

Reflections on Proj 3

Project 3:

- Interesting watch about why MIT stopped teaching the old school “pure” programming class (similar to your experience in 61A filling in functions) vs. the kludgier tool-heavy projects of 61B:
<http://www.posteriorscience.net/?p=206>
- “Sussman said that in the 80s and 90s, engineers built complex systems by combining simple and well-understood parts. The goal of SICP was to provide the abstraction language for reasoning about such systems.”
- “Today, this is no longer the case. Sussman pointed out that engineers now routinely write code for complicated hardware that they don’t fully understand (and often can’t understand because of trade secrecy.)”
- “Programming today is “More like science. You grab this piece of library and you poke at it. You write programs that poke it and see what it does. And you say, ‘Can I tweak it to do the thing I want?’”

Announcements

Project 3 due Wednesday.

- 24 hour grace period for the first 24 hours.
- 5/12ths percent per hour after that.

HW5 released Wednesday: Seam Carving

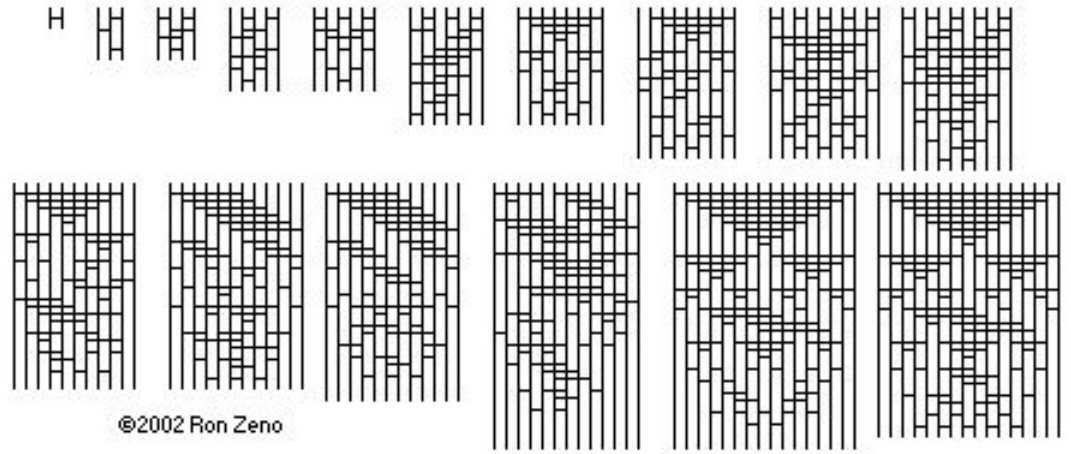
- Roughly the size of Percolation (HW2).
- Due next Wednesday.

Today's lecture a little less dense than usual given proj3 due date.

CS61B

Lecture 35: Sorting IV

- Sorting Summary
- Math Problems out of Nowhere
- Theoretical Bounds on Sorting



Sorting

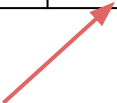
Sorting is a foundational problem.

- Obviously useful for putting things in order.
- But can also be used to solve other tasks, sometimes in non-trivial ways.
 - Sorting improves duplicate finding from a naive N^2 to $N \log N$.
 - Sorting improves 3SUM from a naive N^3 to N^2 .
- There are many ways to sort an array, each with its own interesting tradeoffs and algorithmic features.

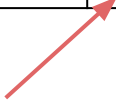
Today we'll discuss the fundamental nature of the sorting problem itself: How hard is it to sort?

Sorts Summary

	Memory	# Compares	Notes	Stable?
Heapsort	$\Theta(1)$	$\Theta(N \log N)$	Bad caching (61C)	No
Insertion	$\Theta(1)$	$\Theta(N^2)$	Best for almost sorted and $N < 15$	Yes
Mergesort	$\Theta(N)$	$\Theta(N \log N)$	Fastest stable sort	Yes
Quicksort LTHS	$\Theta(\log N)$	$\Theta(N \log N)$ expected	Fastest sort	No



This is due to the cost of tracking recursive calls by the computer, and is also an “expected” amount. The difference between $\log N$ and constant memory is trivial.



You can create a stable Quicksort. However, using unstable partitioning schemes (like Hoare partitioning) and using randomness to avoid bad pivots tend to yield better runtimes.

Math Problems out of Nowhere

A Math Problem out of Nowhere

Consider the functions $N!$ and $(N/2)^{N/2}$

Is $N! \in \Omega((N/2)^{N/2})$? Prove your answer.

- Recall that $\in \Omega$ can be informally be interpreted to mean \geq

A Math Problem out of Nowhere

Consider the functions $N!$ and $(N/2)^{N/2}$

Is $N! \in \Omega((N/2)^{N/2})$? Prove your answer.

