Lecture 5: Master Method and Quick-Sort

(CLRS 4.3-4.4 (read this note instead), 7.1-7.2)

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1 Master Method (recurrences)

- We have solved several recurrences using *substitution* and *iteration*.
- Last time we solved several recurrences of the form $T(n) = aT(n/b) + n^c \quad (T(1) = 1)$.
  - Strassen's algorithm $\Rightarrow T(n) = 7T(n/2) + n^2$ ($a = 7, b = 2$, and $c = 2$)
  - Merge-sort $\Rightarrow T(n) = 2T(n/2) + n$ ($a = 2, b = 2$, and $c = 1$).
- It would be nice to have a general solution to the recurrence $T(n) = aT(n/b) + n^c$.
- We do!

$$\boxed{\begin{array}{l} T(n) = aT\left(\frac{n}{b}\right) + n^c \quad a \geq 1, b \geq 1, c > 0 \\ \Downarrow \\ T(n) = \begin{cases} \Theta(n^{\log_b a}) & a > b^c \\ \Theta(n^c \log_b n) & a = b^c \\ \Theta(n^c) & a < b^c \end{cases} \end{array}}$$

Proof (Iteration method)

$$\begin{aligned} T(n) &= aT\left(\tfrac{n}{b}\right) + n^c \\ &= n^c + a\left(\left(\tfrac{n}{b}\right)^c + aT\left(\tfrac{n}{b^2}\right)\right) \\ &= n^c + \left(\tfrac{a}{b^c}\right)n^c + a^2T\left(\tfrac{n}{b^2}\right) \\ &= n^c + \left(\tfrac{a}{b^c}\right)n^c + a^2\left(\left(\tfrac{n}{b^2}\right)^c + aT\left(\tfrac{n}{b^3}\right)\right) \\ &= n^c + \left(\tfrac{a}{b^c}\right)n^c + \left(\tfrac{a}{b^c}\right)^2 n^c + a^3T\left(\tfrac{n}{b^3}\right) \\ &= \ldots \\ &= n^c + \left(\tfrac{a}{b^c}\right)n^c + \left(\tfrac{a}{b^c}\right)^2 n^c + \left(\tfrac{a}{b^c}\right)^3 n^c + \left(\tfrac{a}{b^c}\right)^4 n^c + \ldots + \left(\tfrac{a}{b^c}\right)^{\log_b n - 1} n^c + a^{\log_b n}T(1) \\ &= n^c \sum_{k=0}^{\log_b n - 1}\left(\tfrac{a}{b^c}\right)^k + a^{\log_b n} \\ &= n^c \sum_{k=0}^{\log_b n - 1}\left(\tfrac{a}{b^c}\right)^k + n^{\log_b a} \end{aligned}$$

Recall geometric sum $\sum_{k=0}^{n} x^k = \frac{x^{n+1}-1}{x-1} = \Theta(x^n)$

- $\boxed{a < b^c}$

  $a < b^c \Leftrightarrow \frac{a}{b^c} < 1 \Rightarrow \sum_{k=0}^{\log_b n - 1}\left(\frac{a}{b^c}\right)^k \leq \sum_{k=0}^{+\infty}\left(\frac{a}{b^c}\right)^k = \frac{1}{1-\left(\frac{a}{b^c}\right)} = \Theta(1)$

  $a < b^c \Leftrightarrow \log_b a < \log_b b^c = c$

$$\begin{aligned} T(n) &= n^c \sum_{k=0}^{\log_b n - 1}\left(\tfrac{a}{b^c}\right)^k + n^{\log_b a} \\ &= n^c \cdot \Theta(1) + n^{\log_b a} \\ &= \Theta(n^c) \end{aligned}$$

- $\boxed{a = b^c}$

  $a = b^c \Leftrightarrow \frac{a}{b^c} = 1 \Rightarrow \sum_{k=0}^{\log_b n-1} \left(\frac{a}{b^c}\right)^k = \sum_{k=0}^{\log_b n-1} 1 = \Theta(\log_b n)$
  $a = b^c \Leftrightarrow \log_b a = \log_b b^c = c$

  $$\begin{aligned} T(n) &= \sum_{k=0}^{\log_b n-1} \left(\frac{a}{b^c}\right)^k + n^{\log_b a} \\ &= n^c \Theta(\log_b n) + n^{\log_b a} \\ &= \Theta(n^c \log_b n) \end{aligned}$$

- $\boxed{a > b^c}$

  $a > b^c \Leftrightarrow \frac{a}{b^c} > 1 \Rightarrow \sum_{k=0}^{\log_b n-1} \left(\frac{a}{b^c}\right)^k = \Theta\left(\left(\frac{a}{b^c}\right)^{\log_b n}\right) = \Theta\left(\frac{a^{\log_b n}}{(b^c)^{\log_b n}}\right) = \Theta\left(\frac{a^{\log_b n}}{n^c}\right)$

  $$\begin{aligned} T(n) &= n^c \cdot \Theta\left(\frac{a^{\log_b n}}{n^c}\right) + n^{\log_b a} \\ &= \Theta(n^{\log_b a}) + n^{\log_b a} \\ &= \Theta(n^{\log_b a}) \end{aligned}$$

- Note: Book states and proves the result slightly differently (don't read it).

