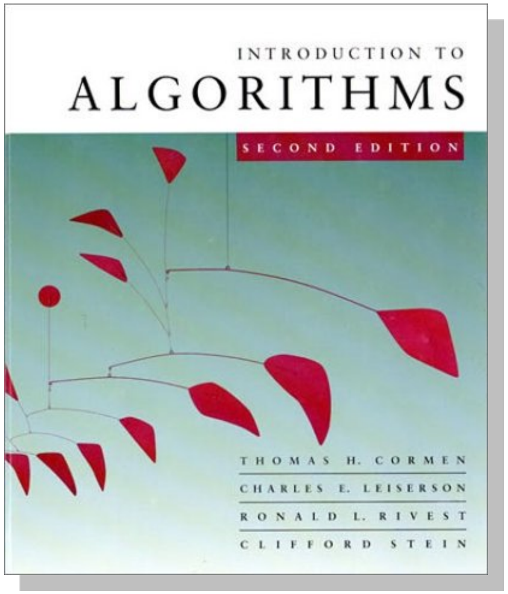
Introduction to Algorithms
6.046J/18.401J

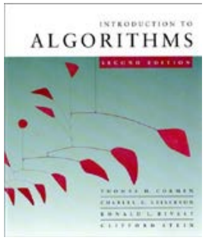


LECTURE 1

Analysis of Algorithms

- Insertion sort
- Asymptotic analysis
- Merge sort
- Recurrences

Prof. Charles E. Leiserson



Course information

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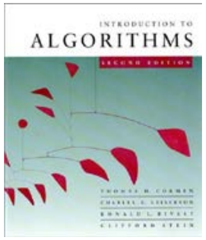
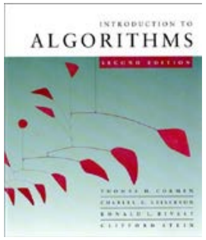


Analysis of algorithms

The theoretical study of computer-program performance and resource usage.

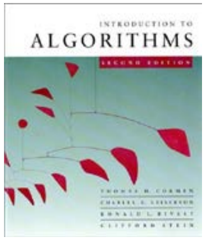
What's more important than performance?

- modularity
- correctness
- maintainability
- functionality
- robustness
- user-friendliness
- programmer time
- simplicity
- extensibility
- reliability



Why study algorithms and performance?

- Algorithms help us to understand ***scalability***.
- Performance often draws the line between what is feasible and what is impossible.
- Algorithmic mathematics provides a ***language*** for talking about program behavior.
- Performance is the ***currency*** of computing.
- The lessons of program performance generalize to other computing resources.
- Speed is fun!



The problem of sorting

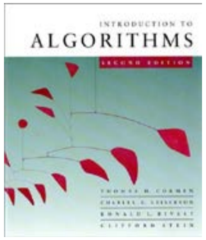
Input: sequence $\langle a_1, a_2, \ldots, a_n \rangle$ of numbers.

Output: permutation $\langle a'_1, a'_2, \ldots, a'_n \rangle$ such that $a'_1 \le a'_2 \le \cdots \le a'_n$.

Example:

Input: 8 2 4 9 3 6

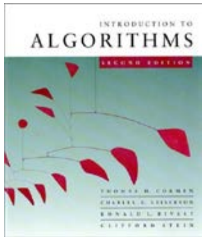
Output: 2 3 4 6 8 9



Insertion sort

"pseudocode"

```
INSERTION-SORT (A, n)        ⊳ A[1 . . n]
    for j ← 2 to n
        do key ← A[ j]
           i ← j – 1
           while i > 0 and A[i] > key
               do A[i+1] ← A[i]
                  i ← i – 1
           A[i+1] = key
```



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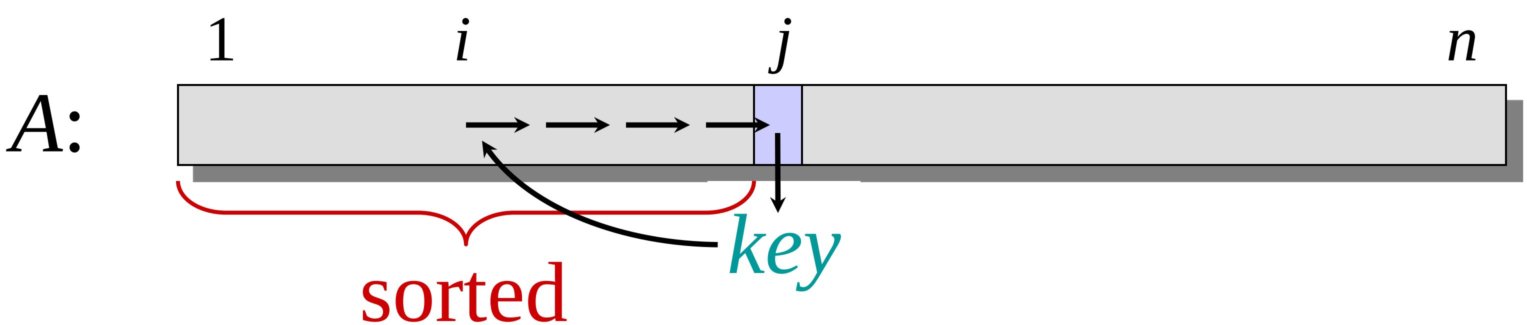

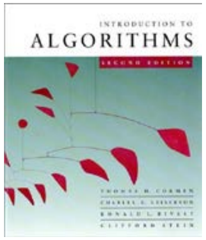

Example of insertion sort

8 2 4 9 3 6

Example of insertion sort

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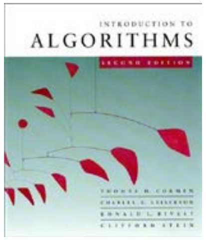

Example of insertion sort

8 **2** 4 9 3 6

2 8 **4** 9 3 6

2 4 8 **9** 3 6

Example of insertion sort

8 2 4 9 3 6

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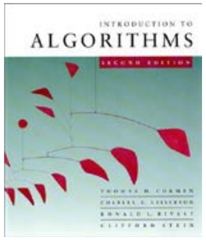
2 4 8 9 3 6

2 4 8 9 3 6

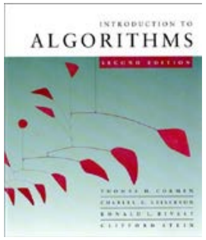
Example of insertion sort

8	2	4	9	3	6
2	8	4	9	3	6
2	4	8	9	3	6
2	4	8	9	3	6



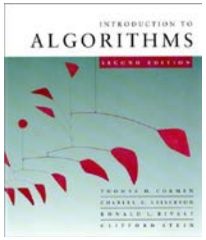
Example of insertion sort

8	2	4	9	3	6
2	8	4	9	3	6
2	4	8	9	3	6
2	4	8	9	3	6
2	3	4	8	9	6



Example of insertion sort

8	**2**	4	9	3	6
2	8	**4**	9	3	6
2	4	8	**9**	3	6
2	4	8	9	**3**	6
2	3	4	8	9	**6**

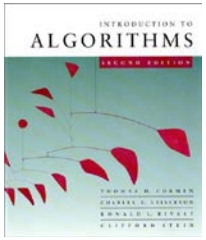


Example of insertion sort

8	**2**	4	9	3	6	
2	8	**4**	9	3	6	
2	4	8	**9**	3	6	
2	4	8	9	**3**	6	
2	3	4	8	9	**6**	
2	3	4	6	8	9	*done*

Running time

- The running time depends on the input: an already sorted sequence is easier to sort.
- Parameterize the running time by the size of the input, since short sequences are easier to sort than long ones.
- Generally, we seek upper bounds on the running time, because everybody likes a guarantee.



Kinds of analyses

Worst-case: (usually)

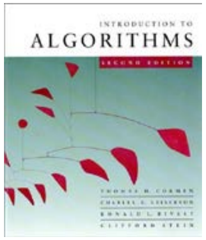
- $T(n)$ = maximum time of algorithm on any input of size n.

Average-case: (sometimes)

- $T(n)$ = expected time of algorithm over all inputs of size n.
- Need assumption of statistical distribution of inputs.

Best-case: (bogus)

- Cheat with a slow algorithm that works fast on *some* input.



Machine-independent time

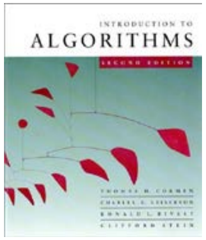
What is insertion sort's worst-case time?

- It depends on the speed of our computer:
    - relative speed (on the same machine),
    - absolute speed (on different machines).

BIG IDEA:

- Ignore machine-dependent constants.
- Look at ***growth*** of $T(n)$ as $n \to \infty$.

"Asymptotic Analysis"



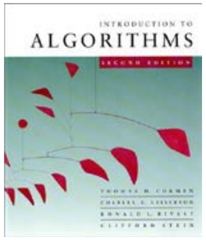
Θ-notation

Math:

$\Theta(g(n)) = \{\, f(n)$: there exist positive constants c_1, c_2, and n_0 such that $0 \le c_1\, g(n) \le f(n) \le c_2\, g(n)$ for all $n \ge n_0 \,\}$

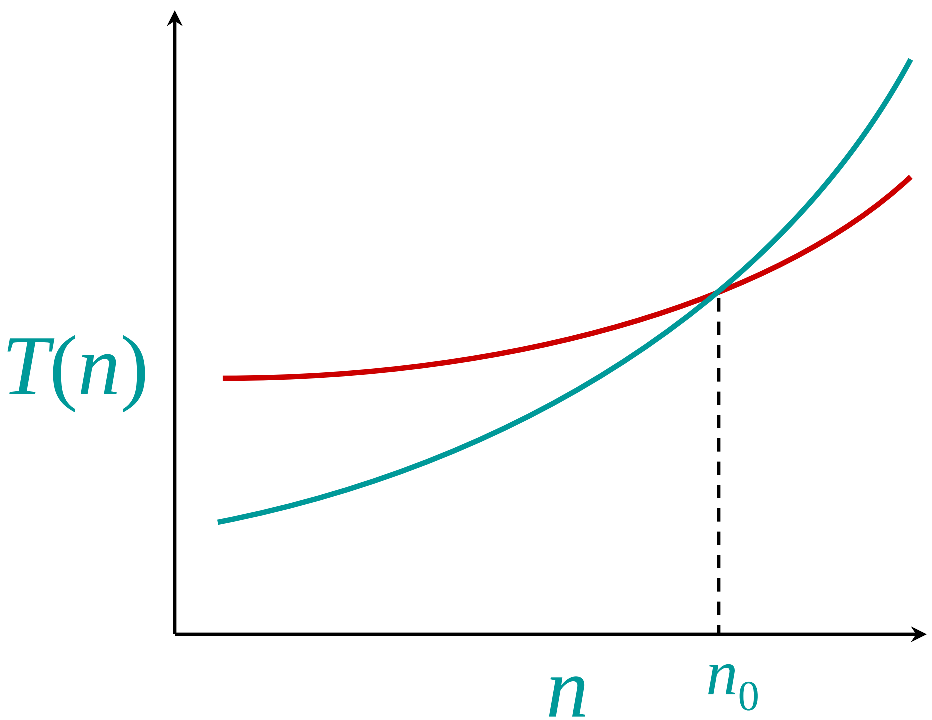
Engineering:

- Drop low-order terms; ignore leading constants.
- Example: $3n^3 + 90n^2 - 5n + 6046 = \Theta(n^3)$

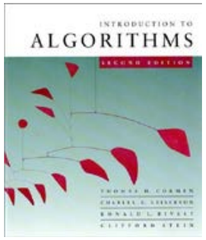


Asymptotic performance

When n gets large enough, a $\Theta(n^2)$ algorithm *always* beats a $\Theta(n^3)$ algorithm.



- We shouldn't ignore asymptotically slower algorithms, however.
- Real-world design situations often call for a careful balancing of engineering objectives.
- Asymptotic analysis is a useful tool to help to structure our thinking.



Insertion sort analysis

Worst case: Input reverse sorted.

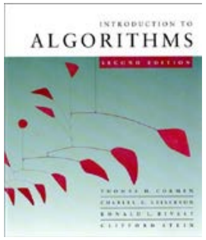
$$T(n) = \sum_{j=2}^{n} \Theta(j) = \Theta\left(n^2\right) \qquad \text{[arithmetic series]}$$

Average case: All permutations equally likely.

$$T(n) = \sum_{j=2}^{n} \Theta(j/2) = \Theta\left(n^2\right)$$

Is insertion sort a fast sorting algorithm?

- Moderately so, for small n.
- Not at all, for large n.

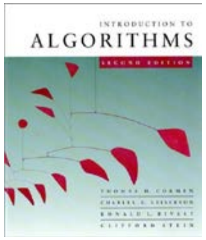


Merge sort

MERGE-SORT $A[1 \,.\,.\, n]$

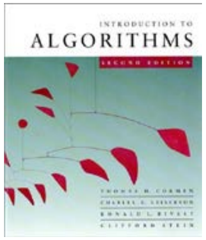
1. If $n = 1$, done.
2. Recursively sort $A[\,1 \,.\,.\, \lceil n/2 \rceil\,]$ and $A[\,\lceil n/2 \rceil + 1 \,.\,.\, n\,]$.
3. "***Merge***" the 2 sorted lists.

Key subroutine: **MERGE**



Merging two sorted arrays

20	12
13	11
7	9
2	1



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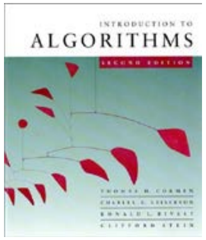
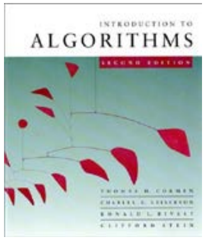


Merging two sorted arrays

20	12	‖	20	12
13	11	‖	13	11
7	9	‖	7	9
2	1	‖	2	

1



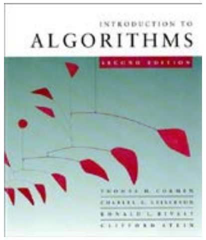
Merging two sorted arrays

20	12	‖	20	12
13	11	‖	13	11
7	9	‖	7	9
2	1	‖	2	

1   2

Merging two sorted arrays

20	12	‖	20	12	‖	20	12
13	11	‖	13	11	‖	13	11
7	9	‖	7	9	‖	7	9
2	1	‖	2		‖		
	1			2			



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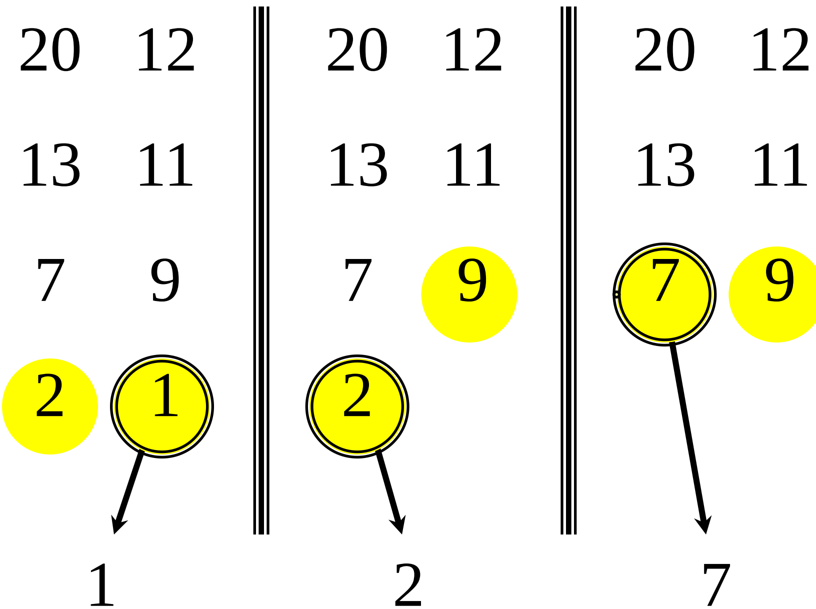

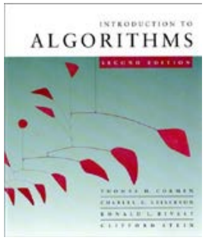

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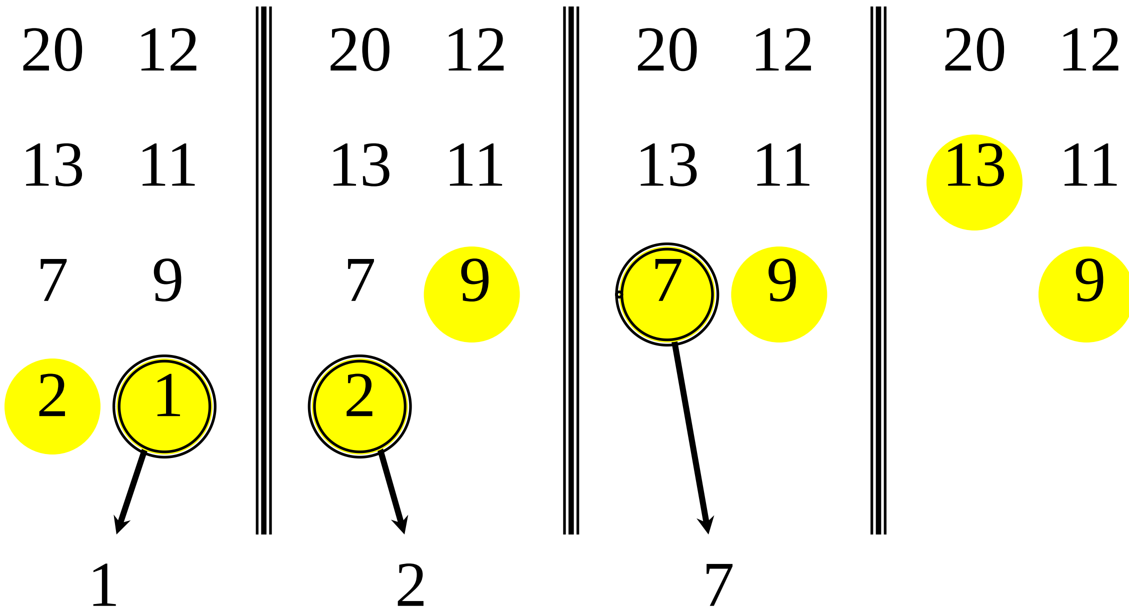

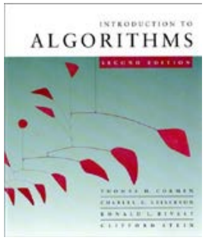

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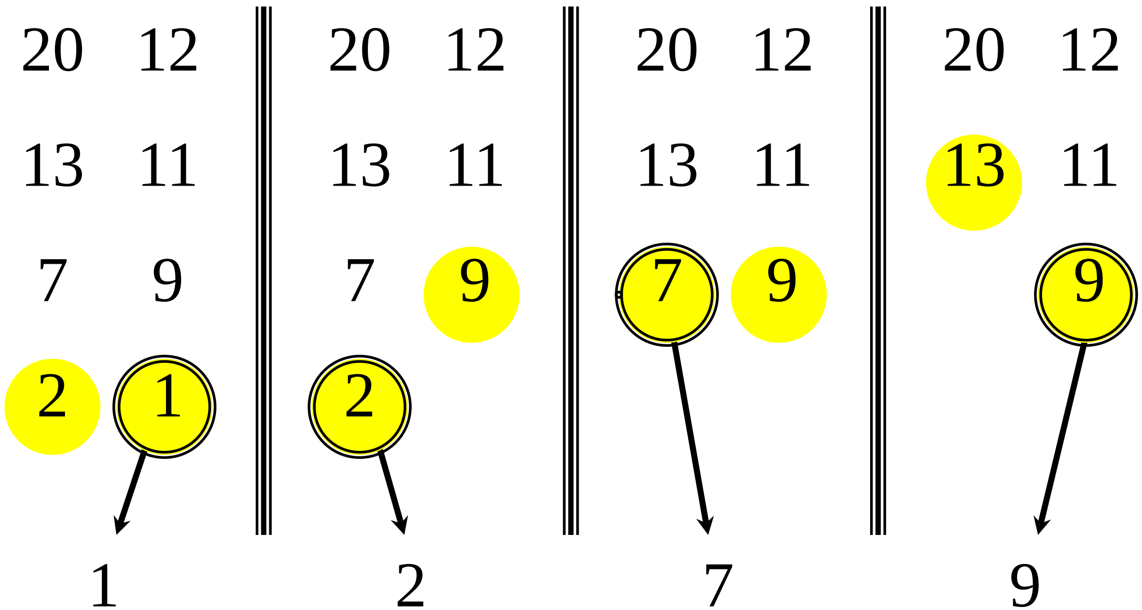

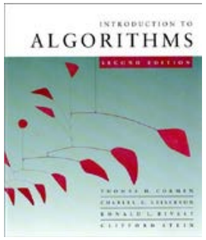

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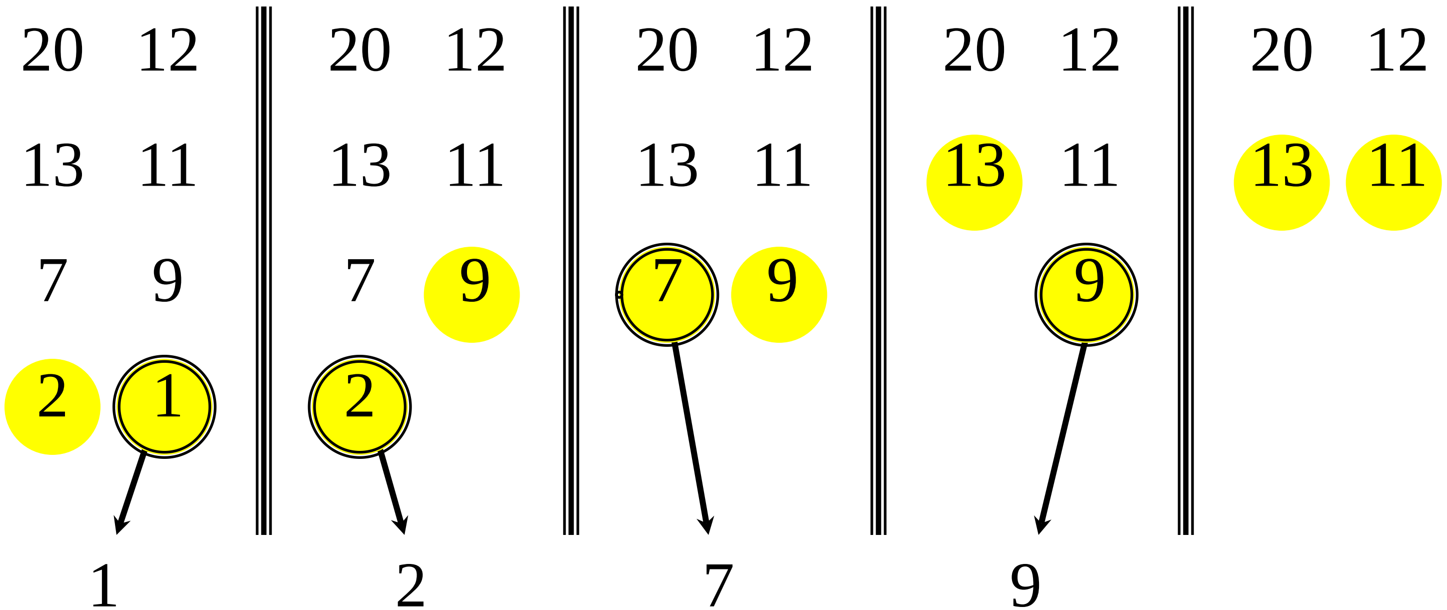

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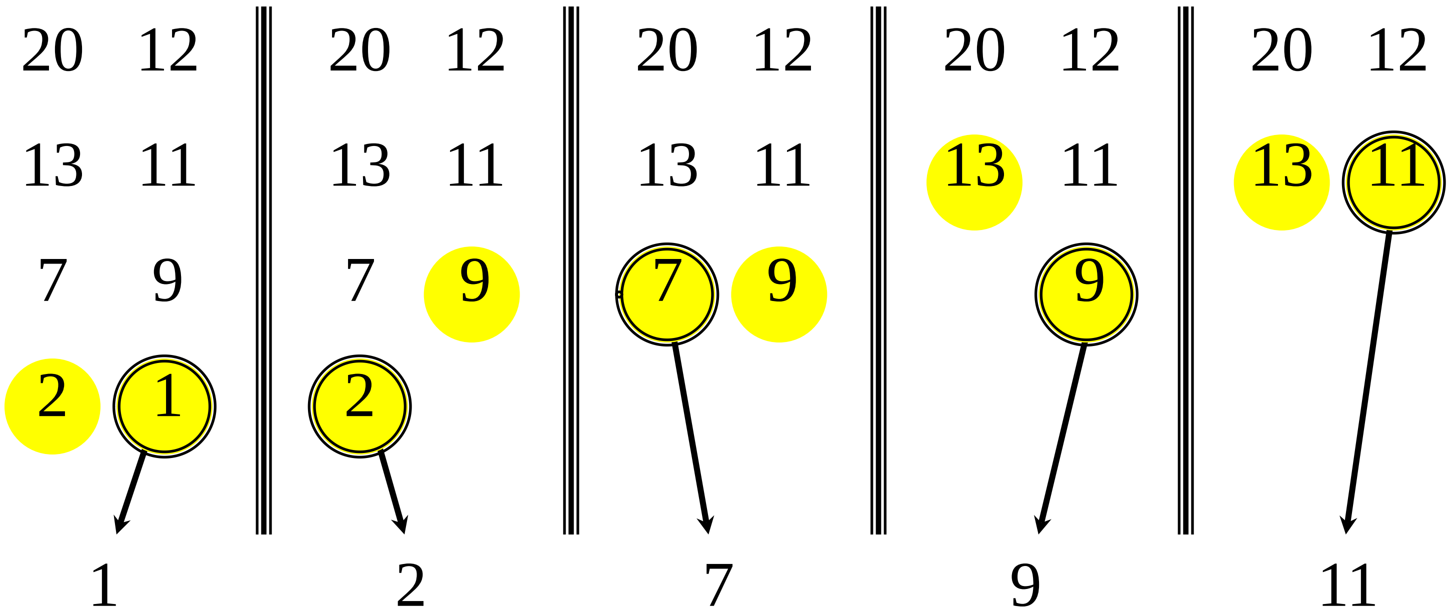

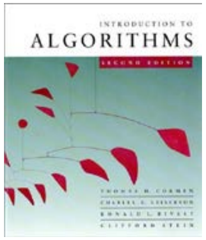

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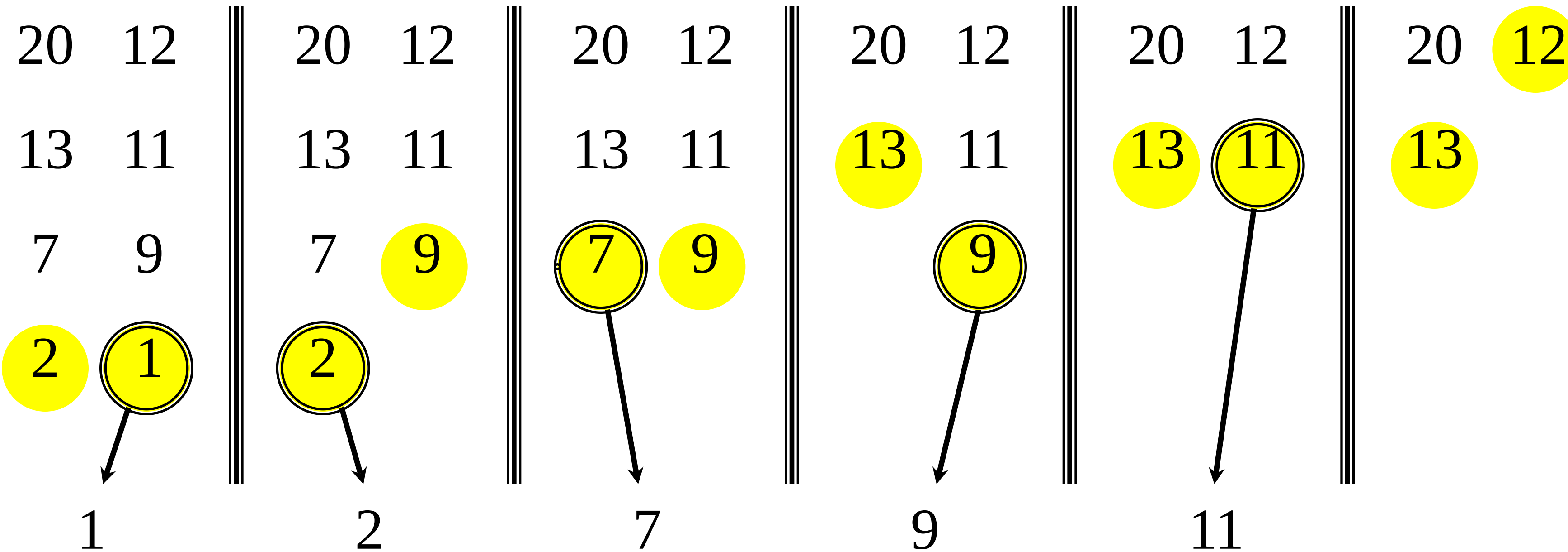

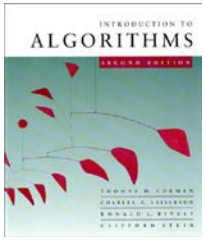

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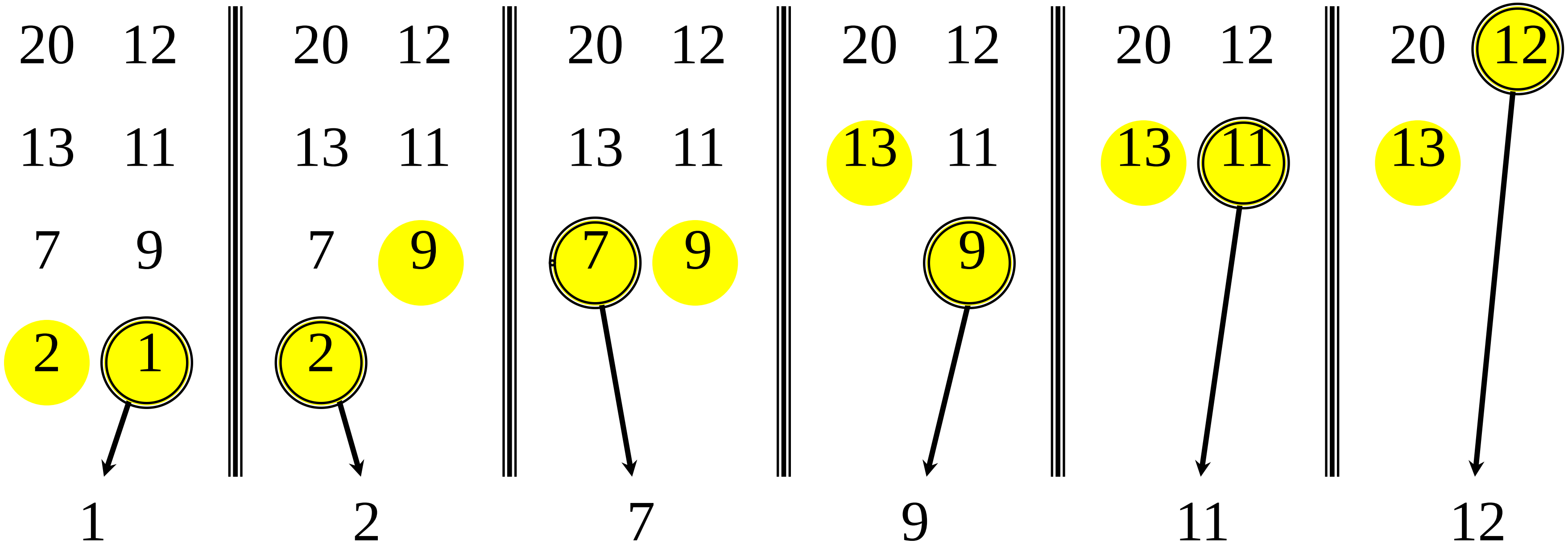

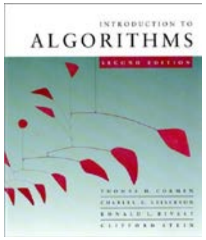

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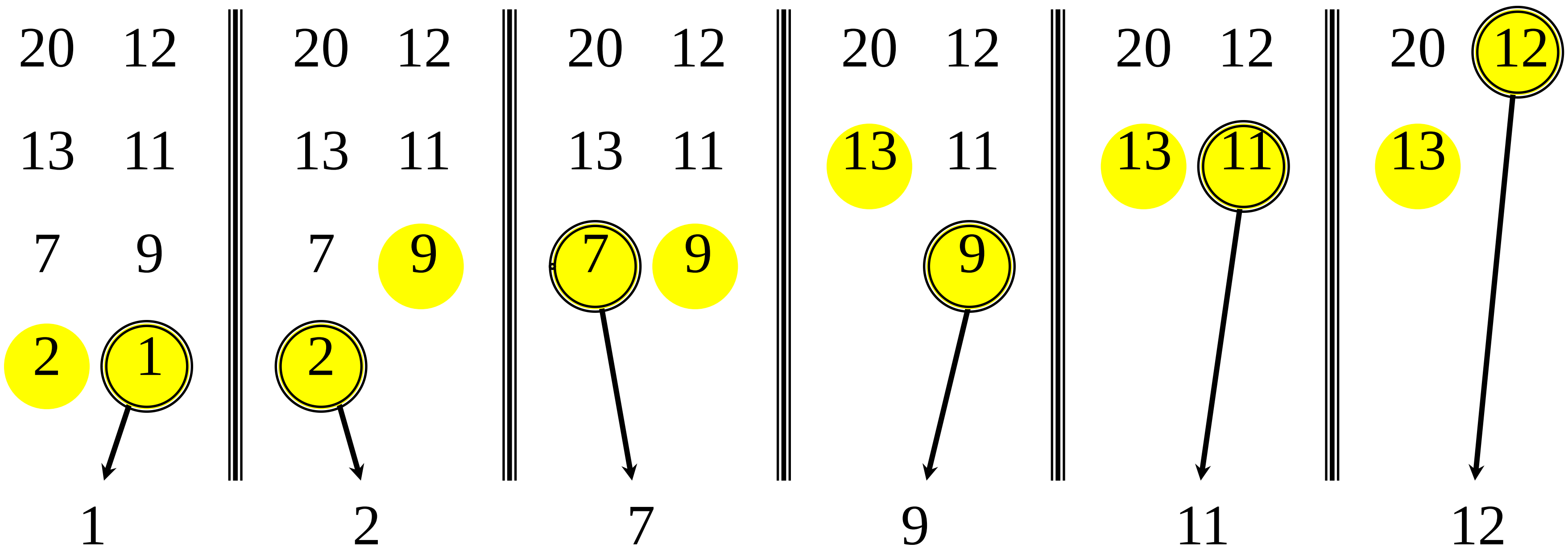
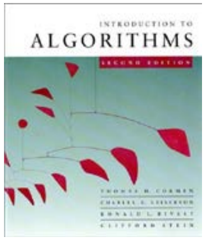


Time = $\Theta(n)$ to merge a total of n elements (linear time).



Analyzing merge sort

$T(n)$

$\Theta(1)$

$2T(n/2)$

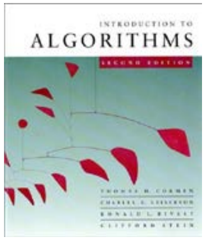
Abuse

$\Theta(n)$

MERGE-SORT $A[1 \,.\,.\, n]$

1. If $n = 1$, done.
2. Recursively sort $A[\,1 \,.\,.\, \lceil n/2 \rceil\,]$ and $A[\,\lceil n/2 \rceil + 1 \,.\,.\, n\,]$.
3. ***"Merge"*** the 2 sorted lists

Sloppiness: Should be $T(\lceil n/2 \rceil) + T(\lfloor n/2 \rfloor)$, but it turns out not to matter asymptotically.



Recurrence for merge sort

$$T(n) = \begin{cases} \Theta(1) \text{ if } n = 1; \\ 2T(n/2) + \Theta(n) \text{ if } n > 1. \end{cases}$$

- We shall usually omit stating the base case when $T(n) = \Theta(1)$ for sufficiently small n, but only when it has no effect on the asymptotic solution to the recurrence.
- CLRS and Lecture 2 provide several ways to find a good upper bound on $T(n)$.

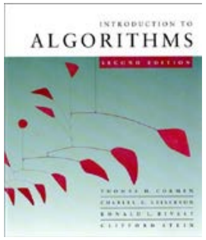
Recursion tree

Solve $T(n) = 2T(n/2) + cn$, where $c > 0$ is constant.

Recursion tree

Solve $T(n) = 2T(n/2) + cn$, where $c > 0$ is constant.

$$T(n)$$

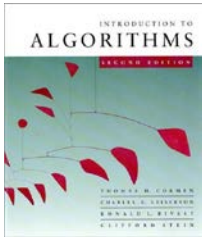


Recursion tree

Solve $T(n) = 2T(n/2) + cn$, where $c > 0$ is constant.

$$cn$$

$$T(n/2) \qquad\qquad\qquad T(n/2)$$



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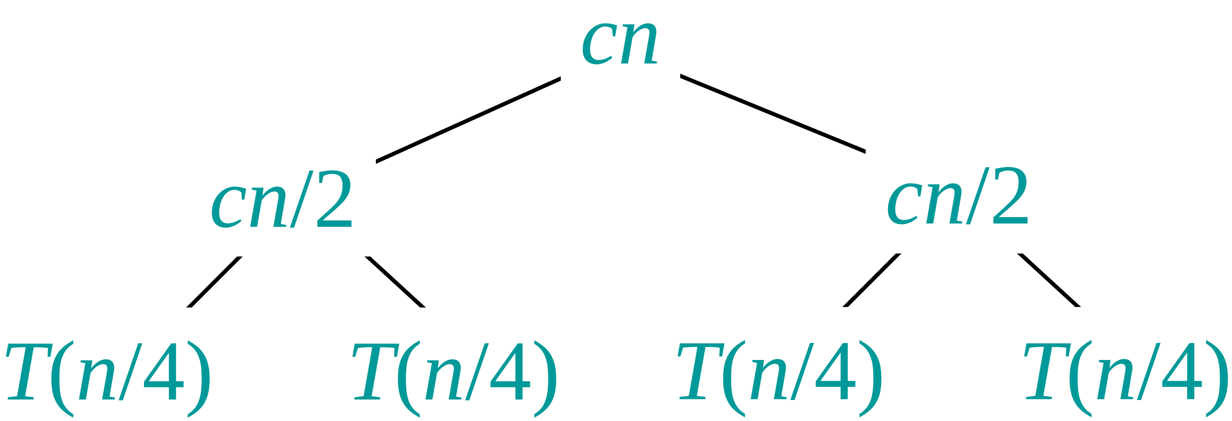

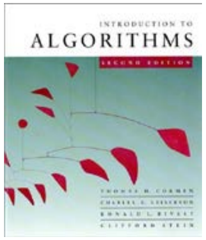

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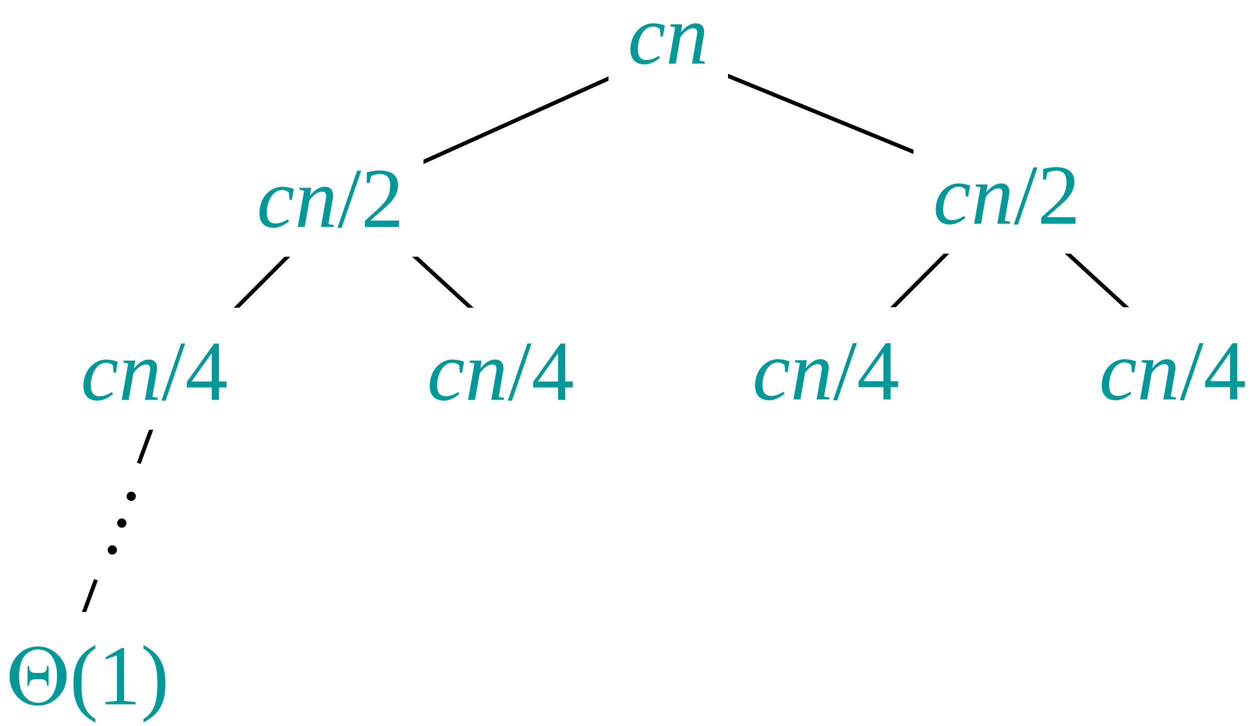

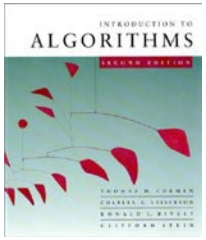

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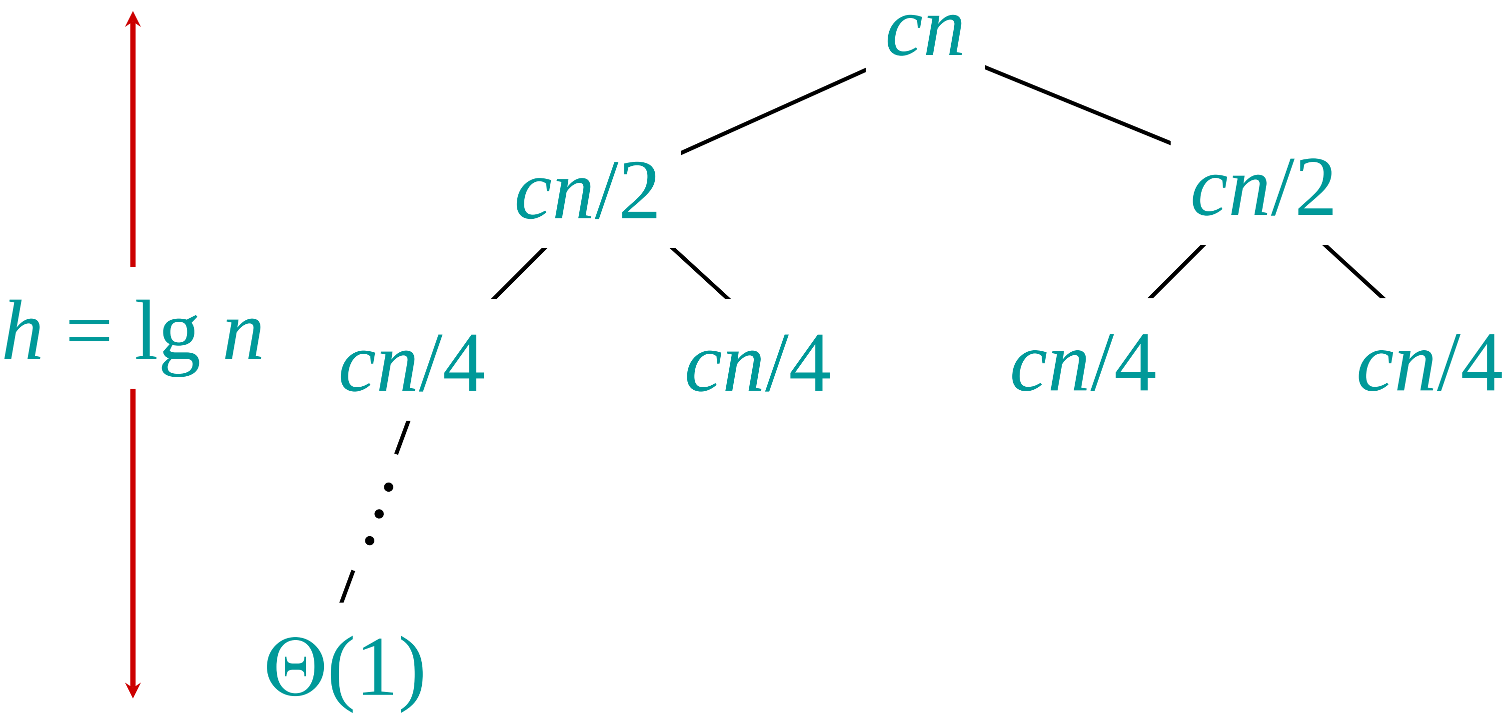

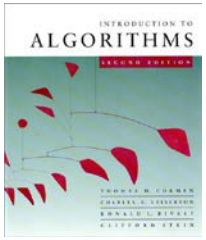

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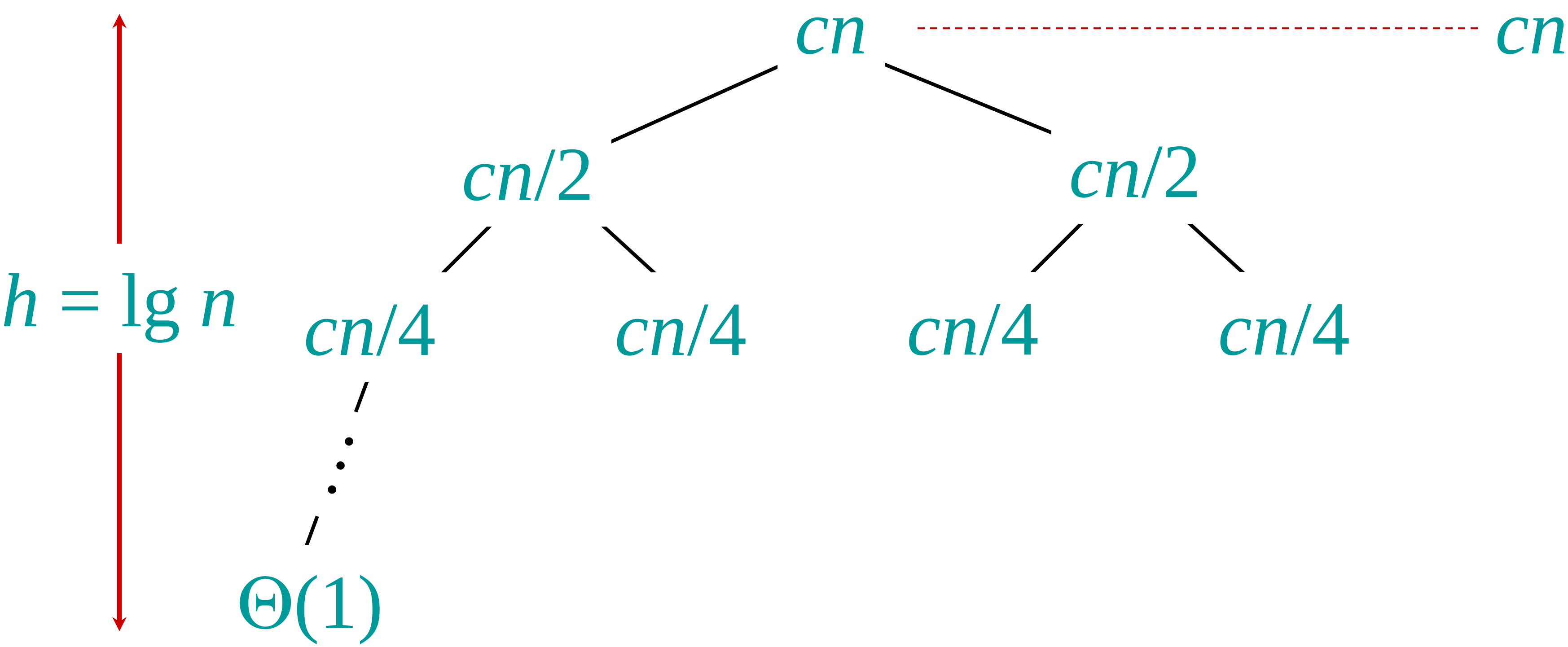

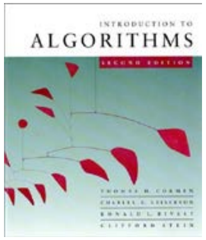

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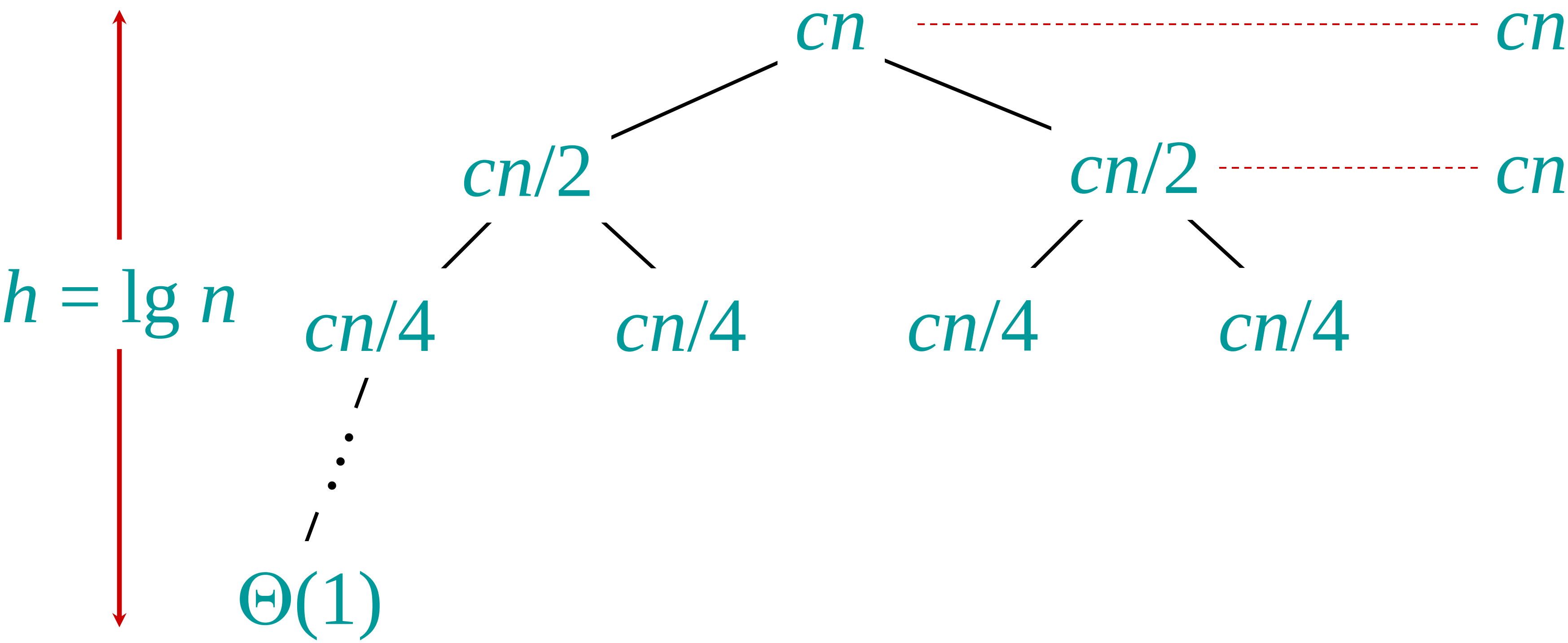
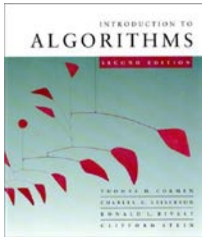
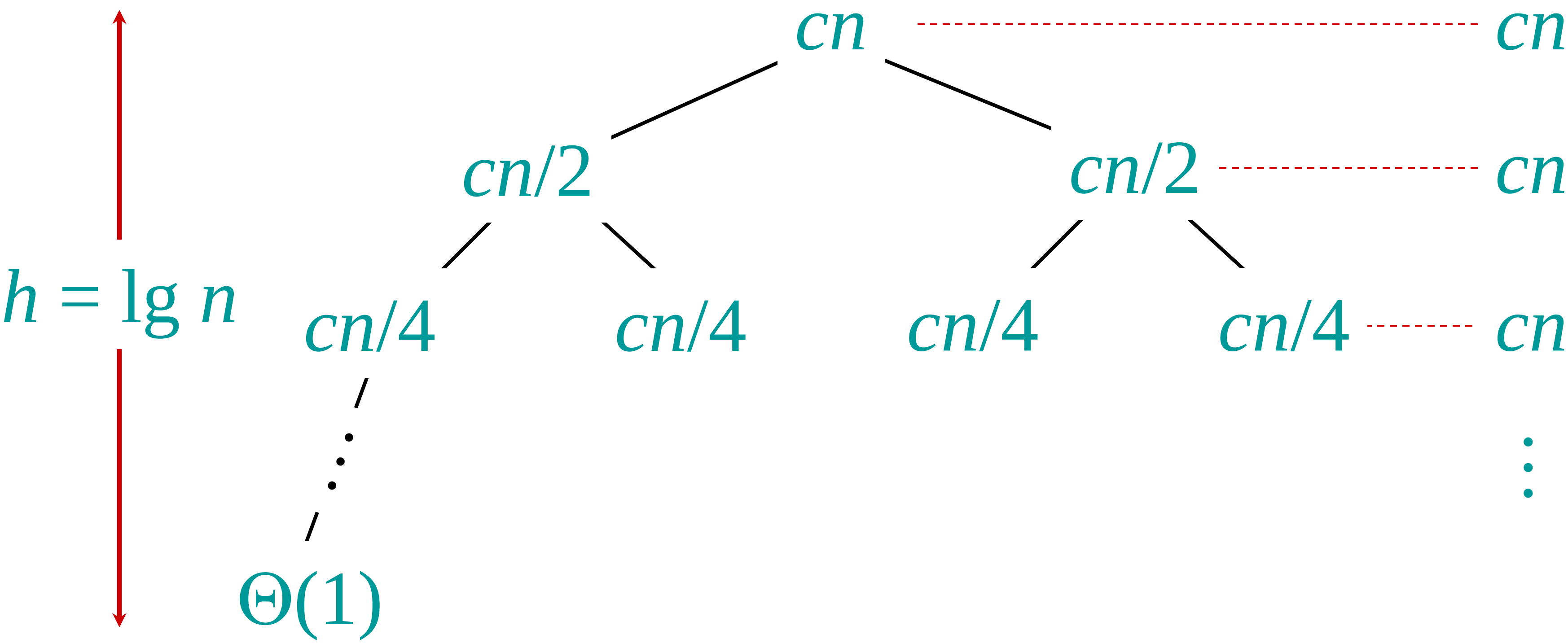
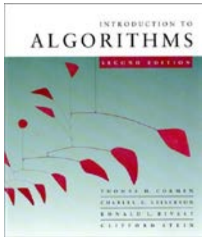




Recursion tree

Solve $T(n) = 2T(n/2) + cn$, where $c > 0$ is constant.





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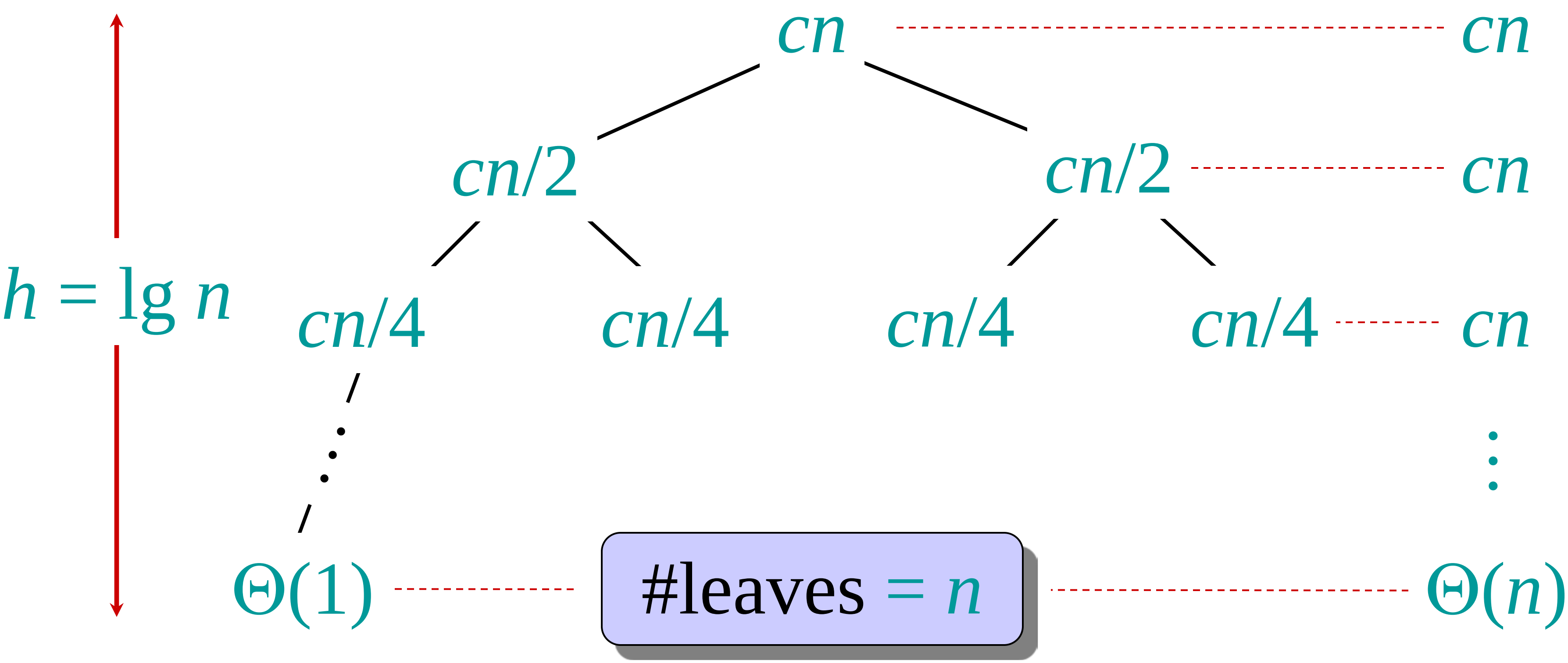

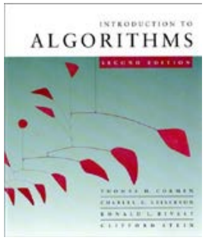

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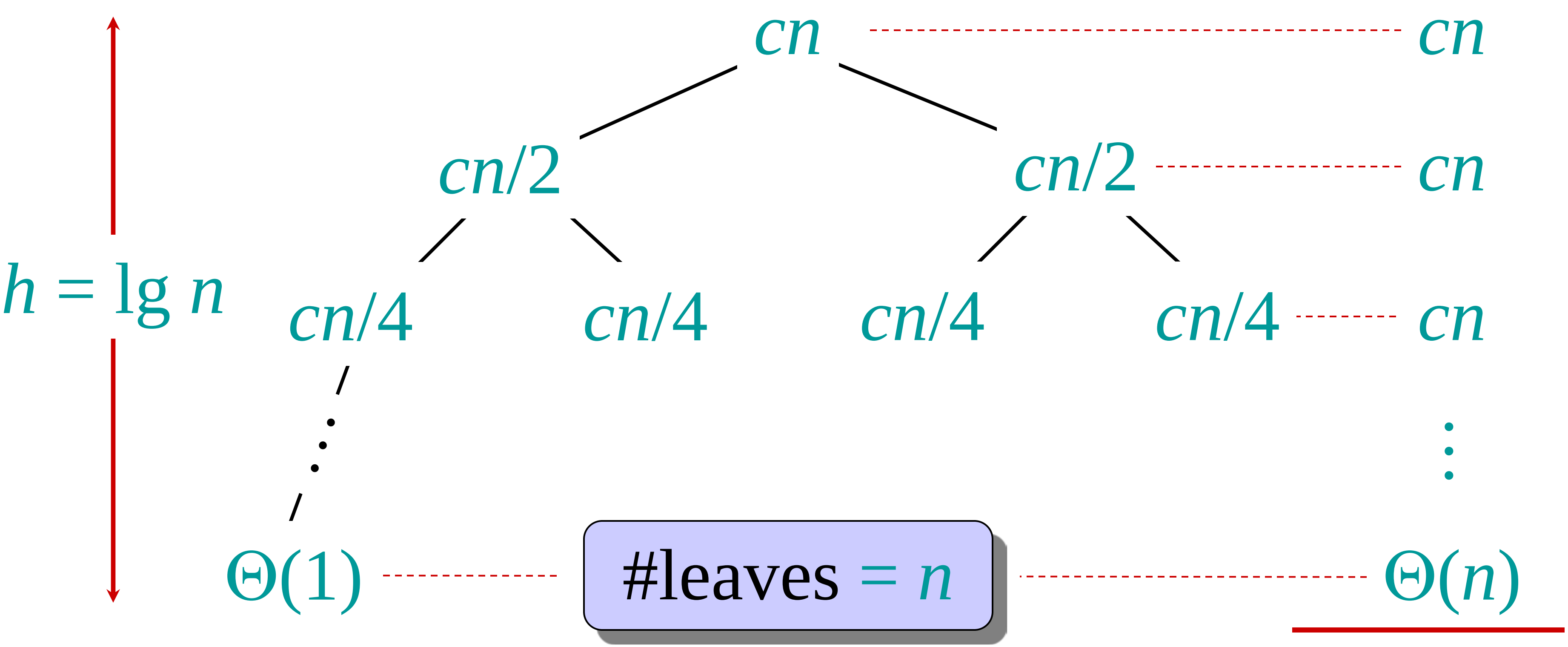
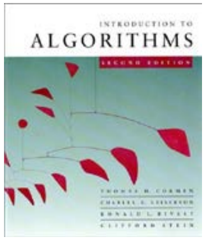


Total $= \Theta(n \lg n)$

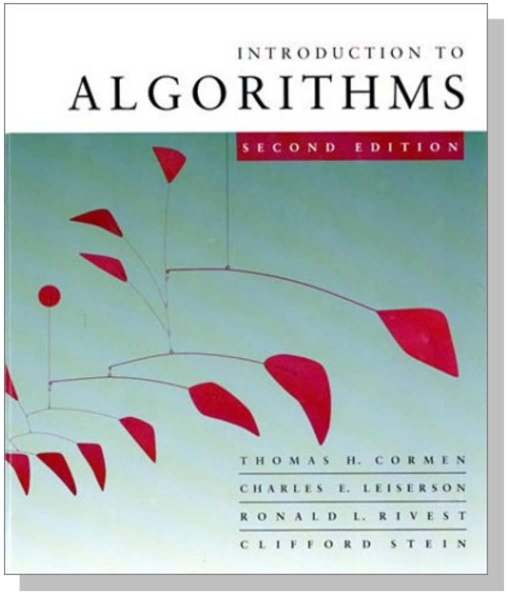


Conclusions

- $\Theta(n \lg n)$ grows more slowly than $\Theta(n^2)$.
- Therefore, merge sort asymptotically beats insertion sort in the worst case.
- In practice, merge sort beats insertion sort for $n > 30$ or so.
- Go test it out for yourself!

Introduction to Algorithms

6.046J/18.401J



LECTURE 2

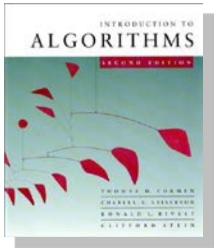
Asymptotic Notation

- *O*-, Ω-, and Θ-notation

Recurrences

- Substitution method
- Iterating the recurrence
- Recursion tree
- Master method

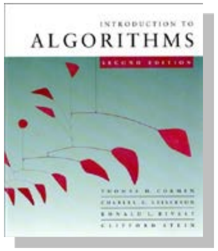
Prof. Erik Demaine



Asymptotic notation

O-notation (upper bounds):

> We write $f(n) = O(g(n))$ if there exist constants $c > 0$, $n_0 > 0$ such that $0 \le f(n) \le cg(n)$ for all $n \ge n_0$.



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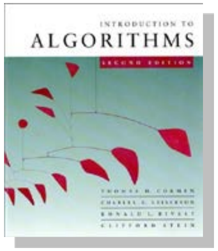
EXAMPLE: $2n^2 = O(n^3)$ $\quad$ ($c = 1$, $n_0 = 2$)



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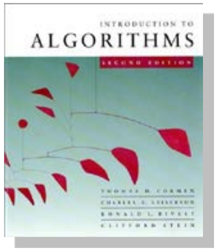
functions, not values



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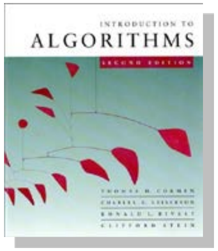
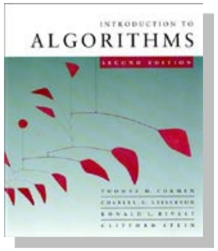
functions, not values

funny, "one-way" equality



Set definition of O-notation

$O(g(n)) = \{ f(n) :$ there exist constants $c > 0$, $n_0 > 0$ such that $0 \le f(n) \le cg(n)$ for all $n \ge n_0$ $\}$



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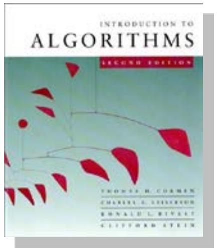

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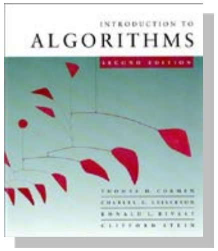
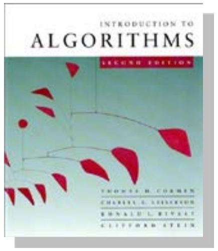
EXAMPLE: $2n^2 \in O(n^3)$

(*Logicians:* $\lambda n.2n^2 \in O(\lambda n.n^3)$, but it's convenient to be sloppy, as long as we understand what's *really* going on.)



Macro substitution

Convention: A set in a formula represents an anonymous function in the set.



Macro substitution

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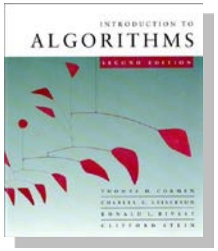
EXAMPLE: $f(n) = n^3 + O(n^2)$

means

$f(n) = n^3 + h(n)$

for some $h(n) \in O(n^2)$.



Macro substitution

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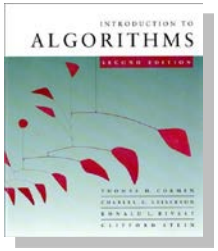
EXAMPLE: $n^2 + O(n) = O(n^2)$

means

for any $f(n) \in O(n)$:

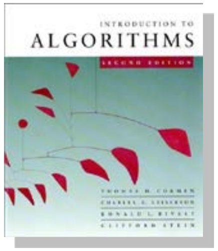
$$n^2 + f(n) = h(n)$$

for some $h(n) \in O(n^2)$.



Ω-notation (lower bounds)

O-notation is an *upper-bound* notation. It makes no sense to say $f(n)$ is at least $O(n^2)$.



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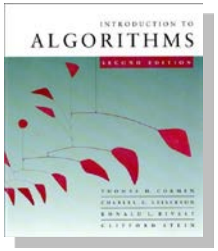
$$\Omega(g(n)) = \{ f(n) : \text{there exist constants } c > 0, n_0 > 0 \text{ such that } 0 \le cg(n) \le f(n) \text{ for all } n \ge n_0 \}$$



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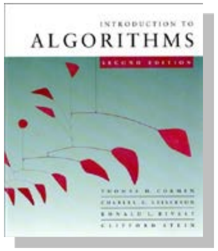
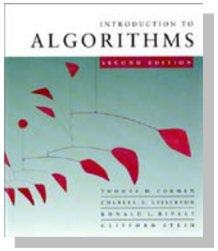
EXAMPLE: $\sqrt{n} = \Omega(\lg n)$ $\quad (c = 1, n_0 = 16)$



Θ-notation (tight bounds)

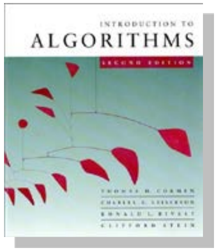
$$\Theta(g(n)) = O(g(n)) \cap \Omega(g(n))$$



Θ-notation (tight bounds)

$$\Theta(g(n)) = O(g(n)) \cap \Omega(g(n))$$

EXAMPLE: $\frac{1}{2}n^2 - 2n = \Theta(n^2)$



o-notation and ω-notation

O-notation and Ω-notation are like $\leq$ and $\geq$.
o-notation and ω-notation are like $<$ and $>$.

$o(g(n)) = \{ f(n)$: for any constant $c > 0$,
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such that $0 \leq f(n) < cg(n)$
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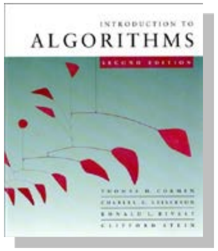
EXAMPLE: $2n^2 = o(n^3)$ $\quad (n_0 = 2/c)$



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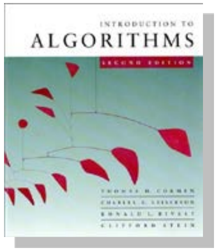
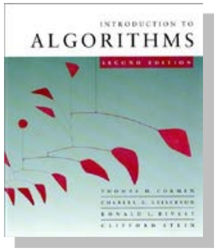
EXAMPLE: $\sqrt{n} = \omega(\lg n)$ $\quad (n_0 = 1+1/c)$



Solving recurrences

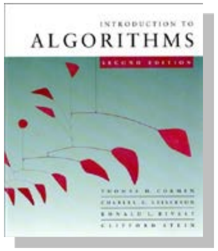
- The analysis of merge sort from ***Lecture 1*** required us to solve a recurrence.
- Recurrences are like solving integrals, differential equations, etc.
    - Learn a few tricks.
- ***Lecture 3***: Applications of recurrences to divide-and-conquer algorithms.



Substitution method

The most general method:

1. ***Guess*** the form of the solution.
2. ***Verify*** by induction.
3. ***Solve*** for constants.



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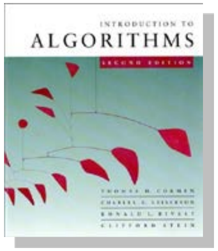
EXAMPLE: $T(n) = 4T(n/2) + n$

- [Assume that $T(1) = \Theta(1)$.]
- Guess $O(n^3)$. (Prove O and Ω separately.)
- Assume that $T(k) \le ck^3$ for $k < n$.
- Prove $T(n) \le cn^3$ by induction.

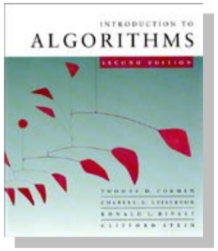


Example of substitution

$$
\begin{aligned}
T(n) &= 4T(n/2) + n \\
&\le 4c(n/2)^3 + n \\
&= (c/2)n^3 + n \\
&= cn^3 - ((c/2)n^3 - n) \longleftarrow \textit{desired} - \textit{residual} \\
&\le cn^3 \longleftarrow \textit{desired}
\end{aligned}
$$

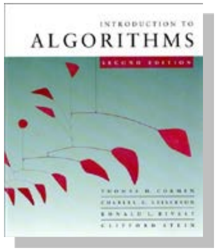
whenever $(c/2)n^3 - n \ge 0$, for example, if $c \ge 2$ and $n \ge 1$.

residual



Example (continued)

- We must also handle the initial conditions, that is, ground the induction with base cases.
- ***Base:*** $T(n) = \Theta(1)$ for all $n < n_0$, where n_0 is a suitable constant.
- For $1 \le n < n_0$, we have "$\Theta(1)$" $\le cn^3$, if we pick c big enough.



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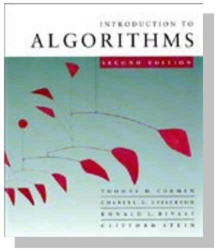
This bound is not tight!

