CSE 12:

Basic data structures and object-oriented design

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Lecture Four
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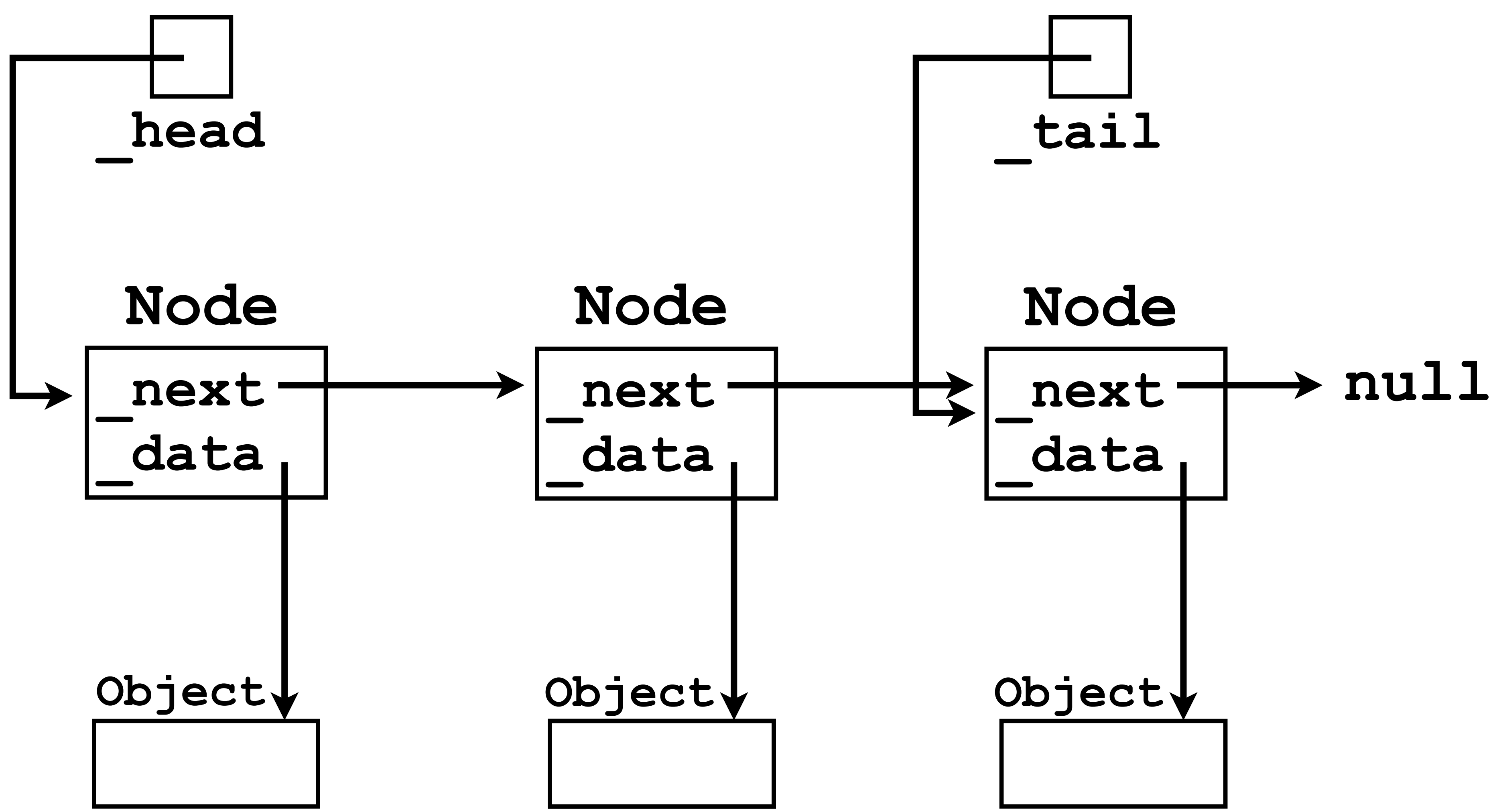
Linked lists, continued.

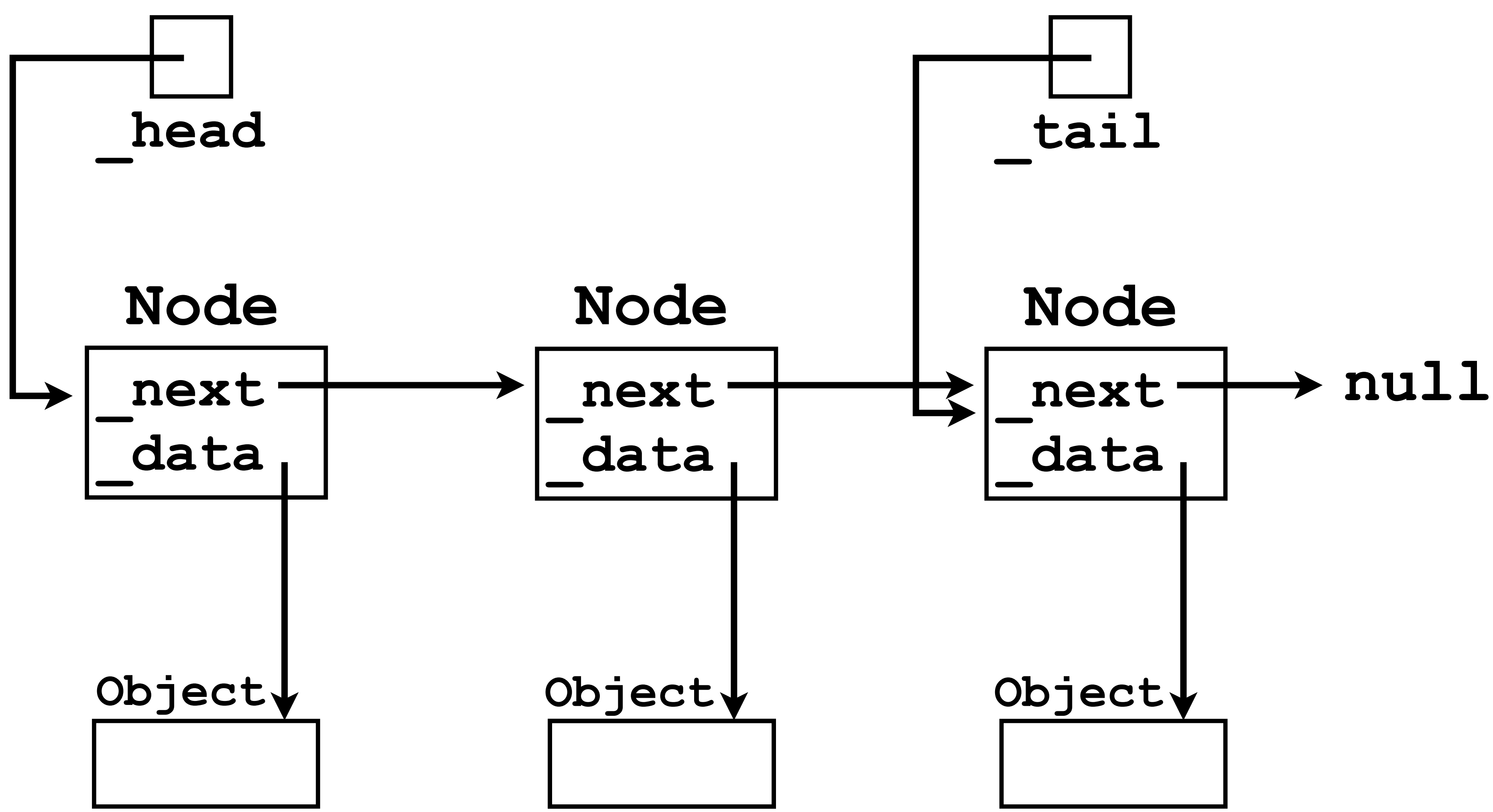
Review from last lecture

- Last lecture we looked briefly at how a linked list could be conceptualized as a "chain" of nodes.
  - A **`Node`** is simply a "link" in the chain.



Review from last lecture

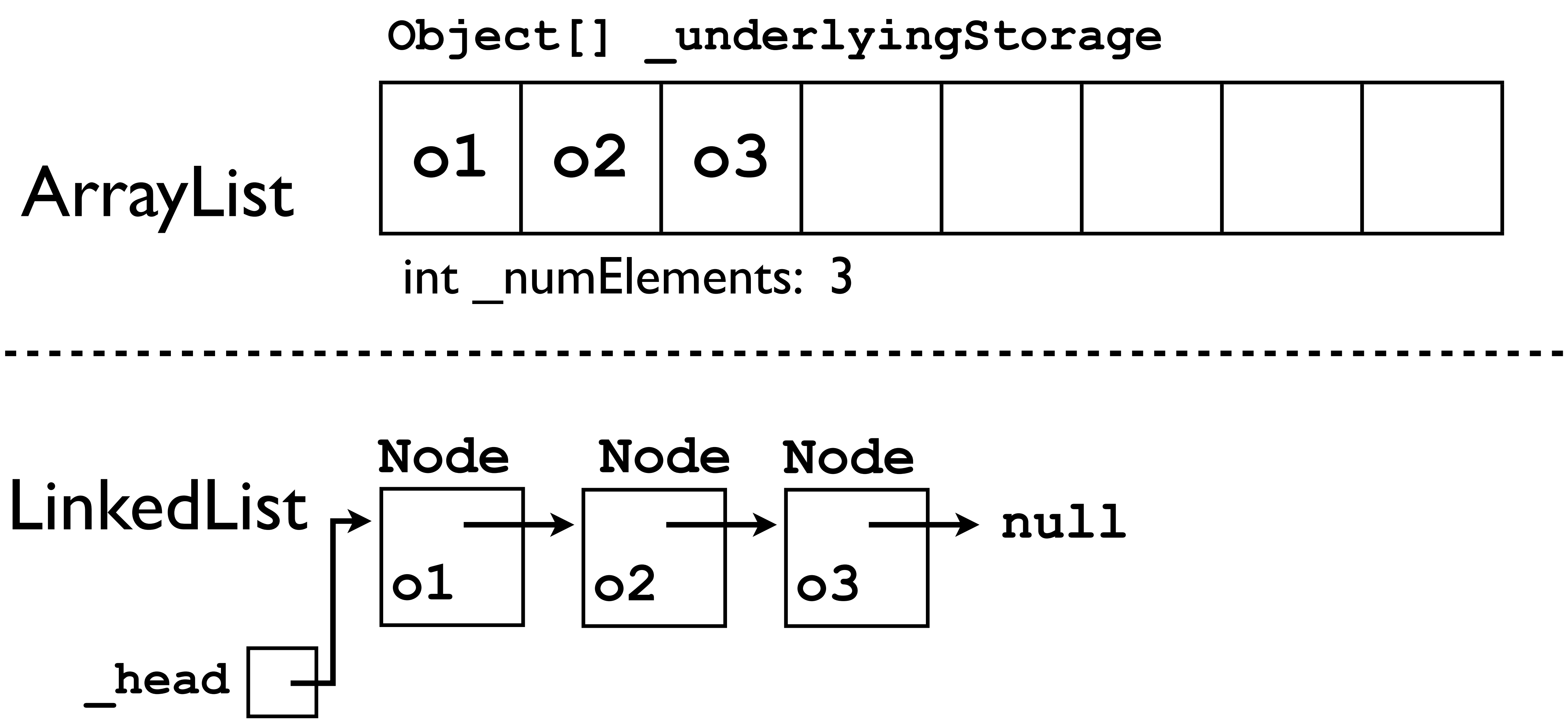
- Each `Node` contains a reference to an `Object` that the user wants to store (`node._data`).
- Each `Node` also contains a reference to the next "link" (`Node`) in the chain (`node._next`).



Nodes

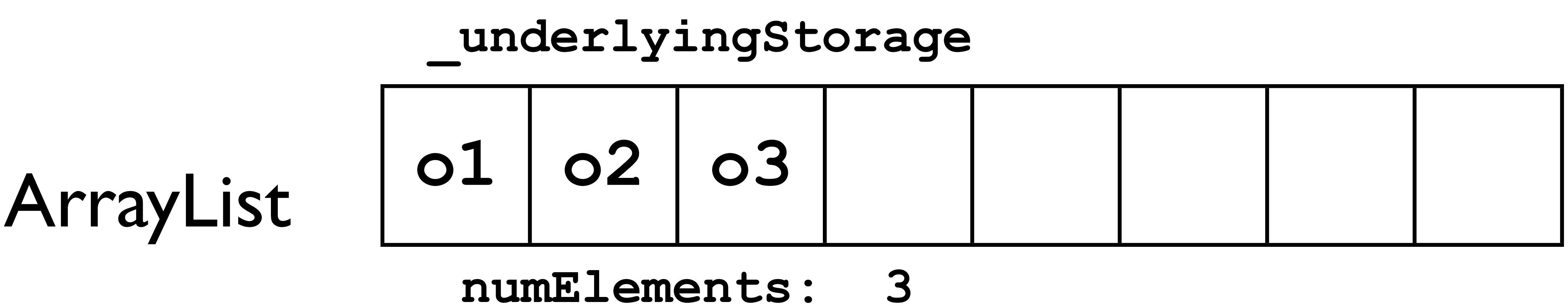
- **`Node`s** in a LinkedList play an analogous role to the “slots” (elements) of an array in an ArrayList.

```
list.add(o1);
list.add(o2);
list.add(o3);
```

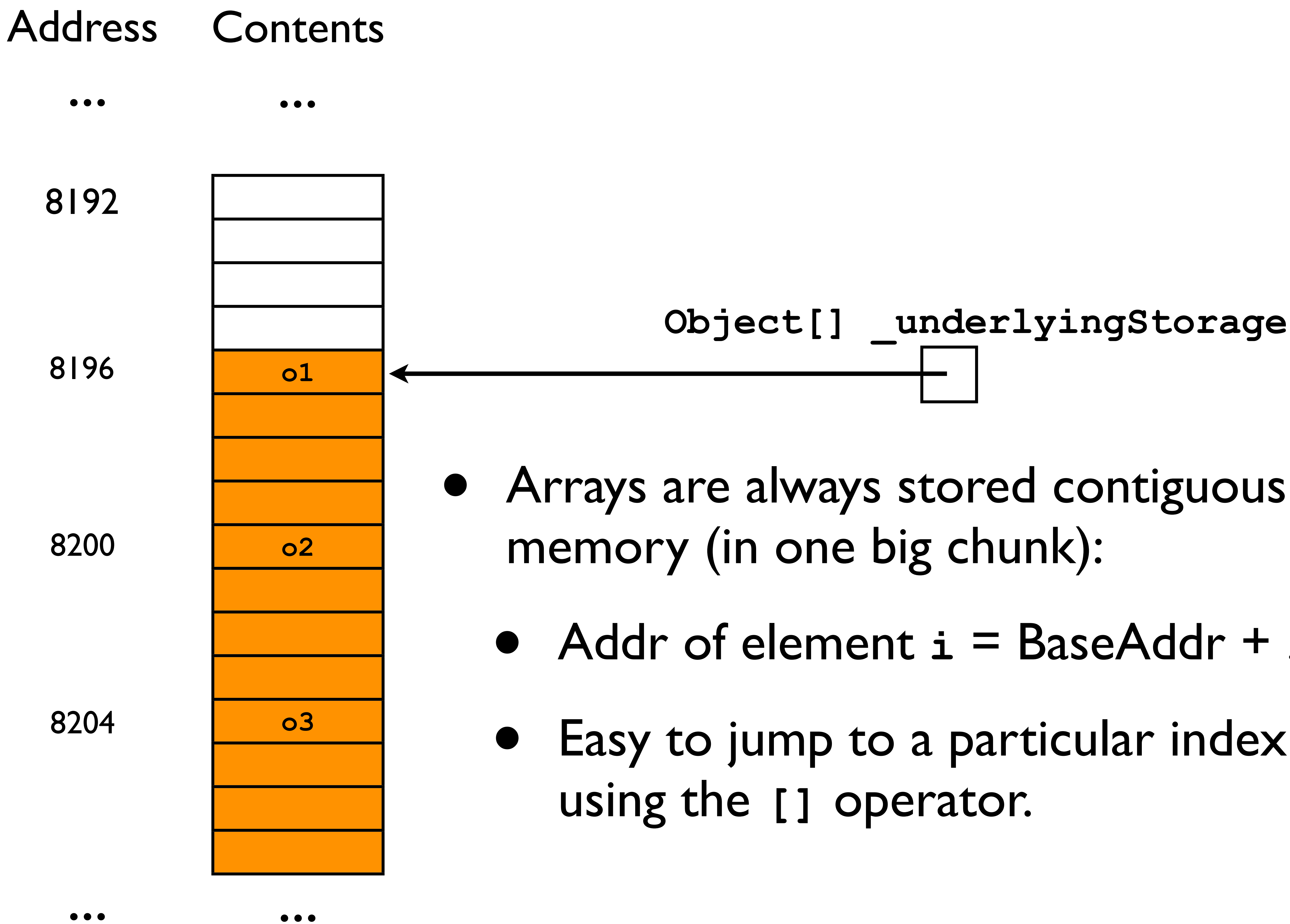


Elements of an array

- In an array, there is no need to link the elements using pointers because array elements are always adjacent to each other in memory.
  - For an `Object[]` array, the address of element 1 is just 4 bytes more than the address of element 0.



