Linked List

Faster Insert & Erase but slower access

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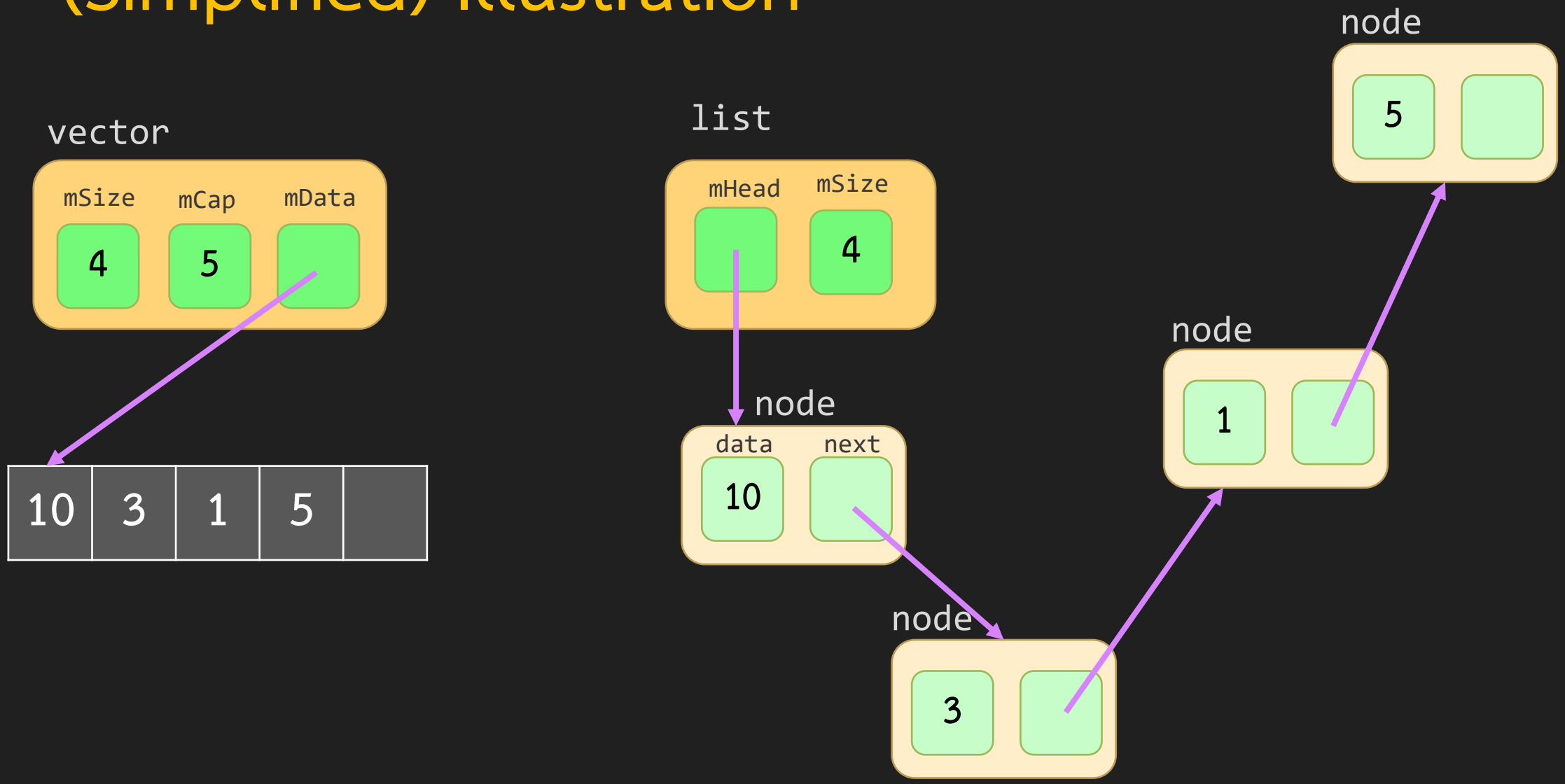
Overview

- Vector takes O(n) in insert/erase at position specified by an iterator
  - But it is very fast to access any member, O(1)
- List gives better performance on insert/erase as O(1), providing that we have iterator to the position of insertion/erase
- Achieved by storing data into a node and each node use a pointer to identify the next element
  - Access to any elements is O(n), if we don't have an iterator to that element
- Use more memory than vector

(Simplified) Illustration



List vs Vector

List

- Allocate each data separately
  - Each data points where is the next data
  - Very fast insert/erase (just change some pointer)
  - Very slow access because we don’t know where k-th element is

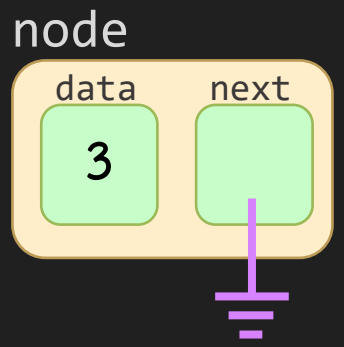
Vector

- Allocate data as a consecutive block
  - Very fast to access any element
  - Very slow Insert/erase requires every element after point of insertion

v0.1 node

- Simple object that stores a data and a link to another node
- NULL is a special value for any pointer that points to nowhere
  - Draw as a ground