$10!$

- $10 * 9 * 8 * 7 * 6 * \dots * 1$

5^5

- $5 * 5 * 5 * 5 * 5$

$N! > (N/2)^{N/2}$, for large N , therefore $N! \in \Omega((N/2)^{N/2})$

Another Math Problem

Given: $N! > (N/2)^{N/2}$, which we used to prove our answer to the previous problem.

Show that $\log(N!) \in \Omega(N \log N)$.

- Recall: \log means an unspecified base.

Another Math Problem

Given that $N! > (N/2)^{N/2}$

Show that $\log(N!) \in \Omega(N \log N)$.

We have that $N! > (N/2)^{N/2}$

- Taking the log of both sides, we have that $\log(N!) > \log((N/2)^{N/2})$.
- Bringing down the exponent we have that $\log(N!) > N/2 \log(N/2)$.
- Discarding the unnecessary constant, we have $\log(N!) \in \Omega(N \log (N/2))$.
- From there, we have that $\log(N!) \in \Omega(N \log N)$.

Since $\log(N/2)$ is the same thing asymptotically as $\log(N)$.

In other words, $\log(N!)$ grows at least as quickly as $N \log N$.

Last Math Problem

In the previous problem, we showed that $\log(N!) \in \Omega(N \log N)$.

Now show that $N \log N \in \Omega(\log(N!))$.

Last Math Problem

Show that $N \log N \in \Omega(\log(N!))$

Proof:

- $\log(N!) = \log(N) + \log(N-1) + \log(N-2) + \dots + \log(1)$
- $N \log N = \log(N) + \log(N) + \log(N) + \dots \log(N)$
- Therefore $N \log N \in \Omega(\log(N!))$

Omega and Theta: yellkey.com/quickly

Given:

- $N \log N \in \Omega(\log(N!))$
- $\log(N!) \in \Omega(N \log N)$

Which of the following can we say?

- A. $N \log N \in \Theta(\log N!)$
- B. $\log N! \in \Theta(N \log N)$
- C. Both A and B
- D. Neither

Omega and Theta

Given:

- $N \log N \in \Omega(\log(N!))$

Informally: $N \log N \geq \log(N!)$

- $\log(N!) \in \Omega(N \log N)$

Informally: $\log(N!) \geq N \log N$

Which of the following can we say?

A. $N \log N \in \Theta(\log N!)$

B. $\log N! \in \Theta(N \log N)$

Informally: $N \log N = \log(N!)$

C. **Both A and B**

D. Neither

Summary

We've shown that $\log(N!) \in \Theta(N \log N)$.

- In other words, these two functions grow at the same rate asymptotically.

As for why we did this, we will see in a little while...

Theoretical Bounds on Sorting

Sorting

We have shown several sorts to require $\Theta(N \log N)$ worst case time.

- Can we build a better sorting algorithm?

By comparison sort, I mean that it uses e.g. the `compareTo` method in Java to make decisions.

Let the ultimate comparison sort (TUCS) be the asymptotically fastest possible comparison sorting algorithm, possibly yet to be discovered, and let $R(N)$ be its worst case runtime.

Give the best Ω and O bounds you can for $R(N)$.

It might seem strange to give Ω and O bounds for an algorithm whose details are completely unknown, but you can, I promise!

Sorting

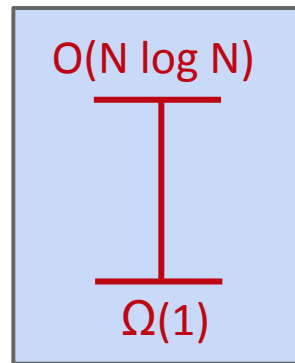
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- Can we build a better sorting algorithm?

By comparison sort, I mean that it uses e.g. the `compareTo` method in Java to make decisions.

Let the ultimate comparison sort (TUCS) be the asymptotically fastest possible comparison sorting algorithm, possibly yet to be discovered, and let $R(N)$ be its worst case runtime.

- Worst case run-time of TUCS, $R(N)$ is $O(N \log N)$.
 - Obvious: Mergesort is $\Theta(N \log N)$ so $R(N)$ can't be worse!
- Worst case run-time of TUCS, $R(N)$ is $\Omega(1)$.
 - Obvious: Problem doesn't get easier with N .
 - Can we make a stronger statement than $\Omega(1)$?

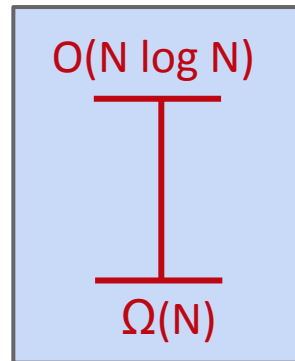


TUCS Worst
Case Θ Runtime

Sorting

Let TUCS be the asymptotically fastest possible comparison sorting algorithm, possibly yet to be discovered.

- Worst case run-time of TUCS, $R(N)$ is $O(N \log N)$. Why?
- Worst case run-time of TUCS, $R(N)$ is also $\Omega(N)$.
 - Have to at least look at every item.