A tighter upper bound?

We shall prove that $T(n) = O(n^2)$.



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Assume that $T(k) \leq ck^2$ for $k < n$:

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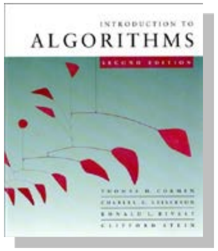
\begin{aligned}
T(n) &= 4T(n/2) + n \\
&\leq 4c(n/2)^2 + n \\
&= cn^2 + n \\
&= O(n^2)
\end{aligned}
$$



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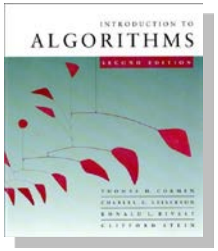
$$

Wrong! We must prove the I.H.



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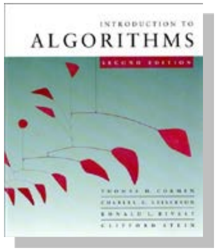
&\le 4c(n/2)^2 + n \\
&= cn^2 + n \\
&= \cancel{O(n^2)} \quad \textbf{\textit{Wrong!}} \text{ We must prove the I.H.} \\
&= cn^2 - (-n) \quad [\text{ desired } - \text{ residual }] \\
&\le cn^2 \quad \text{for } \textbf{\textit{no}} \text{ choice of } c > 0. \text{ Lose!}
\end{aligned}
$$



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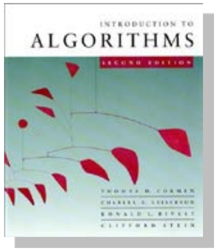
IDEA: Strengthen the inductive hypothesis.

• ***Subtract*** a low-order term.

Inductive hypothesis: $T(k) \le c_1k^2 - c_2k$ for $k < n$.



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&= c_1n^2 - 2c_2n + n \\
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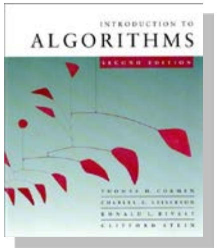
&\le c_1n^2 - c_2n \ \text{ if } c_2 \ge 1.
\end{aligned}
$$



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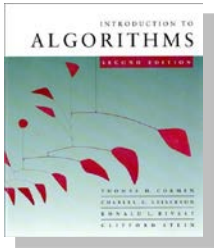
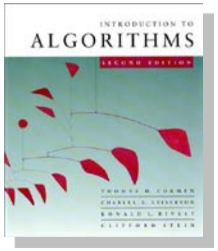
\end{aligned}
$$

Pick c_1 big enough to handle the initial conditions.



Recursion-tree method

- A recursion tree models the costs (time) of a recursive execution of an algorithm.
- The recursion-tree method can be unreliable, just like any method that uses ellipses (…).
- The recursion-tree method promotes intuition, however.
- The recursion tree method is good for generating guesses for the substitution method.



Example of recursion tree

Solve $T(n) = T(n/4) + T(n/2) + n^2$:

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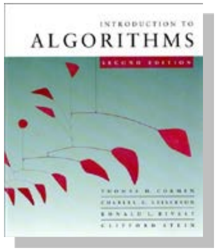
$$T(n)$$



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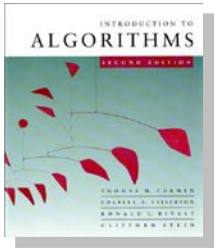
Solve $T(n) = T(n/4) + T(n/2) + n^2$:

$$n^2$$

$$T(n/4) \qquad\qquad\qquad T(n/2)$$



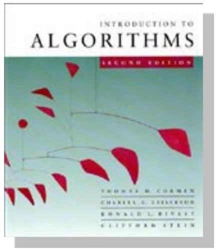
Example of recursion tree

Solve $T(n) = T(n/4) + T(n/2) + n^2$:

$$n^2$$

$$(n/4)^2 \qquad\qquad (n/2)^2$$

$$T(n/16) \quad T(n/8) \quad T(n/8) \quad T(n/4)$$



Example of recursion tree

Solve $T(n) = T(n/4) + T(n/2) + n^2$:

$$n^2$$

$$(n/4)^2 \qquad\qquad (n/2)^2$$

$$(n/16)^2 \quad (n/8)^2 \quad (n/8)^2 \quad (n/4)^2$$

$$\vdots$$

$$\Theta(1)$$

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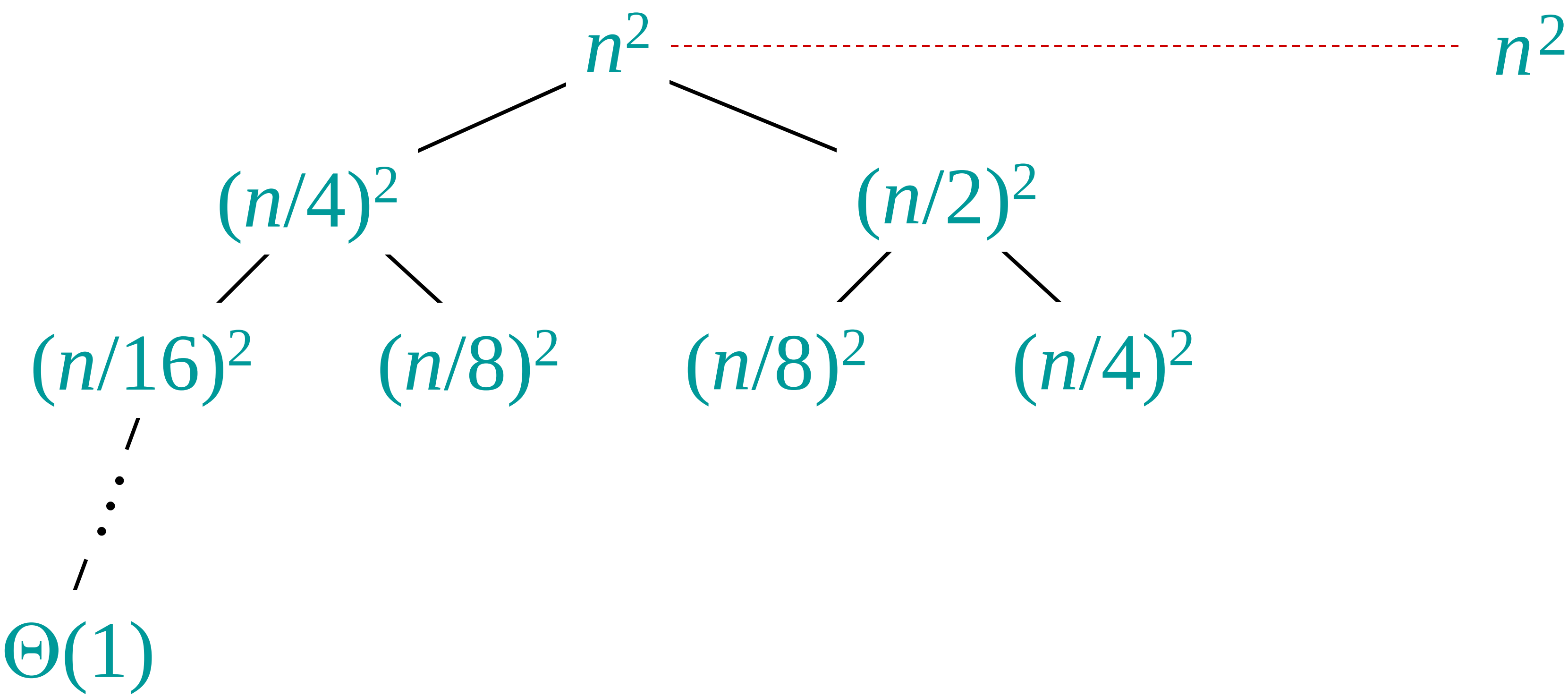
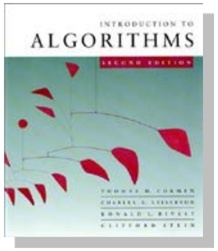




Example of recursion tree

Solve $T(n) = T(n/4) + T(n/2) + n^2$:

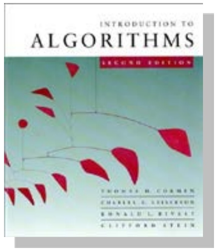
$$n^2 \qquad\qquad n^2$$

$$(n/4)^2 \qquad (n/2)^2 \qquad\qquad \frac{5}{16}n^2$$

$$(n/16)^2 \quad (n/8)^2 \quad (n/8)^2 \quad (n/4)^2$$

$$\vdots$$

$$\Theta(1)$$



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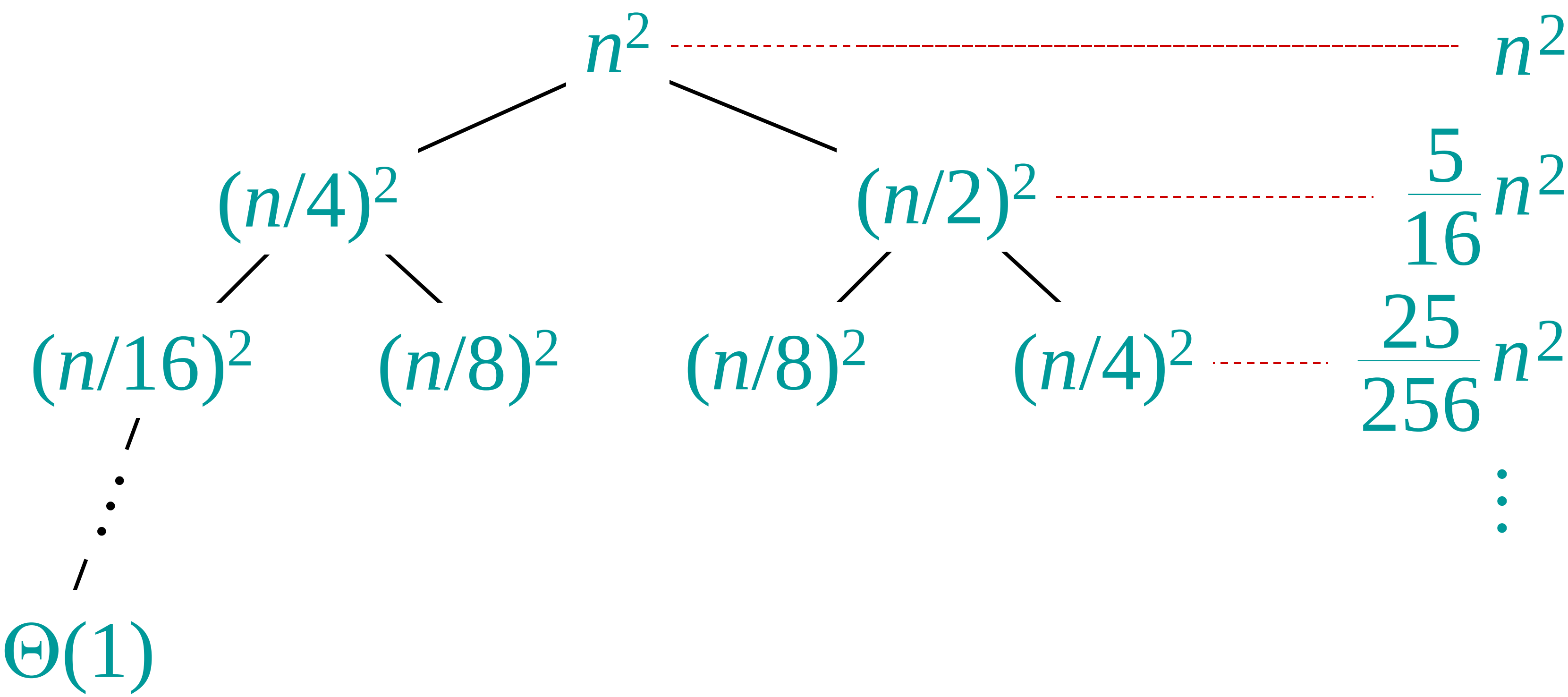
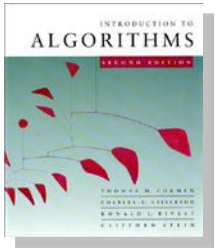




Example of recursion tree

Solve $T(n) = T(n/4) + T(n/2) + n^2$:

$$n^2 \quad \cdots\cdots\cdots \quad n^2$$

$$(n/4)^2 \qquad (n/2)^2 \quad \cdots\cdots \quad \frac{5}{16}n^2$$

$$(n/16)^2 \qquad (n/8)^2 \qquad (n/8)^2 \qquad (n/4)^2 \quad \cdots \quad \frac{25}{256}n^2$$

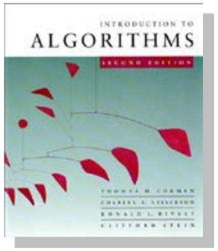
$$\vdots \qquad\qquad \vdots$$

$$\Theta(1)$$

$$\text{Total} = n^2\left(1 + \frac{5}{16} + \left(\frac{5}{16}\right)^2 + \left(\frac{5}{16}\right)^3 + \cdots\right)$$

$$= \Theta(n^2)$$

geometric series

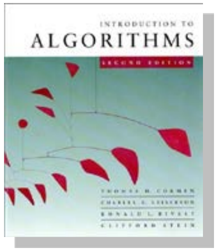


The master method

The master method applies to recurrences of the form

$$T(n) = a\,T(n/b) + f(n)\ ,$$

where $a \geq 1$, $b > 1$, and f is asymptotically positive.

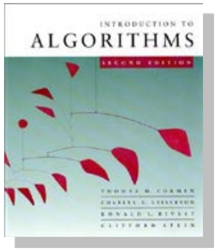


Three common cases

Compare $f(n)$ with $n^{\log_b a}$:

1. $f(n) = O(n^{\log_b a - \varepsilon})$ for some constant $\varepsilon > 0$.
   - $f(n)$ grows polynomially slower than $n^{\log_b a}$ (by an n^{ε} factor).

Solution: $T(n) = \Theta(n^{\log_b a})$.



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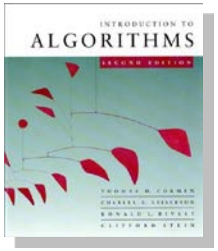
   Solution: $T(n) = \Theta(n^{\log_b a})$.

2. $f(n) = \Theta(n^{\log_b a} \lg^k n)$ for some constant $k \geq 0$.
   - $f(n)$ and $n^{\log_b a}$ grow at similar rates.

   Solution: $T(n) = \Theta(n^{\log_b a} \lg^{k+1} n)$.



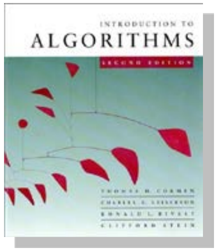
Three common cases (cont.)

Compare $f(n)$ with $n^{\log_b a}$:

3. $f(n) = \Omega(n^{\log_b a + \varepsilon})$ for some constant $\varepsilon > 0$.
   - $f(n)$ grows polynomially faster than $n^{\log_b a}$ (by an n^{ε} factor),

   and $f(n)$ satisfies the ***regularity condition*** that $a f(n/b) \le c f(n)$ for some constant $c < 1$.

   Solution: $T(n) = \Theta(f(n))$.



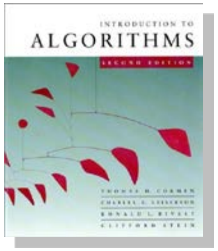
Examples

Ex. $T(n) = 4T(n/2) + n$

$a = 4$, $b = 2 \Rightarrow n^{\log_b a} = n^2$; $f(n) = n$.

Case 1: $f(n) = O(n^{2-\varepsilon})$ for $\varepsilon = 1$.

$\therefore\ T(n) = \Theta(n^2)$.



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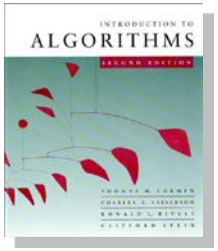
Ex. $T(n) = 4T(n/2) + n^2$

$a = 4$, $b = 2 \Rightarrow n^{\log_b a} = n^2$; $f(n) = n^2$.

CASE 2: $f(n) = \Theta(n^2 \lg^0 n)$, that is, $k = 0$.

$\therefore\ T(n) = \Theta(n^2 \lg n)$.



Examples

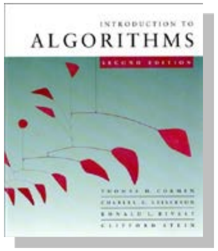
Ex. $T(n) = 4T(n/2) + n^3$

$a = 4,\ b = 2 \Rightarrow n^{\log_b a} = n^2;\ f(n) = n^3.$

Case 3: $f(n) = \Omega(n^{2+\varepsilon})$ for $\varepsilon = 1$

and $4(n/2)^3 \le cn^3$ (reg. cond.) for $c = 1/2$.

$\therefore\ T(n) = \Theta(n^3)$.



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$\therefore\ T(n) = \Theta(n^3)$.

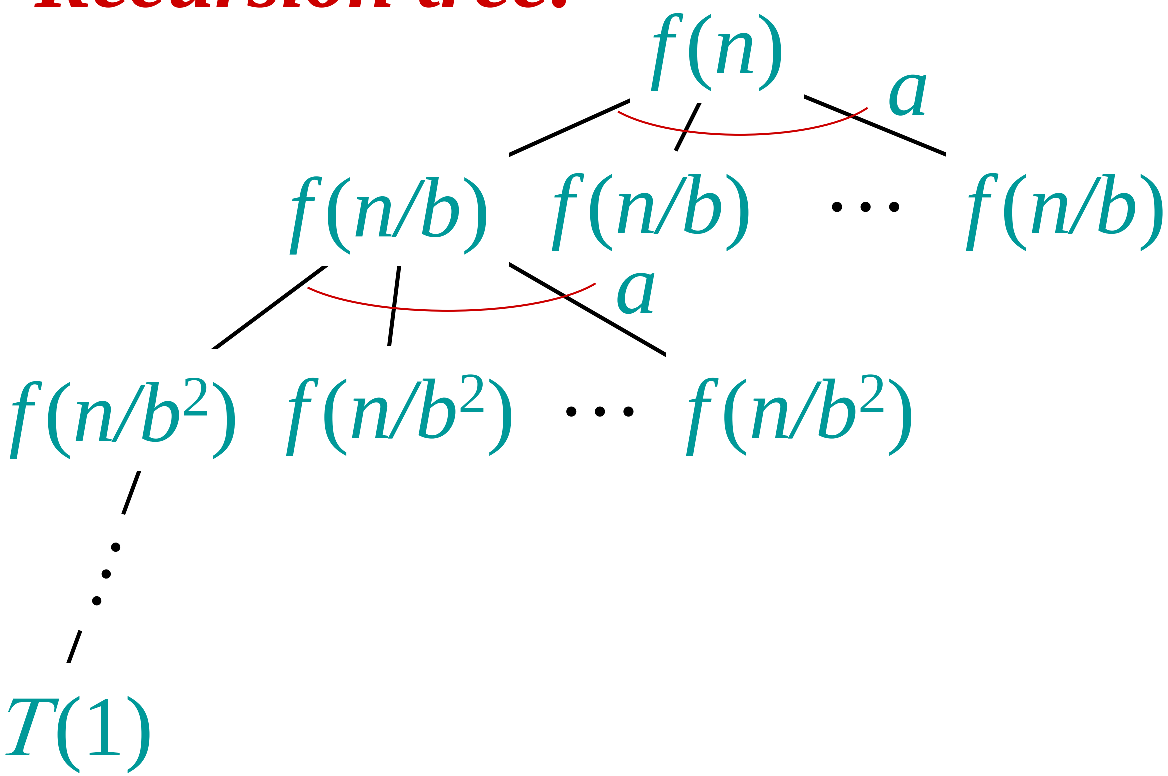
Ex. $T(n) = 4T(n/2) + n^2/\lg n$

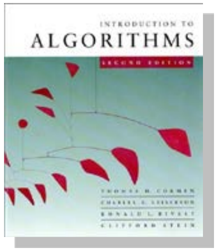
$a = 4,\ b = 2 \Rightarrow n^{\log_b a} = n^2;\ f(n) = n^2/\lg n.$

Master method does not apply. In particular, for every constant $\varepsilon > 0$, we have $n^\varepsilon = \omega(\lg n)$.

Idea of master theorem

Recursion tree:





Idea of master theorem

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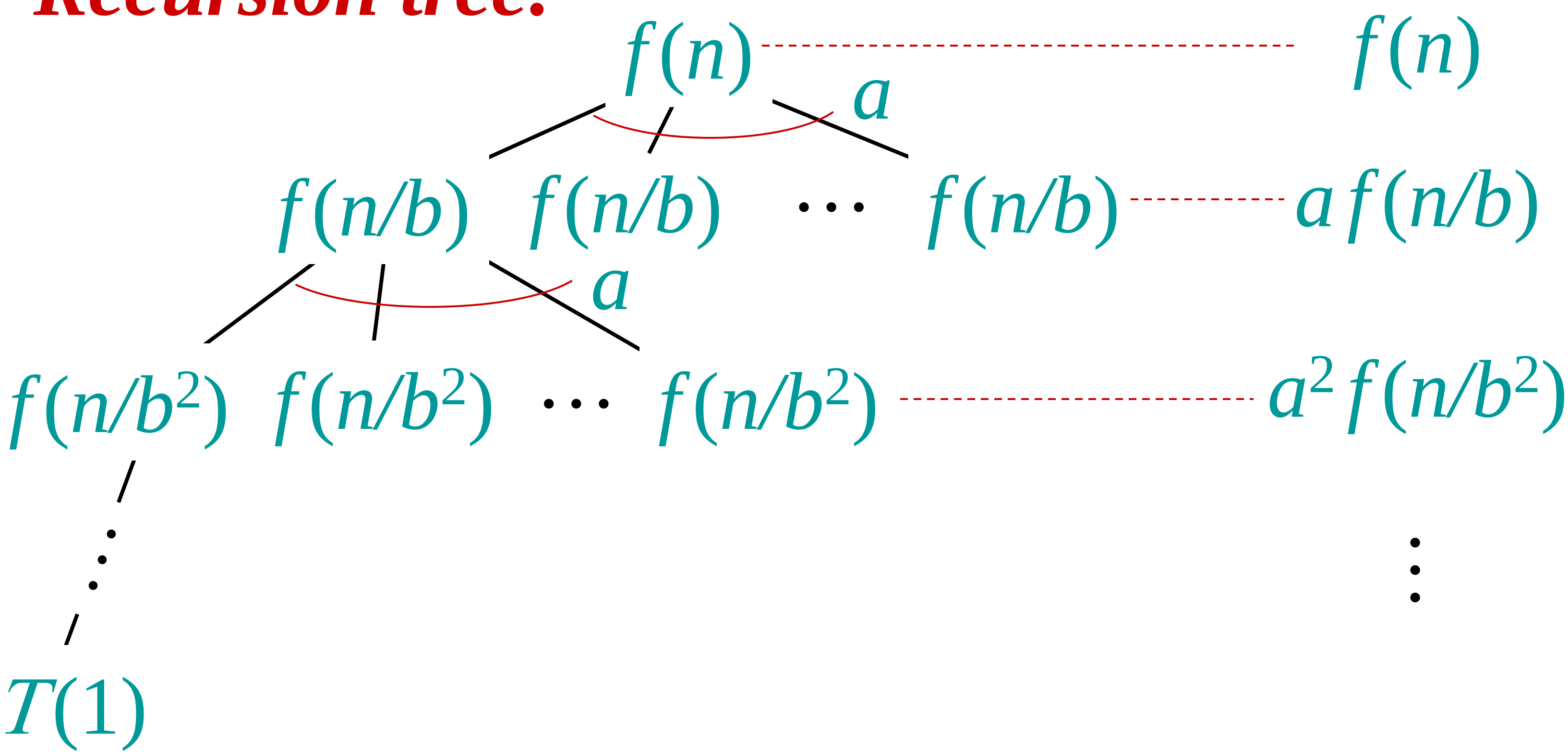

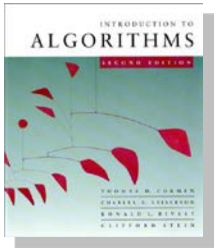

Idea of master theorem

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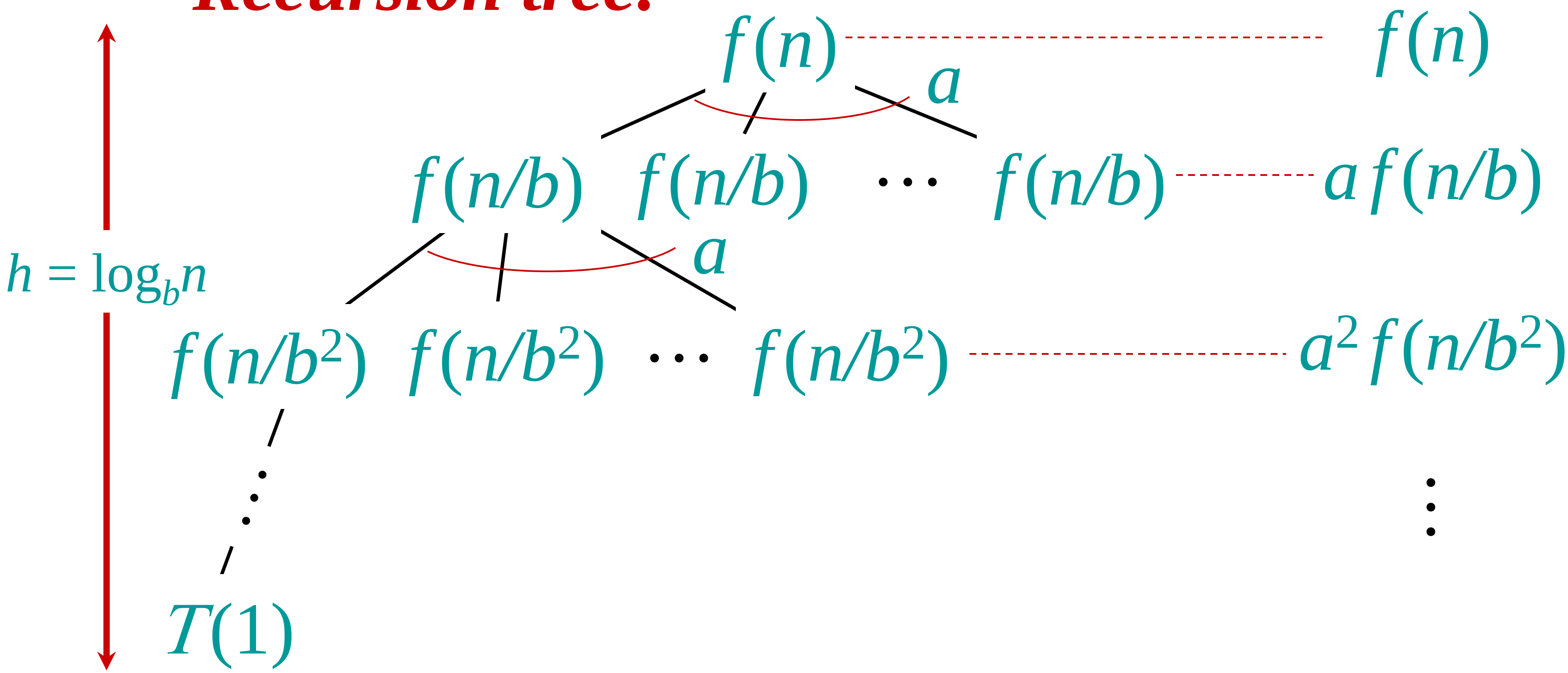
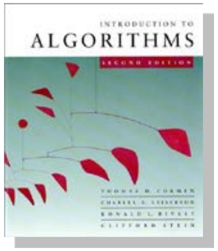




Idea of master theorem

Recursion tree:

$f(n)$ ……………… $f(n)$

a

$f(n/b) \quad f(n/b) \quad \cdots \quad f(n/b)$ ……… $a\,f(n/b)$

a

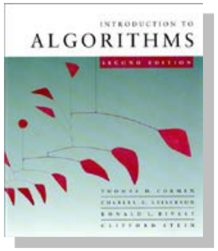
$h = \log_b n$

$f(n/b^2) \quad f(n/b^2) \quad \cdots \quad f(n/b^2)$ ……… $a^2 f(n/b^2)$

$\vdots$

$T(1)$ ……… $n^{\log_b a}\,T(1)$

$$\#\text{leaves} = a^h = a^{\log_b n} = n^{\log_b a}$$



Idea of master theorem

Recursion tree:

$$f(n) \qquad\qquad\qquad\qquad f(n)$$

a

$$f(n/b) \quad f(n/b) \quad \cdots \quad f(n/b) \qquad a\,f(n/b)$$

a

$h = \log_b n$

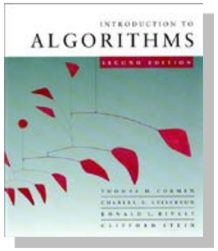
$$f(n/b^2) \quad f(n/b^2) \quad \cdots \quad f(n/b^2) \qquad a^2 f(n/b^2)$$

$$\vdots$$

$$T(1) \qquad\qquad\qquad\qquad n^{\log_b a}\,T(1)$$

CASE 1: The weight increases geometrically from the root to the leaves. The leaves hold a constant fraction of the total weight.

$$\Theta(n^{\log_b a})$$



Idea of master theorem

Recursion tree:

$h = \log_b n$

$f(n)$ .... $f(n)$

a

$f(n/b)$ $f(n/b)$ $\cdots$ $f(n/b)$ .... $a\,f(n/b)$

a

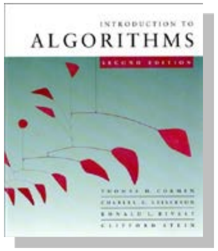
$f(n/b^2)$ $f(n/b^2)$ $\cdots$ $f(n/b^2)$ .... $a^2 f(n/b^2)$

$\vdots$

$T(1)$ .... $n^{\log_b a}\,T(1)$

CASE 2: ($k = 0$) The weight is approximately the same on each of the $\log_b n$ levels.

$\Theta(n^{\log_b a} \lg n)$



Idea of master theorem

Recursion tree:

$$f(n) \quad \cdots\cdots\cdots\cdots \quad f(n)$$

a

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$$h = \log_b n$$

$$f(n/b^2) \quad f(n/b^2) \quad \cdots \quad f(n/b^2) \quad \cdots\cdots \quad a^2 f(n/b^2)$$

$$\vdots$$

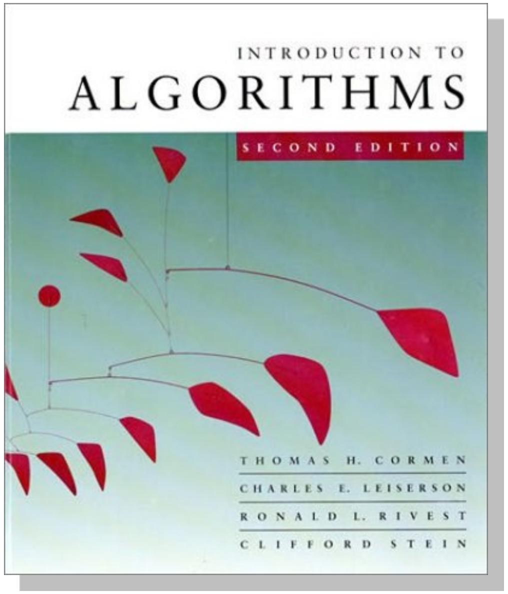
$$T(1) \quad \cdots\cdots \quad n^{\log_b a}\,T(1)$$

CASE 3: The weight decreases geometrically from the root to the leaves. The root holds a constant fraction of the total weight.

$$\Theta(f(n))$$

Introduction to Algorithms

6.046J/18.401J

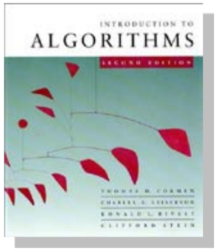


LECTURE 3

Divide and Conquer

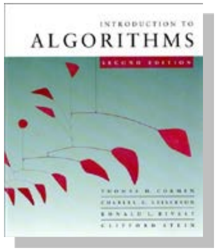
- Binary search
- Powering a number
- Fibonacci numbers
- Matrix multiplication
- Strassen's algorithm
- VLSI tree layout

Prof. Erik D. Demaine



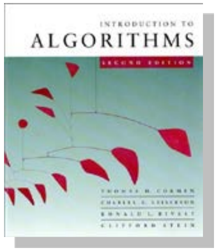
The divide-and-conquer design paradigm

1. ***Divide*** the problem (instance) into subproblems.
2. ***Conquer*** the subproblems by solving them recursively.
3. ***Combine*** subproblem solutions.



Merge sort

1. ***Divide:*** Trivial.
2. ***Conquer:*** Recursively sort 2 subarrays.
3. ***Combine:*** Linear-time merge.



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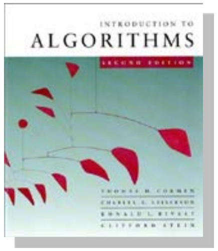
$$T(n) = 2\,T(n/2) + \Theta(n)$$

 # subproblems

subproblem size

work dividing and combining



Master theorem (reprise)

$$T(n) = a\,T(n/b) + f(n)$$

CASE 1: $f(n) = O(n^{\log_b a - \varepsilon})$, constant $\varepsilon > 0$

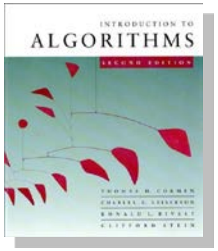
$\Rightarrow T(n) = \Theta(n^{\log_b a})$.

CASE 2: $f(n) = \Theta(n^{\log_b a} \lg^k n)$, constant $k \geq 0$

$\Rightarrow T(n) = \Theta(n^{\log_b a} \lg^{k+1} n)$.

CASE 3: $f(n) = \Omega(n^{\log_b a + \varepsilon})$, constant $\varepsilon > 0$, and regularity condition

$\Rightarrow T(n) = \Theta(f(n))$.



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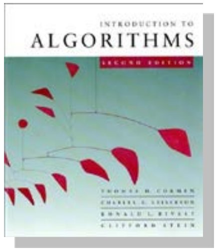
Merge sort: $a = 2$, $b = 2 \;\Rightarrow\; n^{\log_b a} = n^{\log_2 2} = n$

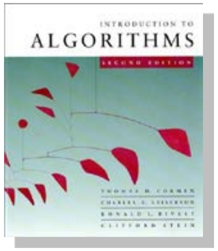
$\Rightarrow$ CASE 2 $(k = 0) \;\Rightarrow\; T(n) = \Theta(n \lg n)$.



Binary search

Find an element in a sorted array:

1. ***Divide:*** Check middle element.
2. ***Conquer:*** Recursively search 1 subarray.
3. ***Combine:*** Trivial.



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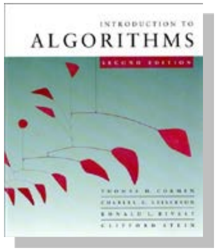
Example: Find 9

3	5	7	8	9	12	15



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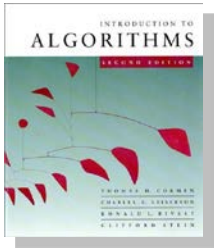

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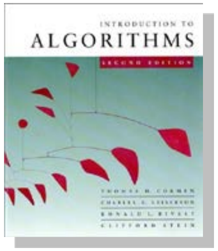

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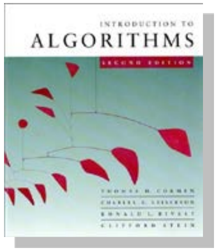

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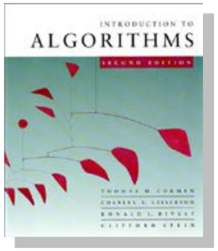

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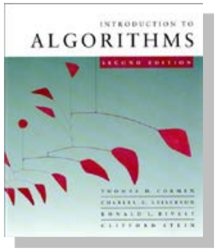


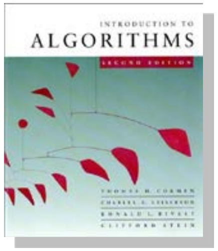
Recurrence for binary search

$$T(n) = 1\,T(n/2) + \Theta(1)$$

 # subproblems

subproblem size

work dividing and combining



Recurrence for binary search

$$T(n) = 1\,T(n/2) + \Theta(1)$$

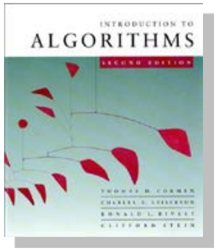
 # subproblems

subproblem size

work dividing and combining

$$n^{\log_b a} = n^{\log_2 1} = n^0 = 1 \Rightarrow \text{CASE 2 } (k = 0)$$

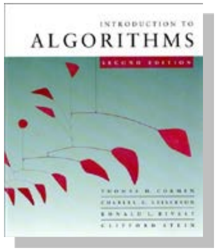
$$\Rightarrow T(n) = \Theta(\lg n)\,.$$



Powering a number

Problem: Compute a^n, where $n \in \mathbb{N}$.

Naive algorithm: $\Theta(n)$.



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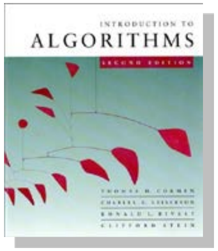
Naive algorithm: $\Theta(n)$.

Divide-and-conquer algorithm:

$$a^n = \begin{cases} a^{n/2} \cdot a^{n/2} & \text{if } n \text{ is even;} \\ a^{(n-1)/2} \cdot a^{(n-1)/2} \cdot a & \text{if } n \text{ is odd.} \end{cases}$$



Powering a number

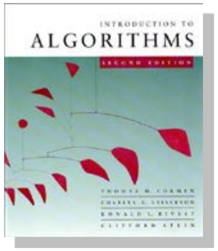
Problem: Compute a^n, where $n \in \mathbb{N}$.

Naive algorithm: $\Theta(n)$.

Divide-and-conquer algorithm:

$$a^n = \begin{cases} a^{n/2} \cdot a^{n/2} & \text{if } n \text{ is even;} \\ a^{(n-1)/2} \cdot a^{(n-1)/2} \cdot a & \text{if } n \text{ is odd.} \end{cases}$$

$$T(n) = T(n/2) + \Theta(1) \Rightarrow T(n) = \Theta(\lg n) .$$



Fibonacci numbers

Recursive definition:

$$F_n = \begin{cases} 0 & \text{if } n = 0; \\ 1 & \text{if } n = 1; \\ F_{n-1} + F_{n-2} & \text{if } n \geq 2. \end{cases}$$

$$0 \quad 1 \quad 1 \quad 2 \quad 3 \quad 5 \quad 8 \quad 13 \quad 21 \quad 34 \quad \cdots$$

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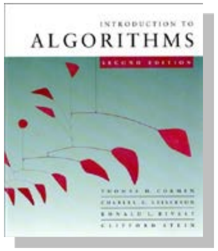
$0 \quad 1 \quad 1 \quad 2 \quad 3 \quad 5 \quad 8 \quad 13 \quad 21 \quad 34 \quad \cdots$

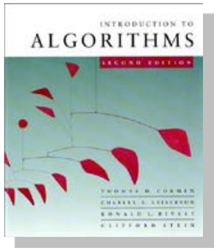
Naive recursive algorithm: $\Omega(\phi^n)$ (exponential time), where $\phi = (1 + \sqrt{5})/2$ is the ***golden ratio***.



Computing Fibonacci numbers

Bottom-up:

- Compute $F_0, F_1, F_2, \ldots, F_n$ in order, forming each number by summing the two previous.
- Running time: $\Theta(n)$.



Computing Fibonacci numbers

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- Compute $F_0, F_1, F_2, \ldots, F_n$ in order, forming each number by summing the two previous.
- Running time: $\Theta(n)$.

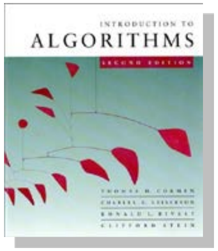
Naive recursive squaring:

$F_n = \phi^n / \sqrt{5}$ rounded to the nearest integer.

- Recursive squaring: $\Theta(\lg n)$ time.
- This method is unreliable, since floating-point arithmetic is prone to round-off errors.

Recursive squaring

Theorem: $\begin{bmatrix} F_{n+1} & F_n \\ F_n & F_{n-1} \end{bmatrix} = \begin{bmatrix} 1 & 1 \\ 1 & 0 \end{bmatrix}^n .$



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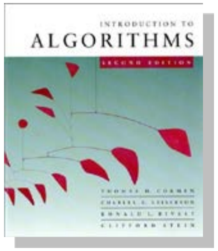
Algorithm: Recursive squaring.

Time = $\Theta(\lg n)$.



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Algorithm: Recursive squaring.

Time = $\Theta(\lg n)$.

Proof of theorem. (Induction on n.)

Base ($n = 1$): $$\begin{bmatrix} F_2 & F_1 \\ F_1 & F_0 \end{bmatrix} = \begin{bmatrix} 1 & 1 \\ 1 & 0 \end{bmatrix}^1 .$$

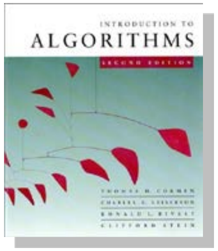
Recursive squaring

Inductive step ($n \geq 2$):

$$\begin{bmatrix} F_{n+1} & F_n \\ F_n & F_{n-1} \end{bmatrix} = \begin{bmatrix} F_n & F_{n-1} \\ F_{n-1} & F_{n-2} \end{bmatrix} \cdot \begin{bmatrix} 1 & 1 \\ 1 & 0 \end{bmatrix}.$$

$$= \begin{bmatrix} 1 & 1 \\ 1 & 0 \end{bmatrix}^{n-1} \cdot \begin{bmatrix} 1 & 1 \\ 1 & 0 \end{bmatrix}.$$

$$= \begin{bmatrix} 1 & 1 \\ 1 & 0 \end{bmatrix}^{n} \qquad \blacksquare$$



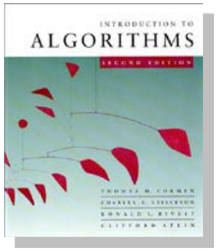
Matrix multiplication

Input: $A = [a_{ij}], B = [b_{ij}].$
Output: $C = [c_{ij}] = A \cdot B.$

$\left.\right\}\ i, j = 1, 2, \ldots, n.$

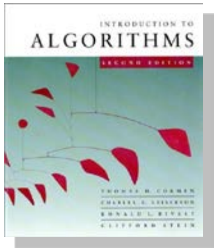
$$
\begin{bmatrix}
c_{11} & c_{12} & \cdots & c_{1n} \\
c_{21} & c_{22} & \cdots & c_{2n} \\
\vdots & \vdots & \ddots & \vdots \\
c_{n1} & c_{n2} & \cdots & c_{nn}
\end{bmatrix}
=
\begin{bmatrix}
a_{11} & a_{12} & \cdots & a_{1n} \\
a_{21} & a_{22} & \cdots & a_{2n} \\
\vdots & \vdots & \ddots & \vdots \\
a_{n1} & a_{n2} & \cdots & a_{nn}
\end{bmatrix}
\cdot
\begin{bmatrix}
b_{11} & b_{12} & \cdots & b_{1n} \\
b_{21} & b_{22} & \cdots & b_{2n} \\
\vdots & \vdots & \ddots & \vdots \\
b_{n1} & b_{n2} & \cdots & b_{nn}
\end{bmatrix}
$$

$$c_{ij} = \sum_{k=1}^{n} a_{ik} \cdot b_{kj}$$



Standard algorithm

for $i \leftarrow 1$ **to** n
  do for $j \leftarrow 1$ **to** n
    do $c_{ij} \leftarrow 0$
      for $k \leftarrow 1$ **to** n
        do $c_{ij} \leftarrow c_{ij} + a_{ik} \cdot b_{kj}$



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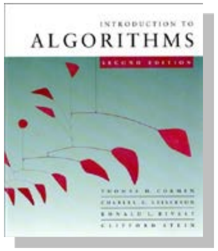
Running time $= \Theta(n^3)$



Divide-and-conquer algorithm

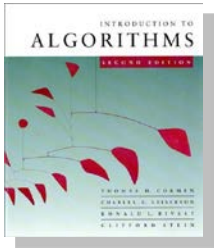
IDEA:

$n \times n$ matrix = 2×2 matrix of $(n/2) \times (n/2)$ submatrices:

$$\left[\begin{array}{c|c} r & s \\ \hline t & u \end{array}\right] = \left[\begin{array}{c|c} a & b \\ \hline c & d \end{array}\right] \cdot \left[\begin{array}{c|c} e & f \\ \hline g & h \end{array}\right]$$

$$C \quad = \quad A \quad \cdot \quad B$$

$$\left.\begin{aligned} r &= ae + bg \\ s &= af + bh \\ t &= ce + dg \\ u &= cf + dh \end{aligned}\right\} \begin{array}{l} 8 \text{ mults of } (n/2)\times(n/2) \text{ submatrices} \\ 4 \text{ adds of } (n/2)\times(n/2) \text{ submatrices} \end{array}$$



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$$C \quad = \quad A \quad \cdot \quad B$$

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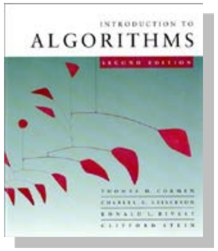
<u>*recursive*</u>

8 mults of $(n/2)\times(n/2)$ submatrices

4 adds of $(n/2)\times(n/2)$ submatrices



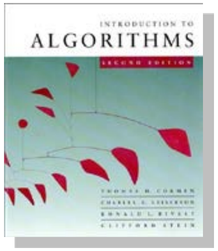
Analysis of D&C algorithm

$$T(n) = 8\,T(n/2) + \Theta(n^2)$$

 # submatrices

submatrix size

work adding submatrices



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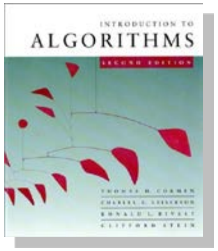
$$n^{\log_b a} = n^{\log_2 8} = n^3 \;\Rightarrow\; \text{CASE 1} \;\Rightarrow\; T(n) = \Theta(n^3).$$



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 # submatrices

submatrix size

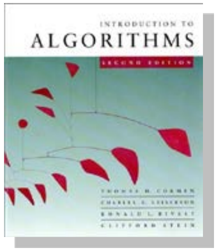
work adding submatrices

$n^{\log_b a} = n^{\log_2 8} = n^3 \;\Rightarrow\;$ CASE 1 $\;\Rightarrow\; T(n) = \Theta(n^3)$.

No better than the ordinary algorithm.

Strassen's idea

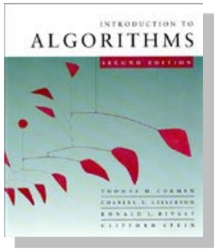
- Multiply 2×2 matrices with only 7 recursive mults.



Strassen's idea

- Multiply 2×2 matrices with only 7 recursive mults.

$$P_1 = a \cdot (f - h)$$
$$P_2 = (a + b) \cdot h$$
$$P_3 = (c + d) \cdot e$$
$$P_4 = d \cdot (g - e)$$
$$P_5 = (a + d) \cdot (e + h)$$
$$P_6 = (b - d) \cdot (g + h)$$
$$P_7 = (a - c) \cdot (e + f)$$



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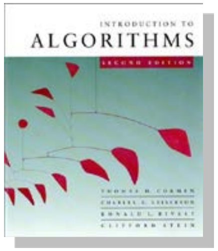
\end{aligned}
$$

$$
\begin{aligned}
r &= P_5 + P_4 - P_2 + P_6 \\
s &= P_1 + P_2 \\
t &= P_3 + P_4 \\
u &= P_5 + P_1 - P_3 - P_7
\end{aligned}
$$



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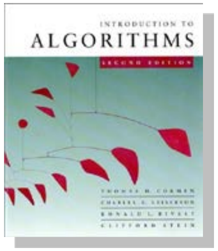
\end{aligned}
$$

7 mults, 18 adds/subs.
Note: No reliance on commutativity of mult!



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P_7 &= (a - c) \cdot (e + f)
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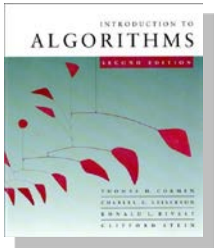
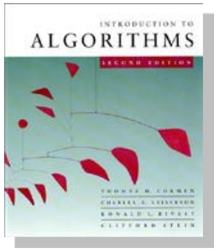
$$

$$
\begin{aligned}
r &= P_5 + P_4 - P_2 + P_6 \\
&= (a + d)(e + h) \\
&\quad + d(g - e) - (a + b)h \\
&\quad + (b - d)(g + h) \\
&= ae + ah + de + dh \\
&\quad + dg - de - ah - bh \\
&\quad + bg + bh - dg - dh \\
&= ae + bg
\end{aligned}
$$



Strassen's algorithm

1. ***Divide:*** Partition A and B into $(n/2)\times(n/2)$ submatrices. Form terms to be multiplied using $+$ and $-$.
2. ***Conquer:*** Perform 7 multiplications of $(n/2)\times(n/2)$ submatrices recursively.
3. ***Combine:*** Form C using $+$ and $-$ on $(n/2)\times(n/2)$ submatrices.



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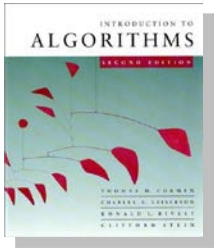

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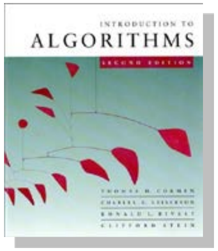

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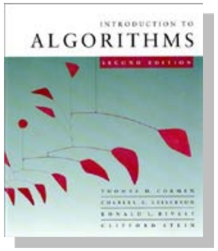
$$T(n) = 7\,T(n/2) + \Theta(n^2)$$

$$n^{\log_b a} = n^{\log_2 7} \approx n^{2.81} \;\Rightarrow\; \text{Case 1} \;\Rightarrow\; T(n) = \Theta(n^{\lg 7}).$$



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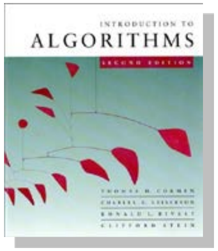
The number 2.81 may not seem much smaller than 3, but because the difference is in the exponent, the impact on running time is significant. In fact, Strassen's algorithm beats the ordinary algorithm on today's machines for $n \geq 32$ or so.



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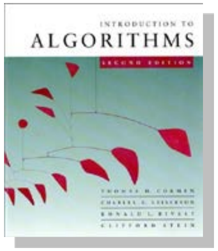
Best to date (of theoretical interest only): $\Theta(n^{2.376\cdots})$.



VLSI layout

Problem: Embed a complete binary tree with n leaves in a grid using minimal area.

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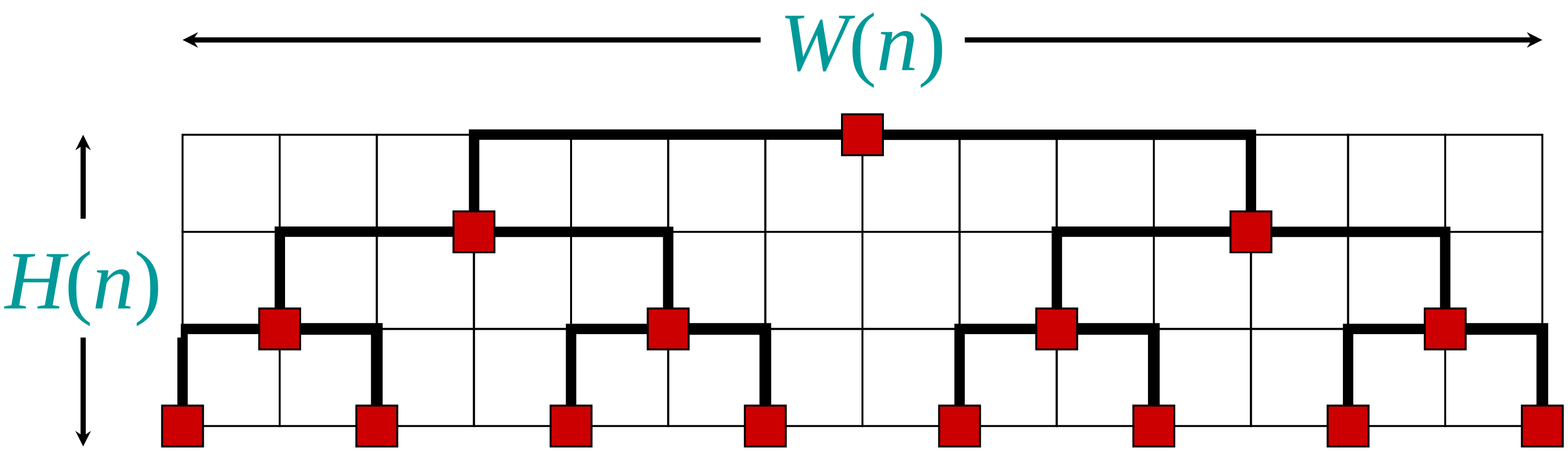

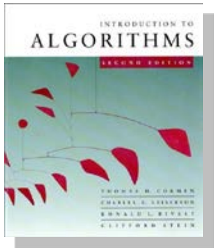

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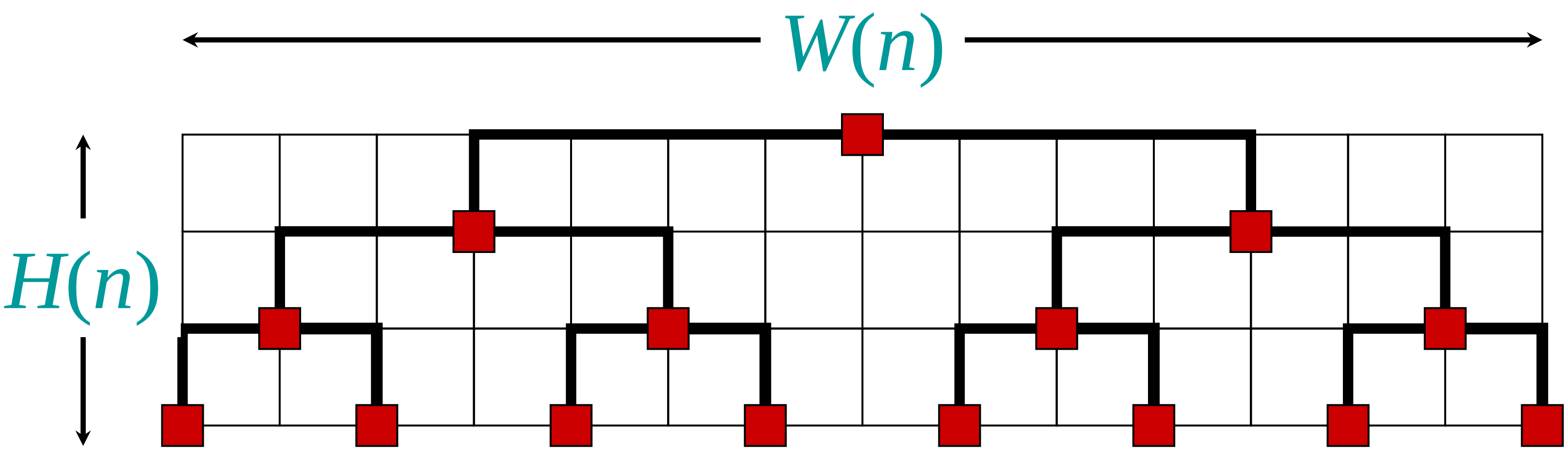
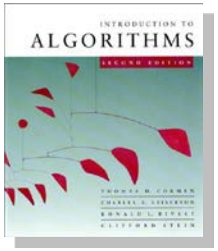


$$
\begin{aligned}
H(n) &= H(n/2) + \Theta(1) \\
&= \Theta(\lg n)
\end{aligned}
$$



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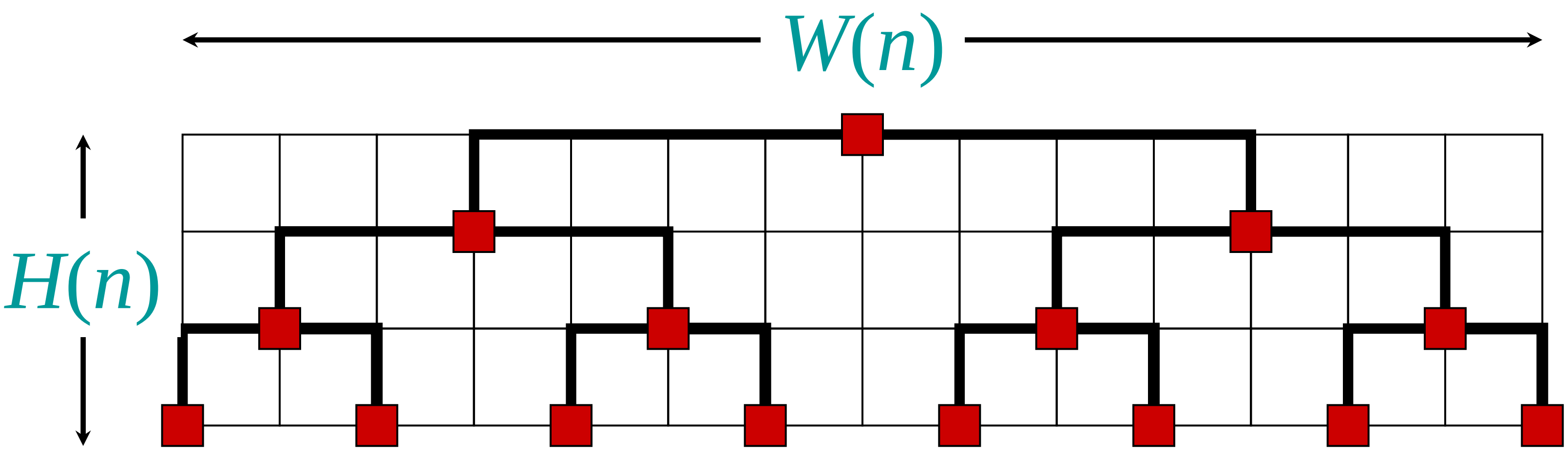

$$H(n) = H(n/2) + \Theta(1) = \Theta(\lg n)$$

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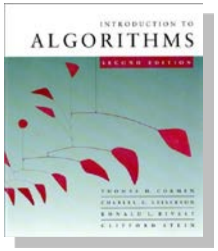

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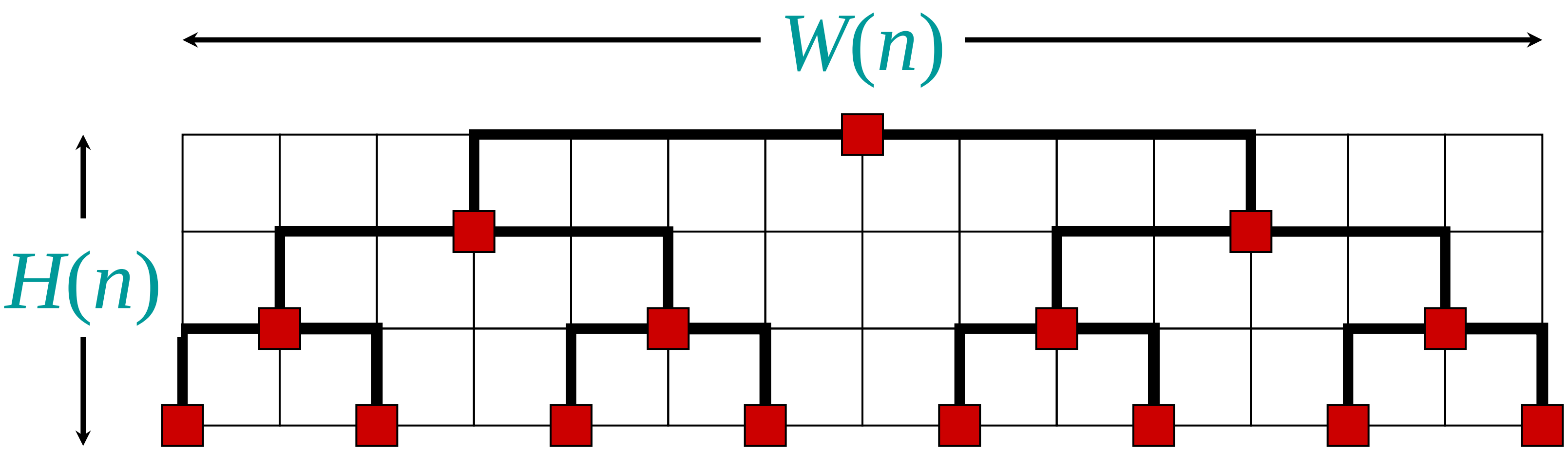
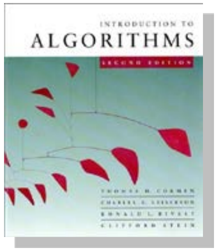


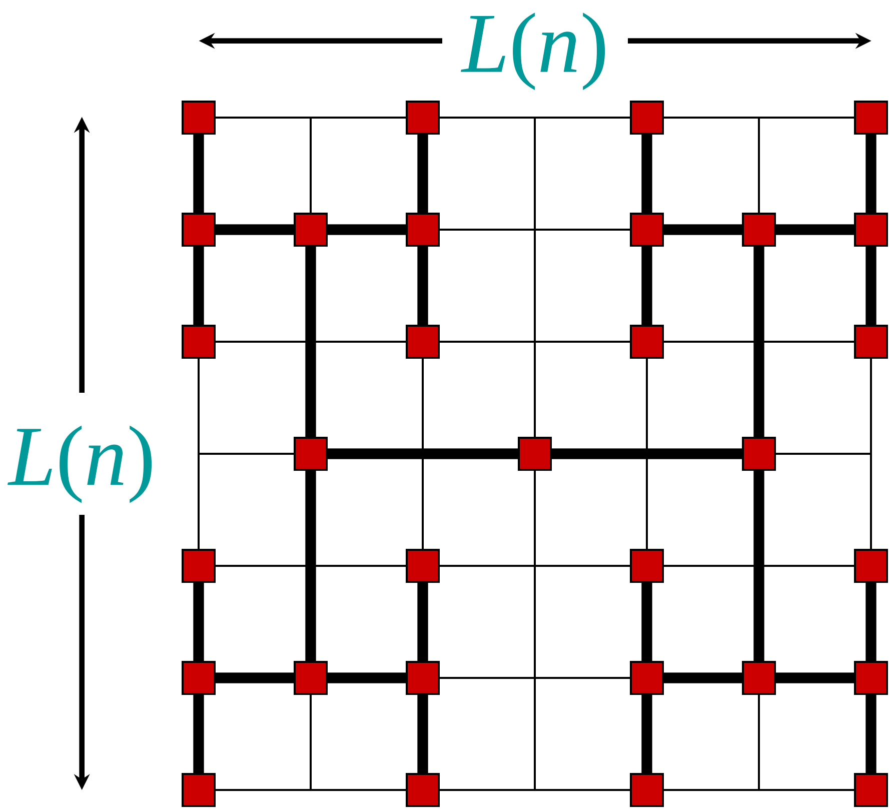
$$H(n) = H(n/2) + \Theta(1) = \Theta(\lg n)$$

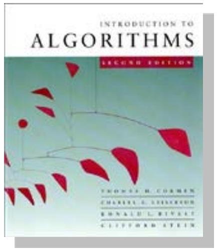
$$W(n) = 2W(n/2) + \Theta(1) = \Theta(n)$$

$$\text{Area} = \Theta(n \lg n)$$

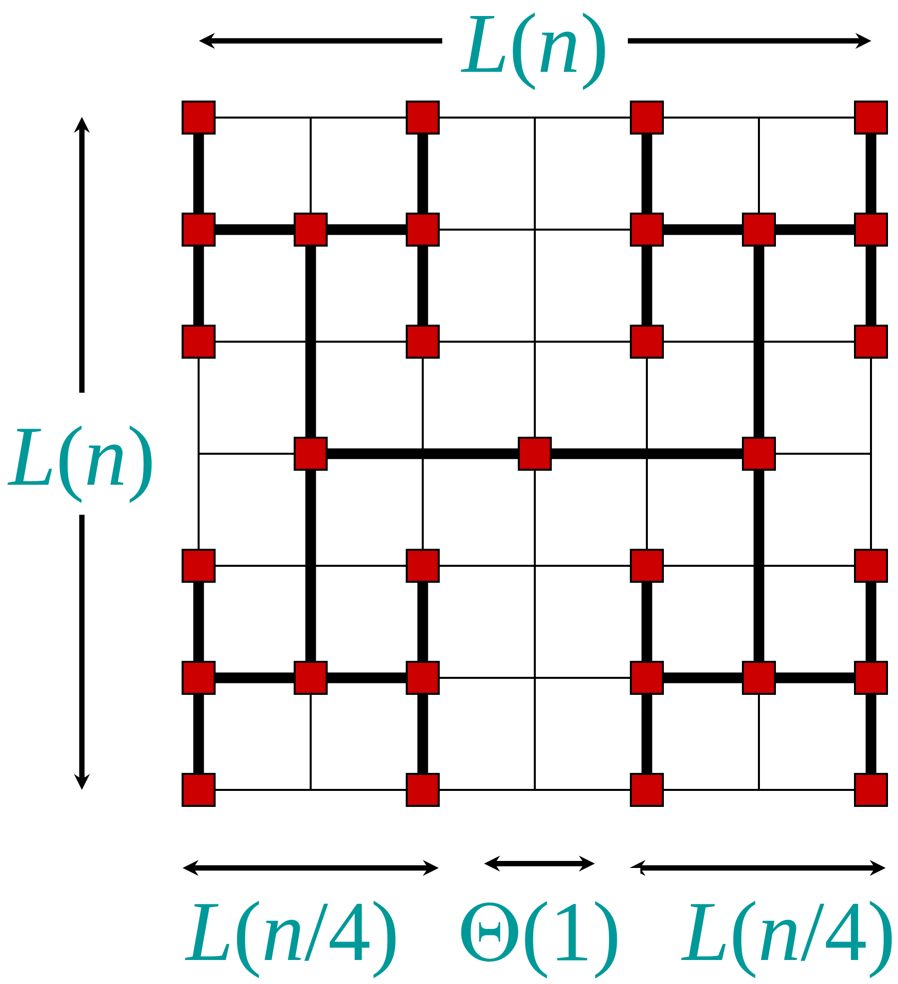


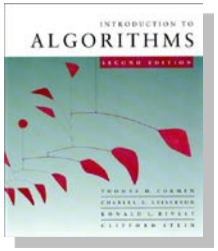
H-tree embedding



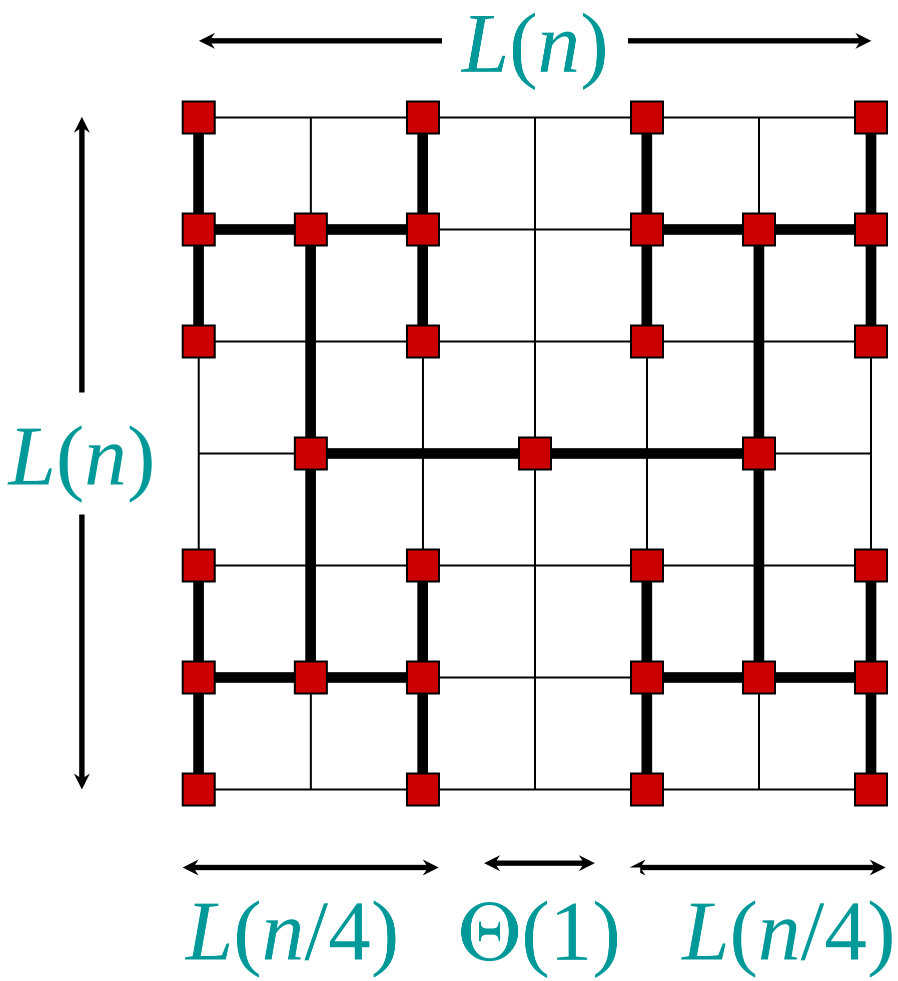


H-tree embedding



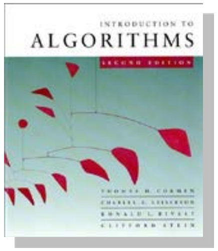


H-tree embedding



$$L(n) = 2L(n/4) + \Theta(1)$$
$$= \Theta(\sqrt{n})$$

Area = $\Theta(n)$

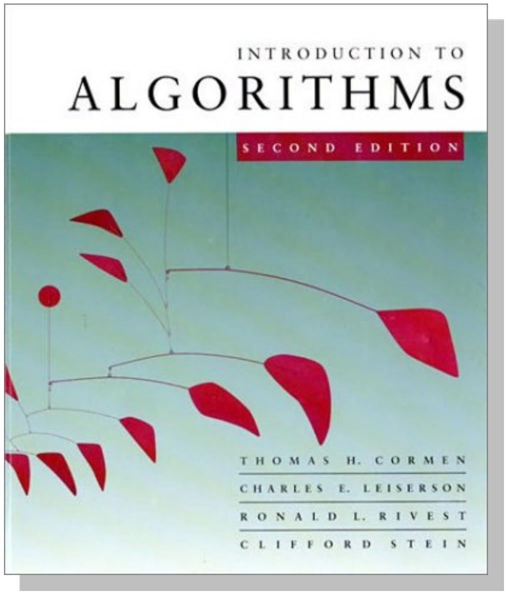


Conclusion

- Divide and conquer is just one of several powerful techniques for algorithm design.
- Divide-and-conquer algorithms can be analyzed using recurrences and the master method (so practice this math).
- The divide-and-conquer strategy often leads to efficient algorithms.

Introduction to Algorithms

6.046J/18.401J

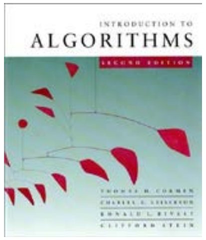


LECTURE 4

Quicksort

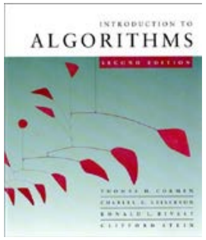
- Divide and conquer
- Partitioning
- Worst-case analysis
- Intuition
- Randomized quicksort
- Analysis

Prof. Charles E. Leiserson



Quicksort

- Proposed by C.A.R. Hoare in 1962.
- Divide-and-conquer algorithm.
- Sorts "in place" (like insertion sort, but not like merge sort).
- Very practical (with tuning).



Divide and conquer

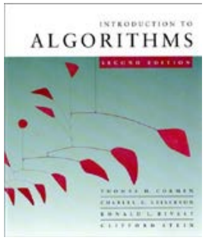
Quicksort an n-element array:

1. ***Divide:*** Partition the array into two subarrays around a ***pivot*** x such that elements in lower subarray $\leq x \leq$ elements in upper subarray.

$\leq x$	x	$\geq x$

2. ***Conquer:*** Recursively sort the two subarrays.
3. ***Combine:*** Trivial.

