Asymptotic Notation, Recurrences

Asymptotic growth rates

Let $g : \mathbb{N} \to \mathbb{R}$.

O-notation: $O(g)$ is the set of all functions $f : \mathbb{N} \to \mathbb{R}$ for which there are constants $c > 0$ and $n_0 \geq 0$ such that

$$0 \leq f(n) \leq c \cdot g(n), \quad \text{for all } n \geq n_0.$$

"Rate of change of $f(n)$ is at most that of $g(n)$"

Ω-notation: $\Omega(g)$ is the set of all functions $f : \mathbb{N} \to \mathbb{R}$ for which there are constants $c > 0$ and $n_0 \geq 0$ such that

$$0 \leq c \cdot g(n) \leq f(n), \quad \text{for all } n \geq n_0.$$

"Rate of change of $f(n)$ is at least that of $g(n)$"

Θ-notation: $\Theta(g)$ is the set of all functions $f : \mathbb{N} \to \mathbb{R}$ for which there are constants $c_1, c_2 > 0$ and $n_0 \geq 0$ such that

$$0 \leq c_1 \cdot g(n) \leq f(n) \leq c_2 \cdot g(n), \quad \text{for all } n \geq n_0.$$

"Rate of change of $f(n)$ and $g(n)$ are about the same"

Examples

- Let $f(n) = 0.01 \cdot n^2$ and $g(n) = n$. Then $g = O(f)$.
- Let $f(n) = \ln(n)$ and $g(n) = n$. Then $g = \Omega(f)$.
- Let $f(n) = 10n + \ln(n)$ and $g(n) = n$. Then $g = \Theta(f)$.

  Sometimes $O(\dots)$ appears within a formula, rather than simply forming the right hand side of an equation. We make sense of this by thinking of $O(\dots)$ as standing for some anonymous (but fixed) function from the set of the same name.
  For example, $h(n) = 2^{O(n)}$ means $\exists c > 0$, $n_0 \in \mathbb{N}$ such that

$$h(n) \leq 2^{cn} \text{ for all } n > n_0.$$

Consequences

Suppose $f(n) = O(g(n))$ AND $g(n) = O(f(n))$. What can we say?

What if $f(n) = O(g(n))$ AND $f(n) = \Omega(g(n))$?

Various consequences of the above conventions:

$$\begin{aligned}
\Theta(n) \times \Theta(n^2) &= \Theta(n^3), \\
\Theta(n) + \Theta(n^2) &= \Theta(n^2), \\
\Theta(n) + \Theta(n) &= \Theta(n).
\end{aligned}$$

Reminder of InsertionSort

Algorithm Insertion-Sort(A)

```
for j ← 2 to length[A] do
        key ← A[j]
        (now insert A[j] into the sorted sequence A[1 ... j − 1])
        i ← j − 1
        while i > 0 and A[i] > key do
                A[i + 1] ← A[i]
                i ← i − 1
        A[i + 1] ← key
```

Array A is indexed from $j = 1$ to $n = length[A]$ (different from Java).

running-time of InsertionSort

- The for-loop on line 1 is iterated $n-1$ times
- For each execution of the for, the while does $\leq j$ iterations;
- Each of the comparisons/assignments requires only $O(1)$ basic steps;
- Therefore the total number of steps (=time) is at most

$$O(1)\sum_{j=1}^{n} j = O(1)\frac{n(n+1)}{2} = O(n^2).$$

- This is essentially tight - sorting the list $n, n-1, n-2, \ldots, 3, 2, 1$ takes $\Omega(n^2)$ time. **Exercise**.

reminder of MergeSort

Input: A list A of natural numbers, $p, r : 1 \le p \le r \le n$.
Output: A sorted (increasing order) permutation of $A[p \dots r]$.