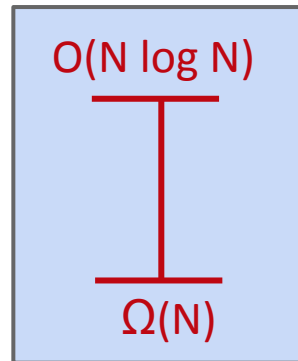


TUCS Worst
Case Θ Runtime

Sorting

We know that TUCS “lives” between N and $N \log N$.

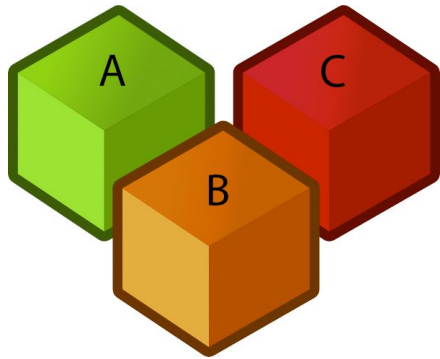
- Worst case asymptotic runtime of TUCS is between $\Theta(N)$ and $\Theta(N \log N)$.
- Can we make an even stronger statement on the lower bound?
 - With a clever argument, yes (as we’ll see soon see).
 - Spoiler alert: It will turn out to be $\Omega(N \log N)$
 - This lower bound means that across the infinite space of all possible ideas that any human might ever have for sorting using sequential comparisons, NONE has a worst case runtime that is better than $\Theta(N \log N)$.



TUCS Worst
Case Θ Runtime

The Game of Puppy, Cat, Dog

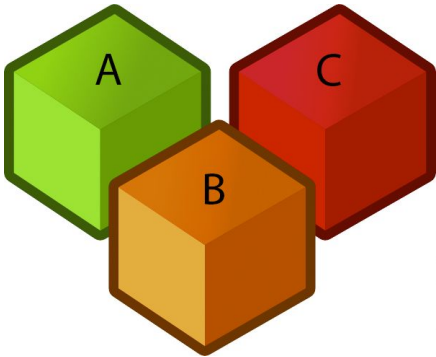
Suppose we have a puppy, a cat, and a dog, each in an opaque soundproof box labeled A, B, and C. We want to figure out which is which using a scale.



The Game of Puppy, Cat, Dog

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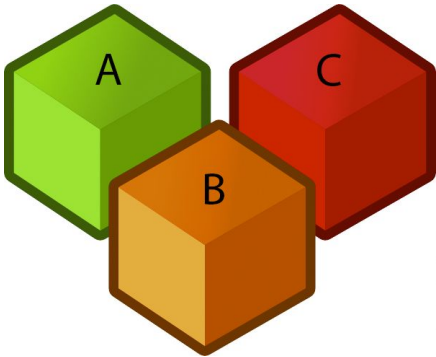
$a < b$	$b < c$		Which is which?
Yes	Yes		



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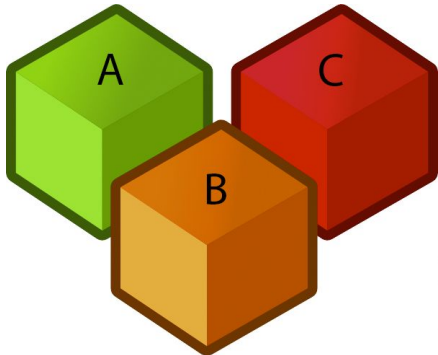
$a < b$	$b < c$		Which is which?
Yes	Yes		a: puppy, b: cat, c: dog (sorted order: abc)
No	No		



The Game of Puppy, Cat, Dog

Suppose we have a puppy, a cat, and a dog, each in an opaque soundproof box labeled A, B, and C. We want to figure out which is which using a scale.

a < b	b < c		Which is which?
Yes	Yes		a: puppy, b: cat, c: dog (sorted order: abc)
No	No		c: puppy, b: cat, a: dog (sorted order: cba)



The Game of Puppy, Cat, Dog: <http://yellkey.com/arm>

Suppose we have a puppy, a cat, and a dog, each in an opaque soundproof box labeled A, B, and C. We want to figure out which is which using a scale.

$a < b$	$b < c$		Which is which?
Yes	Yes		a: puppy, b: cat, c: dog (sorted order: abc)
No	No		c: puppy, b: cat, a: dog (sorted order: cba)
Yes	No		

Which is which?

1. a: puppy, b: cat, c: dog (sorted order: abc)
2. a: puppy, c: cat, b: dog (sorted order: acb)
3. c: puppy, a: cat, b: dog (sorted order: cab)
4. c: puppy, b: cat, a: dog (sorted order: cba)

The Game of Puppy, Cat, Dog

Suppose we have a puppy, a cat, and a dog, each in an opaque soundproof box labeled A, B, and C. We want to figure out which is which using a scale.

a < b	b < c		Which is which?
Yes	Yes		a: puppy, b: cat, c: dog (sorted order: abc)
No	No		c: puppy, b: cat, a: dog (sorted order: cba)
Yes	No		

Which is which? How do we resolve the ambiguity?

