Templates &

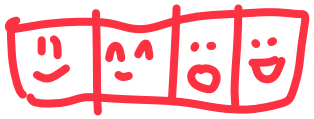
Data Structures

Lists and List ADT

CS 225

Brad Solomon

August 28, 2026



UNIVERSITY OF ILLINOIS URBANA-CHAMPAIGN

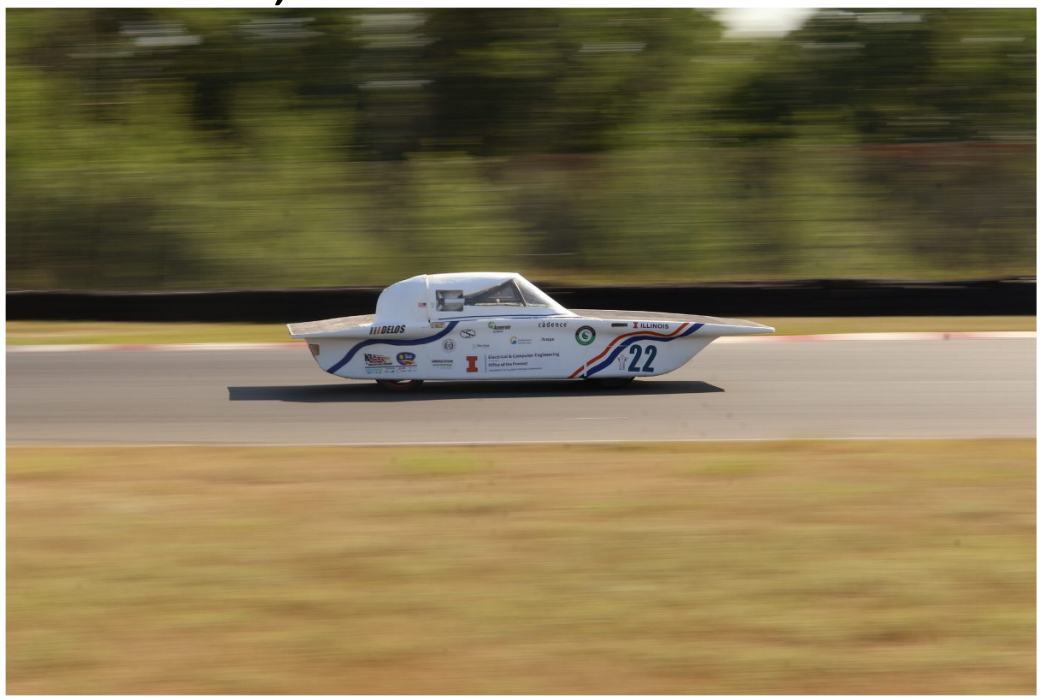
Department of Computer Science

Illini Solar Car Strategy & Telemetry

Strategy

How to drive the car most efficiently? (not always fast)

Physics simulation, data analysis, statistics, and ML



Telemetry

Ingest real-time data, show visualizations, run strategy models

Frontend, backend, databases, cloud

Interest Form >>>>

Bonus Video: Practice Exam 0 Releasing Today

Goes over every practice problem on exam

Gives some loose tips on study / exam habits

Look at it after running exam yourself!

MP_Stickers Releasing Today

An introduction to assignments in CS 225

A focused look at memory management / Rule of Three

Practice with Image processing / code testing

No extra credit / early submission for this MP!

Be sure to set up your Illinois CS 225 Git repo!

General MP Tips

Start by reading the web page!

Take a look at the doxygen for **interface** requirements

The **implementation** is decided by you!

Most autograder tests are provided for you locally

MP_Stickers Highlights

Part 2: StickerSheet

Big Picture: Memory Management! (Who owns what?)

Read the docs!

◆ render()

Image StickerSheet::render ( ) const

Renders the whole **StickerSheet** on one **Image** and returns that **Image**.

The base picture is drawn first and then each sticker is drawn in order starting with layer zero (0), then layer one (1), and so on.

If a pixel's alpha channel in a sticker is zero (0), no pixel is drawn for that sticker at that pixel. If the alpha channel is non-zero, a pixel is drawn. (Alpha blending is awesome, but not required.)

The returned image always includes the full contents of the picture and all stickers. It should expand in each corresponding direction if stickers go beyond the edge of the picture.

Returns

An **Image** object representing the drawn scene

Draw it out!

Exam 0 (9/2 — 9/4)

An introduction to CBTF exam environment / expectations

Quiz on foundational knowledge from all pre-reqs

Practice questions can be found on PL

Topics covered can be found on website

Registration open now :)

https://courses.engr.illinois.edu/cs225/exams/

Learning Objectives

Review memory management and **templates**

Define the functions and operations of the List ADT

Discuss list implementation strategies

Explore how to code and use a linked list

Practice fundamentals of C++ in the context of lists

Last time: Memory management

Local memory on the stack is managed by the computer

Heap memory allocated by **new** and freed by **delete**

Pass by value makes a copy of the object

Pass by pointer can be dereferenced to modify an object

Pass by reference modifies the object directly

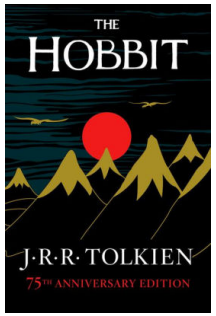
Memory Management - Parameters

Pass by **Value:**

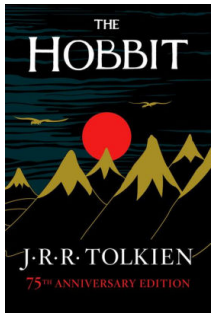
A local copy of the original

Ex: addBook(Book book)

Copy



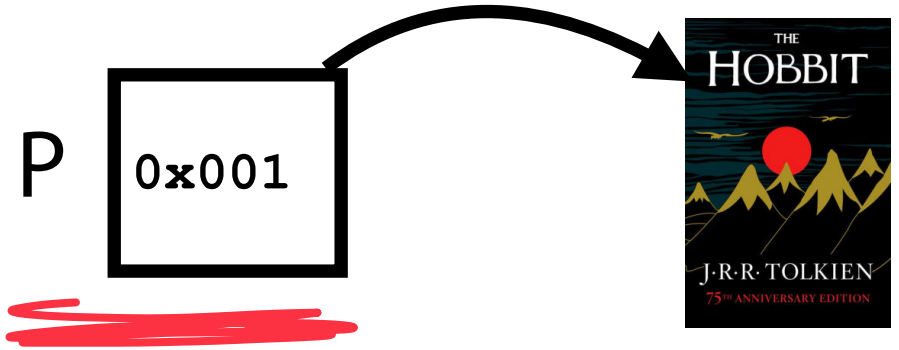
Original



Pass by **Pointer to Value:**

An address on the heap

Ex: addBook(Book* book)



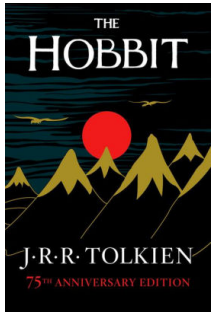
Pass by **Reference:**

An *alias* to an existing variable

Ex: addBook(Book& book)

Local var Y
is X

X=



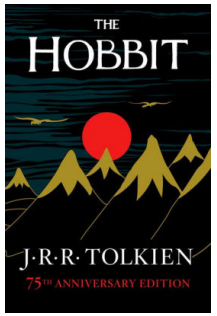
Memory Management - Ownership

Pass by **Value:**

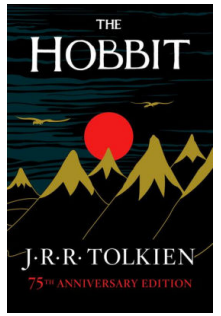
Local scope owns local copies

(They are stack copies)

