Today

• Finish up Binary Heaps  
• Analyzing Recursive Code  
• Solving Recurrences
Analyzing code (“worst case”)

Basic operations take “some amount of” constant time
  – Arithmetic
  – Assignment
  – Access one Java field or array index
  – Etc.

(This is an approximation of reality: a very useful “lie”.)

Consecutive statements
  Sum of time of each statement
Loops
  Num iterations * time for loop body
Conditionals
  Time of condition plus time of slower branch
Function Calls
  Time of function’s body
Recursion
  Solve recurrence equation
**Linear search**

| 2 | 3 | 5 | 16 | 37 | 50 | 73 | 75 | 126 |

Find an integer in a *sorted* array

// requires array is sorted
// returns whether k is in array
boolean find(int[] arr, int k) {
    for (int i = 0; i < arr.length; ++i)
        if (arr[i] == k)
            return true;
    return false;
}

Best case: 6 “ish” steps = $O(1)$
Worst case: 5 “ish” * (arr.length) = $O(arr.length)$
Analyzing Recursive Code

- Computing run-times gets interesting with recursion
- Say we want to perform some computation recursively on a list of size n
  - Conceptually, in each recursive call we:
    - Perform some amount of work, call it \( w(n) \)
    - Call the function recursively with a smaller portion of the list

- So, if we do \( w(n) \) work per step, and reduce the problem size in the next recursive call by 1, we do total work:
  \[
  T(n) = w(n) + T(n-1)
  \]
- With some base case, like \( T(1) = 5 = O(1) \)
Example Recursive code: sum array

Recursive:
- Recurrence is some constant amount of work $O(1)$ done $n$ times

```java
int sum(int[] arr){
    return help(arr, 0);
}
int help(int[] arr, int i) {
    if(i==arr.length)
        return 0;
    return arr[i] + help(arr, i+1);
}
```

Each time `help` is called, it does that $O(1)$ amount of work, and then calls `help` again on a problem one less than previous problem size.

Recurrence Relation: $T(n) = O(1) + T(n-1)$
Solving Recurrence Relations

• Say we have the following recurrence relation:
  \[ T(n) = 6 \text{ “ish”} + T(n-1) \]
  \[ T(1) = 9 \text{ “ish”} \leftarrow \text{base case} \]

• Now we just need to solve it; that is, reduce it to a closed form.

• Start by writing it out:
  \[ T(n) = 6 + T(n-1) \]
  \[ = 6 + 6 + T(n-2) \]
  \[ = 6 + 6 + 6 + T(n-3) \]
  \[ = 6 + 6 + 6 + \ldots + T(1) = 6 + 6 + 6 + \ldots + 6 + 9 \]
  \[ = 6k + T(n-k) \]
  \[ = 6k + 9, \text{ where } k \text{ is the # of times we expanded } T() \]

• We expanded it out \( n-1 \) times, so
  \[ T(n) = 6k + T(n-k) \]
  \[ = 6(n-1) + T(1) = 6(n-1) + 9 \]
  \[ = 6n + 3 = O(n) \]

Or When does \( n-k=1? \)
Answer: when \( k=n-1 \)
**Binary search**

Find an integer in a *sorted* array

– Can also be done non-recursively but “doesn’t matter” here

```java
// requires array is sorted
// returns whether k is in array
boolean find(int[] arr, int k) {
    return help(arr, k, 0, arr.length);
}

boolean help(int[] arr, int k, int lo, int hi) {
    int mid = (hi+lo)/2; // i.e., lo+(hi-lo)/2
    if(lo==hi) return false;
    if(arr[mid]==k) return true;
    if(arr[mid]< k) return help(arr, k, mid+1, hi);
    else return help(arr, k, lo, mid);
}
```
Binary search

Best case: 9 “ish” steps = $O(1)$
Worst case: $T(n) = 10$ “ish” + $T(n/2)$ where $n$ is $hi-lo$

- $O(\log n)$ where $n$ is array.length
- Solve recurrence equation to know that...

```java
// requires array is sorted
// returns whether k is in array
boolean find(int[] arr, int k) {
    return help(arr, k, 0, arr.length);
}

boolean help(int[] arr, int k, int lo, int hi) {
    int mid = (hi + lo) / 2;
    if (lo == hi) return false;
    if (arr[mid] == k) return true;
    if (arr[mid] < k) return help(arr, k, mid + 1, hi);
    else return help(arr, k, lo, mid);
}
```
Solving Recurrence Relations

1. Determine the recurrence relation. What is the base case?
   - \( T(n) = 10 + T(n/2) \quad T(1) = 15 \)

2. “Expand” the original relation to find an equivalent general expression *in terms of the number of expansions*.