Key: *Linear-time partitioning subroutine.*

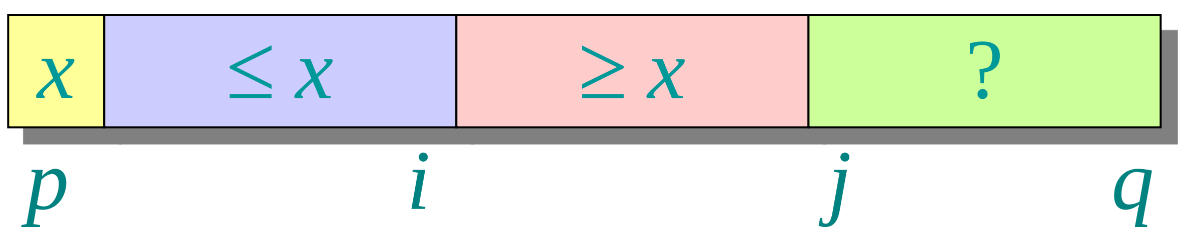


Partitioning subroutine

PARTITION(A, p, q) ⊳ $A[p \,.\,.\, q]$
    $x \leftarrow A[p]$ ⊳ pivot $= A[p]$
    $i \leftarrow p$
    for $j \leftarrow p + 1$ **to** q
        do if $A[j] \le x$
            then $i \leftarrow i + 1$
                exchange $A[i] \leftrightarrow A[j]$
    exchange $A[p] \leftrightarrow A[i]$
    return i

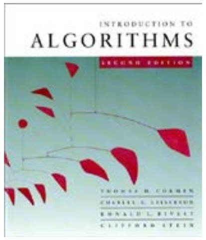
Running time $= O(n)$ for n elements.

Invariant:



Example of partitioning

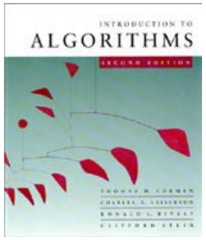
6	10	13	5	8	3	2	11
i	j						



Example of partitioning

6	10	13	5	8	3	2	11

i $\longrightarrow$ j



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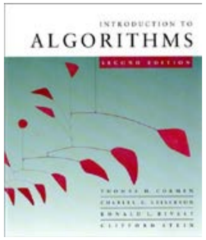

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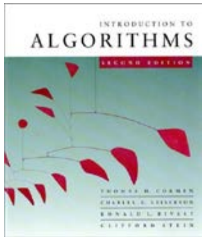
6	10	13	5	8	3	2	11

6	5	13	10	8	3	2	11
	i			j			



Example of partitioning

6	10	13	5	8	3	2	11

6	5	13	10	8	3	2	11

i $\qquad\qquad\qquad\qquad$ j

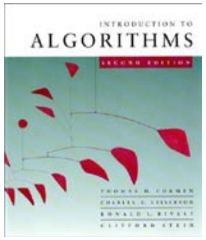
Example of partitioning

6	10	13	5	8	3	2	11

6	5	13	10	8	3	2	11

6	5	3	10	8	13	2	11

i j



Example of partitioning

6	10	13	5	8	3	2	11
6	5	13	10	8	3	2	11
6	5	3	10	8	13	2	11
		i				j	

Example of partitioning

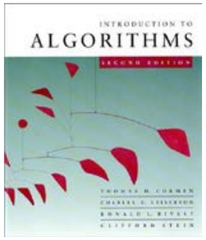
6	10	13	5	8	3	2	11

6	5	13	10	8	3	2	11

6	5	3	10	8	13	2	11

6	5	3	2	8	13	10	11

i j



Example of partitioning

6	10	13	5	8	3	2	11

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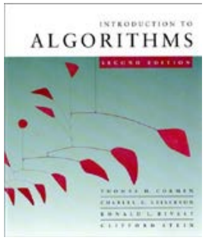
6	5	3	2	8	13	10	11
			i				$\longrightarrow j$



Example of partitioning

6	10	13	5	8	3	2	11

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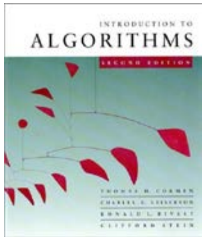
6	5	3	10	8	13	2	11

6	5	3	2	8	13	10	11

i $\qquad\qquad\qquad \longrightarrow j$



Example of partitioning

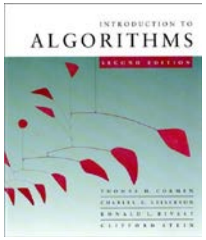
6	10	13	5	8	3	2	11

6	5	13	10	8	3	2	11

6	5	3	10	8	13	2	11

6	5	3	2	8	13	10	11

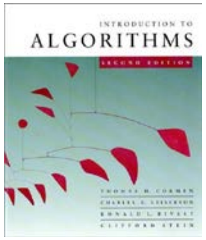
2	5	3	6	8	13	10	11
			i				



Pseudocode for quicksort

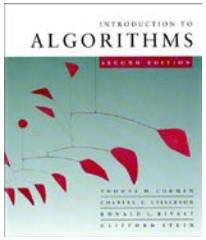
QUICKSORT(A, p, r)
  if $p < r$
    then $q \leftarrow$ PARTITION(A, p, r)
      QUICKSORT(A, p, q–1)
      QUICKSORT(A, q+1, r)

Initial call: QUICKSORT(A, 1, n)



Analysis of quicksort

- Assume all input elements are distinct.
- In practice, there are better partitioning algorithms for when duplicate input elements may exist.
- Let $T(n)$ = worst-case running time on an array of n elements.



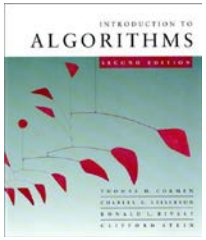
Worst-case of quicksort

- Input sorted or reverse sorted.
- Partition around min or max element.
- One side of partition always has no elements.

$$
\begin{aligned}
T(n) &= T(0) + T(n-1) + \Theta(n) \\
&= \Theta(1) + T(n-1) + \Theta(n) \\
&= T(n-1) + \Theta(n) \\
&= \Theta(n^2) \qquad \textbf{\textit{(arithmetic series)}}
\end{aligned}
$$

Worst-case recursion tree

$$T(n) = T(0) + T(n-1) + cn$$



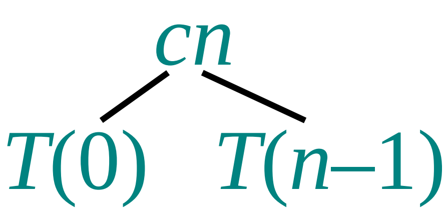
Worst-case recursion tree

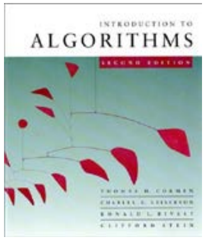
$$T(n) = T(0) + T(n-1) + cn$$

$$T(n)$$

Worst-case recursion tree

$$T(n) = T(0) + T(n-1) + cn$$





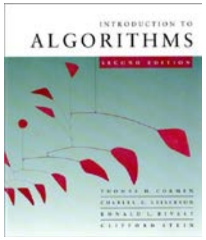
Worst-case recursion tree

$$T(n) = T(0) + T(n-1) + cn$$

$$cn$$

$$T(0) \qquad c(n-1)$$

$$T(0) \qquad T(n-2)$$



Worst-case recursion tree

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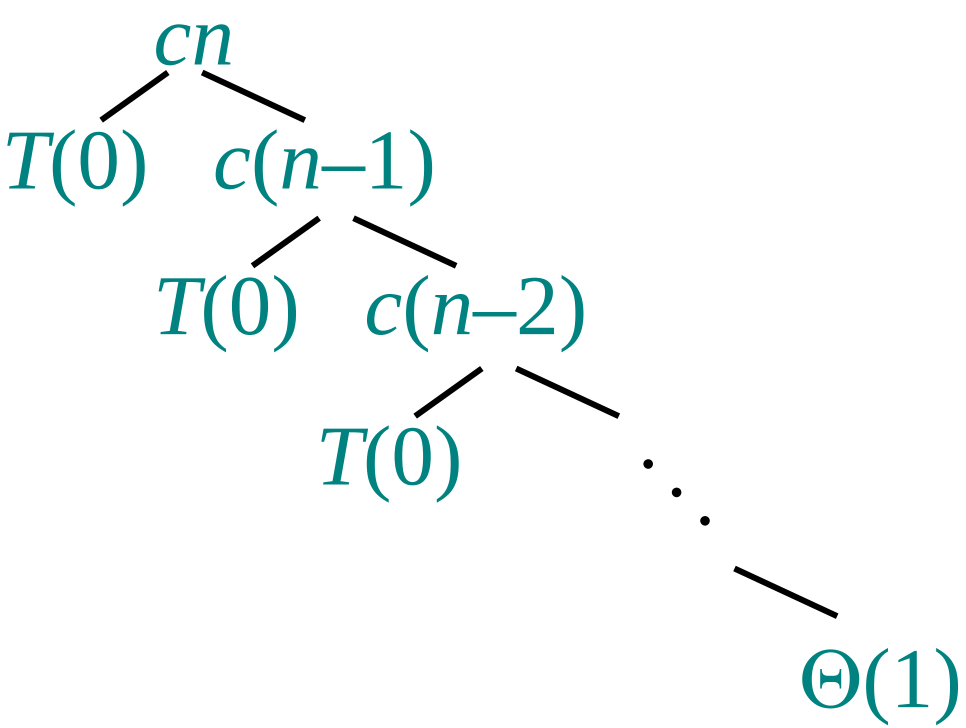
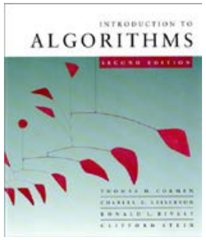
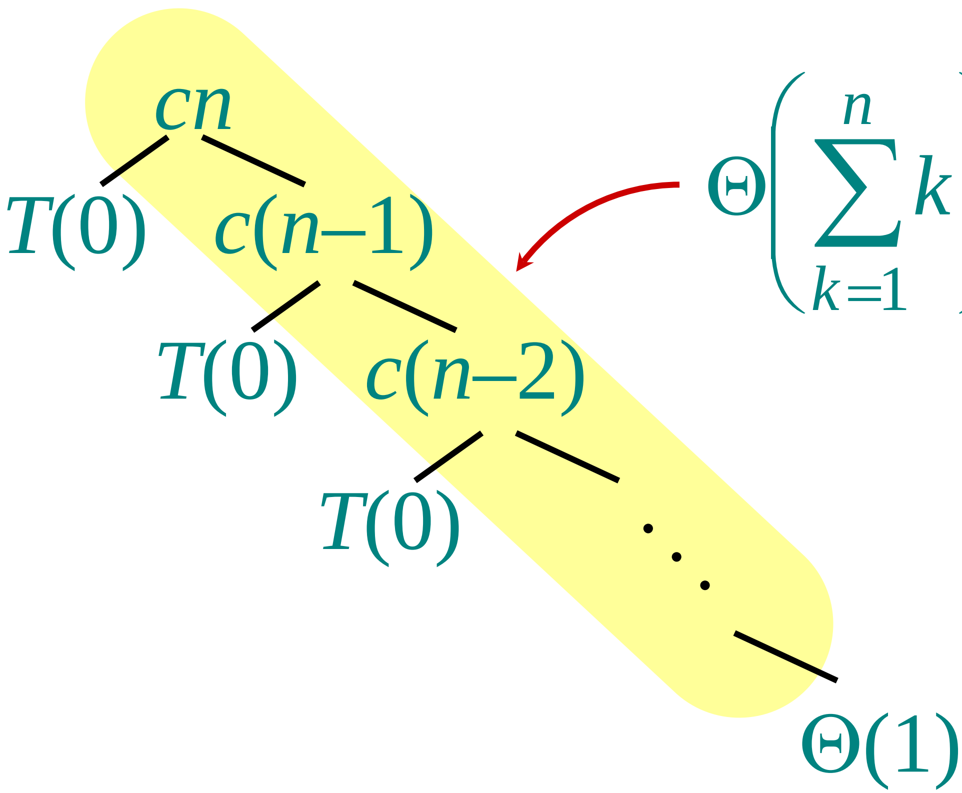


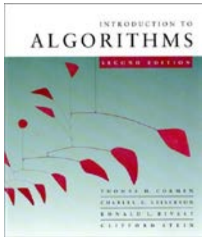


Worst-case recursion tree

$$T(n) = T(0) + T(n-1) + cn$$

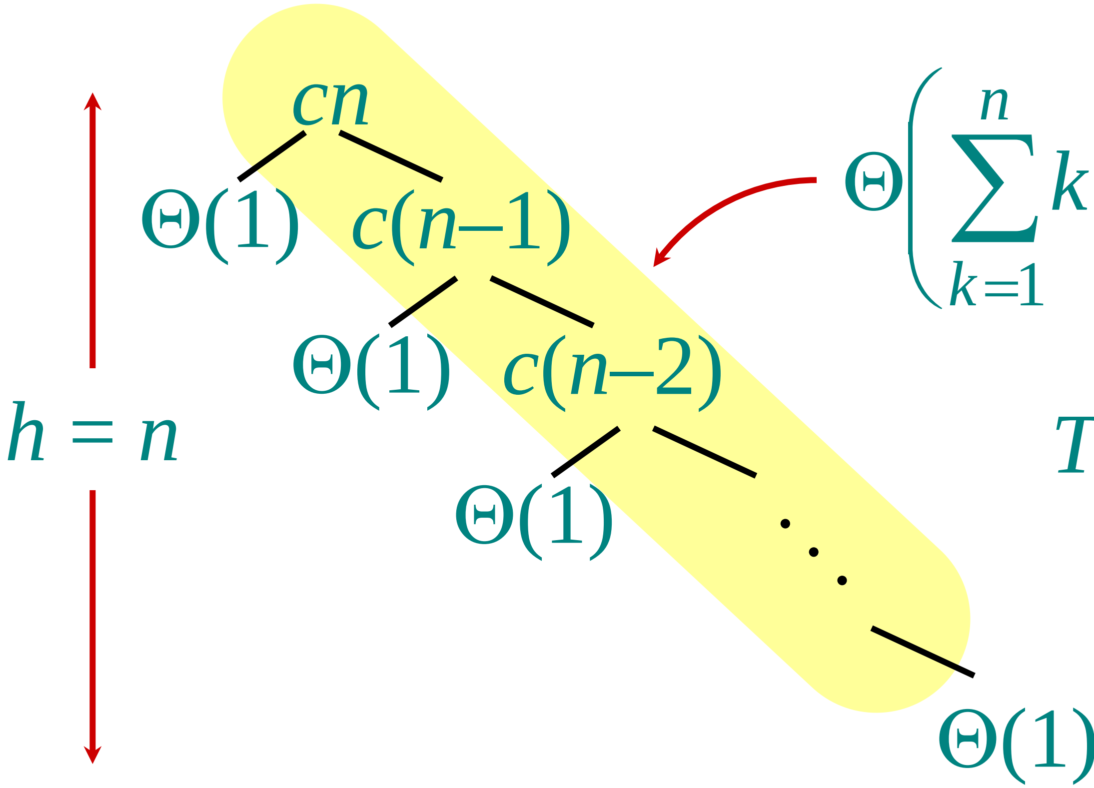


$$\Theta\left(\sum_{k=1}^{n} k\right) = \Theta\left(n^2\right)$$



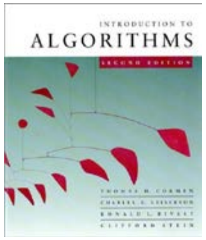
Worst-case recursion tree

$$T(n) = T(0) + T(n-1) + cn$$



$$\Theta\left(\sum_{k=1}^{n} k\right) = \Theta\left(n^2\right)$$

$$\begin{aligned} T(n) &= \Theta(n) + \Theta(n^2) \\ &= \Theta(n^2) \end{aligned}$$



Best-case analysis

(For intuition only!)

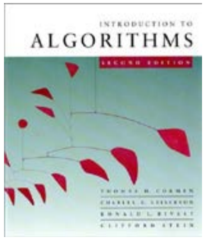
If we're lucky, PARTITION splits the array evenly:

$$\begin{aligned} T(n) &= 2T(n/2) + \Theta(n) \\ &= \Theta(n \lg n) \end{aligned}$$ (same as merge sort)

What if the split is always $\frac{1}{10} : \frac{9}{10}$?

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

What is the solution to this recurrence?



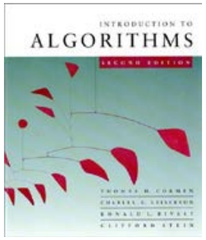
Analysis of “almost-best” case

$$T(n)$$

Analysis of "almost-best" case

$$cn$$

$$T\left(\tfrac{1}{10}n\right) \qquad\qquad T\left(\tfrac{9}{10}n\right)$$



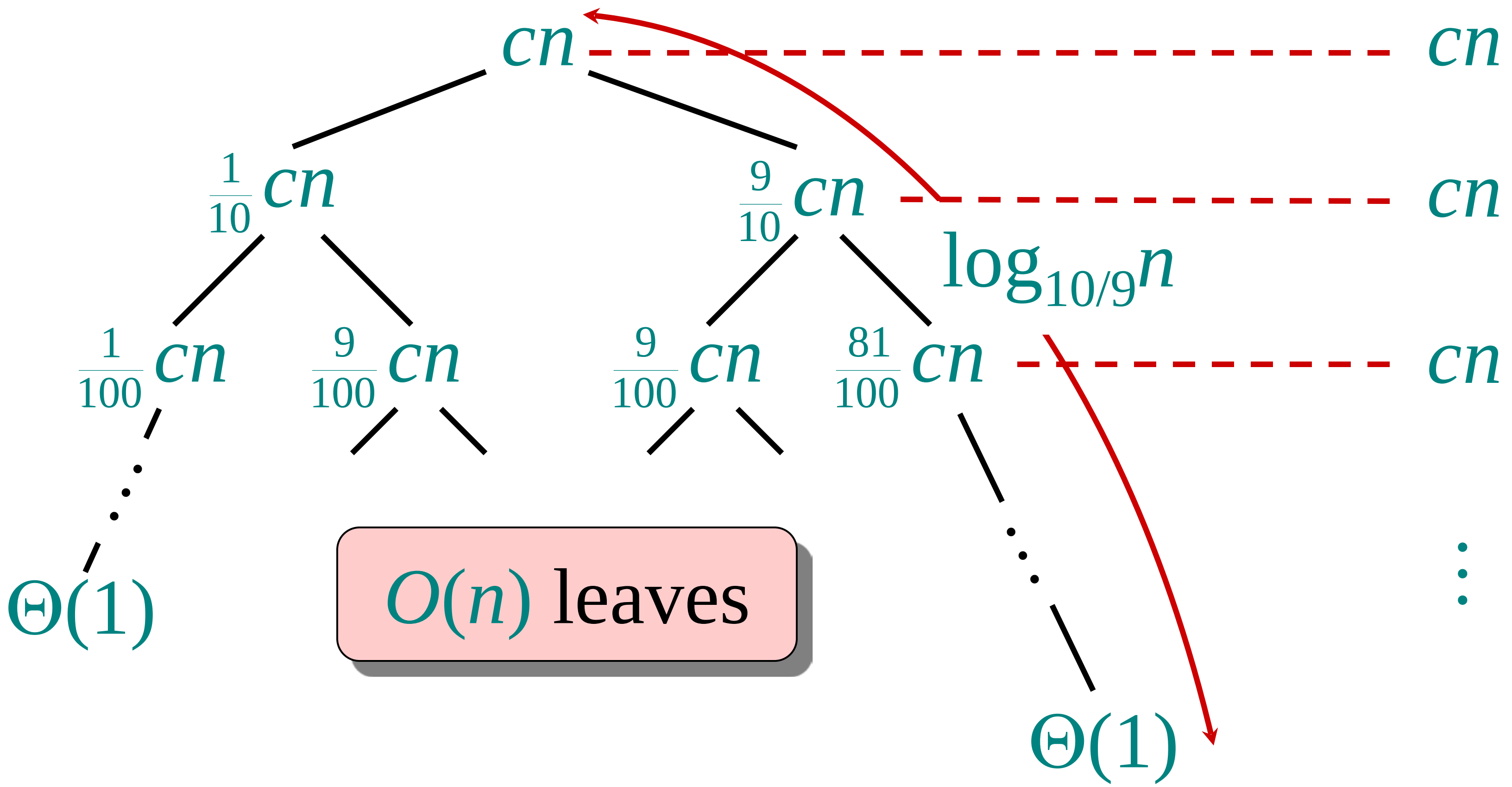
Analysis of “almost-best” case

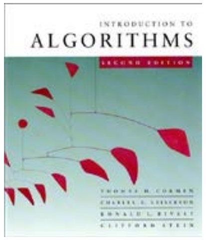
$$cn$$

$$\tfrac{1}{10}cn \qquad\qquad \tfrac{9}{10}cn$$

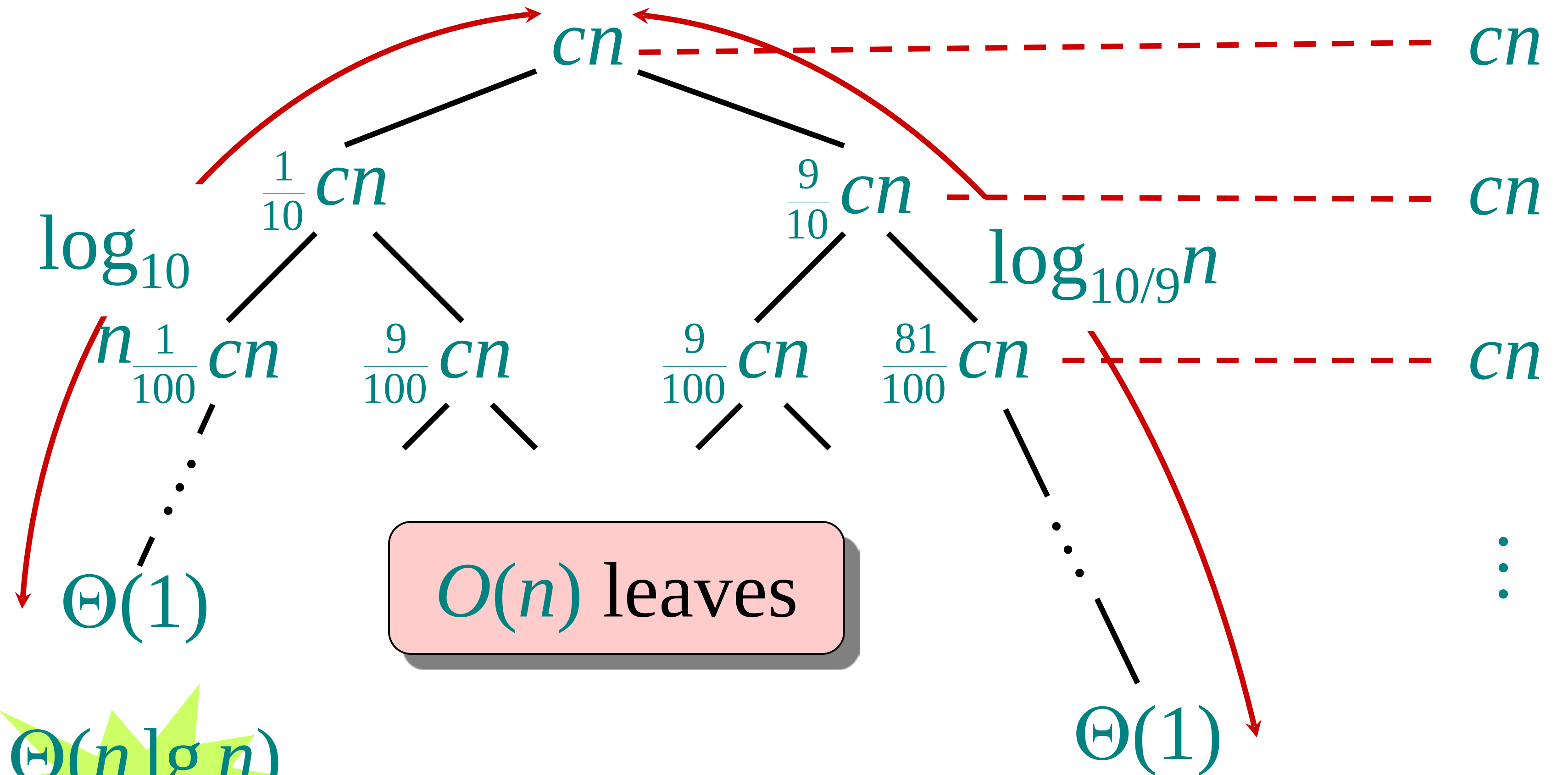
$$T\left(\tfrac{1}{100}n\right) \quad T\left(\tfrac{9}{100}n\right) \qquad T\left(\tfrac{9}{100}n\right) \quad T\left(\tfrac{81}{100}n\right)$$

Analysis of “almost-best” case





Analysis of “almost-best” case



$\Theta(n \lg n)$

Lucky!

$$cn \log_{10} n \le T(n) \le cn \log_{10/9} n + O(n)$$

More intuition

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

$$L(n) = 2U(n/2) + \Theta(n) \quad \textbf{\textit{lucky}}$$

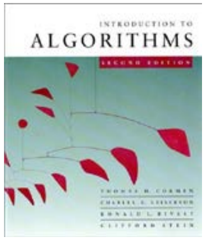
$$U(n) = L(n-1) + \Theta(n) \quad \textbf{\textit{unlucky}}$$

Solving:

$$\begin{aligned} L(n) &= 2(L(n/2 - 1) + \Theta(n/2)) + \Theta(n) \\ &= 2L(n/2 - 1) + \Theta(n) \\ &= \Theta(n \lg n) \end{aligned}$$

Lucky!

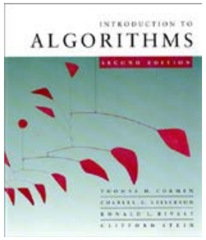
How can we make sure we are usually lucky?



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.



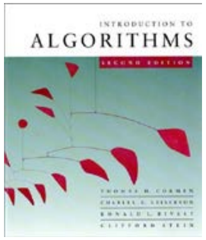
Randomized quicksort analysis

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 $k = 0, 1, \ldots, n-1$, define the ***indicator random variable***

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

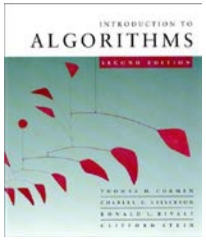
$E[X_k] = \Pr\{X_k = 1\} = 1/n$, since all splits are equally likely, assuming elements are distinct.



Analysis (continued)

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

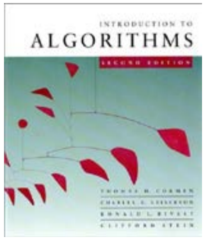
$$= \sum_{k=0}^{n-1} X_k \big(T(k) + T(n-k-1) + \Theta(n)\big)$$



Calculating expectation

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

Take expectations of both sides.

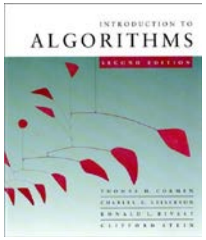


Calculating expectation

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

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

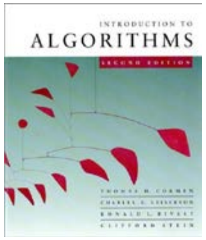
Linearity of expectation.



Calculating expectation

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

Independence of X_k from other random choices.



Calculating expectation

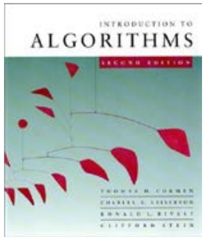
$$E[T(n)] = E\left[\sum_{k=0}^{n-1} X_k\big(T(k) + T(n-k-1) + \Theta(n)\big)\right]$$

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

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

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

Linearity of expectation; $E[X_k] = 1/n$.



Calculating expectation

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

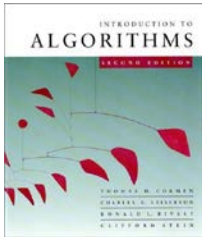
$$= \sum_{k=0}^{n-1} E\big[X_k\big(T(k)+T(n-k-1)+\Theta(n)\big)\big]$$

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

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

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

Summations have identical terms.



Hairy recurrence

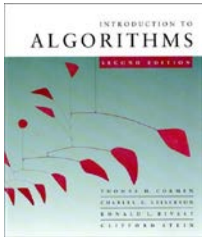
$$E[T(n)] = \frac{2}{n} \sum_{k=2}^{n-1} E[T(k)] + \Theta(n)$$

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

Prove: $E[T(n)] \le a n \lg n$ for constant $a > 0$.

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

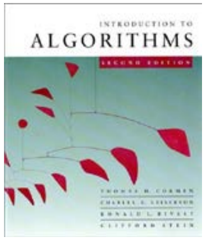
Use fact: $\displaystyle\sum_{k=2}^{n-1} k \lg k \le \tfrac{1}{2} n^2 \lg n - \tfrac{1}{8} n^2$ (exercise).



Substitution method

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

Substitute inductive hypothesis.

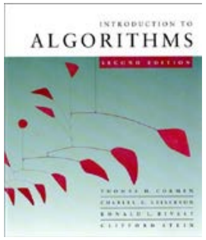


Substitution method

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

$$\le \frac{2a}{n}\left(\frac{1}{2}n^2\lg n - \frac{1}{8}n^2\right) + \Theta(n)$$

Use fact.



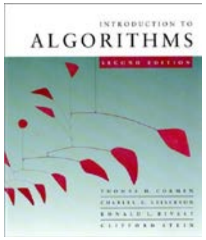
Substitution method

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

$$\le \frac{2a}{n}\left(\frac{1}{2}n^2 \lg n - \frac{1}{8}n^2\right) + \Theta(n)$$

$$= an \lg n - \left(\frac{an}{4} - \Theta(n)\right)$$

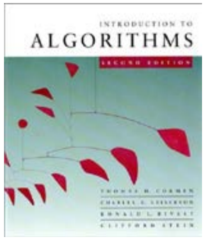
Express as ***desired – residual***.



Substitution method

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

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

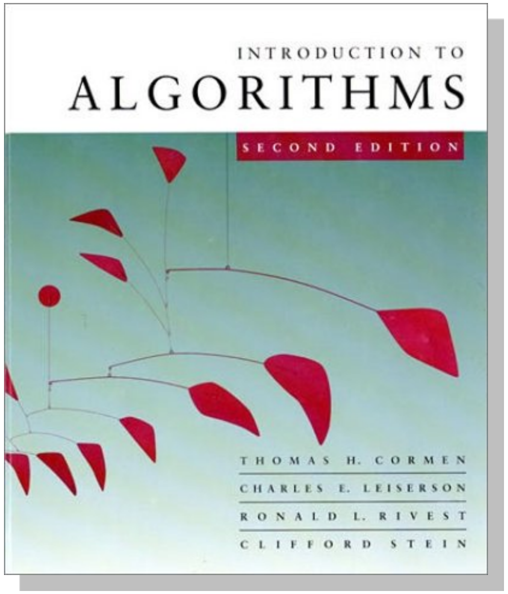


Quicksort in practice

- Quicksort is a great general-purpose sorting algorithm.
- Quicksort is typically over twice as fast as merge sort.
- Quicksort can benefit substantially from ***code tuning***.
- Quicksort behaves well even with caching and virtual memory.

Introduction to Algorithms

6.046J/18.401J



LECTURE 5

Sorting Lower Bounds

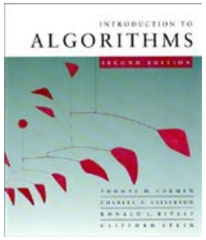
- Decision trees

Linear-Time Sorting

- Counting sort
- Radix sort

Appendix: Punched cards

Prof. Erik Demaine



How fast can we sort?

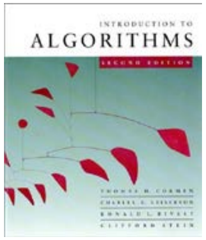
All the sorting algorithms we have seen so far are ***comparison sorts***: only use comparisons to determine the relative order of elements.

- *E.g.*, insertion sort, merge sort, quicksort, heapsort.

The best worst-case running time that we've seen for comparison sorting is $O(n \lg n)$.

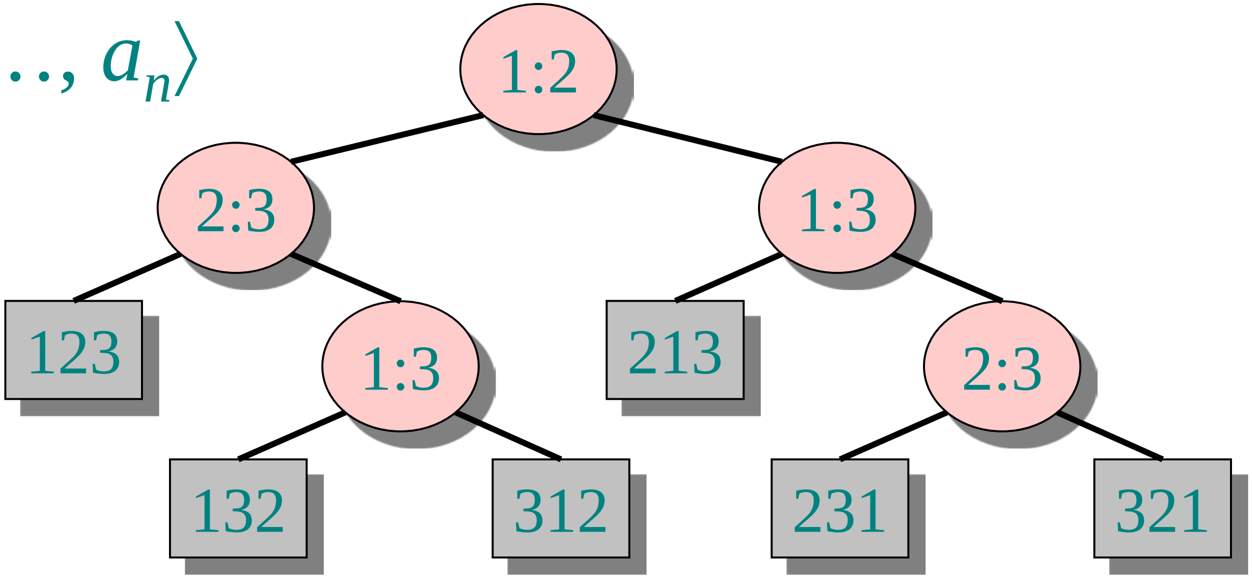
Is $O(n \lg n)$ the best we can do?

Decision trees can help us answer this question.



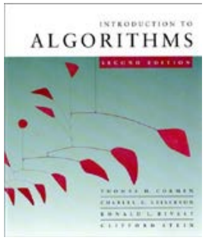
Decision-tree example

Sort $\langle a_1, a_2, \ldots, a_n \rangle$



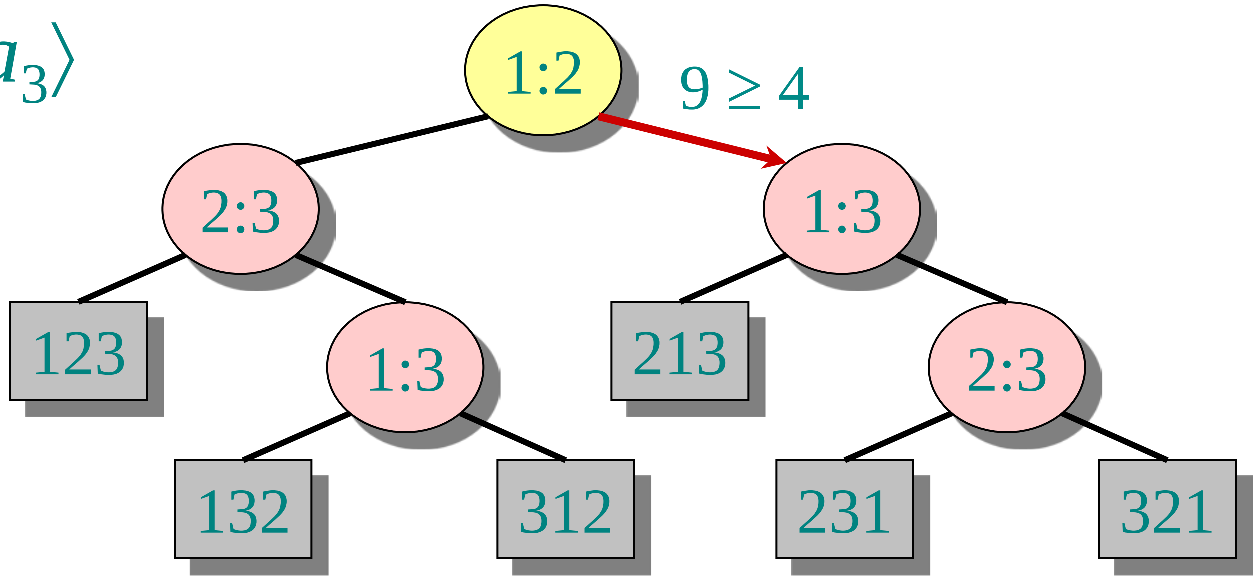
Each internal node is labeled $i{:}j$ for $i, j \in \{1, 2, \ldots, n\}$.

- The left subtree shows subsequent comparisons if $a_i \le a_j$.
- The right subtree shows subsequent comparisons if $a_i > a_j$.



Decision-tree example

Sort $\langle a_1, a_2, a_3 \rangle$
$= \langle 9, 4, 6 \rangle$:



Each internal node is labeled $i{:}j$ for $i, j \in \{1, 2, \ldots, n\}$.

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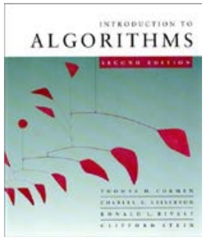

Decision-tree example

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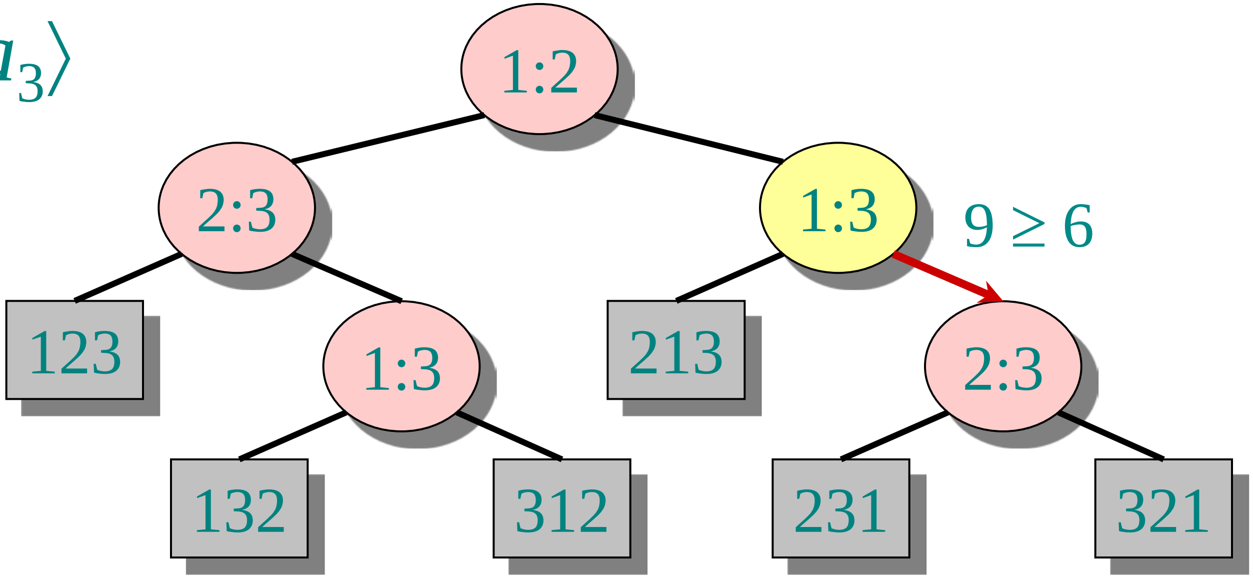

Each internal node is labeled $i{:}j$ for $i, j \in \{1, 2, \ldots, n\}$.

- The left subtree shows subsequent comparisons if $a_i \leq a_j$.
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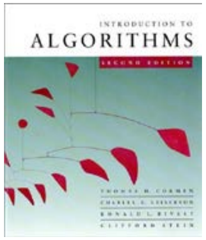
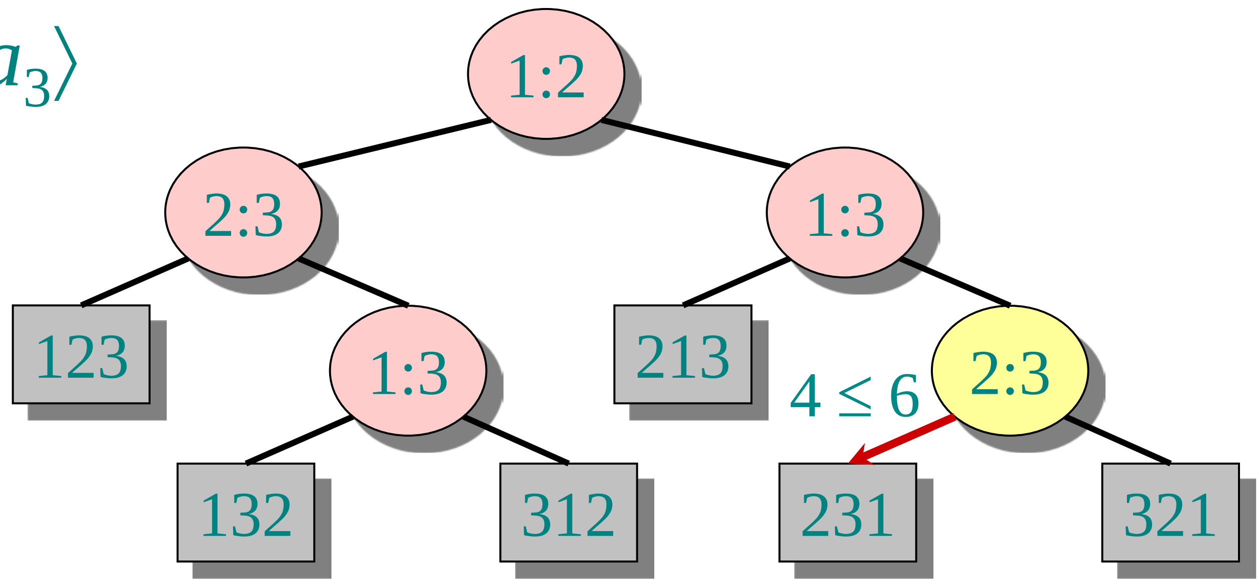


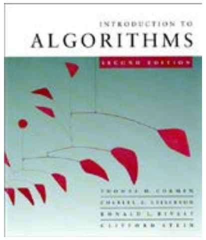
Decision-tree example

Sort $\langle a_1, a_2, a_3 \rangle$ $= \langle\, 9, 4, 6 \,\rangle$:



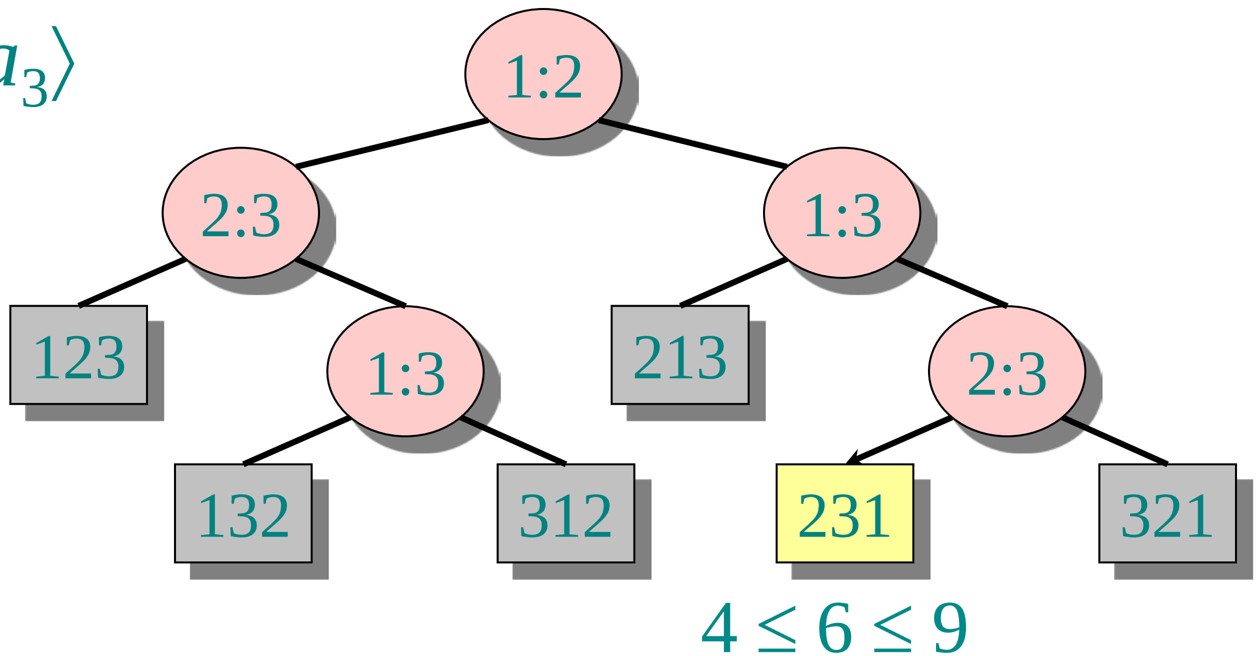
Each internal node is labeled $i{:}j$ for $i, j \in \{1, 2, \ldots, n\}$.

- The left subtree shows subsequent comparisons if $a_i \leq a_j$.
- The right subtree shows subsequent comparisons if $a_i > a_j$.

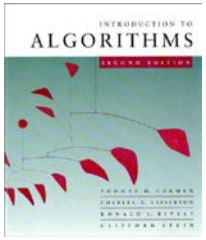


Decision-tree example

Sort $\langle a_1, a_2, a_3 \rangle$
$= \langle\ 9, 4, 6\ \rangle$:



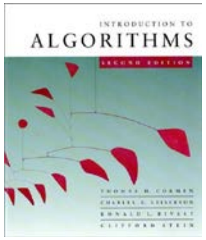
Each leaf contains a permutation $\langle \pi(1), \pi(2), \ldots, \pi(n) \rangle$ to indicate that the ordering $a_{\pi(1)} \leq a_{\pi(2)} \leq \cdots \leq a_{\pi(n)}$ has been established.



Decision-tree model

A decision tree can model the execution of any comparison sort:

- One tree for each input size n.
- View the algorithm as splitting whenever it compares two elements.
- The tree contains the comparisons along all possible instruction traces.
- The running time of the algorithm $=$ the length of the path taken.
- Worst-case running time $=$ height of tree.

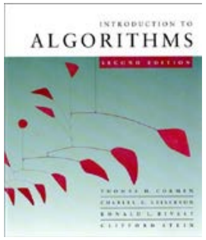


Lower bound for decision-tree sorting

Theorem. Any decision tree that can sort n elements must have height $\Omega(n \lg n)$.

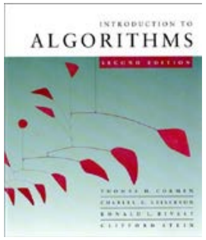
Proof. The tree must contain $\geq n!$ leaves, since there are $n!$ possible permutations. A height-h binary tree has $\leq 2^h$ leaves. Thus, $n! \leq 2^h$.

$$\begin{aligned}
\therefore\ h &\geq \lg(n!) && \text{(lg is mono. increasing)} \\
&\geq \lg((n/e)^n) && \text{(Stirling's formula)} \\
&= n \lg n - n \lg e \\
&= \Omega(n \lg n)\,. \quad \square
\end{aligned}$$



Lower bound for comparison sorting

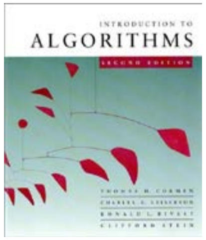
Corollary. Heapsort and merge sort are asymptotically optimal comparison sorting algorithms.



Sorting in linear time

Counting sort: No comparisons between elements.

- ***Input***: $A[1 \,.\,.\, n]$, where $A[j] \in \{1, 2, \ldots, k\}$.
- ***Output***: $B[1 \,.\,.\, n]$, sorted.
- ***Auxiliary storage***: $C[1 \,.\,.\, k]$.



Counting sort

for $i \leftarrow 1$ **to** k

    do $C[i] \leftarrow 0$

for $j \leftarrow 1$ **to** n

    do $C[A[j]] \leftarrow C[A[j]] + 1$ $\triangleright$ $C[i] = |\{\text{key} = i\}|$

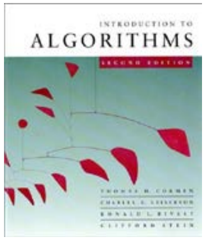
for $i \leftarrow 2$ **to** k

    do $C[i] \leftarrow C[i] + C[i-1]$ $\triangleright$ $C[i] = |\{\text{key} \leq i\}|$

for $j \leftarrow n$ **downto** 1

    do $B[C[A[j]]] \leftarrow A[j]$

        $C[A[j]] \leftarrow C[A[j]] - 1$

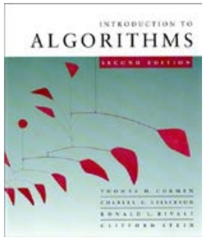


Counting-sort example

	1	2	3	4	5
A:	4	1	3	4	3

	1	2	3	4
C:				

B:					



Loop 1

A:

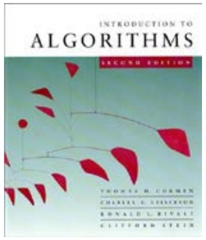
1	2	3	4	5
4	1	3	4	3

C:

1	2	3	4
0	0	0	0

B:

for $i \leftarrow 1$ **to** k
  do $C[i] \leftarrow 0$



Loop 2

A:

1	2	3	4	5
4	1	3	4	3

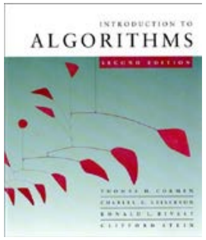
C:

1	2	3	4
0	0	0	1

B:

for $j \leftarrow 1$ **to** n

  do $C[A[j]] \leftarrow C[A[j]] + 1$ $\rhd$ $C[i] = |\{\text{key} = i\}|$



Loop 2

A:

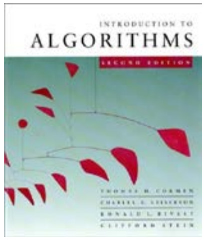
1	2	3	4	5
4	1	3	4	3

C:

1	2	3	4
1	0	0	1

B:

for $j \leftarrow 1$ **to** n
  do $C[A[j]] \leftarrow C[A[j]] + 1$ $\triangleright$ $C[i] = |\{\text{key} = i\}|$



Loop 2

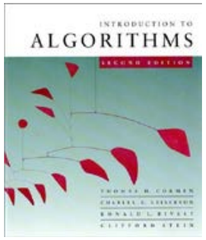
	1	2	3	4	5
A:	4	1	3	4	3

	1	2	3	4
C:	1	0	1	1

B:					

for $j \leftarrow 1$ **to** n

  do $C[A[j]] \leftarrow C[A[j]] + 1$ $\quad \rhd\ C[i] = |\{\text{key} = i\}|$



Loop 2

A:

1	2	3	4	5
4	1	3	4	3

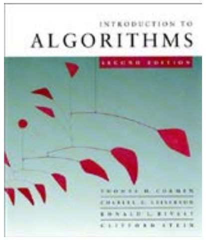
C:

1	2	3	4
1	0	1	2

B:

for $j \leftarrow 1$ **to** n

  do $C[A[j]] \leftarrow C[A[j]] + 1$ $\rhd$ $C[i] = |\{\text{key} = i\}|$



Loop 2

A:

1	2	3	4	5
4	1	3	4	3

C:

1	2	3	4
1	0	2	2

B:

for $j \leftarrow 1$ **to** n

  do $C[A[j]] \leftarrow C[A[j]] + 1 \quad \triangleright\ C[i] = |\{\text{key} = i\}|$

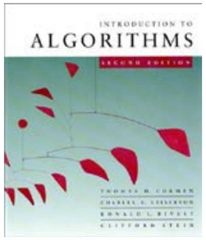
Loop 3

	1	2	3	4	5
A:	4	1	3	4	3
B:					

	1	2	3	4
C:	1	0	2	2
C':	1	1	2	2

for $i \leftarrow 2$ **to** k

  do $C[i] \leftarrow C[i] + C[i–1]$ ⊳ $C[i] = |\{\text{key} \le i\}|$



Loop 3

A:

1	2	3	4	5
4	1	3	4	3

C:

1	2	3	4
1	0	2	2

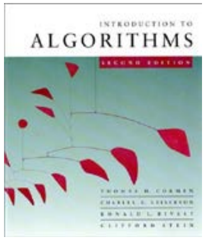
B:

C':

1	1	3	2

for $i \leftarrow 2$ **to** k

  do $C[i] \leftarrow C[i] + C[i-1]$ ⊳ $C[i] = |\{\text{key} \le i\}|$



Loop 3

A:

1	2	3	4	5
4	1	3	4	3

C:

1	2	3	4
1	0	2	2

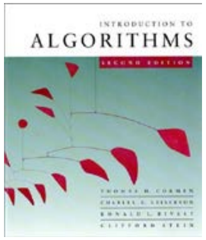
B:

C':

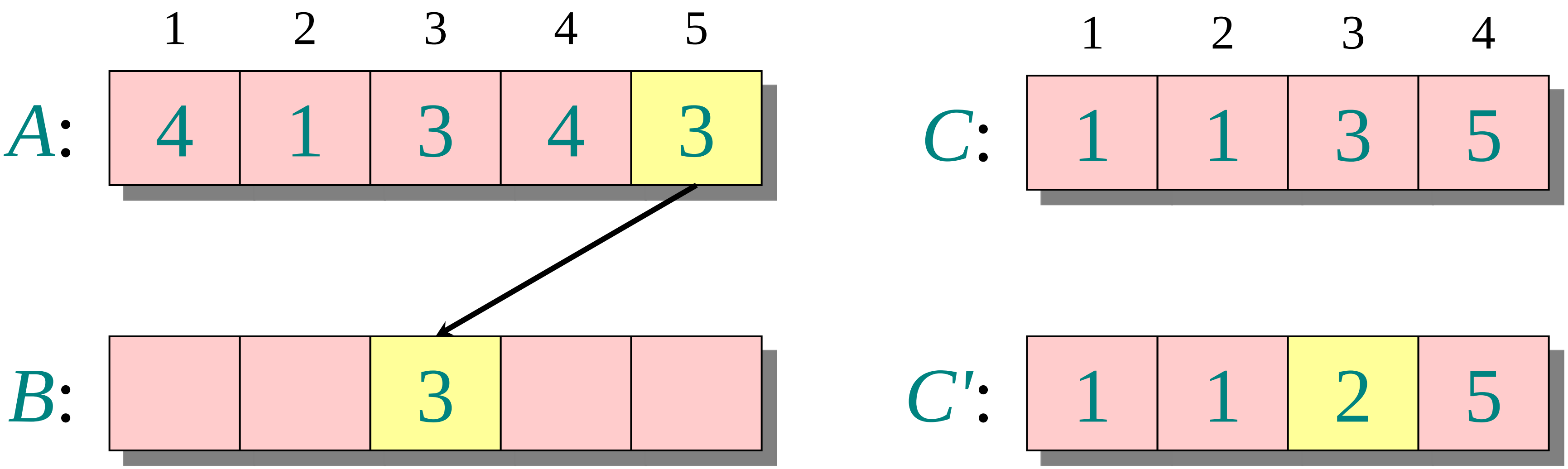
1	1	3	5

for $i \leftarrow 2$ **to** k

  do $C[i] \leftarrow C[i] + C[i–1]$ ⊳ $C[i] = |\{\text{key} \le i\}|$



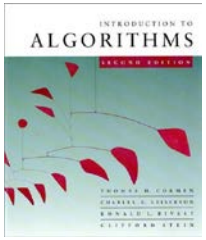
Loop 4



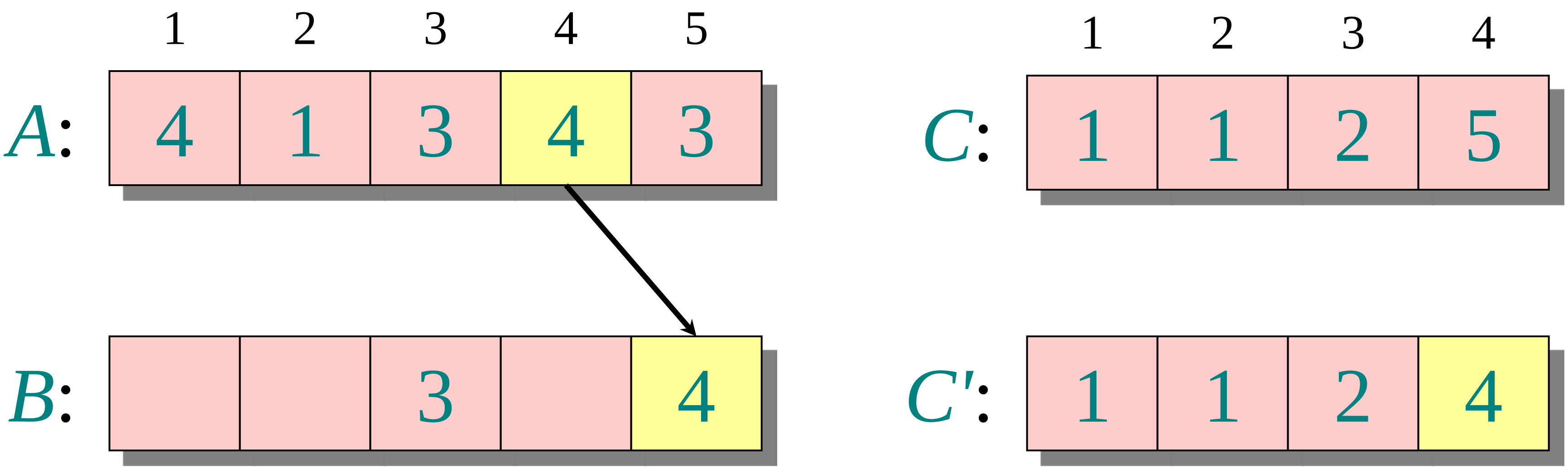
for $j \leftarrow n$ **downto** 1

do $B[C[A[j]]] \leftarrow A[j]$

$C[A[j]] \leftarrow C[A[j]] - 1$



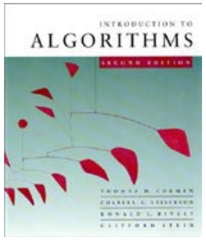
Loop 4



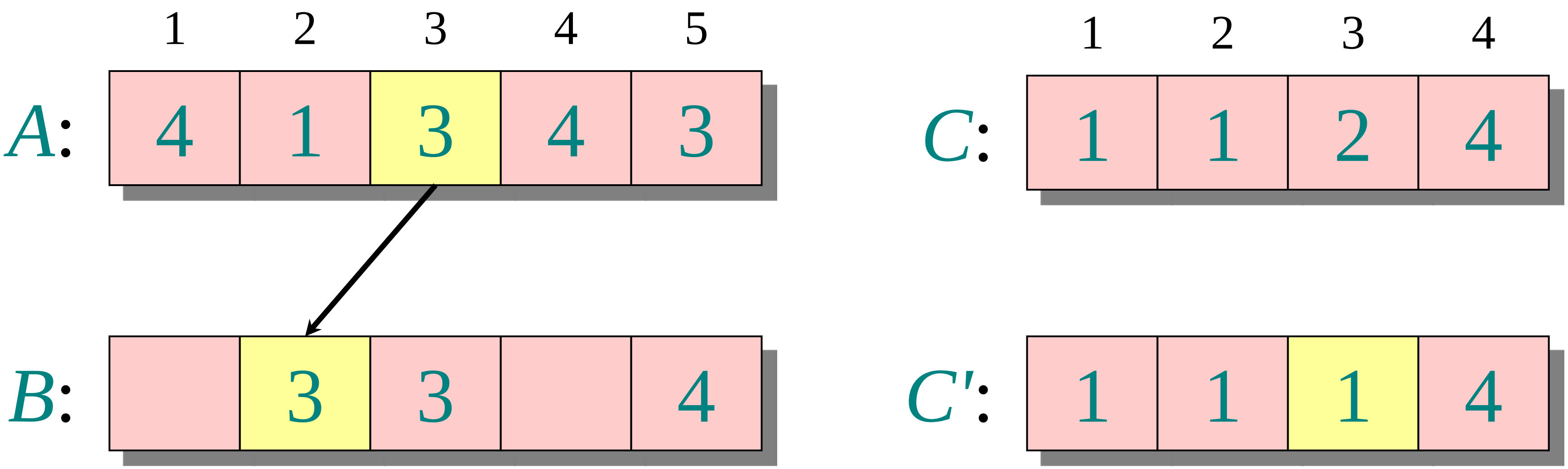
for $j \leftarrow n$ **downto** 1

do $B[C[A[j]]] \leftarrow A[j]$

$C[A[j]] \leftarrow C[A[j]] - 1$



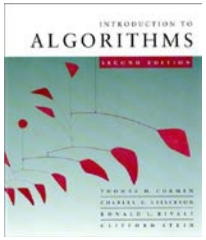
Loop 4



for $j \leftarrow n$ **downto** 1

do $B[C[A[j]]] \leftarrow \mathrm{A}[j]$

$C[A[j]] \leftarrow C[A[j]] - 1$



Loop 4

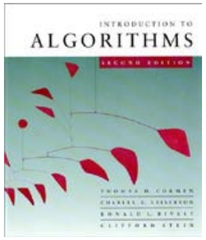
	1	2	3	4	5
A:	4	1	3	4	3
B:	1	3	3		4

	1	2	3	4
C:	1	1	1	4
C':	0	1	1	4

for $j \leftarrow n$ **downto** 1

  do $B[C[A[j]]] \leftarrow A[j]$

    $C[A[j]] \leftarrow C[A[j]] - 1$



Loop 4

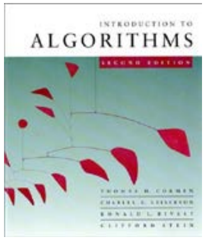
	1	2	3	4	5
A:	4	1	3	4	3
B:	1	3	3	4	4

	1	2	3	4
C:	0	1	1	4
C':	0	1	1	3

for $j \leftarrow n$ **downto** 1

  do $B[C[A[j]]] \leftarrow A[j]$

    $C[A[j]] \leftarrow C[A[j]] - 1$



Analysis

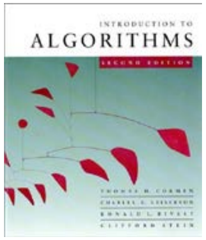
$\Theta(k)$
for $i \leftarrow 1$ **to** k
  do $C[i] \leftarrow 0$

$\Theta(n)$
for $j \leftarrow 1$ **to** n
  do $C[A[j]] \leftarrow C[A[j]] + 1$

$\Theta(k)$
for $i \leftarrow 2$ **to** k
  do $C[i] \leftarrow C[i] + C[i–1]$

$\Theta(n)$
for $j \leftarrow n$ **downto** 1
  do $B[C[A[j]]] \leftarrow A[j]$
    $C[A[j]] \leftarrow C[A[j]] – 1$

$\Theta(n + k)$



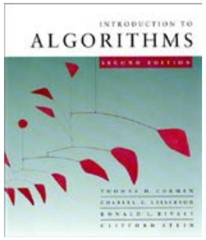
Running time

If $k = O(n)$, then counting sort takes $\Theta(n)$ time.

- But, sorting takes $\Omega(n \lg n)$ time!
- Where's the fallacy?

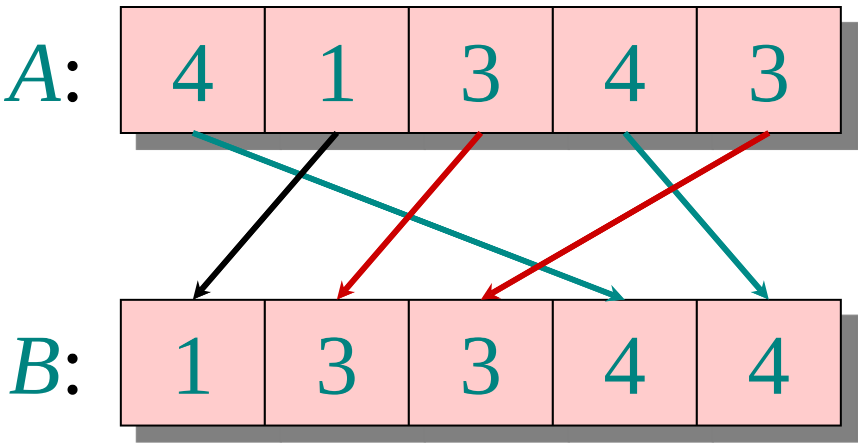
Answer:

- ***Comparison sorting*** takes $\Omega(n \lg n)$ time.
- Counting sort is not a ***comparison sort***.
- In fact, not a single comparison between elements occurs!

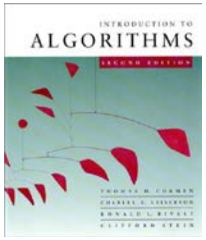


Stable sorting

Counting sort is a ***stable*** sort: it preserves the input order among equal elements.



Exercise: What other sorts have this property?

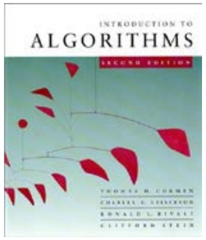


Radix sort

- ***Origin***: Herman Hollerith's card-sorting machine for the 1890 U.S. Census. (See Appendix .)
- Digit-by-digit sort.
- Hollerith's original (bad) idea: sort on most-significant digit first.
- Good idea: Sort on ***least-significant digit first*** with auxiliary ***stable*** sort.

Operation of radix sort

3 2 9	7 2 0	7 2 0	3 2 9
4 5 7	3 5 5	3 2 9	3 5 5
6 5 7	4 3 6	4 3 6	4 3 6
8 3 9	4 5 7	8 3 9	4 5 7
4 3 6	6 5 7	3 5 5	6 5 7
7 2 0	3 2 9	4 5 7	7 2 0
3 5 5	8 3 9	6 5 7	8 3 9

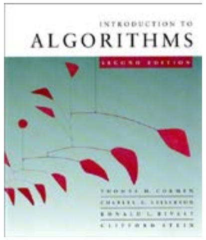


Correctness of radix sort

Induction on digit position

- Assume that the numbers are sorted by their low-order $t - 1$ digits.
- Sort on digit t

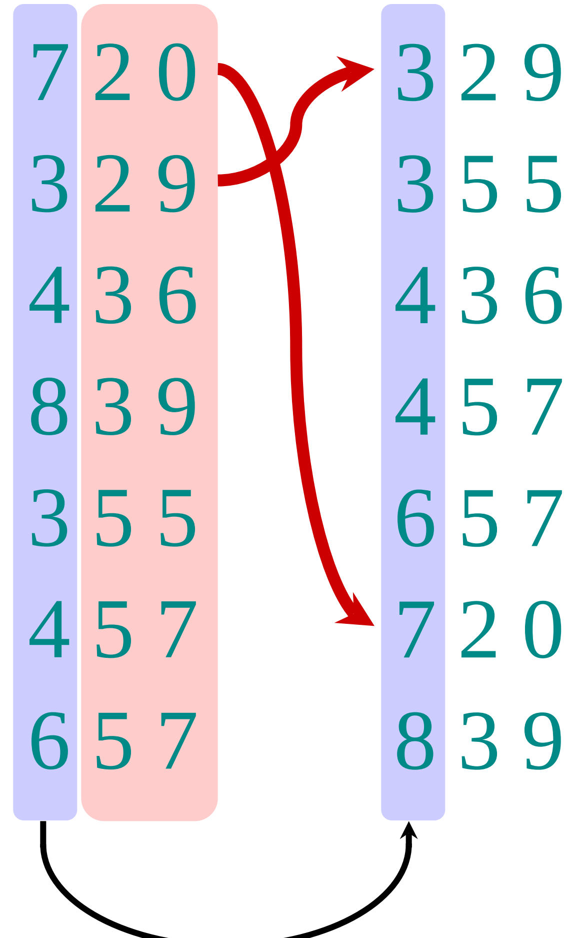
7 2 0	3 2 9
3 2 9	3 5 5
4 3 6	4 3 6
8 3 9	4 5 7
3 5 5	6 5 7
4 5 7	7 2 0
6 5 7	8 3 9



Correctness of radix sort

Induction on digit position

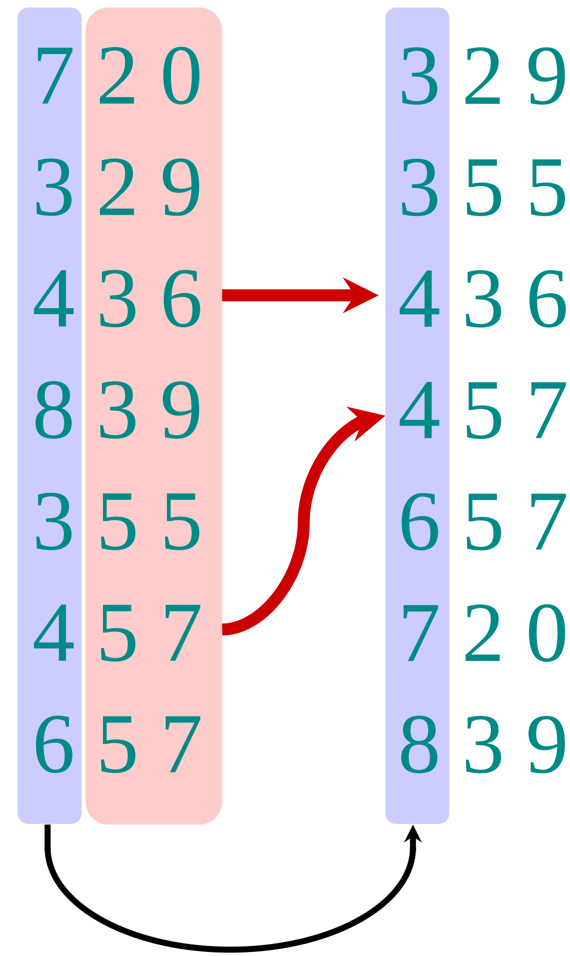
- Assume that the numbers are sorted by their low-order $t - 1$ digits.
- Sort on digit t
  - Two numbers that differ in digit t are correctly sorted.

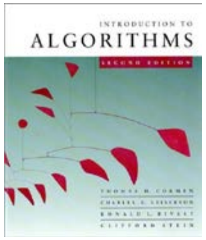


Correctness of radix sort

Induction on digit position

- Assume that the numbers are sorted by their low-order $t - 1$ digits.
- Sort on digit t
  - Two numbers that differ in digit t are correctly sorted.
  - Two numbers equal in digit t are put in the same order as the input $\Rightarrow$ correct order.

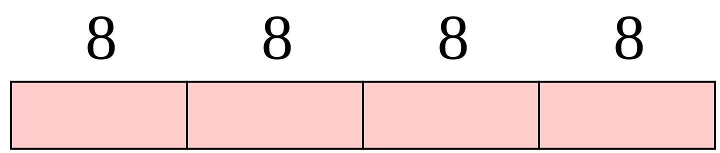




Analysis of radix sort

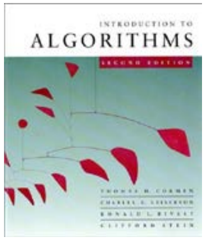
- Assume counting sort is the auxiliary stable sort.
- Sort n computer words of b bits each.
- Each word can be viewed as having b/r base-2^r digits.

Example: 32-bit word



$r = 8 \Rightarrow b/r = 4$ passes of counting sort on base-2^8 digits; or $r = 16 \Rightarrow b/r = 2$ passes of counting sort on base-2^{16} digits.

How many passes should we make?



Analysis (continued)

Recall: Counting sort takes $\Theta(n + k)$ time to sort n numbers in the range from 0 to $k - 1$.

If each b-bit word is broken into r-bit pieces, each pass of counting sort takes $\Theta(n + 2^r)$ time. Since there are b/r passes, we have

$$T(n,b) = \Theta\left(\frac{b}{r}\left(n + 2^r\right)\right).$$

Choose r to minimize $T(n, b)$:

- Increasing r means fewer passes, but as $r \gg \lg n$, the time grows exponentially.

Choosing r

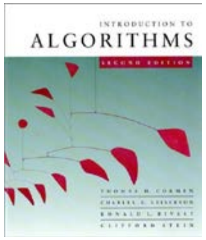
$$T(n,b) = \Theta\left(\frac{b}{r}\left(n + 2^r\right)\right)$$

Minimize $T(n, b)$ by differentiating and setting to 0.