Elements of an array



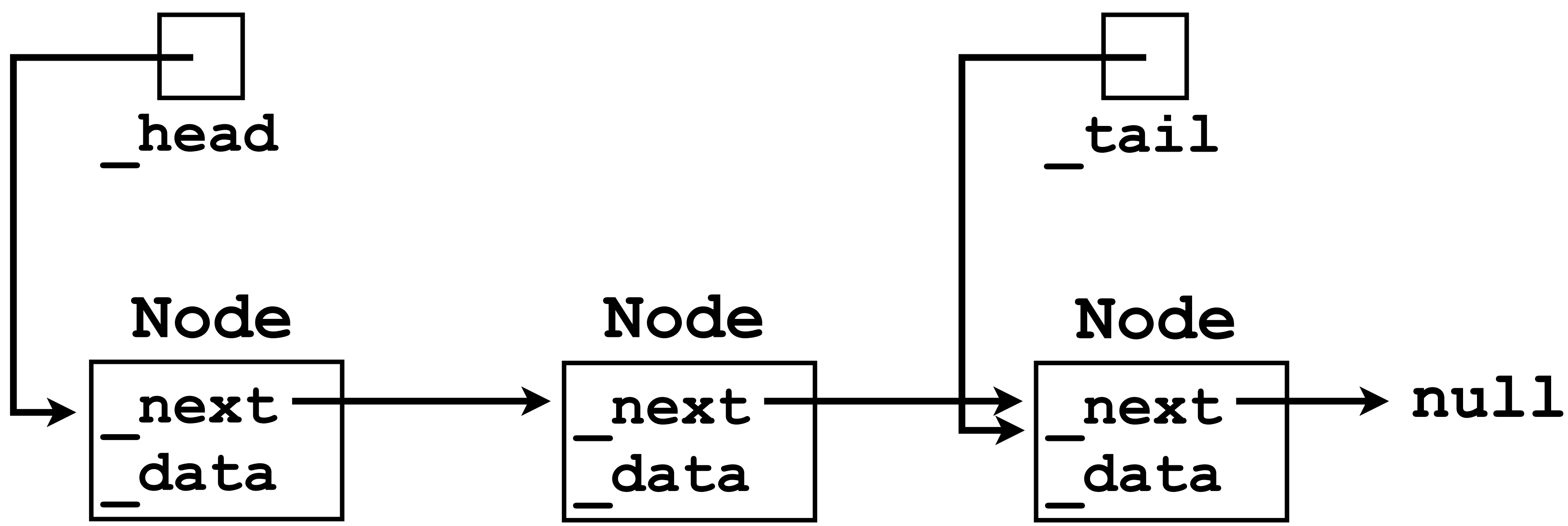
- Arrays are always stored contiguously in memory (in one big chunk):
  - Addr of element `i` = BaseAddr + `i` * 4
  - Easy to jump to a particular index using the `[]` operator.

Nodes of a linked list

- With linked lists, nodes can be allocated anywhere in memory.
  - No need for contiguity; hence, more flexible.
- However, this means that it takes more effort to compute the address of any particular node.
  - We must "iterate through" all nodes before it.

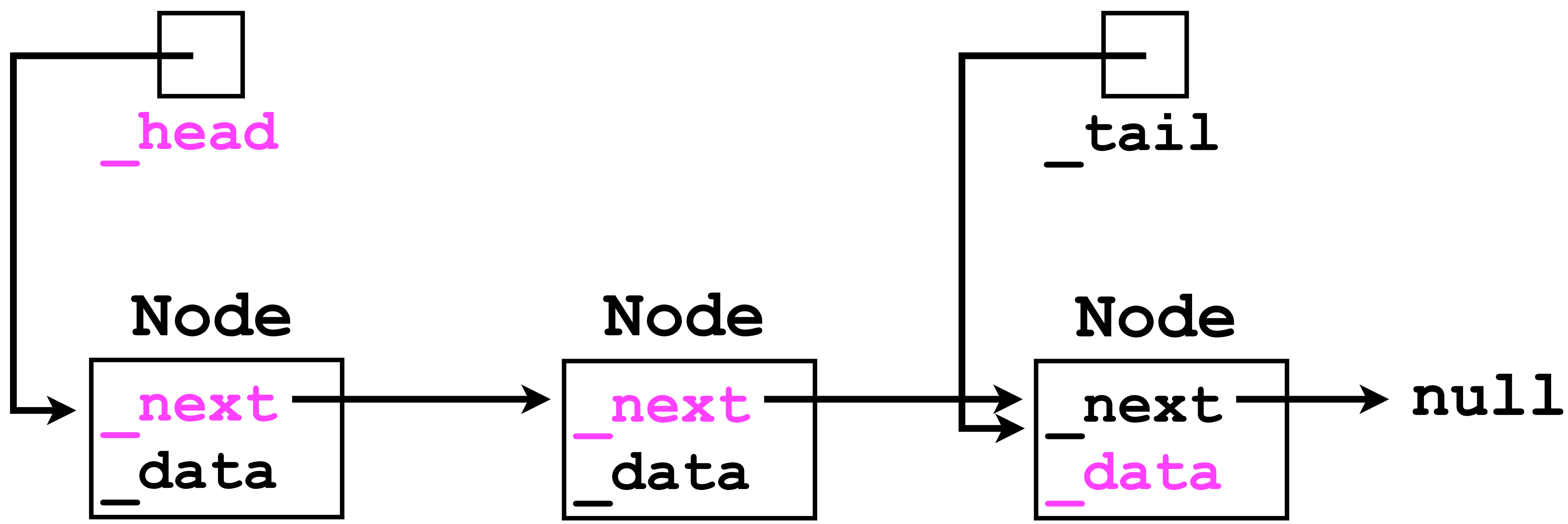
Finding a particular node

- Let's assume we have a linked list containing 3 nodes.
- We have a `_head` pointer to the first node.
- How do we access the `_data` contained in the 3rd node?



Finding a particular node

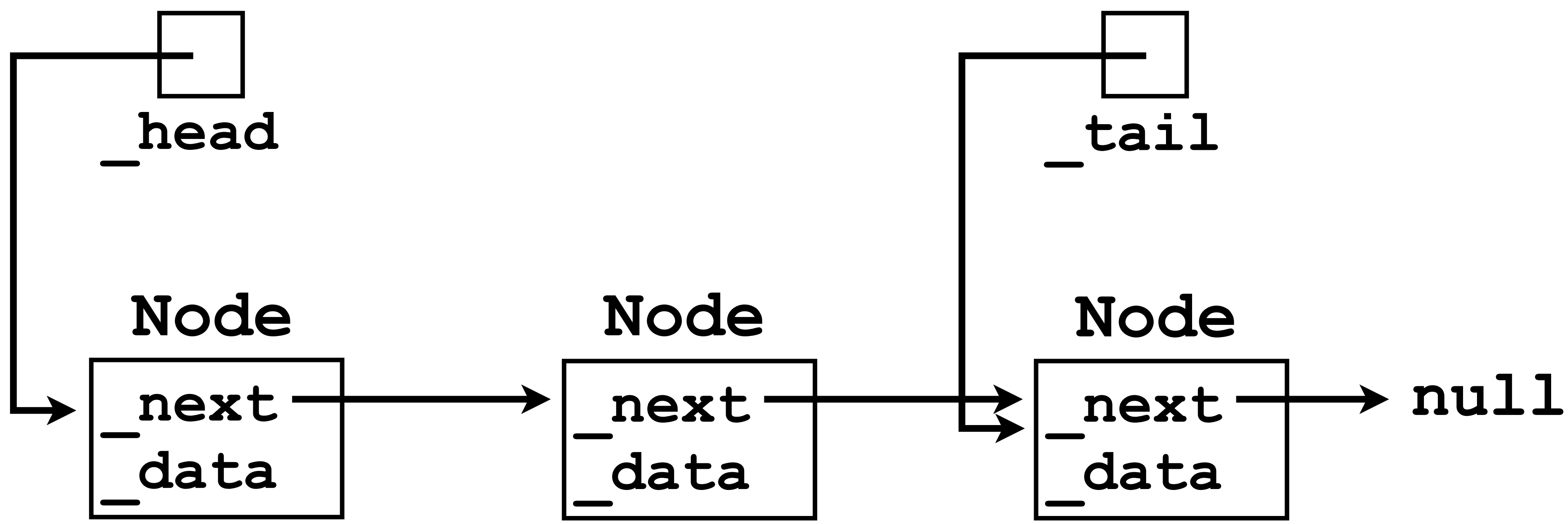
```
final Object thirdElement = _head._next._next._data;
```



Finding a particular node

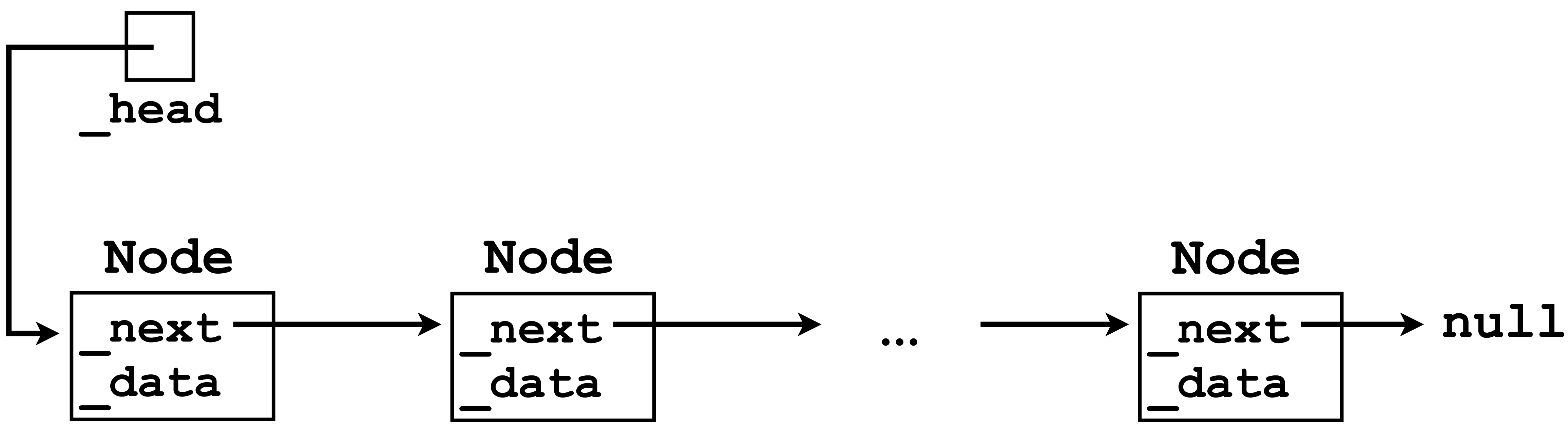
- Alternatively, we could use a *for*-loop:

```
Node cursor = _head;
for (int i = 0; i < 2; i++) {  // Why only 2?
  cursor = cursor._next;
}
final Object thirdElement = cursor._data;
```



Iterating through the whole list

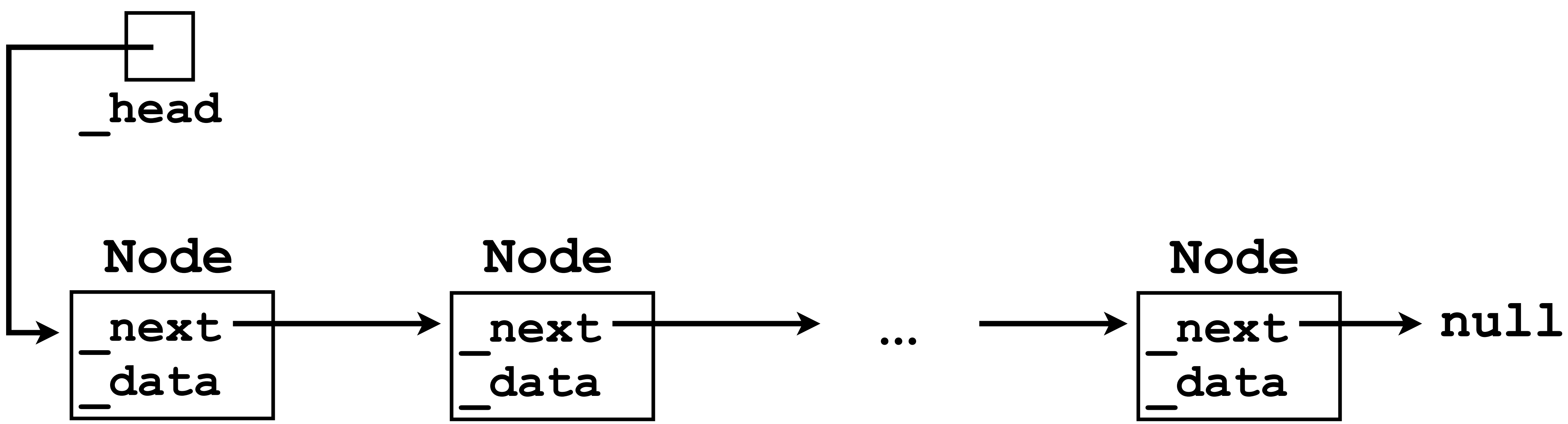
- Suppose we wish to iterate through the *entire list* and print out the **`_data`** in each node?



Iterating through the whole list

- Suppose we wish to iterate through the *entire list* and print out the **`_data`** in each node?

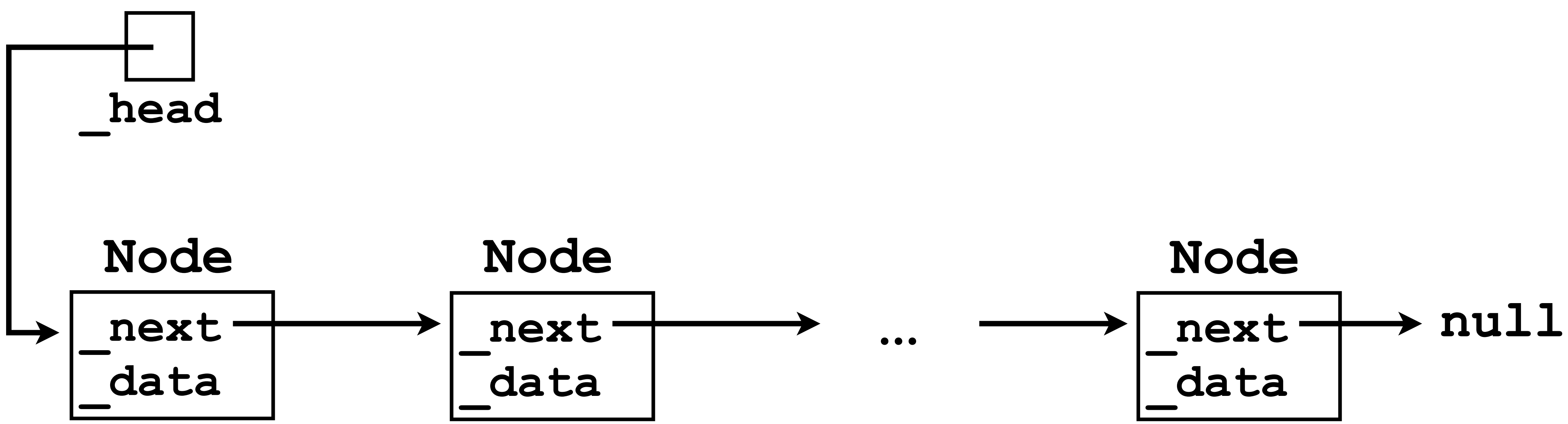
```
Node cursor = _head;
```



Iterating through the whole list

- Suppose we wish to iterate through the *entire list* and print out the `_data` in each node?

