Average Case Analysis of Quicksort

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We assume that all elements are equally likely to be chosen as the pivot element in PARTITION. When partitioning an array of size n into two subarrays, we have the following possible sizes of the subarrays.

left array	right array
$n-1$	0
$n-2$	1
$n-3$	2
.	.
.	.
.	.
1	$n-2$
0	$n-1$

So we have

$$T(n) = \frac{1}{n}\sum_{j=0}^{n-1}(T(j) + T(n-j-1)) + n \quad (1)$$

$$= \frac{2}{n}\sum_{k=0}^{n-1} T(k) + n \quad (2)$$

$$= \frac{2}{n}\sum_{k=1}^{n-1} T(k) + n \quad \text{(no recursive call for 0-sized subproblem)} \quad (3)$$

Replacing n with $n-1$, we get

$$T(n-1) = \frac{2}{n-1}\sum_{k=1}^{n-2} T(k) + n - 1 \quad (4)$$

Multiplying (3) by n and (4) by $n-1$:

$$nT(n) = 2\sum_{k=1}^{n-1} T(k) + n^2 \quad (5)$$

$$(n-1)T(n-1) = 2\sum_{k=1}^{n-2} T(k) + (n-1)^2 \quad (6)$$

Subtracting (6) from (5), we get

$$nT(n) - (n-1)T(n-1) = 2T(n-1) + 2n - 1 \quad (7)$$

$$\Longrightarrow nT(n) = (n+1)T(n-1) + 2n - 1 \quad (8)$$

$$\Longrightarrow T(n) = \frac{n+1}{n}T(n-1) + 2 - \frac{1}{n}. \quad (9)$$

Ignoring the $1/n$ term in (9), we have

$$T(n) \leq \frac{n+1}{n}T(n-1) + 2 \quad (10)$$

Method 1: We solve (10) by iteration:

$$
\begin{aligned}
T(n) &\le 2 + \frac{n+1}{n}T(n-1) \\
&\le 2 + \frac{n+1}{n}(2 + \frac{n}{n-1}T(n-2)) \\
&= 2 + 2\frac{n+1}{n} + \frac{n+1}{n-1} + T(n-2) \\
&\le 2 + 2\frac{n+1}{n} + \frac{n+1}{n-1}(2 + \frac{n-1}{n-2}T(n-3)) \\
&= 2 + 2\frac{n+1}{n} + 2\frac{n+1}{n-1} + \frac{n+1}{n-2}T(n-3) \\
&= 2\frac{n+1}{n+1} + 2\frac{n+1}{n} + 2\frac{n+1}{n-1} + \frac{n+1}{n-2}T(n-3) \\
&. \\
&. \\
&. \\
&= 2(n+1)\sum_{i=0}^{k-1}\frac{1}{(n+1)-i} + \frac{n+1}{n-(k-1)}T(n-k) \\
&= 2(n+1)\sum_{i=0}^{n-2}\frac{1}{(n+1)-i} + \frac{n+1}{2}T(1) \\
&= 2(n+1)\sum_{j=3}^{n+1}\frac{1}{j} + \frac{n+1}{2}\Theta(1) \\
&= 2(n+1)\Theta(\ln n) + \Theta(n) \\
&= \Theta(n\log n)
\end{aligned}
$$

Method 2: Dividing (10) by $n+1$:

$$\frac{T(n)}{n+1} \le \frac{T(n-1)}{n} + \frac{2}{n+1}$$

Let $R(n) = \frac{T(n)}{n+1}$ (and thus, $R(n-1) = \frac{T(n-1)}{n}$). We have

$$R(n) \le R(n-1) + \frac{2}{n+1}$$

Note that $R(1) = \frac{T(1)}{1+1} = \Theta(1)$. We get

$$
\begin{aligned}
R(n) &\le \frac{2}{n+1} + \frac{2}{n} + \frac{2}{n-1} + \cdots + \frac{2}{3} + R(1) \\
&= 2\sum_{k=3}^{n+1}\frac{1}{k} + \Theta(1) \\
&= \Theta(\ln n)
\end{aligned}
$$

Therefore,

$$
\begin{aligned}
T(n) &= (n+1)R(n) \\
&= (n+1)\Theta(\ln n) \\
&= \Theta(n\ln n)
\end{aligned}
$$