Copy



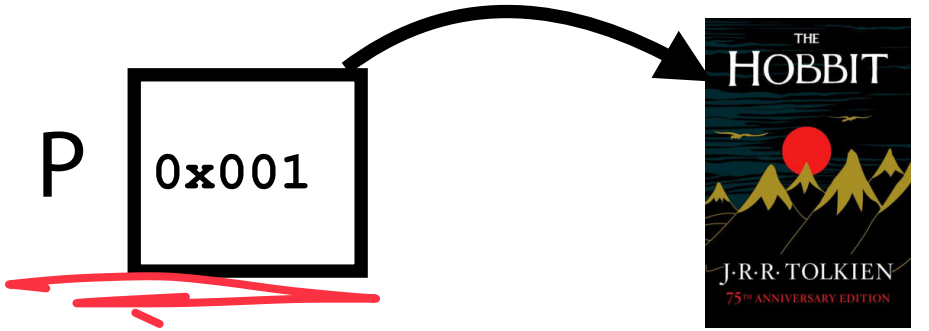
Original



Pass by **Pointer to Value:**

Local scope owns local pointer

NOT original data value



Pass by **Reference:**

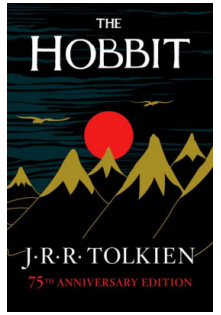
Compiler alias with local scope

Don't own original data value

Local var Y

is X

X=



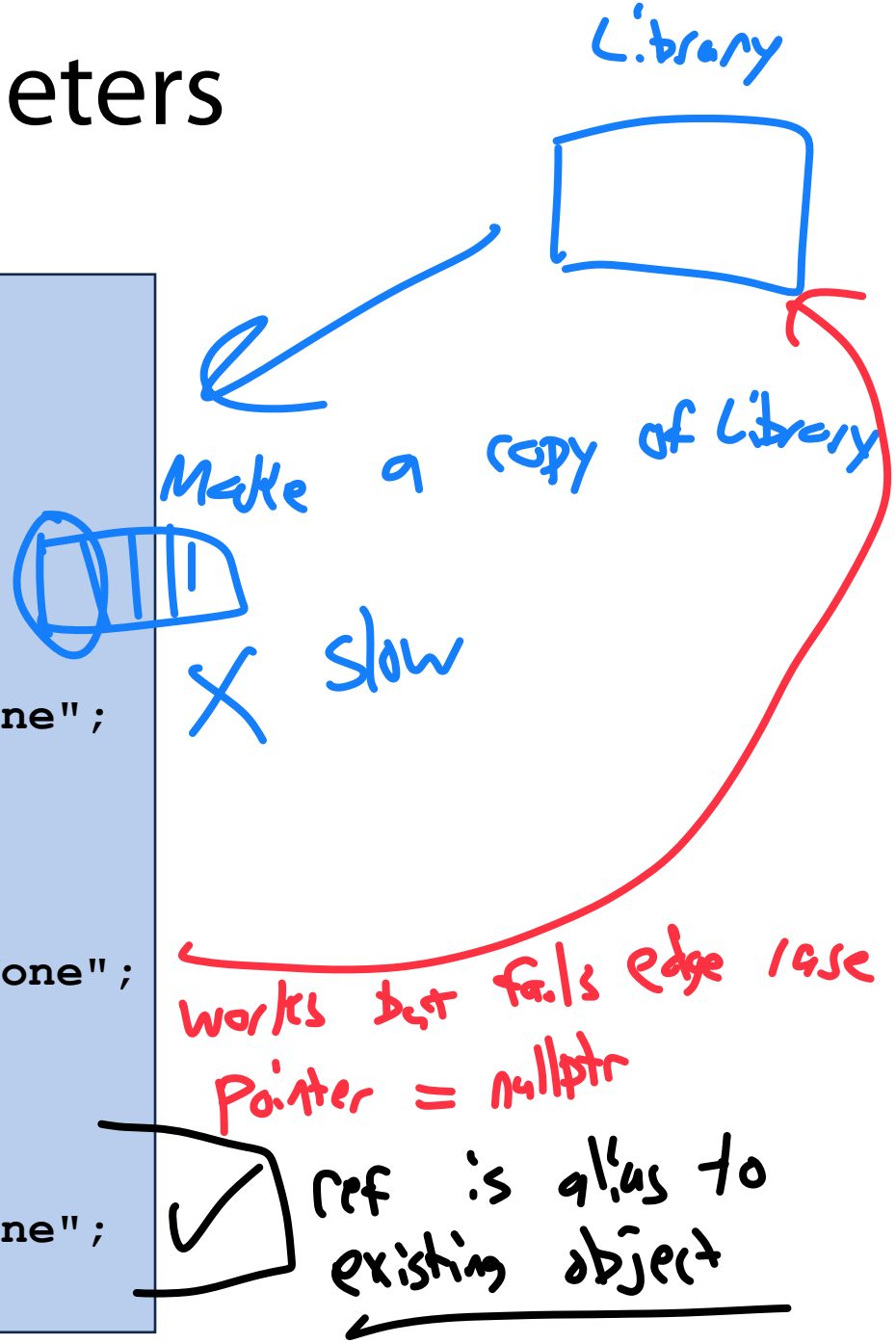
Memory Management - Parameters

Which implementation do you prefer?

```
1  class Library {
2  public:
3      int numBooks;
4      std::string * titles;
5  };
6
7
8  // *** Function A ***
9  std::string getFirstBook(Library l){
10     return (l.numBooks > 0) ? l.titles[0] : "None";
11 }
12
13
14 // *** Function B ***
15 std::string getFirstBook(Library * l){
16     return(l->numBooks > 0) ? l->titles[0] : "None";
17 }
18
19
20 // *** Function C ***
21 std::string getFirstBook(Library & l){
22     return (l.numBooks > 0) ? l.titles[0] : "None";
23 }
24
```

static array

nullptr → numBooks



The Rule of Three

If it is necessary to **define any one** of these three functions in a class, it will be necessary to **define all three** of these functions:

1. Destructor — Called when we delete object

2. Copy Constructor — Make a new object as a copy of an existing one

3. Copy assignment operator — Assign value from existing X to Y

‘The Rule of Zero'

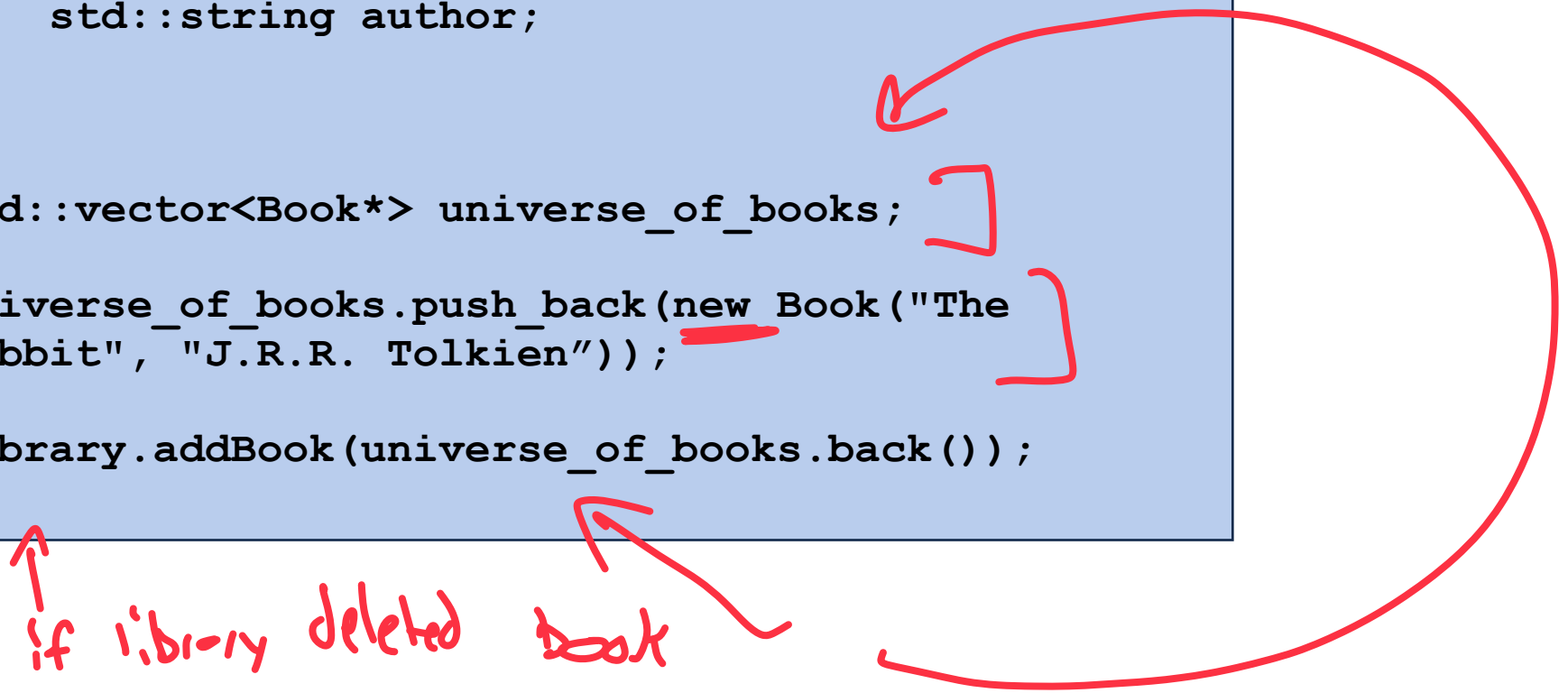
A corollary to Rule of Three

Classes that **declare** custom destructors, copy/move constructors or copy/move assignment operators should deal exclusively with ownership. Other classes **should not declare** custom destructors, copy/move constructors or copy/move assignment operators

