CSE 12:
Basic data structures and object-oriented design

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Lecture Four
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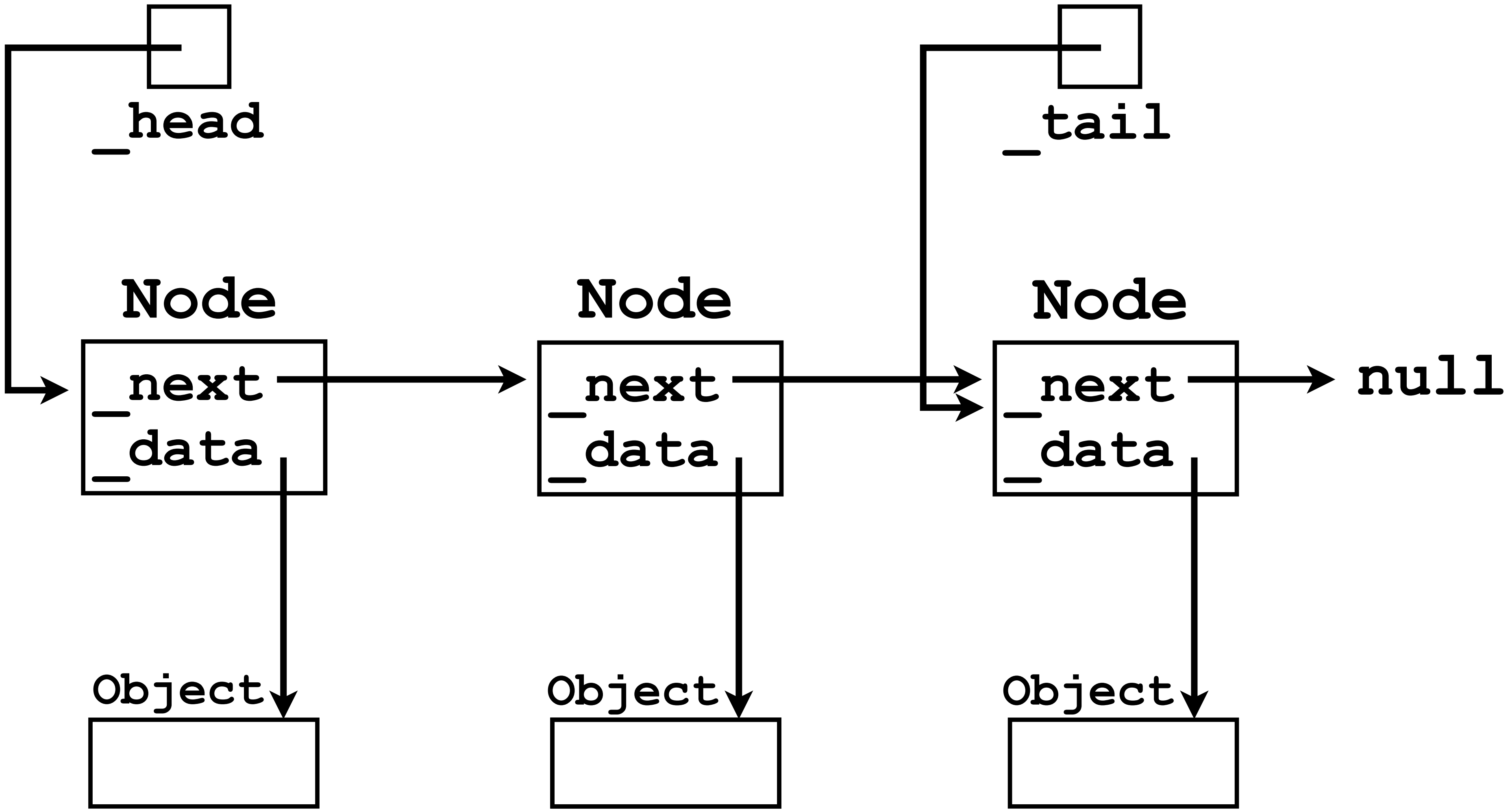
Linked lists, continued.

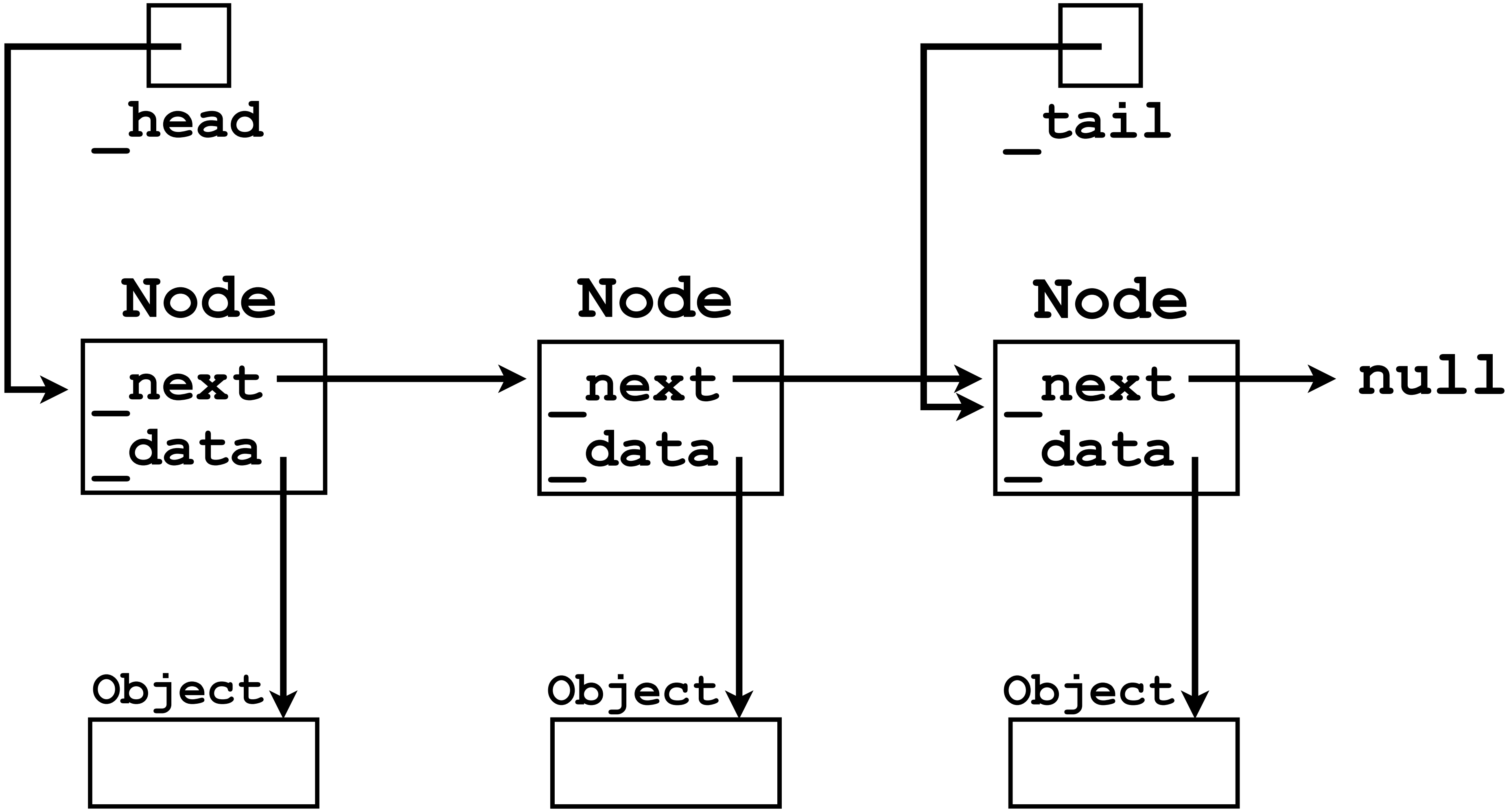
Review from last lecture

- 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

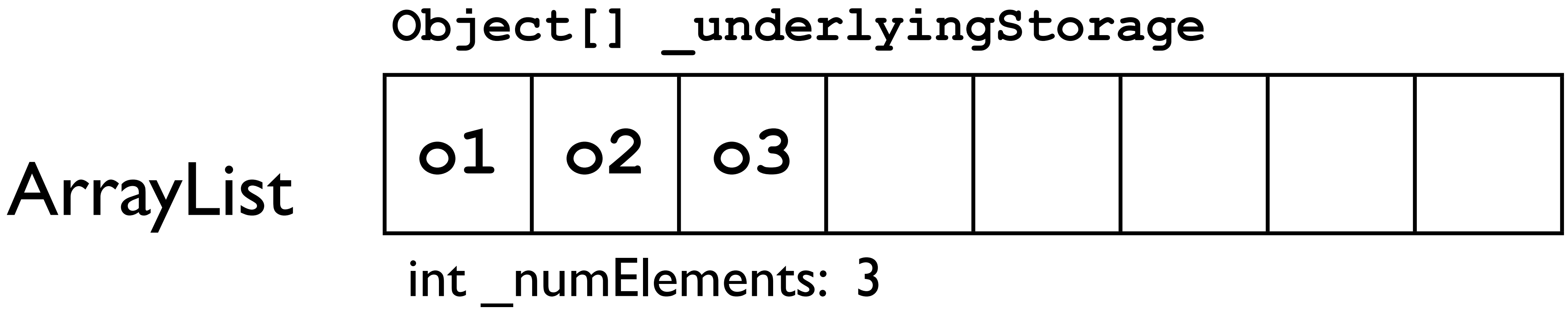
- Each `Node` contains a reference to an `Object` that the user wants to store (`node._data`).
- Each `Node` also contains a reference to the next "link" (`Node`) in the chain (`node._next`).