1.

a: puppy, b: cat, c: dog (sorted order: abc)

2.

a: puppy, c: cat, b: dog (sorted order: acb)

3.

c: puppy, a: cat, b: dog (sorted order: cab)

4.

c: puppy, b: cat, a: dog (sorted order: cba)
- a?

c?

b

c?

a?

b

The Game of Puppy, Cat, Dog

Suppose we have a puppy, a cat, and a dog, each in an opaque soundproof box labeled A, B, and C. We want to figure out which is which using a scale.

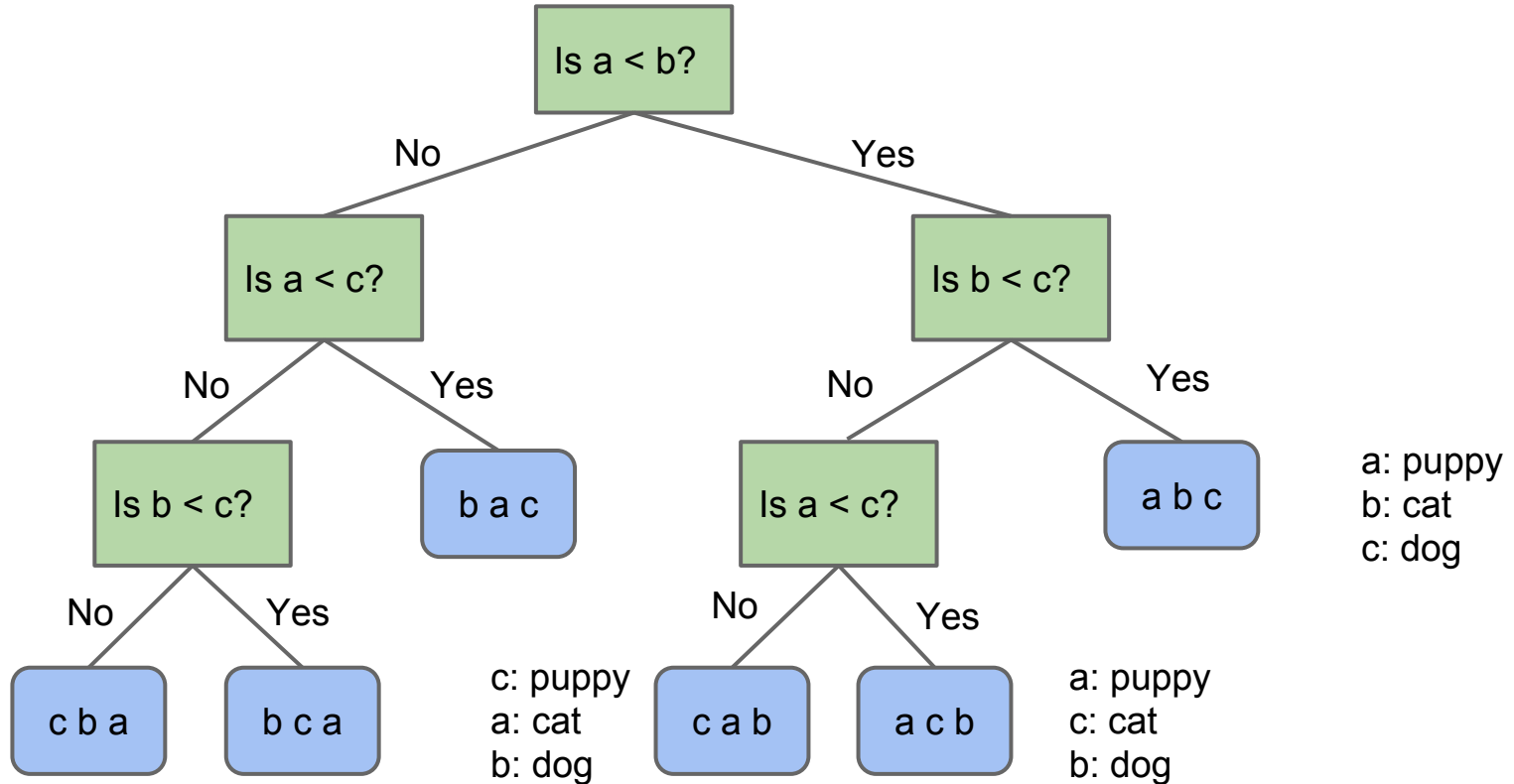
$a < b$	$b < c$	$a < c?$	Which is which?
Yes	Yes	N/A	a: puppy, b: cat, c: dog (sorted order: abc)
No	No	N/A	c: puppy, b: cat, a: dog (sorted order: cba)
Yes	No	Yes	a: puppy, c: cat, b: dog (sorted order: acb)

Which is which? How do we resolve the ambiguity? Ask if $a < c$.