— Scott Meyers

Memory Management — Ownership

```
 1 class Book{
 2 public:
 3     Book(std::string title, std::string author);
 4
 5     std::string title;
 6
 7
 8     std::string author;
 9
10 };
11
12 std::vector<Book*> universe_of_books;
13
14 universe_of_books.push_back(new Book("The
15 Hobbit", "J.R.R. Tolkien"));
16
17 library.addBook(universe_of_books.back());
18
```



```
 1 class Library {
 2 public:
 3     int numBooks;
 4     std::string * titles;
 5     ~Library();
 6     Library( int num, std::string* list );
 7 };
 8
 9 Library::~Library(){
10    delete[] titles;
11    titles = nullptr;
12 }
13
14 Library::Library(int num, std::string* list){
15     numBooks = num;
16     titles = new std::string[ num ];
17     std::copy(inList, inList + num, titles);
18 }
19
20 int main(){
21    std::string myBooks[3] = {"A", "B", "C"};
22    Library L1( 3, myBooks );
23    Library L2( L1 );
24    return 0;
25 }
```

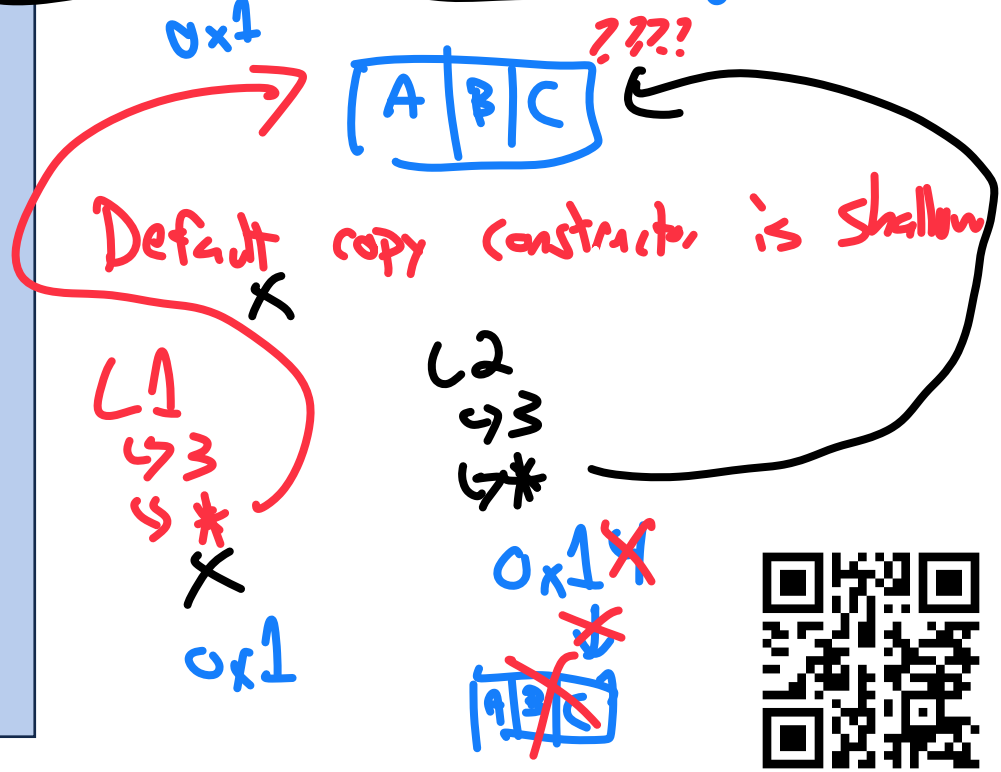
```
1  class Library {
2  public:
3      int numBooks;
4      std::string * titles;
5      ~Library();
6      Library( int num, std::string* list );
7  };
8
9  Library::~Library(){
10     delete[] titles;
11     titles = nullptr;
12 }
13
14 Library::Library(int num, std::string* list){
15     numBooks = num;
16     titles = new std::string[ num ];
17     std::copy(inList, inList + num, titles);
18 }
19
20 int main(){
21     std::string myBooks[3] = {"A", "B", "C"};
22     Library L1( 3, myBooks );
23     Library L2( L1 );
24     return 0;
25 }
```

Whats wrong with this code?

A. Can't create L2 Library obj

B. Don't delete either Library

C. The second object being deleted crashes



Questions?

Templates

A way to write generic code whose type is determined during compilation

Templates

A way to write generic code whose type is determined during compilation

1. Templates are a recipe for code using generic types

```
T sum(T a, T b){

    return a+b;

}
```

sum(1, 2)
↳ looks up recipe for T sum
↳ creates & compiles
int sum(int a, int b)

sum<float>(1, 2)
↳ float sum(float a, float b)

Templates

A way to write generic code whose type is determined during compilation

1. Templates are a recipe for code using generic types

2. The compiler uses templates to generate C++ code **when needed**

if I don't call sum in main.cpp

```
T sum(T a, T b){
...
}
```

template1.hpp

```
1  template <typename T>
2  T max(T a, T b) {
3    T result;
4    result = (a > b) ? a : b;
5    return result;
6  }
7
```

to declare template function

T is design decision

template <typename Q>

<typename A, typename B>

Templates are very useful!

vector<int>

vector<float>

vector<string>

MP_Stickers Highlights

You write Image.h / PNG

Part 1: test_invert()

The same interface ✓

Your first example of a templated function!

```
 1  template <class T>
 2  bool test_invert(){
 3    // Your code here
 4    // (As this is the only
 5  templated function, we aren't
 …  using a .hpp file in this
28  instance)
29    return false;
30  }
31
32
33
34
```

T1_Image

T PNG

↳ True or false ✓

T2_Image

HSLA_Pixel

Existing test files

Look both of those up

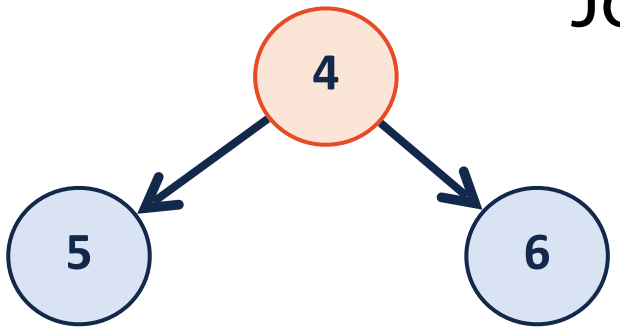
What is your favorite data structure?