Algorithm Merge-Sort(A, p, r)

```
if p < r then
        q ← ⌊(p+r)/2⌋
        Merge-Sort(A, p, q)
        Merge-Sort(A, q + 1, r)
        Merge(A, p, q, r)
```

reminder of Merge

(recall that $A[p \dots q]$ and $A[q+1 \dots r]$ both come (individually) sorted)

Algorithm Merge(A, p, q, r)

```
n ← r − p + 1, n_1 ← q − p + 1, n_2 ← r − q
create an array B of length n
i ← p, j ← q + 1, k ← 1
while ((i ≤ q) || (j ≤ r))
        if ((j > r) || ((i ≤ q) && (A[i] ≤ A[j])))
                B[k] ← A[i]
                i ← i + 1
        else
                B[k] ← A[j]
                j ← j + 1
        k ← k + 1
for i = 1 to n
        A[(p − 1) + i] ← B[i]
```

Analysis of MERGE

We have $n = (r - p) + 1$, $n_1 = (q - p) + 1$, $n_2 = r - q$ (note $n = n_1 + n_2$).
MERGE carries out the following steps:

- Initialisation/maintenance work in steps 1., 2., 3., uses $3 + n + 3$ operations (n for setting up B).
- Over all n iterations of **while**, line 4. will carry out between n and $n + n_2$ index comparisons
- Over all n iterations of **while**, line 5 will carry out between n and $n + n_1$ index comparisons and between n_1 and n key comparisons.
- Over all n iterations of **while**, lines 6.-11. will carry out $2n$ index updates and n copy operations (keys being copied into B)
- Lines 12.-13. take $2n$ steps.

Therefore the running-time of MERGE satisfies the following:

$$8n + n_1 + 6 \leq T_{\text{MERGE}}(n : n_1, n_2) \leq 9n + n_1 + n_2 + 6$$

We can express a neater bound as

$$8n \leq T_{\text{MERGE}}(n : n_1, n_2) \leq 13n \leq 14n.$$

($n_1 + n_2 = n$, and since $n \geq 2$ we have $3n \geq 6$.)

Running-time of MergeSort

$n = r - p + 1$.
Running time $T_{\mathrm{MS}}(n)$ satisfies:

$$T_{\mathrm{MS}}(n) = \begin{cases} \Theta(1) & \text{if } n = 1, \\ T_{\mathrm{MS}}(\lceil n/2 \rceil) + T_{\mathrm{MS}}(\lfloor n/2 \rfloor) + \Theta(n) & \text{if } n > 1. \end{cases}$$

The $\Theta(n)$ is from analysis of Merge on the previous slide. Analysis of MergeSort gives $\lfloor \frac{n+1}{2} \rfloor$ and $\lceil \frac{n-1}{2} \rceil$ as the subarray sizes - these are same as $\lfloor \frac{n}{2} \rfloor$ and $\lceil \frac{n}{2} \rceil$.

Solving recurrences

Methods for deriving/verifying solutions to recurrences:

Induction Guess the solution and verify by induction on n.

Lovely if your recurrence is "NICE" enough that you can guess-and-verify. Rare.

Unfold and sum "Unfold" the recurrence by iterated substitution on the "neat" values of n (often power of 2 case). At some point a pattern emerges. The "solution" is obtained by evaluating a sum that arises from the pattern.
Since the pattern is just for the "neat" n, the method is rigorous only if we verify the solution (e.g., by a direct induction proof).

Often the only way to do the PROOF neatly is to RELATE to "neat" values of n ... sometimes powers-of-2

"Master Theorem" Match the recurrence against a template. Read off the solution from the Master Theorem.

Upper bounds by first principles

Proof by "first principles"

When working from first principles, need to replace "extra work" terms ($\Theta(n)$ for $\textsc{MergeSort}$*) by terms with explicit constants.*

So we check slide 10 again.

$$T_{\mathrm{MS}}(n) \leq \begin{cases} 1 & \text{if } n = 1, \\ T_{\mathrm{MS}}(\lceil n/2 \rceil) + T_{\mathrm{MS}}(\lfloor n/2 \rfloor) + 14n & \text{if } n > 1. \end{cases} \tag{1}$$

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Unfold-and-sum will give a "guess" for the upper bound:

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Unfold-and-sum will give a "guess" for the upper bound:

$$T_{\mathrm{MS}}(n) \leq 14n\lg(n) + n.$$

Upper bound for MergeSort (n a power-of-2)

$$T'_{\mathrm{MS}}(n) = \begin{cases} 1 & \text{if } n = 1, \\ T'_{\mathrm{MS}}(\lceil n/2 \rceil) + T'_{\mathrm{MS}}(\lfloor n/2 \rfloor) + 14n & \text{if } n > 1. \end{cases} \tag{2}$$

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$$\begin{aligned} T'_{\mathrm{MS}}(n) &= T'_{\mathrm{MS}}(\lceil 2^{k-1} \rceil) + T'_{\mathrm{MS}}(\lfloor 2^{k-1} \rfloor) + 14n \\ &= 2 \cdot T'_{\mathrm{MS}}(2^{k-1}) + 14n \end{aligned}$$

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AS REQUIRED.