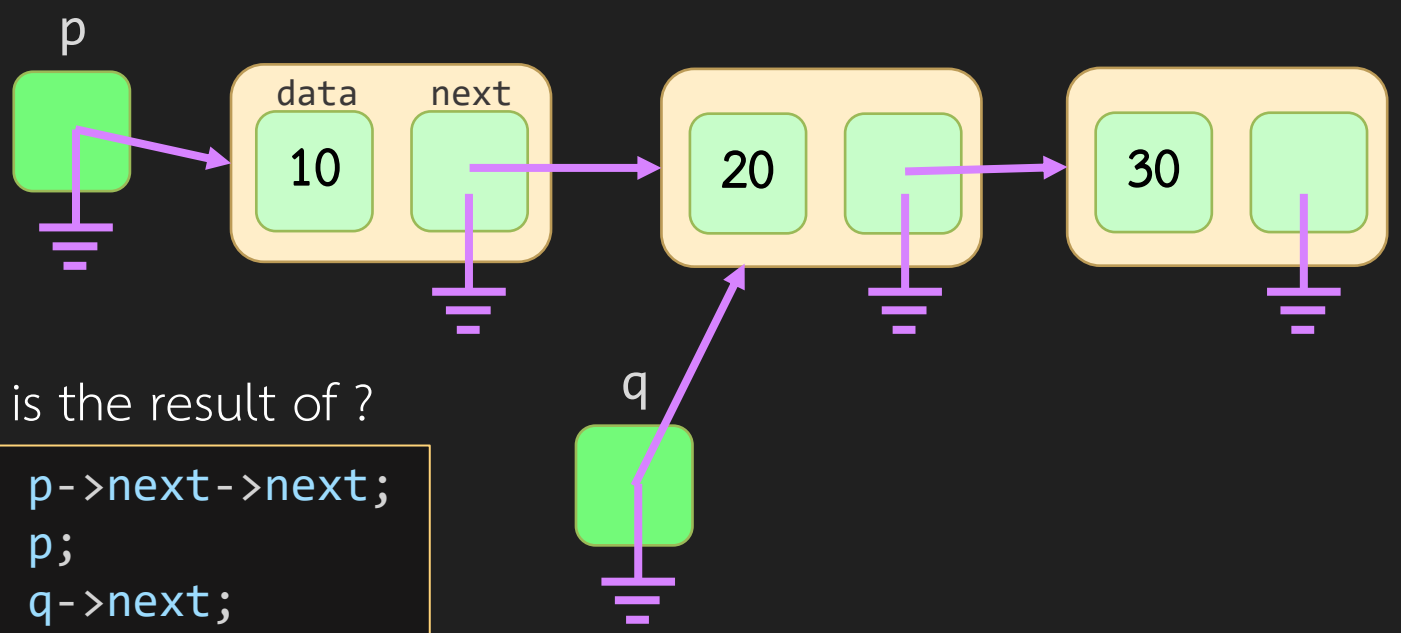
```
template <typename T>
class node {
  public:
    T data;
    node *next;
    node() :
      data( T() ), next( NULL ) { }

    node(const T& data, node* next) :
      data ( T(data) ), next( next ) { }
};
```



Pointer to Node

- Working with linked list needs a pointer to a node

```
int main() {
  CP::node<int> *p = NULL;
  p = new CP::node<int>(10,NULL);
  CP::node<int> *q;
  q = new CP::node<int>(20,NULL);
  p->next = q;
  q->next = new CP::node<int>(30,NULL);
}
```



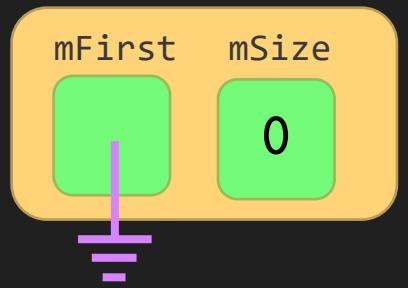
What is the result of ?

```
p = p->next->next;
q = p;
q = q->next;
```

v0.1 Simple (Singly) Linked List

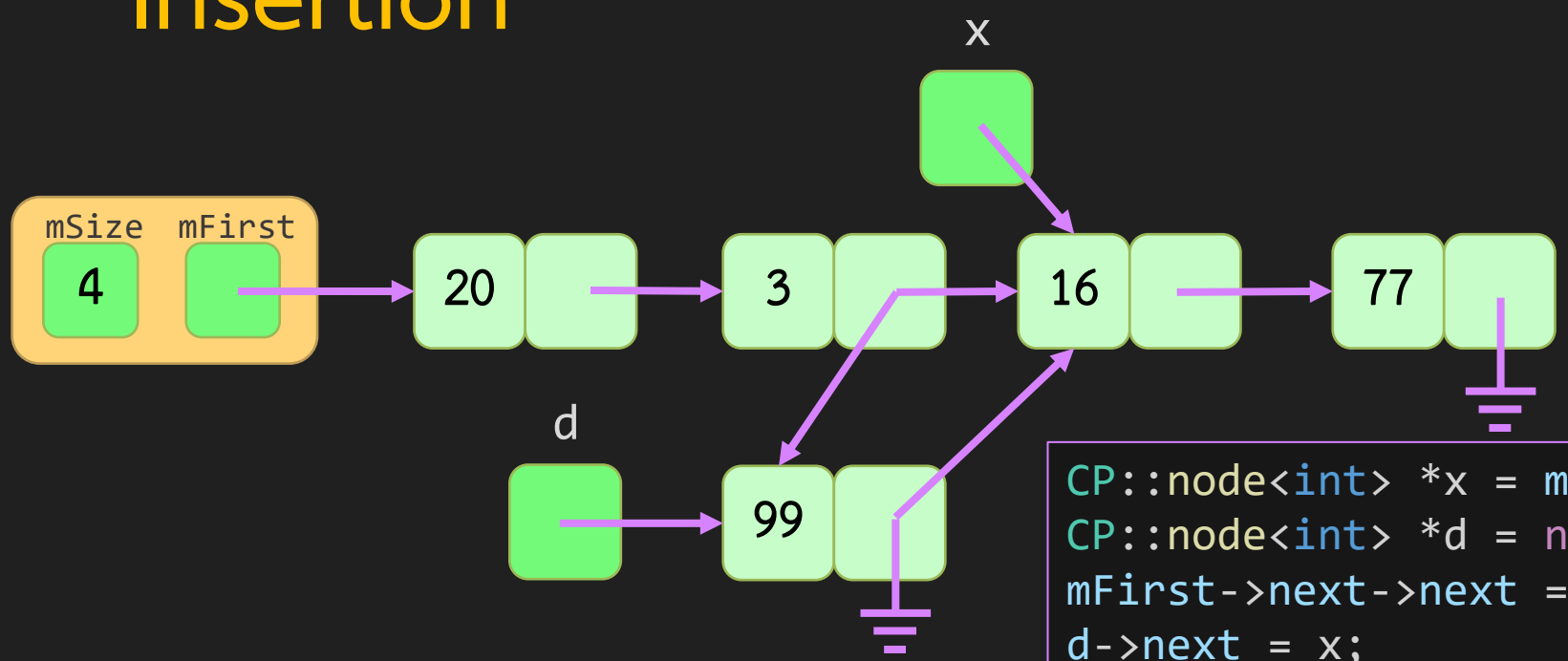
```
template <typename T>
class list {
  protected:
    class node {
      friend class list;
      public:
        T data;
        node *next;
        node() :
          data( T() ), next( NULL ) { }

        node(const T& data, node* next) :
          data ( T(data) ), next( next ) { }
    };
  protected:
    node *mFirst;
    size_t mSize;
  public:
    list() : mFirst( NULL ), mSize( 0 ) { }
    ~list() { clear(); }
    //... more function
};
```