Join Code: 225

A) Lists

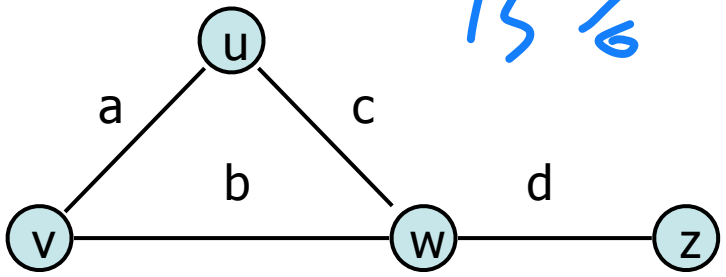
~26%

B) Trees



~40%

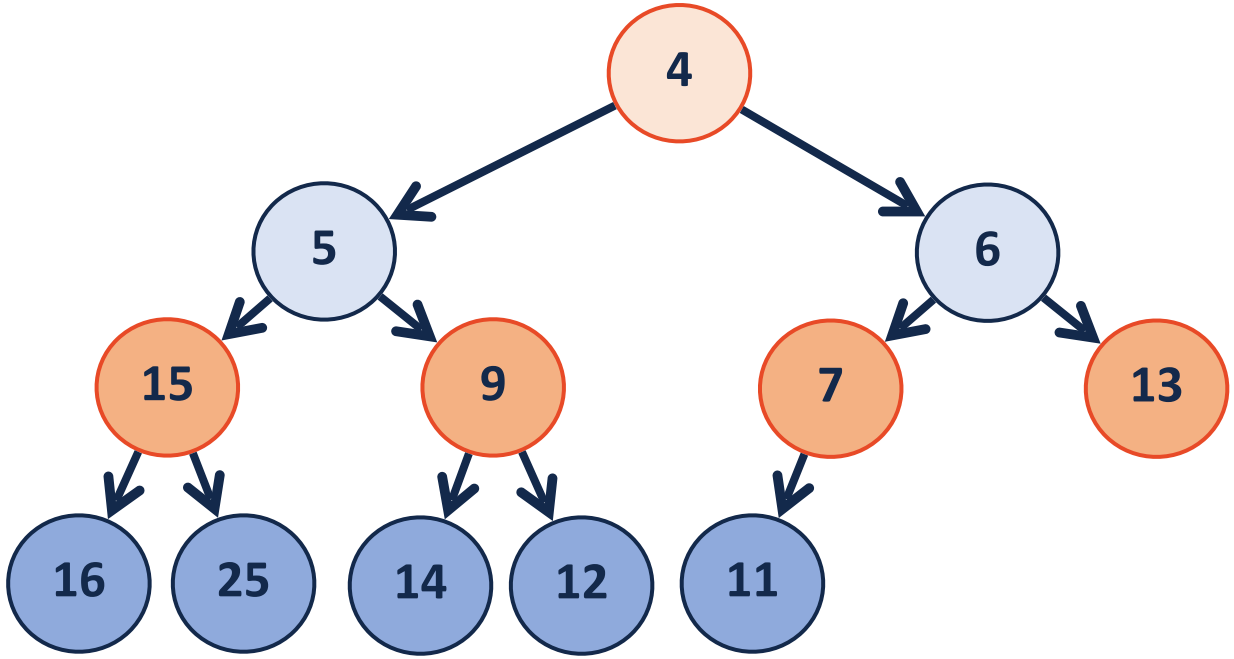
C) Graphs ~15%



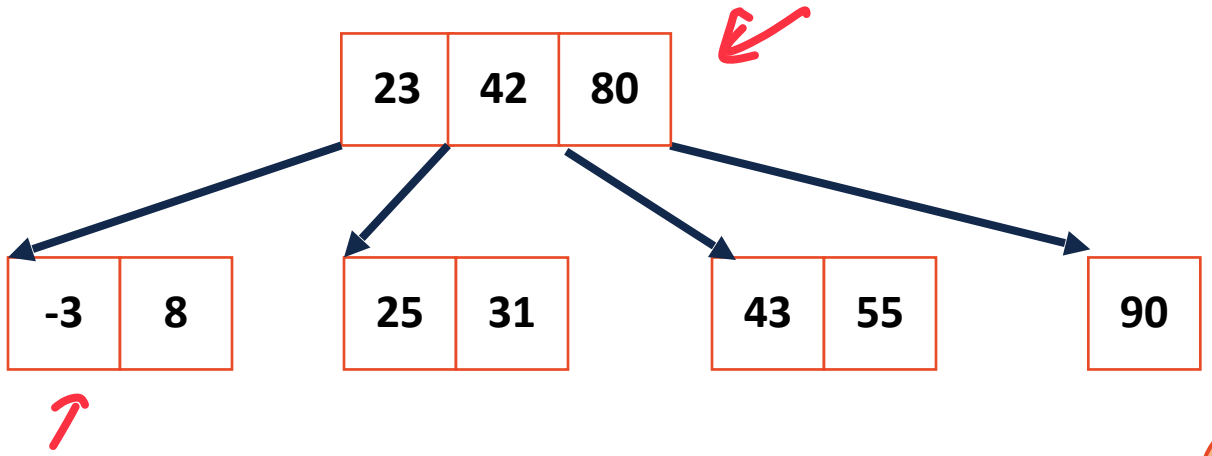
D) Hash Tables ~15%

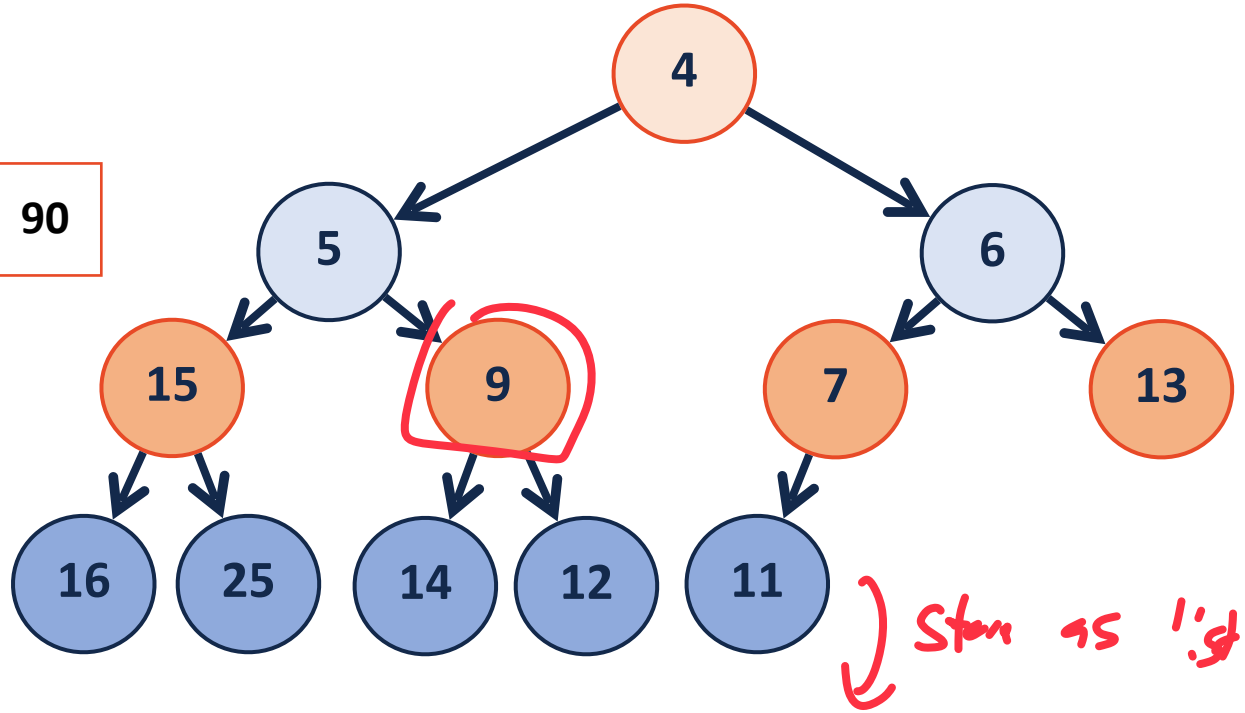
0	Apple
1	∅
2	Pear

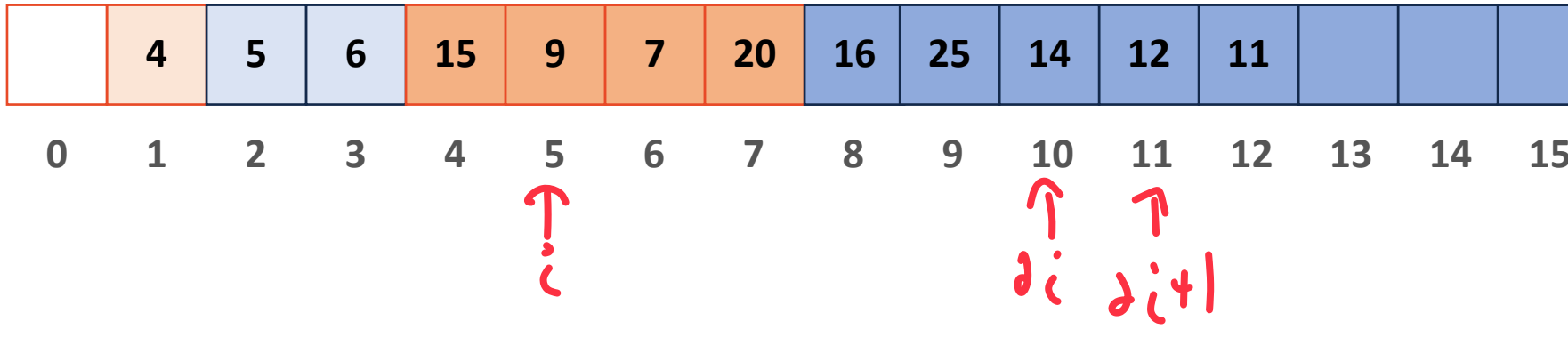
Your favorite data structure: Trees



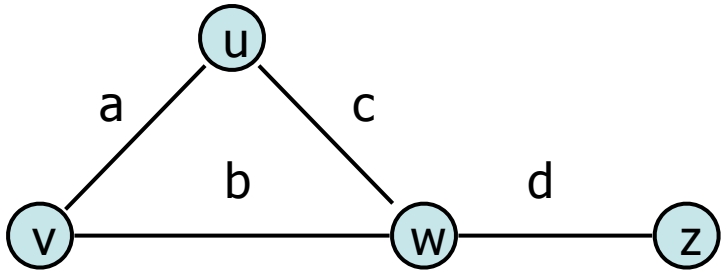
Your favorite data structure: ~~Trees~~ Lists