Upper bounds for general n

Three steps for turning a "proof for the neat case" into a "proof for all n".

- STEP 1: Prove an exact expression for "neat" n for an equality version $T'(\cdot)$ of the recurrence.

  Done for $T'_{\mathrm{MS}}(n)$ (the proof for $T'_{\mathrm{MS}}(n)$ on slide 14). "Neat" was powers-of-2.

- STEP 2: Prove that the equality version of the recurrence is monotone increasing; ie, that we have $T'(n) \leq T'(m)$ for all n, m with $n < m$ (not just for "neat" n, m).

  This step is why we need to introduce an "equality version" (to prove STEP 2 we will need to work with $T'(n) =$, $T'(m) =$).

- STEP 3: For "not-neat n", choose a close-by "neat $\widehat{n}$" (for proving $O(\cdot)$ bounds, $\widehat{n}$ should be larger; for $\Omega(\cdot)$ bounds, $\widehat{n}$ should be smaller).

  Then apply monotonicity (STEP 2) to show a relationship between $T'(n)$ and $T'(\widehat{n})$, and then substitute the exact expression (from STEP 1) to $T'(\widehat{n})$ to work out an upper bound for $T'(n)$.

Upper bound for MergeSort (general n)

STEP 2: Prove that $T'_{\mathrm{MS}}(n)$ is *monotone increasing*.

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If $n \in \mathbb{N}$ then $T'_{\mathrm{MS}}(n) < T'_{\mathrm{MS}}(m)$ for all $n < m$.

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Induction Hypothesis (IH): Claim holds for all $n = 1, \ldots, h$ (with any $m > n$).

Base Case ($h = 1$):
$T'_{\mathrm{MS}}(1) = 1$.
For $m \geq 2$, $T'_{\mathrm{MS}}(m) \geq 14m \geq 28$, and $28 > T'_{\mathrm{MS}}(1)$, as needed.

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Upper bound for MergeSort (general n) cont'd.

STEP 2 cont'd.

Induction Step (n): Suppose true for all $n \in \mathbb{N}, n = 1, \ldots, h$. Consider $n = h + 1$. We know $n \geq 2$, so the recurrence for n is

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$n \geq 2$ implies $\lfloor \frac{n}{2} \rfloor = \lfloor \frac{h+1}{2} \rfloor < n$ (need strict $<$) so $\lfloor \frac{n}{2} \rfloor \in \{1, \ldots h\}$. So the (IH) can be applied to $\lfloor \frac{n}{2} \rfloor$ with appropriate m-values. $m > n$ implies $\lfloor \frac{m}{2} \rfloor \geq \lfloor \frac{n}{2} \rfloor$, so

- either $\lfloor \frac{n}{2} \rfloor = \lfloor \frac{m}{2} \rfloor$, and hence $T'_{\mathrm{MS}}(\lfloor \frac{n}{2} \rfloor) = T'_{\mathrm{MS}}(\lfloor \frac{m}{2} \rfloor)$.
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Same argument goes through with $\lceil \frac{n}{2} \rceil$. Hence the (IH) shows that each of the first two terms for $T'_{\mathrm{MS}}(n)$ are $\leq$ than the corresponding terms for $T'_{\mathrm{MS}}(m)$.

Upper bound for MergeSort (general n) cont'd.

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- either $\lfloor \frac{n}{2} \rfloor = \lfloor \frac{m}{2} \rfloor$, and hence $T'_{\mathrm{MS}}(\lfloor \frac{n}{2} \rfloor) = T'_{\mathrm{MS}}(\lfloor \frac{m}{2} \rfloor)$.
- or else $\lfloor \frac{m}{2} \rfloor > \lfloor \frac{n}{2} \rfloor$ and taking this together with $\lfloor \frac{n}{2} \rfloor \leq h$, the (IH) implies that $T'_{\mathrm{MS}}(\lfloor \frac{n}{2} \rfloor) < T'_{\mathrm{MS}}(\lfloor \frac{m}{2} \rfloor)$.