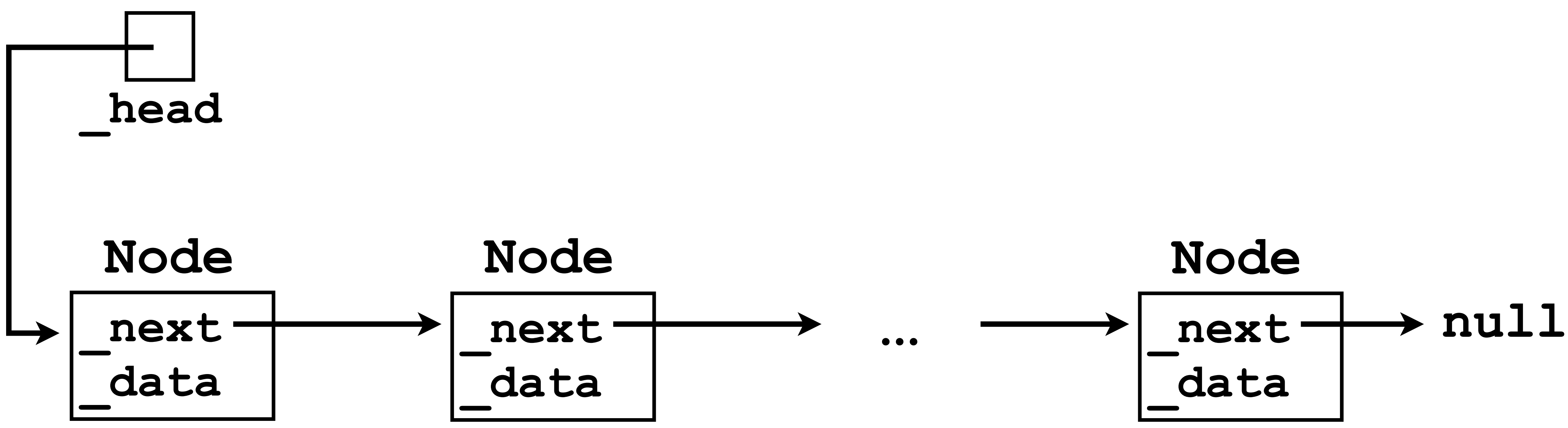
```
Node cursor = _head;
while (                 ) {


}
```



Iterating through the whole list

- Suppose we wish to iterate through the *entire list* and print out the `_data` in each node?

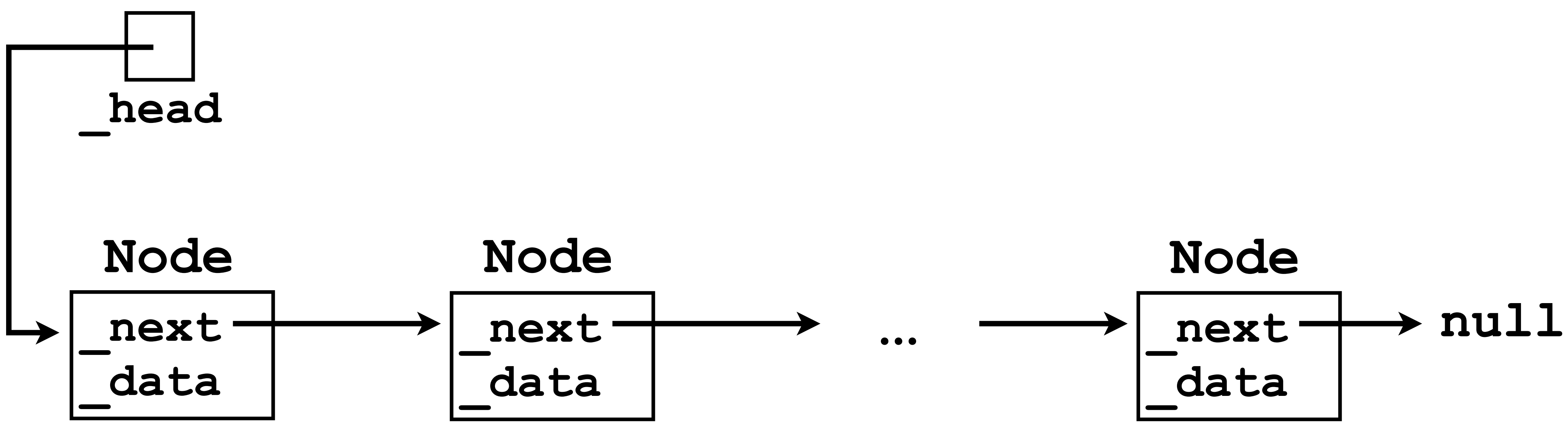
```
Node cursor = _head;
while (cursor != null) {


}
```



Iterating through the whole list

- Suppose we wish to iterate through the *entire list* and print out the `_data` in each node?

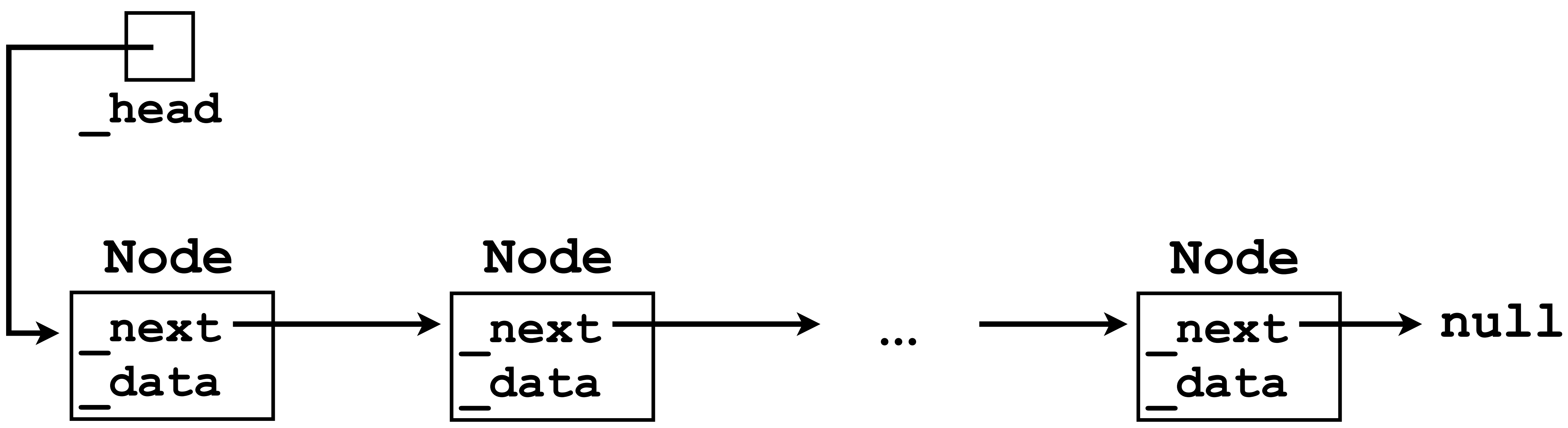
```
Node cursor = _head;
while (cursor != null) {
  System.out.println(cursor._data);

}
```



Iterating through the whole list

- Suppose we wish to iterate through the *entire list* and print out the **`_data`** in each node?

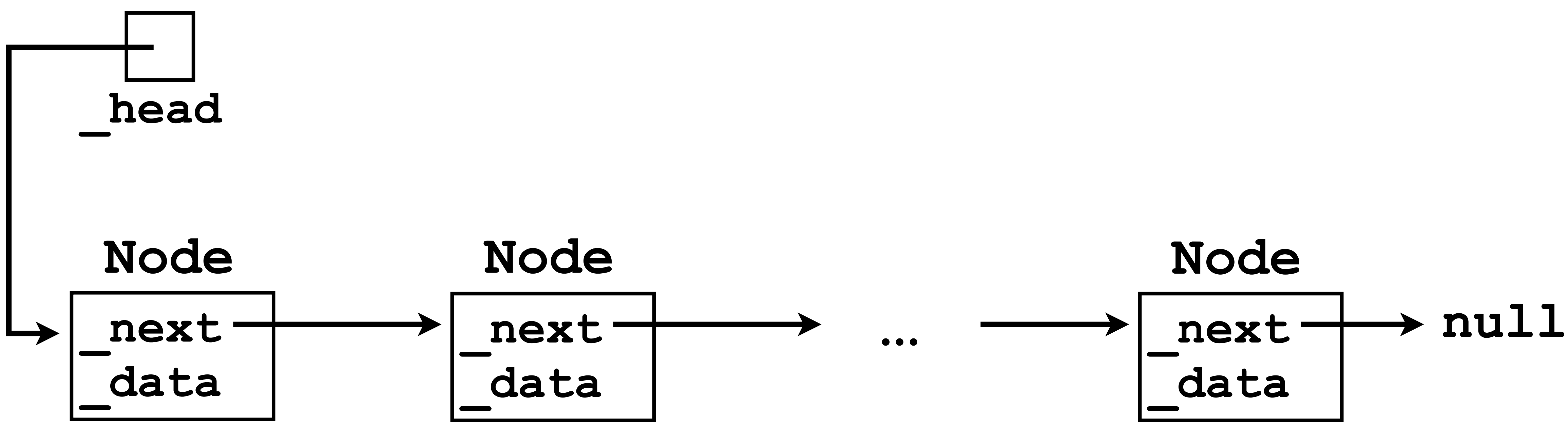
```
Node cursor = _head;
while (cursor != null) {
  System.out.println(cursor._data);
  cursor = cursor._next;
}
// Done!
```



Iterating through the whole list

- Alternatively, we could use a *for*-loop:

```
for (Node cursor = _head;
         cursor != null;
         cursor = cursor._next) {
  System.out.println(cursor._data);
}
// Done!
```



Adding a new node

- The "iteration" code described above assumes that a linked list already exists.
- How is the "chain of nodes" actually constructed?

class SinglyLinkedList

- Before discussing how to implement the `add(o)` method, let's first "concretify" the linked list class itself.
- Let's create a `SinglyLinkedList` class that implements the simple `List` interface from Lecture Two...

```
public interface List {
  // Adds o to the “back” of the list, i.e.,
  // o becomes the element with the highest
  // index in the List.
  void add (Object o);

  // Returns the element stored at the specified
  // index.
  Object get (int index)
    throws IndexOutOfBoundsException;

  // Removes the element stored at the specified
  // index.
  void remove (int index)
   throws IndexOutOfBoundsException;

  // Returns the number of elements stored in
  // the List.
  int size ();
}
```

class SinglyLinkedList

- We will implement the **`Node`** class as an *inner-class* of **`SinglyLinkedList`**.
  - More on inner-classes later.
- We will use two instance variables:
  `Node _head, _tail;`

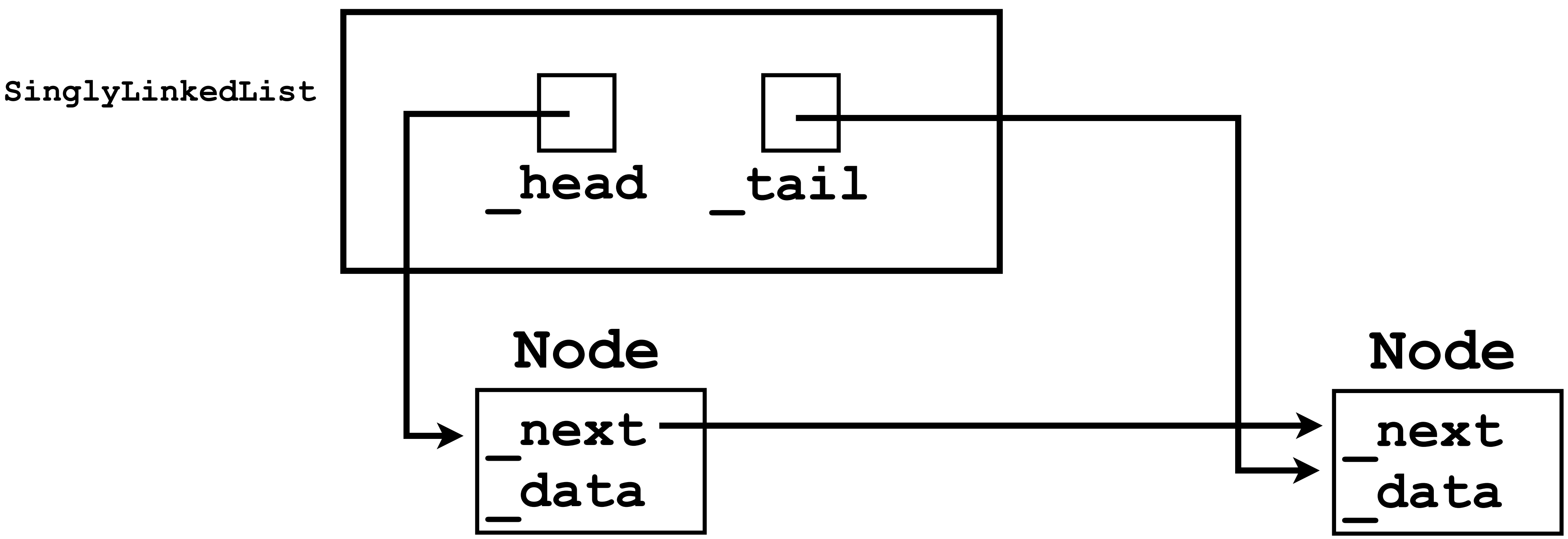
class SinglyLinkedList

- Note the slight inconsistency with previous slides:
  - In our **`SinglyLinkedList`** implementation, we will be using "dummy nodes" for the head and tail.
  - These nodes will *simplify* the implementation.
- Dummy nodes are **`Nodes`** whose **`_data`** fields are always **`null`** -- they contain no data from the "user".
- The dummy nodes will *always exist*, *even if the user hasn't added any data yet.*
  - **`Nodes`** for the user's data will be created *between* the dummy head and tail nodes.

```
public class SinglyLinkedList implements List {
  class Node {  // Inner-class
    Node _next;
    Object _data;
  }
  private Node _head, _tail;

  SinglyLinkedList () {
    // Instantiate dummy head and tail nodes
    _head = new Node();
    _tail = new Node();

    // Link _head to _tail
    _head._next = _tail;
  }

  void add (Object o) {  ... }
  Object get (int index)
    throws IndexOutOfBoundsException {  ... }
  void remove (int index)
    throws IndexOutOfBoundsException {  ... }
  int size () { ... }
}
```

After construction

- After the constructor has been called, our **SinglyLinkedList** object looks like this:



`void add (Object o)`

- Let's consider how to implement the `add(o)` method.
- As a "rule" when implementing `add(o)`, we will maintain the *invariant* that `_head` and `_tail` point to dummy nodes.
  - We will never use them to store real user data.
- An invariant is a condition that always holds true.

`void add (Object o)`

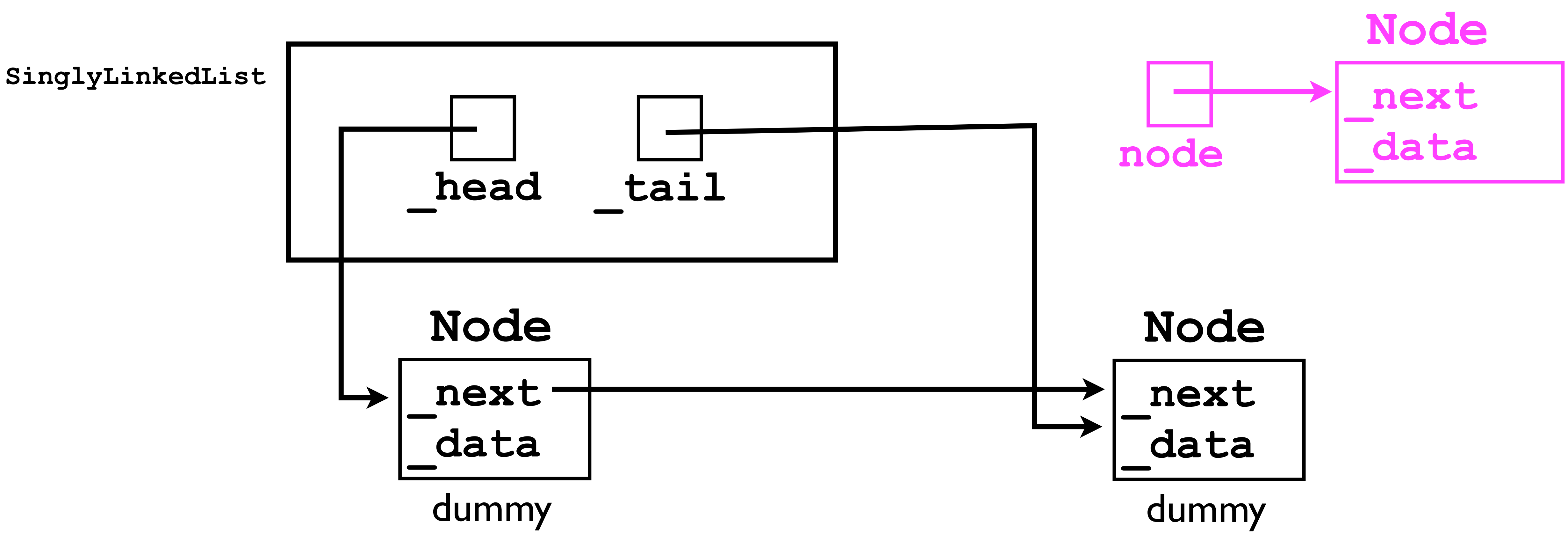
- Given the dummy head and tail nodes, we can add a new node to our chain in 4 steps:

  1. Instantiate a new `Node` object.
  2. Set its `_data` field to equal `o`.
  3. Iterate a "cursor" from the dummy head towards the tail, stopping just before the dummy tail.
  4. Insert the new `Node` just after cursor.

void add (Object o)