- Node is an inner class



Insertion

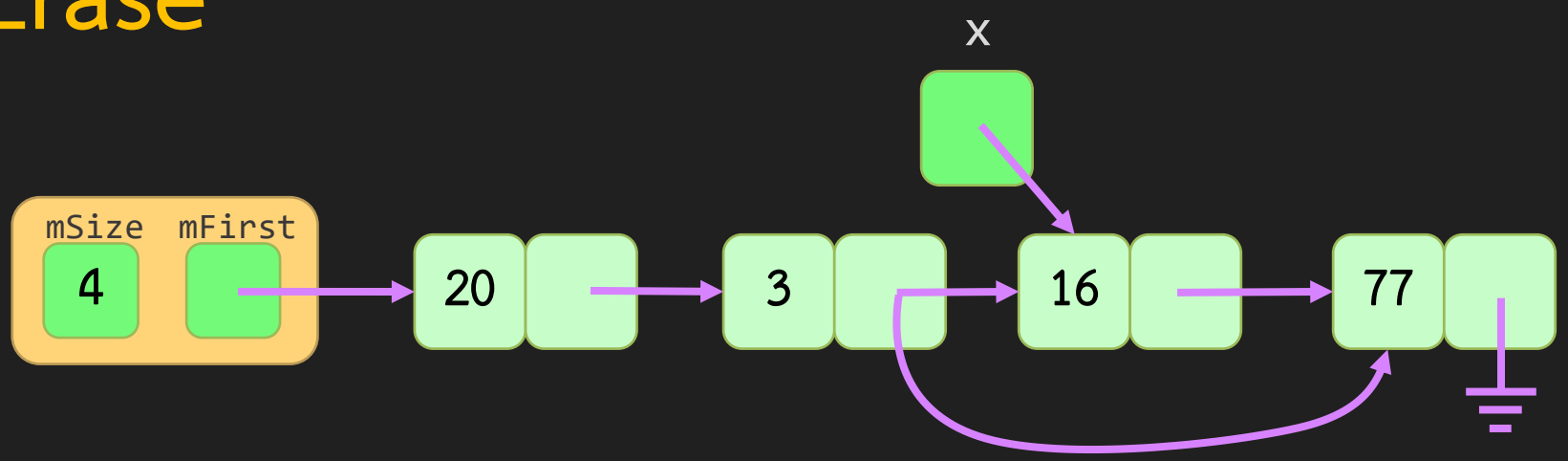
For clarity, node will be drawn as light green box




```
CP::node<int> *x = mFirst->next->next;
CP::node<int> *d = new CP::node<int>(99,NULL);
mFirst->next->next = d;
d->next = x;
```

- To insert a value 99 before value 16, Let x be a pointer that point to the node of 16
  1. Create a new node d containing a data to be inserted
  2. Change pointer of a node before x (which point to x) to point to d instead
  3. Make pointer of d points to x

Erase




```
CP::node<int> *x = mFirst->next->next;
mFirst->next->next = x->next;
delete x;
```

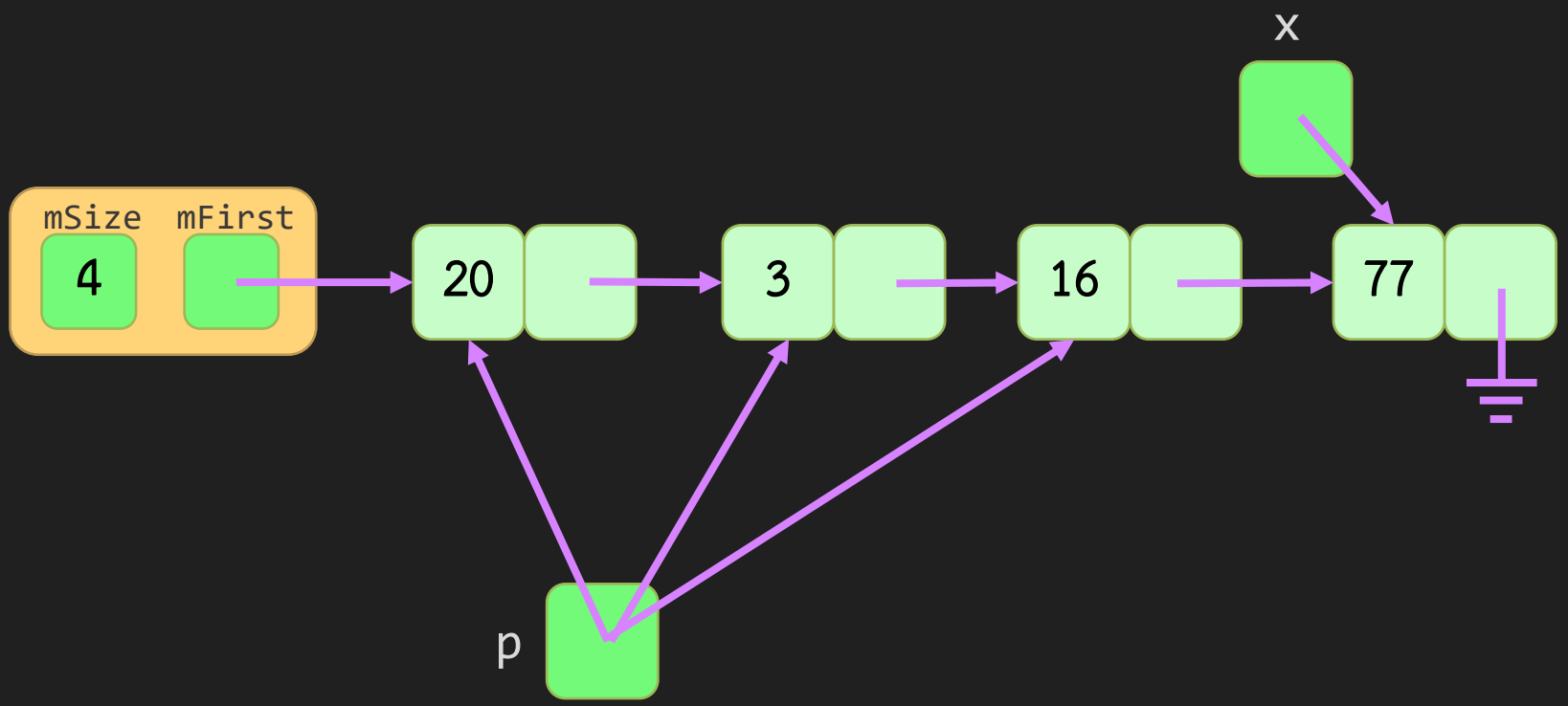
- To delete a value 16, in the node pointed by x
  1. Change pointer of a node before x (which point to x) to point to the node that x points to instead
  2. Don’t forget to delete x