Same argument goes through with $\lceil \frac{n}{2} \rceil$. Hence the (IH) shows that each of the first two terms for $T'_{\mathrm{MS}}(n)$ are $\leq$ than the corresponding terms for $T'_{\mathrm{MS}}(m)$. But also $14n < 14m$, so $\ldots \Rightarrow T'_{\mathrm{MS}}(n) < T'_{\mathrm{MS}}(m)$.

Upper bound for MERGESORT (general n) cont'd.

STEP 2 cont'd.

Induction Step (n): Suppose true for all $n \in \mathbb{N}, n = 1, \ldots, h$. Consider $n = h + 1$. We know $n \geq 2$, so the recurrence for n is

$$T'_{\mathrm{MS}}(n) \quad = \quad T'_{\mathrm{MS}}(\lceil n/2 \rceil) + T'_{\mathrm{MS}}(\lfloor n/2 \rfloor) + 14n. \tag{3}$$

We are considering $m > n$ (so definitely $m \geq 2$), and the recurrence for m is

$$T'_{\mathrm{MS}}(m) \quad = \quad T'_{\mathrm{MS}}(\lceil m/2 \rceil) + T'_{\mathrm{MS}}(\lfloor m/2 \rfloor) + 14m.$$

$n \geq 2$ implies $\lfloor \frac{n}{2} \rfloor = \lfloor \frac{h+1}{2} \rfloor < n$ (need strict $<$) so $\lfloor \frac{n}{2} \rfloor \in \{1, \ldots h\}$. So the (IH) can be applied to $\lfloor \frac{n}{2} \rfloor$ with appropriate m-values. $m > n$ implies $\lfloor \frac{m}{2} \rfloor \geq \lfloor \frac{n}{2} \rfloor$, so

- either $\lfloor \frac{n}{2} \rfloor = \lfloor \frac{m}{2} \rfloor$, and hence $T'_{\mathrm{MS}}(\lfloor \frac{n}{2} \rfloor) = T'_{\mathrm{MS}}(\lfloor \frac{m}{2} \rfloor)$.
- or else $\lfloor \frac{m}{2} \rfloor > \lfloor \frac{n}{2} \rfloor$ and taking this together with $\lfloor \frac{n}{2} \rfloor \leq h$, the (IH) implies that $T'_{\mathrm{MS}}(\lfloor \frac{n}{2} \rfloor) < T'_{\mathrm{MS}}(\lfloor \frac{m}{2} \rfloor)$.

Same argument goes through with $\lceil \frac{n}{2} \rceil$. Hence the (IH) shows that each of the first two terms for $T'_{\mathrm{MS}}(n)$ are $\leq$ than the corresponding terms for $T'_{\mathrm{MS}}(m)$.
But also $14n < 14m$, so $\ldots \Rightarrow T'_{\mathrm{MS}}(n) < T'_{\mathrm{MS}}(m)$.
Hence by Induction, $T'_{\mathrm{MS}}(n) < T'_{\mathrm{MS}}(m)$ for all n, for all $m > n$.

Upper bound for MergeSort (general n) cont'd.

STEP 3: Choose a "power of 2" to relate to n.

Upper bound for MergeSort (general n) cont'd.

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- Want an upper bound, so need a power of 2 *greater than* n.

Upper bound for MERGESORT (general n) cont'd.

STEP 3: Choose a "power of 2" to relate to n.

- Want an upper bound, so need a power of 2 *greater than n*.
- So define $\widehat{n} = 2^{\lceil \lg(n) \rceil}$ (this will be "m").

Upper bound for MERGESORT (general n) cont'd.

STEP 3: Choose a "power of 2" to relate to n.

- Want an upper bound, so need a power of 2 *greater than* n.
- So define $\widehat{n} = 2^{\lceil \lg(n) \rceil}$ (this will be "m").
- We know $n \leq \widehat{n}$ but $\widehat{n} < 2n$.

Upper bound for MergeSort (general n) cont'd.

STEP 3: Choose a "power of 2" to relate to n.

- Want an upper bound, so need a power of 2 *greater than n*.
- So define $\widehat{n} = 2^{\lceil \lg(n) \rceil}$ (this will be "m").
- We know $n \leq \widehat{n}$ but $\widehat{n} < 2n$.
- Monotonicity property from STEP 2 tells us $T'_{\mathrm{MS}}(n) \leq T'_{\mathrm{MS}}(\widehat{n})$

Upper bound for MergeSort (general n) cont'd.