Or, just observe that we don't want $2^r \gg n$, and there's no harm asymptotically in choosing r as large as possible subject to this constraint.

Choosing $r = \lg n$ implies $T(n, b) = \Theta(bn/\lg n)$.

- For numbers in the range from 0 to $n^d - 1$, we have $b = d \lg n \Rightarrow$ radix sort runs in $\Theta(d\,n)$ time.



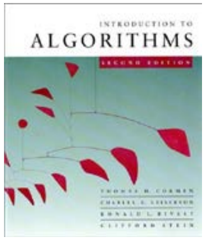
Conclusions

In practice, radix sort is fast for large inputs, as well as simple to code and maintain.

Example (32-bit numbers):

- At most 3 passes when sorting ≥ 2000 numbers.
- Merge sort and quicksort do at least $\lceil \lg 2000 \rceil = 11$ passes.

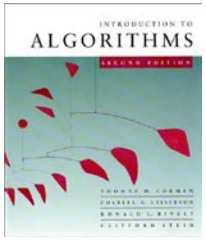
Downside: Unlike quicksort, radix sort displays little locality of reference, and thus a well-tuned quicksort fares better on modern processors, which feature steep memory hierarchies.



Appendix: Punched-card technology

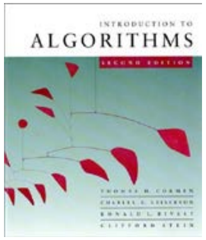
- Herman Hollerith (1860-1929)
- Punched cards
- Hollerith's tabulating system
- Operation of the sorter
- Origin of radix sort
- "Modern" IBM card
- Web resources on punched-card technology

Return to last slide viewed.



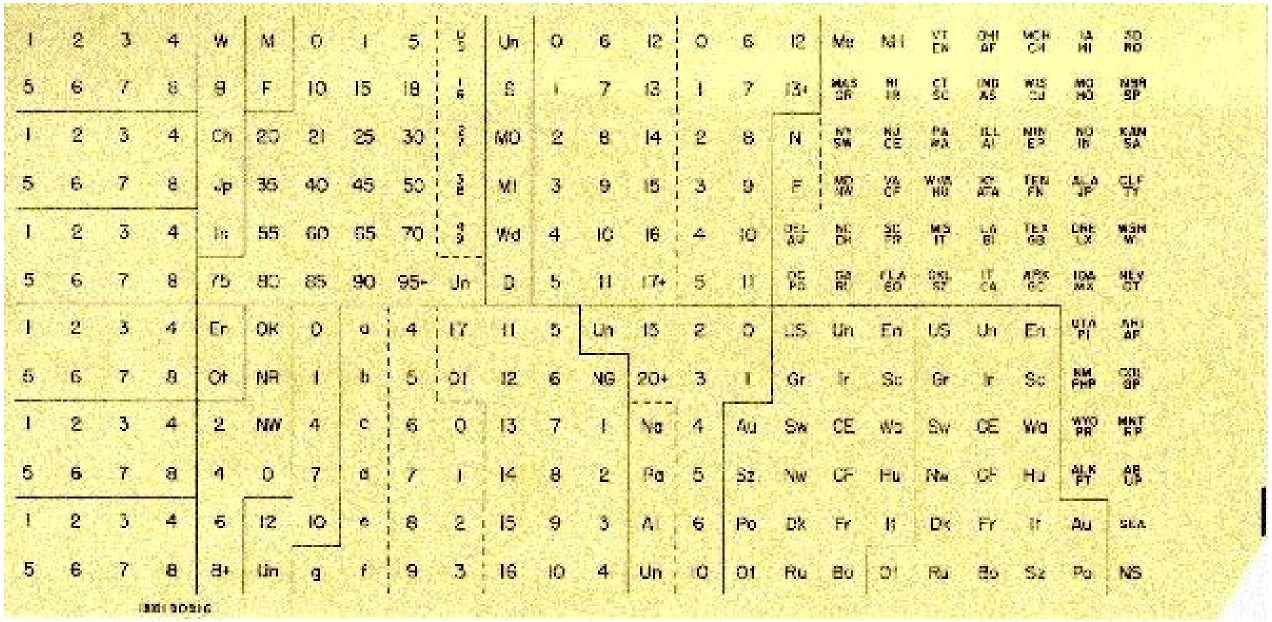
Herman Hollerith (1860-1929)

- The 1880 U.S. Census took almost 10 years to process.
- While a lecturer at MIT, Hollerith prototyped punched-card technology.
- His machines, including a "card sorter," allowed the 1890 census total to be reported in 6 weeks.
- He founded the Tabulating Machine Company in 1911, which merged with other companies in 1924 to form International Business Machines.

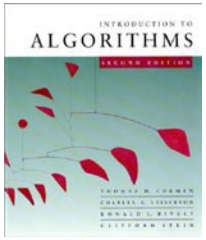


Punched cards

- Punched card = data record.
- Hole = value.
- Algorithm = machine + human operator.



Replica of punch card from the 1900 U.S. census. [Howells 2000]



Hollerith's tabulating system

- Pantograph card punch
- Hand-press reader
- Dial counters
- Sorting box

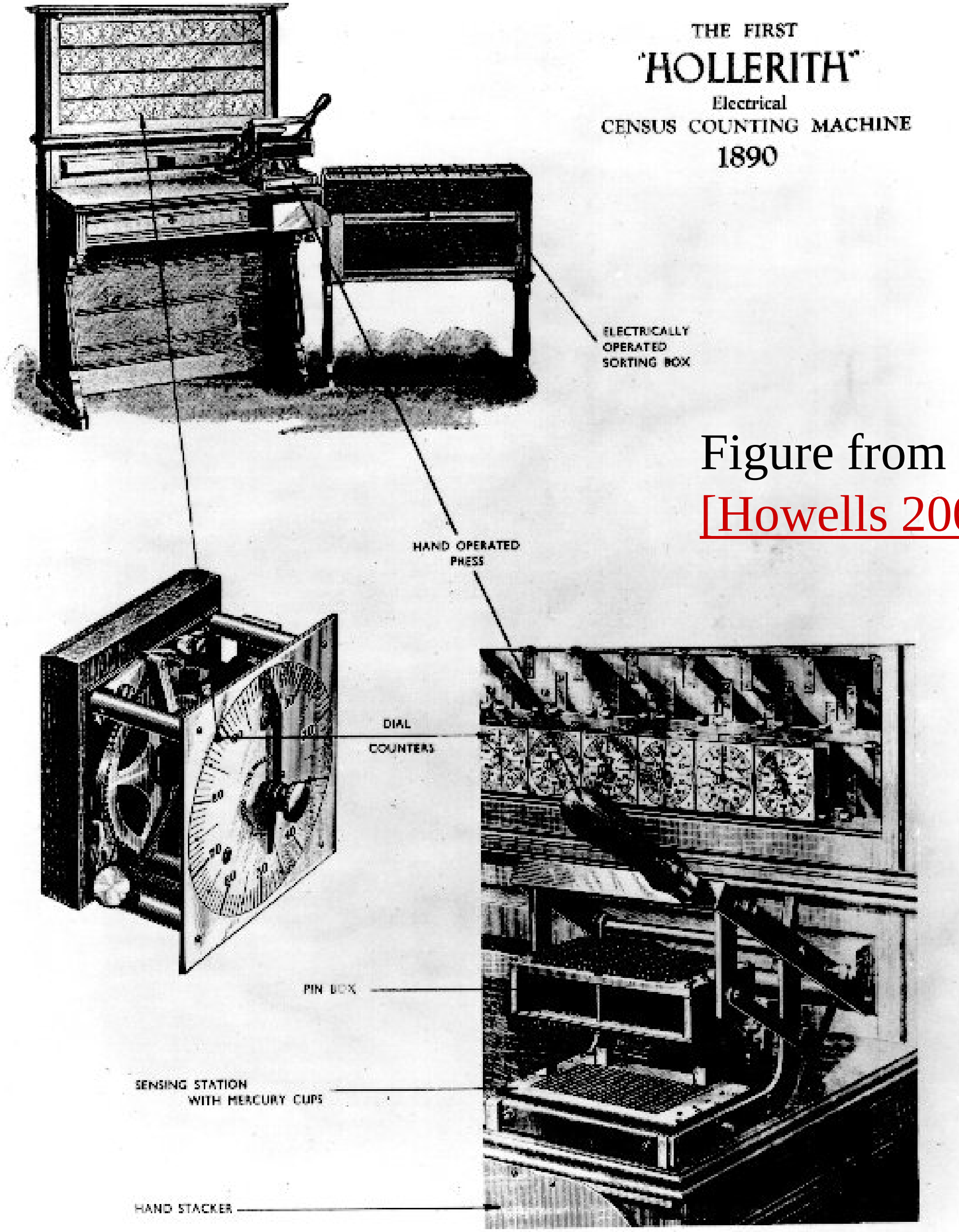
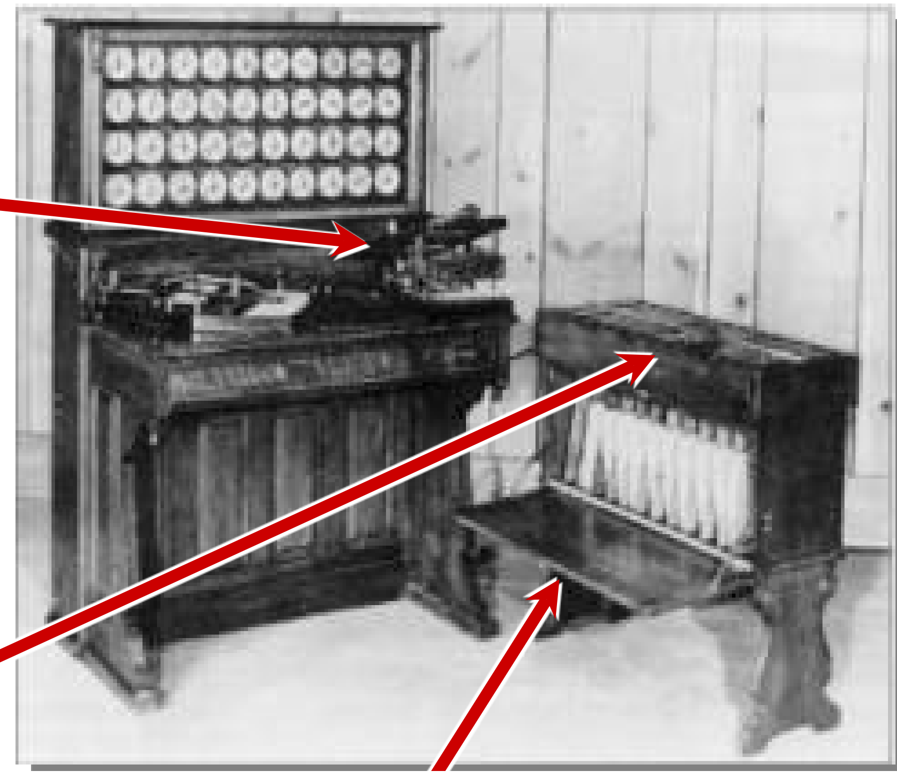


Figure from [Howells 2000].

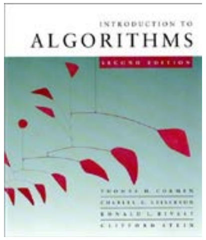
Operation of the sorter

- An operator inserts a card into the press.
- Pins on the press reach through the punched holes to make electrical contact with mercury-filled cups beneath the card.
- Whenever a particular digit value is punched, the lid of the corresponding sorting bin lifts.
- The operator deposits the card into the bin and closes the lid.



Hollerith Tabulator, Pantograph, Press, and Sorter

- When all cards have been processed, the front panel is opened, and the cards are collected in order, yielding one pass of a stable sort.

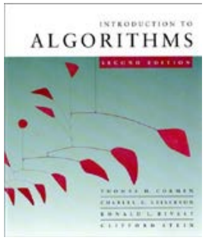


Origin of radix sort

Hollerith's original 1889 patent alludes to a most-significant-digit-first radix sort:

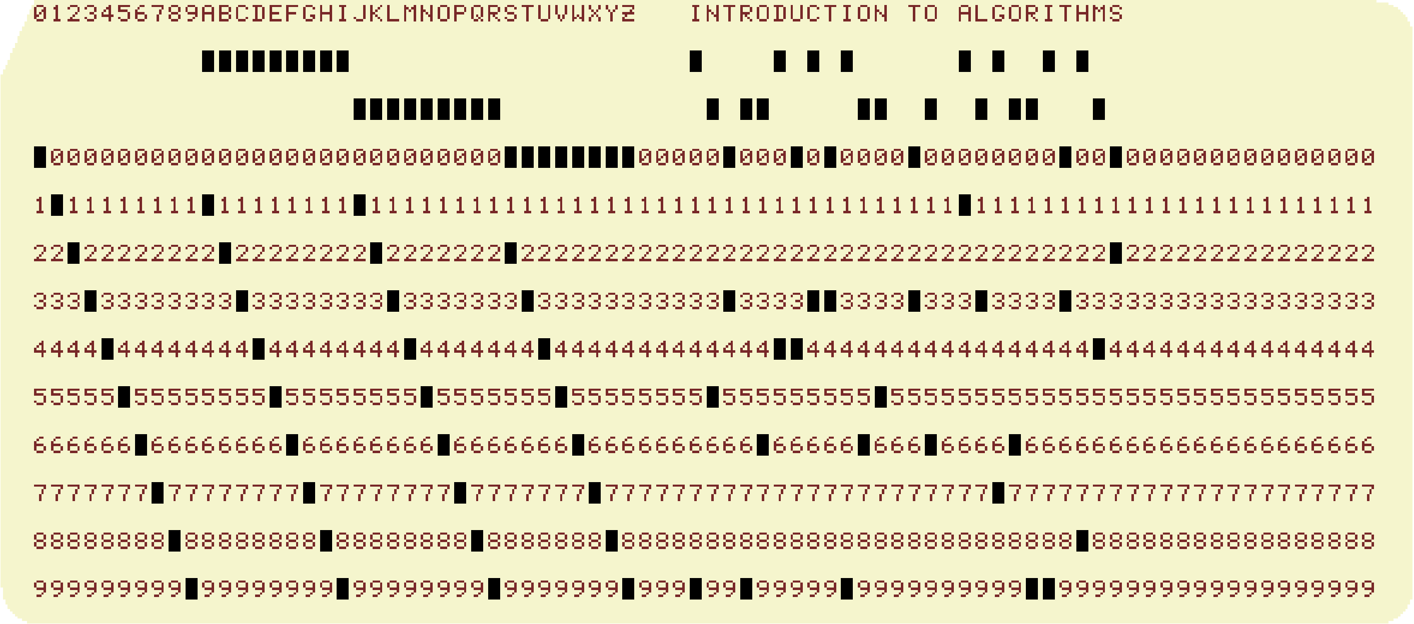
> *"The most complicated combinations can readily be counted with comparatively few counters or relays by first assorting the cards according to the first items entering into the combinations, then reassorting each group according to the second item entering into the combination, and so on, and finally counting on a few counters the last item of the combination for each group of cards."*

Least-significant-digit-first radix sort seems to be a folk invention originated by machine operators.



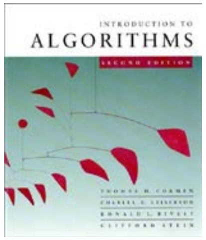
"Modern" IBM card

- One character per column.



Produced by the WWW Virtual Punch-Card Server.

So, that's why text windows have 80 columns!



Web resources on punched-card technology

- Doug Jones's punched card index
- Biography of Herman Hollerith
- The 1890 U.S. Census
- Early history of IBM
- Pictures of Hollerith's inventions
- Hollerith's patent application (borrowed from Gordon Bell's CyberMuseum)
- Impact of punched cards on U.S. history

Introduction to Algorithms

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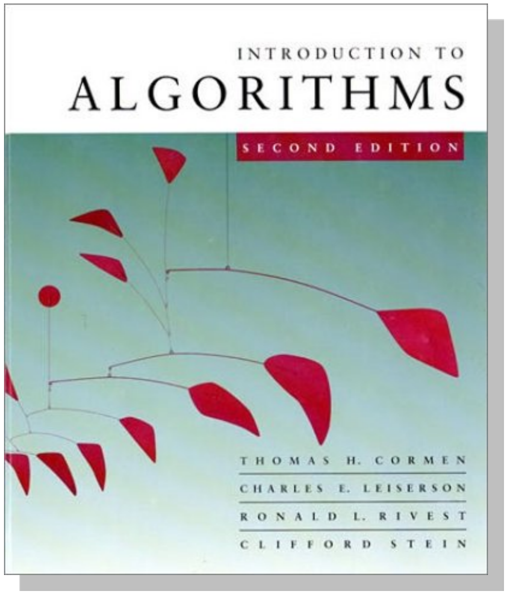
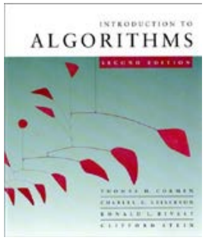


LECTURE 6

Order Statistics

- Randomized divide and conquer
- Analysis of expected time
- Worst-case linear-time order statistics
- Analysis

Prof. Erik Demaine



Order statistics

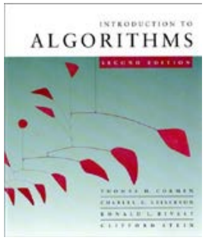
Select the ith smallest of n elements (the element with ***rank*** i).

- $i = 1$: ***minimum***;
- $i = n$: ***maximum***;
- $i = \lfloor (n+1)/2 \rfloor$ or $\lceil (n+1)/2 \rceil$: ***median***.

Naive algorithm: Sort and index ith element.

Worst-case running time $= \Theta(n \lg n) + \Theta(1)$
$\qquad\qquad\qquad\qquad\qquad\qquad = \Theta(n \lg n)$,

using merge sort or heapsort (*not* quicksort).



Randomized divide-and-conquer algorithm

RAND-SELECT(A, p, q, i) ⊳ ith smallest of $A[p \,..\, q]$

if $p = q$ **then return** $A[p]$

$r \leftarrow$ RAND-PARTITION(A, p, q)

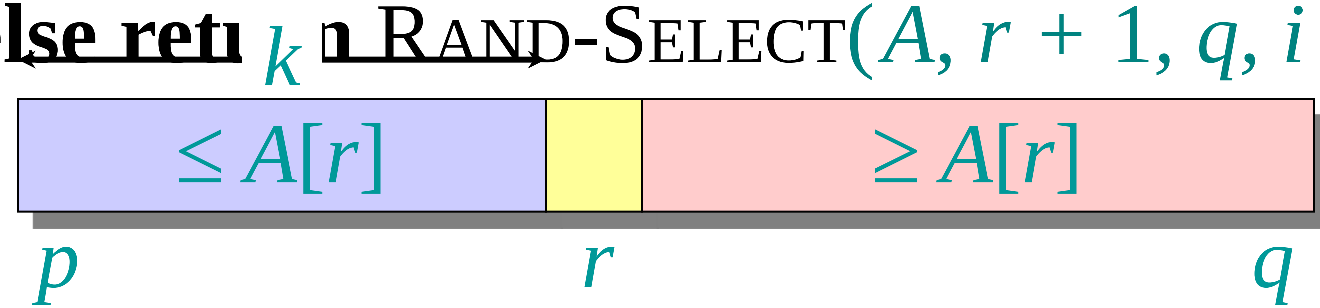
$k \leftarrow r - p + 1$ ⊳ $k = \mathrm{rank}(A[r])$

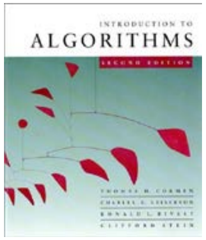
if $i = k$ **then return** $A[r]$

if $i < k$

  then return RAND-SELECT$(A, p, r - 1, i)$

  else return RAND-SELECT$(A, r + 1, q, i - k)$





Example

Select the $i = 7$th smallest:

6	10	13	5	8	3	2	11

$i = 7$

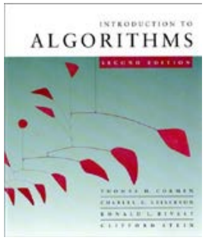
pivot

Partition:

2	5	3	6	8	13	10	11

$k = 4$

Select the $7 - 4 = 3$rd smallest recursively.



Intuition for analysis

(All our analyses today assume that all elements are distinct.)

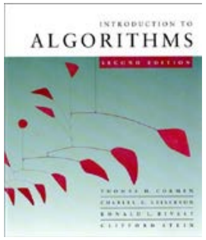
Lucky:

$$T(n) = T(9n/10) + \Theta(n) \qquad n^{\log_{10/9} 1} = n^0 = 1$$
$$= \Theta(n) \qquad \textsc{Case } 3$$

Unlucky:

$$T(n) = T(n-1) + \Theta(n) \qquad \text{arithmetic series}$$
$$= \Theta(n^2)$$

Worse than sorting!



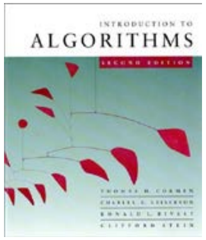
Analysis of expected time

The analysis follows that of randomized quicksort, but it's a little different.

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

For $k = 0, 1, \ldots, n–1$, define the ***indicator random variable***

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

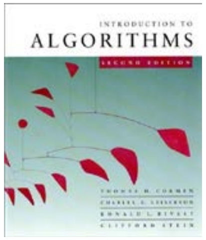


Analysis (continued)

To obtain an upper bound, assume that the i th element always falls in the larger side of the partition:

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

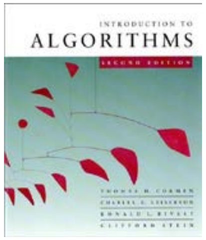
$$= \sum_{k=0}^{n-1} X_k \left(T(\max\{k, n-k-1\}) + \Theta(n) \right).$$



Calculating expectation

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

Take expectations of both sides.

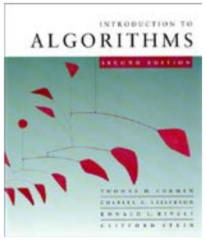


Calculating expectation

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

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

Linearity of expectation.



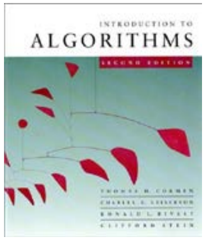
Calculating expectation

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

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

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

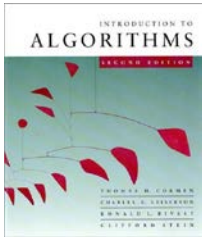
Independence of X_k from other random choices.



Calculating expectation

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

Linearity of expectation; $E[X_k] = 1/n$.



Calculating expectation

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

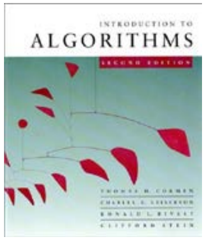
$$= \sum_{k=0}^{n-1} E\left[X_k \big(T(\max\{k, n-k-1\}) + \Theta(n)\big)\right]$$

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

$$= \frac{1}{n} \sum_{k=0}^{n-1} E[T(\max\{k, n-k-1\})] + \frac{1}{n} \sum_{k=0}^{n-1} \Theta(n)$$

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

Upper terms appear twice.



Hairy recurrence

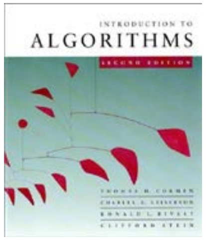
(But not quite as hairy as the quicksort one.)

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

Prove: $E[T(n)] \le cn$ for constant $c > 0$.

- The constant c can be chosen large enough so that $E[T(n)] \le cn$ for the base cases.

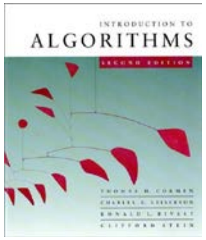
Use fact: $\sum_{k=\lfloor n/2 \rfloor}^{n-1} k \le \frac{3}{8} n^2$ (exercise).



Substitution method

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

Substitute inductive hypothesis.

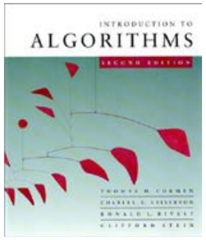


Substitution method

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

$$\le \frac{2c}{n}\left(\frac{3}{8}n^2\right) + \Theta(n)$$

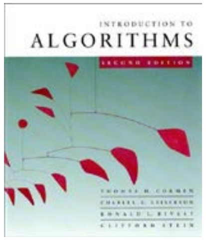
Use fact.



Substitution method

$$
\begin{aligned}
E[T(n)] &\le \frac{2}{n} \sum_{k=\lfloor n/2 \rfloor}^{n-1} ck + \Theta(n) \\
&\le \frac{2c}{n}\left(\frac{3}{8}n^2\right) + \Theta(n) \\
&= cn - \left(\frac{cn}{4} - \Theta(n)\right)
\end{aligned}
$$

Express as ***desired*** **–** ***residual***.



Substitution method

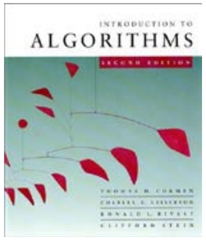
$$E[T(n)] \le \frac{2}{n} \sum_{k=\lfloor n/2 \rfloor}^{n-1} ck + \Theta(n)$$

$$\le \frac{2c}{n}\left(\frac{3}{8}n^2\right) + \Theta(n)$$

$$= cn - \left(\frac{cn}{4} - \Theta(n)\right)$$

$$\le cn,$$

if c is chosen large enough so that $cn/4$ dominates the $\Theta(n)$.



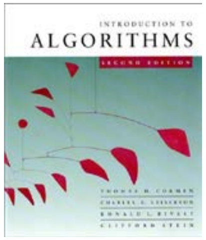
Summary of randomized order-statistic selection

- Works fast: linear expected time.
- Excellent algorithm in practice.
- But, the worst case is ***very*** bad: $\Theta(n^2)$.

Q. Is there an algorithm that runs in linear time in the worst case?

A. Yes, due to Blum, Floyd, Pratt, Rivest, and Tarjan [1973].

IDEA: Generate a good pivot recursively.



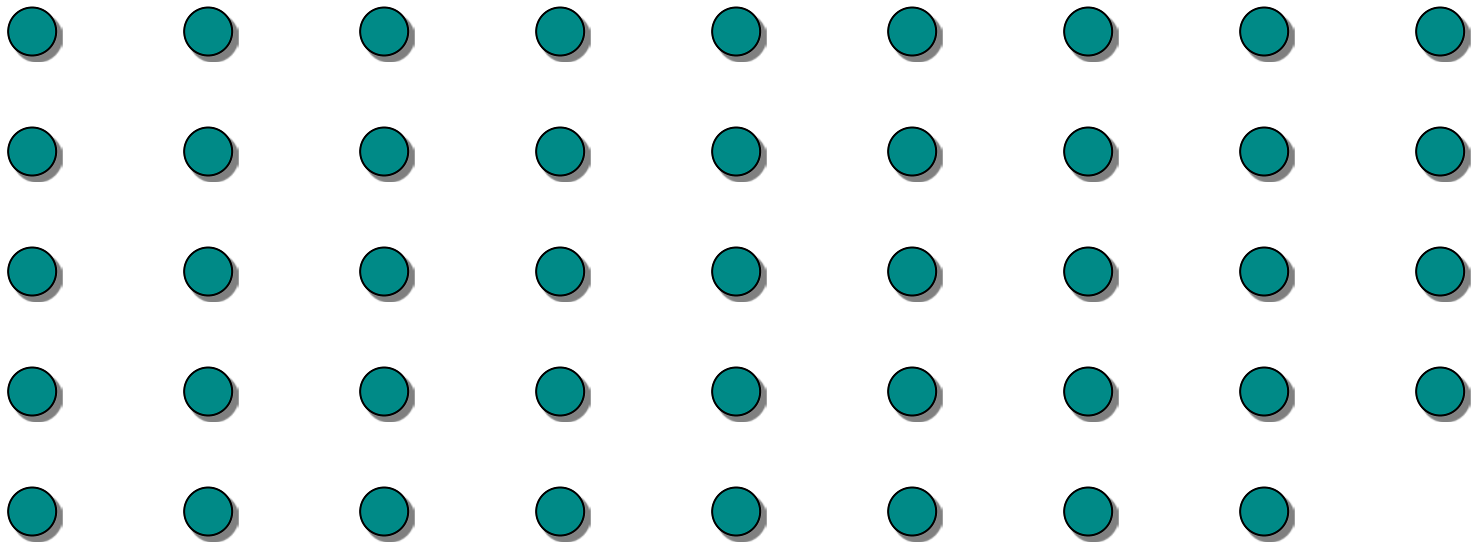
Worst-case linear-time order statistics

SELECT(i, n)

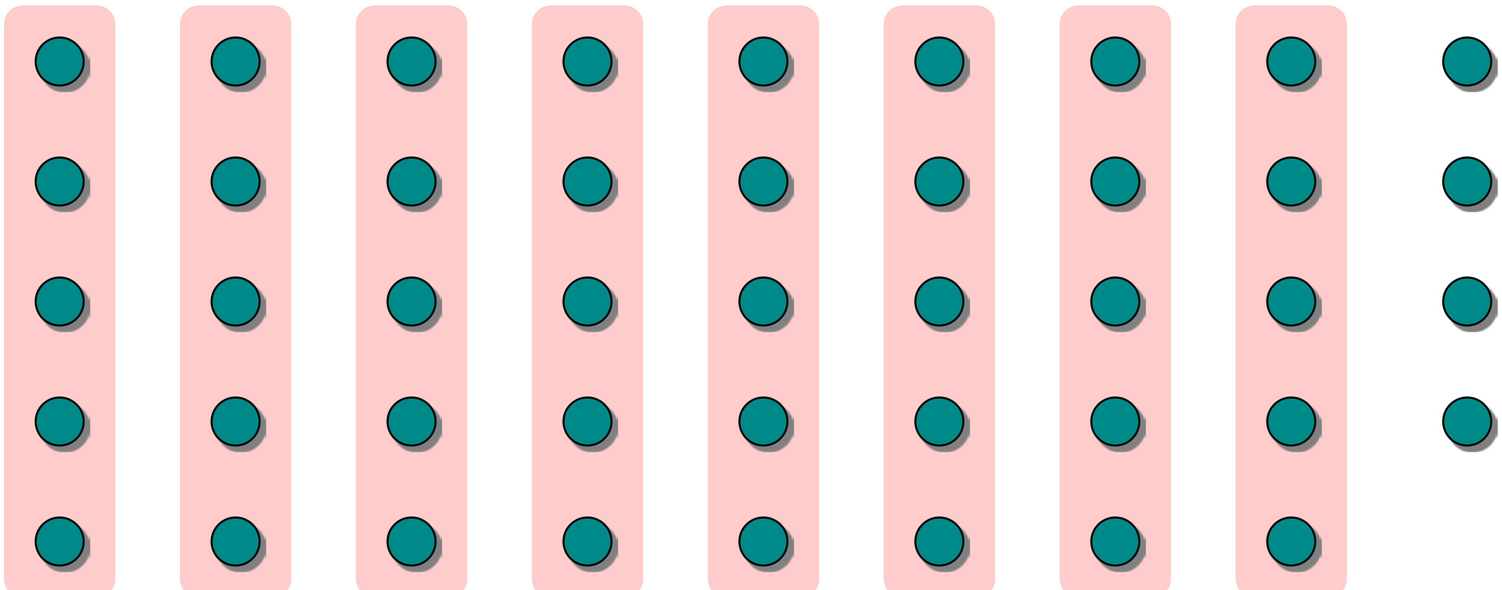
1. Divide the n elements into groups of 5. Find the median of each 5-element group by rote.
2. Recursively SELECT the median x of the $\lfloor n/5 \rfloor$ group medians to be the pivot.
3. Partition around the pivot x. Let $k = \text{rank}(x)$.
4. **if** $i = k$ **then return** x
   elseif $i < k$
       then recursively SELECT the ith smallest element in the lower part
       else recursively SELECT the $(i–k)$th smallest element in the upper part

Same as RAND-SELECT

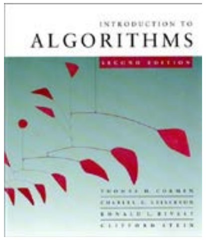
Choosing the pivot



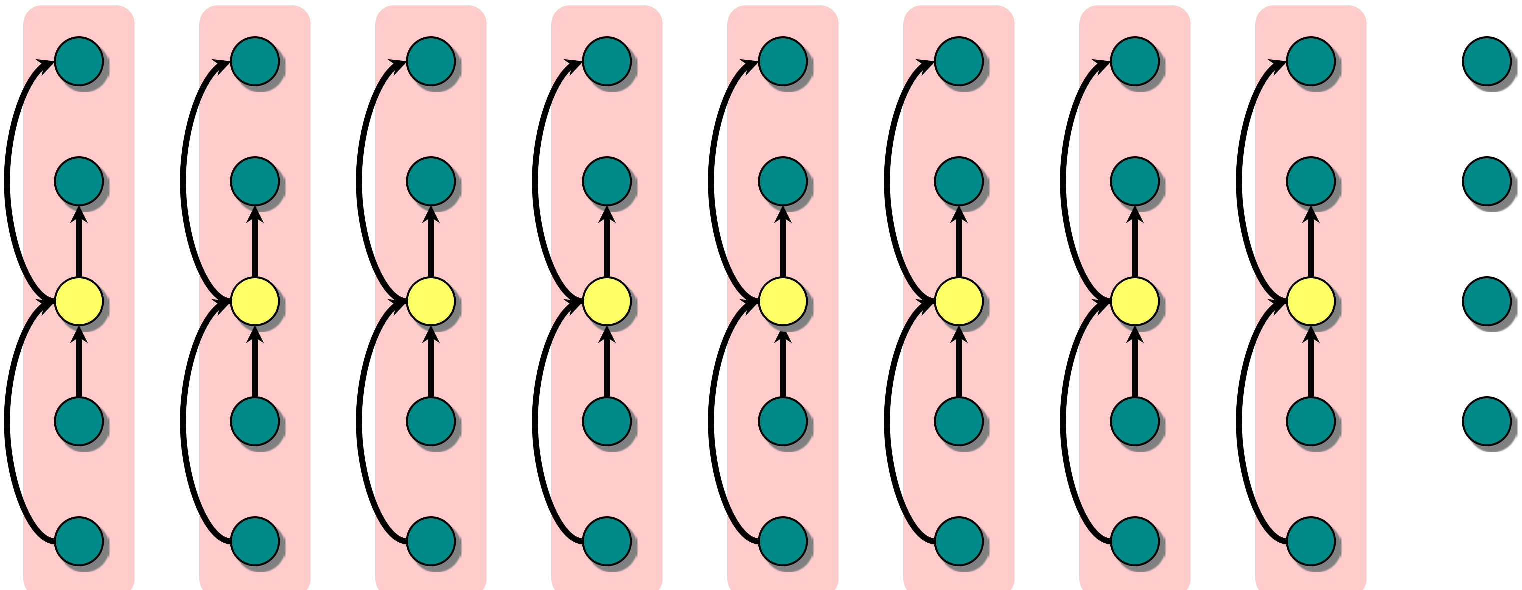
Choosing the pivot



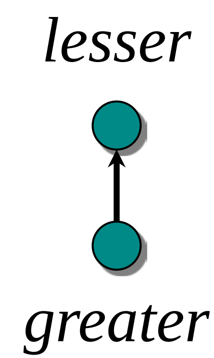
1. Divide the n elements into groups of 5.



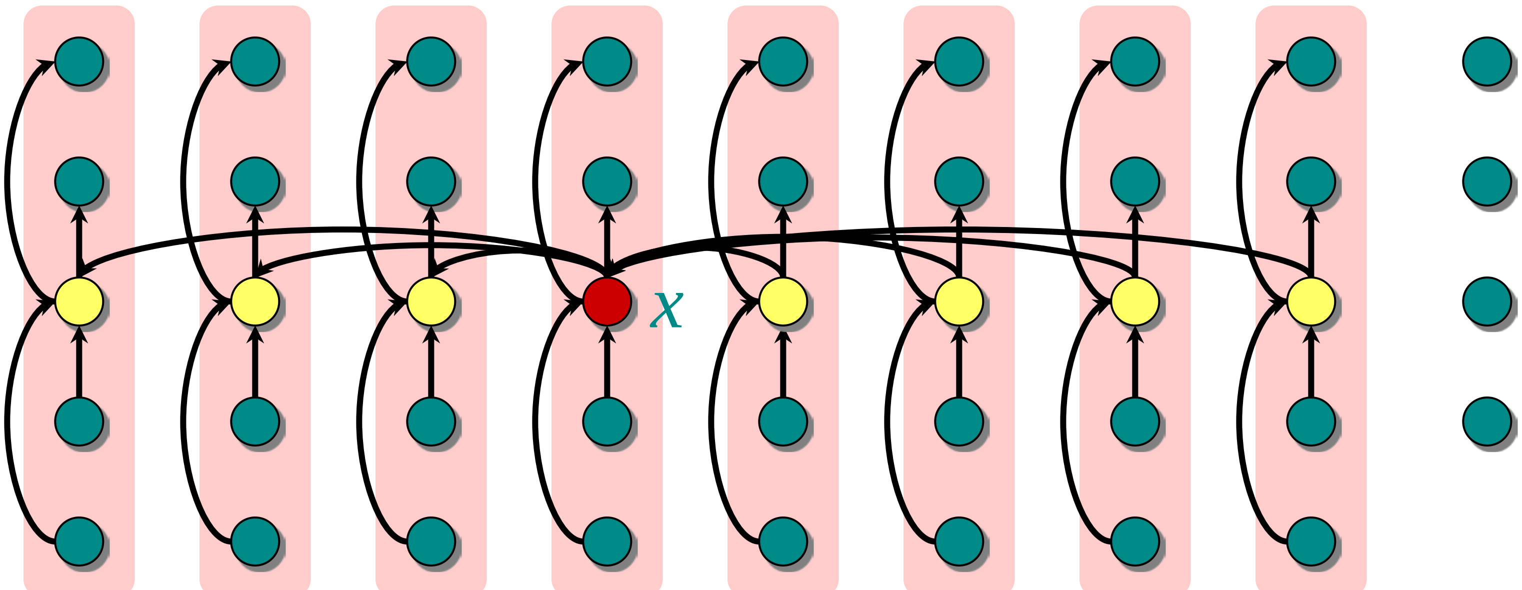
Choosing the pivot



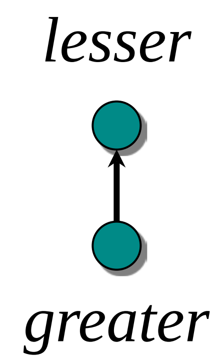
1. Divide the n elements into groups of 5. Find the median of each 5-element group by rote.

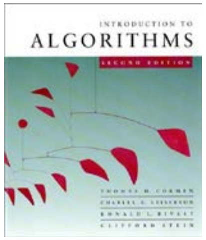


Choosing the pivot

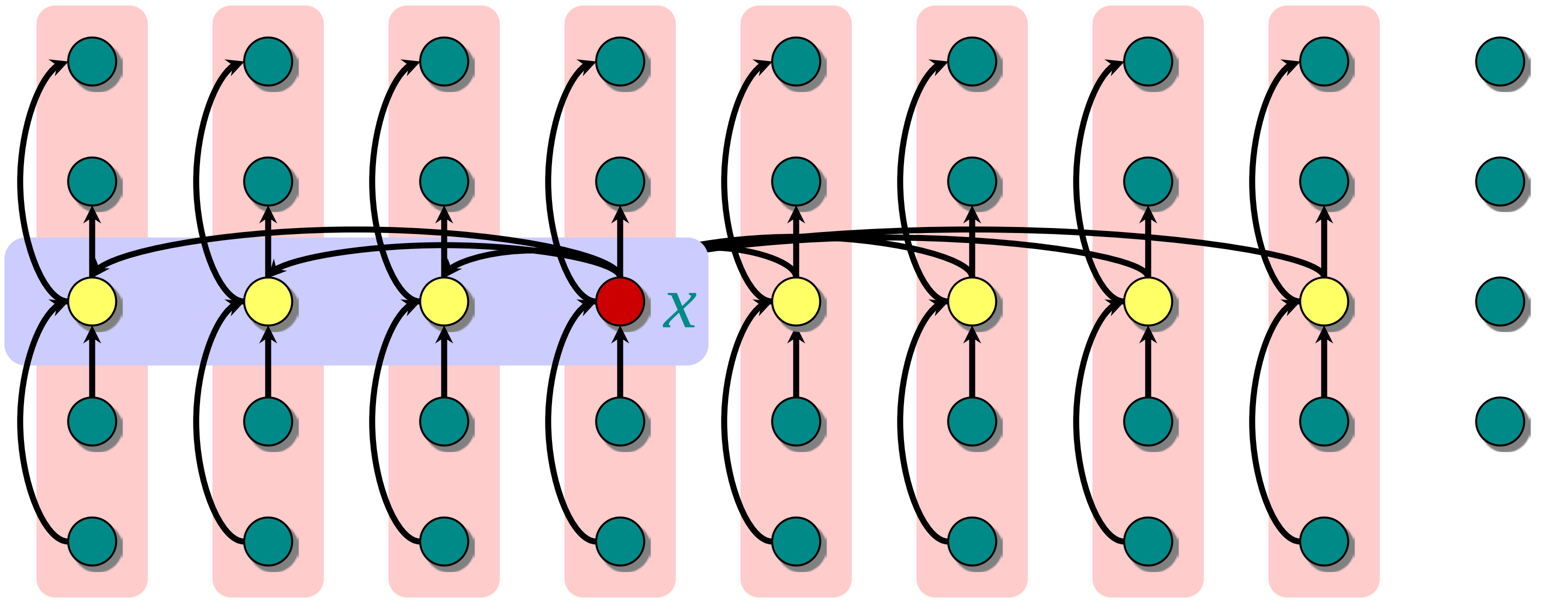


1. Divide the n elements into groups of 5. Find the median of each 5-element group by rote.
2. Recursively SELECT the median x of the $\lfloor n/5 \rfloor$ group medians to be the pivot.

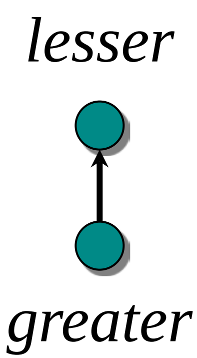


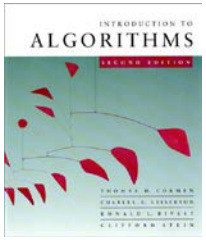


Analysis

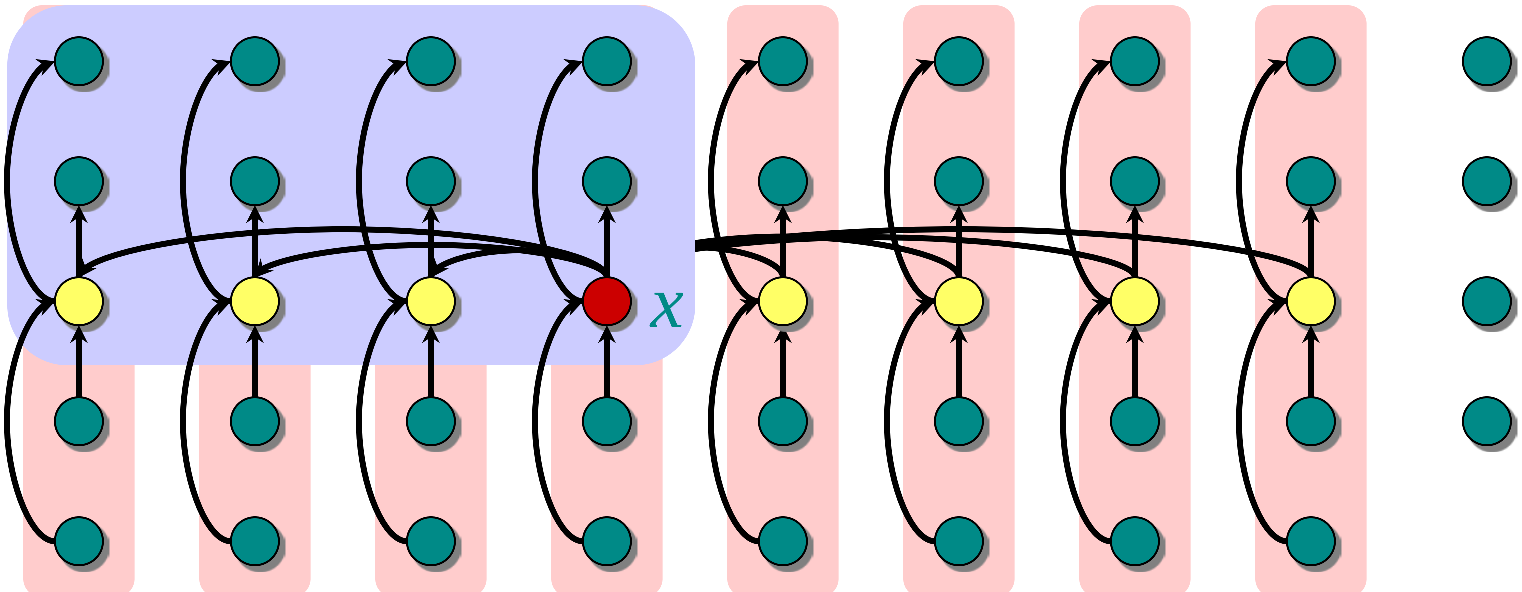


At least half the group medians are $\le x$, which is at least $\lfloor \lfloor n/5 \rfloor /2 \rfloor = \lfloor n/10 \rfloor$ group medians.



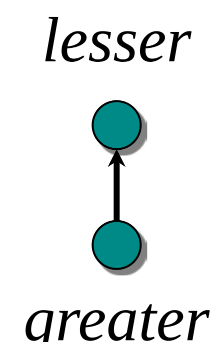


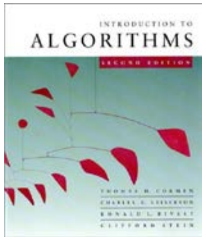
Analysis (Assume all elements are distinct.)



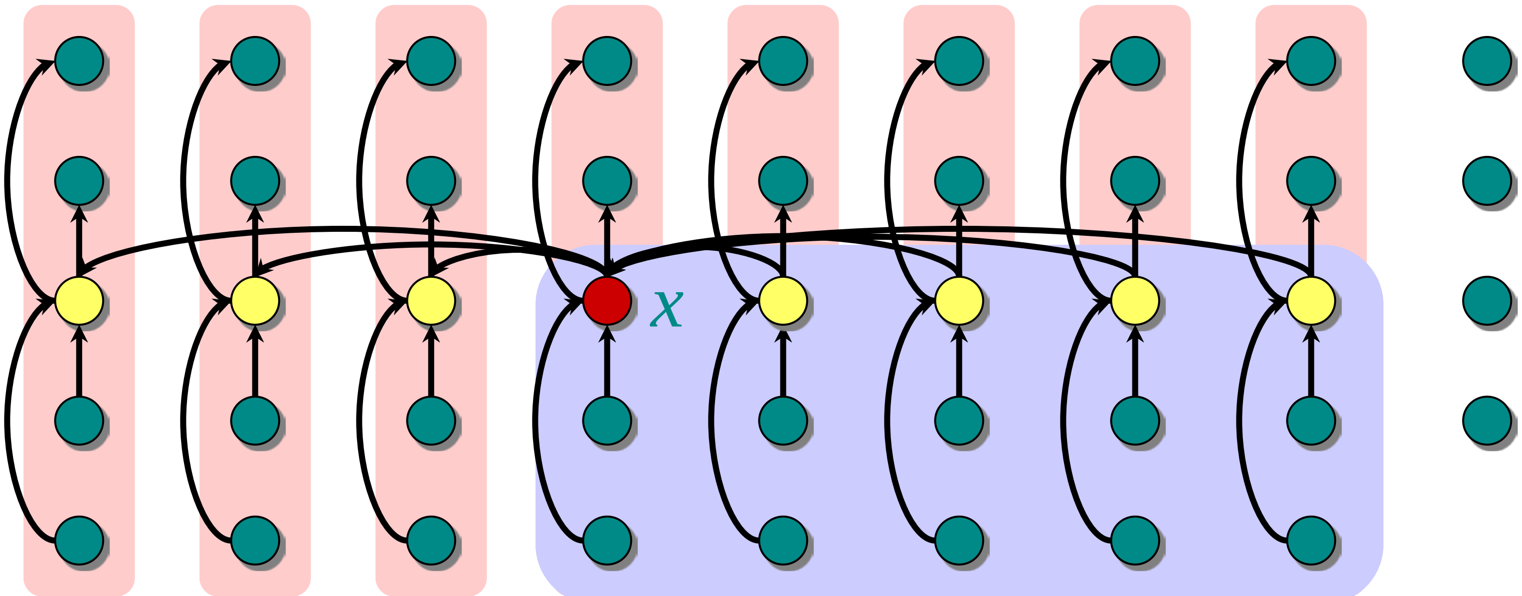
At least half the group medians are $\leq x$, which is at least $\lfloor \lfloor n/5 \rfloor /2 \rfloor = \lfloor n/10 \rfloor$ group medians.

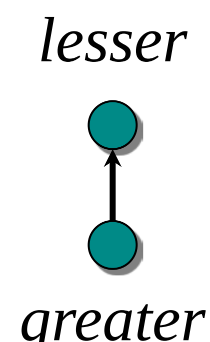
- Therefore, at least $3\lfloor n/10 \rfloor$ elements are $\leq x$.





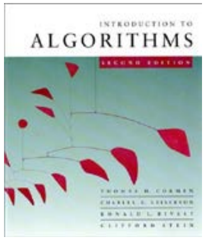
Analysis (Assume all elements are distinct.)





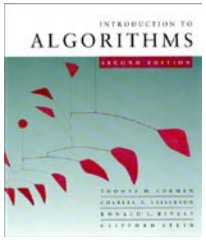
At least half the group medians are $\leq x$, which is at least $\lfloor \lfloor n/5 \rfloor /2 \rfloor = \lfloor n/10 \rfloor$ group medians.

- Therefore, at least $3\lfloor n/10 \rfloor$ elements are $\leq x$.
- Similarly, at least $3\lfloor n/10 \rfloor$ elements are $\geq x$.



Minor simplification

- For $n \geq 50$, we have $3\lfloor n/10 \rfloor \geq n/4$.
- Therefore, for $n \geq 50$ the recursive call to SELECT in Step 4 is executed recursively on $\leq 3n/4$ elements.
- Thus, the recurrence for running time can assume that Step 4 takes time $T(3n/4)$ in the worst case.
- For $n < 50$, we know that the worst-case time is $T(n) = \Theta(1)$.



Developing the recurrence

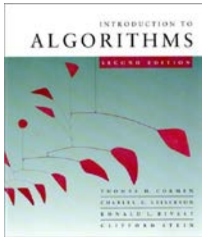
$T(n)$ SELECT(i, n)

$\Theta(n)$ 1. Divide the n elements into groups of 5. Find the median of each 5-element group by rote.

$T(n/5)$ 2. Recursively SELECT the median x of the $\lfloor n/5 \rfloor$ group medians to be the pivot.

$\Theta(n)$ 3. Partition around the pivot x. Let $k = \text{rank}(x)$.

$T(3n/4)$ 4. **if** $i = k$ **then return** x
elseif $i < k$
then recursively SELECT the ith smallest element in the lower part
else recursively SELECT the $(i–k)$th smallest element in the upper part



Solving the recurrence

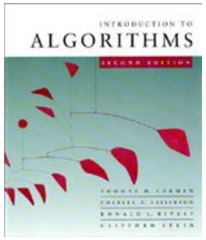
$$T(n) = T\left(\frac{1}{5}n\right) + T\left(\frac{3}{4}n\right) + \Theta(n)$$

Substitution:

$T(n) \le cn$

$$\begin{aligned} T(n) &\le \frac{1}{5}cn + \frac{3}{4}cn + \Theta(n) \\ &= \frac{19}{20}cn + \Theta(n) \\ &= cn - \left(\frac{1}{20}cn - \Theta(n)\right) \\ &\le cn \quad , \end{aligned}$$

if c is chosen large enough to handle both the $\Theta(n)$ and the initial conditions.



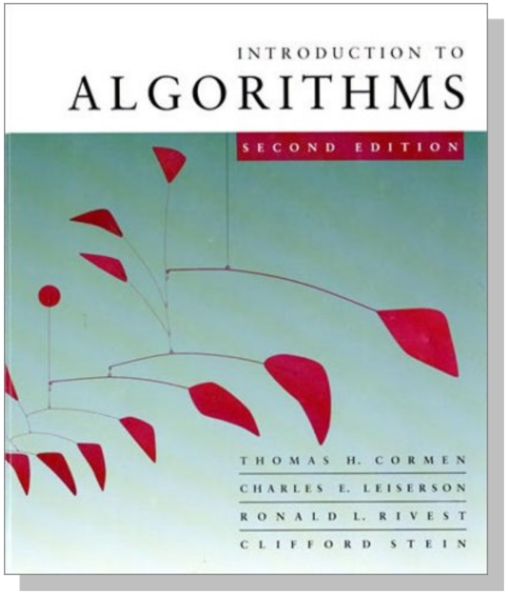
Conclusions

- Since the work at each level of recursion is a constant fraction (19/20) smaller, the work per level is a geometric series dominated by the linear work at the root.
- In practice, this algorithm runs slowly, because the constant in front of n is large.
- The randomized algorithm is far more practical.

Exercise: *Why not divide into groups of 3?*

Introduction to Algorithms

6.046J/18.401J



LECTURE 7

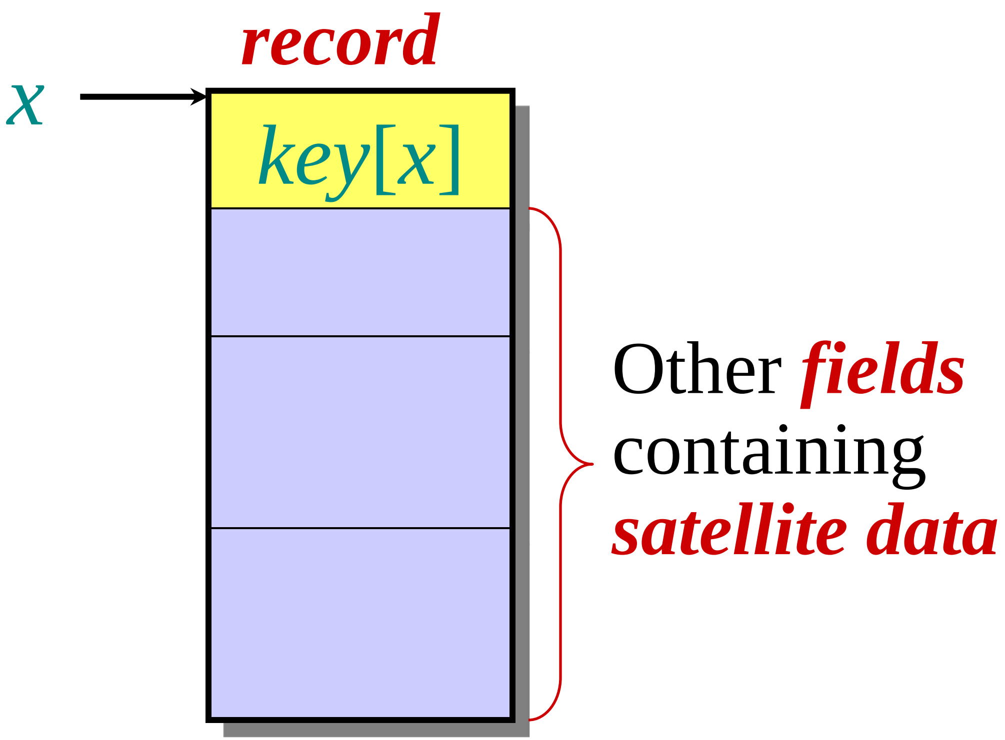
Hashing I

- Direct-access tables
- Resolving collisions by chaining
- Choosing hash functions
- Open addressing

Prof. Charles E. Leiserson

Symbol-table problem

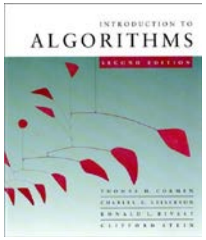
Symbol table S holding n ***records***:



Operations on S:

- INSERT(S, x)
- DELETE(S, x)
- SEARCH(S, k)

How should the data structure S be organized?



Direct-access table

IDEA: Suppose that the keys are drawn from the set $U \subseteq \{0, 1, \ldots, m-1\}$, and keys are distinct. Set up an array $T[0 \,..\, m-1]$:

$$T[k] = \begin{cases} x & \text{if } x \in K \text{ and } key[x] = k, \\ \text{NIL} & \text{otherwise.} \end{cases}$$

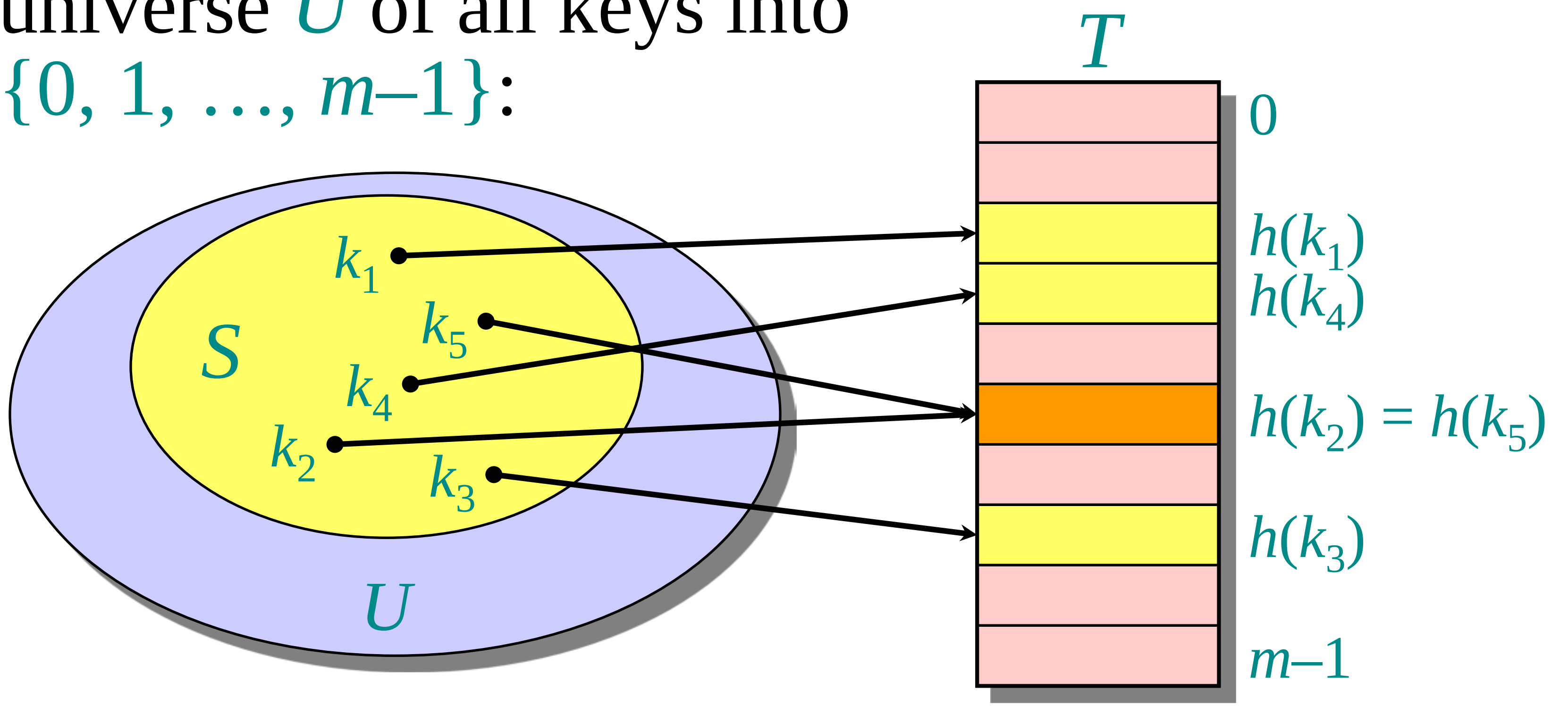
Then, operations take $\Theta(1)$ time.

Problem: The range of keys can be large:

- 64-bit numbers (which represent 18,446,744,073,709,551,616 different keys),
- character strings (even larger!).

Hash functions

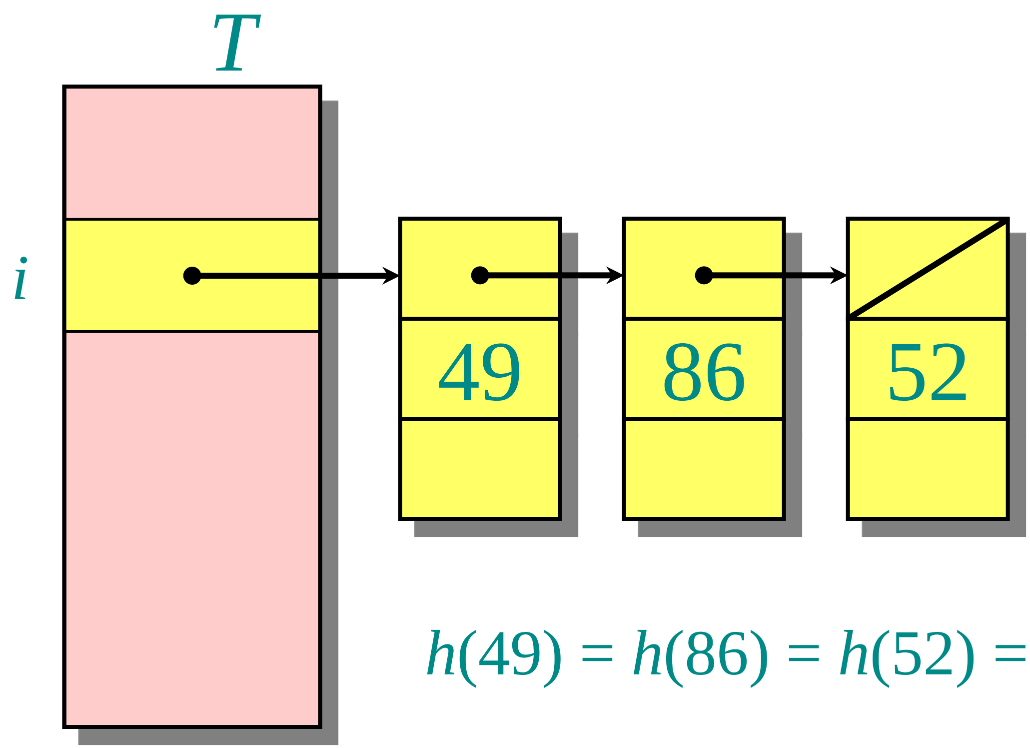
Solution: Use a ***hash function*** h to map the universe U of all keys into $\{0, 1, \ldots, m-1\}$:



When a record to be inserted maps to an already occupied slot in T, a ***collision*** occurs.

Resolving collisions by chaining

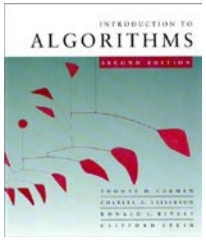
- Link records in the same slot into a list.



$h(49) = h(86) = h(52) = i$

Worst case:

- Every key hashes to the same slot.
- Access time $= \Theta(n)$ if $|S| = n$



Average-case analysis of chaining

We make the assumption of ***simple uniform hashing:***

- Each key $k \in S$ is equally likely to be hashed to any slot of table T, independent of where other keys are hashed.

Let n be the number of keys in the table, and let m be the number of slots.

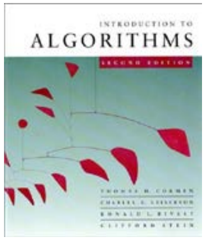
Define the ***load factor*** of T to be

$$\alpha = n/m$$

$=$ average number of keys per slot.

Search cost

The expected time for an ***unsuccessful*** search for a record with a given key is $= \Theta(1 + \alpha)$.

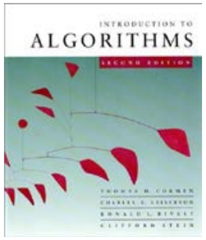


Search cost

The expected time for an ***unsuccessful*** search for a record with a given key is $= \Theta(1 + \alpha)$.

search the list

apply hash function and access slot



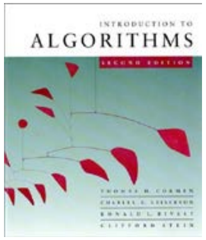
Search cost

The expected time for an ***unsuccessful*** search for a record with a given key is $= \Theta(1 + \alpha)$.

search the list

apply hash function and access slot

Expected search time $= \Theta(1)$ if $\alpha = O(1)$, or equivalently, if $n = O(m)$.



Search cost

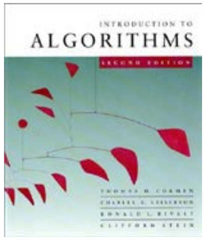
The expected time for an ***unsuccessful*** search for a record with a given key is $= \Theta(1 + \alpha)$.

search the list

apply hash function and access slot

Expected search time $= \Theta(1)$ if $\alpha = O(1)$, or equivalently, if $n = O(m)$.

A ***successful*** search has same asymptotic bound, but a rigorous argument is a little more complicated. (See textbook.)

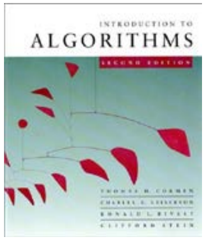


Choosing a hash function

The assumption of simple uniform hashing is hard to guarantee, but several common techniques tend to work well in practice as long as their deficiencies can be avoided.

Desirata:

- A good hash function should distribute the keys uniformly into the slots of the table.
- Regularity in the key distribution should not affect this uniformity.



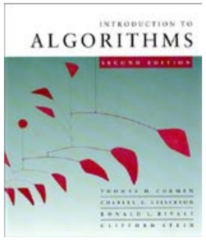
Division method

Assume all keys are integers, and define
$$h(k) = k \bmod m.$$

Deficiency: Don't pick an m that has a small divisor d. A preponderance of keys that are congruent modulo d can adversely affect uniformity.

Extreme deficiency: If $m = 2^r$, then the hash doesn't even depend on all the bits of k:

- If $k = 1011000111\underbrace{011010}_{h(k)}{}_2$ and $r = 6$, then $h(k) = 011010_2$.



Division method (continued)

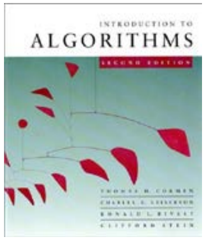
$$h(k) = k \bmod m.$$

Pick m to be a prime not too close to a power of 2 or 10 and not otherwise used prominently in the computing environment.

Annoyance:

- Sometimes, making the table size a prime is inconvenient.

But, this method is popular, although the next method we'll see is usually superior.



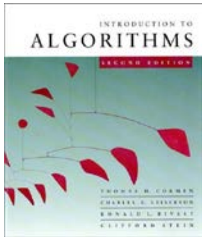
Multiplication method

Assume that all keys are integers, $m = 2^r$, and our computer has w-bit words. Define

$$h(k) = (A \cdot k \bmod 2^w) \text{ rsh } (w - r),$$

where rsh is the "bitwise right-shift" operator and A is an odd integer in the range $2^{w-1} < A < 2^w$.

- Don't pick A too close to 2^{w-1} or 2^w.
- Multiplication modulo 2^w is fast compared to division.
- The rsh operator is fast.

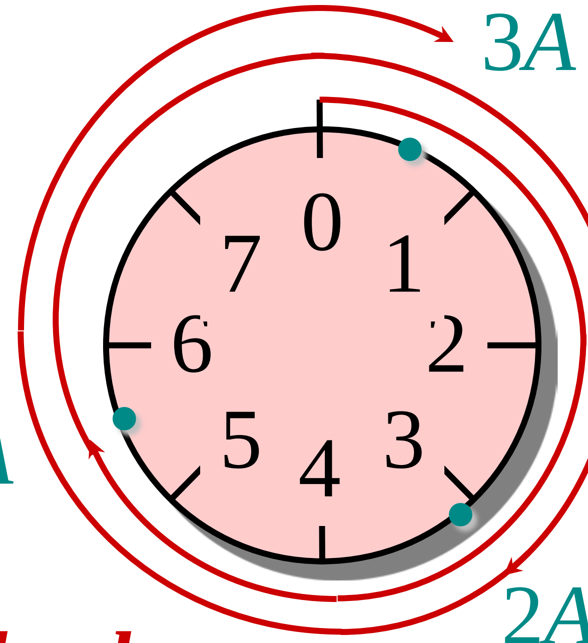


Multiplication method example

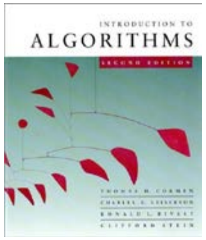
$$h(k) = (A \cdot k \bmod 2^w) \text{ rsh } (w - r)$$

Suppose that $m = 8 = 2^3$ and that our computer has $w = 7$-bit words:

$$\begin{array}{rl} 1\,0\,1\,1\,0\,0\,1 & = A \\ \times \quad 1\,1\,0\,1\,0\,1\,1 & = k \\ \hline 1\,0\,0\,1\,0\,1\,0\,0\,\underbrace{0\,1\,1}_{h(k)}\,0\,0\,1\,1 & \end{array}$$



Modular wheel



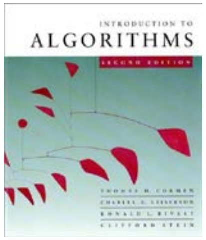
Resolving collisions by open addressing

No storage is used outside of the hash table itself.

- Insertion systematically probes the table until an empty slot is found.
- The hash function depends on both the key and probe number:

  $$h : U \times \{0, 1, \ldots, m-1\} \rightarrow \{0, 1, \ldots, m-1\}.$$

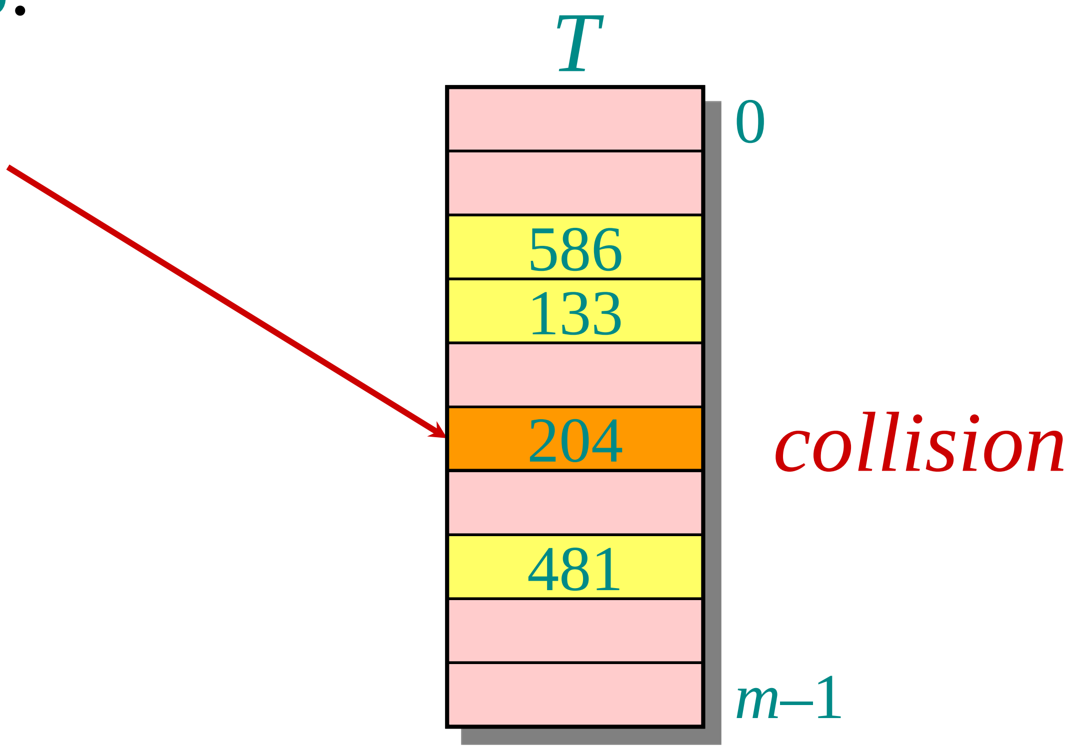
- The probe sequence $\langle h(k,0), h(k,1), \ldots, h(k,m-1)\rangle$ should be a permutation of $\{0, 1, \ldots, m-1\}$.
- The table may fill up, and deletion is difficult (but not impossible).

