

Lecture 2: Concrete Models and Tight Upper and Lower Bounds

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Theme: Tight Upper and Lower Bounds

- Number of comparisons to sort an array
- Number of exchanges to sort an array
- Number of comparisons needed to find the largest and second-largest elements in an array
- Number of probes into a graph needed to determine if the graph is connected

Formal Model

- Look at models which specify exactly which operations may be performed on the input, and what they cost
 - E.g., performing a comparison, or swapping a pair of elements
- An upper bound of $f(n)$ means the algorithm takes at most $f(n)$ steps on any input of size n
- A lower bound of $g(n)$ means for any algorithm there exists an input for which the algorithm takes at least $g(n)$ steps on that input

Sorting in the Comparison Model

- **Definition:** in the comparison model, we have an input consisting of n items (typically in some initial order). An algorithm may compare two items (asking is $a_i > a_j$?) at a cost of 1. Moving the items around is free.
- No other operations are allowed, such as using the items as indices, XORing them, hashing, etc.
- Sorting: given an array $a = [a_1, \dots, a_n]$, the output is a permutation $\pi(a) = [a_{\pi(1)}, \dots, a_{\pi(n)}]$ in which the elements are in increasing order

Sorting Lower Bound

- **Theorem:** Any deterministic comparison-based sorting algorithm must perform at least $\lg(n!)$ comparisons to sort n elements in the worst case, i.e., for any sorting algorithm A and $n \geq 2$, there is an input I of size n so that A makes $\geq \lg(n!) = \Omega(n \log n)$ comparisons to sort I .
- Need to rule out *any* possible algorithm
- Proof is information-theoretic

Sorting Lower Bound

- **Proof:** Suppose there is a problem with M possible outputs
 - For sorting $M = n!$ since for each possible output permutation π , there is an input for which the output is π
- Further, suppose for each possible output to the problem, there is an input for which that output is the only correct answer
 - For sorting there are inputs for which π is the only correct answer
- Then there is a lower bound of $\lg M$
 - Consider a set of inputs in one-to-one correspondence with the M possible outputs. Algorithm needs to find out which of the M outputs is the right one for a given input, and each comparison can be answered in a way that removes at most half of the possible inputs remaining from consideration

Sorting Lower Bound

- Information-theoretic: need $\lg(n!)$ bits of information about the input before we can correctly decide on the output
- $\lg(n!) = \lg(n) + \lg(n - 1) + \lg(n - 2) + \dots + \lg(1) < n \lg n$
- $\lg(n!) = \lg(n) + \lg(n - 1) + \lg(n - 2) + \dots + \lg(1) > \left(\frac{n}{2}\right) \lg\left(\frac{n}{2}\right) = \Omega(n \lg n)$
- $n! \in \left[\left(\frac{n}{e}\right)^n, n^n\right]$, so $n \lg n - n \lg e < \lg(n!) < n \lg n$
 $n \lg n - 1.443n < \lg(n!) < n \lg n$
- $\lg(n!) = (n \lg n) (1 - o(1))$

Sorting Upper Bounds

- Suppose for simplicity n is a power of 2
- Binary insertion sort: using binary search to insert each new element, the number of comparisons is $\sum_{k=2, \dots, n} \lceil \lg k \rceil \leq n \lg n$
 - **Note:** may need to move items around a lot, but only counting comparisons
- Mergesort: merging two lists of $n/2$ elements requires at most $n-1$ comparisons
 - Unrolling the recurrence, total number of comparisons is
$$(n - 1) + 2 \left(\frac{n}{2} - 1 \right) + \dots + \frac{n}{2} (2 - 1) = n \lg n - (n - 1) < n \lg n$$

Selection in the Comparison Model

- How many comparisons are necessary and sufficient to find the maximum of n elements in the comparison model?
- **Claim:** $n-1$ comparisons are sufficient
- Proof: scan from left to right, keep track of the largest element so far
- For lower bounds, what does our earlier information-theoretic argument give?
 - Only $\Omega(\log n)$, which is too weak
- Also, we have to look at all elements, otherwise we may have not looked at the largest, but that can be done with $n/2$ comparisons, also not tight

Lower Bound for Finding the Maximum

- **Claim:** $n-1$ comparisons are needed in the worst-case to find the maximum of n elements
- **Proof:** suppose A is an algorithm which finds the maximum of n distinct elements using fewer than $n-1$ comparisons
- Construct a graph G in which we join two elements by an edge if they are compared by A
- G has at least 2 connected components C_1 and C_2
- Suppose A outputs element u as the maximum, and $u \in C_1$
- Add a large positive number to each element in C_2
- Does not change any of the comparisons made by A , so will still output u
- But now u is not the maximum, so A is incorrect