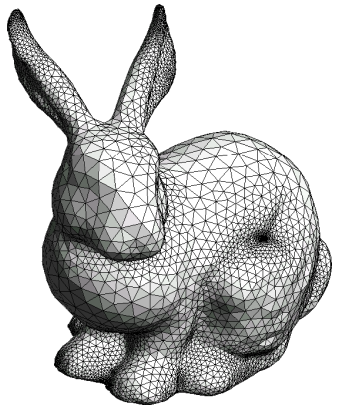


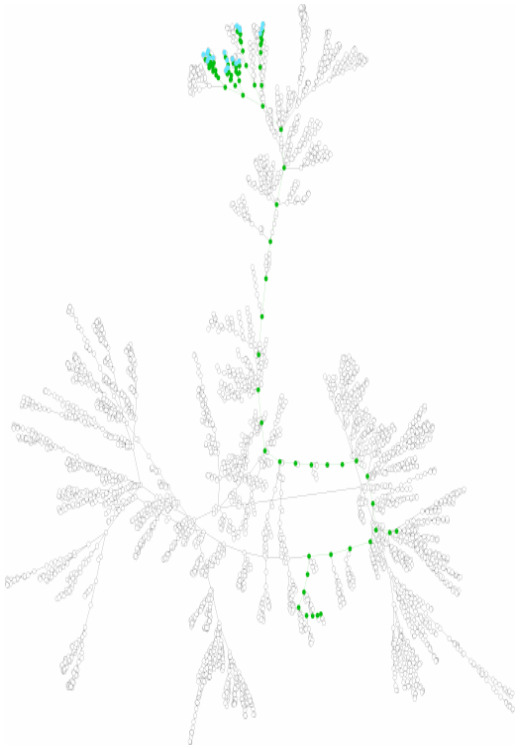


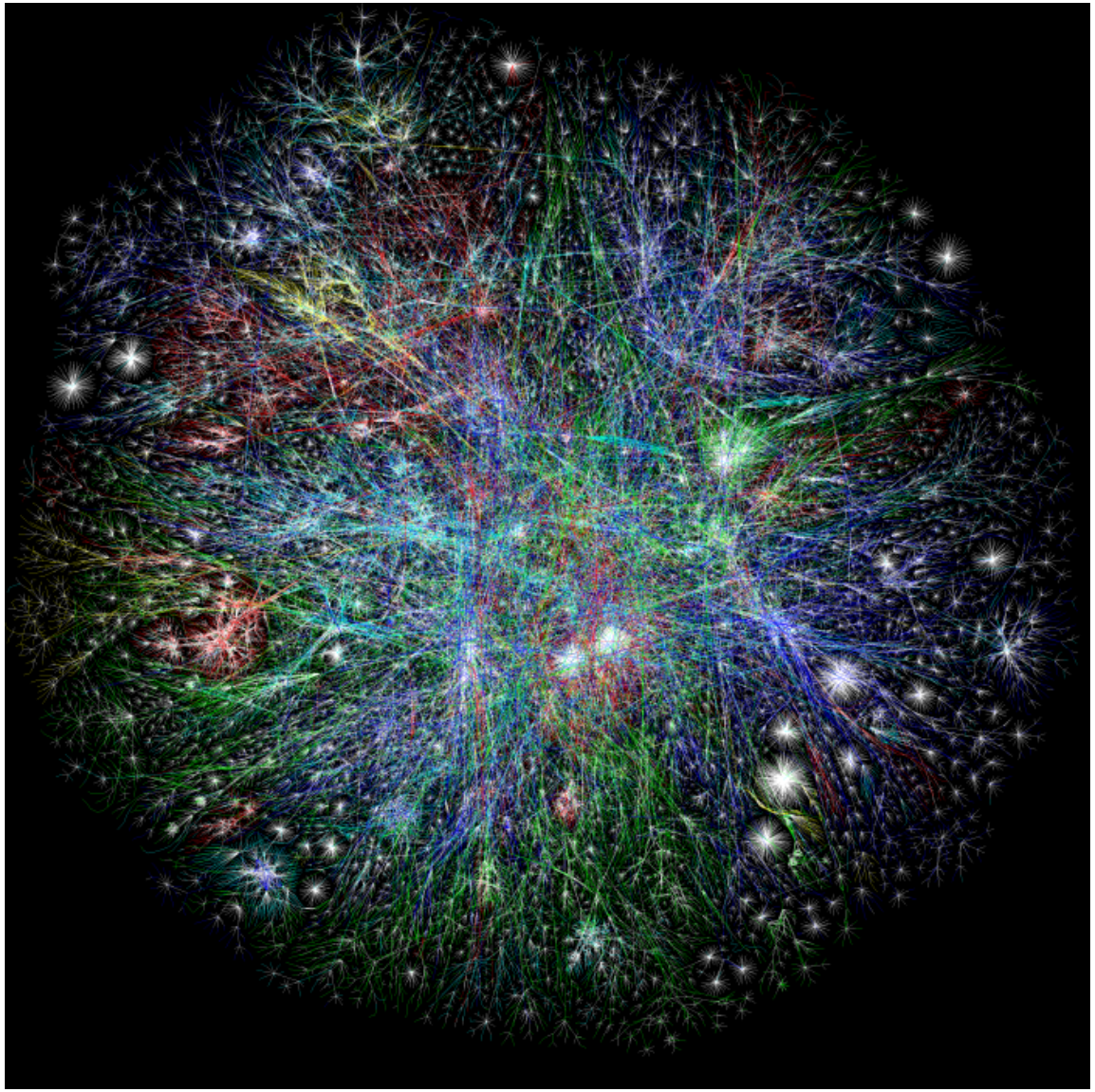


Your favorite data structure: Graphs

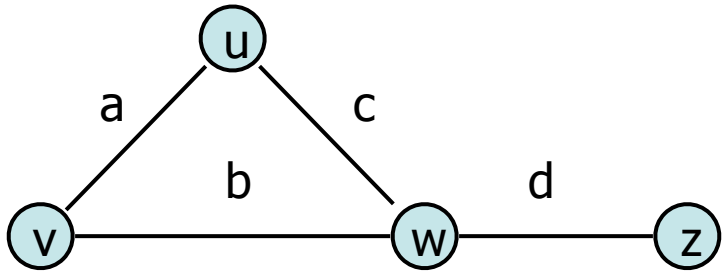








Your favorite data structure: ~~Graphs~~ Lists



Vertex list

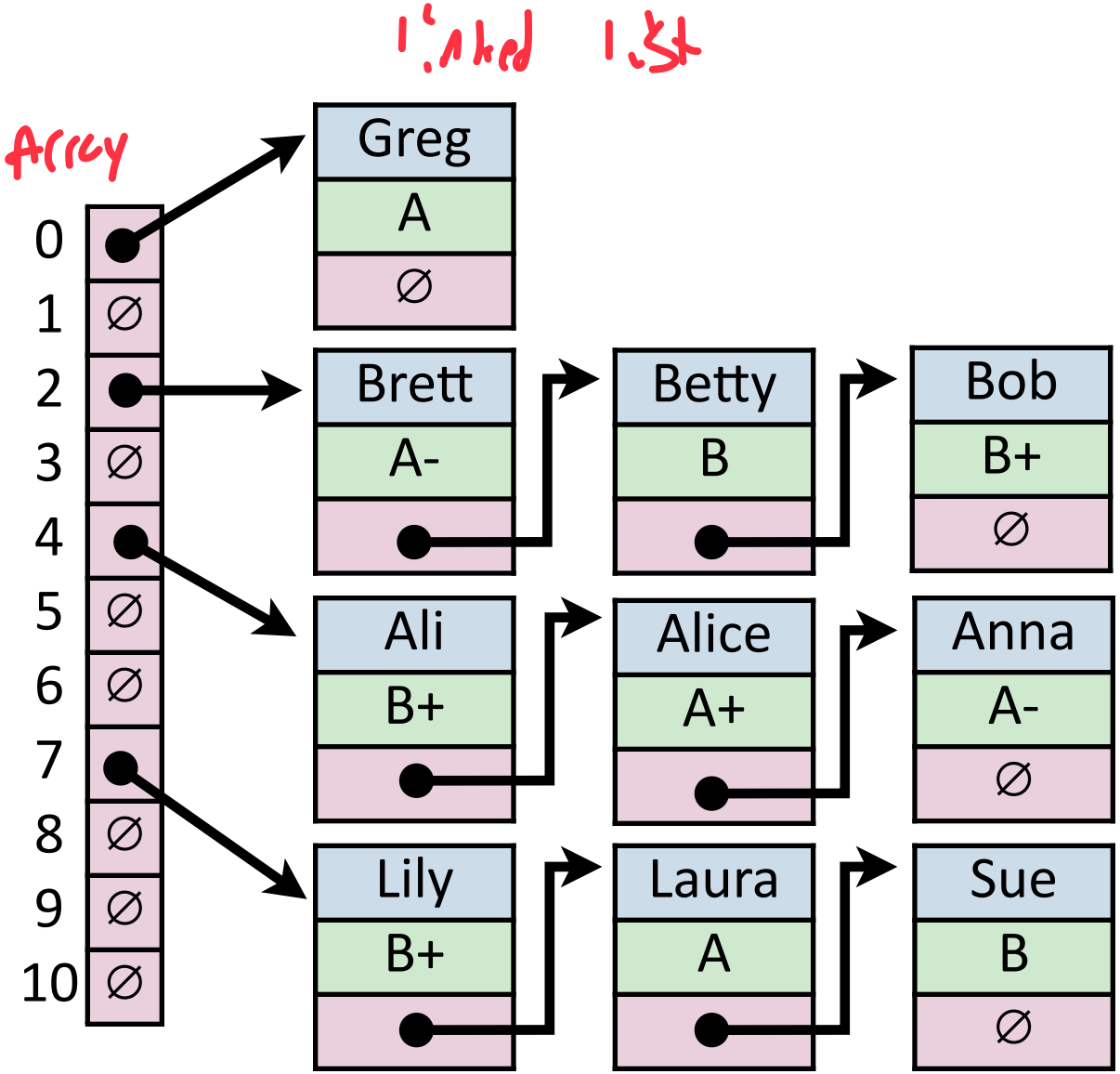
u
v
w
z

Start end weight

u	v	a
v	w	b
u	w	c
w	z	d

Edge list

Your favorite data structure: Hash Tables

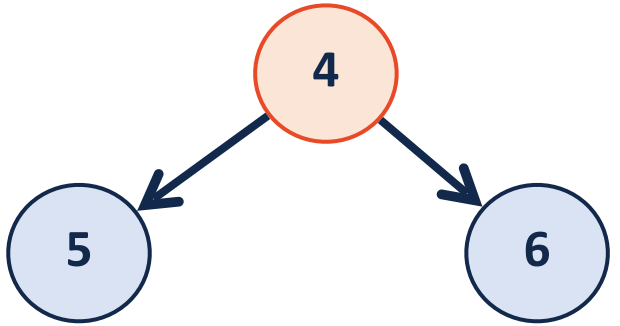


$$H = \{h_1, h_2, \ldots, h_k\}$$

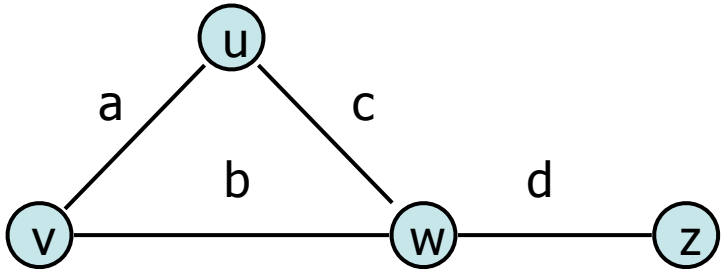
So 100% of people are excited about lists!

A) Lists

B) Trees



C) Graphs



D) Hash Tables

0	Apple
1	∅
2	Pear

Note: Not every tree / graph / hash is actually a list :)

Abstract Data Types → Interface!