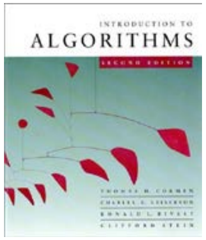


Example of open addressing

Insert key $k = 496$:

0. Probe $h(496,0)$

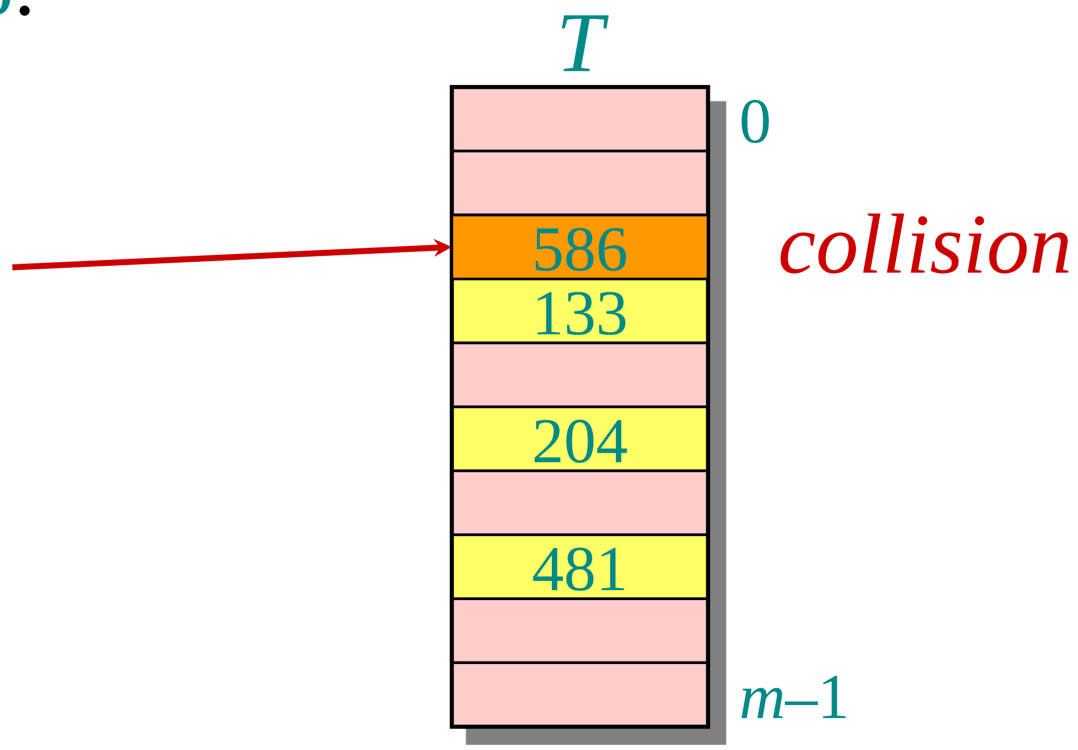


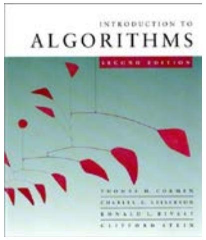


Example of open addressing

Insert key $k = 496$:

0. Probe $h(496,0)$
1. Probe $h(496,1)$

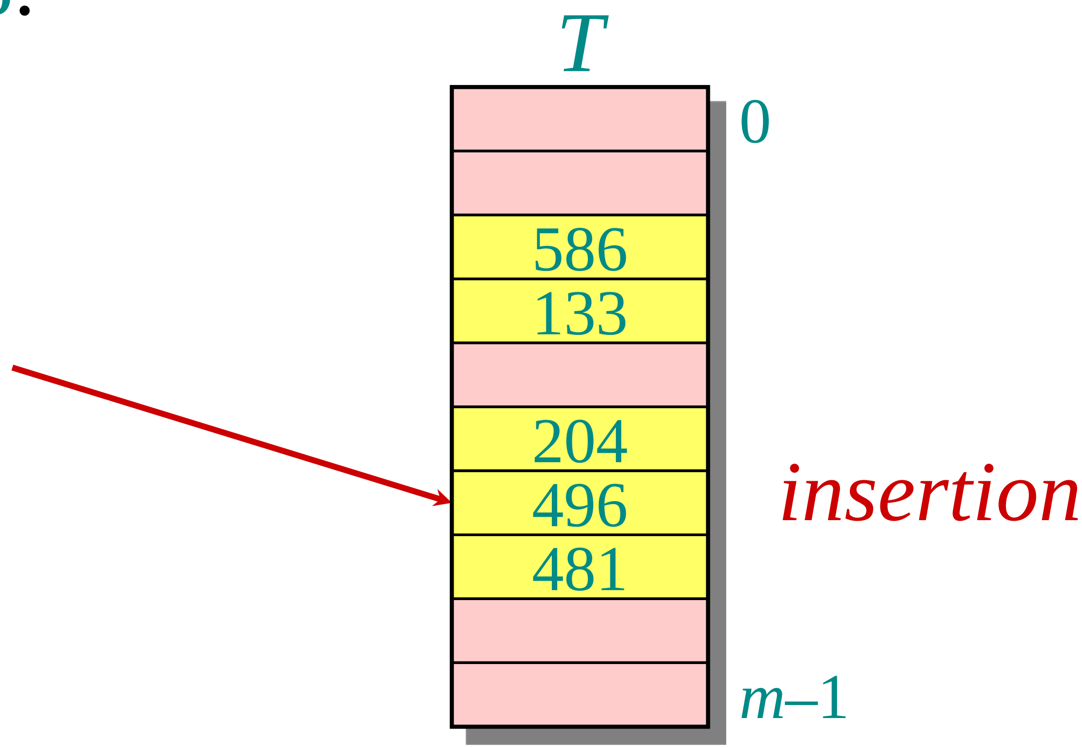


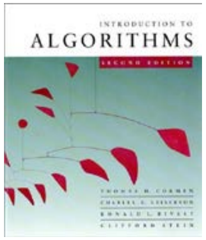


Example of open addressing

Insert key $k = 496$:

0. Probe $h(496,0)$
1. Probe $h(496,1)$
2. Probe $h(496,2)$

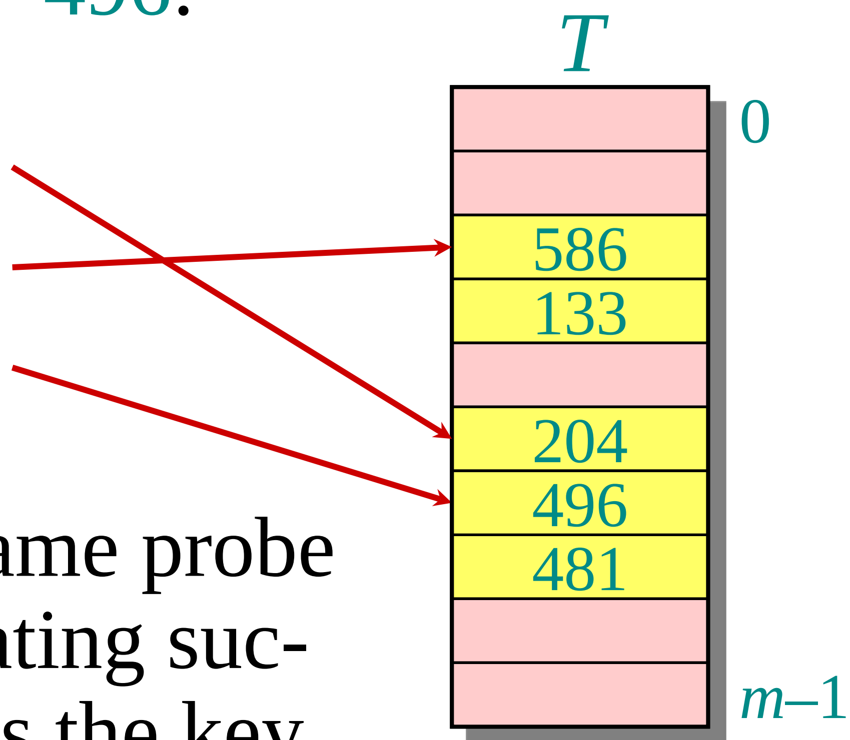




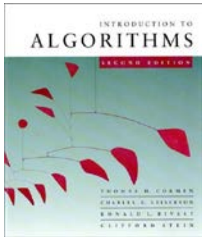
Example of open addressing

Search for key $k = 496$:

0. Probe $h(496,0)$
1. Probe $h(496,1)$
2. Probe $h(496,2)$



Search uses the same probe sequence, terminating successfully if it finds the key and unsuccessfully if it encounters an empty slot.



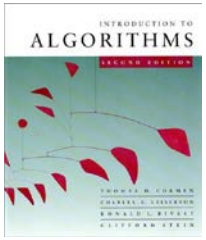
Probing strategies

Linear probing:

Given an ordinary hash function $h'(k)$, linear probing uses the hash function

$$h(k,i) = (h'(k) + i) \bmod m.$$

This method, though simple, suffers from ***primary clustering***, where long runs of occupied slots build up, increasing the average search time. Moreover, the long runs of occupied slots tend to get longer.



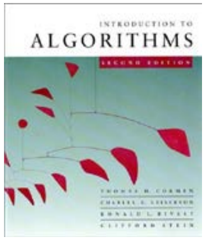
Probing strategies

Double hashing

Given two ordinary hash functions $h_1(k)$ and $h_2(k)$, double hashing uses the hash function

$$h(k,i) = (h_1(k) + i \cdot h_2(k)) \bmod m.$$

This method generally produces excellent results, but $h_2(k)$ must be relatively prime to m. One way is to make m a power of 2 and design $h_2(k)$ to produce only odd numbers.



Analysis of open addressing

We make the assumption of ***uniform hashing:***

- Each key is equally likely to have any one of the $m!$ permutations as its probe sequence.

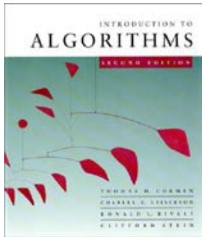
Theorem. Given an open-addressed hash table with load factor $\alpha = n/m < 1$, the expected number of probes in an unsuccessful search is at most $1/(1–\alpha)$.

Proof of the theorem

Proof.

- At least one probe is always necessary.
- With probability n/m, the first probe hits an occupied slot, and a second probe is necessary.
- With probability $(n–1)/(m–1)$, the second probe hits an occupied slot, and a third probe is necessary.
- With probability $(n–2)/(m–2)$, the third probe hits an occupied slot, etc.

Observe that $\dfrac{n-i}{m-i} < \dfrac{n}{m} = \alpha$ for $i = 1, 2, \ldots, n$.



Proof (continued)

Therefore, the expected number of probes is

$$1+\frac{n}{m}\left(1+\frac{n-1}{m-1}\left(1+\frac{n-2}{m-2}\left(\cdots\left(1+\frac{1}{m-n+1}\right)\cdots\right)\right)\right)$$

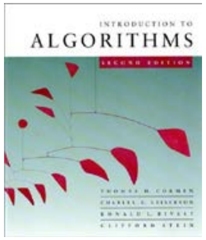
$$\le 1+\alpha(1+\alpha(1+\alpha(\cdots(1+\alpha)\cdots)))$$

$$\le 1+\alpha+\alpha^2+\alpha^3+\cdots$$

$$=\sum_{i=0}^{\infty}\alpha^i$$

$$=\frac{1}{1-\alpha}\;.\;\square$$

The textbook has a more rigorous proof and an analysis of successful searches.

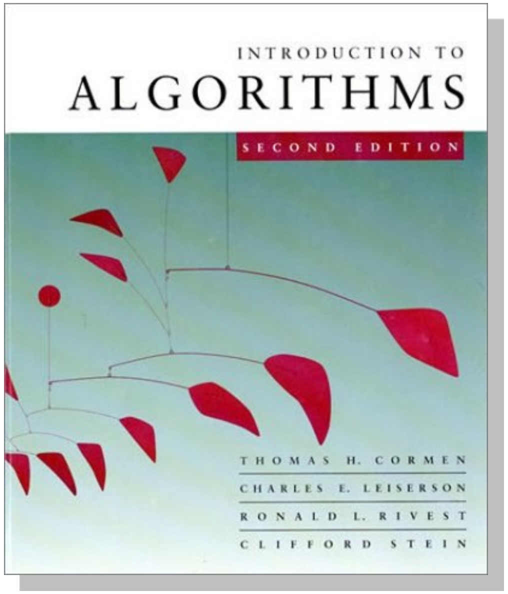


Implications of the theorem

- If α is constant, then accessing an open-addressed hash table takes constant time.
- If the table is half full, then the expected number of probes is $1/(1-0.5) = 2$.
- If the table is 90% full, then the expected number of probes is $1/(1-0.9) = 10$.

Introduction to Algorithms

6.046J/18.401J



LECTURE 8

Hashing II

- Universal hashing
- Universality theorem
- Constructing a set of universal hash functions
- Perfect hashing

Prof. Charles E. Leiserson

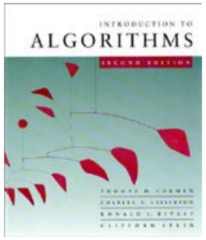
A weakness of hashing

Problem: For any hash function h, a set of keys exists that can cause the average access time of a hash table to skyrocket.

- An adversary can pick all keys from $\{k \in U : h(k) = i\}$ for some slot i.

IDEA: Choose the hash function at random, independently of the keys.

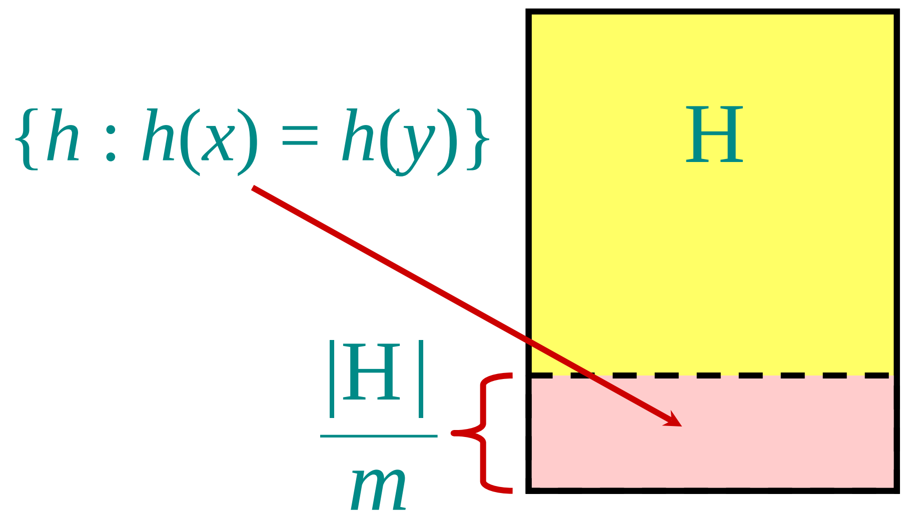
- Even if an adversary can see your code, he or she cannot find a bad set of keys, since he or she doesn't know exactly which hash function will be chosen.

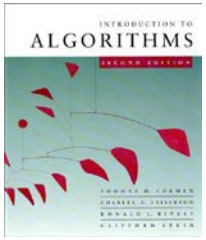


Universal hashing

Definition. Let U be a universe of keys, and let $\mathcal{H}$ be a finite collection of hash functions, each mapping U to $\{0, 1, \ldots, m-1\}$. We say $\mathcal{H}$ is ***universal*** if for all $x, y \in U$, where $x \neq y$, we have $|\{h \in \mathcal{H} : h(x) = h(y)\}| \leq |\mathcal{H}|/m$.

That is, the chance of a collision between x and y is $\leq 1/m$ if we choose h randomly from $\mathcal{H}$.

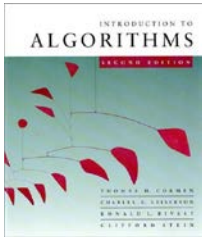




Universality is good

Theorem. Let h be a hash function chosen (uniformly) at random from a universal set $\mathcal{H}$ of hash functions. Suppose h is used to hash n arbitrary keys into the m slots of a table T. Then, for a given key x, we have

$$E[\#\text{collisions with } x] < n/m.$$

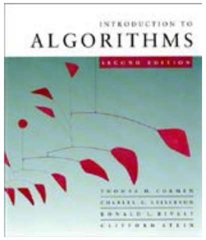


Proof of theorem

Proof. Let C_x be the random variable denoting the total number of collisions of keys in T with x, and let

$$c_{xy} = \begin{cases} 1 & \text{if } h(x) = h(y), \\ 0 & \text{otherwise.} \end{cases}$$

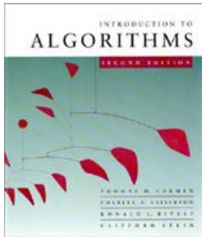
Note: $E[c_{xy}] = 1/m$ and $C_x = \displaystyle\sum_{y \in T - \{x\}} c_{xy}$.



Proof (continued)

$$E[C_x] = E\left[\sum_{y \in T - \{x\}} c_{xy}\right]$$

- Take expectation of both sides.



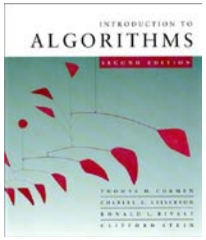
Proof (continued)

$$E[C_x] = E\left[\sum_{y \in T - \{x\}} c_{xy}\right]$$

- Take expectation of both sides.

$$= \sum_{y \in T - \{x\}} E[c_{xy}]$$

- Linearity of expectation.



Proof (continued)

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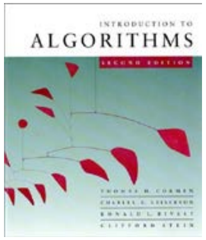
- Take expectation of both sides.

$$= \sum_{y \in T - \{x\}} E[c_{xy}]$$

- Linearity of expectation.

$$= \sum_{y \in T - \{x\}} 1/m$$

- $E[c_{xy}] = 1/m$.



Proof (continued)

$$E[C_x] = E\left[\sum_{y \in T-\{x\}} c_{xy}\right]$$

- Take expectation of both sides.

$$= \sum_{y \in T-\{x\}} E[c_{xy}]$$

- Linearity of expectation.

$$= \sum_{y \in T-\{x\}} 1/m$$

- $E[c_{xy}] = 1/m$.

$$= \frac{n-1}{m} . \quad \square$$

- Algebra.

Constructing a set of universal hash functions

Let m be prime. Decompose key k into $r + 1$ digits, each with value in the set $\{0, 1, \ldots, m-1\}$. That is, let $k = \langle k_0, k_1, \ldots, k_r \rangle$, where $0 \le k_i < m$.

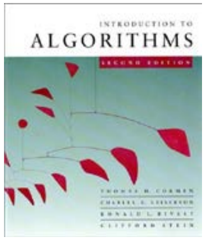
Randomized strategy:

Pick $a = \langle a_0, a_1, \ldots, a_r \rangle$ where each a_i is chosen randomly from $\{0, 1, \ldots, m-1\}$.

Define $h_a(k) = \sum_{i=0}^{r} a_i k_i \bmod m$.

Dot product, modulo m

How big is $\mathcal{H} = \{h_a\}$? $|\mathcal{H}| = m^{r+1}$. ← **REMEMBER THIS!**



Universality of dot-product hash functions

Theorem. The set $H = \{h_a\}$ is universal.

Proof. Suppose that $x = \langle x_0, x_1, \ldots, x_r \rangle$ and $y = \langle y_0, y_1, \ldots, y_r \rangle$ be distinct keys. Thus, they differ in at least one digit position, wlog position 0. For how many $h_a \in H$ do x and y collide?

We must have $h_a(x) = h_a(y)$, which implies that

$$\sum_{i=0}^{r} a_i x_i \equiv \sum_{i=0}^{r} a_i y_i \pmod{m}.$$

Proof (continued)

Equivalently, we have

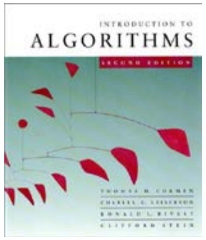
$$\sum_{i=0}^{r} a_i(x_i - y_i) \equiv 0 \pmod{m}$$

or

$$a_0(x_0 - y_0) + \sum_{i=1}^{r} a_i(x_i - y_i) \equiv 0 \pmod{m}\ ,$$

which implies that

$$a_0(x_0 - y_0) \equiv -\sum_{i=1}^{r} a_i(x_i - y_i) \pmod{m}\ .$$



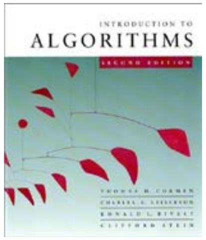
Fact from number theory

Theorem. Let m be prime. For any $z \in \mathrm{Z}_m$ such that $z \neq 0$, there exists a unique $z^{-1} \in \mathrm{Z}_m$ such that

$$z \cdot z^{-1} \equiv 1 \pmod{m}.$$

Example: $m = 7$.

z	1	2	3	4	5	6
z^{-1}	1	4	5	2	3	6



Back to the proof

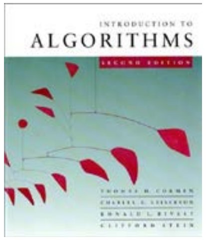
We have

$$a_0(x_0 - y_0) \equiv -\sum_{i=1}^{r} a_i(x_i - y_i) \pmod{m},$$

and since $x_0 \neq y_0$, an inverse $(x_0 - y_0)^{-1}$ must exist, which implies that

$$a_0 \equiv \left(-\sum_{i=1}^{r} a_i(x_i - y_i) \right) \cdot (x_0 - y_0)^{-1} \pmod{m}.$$

Thus, for any choices of $a_1, a_2, \ldots, a_r$, exactly one choice of a_0 causes x and y to collide.



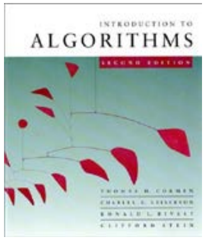
Proof (completed)

Q. How many h_a's cause x and y to collide?

A. There are m choices for each of $a_1, a_2, \ldots, a_r$, but once these are chosen, exactly one choice for a_0 causes x and y to collide, namely

$$a_0 = \left(\left(-\sum_{i=1}^{r} a_i (x_i - y_i) \right) \cdot (x_0 - y_0)^{-1} \right) \bmod m .$$

Thus, the number of h_a's that cause x and y to collide is $m^r \cdot 1 = m^r = |\mathcal{H}|/m$. $\square$

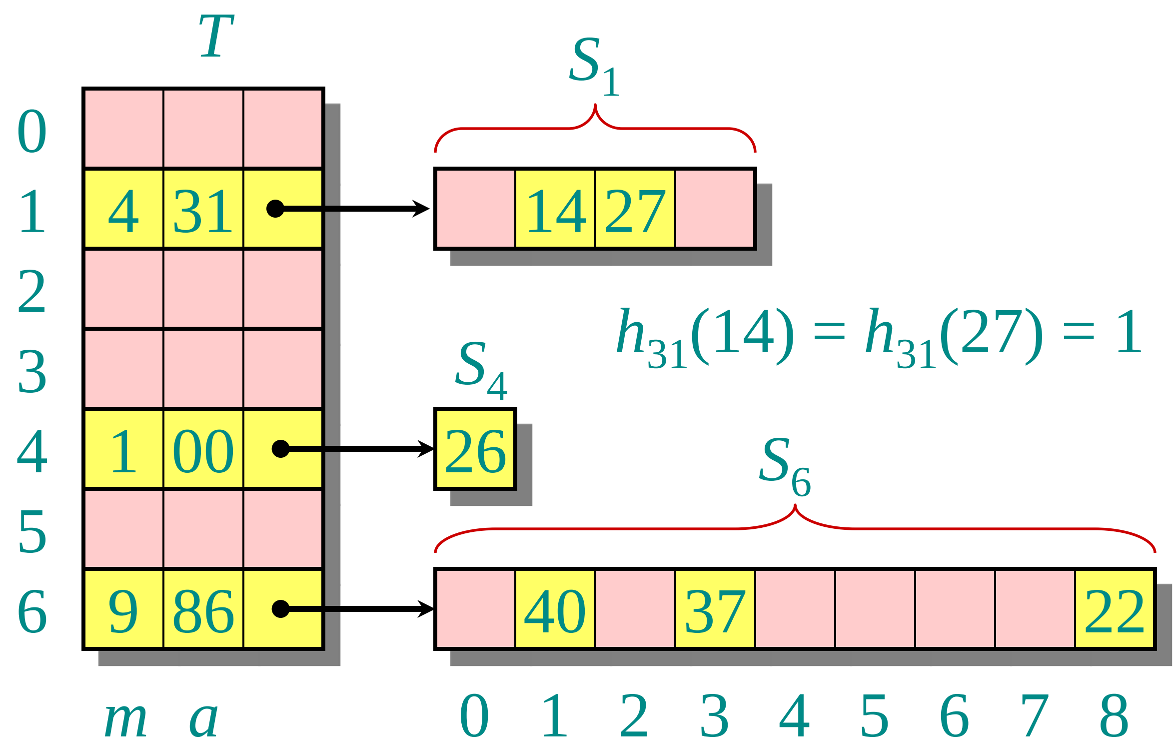


Perfect hashing

Given a set of n keys, construct a static hash table of size $m = O(n)$ such that SEARCH takes $\Theta(1)$ time in the *worst case*.

IDEA: Two-level scheme with universal hashing at both levels.

No collisions at level 2!



Collisions at level 2

Theorem. Let H be a class of universal hash functions for a table of size $m = n^2$. Then, if we use a random $h \in \text{H}$ to hash n keys into the table, the expected number of collisions is at most 1/2.

Proof. By the definition of universality, the probability that 2 given keys in the table collide under h is $1/m = 1/n^2$. Since there are $\binom{n}{2}$ pairs of keys that can possibly collide, the expected number of collisions is

$$\binom{n}{2} \cdot \frac{1}{n^2} = \frac{n(n-1)}{2} \cdot \frac{1}{n^2} < \frac{1}{2}. \quad \square$$

No collisions at level 2

Corollary. The probability of no collisions is at least 1/2.

*Proof. **Markov's inequality*** says that for any nonnegative random variable X, we have

$$\Pr\{X \geq t\} \leq E[X]/t.$$

Applying this inequality with $t = 1$, we find that the probability of 1 or more collisions is at most 1/2. $\square$

Thus, just by testing random hash functions in H, we'll quickly find one that works.

Analysis of storage

For the level-1 hash table T, choose $m = n$, and let n_i be random variable for the number of keys that hash to slot i in T. By using n_i^2 slots for the level-2 hash table S_i, the expected total storage required for the two-level scheme is therefore

$$E\left[\sum_{i=0}^{m-1} \Theta\left(n_i^2\right)\right] = \Theta(n),$$

since the analysis is identical to the analysis from recitation of the expected running time of bucket sort. (For a probability bound, apply Markov.)

Introduction to Algorithms

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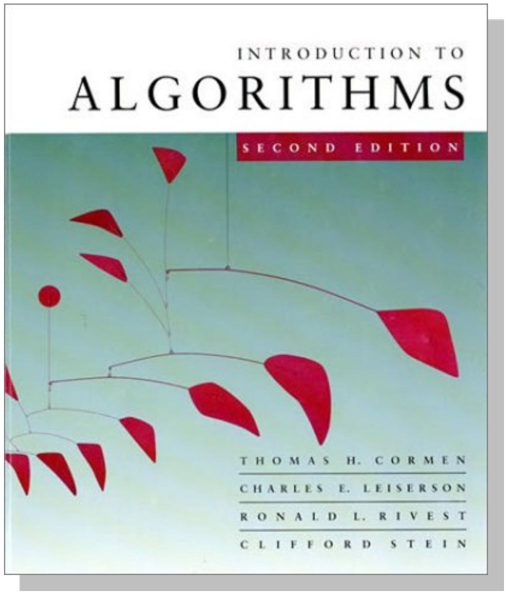
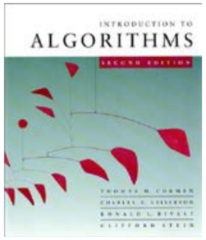


LECTURE 9

Randomly built binary search trees

- Expected node depth
- Analyzing height
  - Convexity lemma
  - Jensen's inequality
  - Exponential height
- Post mortem

Prof. Erik Demaine



Binary-search-tree sort

$T \leftarrow \emptyset$ ▷ Create an empty BST

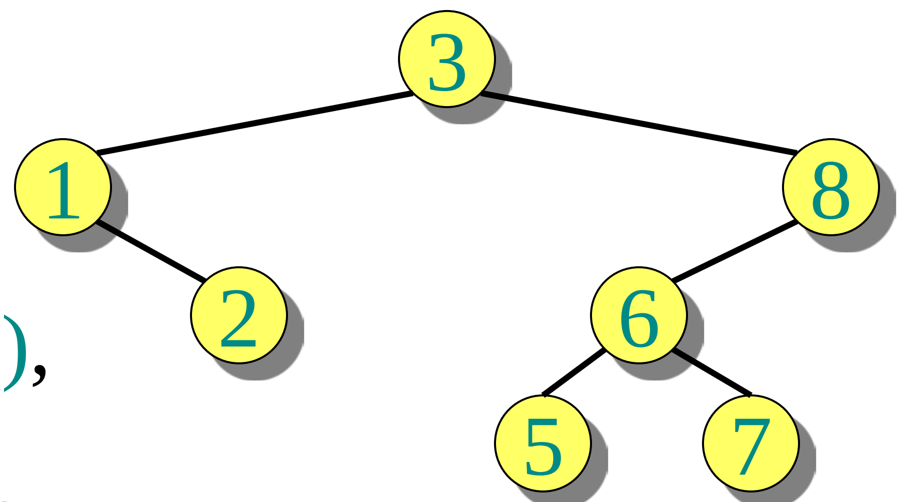
for $i = 1$ to n

  do TREE-INSERT$(T, A[i])$

Perform an inorder tree walk of T.

Example:

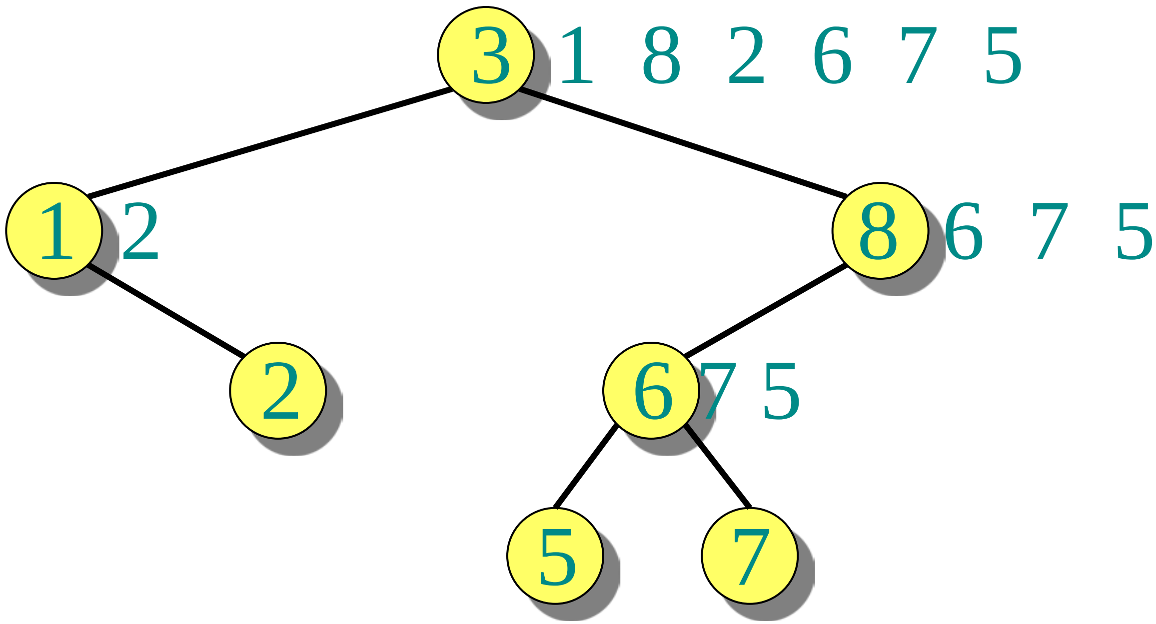
$A = [3\ 1\ 8\ 2\ 6\ 7\ 5]$



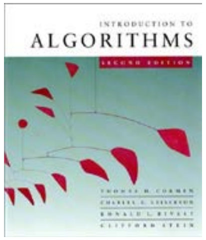
Tree-walk time $= O(n)$, but how long does it take to build the BST?

Analysis of BST sort

BST sort performs the same comparisons as quicksort, but in a different order!



The expected time to build the tree is asymptotically the same as the running time of quicksort.



Node depth

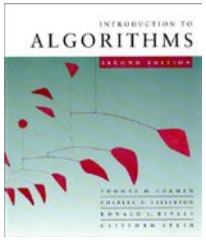
The depth of a node = the number of comparisons made during TREE-INSERT. Assuming all input permutations are equally likely, we have

Average node depth

$$= \frac{1}{n} E\left[\sum_{i=1}^{n} (\#\text{comparisons to insert node } i)\right]$$

$$= \frac{1}{n} O(n \lg n) \qquad \text{(quicksort analysis)}$$

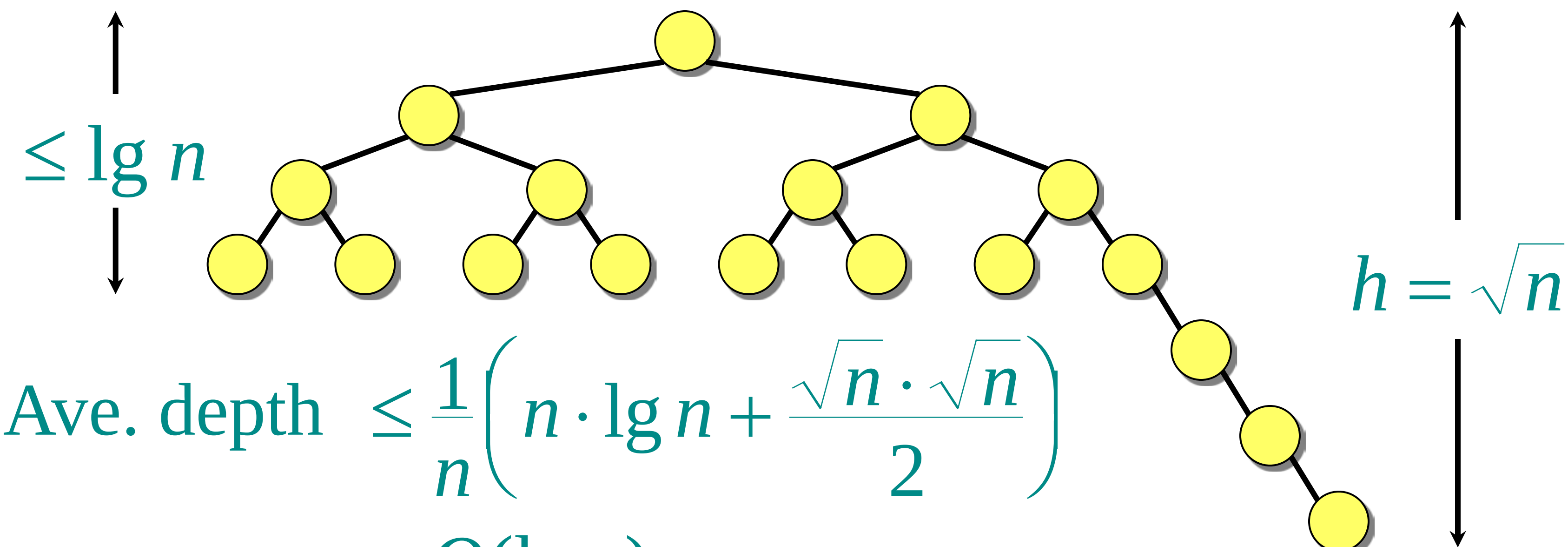
$$= O(\lg n) \; .$$



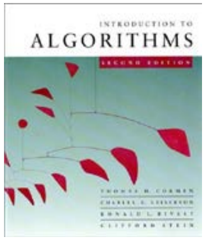
Expected tree height

But, average node depth of a randomly built BST = $O(\lg n)$ does not necessarily mean that its expected height is also $O(\lg n)$ (although it is).

Example.



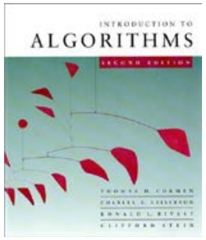
$$\text{Ave. depth} \le \frac{1}{n}\left(n \cdot \lg n + \frac{\sqrt{n} \cdot \sqrt{n}}{2}\right)$$
$$= O(\lg n)$$



Height of a randomly built binary search tree

Outline of the analysis:

- Prove ***Jensen's inequality***, which says that $f(E[X]) \le E[f(X)]$ for any convex function f and random variable X.
- Analyze the ***exponential height*** of a randomly built BST on n nodes, which is the random variable $Y_n = 2^{X_n}$, where X_n is the random variable denoting the height of the BST.
- Prove that $2^{E[X_n]} \le E[2^{X_n}] = E[Y_n] = O(n^3)$, and hence that $E[X_n] = O(\lg n)$.

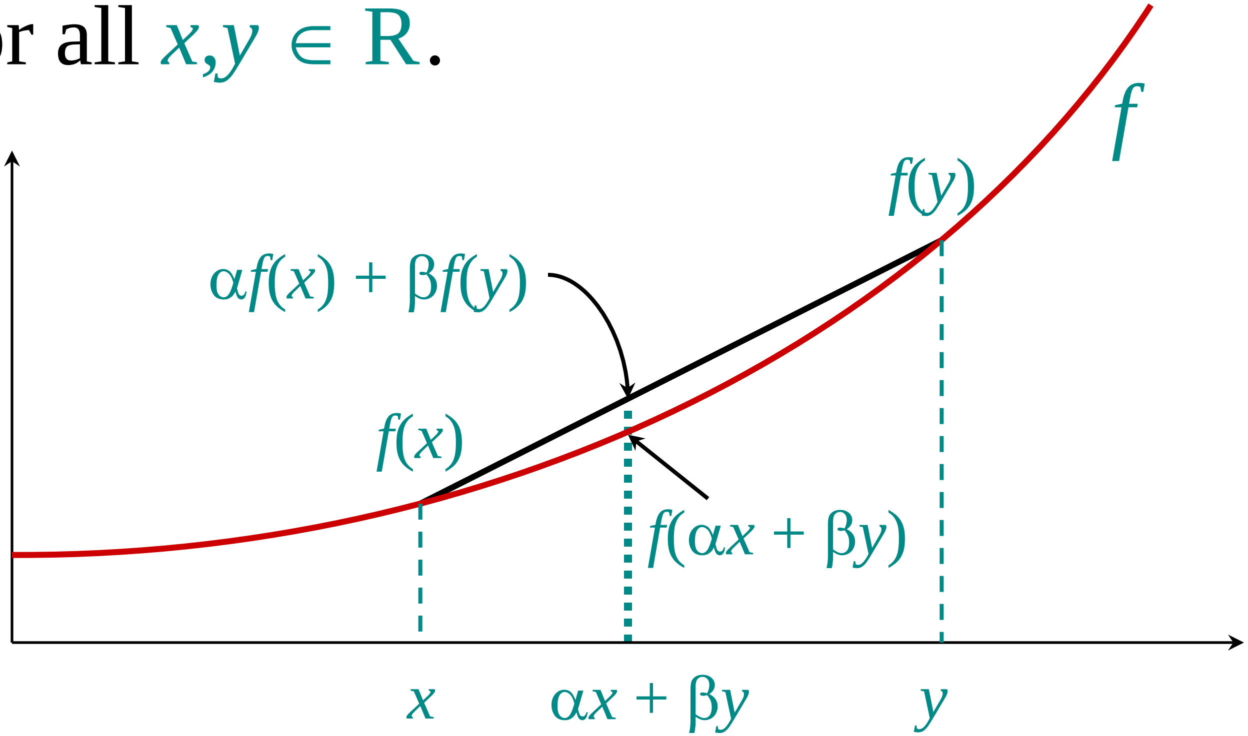


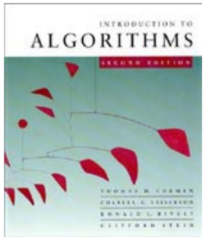
Convex functions

A function $f : \mathrm{R} \to \mathrm{R}$ is ***convex*** if for all $\alpha, \beta \geq 0$ such that $\alpha + \beta = 1$, we have

$$f(\alpha x + \beta y) \leq \alpha f(x) + \beta f(y)$$

for all $x, y \in \mathrm{R}$.



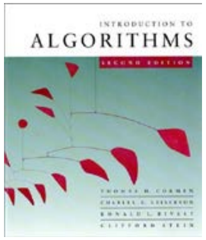


Convexity lemma

Lemma. Let $f : \mathrm{R} \to \mathrm{R}$ be a convex function, and let $\alpha_1, \alpha_2, \ldots, \alpha_n$ be nonnegative real numbers such that $\sum_k \alpha_k = 1$. Then, for any real numbers $x_1, x_2, \ldots, x_n$, we have

$$f\left(\sum_{k=1}^{n} \alpha_k x_k\right) \le \sum_{k=1}^{n} \alpha_k f(x_k) .$$

Proof. By induction on n. For $n = 1$, we have $\alpha_1 = 1$, and hence $f(\alpha_1 x_1) \le \alpha_1 f(x_1)$ trivially.

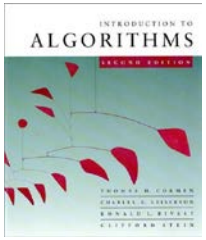


Proof (continued)

Inductive step:

$$f\left(\sum_{k=1}^{n}\alpha_k x_k\right) = f\left(\alpha_n x_n + (1-\alpha_n)\sum_{k=1}^{n-1}\frac{\alpha_k}{1-\alpha_n}x_k\right)$$

Algebra.



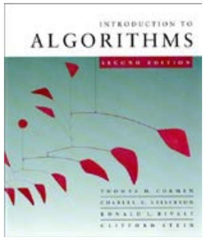
Proof (continued)

Inductive step:

$$f\left(\sum_{k=1}^{n}\alpha_k x_k\right) = f\left(\alpha_n x_n + (1-\alpha_n)\sum_{k=1}^{n-1}\frac{\alpha_k}{1-\alpha_n}x_k\right)$$

$$\leq \alpha_n f(x_n) + (1-\alpha_n) f\left(\sum_{k=1}^{n-1}\frac{\alpha_k}{1-\alpha_n}x_k\right)$$

Convexity.



Proof (continued)

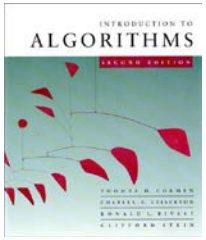
Inductive step:

$$f\left(\sum_{k=1}^{n} \alpha_k x_k\right) = f\left(\alpha_n x_n + (1-\alpha_n)\sum_{k=1}^{n-1} \frac{\alpha_k}{1-\alpha_n} x_k\right)$$

$$\le \alpha_n f(x_n) + (1-\alpha_n) f\left(\sum_{k=1}^{n-1} \frac{\alpha_k}{1-\alpha_n} x_k\right)$$

$$\le \alpha_n f(x_n) + (1-\alpha_n)\sum_{k=1}^{n-1} \frac{\alpha_k}{1-\alpha_n} f(x_k)$$

Induction.



Proof (continued)

Inductive step:

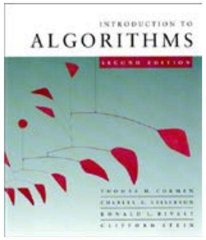
$$f\left(\sum_{k=1}^{n}\alpha_k x_k\right) = f\left(\alpha_n x_n + (1-\alpha_n)\sum_{k=1}^{n-1}\frac{\alpha_k}{1-\alpha_n}x_k\right)$$

$$\le \alpha_n f(x_n) + (1-\alpha_n) f\left(\sum_{k=1}^{n-1}\frac{\alpha_k}{1-\alpha_n}x_k\right)$$

$$\le \alpha_n f(x_n) + (1-\alpha_n)\sum_{k=1}^{n-1}\frac{\alpha_k}{1-\alpha_n}f(x_k)$$

$$= \sum_{k=1}^{n}\alpha_k f(x_k). \quad \square$$

Algebra.

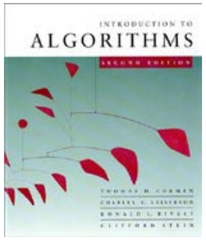


Convexity lemma: infinite case

Lemma. Let $f : \mathrm{R} \to \mathrm{R}$ be a convex function, and let $\alpha_1, \alpha_2, \ldots,$ be nonnegative real numbers such that $\sum_k \alpha_k = 1$. Then, for any real numbers $x_1, x_2, \ldots,$ we have

$$f\left(\sum_{k=1}^{\infty} \alpha_k x_k\right) \le \sum_{k=1}^{\infty} \alpha_k f(x_k) \ ,$$

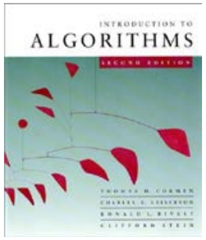
assuming that these summations exist.



Convexity lemma: infinite case

Proof. By the convexity lemma, for any $n \geq 1$,

$$f\left(\sum_{k=1}^{n} \frac{\alpha_k}{\sum_{i=1}^{n} \alpha_i} x_k\right) \leq \sum_{k=1}^{n} \frac{\alpha_k}{\sum_{i=1}^{n} \alpha_i} f(x_k) .$$



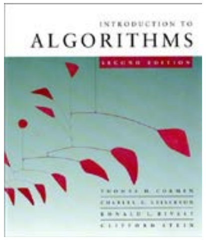
Convexity lemma: infinite case

Proof. By the convexity lemma, for any $n \geq 1$,

$$f\left(\sum_{k=1}^{n} \frac{\alpha_k}{\sum_{i=1}^{n} \alpha_i} x_k\right) \leq \sum_{k=1}^{n} \frac{\alpha_k}{\sum_{i=1}^{n} \alpha_i} f(x_k)\ .$$

Taking the limit of both sides
(and because the inequality is not strict):

$$\lim_{n\to\infty} f\left(\underbrace{\frac{1}{\sum_{i=1}^{n} \alpha_i}}_{\to 1} \underbrace{\sum_{k=1}^{n} \alpha_k x_k}_{\to \sum_{k=1}^{\infty} \alpha_k x_k}\right) \leq \lim_{n\to\infty} \underbrace{\frac{1}{\sum_{i=1}^{n} \alpha_i}}_{\to 1} \underbrace{\sum_{k=1}^{n} \alpha_k f(x_k)}_{\to \sum_{k=1}^{\infty} \alpha_k f(x_k)} \qquad \square$$



Jensen's inequality

Lemma. Let f be a convex function, and let X be a random variable. Then, $f(E[X]) \le E[f(X)]$.

Proof.

$$f(E[X]) = f\left(\sum_{k=-\infty}^{\infty} k \cdot \Pr\{X = k\}\right)$$

Definition of expectation.

Jensen's inequality

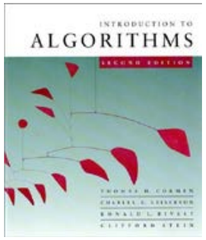
Lemma. Let f be a convex function, and let X be a random variable. Then, $f(E[X]) \le E[f(X)]$.

Proof.

$$f(E[X]) = f\left(\sum_{k=-\infty}^{\infty} k \cdot \Pr\{X = k\}\right)$$

$$\le \sum_{k=-\infty}^{\infty} f(k) \cdot \Pr\{X = k\}$$

Convexity lemma (infinite case).



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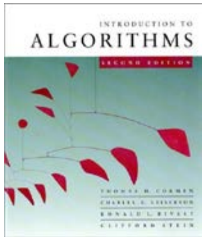
Proof.

$$f(E[X]) = f\left(\sum_{k=-\infty}^{\infty} k \cdot \Pr\{X = k\}\right)$$

$$\le \sum_{k=-\infty}^{\infty} f(k) \cdot \Pr\{X = k\}$$

$$= E[f(X)]. \quad \square$$

Tricky step, but true—think about it.



Analysis of BST height

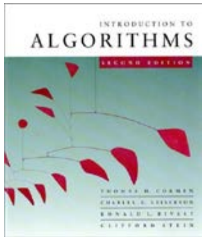
Let X_n be the random variable denoting the height of a randomly built binary search tree on n nodes, and let $Y_n = 2^{X_n}$ be its exponential height.

If the root of the tree has rank k, then

$$X_n = 1 + \max\{X_{k-1}, X_{n-k}\} ,$$

since each of the left and right subtrees of the root are randomly built. Hence, we have

$$Y_n = 2 \cdot \max\{Y_{k-1}, Y_{n-k}\} .$$



Analysis (continued)

Define the indicator random variable Z_{nk} as

$$Z_{nk} = \begin{cases} 1 & \text{if the root has rank } k, \\ 0 & \text{otherwise.} \end{cases}$$

Thus, $\Pr\{Z_{nk} = 1\} = E[Z_{nk}] = 1/n$, and

$$Y_n = \sum_{k=1}^{n} Z_{nk} \left(2 \cdot \max\{Y_{k-1}, Y_{n-k}\}\right) .$$

Exponential height recurrence

$$E[Y_n] = E\left[\sum_{k=1}^{n} Z_{nk}\left(2 \cdot \max\{Y_{k-1}, Y_{n-k}\}\right)\right]$$

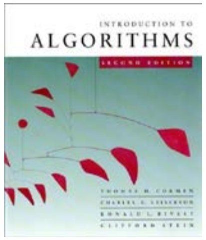
Take expectation of both sides.

Exponential height recurrence

$$E[Y_n] = E\left[\sum_{k=1}^{n} Z_{nk}\left(2\cdot\max\{Y_{k-1}, Y_{n-k}\}\right)\right]$$

$$= \sum_{k=1}^{n} E\left[Z_{nk}\left(2\cdot\max\{Y_{k-1}, Y_{n-k}\}\right)\right]$$

Linearity of expectation.



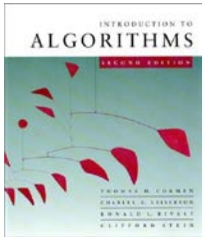
Exponential height recurrence

$$E[Y_n] = E\left[\sum_{k=1}^{n} Z_{nk}\left(2 \cdot \max\{Y_{k-1}, Y_{n-k}\}\right)\right]$$

$$= \sum_{k=1}^{n} E\left[Z_{nk}\left(2 \cdot \max\{Y_{k-1}, Y_{n-k}\}\right)\right]$$

$$= 2\sum_{k=1}^{n} E[Z_{nk}] \cdot E[\max\{Y_{k-1}, Y_{n-k}\}]$$

Independence of the rank of the root from the ranks of subtree roots.



Exponential height recurrence

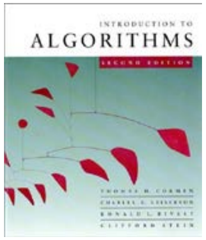
$$E[Y_n] = E\left[\sum_{k=1}^{n} Z_{nk}\left(2 \cdot \max\{Y_{k-1}, Y_{n-k}\}\right)\right]$$

$$= \sum_{k=1}^{n} E[Z_{nk}\left(2 \cdot \max\{Y_{k-1}, Y_{n-k}\}\right)]$$

$$= 2\sum_{k=1}^{n} E[Z_{nk}] \cdot E[\max\{Y_{k-1}, Y_{n-k}\}]$$

$$\leq \frac{2}{n}\sum_{k=1}^{n} E[Y_{k-1} + Y_{n-k}]$$

The max of two nonnegative numbers is at most their sum, and $\mathrm{E}[Z_{nk}] = 1/n$.



Exponential height recurrence

$$E[Y_n] = E\left[\sum_{k=1}^{n} Z_{nk}\left(2 \cdot \max\{Y_{k-1}, Y_{n-k}\}\right)\right]$$

$$= \sum_{k=1}^{n} E[Z_{nk}(2 \cdot \max\{Y_{k-1}, Y_{n-k}\})]$$

$$= 2\sum_{k=1}^{n} E[Z_{nk}] \cdot E[\max\{Y_{k-1}, Y_{n-k}\}]$$

$$\le \frac{2}{n}\sum_{k=1}^{n} E[Y_{k-1} + Y_{n-k}]$$

$$= \frac{4}{n}\sum_{k=0}^{n-1} E[Y_k]$$

Each term appears twice, and reindex.

Solving the recurrence

Use substitution to show that $E[Y_n] \le cn^3$ for some positive constant c, which we can pick sufficiently large to handle the initial conditions.

$$E[Y_n] = \frac{4}{n} \sum_{k=0}^{n-1} E[Y_k]$$

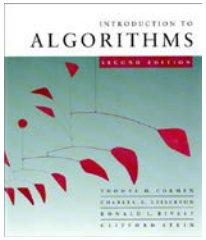
Solving the recurrence

Use substitution to show that $E[Y_n] \le cn^3$ for some positive constant c, which we can pick sufficiently large to handle the initial conditions.

$$E[Y_n] = \frac{4}{n} \sum_{k=0}^{n-1} E[Y_k]$$

$$\le \frac{4}{n} \sum_{k=0}^{n-1} ck^3$$

Substitution.

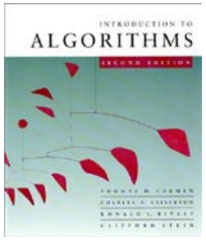


Solving the recurrence

Use substitution to show that $E[Y_n] \le cn^3$ for some positive constant c, which we can pick sufficiently large to handle the initial conditions.

$$
\begin{aligned}
E[Y_n] &= \frac{4}{n} \sum_{k=0}^{n-1} E[Y_k] \\
&\le \frac{4}{n} \sum_{k=0}^{n-1} ck^3 \\
&\le \frac{4c}{n} \int_0^n x^3 dx
\end{aligned}
$$

Integral method.

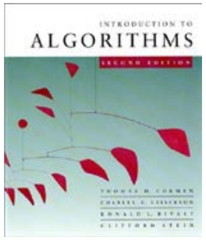


Solving the recurrence

Use substitution to show that $E[Y_n] \le cn^3$ for some positive constant c, which we can pick sufficiently large to handle the initial conditions.

$$
\begin{aligned}
E[Y_n] &= \frac{4}{n}\sum_{k=0}^{n-1} E[Y_k] \\
&\le \frac{4}{n}\sum_{k=0}^{n-1} ck^3 \\
&\le \frac{4c}{n}\int_0^n x^3\,dx \\
&= \frac{4c}{n}\left(\frac{n^4}{4}\right)
\end{aligned}
$$

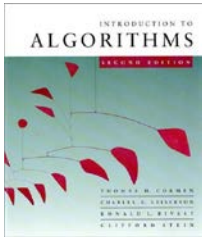
Solve the integral.



Solving the recurrence

Use substitution to show that $E[Y_n] \le cn^3$ for some positive constant c, which we can pick sufficiently large to handle the initial conditions.

$$
\begin{aligned}
E[Y_n] &= \frac{4}{n}\sum_{k=0}^{n-1} E[Y_k] \\
&\le \frac{4}{n}\sum_{k=0}^{n-1} ck^3 \\
&\le \frac{4c}{n}\int_0^n x^3\,dx \\
&= \frac{4c}{n}\left(\frac{n^4}{4}\right) \\
&= cn^3. \qquad \text{Algebra.}
\end{aligned}
$$

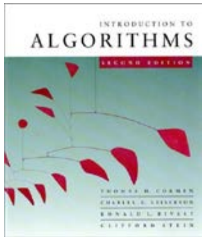


The grand finale

Putting it all together, we have

$$2^{E[X_n]} \le E[2^{X_n}]$$

Jensen's inequality, since
$f(x) = 2^x$ is convex.



The grand finale

Putting it all together, we have

$$
\begin{aligned}
2^{E[X_n]} &\le E[2^{X_n}] \\
&= E[Y_n]
\end{aligned}
$$

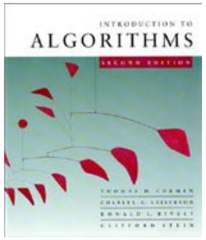
Definition.

The grand finale

Putting it all together, we have

$$\begin{aligned} 2^{E[X_n]} &\le E[2^{X_n}] \\ &= E[Y_n] \\ &\le cn^3 . \end{aligned}$$

What we just showed.



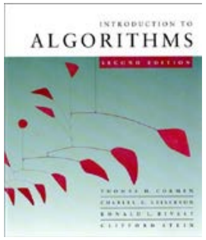
The grand finale

Putting it all together, we have

$$
\begin{aligned}
2^{E[X_n]} &\le E[2^{X_n}] \\
&= E[Y_n] \\
&\le cn^3 .
\end{aligned}
$$

Taking the lg of both sides yields

$$E[X_n] \le 3 \lg n + O(1) .$$



Post mortem

Q. Does the analysis have to be this hard?

Q. Why bother with analyzing exponential height?

Q. Why not just develop the recurrence on

$$X_n = 1 + \max\{X_{k-1}, X_{n-k}\}$$

directly?

Post mortem (continued)

A. The inequality

$$\max\{a, b\} \leq a + b \,.$$

provides a poor upper bound, since the RHS approaches the LHS slowly as $|a - b|$ increases. The bound

$$\max\{2^a, 2^b\} \leq 2^a + 2^b$$

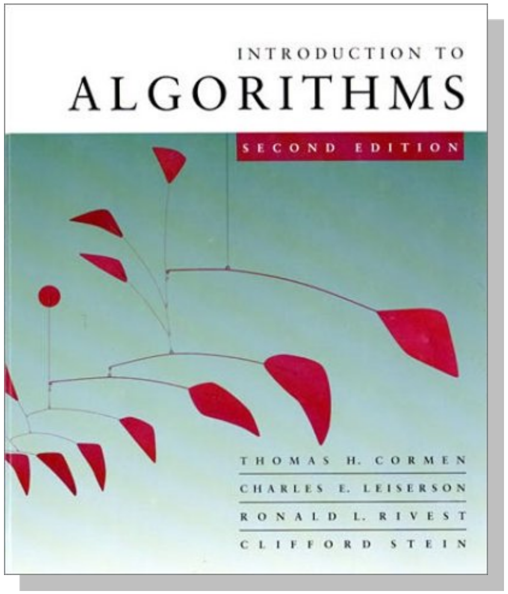
allows the RHS to approach the LHS far more quickly as $|a - b|$ increases. By using the convexity of $f(x) = 2^x$ via Jensen's inequality, we can manipulate the sum of exponentials, resulting in a tight analysis.

Thought exercises

- See what happens when you try to do the analysis on X_n directly.
- Try to understand better why the proof uses an exponential. Will a quadratic do?
- See if you can find a simpler argument. (This argument is a little simpler than the one in the book—I hope it's correct!)

Introduction to Algorithms

6.046J/18.401J

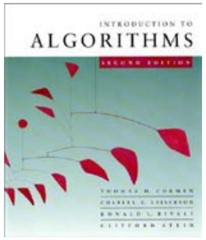


LECTURE 10

Balanced Search Trees

- Red-black trees
- Height of a red-black tree
- Rotations
- Insertion

Prof. Erik Demaine

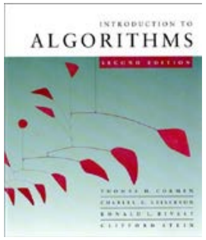


Balanced search trees

Balanced search tree: A search-tree data structure for which a height of $O(\lg n)$ is guaranteed when implementing a dynamic set of n items.

Examples:

- AVL trees
- 2-3 trees
- 2-3-4 trees
- B-trees
- Red-black trees



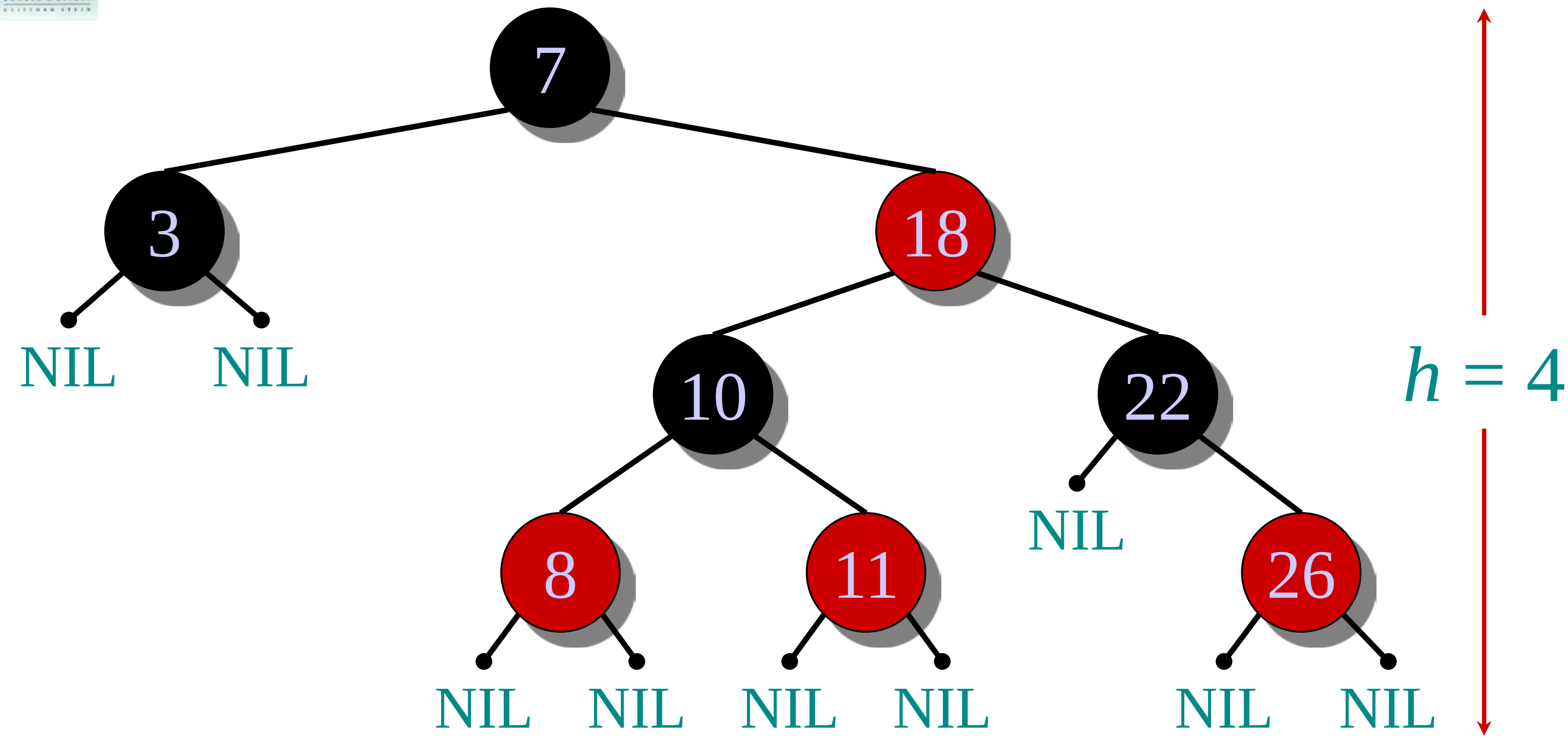
Red-black trees

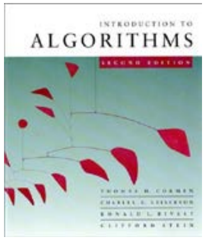
This data structure requires an extra one-bit color field in each node.

Red-black properties:

1. Every node is either red or black.
2. The root and leaves (NIL's) are black.
3. If a node is red, then its parent is black.
4. All simple paths from any node x to a descendant leaf have the same number of black nodes = black-height(x).