Problem with SLL

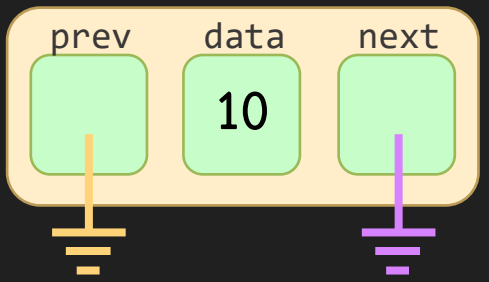
- Erase/insert at iterator X is hard
  - If we have an iterator point to X, we cannot easily go to the node before X
  - Cannot go backward
    - Need to start from mFirst and move on
- Adding data to the end takes long time
  - We have to get iterator that points to the last element (which is O(n))

Finding node before X

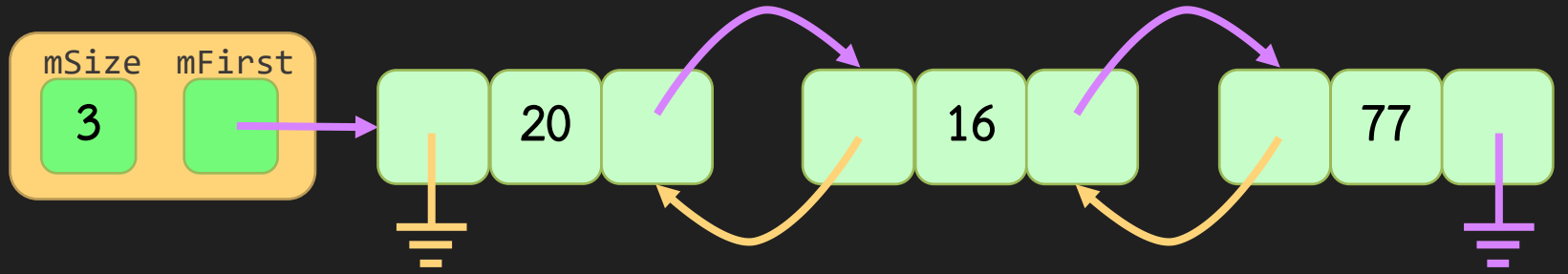
```
node *p = mFirst;
while (p != NULL && p->next != x) p = p->next;
```



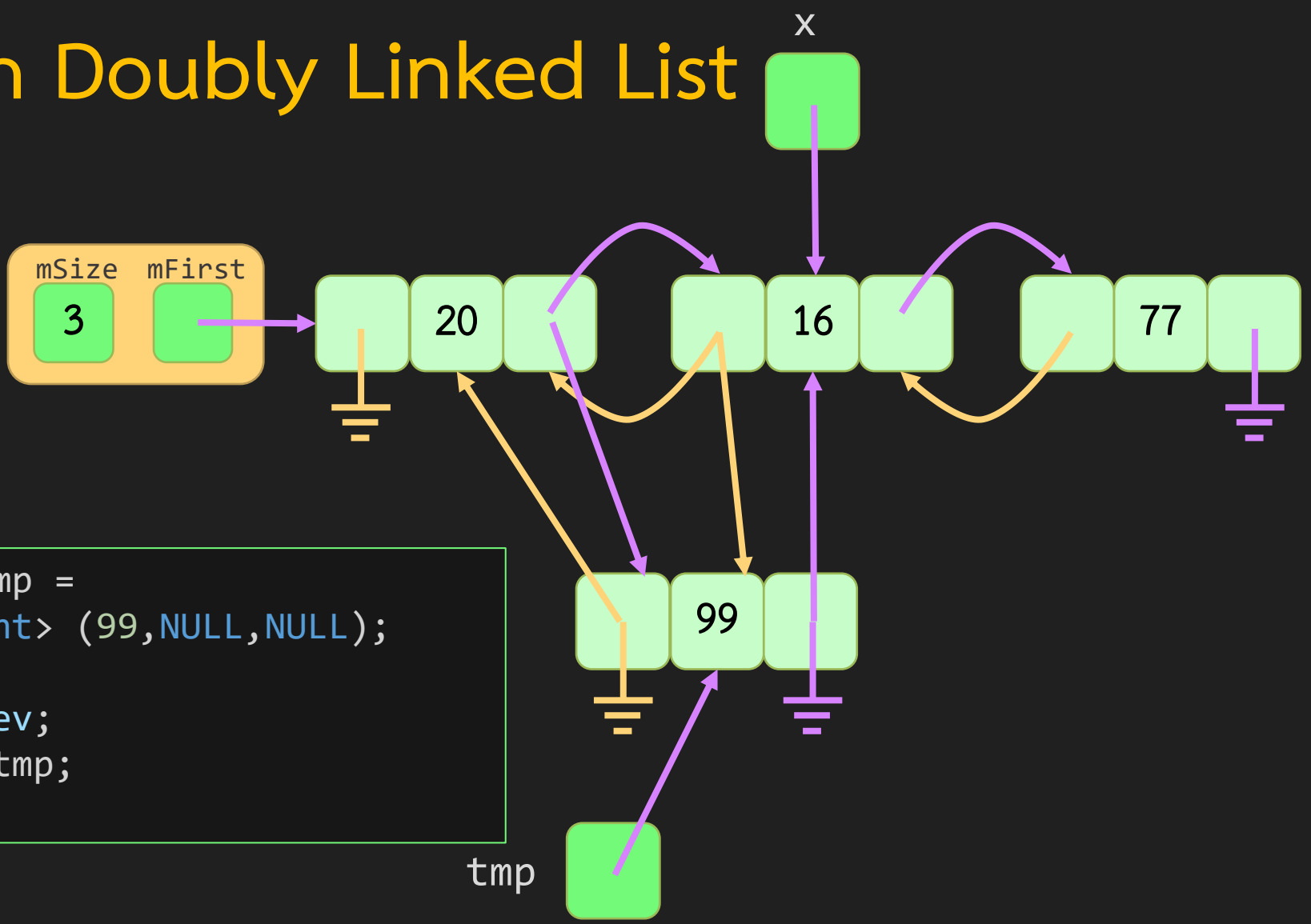
v0.2 Doubly Linked List



- Each node has 2 pointers
  - next and prev
- Can now move forward and backward
- Now, if X is a pointer to a node, we can easily go to node before X and then erase or insert