1. Instantiate a new **Node** object.

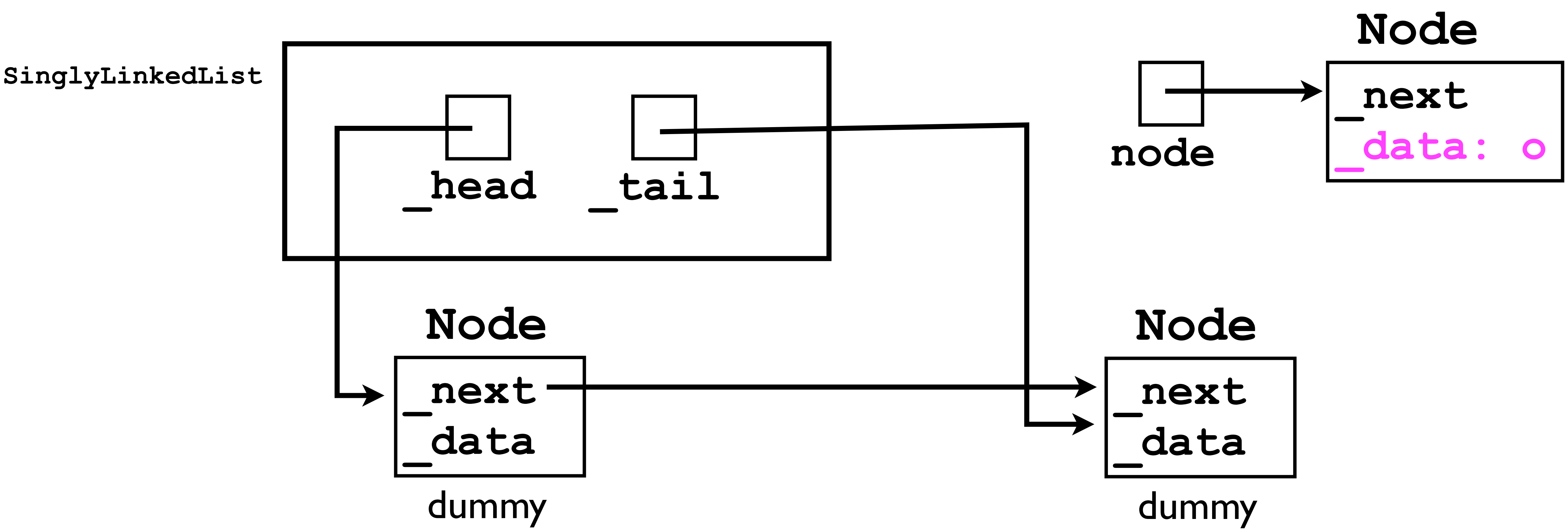
```
final Node node = new Node();
```



void add (Object o)

2. Set its `_data` field to equal `o`.

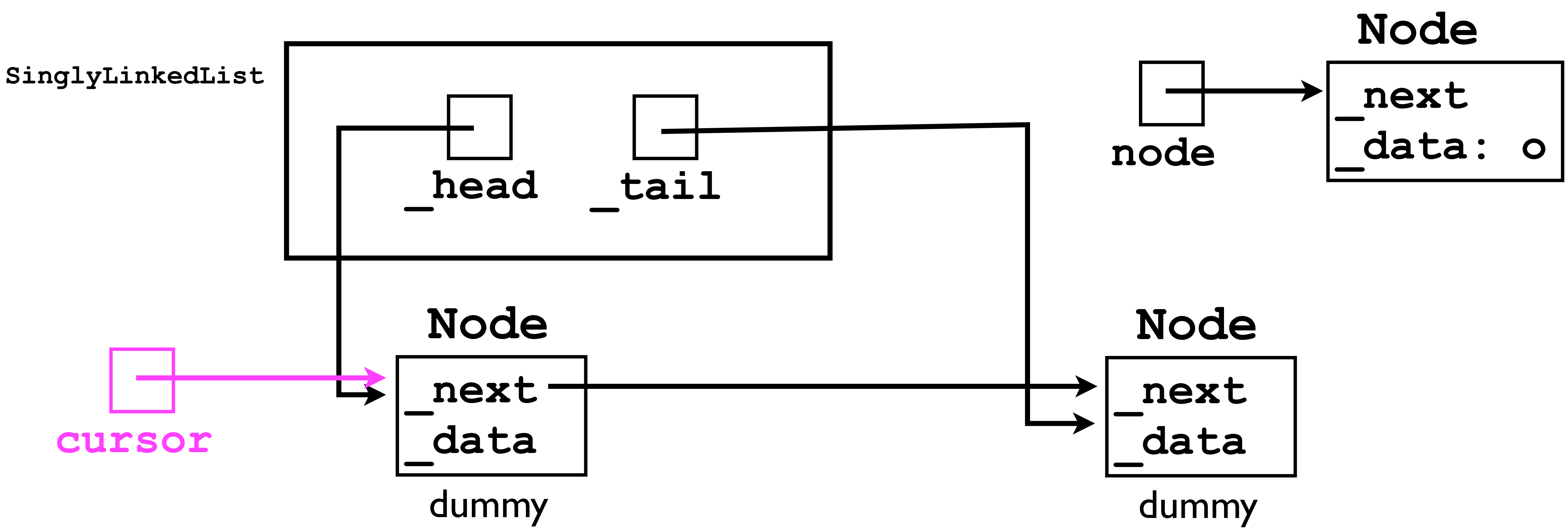
```
node._data = o;
```



void add (Object o)

3. Iterate from the head towards the tail, stopping just before the tail.

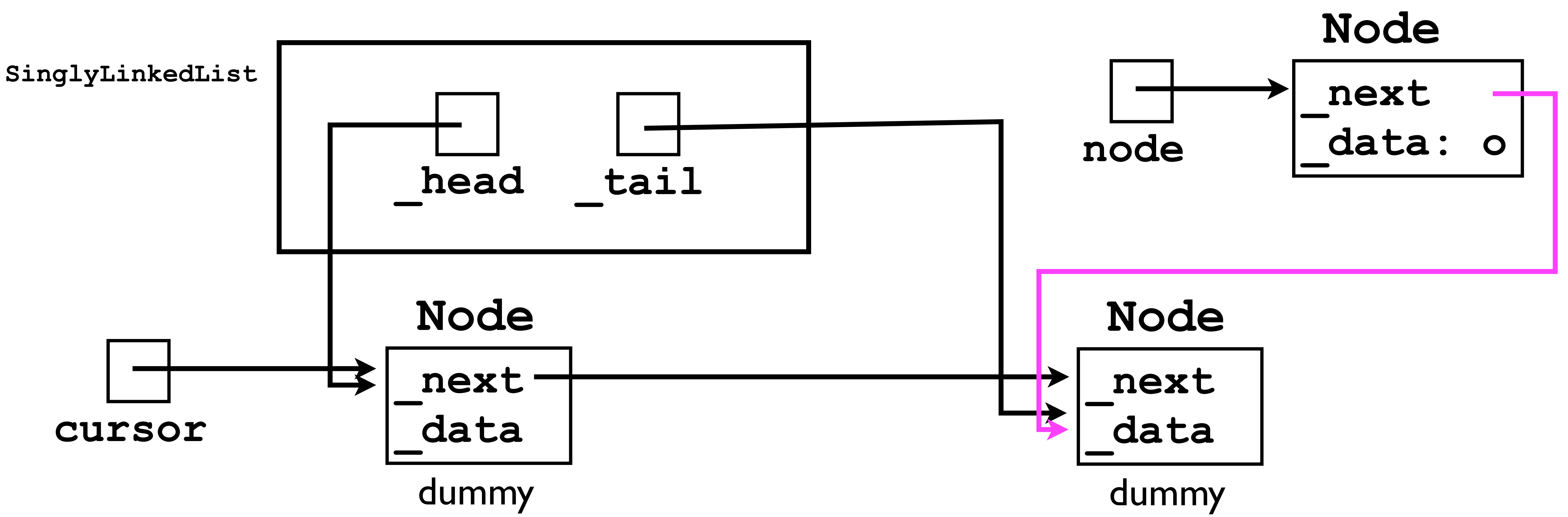
```
Node cursor = _head;
while (cursor._next != _tail) {  // Why?
  cursor = cursor._next;
}
```



void add (Object o)

4. Insert the new **Node** just after cursor.

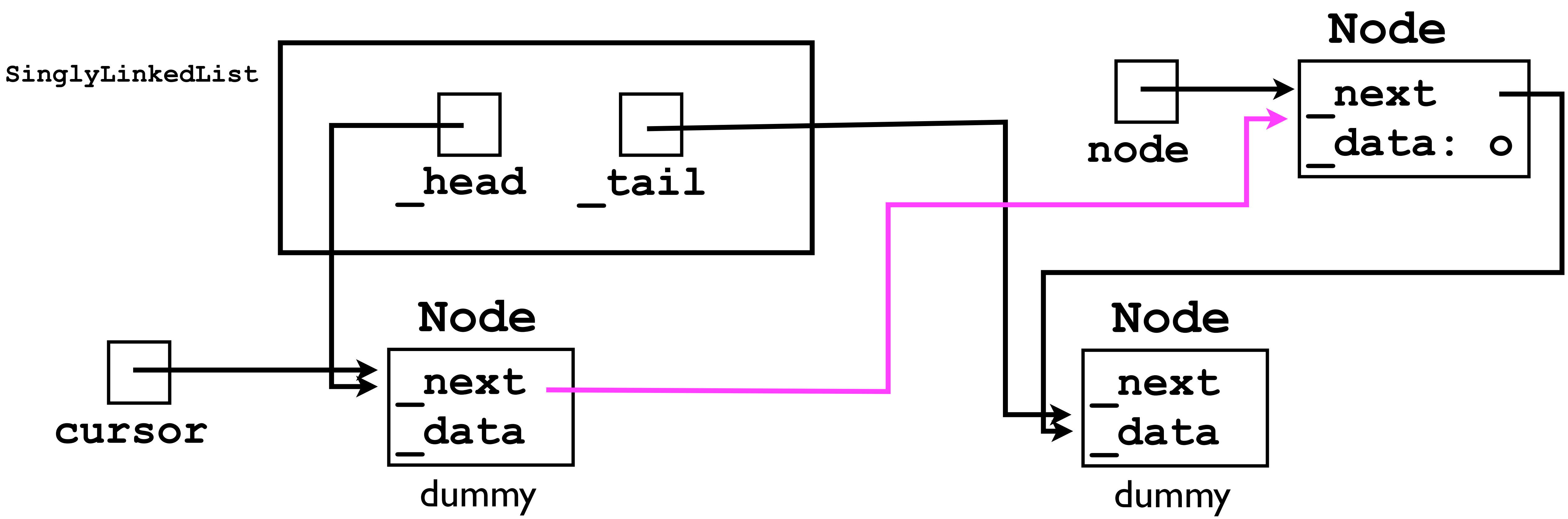
```
node._next = cursor._next;
```



void add (Object o)

4. Insert the new **Node** just after cursor.

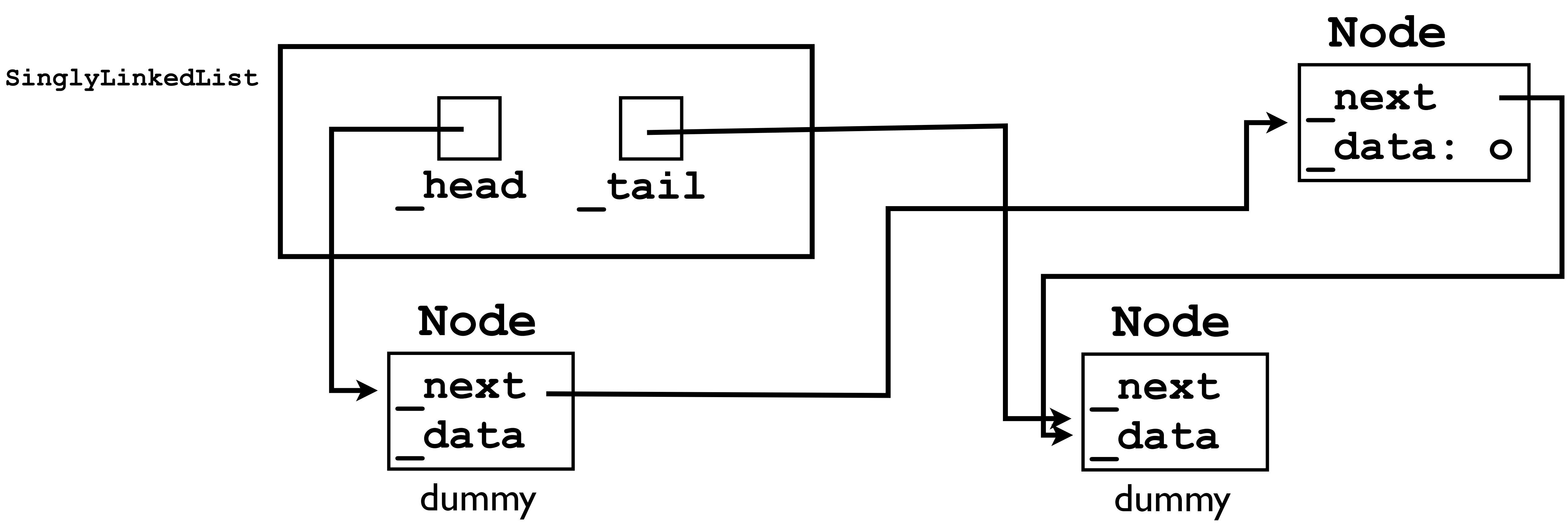
```
node._next = cursor._next;
cursor._next = node;
```



`void add (Object o)`

Done!

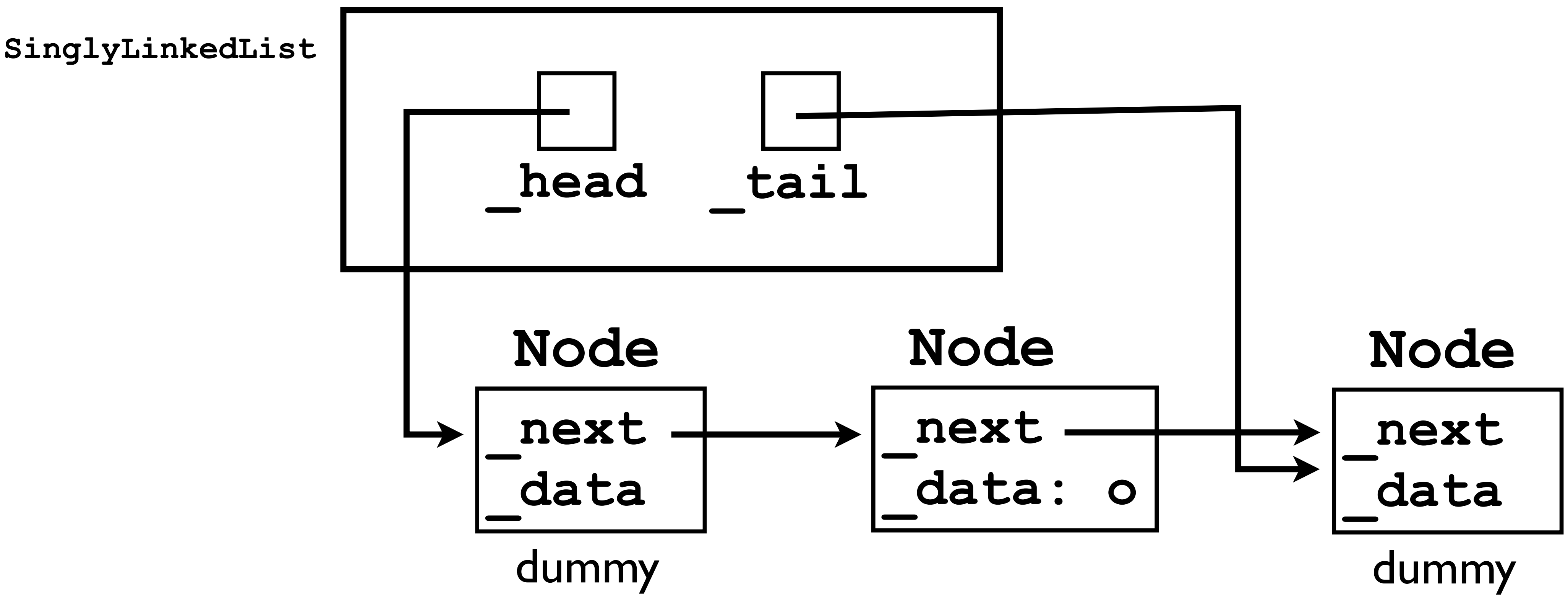
If we pull the chain "taut"...



void add (Object o)

