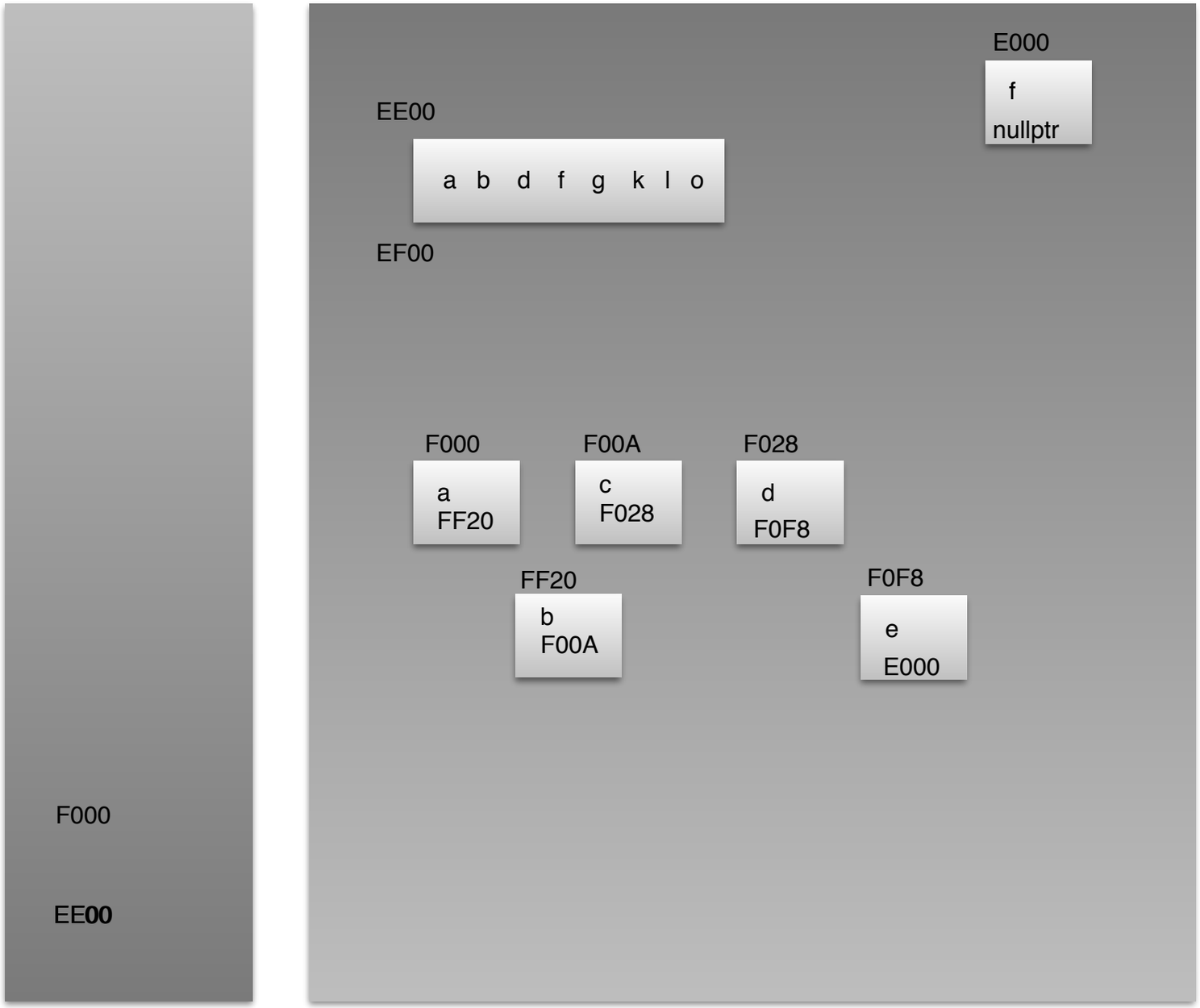
# Lecture 13

# Linked Lists

CS2134

# Thinking about ADT list



Vectors
- allow fast, convenient access to elements using [ ]
- inserting new elements in the front or middle is expensive

# List ADT

$A_1, A_2, A_3, \ldots, A_n,$

This is not a complete list

# STL methods

vector & list methods

int size() const

void clear()

bool empty() const

iter begin()

iter end()

void push_back( const Object & x)

void pop_back()

const Object & back() const

const Object & front() const

iter insert( iter pos, const Object & x )

iter insert( iter pos, Object && x )

iter erase( iter pos )

iter erase( iter start, iter end)

___ operator=( const __ & rhs)

List methods

void push_front( const Object & x)

void pop_front()

void sort( )

template<class Pred>
void sort( Pred pred )

Vector methods

Object & operator[](int idx)

int capacity() const

void reserve(int newCapacity)

Forward_list
- fast
- many methods not included in the forward_list for performance reasons

# List ADT

$A_1, A_2, A_3, \ldots, A_n,$

This is not a complete list

# STL methods

forward_list & list methods

void clear()

bool empty() const

iter begin()

iter end()

void push_front( const Object & x)

void pop_front()

const Object & front() const

void remove( const Object & x)

___ operator=( const __ & rhs)

void sort( )

template<class Pred>
void sort( Pred pred )

List methods

iter erase( iter pos )

iter erase( iter start, iter end)

int size() const

iter insert( iter pos, const Object & x )

iter insert( iter pos, Object && x )

void push_back( const Object & x)

void pop_back()

const Object & back() const

forward_list methods

itr before_begin() const

itr erase_after( itr start)

itr insert_after( itr start)

# Linked Lists

- Arranged in a linear order
  - –Order determined by a pointer to next object
  - –Data stored in a node
- Advantages:
  - –Flexible, add/delete easily
  - –Dynamic, no wasted memory
  - –No slowdowns as in array when the memory is doubled
  - – Changes made by using only a constant number of data movements
- Disadvantages:
  - –Linear time to get to $i^{th}$ element - sequential access
  - –Store address of next item

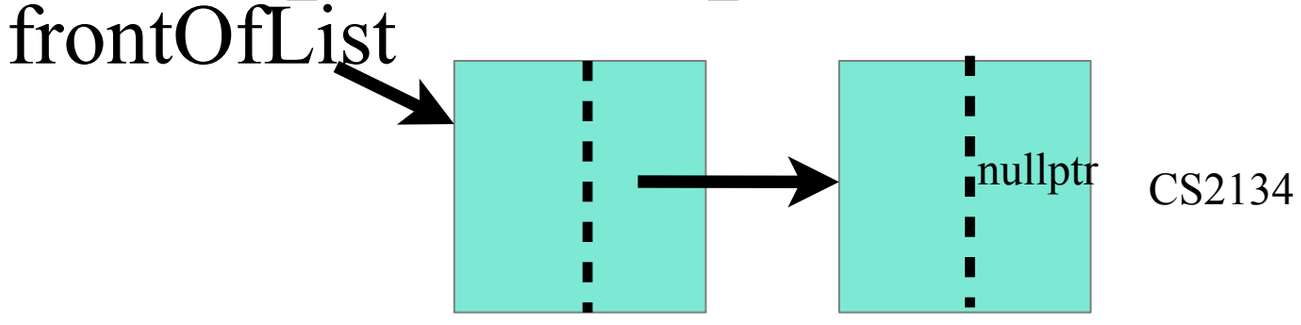
# List Basics

A node is a self referential object; it contains data and a pointer to another node

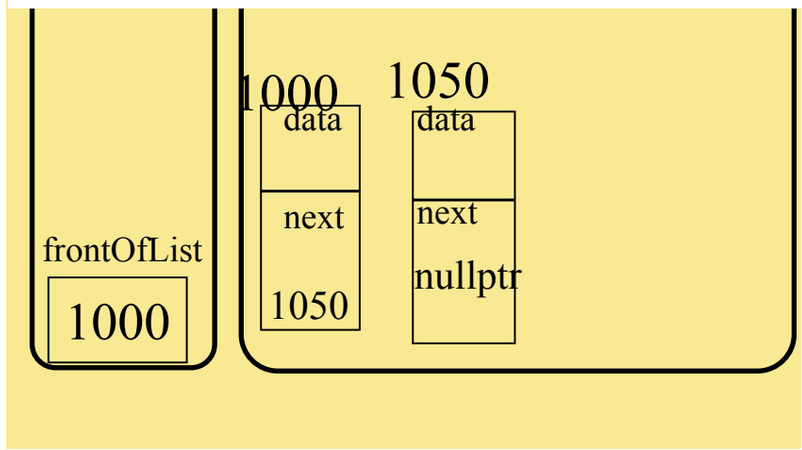
singly linked list

```
template<class Object>
struct Node
{
   Object data;
    Node * next;
}
Node * frontOfList = new Node<char>;
frontOfList->next = nullptr;
frontOfList->next = new Node<char>;
frontOfList->next->next = nullptr;
```

**Conceptual Representation**



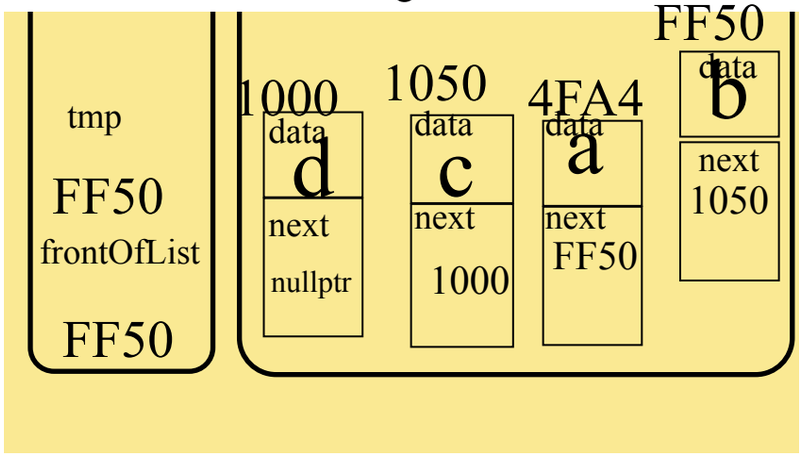

**Memory Level**



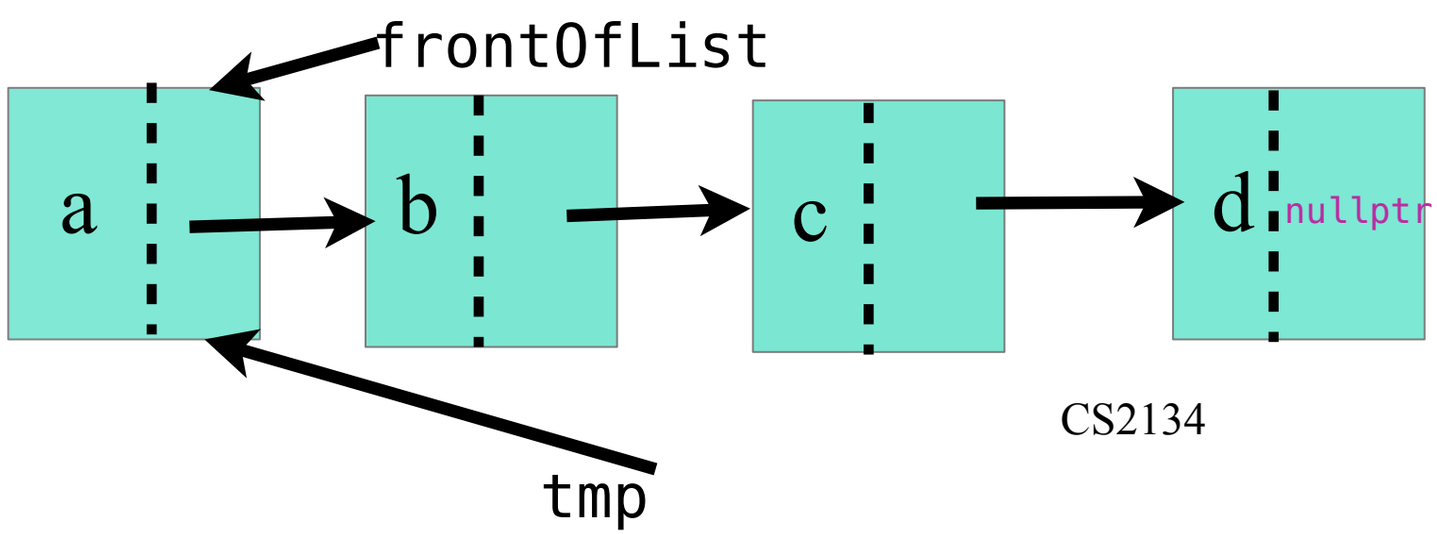
```
template<class Object>
struct Node
{
    Object data;
    Node* next;
};
int main ()
{
    Node<char>* frontOfList = nullptr;
    for (char ch = 'd'; ch >='a'; --ch)
    {
        Node<char>* tmp = new Node<char>;
        tmp->data = ch;
        tmp->next = frontOfList;
        frontOfList   = tmp;
}
```

**ADT** a b c d

**Memory Level**



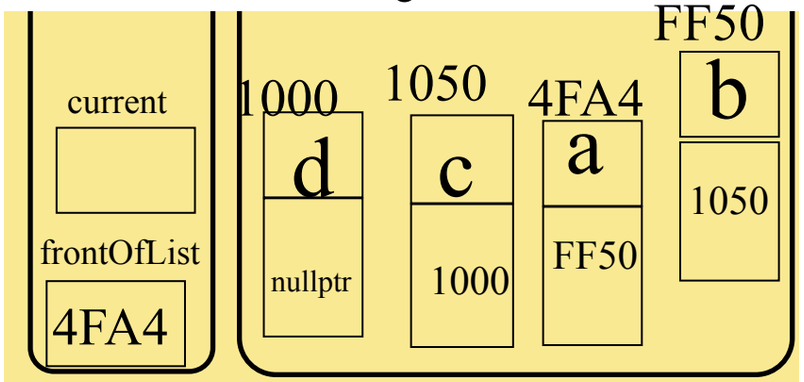

**Conceptual Representation**



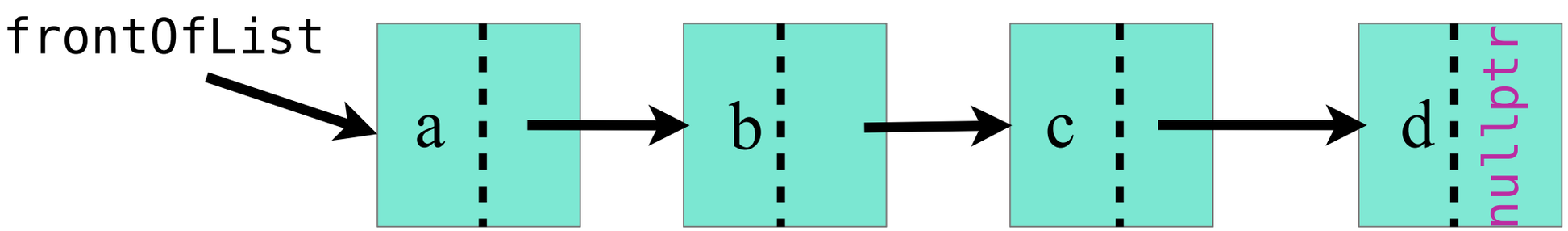
```
template<class Object>
struct Node
{
    Object data;
    Node* next;
};
int main ()
{    // code to enter ‘d’, ‘c’, ‘b’, and ‘a’
     // where frontOfList points to ‘a’.
      Node<char>* current = frontOfList;
      for (   ; current != nullptr; current = current->next)
          cout << current->data << ", ";
}
```