Lower Bound for Finding the Maximum

- **Recap:** upper and lower bounds match at $n-1$
- Argument different from information-theoretic bound for sorting
- Instead,
 - if algorithm makes too few comparisons on some input In and outputs Out ,
 - find another input In' where the algorithm makes the same comparisons and also outputs Out ,
 - but Out is not a correct output for In'

An Adversary Argument

- If algorithm makes “too few” comparisons, fool it into giving an incorrect answer
- Any deterministic algorithm sorting 3 elements must perform at least 3 comparisons
 - If < 2 comparisons, some element not looked at and the algorithm is incorrect
 - After first comparison, 3 elements are w , l , and z , the winner and loser of the first comparison, as well as the uninvolved item
 - If the second query is between w and z , say
 - w is larger
 - If the second query is between l and z , say
 - l is smaller
 - Algorithm needs one more comparison for correctness
- **Goal:** give an adversary answering comparisons so that (a) answers consistent with some input I_n , and (b) answers make the algorithm perform “many” comparisons

First and Second Largest of n Elements

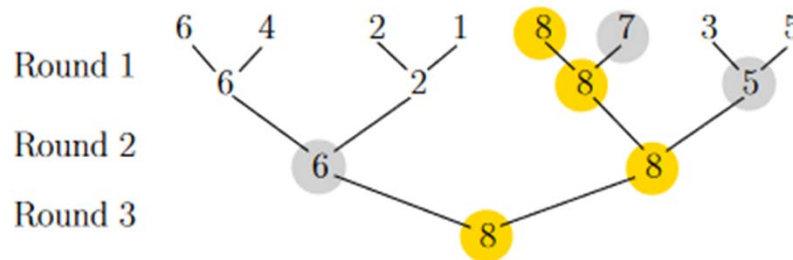
- How many comparisons are necessary (lower bound) and sufficient (upper bound) to find the first and second largest of n distinct elements?
- **Claim:** $n-1$ comparisons are needed in the worst-case
- **Proof:** need to at least find the maximum

What about Upper Bounds?

- **Claim:** $2n-3$ comparisons are sufficient to find the first and second-largest of n elements
- **Proof:** find the largest using $n-1$ comparisons, then find the largest of the remainder using $n-2$ comparisons, so $2n-3$ total
- Upper bound is $2n-3$, and lower bound $n-1$, both are $\Theta(n)$ but can we get tight bounds?

Second Largest of n Elements Upper Bound

- **Claim:** $n + \lg n - 2$ comparisons are sufficient to find the first and second-largest of n elements
- **Proof:** find the maximum element using $n-1$ comparisons by grouping elements into pairs, finding the maximum in each pair, and recursing



- What can we say about the second maximum?
 - Must have been directly compared to the maximum and lost, so $\lg(n)-1$ additional comparisons suffice. Kislitsyn (1964) shows this is optimal

Sorting in the Exchange Model

- Consider a shelf containing n unordered books to be arranged alphabetically. How many swaps do we need to order them?
- **Definition:** In the exchange model, an input consists of n items, and the only operation allowed on the items is to swap a pair of them at a cost of 1 step.
 - All other work is free, e.g., the items can be examined and compared
- How many exchanges are necessary and sufficient?

Sorting in the Exchange Model

- **Claim:** $n-1$ exchanges is sufficient
- **Proof:** here's an algorithm:
 - In first step, swap the smallest item with the item in the first location
 - In second step, swap the second smallest item with the item in the second location
 - In k -th step, swap the k -th smallest item with the item in the k -th location
 - If no swap is necessary, just skip a given step
 - No swap ever undoes our previous work
 - At the end, the last item must already be in the correct location

Lower Bound for Sorting in Exchange Model

- **Claim:** $n-1$ exchanges are necessary in the worst case
- **Proof:** create a directed graph in which the edge (i,j) means the book in location i must end up in location j

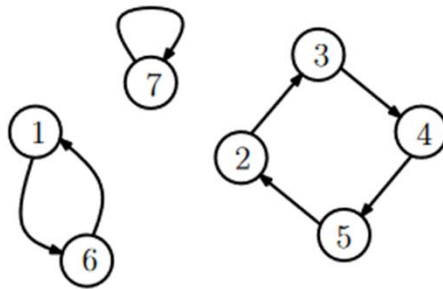
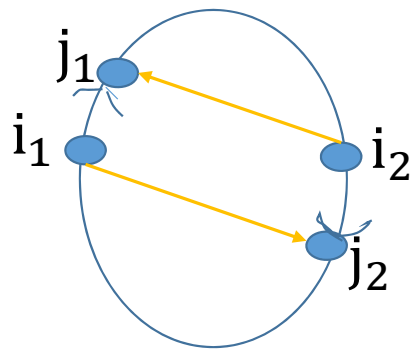


