CSCI-1200 Data Structures — Fall 2017
Lecture 24 – Miscellaneous Data Structures

Review from Lecture 23

- STL's `for_each`, STL's `find_if`, Function Objects, a.k.a. *Functors*
- Hash table collision resolution: separate chaining vs open addressing
- STL's `unordered_set` (and `unordered_map`)
- Using a hash table to implement a set/map

Today's Lecture

- Finish hash table implementation: Iterators, find, insert, and erase
- Some variants on the basic data structures

24.1 The Basic Data Structures

This term we've covered a number of core data structures. These structures have fundamentally different memory layouts. These data structures are classic, and are not unique to C++.

- array / vector
- linked list
- binary search tree
- binary heap / priority queue
- hash table

24.2 A Few Variants of the Basic Data Structures

Many *variants* and *advanced extensions* and *hybrid* versions of these data structures are possible. Different applications with different requirements and patterns of data and data sizes and computer hardware will benefit from or leverage different aspects of these variants.

This term we've already discussed / implemented a number of data structure variants:

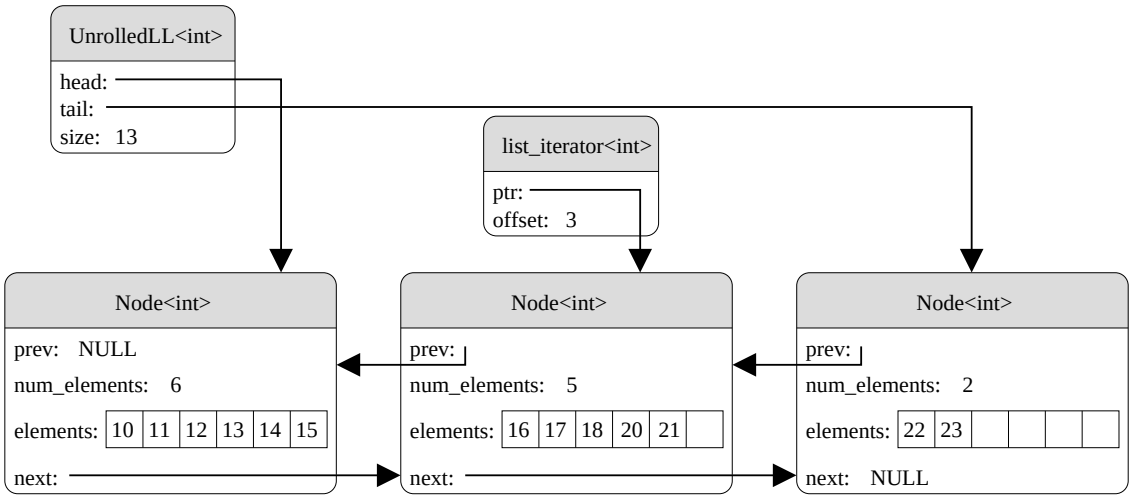
- single vs. doubly linked lists
  using more memory can improve convenience and running time for key operations
- dummy nodes or circular linked lists – *can reduce need for special case / corner case code*
- jagged array (Homework 4)
  avoids overhead of separate memory allocations, pointer arithmetic is faster than pointer dereferencing
- red-black tree – *an algorithm to automatically balance a binary search tree*
- quad trees (Homework 8) – *good for 2D spatial data, in 3D we use an octree*
- stack and queue – *restricted/reduced(!) set of operations on array/vector and list*
- hash table: separate chaining vs open addressing – *reduce memory and avoid pointer dereferencing*
- priority queue with backpointers (Homework 9) – *when you need to update data already in the structure*

We'll discuss just a few additional variants today. The list below is certainly not comprehensive!