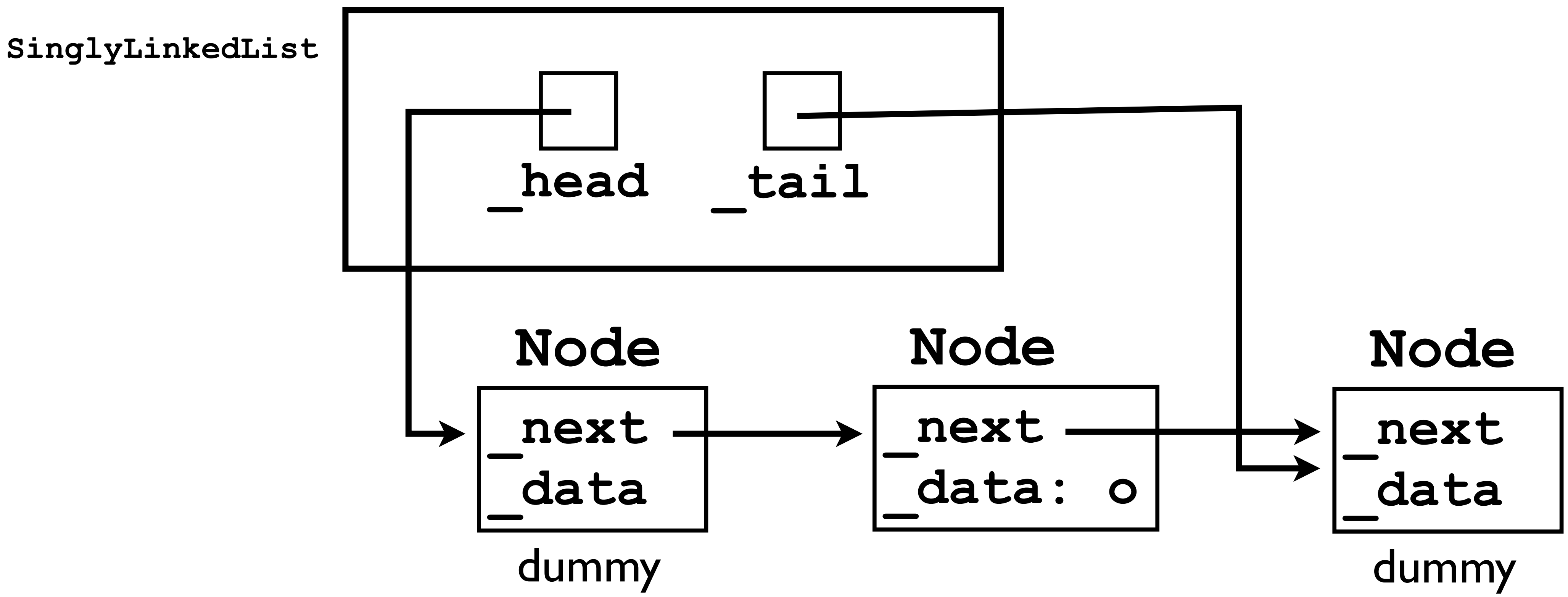
...it will look more like what we started with...

Notice: `_head` and `_tail` still point to the dummy nodes, and they contain no "real" data -- as intended.



Reality check

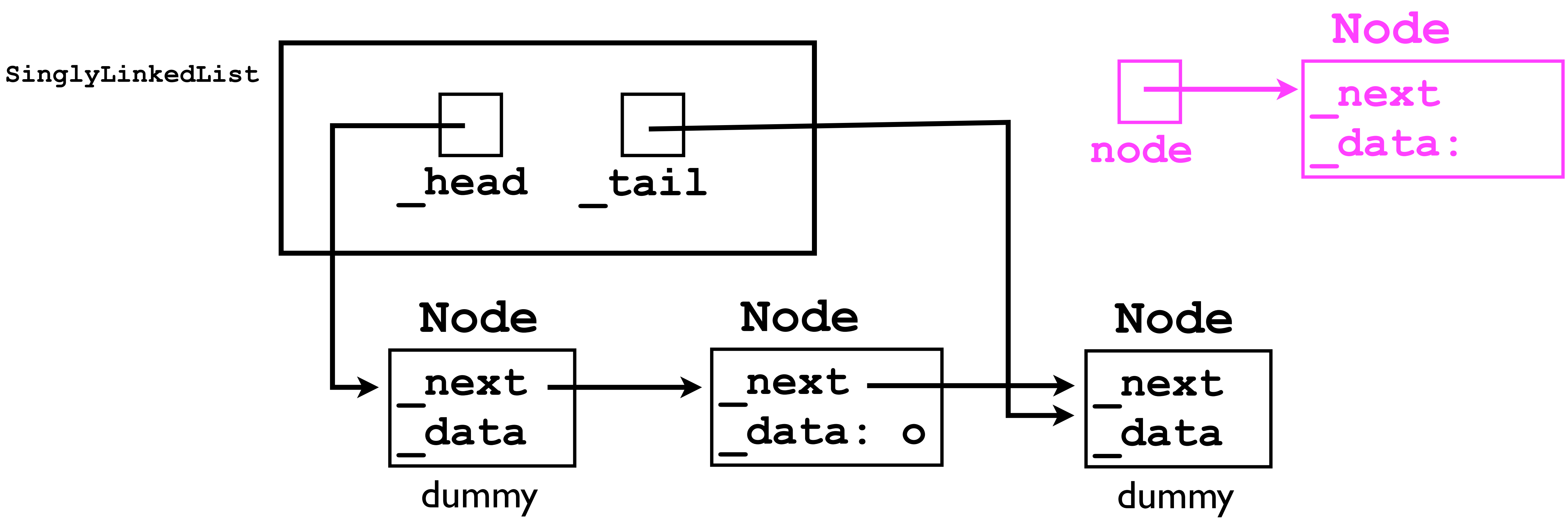
- Why do we need to iterate the cursor to the node just *before* the dummy tail?



Let's add one more node...

1. Instantiate a new **Node** object.

```
final Node node = new Node();
```

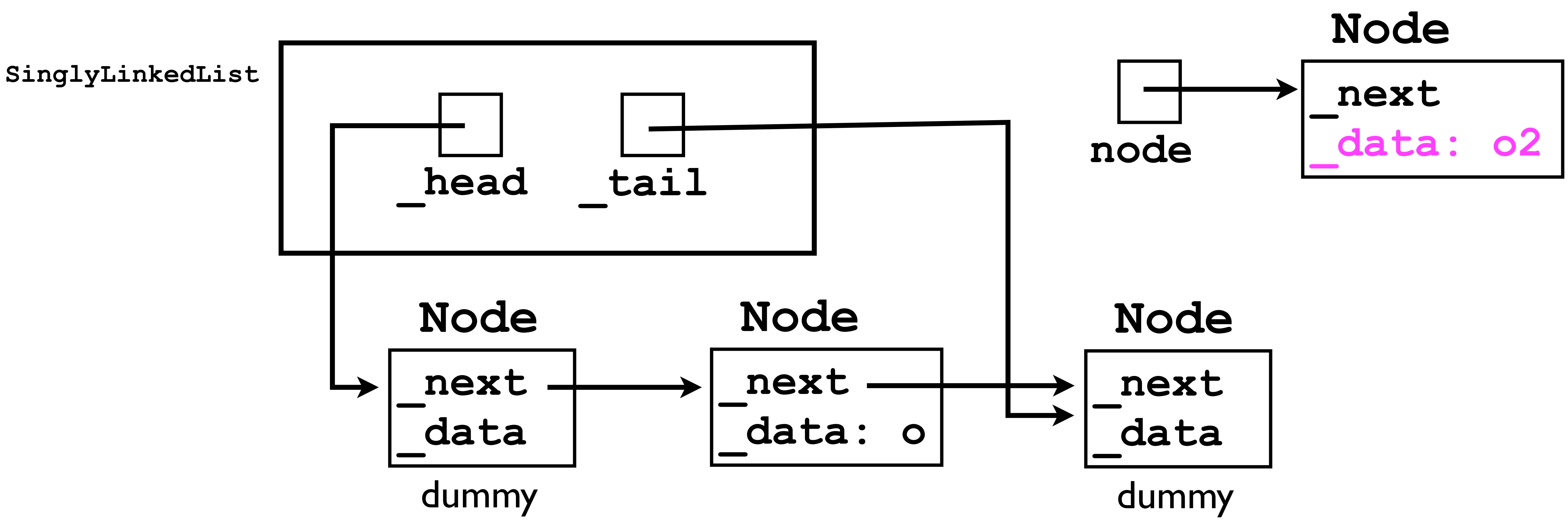


Let's add one more node...

2. Set its `_data` field to equal `o2`.

```
node._data = o2;
```

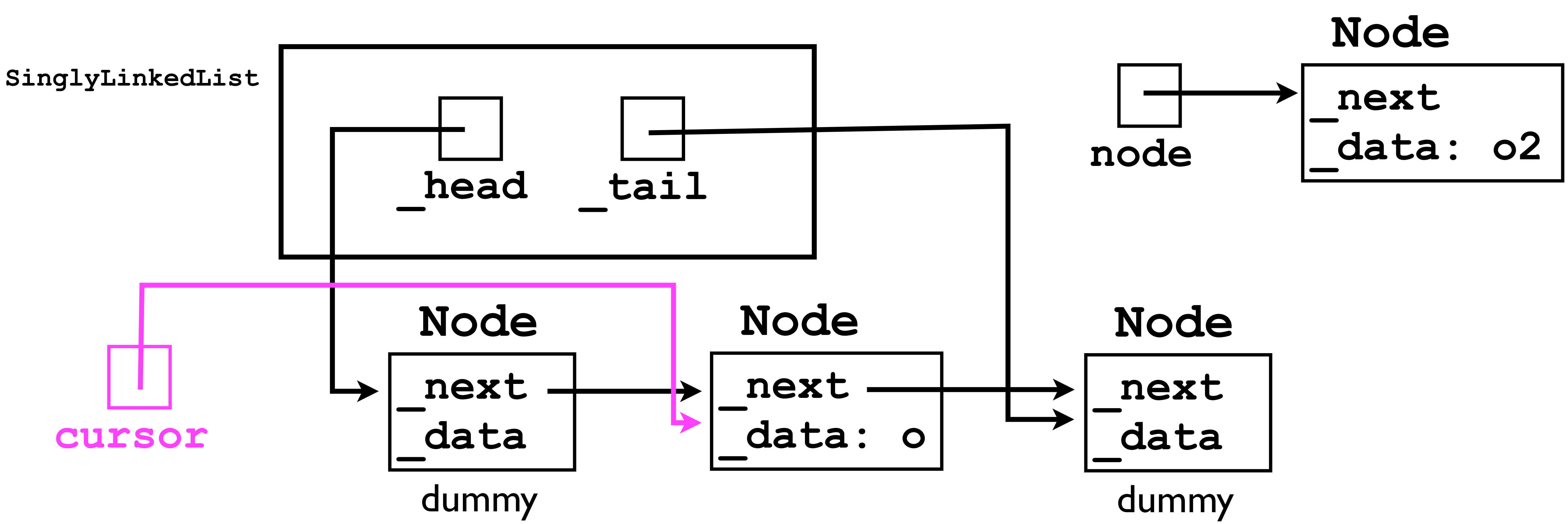
Let's change **o** to **o2** (just in the slides, not in code) to distinguish from the previous Object **o**.



Let's add one more node...

3. Iterate from the head towards the tail, stopping just before the tail.

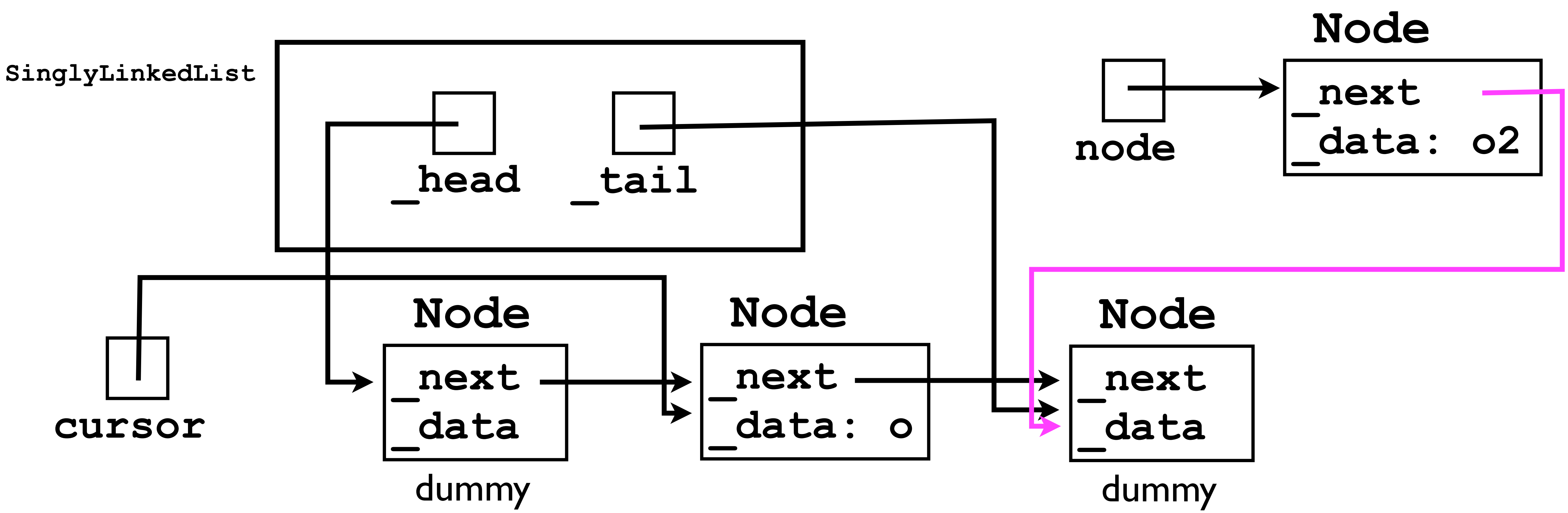
```
Node cursor = _head;
while (cursor._next != _tail) {
  cursor = cursor._next;
}
```



Let's add one more node...

4. Insert the new `Node` just after cursor.

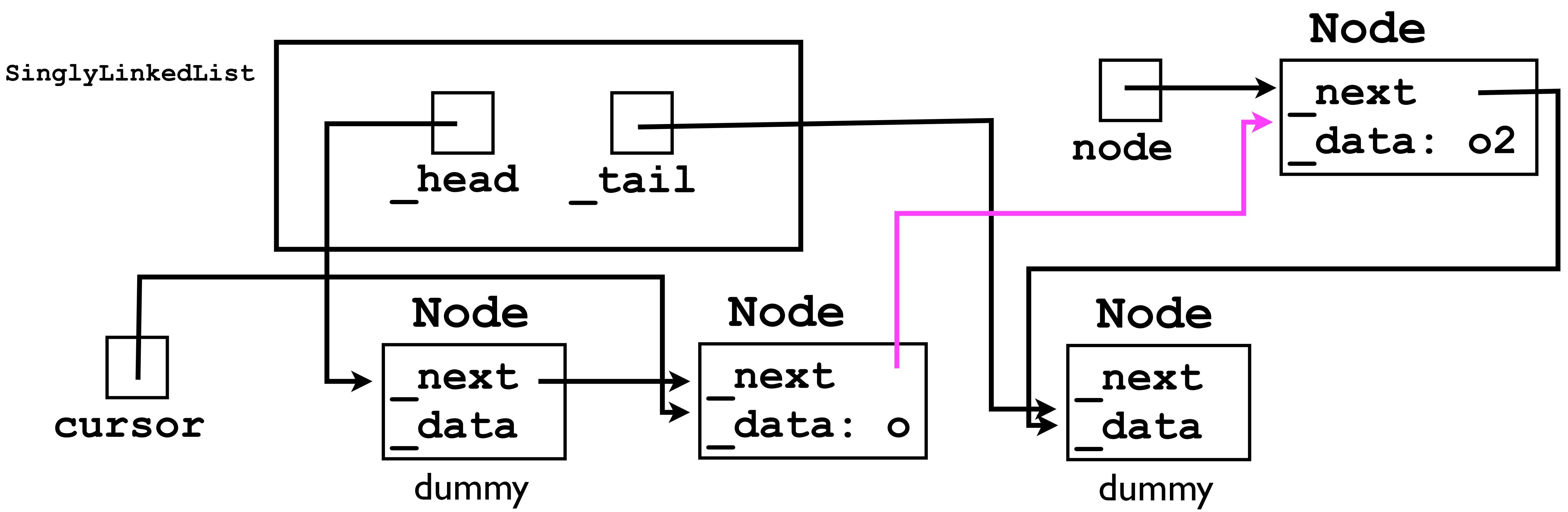
```
node._next = cursor._next;
```



Let's add one more node...

