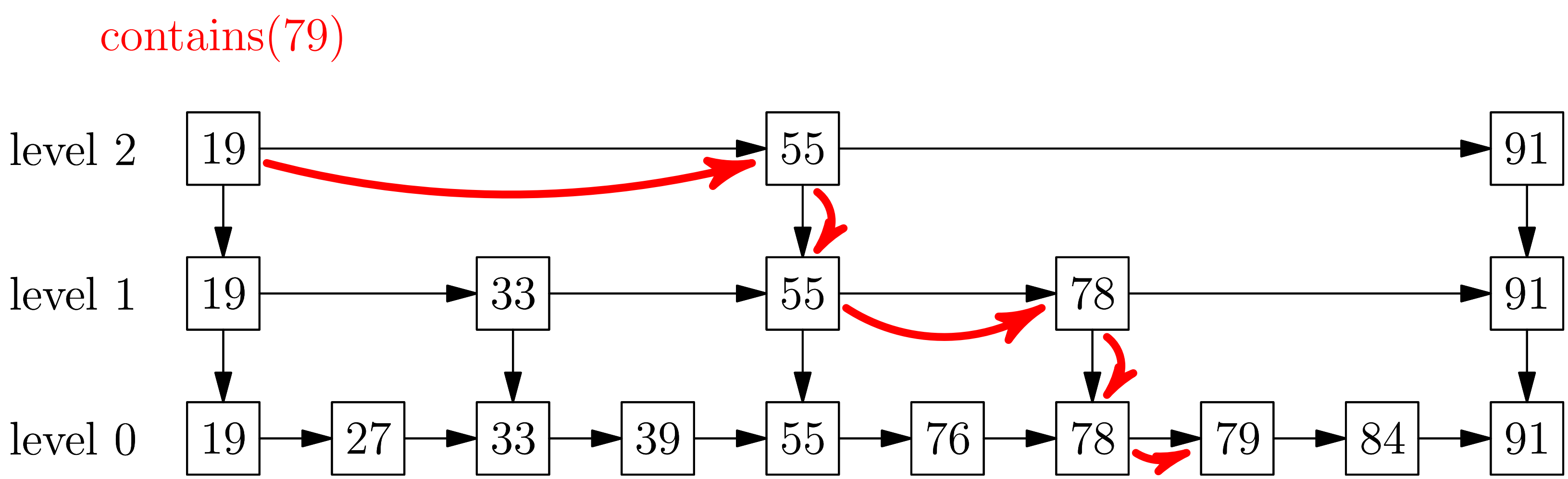

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