Recap – ADTs

We've considered major categories of ADTs for collections, characterized by the access they provide for their elements, and commons ADTs within those categories

- *containers* – based on position, not element value
  - Sequence/List – linear structure with access at any position
  - Stack – insert/remove at the same end (top)
  - Queue – insert/remove at opposite ends (front, back)
- *dictionary* – based on element's key (lookup)
  - Dictionary/Map – find(k), insert(k,v), remove(k)
  - OrderedDictionary – also max/min, successor(k), predecessor(k)
- *priority queue* – ordered, based on element's key
  - PriorityQueue – insert(x), findMin (or max), removeMin (or max)

Recap – Data Structures

We've seen some useful data structures – arrays, linked lists, binary trees, general trees.

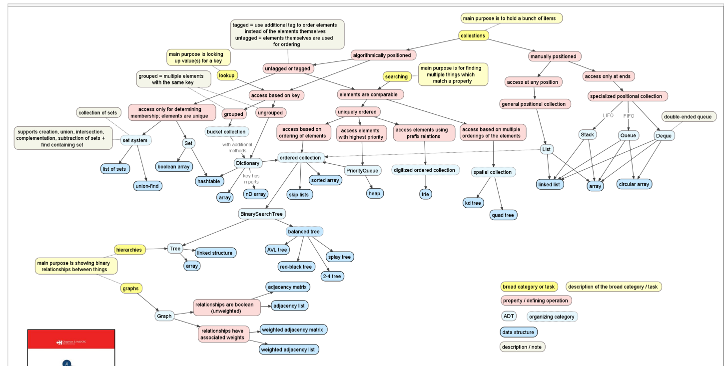
We've seen some clever ways to use and adapt basic data structures to achieve efficient implementations of ADTs.

- sorted array/linked list (vs. unsorted)
- circular arrays
- linked list with tail pointers
- array-based implementation of binary trees
- search trees (binary, multiway) – trees with ordering property for elements
- balanced search trees (AVL, 2-4) – search trees with structural property to maintain log n height
- hashtables – arrays with clever conversion of key to array index
- heaps – trees with ordering + structural properties

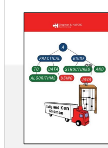
Specialized Data Structures

Be aware that there's more out there.

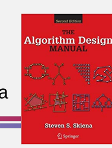
- other implementations
  - dictionaries: splay trees, red-black trees, b-trees, skip lists
  - priority queues: bounded height PQs, Fibonacci heaps, pairing heaps
- string data structures
  - e.g. suffix trees/arrays for pattern matching
  - e.g. prefix trees
- geometric data structures
  - e.g. BSP, kd-trees for fast searching in space
- graph data structures
- set data structures



(adapted from Goldman and Goldman, A Practical Guide to Data Structures and Algorithms Using Java)



A Practical Guide to Data Structures and Algorithms using Java, Goldman and Goldman



The Algorithm Design Manual, Skiena

Choosing Data Structures

"Building algorithms around data structures such as dictionaries and priority queues leads to both clean structure and good performance." [Skiena, ADM]

- first design the ADT – identify how your collection is accessed and what operations are needed
- then choose an implementation that delivers the necessary performance
- isolate the implementation of the data structure from the rest of the code
  - in Java, this means writing a class to implement the ADT with methods for the ADT operations

Choosing Implementations

Consider the characteristics of your task –

- dictionaries
  - how many items? is the size known in advance?
    - if small, simplicity of implementation is most important
    - if very large, running out of memory is an issue
  - what are the relative frequencies of insert, delete, find operations?
    - static (no modifications after construction) and semi-dynamic structures (insertion but no deletion) can be simpler than fully dynamic
  - is the access pattern for keys uniform and random?
    - in some data structures, non-uniform distributions lead to worst-case performance while others can take advantage of temporal locality
  - do individual operations need to be fast, or just minimize the total amount of work of the whole program?
    - focus on achieving good worst case performance vs amortized or expected performance

Implementation Choices for Dictionaries

- for small data sets, unsorted arrays are simple and have better cache performance than linked lists
- for moderate-to-large data sets, hashtables are likely best
- for very large data sets where there isn't enough room in memory, use B-trees
- *self-organizing lists* are often better than sorted or unsorted lists in practice
  - many applications have uneven access frequencies and locality of reference
- sorted arrays OK if not too many insertions or deletions
- the inability to use binary search makes sorted linked lists often not worth it
- for balanced search trees, the best choice is likely the one with the best implementation
- *skip lists* are easier than balanced search trees to implement and analyze

Implementation Choices for Dictionaries

- creating good hashtables
  - open addressing has better cache performance, but overall performance decreases quickly with higher load factors
  - with open addressing, *N* should be 30-50% larger than the maximum number of elements expected at once
    - *N* should be prime
  - use a good hash function + an efficient implementation

$$H(S) = \alpha^{|S|} + \sum_{i=0}^{|S|-1} \alpha^{|S|-(i+1)} \times char(s_i) \pmod{m}$$

    - gather stats on the distribution of keys to see how well the hash function performs

Choosing Implementations

Consider the characteristics of your task –

- priority queues
  - max size? is it known in advance?
    - preallocating the necessary space saves having to grow a container
  - are the key values limited?
  - what operations are needed?
    - if no insertion after construction, no need for PQ – just sort
    - other operations: searching for or removing arbitrary elements vs only the min/max
  - can priorities of elements already in the PQ be changed?
    - implies needing to retrieve elements by key, not just the min/max ones

Implementation Choices for Priority Queues

- sorted array or list when there aren't any insertions
  - very efficient for identifying and removing the smallest element
- binary heaps when the max number of elements is known
  - fixed array size can be mitigated with dynamic arrays
- *bounded-height priority queues* when there is a small, discrete range of keys
- BSTs when other dictionary operations are needed, or when there is an unbounded key range and the max PQ size isn't known in advance
- *Fibonacci and pairing heaps* improve the efficiency of decrease key operations
  - effective for large computations if implemented and used well

Designing Your Own Data Structures

- know what kinds of structures lead to what kinds of running times
  - can use that knowledge to guide/constrain thinking
  - O(n log n) or better is typically required in practice for large data sets
- strategies for rolling your own data structures
  - store more information for faster access – as long as it can be kept up-to-date efficiently
  - add additional properties to speed desired operations – as long as they can be maintained efficiently
- knowledge of complexity is useful
  - for NP-complete problems, look for heuristics rather than optimal solutions

Designing Data Structures

"...in practice, it is more important to avoid using a bad data structure than to identify the single best option available."

[Skiena, ADM]

- ask "do we need to do better?" before "can we do better?"

Design a data structure to efficiently support –

- insert(k) – insert element with key k
- findMin() – find element with smallest key
- removeMin() – remove element with smallest key
- decreaseKey(e,k) – decrease element e's key to k