# ADT a b c d

# Memory Level



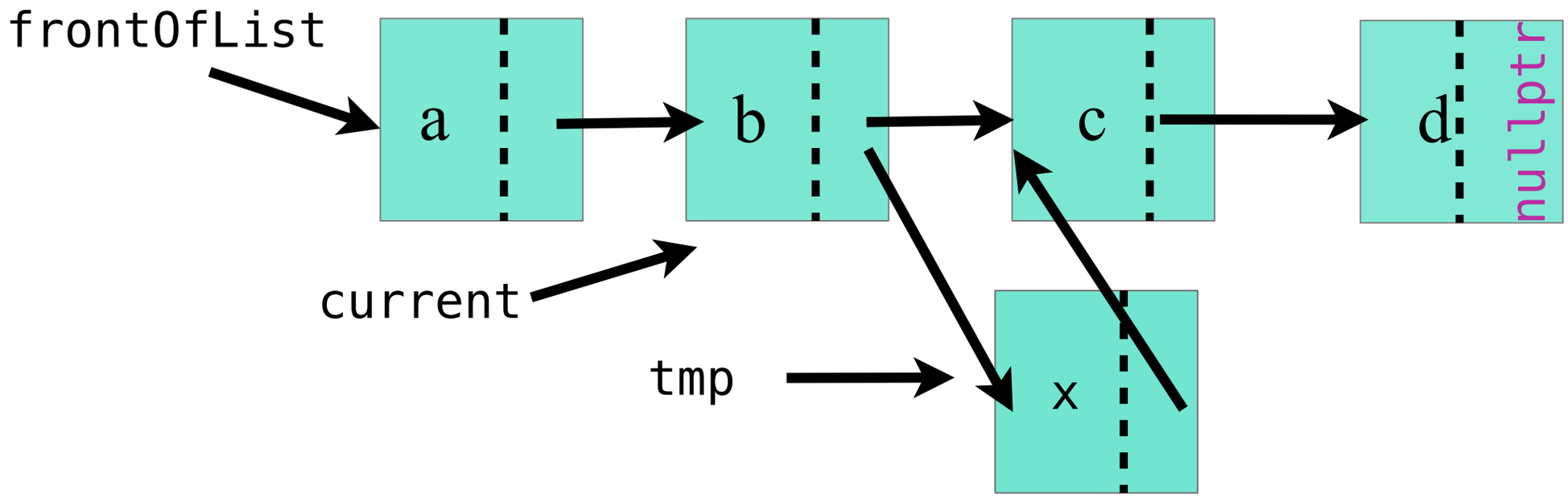

# Conceptual Representation



# Linked Lists

- Review of basic *forward list* ops:
  - insert
    - insert_after( itr, x )
    - push_front( x )
  - erase
    - erase_after( itr )
    - pop_front( )
    - remove( x )
  - traversing a list
    - ?
- Design issues
  - with or without header nodes
  - iterator awareness

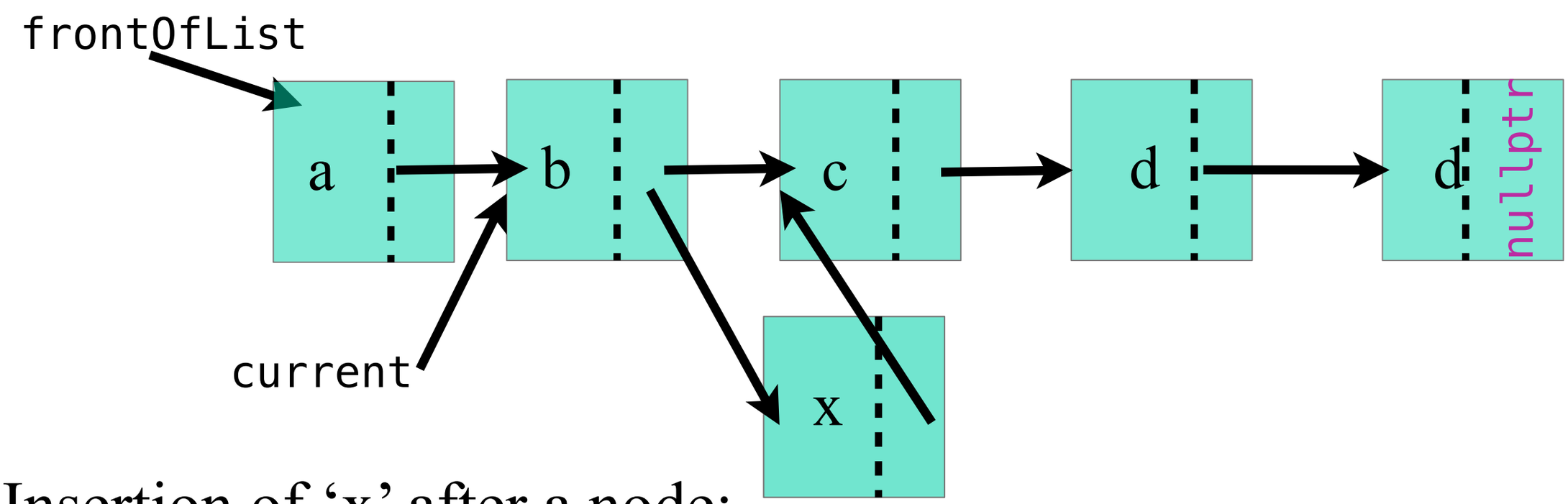
# Insertion of ‘x’ after a node in the list




```
Node<char>* current = frontOfList->next;
Node<char>* tmp;
tmp = new Node<char>;
tmp -> data = 'x';

tmp->next = current->next;
current->next = tmp;
```

# Simplifying the code after adding a constructor that initializes the data

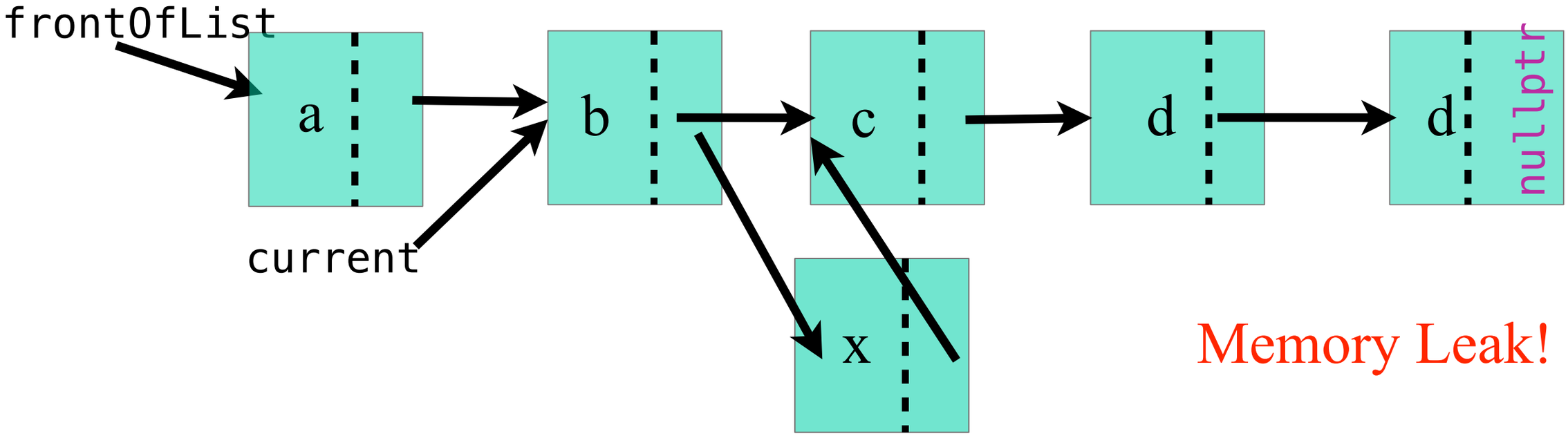
```
template<class Object>
struct Node
{
    Object data;
    Node* next;
    Node(const Object & in = Object(), Node* ptr =nullptr):data(in),next(ptr){}
   Node( Object && d, Node * n = nullptr ): data{ std::move( d ) }, next{ n } { }
};
```




Insertion of ‘x’ after a node:

```
current->next = new Node<char>('x', current->next);
```

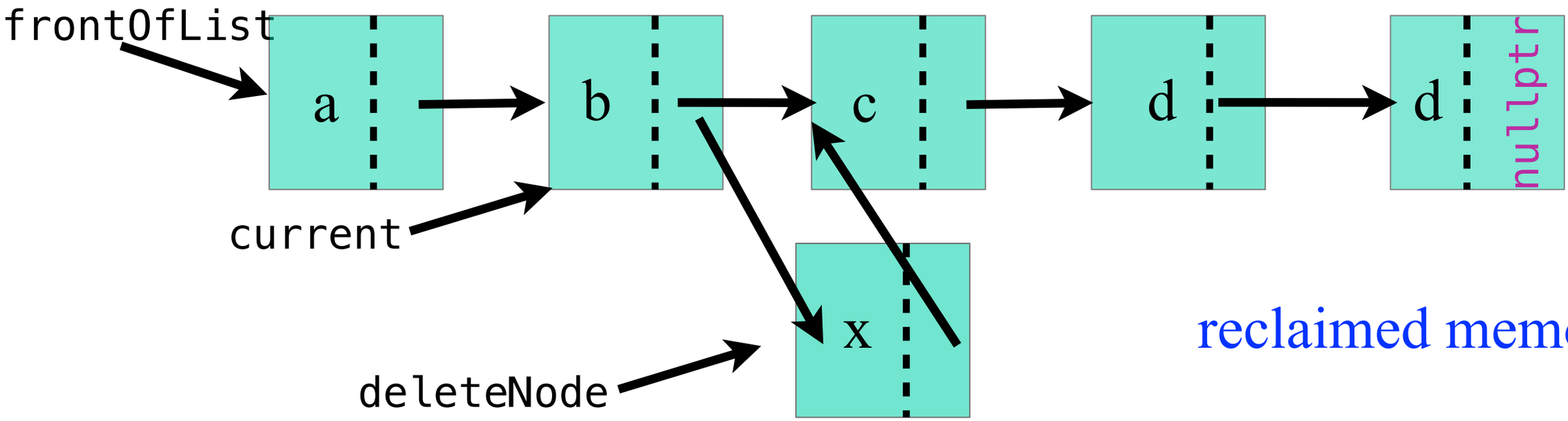
# Deletion of a node in the list, after a pointer to the previous node




Memory Leak!

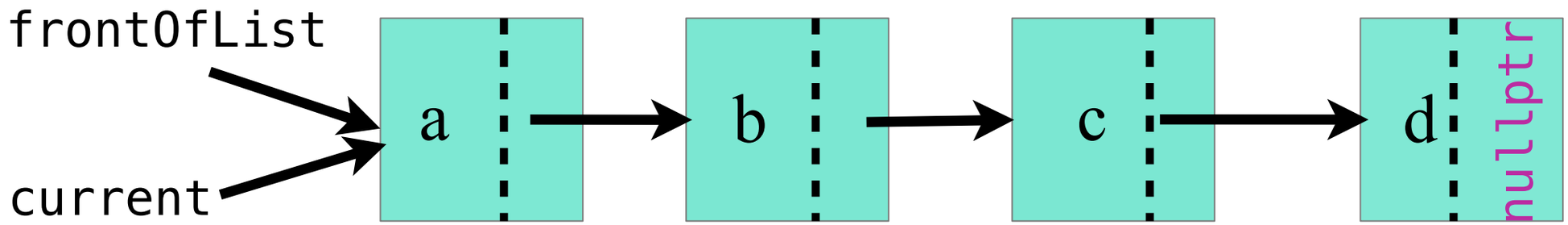
current->next = current->next->next;

# Deletion of a node in the list, after a pointer to the previous node




```
Node<char>* deleteNode = current->next;
current->next = current->next->next;
delete deleteNode;
deleteNode = nullptr;
```

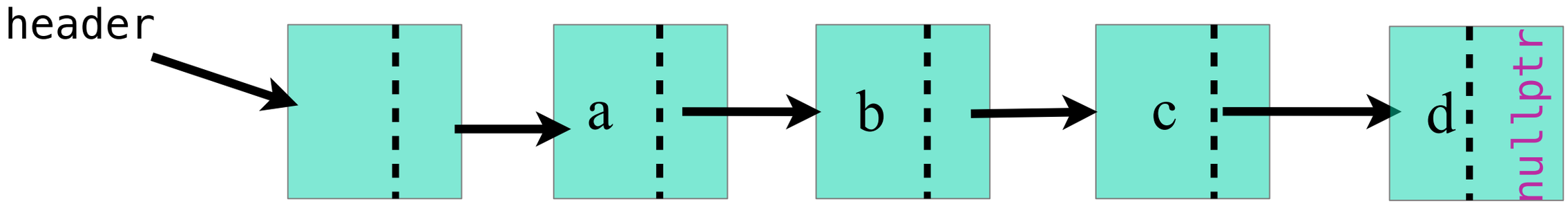
# Insertion and Deletion at the Front of the List

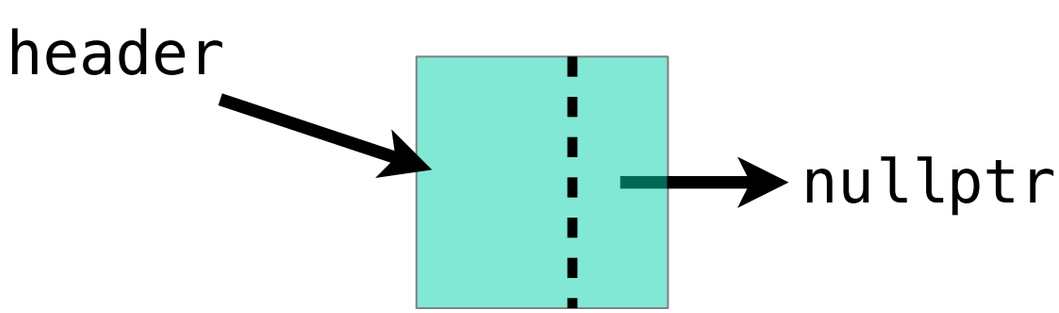



# Special Case

# Header Node

Header Node
Extra node that holds no data. Created so that every node containing an item has a previous node.



