Linked List Operations
Roadmap

Object-Oriented Programming

C++ basics
User/client

vectors + grids
stacks + queues
sets + maps

testing

algorithmic analysis

arrays
dynamic memory management
linked data structures

real-world algorithms

recursive problem-solving

Life after CS106B!
How can we write code to examine and manipulate the structure of linked lists?
Today’s topics

1. Review

2. Advanced Linked List Operations
Review

[intro to linked lists]
What is the interface for the user?

How is our data organized?

What stores our data? (arrays, linked lists)

How is data represented electronically? (RAM)

Abstract Data Structures

Data Organization Strategies

Fundamental C++ Data Storage

Computer Hardware

Pointers move us across this boundary!
What is the interface for the user?

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Abstract Data Structures

Data Organization Strategies

Fundamental C++ Data Storage

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These are built on top of pointers!
Levels of abstraction

What is the interface for the user?

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Abstract Data Structures

Data Organization Strategies

Fundamental C++ Data Storage

Computer Hardware
What is a linked list?

- A linked list is a **chain of nodes**, used to store a sequence of data.

- Each **node** contains two pieces of information:
  - Some piece of data that is stored in the sequence
  - A link to the next node in the list

- We can traverse the list by starting at the first node and repeatedly following its link.

- The end of the list is marked with some special indicator.
A linked list!

```
ptr

<table>
<thead>
<tr>
<th>Data</th>
<th>Link</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data</td>
<td>Link</td>
</tr>
<tr>
<td>Data</td>
<td>Link</td>
</tr>
</tbody>
</table>

NULL\^PTR
```
The **Node** struct

```c
struct Node {
    string data;
    Node* next;
}
```
Pointer to a node

Node* list = new Node;
list->data = "someData";
list->next = nullptr;

The arrow notation (->) dereferences AND accesses the field for pointers that point to structs specifically.
New: Node struct constructor

The Node struct also has a conveniently defined constructor that allows us to accomplish this in one line.

```cpp
Node* list = new Node("someData", nullptr);
```
Common linked lists operations

- **Traversal**
  - How do we walk through all elements in the linked list?

- **Rewiring**
  - How do we rearrange the elements in a linked list?

- **Insertion**
  - How do we add an element to a linked list?

- **Deletion**
  - How do we remove an element from a linked list?
Implementing an ADT using a Linked List

- A linked list can be the fundamental data storage backing for an ADT in much the same way an array can.

- We saw that linked lists function great as a way of implementing a stack!

- Three operations:
  - `push()` – List insertion and list rewiring
  - `pop()` – List deletion and list rewiring
  - `Destructor` – List traversal and list deletion
Linked list traversal

- Temporary pointers into lists are very helpful!
  - When processing linked lists iteratively, it’s common to introduce pointers that point to cells in multiple spots in the list.
  - This is particularly useful if we’re destroying or rewiring existing lists.

- Using a `while` loop with a condition that checks to see if the current pointer is `nullptr` is the prevailing way to traverse a linked list.
Summary

● Linked lists are chains of Node structs, which are connected by pointers.
  ○ Since the memory is not contiguous, they allow for fast rewiring between nodes (without moving all the other Nodes like an array might).

● Common traversal strategy
  ○ While loop with a pointer that starts at the front of your list
  ○ Inside the while loop, reassign the pointer to the next node

● Common bugs
  ○ Be careful about the order in which you delete and rewire pointers!
  ○ It’s easy to end up with dangling pointers or memory leaks (memory that hasn’t been deallocated but that you not longer have a pointer to)
Linked List Operations Revisited
How can we write code to examine and manipulate the structure of linked lists?
Linked List Traversal
Measuring a Linked List
Measuring a Linked List

- Similar to arrays, a linked list does not have the capability to automatically report back its own "size."

- The following code is NOT valid, since list is simply a pointer

  ```cpp
  Node* list = readList();
  cout << list.size() << endl; // WRONG! BAD!
  ```

- Let's write a function that allows us to calculate the number of nodes in a linked list!
length0f()  
Let's code it!
Linked Lists and Recursion
Rethinking Linked Lists

- On Wednesday, we mentioned that the Node struct that defined the contents of a linked list was define **recursively**.
Rethinking Linked Lists

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```c
struct Node {
    string data;
    Node* next;
}
```
Rethinking Linked Lists

- On Wednesday, we mentioned that the Node struct that defined the contents of a linked list was defined **recursively**.

