

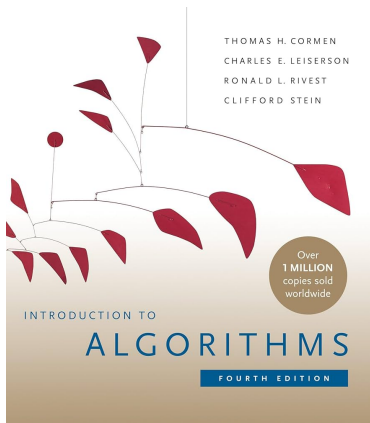
# Introduction to Algorithms

## Lecture 4: Quicksort

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Massachusetts Institute of Technology

August 18, 2025

# Introduction to Algorithms



Content has been extracted from *Introduction to Algorithms*, Fourth Edition, by Cormen, Leiserson, Rivest, and Stein. MIT Press. 2022.

Visit <https://mitpress.mit.edu/9780262046305/introduction-to-algorithms/>.

Original slides from *Introduction to Algorithms 6.046J/18.401J*, Fall 2005 Class by Prof. Charles Leiserson and Prof. Erik Demaine. MIT OpenCourseWare Initiative available at <https://ocw.mit.edu/courses/6-046j-introduction-to-algorithms-sma-5503-fall-2005/>.

# Plan

Description of Quicksort

Divide & Conquer

Partitioning

Worst-case Analysis

Intuition

Randomized Quicksort

Analysis

Expected Running Time

# Quicksort

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- ▶ Divide-and-conquer algorithm.
- ▶ Sorts ‘in place’ (like insertion sort, but not like merge sort).
- ▶ Very practical (with tuning).

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# Divide and Conquer

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Key:

Linear-time partitioning subroutine.

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## Partitioning Subroutine

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2:    $x \leftarrow A[r]$ 
3:    $i \leftarrow p - 1$ 
4:   for  $j \leftarrow p$  to  $r - 1$  do
5:     if  $A[j] \leq x$  then
6:        $i \leftarrow i + 1$ 
7:       exchange  $A[i] \leftrightarrow A[j]$ 
8:     end if
9:   end for
10:  exchange  $A[i + 1] \leftrightarrow A[r]$ 
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$O(n)$  for  $n$  elements.



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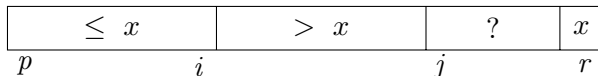
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$O(n)$  for  $n$  elements.

**Invariants:**

$\leq x$	$> x$	?	$x$
$p$	$i$	$j$	$r$

## Loop Invariants: Definition



At the beginning of each iteration of the loop (lines 4–9), for any array index  $k$ :

1. **Low side:** If  $p \leq k \leq i$ , then  $A[k] \leq x$ .
2. **High side:** If  $i + 1 \leq k \leq j - 1$ , then  $A[k] \geq x$ .
3. **Pivot:** If  $k = r$ , then  $A[k] = x$ .

These conditions define the partitioning into three regions:

- ▶ Elements  $\leq x$  (low side).
- ▶ Elements  $> x$  (high side).
- ▶ The pivot element.

# Initialization and Maintenance

## Initialization:

- ▶ Before first iteration:  $i = p - 1$ ,  $j = p$ .
- ▶ No values yet examined, so invariants hold trivially.
- ▶ Line 2 ensures pivot condition (3) holds.

## Maintenance:

- ▶ If  $A[j] > x$ : only increment  $j$ , preserving high side property.
- ▶ If  $A[j] \leq x$ : increment  $i$ , swap  $A[i]$  and  $A[j]$ , then increment  $j$ .
- ▶ Swapping ensures  $A[i] \leq x$  and  $A[i + 1] \dots A[j - 1] > x$ .

# Termination and Correctness

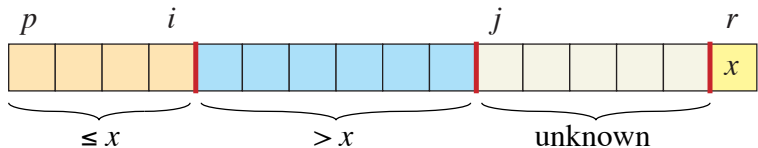
## Termination:

- ▶ Loop ends when  $j = r$ .
- ▶ The unexamined subarray  $A[j \dots r - 1]$  is empty.
- ▶ All entries are in one of the three invariant regions.