Nodes

- **`Nodes`** 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);
```

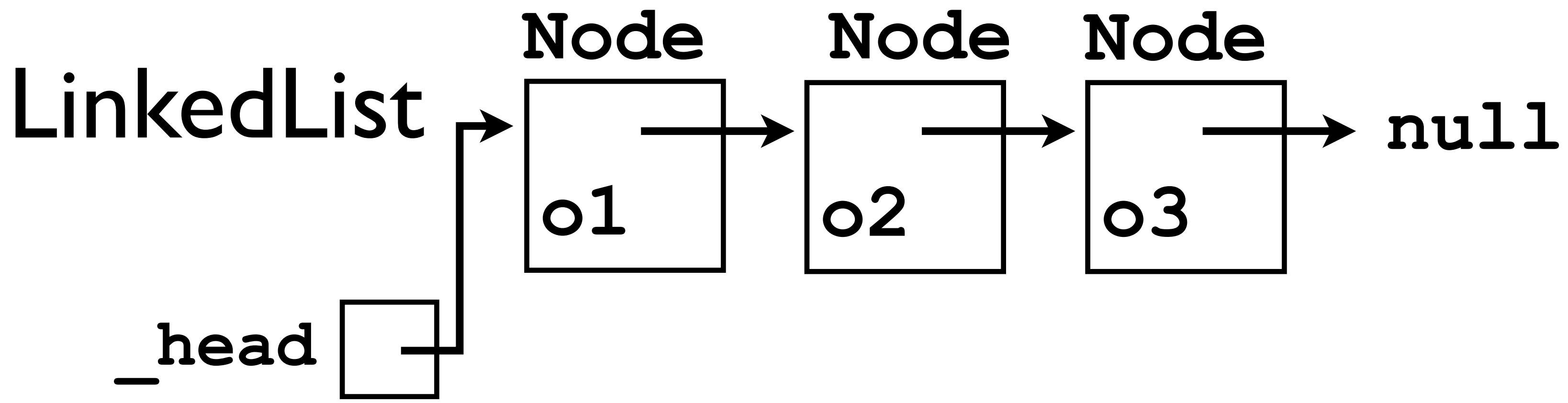


`Object[] _underlyingStorage`

ArrayList

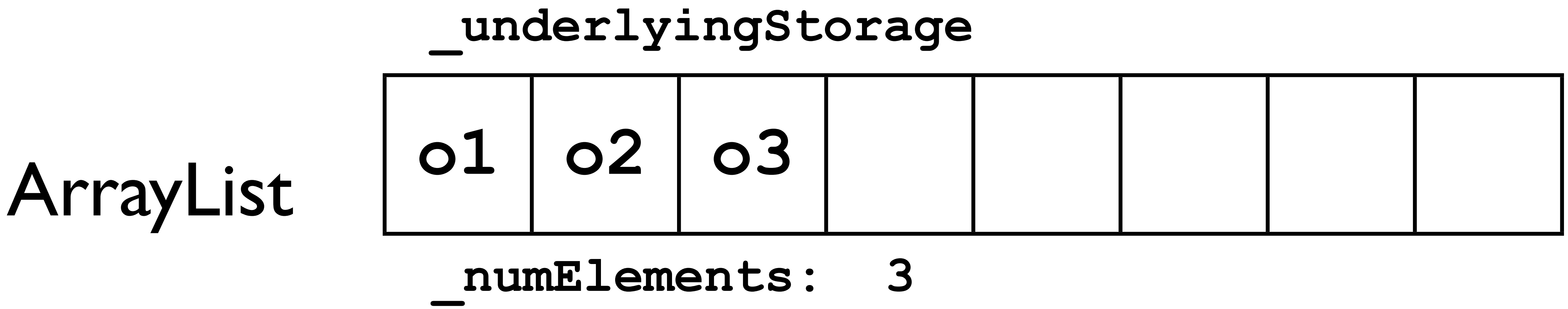
o1	o2	o3					

int _numElements: 3

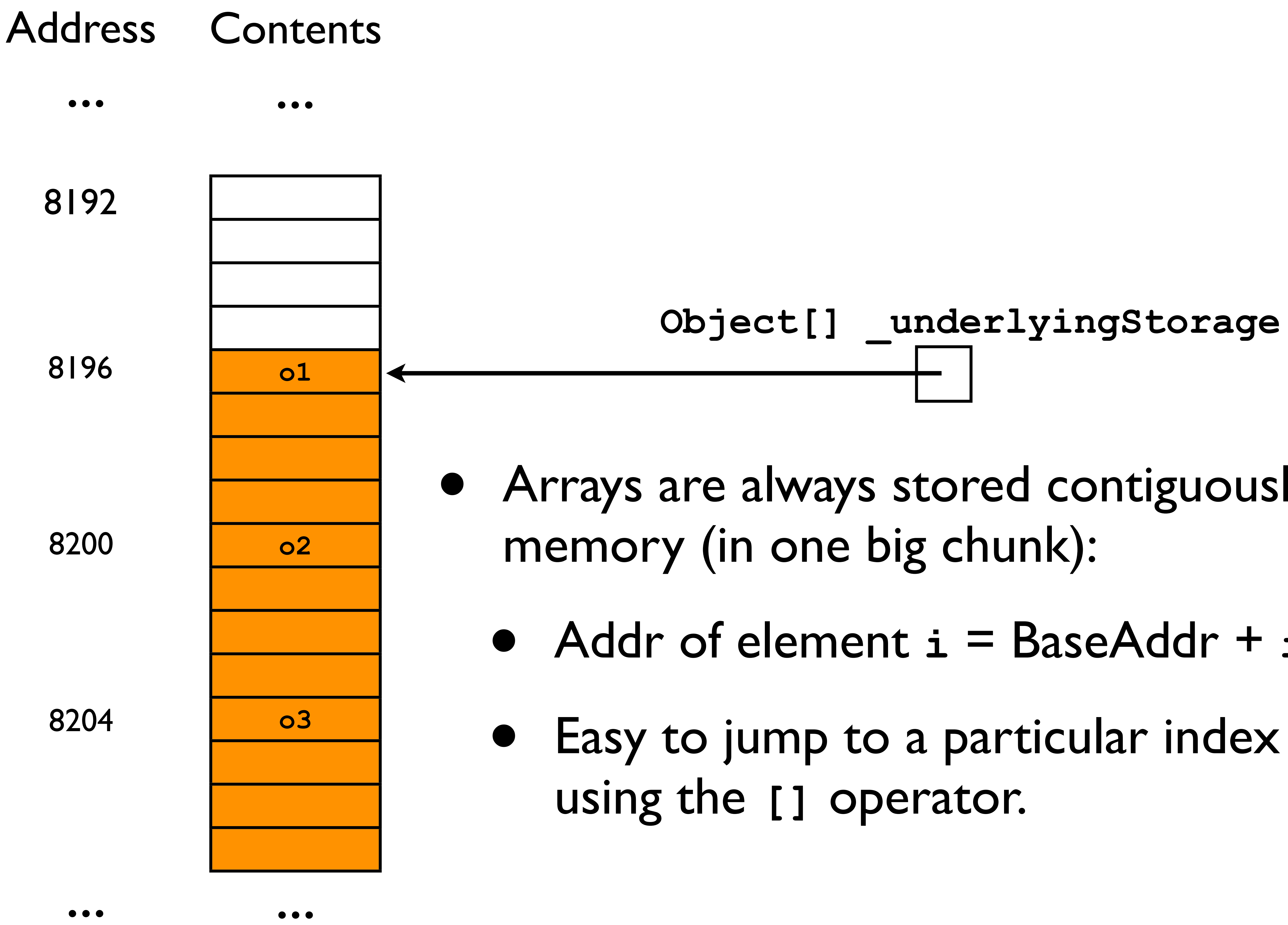


Elements of an array

- 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



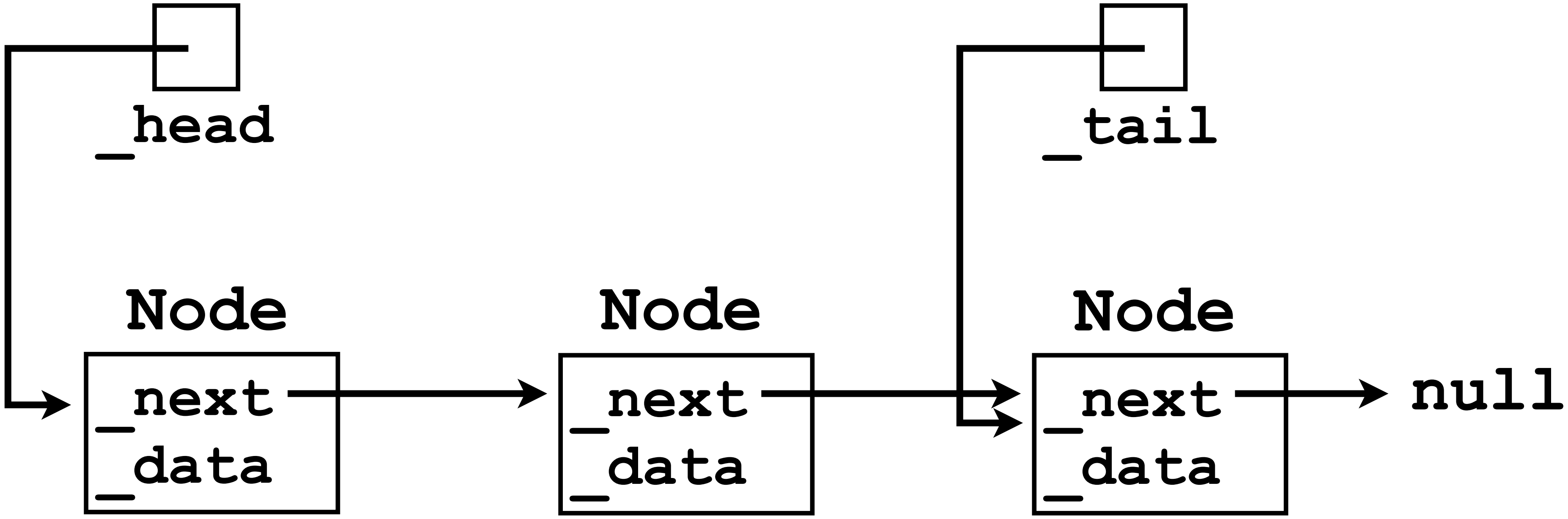
- Arrays are always stored contiguously in memory (in one big chunk):
  - Addr of element `i` = BaseAddr + `i` * 4
  - Easy to jump to a particular index using the `[]` operator.

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.

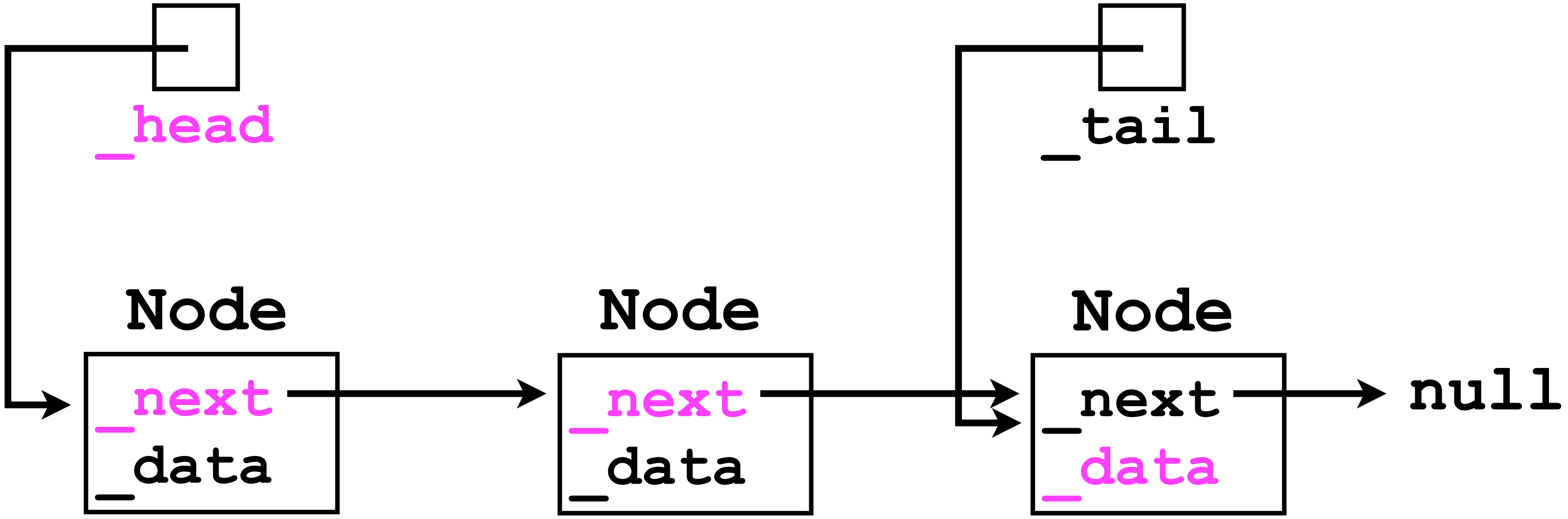
Finding a particular node

- 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

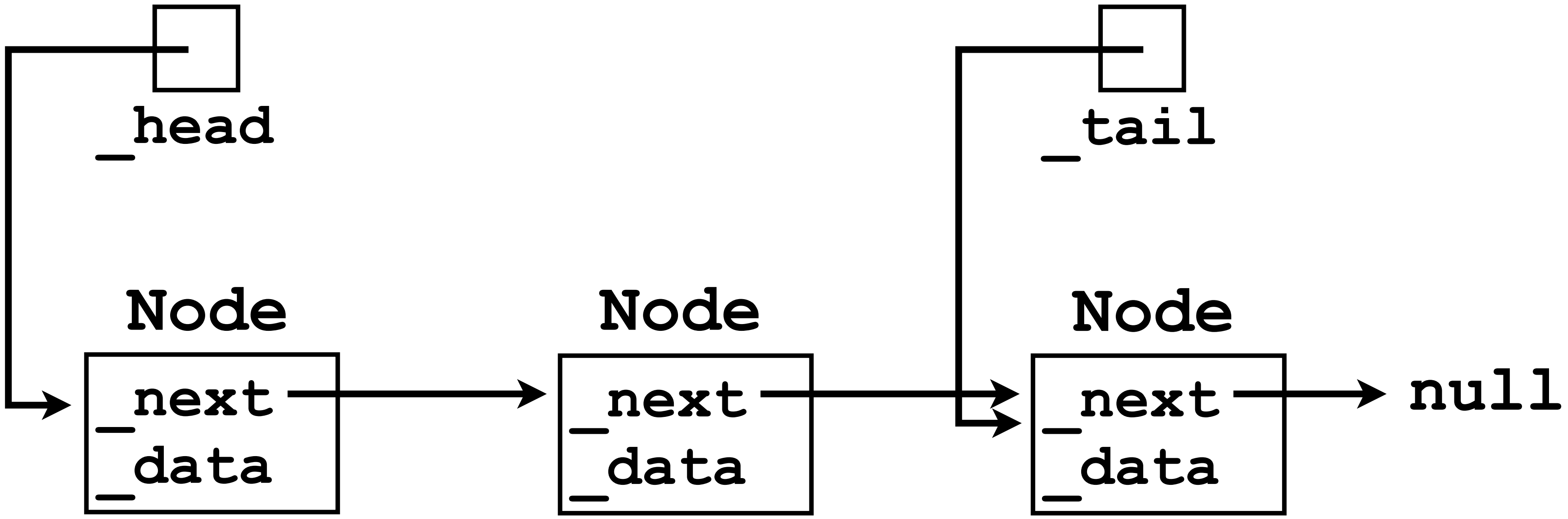
`final Object thirdElement = _head._next._next._data;`



Finding a particular node

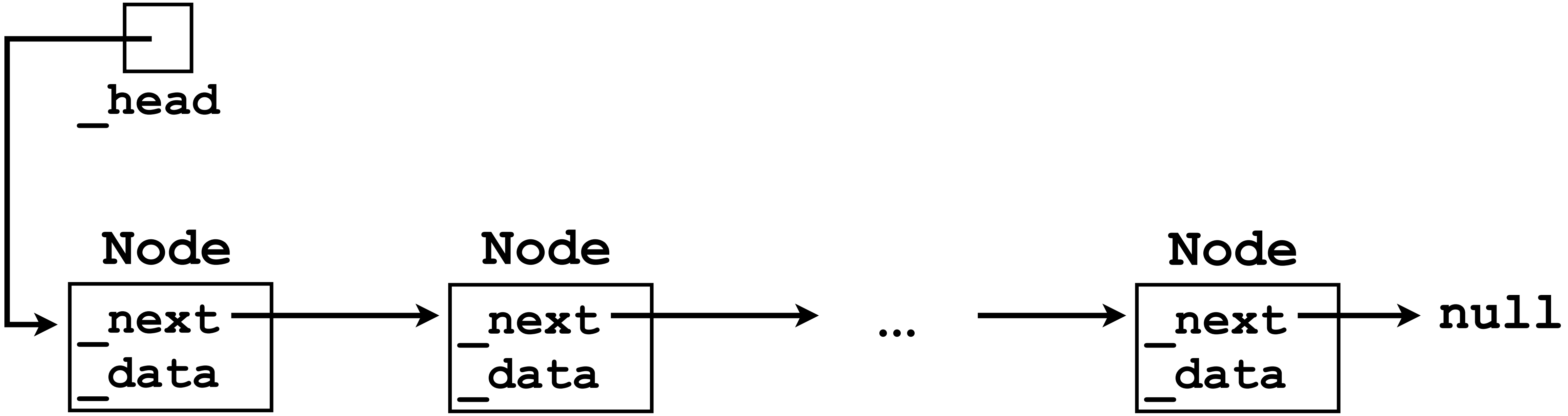
- Alternatively, we could use a *for*-loop:

```
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

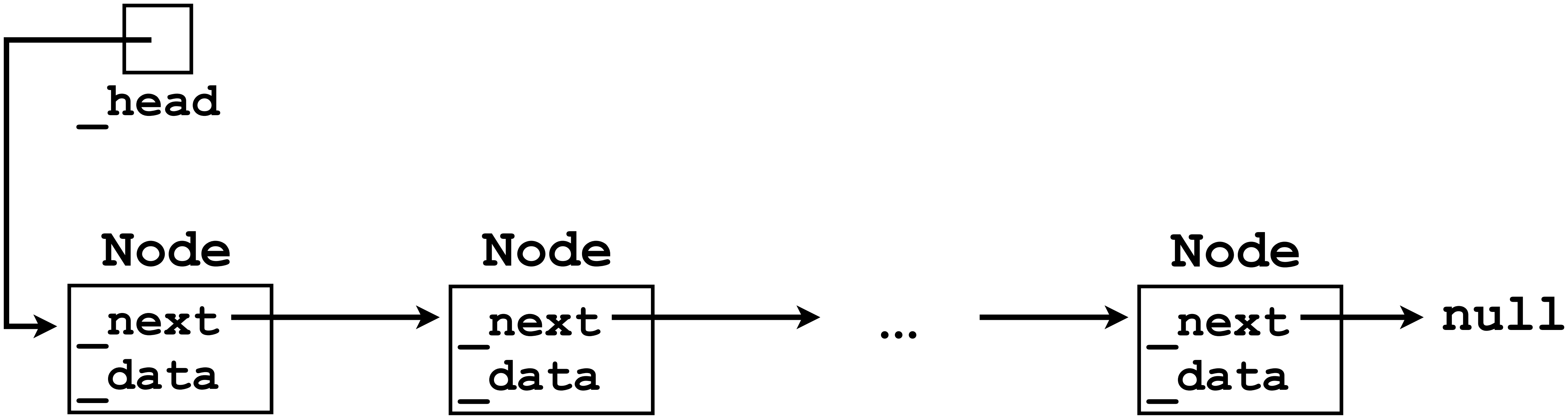
- Suppose we wish to iterate through the *entire list* and print out the **`_data`** in each node?