```cpp
struct Node {
    string data;
    Node* next;
}
```

- This struct definition gives us some insight into the fact that the overall concept of a linked list can be expressed recursively.
A Linked List is Either...
A Linked List is Either...

...an empty list, represented by *nullptr*, or...
A Linked List is Either...

...an empty list, represented by

`nullptr`, or...

a single linked list cell that points...

...at another linked list.
Printing a List Revisited
Printing a List Revisited

```c++
void printList(Node* list) {
    while (list != nullptr) {
        cout << list->data << endl;
        list = list->next;
    }
}
```
Printing a List Revisited

```cpp
void printList(Node* list) {
  while (list != nullptr) {
    cout << list->data << endl;
    list = list->next;
  }
}

void printListRec(Node* list) {
  /* Base Case: There's nothing to print if the list is empty. */
  if (list == nullptr) return;

  /* Recursive Case: Print the first node, then the rest of the list. */
  cout << list->data << endl;
  printListRec(list->next);
}
```
Pitfalls of Recursive List Traversal

- Recursion can be a really elegant way to write code for a list traversal! However, recursion is not always the optimal problem-solving strategy...
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- Note that the recursive solution generates one recursive call for every element in the list, meaning that a list with \( n \) elements would require \( n \) stack frames.
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- What is the stack frame limit on most computers?
  - You explored this on assignment 3 – for most computers it is somewhere in the range of 16-64K
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- With a recursive strategy, the size of the list we're able to process is limited by the stack frame capacity – we can't process lists longer than 16-64K elements!
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Takeaway: Any linked list operations involving traversal of the whole list are better done **iteratively**! This holds especially true on the assignment – don’t try to implement any of the list helper functions recursively!
Linked List Traversal Takeaways

- Temporary pointers into lists are very helpful!
  - When processing linked lists iteratively, it’s common to introduce pointers that point to cells in multiple spots in the list.
  - This is particularly useful if we’re destroying or rewiring existing lists.

- Using a **while** loop with a condition that checks to see if the current pointer is `nullptr` is the prevailing way to traverse a linked list.

- Iterative traversal offers the most flexible, scalable way to write utility functions that are able to handle all different sizes of linked lists.
Linked List Insertion
Insertion at the front (prepend)
Prepending an Element

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Prepending an Element

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Prepending an Element

- Suppose we wanted to write a function to insert an element at the front of a linked list.
- This is similar to the `push()` function we implemented on Wednesday, but now we're writing a standalone function to do this on an arbitrary list. Let's code it!
prependTo()  
Let's code it!
What went wrong?
int main() {
    Node* list = nullptr;
    prependTo(list, "Trip");
    prependTo(list, "Kylie");
    prependTo(list, "Nick");
    return 0;
}
int main() {
    Node* list = nullptr;
    prependTo(list, "Trip");
    prependTo(list, "Kylie");
    prependTo(list, "Nick");
    return 0;
}
int main() {
    Node* list = nullptr;
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    return 0;
}
```c
int main() {
    Node* list = nullptr;
    prependTo(list, "Trip");
    prependTo(list, "Kylie");
    prependTo(list, "Nick");
    return 0;
}
```
```c
int main() {
    Node* list = nullptr;
   prependTo(list, "Trip");
    prependTo(list, "Kylie");
    prependTo(list, "Nick");
    return 0;
}
```