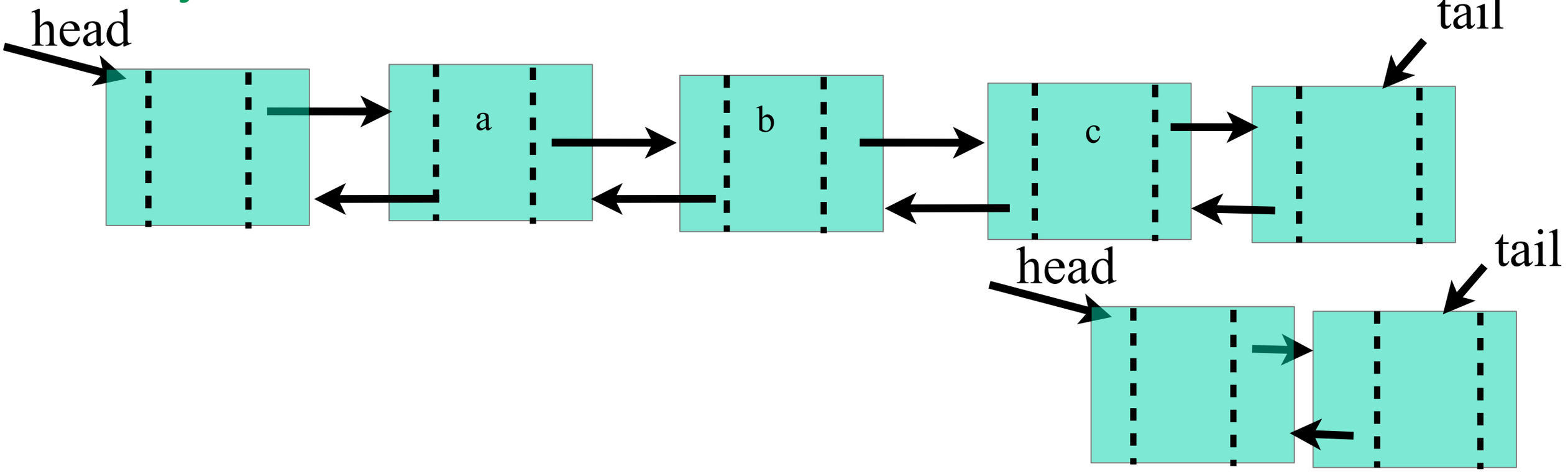




# No Special Case

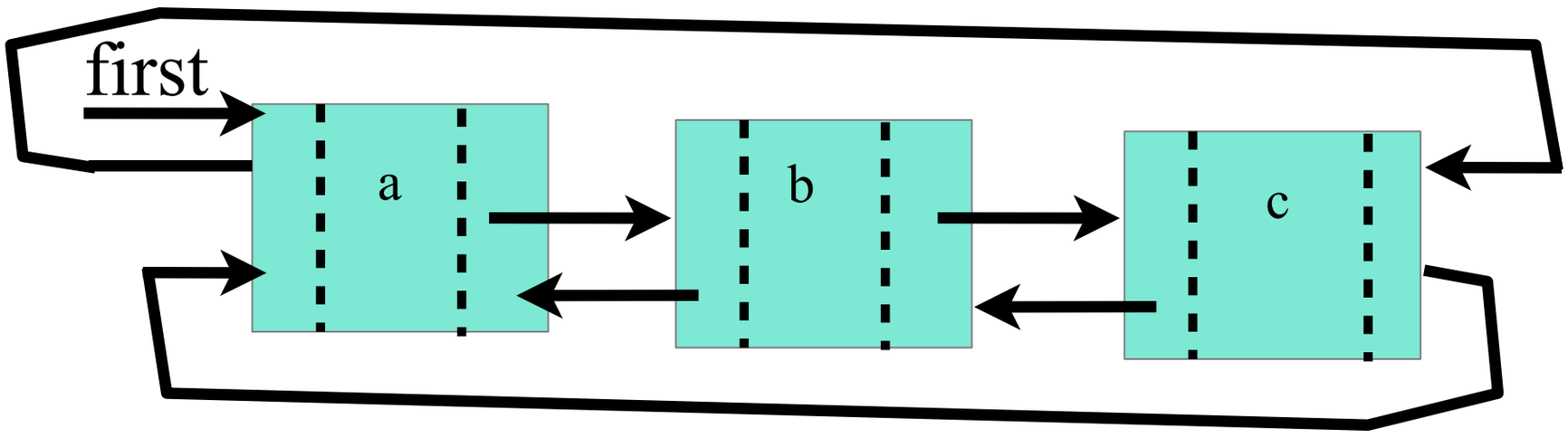
# Other Choices

- singly vs doubly linked list
- header and tail node
- circular lists

# Doubly linked list



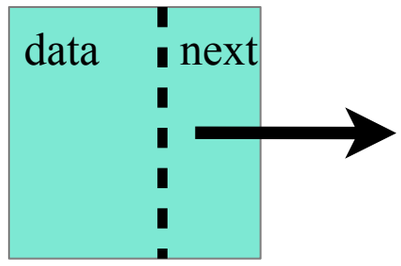

# Circular doubly linked list



# C++ Implementation of a Singly Linked List
(not the same as the STL)

- Node class
- List class
- iterator class ( ++itr, itr++, *itr, ==, != )

# The Node Class (Inside the List Class)

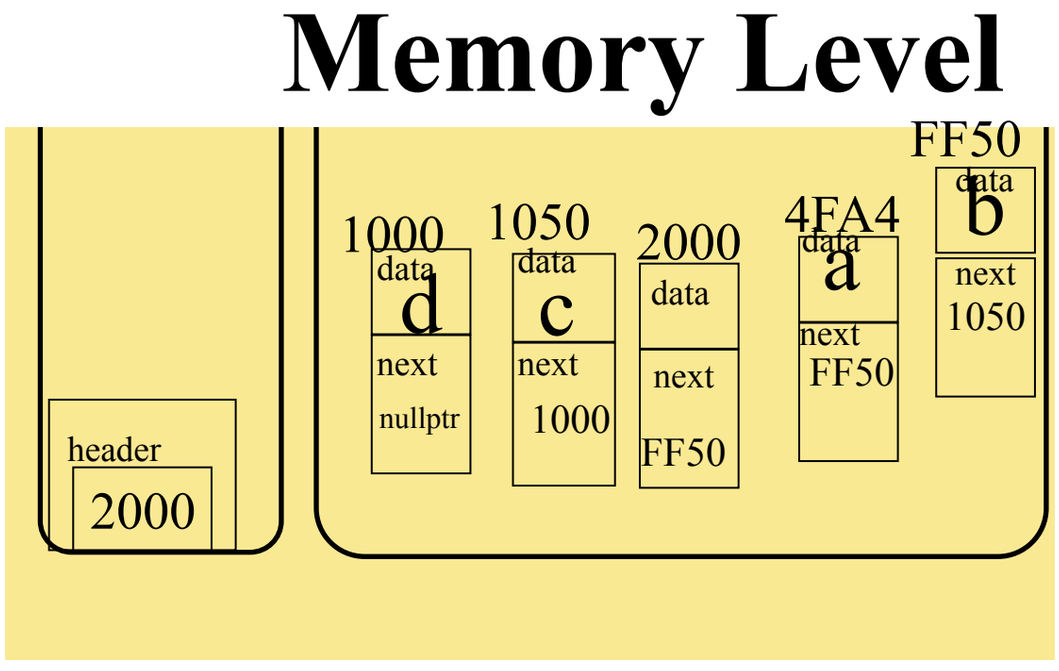



```
struct Node
 {
    Object  data;
    Node  * next;

    Node( const Object & d = Object{ },  Node * n = nullptr )
    : data{ d },  next{ n } { }

    Node( Object && d, Node * n = nullptr )
    : data{ std::move( d ) }, next{ n } { }
};
```

d is an lvalue whose type is an rvalue reference

allowing the resources to be moved

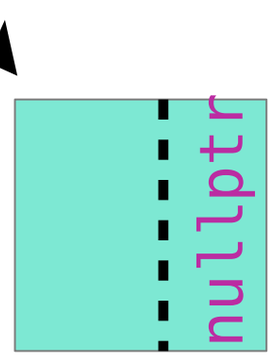
```
template <class Object>
class List
{

  private:
      struct Node
      { // on previous slide
      };

  public:
      class iterator
      { // later in the slides
      };

  public:
     // The big five

    // other methods …

 private:
    LListNode<Object> *header;
};
```




```
List<char> L;
L.push_front('d');
L.push_front('c');
L.push_front('b');
L.push_front('a');
```

constructor: `List( )`

header

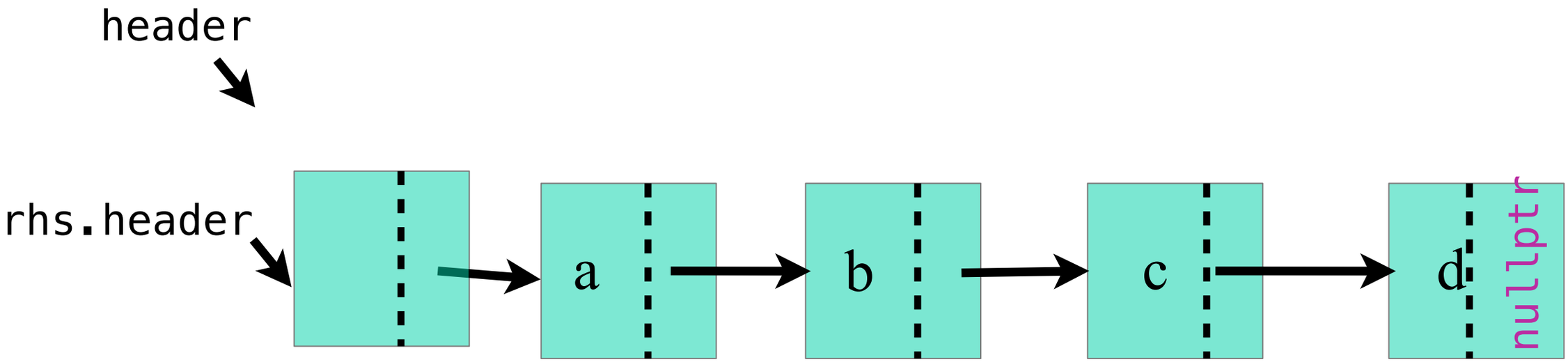



```
struct Node
 {
    Object  data;
    Node  * next;

    Node( const Object & d = Object{ },  Node * n = nullptr )
    : data{ d },  next{ n } { }

    Node( Object && d, Node * n = nullptr )
    : data{ std::move( d ) }, next{ n } { }
 };
```

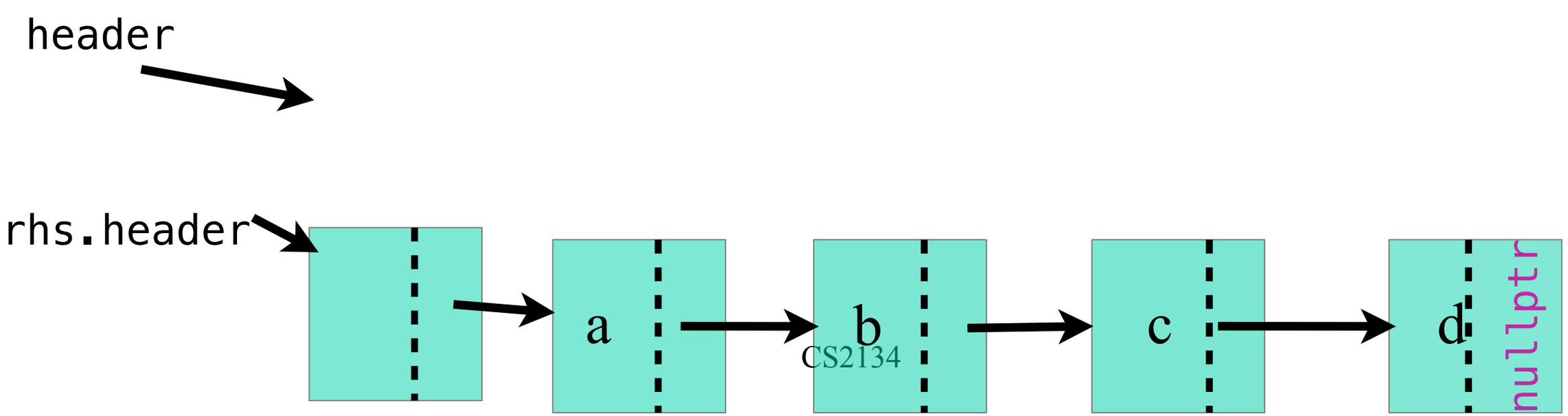
```
// Construct the list.
List( )
{
    header = new Node;
}
```