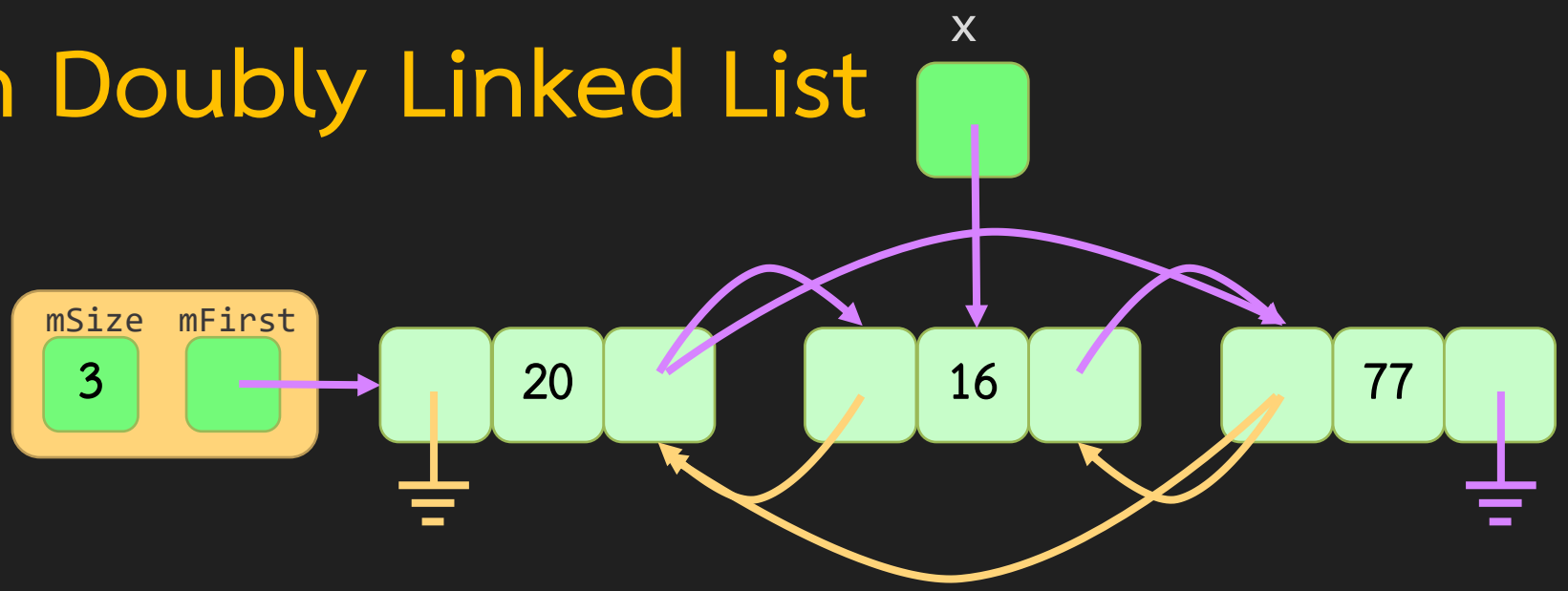


Insert in Doubly Linked List




```
CP::node<int> *tmp =
  new CP::node<int> (99,NULL,NULL);
tmp->next = x;
tmp->prev = x.prev;
x->prev->next = tmp;
x->prev = tmp;
```

Erase in Doubly Linked List



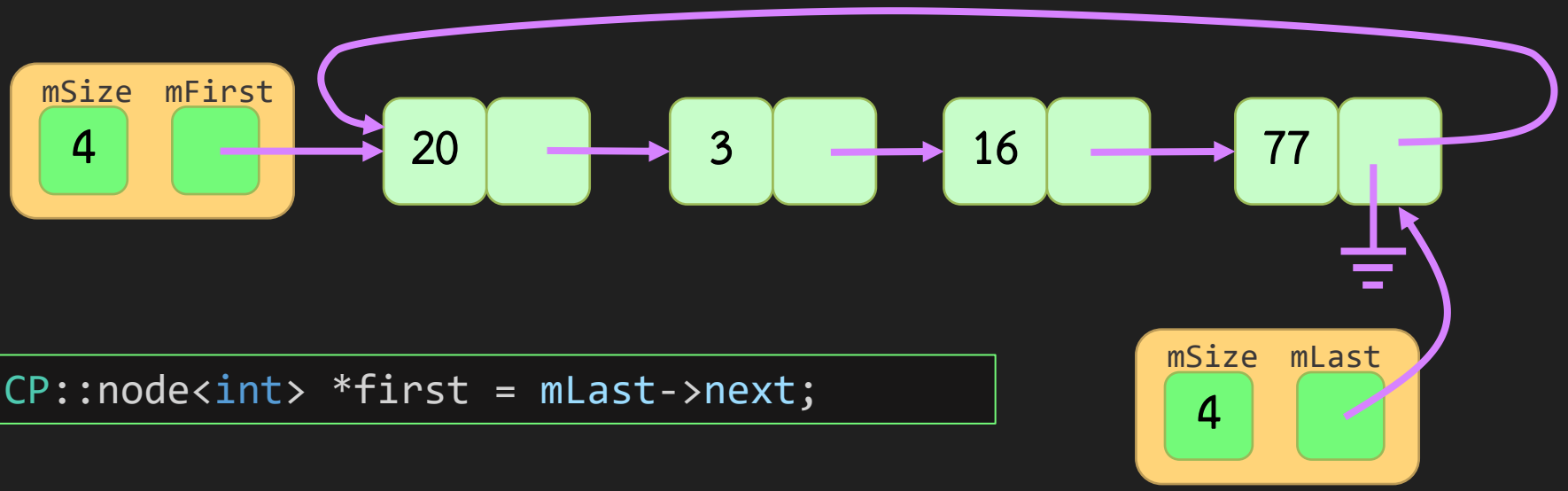

```
x->prev->next = x->next;
x->next->prev = x->prev;
delete x;
```