1. a: puppy, b: cat, c: dog (sorted order: abc)
2. **a: puppy, c: cat, b: dog (sorted order: acb)**
3. **c: puppy, a: cat, b: dog (sorted order: cab)**
4. c: puppy, b: cat, a: dog (sorted order: cba)

Puppy, Cat, Dog - A Graphical Picture for $N = 3$

The full decision tree for puppy, cat, dog:



The Game of Puppy, Cat, Dog, yellkey.com/year

How many questions would you need to ask to definitely solve the “puppy, cat, dog, walrus” problem?

- A. 3
- B. 4
- C. 5
- D. 6

The Game of Puppy, Cat, Dog

How many questions would you need to ask to definitely solve the “puppy, cat, dog, walrus” problem?

- A. 3
- B. 4
- C. 5**
- D. 6

Proof:

- If $N=4$, how many permutations? $4! = 24$
 - For $N=3$: $3!=6$
- So we need a binary tree with 24 leaves.
 - How many levels minimum? $\lg(24) = 4.58$, so 5 is the minimum.
 - \lg just means \log_2 (log base 2)

Generalized Puppy, Cat, Dog

How many questions would you need to ask to definitely solve the generalized “puppy, cat, dog” problem for N items?

- Give your answer in big Omega notation.

Hint: For $N=4$, we said the answer was 5 based on the following argument:

- Decision tree needs $4! = 24$ leaves.
- So we need $\lg(24)$ rounded up levels or 5.

Generalized Puppy, Cat, Dog

How many questions would you need to ask to definitely solve the generalized “puppy, cat, dog” problem for N items?

Answer: $\Omega(\log(N!))$

Hint: For N , we have the following argument:

- Decision tree needs $N!$ leaves.
- So we need $\lg(N!)$ rounded up levels, which is $\Omega(\log(N!))$

Generalizing Puppy, Cat, Dog

Finding an optimal decision tree for the generalized version of puppy, cat, dog (e.g. $N=6$: puppy, cat, dog, monkey, walrus, elephant) is an open problem in mathematics.

- (To my knowledge) Best known trees known for $N=1$ through 15 and $N=22$:
 - For more, see: <http://oeis.org/A036604>

Deriving a sequence of yes/no questions to identify puppy, cat, dog is hard. An alternate approach to solving the puppy, cat, dog problem:

- Sort the boxes using any generic sorting algorithm.
 - Leftmost box is puppy.
 - Middle box is cat.
 - Right box is dog.

Sorting, Puppies, Cats, and Dogs

Why do we care about these (no doubt adorable) critters?

A solution to the sorting problem also provides a solution to puppy, cat, dog.

- In other words, puppy, cat, dog **reduces** to sorting.
- Thus, any lower bound on difficulty of puppy, cat, dog must ALSO apply to sorting.

Physics analogy: Climbing a hill with your legs (CAHWYL) is one way to solve the problem of getting up a hill (GUAH).

- Any lower bound on energy to GUAH must also apply to CAHWYL.
- Example bound: Takes $m \cdot g \cdot h$ energy to climb hill, so using legs to climb the hill takes at least $m \cdot g \cdot h$ energy.

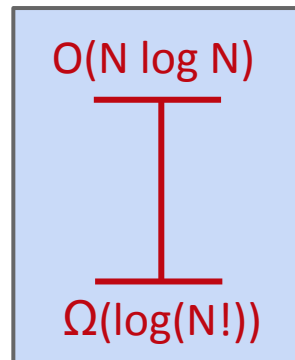
Sorting Lower Bound

We have a lower bound on puppy, cat, dog, namely that it takes $\Omega(\log(N!))$ comparisons to solve such a puzzle.

Since sorting with comparisons can be used to solve puppy, cat, dog, then sorting also takes $\Omega(\log(N!))$ comparisons.

Or in other words:

- Any sorting algorithm using comparisons, no matter how clever, must use at least $k = \lg(N!)$ compares to find the correct permutation. So even TUCS takes at least $\lg(N!)$ comparisons.
- $\lg(N!)$ is trivially $\Omega(\log(N!))$, so TUCS must take $\Omega(\log(N!))$ time.
- So, how does $\log(N!)$ compare to $N \log N$?



TUCS Worst
Case Θ Runtime


Another Math Problem

Earlier, we showed that $\log(N!) \in \Omega(N \log N)$ using the proof below.

- In other words, $\log(N!)$ grows at least as quickly as $N \log N$.

We have that $N! \geq (N/2)^{N/2}$

- Taking the log of both sides, we have that $\log(N!) \geq \log((N/2)^{N/2})$.
- Bringing down the exponent we have that $\log(N!) \geq N/2 \log(N/2)$.
- Discarding unnecessary constants, we have $\log(N!) \in \Omega(N \log N)$

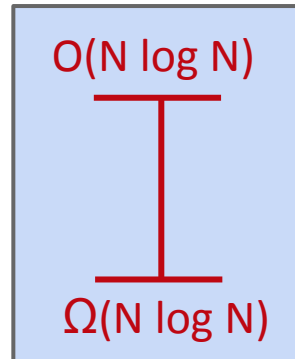


Recall that changing base is just multiplying by a constant.

