Data Structures Toolbox

Key Points

- ADTs vs data structures
- common categories of ADTs
  - common container ADTs – characteristics, properties, operations, applications
- two main kinds of data structures
  - characteristics and tradeoffs
  - array and linked list operations
- basic implementations of containers
- strategies for improving implementations

ADTs vs Data Structures

- an *abstract data type* is defined by its operations (and concept)
  - the ADT is determined by the algorithm's needs
- *concrete data structures* are used to realize the implementation of an ADT
  - generally have choices, with different time/space tradeoffs
  - changing the data structure used to implement a given ADT does not change the correctness of the algorithm, but may have a big influence on time/space requirements
    - choice of implementation data structure goes hand-in-hand with the design of the algorithm

Fundamental ADTs

Common categories of ADTs –

- *containers* provide storage and retrieval of elements independent of value
  - ordering of elements depends on the structure of the container rather than the elements themselves
  - elements can be of any type
- *dictionaries* provide access to elements by value
  - lookup according to an element's key
  - elements can be of any type; the key type must support equality comparison
- *priority queues* provide access to elements in order by content
  - ordered by priority associated with elements
  - elements can be of any type; priority must be comparable (so there is an ordering)

ADTs – Common Containers

typical operations

Vector / List / Sequence	linear order, access by rank (index) or position	rank-based operations • add(x), add(r,x) – add x at the end / with rank r • get(r) – get element with rank r • remove(r) – remove (and return) elt with rank r • replace(r,x) – replace elt at rank r with x position-based operations • first, last() – get first/last position • before(p), after(p) – get position before/after p • addBefore(p,x), addAfter(p,x) – insert x after/before position p • get(p) – get element at position p • remove(p) – remove (and return) elt at pos p • replace(p,x) – replace elt at pos p with x bridge operations • atRank(r) – get pos at rank r • rankOf(p) – get rank of pos p
Stack	linear order, access only at one end • LIFO – insert and remove at the same end	• push(x) – insert x at the top of the stack • top() – return top item (without removal) • pop() – remove and return the top item on the stack
Queue variations • **Deque** – insert/remove at either end	linear order, access only at both ends • FIFO – insert at one end, remove from the other	• enqueue(x) – insert x at the back of the queue • peek() – return front item (without removal) • dequeue() – remove and return the front item in the queue

ADTs for Algorithm Design

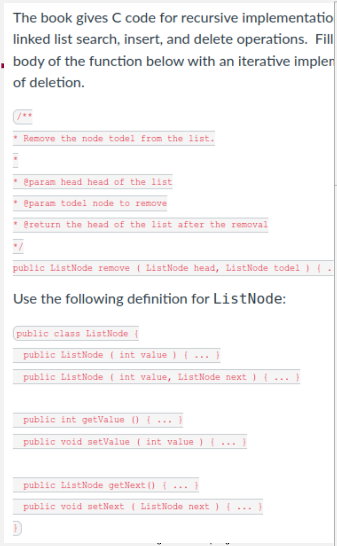
The kind of access to elements imposed by different types of containers can be exploited to achieve algorithmic goals.

ADT	some applications of the ADT
Vector / List / Sequence	general-purpose container round-robin scheduling, taking turns
Stack	match most recent thing, proper nesting, reversing DFS – go deep before backing up has ties to recursive procedures – supports iterative implementation of recursive ideas
Queue	FIFO order minimizes waiting time BFS – spread out in levels round-robin scheduling, taking turns

Data Structures

There are two main kinds of data structures –

- *contiguous structures* occupy consecutive memory locations
  - e.g. arrays
- *linked structures* consist of separate chunks of memory connected by references or pointers
  - e.g. linked lists, many trees, graphs



The book gives C code for recursive implementatio
linked list search, insert, and delete operations. Fill
body of the function below with an iterative implen
of deletion.

```
/**
* Remove the node todel from the list.
*
* @param head head of the list
* @param todel node to remove
* @return the head of the list after the removal
*/
public ListNode remove ( ListNode head, ListNode todel ) { .
```

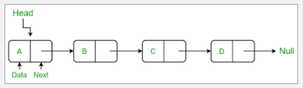
Use the following definition for `ListNode`:

```
public class ListNode {
  public ListNode ( int value ) { ... }
  public ListNode ( int value, ListNode next ) { ... }

  public int getValue () { ... }
  public void setValue ( int value ) { ... }

  public ListNode getNext() { ... }
  public void setNext ( ListNode next ) { ... }
}
```

linked list concepts
– singly-linked list



– insert/remove node involves re-linking rather than shifting or changing elements

common problems

– recursive rather than iterative (loop) solution

– doubly-linked nodes instead of singly-linked

– working with elements instead of nodes (moving elements instead of re-linking nodes, comparing elements rather than nodes)

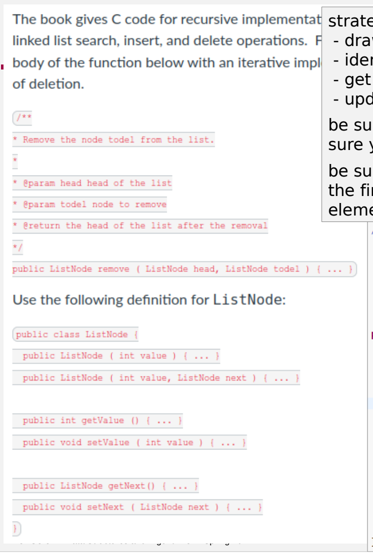
– missing or incorrectly handling special cases (potential special cases: empty list, one-node list, `todel` null, `todel` last, `todel` first, `todel` not actually in the list)