A way of describing a data type as a combination of:

Data being stored by the data type

Operations that can be performed on the data type

The actual implementation details of the ADT aren't relevant!

List ADT (What do we want our list to do?)

- Storing a collection of data type
  - heterogenous (multiple data types)
  - homogenous

(Potentially as linked series of pointers)

- Add new items to list
- Remove items
- Access items
- size or length → (static or dynamic)

List ADT

A list is an **ordered** collection of items

Items can be either **heterogeneous** or **homogenous**

The list can be of a **fixed size** or is **resizable**

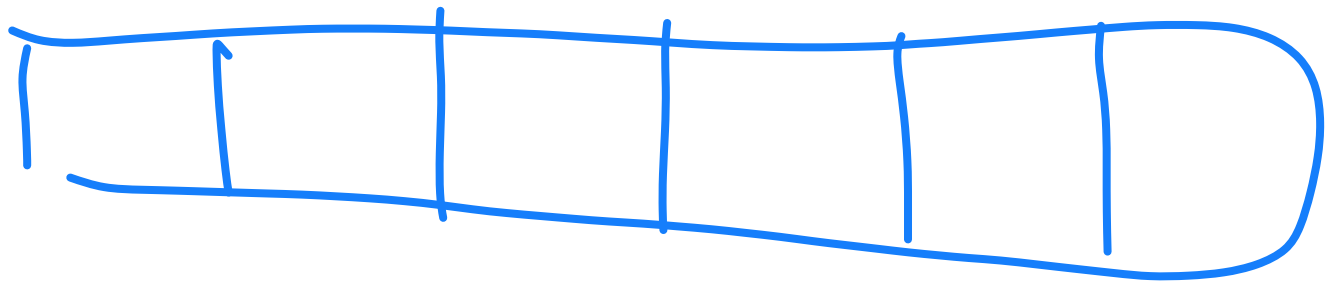
A minimal set of operations (that can be used to create all others):