3. Find a closed-form expression by setting *the number of expansions* to a value which reduces the problem to a base case.
Solving Recurrence Relations

1. Determine the recurrence relation. What is the base case?
   - \( T(n) = 10 + T(n/2) \) \( T(1) = 15 \)

2. “Expand” the original relation to find an equivalent general expression \textit{in terms of the number of expansions}.
   - \( T(n) = 10 + 10 + T(n/4) \)
     - \( = 10 + 10 + 10 + T(n/8) \)
     - \( = \ldots \)
     - \( = 10k + T(n/(2^k)) \) (where \( k \) is the number of expansions)

3. Find a closed-form expression by setting \textit{the number of expansions} to a value which reduces the problem to a base case
   - \( n/(2^k) = 1 \) means \( n = 2^k \) means \( k = \log_2 n \)
   - So \( T(n) = 10 \log_2 n + 15 \) (get to base case and do it)
   - So \( T(n) \) is \( O(\log n) \)
sum array again

Two “obviously” linear algorithms: $T(n) = O(1) + T(n-1)$

Iterative:

```java
int sum(int[] arr) {
    int ans = 0;
    for (int i=0; i<arr.length; ++i) {
        ans += arr[i];
    }
    return ans;
}
```

Recursive:

```java
int sum(int[] arr) {
    return help(arr,0);
}
int help(int[] arr, int i) {
    if (i==arr.length) {
        return 0;
    }
    return arr[i] + help(arr, i+1);
}
```

Recursive:
- Recurrence is $c + c + \ldots + c$ for $n$ times
What about a **binary** version of sum?

```c
int sum(int[] arr)
{
    return help(arr,0,arr.length);
}
int help(int[] arr, int lo, int hi) {
    if(lo==hi)    return 0;
    if(lo==hi-1)  return arr[lo];
    int mid = (hi+lo)/2;
    return help(arr,lo,mid) + help(arr,mid,hi);
}
```
What about a **binary** version of sum?

```java
int sum(int[] arr){
    return help(arr,0,arr.length);
}
int help(int[] arr, int lo, int hi) {
    if(lo==hi)   return 0;
    if(lo==hi-1) return arr[lo];
    int mid = (hi+lo)/2;
    return help(arr,lo,mid) + help(arr,mid,hi);
}
```

Recurrence is $T(n) = O(1) + 2T(n/2)$
- $1 + 2 + 4 + 8 + \ldots$ for $\log n$ times
- $2^{(\log n)} - 1$ which is proportional to $n$ (by definition of logarithm)

Easier explanation: it adds each number once while doing little else

“Obvious”: You can’t do better than $O(n)$ – have to read whole array
Parallelism teaser

• But suppose we could do two recursive calls at the same time
  – Like having a friend do half the work for you!

```java
int sum(int[] arr){
    return help(arr,0,arr.length);
}
int help(int[] arr, int lo, int hi) {
    if(lo==hi) return 0;
    if(lo==hi-1) return arr[lo];
    int mid = (hi+lo)/2;
    return help(arr,lo,mid) + help(arr,mid,hi);
}
```

• If you have as many “friends of friends” as needed, the recurrence is now $T(n) = O(1) + 1 T(n/2)$
  – $O(\log n)$ : same recurrence as for find
Really common recurrences

Should know how to solve recurrences but also recognize some really common ones:

\[ T(n) = O(1) + T(n/2) \quad \text{logarithmic} \]
\[ T(n) = O(1) + 2T(n/2) \quad \text{linear} \]
\[ T(n) = O(1) + T(n-1) \quad \text{linear} \]
\[ T(n) = O(n) + T(n-1) \quad \text{quadratic} \]
\[ T(n) = O(1) + 2T(n-1) \quad \text{exponential} \]
\[ T(n) = O(n) + T(n/2) \quad \text{linear} \]
\[ T(n) = O(n) + 2T(n/2) \quad O(n \log n) \]

Note big-Oh can also use more than one variable

- Example: can sum all elements of an \( n \)-by-\( m \) matrix in \( O(nm) \)