Algorithm 1 Quicksort(A, p, r)

1: if \( p < r \) then
2: \( q \leftarrow \text{Partition}(A, p, r) \)
3: Quicksort(A, p, q - 1)
4: Quicksort(A, q + 1, r)
5: end if
After the partition has been called the following is true:

1. $p \leq q \leq r$.
2. The number $A[q]$ is in its final position. It will never be moved again.

Remember that $q$ is the position of the pivot after partitioning.
The Partition Method

Algorithm 2 Partition(A,p,r)

1: \( x \leftarrow A[r] \) \( \triangleright \) \( x \) is the “pivot”.
2: \( i \leftarrow p - 1 \) \( \triangleright \) \( i \) maintains the “left-right boundary”.
3: \textbf{for} \( j \leftarrow p \) to \( r - 1 \) \textbf{do}
4: \hspace{1em} \textbf{if} \( A[j] \leq x \) \textbf{then}
5: \hspace{2em} \( i \leftarrow i + 1 \)
6: \hspace{1em} \text{exchange} \ A[i] \leftrightarrow A[j]
7: \hspace{1em} \textbf{end if}
8: \textbf{end for}
9: \text{exchange} \ A[i + 1] \leftrightarrow A[r]
10: \textbf{return} \ i + 1
The Partition Method

(a) 2 8 7 1 3 5 6 4
   i p, j r

(b) 2 8 7 1 3 5 6 4
   p, i j r

(c) 2 8 7 1 3 5 6 4
   p, i j r
The Partition Method

(d) $p, i \quad j \quad r$

2 8 7 1 3 5 6 4

(e) $p \quad i \quad j \quad r$

2 1 7 8 3 5 6 4

(f) $p \quad i \quad j \quad r$

2 1 3 8 7 5 6 4

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The Partition Method

(g) 2 1 3 8 7 5 6 4

(h) 2 1 3 8 7 5 6 4

(i) 2 1 3 4 7 5 6 8
Lemma

At the beginning of each iteration:

- $A[p..i]$ are known to be $\leq$ pivot.
- $A[i + 1..j - 1]$ are known to be $> pivot$.
- $A[r]$ is the pivot.
Proof.

Base: When we start out, \( j = p \), \( i = p - 1 \), and the above are trivially true.

At the top of iteration \( j_0 \) of the for loop, \( i \) has the value \( i_0 \). Then by inductive hypothesis, at the top of that iteration of the for loop,

- All entries in \( A[p..i_0] \) are \( \leq \text{pivot} \).
- All entries in \( A[i_0 + 1..j_0 - 1] \) are \( > \text{pivot} \).
- \( A[j_0..r - 1] \) consists of elements whose contents have not yet been examined.
- \( A[r] = \text{pivot} \).
Proof.

- $A[j_0]$ and $A[i_0 + 1]$ are interchanged.
- $i_0 \to i_1 = i_0 + 1$, which is the value of $i$ at the top of the next iteration of the for loop.

At the next iteration of the for loop $j \to j_1 = j_0 + 1$. Thus, since we interchanged $A[j_0]$ and $A[i_0 + 1]$, we have

- All entries in $A[p..i_1]$ are $\leq$ pivot.
- All entries in $A[i_1 + 1..j_1 - 1]$ are $> pivot$. (These are the same elements that were originally in $A[i_0 + 1..j_0 - 1]$. The first one has been moved up to the end.)
- $A[j_1..r - 1]$ have not yet been examined.

And this is just the inductive hypothesis at the top of the $j_0 + 1 = j_1$ iteration of the for loop.
Proof.

Nothing is done. At the next iteration of the for loop, we have

- $i_1 = i_0$ (because we didn’t increment $i$).
- $j_1 = j_0 + 1$ (because we always increment $j$ when we go to the next iteration).
- No change was made to the elements of the array $A$.

Thus, we have

- All entries in $A[p..i_1]$ continue to be $\leq$ $\text{pivot}$.
- All entries in $A[i_1 + 1..j_1 - 1]$ are $>$ the pivot. These are the original elements $A[i_0 + 1..j_0 - 1]$ plus $A[j_1 - 1] = A[j0]$
- $A[j_1..r - 1]$ have not yet been examined.
- $A[r] = \text{pivot}$

And this is just the the inductive hypothesis at the top of the $j_0 + 1 = j_1$ iteration of the for loop. This completes the proof.  