The Sorting Lower Bound (Finally)

Since TUCS is $\Omega(\lg N!)$ and $\lg N!$ is $\Omega(N \log N)$, we have that **TUCS is $\Omega(N \log N)$** .

Any comparison based sort requires at least order $N \log N$ comparisons.



TUCS Worst
Case Θ Runtime

The Sorting Lower Bound (Finally)

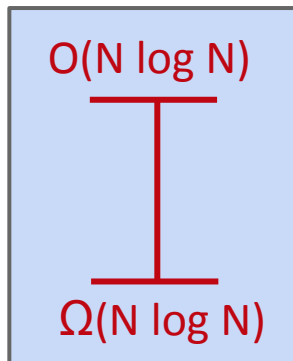
Since TUCS is $\Omega(\lg N!)$ and $\lg N!$ is $\Omega(N \log N)$, we have that **TUCS is $\Omega(N \log N)$** .

Any comparison based sort requires at least order $N \log N$ comparisons.

Proof summary:

- Puppy, cat, dog is $\Omega(\lg N!)$, i.e. requires $\lg N!$ comparisons.
- TUCS can solve puppy, cat, dog, and thus takes $\Omega(\lg N!)$ compares.
- $\lg(N!)$ is $\Omega(N \log N)$
 - This was because $N!$ is $\Omega(N/2)^{N/2}$

Informally: $\text{TUCS} \geq \text{puppy, cat, dog} \geq \lg N! \geq N \log N$



TUCS Worst
Case Θ Runtime

Optimality

	Memory	# Compares	Notes	Stable?
Heapsort	$\Theta(1)$	$\Theta(N \log N)$	Bad caching (61C)	No
Insertion	$\Theta(1)$	$\Theta(N^2)$	Best for almost sorted and $N < 15$	Yes
Mergesort	$\Theta(N)$	$\Theta(N \log N)$	Fastest stable sort	Yes
Quicksort LTHS	$\Theta(\log N)$	$\Theta(N \log N)$ expected	Fastest sort	No

The punchline:

- Our best sorts have achieved absolute asymptotic optimality.
 - Mathematically impossible to sort using fewer comparisons.
 - Note: Randomized quicksort is only probabilistically optimal, but the probability is extremely high for even modest N . Are you worried about quantum teleportation? Then don't worry about Quicksort.

Next Time...

Today we proved that any sort that uses comparisons has runtime $\Omega(N \log N)$.

Next time we'll discuss how we can sort in $\Theta(N)$ time.

- Not impossible, just can't compare anything while we sort!

Have we proven that we can't find an algorithm whose average case is better than $N \log N$.

- Our proof does not apply.

Average Case of Quicksort

We had two little “proofs”:

- The $X\%$ case, and we showed that even if you land within $X\%$ of the edge, runtime is still $N \log N$.
- By analogy with BST insertion. Random insertion into a BST is $N \log N$ (not proven but mentioned), so Quicksort is also average $N \log N$.
- A true proof involves random variables and integrals, isn't too bad. See Tim Roughgarden's Algorithms course if curious.

Average Case of Quicksort

How do we sort a stream of items?

- Keep in a PQ, though this is a little funny because you have to be able to traverse the PQ in order, which requires destroying it.
- Insertion sort is interesting, because the array is always “almost sorted”, but each set of exchanges can take N time, so overall could end up being N^2 .
- Use a BST. Is a vanilla BST with no self-balancing features safe?
 - No, could be in sorted or (reverse sorted) or (almost reverse sorted) order.
- The stream is infinite, but we can maintain what we’ve so far in sorted order.
- Elements coming into the stream are totally random, is vanilla ok?
 - Yes, for a reasonable definition of “ok”.

Random Qs

Quicksort uses partitioning to put items in order.

- Worst case N^2 , average case $N \log N$.

Quickselect uses partitioning to find the median.

- Worst case N^2 , average case N .

For more content like today:

- CS70 a little.
- CS170 a fair amount (172/174/176).
- <https://www.coursera.org/specializations/algorithms>
- <https://www.coursera.org/learn/analytic-combinatorics>

Random Qs

When you do partitioning such that you STOP on items equal to the pivot, what good is that?

- It is just good for ensuring $N \log N$ behavior on arrays of almost all duplicates.
 - This happens because it keeps the pivot somewhere near the middle after partitioning.

When partitioning and you have a greater than array. What order do you put them in?

- Any order works.

$N * N! = \Theta(N!)$ -- No.

Does there exist hash sort? Next lecture is kinda hashsort.

Random Qs

What is the optimal known quicksort?

- It's the one in Java called dual pivot quicksort.

AMA

How do we get random numbers?