Example of a red-black tree





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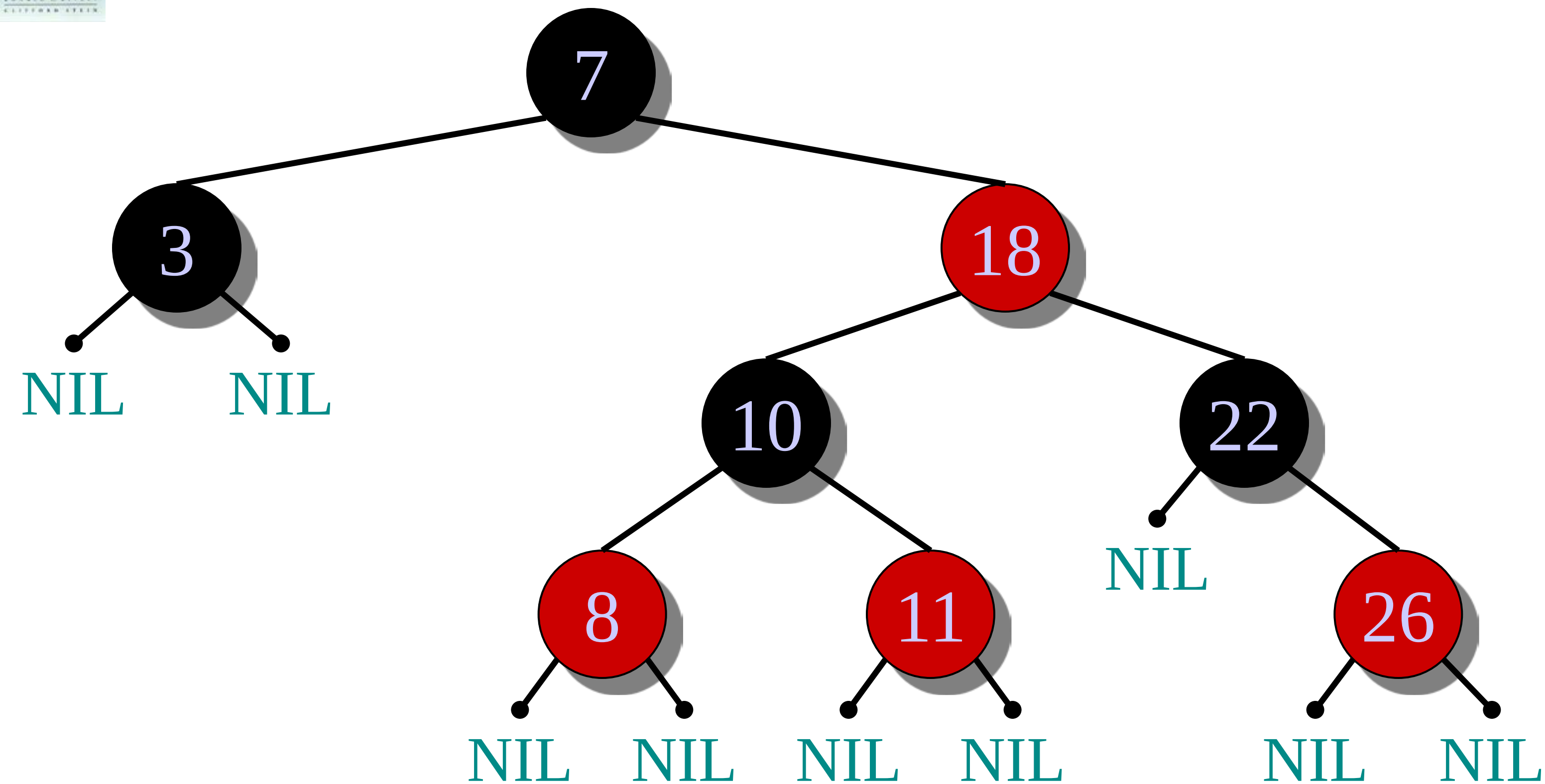
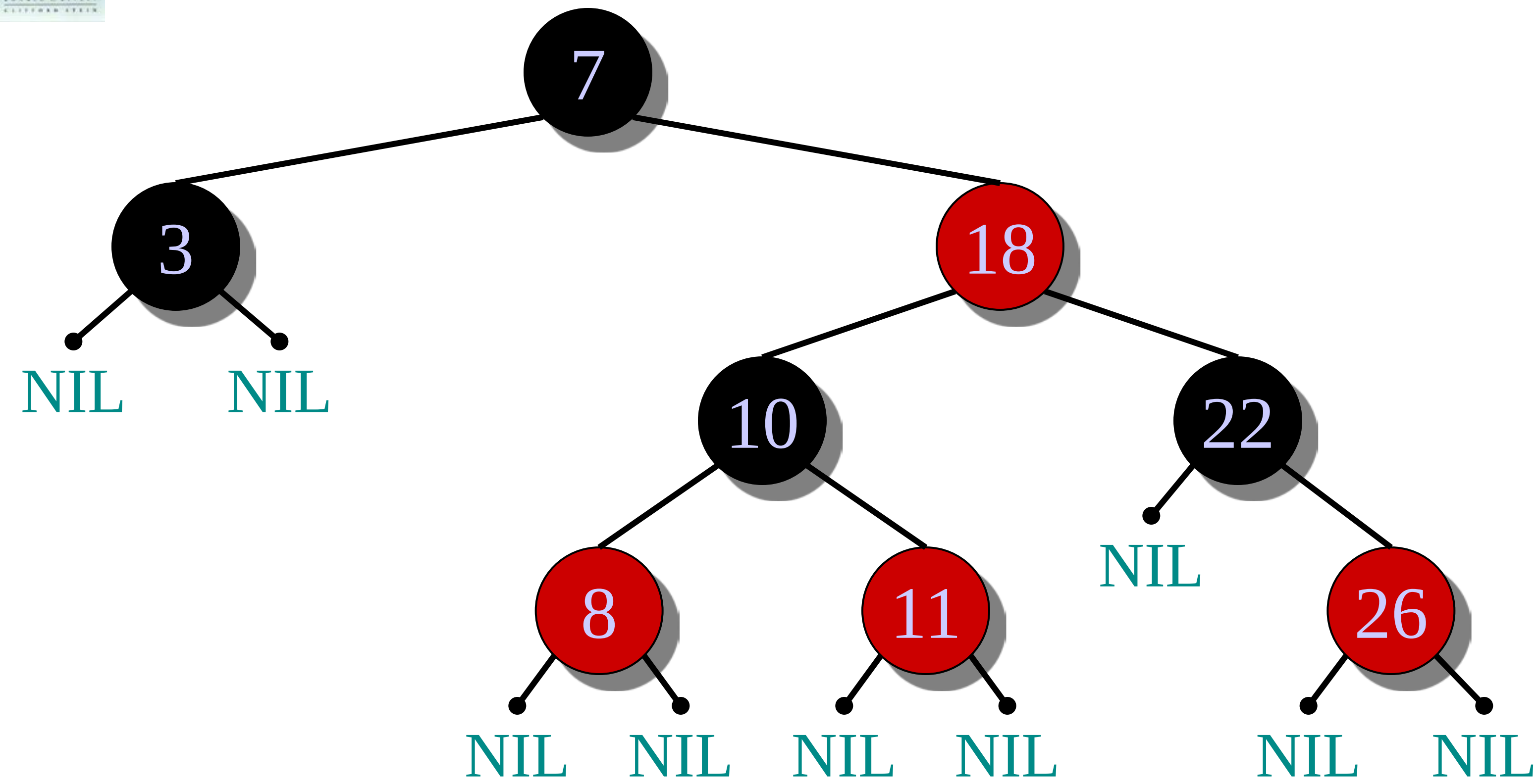
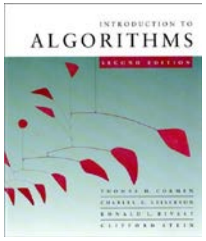


1. Every node is either red or black.

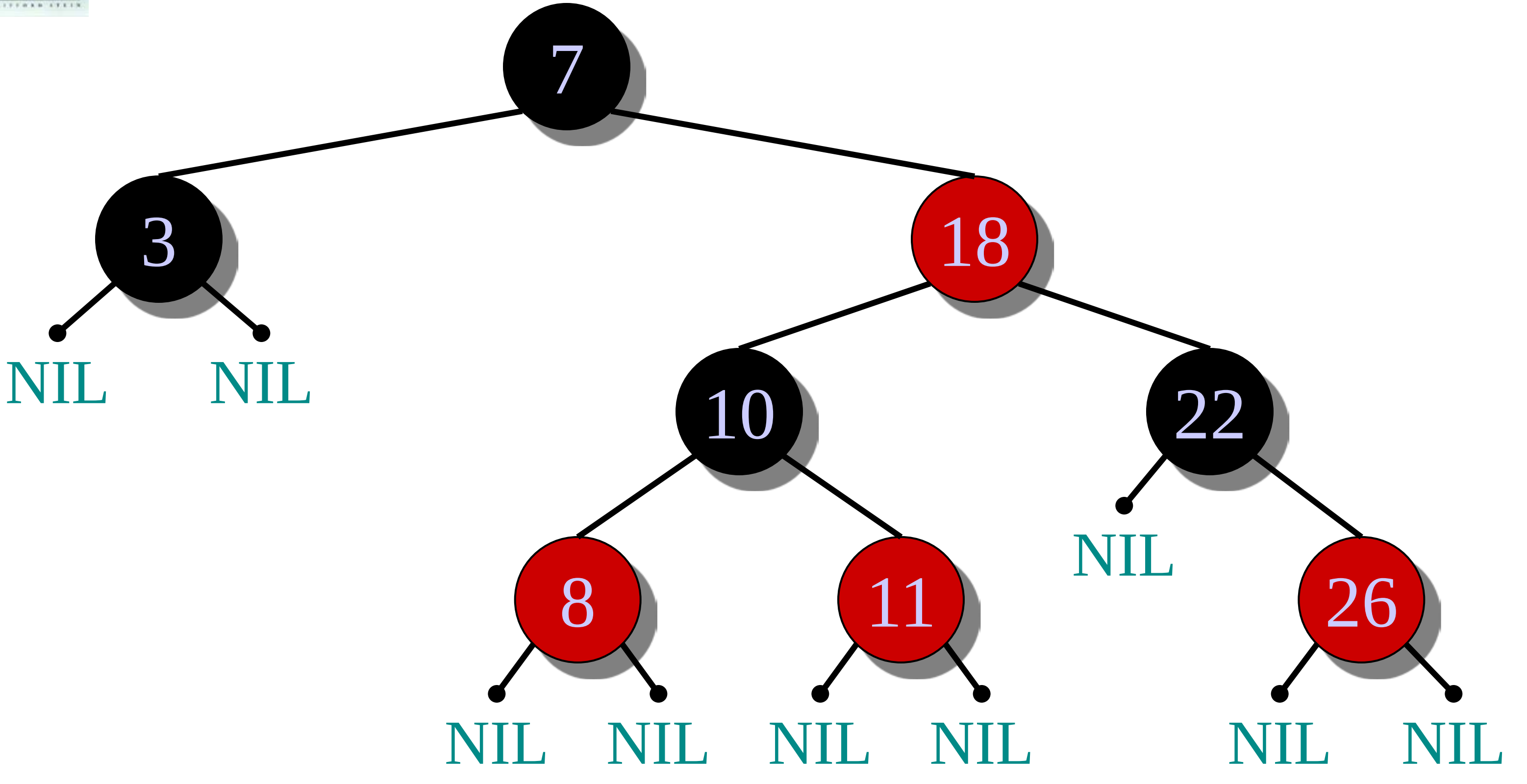
Example of a red-black tree



2. The root and leaves (NIL's) are black.

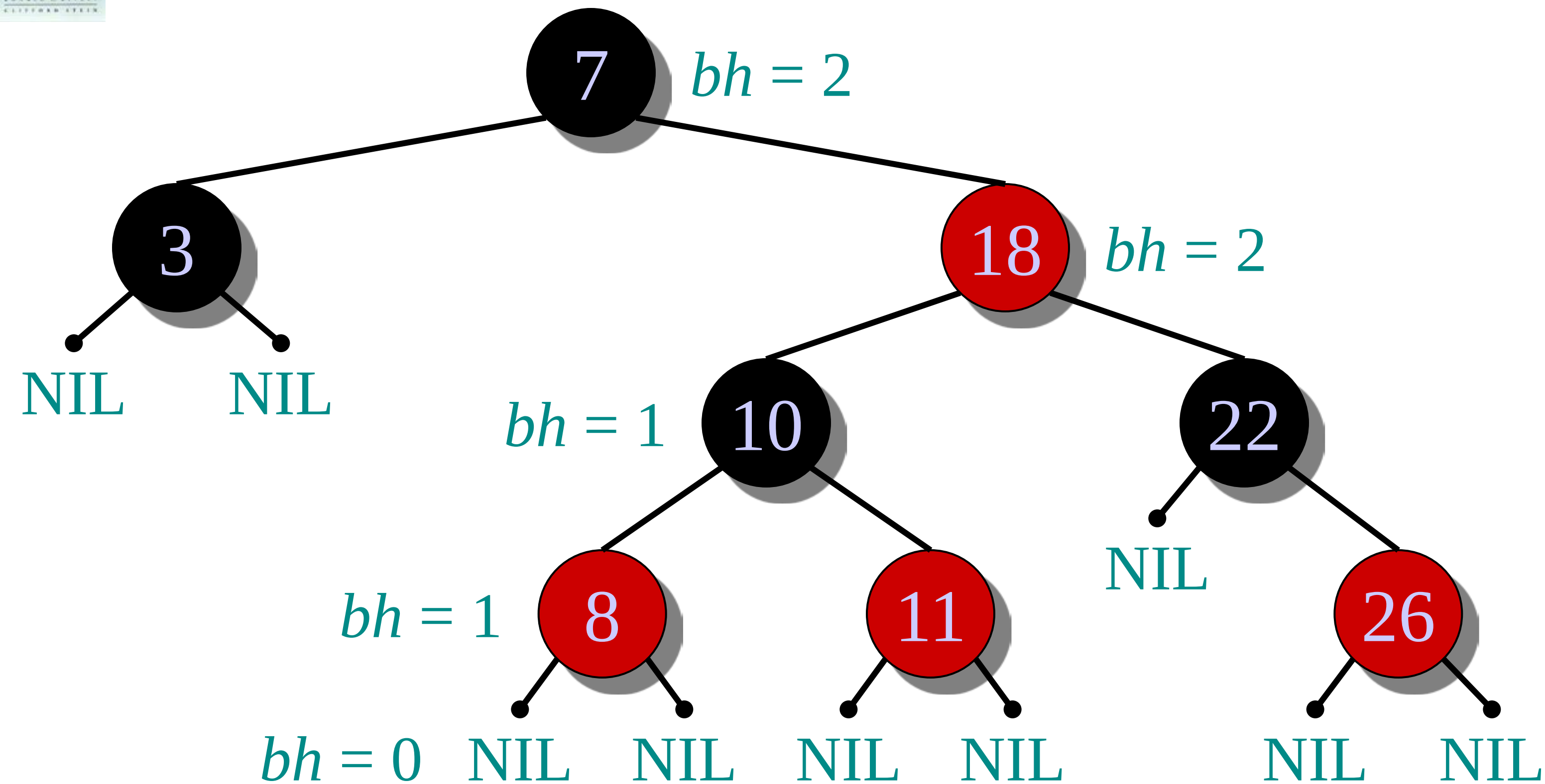


Example of a red-black tree

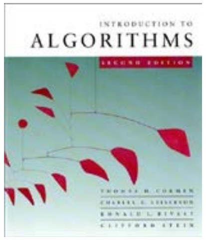


3. If a node is red, then its parent is black.

Example of a red-black tree



4. All simple paths from any node x to a descendant leaf have the same number of black nodes = *black-height*(x).



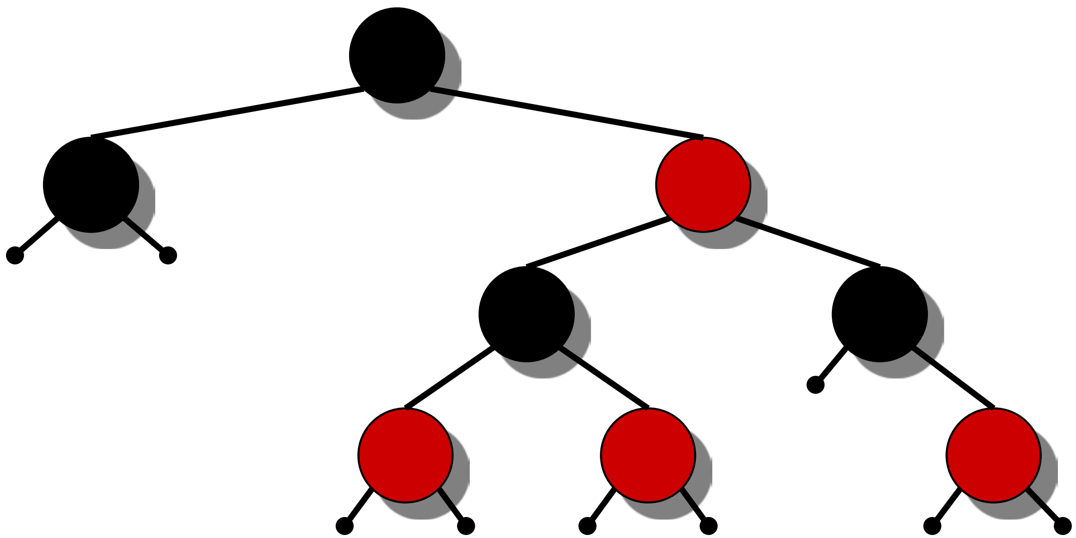
Height of a red-black tree

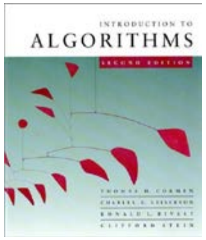
Theorem. A red-black tree with n keys has height
$$h \leq 2 \lg(n + 1).$$

Proof. (The book uses induction. Read carefully.)

INTUITION:

- Merge red nodes into their black parents.





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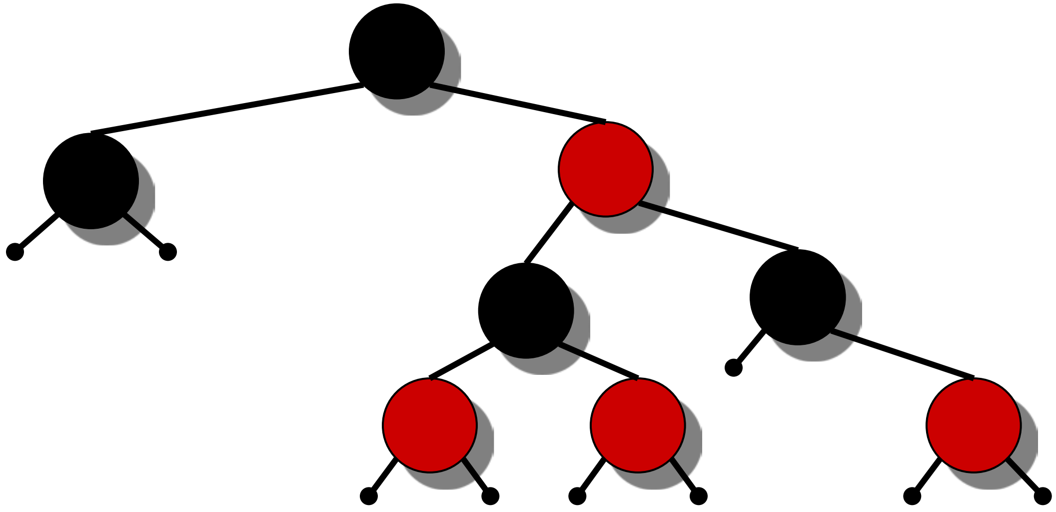

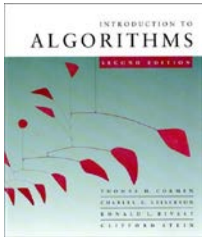

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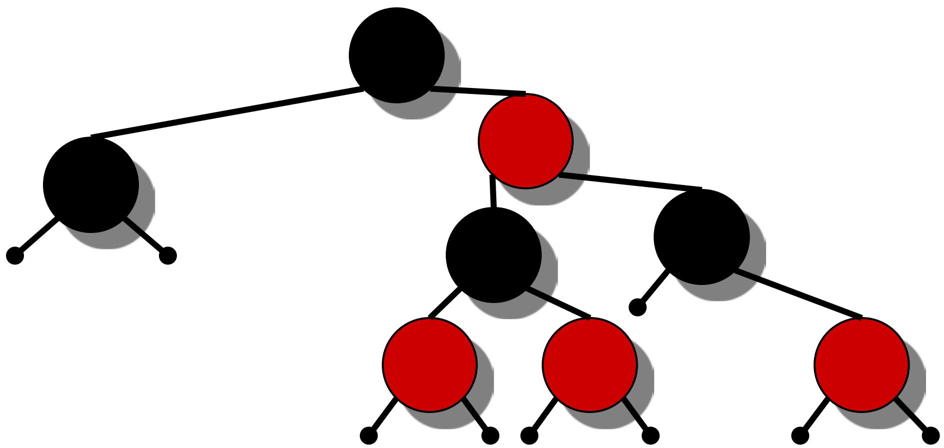

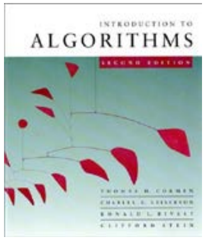

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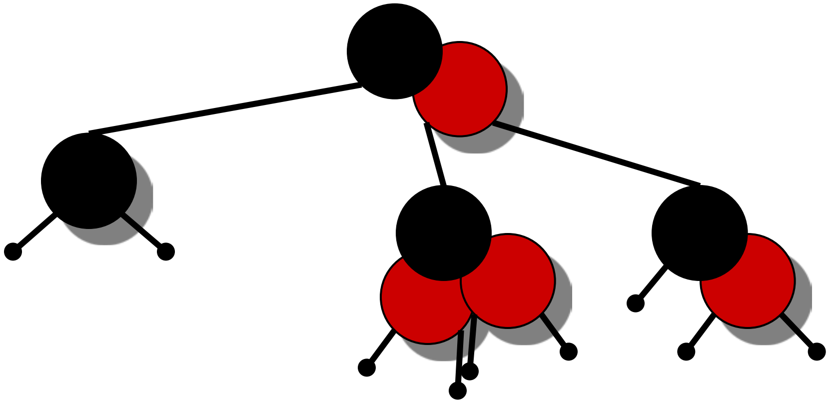

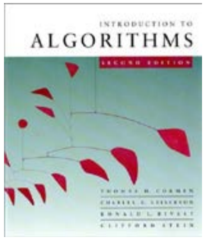

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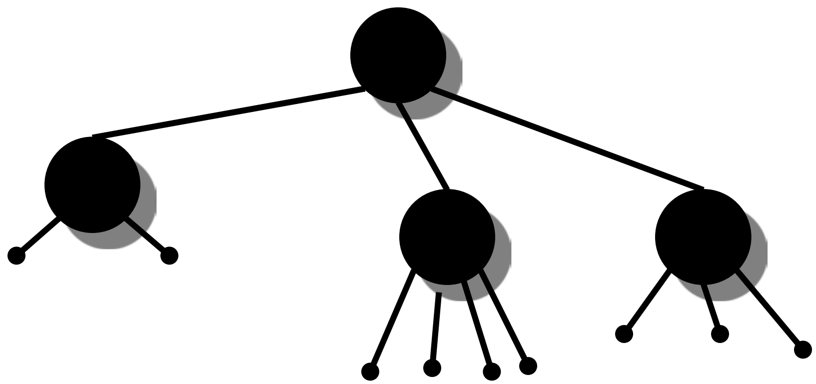

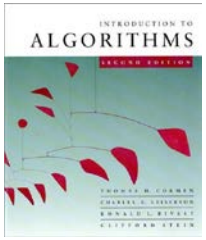

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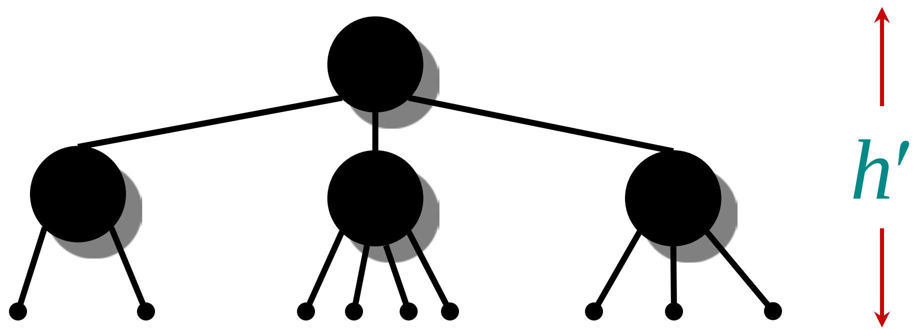
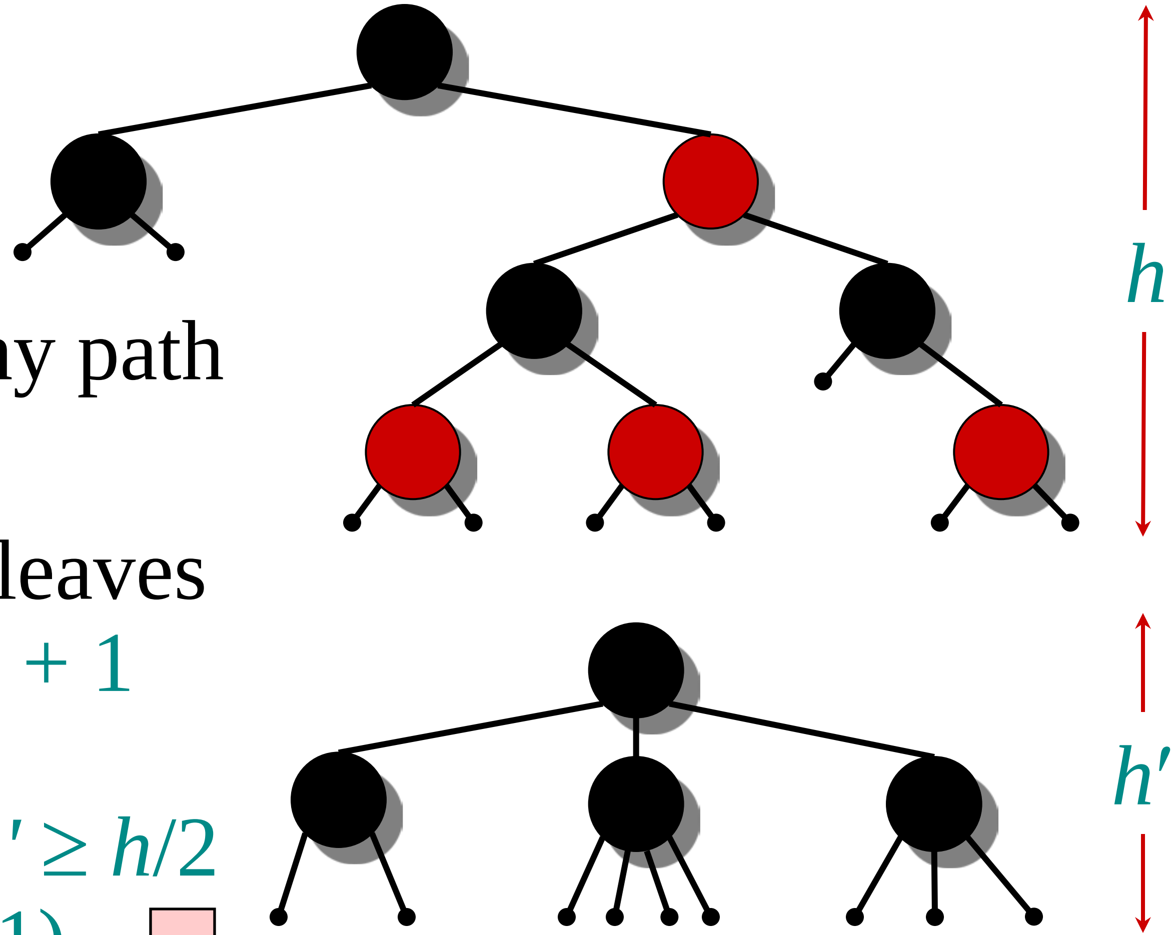
INTUITION:



- Merge red nodes into their black parents.
- This process produces a tree in which each node has 2, 3, or 4 children.
- The 2-3-4 tree has uniform depth h' of leaves.

Proof (continued)

- We have $h' \geq h/2$, since at most half the leaves on any path are red.
- The number of leaves in each tree is $n + 1$
  $\Rightarrow n + 1 \geq 2^{h'}$
  $\Rightarrow \lg(n + 1) \geq h' \geq h/2$
  $\Rightarrow h \leq 2 \lg(n + 1)$. □



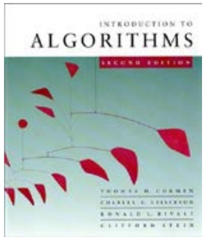
Query operations

Corollary. The queries SEARCH, MIN, MAX, SUCCESSOR, and PREDECESSOR all run in $O(\lg n)$ time on a red-black tree with n nodes.

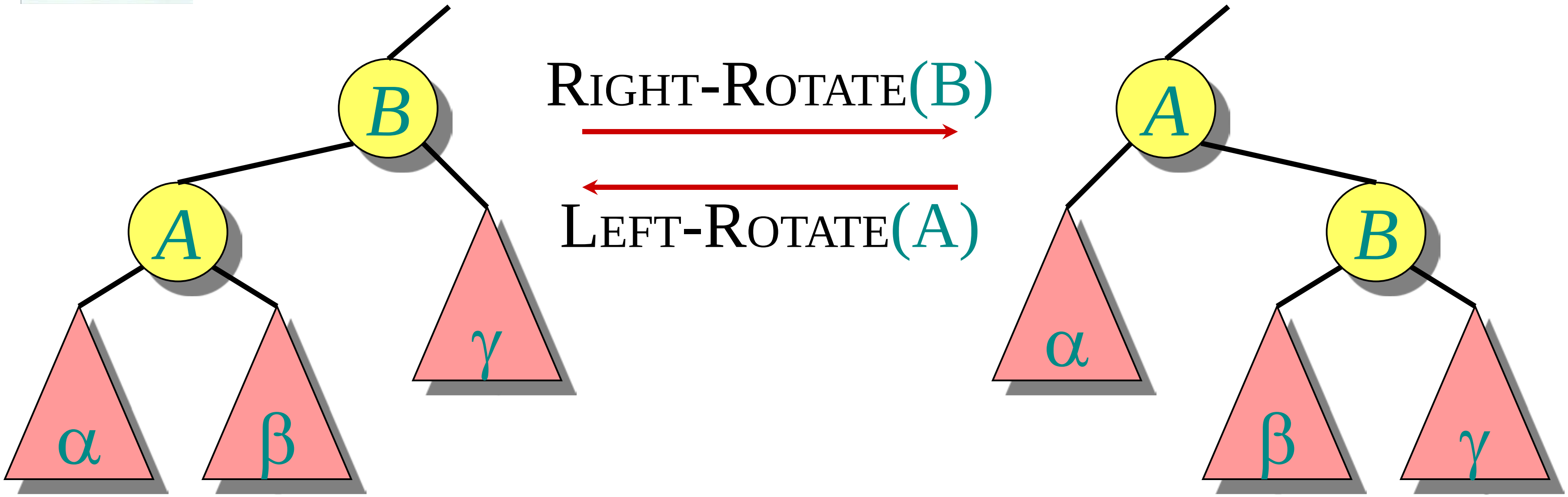
Modifying operations

The operations INSERT and DELETE cause modifications to the red-black tree:

- the operation itself,
- color changes,
- restructuring the links of the tree via ***"rotations"***.



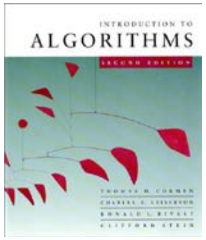
Rotations



Rotations maintain the inorder ordering of keys:

- $a \in \alpha, b \in \beta, c \in \gamma \Rightarrow a \le A \le b \le B \le c$.

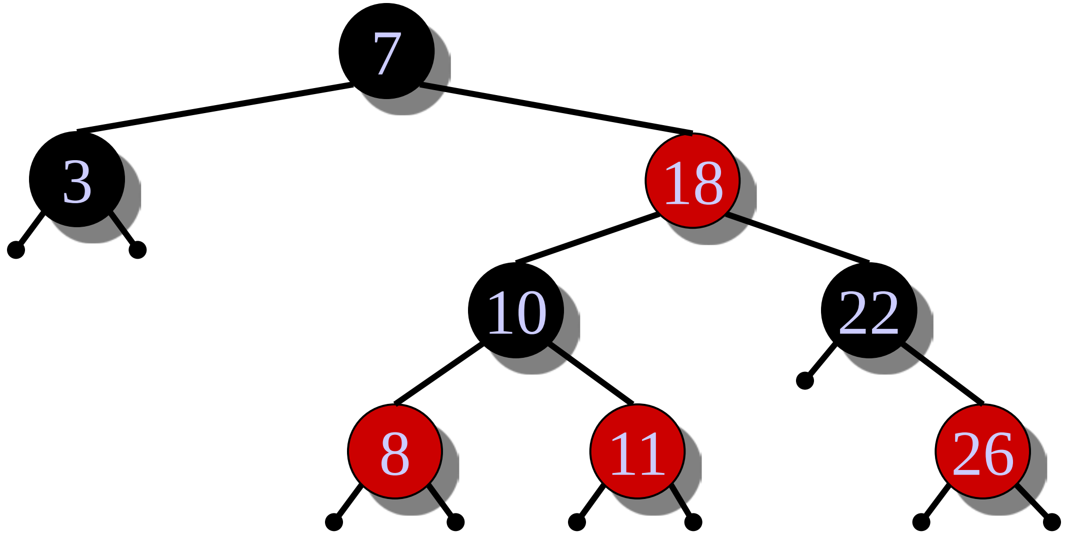
A rotation can be performed in $O(1)$ time.



Insertion into a red-black tree

IDEA: Insert *x* in tree. Color *x* red. Only red-black property 3 might be violated. Move the violation up the tree by recoloring until it can be fixed with rotations and recoloring.

Example:

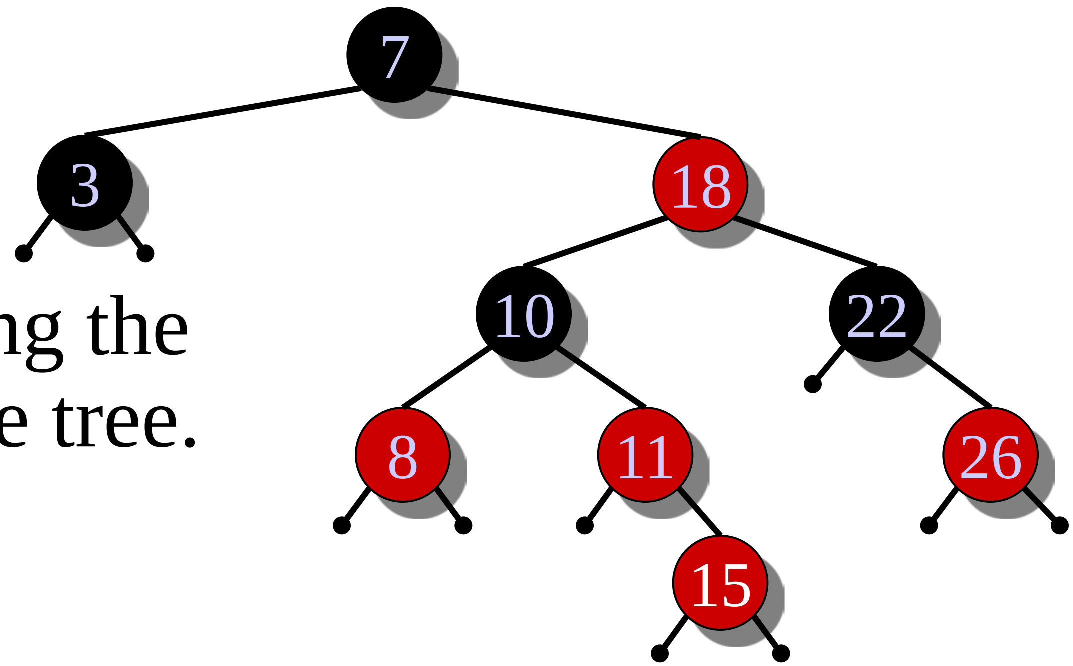


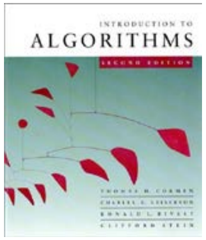
Insertion into a red-black tree

IDEA: Insert *x* in tree. Color *x* red. Only red-black property 3 might be violated. Move the violation up the tree by recoloring until it can be fixed with rotations and recoloring.

Example:

- Insert *x* =15.
- Recolor, moving the violation up the tree.





Insertion into a red-black tree

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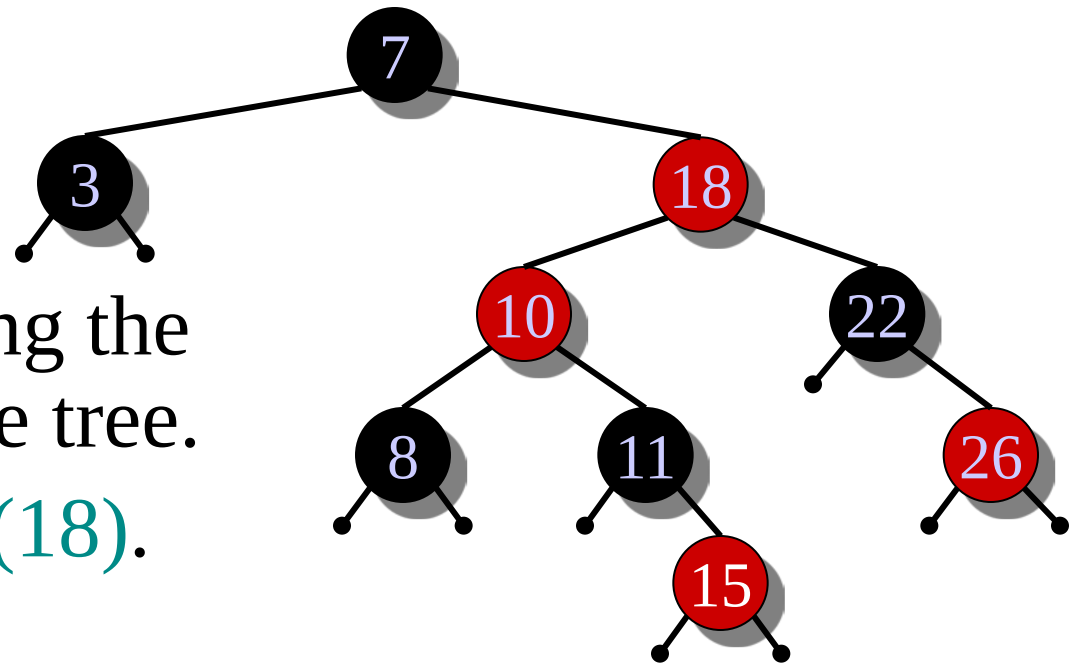
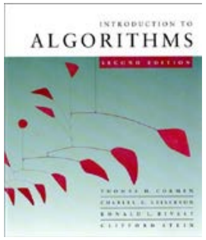
Example:

- Insert $x = 15$.
- Recolor, moving the violation up the tree.
- RIGHT-ROTATE(18).



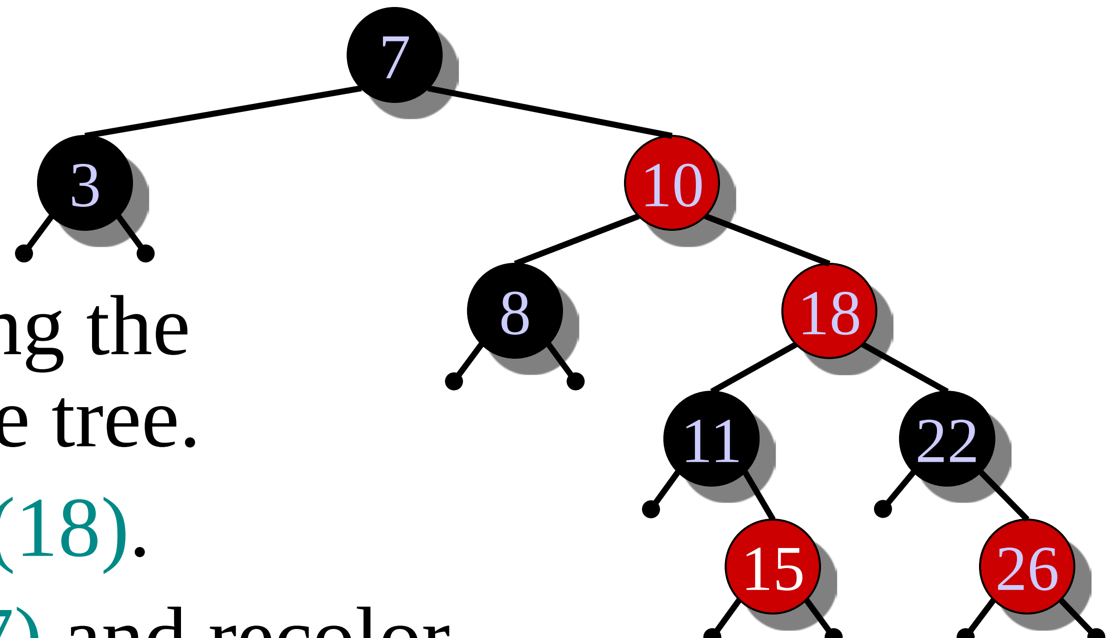


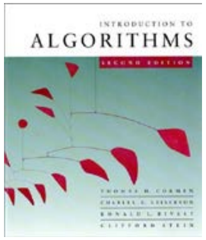
Insertion into a red-black tree

IDEA: Insert *x* in tree. Color *x* red. Only red-black property 3 might be violated. Move the violation up the tree by recoloring until it can be fixed with rotations and recoloring.

Example:

- Insert x =15.
- Recolor, moving the violation up the tree.
- RIGHT-ROTATE(18).
- LEFT-ROTATE(7) and recolor.





Insertion into a red-black tree

IDEA: Insert x in tree. Color x red. Only red-black property 3 might be violated. Move the violation up the tree by recoloring until it can be fixed with rotations and recoloring.

Example:

- Insert $x = 15$.
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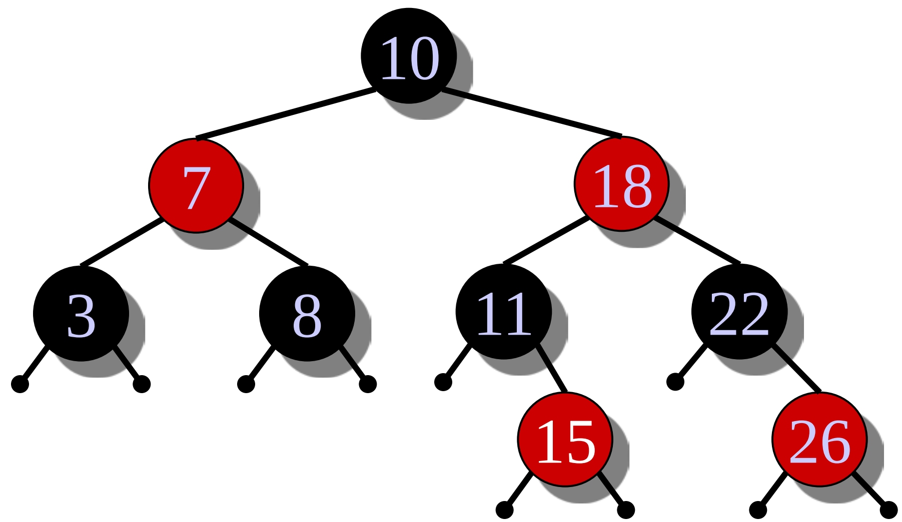
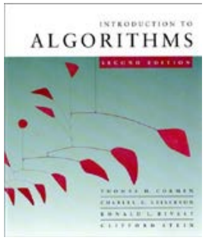




Pseudocode

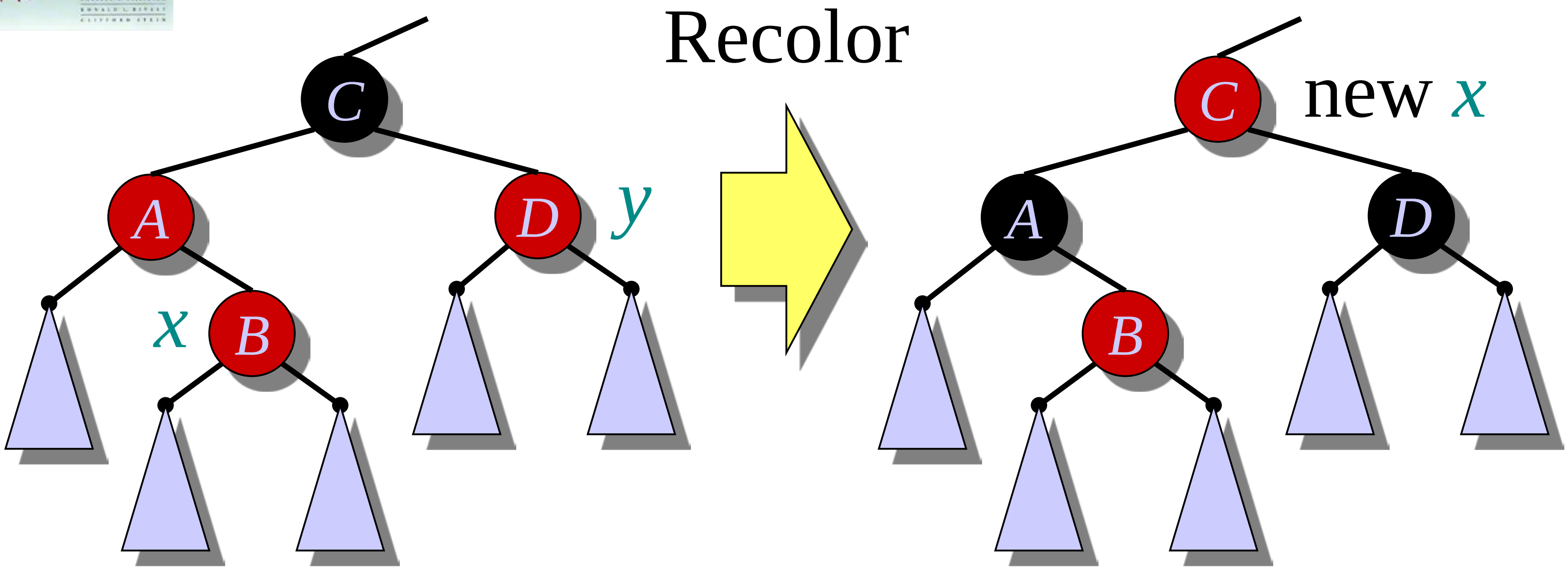
```
RB-INSERT(T, x)
    TREE-INSERT(T, x)
    color[x] ← RED      ⊳ only RB property 3 can be violated
    while x ≠ root[T] and color[p[x]] = RED
        do if p[x] = left[p[p[x]]]
            then y ← right[p[p[x]]]      ⊳ y = aunt/uncle of x
                 if color[y] = RED
                  then ⟨Case 1⟩
                  else  if x = right[p[x]]
                          then ⟨Case 2⟩    ⊳ Case 2 falls into Case 3
                        ⟨Case 3⟩
            else ⟨"then" clause with "left" and "right" swapped⟩
    color[root[T]] ← BLACK
```

Graphical notation

Let denote a subtree with a black root.

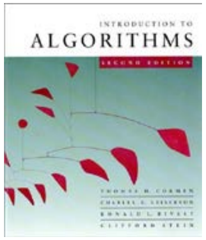
All ’s have the same black-height.

Case 1

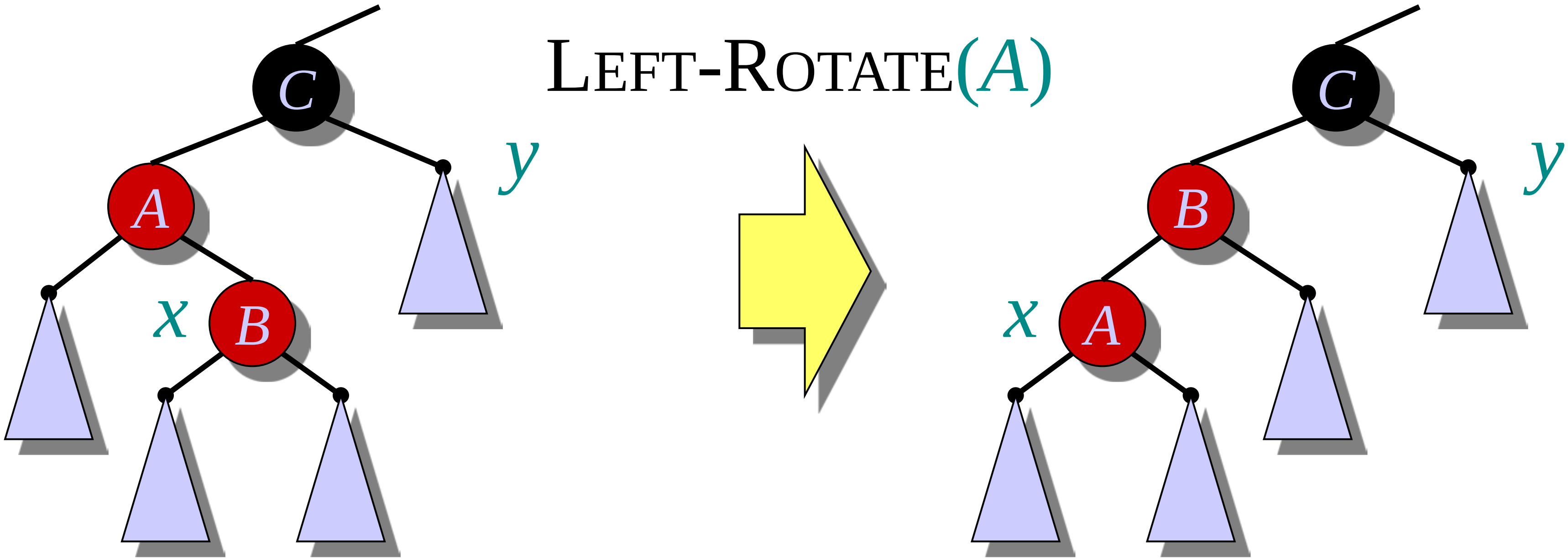


(Or, children of *A* are swapped.)

Push *C*'s black onto *A* and *D*, and recurse, since *C*'s parent may be red.

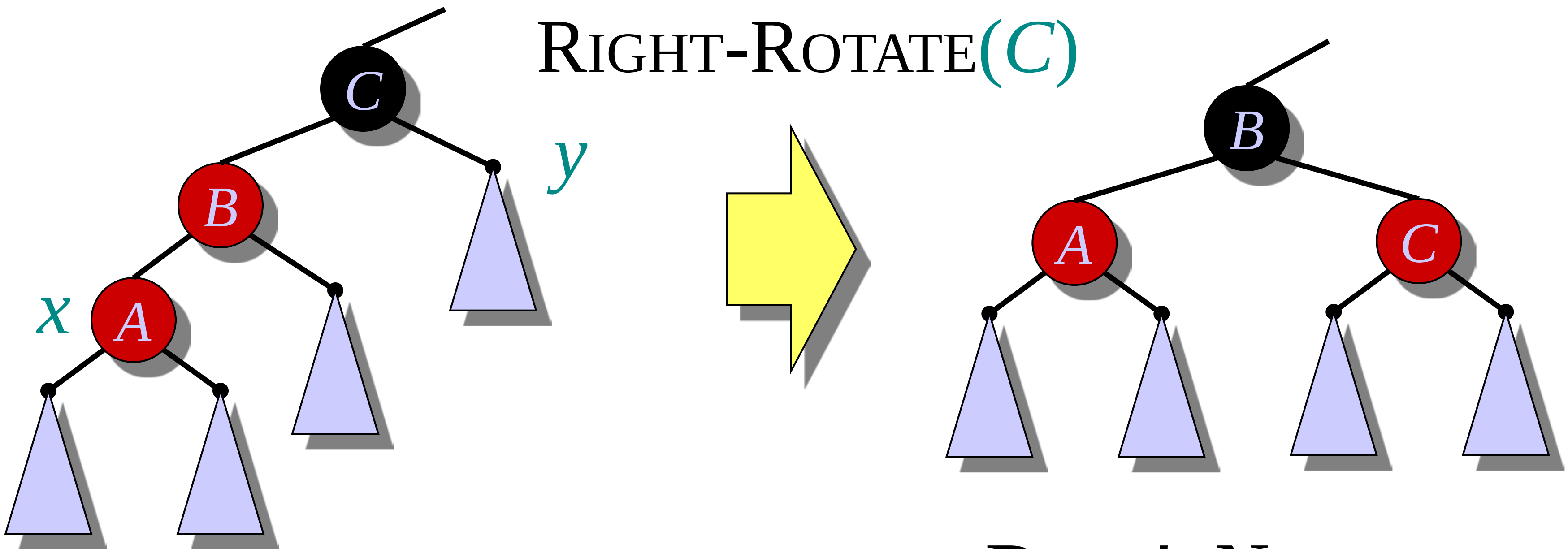


Case 2

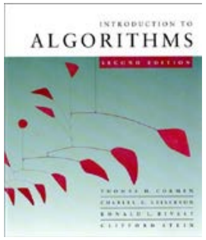


Transform to Case 3.

Case 3



Done! No more violations of RB property 3 are possible.



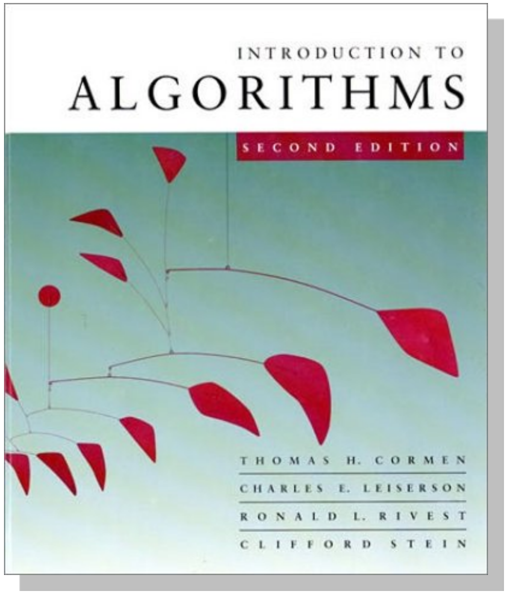
Analysis

- Go up the tree performing Case 1, which only recolors nodes.
- If Case 2 or Case 3 occurs, perform 1 or 2 rotations, and terminate.

Running time: $O(\lg n)$ with $O(1)$ rotations.

RB-DELETE — same asymptotic running time and number of rotations as RB-INSERT (see textbook).

Introduction to Algorithms
6.046J/18.401J

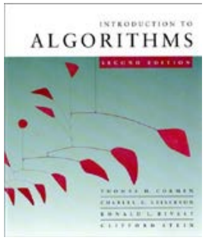


LECTURE 11

Augmenting Data Structures

- Dynamic order statistics
- Methodology
- Interval trees

Prof. Charles E. Leiserson



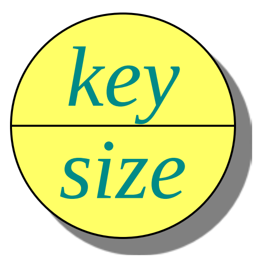
Dynamic order statistics

OS-SELECT(i, S): returns the ith smallest element in the dynamic set S.

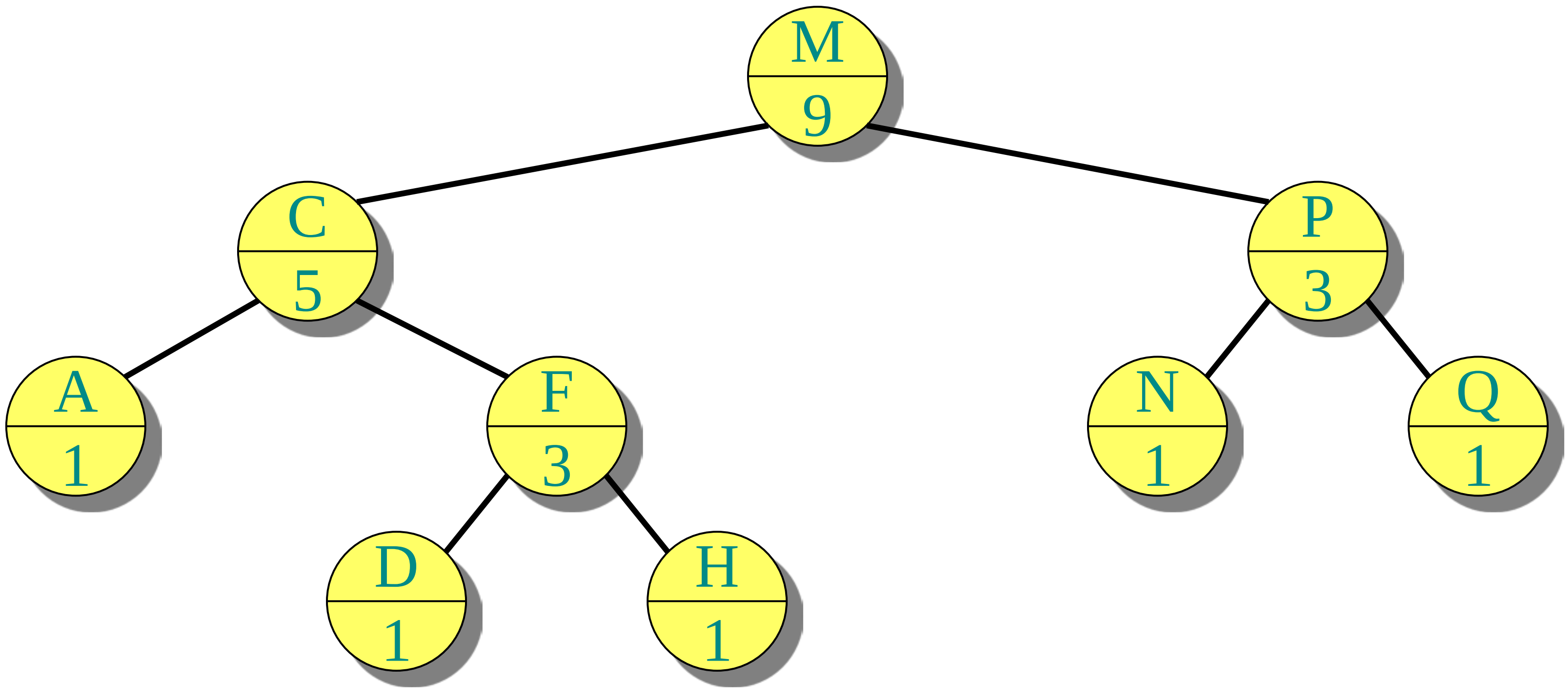
OS-RANK(x, S): returns the rank of $x \in S$ in the sorted order of S's elements.

IDEA: Use a red-black tree for the set S, but keep subtree sizes in the nodes.

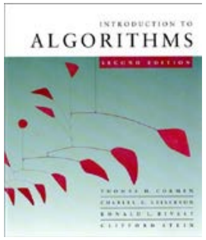
Notation for nodes:



Example of an OS-tree



$$size[x] = size[left[x]] + size[right[x]] + 1$$



Selection

Implementation trick: Use a ***sentinel*** (dummy record) for NIL such that $size[\text{NIL}] = 0$.

OS-SELECT(x, i) ⊳ ith smallest element in the subtree rooted at x

$k \leftarrow size[left[x]] + 1$ ⊳ $k = \text{rank}(x)$

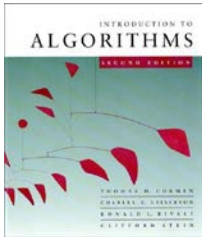
if $i = k$ **then return** x

if $i < k$

then return OS-SELECT$(left[x], i)$

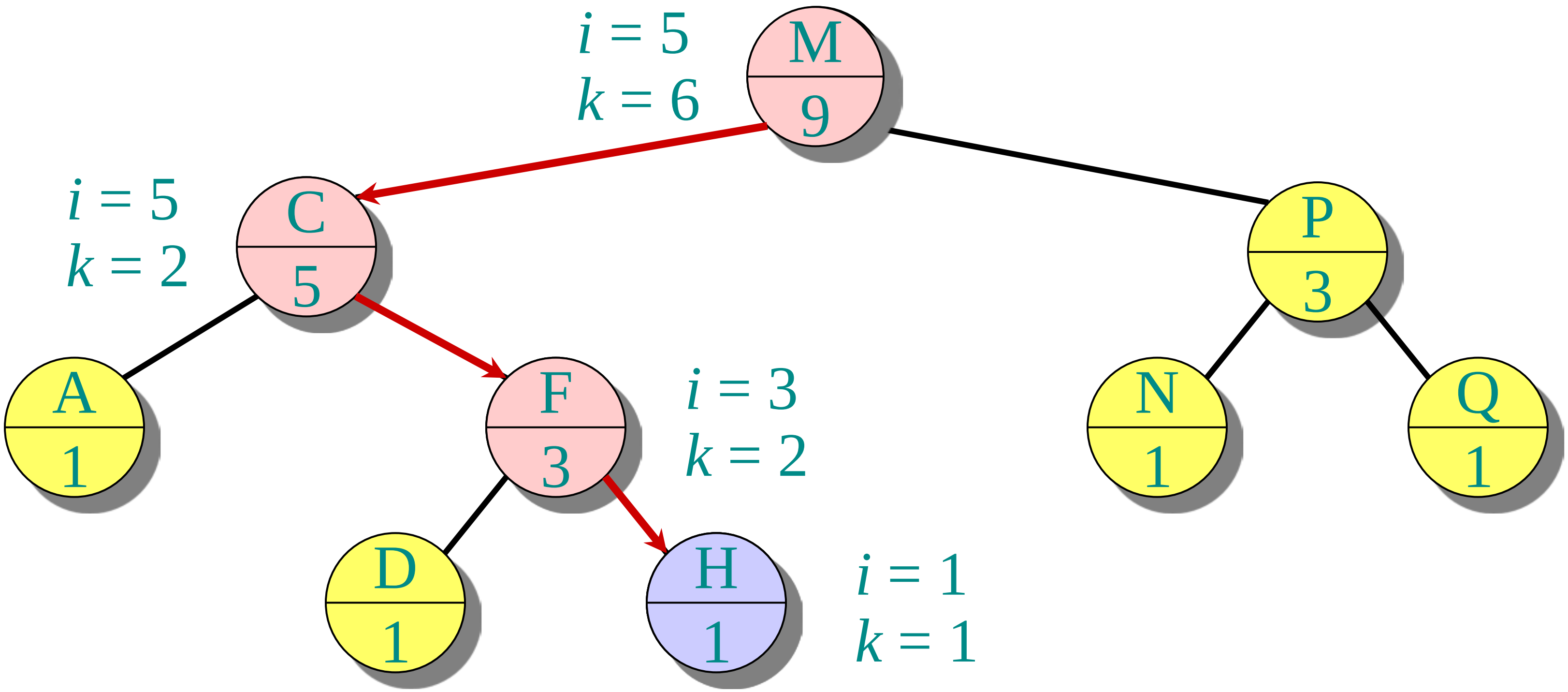
else return OS-SELECT$(right[x], i - k)$

(OS-RANK is in the textbook.)

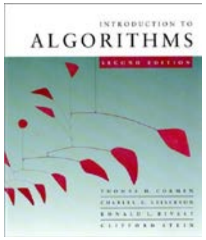


Example

OS-SELECT(*root*, 5)



Running time $= O(h) = O(\lg n)$ for red-black trees.



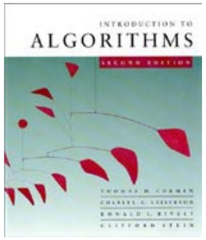
Data structure maintenance

Q. Why not keep the ranks themselves in the nodes instead of subtree sizes?

A. They are hard to maintain when the red-black tree is modified.

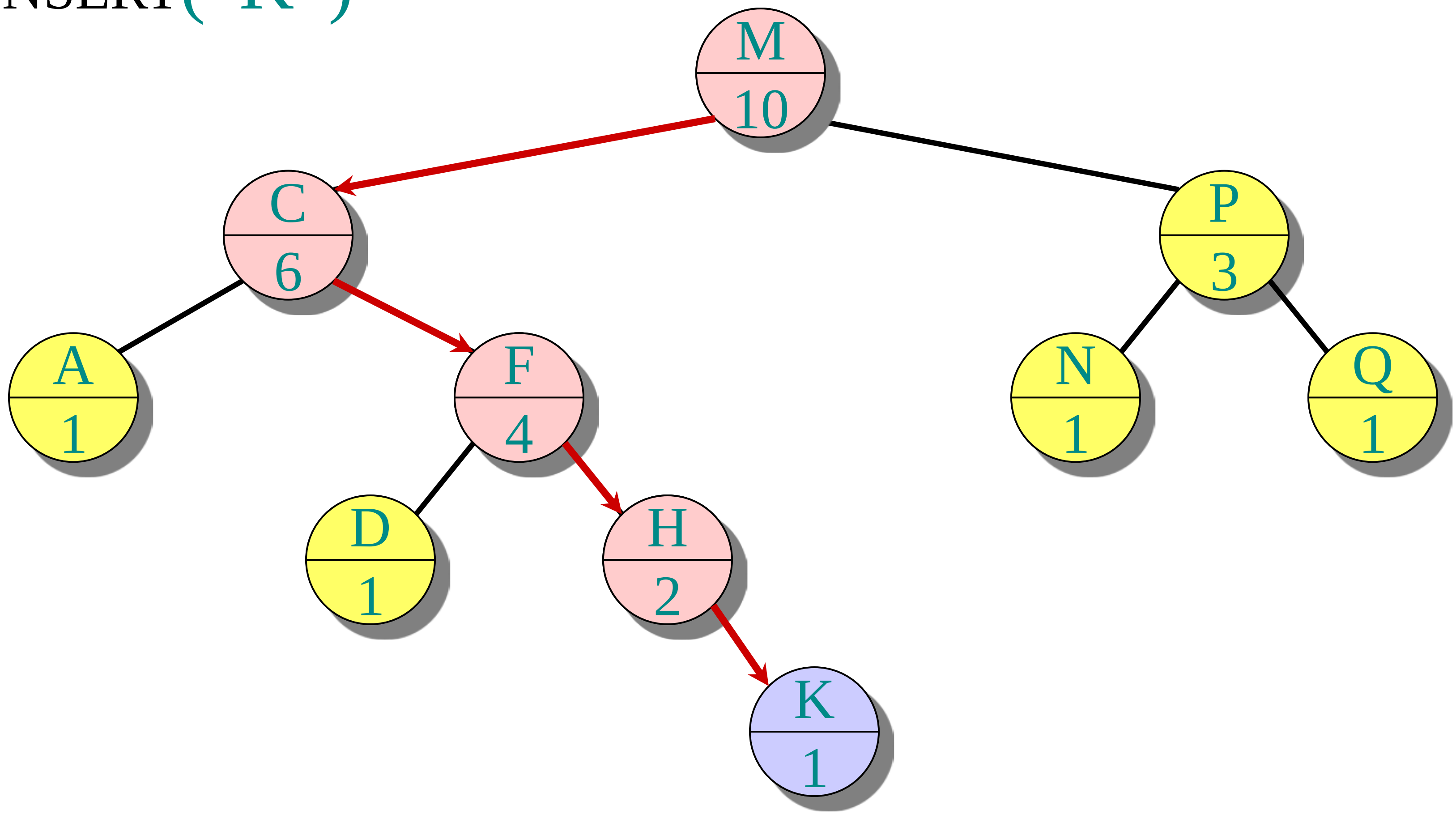
Modifying operations: INSERT and DELETE.

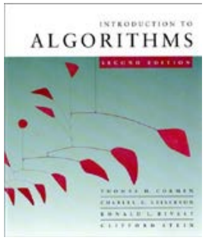
Strategy: Update subtree sizes when inserting or deleting.



Example of insertion

INSERT("K")



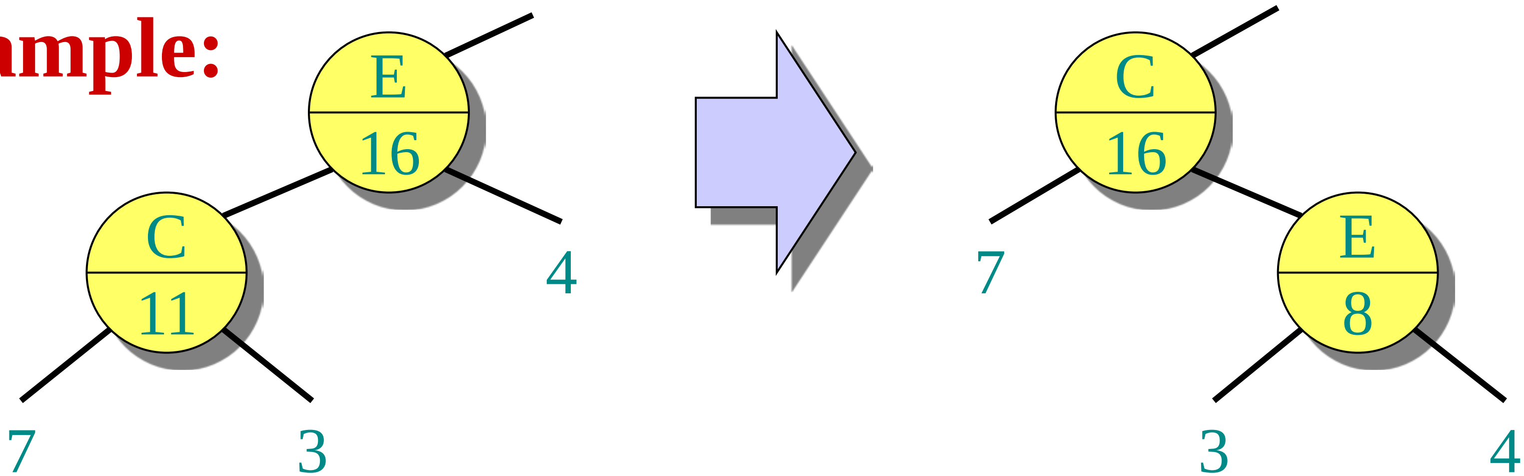


Handling rebalancing

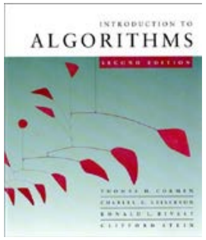
Don't forget that RB-INSERT and RB-DELETE may also need to modify the red-black tree in order to maintain balance.

- *Recolorings*: no effect on subtree sizes.
- *Rotations*: fix up subtree sizes in $O(1)$ time.

Example:



$\therefore$ RB-INSERT and RB-DELETE still run in $O(\lg n)$ time.

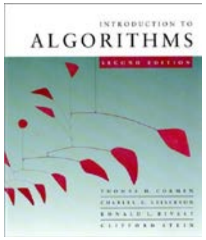


Data-structure augmentation

Methodology: (*e.g., order-statistics trees*)

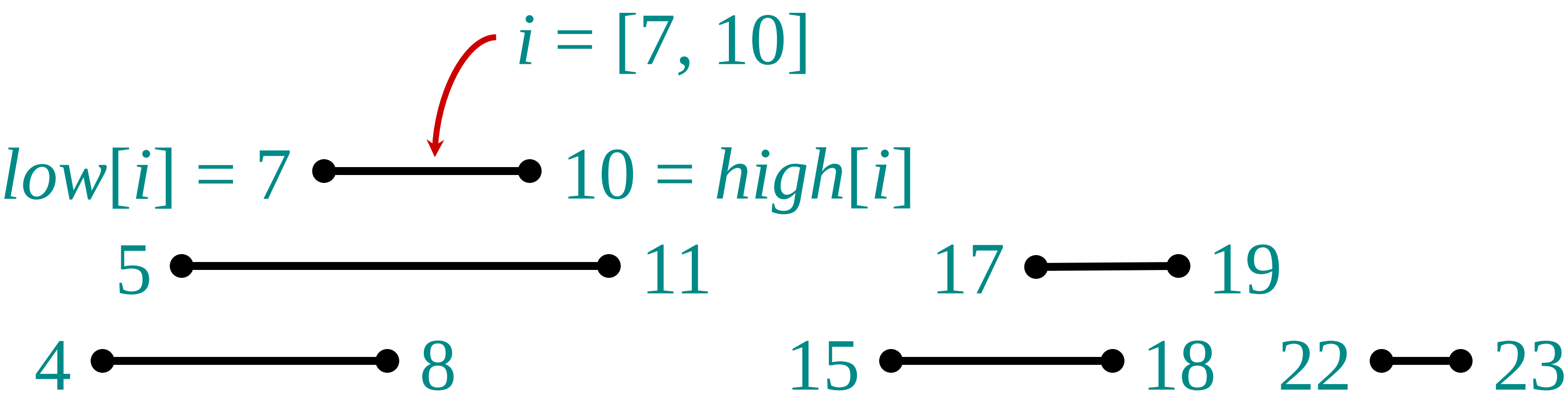
1. Choose an underlying data structure (*red-black trees*).
2. Determine additional information to be stored in the data structure (*subtree sizes*).
3. Verify that this information can be maintained for modifying operations (*RB-INSERT, RB-DELETE — don't forget rotations*).
4. Develop new dynamic-set operations that use the information (*OS-SELECT and OS-RANK*).

These steps are guidelines, not rigid rules.



Interval trees

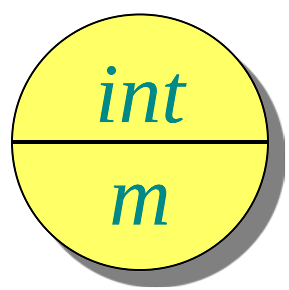
Goal: To maintain a dynamic set of intervals, such as time intervals.



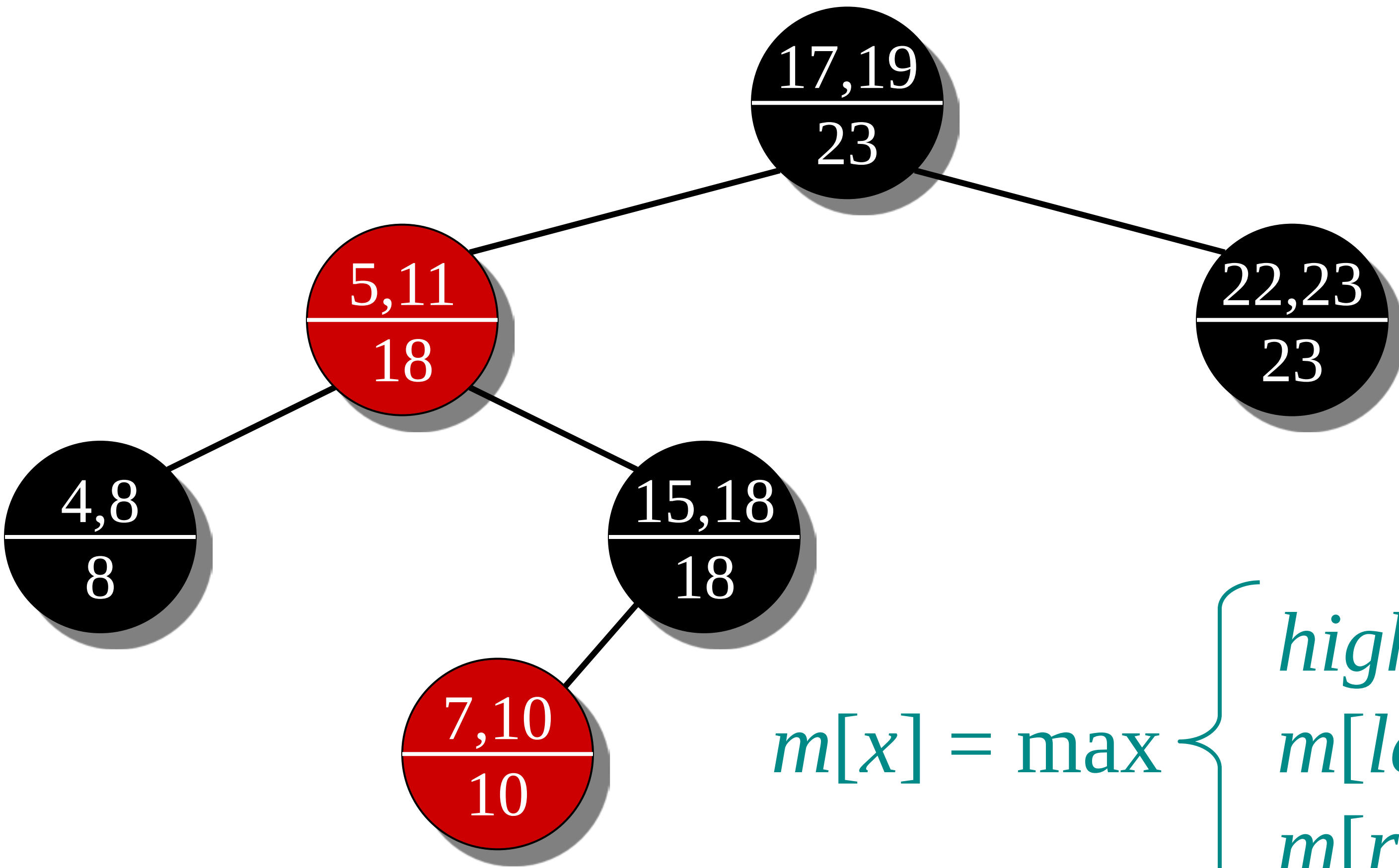
Query: For a given query interval i, find an interval in the set that overlaps i.

Following the methodology

1. *Choose an underlying data structure.*
   - Red-black tree keyed on low (left) endpoint.
2. *Determine additional information to be stored in the data structure.*
   - Store in each node x the largest value $m[x]$ in the subtree rooted at x, as well as the interval $int[x]$ corresponding to the key.



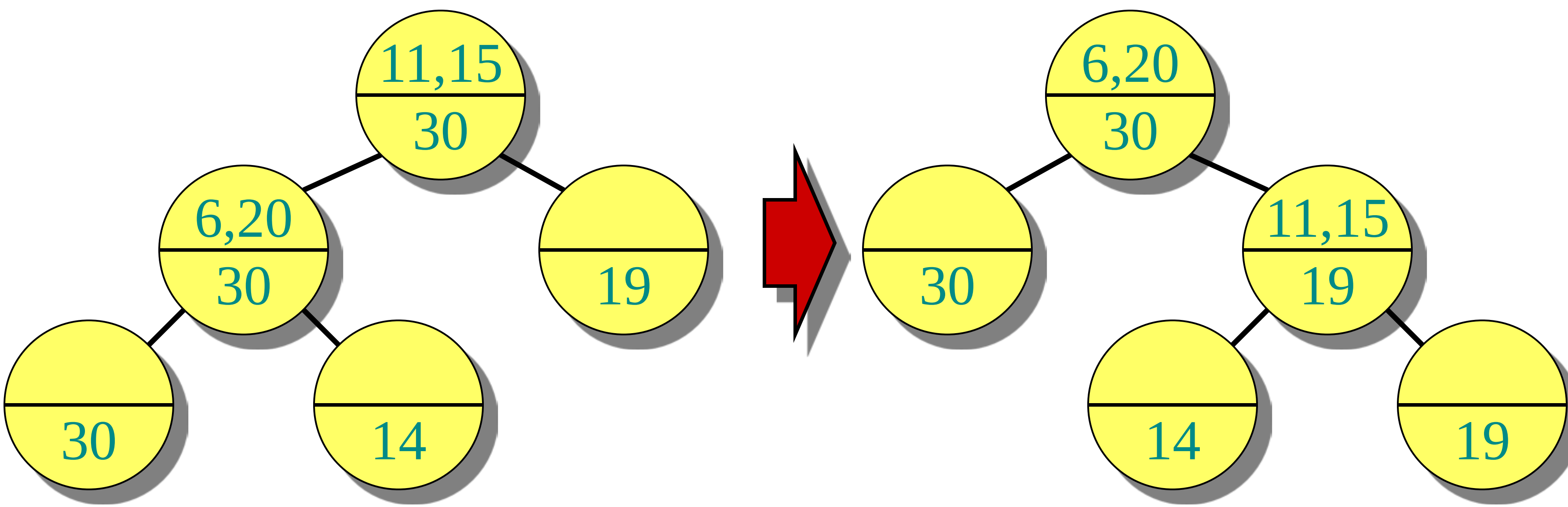
Example interval tree



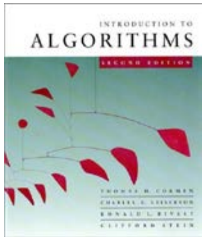
$$m[x] = \max \begin{cases} high[int[x]] \\ m[left[x]] \\ m[right[x]] \end{cases}$$

Modifying operations

3. *Verify that this information can be maintained for modifying operations.*
   - INSERT: Fix *m*'s on the way down.
   - Rotations — Fixup = $O(1)$ time per rotation:



Total INSERT time = $O(\lg n)$; DELETE similar.