Problem solved

- Erase/insert at iterator X is now easy
- But, adding data at the end (push_back) is still hard
  - Need to get X to point to the last element
  - push_back is popular in real world
  - Right now we have only push_front (fast addition to the first)
- Also some minor issue about code cleanliness
  - Insert/erase the first/last node

v0.3 Circular Singly Linked List

- Use mLast instead of mFirst
- Fast access to both first and last element

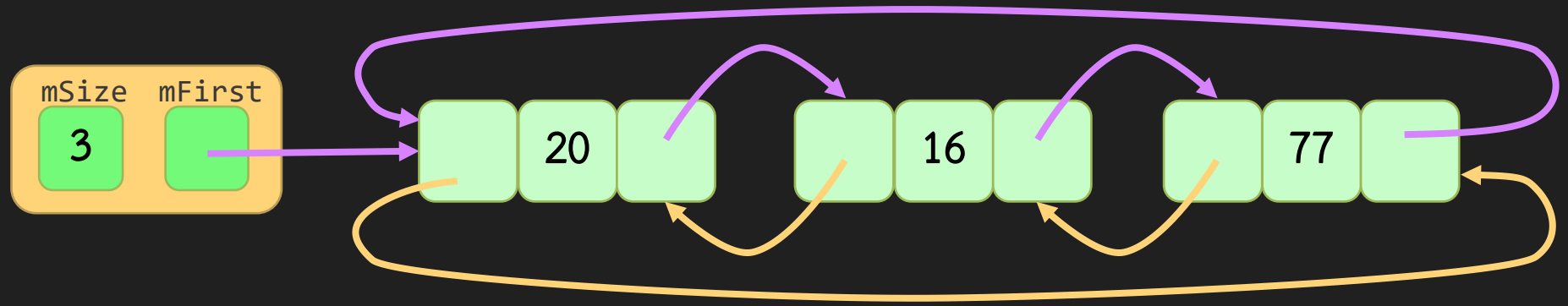



```
CP::node<int> *first = mLast->next;
```

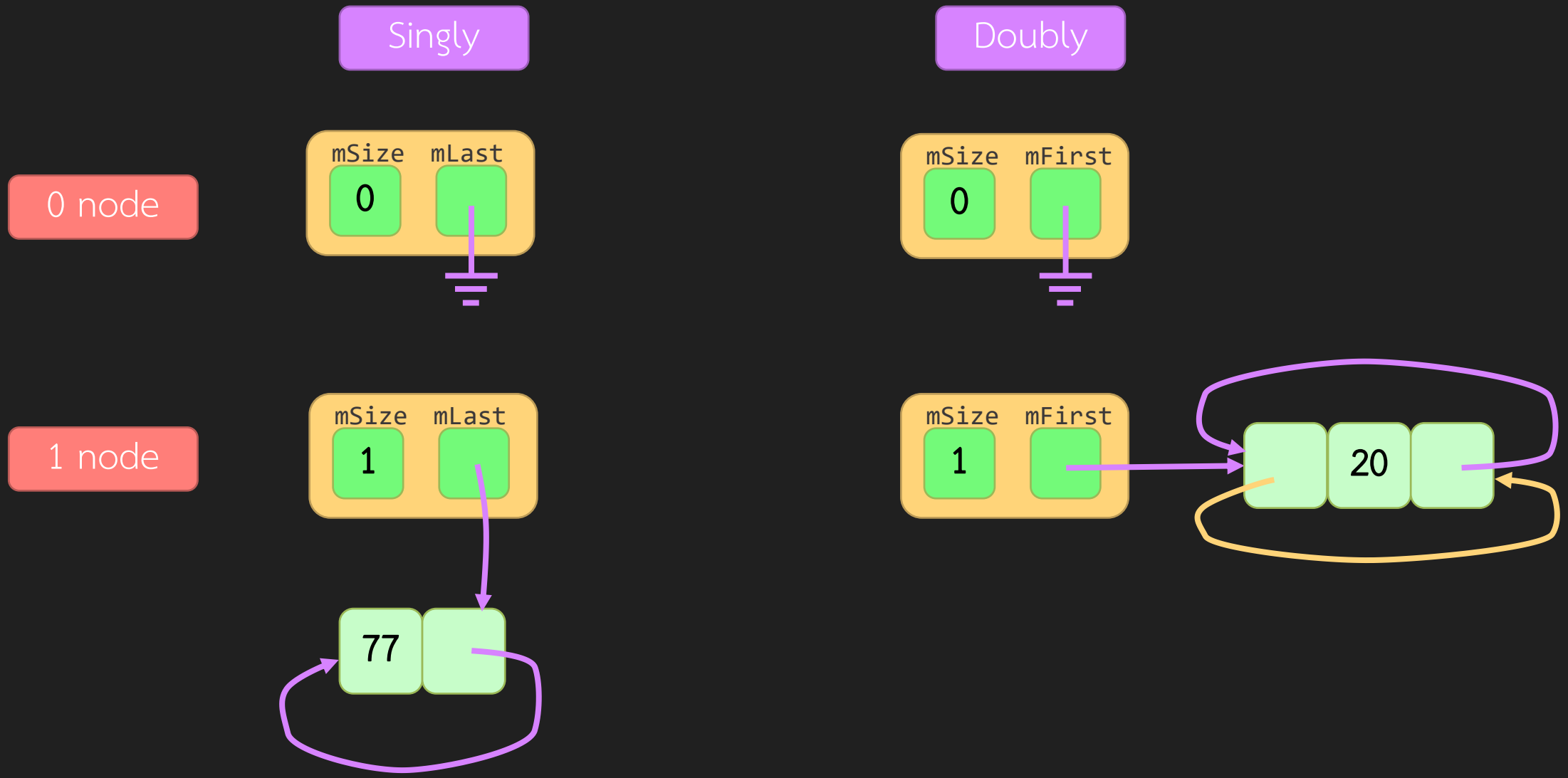
v0.4 Circular Doubly Linked List

- Special linking to last element
  - Fast access to both first and last element
  - Can now easily insert at the end

```
CP::node<int> *last = mFirst->next->prev;
```



More Circular Example



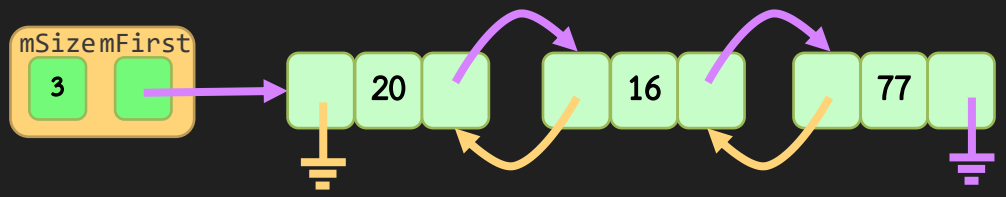
Minor problem

- Code is not really clean because of the first element (or the last element)
- Consider insert at the first node and insert at the second node of Doubly Linked List
  - Assume we have a pointer to that node

```
// assume that s points to the second node
CP::node<int> *tmp =
  new CP::node<int>(99,NULL,NULL);
tmp->next = s;
tmp->prev = s->prev;
s->prev->next = tmp;
s->prev = tmp;
```

```
// assume that f points to the first node
CP::node<int> *tmp =
  new CP::node<int>(99,NULL,NULL);
tmp->next = f;
tmp->prev = f.prev;
mFirst = tmp;
f->prev = tmp;
```