- Record random stuff like noise in the room, gamma rays.
 - System clock is one -- but one issue is that the granularity is poor (only changes every millisecond) -- often used instead as a random number seed.
- Rely on pseudorandomness [actually deterministic]
 - For example multiplicative overflow.
- I will get a dog someday.
- Lightbulb no money from the Green Creative people.
- Timing things for raster: Weird timing issues in Java.
 - Different processes competing for resources.
 - Just in time compilation.
 -

Sounds of Sorting Algorithms

Starts with selection sort: <https://www.youtube.com/watch?v=kPRA0W1kECg>

Insertion sort: <https://www.youtube.com/watch?v=kPRA0W1kECg&t=0m9s>

Quicksort: <https://www.youtube.com/watch?v=kPRA0W1kECg&t=0m38s>

Mergesort: <https://www.youtube.com/watch?v=kPRA0W1kECg&t=1m05s>

Heapsort: <https://www.youtube.com/watch?v=kPRA0W1kECg&t=1m28s>

LSD sort: <https://www.youtube.com/watch?v=kPRA0W1kECg&t=1m54s>

MSD sort: <https://www.youtube.com/watch?v=kPRA0W1kECg&t=2m10s>

Shell's sort: <https://www.youtube.com/watch?v=kPRA0W1kECg&t=3m37s>

Questions to ponder (later... after class):

- How many items for selection sort?
- Why does insertion sort take longer / more compares than selection sort?
- At what time stamp does the first partition complete for Quicksort?
- Could the size of the input to mergesort be a power of 2?
- What do the colors mean for heapsort?

Sorting Implementations (Extra)

A Note on Implementations

Concrete implementations are nice for solidifying understanding.

- Implementing these yourself provides much deeper understanding than just reading my code.
- You are not responsible for the details of these specific implementations.
- Given enough time, you should be able to implement any of these sorts.

Utility Methods For Sorting

```
/** Returns true if v < w, false otherwise. */  
private static boolean less(Comparable v, Comparable w) {  
    return (v.compareTo(w) < 0);  
}
```

```
/** Swaps a[i] and a[j]. */  
private static void exch(Object[] a, int i, int j) {  
    Object swap = a[i];  
    a[i] = a[j];  
    a[j] = swap;  
}
```

Selection Sort

```
public static void selSort(Comparable[] a) {
    int N = a.length;
    for (int i = 0; i < N; i += 1) {
        int min = i;

        /** Find smallest item among unfixed items. */
        for (int j = i+1; j < N; j += 1) {
            if (less(a[j], a[min])) {
                min = j;
            }
        }

        exch(a, i, min);
    }
}
```

Key ideas: Among unfixed items, find minimum in $\Theta(N)$ time and swap to the front. Subproblem has size $N-1$. Total runtime is $N + N-1 + \dots + 1 = \Theta(N^2)$.

Insertion Sort

```
public static void insSort(Comparable[] a) {  
    int N = a.length;  
    for (int i = 0; i < N; i++) {  
  
        /* Swap item until it is in correct position. */  
        for (int j = i; j > 0; j -= 1) {  
  
            /* If left neighbor is less than me, stop. */  
            if less(a[j-1], a[j]) {  
                break;  
            }  
            exch(a, j, j-1);  
        }  
    }  
}
```

Key ideas: For each item (starting at leftmost), swap leftwards until in place. For item k , takes $\Theta(k)$ worst case time. Runtime is $1 + 2 + \dots + N = \Theta(N^2)$.

Selection and Insertion Sort Runtimes (Code Analysis)

Selection sort: Runtime is independent of input, always $\Theta(N^2)$.

- $\sim N^2/2$ compares and $\sim N^2/2$ exchanges. $\Theta(N^2)$ runtime.

Insertion sort: Runtime is strongly dependent on input. $\Omega(N)$, $O(N^2)$

- Best case (sorted): $\sim N$ compares, 0 exchanges: $\Theta(N)$
- Worst case (reverse sorted): $\sim N^2/2$ compares, $\sim N^2/2$ exchanges: $\Theta(N^2)$

```
for (int i = 0; i < N; i += 1) {
    int min = i;
    for (int j = i+1; j < N; j += 1) {
        if (less(a[j], a[min])) {
            min = j;
        }
    }
    exch(a, i, min);
}
```

```
for (int i = 0; i < N; i++) {
    for (int j = i; j > 0; j -= 1) {
        if (less(a[j-1], a[j])) {
            break;
        }
        exch(a, j, j-1);
    }
}
```

Mergesort (Merge Method)

```
/** Given sorted arrays a and b, return sorted array
 * containing all items from a and b. Can be optimized
 * to avoid creating new arrays for every merge. */
private static Comparable[] merge(Comparable[] a, Comparable[] b) {
    Comparable[] c = new Comparable[a.length + b.length];
    int i = 0, j = 0;
    for (int k = 0; k < c.length; k++) {
        if (i >= a.length) { c[k] = b[j]; j += 1; }
        else if (j >= b.length) { c[k] = a[i]; i += 1; }
        else if (less(b[j], a[i])) { c[k] = a[j]; j += 1; }
        else { c[k] = b[i]; i += 1; }
    }
    return c;
}
```