New operations

4. Develop new dynamic-set operations that use the information.

INTERVAL-SEARCH(i)

$x \leftarrow root$

while $x \neq \text{NIL}$ and $(low[i] > high[int[x]]$

or $low[int[x]] > high[i])$

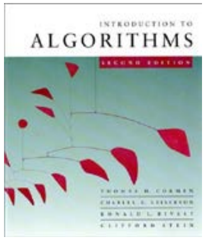
do $\triangleright$ i and $int[x]$ don't overlap

if $left[x] \neq \text{NIL}$ and $low[i] \leq m[left[x]]$

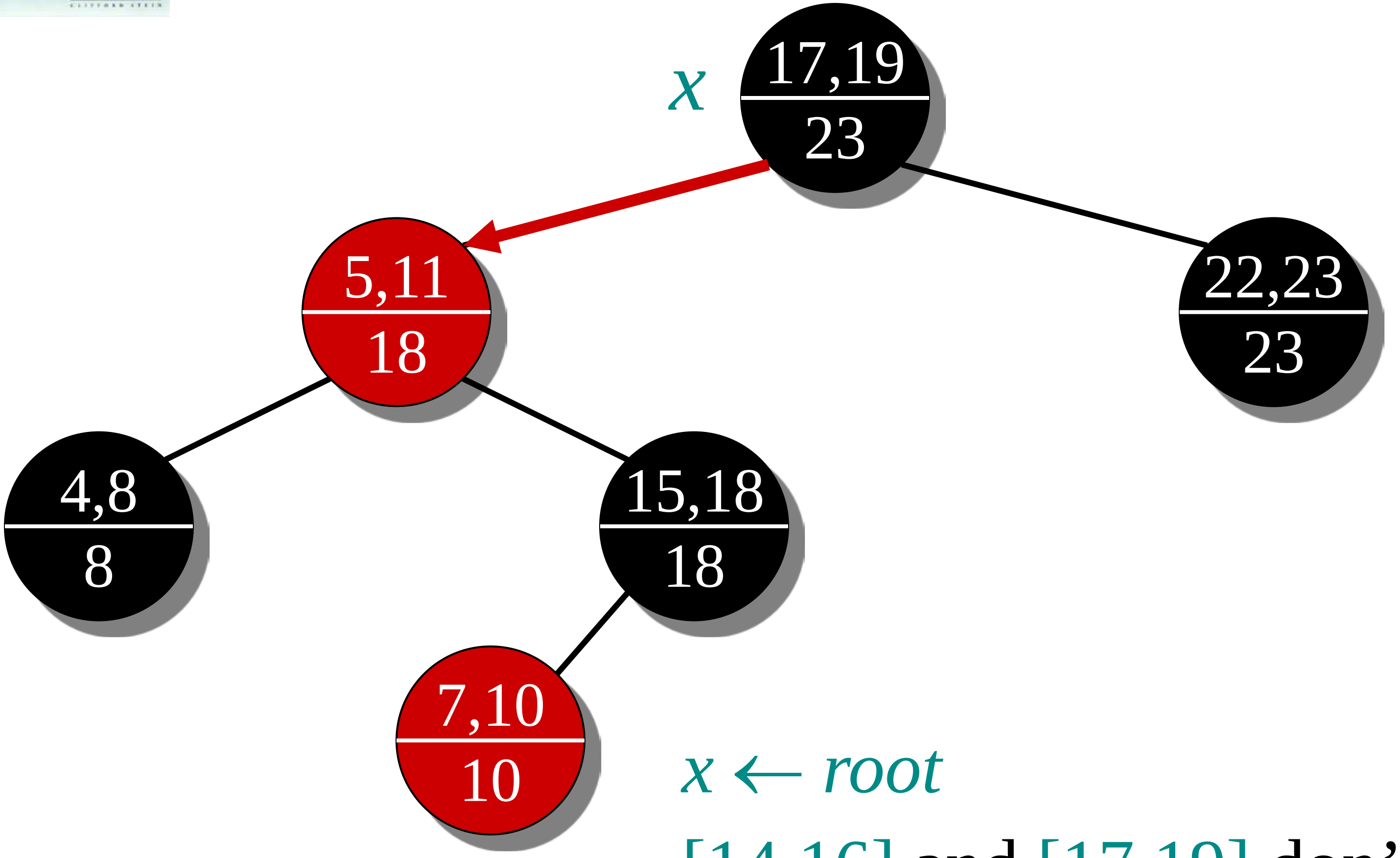
then $x \leftarrow left[x]$

else $x \leftarrow right[x]$

return x



Example 1: INTERVAL-SEARCH([14,16])

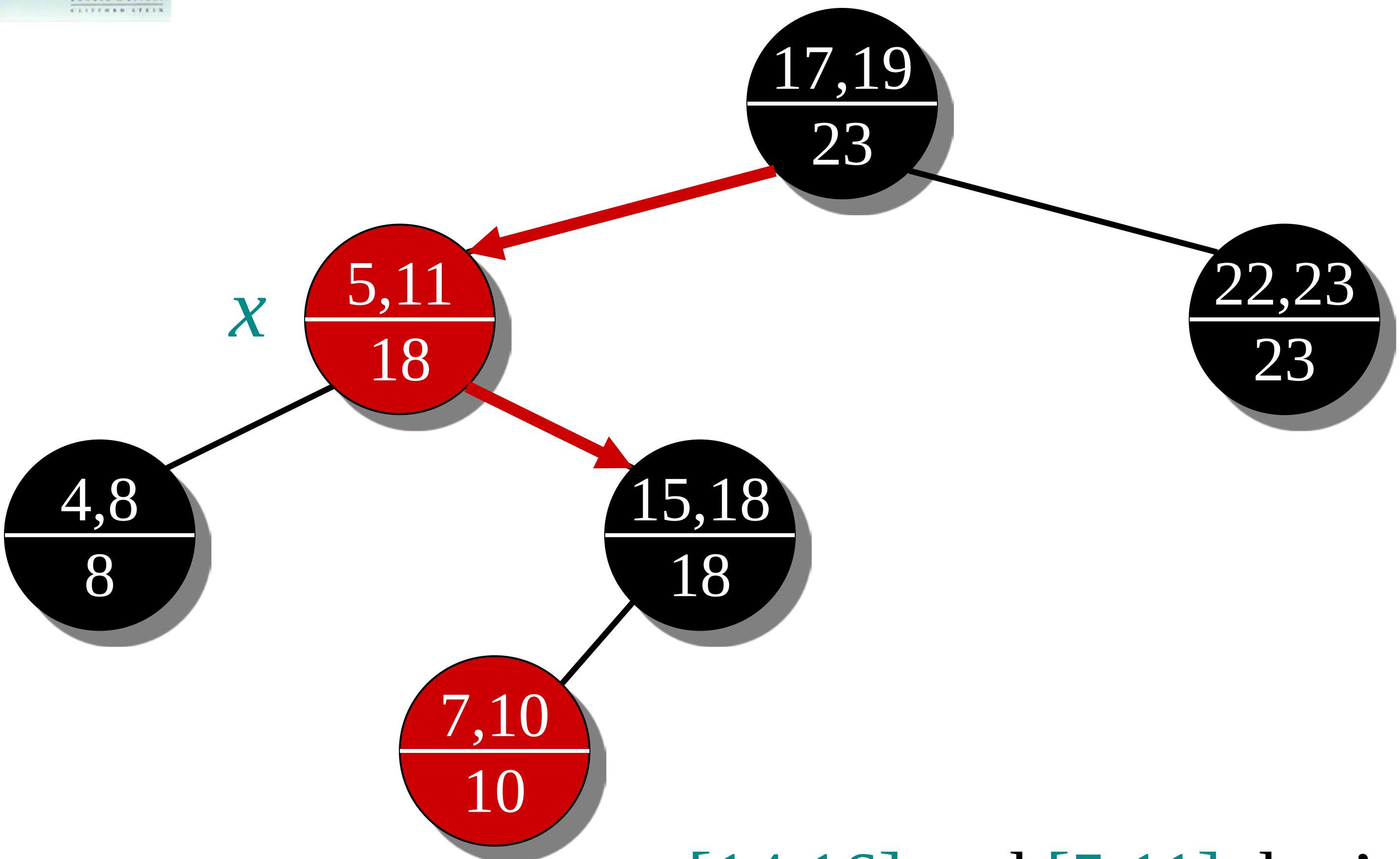


$x \leftarrow root$

[14,16] and [17,19] don't overlap

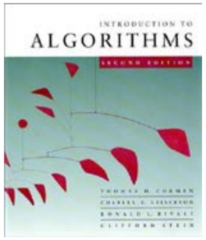
$14 \le 18 \Rightarrow x \leftarrow left[x]$

Example 1: Interval-Search([14,16])

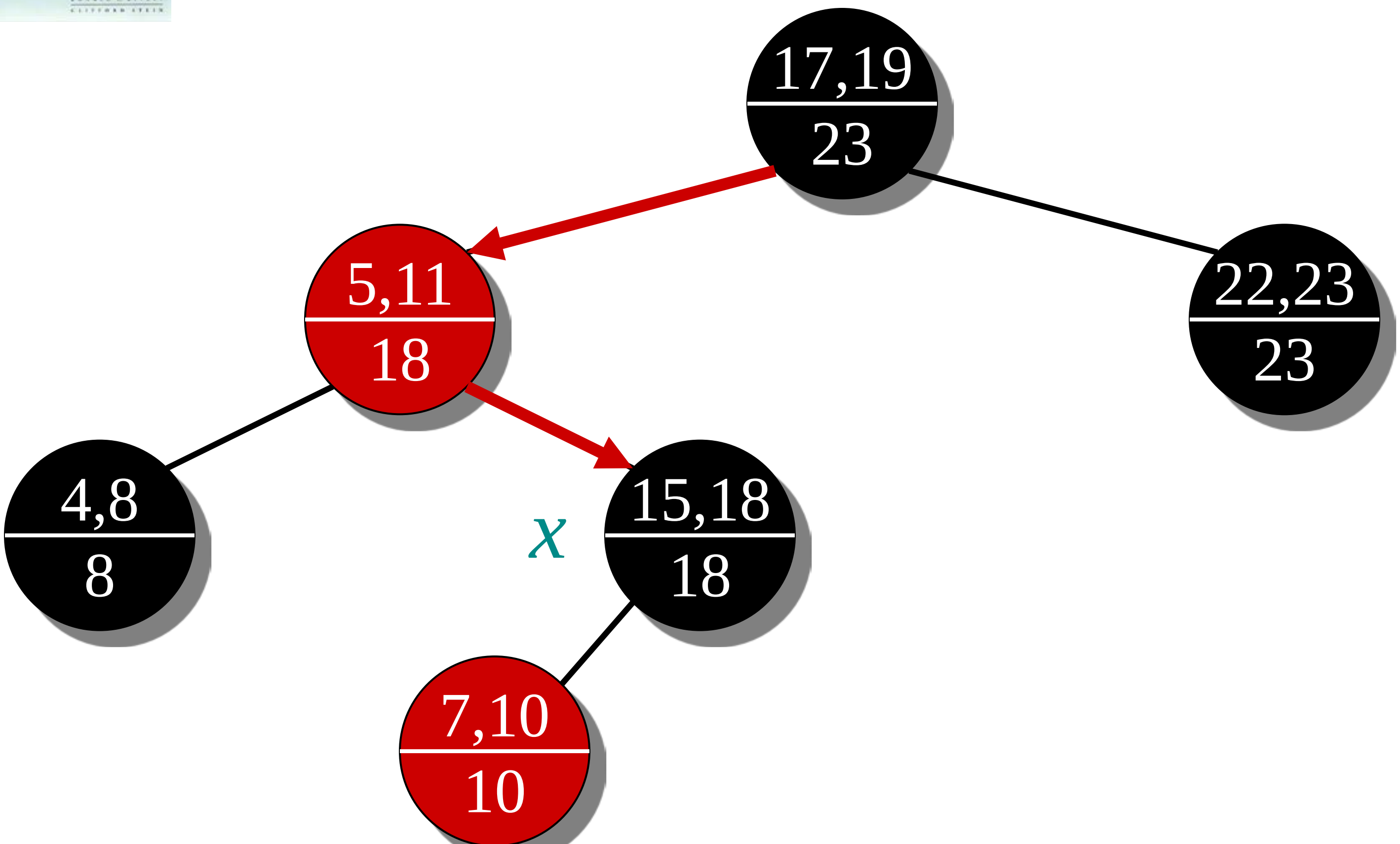


[14,16] and [5,11] don't overlap

$14 > 8 \Rightarrow x \leftarrow right[x]$



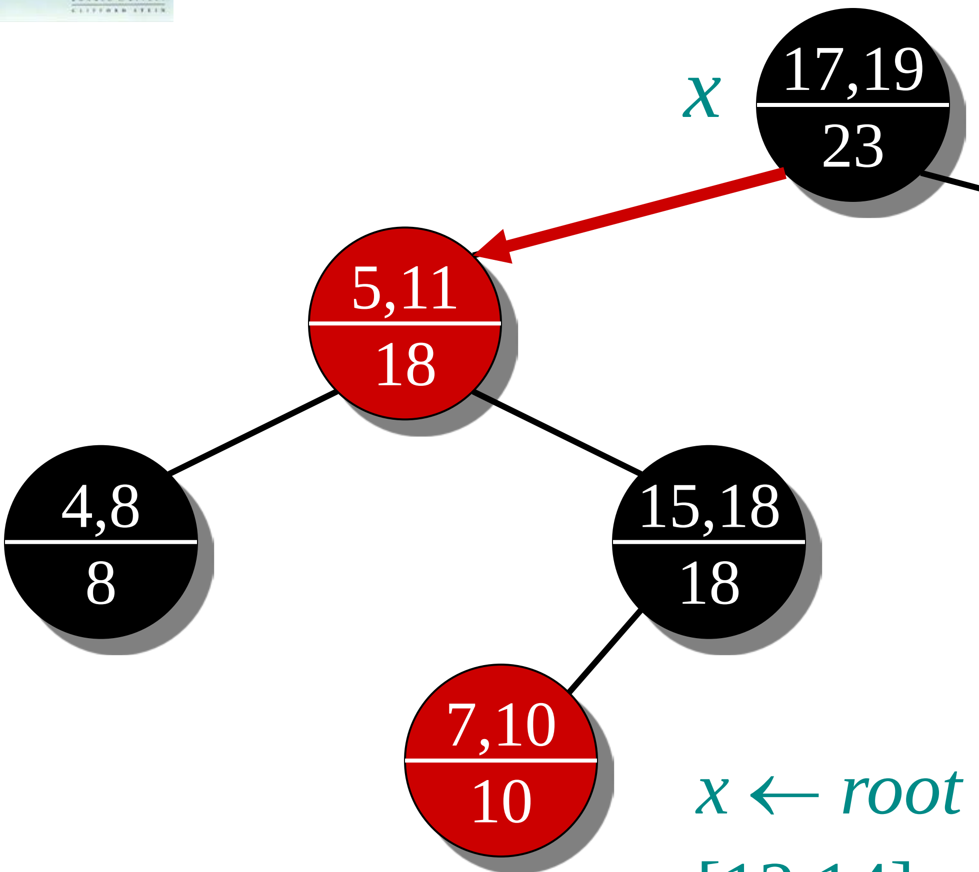
Example 1: INTERVAL-SEARCH([14,16])



[14,16] and [15,18] overlap

return [15,18]

Example 2: INTERVAL-SEARCH([12,14])

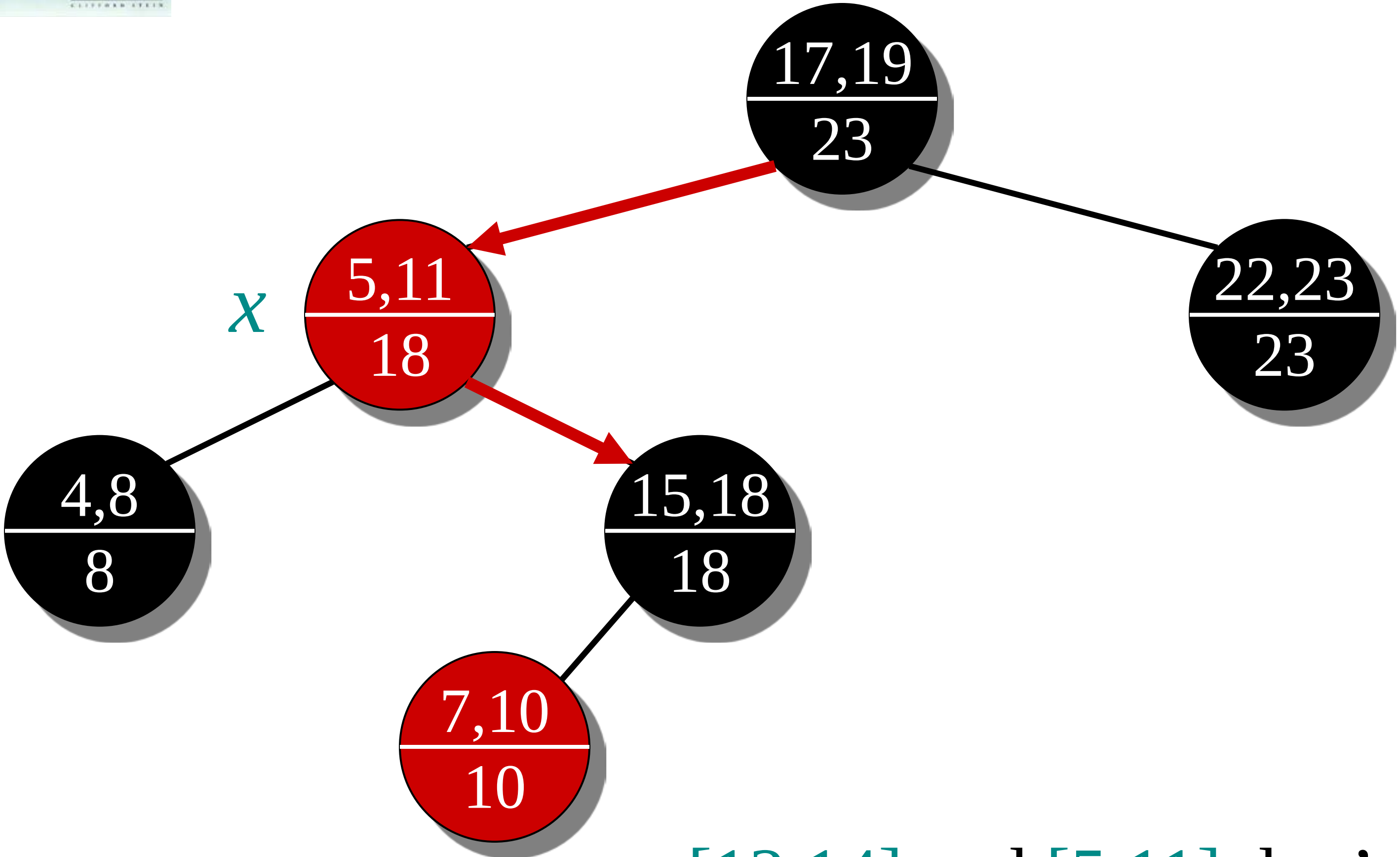


$x \leftarrow root$

[12,14] and [17,19] don't overlap

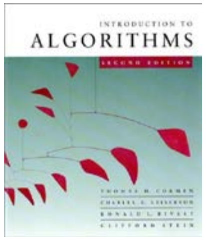
$12 \le 18 \Rightarrow x \leftarrow left[x]$

Example 2: INTERVAL-SEARCH([12,14])

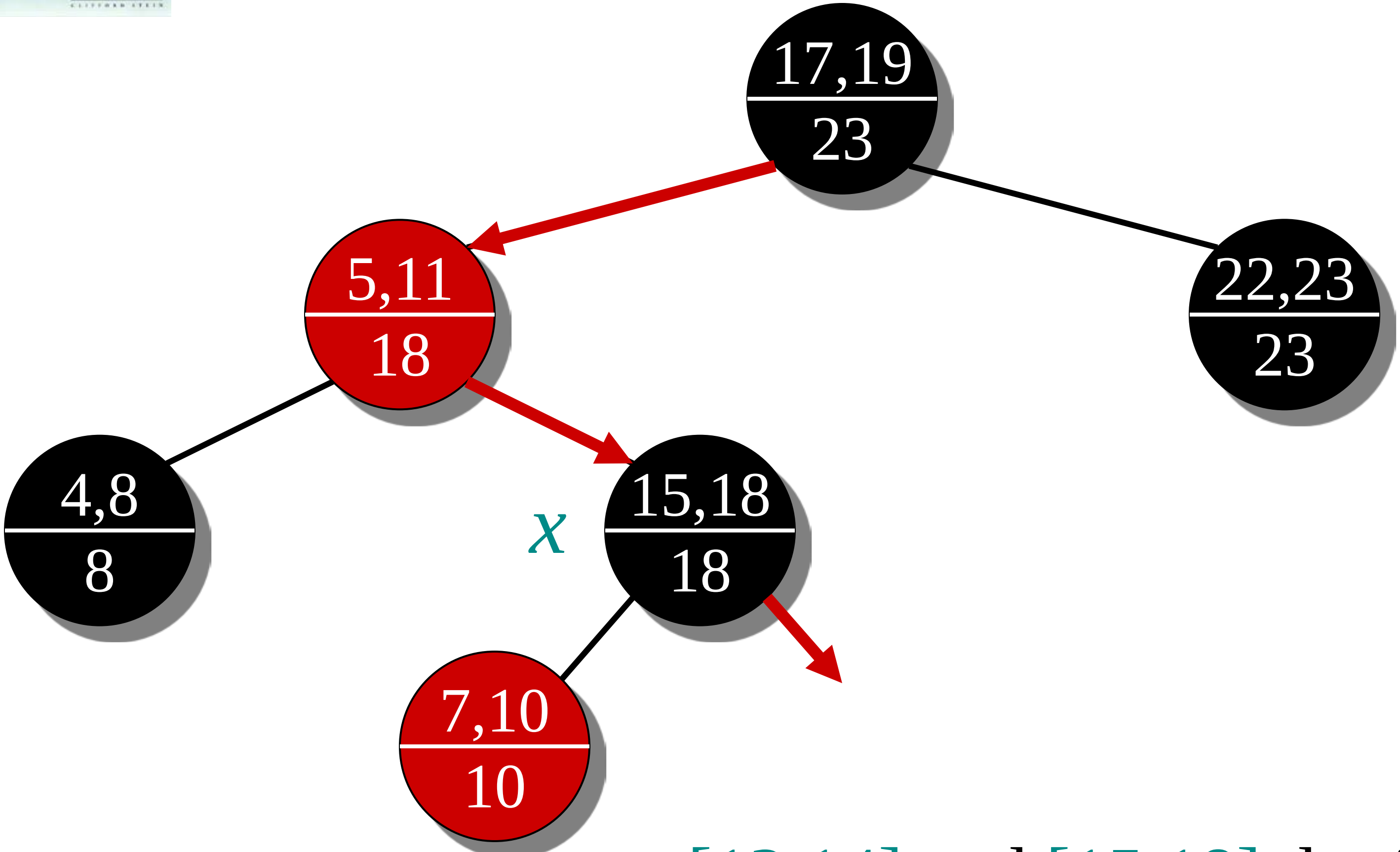


[12,14] and [5,11] don't overlap

$12 > 8 \Rightarrow x \leftarrow right[x]$

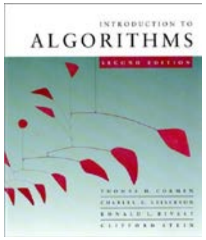


Example 2: INTERVAL-SEARCH([12,14])

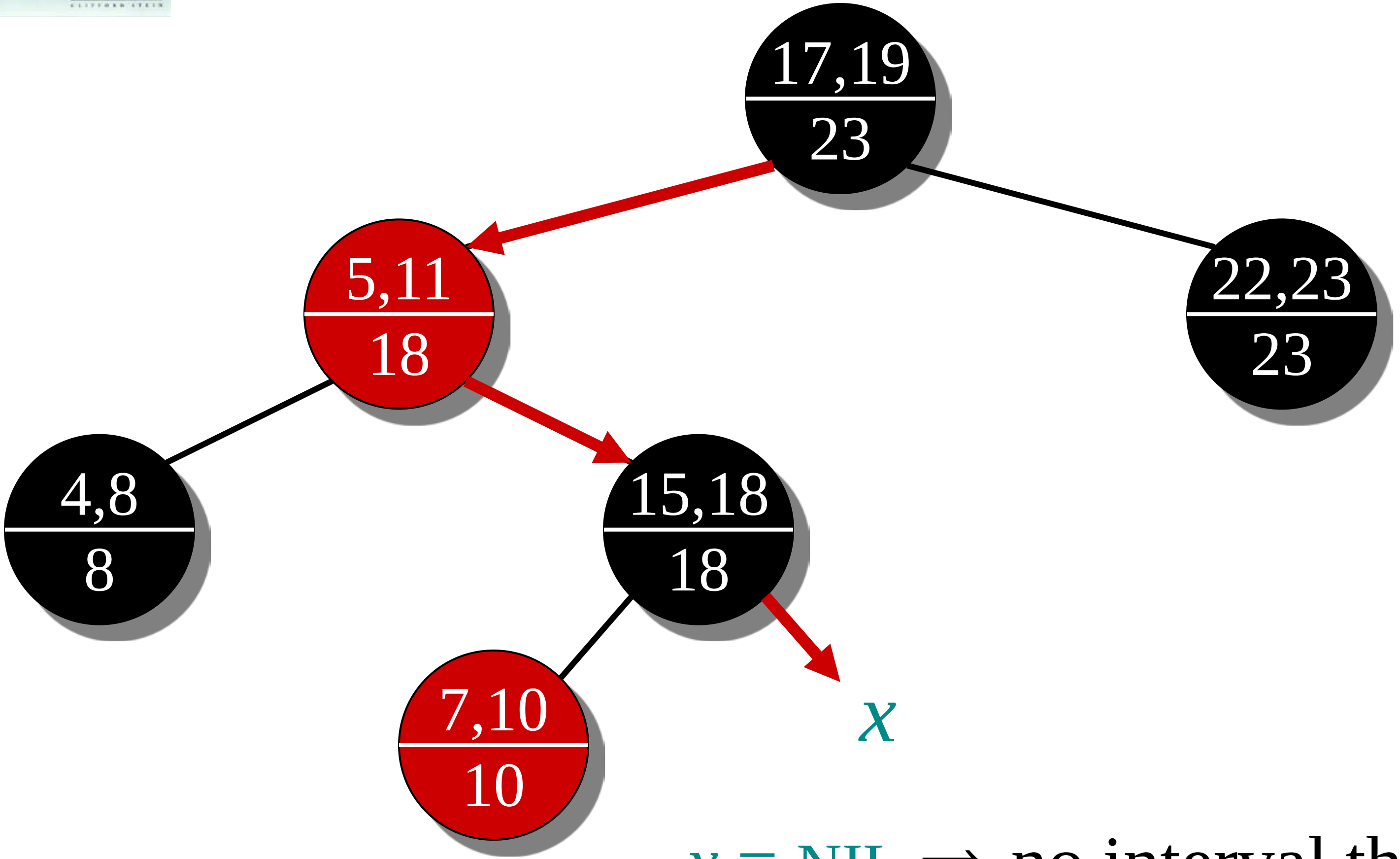


[12,14] and [15,18] don’t overlap

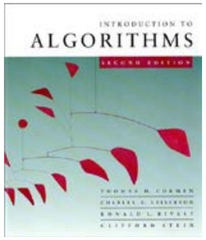
$12 > 10 \Rightarrow x \leftarrow right[x]$



Example 2: INTERVAL-SEARCH([12,14])



x = NIL ⇒ no interval that overlaps [12,14] exists



Analysis

Time = $O(h) = O(\lg n)$, since INTERVAL-SEARCH does constant work at each level as it follows a simple path down the tree.

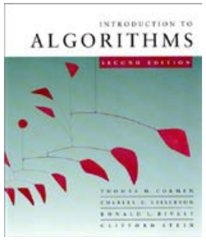
List *all* overlapping intervals:

- Search, list, delete, repeat.
- Insert them all again at the end.

Time = $O(k \lg n)$, where k is the total number of overlapping intervals.

This is an ***output-sensitive*** bound.

Best algorithm to date: $O(k + \lg n)$.



Correctness

Theorem. Let L be the set of intervals in the left subtree of node x, and let R be the set of intervals in x's right subtree.

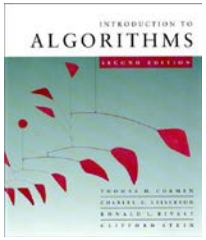
- If the search goes right, then

$$\{\, i' \in L : i' \text{ overlaps } i \,\} = \emptyset.$$

- If the search goes left, then

$$\{i' \in L : i' \text{ overlaps } i \,\} = \emptyset$$
$$\Rightarrow \{i' \in R : i' \text{ overlaps } i \,\} = \emptyset.$$

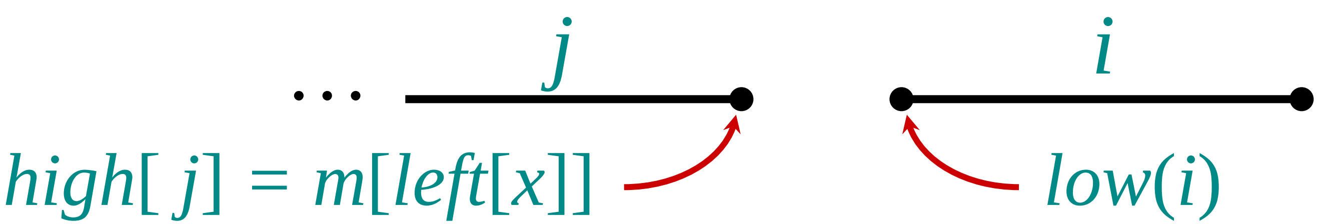
In other words, it's always safe to take only 1 of the 2 children: we'll either find something, or nothing was to be found.



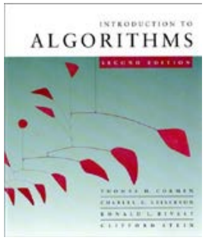
Correctness proof

Proof. Suppose first that the search goes right.

- If $left[x] = \text{NIL}$, then we're done, since $L = \emptyset$.
- Otherwise, the code dictates that we must have $low[i] > m[left[x]]$. The value $m[left[x]]$ corresponds to the high endpoint of some interval $j \in L$, and no other interval in L can have a larger high endpoint than $high[\,j]$.



- Therefore, $\{i' \in L : i'$ overlaps $i\,\} = \emptyset$.

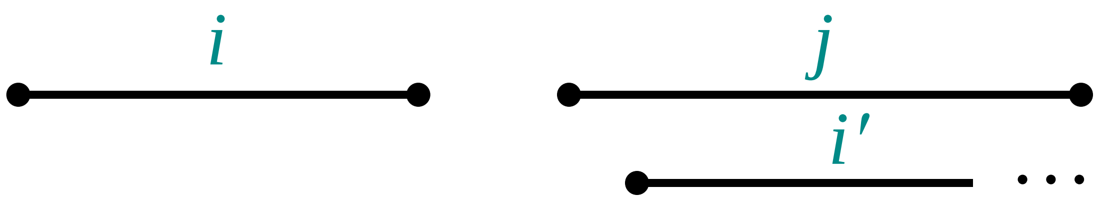


Proof (continued)

Suppose that the search goes left, and assume that

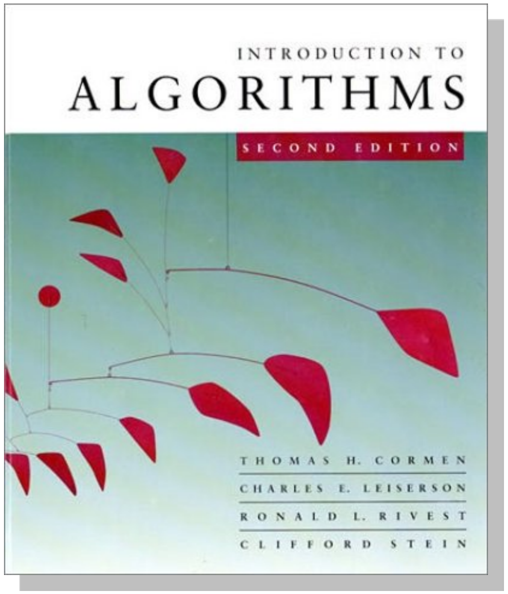
$$\{i' \in L : i' \text{ overlaps } i\} = \emptyset.$$

- Then, the code dictates that $low[i] \le m[left[x]] = high[j]$ for some $j \in L$.
- Since $j \in L$, it does not overlap i, and hence $high[i] < low[j]$.
- But, the binary-search-tree property implies that for all $i' \in R$, we have $low[j] \le low[i']$.
- But then $\{i' \in R : i' \text{ overlaps } i\} = \emptyset$. ∎



Introduction to Algorithms

6.046J/18.401J



LECTURE 12

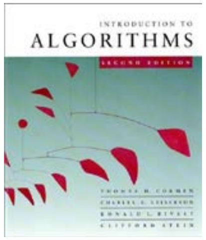
Skip Lists

- Data structure
- Randomized insertion
- With-high-probability bound
- Analysis
- Coin flipping

Prof. Erik D. Demaine

Skip lists

- Simple randomized dynamic search structure
  - Invented by William Pugh in 1989
  - Easy to implement
- Maintains a dynamic set of n elements in $O(\lg n)$ time per operation in expectation and *with high probability*
  - Strong guarantee on tail of distribution of $T(n)$
  - $O(\lg n)$ "almost always"

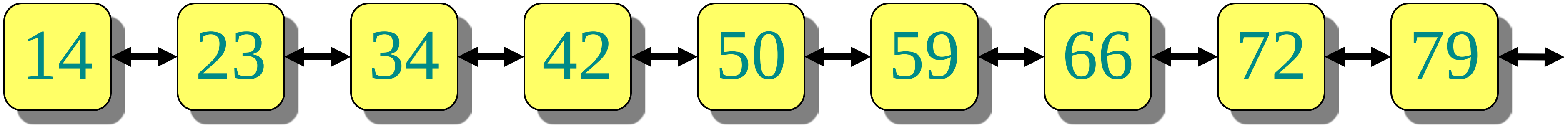


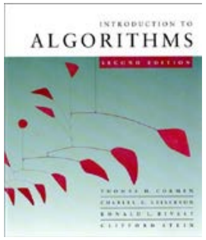
One linked list

Start from simplest data structure:

(sorted) linked list

- Searches take $\Theta(n)$ time in worst case
- How can we speed up searches?

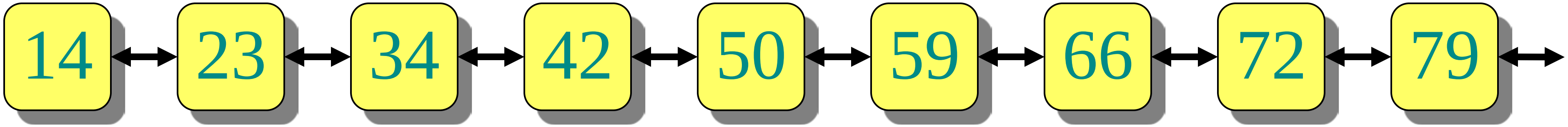


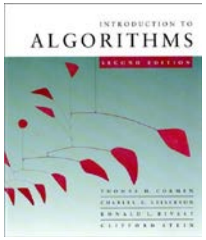


Two linked lists

Suppose we had *two* sorted linked lists (on subsets of the elements)

- Each element can appear in one or both lists
- How can we speed up searches?

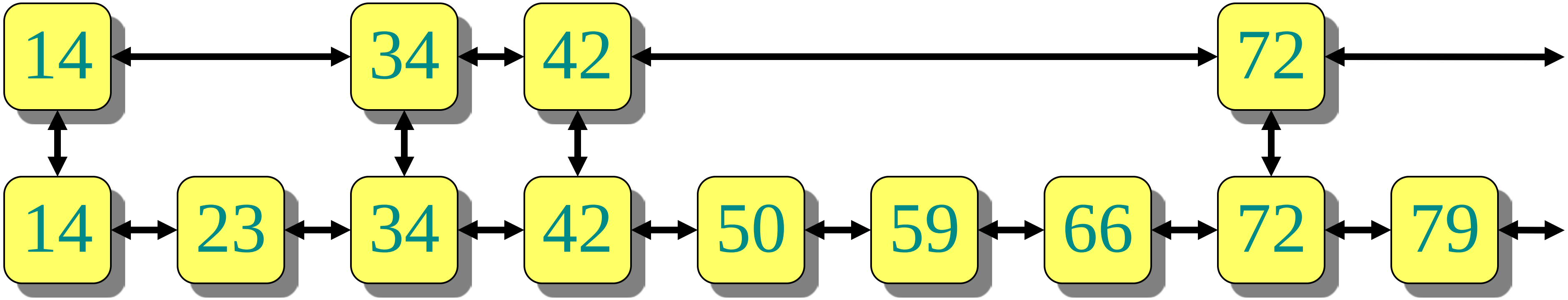


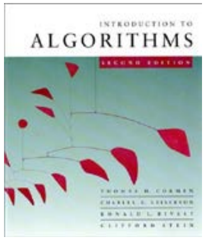


Two linked lists as a subway

IDEA: Express and local subway lines (à la New York City 7th Avenue Line)

- Express line connects a few of the stations
- Local line connects all stations
- Links between lines at common stations

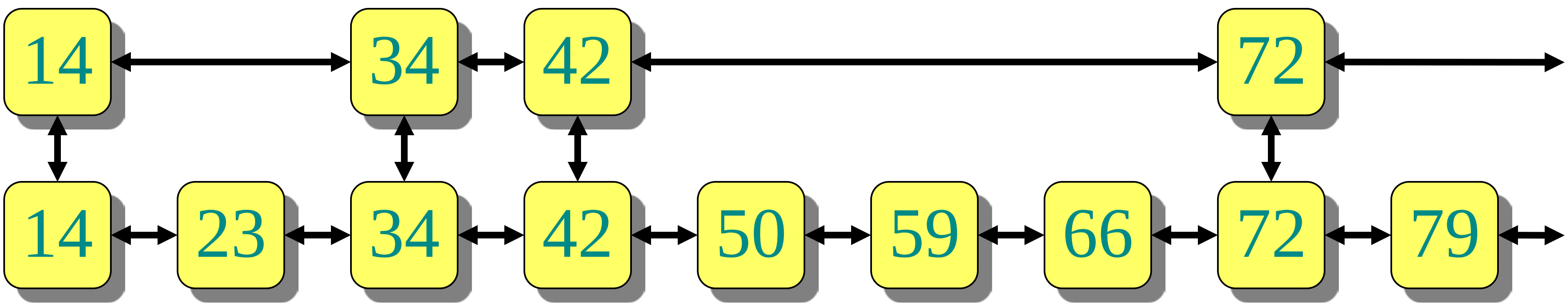


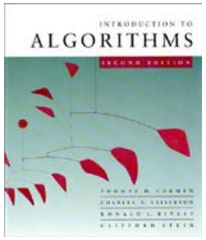


Searching in two linked lists

SEARCH(x):

- Walk right in top linked list (L_1) until going right would go too far
- Walk down to bottom linked list (L_2)
- Walk right in L_2 until element found (or not)

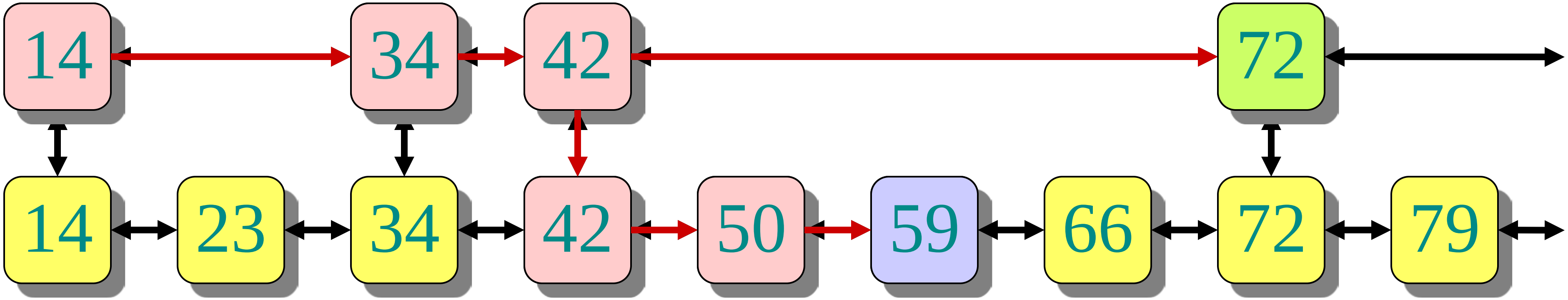




Searching in two linked lists

EXAMPLE: SEARCH(59)

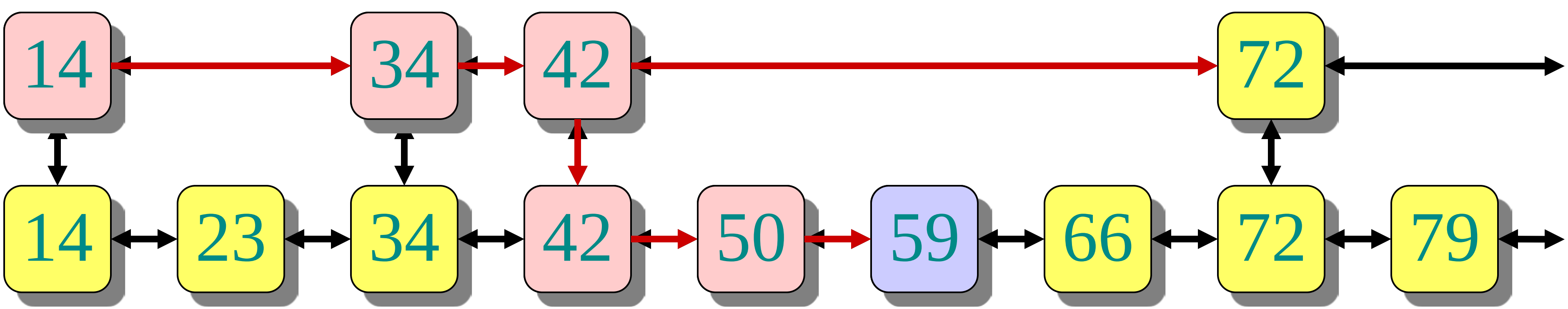
Too far:
59 < 72

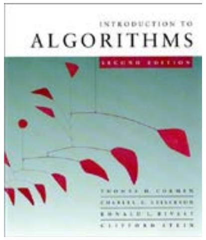


Design of two linked lists

QUESTION: Which nodes should be in L_1?

- In a subway, the "popular stations"
- Here we care about *worst-case performance*
- **Best approach:** Evenly space the nodes in L_1
- But *how many nodes* should be in L_1?

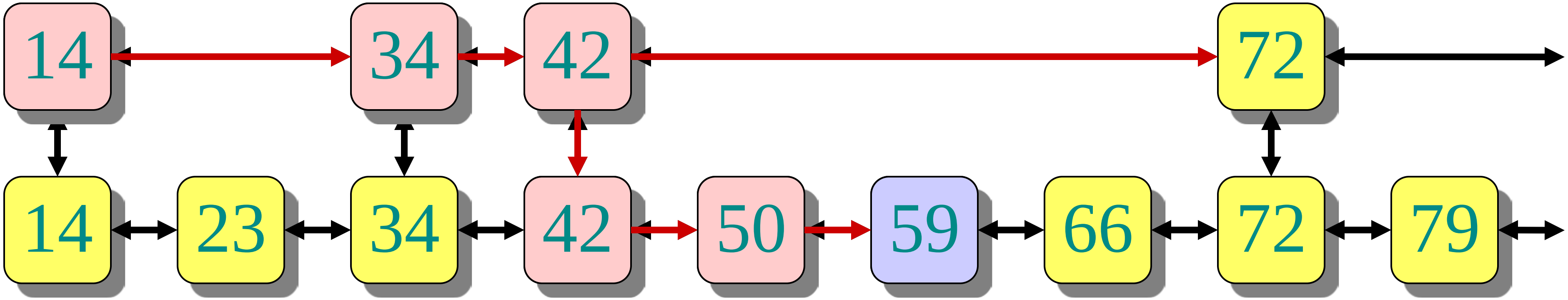


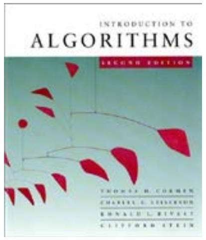


Analysis of two linked lists

ANALYSIS:

- Search cost is roughly $|L_1| + \frac{|L_2|}{|L_1|}$
- Minimized (up to constant factors) when terms are equal
- $|L_1|^2 = |L_2| = n \Rightarrow |L_1| = \sqrt{n}$



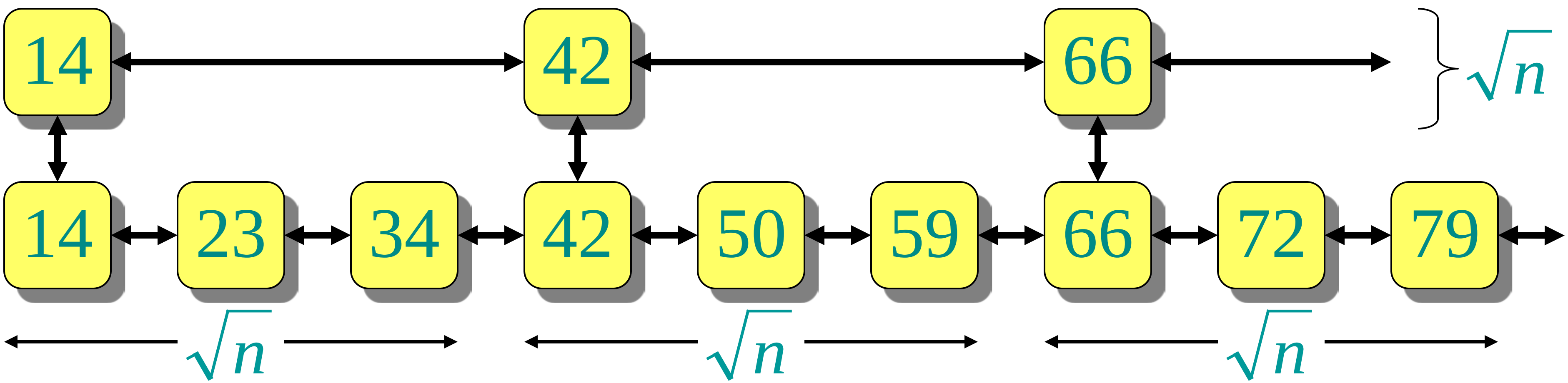


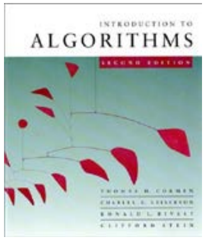
Analysis of two linked lists

ANALYSIS:

- $|L_1| = \sqrt{n}\,, \qquad |L_2| = n$
- Search cost is roughly

$$|L_1| + \frac{|L_2|}{|L_1|} = \sqrt{n} + \frac{n}{\sqrt{n}} = 2\sqrt{n}$$

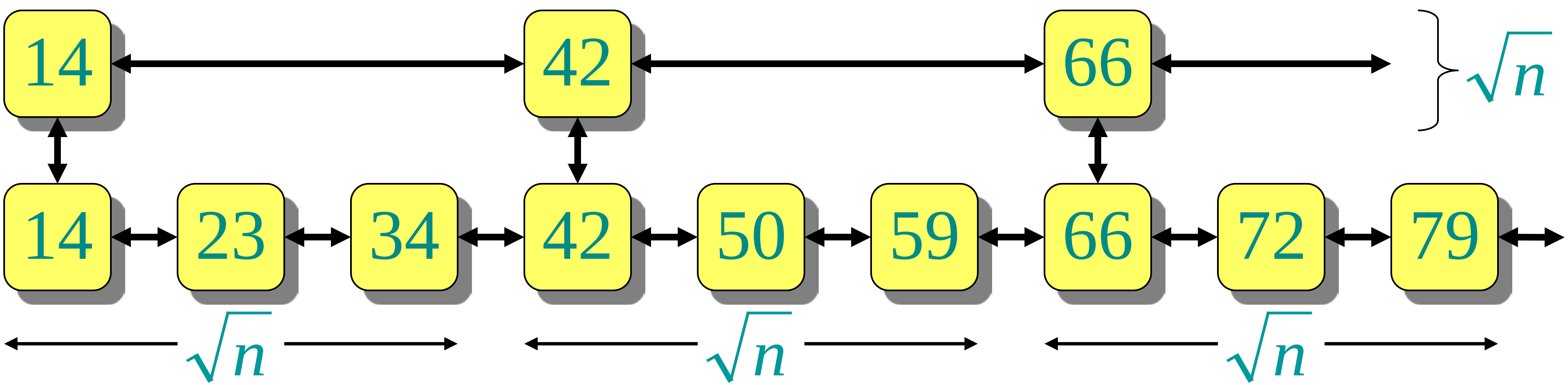


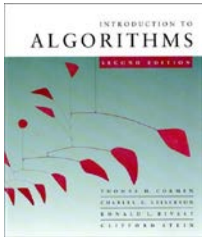


More linked lists

What if we had more sorted linked lists?

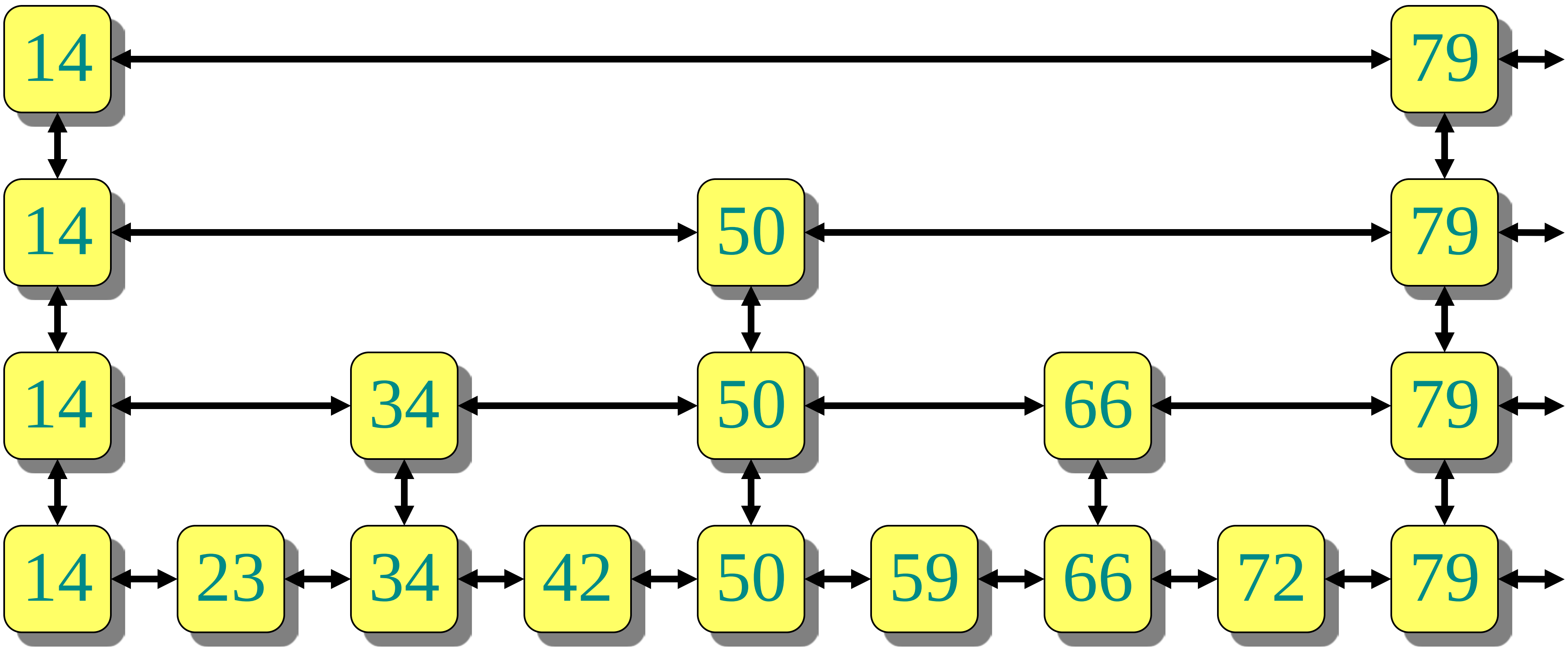
- 2 sorted lists $\Rightarrow 2 \cdot \sqrt{n}$
- 3 sorted lists $\Rightarrow 3 \cdot \sqrt[3]{n}$
- k sorted lists $\Rightarrow k \cdot \sqrt[k]{n}$
- $\lg n$ sorted lists $\Rightarrow \lg n \cdot \sqrt[\lg n]{n} = 2 \lg n$

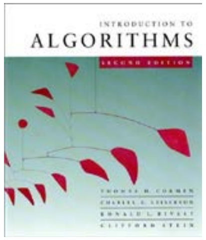




lg *n* linked lists

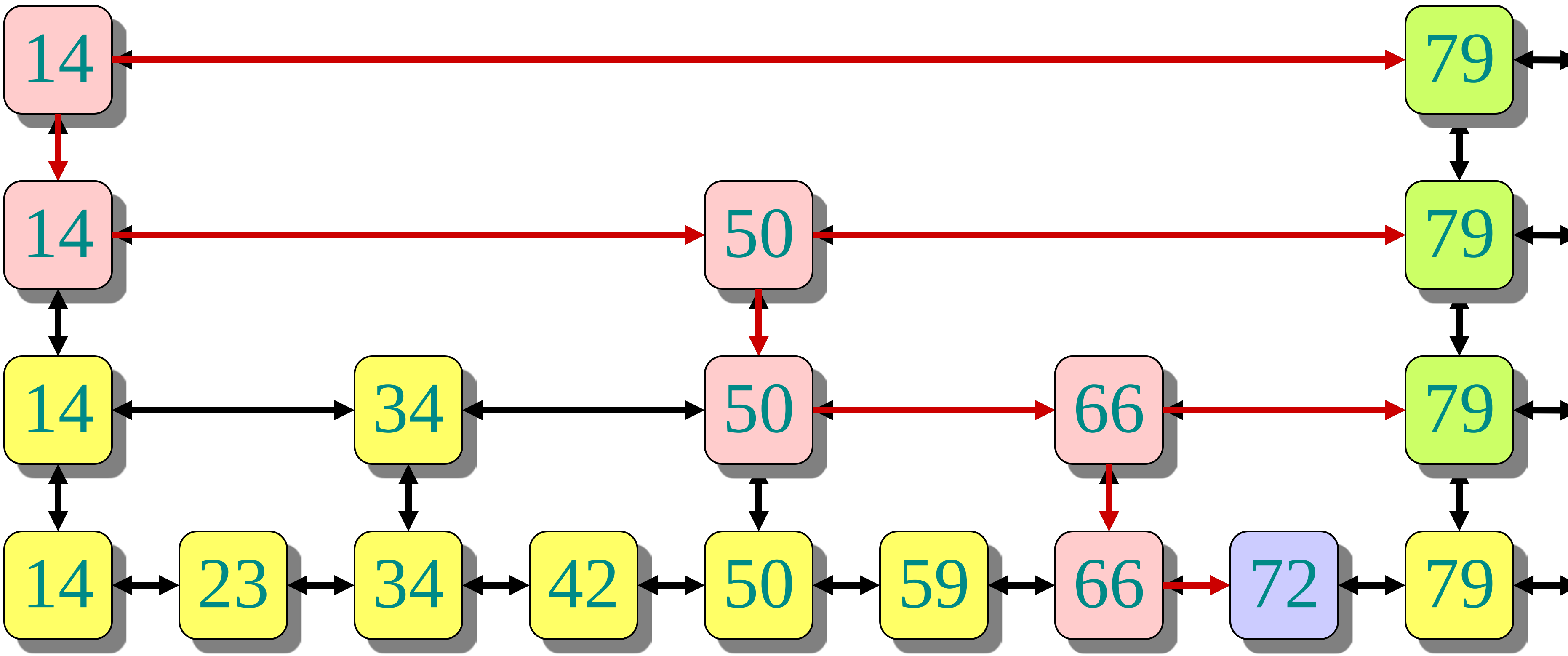
lg *n* sorted linked lists are like a binary tree
(in fact, level-linked B⁺-tree; see Problem Set 5)

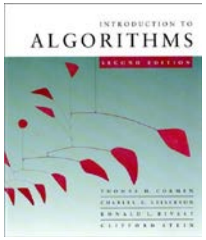




Searching in lg *n* linked lists

EXAMPLE: SEARCH(72)

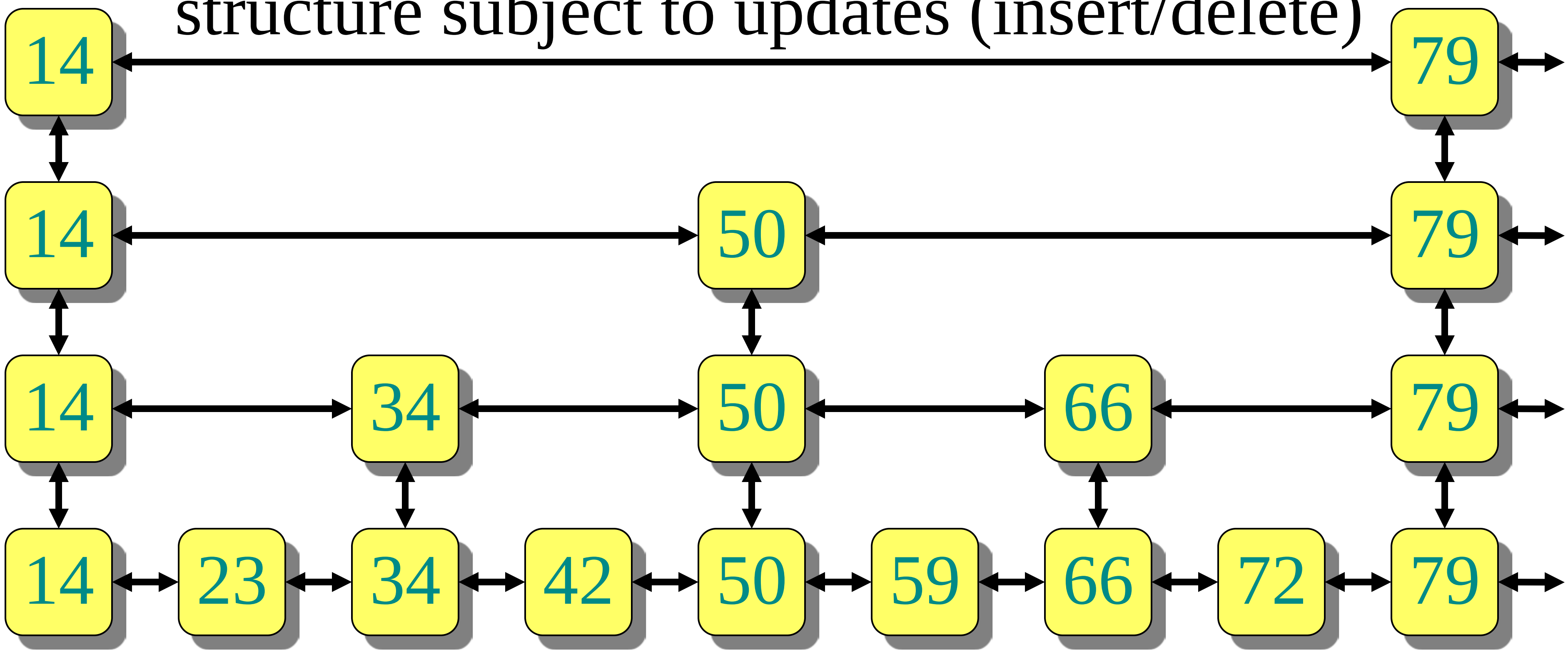


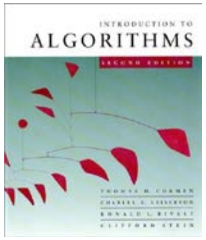


Skip lists

Ideal skip list is this lg n linked list structure

Skip list data structure maintains roughly this structure subject to updates (insert/delete)





INSERT(x)

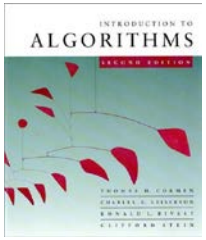
To insert an element x into a skip list:

- SEARCH(x) to see where x fits in bottom list
- Always insert into bottom list

INVARIANT: Bottom list contains all elements

- Insert into some of the lists above…

QUESTION: To which other lists should we add x?



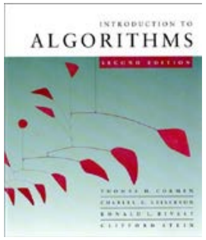
INSERT(x)

QUESTION: To which other lists should we add x?

IDEA: Flip a (fair) coin; if HEADS,
promote x to next level up and flip again

- Probability of promotion to next level = 1/2
- On average:
  - 1/2 of the elements promoted 0 levels
  - 1/4 of the elements promoted 1 level
  - 1/8 of the elements promoted 2 levels
  - etc.

Approx. balanced?

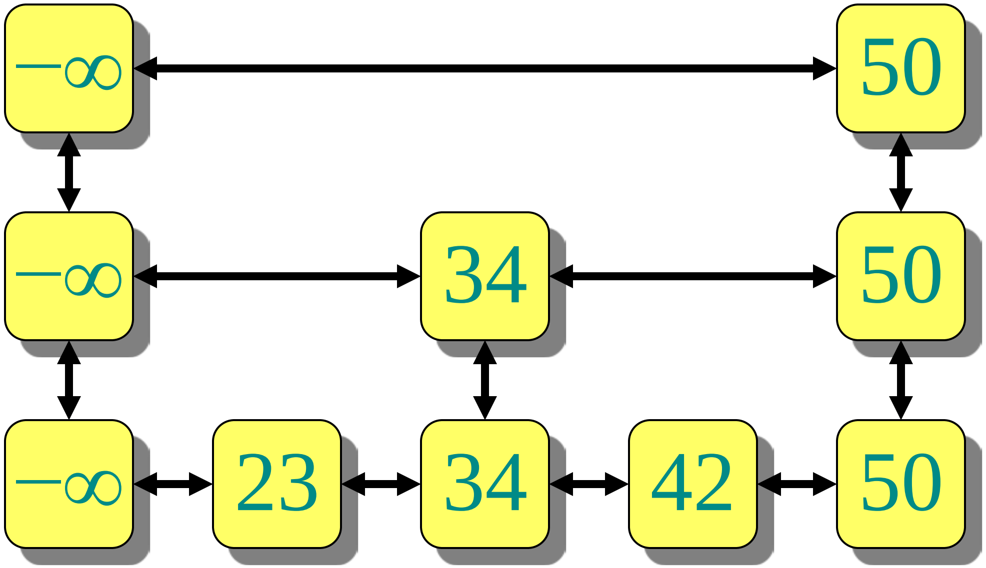


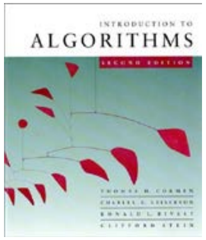
Example of skip list

EXERCISE: Try building a skip list from scratch by repeated insertion using a real coin

Small change:

- Add special $-\infty$ value to *every* list $\Rightarrow$ can search with the same algorithm

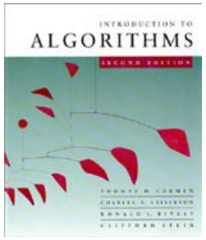




Skip lists

A ***skip list*** is the result of insertions (and deletions) from an initially empty structure (containing just $-\infty$)

- INSERT(x) uses random coin flips to decide promotion level
- DELETE(x) removes x from all lists containing it



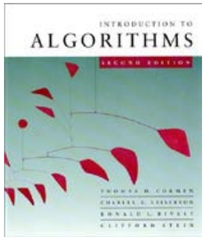
Skip lists

A ***skip list*** is the result of insertions (and deletions) from an initially empty structure (containing just $-\infty$)

- INSERT(x) uses random coin flips to decide promotion level
- DELETE(x) removes x from all lists containing it

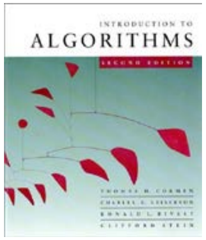
How good are skip lists? (speed/balance)

- **INTUITIVELY:** Pretty good on average
- **CLAIM:** Really, really good, almost always



With-high-probability theorem

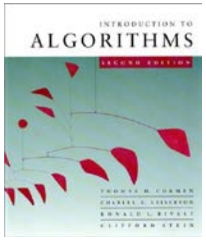
THEOREM: *With high probability*, every search in an n-element skip list costs $O(\lg n)$



With-high-probability theorem

THEOREM: *With high probability*, every search in a skip list costs $O(\lg n)$

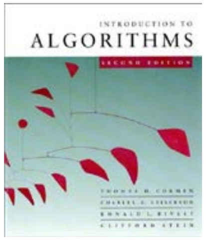
- **INFORMALLY:** Event E occurs ***with high probability*** (***w.h.p.***) if, for any $\alpha \geq 1$, there is an appropriate choice of constants for which E occurs with probability at least $1 - O(1/n^{\alpha})$
  - In fact, constant in $O(\lg n)$ depends on α
- **FORMALLY:** Parameterized event E_α occurs ***with high probability*** if, for any $\alpha \geq 1$, there is an appropriate choice of constants for which E_α occurs with probability at least $1 - c_\alpha/n^{\alpha}$



With-high-probability theorem

Theorem: With high probability, every search in a skip list costs $O(\lg n)$

- **Informally:** Event E occurs ***with high probability*** (***w.h.p.***) if, for any $\alpha \geq 1$, there is an appropriate choice of constants for which E occurs with probability at least $1 - O(1/n^\alpha)$
- **Idea:** Can make ***error probability*** $O(1/n^\alpha)$ very small by setting α large, e.g., 100
- Almost certainly, bound remains true for entire execution of polynomial-time algorithm



Boole's inequality / union bound

Recall:

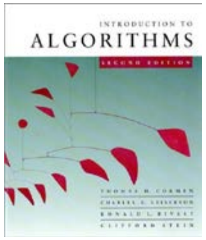
BOOLE'S INEQUALITY / UNION BOUND:

For any random events $E_1, E_2, \ldots, E_k$,

$$\Pr\{E_1 \cup E_2 \cup \ldots \cup E_k\}$$
$$\leq \Pr\{E_1\} + \Pr\{E_2\} + \ldots + \Pr\{E_k\}$$

Application to with-high-probability events:

If $k = n^{O(1)}$, and each E_i occurs with high probability, then so does $E_1 \cap E_2 \cap \ldots \cap E_k$

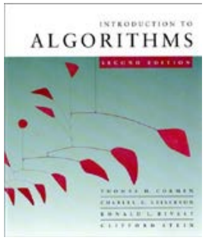


Analysis Warmup

LEMMA: With high probability, n-element skip list has $O(\lg n)$ levels

PROOF:

- Error probability for having at most $c \lg n$ levels
  $= \Pr\{\text{more than } c \lg n \text{ levels}\}$
  $\le n \cdot \Pr\{\text{element } x \text{ promoted at least } c \lg n \text{ times}\}$
  (by Boole's Inequality)
  $= n \cdot (1/2^{c \lg n})$
  $= n \cdot (1/n^c)$
  $= 1/n^{c-1}$

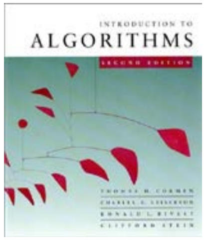


Analysis Warmup

LEMMA: With high probability, n-element skip list has $O(\lg n)$ levels

PROOF:

- Error probability for having at most $c \lg n$ levels $\leq 1/n^{c-1}$
- This probability is ***polynomially small***, i.e., at most n^{α} for $\alpha = c - 1$.
- We can make α arbitrarily large by choosing the constant c in the $O(\lg n)$ bound accordingly. $\square$

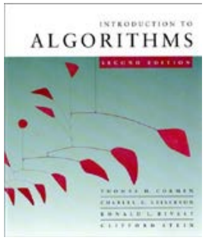


Proof of theorem

THEOREM: With high probability, every search in an n-element skip list costs $O(\lg n)$

COOL IDEA: Analyze search backwards—leaf to root

- Search starts [ends] at leaf (node in bottom level)
- At each node visited:
  – If node wasn't promoted higher (got TAILS here), then we go [came from] left
  – If node was promoted higher (got HEADS here), then we go [came from] up
- Search stops [starts] at the root (or $-\infty$)



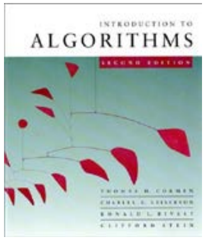
Proof of theorem

THEOREM: With high probability, every search in an n-element skip list costs $O(\lg n)$

COOL IDEA: Analyze search backwards—leaf to root

PROOF:

- Search makes "up" and "left" moves until it reaches the root (or $-\infty$)
- Number of "up" moves $<$ number of levels $\leq c \lg n$ w.h.p. *(Lemma)*
- $\Rightarrow$ w.h.p., number of moves is at most the number of times we need to flip a coin to get $c \lg n$ HEADS



Coin flipping analysis

CLAIM: Number of coin flips until $c \lg n$ HEADS
$= \Theta(\lg n)$ with high probability

PROOF:

Obviously $\Omega(\lg n)$: at least $c \lg n$

Prove $O(\lg n)$ "by example":

- Say we make $10\, c \lg n$ flips
- When are there at least $c \lg n$ HEADS?

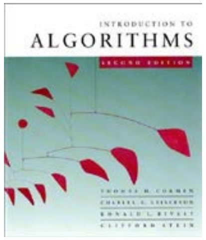
(Later generalize to arbitrary values of 10)

Coin flipping analysis

CLAIM: Number of coin flips until $c \lg n$ HEADS $= \Theta(\lg n)$ with high probability

PROOF:

- $\Pr\{\text{exactly } c \lg n \text{ HEADS}\} = \underbrace{\binom{10c\lg n}{c\lg n}}_{\text{orders}} \cdot \underbrace{\left(\frac{1}{2}\right)^{c\lg n}}_{\text{HEADS}} \cdot \underbrace{\left(\frac{1}{2}\right)^{9c\lg n}}_{\text{TAILS}}$
- $\Pr\{\text{at most } c \lg n \text{ HEADS}\} \le \underbrace{\binom{10c\lg n}{c\lg n}}_{\substack{\text{overestimate}\\\text{on orders}}} \cdot \underbrace{\left(\frac{1}{2}\right)^{9c\lg n}}_{\text{TAILS}}$



Coin flipping analysis (cont'd)

- Recall bounds on $\binom{y}{x}$: $\left(\frac{y}{x}\right)^x \le \binom{y}{x} \le \left(e\frac{y}{x}\right)^x$
- Pr{at most $c \lg n$ HEADS} $\le \binom{10c\lg n}{c\lg n} \cdot \left(\frac{1}{2}\right)^{9c\lg n}$

$$
\begin{aligned}
&\le \left(e\frac{10c\lg n}{c\lg n}\right)^{c\lg n} \cdot \left(\frac{1}{2}\right)^{9c\lg n} \\
&= (10e)^{c\lg n} 2^{-9c\lg n} \\
&= 2^{\lg(10e)\cdot c\lg n} 2^{-9c\lg n} \\
&= 2^{[\lg(10e)-9]\cdot c\lg n} \\
&= 1/n^{\alpha} \quad \text{for} \quad \alpha = [9 - \lg(10e)]\cdot c
\end{aligned}
$$

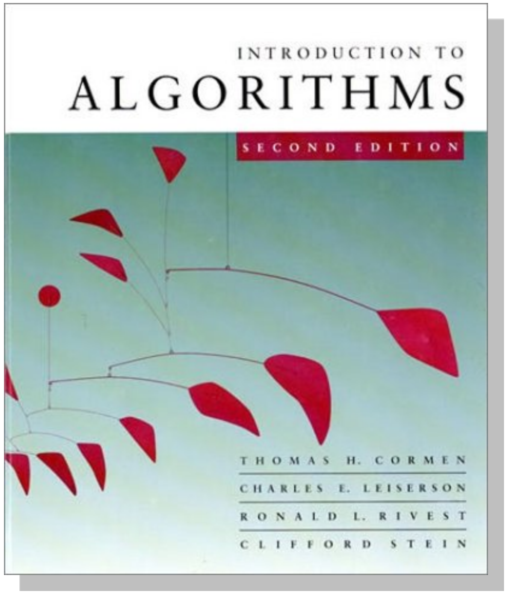
Coin flipping analysis (cont'd)

- $\Pr\{$at most $c \lg n$ HEADS$\} \le 1/n^{\alpha}$ for $\alpha = [9 - \lg(10e)]c$
- **KEY PROPERTY:** $\alpha \to \infty$ as $10 \to \infty$, for any c
- So set 10, i.e., constant in $O(\lg n)$ bound, large enough to meet desired α

This completes the proof of the coin-flipping claim and the proof of the theorem.