# The big five!

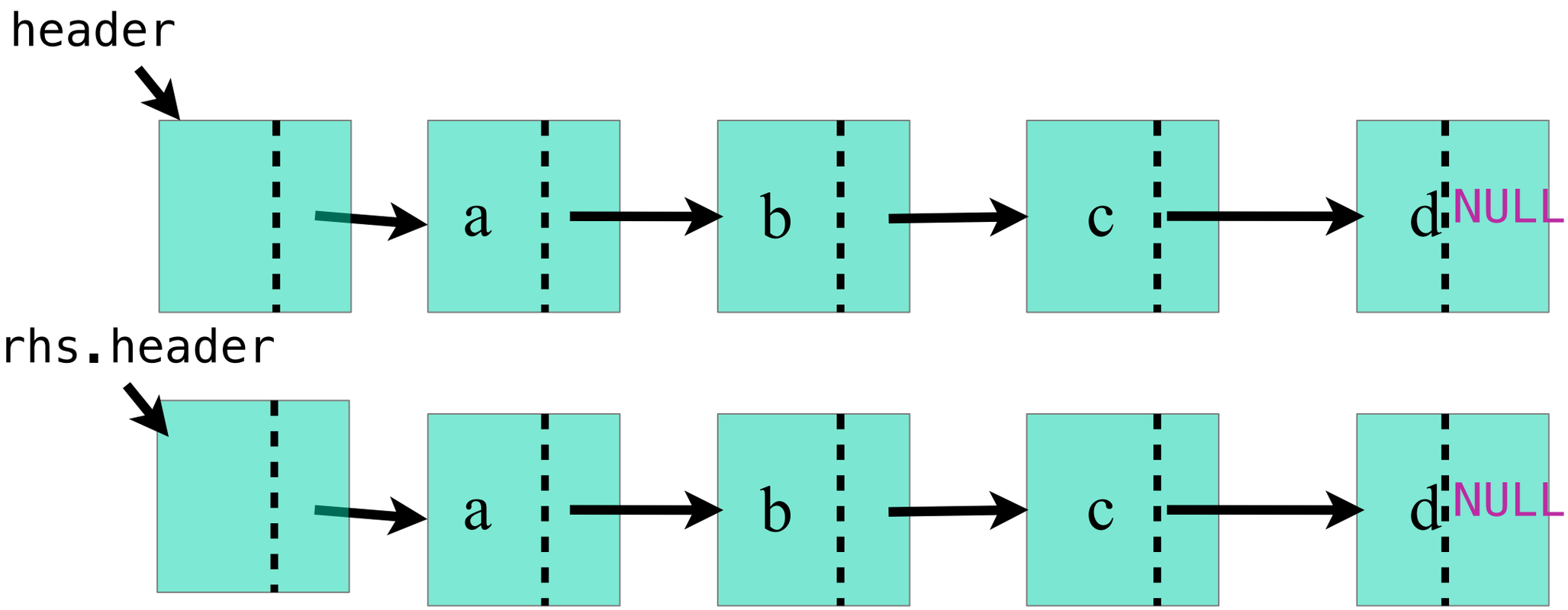
copy constructor: `List( const List<Object> & rhs )`




move constructor: `List( List<Object> && rhs )`

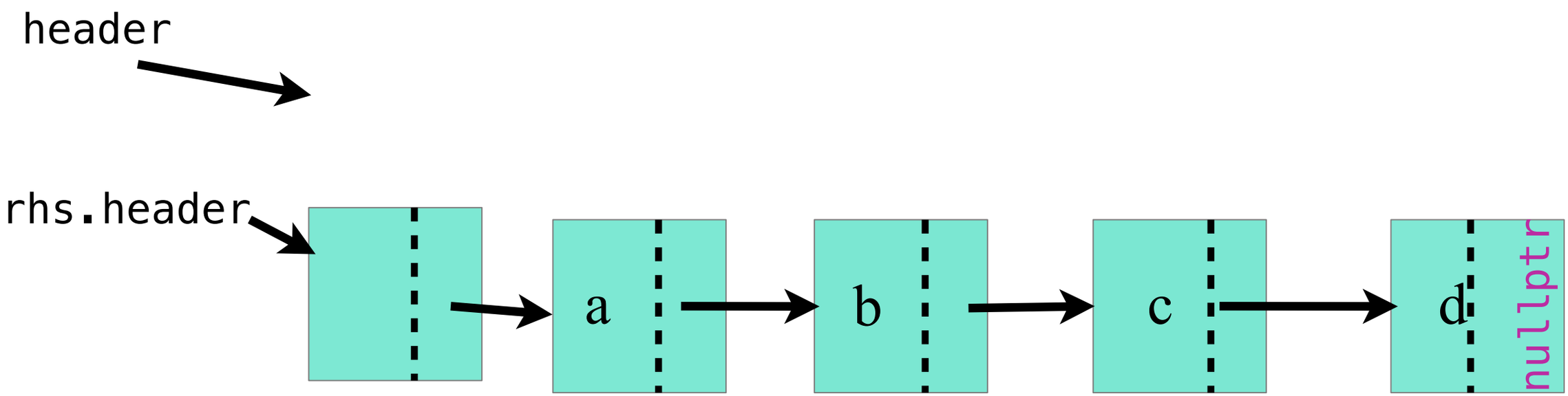


# copy constructor



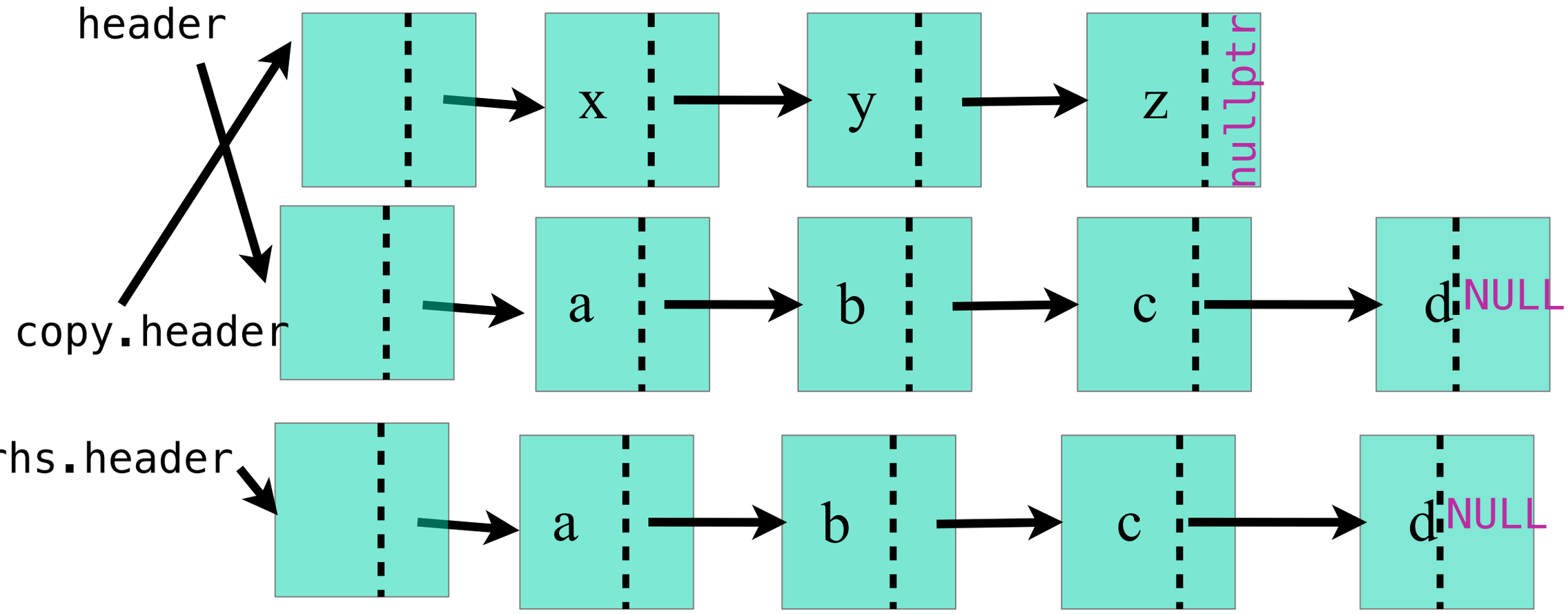

```
// Copy constructor.
List( const List & rhs )
{
        Homework!

}
```

# move constructor

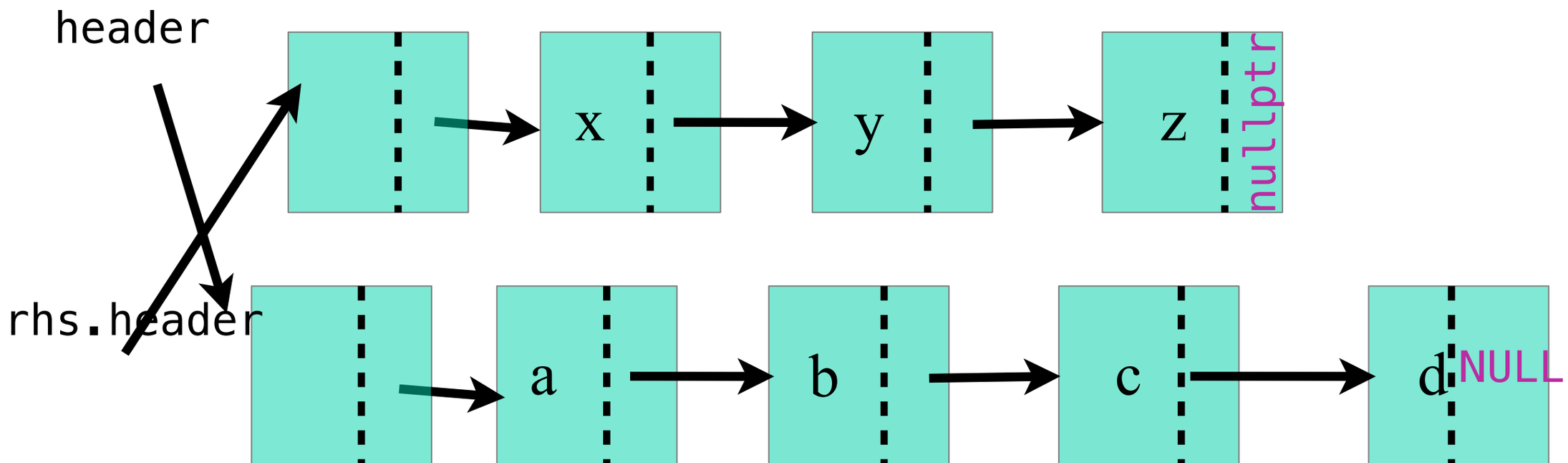



```
                    nullptr
// Move constructor.
List( List<Object> && rhs ):header(new Node)
{
    header->next = rhs.header->next;
    rhs.header->next = nullptr;
}
```