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;
```

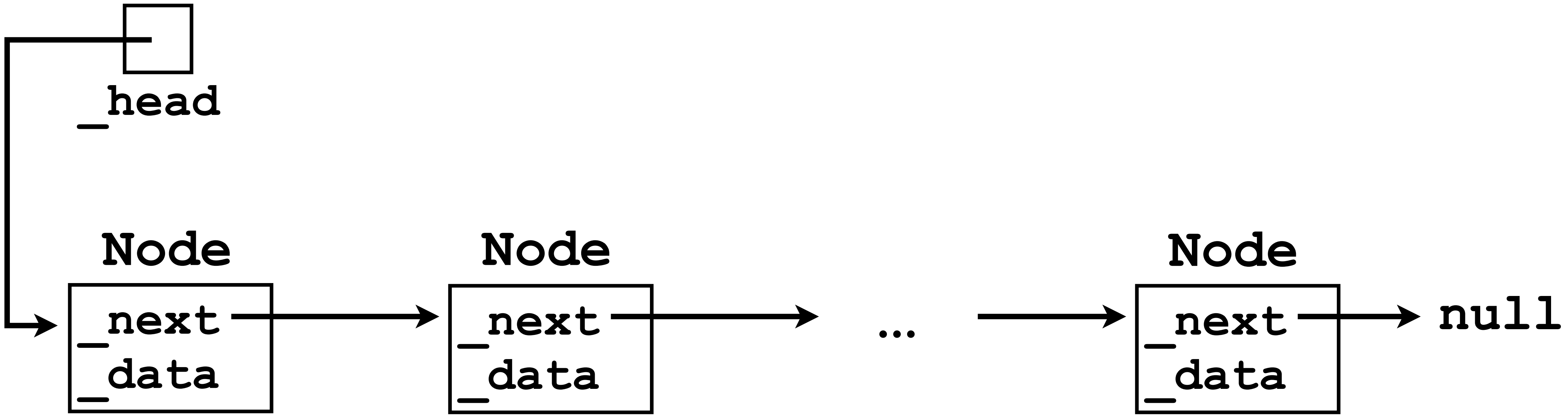


Iterating through the whole list

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

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


}
```

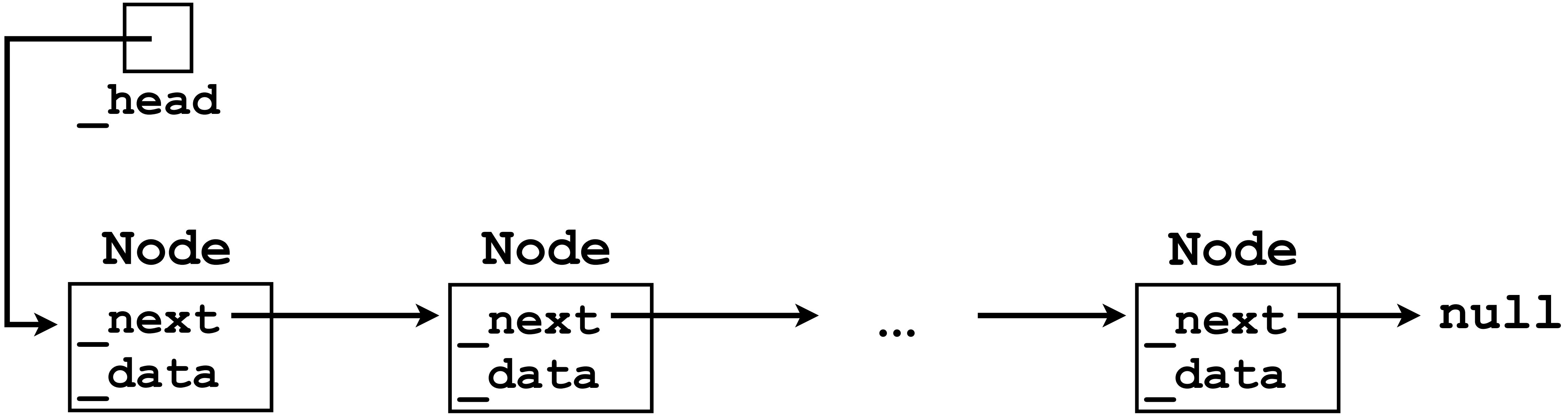


Iterating through the whole list

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

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


}
```

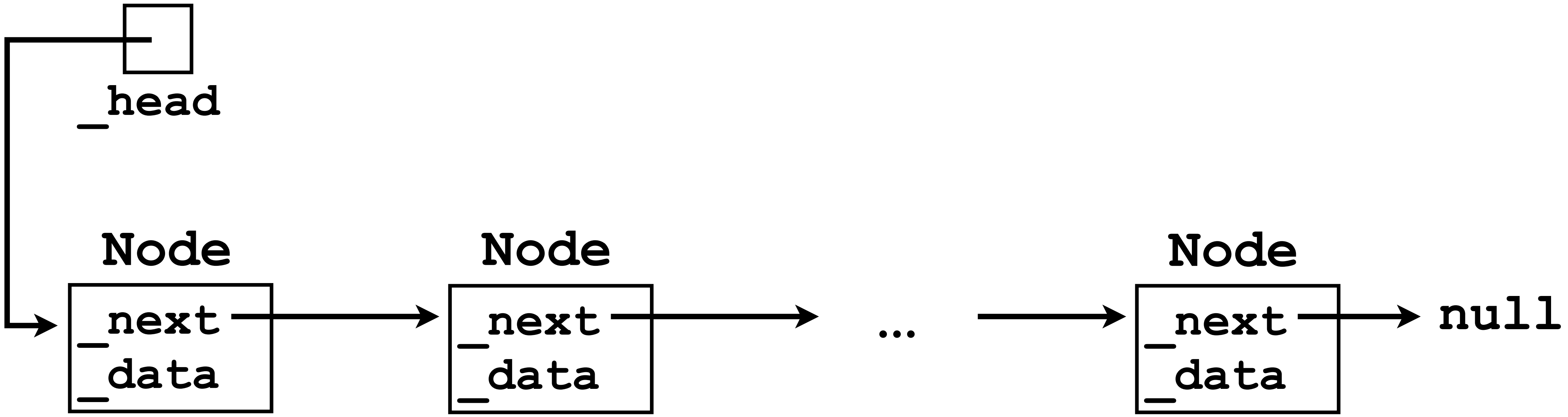


Iterating through the whole list

- 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);

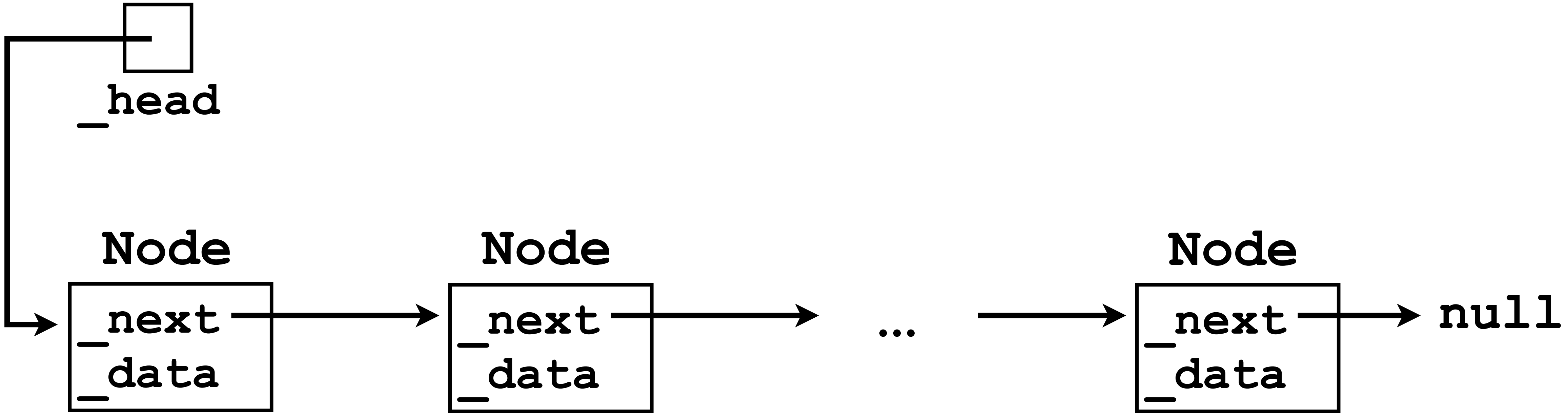
}
```



Iterating through the whole list

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

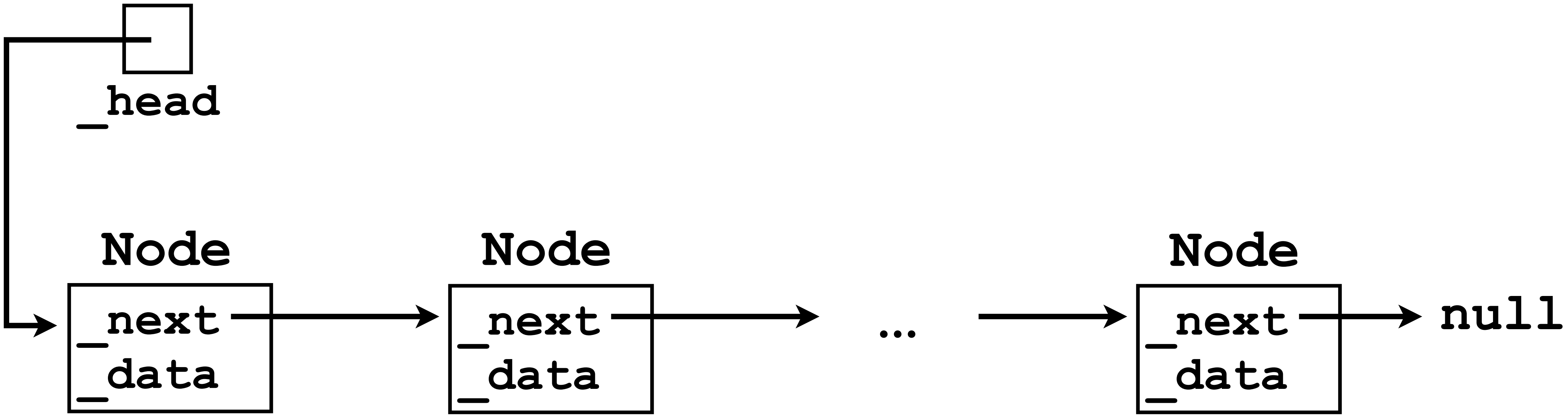
```
Node cursor = _head;
while (cursor != null) {
  System.out.println(cursor._data);
  cursor = cursor._next;
}
// Done!
```



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!
```



_head

Node **Node** **Node**

_next **_next** ... **_next** **null**

_data **_data** **_data**

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 an (expanded) **`List`** interface...

```
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 **`Node`**s 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.*
    - **`Node`**s 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;

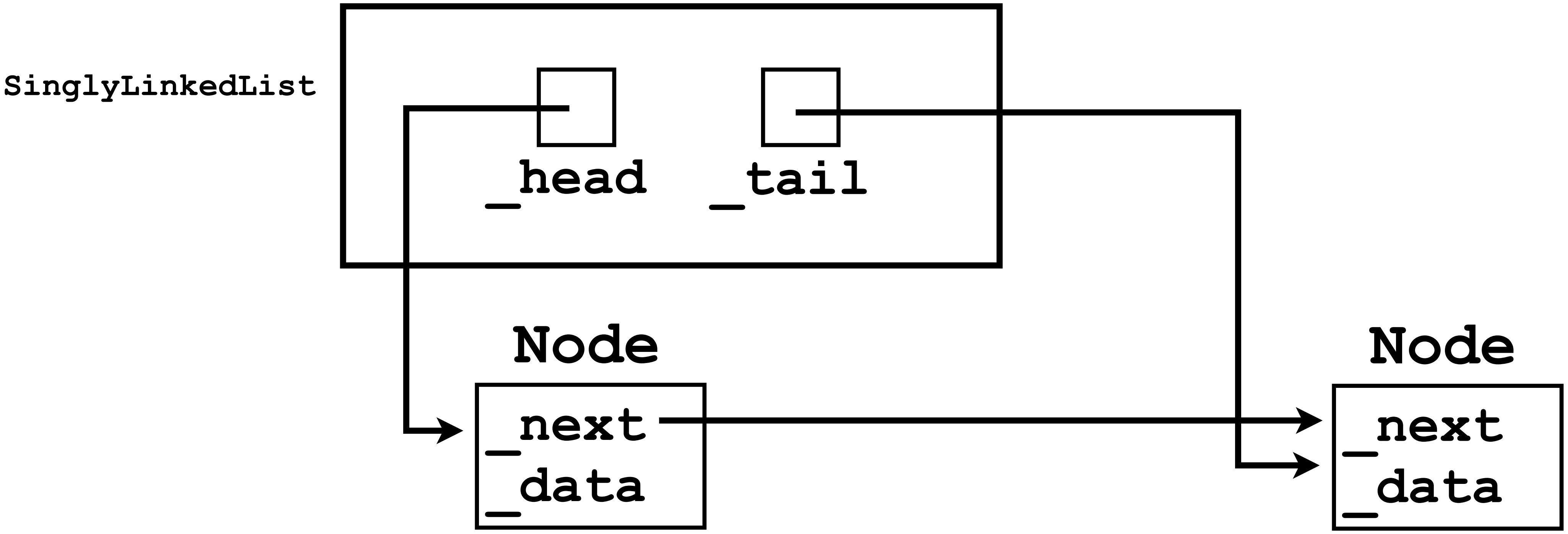
  SinglyLinkedList () {
    // Instantiate dummy head and tail nodes
    _head = new Node();
    _tail = new Node();

    // 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)`

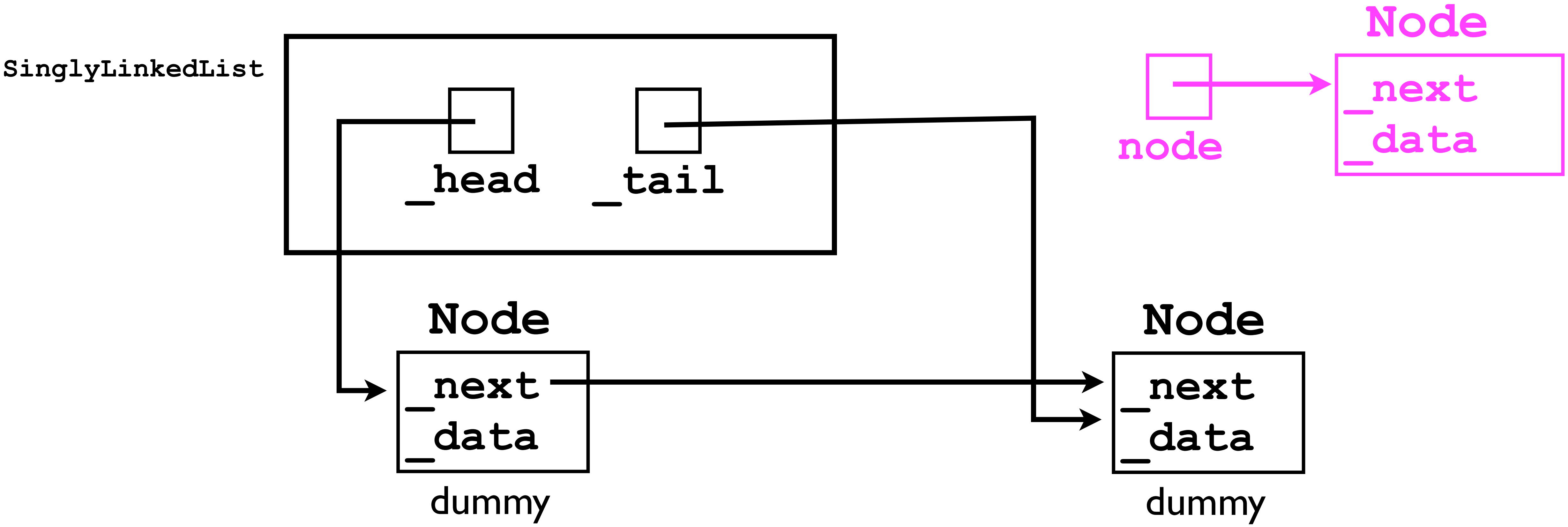
- Given the dummy head and tail nodes, we can add a new node to our chain in 4 steps:

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.

