Recitation 11

Analysis of Algorithms and Inductive Proofs

Review: Big O definition

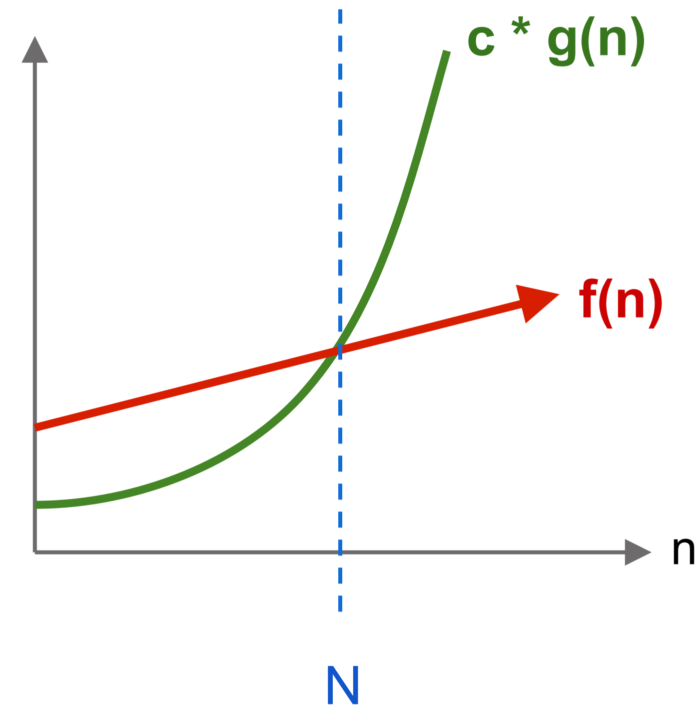
f(n) is O(g(n))

iff

There exists c > 0 and N > 0

such that:

f(n) ≤ **c * g(n)** for n ≥ N



Example: n+6 is O(n)

n + 6 ---this is f(n)
<= <if 6 <= n, write as>
n + n
= <arith>
2*n
<choose c = 2>
= c*n ---this is c * g(n)

So choose c = 2 and N = 6

f(n) is O(g(n)): There exist $c > 0$, $N > 0$ such that:

$f(n) \leq c * g(n)$ for $n \geq N$

Review: Big O

Is used to classify algorithms by how they respond to changes in input size n.

Important vocabulary:

- Constant time: O(1)
- Logarithmic time: O(log n)
- Linear time: O(n)
- Quadratic time: $O(n^2)$
- Exponential time: $O(2^n)$

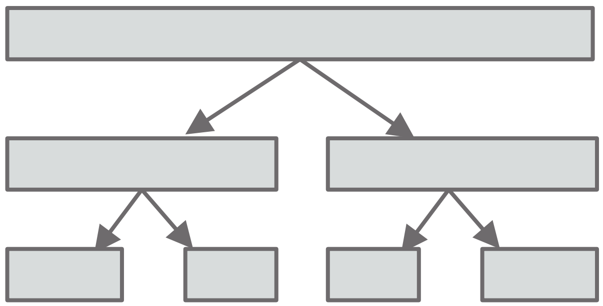
Review: Big O

1. $\log(n) + 20$	is	$O(\log(n))$	(logarithmic)
2. $n + \log(n)$	is	$O(n)$	(linear)
3. $n/2$ and $3*n$	are	$O(n)$	
4. $n * \log(n) + n$	is	$n * \log(n)$	
5. $n^2 + 2*n + 6$	is	$O(n^2)$	(quadratic)
6. $n^3 + n^2$	is	$O(n^3)$	(cubic)
7. $2^n + n5$	is	$O(2^n)$	(exponential)

Merge Sort

Runtime of merge sort

```
/** Sort b[h..k]. */
public static void mS(Comparable[] b, int h, int k) {
      if (h >= k) return;
      int e= (h+k)/2;
      mS(b, h, e);
      mS(b, e+1, k);
      merge(b, h, e, k);
}
```



mS is **mergeSort** for readability

Runtime of merge sort

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/** Sort b[h..k]. */
public static void mS(Comparable[] b, int h, int k) {
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      mS(b, h, e);
      mS(b, e+1, k);
      merge(b, h, e, k);
}
```

mS is **mergeSort** for readability

- We will *count* the number of comparisons mS makes
- Use **T(n)** for the number of array element comparisons that mS makes on an array segment of size *n*

Runtime of merge sort

```
/** Sort b[h..k]. */
public static void mS(Comparable[] b, int h, int k) {
      if (h >= k) return;
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      mS(b, h, e);
      mS(b, e+1, k);
      merge(b, h, e, k);
}
```

T(0) = 0
T(1) = 0

Use **T(n)** for the number of array element comparisons that mergeSort makes on an array of size *n*

Runtime of merge sort

```
/** Sort b[h..k]. */
public static void mS(Comparable[] b, int h, int k) {
      if (h >= k) return;
      int e= (h+k)/2;
      mS(b, h, e);         T(e+1-h) comparisons = T(n/2)
      mS(b, e+1, k);       T(k-e)   comparisons = T(n/2)
      merge(b, h, e, k);            How long does merge
take?
}
```

Runtime of merge

pseudocode for merge

```
/** Pre: b[h..e] and b[e+1..k] are already sorted */
merge(Comparable[] b, int h, int e, int k)
    Copy both segments
    While both copies are non-empty
        Compare the first element of each segment
        Set the next element of b to the smaller value
        Remove the smaller element from its segment
```

One comparison, one add, one remove

k-h loops must empty one segment

Runtime is O(k-h)

Runtime of merge sort