1. Insert
2. Delete
3. isEmpty
4. getData
5. Create an empty list

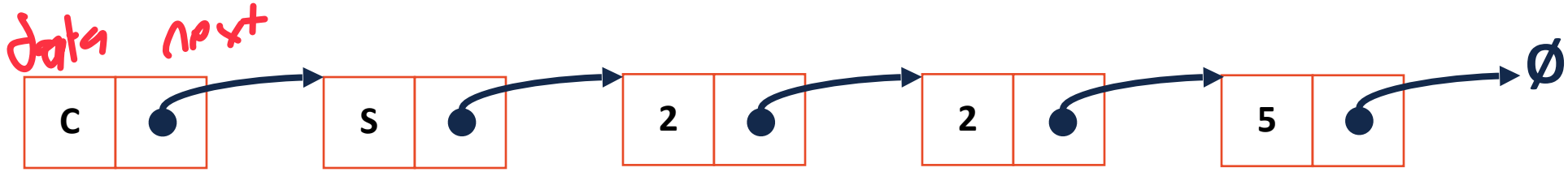
List Implementations

1. Linked List

2. Array List



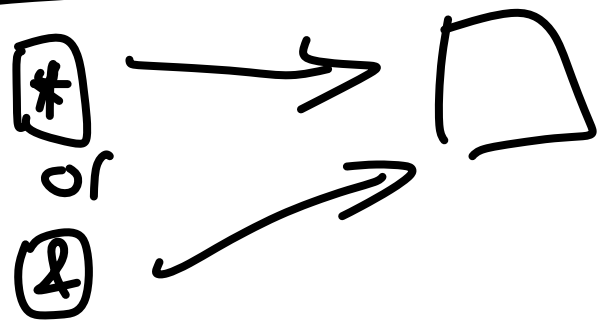
Linked List



A series of Nodes

class ListNode {
T & data;
ListNode* next;
};

Good choice: 2 terabyte image



List.h

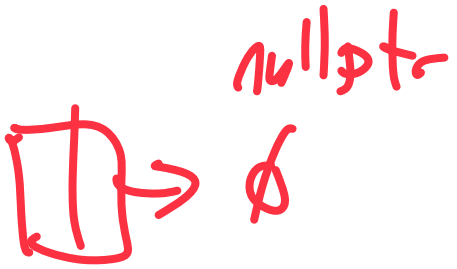
```
28  class ListNode {
29    T & data;
30    ListNode * next;
31    ListNode(T & data) : data(data), next(NULL) { }
32  };
```

Why is **data** stored as a reference?

↳ could be pointer

Why is **next** a pointer?

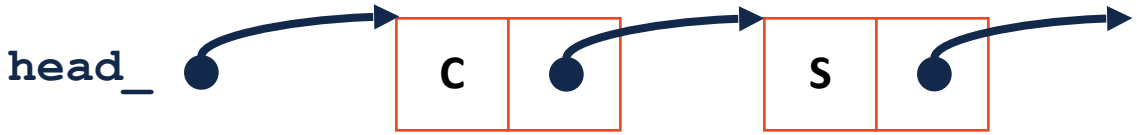
↳ It cannot be a ref b/c ref cannot be nullptr



List.h

```
 1  #pragma once
 2
 3
 4  class List {
 5    public:
 …      /* ... */
28    void insertAtFront(const T& t);
29
30    private:
31      class ListNode {
32        T & data;
33        ListNode * next;
34        ListNode(T & data) :
35         data(data), next(NULL) { }
36      };
37
38      ListNode *head_;
39
40      /* ... */
 …
 …  };
 …
79
```

How do I access list given head_?



Stopped here!

List.h

```
 1  #pragma once
 2
 3
 4  class List {
 5    public:
…       /* ... */
28    void insertAtFront(const T& t);
29
30    private:
31      class ListNode {
32        T & data;
33        ListNode * next;
34        ListNode(T & data) :
35         data(data), next(NULL) { }
36      };
37
38      ListNode *head_;
39
40      /* ... */
…
…   };
…
79
```

What is missing in this code?

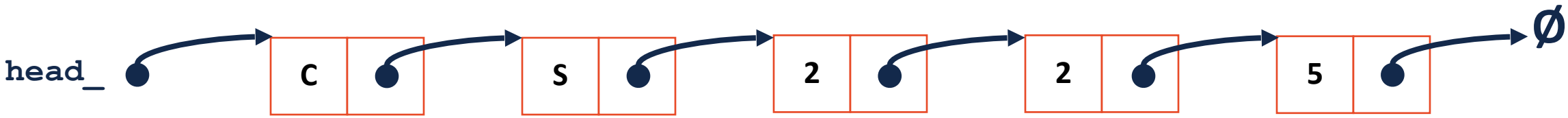
List.h

```
 1  #pragma once
 2
 3  template <typename T>
 4  class List {
 5    public:
 …      /* ... */
28    void insertAtFront(const T& t);
29
30    private:
31      class ListNode {
32        T & data;
33        ListNode * next;
34        ListNode(T & data) :
35         data(data), next(NULL) { }
36      };
37
38      ListNode *head_;
39
40      /* ... */
 …
 …  };
 …
79  #include "List.hpp"
```

List.hpp

```
 1
 2
 3
 4  void List<T>::insertAtFront(const T& t)
 5  {
 6
 7
 8
 9
10
11
12
13
14
15
16
17
18
19
20
21
22  }
```

Linked List: `insertAtFront(data)`



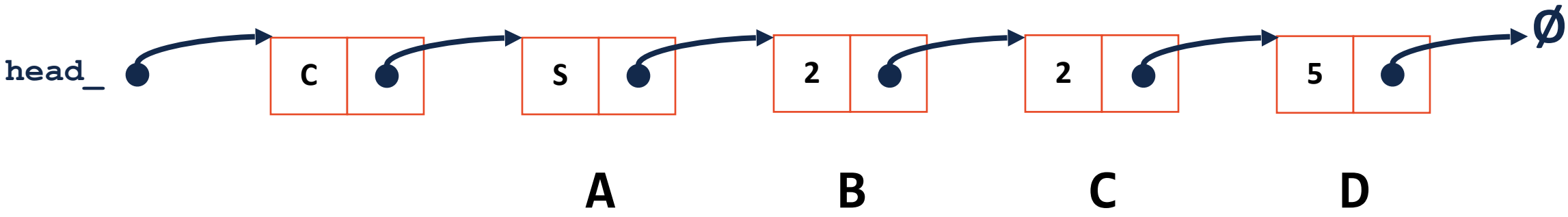
List.h

```
1  #pragma once
2
3  template <typename T>
4  class List {
5    public:
…      /* ... */
28   private:
29     class ListNode {
30       T & data;
31       ListNode * next;
32       ListNode(T & data) :
          data(data), next(NULL) { }
33     };
34
35     ListNode *head_;
36
37     /* ... */
38
39 };
…
…
79 #include "List.hpp"
```

List.hpp

```
1
2
3  template <typename T>
4  void List<T>::insertAtFront(const T& t)
5  {
6
7    ListNode *tmp = new ListNode(data);
8
9
10   tmp->next = head_;
11
12
13   head_ = tmp;
14
15 }
16
17
18
19
20
21
22
```

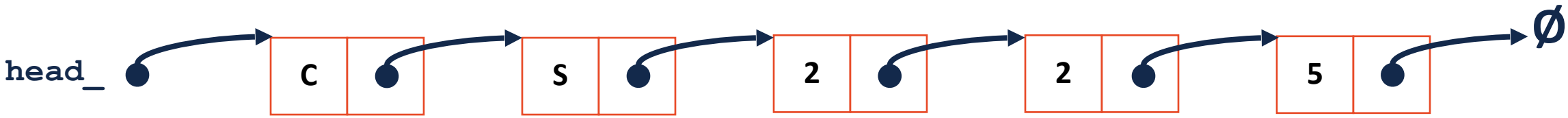
Linked List: `insert(data, index)` `insert(d,3)`



To insert a new ListNode at index 3, we need to **modify** which node?

Join Code: 225

Linked List: `insert(data, index)` `insert(d,3)`



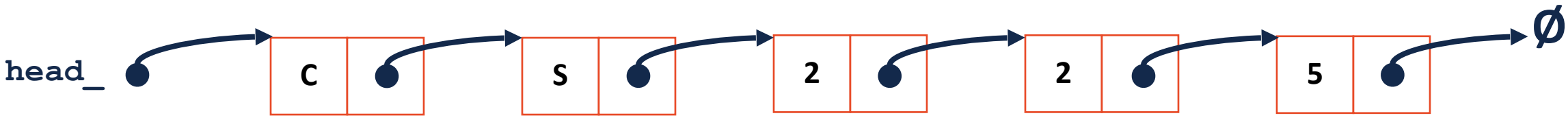
1) Get access to node @ position index - 1

We ***could*** code up a solution to insert which uses some previous var

But lets be smarter!