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Proof.

- At the conclusion of the for loop, element $r$ (which is the pivot element) is exchanged with element $i+1$ (which is the left-most element that is greater than the pivot element).
- This ensures that all the elements to the left of the pivot element have values $\leq$ the pivot, and all the elements to the right of the pivot element have values $>\$ the pivot.
The runtime of partition is clearly $\Theta(n)$.

The best case is when the array is partitioned into two equal parts.

In this case the recurrence is $T(n) = 2T(n/2) + \Theta(n)$.

We already know this is $\Theta(n \log n)$.
The worst case happens when the pivot partitions the array into two sub arrays of size n-1 and 0.

With our setting, this happens when the array is already sorted.

Thus we have:

\[ T(n) = T(n - 1) + T(0) + \Theta(n) \]

\[ = T(n - 1) + \Theta(n) = \sum_{j=0}^{n} \Theta(j) = \Theta\left(\frac{n(n+1)}{2}\right) = \Theta(n^2) \]
We know the average runtime is $O(n \log n)$.
This means that on average we hit a "good" case.
This is quite untypical, as usually the average case is no better than the worst case.
What happens if the pivot divides the array into two sub-arrays of 0.9n and 0.1n?

\[ T(n) \leq cn \]

\[ T\left( \frac{1}{10} n \right) \]

\[ T\left( \frac{1}{100} n \right) \]

\[ T(1) \]

level \( \log_{10} n \)

\[ T\left( \frac{9}{10} n \right) \]

\[ T\left( \frac{9}{100} n \right) \]

level \( \log_{10/9} n \)

\[ T\left( \frac{81}{100} n \right) \]

\[ T\left( \frac{729}{1000} n \right) \]

\[ \leq cn \]

\[ T(1) \leq cn \]
Running Time – Average Case

- There are $1 + \log_{(10/9)} n$ levels and each has $O(n)$ cost.
- The total cost is therefore $O(n \log n)$.
- In other words – quicksort is not THAT sensitive to the choice of pivot.
- But – the pivot is not always at the same relative position.
- What happens if occasionally it is as bad as can be?
- Suppose every other iteration the pivot is the largest element.
We simply double the number of levels, it is still $O(n \log(n))$
Randomized Analysis

- Remember the average runtime analysis of insertion sort.
- We averaged the running time over all possible inputs assuming they are all equally likely – random input, distributed uniformly.
- To do an average runtime analysis we have to know the distribution of the input.
• Probabilistic analysis is the use of probability to analyze the runtime of an algorithm.
• It is used to calculate the average running time, assuming knowledge of the distribution of the input.
• A randomized algorithm is an algorithm that involves some randomness as part of its run.
• This doesn’t mean the input is random.
We have a random number generator Random(p,r) which produces numbers between p and r, each with equal probability.

- The selected number is the pivot index.
- In practice most random algorithms produce pseudo-random numbers.
- When analyzing the running time of a randomized algorithm we take the expected run time over all inputs.
Define a function as follows:

**Algorithm 3 RandomizedPartition(A,p,r)**

1. \(i \leftarrow \text{Random}(p, r)\)
2. \(\text{Exchange} A[i] \leftrightarrow A[r]\)
3. \text{return} \hspace{0.5em} \text{Partition}(A, p, r)
Accordingly:

**Algorithm 4 RandomizedQuicksort(A,p,r)**

1. **if** $p < r$ **then**
2. $q \leftarrow \text{RandomizedPartition}(A, p, r)$
3. $\text{RandomizedQuicksort}(A, p, q - 1)$
4. $\text{RandomizedQuicksort}(A, q + 1, r)$
5. **end if**
Let $T(n)$ be the worst case running time for quicksort (or randomized quicksort).

We know there is a constant $a > 0$ such that

$$T(n) \leq \max_{0 \leq q \leq n-1} \left( T(q) + T(n - q - 1) \right) + an$$

We know that probably $T(n) = O(n^2)$.

This means there is a constant $c$ such that $T(n) \leq cn^2$. 

Proof by induction.

- This is certainly true for \( k=1 \).
- Suppose this is true for all \( k < n \) with some fixed constant \( c \).

\[
T(n) \leq \max_{0 \leq q \leq n-1} \left( T(q) + T(n - q - 1) \right) + an
\]

\[
\leq c \max_{0 \leq q \leq n-1} \left( q^2 + (n - q - 1)^2 \right) + an
\]

- The expression \( (q^2 + (n - q - 1)^2) \) is a convex function, achieving a maximum at the endpoints – 0 and \( n-1 \).
- In those endpoints the value is \( (n - 1)^2 \).
Proof by induction, Cont.