1.1 Other recurrences

Some important/typical bounds on recurrences not covered by master method:

- Logarithmic: $\Theta(\log n)$
  - Recurrence: $T(n) = 1 + T(n/2)$
  - Typical example: Recurse on half the input (and throw half away)
  - Variations: $T(n) = 1 + T(99n/100)$
- Linear: $\Theta(N)$
  - Recurrence: $T(n) = 1 + T(n-1)$
  - Typical example: Single loop
  - Variations: $T(n) = 1 + 2T(n/2), T(n) = n + T(n/2), T(n) = T(n/5) + T(7n/10 + 6) + n$
- Quadratic: $\Theta(n^2)$
  - Recurrence: $T(n) = n + T(n-1)$
  - Typical example: Nested loops
- Exponential: $\Theta(2^n)$
  - Recurrence: $T(n) = 2T(n-1)$

2 Quick-sort

- We previously saw how divide-and-conquer can be used to design sorting algorithm—Merge-sort
  - Partition n elements array A into two subarrays of $n/2$ elements each
  - Sort the two subarrays recursively
  - Merge the two subarrays

  Running time: $T(n) = 2T(n/2) + \Theta(n) \Rightarrow T(n) = \Theta(n \log n)$

- Another possibility is to used the "opposite" version of divide-and-conquer—Quick-sort
  - Partition $A[1...n]$ into subarrays $A' = A[1..q]$ and $A" = A[q+1...n]$ such that all elements in $A"$ are larger than all elements in A'.
  - Recursively sort A' and $A"$.
  - (nothing to combine/merge. A already sorted after sorting A' and $A"$)

  If $q = n/2$ and we divide in $\Theta(n)$ time, we again get the recurrence $T(n) = 2T(n/2) + \Theta(n)$ for the running time $\Rightarrow T(n) = \Theta(n \log n)$

  The problem is that it is hard to develop partition algorithm which always divide A in two halves

- Pseudo code for Quick-sort:

```
QUICKSORT(A, p, r)
IF p < r THEN
    q=PARTITION(A, p, r)
    QUICKSORT(A, p, q − 1)
    QUICKSORT(A, q + 1, r)
FI
```

  Sort using QUICKSORT$(A, 1, n)$

```
PARTITION(A, p, r)
x = A[r]
i = p − 1
FOR j = p TO r − 1 DO
    IF A[j] ≤ x THEN
        i = i + 1
        Exchange A[i] and A[j]
    FI
OD
Exchange A[i + 1] and A[r]
RETURN i + 1
```

- PARTITION runs in time $\Theta(n)$

- Correctness:
  - Clear if PARTITION divides correctly
  - Example:

$$\begin{array}{ll}
\vert\ 2\ \ 8\ \ 7\ \ 1\ \ 3\ \ 5\ \ 6\ \ 4 & \text{i=0, j=1} \\
2\ \vert\ 8\ \ 7\ \ 1\ \ 3\ \ 5\ \ 6\ \ 4 & \text{i=1, j=2} \\
2\ \vert\ 8\ \vert\ 7\ \ 1\ \ 3\ \ 5\ \ 6\ \ 4 & \text{i=1, j=3} \\
2\ \vert\ 8\ \ 7\ \vert\ 1\ \ 3\ \ 5\ \ 6\ \ 4 & \text{i=1, j=4} \\
2\ \ 1\ \vert\ 7\ \ 8\ \vert\ 3\ \ 5\ \ 6\ \ 4 & \text{i=2, j=5} \\
2\ \ 1\ \ 3\ \vert\ 8\ \ 7\ \vert\ 5\ \ 6\ \ 4 & \text{i=3, j=6} \\
2\ \ 1\ \ 3\ \vert\ 8\ \ 7\ \ 5\ \vert\ 6\ \ 4 & \text{i=3, j=7} \\
2\ \ 1\ \ 3\ \vert\ 8\ \ 7\ \ 5\ \ 6\ \vert\ 4 & \text{i=3, j=8} \\
2\ \ 1\ \ 3\ \vert\ 4\ \vert\ 7\ \ 5\ \ 6\ \ 8 & \text{q=4}
\end{array}$$

  - PARTITION can be proved correct (by induction) using the loop invariant:
    - $A[k] \leq x$ for $p \leq k \leq i$
    - $A[k] > x$ for $i + 1 \leq k \leq j - 1$
    - $A[k] = x$ for $k = r$
- Running time depends on how well PARTITION divides A.
  - In the example it does reasonably well.
  - In the worst case q is always p and the running time becomes $T(n) = \Theta(n) + T(1) + T(n-1) \Rightarrow T(n) = \Theta(n^2)$.
    - and what is maybe even worse, the worst case is when A is already sorted.
- So why is it called "quick"-sort? Because it "often" performs very well—can we theoretically justify this?
  - Even if all the splits are relatively bad, we get $\Theta(n \log n)$ time:
    - Example: Split is $\frac{9}{10}n$, $\frac{1}{10}n$.
      $T(n) = T(\frac{9}{10}n) + T(\frac{1}{10}n) + n$
      Solution?
      Guess: $T(n) \leq cn \log n$
      Induction

$$\begin{aligned}
T(n) &= T(\frac{9}{10}n) + T(\frac{1}{10}n) + n \\
&\leq \frac{9cn}{10}\log(\frac{9n}{10}) + \frac{cn}{10}\log(\frac{n}{10}) + n \\
&\leq \frac{9cn}{10}\log n + \frac{9cn}{10}\log(\frac{9}{10}) + \frac{cn}{10}\log n + \frac{cn}{10}\log(\frac{1}{10}) + n \\
&\leq cn\log n + \frac{9cn}{10}\log 9 - \frac{9cn}{10}\log 10 - \frac{cn}{10}\log 10 + n \\
&\leq cn\log n - n(c\log 10 - \frac{9c}{10}\log 9 - 1)
\end{aligned}$$

$T(n) \leq cn \log n$ if $c \log 10 - \frac{9c}{10}\log 9 - 1 > 0$ which is definitely true if $c > \frac{10}{\log 10}$

- So, in other words, if just the splits happen at a constant fraction of n we get $\Theta(n \lg n)$—or, its almost never bad!

- Next time we will further justify the good practical performance by looking at average case running time.