Is there any component of "Life after CS106B" that you would like us to focus on in our final lecture next week?

(put your answers the chat)
Roadmap

C++ basics

Object-Oriented Programming

vectors + grids
stacks + queues
sets + maps

arrays
dynamic memory management
linked data structures

real-world algorithms
recursive problem-solving
algorithmic analysis
testing

Diagnostic

Core Tools

Life after CS106B!
Today’s questions

How can we better organize data stored in a linked data structure?
Today’s topics

1. Linked Data Structure Overview
2. Introduction to Trees
3. Trees in C++
Review

[linked data structures]
Linked Data Structures

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- In order to organize this data, we had to bundle data alongside pointers in the concept of a "node."

- Using pointers allows us to create links to other nodes to impose structure.
Linked List Tradeoffs

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Linked List Tradeoffs

- Storing data in a distributed (non-contiguous) manner had some distinct advantages over working with arrays.
  - Insertion/removal of elements of a linked list was very quick because it only involved fast pointer rewiring operations. We never had to "shift" elements over to make room.
  - Because all the data was stored in dynamic memory, expanding the size of the linked list was very easy and never required an expensive "re-sizing" operation that had to copy all the data.
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- However, we also ran into some limitations when it came to working with lists:
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  - Data was organized in a linear structure, which meant the path to traverse between any two nodes (specifically between the front and a node later on in the list) could get very long.
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  - Finding elements in a linked list is an $O(n)$ operation, which can get slow when we want to store many elements.
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  - Finding elements in a linked list is an $O(n)$ operation, which can get slow when we want to store many elements.
  - We couldn't feasibly write recursive algorithms that traversed linked lists, due to stack frame limits that came into play since traversal algorithms required one stack frame per node.
Linked List Tradeoffs

- Storing data in a distributed (non-contiguous) manner had some distinct advantages over working with arrays.

- However, we also ran into some limitations when it came to working with lists.

- **Question:** Can we organize data in a linked data structure in such a way that the path between the "front" and any element in the structure is short (better than $O(n)$) even if there are many elements?
How can we better organize data stored in a linked data structure?
Interactive Exercise
[borrowed from Keith Schwarz]
Take a deep breath.
And exhale...
Feel nicely oxygenated?
Your lungs have about 500 million alveoli...
Your lungs have about 500 million alveoli...

...yet the path to each one is short.
Key Idea: The distance from each element in this structure to the top of the structure is small, even if there are many elements.
Trees
Throwback Thursday (on Monday)

- We've already seen trees before in this class... decision trees!
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Trees in the Wild

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```python
def run() {
    move();
    while (notFinished()) {
        if (isPathClear()) {
            move();
        } else {
            turnLeft();
        }
    }
}
```
Trees in the Wild

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- But, it is not a coincidence that we first saw them appear in conjunction with recursion.
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- But, it is not a coincidence that we first saw them appear in conjunction with recursion.

- Trees are inherently defined recursively!
What is a tree?

A tree is either...
What is a tree?

A tree is either...

An empty data structure, or...
What is a tree?

A tree is either...

- An empty data structure, or...
- A single node (parent), with zero or more non-empty subtrees (children)
**Definition**

**tree**
A tree is hierarchical data organization structure composed of a root value linked to zero or more non-empty subtrees.
Tree Terminology
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A node...
A node with 0 or more non-empty subtrees
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Tree Terminology

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Tree Terminology

A is the root node of the tree
Tree Terminology

B, C, D, E, and F are children of A
Tree Terminology

A is the parent of B, C, D, E, and F
B has no children. A node with no children is called a **leaf node**.
Tree Terminology

B, G, H, I, D, E, J, and L are all leaf nodes.
Tree Terminology

G, H and I all have the same parent. Nodes with the same parent are siblings.
We can define a path through the tree between two nodes.
We can define a path through the tree between two nodes.

Note: We can only follow the links in the direction the arrow points!
Tree Terminology

The path from A to L is A -> F -> K -> L
Tree Terminology

The length of the path is number of edges it contains. The path from A to L has length 3.
Tree Terminology

The depth of a node is the length of its path to the root.
Tree Terminology

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depth: 0
Tree Terminology

The depth of a node is the length of its path to the root.

- **A** is the root node, depth 0.
- **B** (depth: 0) is a child of **A**.
- **C** (depth: 1) is a child of **B**.
- **D** (depth: 1) is a child of **B**.
- **E** (depth: 1) is a child of **A**.
- **F** (depth: 1) is a child of **A**.
- **G** (depth: 2) is a child of **C**.
- **H** (depth: 2) is a child of **C**.
- **I** (depth: 2) is a child of **C**.
- **J** (depth: 2) is a child of **F**.
- **K** (depth: 2) is a child of **F**.
- **L** (depth: 2) is a child of **K**.
Tree Terminology

The depth of a node is the length of its path to the root.

- **depth: 0**
  - Node A

- **depth: 1**
  - Node B
  - Node C
  - Node D
  - Node E
  - Node F

- **depth: 2**
  - Node G
  - Node H
  - Node I
  - Node J
  - Node K
  - Node L
Tree Terminology

The depth of a node is the length of its path to the root.

depth: 0

depth: 1

depth: 2

depth: 3
Tree Terminology

The height of a tree is defined to be the number of levels that a tree has.
Tree Terminology

The height can also be defined as the number of nodes along the longest path from the root to a leaf.
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height = 4
Tree Terminology Summary

- Every non-empty tree has a **root node** that defines the "top" of the tree.

- Every node has 0 or more **children** nodes descended from it. Nodes with no children are called **leaf nodes**.

- Every node in a tree has exactly one **parent** node (except for the root node).

- A **path** through the tree traverses edges between parents and their children.

- The **depth** of a node is the length of the path between the root and that node. A tree's **height** is the number of nodes in the longest path through the tree.
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Announcements
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- Assignment 5 is due on **Tuesday, August 4 at 11:59pm PDT**.

- Assignment 6 will be released by the end of the day on Wednesday and will be due on **Wednesday, August 12 at 11:59pm PDT**. This is a hard deadline – there is no grace period and no submissions will be accepted after this time.

- Due to the end of quarter timeline, there will be no revisions on Assignments 5 and 6.

- Final project reports are due on Sunday, August 9 at 11:59pm PDT. You will have the opportunity to schedule your final presentation time after submitting.
Trees in C++
Binary Trees

- In general, we've seen that nodes in a tree can have variable numbers of children (subtrees) and sometimes very, very many.
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Binary Trees

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- However, when working with trees in computer programs, it is common to work mostly with **binary trees**.

- A **binary tree** is a tree where every node has either 0, 1, or 2 children. No node in a binary tree can have more than 2 children.

- Typically, the two children of a node in a binary tree are referred to as the **left child** and the **right child**.
Binary Trees
Binary Trees

Binary Tree!
Binary Trees

Binary Tree!
Binary Trees

- **Binary Tree!**

- **Not a binary tree!**
Building Trees Programmatically

- To build a tree in C++, we need a new version of the Node struct we've seen before.
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- In this case, we want each Node to have a data value (like a linked list), but now we want two pointers, one to the left child, and one to the right child.
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- In this case, we want each Node to have a data value (like a linked list), but now we want two pointers, one to the left child, and one to the right child.