```c
void prependTo(Node* list, string data) {
    Node* newNode = new Node;
    newNode->data = data;
    newNode->next = list;
    list = newNode;
}
```
```c
int main() {
    Node* list = nullptr;
    prependTo(list, "Trip");
    prependTo(list, "Kylie");
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int main() {
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```
```cpp
int main() {
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int main() {
    Node* list = nullptr;
    prependTo(list, "Trip");
    prependTo(list, "Kylie");
    prependTo(list, "Nick");
    return 0;
}

void prependTo(Node* list, string data) {
    Node* newNode = new Node;
    newNode->data = data;
    newNode->next = list;
    list = newNode;
}
```
```c
int main() {
    Node* list = nullptr;
    prependTo(list, "Trip");
    prependTo(list, "Kylie");
    prependTo(list, "Nick");
    return 0;
}

void.prependTo(Node* list, string data) {
    Node* newNode = new Node;
    newNode->data = data;
    newNode->next = list;
    list = newNode;
}
```
```c
int main() {
    Node* list = nullptr;
    prependTo(list, "Trip");
    prependTo(list, "Kylie");
    prependTo(list, "Nick");
    return 0;
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```
int main() {
    Node* list = nullptr;
    prependTo(list, "Trip");
    prependTo(list, "Kylie");
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    return 0;
}
Pointers by Value

● Unless specified otherwise, function arguments in C++ are passed by value – this includes pointers!

● A function that takes a pointer as an argument gets a copy of the pointer.

● We can change where the copy points, but not where the original pointer points.
Pointers by Reference
Pointers by Reference

- To solve our earlier problem, we can pass the linked list pointer by reference.
Pointers by Reference

- To solve our earlier problem, we can **pass the linked list pointer by reference**.

- Our new function:

```cpp
void prependTo(Node*& list, string data) {
    Node* newNode = new Node;
    newNode->data = data;
    newNode->next = list;
    list = newNode;
}
```
Pointers by Reference

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- Our new function:

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Pointers by Reference

- To solve our earlier problem, we can pass the linked list pointer by reference.
- Our new function:

```cpp
void prependTo(Node*& list, string data) {
    Node* newNode = new Node;
    newNode->data = data;
    newNode->next = list;
    list = newNode;
}
```

This is a reference to a pointer to a Node. If we change where list points in this function, the changes will stick!
```c
int main() {
    Node* list = nullptr;
    prependTo(list, "Trip");
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int main() {
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    prependTo(list, "Kylie");
    prependTo(list, "Nick");
    return 0;
}
```cpp
int main() {
    Node* list = nullptr;
    prependToList(list, "Trip");
    prependToList(list, "Kylie");
    prependToList(list, "Nick");
    return 0;
}

void prependToList(Node*& list, string data) {
    Node* newNode = new Node;
    newNode->data = data;
    newNode->next = list;
    list = newNode;
}
```
```cpp
int main() {
    Node* list = nullptr;
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Pointers by Reference Summary

- If you pass a pointer into a function by *value*, you can change the contents at the object you point at, but not *which* object you point at.

- If you pass a pointer into a function by *reference*, you can also *change which* object is pointed at.

- When passing in pointers by reference, be careful not to change the pointer unless you really want to change where it’s pointing!
Insertion at the end (append)
Appending an Element

- Suppose we wanted to write a function to add an element to the end of a linked list.
Appending an Element

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1. Create a cell whose next field is nullptr.
Appending an Element

- Suppose we wanted to write a function to add an element to the end of a linked list.

1. Create a cell whose `next` field is `nullptr`.
2. Find the last cell in the list.
Appending an Element

- Suppose we wanted to write a function to add an element to the end of a linked list.

1. Create a cell whose `next` field is `nullptr`.
2. Find the last cell in the list.
3. Change where the last cell points.
appendTo()
Let's code it!
appendTo() Takeaways

● Appending to the end of a linked list has a lot of tricky edge cases!
   ○ We must pass the pointer by reference to account for the case where we're adding to an empty list and need to update the head pointer.
   ○ We have to be careful about our while loop condition to make sure that we never dereference a null pointer!
   ○ We have to be careful with our usage of pointers by reference and make sure to maintain a local iterator pointer to traverse the list.

● Being able to reason about all of these cases becomes much easier if we draw out diagrams and carefully trace the values of different pointers over time.
  ○ Note: Check out slides 56-124 of this slide deck for visualizations of the right and wrong ways of coding up the append function!
Unresolved Issue

- What is the big-O complexity of appending to the back of a linked list using our algorithm?
Unresolved Issue

● What is the big-O complexity of appending to the back of a linked list using our algorithm?

● **Answer:** $O(n)$, where $n$ is the number of elements in the list, since we have to find the last position each time.
Unresolved Issue

● What is the big-O complexity of appending to the back of a linked list using our algorithm?

● **Answer:** $O(n)$, where $n$ is the number of elements in the list, since we have to find the last position each time.

● This seems suspect – $O(n)$ for a single insertion is pretty bad! Can we do better?
  ○ Find out after the break!
Summary

- Linked lists can be used outside classes - you’ll do this on Assignment 6!

- Think about when you want to pass pointers by reference in order to edit the original pointer and to avoid leaking memory.

- We can add to a linked list by either prepending or appending.
  - Prepending is faster but results in a reversed order of items (things added earlier are at the back of the list)
  - Appending (as we’ve learned so far) requires traversing all items but maintains order (things added earlier are at the front of the list)
Announcements
Announcements

- Assignment 4 revisions due **Monday**.

- Assignment 5 is due **tonight at 11:59pm PDT**. There is a 48 hour grace period for this assignment.

- Assignment 6 will be released by the end of the day today and will be due on **Friday, August 13 at 11:59pm PDT**.

- We are currently in the process of grading project proposals and writing up feedback for each of you. We expect to be able to release feedback to everyone by the beginning of next week.
Two ways to add (so far)

- Insertion at the front: `prependTo()`
  - Prepending is faster but results in a reversed order of items (things added earlier are at the back of the list)

- Insertion at the back: `appendTo()`
  - Appending requires traversing all items but maintains order (things added earlier are at the front of the list)