Because first node is different



Special First Node Problem

- First node (and last node) is different from other nodes in both singly or doubly linked list
- For circular singly and circular doubly, each node look the same but we also have to adjust the mFirst (or mLast)
- This affects both insert and erase
- Also need to deal when mFirst is NULL (when mSize == 0)

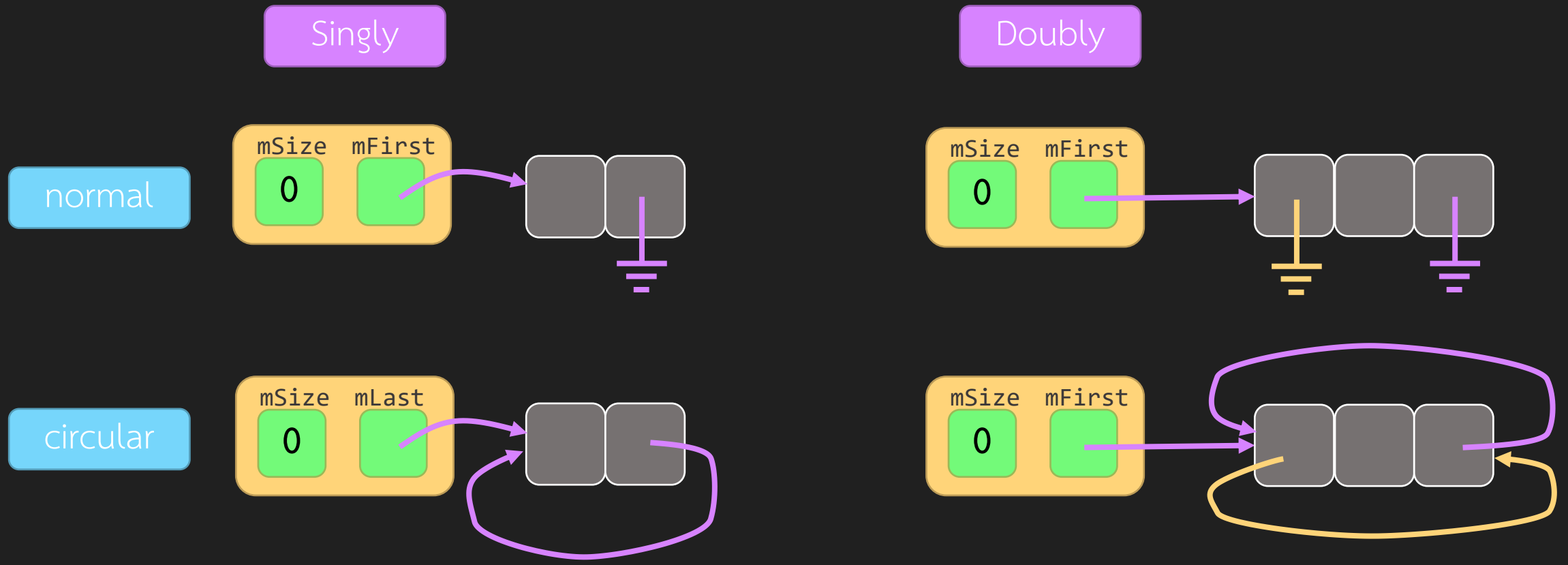
```
//circular doubly linked list
void push_front(const T& e) {
  if (mSize == 0) {
    mFirst = new node(e,NULL,NULL);
    mFirst->next = mFirst;
    mFirst->prev = mFirst;
  } else {
    node* tmp =
      new node(e,mFirst->prev,mFirst);
    mFirst->prev->next = tmp;
    mFirst->prev = tmp;
    mFirst = tmp;
  }
}
```

Another Example

- Remove for circular doubly linked list
- Remove is find and then erase

```
//circular doubly linked list
void remove(const &T e) {
  node *p = mFirst;
  for (size_t i = 0;i < mSize;i++, p=p->next) {
    if (p->data == e) {
      p->next->prev = p->prev;
      p->prev->next = p->next;
      if (p == mFirst) {
        mFirst = p->next;
      }
      delete p;
      mSize--;
      break;
    }
  }
  if (mSize == 0) mFirst = NULL;
}
```

Linked List with Header



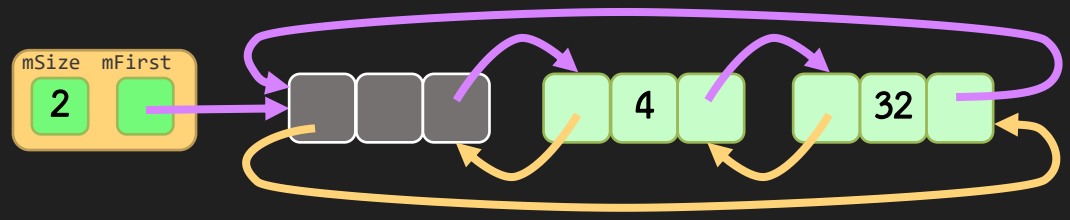
- Add a special node that will not be used to stored data

Simpler Code with header

```
void push_front(const T& e) {
  node* f = mFirst->next;
  node* tmp = new node(e,f,mFirst);
  mFirst->next = tmp;
  f->prev = tmp;
}
```

```
void remove(const T& e) {
  node *p = mFirst->next;
  while (p != mHeader && p->data != e)
    p = p->next;
  if (p !=  mHeader) {
    p->next->prev = p->prev;
    p->prev->next = p->next;
    mSize--;
  }
}
```

- Header simplify code
  - Because mFirst always points to the header (mFirst never is NULL)



Variant Summary

- Circular makes accessing first and last element fast
- Doubly makes accessing previous element fast
  - Also making erase at node p easy if we have pointer to p
  - Need more space for prev pointer
- Header makes code simpler
  - Need more space for header node

Final Version

- CP::list is “circular doubly linked list with header”
  - Simple code for insert/erase
  - Use most space (two pointers per nodes, need header nodes)
  - Can push_back, pop_back, push_front, pop_front
- Also need custom iterator class
  - Iterator just store a pointer to a node
  - We cannot directly use a pointer to a node (node*) because we need to override some operator (--, ++ and something else)

Layout

- Inner class is a class inside another class
  - Inner class can access any members of outer class
  - Outer class cannot access protected or private of the inner class
- Friend class allow other class to access

```
template <typename T>
class list {
  protected:
    class node {
      friend class list;
      public:
        T data;
        node *prev, *next;
        //some functions
    };
    class list_iterator {
      friend class list;
      protected:
        node* ptr;
      public:
       //some functions && operators
    };
  public:
    typedef list_iterator iterator;
  protected:
    node *mHeader; // pointer to a header node
     size_t mSize;
  public:
    //funcions
};
```