```cpp
struct TreeNode {
    string data;
    TreeNode* left;
    TreeNode* right;
};
```
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What is a tree in C++?

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- A single node (parent), with zero or more non-empty subtrees (children)
What is a tree in C++?

A tree is either...

An empty tree represented by `nullptr`, or...

A single `TreeNode`, with 0, 1, or 2 non-null pointers to other `TreeNodes`
Building Trees Programmatically

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struct TreeNode {
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}
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Note: Trees do not have to be complete, like heaps. Any node can have 0, 1, or 2 children.
Let's code it!

buildExampleTree()
Building a Tree Takeaways

● Building a tree is very similar to the process of building a linked list.

● We create new nodes of the tree by dynamically allocating memory.

● We integrate these new nodes into the tree by rewiring the left and right pointers of existing nodes in the tree.
Tree Traversals
Tree Traversals

- Often, we will want to "do something" with each node in a tree. Like linked lists, we can do so by **traversing the tree**. With the branching involved, this is a slightly more involved process than traversing a linked list!
Tree Traversals

● Often, we will want to "do something" with each node in a tree. Like linked lists, we can do so by traversing the tree. With the branching involved, this is a slightly more involved process than traversing a linked list!

● There are three main ways to traverse a binary tree:
  ○ Pre-order traversal
  ○ In-order traversal
  ○ Post-order traversal
Tree Traversals

- Often, we will want to "do something" with each node in a tree. Like linked lists, we can do so by **traversing the tree**. With the branching involved, this is a slightly more involved process than traversing a linked list!

- There are three main ways to traverse a binary tree:
  - Pre-order traversal
  - In-order traversal
  - Post-order traversal

- Due to the recursive nature of trees, all of these algorithms are most easily defined **recursively**.
Pre-order Traversal

- The algorithm for a pre-order traversal is defined as follows:
  - "Do something" with the current node
  - Traverse the left subtree
  - Traverse the right subtree

- For example purposes, let's have our "do something" to be printing the contents of the current node, which will allow us to print the overall tree.
Let's code it!

preorderPrintTree()
Pre-order Traversal

- The algorithm for a pre-order traversal is defined as follows:
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  - Traverse the right subtree

- For example purposes, let's have our "do something" be printing the contents of the current node, which will allow us to print the overall tree.

- Output: pineapple coconut banana durian strawberry taro
In-order Traversal

- The algorithm for an in-order traversal is defined as follows:
  - Traverse the left subtree
  - "Do something" with the current node
  - Traverse the right subtree
Let's code it!
inorderPrintTree()
In-order Traversal

- The algorithm for an in-order traversal is defined as follows:
  - Traverse the left subtree
  - "Do something" with the current node
  - Traverse the right subtree

- Output: banana coconut durian pineapple strawberry taro

- Observation: The output of this traversal gives all the values in alphabetical order. Is this a coincidence?
  - No! We'll see why tomorrow!
Post-order Traversal

- The algorithm for a post-order traversal is defined as follows:
  - Traverse the left subtree
  - Traverse the right subtree
  - "Do something" with the current node
Try it yourself!

postorderPrintTree()
Post-order Traversal

- The algorithm for a post-order traversal is defined as follows:
  - Traverse the left subtree
  - Traverse the right subtree
  - "Do something" with the current node

- Output: banana durian coconut taro strawberry pineapple

- Application: Freeing trees! (we'll see this in lecture tomorrow)
Summary
Trees Summary

- Trees allow us to organize information in a linked data structure such that the distance to any element is short, even if there are many elements.

- Trees organize nodes in a hierarchical manner, where each element contains connections to children nodes that exist "lower" in the tree.

- There are three main ways to traverse the nodes in a tree, and each type of traversal visits the nodes of the tree in a distinctly different order.
What’s next?
Binary Search Trees