Mergesort

```
/** Mergesort. Can be optimized to avoid creation of subarrays. */  
public static Comparable[] mergesort(Comparable[] input) {  
    int N = input.length;  
    if (N <= 1) return input;  
    Comparable[] a = new Comparable[N/2];  
    Comparable[] b = new Comparable[N - N/2];  
    for (int i = 0; i < a.length; i += 1) a[i] = input[i];  
    for (int i = 0; i < b.length; i += 1) b[i] = input[i + N/2];  
    return merge(mergesort(a), mergesort(b));  
}
```

Key ideas: Each merge costs $\Theta(N)$ time and $\Theta(N)$ space, and generates two subproblems of size $N/2$. At level L of the sort, there are 2^L subproblems of size $N/2^L$. Since $L = \Theta(\log N)$, runtime is $\Theta(N \log N)$.

Interview Question

```
/** Mergesort. Can be optimized to avoid creation of subarrays. */  
public static Comparable[] mergesort(Comparable[] input) {  
    int N = input.length;  
    if (N <= 1) return input;  
    Comparable[] a = new Comparable[N/2];  
    Comparable[] b = new Comparable[N - N/2];  
    for (int i = 0; i < a.length; i += 1) a[i] = input[i];  
    for (int i = 0; i < b.length; i += 1) b[i] = input[i + N/2];  
    return merge(mergesort(a), mergesort(b));  
}
```

How can the above mergesort implementation be improved?

- Try and avoid making copies a and b, by adding parameters to the merge routine. `merge(input, 0, 5, 6, 10);`
- Use a different for small N: Like maybe insertion sort. Industrial strength mergesorts, use insertion sort for $N < 15$.

Interview Question

```
/** Mergesort. Can be optimized to avoid creation of subarrays. */
public static Comparable[] mergesort(Comparable[] input) {
    int N = input.length;
    if (N <= 1) return input;
    Comparable[] a = new Comparable[N/2];
    Comparable[] b = new Comparable[N - N/2];
    for (int i = 0; i < a.length; i += 1) a[i] = input[i];
    for (int i = 0; i < b.length; i += 1) b[i] = input[i + N/2];
    return merge(mergesort(a), mergesort(b));
}
```

How can the above mergesort implementation be improved?

Heapsort With Separate PQ

```
/** Uses a MaxPQ to do the sorting. Requires  $\Theta(N)$  space. */
public static void lameHeapsort(Comparable[] items) {
    MaxPQ<Comparable> maxPQ = new MaxPQ<Comparable>();
    for (Comparable c : items) {
        maxPQ.insert(c);
    }
    /** Repeatedly remove largest item and put at end of array.
        Using a MinPQ is more intuitive, but a MaxPQ can be
        adapted to use no extra space (next slide). */
    for (int i = items.length - 1; i >= 0; i -= 1) {
        items[i] = maxPQ.removeLargest();
    }
}
```

Key ideas: Create a max heap of all items [$\Theta(N \log N)$], then delete max N times [$\Theta(\log N)$ per delete]. Requires $\Theta(N)$ space.

In-Place Heapsort (with root in position 0).

```
/** Sorts the given array by first heapifying, then removing
 * each item from the max heap, one-by-one. */
public static void sort(Comparable[] pq) {
    int N = pq.length;
    /* Sink in reverse level order. Can be optimized
       to exclude the bottom level. */
    for (int k = N; k >= 0; k -= 1) {
        sink(pq, k, N);
    }
    while (N > 1) {
        exch(pq, 0, N); // swap root and last item
        N -= 1;         // mark deleted item as off limits
        sink(pq, 0, N); // sink the root
    }
}
```

Key ideas: Max-Heapfiy [$\Theta(N)$], then delete max N times [$\Theta(\log N)$ per delete]

In-Place Heapsort Sink Operation (with root in position 0).

```
/** Given item in position pq[cur], repeatedly swaps the item
 * with its largest child if necessary for heap property. */
private static void sink(Comparable[] pq, int cur, int N) {
    /* Repeatedly sink until no children are left. */
    while (2 * cur <= N) {
        int left = 2 * cur + 1; // 0-based array
        int right = left + 1;
        int largerChild = left;
        /* If right child exists and is larger. */
        if (right <= N && less(pq[left], pq[right])) {
            largerChild = right;
        }
        if (!less(pq[cur], pq[largerChild])) {
            break;
        }
        exch(pq, cur, largerChild);
        cur = largerChild;
    }
}
```

Citations

Title image: <http://www.angelfire.com/blog/ronz/Articles/999SortingNetworksReferen.html>

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Cat: <http://animalia-life.com/cat.html>

Dog: <http://animalia-life.com/dogs.html>