- unrolled linked list
- skip list
- leftist heap (notes from Lecture 21)
- trie (a.k.a. prefix tree)
- suffix tree

24.3 Unrolled Linked List - Overview

- An *unrolled linked list* data structure is a hybrid of an array / vector and a linked list. It is very similar to a standard doubly linked list, except that *more than one element* may be stored at each node.
- This data structure can have performance advantages (both in memory and running time) over a standard linked list when storing small items and can be used to better align data in the cache.
- Here's a diagram of an unrolled linked list:



- Each `Node` object contains a *fixed size* array (size = 6 in the above example) that will store 1 or more elements from the list. The elements are ordered from left to right.
- From the outside, this unrolled linked list should perform exactly like an STL list containing the numbers 10 through 23 in sorted order, except we've just erased '19'. Note that to match the behavior, the `list_iterator` object must also change. The iterator must keep track of not only which `Node` it refers to, but also which element within the `Node` it's on. This can be done with a simple offset index. In the above example, the iterator refers to the element "20".
- Just like regular linked lists, the unrolled linked list supports speedy `insert` and `erase` operations in the middle of the list. The diagram above illustrates that after erasing an item it is often more efficient to store one fewer item in the affected `Node` than to shift *all* elements (like we have to with an array/vector).
- And when we insert an item in the middle, we might need to splice a new `Node` into the chain if the current `Node` is "full" (there's not an empty slot).

24.4 Unrolled Linked List - Discussion

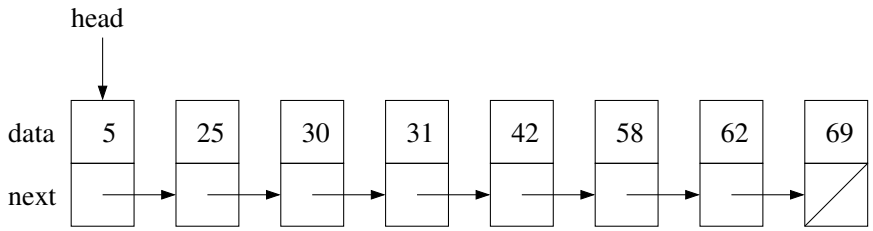
- Say that `Foo` is a custom C++ class that requires 16 bytes of memory. If we create a basic doubly-linked list of n `Foo` objects on a 64 bit machine, how much total memory will we use? Assume that each blob of memory allocated on the heap has an 8 byte header.

- Now instead, let's store n booleans in a basic doubly-linked list. How much total memory will that use? Assume that heap allocations must round up to the nearest 8 byte total size.

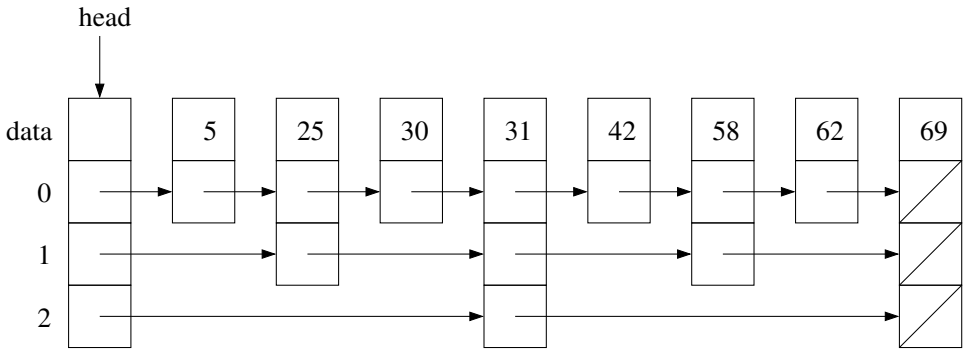
- Finally, let's instead use an unrolled linked list. How many boolean values items should we store per `Node`? Call that number k. How much total memory will we use to store n booleans? What if the nodes are all 100% "full"? What if the nodes are on average 50% "full"?

24.5 Skip List - Overview

- Consider a classic singly-linked list storing a collection of n integers in sorted order.



- If we want to check to see if '42' is in the list, we will have to linearly scan through the structure, with $O(n)$ running time.
- Even though we know the data is sorted... The problem is that unlike an array / vector, we can't quickly jump to the middle of a linked list to perform a binary search.
- What if instead we stored a additional pointers to be able to jump to the middle of the chain? A skip list stores sorted data with multiple levels of linked lists. Each level contains roughly half the nodes of the previous level, approximately every other node from the previous level.



- Now, to find / search for a specific element, we start at the highest level (level 2 in this example), and ask if the element is before or after each element in that chain. Since it's after '31', we start at node '31' in the next lowest level (level 1). '42' is after '31', but before '58', so we start at node '31' in the next lowest level (level 0). And then scanning forward we find '42' and return 'true' = yes, the query element is in the structure.