– mixing up `.equals` and `==`

– creating a new node object instead of only a new node variable

style considerations

– loop body shouldn't contain steps only done at the very beginning or the very end



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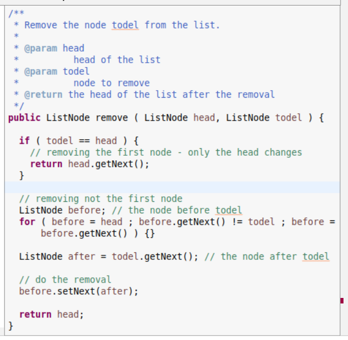
strategy – use examples!
- draw before and after pictures
- identify what changes
- get convenient references for those things
- update the values

be sure to consider several cases to make sure your solution works in general

be sure to consider special cases such as the first and last things, empty or one-element list, `null` values



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 * @param head
 *          head of the list
 * @param todel
 *          node to remove
 * @return the head of the list after the removal
 */
public ListNode remove ( ListNode head, ListNode todel ) {

  if ( todel == head ) {
    // removing the first node - only the head changes
    return head.getNext();
  }

  // removing not the first node
  ListNode before; // the node before todel
  for ( before = head ; before.getNext() != todel ; before =
      before.getNext() ) {}

  ListNode after = todel.getNext(); // the node after todel

  // do the removal
  before.setNext(after);

  return head;
}
```

Characteristics and Tradeoffs

arrays	linked structures
access – constant time given the index (efficient random access)	access – time depends on position relative to the beginning (inefficient random access)
space efficiency – no overhead (links, end-of-record markers) beyond the data elts themselves though to efficiently handle resizing, up to O(n) empty slots are allowed	overhead of at least one pointer per data value
memory locality – iterating through involves access to nearby memory blocks which can be efficiently loaded into a cache	no memory locality
fixed size – must resize or waste space dynamic arrays support resizing (when doubled in size) in O(1) amortized time and still O(n) space, but O(n) worst case insert and ~2x constant factors	no overflow, growing is O(1) when the insert position is known
insert, remove other than at the end requires shifting (O(n))	insert, remove at any position O(1), given a node pointer

Basic Implementation of Containers

How to use the data structure to realize the ADT operations?

- decide how container elements will be arranged in the data structure – use linear order of array or linked list to store the linear order of the container
- options: forward or reverse?
  - beginning of array / head of linked list can match beginning / top / front of container
  - end of array / head of linked list can match beginning / top / front of container

Vector / List / Sequence	classic array vs linked list tradeoffs • insert/remove not at the end requires shifting in the array (O(n)), but access by rank (index) is O(r) for linked list • dynamic array has overhead in time (resizing) and space (empty slots), linked list has overhead in space (pointers)
Stack	O(1) push, pop with array and linked list • top of stack = end of array, head of linked list choice of array vs linked list is largely determined by whether there is an upper bound on the size of the stack that is known in advance (static array) or not (dynamic array or linked list – time vs space overhead tradeoff)
Queue	O(1) enqueue or dequeue, O(n) for other with array, linked list

How Do We Apply This Stuff?

- ADTs
  - algorithm may boil down to just manipulating the right ADT, or become much simpler
  - once you have an algorithm, identify the operations it needs
  - find a standard ADT that provides those operations (and ideally little else) and choose an efficient implementation, or design a new implementation to efficiently support those operations
- data structures
  - to choose an efficient implementation for standard ADT
  - to design your own data structure or customize a standard implementation if a standard ADT/implementation doesn't meet your needs

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Can we do better?

- Vector/List/Sequence – tradeoff is due to the nature of the data structures (random access vs sequential access)
- Stack – can't beat O(1)
- Queue – …

Improving an Implementation – Queue

Consider the linked list implementation with the head of the queue at the beginning of the list.

- enqueue(x) is O(n) – inserting at the end of the list requires finding the last node
- dequeue() is O(1) – removing from head just involves updating pointers

enqueue is slow because we have to find the tail of the list.

Can we store a tail pointer instead?

- enqueue – O(1) to locate the node before the insertion point (current tail), O(1) to create new node and link to current tail, O(1) to update current tail to new node
- dequeue is not affected (unless the last element is removed – tail becomes `null`)

→ O(1) enqueue and dequeue using a linked list with a tail pointer

Improving an Implementation – Queue

Consider the array implementation with the head of the queue at the beginning of the array.

- enqueue(x) is O(1) – insert at the end of the array
- dequeue() is O(n) – removing from head of array requires shifting

Do we have to shift?

- we shift to keep the head of the queue at 0 and the tail position based on the size

Can we store the head and tail positions instead?

- O(1) to locate head/tail
- O(1) to update head/tail – new value is next position
  - "next position" at the end of the array wraps around to 0

→ O(1) enqueue and dequeue using a circular array

Doing Better

- if the slowness is because of having to find or compute something, can you store it instead?
  - must consider the cost of updating the stored info
  -
- if the slowness is the result of not storing something, can you store it instead?
  - must consider the cost of updating the additional info stored

Containers in Java

ADT	**in Java**
Vector / List / Sequence	`List` – interface `LinkedList` – linked list implementation `ArrayList` – array implementation `Vector` – legacy class and use is discouraged (array implementation) `Deque` (double-ended queue) – interface `ArrayDeque` – array implementation `LinkedList` – linked list implementation
Stack	`Stack` – legacy class, `Deque` preferred
Queue	`Queue` – interface `ArrayDeque` – array implementation `LinkedList` – linked list implementation

Collections Framework overview:
https://docs.oracle.com/en/java/javase/17/docs/api/java.base/java/util/doc-files/coll-overview.html