```
/** Sort b[h..k]. */
public static void mS(Comparable[] b, int h, int k) {
      if (h >= k) return;
      int e= (h+k)/2;
      mS(b, h, e);        T(e+1-h) comparisons = T(n/2)
      mS(b, e+1, k);      T(k-e)   comparisons = T(n/2)
      merge(b, h, e, k);       O(k-h)   comparisons =
O(n)
}
```

Recursive Case:

T(n) = 2T(n/2) + O(n)

Runtime

We determined that

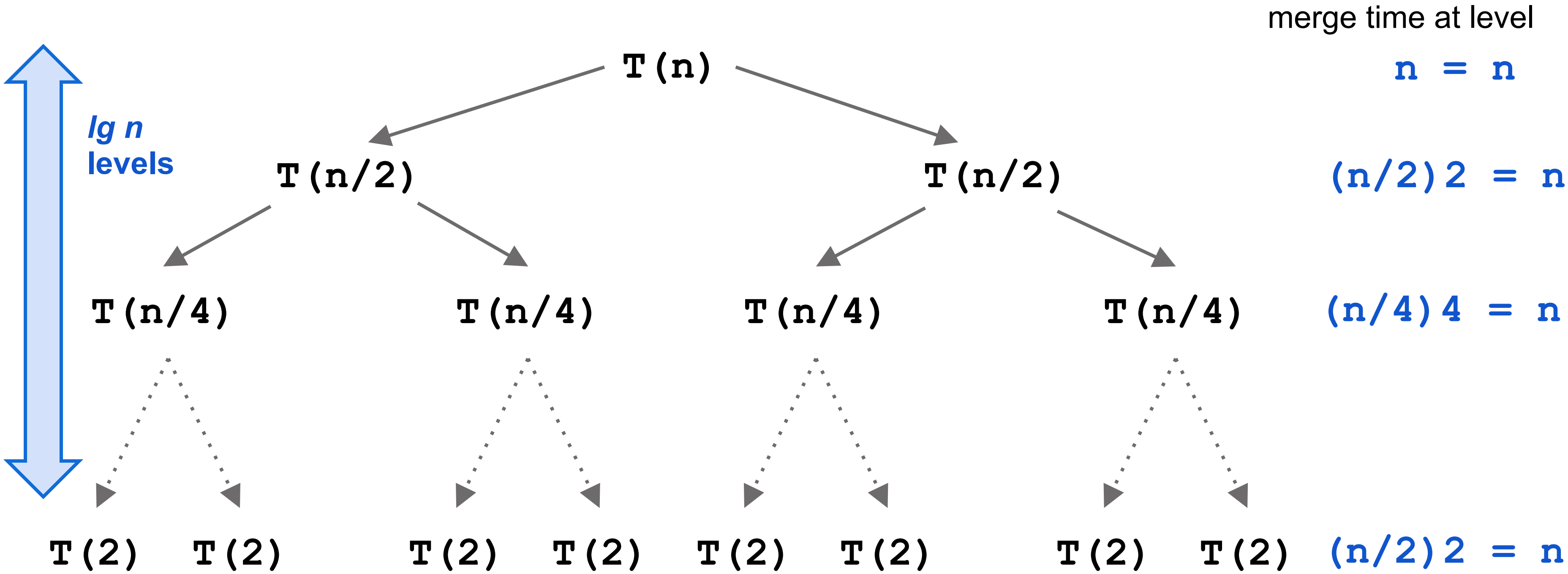
$T(1) = 0$

$T(n) = 2T(n/2) + n$ for $n > 1$

We will prove that

$T(n) = n \log_2 n$ (or $n \lg n$ for short)

Recursion tree



lg n levels * n comparisons is O(n log n)

Proof by induction

To prove **T(n) = n lg n**,
we can assume true for smaller values of **n** (like recursion)

T(n) = 2T(n/2) + n
= 2(n/2)lg(n/2) + n
= n(lg n - lg 2) + n ← Property of logarithms
= n(lg n - 1) + n ← $\log_2 2 = 1$
= n lg n - n + n
= n lg n

Heap Sort

Heap Sort

Very simple idea:

1. Turn the array into a max-heap
2. Pull each element out

```
/** Sort b */
public static void heapSort(Comparable[] b) {
    heapify(b);
    for (int i= b.length-1; i >= 0; i--) {
        b[i]= poll(b, i);
    }
}
```

Heap Sort

```
/** Sort b */
public static void heapSort(Comparable[] b) {
    heapify(b);
    for (int i= b.length-1; i >= 0; i--) {
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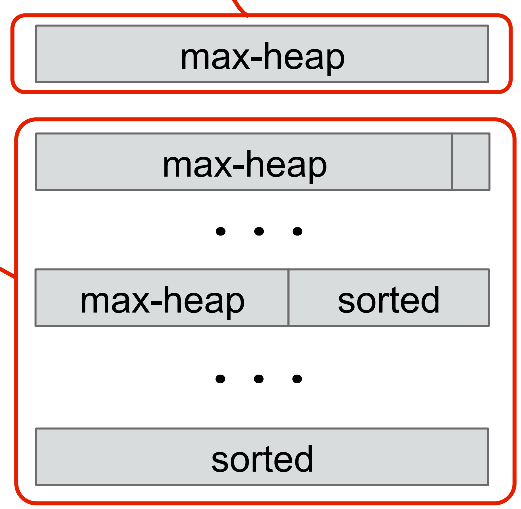

Why does it have to be a max-heap?

Heap Sort runtime

```
/** Sort b */
public static void heapSort(Comparable[] b) {
    heapify(b);                                     O(n lg n)
    for (int i= b.length-1; i >= 0; i--) {
        b[i]= poll(b, i);
    }                                               loops n times
}                    O(lg n)
```

Total runtime:

O(n lg n) + n*O(lg n) = O(n lg n)