24.6 Skip List - Discussion

- How are elements inserted & erased? (Once the location is found) Just edit the chain at each level.
- But how do we determine what nodes go at each level? Upon insertion, generate a top level for that element at random (from [0,log n] where n is the # of elements currently in the list ... *details omitted!*)
- The overall hierarchy of a skip list is similar to a binary search tree. Both a skip list and a binary search tree work best when the data is balanced.

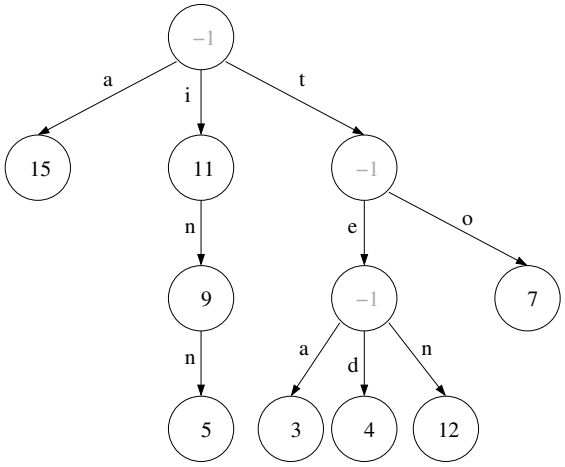
  Draw an (approximately) balanced binary search tree with the data above. How much total memory does the skip list use vs. the BST? Be sure to count all pointers – and don't forget the parent pointers!

- What is the height over a skip list storing n elements? What is the running time for `find`, `insert`, and `erase` in a skip list?

- Compared to BSTs, in practice, *balanced* skip lists are simpler to implement, faster (same order notation, but smaller coefficient), require less total memory, and work better in parallel. Or maybe they are similar...

24.7 Trie / Prefix Tree - Overview

- Next up, let's look at an alternate to a hash table for storing *key* strings and an associated *value* type.
- In a trie or prefix tree, the key is defined not by storing the data at the node or leaf, but instead by the path of to get to that node. Each *edge* from the root node stores one character of the string. The node stores the value for the key (or NULL or a special value, e.g., '-1', if the path to that point is not a valid key in the structure).



key	value
a	15
i	11
in	9
inn	5
tea	3
ted	4
ten	12
to	7

- Lookup in the structure is fast, O(m) where m is the length (# of characters) in the string. A hash table has similar lookup (since we have to hash the string which generally involves looking at every letter). If $m << n$, we can say this is O(1).

24.8 Trie / Prefix Tree - Discussion

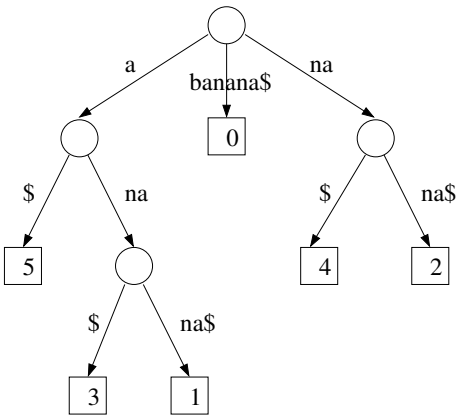
- What is the worst case # of children for a single node? What are the member variables for the `Node` class?

- Unlike a hash table, we can iterate over the keys in a trie / prefix tree in sorted order.
  Exercise: Implement the trie sorted-order iterator (in code or pseudocode) and print the table on the right.

24.9 Suffix Tree - A Brief Introduction...

- Instead of only encoding the complete string when walking from root to leaf... let's store every possibly substring of the input.
- This toy example stores 'banana', and all suffix substrings of 'banana'. Each leaf node stores the start position of the substring within the original string. The '$' character is a special terminal character.
- Suffix trees clearly require much more memory than other data structures to store the input string, but do so to gain performance on certain operations....

  Suffix trees help us efficiently find the longest common substring – *in linear time*. This is an important problem in genome sequencing and computational biology.
- Clever algorithms have been developed to efficiently construct suffix trees.



... and we're certainly out of time for today. There are many more wonderful data structures to explore. This semester you have learned the tools to study new structures, compare and contrast operation efficiency and memory usage of different structures, and to develop your own data structures for specific applications.