4. Insert the new **`Node`** just after cursor.

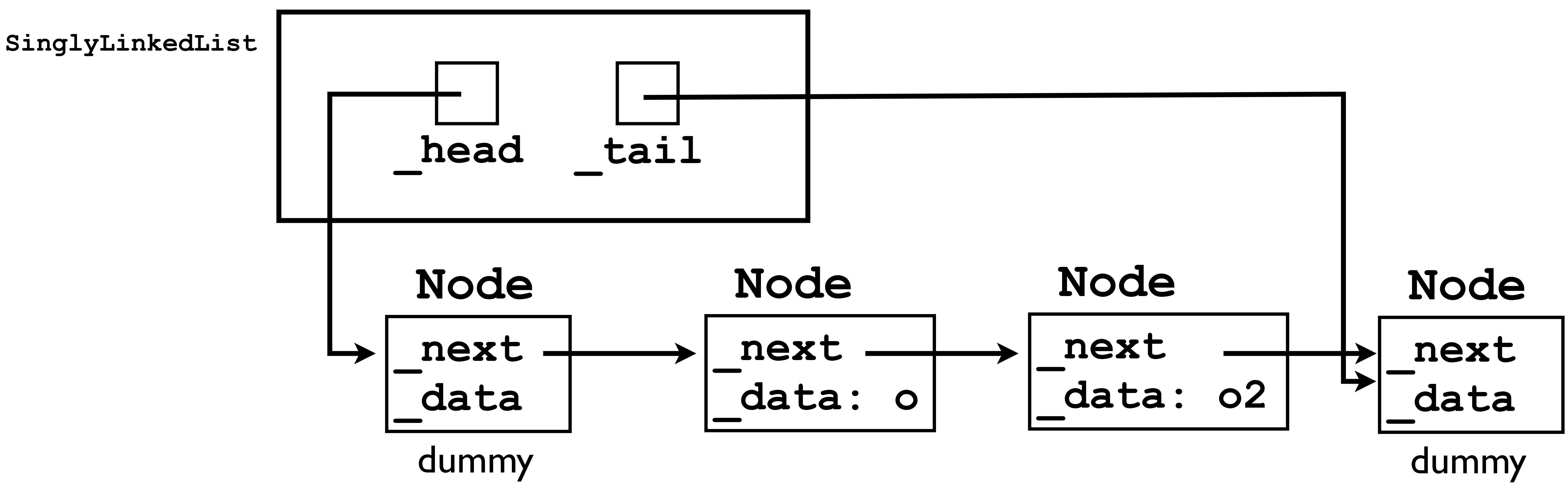
```
node._next = cursor._next;
cursor._next = node;
```



Let's add one more node...

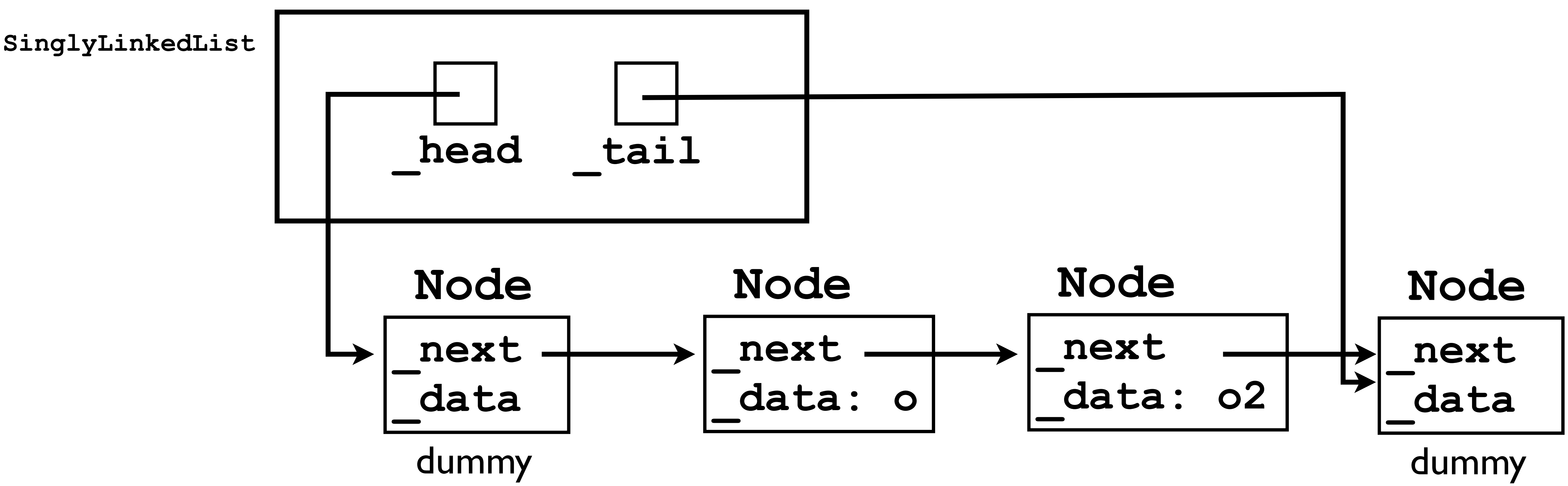
Done (and pulled taut again)!

Notice: Object `o2` is stored just "after" `o`, as required by `add(o)` specification in our `List` interface.



Reality check

- Which objects should `get(0)` and `get(1)` return on this list below?



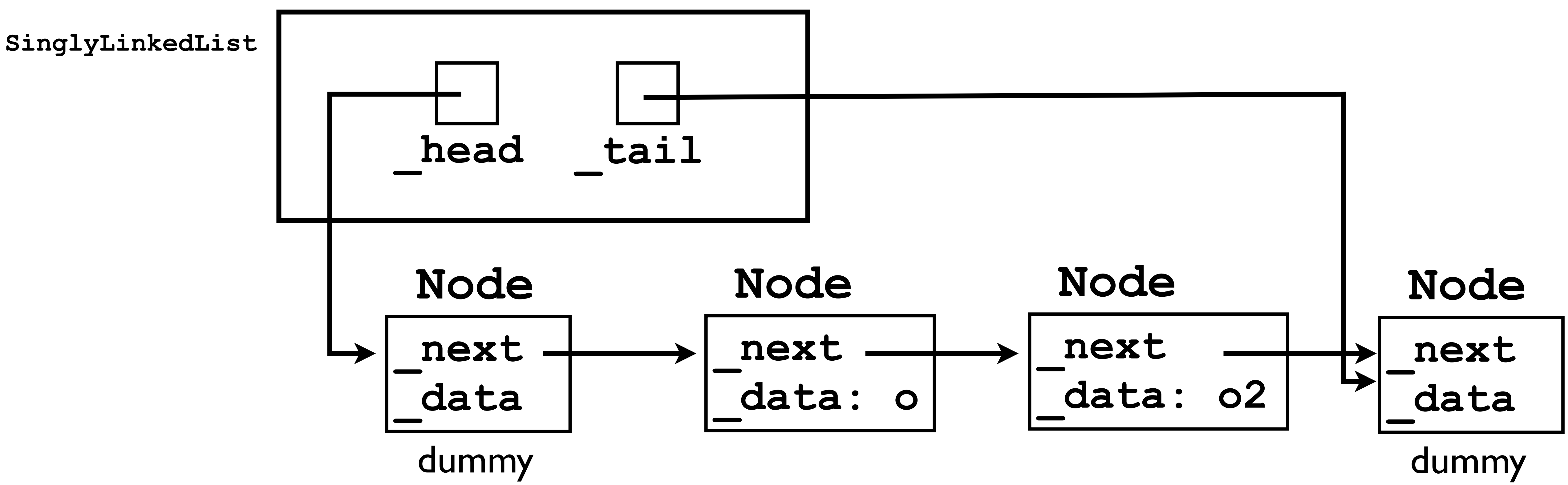
`void remove (int index)`

- Now let's consider how to implement the `remove(index)` method:

  1. Iterate a cursor from the dummy head towards the dummy tail until just *before* the node corresponding to `index`.
     - Index `0` is just after the dummy head.
     - Index `size-1` is just before the dummy tail.
  2. "Unlink" the `cursor._next` node from the chain.

void remove (int index)

- Now let's consider how to implement the **remove(index)** method:
  - As an example, let's show how **remove(1)** works on the **SinglyLinkedList** to which we just added two elements.

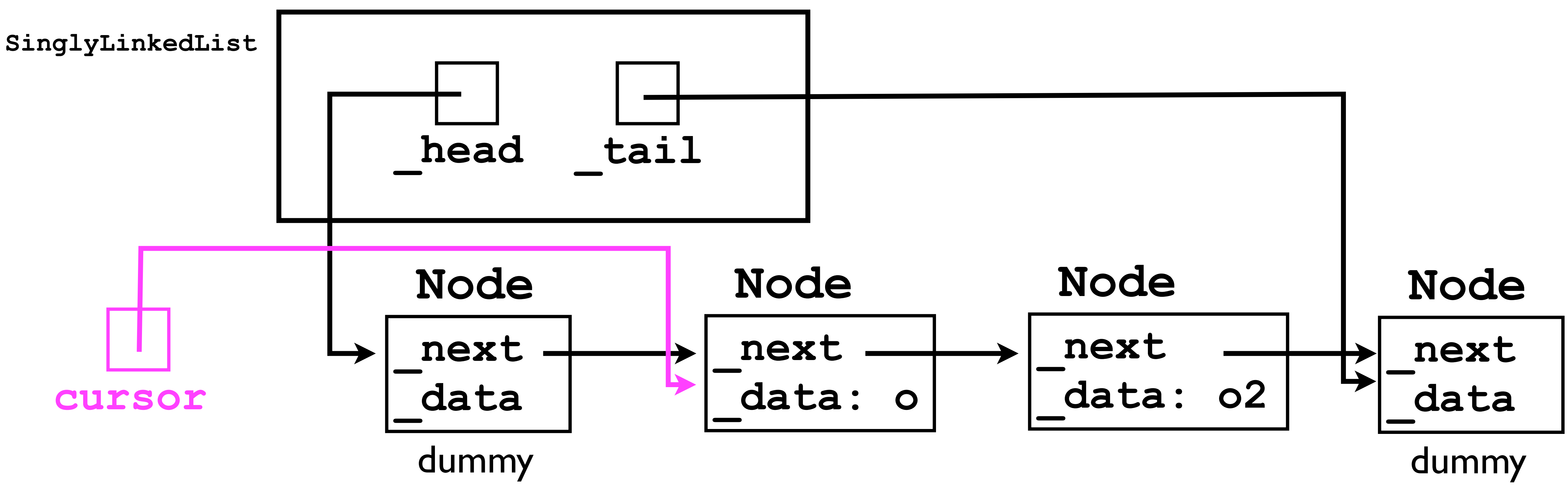


void remove (int index)

1. Iterate until just before the node corresponding to **index**.

```
Node cursor = _head;
for (int i = 0; i < index; i++) {
  cursor = cursor._next;
}
```

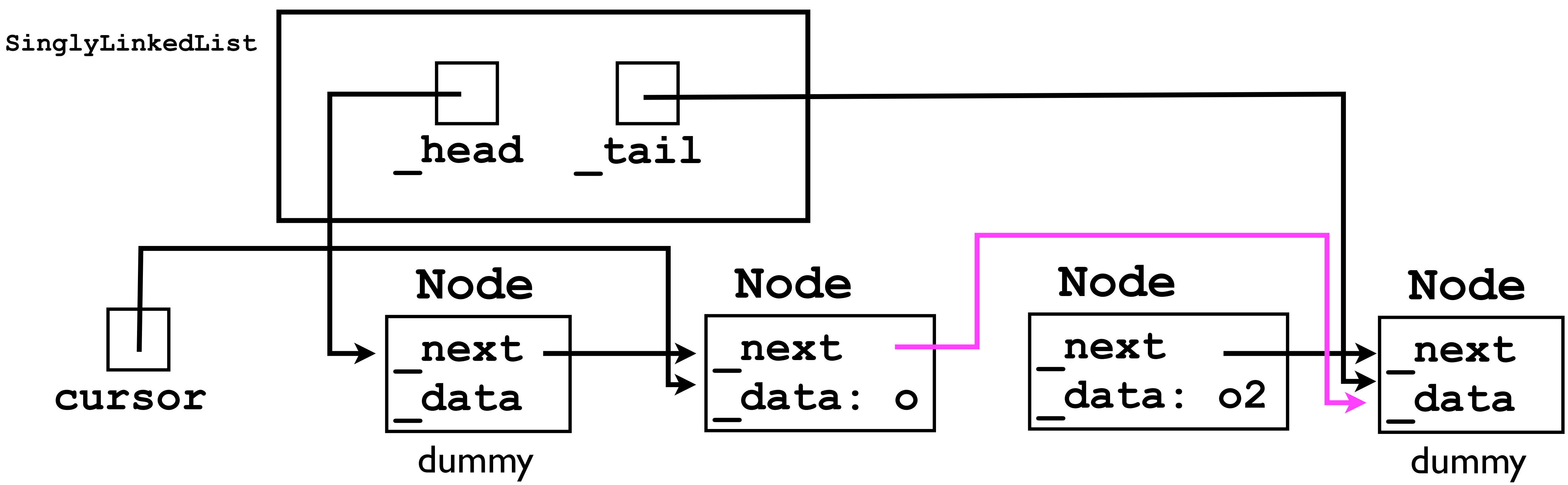
Let's assume for now that **index** is valid.



void remove (int index)

1. "Unlink" `cursor._next` from the chain.

```
cursor._next = cursor._next._next;
```

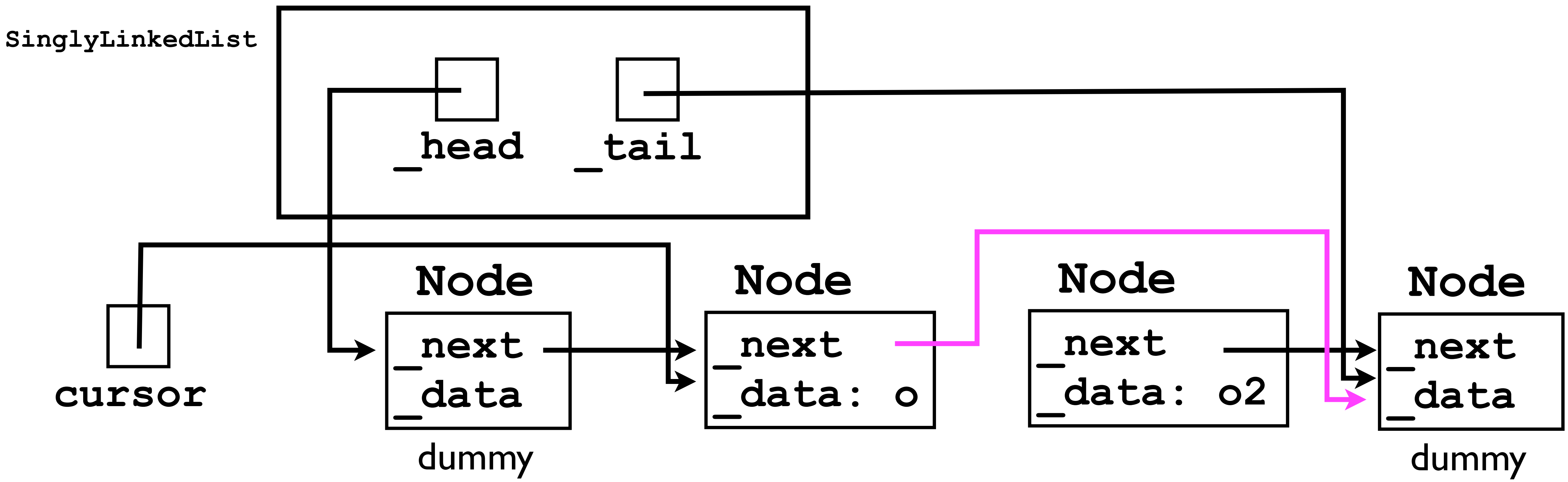


void remove (int index)

1. "Unlink" **cursor._next** from the chain.

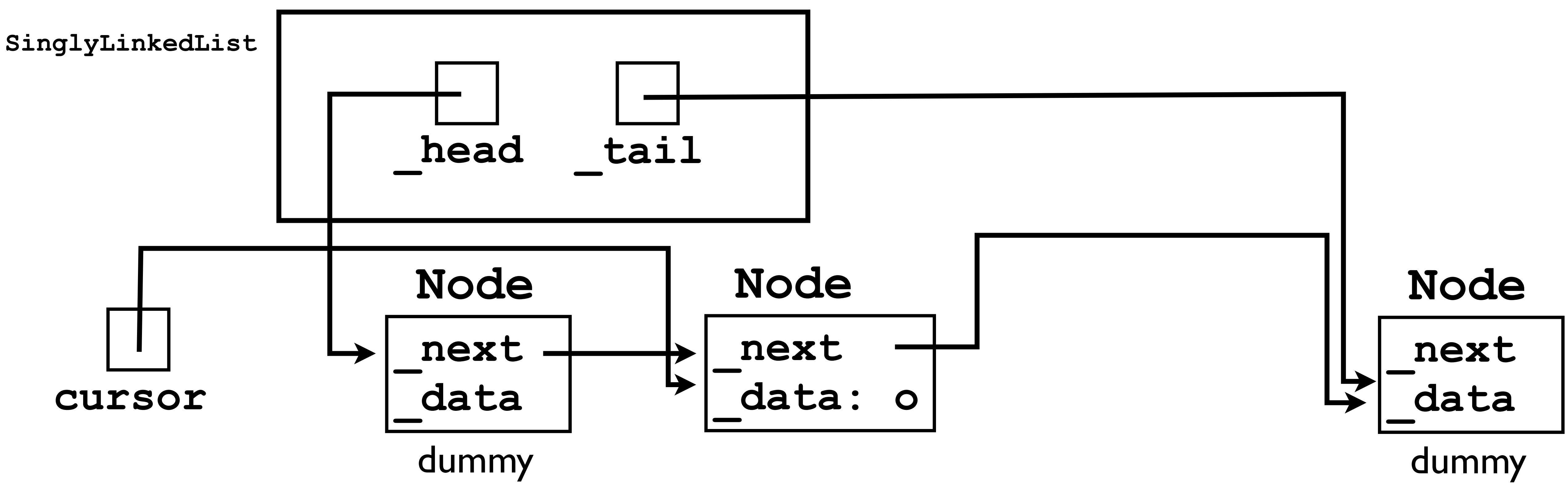
```
cursor._next = cursor._next._next;
```

Notice that *nothing points to* the **Node** we just unlinked; hence, the JVM garbage collector will eventually remove it...



void remove (int index)

Done! (You can pull it taut yourself.)