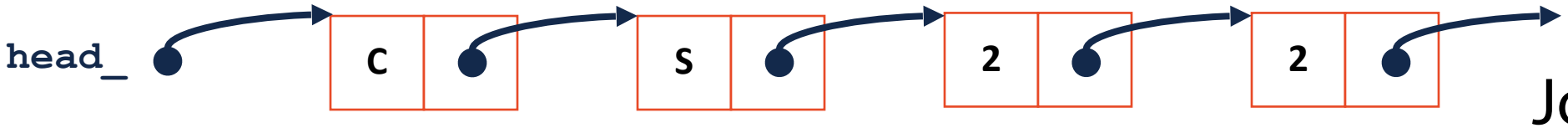
Coding tip from earlier lecture: **Consider the entire interface**

Linked List: `_index(index)`



Lets write one function which is useful for insert / remove AND find

Linked List: `_index(index)`



Join Code: 225

What should the return type of `_index()` be?

```
[template <class T>]
```

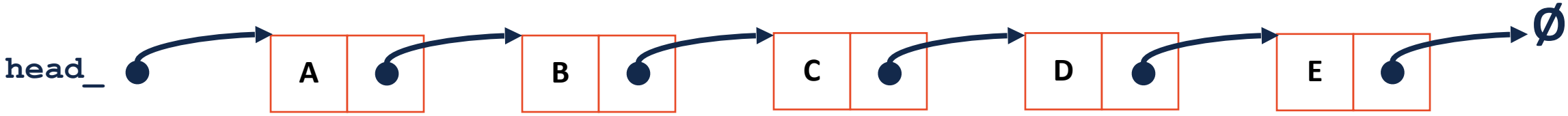
(A) `T &`

(B) `ListNode`

(C) `ListNode *`

(D) `ListNode *&`

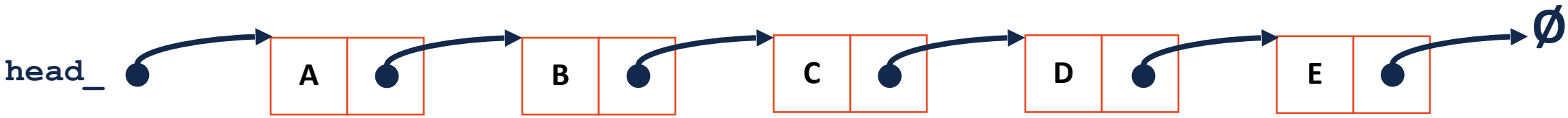
Comparing pointer to reference-to-pointer




```
ListNode * curr = _index(3);
```

```
ListNode *& curr = _index(3);
```

Comparing pointer to reference-to-pointer




```
ListNode * curr = _index(3);
```

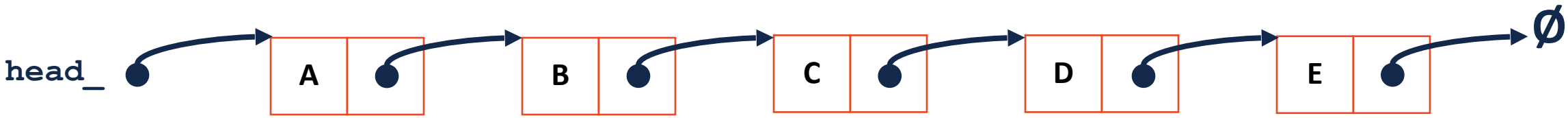
We can access **curr->data** and **curr->next** but not **previous.next**

```
ListNode *& curr = _index(3);
```

We can access **curr.data, curr.next and...**

curr == previous.next

Comparing pointer to reference-to-pointer



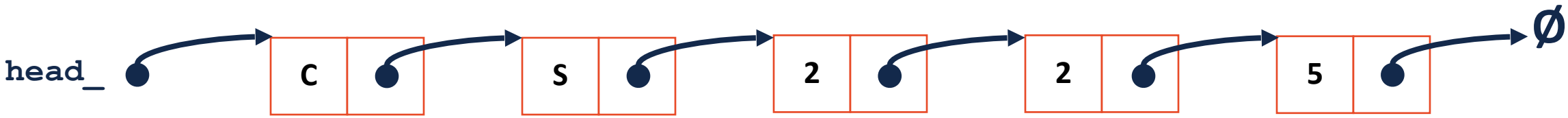

```
ListNode * curr = _index(3);

curr = new ListNode(x);
```

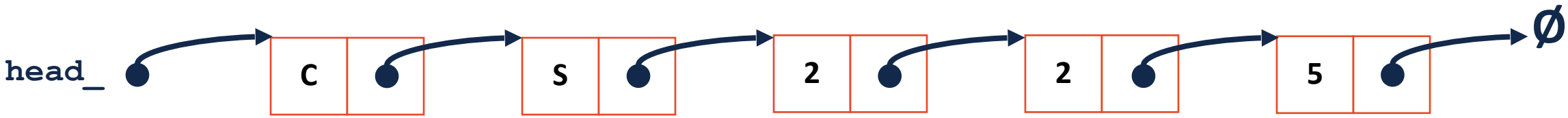
```
ListNode *& curr = _index(3);

curr = new ListNode(x);
```

LinkedList *& _index(index)



Linked List: `_index(index)`



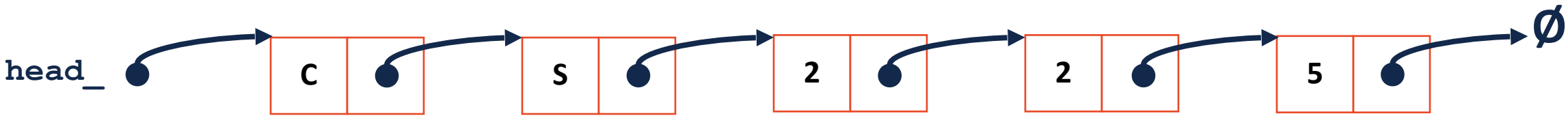
A brief tangent…

List.hpp

```
58  template <typename T>
59  typename List<T>::ListNode *& List<T>::_index(unsigned index){
60          return _index(index, head_)
61  }
```

```
63  template <typename T>
64  typename List<T>::ListNode *& List<T>::_index(unsigned index, ListNode *& root){
65
66
67
68
69
70
71
72
73
74
75
76
77
78
79
80  }
```

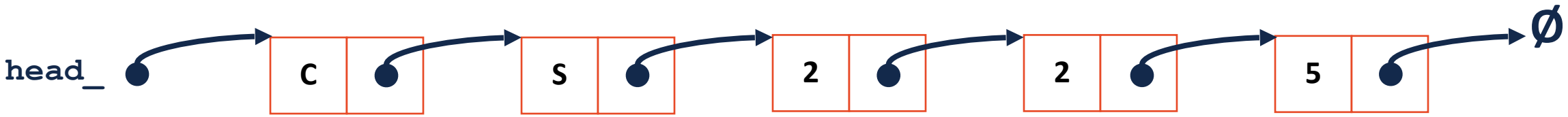
Linked List: `insert(data, index)`



1) Get reference to previous node's next

```
ListNode *& curr = _index(index);
```

Linked List: `insert(data, index)`



1) Get reference to previous node's next

```
ListNode *& curr = _index(index);
```

2) Create new ListNode

```
ListNode * tmp = new ListNode(data);
```

3) Update new ListNode's next

```
tmp->next = curr;
```

4) Modify the previous node to point to new ListNode

```
curr = tmp;
```

Lets compare…

```
1
2  template <typename T>
3  void List<T>::insertAtFront(const T& t)
4  {
5    ListNode *tmp = new ListNode(t);
6
7    tmp->next = head_;
8
9    head_ = tmp;
10
11 }
12
13
14
15
16
17
18
19
20
21
22
```

List.hpp

```
1
2  template <typename T>
3  void List<T>::insert(const T & data,
4  unsigned index) {
5
6
7
8    ListNode *& curr = _index(index);
9
10
11
12   ListNode * tmp = new ListNode(data);
13
14
15
16   tmp->next = curr;
17
18
19
20   curr = tmp;
21 }
22
```

What is the Big O of insert?

List.hpp

```
1
2  template <typename T>
3  void List<T>::insert(const T & data,
4  unsigned index) {
5
6
7
8    ListNode *& curr = _index(index);
9
10
11
12   ListNode * tmp = new ListNode(data);
13
14
15
16   tmp->next = curr;
17
18
19
20   curr = tmp;
21 }
22
```

Join Code: 225

Next Time: List Random Access [ ]

Given a list L, what operations can we do on L[ ]?

What return type should this function have?