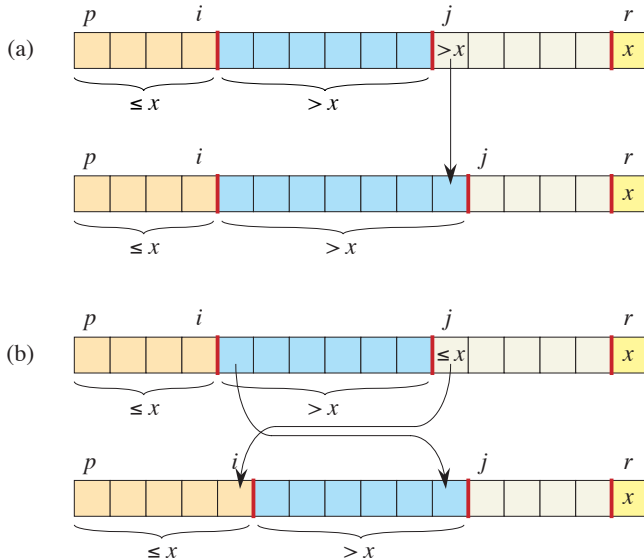
## Correctness:

- ▶ Array is partitioned into:
  1. Elements  $\leq x$  (low side).
  2. Elements  $> x$  (high side).
- ▶ Pivot is placed immediately after the low side.

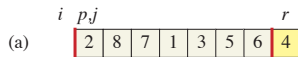
# Regions in the Partition Procedure



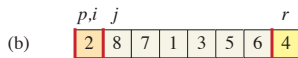
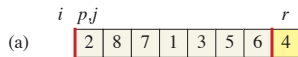
# Handling Cases During Partition



# Example of partitioning

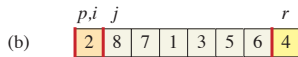
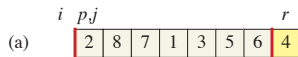


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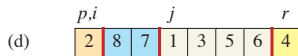
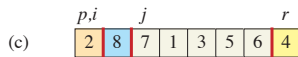
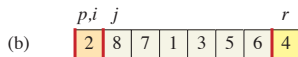
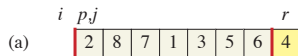




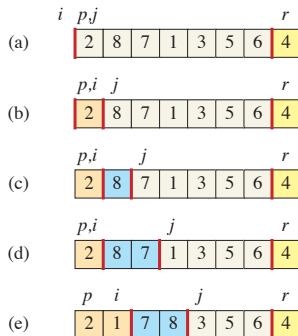
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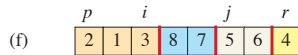
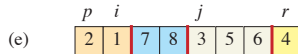
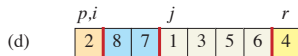
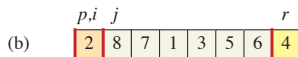
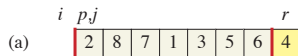
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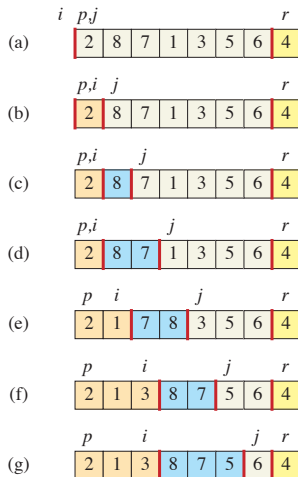
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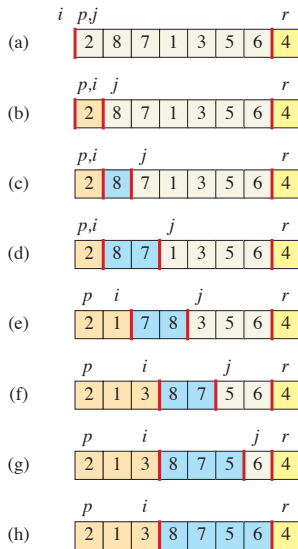
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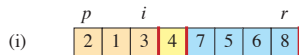
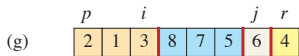
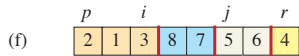
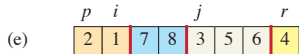
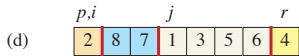
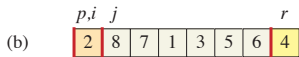
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# Pseudocode for Quicksort

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Initial call:

QUICKSORT( $A, 1, n$ )

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- ▶ Let  $T(n)$  = worst-case running time on an array of  $n$  elements.