Figure 1: Graph for input [f c d e b a g]

- Graph is a set of cycles
 - Indegree and Outdegree of each node is 1

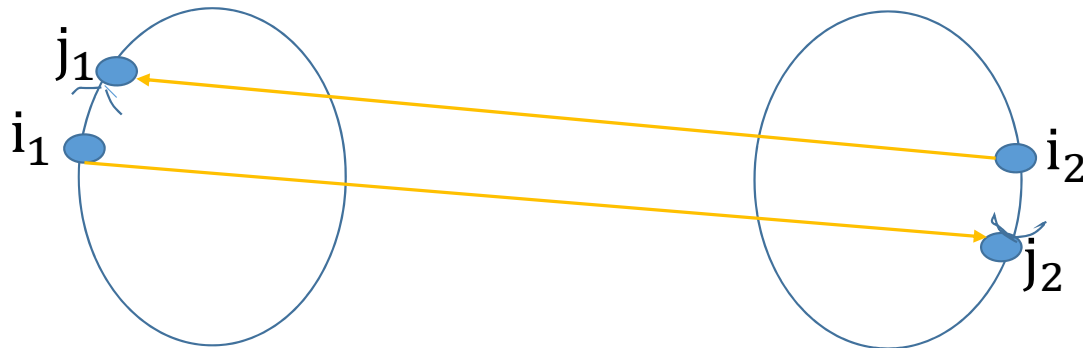
Lower Bound for Sorting in Exchange Model

- What is the effect of exchanging any two elements in the same cycle?
 - Suppose we have edges (i_1, j_1) and (i_2, j_2) and swap elements in locations i_1 and i_2
 - This replaces these edges with (i_2, j_1) and (i_1, j_2) since now the item in position i_2 need to go to j_1 and item in position i_1 need to go to j_2
 - Since i_1 and i_2 in the same cycle, now we get two disjoint cycles



Lower Bound for Sorting in Exchange Model

- What is the effect of exchanging any two elements in different cycles?
 - If we swap elements i_1 and i_2 in different cycles, similar argument shows this merges two cycles into one cycle



Lower Bound for Sorting in Exchange Model

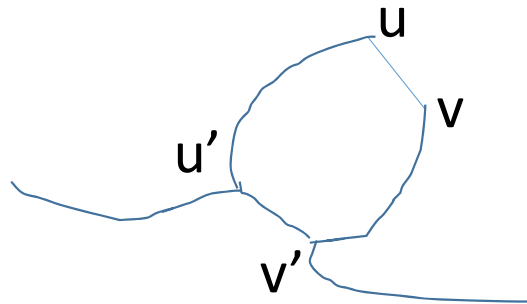
- What is the effect of exchanging any two elements in the same cycle?
 - Get two disjoint cycles
- What is the effect of exchanging any two elements in different cycles?
 - Merges two cycles into one cycle
- How many cycles are in the final sorted array?
 - n cycles
- Suppose we begin with an array $[n, 1, 2, \dots, n-1]$ with one big cycle
- Each step increases the number of cycles by at most 1, so need $n-1$ steps

Query Models and Evasiveness

- Let G be the adjacency matrix of an n -node graph
 - $G[i,j] = 1$ if there is an edge between i and j , else $G[i,j] = 0$
- In 1 step, we can query any element of G . All other computation is free
- How many queries do we need to tell if G is connected?
- **Claim:** $n(n-1)/2$ queries suffice
- **Proof:** Just query every pair $\{i,j\}$ to learn G , then check if G is connected
- *What about lower bounds?*

Connectivity is an Evasive Graph Property

- **Theorem:** $n(n-1)/2$ queries are necessary to determine connectivity
- **Proof:** adversary strategy: given a query $G[u,v]$, answer 0 *unless* that would cause the graph to become disconnected
- Invariant: for any unasked pair $\{u,v\}$, the graph revealed so far has no path from u to v
- Reason: consider the last edge $\{u',v'\}$ revealed on that path. Could have answered 0 and kept same connectivity by having edge $\{u,v\}$ be present



Connectivity is an Evasive Graph Property

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- **Proof:** adversary strategy: given a query $G[u,v]$, answer 0 *unless* that would cause the graph to become disconnected
- Invariant: for any unasked pair $\{u,v\}$, the graph revealed so far has no path from u to v
- Suppose there is some unasked pair $\{u,v\}$ by the algorithm
 - If algorithm says “connected”, we place all 0s on unasked pairs
 - If algorithm says “disconnected”, we place all 1s on unasked pairs
- So algorithm needs to query every pair