CSE 332

Data Abstractions

Welcome to CSE 332!

Outline

1. Administrivia

2. A Data Structures Problem

3. Review of Stacks & Queues

What Am I Getting Into?

Course Material

- "Classic" Data Structures/Algorithms
- Rigorously analyze efficiency
- When to use each type of data structure
- Sorting
- Dictionary ADT
- Parallelism and Concurrency
- ...

CSE 143 vs. CSE 332

- Client of Priority Queue vs. Implementor of Priority Queue
- Linked Lists vs. Graphs
- BST vs. Balanced BST
- Merge Sort vs. Advanced Sorting
- X vs. Parallelism

During the course, we will. . .

- Implement many different data structures
- Discuss trade-offs between them
- Rigorously analyze the algorithms that use them (math!)
- Be able to pick "the right one for the job"
- Experience the purposes and headaches of multithreading

After the course, you will be able to. . .

- make good design choices as a developer, project manager, or system customer
- justify and communicate your design decisions

This is the course where you stop thinking like a "Java Programmer" and start thinking like a Computer Scientist!

Support and Asking for Help

Resources

- Section every week!
- Lots of office hours!
- Piazza!

Asking for help is not a sign of weakness; it's a sign of strength.

Boring Administrivia

Course Website

`http://cs.uw.edu/332`

Grading

- 25% programming projects, 25% theory write-ups, 20% midterm, 30% final
- 3 "free late days"; -10% for subsequent days late; up to **2** days late on each hw

Textbook

Data Structures and Algorithm Analysis in Java (3rd edition) by Weiss

Do what helps you most.

Choose a **data structure** and **algorithms** to solve the following problem:

Prefix Sums

Input: An array `arr` of size n.
Methods:

- `arr.sum(i)` should return $\sum_{k=0}^{i}$ `arr[k]`
- `arr.update(i, value)` should update the value of the array at index i with `value`.

Then, analyze how good your solution is.

Naïve Implementation

Structure: The input array.
arr.sum(i): Loop from 0 to i adding up the elements.
arr.update(i, value): Update index i with `value`.

How good is it? `sum` is $\mathcal{O}(n)$; `update` is $\mathcal{O}(1)$.

Suppose we know `update` is going to happen very rarely but `sum` will happen a lot. Can we do better?

Prefix Sums

Input: An array `arr` of size n.

Methods:

- `arr.sum(i)` should return $\sum_{k=0}^{i}$ `arr[k]`
- `arr.update(i, value)` should update the value of the array at index i with `value`.

Then, analyze how good your solution is.

Another Try (?)

Structure: An array, `partials` of partial sums (e.g. `[3, 1, 9]` $\rightarrow$ `[3, 4, 13]`) .

arr.sum(i): Return `partials[i]`.

arr.update(i, value): Update every index from i to the end by adding the difference between old and new.

How good is it? `sum` is $\mathcal{O}(1)$; `update` is $\mathcal{O}(n)$.

Which is better?

First Solution

- `sum` is $\mathcal{O}(n)$
- `update` is $\mathcal{O}(1)$

Second Solution

- `sum` is $\mathcal{O}(1)$
- `update` is $\mathcal{O}(n)$

This is a design trade-off!

The answer is sometimes the left and sometimes the right.

The left is better when...

- `sum` is rare; `update` is frequent
- We aren't allowed to change the data structure (or we're not allowed extra space).

The right is better when...

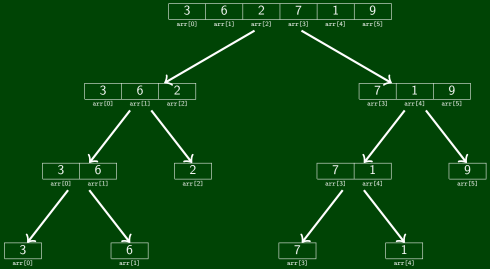
- `sum` is frequent; `update` is rare
- We're more concerned with the time complexity of `sum` than our space efficiency

EVEN BETTER

Consider the following input array:

arr:	arr[0]	arr[1]	arr[2]	arr[3]	arr[4]	arr[5]
	3	6	2	7	1	9

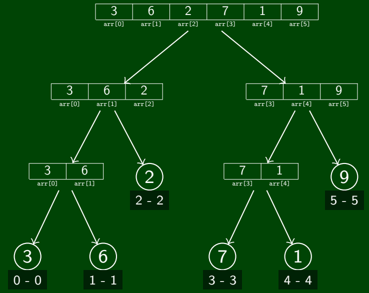
Let's get fancy now. Consider the following split of the array:



Consider the following input array:

arr:	3	6	2	7	1	9
	arr[0]	arr[1]	arr[2]	arr[3]	arr[4]	arr[5]

Let's build up a tree that stores **partial sums** in each node. Start at the leaves:

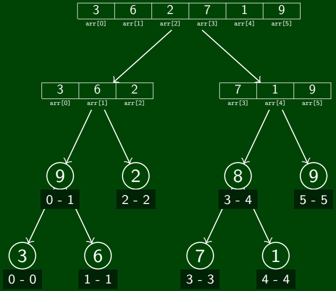


Consider the following input array:

arr:

3	6	2	7	1	9
arr[0]	arr[1]	arr[2]	arr[3]	arr[4]	arr[5]

Let's build up a tree that stores **partial sums** in each node. Now go one level up:

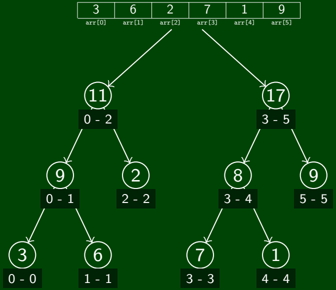


Consider the following input array:

arr:

arr[0]	arr[1]	arr[2]	arr[3]	arr[4]	arr[5]
3	6	2	7	1	9

Let's build up a tree that stores **partial sums** in each node. And another. . .

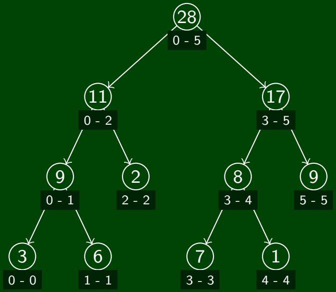


EVEN BETTER

Consider the following input array:

	arr[0]	arr[1]	arr[2]	arr[3]	arr[4]	arr[5]
arr:	3	6	2	7	1	9

And finally, we get:



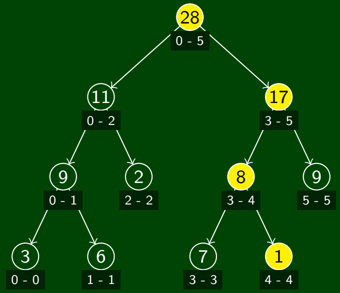
Let's use THIS as our data structure.

(For reference, this data structure is called a **Segment Tree**.)

EVEN BETTER

Consider the following input array:

arr:	3	6	2	7	1	9
	`arr[0]`	`arr[1]`	`arr[2]`	`arr[3]`	`arr[4]`	`arr[5]`



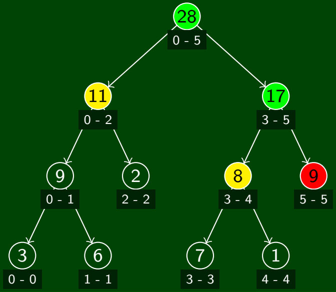
How Do We Write `update`?

Walk up the tree from the leaf node that represents the index we're updating. Change each node accordingly.

What is the complexity of `update`?

It's $\mathcal{O}(\log n)$, because the tree is balanced.

EVEN BETTER



How Do We Write `sum(i)`?

```
sum(i) = sum(i, root);
sum(i, node) {
   if (node.range is completely outside (0, i)) {
      return 0;
   }
   else if ((0, i) is contained in node.range) {
      return sum(i, node.left) + sum(i, node.right);
   }
   else {
      return node.value;
   }
}
```

See above for sum(4).

This is $\mathcal{O}(\log n)$, btw.

Putting It All Together

While trying to solve this problem, we did the following things:

- Considered an algorithmic problem and attempted to solve it
- Chose data structures and algorithms to solve the problem (duh. . .)
- Analyzed code for runtime
- Considered trade-offs between different implementations
- Learned a new data structure which helped us solve the problem **much better than before**
- Ran into analyzing a recursive runtime

One thing we didn't consider (but that we will later!) was how to solve the problem **if we had multiple processors**.

This course is about learning fundamental data structures and algorithms to help you solve Computer Science problems.

Excited yet? Okay. . . what if I told you this is an interview question?

Definition (Abstract Data Type [ADT])

An **Abstract Data Type** is a **mathematical model** of the properties necessary for a data structure to be a particular data type. To put it another way, an ADT specifies what a data type **is** and the valid **operations** on it.

Definition (Data Structure)

A **Data Structure** is a particular implementation of an ADT.

ADT	Data Structure	Implementation
`Stack`	`ArrayList`	`java.util.Stack`
`Stack`	`LinkedList`	–
`Queue`	`LinkedList`	`java.util.LinkedList`

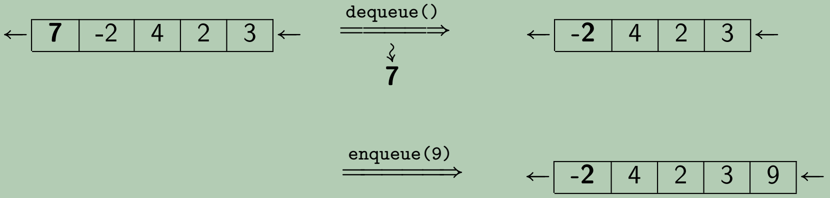
Queue ADT

`enqueue(`**val**`)`	Adds **val** to the queue.
`dequeue()`	Returns the **least-recent** item not already returned by a `dequeue`. (Errors if empty.)
`peek()`	Returns the **least-recent** item not already returned by a `dequeue`. (Errors if empty.)
`isEmpty()`	Returns true if all inserted elements have been returned by a `dequeue`.