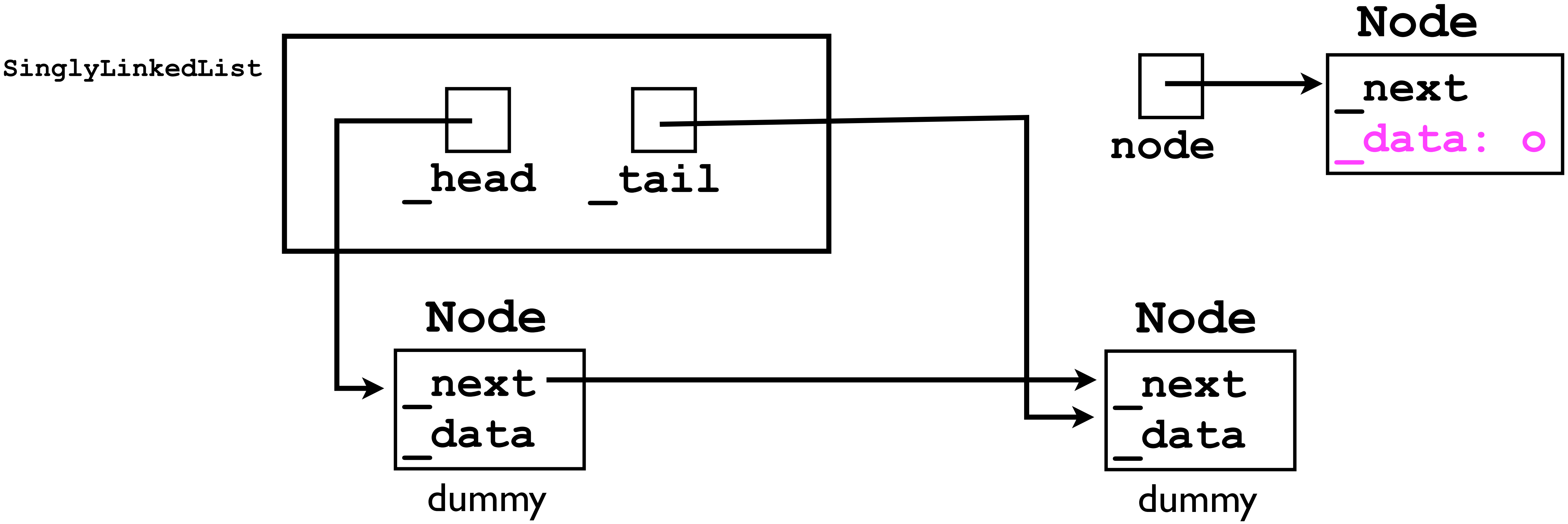
```
final Node node = new Node();
```



`void add (Object o)`

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

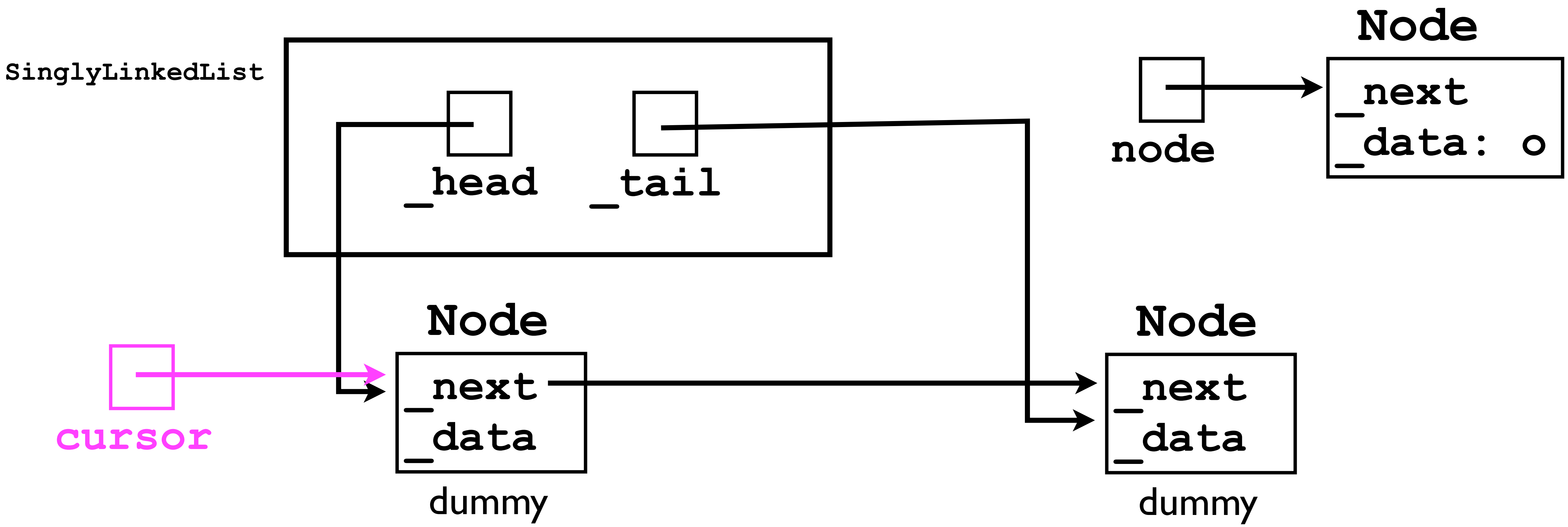
```
node._data = o;
```



`void add (Object o)`

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

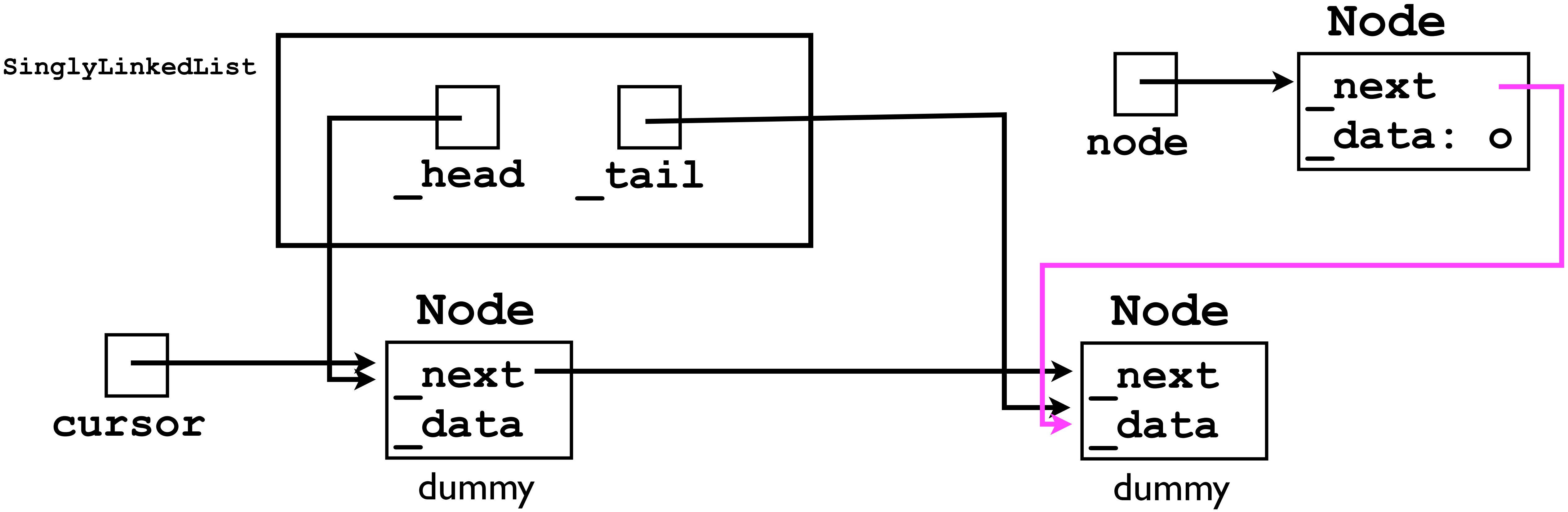
```
Node cursor = _head;
while (cursor._next != _tail) {  // Why?
   cursor = cursor._next;
}
```



`void add (Object o)`

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

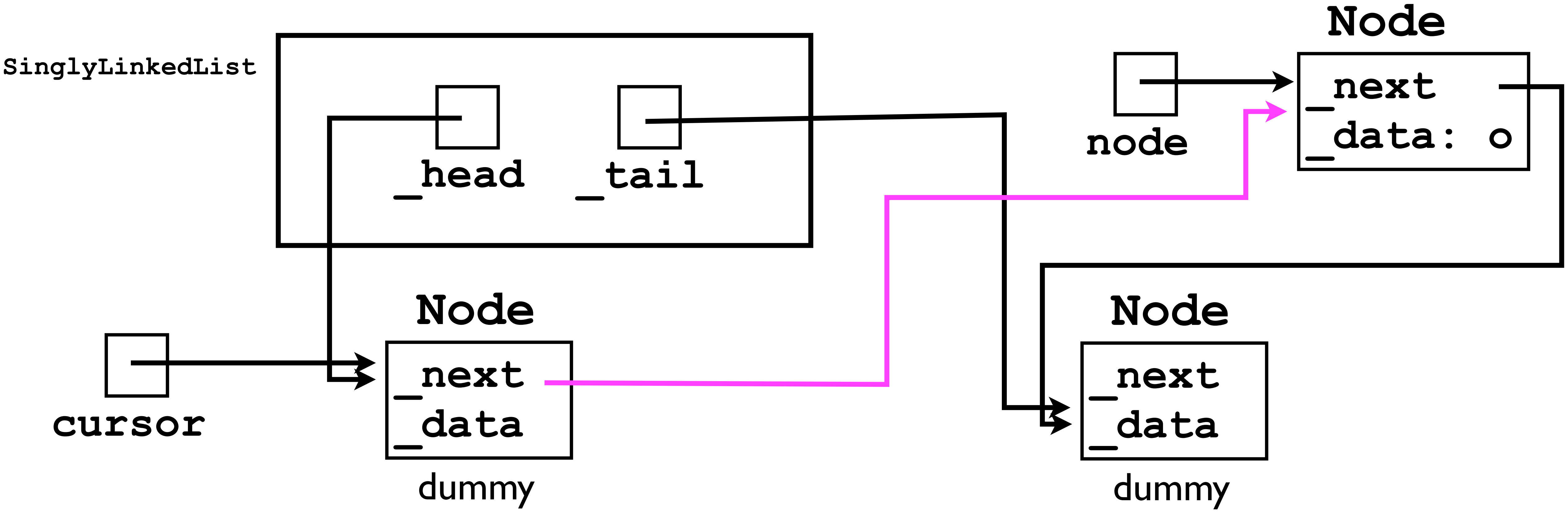
```
node._next = cursor._next;
```



`void add (Object o)`

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

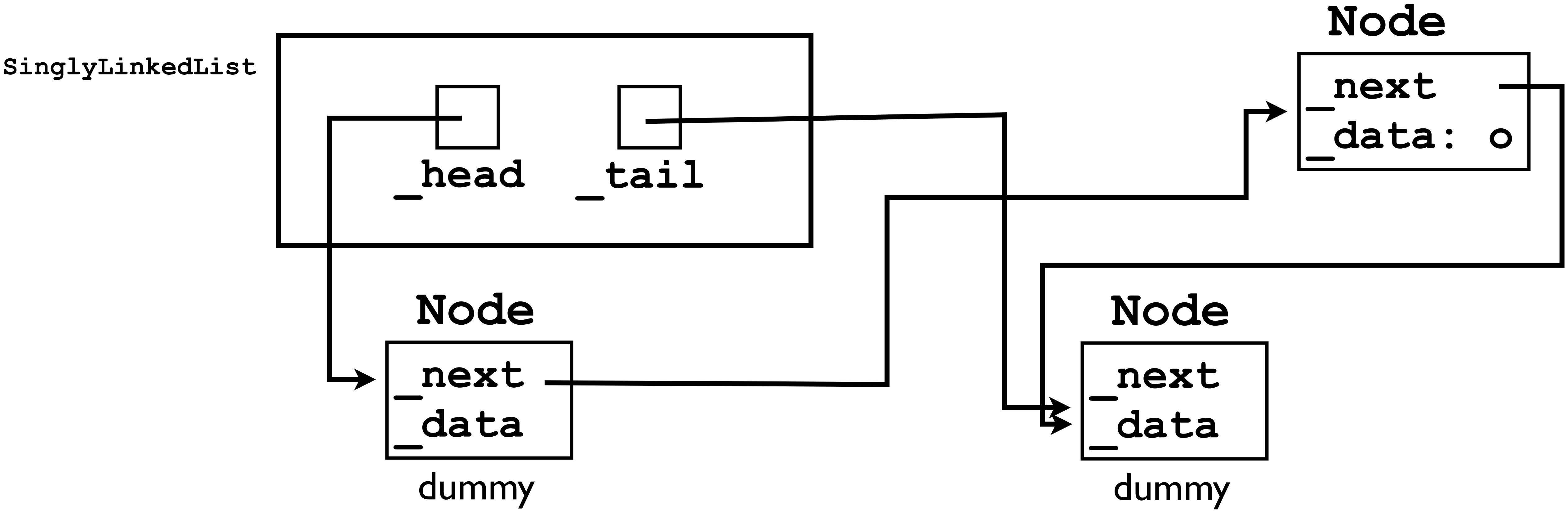
```
node._next = cursor._next;
cursor._next = node;
```



`void add (Object o)`

Done!