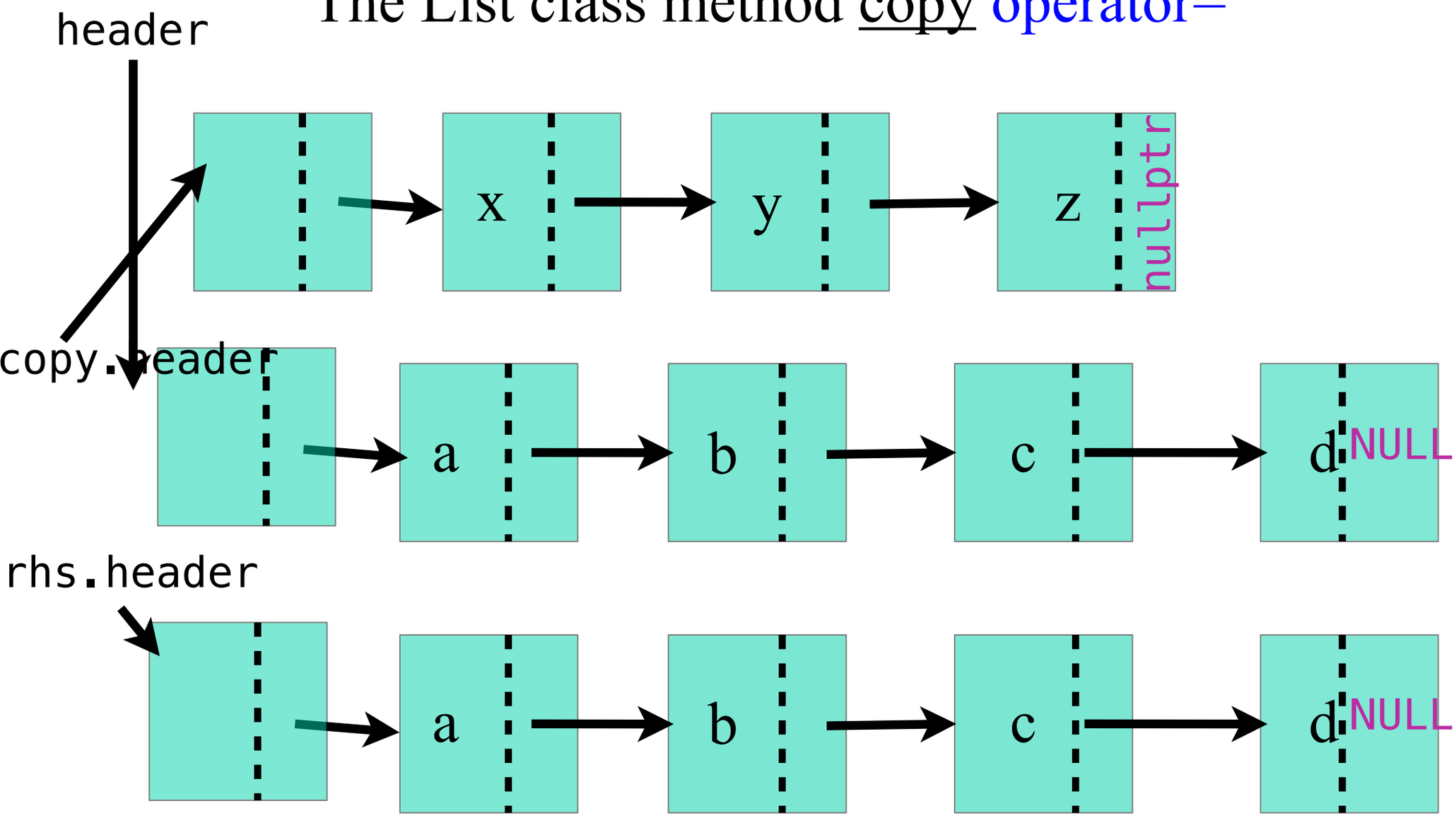
# The List class method copy operator=




# The List class method move operator=

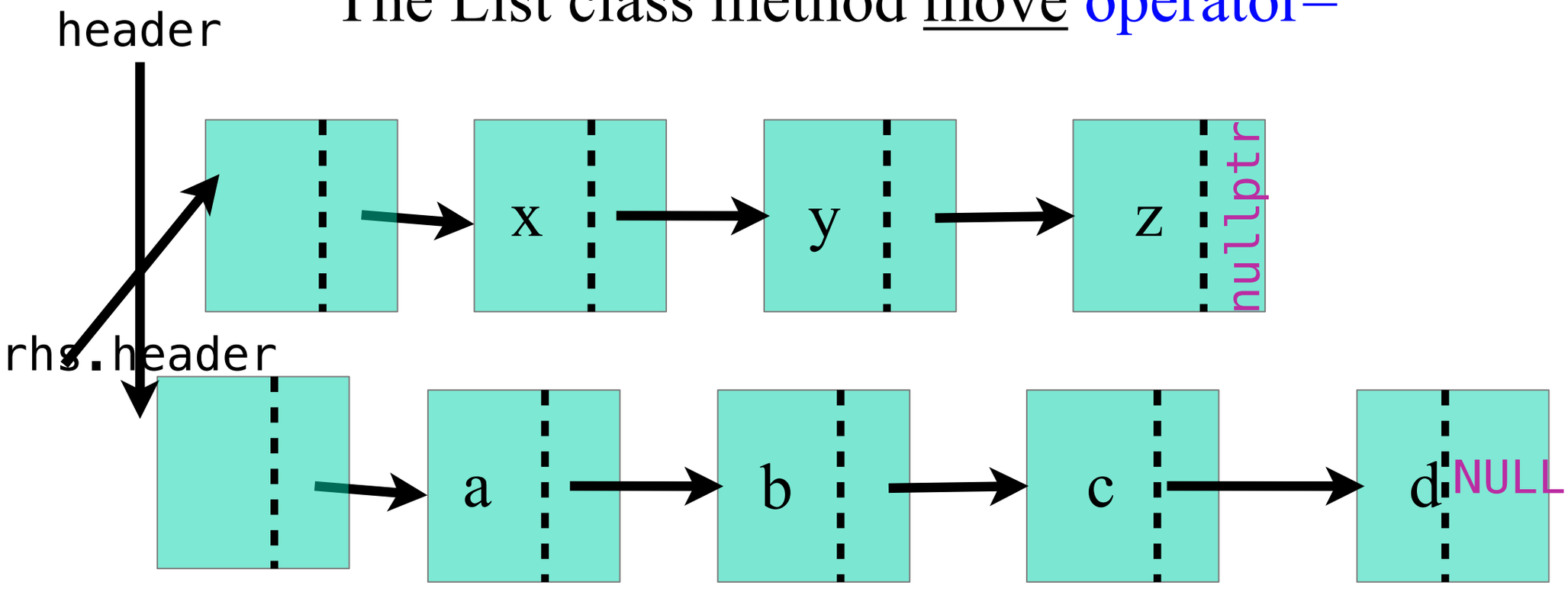


# The List class method copy operator=



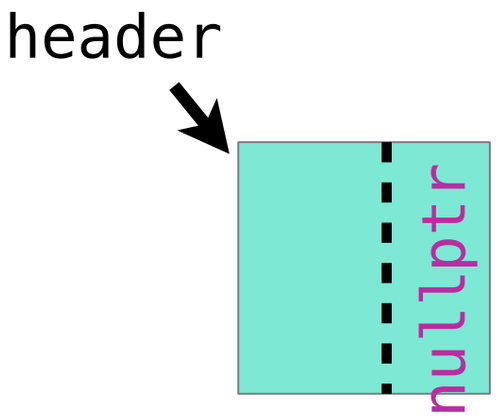

```
List & operator=(const List & rhs)
{
        List copy(rhs);
        std::swap( copy.header, header );
        return *this;
}
```

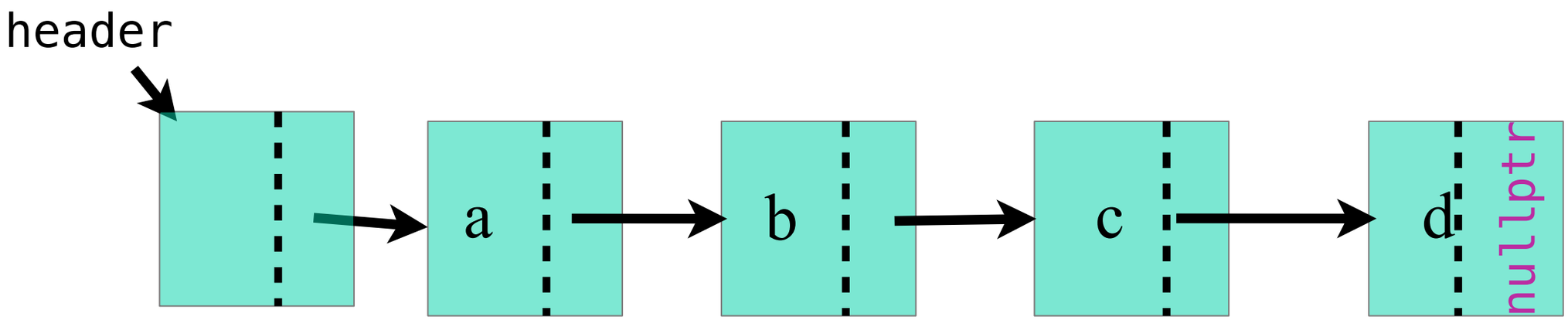
# The List class method move operator=




```
List & operator=( List && rhs)
{
        std::swap( header, rhs.header);
       return *this;
}
```

destructor: ~List( )




```
// destructor.
~List(  )
{
        Homework!

}
```

# How much access should be allowed to the list class?

- Primitive strategy is to allow the user to have access to the list by a pointer.

  What could go wrong?

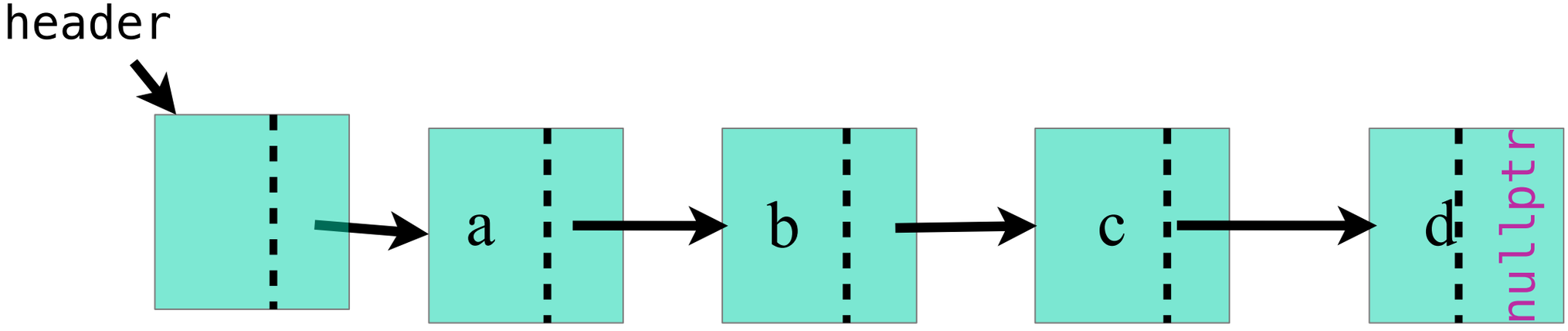
- Another strategy is to have a member variable be a pointer to a node and control how it is used.

  What could go wrong?

- Another strategy is to define a separate iterator class. Advantages?

# Writing a non member function that returns the number of items in a linked list.

```
template<class Object>
int listSize( const List<Object> & theList)
{
   typename List<Object>::iterator itr;

   int size = 0;
   for ( itr = theList.begin(); itr != theList.end(); ++itr )
      size++;
   return size;
}
```

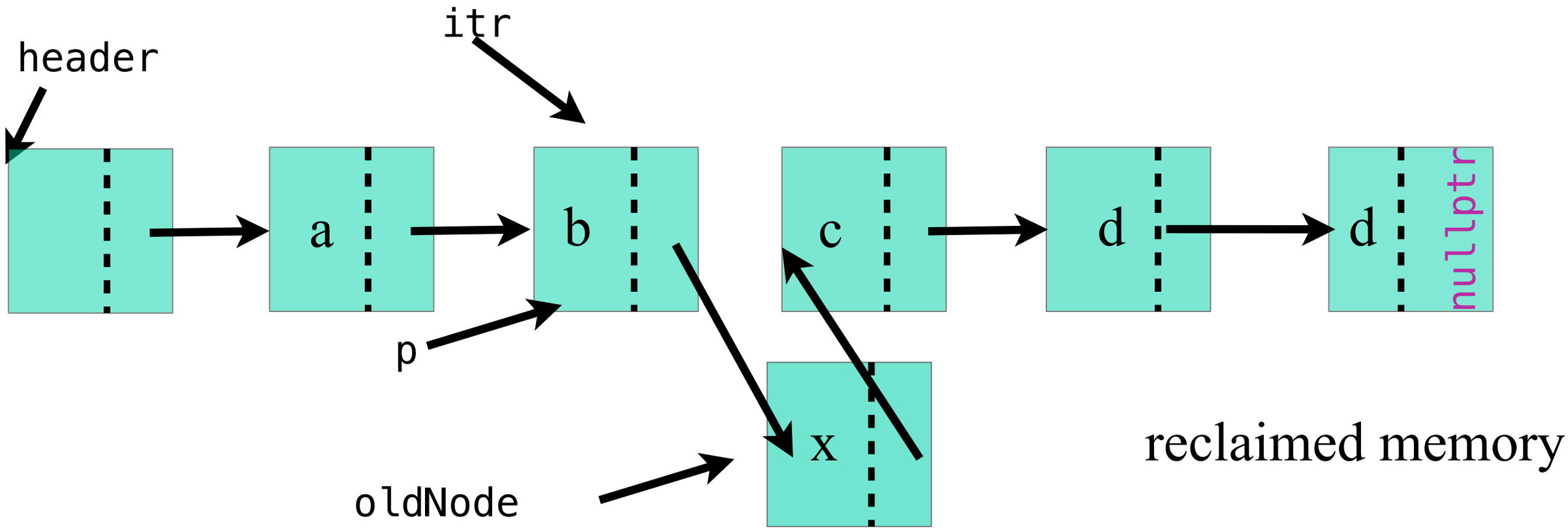


```
template <typename Object>
class List
{
        // Node class
    public:
        class iterator
          {
          public:
            iterator( ) : current( nullptr ) { }
            Object & operator* ( )   { return current->data; }
            const Object & operator* ( ) const{ return  current->data; }

           iterator & operator++ ( )
           {
              current = current->next;
              return *this;
            }
            iterator operator++ ( int )
            {
               iterator old = *this;
               ++( *this );
               return old;
             }

            bool operator== ( const iterator & rhs ) const   { return current == rhs.current; }
            bool operator!= ( const iterator & rhs ) const   { return !( *this == rhs ); }
         private:
            Node * current;

            iterator( Node *p )    : current{ p }{ }
            friend class List<Object>;
         };
       // Other methods
 private:
    List<Object> *header;
};
```

zero parameter constructor so we can create a vector of iterators

what we use in our code!

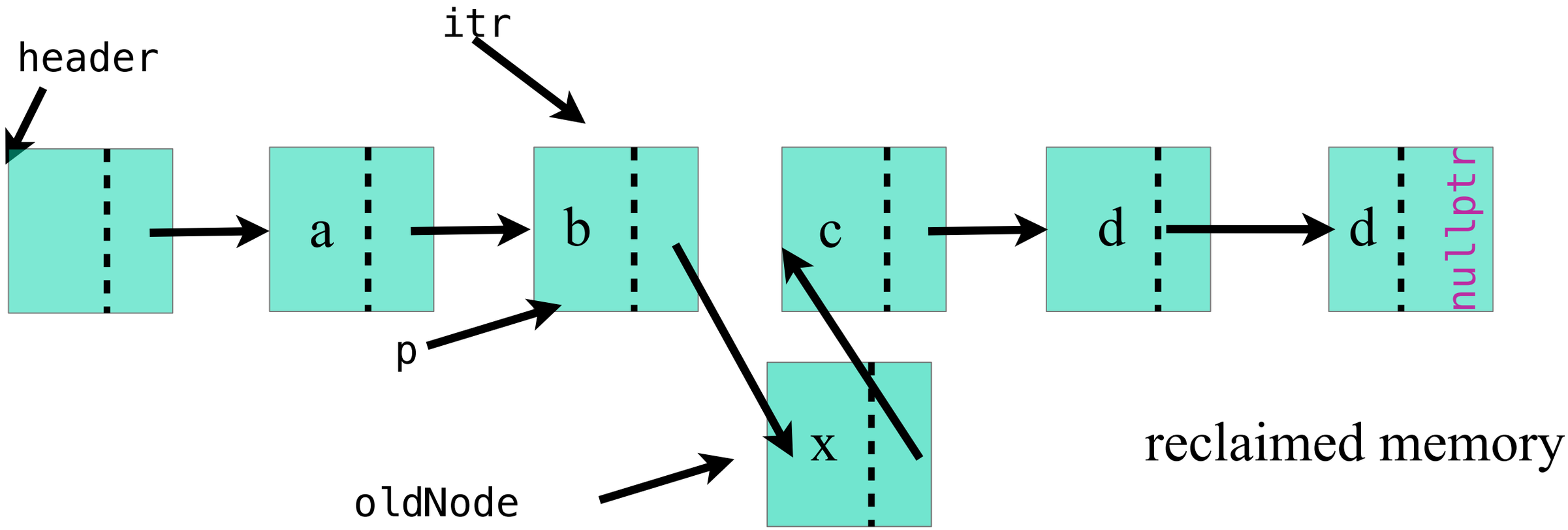
## iterator erase_after( iterator itr ) method




// Erase item after itr.

```
iterator erase_after( iterator itr )
{
        Node *p = itr.current;
        Node *oldNode = p->next;

        p->next = oldNode->next;
        delete oldNode;
        oldNode = nullptr

        return iterator( p->next );
}
```

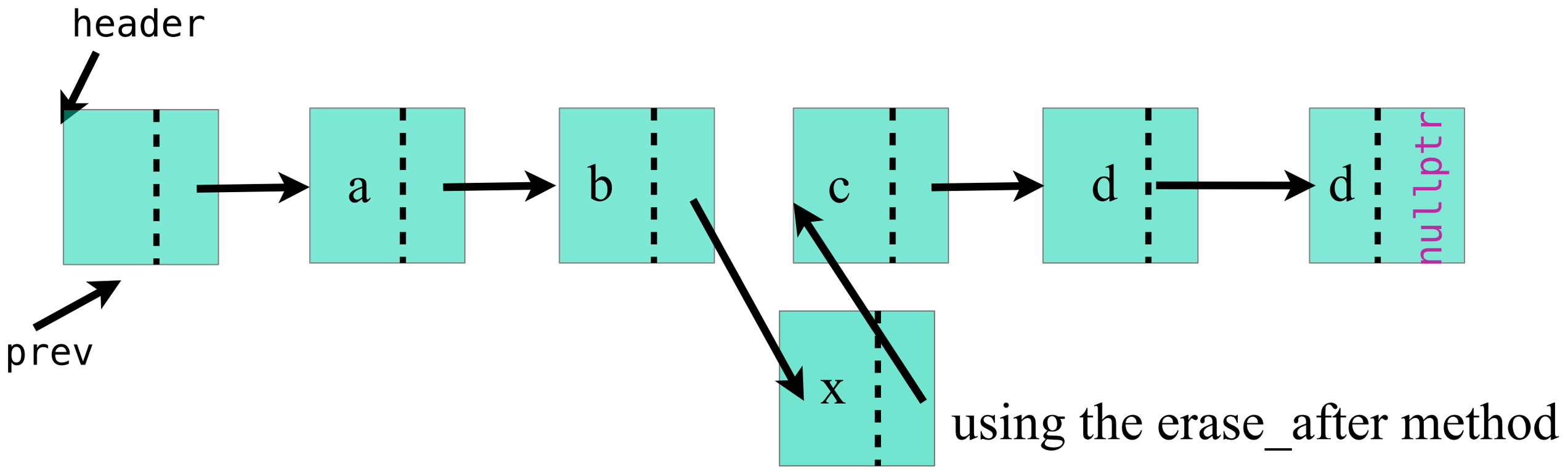
## iterator erase_after( iterator itr ) method




// Erase item after itr.