STEP 3: Choose a "power of 2" to relate to n.

- Want an upper bound, so need a power of 2 *greater than n*.
- So define $\widehat{n} = 2^{\lceil \lg(n) \rceil}$ (this will be "m").
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- Proof of Upper bound for POWERS OF 2 tells us $T'_{\mathrm{MS}}(\widehat{n}) \leq 14\widehat{n}\lg(\widehat{n}) + \widehat{n}$.

Upper bound for MERGESORT (general n) cont'd.

STEP 3: Choose a "power of 2" to relate to n.

- Want an upper bound, so need a power of 2 *greater than* n.
- So define $\widehat{n} = 2^{\lceil \lg(n) \rceil}$ (this will be "m").
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- Proof of Upper bound for POWERS OF 2 tells us $T'_{\mathrm{MS}}(\widehat{n}) \leq 14\widehat{n}\lg(\widehat{n}) + \widehat{n}$.
- By $\widehat{n} < 2n$, we get

$$T'_{\mathrm{MS}}(n) \leq T'_{\mathrm{MS}}(\widehat{n}) \leq 14\widehat{n}(\lg(\widehat{n})) + \widehat{n} < 14(2n)\lg(2n) + 2n = 28n\lg(n) + 30n.$$

Upper bound for MergeSort (general n) cont'd.

STEP 3: Choose a "power of 2" to relate to n.

- Want an upper bound, so need a power of 2 *greater than* n.
- So define $\widehat{n} = 2^{\lceil \lg(n) \rceil}$ (this will be "m").
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So for any $n \in \mathbb{N}$ we have $T'_{\mathrm{MS}}(n) \leq 28n\lg(n) + 30n$.

Upper bound for MERGESORT (general n) cont'd.

STEP 3: Choose a "power of 2" to relate to n.

- Want an upper bound, so need a power of 2 *greater than* n.
- So define $\widehat{n} = 2^{\lceil \lg(n) \rceil}$ (this will be "m").
- We know $n \leq \widehat{n}$ but $\widehat{n} < 2n$.
- Monotonicity property from STEP 2 tells us $T'_{\mathrm{MS}}(n) \leq T'_{\mathrm{MS}}(\widehat{n})$
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- By $\widehat{n} < 2n$, we get

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So for any $n \in \mathbb{N}$ we have $T'_{\mathrm{MS}}(n) \leq 28n\lg(n) + 30n$.

Hence $T'_{\mathrm{MS}}(n) = O(n\lg(n))$, and (of course) $T_{\mathrm{MS}}(n) = O(n\lg(n))$.

Proving a lower bound

The "first principles" proof is essentially a *direct* proof of a sub-case of the Master Theorem.

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The "first principles" proof is essentially a *direct* proof of a sub-case of the Master Theorem.

Slide 15 described the usual structure of proving $O(\cdot)$ bounds for general $n \in \mathbb{N}$. When wanting to instead give a "first principles" proof of $\Omega(\cdot)$ for a recurrence $T(n)$, there are slight differences:

- (different) Consider an equality version $T'(\cdot)$ of the recurrence $T(\cdot)$ such that $T(n) \geq T'(n)$ holds *for all* $n \in \mathbb{N}$.
- (same) STEP 1: Prove an exact expression for T' for the "NEAT" case (power-of-2 here, but would be power-of-d if $\lfloor n/d \rfloor, \lceil n/d \rceil$ was involved)
- (same) STEP 2: Prove $T'(n)$ is monotonically increasing with n for general n.
- (different) STEP 3: Consider the closest power-of-d *less than* n, say $\widehat{n}$, for a non-neat $n \in \mathbb{N}$. Then exploit $T(n) \geq T'(n)$ (by definition), $T'(n) \geq T'(\widehat{n})$ (from STEP 2), and then substitute in the exact expression for $T'(\widehat{n})$ (because $\widehat{n}$ is "NEAT") and work from there.

Reading and Working

Reading Assignment

Inf2B ADS Lecture Notes 2 and 8.

[CLRS] Sections 2.1, 2.2 and 2.3 (of 3rd or 2nd edition). Also Section 3.1 (omitting the bits on the little-o and little-ω notation at the end).

(all this material should be familiar from Inf2B and your math classes)