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**Arithmetic Series!**

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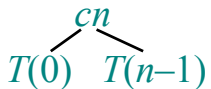
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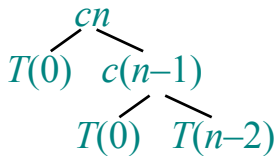
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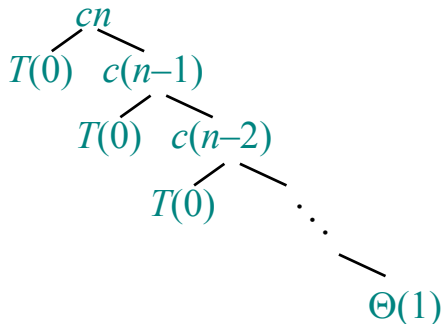
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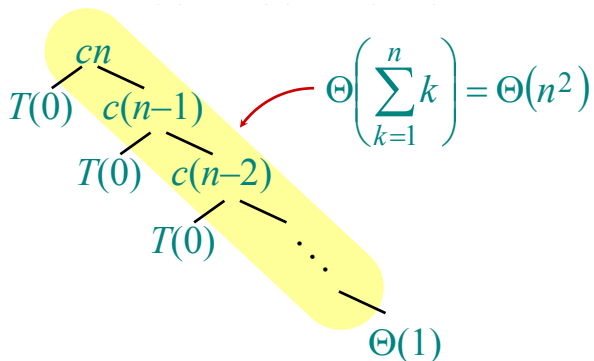
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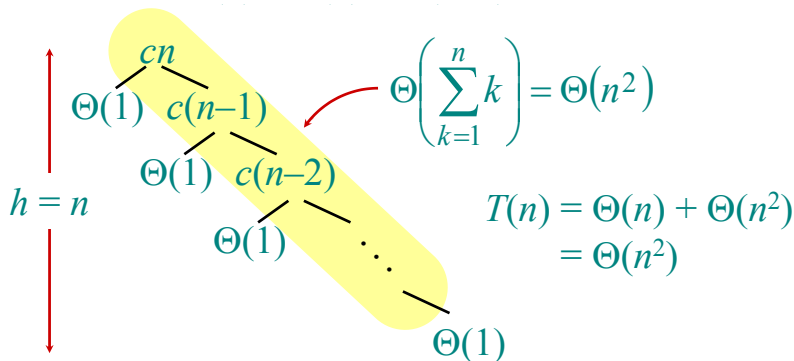
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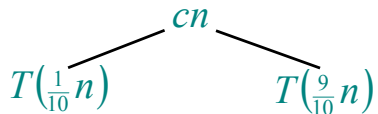
$$T(n) = T\left(\frac{1}{10}n\right) + T\left(\frac{9}{10}n\right) + \Theta(n)$$

What is the solution to this recurrence?

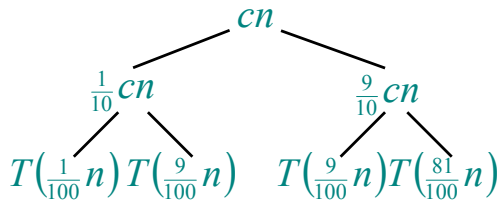
# Performance of “Almost-best” Case

$$T(n)$$

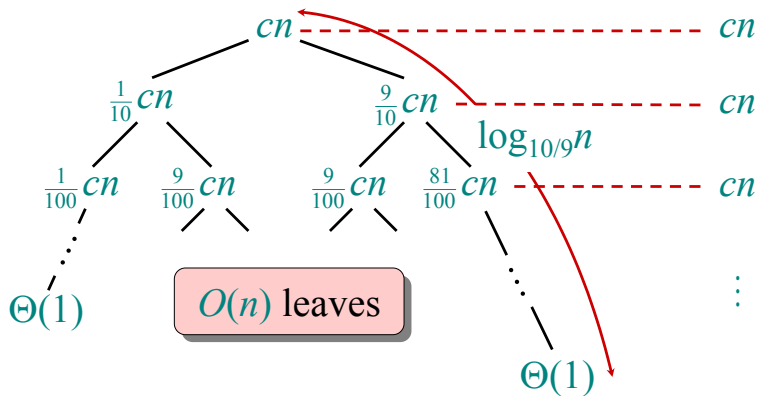
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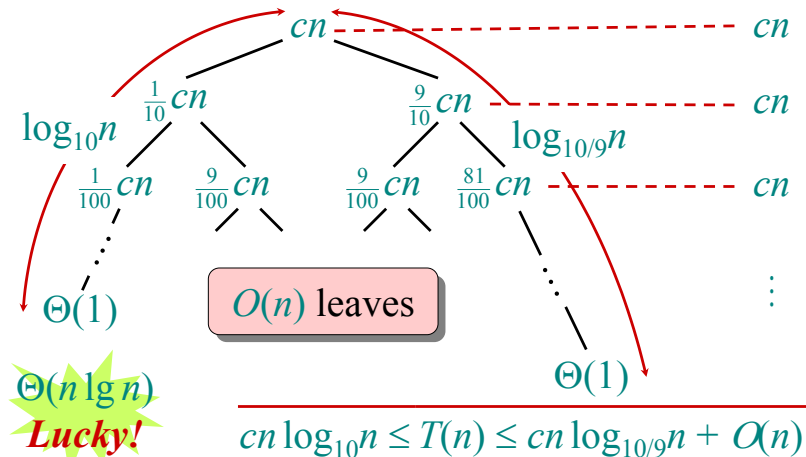
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## Performance of “Almost-best” Case