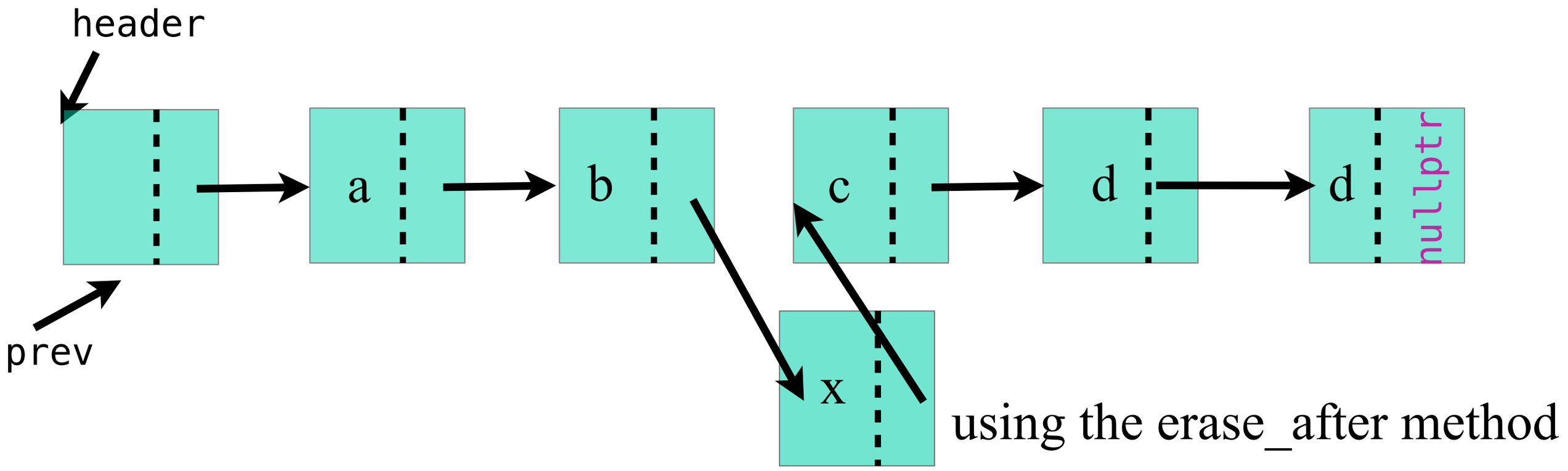
```
iterator erase_after( iterator itr )
{
        Node *p = itr.current;
        Node *oldNode = p->next;

        p->next = oldNode->next;
        delete oldNode;
        oldNode = nullptr;

        return iterator( p->next );
}
```

# void remove(const Object & x) method



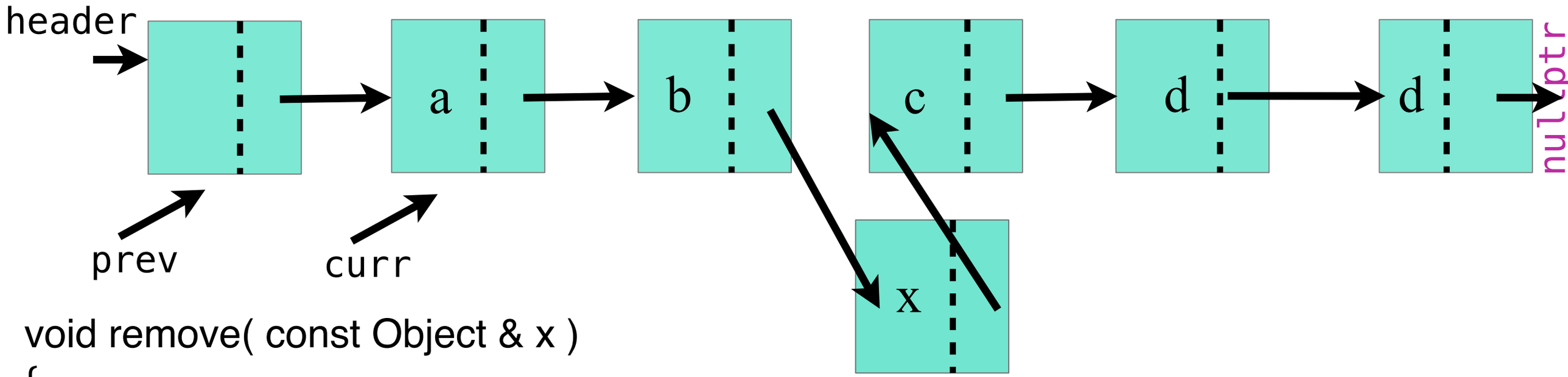

```
void remove( const Object & x )
{
      Node * prev = header;

       while ( prev->next != nullptr )
       {
          if ( prev->next->data == x )
             erase_after( iterator(prev) );
          else
             prev = prev->next;
      }
}
```

# void remove(const Object & x) method




```
void remove( const Object & x )
{
      Node * prev = header;

       while ( prev->next != nullptr )
       {
          if ( prev->next->data == x )
             erase_after( iterator(prev) );
          else
             prev = prev->next;
      }
}
```

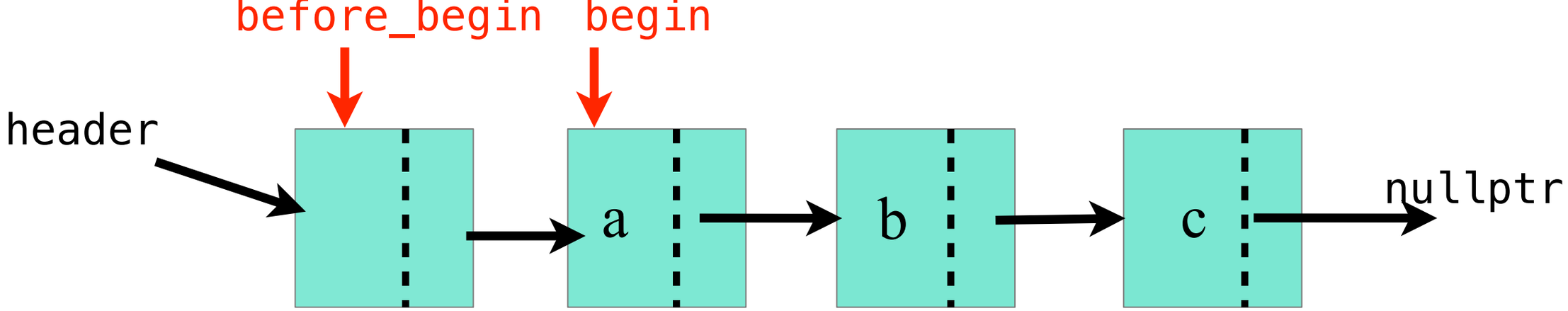
# another way to write the remove method

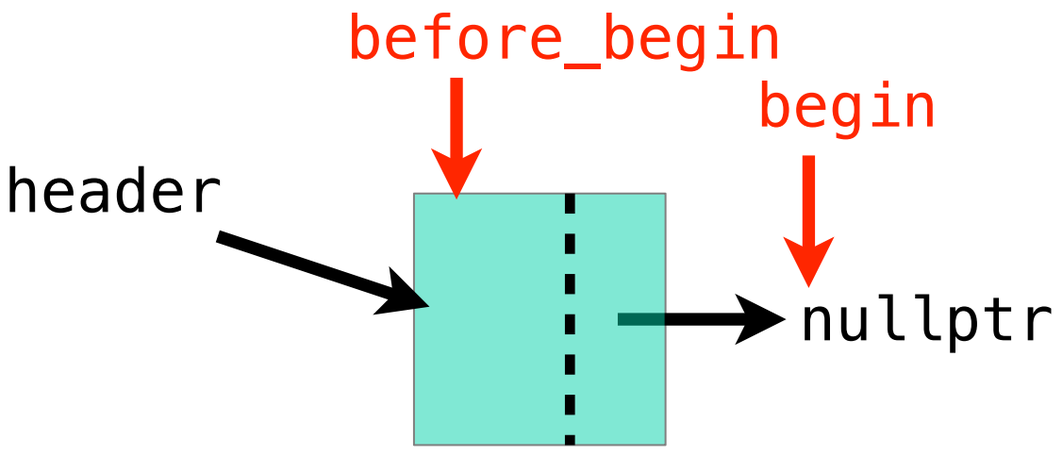



```
void remove( const Object & x )
{
    Node * prev = header;
    Node * curr = header->next;
    while ( curr != nullptr )
    {
        if ( curr->data == x )
        {
            curr = erase_after( iterator( prev ) ).current;    //or
                                                               // erase_after( iterator(prev) );
                                                               // curr = prev->next;
        }
        else
        {
            prev = prev->next;
            curr = curr->next;
        }
}}
```

ah that is better

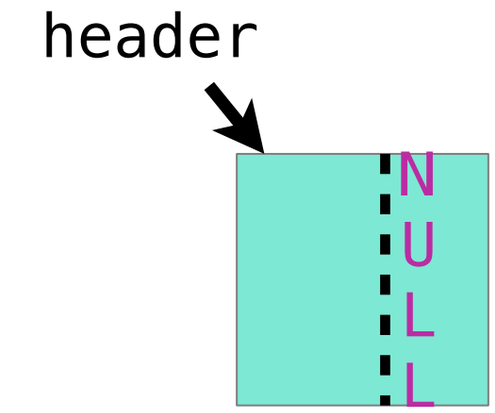
using the erase_after method



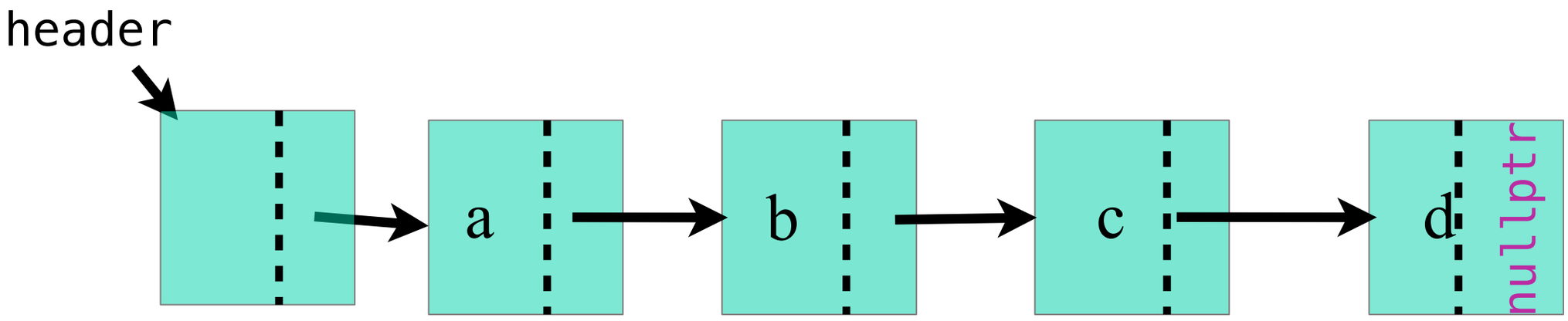




```
// Return an iterator representing the header node.
iterator before_begin( ) const
{
    return iterator( header );
}
// Return an iterator representing the first node in the list.
iterator begin( ) const
{
    return iterator( header->next );
}
```

# method empty( )



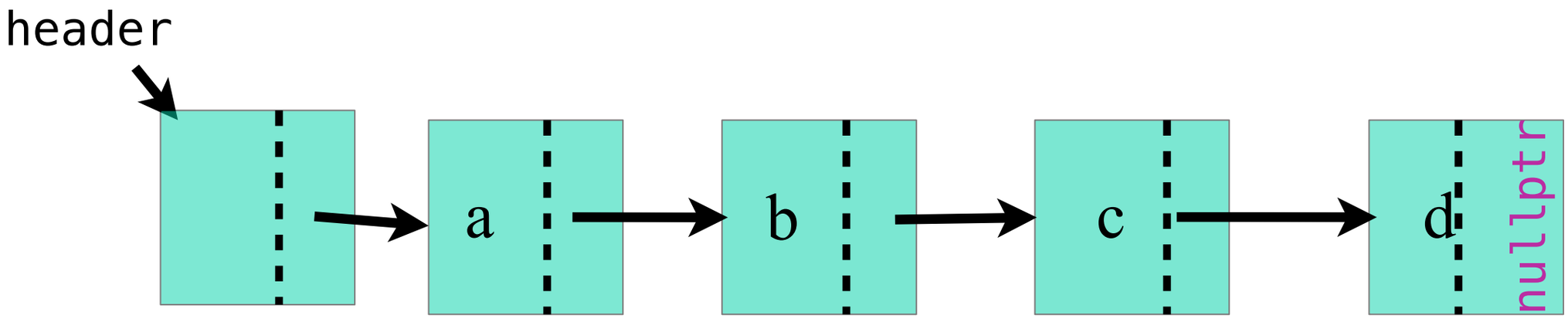

true!