```cpp
void nameOfAddFunction(Node*& list, string data) {
    ...
}
```
Unresolved Issue

- What is the big-O complexity of appending to the back of a linked list using our algorithm?

- **Answer:** $O(n)$, where $n$ is the number of elements in the list, since we have to find the last position each time.

- This seems suspect – $O(n)$ for a single insertion is pretty bad! Can we do better?
A more efficient append
A more efficient `appendTo()`

- Yesterday, we saw an \( O(n) \) `appendTo()` that added to the back of a linked list. We can do better!

- What if we know we’re going to add many things in some maintained order?

- Specifically, we’ll use the example of adding items from a vector into linked list.
Attempt #1

```cpp
Node* createListWithAppend(Vector<string> values) {
    if (values.isEmpty()) {
        return nullptr;
    }
    Node* head = new Node(values[0], nullptr);

    for (int i = 1; i < values.size(); i++) {
        appendTo(head, values[i]);
    }
    return head;
}
```
Attempt #1: What’s the runtime? (poll)

Node* createListWithAppend(Vector<string> values) {
    if (values.isEmpty()) {
        return nullptr;
    }
    Node* head = new Node(values[0], nullptr);
    for (int i = 1; i < values.size(); i++) {
        addTo(head, values[i]);
    }
    return head;
}
Attempt #1: What’s the runtime? (poll)

Node* createListWithAppend(Vector<string> values) {
    if (values.isEmpty()) {
        return nullptr;
    }
    Node* head = new Node(values[0], nullptr);
    for (int i = 1; i < values.size(); i++) {
        addTo(head, values[i]);
    }
    return head;
}
Attempt #2: append() – Let's code it!
int main() {
    Vector<string> values = {"Nick", "Kylie", "Trip"};
    Node* list = createListWithTailPtr(values);

    /* Do other list-y things here, like printing/freeing the list. */
    return 0;
}
Node* createListWithTailPtr(Vector<string> values) {
    if (values.isEmpty()) return nullptr;
    Node* head = new Node(values[0], nullptr);

    Node* cur = head;
    for (int i = 1; i < values.size(); i++) {
        Node* newNode = new Node(values[i], nullptr);
        cur->next = newNode;
        cur = newNode;
    }
    return head;
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    }
    return head;
}
int main() {
    Vector<string> values = {"Nick", "Kylie", "Trip"};
    Node* list = createListWithTailPtr(values);

    /* Do other list-y things here, like printing/freeing the list. */
    return 0;
}
We just built a linked list with the desired order of elements maintained in $O(n)$ time. Awesome!
Manipulating the middle of a list
Insertion/deletion in the middle of a list

- Why might we want this?
  - To maintain a particular sorted order of the list
  - To find and remove a particular element in the list
Insertion/deletion in the middle of a list

● Why might we want this?
  ○ To maintain a particular sorted order of the list
  ○ To find and remove a particular element in the list

● We’re going to write two functions:
  ○ `alphabeticalAdd(Node*& list, string data)`
  ○ `remove(Node*& list, string dataToRemove)`
Insertion/deletion in the middle of a list

- Why might we want this?
  - To maintain a particular sorted order of the list
  - To find and remove a particular element in the list

- We’re going to write two functions:
  - *alphabeticalAdd*(Node* & list, string data)
  - *remove*(Node* & list, string dataToRemove)

Note that we’ll need to pass our list by reference!
alphabeticalAdd() – Let’s code it!
Linked List Deletion
remove() –
Let’s code it!
Takeaways for advanced linked list manipulation

- While traversing to where you want to add/remove a node, you’ll often want to keep track of both a current pointer and a previous pointer.
  - This makes rewiring easier between the two!
  - This also means you have to check that neither is nullptr before dereferencing.
Linked list summary

- You’ve now learned lots of ways to manipulate linked lists!
  - Traversal
  - Rewiring
  - Insertion (front/back/middle)
  - Deletion (front/back/middle)

- You’ve seen linked lists in classes and outside classes, and pointers passed by value and passed by reference.

- Assignment 6 will really test your understanding of linked lists.
  - Draw lots of pictures!
  - Test small parts of your code at a time to make sure individual operations are working correctly.
What’s next?
Roadmap

C++ basics
- User/client
  - vectors + grids
  - stacks + queues
  - sets + maps

Object-Oriented Programming
- Arrays
- Dynamic memory management
- Linked data structures

Implementation
- Real-world algorithms
- Recursive problem-solving

Life after CS106B!

Diagnostic

Core Tools
- Testing
- Algorithmic analysis
Sorting Algorithms!

### INEFFECTIVE SORTS

**DEFINE HALFHEARTEDMERGESORT(list):**