## More Intuition

Suppose we alternate lucky, unlucky, lucky, unlucky, lucky, ...

$$L(n) = 2U\left(\frac{n}{2}\right) + \Theta(n) \quad \textit{lucky}$$

$$U(n) = L(n-1) + \Theta(n) \quad \textit{unlucky}$$

Solving:

$$\begin{aligned} L(n) &= 2\left(L\left(\frac{n}{2} - 1\right) + \Theta\left(\frac{n}{2}\right)\right) + \Theta(n) \\ &= 2L\left(\frac{n}{2} - 1\right) + \Theta(n) \\ &= \Theta(n \lg n) \quad \textbf{Lucky!} \end{aligned}$$

How can we make sure we are usually lucky?

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# Randomized Quicksort

## IDEA:

Partition around a **random** element.

- ▶ Running time is independent of the input order.
- ▶ No assumptions need to be made about the input distribution.
- ▶ No specific input elicits the worst-case behavior.
- ▶ The worst case is determined only by the output of a random-number generator.

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# Randomized Quicksort Analysis

Let  $T(n)$  = the random variable for the running time of randomized quicksort on an input of size  $n$ , assuming random numbers are independent.

For  $k = 0, 1, \dots, n-1$ , define the **indicator random variable**.

$$X_k = \begin{cases} 1 & \text{if PARTITION generates a } k : n - k - 1 \text{ split,} \\ 0 & \text{otherwise.} \end{cases}$$

$E[X_k] = Pr\{X_k = 1\} = \frac{1}{n}$ , since all splits are equally likely, assuming element are distinct.

## Analysis (Cont.)

$$T(n) = \begin{cases} T(0) + T(n-1) + \Theta(n) & \text{if } 0 : n-1 \text{ split,} \\ T(1) + T(n-2) + \Theta(n) & \text{if } 1 : n-2 \text{ split,} \\ \vdots & \\ T(n-1) + T(0) + \Theta(n) & \text{if } n-1 : 0 \text{ split.} \end{cases}$$

$$= \sum_{k=0}^{n-1} X_k (T(k) + T(n-k-1) + \Theta(n))$$

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# Calculating expectation

Take expectations of both sides.

$$E[T(n)] = E \left[ \sum_{k=0}^{n-1} X_k (T(k) + T(n - k - 1) + \Theta(n)) \right]$$

# Calculating expectation

Linearity of expectation.

$$\begin{aligned} E[T(n)] &= E \left[ \sum_{k=0}^{n-1} X_k(T(k) + T(n - k - 1) + \Theta(n)) \right] \\ &= \sum_{k=0}^{n-1} E [X_k(T(k) + T(n - k - 1) + \Theta(n))] \end{aligned}$$

# Calculating expectation

Independence of  $X_k$  from other random choices.

$$\begin{aligned} E[T(n)] &= E \left[ \sum_{k=0}^{n-1} X_k (T(k) + T(n - k - 1) + \Theta(n)) \right] \\ &= \sum_{k=0}^{n-1} E [X_k (T(k) + T(n - k - 1) + \Theta(n))] \\ &= \sum_{k=0}^{n-1} E[X_k] \cdot E[T(k) + T(n - k - 1) + \Theta(n)] \end{aligned}$$



# Calculating expectation

Linearity of expectation:  $E[X_k] = \frac{1}{n}$ .