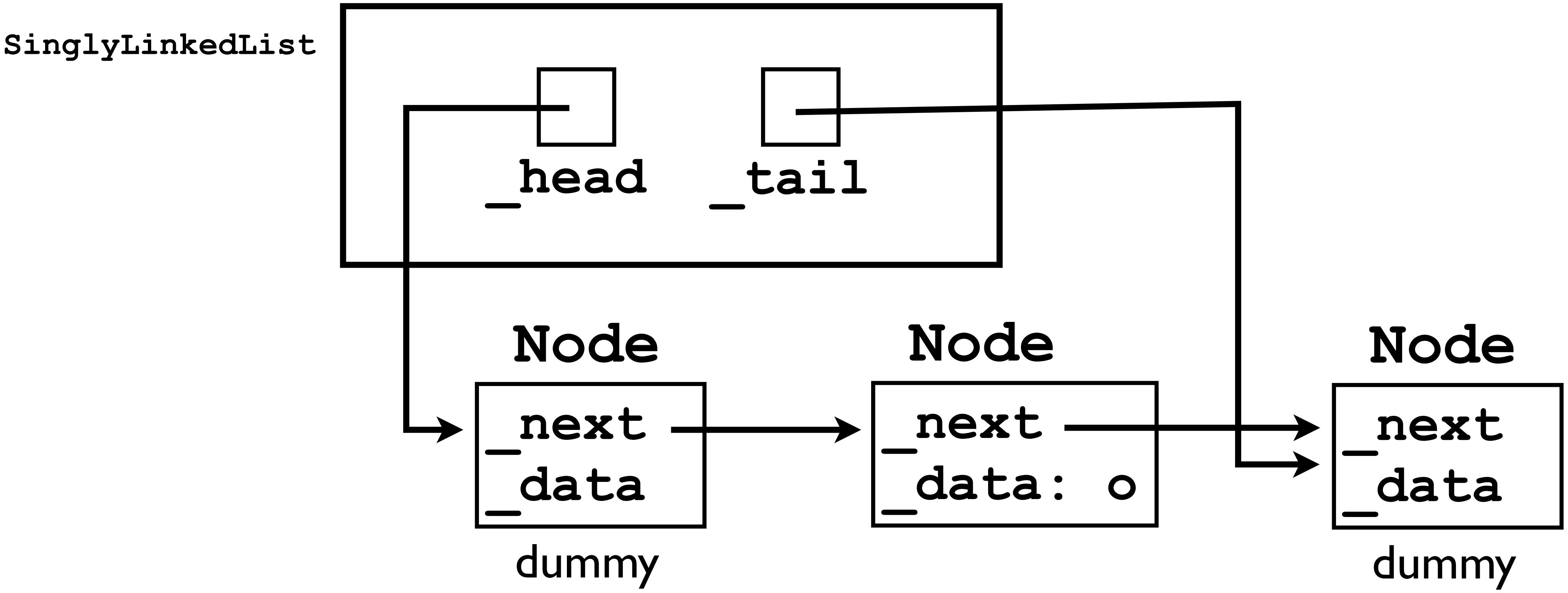
If we pull the chain “taut”...



`void add (Object o)`

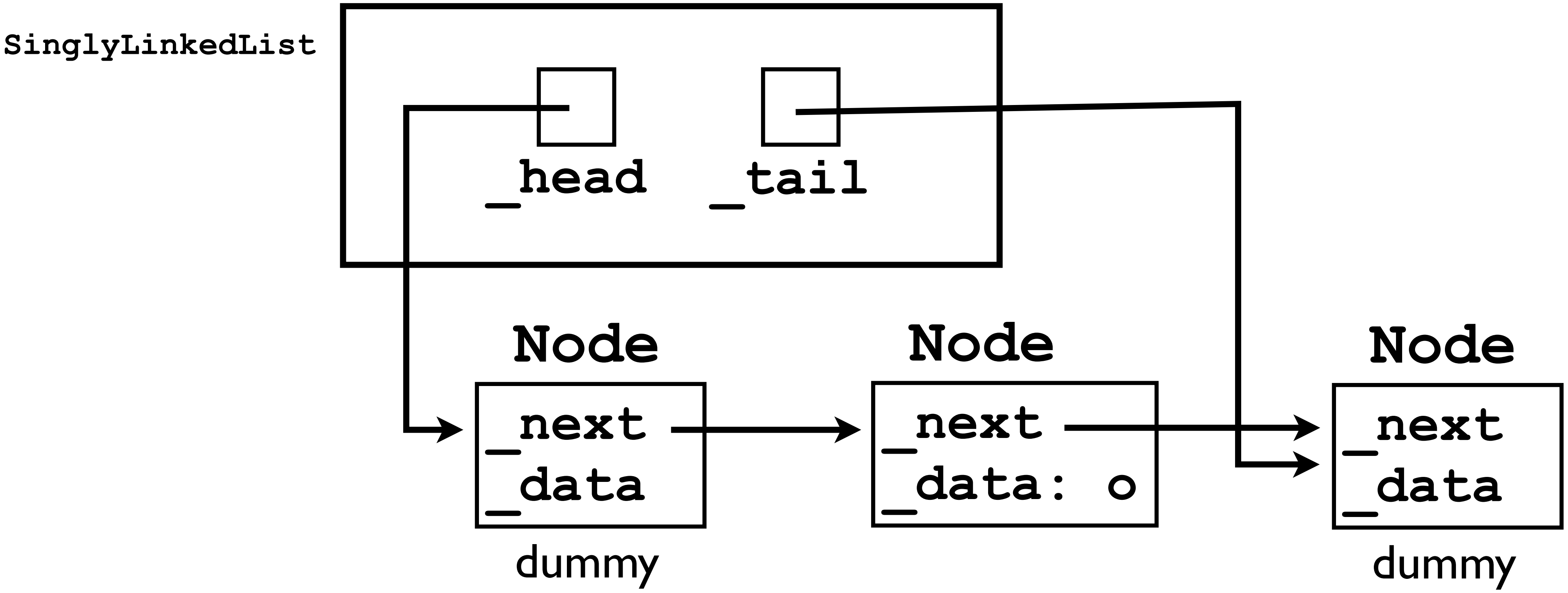
...it will look more like what we started with...

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



Reality check

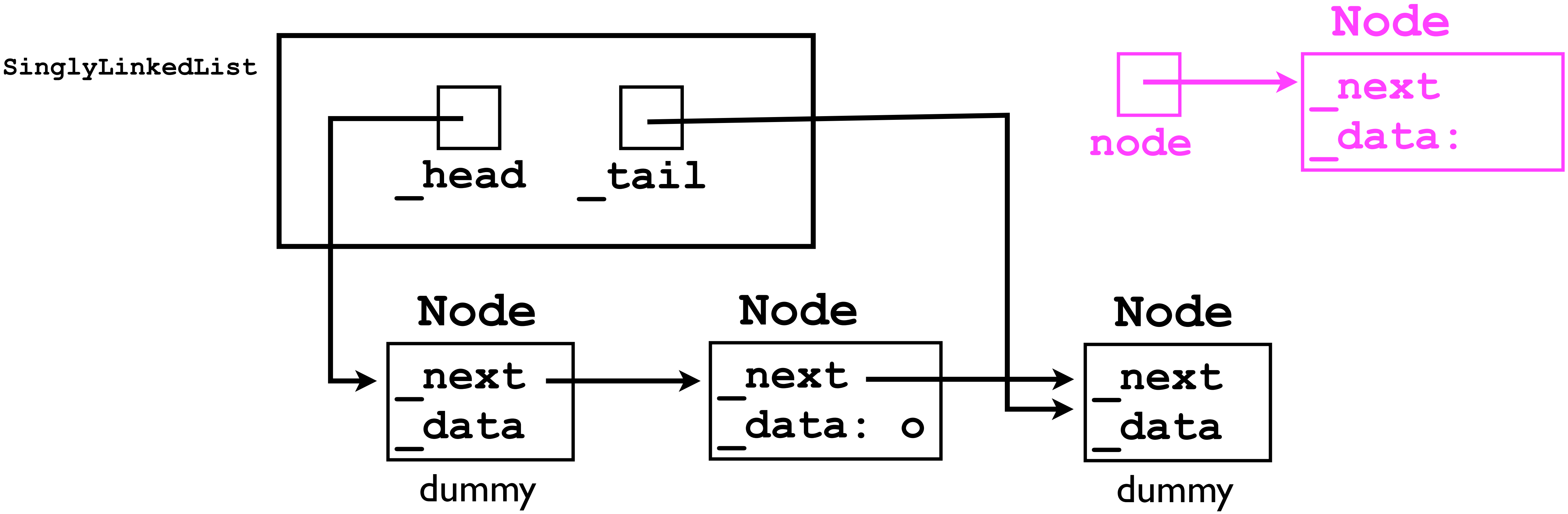
- Why do we need to iterate the cursor to the node just *before* the dummy tail?



Let's add one more node...

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

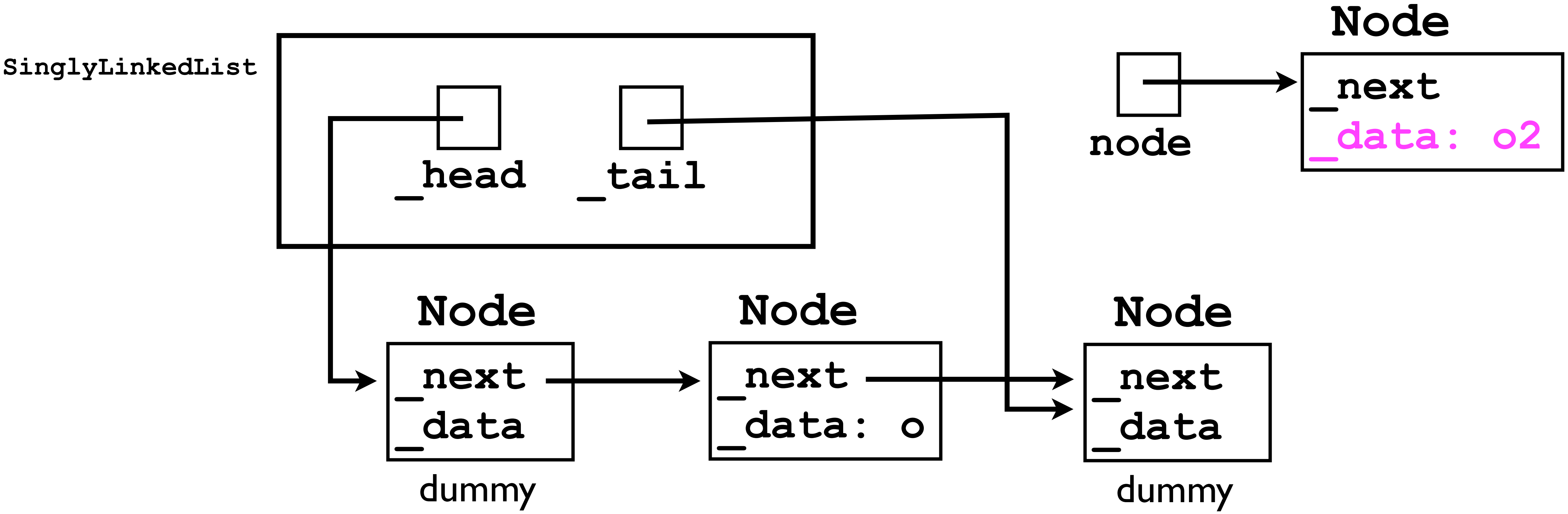
`final Node node = new Node();`



Let’s add one more node...

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

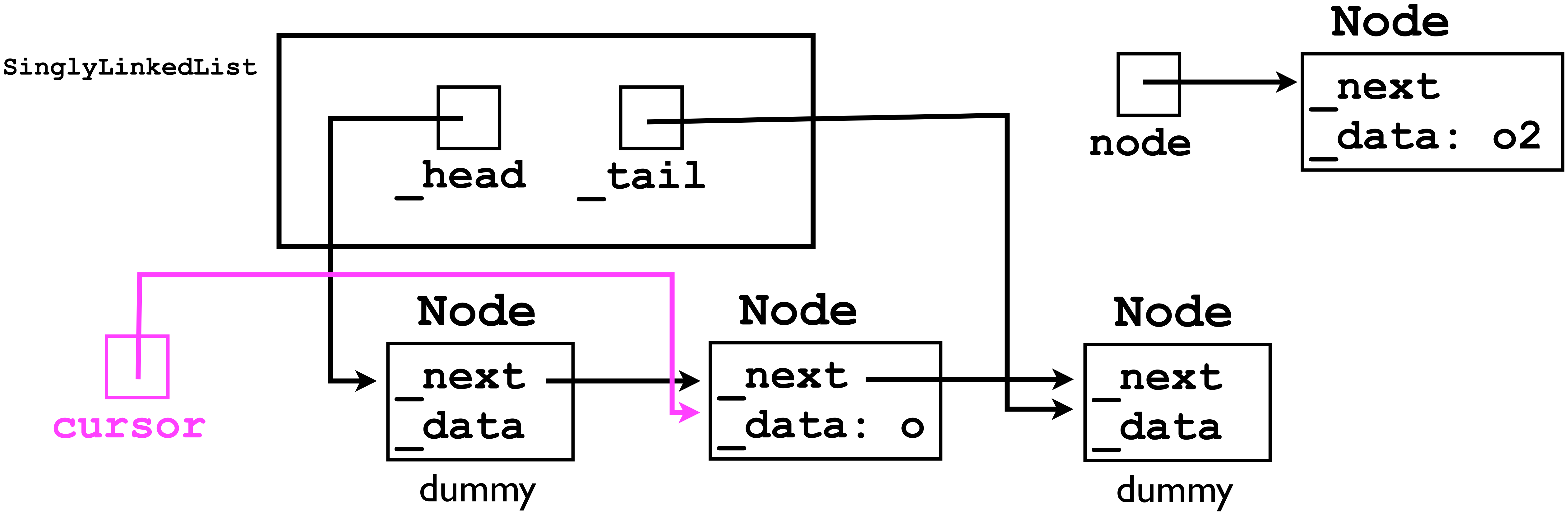
```
node._data = o;
```



Let's add one more node...

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

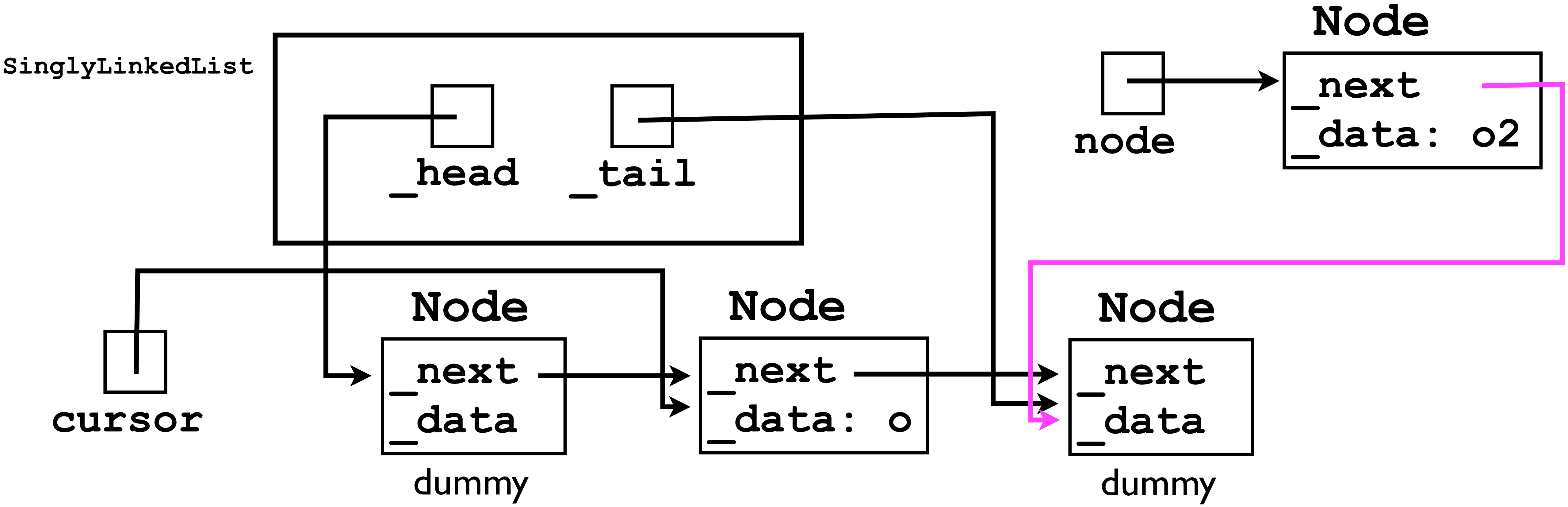
```
Node cursor = _head;
while (cursor._next != _tail) {
  cursor = cursor._next;
}
```



Let's add one more node...