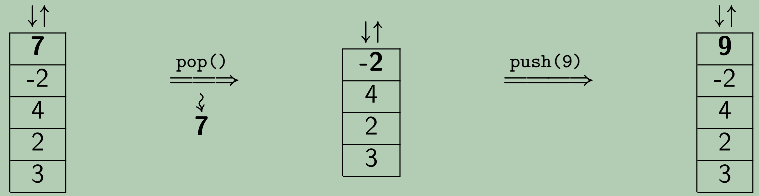
Stack ADT

`push(`**val**`)`	Adds **val** to the stack.
`pop()`	Returns the **most-recent** item not already returned by a `pop`. (Errors if empty.)
`peek()`	Returns the **most-recent** item not already returned by a `pop`. (Errors if empty.)
`isEmpty()`	Returns true if all inserted elements have been returned by a `pop`.

Queue Examples



Stack Examples



ADTs are used to COMMUNICATE ideas more easily!

Parentheses Matching

Given a string of parentheses (i.e. `(`, `)`, `[`, `]`), figure out if the parentheses are matched.

WORST: A particular implementation in a particular language using the wrong ADT

```
for (int i = 0; i < str.length(); i++) {
   if (str.charAt(i) == '(' || str.charAt(i) == '[') {
      list.add(str.charAt(i));
   }
   else if ((str.charAt(i) == ')' && list.get(list.length() - 1) == '(') ||
            (str.charAt(i) == ']' && list.get(list.length() - 1) == '[')) {
      list.remove(list.length() - 1);
   }
   else {
      throw new Exception();
   }
}
```

ADTs are used to COMMUNICATE ideas more easily!

Parentheses Matching

Given a string of parentheses (i.e. `(`, `)`, `[`, `]`), figure out if the parentheses are matched.

REALLY BAD: A particular implementation, in a particular language

```
for (int i = 0; i < str.length(); i++) {
   if (str.charAt(i) == '(' || str.charAt(i) == '[') {
      stack.push(str.charAt(i));
   }
   else if ((str.charAt(i) == ')' && stack.peek() == '(') ||
            (str.charAt(i) == ']' && stack.peek() == '[')) {
      stack.pop();
   }
   else {
      throw new Exception();
   }
}
```

ADTs are used to COMMUNICATE ideas more easily!

Parentheses Matching

Given a string of parentheses (i.e. `(`, `)`, `[`, `]`), figure out if the parentheses are matched.

BETTER: Pseudo-code using the right ADT

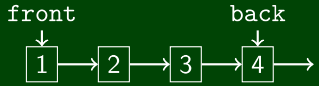
```
for (index in str) {
   if (str[index] is open) {
      put it on the stack
   }
   else if (str[index] is top of stack and it matches the top element) {
      pop the top element off the stack
   }
   else {
      throw error
   }
}
```

BEST: High-level description using the right ADT

To match parentheses, loop through the string pushing open parens onto the stack. When we see a close paren, make sure it matches and pop it off.

We can implement the **Queue** **ADT** using multiple ideas:

- **Linked List Queue Data Structure**

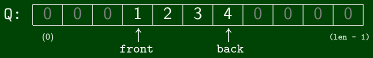


  - Empty queue?
  - Time complexities?

Data Structure

```
enqueue(x) {
   back.next = new Node(x);
   back = back.next;
}
dequeue() {
   x = front.item;
   front = front.next;
   return x;
}
```

- **Circular Array Queue Data Structure**



  - Empty queue?
  - Time complexities?

Data Structure

```
enqueue(x) {
   Q[back] = x;
   back = (back + 1) % size;
}
dequeue() {
   x = Q[front];
   front = (front + 1) % size;
   return x;
}
```

Trade-Offs?

	`LinkedList` Queue	`CircularArray` Queue
Space (in queue)?	No wasted space	Extra (or too little?)
Space (per element)?	Larger	Smaller
Operation Times?	Fast	Fast
Other Concerns?	Never runs out of space	**Can** run out of space

Question: Why would we ever use a circular array queue?

Answer:
In practice, creating new Nodes **can fail**! Memory allocation can be expensive.

Today's Takeaways!

- Hopefully you're excited!
- What is an ADT? What is a Data Structure?
- Understand Stack and Queue ADTs
- Understand Queue implementations