`Object get (int index)`

- If you followed the **`add(o)`** and **`remove(index)`** methods, then this one should be straightforward.

```
Object get (int index)
  throws IndexOutOfBoundsException {
  // TODO: check whether index is valid

  Node cursor = _head._next;
  for (int i = 0; i < index; i++) {
    cursor = cursor._next;
  }
  return cursor._data;
}
```

`int size ()`

- Finally, we need to implement a simple `size()` method.
- Two possible strategies:
  1. Add another instance variable int `_size` to `SinglyLinkedList`, which we increment/ decrement whenever `add`/`remove` is called.
  2. Don't add another variable; instead, count the number of nodes between the head and the tail whenever `size()` is called.
- Each strategy has its advantages & disadvantages.

`int size ()`

- On the one hand:
  - Using a `_size` instance variable is much faster -- whenever `size()` is called, we can return the result immediately.
    - Without a `_size` variable, we have to iterate over the whole list -- slow!
- On the other hand:
  - Adding a new variable always creates code complexity. In a sense, `_size` is *redundant* -- the size is already *implicitly* encoded in the number of nodes in the list. Maintaining a "copy" of the size in a `_size` variable gives us more opportunities to mess up.

`int size ()`

- In a linked list, updating `_size` is fairly easy.
  - In this case, it's probably worth adding a `_size` variable to reduce the time cost of the `size()` method, especially if we expect `size()` to be called frequently by the user.

SinglyLinkedList ADT

- Now that we know how to implement the four operations `add`, `remove`, `get`, and `size`, we can complete our `SinglyLinkedList` class.
- We now have two complete implementations of List:
  - `ArrayList`
  - `LinkedList`
- The "user" can use either implementation of `List` by *calling the same methods*.

`List` interface

```
final List list = new LinkedList();

list.add(“first”);
list.add(“second”);
list.add(“third”);
System.out.println(list.get(1));  // “second”
list.remove(0);
System.out.println(list.get(1));  // “third”
```

List interface

```
final List list = new ArrayList();

list.add("first");
list.add("second");
list.add("third");
System.out.println(list.get(1));  // "second"
list.remove(0);
System.out.println(list.get(1));  // "third"
```

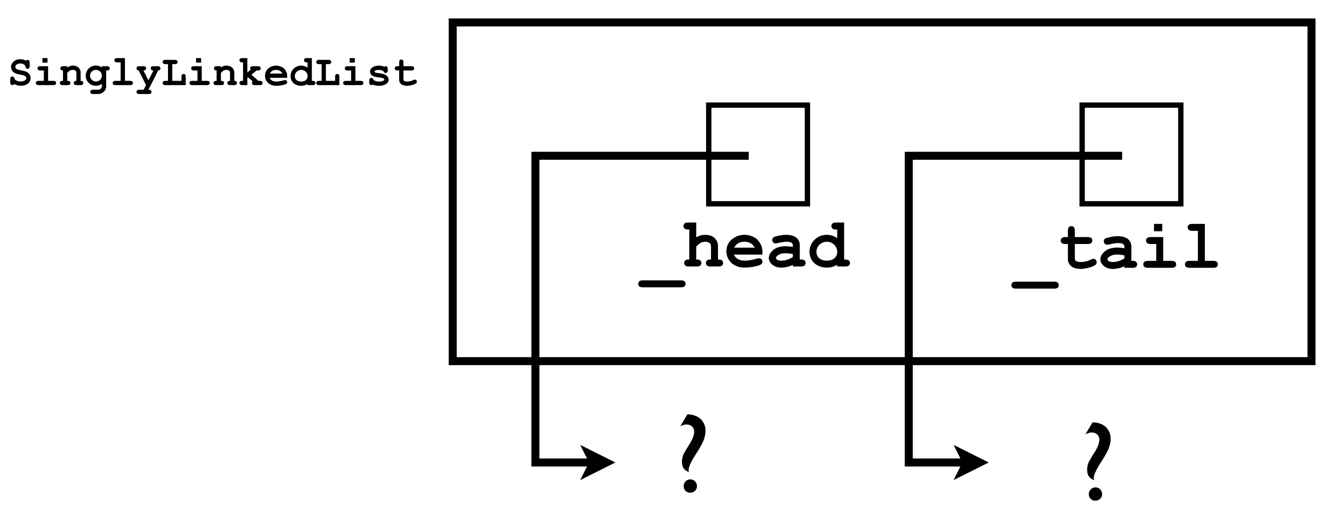
The user can change from a LinkedList to an ArrayList by changing one line of code. None of the remaining code need change at all.

Dummy nodes, revisited

- Let's now go back to our **`SinglyLinkedList`** ADT and consider how to implement it *without* dummy nodes.
- In this case, the **`_head`** points to the first node, and **`_tail`** points to the last node.
  - All nodes are "real" -- their **`_data`** pointers all point to data the user added.

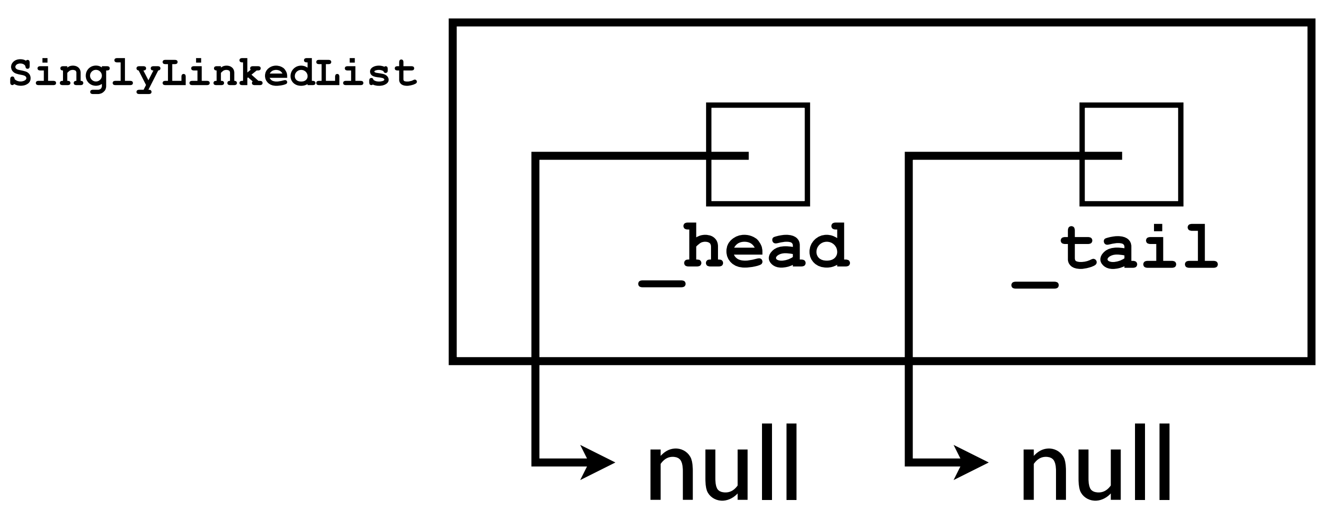
Dummy nodes, revisited

- But what if the list is empty? What should `_head` and `_tail` point to?



Dummy nodes, revisited

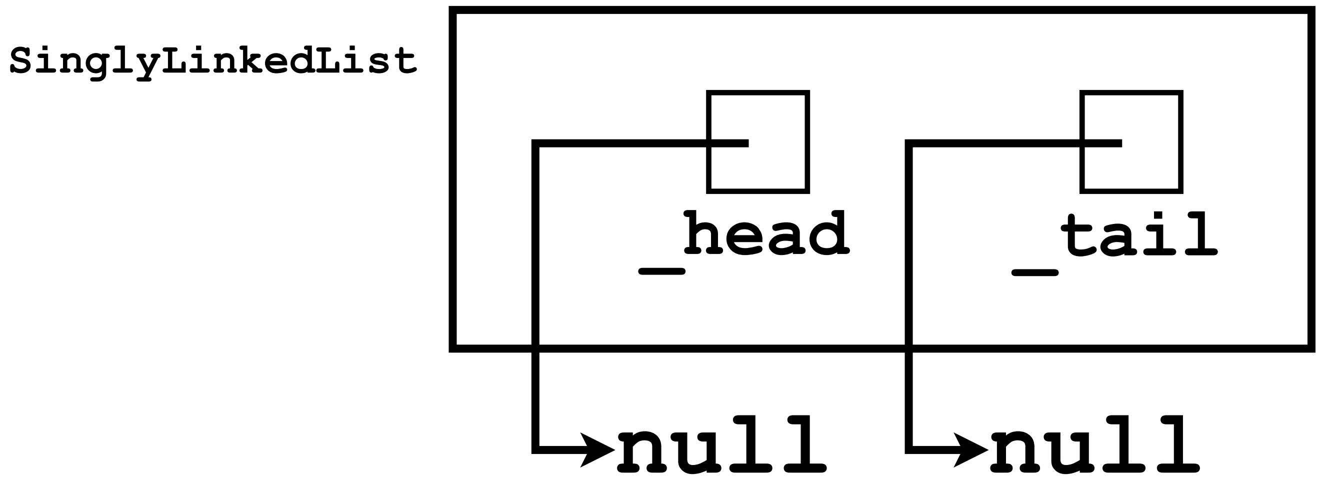
- If the list is empty, let's just set them both to **`null`**.
- Let's now consider how to implement **`add(o)`** without the dummy nodes.



`add(o)` without dummy nodes

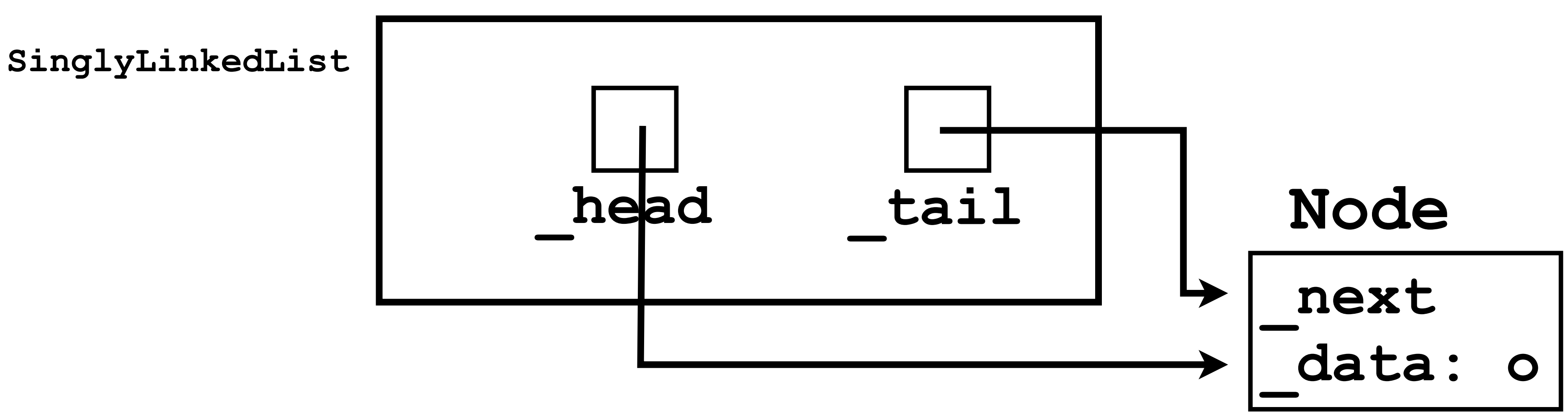
- What if `add(o)` is being called for the first time (i.e., on an empty list)?
  - To which node should the new **`Node`** be linked?

```
final Node node = new Node();
node._data = o;

...  // ??
```



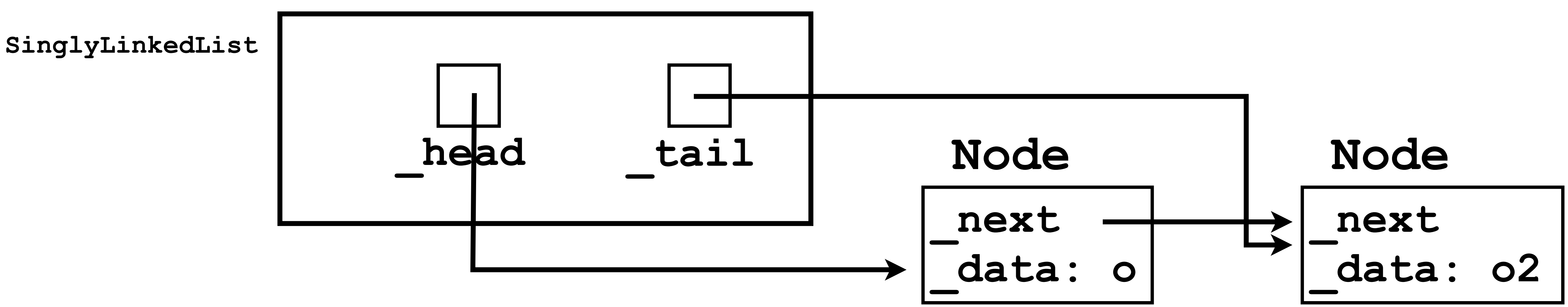
`add(o)` without dummy nodes

- What if `add(o)` is being called for the first time (i.e., on an empty list)?
  - To which node should the new `Node` be linked?
    - None -- *there is no other* `Node` yet.
    - We just set `_head` and `_tail` to the new `Node`.



`add(o)` without dummy nodes

- What if `add(o)` is being called for the second (or later) time?
  - To which `Node` should the new `Node` be linked?
    - The *tail* -- now it actually exists.



`add(o)` without dummy nodes

- Without dummy nodes, the `add(o)` method must be implemented with an *if*-statement:

```
final Node node = new Node();
node._data = o;
if (_head == null) {  // List is empty
   _head = _tail = node;
} else {  // List is not empty
   _tail._next = node;
   _tail = node;
}
```

- The *if*-statement makes the `add(o)` method more complicated than when using dummy nodes.

`SinglyLinkedList` without dummy nodes

- Similarly, when implementing **`remove(index)`** without dummy nodes, there must be an *if*-statement to distinguish two cases:
  - Removing a node from a list of size 1.
  - Removing a node from a list of size >1.
- The dummy nodes require a bit more space (two "wasted" nodes), but they make the programming easier -- a worthwhile trade-off.

Doubly linked lists.

Problems with singly-linked lists

- Singly-linked list ADTs are useful because they:

  1. Grow automatically as the user adds more data.
  2. Do not suffer from the "contiguity" problem like ArrayLists do.
  3. Store only as many nodes as required (maybe +2 dummy nodes, but 2 nodes is not a big cost).

Problems with singly-linked lists

- However, singly-linked list ADT also suffer from a few drawbacks:

  1. Expensive to "jump" to particular element index.

     - Have to iterate from the head towards the tail.

Problems with singly-linked lists

- However, singly-linked list ADT also suffer from a few drawbacks:
  1. Expensive to "jump" to particular element index.
     - Have to iterate from the head towards the tail.
       - "Iterating" to the desired element is fundamental to linked lists -- there's no real way to avoid this.

Problems with singly-linked lists

2. There's no easy way to iterate *backwards*.

- Each node only contains a **`_next`** pointer.

Problems with singly-linked lists

2. There's no easy way to iterate *backwards*.

- Each node only contains a **`_next`** pointer.
- This can be remedied using a *doubly*-linked list.