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

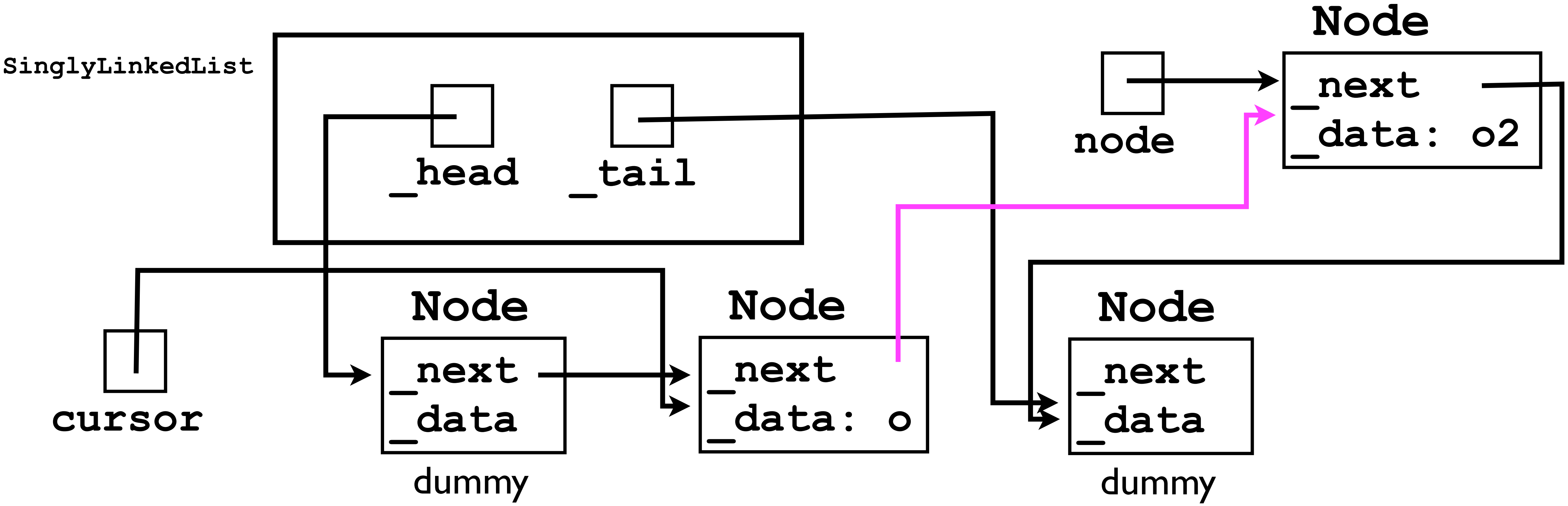
```
node._next = cursor._next;
```



Let's add one more node...

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

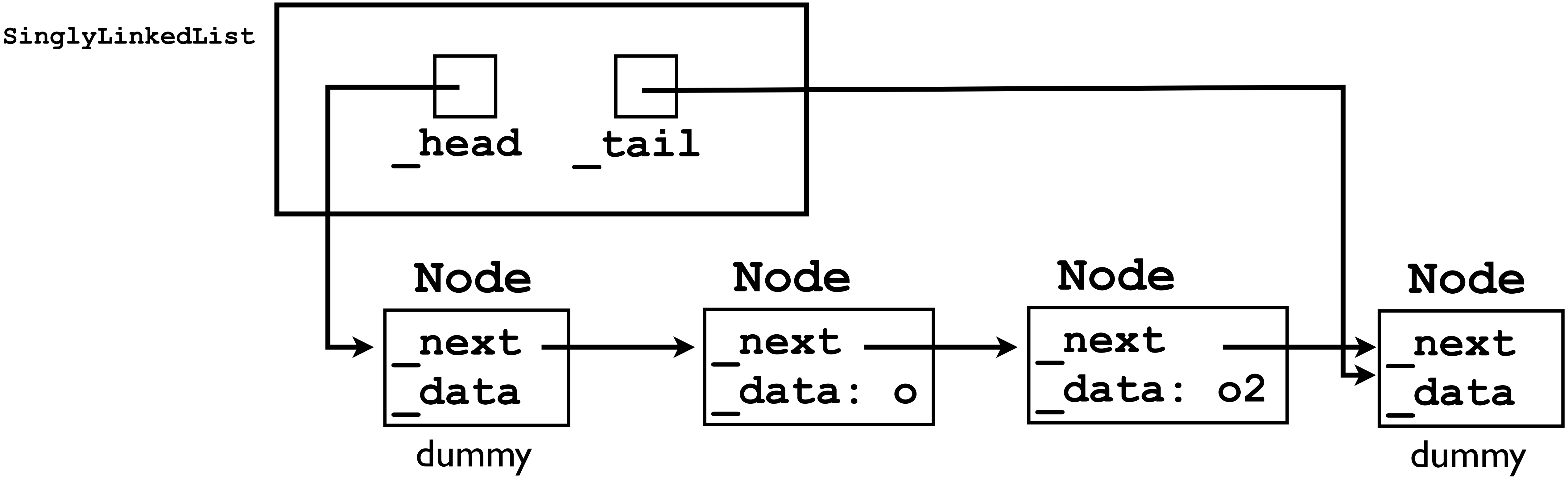
```
node._next = cursor._next;
cursor._next = node;
```



Let’s add one more node...

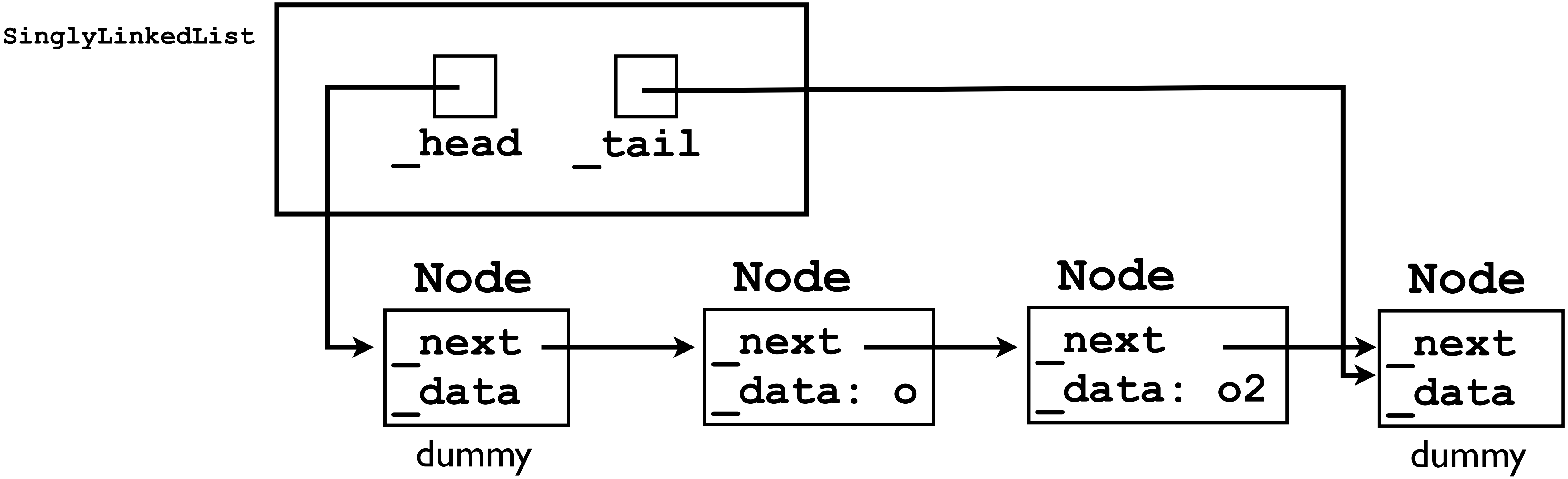
Done (and pulled taut again)!

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?



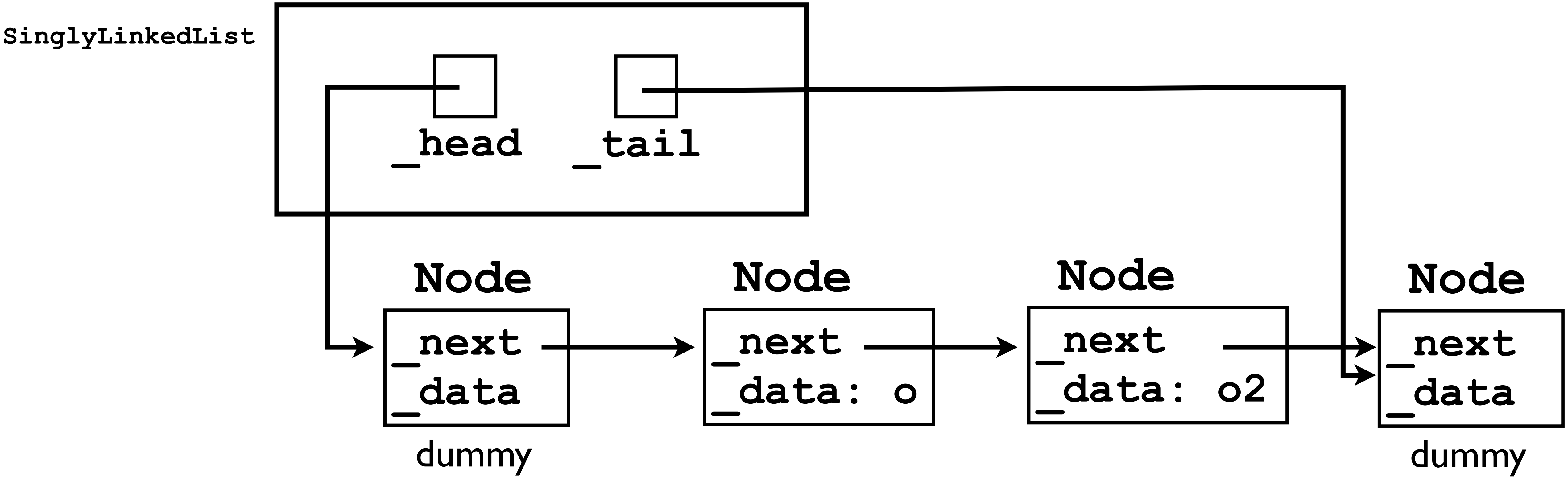
`void remove (int index)`

- 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.

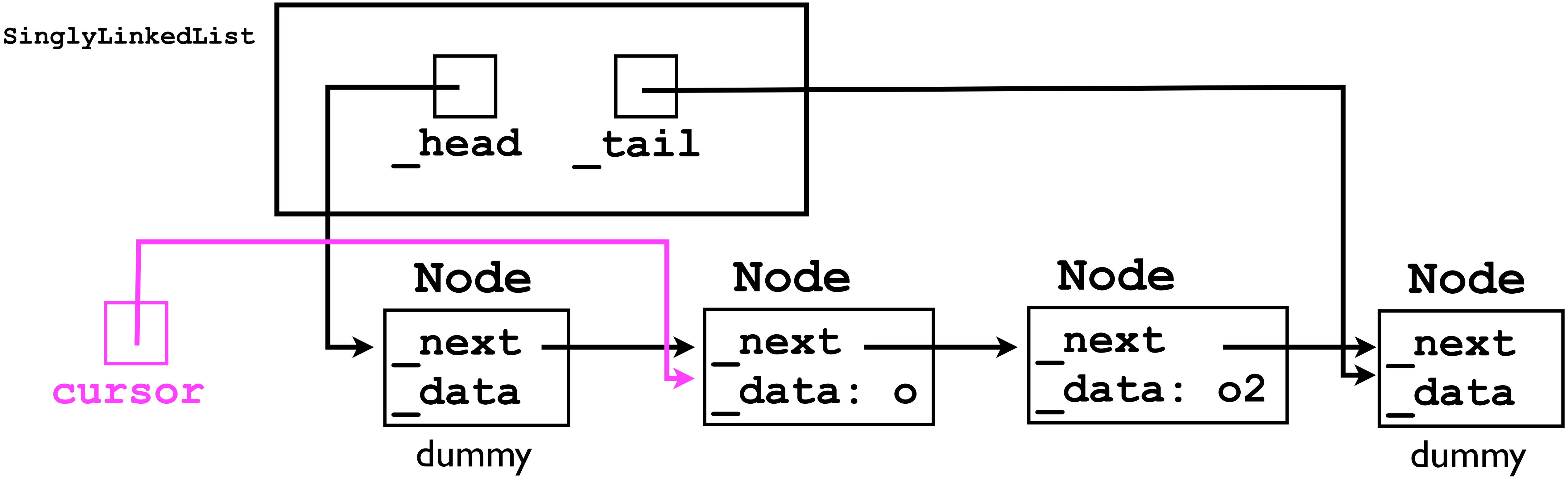


`void remove (int index)`

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

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

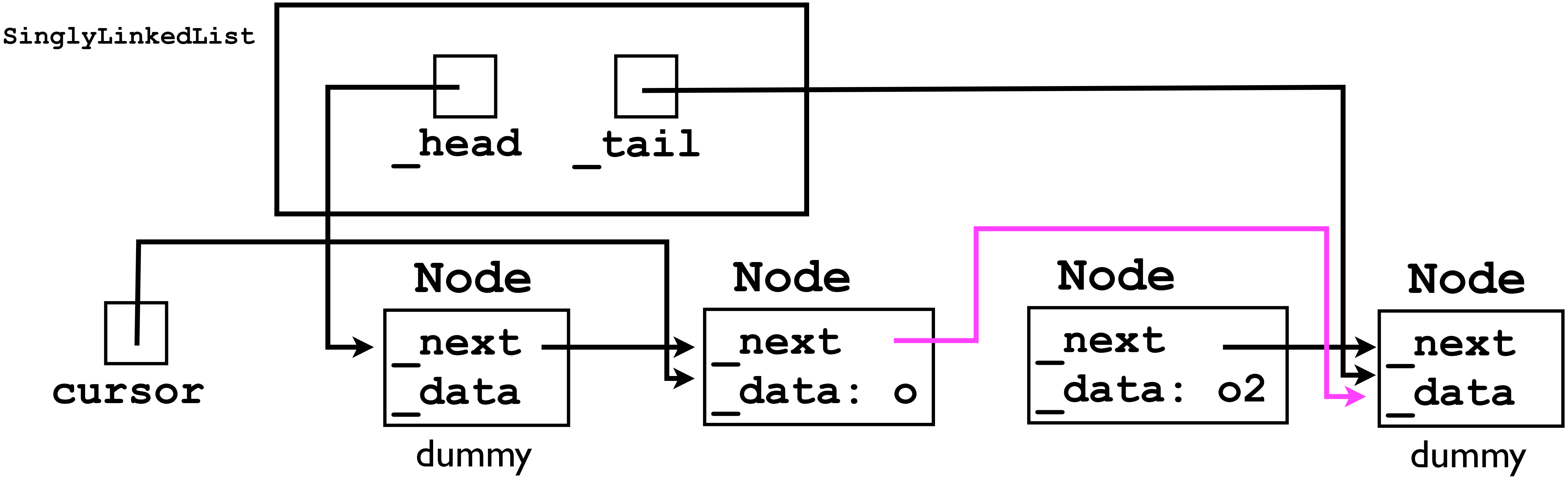
Let's assume for now that **`index`** is valid.