Doubly Linked List Node

```
class node {
  friend class list;
  public:
    T data;
    node *prev;
    node *next;

    node() :
      data( T() ), prev( this ), next( this ) { }
    node(const T& data,node* prev, node* next) :
      data ( T(data) ), prev( prev ), next( next ) { }
};
```

- Inner class can use template T of the outer class

Constructor

```
// default constructor
list() : mHeader( new node() ), mSize( 0 ) { }

// copy constructor
list(const list<T>& a) : mHeader( new node() ), mSize( 0 ) {
  for (auto &x : *this) {
    push_back(x);
  }
}

list<T>& operator=(list<T> other) {
  using std::swap;
  swap(this->mHeader, other.mHeader);
  swap(this->mSize, other.mSize);
  return *this;
}

~list() {
  clear();
  delete mHeader;
}
```

Small Functions

```
//------------- capacity function -------------------
bool empty()  const { return mSize == 0; }
size_t size() const { return mSize; }

//----------------- access -----------------
T& front() { return mHeader->next->data; }
T& back() { return mHeader->prev->data; }

//----------------- modifier -------------
void push_back(const T& element) {
  insert(end(),element);
}
void push_front(const T& element) {
  insert(begin(),element);
}
void pop_back() {
  erase(iterator(mHeader->prev));
}
void pop_front() {
  erase(begin());
}
```

- Task is delegated to insert and erase
- Need iterator

Iterator

```
class list_iterator {
  friend class list;
  protected:
    node* ptr;
  public:

    list_iterator() : ptr( NULL ) { }
    list_iterator(node *a) : ptr(a) { }

    list_iterator& operator++() {
      ptr = ptr->next;
      return (*this);
    }

    list_iterator& operator--() {
      ptr = ptr->prev;
      return (*this);
    }
```

- Has custom constructor that takes node pointer

Iterator

```
class list_iterator {
  friend class list;
  protected:
    node* ptr;
  public:

    list_iterator operator++(int) {
      list_iterator tmp(*this);
      operator++();
      return tmp;
    }

    list_iterator operator--(int) {
      list_iterator tmp(*this);
      operator--();
      return tmp;
    }
```

- operator++() is an operator for ++it
- operator++(int) is a syntax for it++
- operator++(int) delegates to operator++()
- Same for operator--

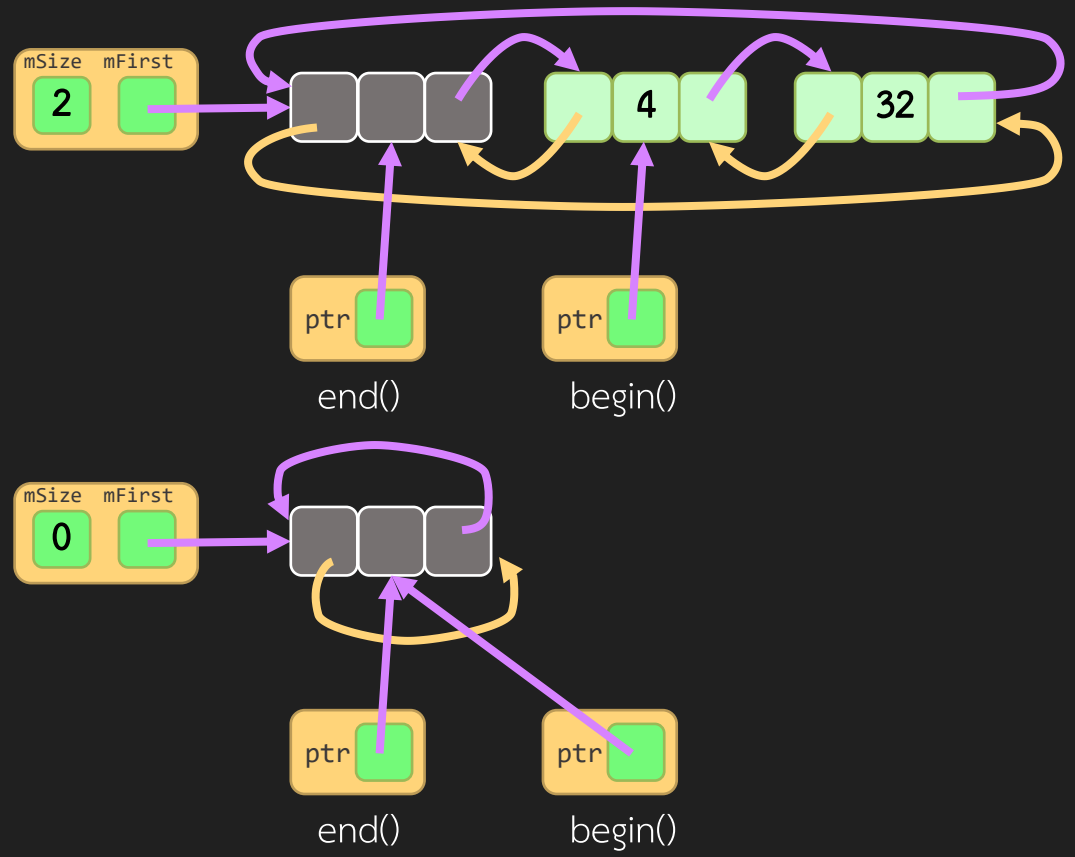
Iterator

```
class list_iterator {
  friend class list;
  protected:
    node* ptr;
  public:

    T& operator*() { return ptr->data; }
    T* operator->() { return &(ptr->data); }

    bool operator==(const list_iterator& other) {
      return other.ptr == ptr;
    }

    bool operator!=(const list_iterator& other) {
      return other.ptr != ptr;
    }
```

- Nothing special here
  - Just syntax

Other small function

```
iterator begin() {
  return iterator(mHeader->next);
}

iterator end() {
  return iterator(mHeader);
}

void clear() {
  while (mSize > 0) erase(begin());
}
```



Insert & Erase

```
iterator insert(iterator it,const T& element) {
  node *n = new node(element,it.ptr->prev, it.ptr);
  it.ptr->prev->next = n;
  it.ptr->prev = n;
  mSize++;
  return iterator(n);
}

iterator erase(iterator it) {
  iterator tmp(it.ptr->next);
  it.ptr->prev->next = it.ptr->next;
  it.ptr->next->prev = it.ptr->prev;
  delete it.ptr;
  mSize--;
  return tmp;
}
```

- Header make insert/erase very simple