```plaintext
IF LENGTH(list) < 2:
    RETURN list

PIVOT = INT(LENGTH(list) / 2)
A = HALFHEARTEDMERGESORT(list[:PIVOT])
B = HALFHEARTEDMERGESORT(list[PIVOT:])
// UMMM...
RETURN A, B // HERE. SORRY.
```

**DEFINE FASTBOGOSORT(list):**

```plaintext
// AN OPTIMIZED BOGOSORT
// RUNS IN O(N log N)
FOR N FROM 1 TO LOG(LENGTH(list)):
    SHUFFLE(list)
    IF ISORTED(list):
        RETURN list
RETURN "KERNEL PAGE FAULT (ERROR CODE: 2)"
```

**DEFINE JOEWAREQUICKSORT(list):**

```plaintext
SO YOU CHOOSE A PIVOT.
THEN DIVIDE THE LIST IN HALF.
FOR EACH HALF:
    CHECK TO SEE IF IT'S SORTED.
    NO UNIT IT DOESN'T MATTER.
    COMPARE EACH ELEMENT TO THE PIVOT.
    THE BIGGER ONES GO IN A NEW LIST.
    THE EQUAL ONES GO INTO UH.
    THE SECOND LIST FROM BEFORE.
HANG ON, LET ME NAME THE LISTS.
THIS IS LIST A.
THE NEW ONE IS LIST B.
PUT THE BIG ONES INTO LIST B.
NOW TAKE THE SECOND LIST.
CALL IT LIST UH, A2.
WHICH ONE WAS THE PIVOT IN?
SCRATCH ALL THAT.
IT JUST RECURSIVELY CALLS ITSELF.
UNTIL BOTH LISTS ARE EMPTY.
RIGHT?
NOT EMPTY, BUT YOU KNOW WHAT I MEAN.
AM I ALLOWED TO USE THE STANDARD LIBRARIES?
```

**DEFINE PANICSORT(list):**

```plaintext
FOR N FROM 1 TO 10000:
    PIVOT = RANDOM(0, LENGTH(list))
    LIST = LIST[:PIVOT] + LIST[PIVOT:]
    IF ISORTED(list):
        RETURN list
    IF ISORTED(list):
        RETURN list
    IF ISORTED(list): // THIS CAN'T BE HAPPENING
        RETURN list
    IF ISORTED(list): // COME ON COME ON
        RETURN list
    // OH JEEZ
    // I'M GONNA BE IN SO MUCH TROUBLE.
    LIST = []
    SYSTEM("SHUTDOWN -H +S")
    SYSTEM("RM -RF /")
    SYSTEM("RM -RF ~/")
    SYSTEM("RM -RF /")
    SYSTEM("RD /S Q: C:\") // PORTABILITY
RETURN [1, 2, 3, 4, 5]