`void remove (int index)`

1. “Unlink” `cursor._next` from the chain.

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

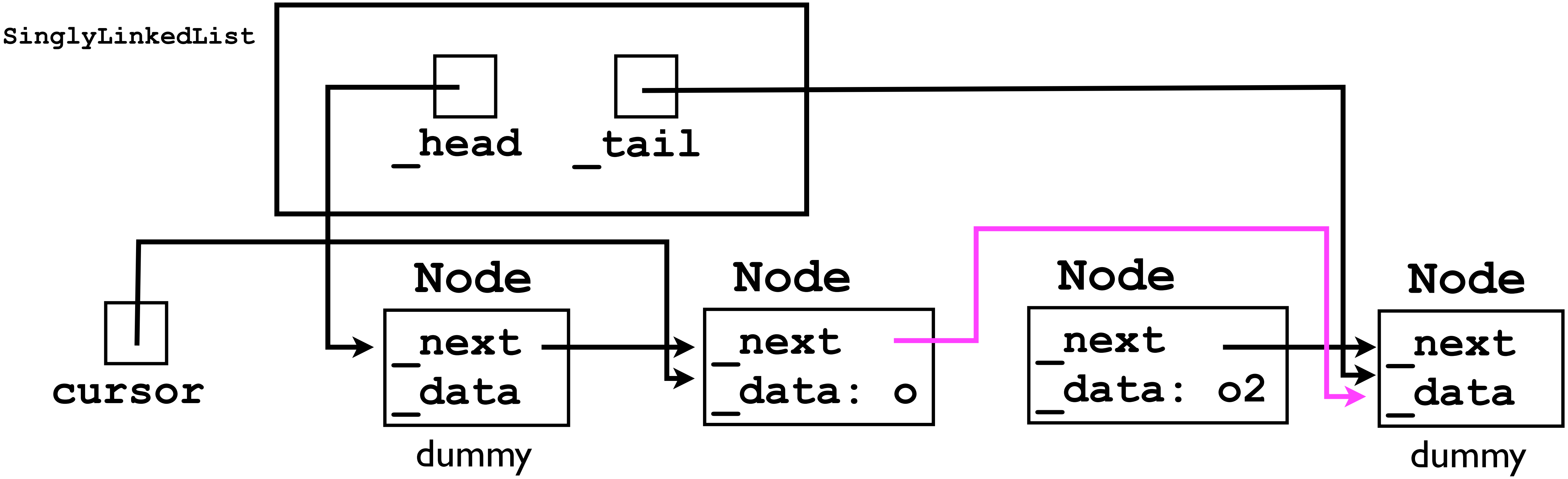


`void remove (int index)`

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

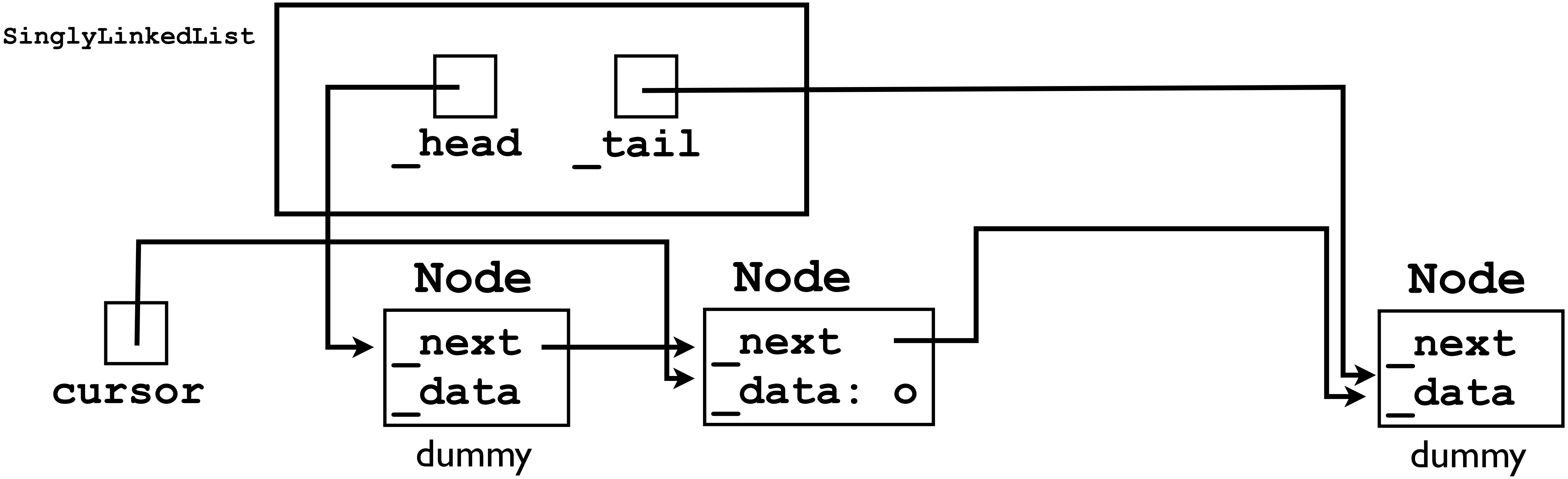
```
cursor._next = cursor._next._next;
```

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.

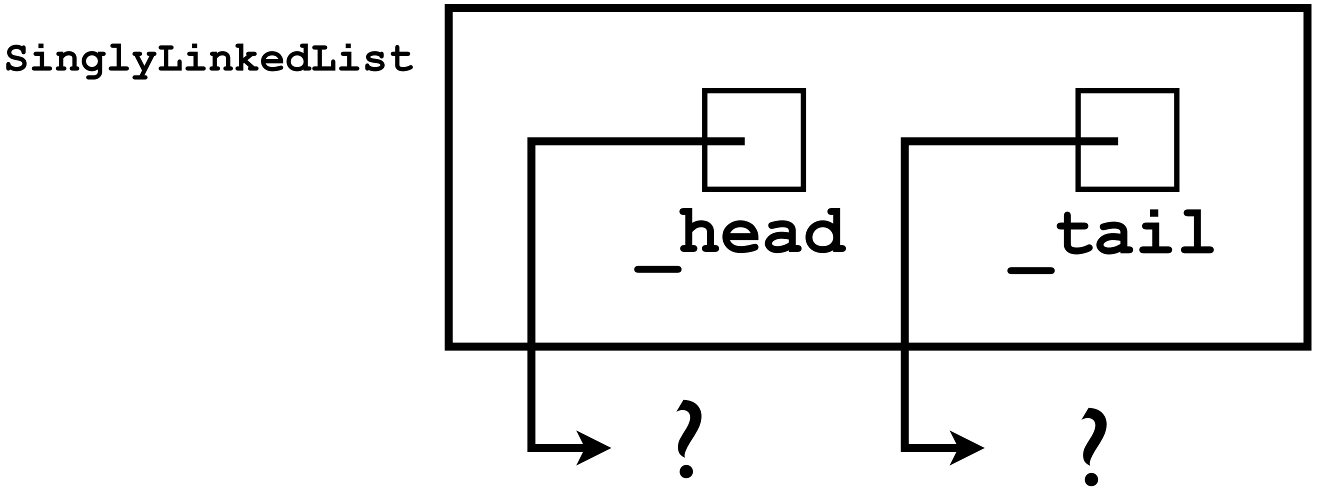
Confetti demo

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.

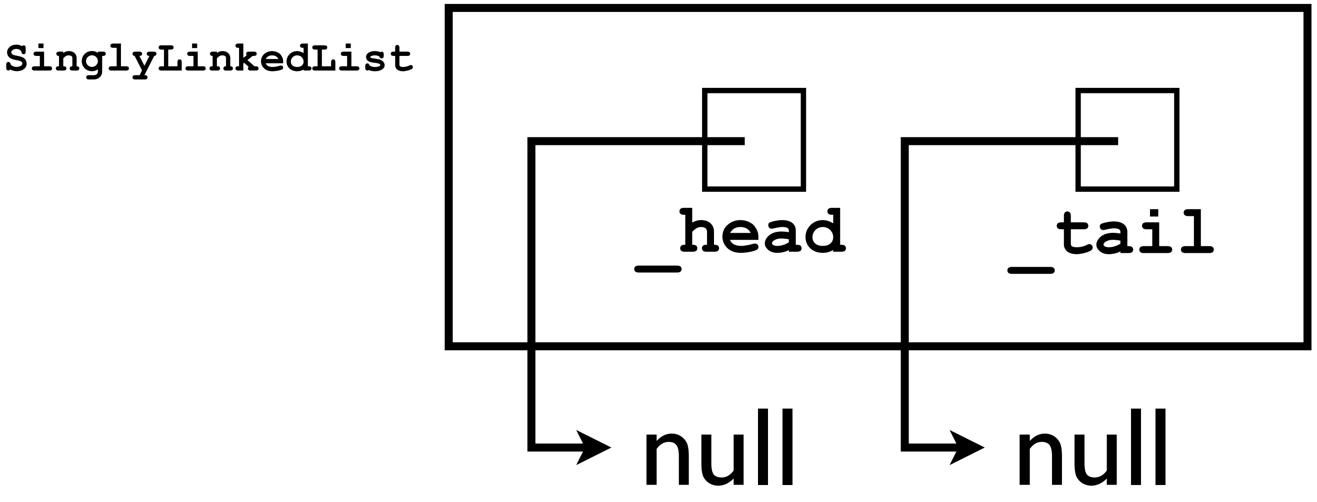
Dummy nodes, revisited

- 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.

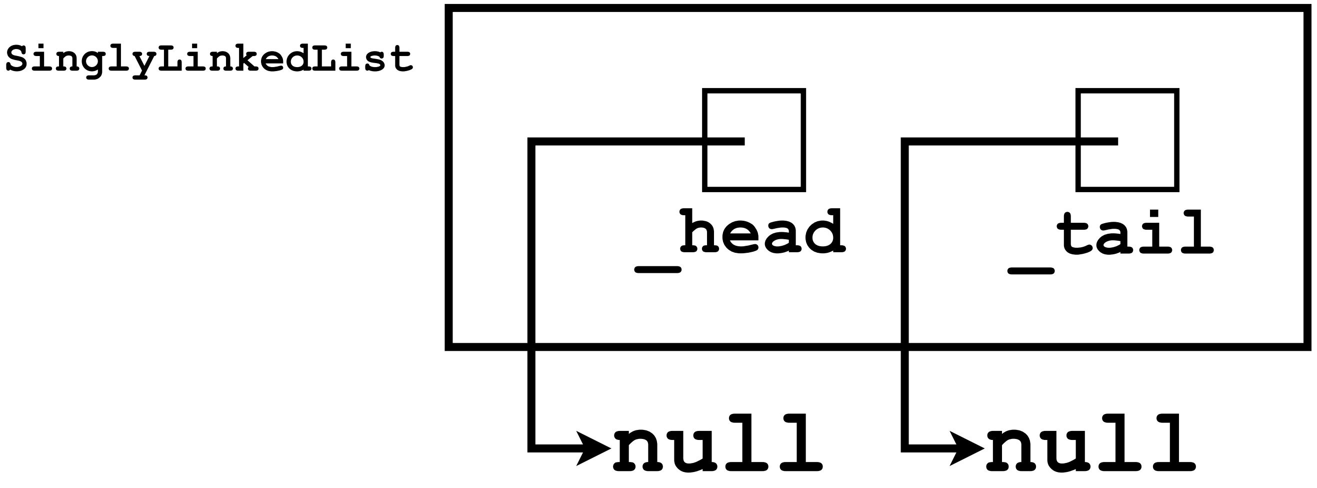


`add(o)` without dummy nodes

- 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?

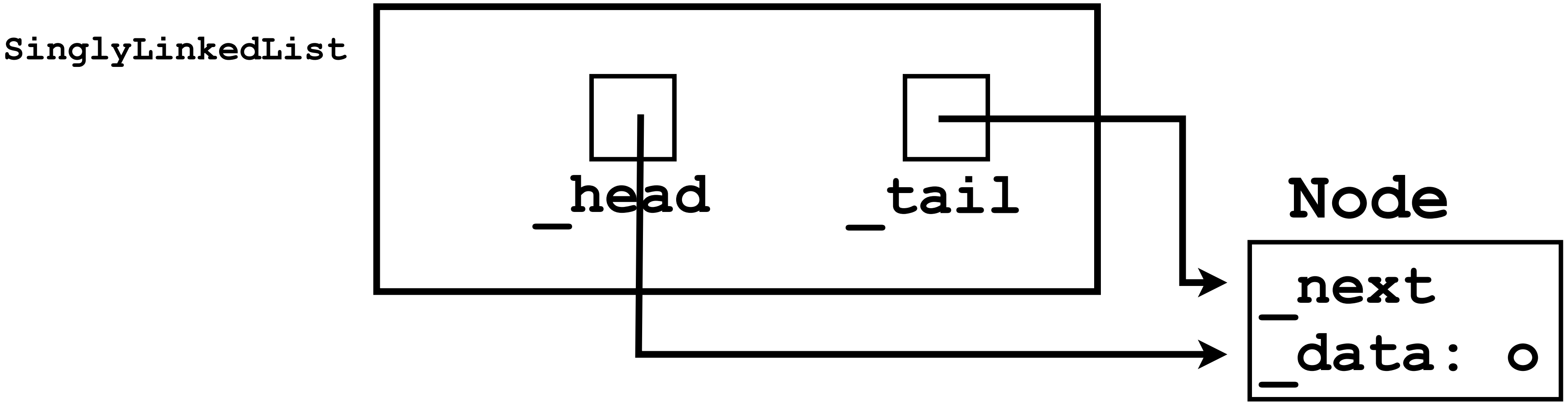
```
final Node node = new Node();
node._data = o;

...  // ??
```



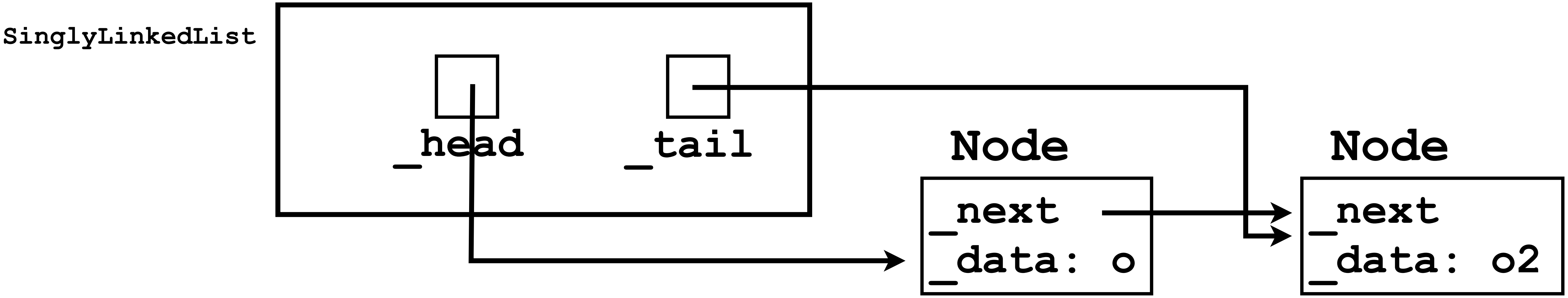
`add(o)` without dummy nodes

- 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.