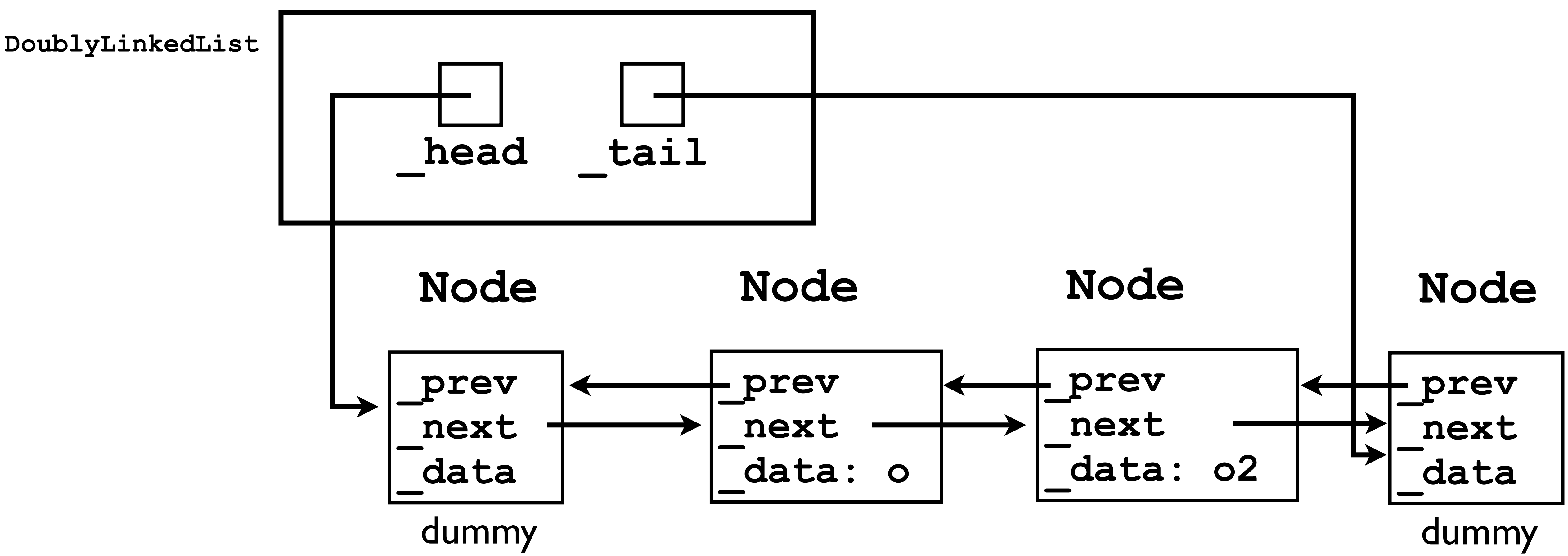
Doubly-linked lists

- In a doubly-linked list, each **`Node`** object has both a **`_next`** and a **`_prev`** pointer:

```
class Node {
  Node _next, _prev;
  Object _data;
}
```

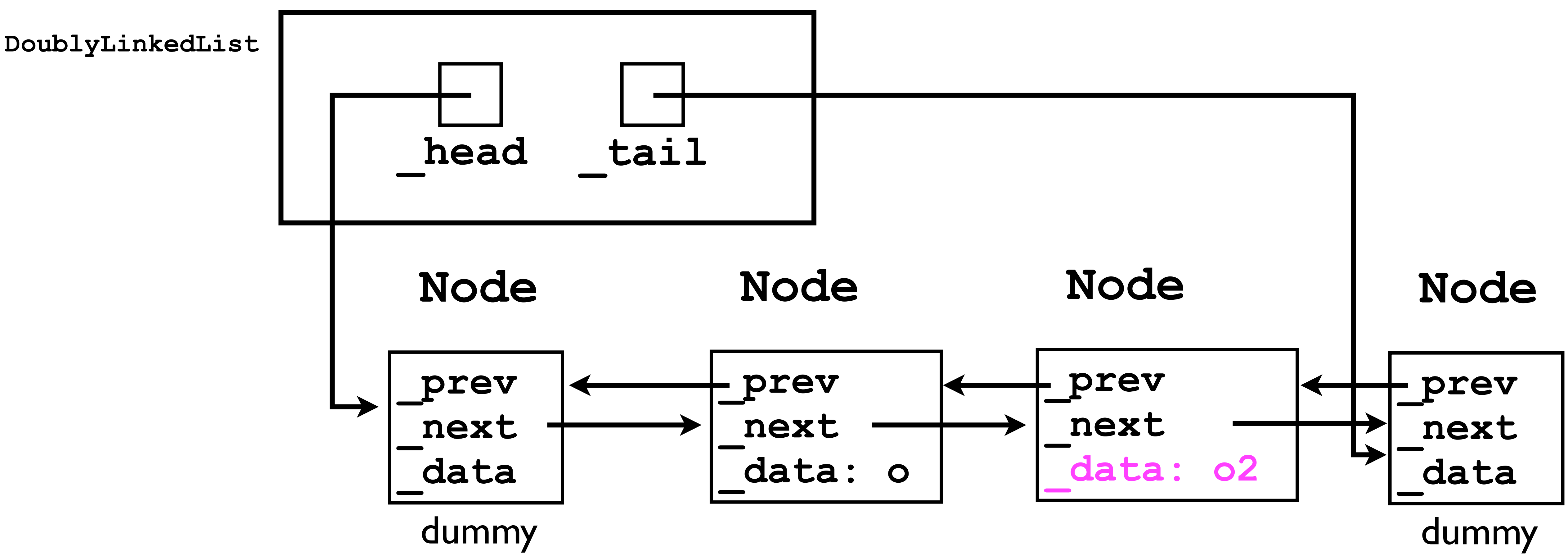
Doubly-linked lists

- A doubly-linked list containing 2 “real” nodes, and using 2 dummy nodes, would look like:



Doubly-linked lists

- With doubly-linked lists, it's very fast to access nodes close to the tail, e.g.:
```
final Object lastElement = _tail._prev._data;
```



Doubly-linked lists

- In particular, it is fast to remove an element from either end of the list.
  - Just "unlink" the node **`_tail._prev`**.
  - No need to "iterate through" the list (starting at the head) to get to the tail.

Linked list variants

- There exist other linked-list "variants" as well, e.g., circular lists.
- We will cover these next week.

P1

- In programming project 1, you must implement a doubly-linked list to implement the `List12` interface.
- It's up to you whether you use dummy nodes or not. (I recommend you do because it simplifies the code.)
- Make sure to carefully adhere to the `List12` *interface specification*.

P1

- As a specific requirement, your **`addToFront()`**, **`addToBack()`**, **`removeFront()`**, and **`removeBack()`** methods *must* operate "efficiently".
  - Since you are implementing a doubly-linked list, there is no need to always "iterate through" the list starting at the head.
  - If you're implementing **`addToFront()`** or **`removeFront()`**, start at the *head*.
  - If you're implementing **`addToBack()`** or **`removeBack()`**, start at the *tail*.

P1

- Your `DoublyLinkedList12` class must *implement* the `List12` interface.
- `List12` is a *subinterface* of `Iterable`.
  - In a similar way that a subclass extends its parent class, a subinterface extends its parent interface.
- Therefore, your `DoublyLinkedList12` must also be `Iterable`.
- What defines an "`Iterable`" class?
  - It must implement the following method: `Iterator iterator ();`

P1

- But what is an `Iterator`?

Iterators.

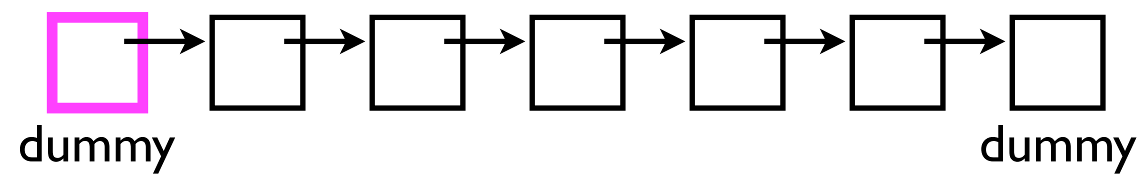
Iterating over elements of a data structure.

- Many ADTs offer the user the ability to iterate over all of their elements in some "natural order".
- With the simple `List` interface defined during lectures, this is already possible using the `get(index)` methods:

```
final int size = linkedList.size();
for (int i = 0; i < size; i++) {
  System.out.println(linkedList.get(i));
}
```

Iterating over elements of a data structure.

- However, that approach will also be very *slow*:
- **`linkedList.get(0)`**



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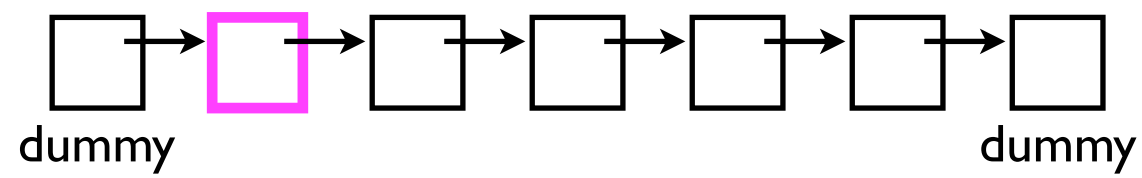

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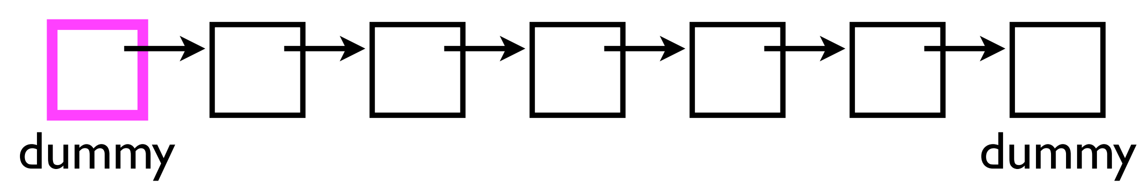

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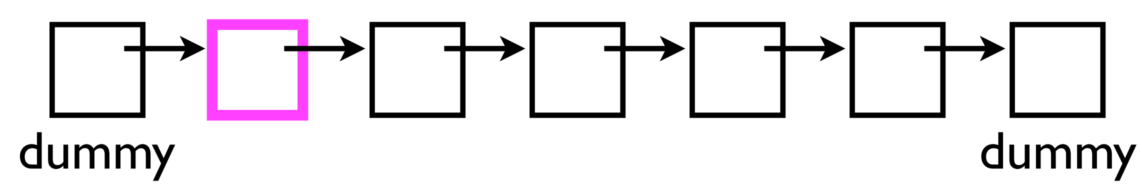

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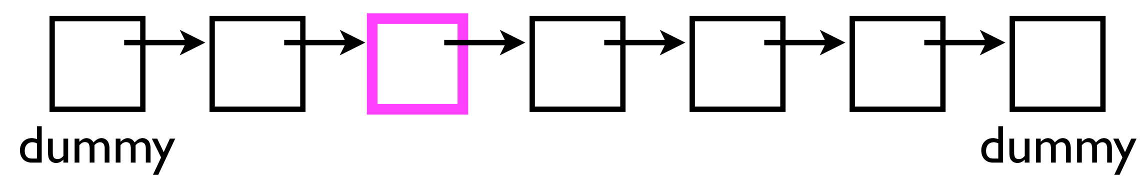

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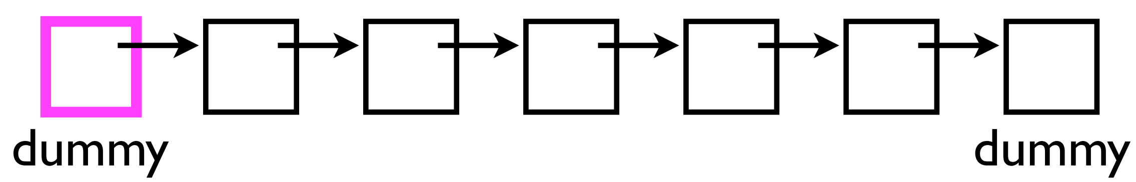

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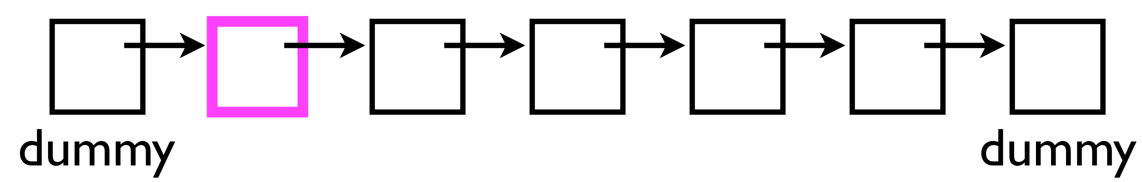

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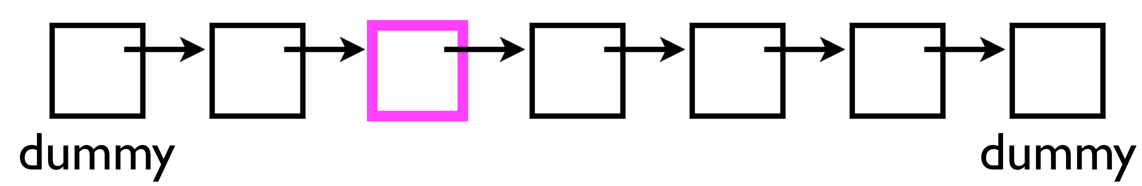

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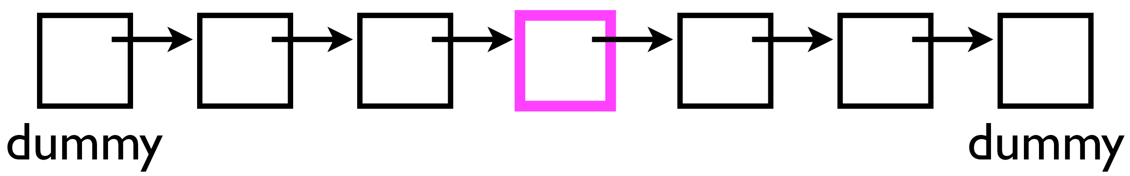

We keep "re-iterating" -- starting from scratch back at the head. This is computationally wasteful. Why can't we just pick up where we left off?

Iterators: performance benefits

- An “iterator” object helps us to avoid this wasted computation.
- An iterator is a “helper object” with which the user can iterate across all elements in a data structure.
- The iterator will “remember” where it left off.

Iterators: software design gain

- Iterators are also useful because they offer a *uniform* way of accessing all of a data structure's elements.
  - Even very different data structures -- e.g., graphs and lists -- can both support iterators.
  - An "iterator" is one of the fundamental *design patterns* of software engineering. (More on this later.)

interface Iterator

- In Java, the `Iterator` interface contains three method signatures:

```
boolean hasNext();
Object next();
void remove();
```

`interface Iterator`

- Your **`DoublyLinkedList12`** class must implement the method:
  `Iterator iterator();`
- I.e., it must return an **`Iterator`** via the **`iterator()`** method.
- But **`Iterator`** is itself an interface, not a class.
- This means that your **`iterator()`** method is allowed to return an object of *any* class that implements **`Iterator`**.
  - It will be most convenient (and required in P1) to implement your **`Iterator`** as an inner-class, e.g., **`DoublyLinkedList12Iterator`**.

How `Iterators` are used

- Here's how the "user" would use an **`Iterator`** to print out every element in a linked list.

```
final Iterator iterator = linkedList.iterator();
while (iterator.hasNext()) {
  System.out.println(iterator.next());
}
```

How `Iterators` are used

- Here's how the "user" would use an **`Iterator`** to print out every element in a linked list.

User calls **`hasNext()`** to "ask" the Iterator if there's another element to fetch.

```
final Iterator iterator = linkedList.iterator();
while (iterator.hasNext()) {
  System.out.println(iterator.next());
}
```

User calls **`next()`** to actually fetch the next element from the Iterator.

`hasNext()` and **`next()`**

- Note that the user is not "required" by the **`Iterator`** interface to call the **`hasNext()`** method.
  - **`next()`** will still work correctly without previously calling **`hasNext()`**.
  - (But practically speaking, how else will the user know he/she is "done" iterating?)

`remove()`

- The Iterator interface also gives the user the ability to remove elements from the linked list *while iterating through them*.

`remove()`

- E.g., consider a linked list containing 5 objects (`o1`, `o2`, `o3`, `o4`, `o5`).

```
final Iterator iterator = linkedList.iterator();
iterator.next();  // returns o1
iterator.next();  // returns o2
iterator.next();  // returns o3
iterator.remove();// removes o3
iterator.next();  // returns o4
iterator.next();  // returns o5
```

- If you subsequently called `linkedList.size()`, you would get 4 -- *the linked list itself has changed.*
  - The `Iterator` object returned by `linkedList.iterator()` is "tied" to the underlying `LinkedList` object.

`remove()` and **`next()`**

- Before the user is "allowed" to call the **`remove()`** method, he/she *must* first call the **`next()`** method.
  - If he/she does not, the Iterator *must* throw an **`InvalidStateException`**.

Implementing Iterators

- The tricky thing about implementing an Iterator is that "you the implementor" do not get to decide when to traverse from one node to the next (e.g., `node = node._next`) -- the *user* decides that.
- The `Iterator` objects that your linked-list constructs (and returns in `iterator()`) must *remember* their position in the linked list -- and pick off where it left off when the user calls `next()` again.