Therefore:

\[ T(n) \leq \max_{0 \leq q \leq n-1} \left( T(q) + T(n - q - 1) \right) + an \]

\[ \leq c \max_{0 \leq q \leq n-1} \left( q^2 + (n - q - 1)^2 \right) + an \]

\[ \leq cn^2 - c(2n - 1) + an \]

\[ = cn^2 - (2c - a)n + c \]

\[ \leq cn^2 - (2c - a)n + cn \]

\[ = cn^2 - (c - a)n \]

Assuming \( n \geq 1 \) and picking a large enough \( c \) so that \( c \geq a \).

† Here’s where we use the assumption that \( n \geq 1 \).
The above gives an upper bound to the worst case runtime.

Previously we have seen a case where the runtime is quadratic.

That's when the pivot always divides the array into n-1 and 0 sub-arrays.

We now saw that $T(n) = O(n^2)$.

So in the worst case $T(n) = \Theta(n^2)$. 
It is easy to use Randomized-Quicksort.

Let $T(n)$ be the average runtime for an array of size $n$:

$$T(n) = \frac{1}{n} \sum_{q=0}^{n-1} (T(q) + T(n - q - 1)) + cn + \Theta(1).$$

Which is actually $T(n) = \frac{2}{n} \sum_{q=0}^{n-1} T(q) + cn + \Theta(1)$.

We wrote $cn + \Theta(1)$ rather than $\Theta(n)$ since we can assume we do “everything” every time we call Partition.

This is a worst case assumption that allows us to do something really nice mathematically.
Multiplying by $n$ we get:
\[ nT(n) = 2 \sum_{q=0}^{n-1} T(q) + cn^2 + \Theta(n) \]

Multiplying by $n + 1$ we get:
\[ (n + 1)T(n + 1) = 2 \sum_{q=0}^{n} T(q) + c(n + 1)^2 + \Theta(n) \]

Subtracting the two cancels most terms out:
\[ (n + 1)T(n + 1) - nT(n) = 2T(n) + \Theta(n) \]
- Collecting terms: \((n + 1)T(n + 1) = (n + 2)T(n) + \Theta(n)\)
- Dividing by \((n + 1)(n + 2)\) we get: \(\frac{T(n+1)}{n+2} = \frac{T(n)}{n+1} + \Theta\left(\frac{1}{n}\right)\)
- Defining \(g(n) = \frac{T(n)}{(n+1)}\): \(g(n + 1) = g(n) + \Theta\left(\frac{1}{n}\right)\)
- Thus: \(g(n) = \Theta\left(\sum_{k=1}^{n-1} \frac{1}{k}\right) = \Theta(\log n)\)
- Going back to \(T\): \(T(n) = (n + 1)g(n) = \Theta(n \log n)\)
The total cost = the sum of the costs of all the calls to RandomizedPartition.

The cost of a call to RandomizedPartition is $O(\text{No. for loop executions})$ which is $O(\text{No. comparisons})$.

The expected cost of RandomizedQuicksort is $O(\text{expected number of comparisons})$.

Notice that once a key $x_k$ is chosen as pivot, the elements to its left will never be compared to the elements to its right.
Consider \( \{x_i, x_{i+1}, \ldots, x_{j-1}, x_j\} \), the set of keys in sorted order.

Any two keys here are compared only if one of them is pivot and that is the last time they are all in the same partition.

Each key is equally likely to be chosen.

\( x_i \) and \( x_j \) can be compared only if one of them is pivot and this will only happen if this is the first pivot from the set \( \{x_i, x_{i+1}, \ldots, x_{j-1}, x_j\} \).

The probability of this is \( \frac{2}{(j-i+1)} \).
The expected number of comparisons is:

$$\sum_{i<j} \frac{2}{j - i + 1} = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \frac{2}{j - i + 1} = \sum_{i=1}^{n-1} \sum_{k=1}^{n-i} \frac{2}{k + 1} \leq \sum_{i=1}^{n-1} \sum_{k=1}^{n} \frac{2}{k} = 2(n - 1)H_n = O(n \log n)$$