false

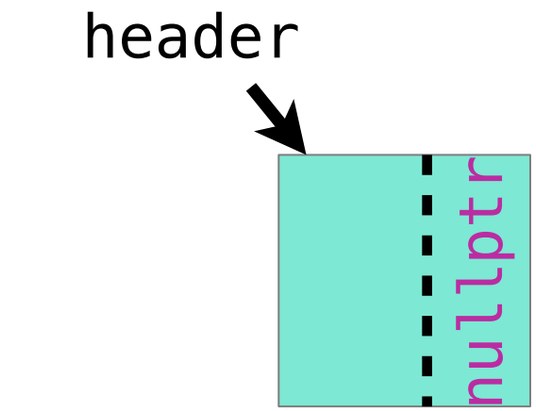
```
// Test if the list is logically empty.
bool empty( ) const
{
   return header->next == nullptr;
}
```

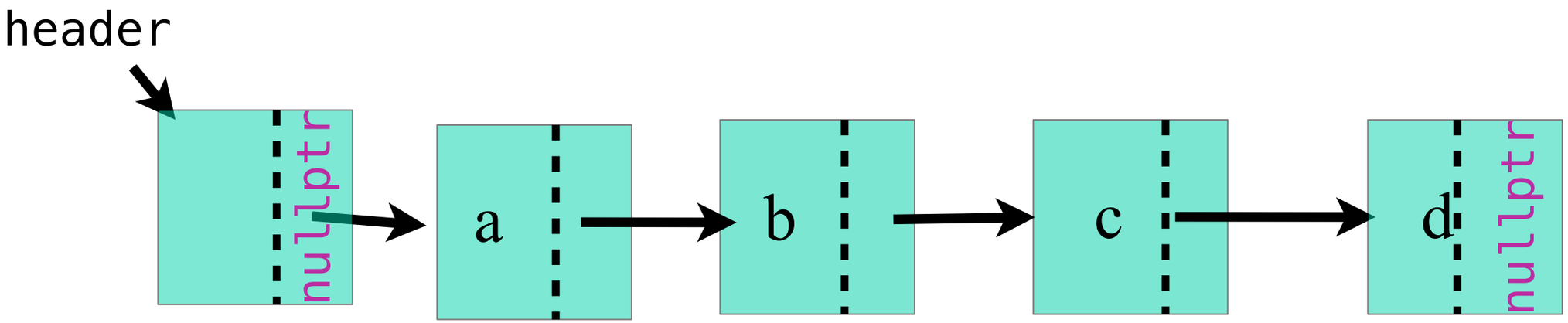
# method pop_front( )




```
void pop_front( )
{
    erase_after( before_begin( ) );
}
```

# method clear( ), making the list logically empty

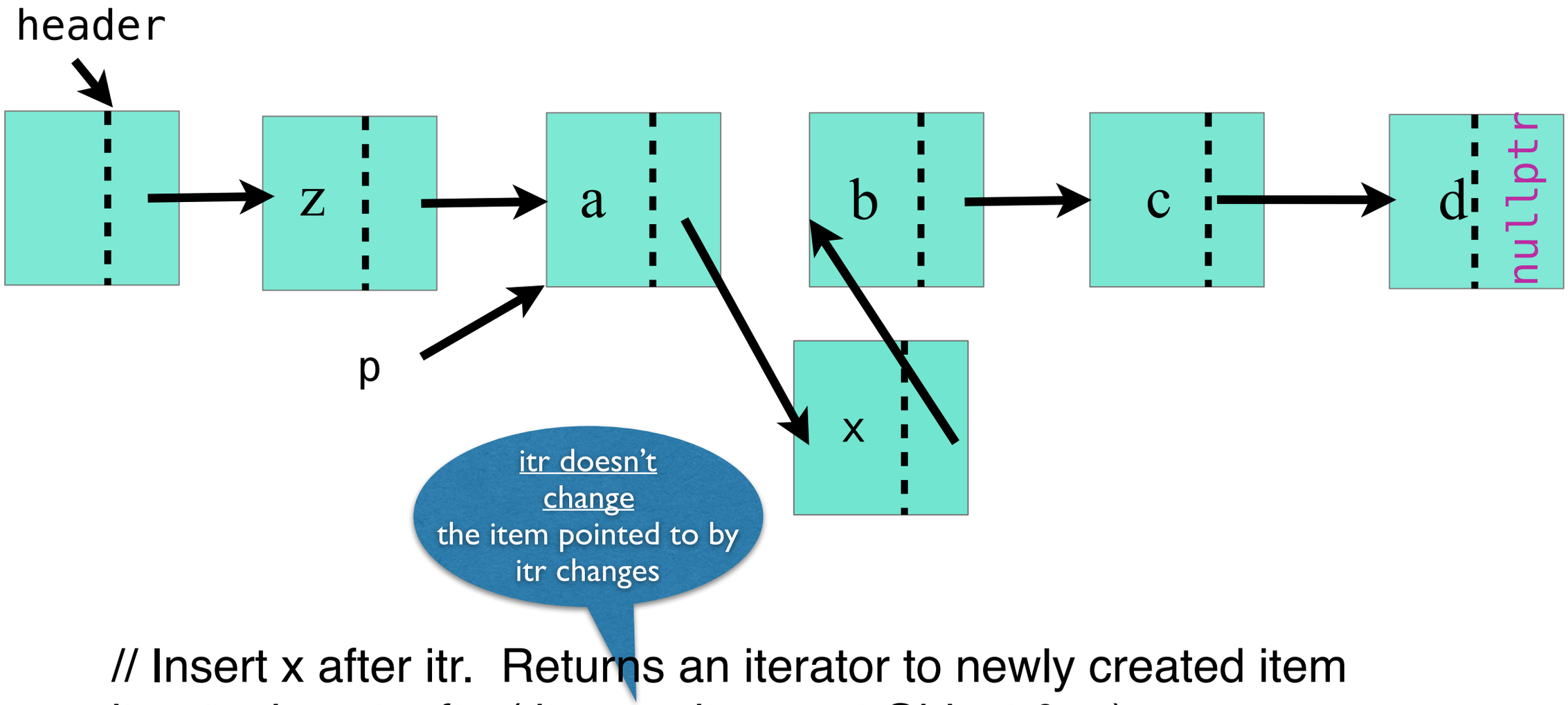



```
void clear( )
{
    while( !empty( ) )
        pop_front( );
}
```

# Insertion

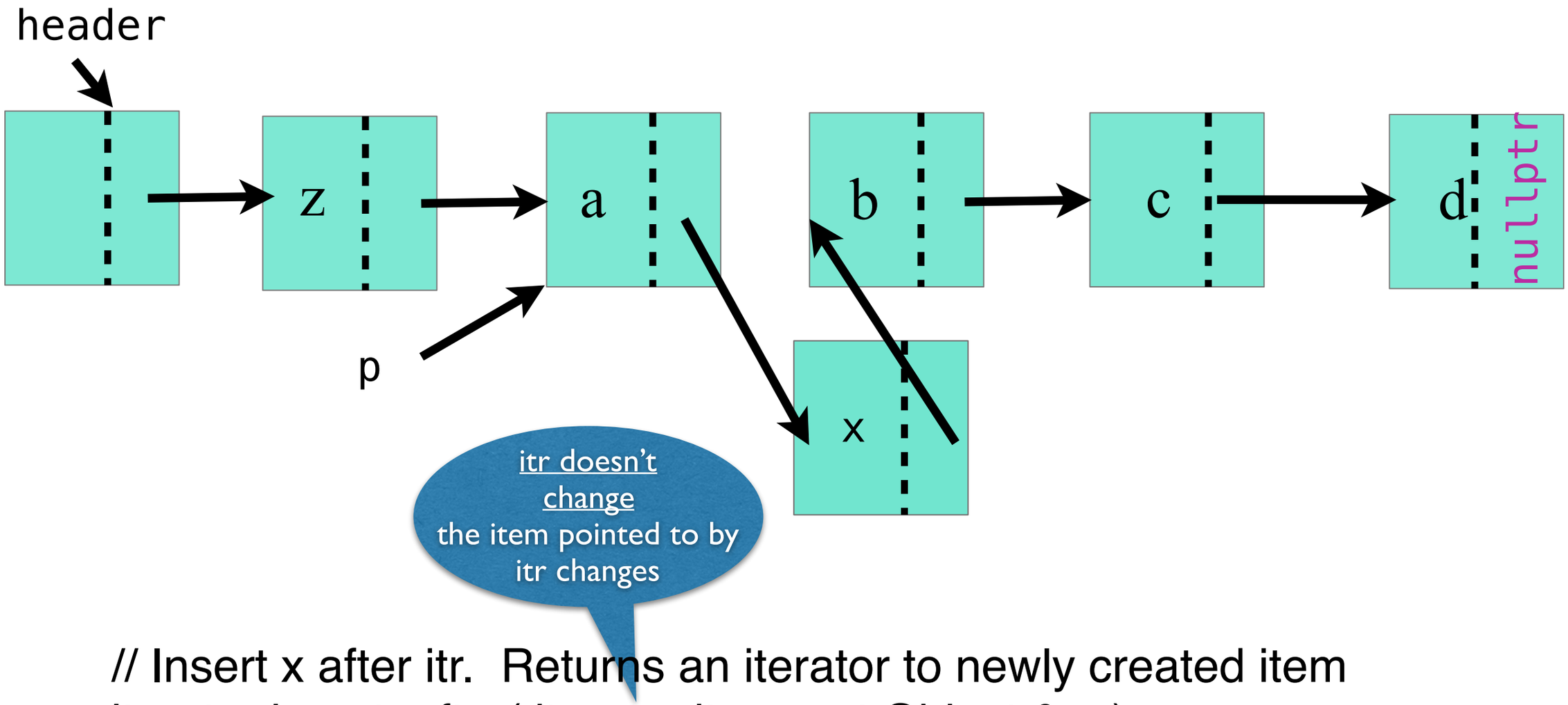
iterator insert_after( iterator itr, const Object & x );




```
// Insert x after itr.  Returns an iterator to newly created item
iterator insert_after( iterator itr, const Object & x )
{
        Node *p = itr.current;
        p->next = new Node{ x, p->next };

        return iterator(p->next);
}
```

# Insertion

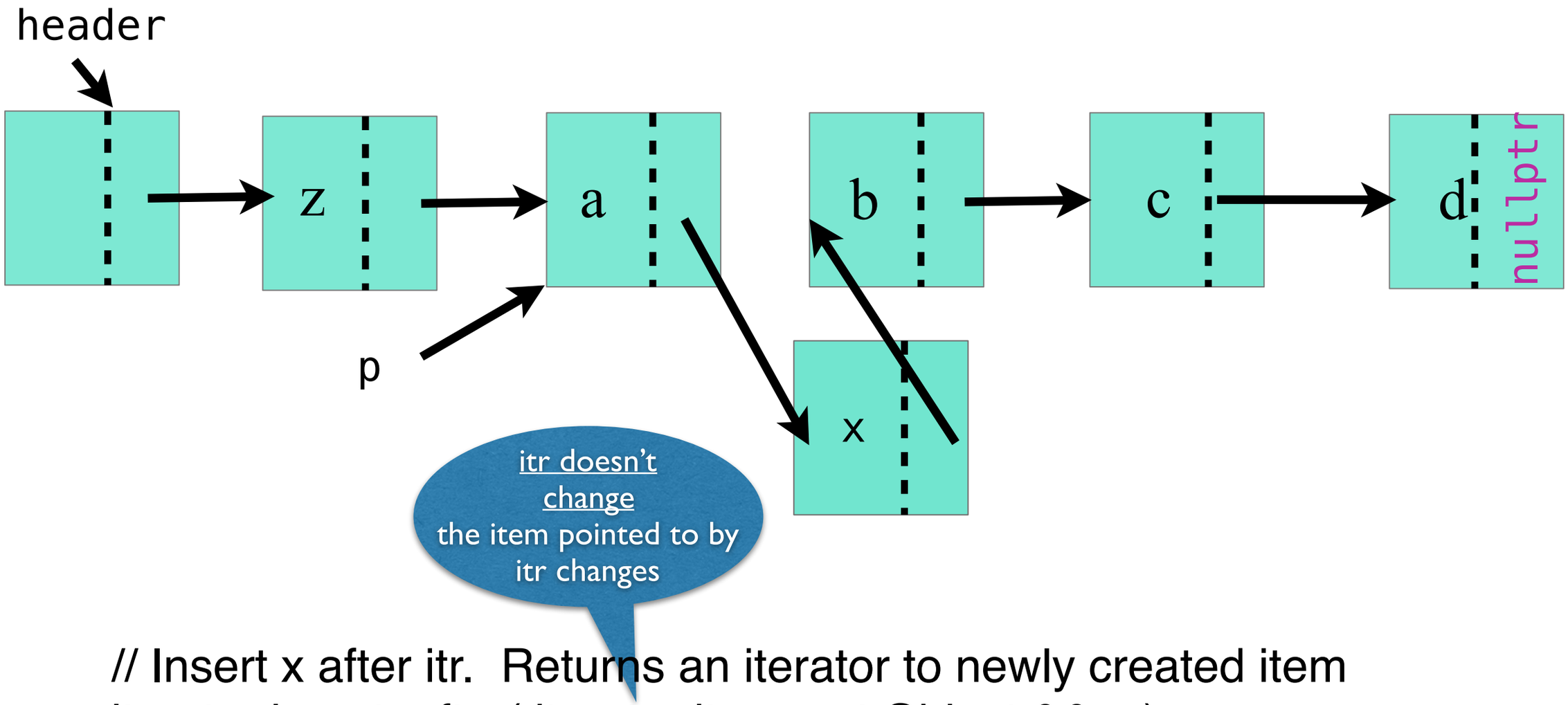
iterator insert_after( iterator itr, const Object & x );




```
// Insert x after itr.  Returns an iterator to newly created item
iterator insert_after( iterator itr, const Object & x )
{
        Node *p = itr.current;
        p->next = new Node{ x, p->next };

        return iterator(p->next);
}
```

# Insertion

iterator insert_after( iterator itr, const Object && x );