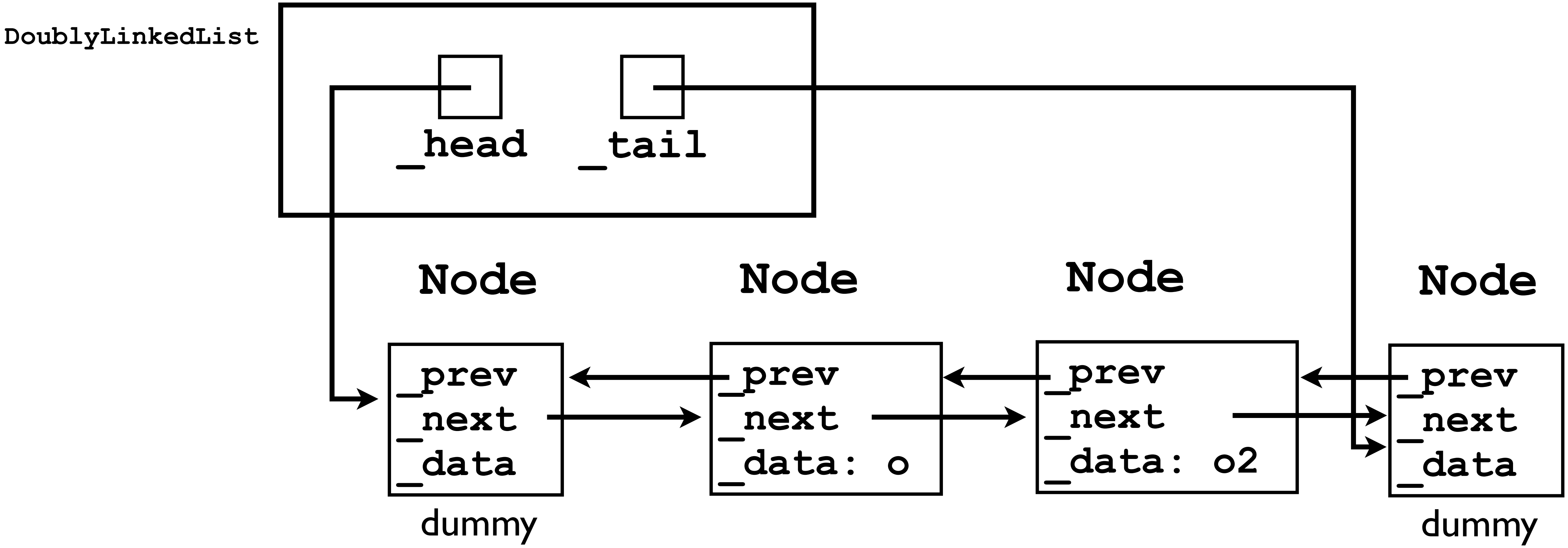
Doubly-linked lists

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

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

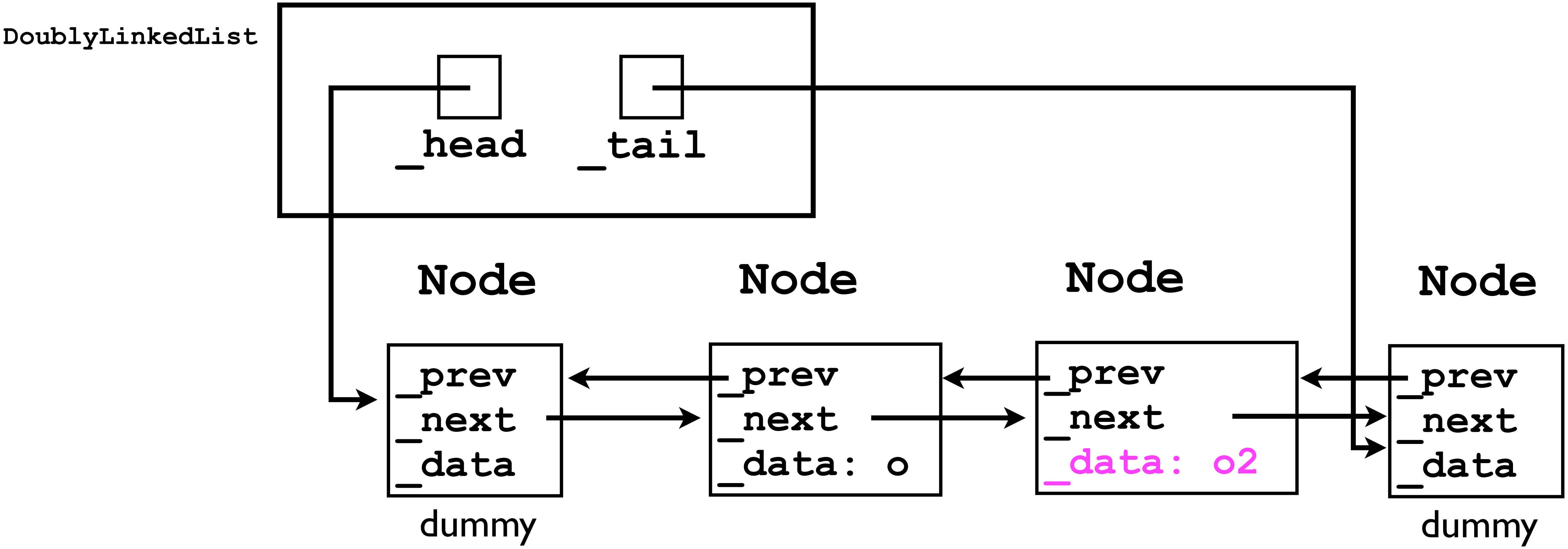
Doubly-linked lists

- 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.:
`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 later this 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

- One of the requirements of a class implementing the **`List12`** interface is the **`iterator()`** method.
  - But what is an **`Iterator`**?

Iterators.

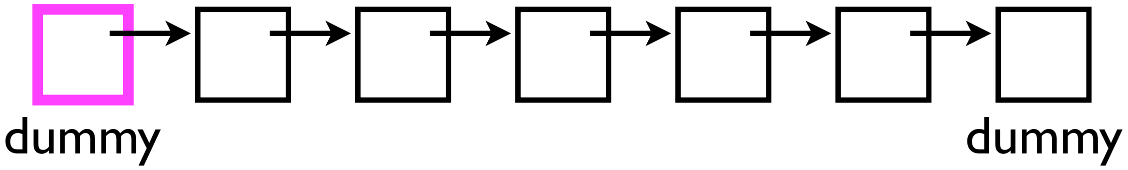
Iterating over elements of a data structure.

- 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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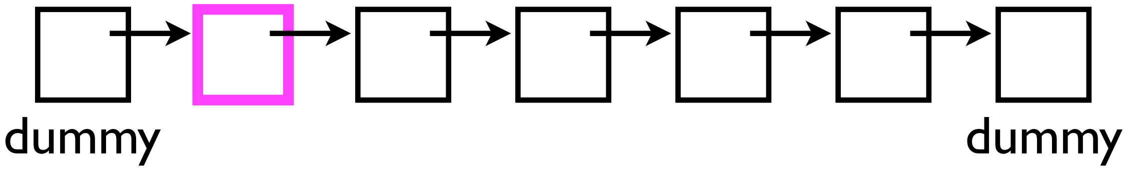

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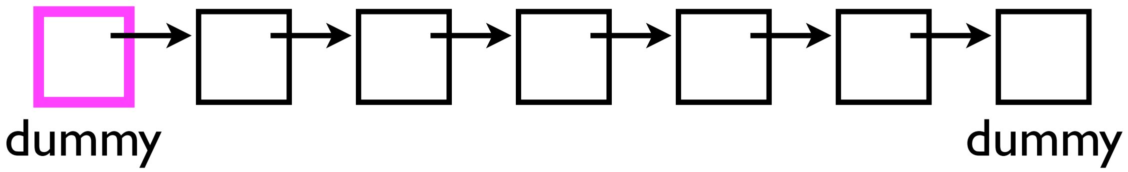

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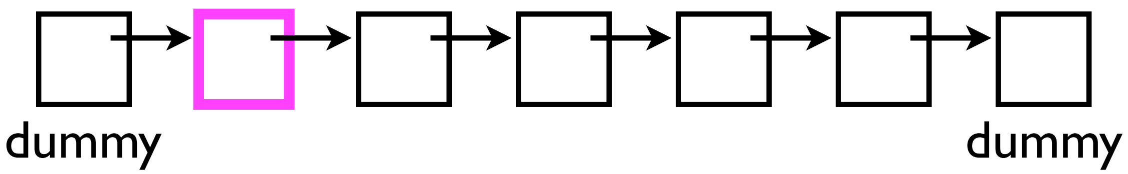

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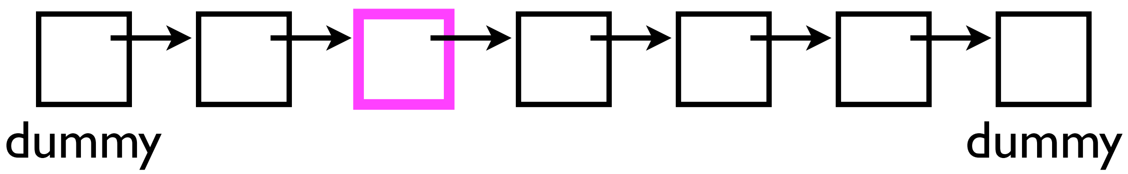

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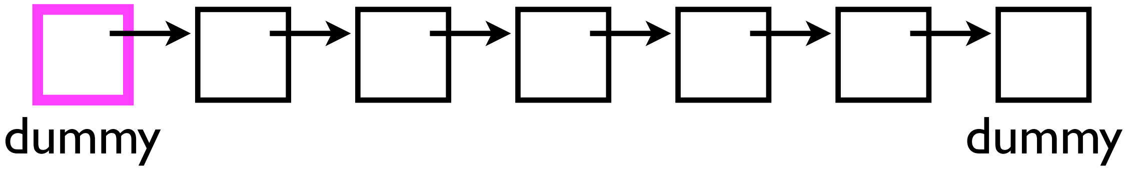

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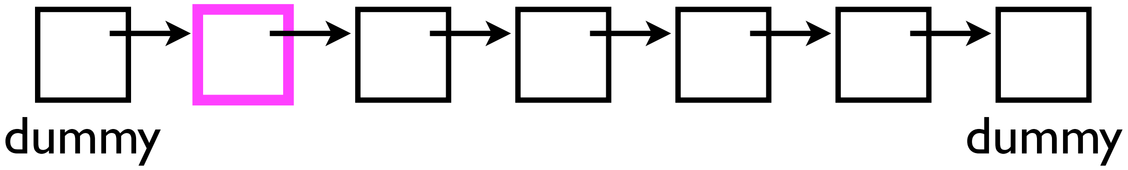

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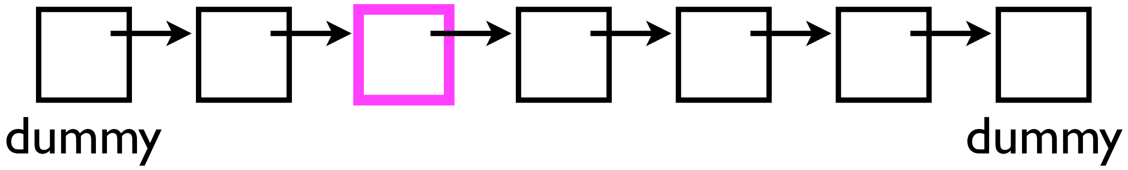

Iterating over elements of a data structure.

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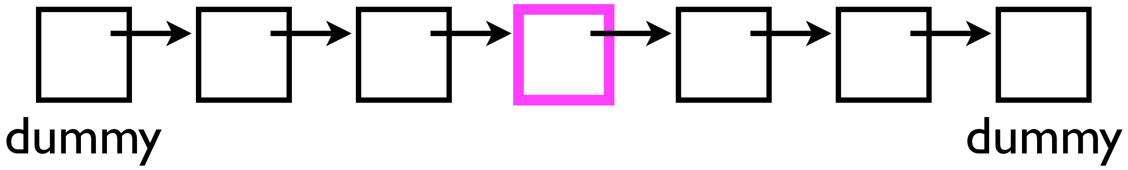

We keep "re-iterating" -- starting from scratch back at the head. This is computationally wasteful. Why can't we just pick up where we left off?

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.

`interface Iterator`

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

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

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.

Restrictions on using an **`Iterator`**

- 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`**.

Restrictions on using an `Iterator`

- The `Iterator` interface also specifies that “the behavior of an iterator is unspecified if the underlying collection is modified while the iteration is in progress in any way other than by calling this method.”

`Iterator` interface

Unspecified means that the implementor is "absolved of any responsibility" for maintaining correct functionality in the **`Iterator`** if the user modifies the **`DoublyLinkedList12`** while he/she is iterating over it.

- The **`Iterator`** interface also specifies that "the behavior of an iterator is unspecified if the underlying collection is modified while the iteration is in progress in any way other than by calling this method."

Modifications in the case of **`DoublyLinkedList12`** mean **`addToFront()`**, **`removeFront()`**, etc. -- anything that changes the contents of the list.

Interface as a “contract”

- An interface specification serves as a *contract* between user and implementor of the interface.
- The method signatures specify to the user what each method does, and how it is called (i.e., parameters).
- The comments describe to the implementor what each method must do and what values to return.

Interface as a "contract"

- The comments may also prescribe to the user various *constraints* on how the methods are called, e.g., "**`next()`** must be called before **`remove()`**.
- If the user does not adhere to these constraints, then he/she is in *violation of contract.*
- If the user violates the contract, then the implementor may:
  - Throw an exception (e.g., **`InvalidStateException`**).
  - Be "absolved of responsibility" to keep working correctly ("behavior is...unspecified").
    - E.g., calls to **`next()`**/**`remove()`**/**`hasNext()`** may stop working correctly, and this is *no longer the implementor's fault.*

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.

`Iterator` schematic

```
class StudentDatabaseApplication {
  void doSomethingInteresting () {
    List12 list =
      new DoublyLinkedList12();

    ...

    list.add(new Student(“Bob”));
    list.add(new Student(“Lulu));

    ...





  }
}
```

`Iterator` schematic

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```

```
class DoublyLinkedList12 implements List12
{
  static class Node {
    ...
  }









  void add (Object o) { ... }
  int size () { ... }

  ...

  Iterator iterator () {
    ...
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    Iterator iter = list.iterator();
    while (iter.hasNext()) {
      Student s = (Student) iter.next();
      System.out.println(s._name);
    }
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  Iterator iterator () {
    return new Iterator();
  }
}
```

Won’t compile because `Iterator` is an interface, not a class!

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Somewhere in `next()` will be code “`cursor = cursor._next;`”

Iterator schematic

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    Iterator iter = list.iterator();
    while (iter.hasNext()) {
      Student s = (Student) iter.next();
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    }
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}
```

But when this is called is determined by when the *user* calls “`iter.next();`”.

```
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{
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  class DLL12Iterator implements Iterator {
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```
  }

  void add (Object o) { ... }
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  ...

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```

END