$$\begin{aligned} E[T(n)] &= E \left[ \sum_{k=0}^{n-1} X_k (T(k) + T(n-k-1) + \Theta(n)) \right] \\ &= \sum_{k=0}^{n-1} E [X_k (T(k) + T(n-k-1) + \Theta(n))] \\ &= \sum_{k=0}^{n-1} E[X_k] \cdot E[T(k) + T(n-k-1) + \Theta(n)] \\ &= \frac{1}{n} \sum_{k=0}^{n-1} E[T(k)] + \frac{1}{n} \sum_{k=0}^{n-1} E[T(n-k-1)] + \frac{1}{n} \sum_{k=0}^{n-1} \Theta(n) \end{aligned}$$

# Calculating expectation

Summations have identical terms.

$$\begin{aligned} E[T(n)] &= E \left[ \sum_{k=0}^{n-1} X_k (T(k) + T(n - k - 1) + \Theta(n)) \right] \\ &= \sum_{k=0}^{n-1} E [X_k (T(k) + T(n - k - 1) + \Theta(n))] \\ &= \sum_{k=0}^{n-1} E[X_k] \cdot E[T(k) + T(n - k - 1) + \Theta(n)] \\ &= \frac{1}{n} \sum_{k=0}^{n-1} E[T(k)] + \frac{1}{n} \sum_{k=0}^{n-1} E[T(n - k - 1)] + \frac{1}{n} \sum_{k=0}^{n-1} \Theta(n) \\ &= \frac{2}{n} \sum_{k=0}^{n-1} E[T(k)] + \Theta(n) \end{aligned}$$

## Hairy recurrence

$$E[T(n)] = \frac{2}{n} \sum_{k=2}^{n-1} E[T(k)] + \Theta(n)$$

(The  $k = 0, 1$  terms can be absorbed in the  $\Theta(n)$ .)

**Prove:**

$E[T(n)] \leq an \lg n$  for constant  $a > 0$ .

- Choose  $a$  large enough so that  $an \lg n$  dominates  $E[T(n)]$  for sufficiently small  $n \geq 2$ .

**Use fact:**

$$\sum_{k=2}^{n-1} k \lg k \leq \frac{1}{2} n^2 \lg n - \frac{1}{8} n^2 \text{ (exercise).}$$

# Substitution method

Substitute inductive hypothesis.

$$E[T(n)] \leq \frac{2}{n} \sum_{k=2}^{n-1} ak \lg k + \Theta(n)$$

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Use fact.

$$\begin{aligned} E[T(n)] &\leq \frac{2}{n} \sum_{k=2}^{n-1} ak \lg k + \Theta(n) \\ &\leq \frac{2a}{n} \left( \frac{1}{2} n^2 \lg n - \frac{1}{8} n^2 \right) + \Theta(n) \end{aligned}$$

## Substitution method

$$\begin{aligned} E[T(n)] &\leq \frac{2}{n} \sum_{k=2}^{n-1} ak \lg k + \Theta(n) \\ &\leq \frac{2a}{n} \left( \frac{1}{2} n^2 \lg n - \frac{1}{8} n^2 \right) + \Theta(n) \\ &= an \lg n - \left( \frac{an}{4} - \Theta(n) \right) \\ &\leq an \lg n, \end{aligned}$$

if  $a$  is chosen large enough so that  $\frac{an}{4}$  dominates the  $\Theta(n)$ .

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End of Lecture 4.



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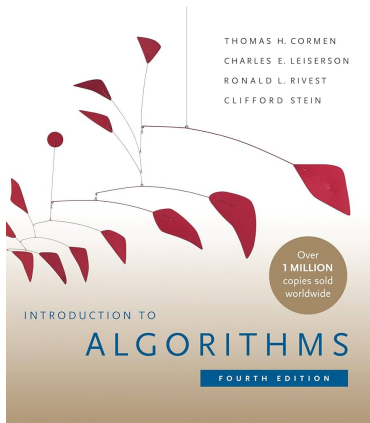
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- 1 **Quicksort is Highly Efficient in Practice** – It outperforms merge sort in most cases and benefits from hardware optimizations.

# Introduction to Algorithms



Content has been extracted from *Introduction to Algorithms*, Fourth Edition, by Cormen, Leiserson, Rivest, and Stein. MIT Press. 2022.

Visit <https://mitpress.mit.edu/9780262046305/introduction-to-algorithms/>.

Original slides from *Introduction to Algorithms 6.046J/18.401J*, Fall 2005 Class by Prof. Charles Leiserson and Prof. Erik Demaine. MIT OpenCourseWare Initiative available at <https://ocw.mit.edu/courses/6-046j-introduction-to-algorithms-sma-5503-fall-2005/>.