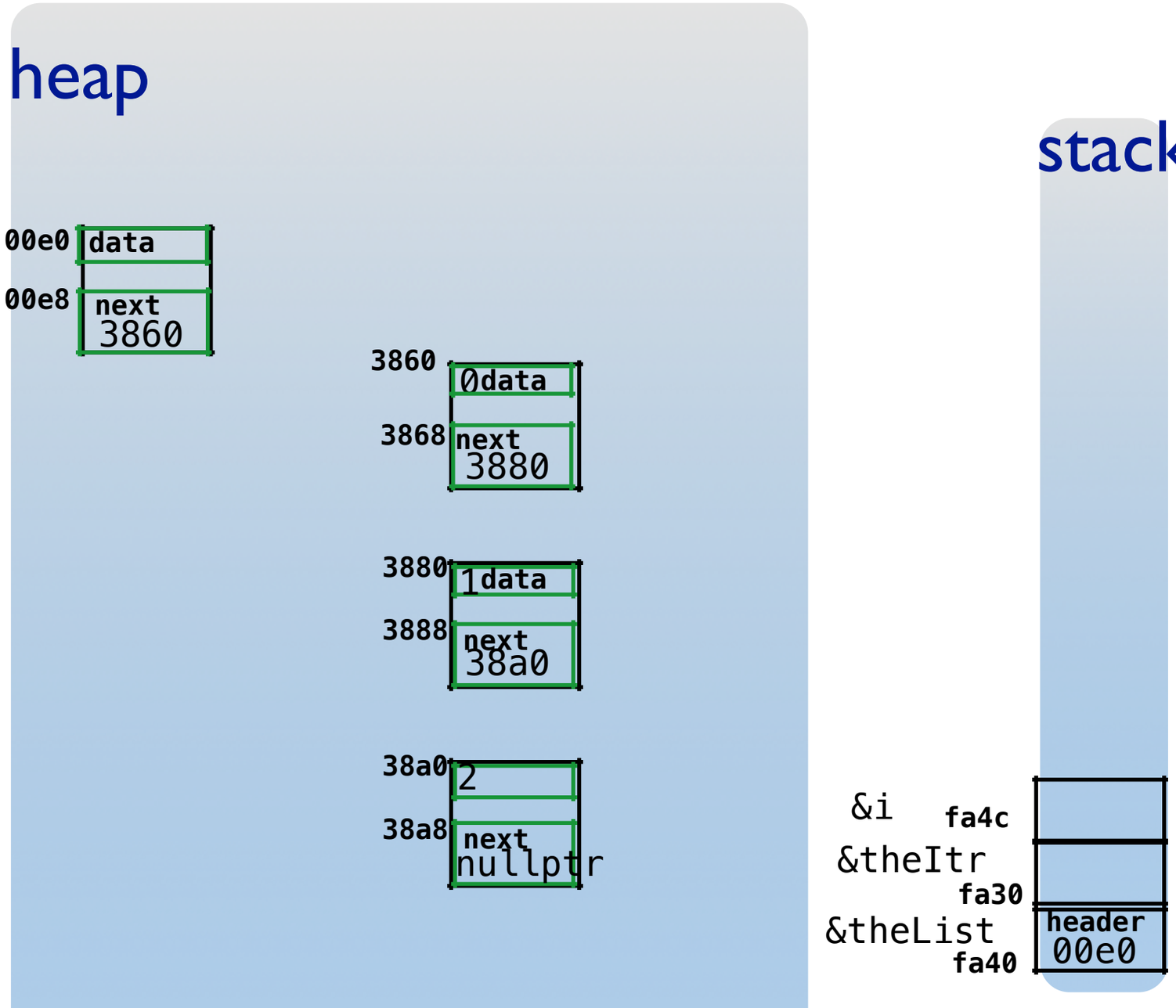



```
// Insert x after itr.  Returns an iterator to newly created item
iterator insert_after( iterator itr, const Object && x )
{
        Node *p = itr.current;
        p->next = new Node{ std::move( x ), p->next };

        return iterator(p->next);
}
```

# Using the class

# Using the LList class

```
int main( ) {
   List<int>  theList;
   List<int>::iterator theItr = theList.before_begin();

   int i;

   for( i = 0; i < 3; i++ )
   {
      theList.insert_after( theItr, i );
      ++theItr;
   }

   for( i = 0; i < 3; i ++ )
      theList.remove( i );

   return 0;
}
```



# Our List - Forward Iterator

| | |
|---|---|
| • sl.empty( ) | O(1) |
| • s.clear( ) | O(n) |
| • sl.remove(x) | O(n) |
| • sl.insert_after(itr, x) | O(1) |
| • sl.begin( ) | O(1) |
| • sl.before_begin( ) | O(1) |
| • sl.end( ) | O(1) |
| • sl.erase_after(itr) | O(1) |
| • sl_lhs = sl_rhs | O(n) |

Note: all these times do not include constructor/destructor times which many vary according to the type

# List Traversals

- Lots of applications require iteration through list, accessing each element (until end or until some condition is met)
- Sometimes useful to keep additional iterators, such as “prev” (sometimes called “trailer”) that stays one step behind “current” iterator or pointer.

# Example

## finding the first negative element in the list

```
List<int>  L;  // … assume L has some elements

List<int>::iterator curr = L.begin();

while ( curr != L.end() && ( *curr >= 0 ) )
        ++curr;

if ( curr != L.end() )
    cout << “First negative element is “ << *curr;
else
    cout << “All elements are positive.”
```

# Example 2

## Removing the first negative element from the list

```
LList<int>  L;
…
 List<int>::iterator curr = L.begin();
 List<int>::iterator prev = L.before_begin();

while ( curr != L.end() && ( *curr >= 0) )
{
            prev = curr;
            ++curr;
 }
 if ( curr != L.end() )
      L.erase_after(prev);
```

# STL Lists

- http://www.sgi.com/tech/stl/List.html
- Doubly linked list with
  - –Forward & reverse iterators
  - –O(1) insertion and deletion at front, back and arbitrary points
  - –Iterators not invalidated on insertion, splicing or removal (except removed node)
  - –…
- STL also provides singly linked list: forward_list

# list - Bidirectional Iterators

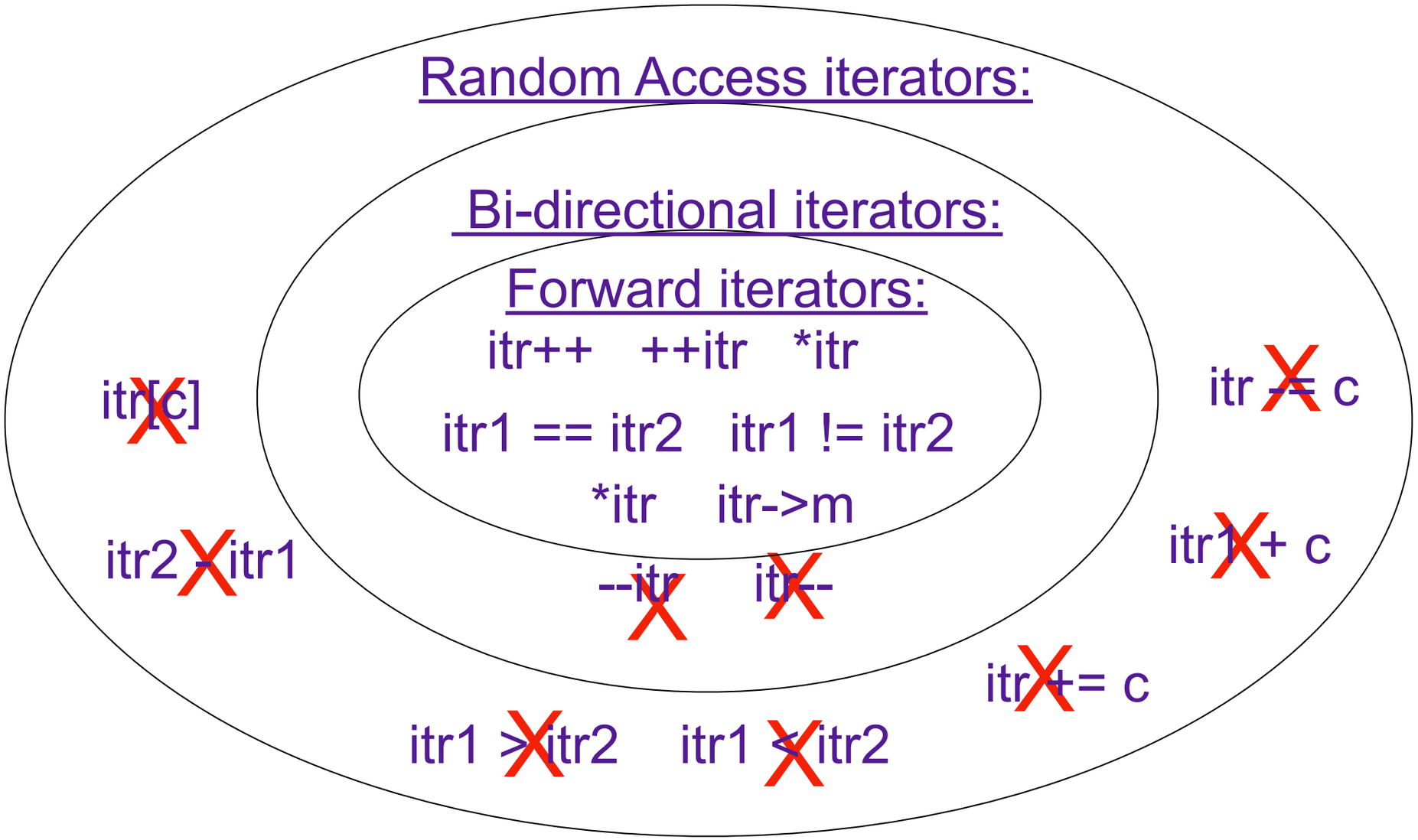
#include<list>

- l.push_back(value) O(1)
- l.push_front(value) O(1)
- l.erase(v.begin( ),v.end( )) O(n)
- l.erase(iterator) O(1)
- l.clear( ) O(n)
- l.size( ) O(1)
- l.insert(iterator,value) //inserts before iterator O(1)
- l.begin( ) O(1)
- l.end( ) O(1)
- l.sort( ) & l.sort(comparator) O(nlog(n))

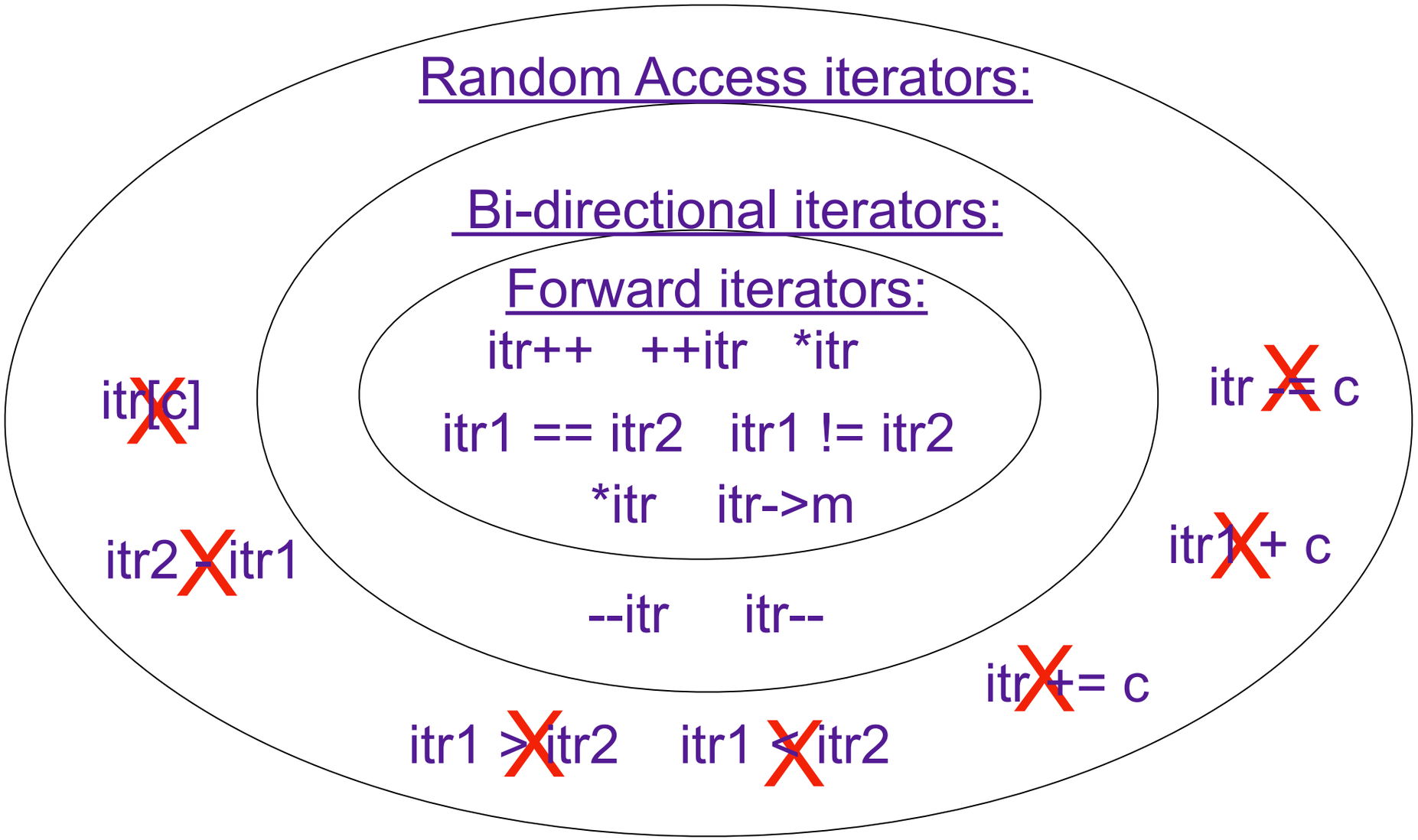
Note: all these times do not include constructor/destructor times which many vary according to the type

# Iterators

# What type of iterator operations for a singly linked list?



# What type of iterator operations for a doubly linked list?



# Instantiating an Iterator

Random Access Iterators

vector<T>::iterator vecItr;  vector<T>::const_iterator constVecItr;

Bidirectional Iterators

list<T>::iterator listIter;  list<T>::const_iterator const_listItr;

map<K, V>::iterator mapItr;  map<K, V>::const_iterator const_mapItr;

set<K, V>::iterator setItr;  set<K, V>::const_iterator const_setItr;

Forward Iterators

forward_list<T>::iterator slistIter;  forward_list<T>::const_iterator const_sListItr;