Introduction to Algorithms

6.046J/18.401J



LECTURE 13

Amortized Analysis

- Dynamic tables
- Aggregate method
- Accounting method
- Potential method

Prof. Charles E. Leiserson

How large should a hash table be?

Goal: Make the table as small as possible, but large enough so that it won't overflow (or otherwise become inefficient).

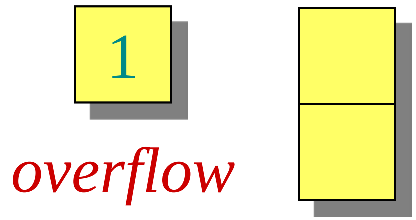
Problem: What if we don't know the proper size in advance?

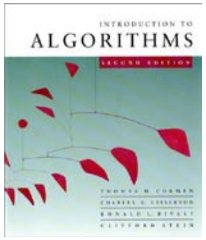
Solution: ***Dynamic tables.***

IDEA: Whenever the table overflows, "grow" it by allocating (via **`malloc`** or **`new`**) a new, larger table. Move all items from the old table into the new one, and free the storage for the old table.

Example of a dynamic table

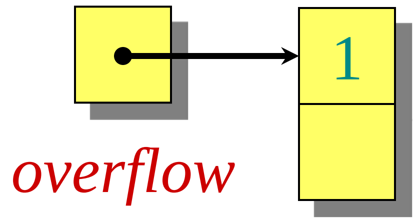
1. INSERT
2. INSERT





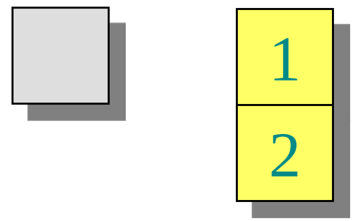
Example of a dynamic table

1. INSERT
2. INSERT



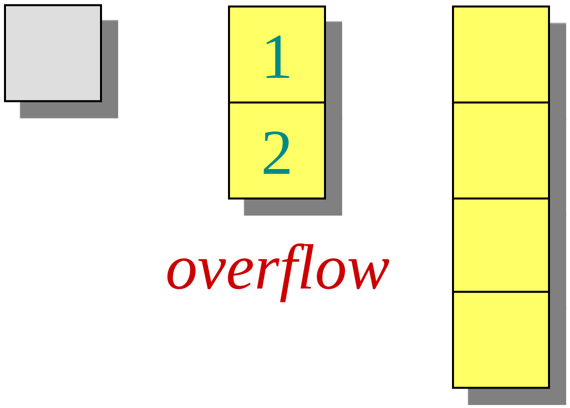
Example of a dynamic table

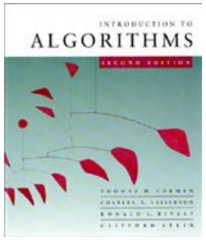
1. INSERT
2. INSERT



Example of a dynamic table

1. INSERT
2. INSERT
3. INSERT





Example of a dynamic table

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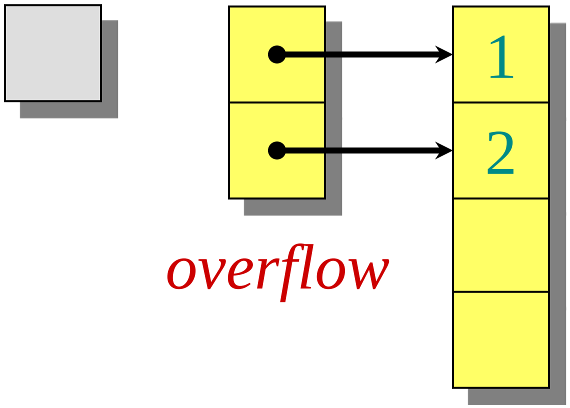

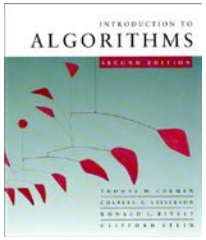

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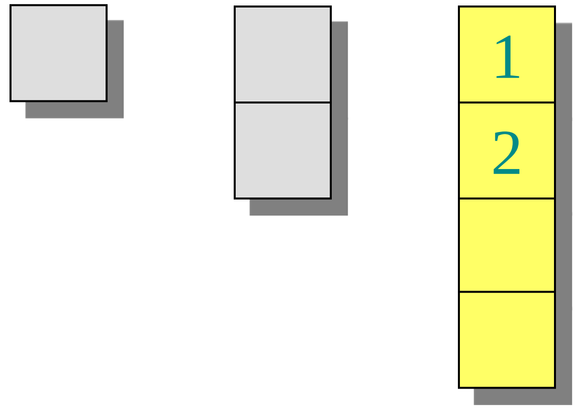
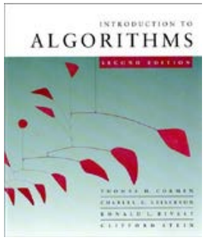
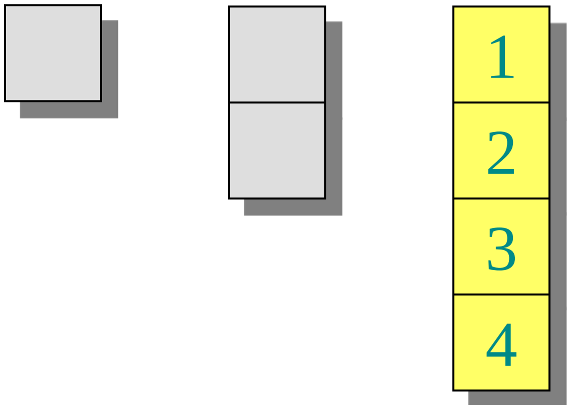




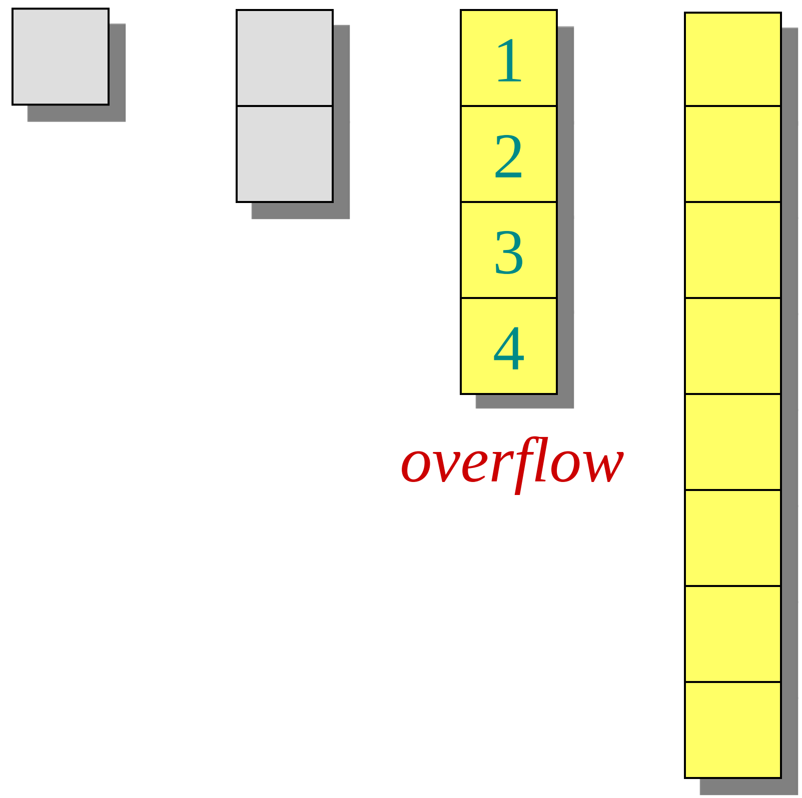
Example of a dynamic table

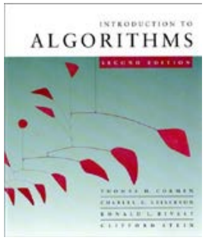
1. INSERT
2. INSERT
3. INSERT
4. INSERT



Example of a dynamic table

1. INSERT
2. INSERT
3. INSERT
4. INSERT
5. INSERT





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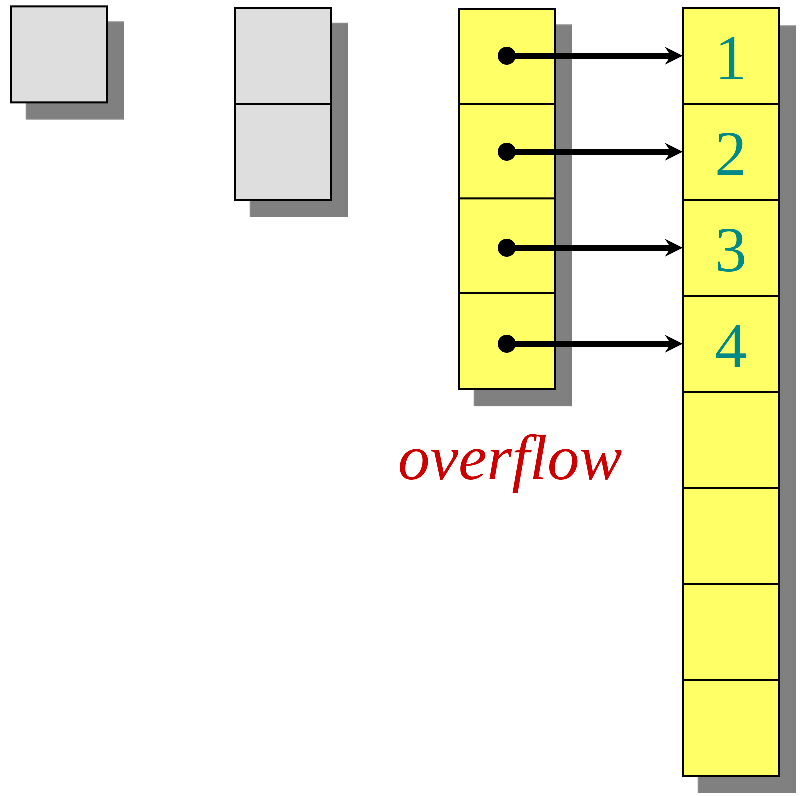

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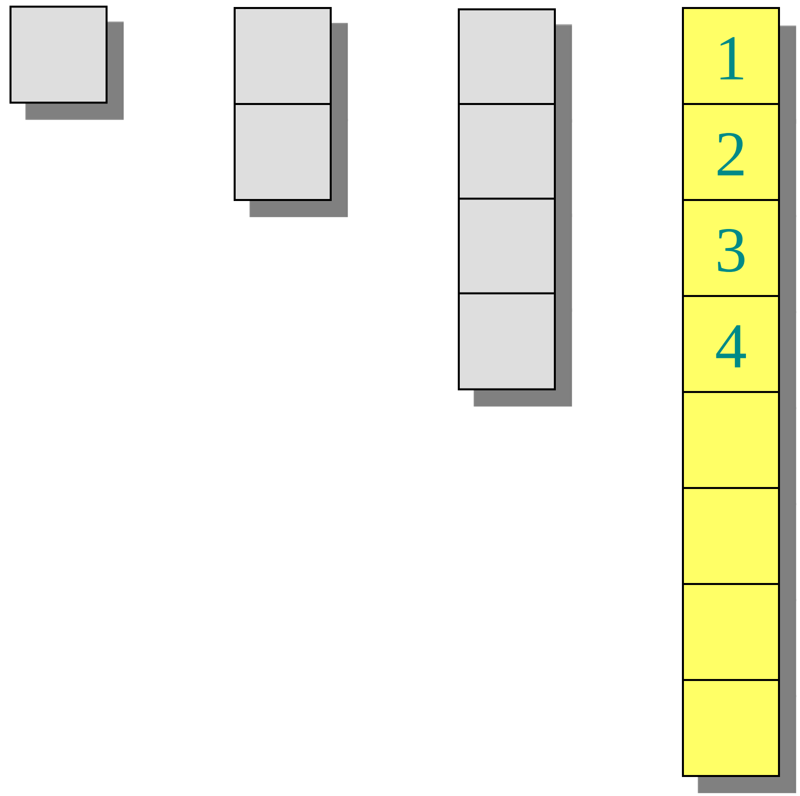
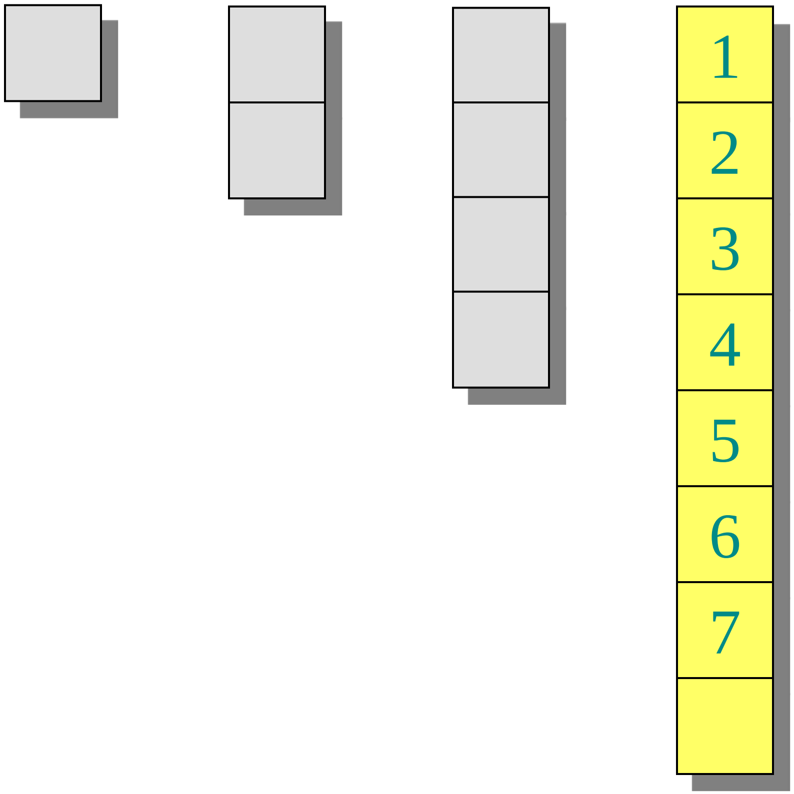
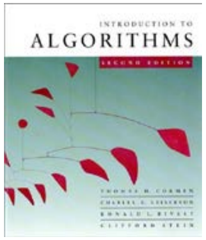


Example of a dynamic table

1. INSERT
2. INSERT
3. INSERT
4. INSERT
5. INSERT
6. INSERT
7. INSERT



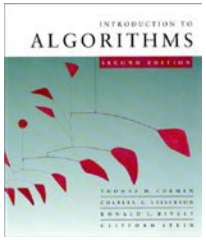


Worst-case analysis

Consider a sequence of n insertions. The worst-case time to execute one insertion is $\Theta(n)$. Therefore, the worst-case time for n insertions is $n \cdot \Theta(n) = \Theta(n^2)$.

WRONG! In fact, the worst-case cost for n insertions is only $\Theta(n) \ll \Theta(n^2)$.

Let's see why.

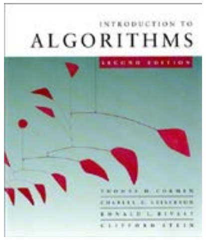


Tighter analysis

Let c_i = the cost of the i th insertion

$$= \begin{cases} i & \text{if } i-1 \text{ is an exact power of } 2, \\ 1 & \text{otherwise.} \end{cases}$$

i	1	2	3	4	5	6	7	8	9	10
$size_i$	1	2	4	4	8	8	8	8	16	16
c_i	1	2	3	1	5	1	1	1	9	1



Tighter analysis

Let c_i = the cost of the i th insertion

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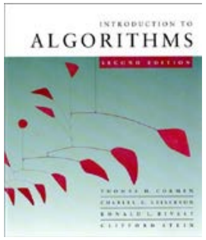
i	1	2	3	4	5	6	7	8	9	10
$size_i$	1	2	4	4	8	8	8	8	16	16
c_i	1	1	1	1	1	1	1	1	1	1
		1	2		4				8	



Tighter analysis (continued)

$$
\begin{aligned}
\text{Cost of } n \text{ insertions} &= \sum_{i=1}^{n} c_i \\
&\le n + \sum_{j=0}^{\lfloor \lg(n-1) \rfloor} 2^j \\
&\le 3n \\
&= \Theta(n) .
\end{aligned}
$$

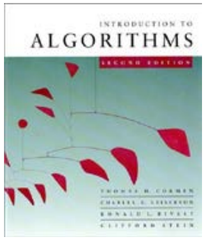
Thus, the average cost of each dynamic-table operation is $\Theta(n)/n = \Theta(1)$.

Amortized analysis

An ***amortized analysis*** is any strategy for analyzing a sequence of operations to show that the average cost per operation is small, even though a single operation within the sequence might be expensive.

Even though we're taking averages, however, probability is not involved!

- An amortized analysis guarantees the average performance of each operation in the *worst case*.



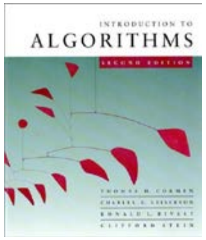
Types of amortized analyses

Three common amortization arguments:

- the ***aggregate*** method,
- the ***accounting*** method,
- the ***potential*** method.

We've just seen an aggregate analysis.

The aggregate method, though simple, lacks the precision of the other two methods. In particular, the accounting and potential methods allow a specific ***amortized cost*** to be allocated to each operation.

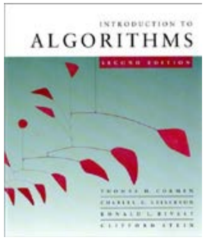


Accounting method

- Charge i th operation a fictitious ***amortized cost*** $\hat{c}_i$, where \$1 pays for 1 unit of work (*i.e.*, time).
- This fee is consumed to perform the operation.
- Any amount not immediately consumed is stored in the ***bank*** for use by subsequent operations.
- The bank balance must not go negative! We must ensure that

$$\sum_{i=1}^{n} c_i \le \sum_{i=1}^{n} \hat{c}_i$$

  for all n.
- Thus, the total amortized costs provide an upper bound on the total true costs.



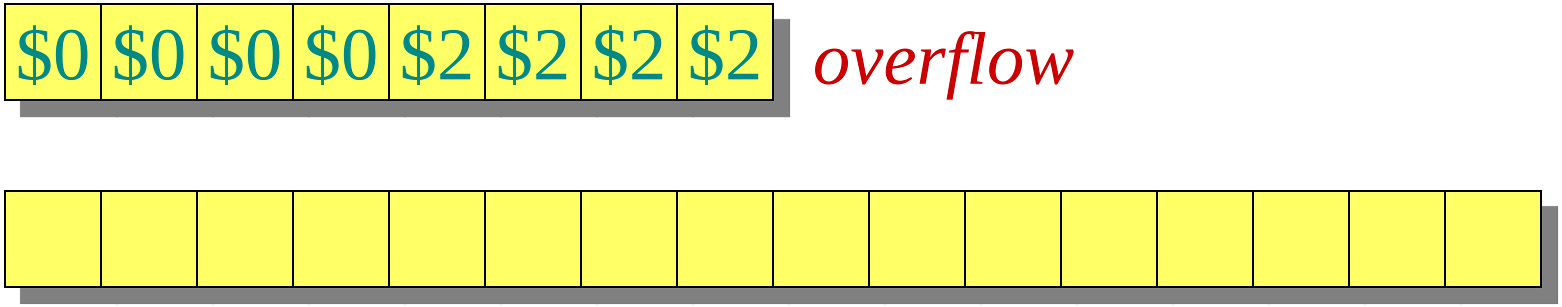
Accounting analysis of dynamic tables

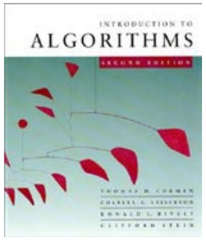
Charge an amortized cost of $\hat{c}_i = \$3$ for the ith insertion.

- $1 pays for the immediate insertion.
- $2 is stored for later table doubling.

When the table doubles, $1 pays to move a recent item, and $1 pays to move an old item.

Example:





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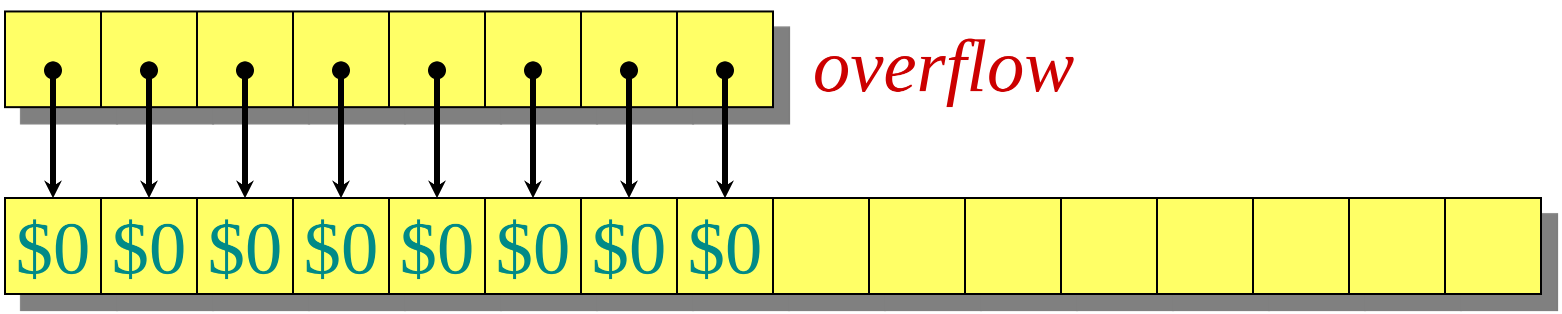

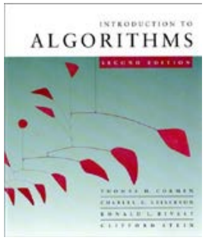

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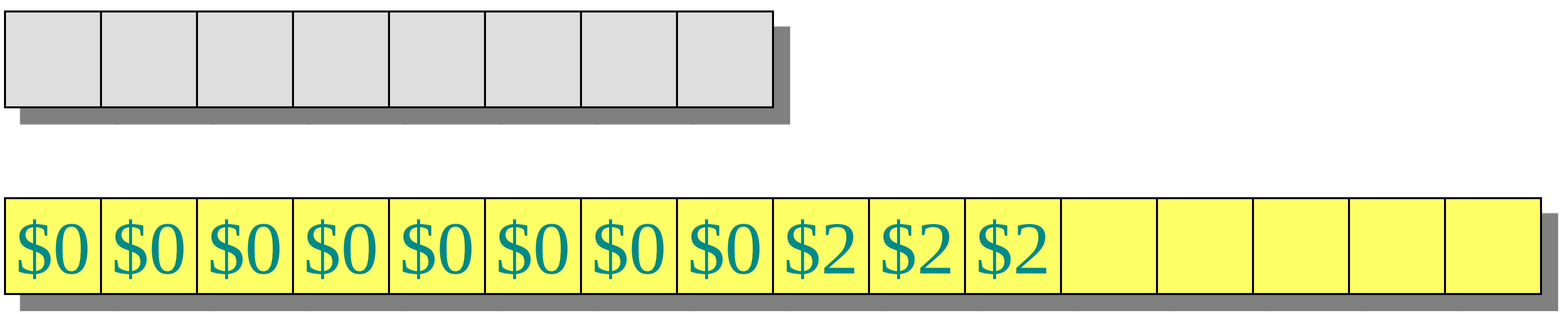
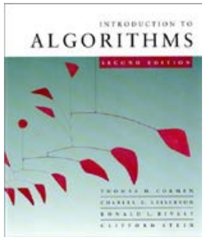


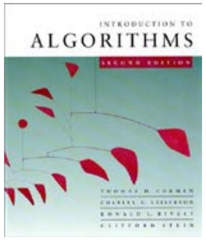


Accounting analysis (continued)

Key invariant: Bank balance never drops below 0. Thus, the sum of the amortized costs provides an upper bound on the sum of the true costs.

i	1	2	3	4	5	6	7	8	9	10
$size_i$	1	2	4	4	8	8	8	8	16	16
c_i	1	2	3	1	5	1	1	1	9	1
$\hat{c}_i$	2*	3	3	3	3	3	3	3	3	3
$bank_i$	1	2	2	4	2	4	6	8	2	4

*Okay, so I lied. The first operation costs only $2, not $3.

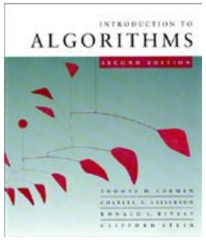


Potential method

IDEA: View the bank account as the potential energy (*à la* physics) of the dynamic set.

Framework:

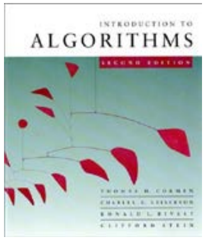
- Start with an initial data structure D_0.
- Operation i transforms D_{i-1} to D_i.
- The cost of operation i is c_i.
- Define a ***potential function*** $\Phi : \{D_i\} \to \mathbb{R}$, such that $\Phi(D_0) = 0$ and $\Phi(D_i) \geq 0$ for all i.
- The ***amortized cost*** $\hat{c}_i$ with respect to Φ is defined to be $\hat{c}_i = c_i + \Phi(D_i) - \Phi(D_{i-1})$.



Understanding potentials

$$\hat{c}_i = c_i + \underbrace{\Phi(D_i) - \Phi(D_{i-1})}_{\textit{potential difference } \Delta\Phi_i}$$

- If $\Delta\Phi_i > 0$, then $\hat{c}_i > c_i$. Operation i stores work in the data structure for later use.
- If $\Delta\Phi_i < 0$, then $\hat{c}_i < c_i$. The data structure delivers up stored work to help pay for operation i.



The amortized costs bound the true costs

The total amortized cost of n operations is

$$\sum_{i=1}^{n} \hat{c}_i = \sum_{i=1}^{n} \left(c_i + \Phi(D_i) - \Phi(D_{i-1}) \right)$$

Summing both sides.

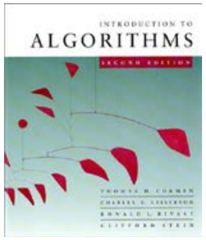
The amortized costs bound the true costs

The total amortized cost of n operations is

$$\sum_{i=1}^{n} \hat{c}_i = \sum_{i=1}^{n} \left(c_i + \Phi(D_i) - \Phi(D_{i-1}) \right)$$

$$= \sum_{i=1}^{n} c_i + \Phi(D_n) - \Phi(D_0)$$

The series telescopes.



The amortized costs bound the true costs

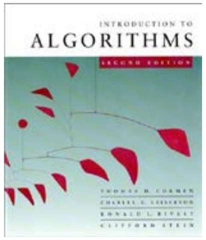
The total amortized cost of n operations is

$$\sum_{i=1}^{n} \hat{c}_i = \sum_{i=1}^{n} \left(c_i + \Phi(D_i) - \Phi(D_{i-1})\right)$$

$$= \sum_{i=1}^{n} c_i + \Phi(D_n) - \Phi(D_0)$$

$$\geq \sum_{i=1}^{n} c_i$$

since $\Phi(D_n) \geq 0$ and $\Phi(D_0) = 0$.



Potential analysis of table doubling

Define the potential of the table after the ith insertion by $\Phi(D_i) = 2i - 2^{\lceil \lg i \rceil}$. (Assume that $2^{\lceil \lg 0 \rceil} = 0$.)

Note:

- $\Phi(D_0) = 0$,
- $\Phi(D_i) \geq 0$ for all i.

Example:

•	•	•	•	•	•		

$\Phi = 2 \cdot 6 - 2^3 = 4$

(

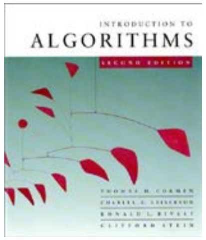
\$0	\$0	\$0	\$0	\$2	\$2		

accounting method)

Calculation of amortized costs

The amortized cost of the i th insertion is

$$\hat{c}_i = c_i + \Phi(D_i) - \Phi(D_{i-1})$$



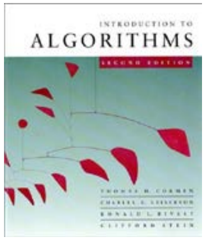
Calculation of amortized costs

The amortized cost of the i th insertion is

$$\hat{c}_i = c_i + \Phi(D_i) - \Phi(D_{i-1})$$

$$= \left.\begin{cases} i & \text{if } i - 1 \text{ is an exact power of } 2, \\ 1 & \text{otherwise;} \end{cases}\right\}$$

$$+ \left(2i - 2^{\lceil \lg i \rceil}\right) - \left(2(i-1) - 2^{\lceil \lg (i-1) \rceil}\right)$$



Calculation of amortized costs

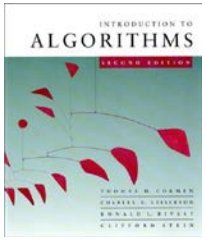
The amortized cost of the i th insertion is

$$
\begin{aligned}
\hat{c}_i &= c_i + \Phi(D_i) - \Phi(D_{i-1}) \\
&= \begin{cases} i & \text{if } i-1 \text{ is an exact power of } 2, \\ 1 & \text{otherwise;} \end{cases} \\
&\quad + \left(2i - 2^{\lceil \lg i \rceil}\right) - \left(2(i-1) - 2^{\lceil \lg (i-1) \rceil}\right) \\
&= \begin{cases} i & \text{if } i-1 \text{ is an exact power of } 2, \\ 1 & \text{otherwise;} \end{cases} \\
&\quad + 2 - 2^{\lceil \lg i \rceil} + 2^{\lceil \lg (i-1) \rceil}.
\end{aligned}
$$

Calculation

Case 1: $i - 1$ is an exact power of 2.

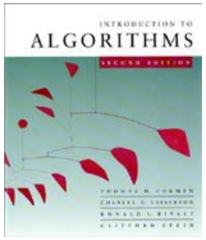
$$\hat{c}_i = i + 2 - 2^{\lceil \lg i \rceil} + 2^{\lceil \lg (i-1) \rceil}$$



Calculation

Case 1: $i - 1$ is an exact power of 2.

$$\begin{aligned}\hat{c}_i &= i + 2 - 2^{\lceil \lg i \rceil} + 2^{\lceil \lg (i-1) \rceil} \\ &= i + 2 - 2(i-1) + (i-1)\end{aligned}$$



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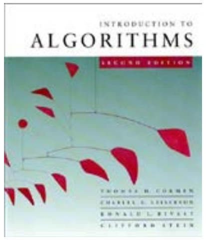
$$
\begin{aligned}
\hat{c}_i &= i + 2 - 2^{\lceil \lg i \rceil} + 2^{\lceil \lg (i-1) \rceil} \\
&= i + 2 - 2(i - 1) + (i - 1) \\
&= i + 2 - 2i + 2 + i - 1
\end{aligned}
$$



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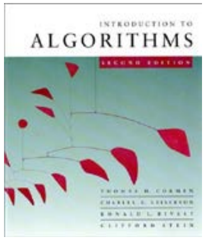
&= i + 2 - 2(i - 1) + (i - 1) \\
&= i + 2 - 2i + 2 + i - 1 \\
&= 3
\end{aligned}
$$



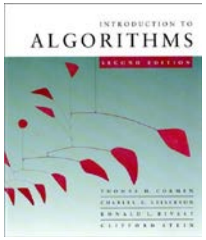
Calculation

Case 1: $i - 1$ is an exact power of 2.

$$\hat{c}_i = i + 2 - 2^{\lceil \lg i \rceil} + 2^{\lceil \lg (i-1) \rceil}$$
$$= i + 2 - 2(i - 1) + (i - 1)$$
$$= i + 2 - 2i + 2 + i - 1$$
$$= 3$$

Case 2: $i - 1$ is *not* an exact power of 2.

$$\hat{c}_i = 1 + 2 - 2^{\lceil \lg i \rceil} + 2^{\lceil \lg (i-1) \rceil}$$



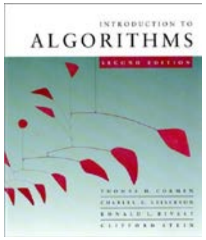
Calculation

Case 1: $i - 1$ is an exact power of 2.

$$\begin{aligned}\hat{c}_i &= i + 2 - 2^{\lceil \lg i \rceil} + 2^{\lceil \lg (i-1) \rceil} \\ &= i + 2 - 2(i-1) + (i-1) \\ &= i + 2 - 2i + 2 + i - 1 \\ &= 3\end{aligned}$$

Case 2: $i - 1$ is *not* an exact power of 2.

$$\begin{aligned}\hat{c}_i &= 1 + 2 - 2^{\lceil \lg i \rceil} + 2^{\lceil \lg (i-1) \rceil} \\ &= 3 \qquad \text{(since } 2^{\lceil \lg i \rceil} = 2^{\lceil \lg (i-1) \rceil}\text{)}\end{aligned}$$



Calculation

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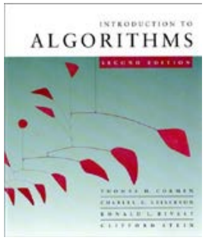
$$\begin{aligned}\hat{c}_i &= 1 + 2 - 2^{\lceil \lg i \rceil} + 2^{\lceil \lg (i-1) \rceil} \\ &= 3\end{aligned}$$

Therefore, n insertions cost $\Theta(n)$ in the worst case.



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$$\begin{aligned}\hat{c}_i &= 1 + 2 - 2^{\lceil \lg i \rceil} + 2^{\lceil \lg (i-1) \rceil} \\ &= 3\end{aligned}$$

Therefore, n insertions cost $\Theta(n)$ in the worst case.

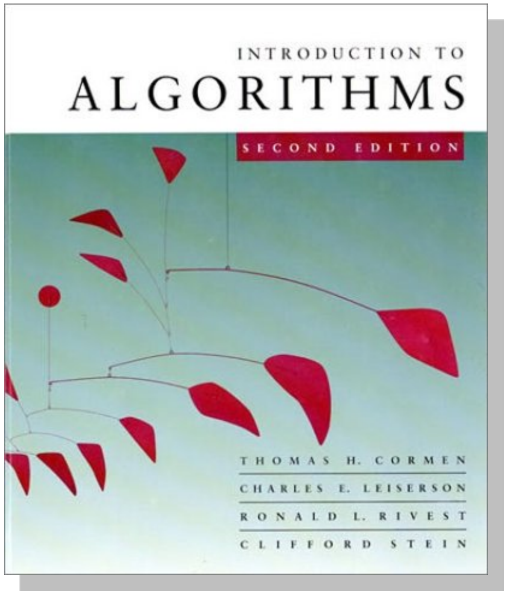
Exercise: Fix the bug in this analysis to show that the amortized cost of the first insertion is only 2.

Conclusions

- Amortized costs can provide a clean abstraction of data-structure performance.
- Any of the analysis methods can be used when an amortized analysis is called for, but each method has some situations where it is arguably the simplest or most precise.
- Different schemes may work for assigning amortized costs in the accounting method, or potentials in the potential method, sometimes yielding radically different bounds.

Introduction to Algorithms

6.046J/18.401J

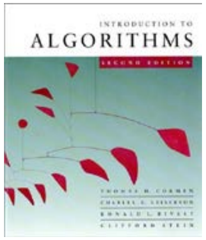


LECTURE 14

Competitive Analysis

- Self-organizing lists
- Move-to-front heuristic
- Competitive analysis of MTF

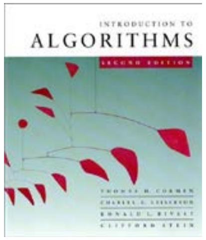
Prof. Charles E. Leiserson



Self-organizing lists

List L of n elements

- The operation ACCESS(x) costs $\mathrm{rank}_L(x) =$ distance of x from the head of L.
- L can be reordered by transposing adjacent elements at a cost of 1.



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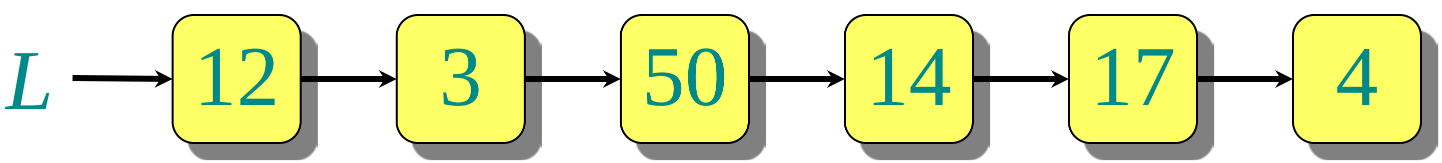

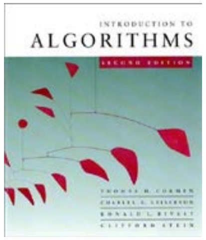

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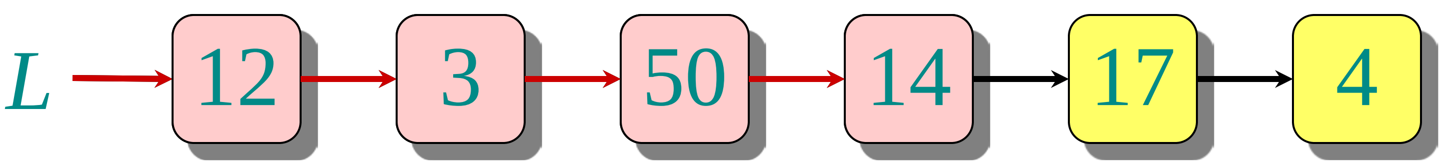
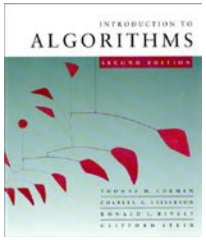


Accessing the element with key 14 costs 4.



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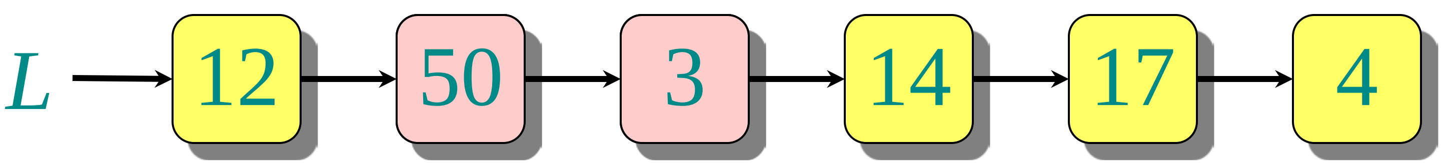
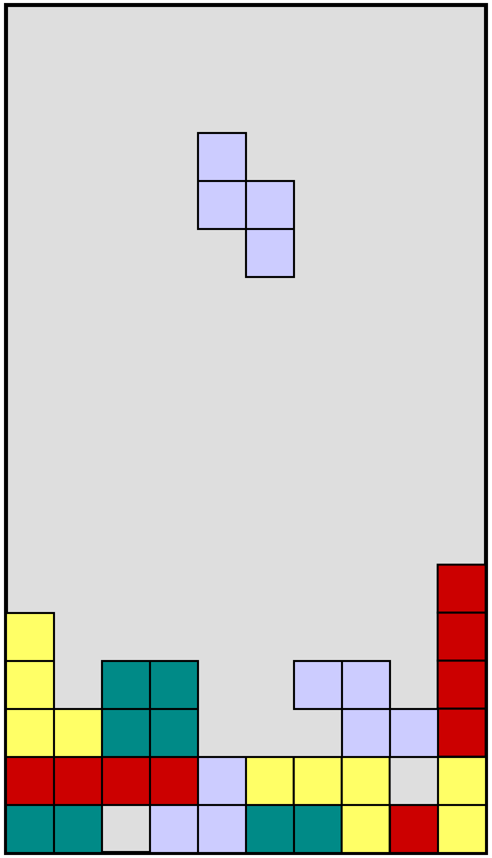


Transposing 3 and 50 costs 1.

On-line and off-line problems

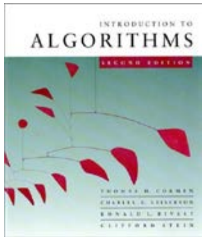
Definition. A sequence S of operations is provided one at a time. For each operation, an ***on-line*** algorithm A must execute the operation immediately without any knowledge of future operations (e.g., *Tetris*).

An ***off-line*** algorithm may see the whole sequence S in advance.



The game of Tetris

Goal: Minimize the total cost $C_A(S)$.

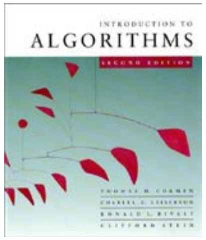


Worst-case analysis of self-organizing lists

An adversary always accesses the tail (nth) element of L. Then, for any on-line algorithm A, we have

$$C_A(S) = \Omega(|S| \cdot n)$$

in the worst case.



Average-case analysis of self-organizing lists

Suppose that element x is accessed with probability $p(x)$. Then, we have

$$E[C_A(S)] = \sum_{x \in L} p(x) \cdot \mathrm{rank}_L(x),$$

which is minimized when L is sorted in decreasing order with respect to p.

Heuristic: Keep a count of the number of times each element is accessed, and maintain L in order of decreasing count.

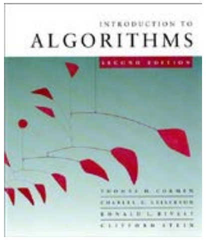
The move-to-front heuristic

Practice: Implementers discovered that the ***move-to-front (MTF)*** heuristic empirically yields good results.

IDEA: After accessing x, move x to the head of L using transposes:

$$\text{cost} = 2 \cdot \text{rank}_L(x)\ .$$

The MTF heuristic responds well to locality in the access sequence S.



Competitive analysis

Definition. An on-line algorithm A is ***α-competitive*** if there exists a constant k such that for any sequence S of operations,

$$C_A(S) \le \alpha \cdot C_{\mathrm{OPT}}(S) + k\ ,$$

where OPT is the optimal off-line algorithm ("God's algorithm").

MTF is O(1)-competitive

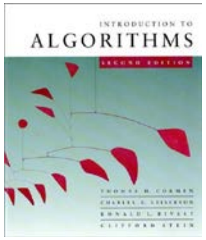
Theorem. MTF is 4-competitive for self-organizing lists.

MTF is O(1)-competitive

Theorem. MTF is 4-competitive for self-organizing lists.

Proof. Let L_i be MTF's list after the ith access, and let L_i* be OPT's list after the ith access.

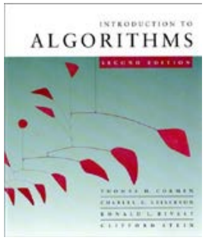
Let c_i = MTF's cost for the ith operation
$= 2 \cdot \text{rank}_{L_{i-1}}(x)$ if it accesses x;
c_i* = OPT's cost for the ith operation
$= \text{rank}_{L_{i-1}*}(x) + t_i$,
where t_i is the number of transposes that OPT performs.



Potential function

Define the potential function $\Phi:\{L_i\} \to \mathbb{R}$ by

$$\Phi(L_i) = 2 \cdot |\{(x, y) : x \prec_{L_i} y \text{ and } y \prec_{L_i{}^*} x\}|$$
$$= 2 \cdot \#\ \textbf{\textit{inversions}}\ .$$



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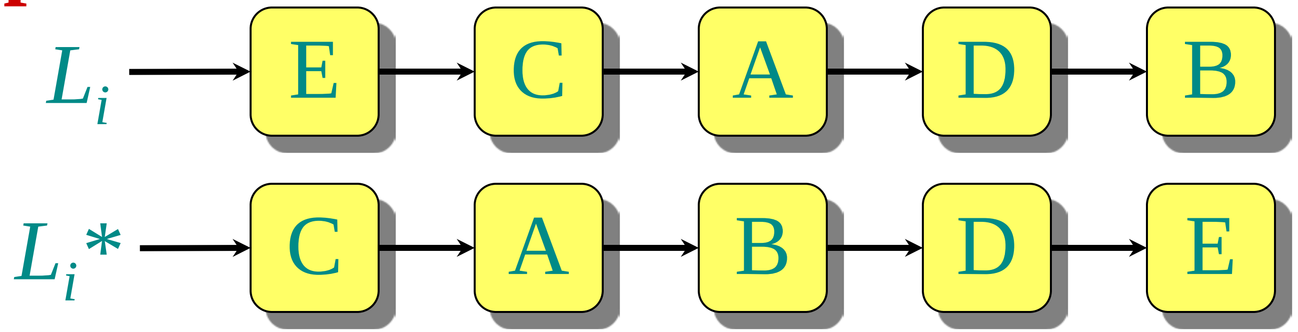

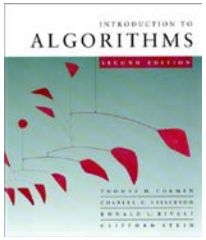

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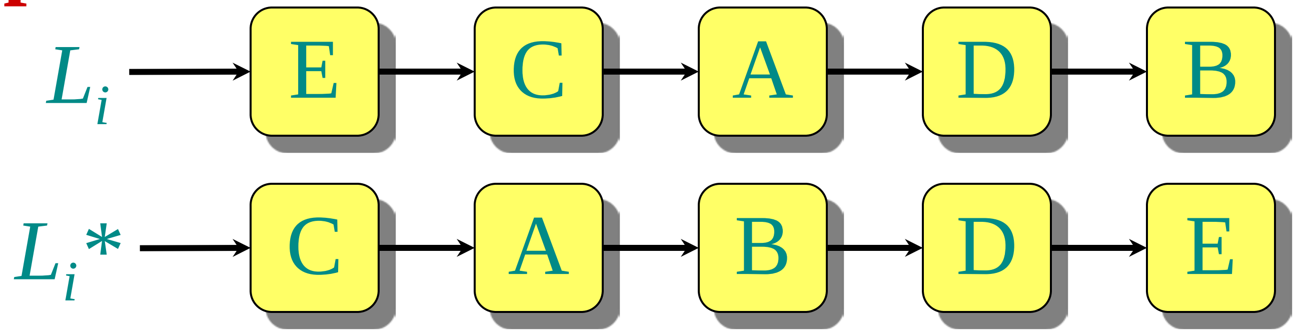
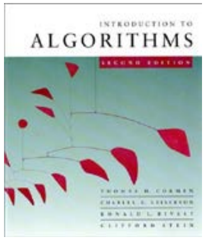


$$\Phi(L_i) = 2 \cdot |\{\ldots\}|$$



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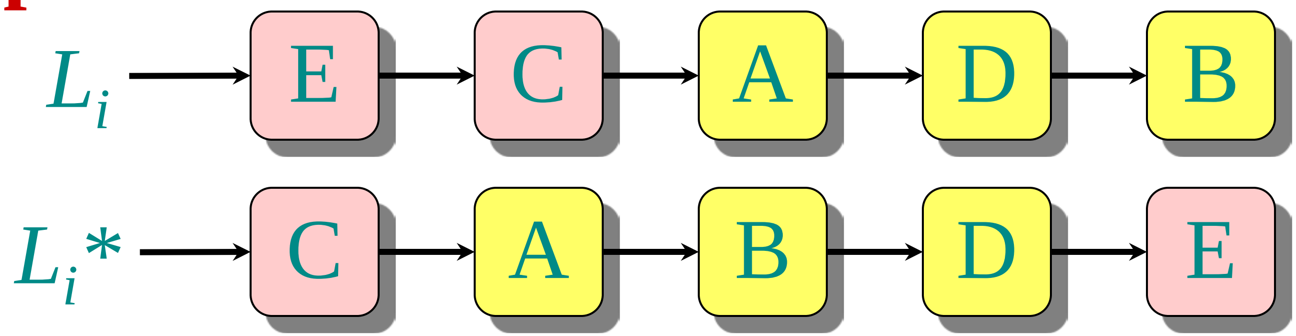
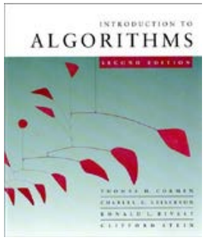


$$\Phi(L_i) = 2 \cdot |\{(E,C), \ldots\}|$$



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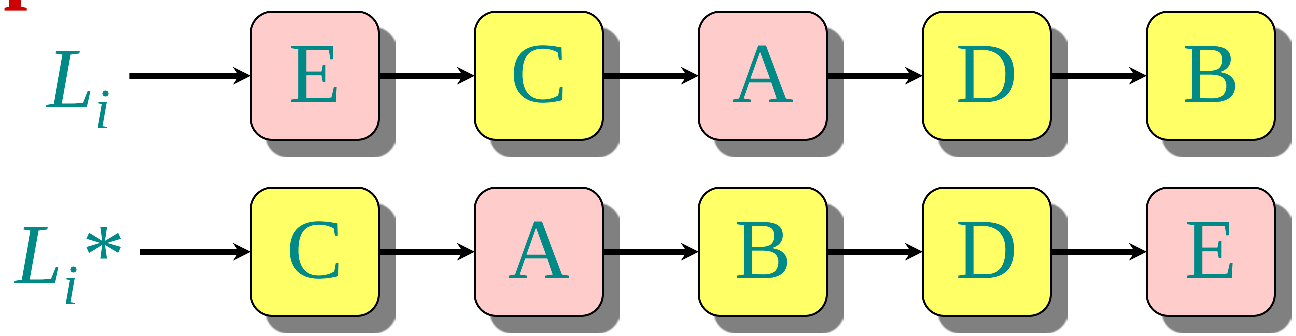
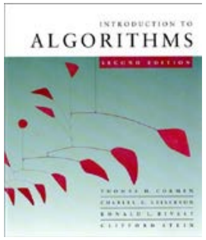


$$\Phi(L_i) = 2 \cdot |\{(E,C), (E,A), \ldots\}|$$



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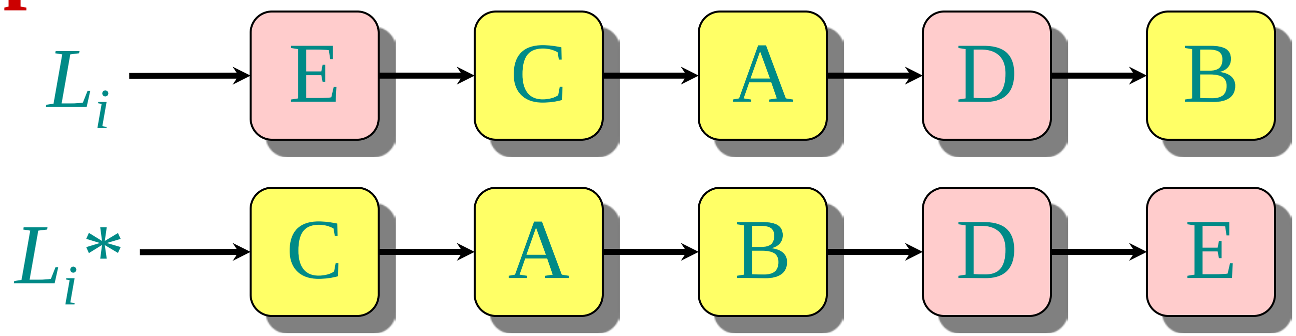
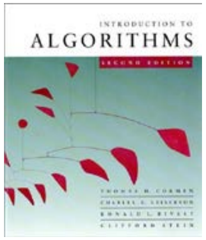


$$\Phi(L_i) = 2 \cdot |\{(\mathrm{E,C}), (\mathrm{E,A}), (\mathrm{E,D}), \ldots\}|$$



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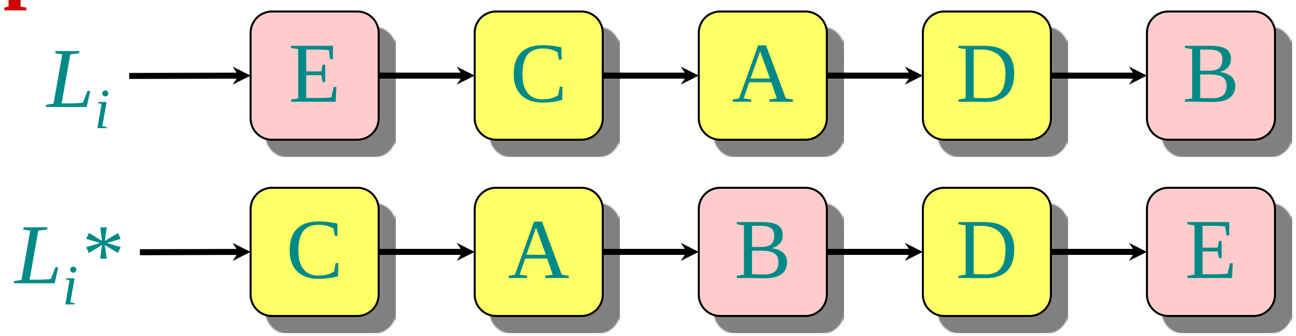

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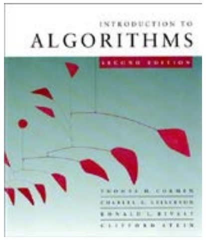

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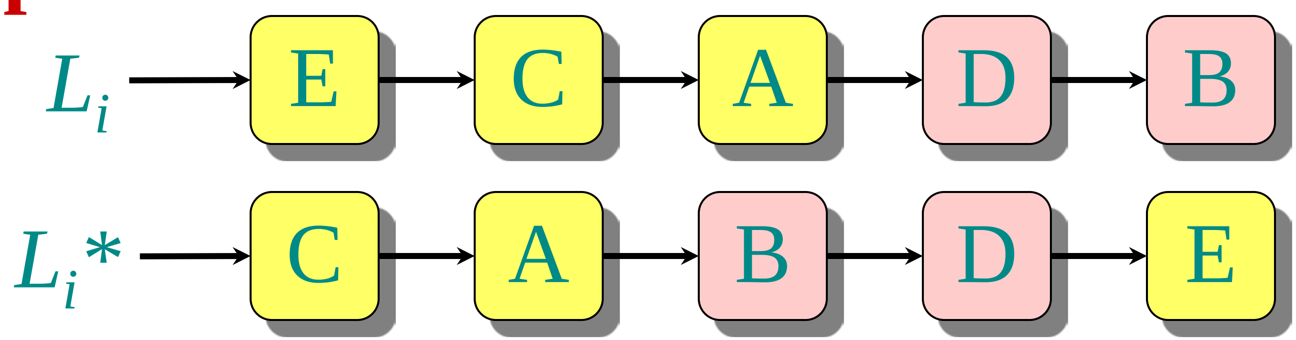

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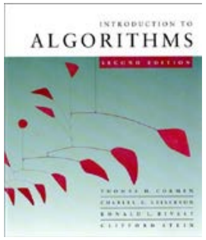

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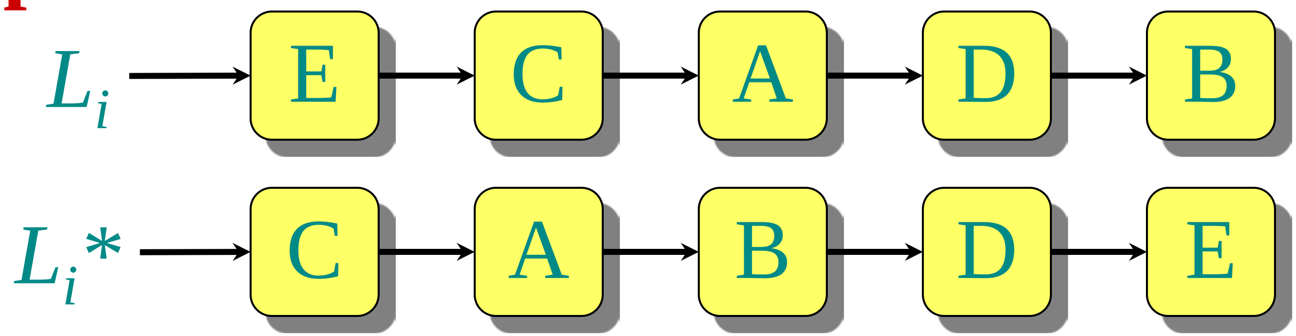

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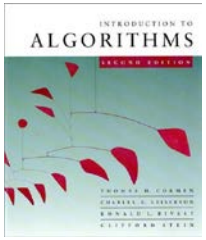
$$= 10\ .$$



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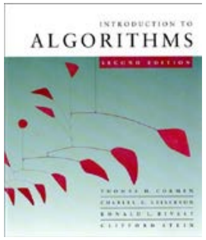

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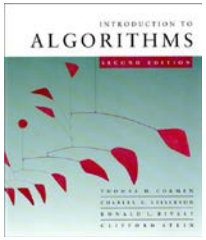
Note that

- $\Phi(L_i) \geq 0$ for $i = 0, 1, \ldots,$
- $\Phi(L_0) = 0$ if MTF and OPT start with the same list.



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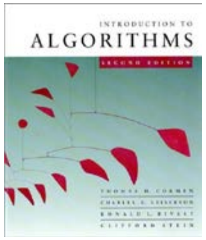
How much does Φ change from 1 transpose?

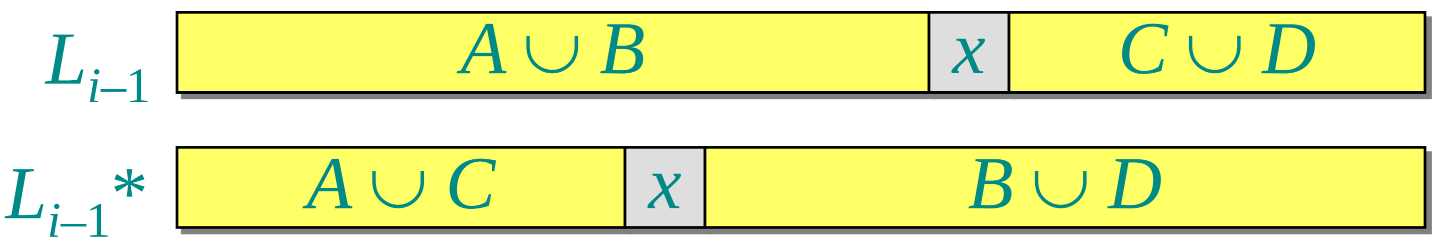
- A transpose creates/destroys 1 inversion.
- $\Delta\Phi = \pm 2$.



What happens on an access?

Suppose that operation i accesses element x, and define

$$
\begin{aligned}
A &= \{y \in L_{i-1} : y \prec_{L_{i-1}} x \text{ and } y \prec_{L_{i-1}^*} x\}, \\
B &= \{y \in L_{i-1} : y \prec_{L_{i-1}} x \text{ and } y \succ_{L_{i-1}^*} x\}, \\
C &= \{y \in L_{i-1} : y \succ_{L_{i-1}} x \text{ and } y \prec_{L_{i-1}^*} x\}, \\
D &= \{y \in L_{i-1} : y \succ_{L_{i-1}} x \text{ and } y \succ_{L_{i-1}^*} x\}.
\end{aligned}
$$



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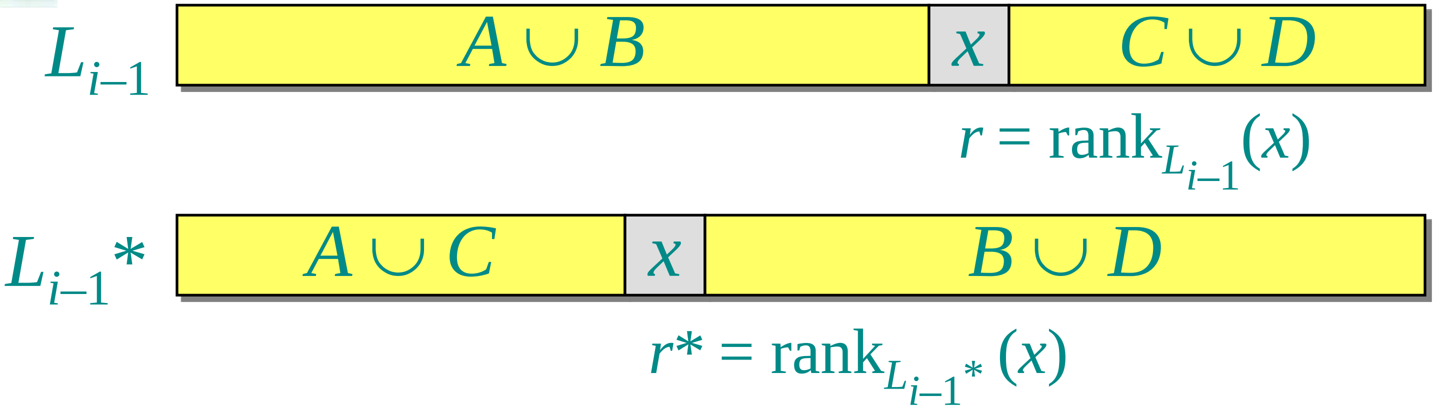
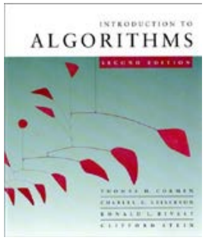


We have $r = |A| + |B| + 1$ and $r* = |A| + |C| + 1$.



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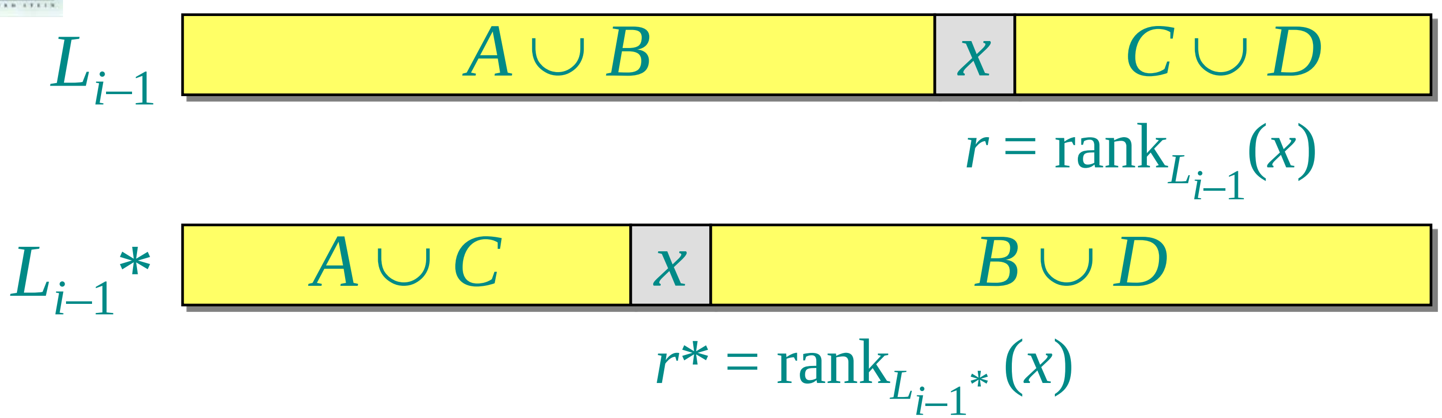
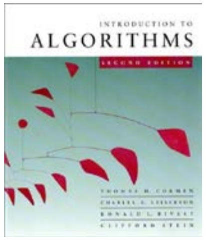


We have $r = |A| + |B| + 1$ and $r^* = |A| + |C| + 1$.

When MTF moves x to the front, it creates $|A|$ inversions and destroys $|B|$ inversions. Each transpose by OPT creates ≤ 1 inversion. Thus, we have

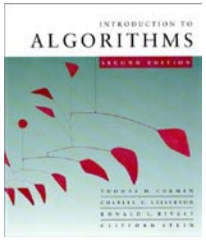
$$\Phi(L_i) - \Phi(L_{i-1}) \leq 2(|A| - |B| + t_i) .$$



Amortized cost

The amortized cost for the ith operation of MTF with respect to Φ is

$$\hat{c}_i = c_i + \Phi(L_i) - \Phi(L_{i-1})$$



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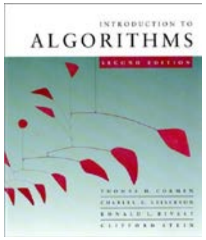
$$\begin{aligned}\hat{c}_i &= c_i + \Phi(L_i) - \Phi(L_{i-1}) \\ &\le 2r + 2(|A| - |B| + t_i)\end{aligned}$$



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$$\begin{aligned}\hat{c}_i &= c_i + \Phi(L_i) - \Phi(L_{i-1}) \\ &\le 2r + 2(|A| - |B| + t_i) \\ &= 2r + 2(|A| - (r - 1 - |A|) + t_i)\end{aligned}$$

(since $r = |A| + |B| + 1$)

Amortized cost

The amortized cost for the *i*th operation of MTF with respect to Φ is

$$
\begin{aligned}
\hat{c}_i &= c_i + \Phi(L_i) - \Phi(L_{i-1}) \\
&\le 2r + 2(|A| - |B| + t_i) \\
&= 2r + 2(|A| - (r - 1 - |A|) + t_i) \\
&= 2r + 4|A| - 2r + 2 + 2t_i
\end{aligned}
$$

Amortized cost

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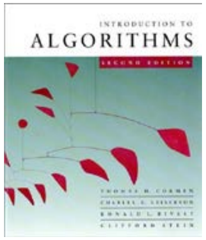

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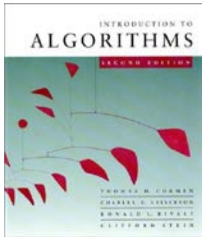
&= 2r + 4|A| - 2r + 2 + 2t_i \\
&= 4|A| + 2 + 2t_i \\
&\le 4(r^* + t_i)
\end{aligned}
$$

(since $r^* = |A| + |C| + 1 \ge |A| + 1$)



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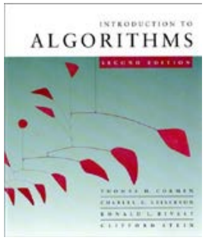
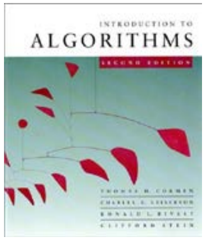
&= 2r + 4|A| - 2r + 2 + 2t_i \\
&= 4|A| + 2 + 2t_i \\
&\le 4(r^* + t_i) \\
&= 4c_i^*.
\end{aligned}$$



The grand finale

Thus, we have

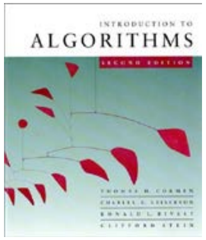
$$C_{\mathrm{MTF}}(S) = \sum_{i=1}^{|S|} c_i$$



The grand finale

Thus, we have

$$
\begin{aligned}
C_{\mathrm{MTF}}(S) &= \sum_{i=1}^{|S|} c_i \\
&= \sum_{i=1}^{|S|} \left(\hat{c}_i + \Phi(L_{i-1}) - \Phi(L_i) \right)
\end{aligned}
$$



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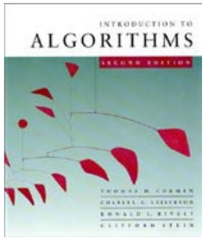
&\le \left(\sum_{i=1}^{|S|} 4c_i^*\right) + \Phi(L_0) - \Phi(L_{|S|})
\end{aligned}
$$

The grand finale

Thus, we have

$$
\begin{aligned}
C_{\mathrm{MTF}}(S) &= \sum_{i=1}^{|S|} c_i \\
&= \sum_{i=1}^{|S|} \left(\hat{c}_i + \Phi(L_{i-1}) - \Phi(L_i)\right) \\
&\le \left(\sum_{i=1}^{|S|} 4c_i^*\right) + \Phi(L_0) - \Phi(L_{|S|}) \\
&\le 4 \cdot C_{\mathrm{OPT}}(S),
\end{aligned}
$$

since $\Phi(L_0) = 0$ and $\Phi(L_{|S|}) \ge 0$. ∎



Addendum

If we count transpositions that move x toward the front as "free" (models splicing x in and out of L in constant time), then MTF is 2-competitive.

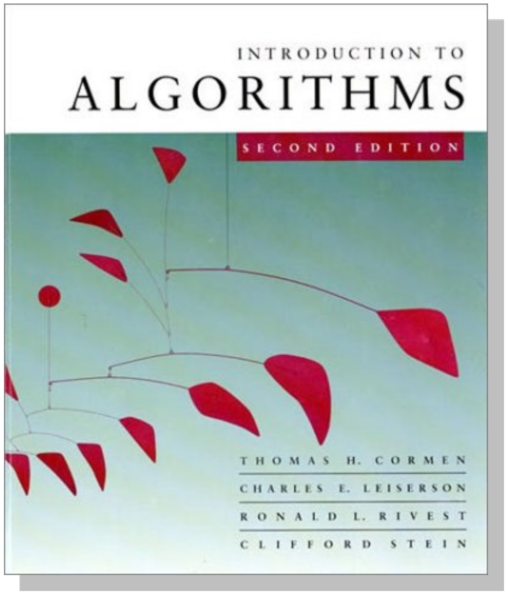
Addendum

If we count transpositions that move x toward the front as “free” (models splicing x in and out of L in constant time), then MTF is 2-competitive.

What if $L_0 \neq L_0{}^*$?

- Then, $\Phi(L_0)$ might be $\Theta(n^2)$ in the worst case.
- Thus, $C_{\text{MTF}}(S) \leq 4 \cdot C_{\text{OPT}}(S) + \Theta(n^2)$, which is still 4-competitive, since n^2 is constant as $|S| \to \infty$.

Introduction to Algorithms
6.046J/18.401J

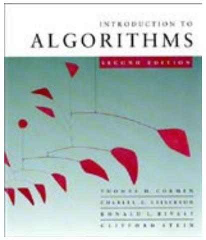


LECTURE 15

Dynamic Programming

- Longest common subsequence
- Optimal substructure
- Overlapping subproblems

Prof. Charles E. Leiserson

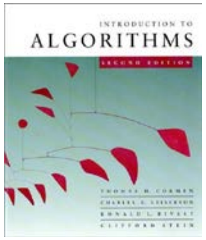


Dynamic programming

Design technique, like divide-and-conquer.

Example: ***Longest Common Subsequence (LCS)***

- Given two sequences $x[1 \,.\,.\, m]$ and $y[1 \,.\,.\, n]$, find a longest subsequence common to them both.



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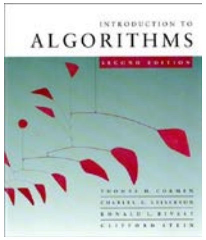

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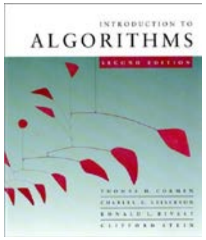
x: A B C B D A B

y: B D C A B A



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Design technique, like divide-and-conquer.

Example: *Longest Common Subsequence (LCS)*

- Given two sequences $x[1 \,..\, m]$ and $y[1 \,..\, n]$, find a longest subsequence common to them both.

"a" *not* "the"

x: A B C B D A B

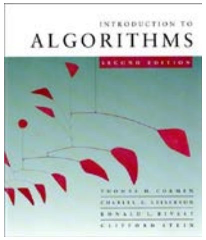
y: B D C A B A

BCBA = LCS(x, y)

functional notation, but not a function

Brute-force LCS algorithm

Check every subsequence of $x[1 \,.\,.\, m]$ to see if it is also a subsequence of $y[1 \,.\,.\, n]$.



Brute-force LCS algorithm

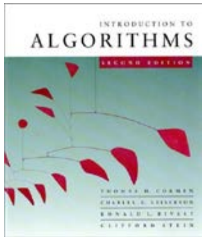
Check every subsequence of $x[1 \,.\,.\, m]$ to see if it is also a subsequence of $y[1 \,.\,.\, n]$.

Analysis

- Checking $= O(n)$ time per subsequence.
- 2^m subsequences of x (each bit-vector of length m determines a distinct subsequence of x).

Worst-case running time $= O(n2^m)$

$= \text{exponential time.}$



Towards a better algorithm

Simplification:

1. Look at the *length* of a longest-common subsequence.
2. Extend the algorithm to find the LCS itself.

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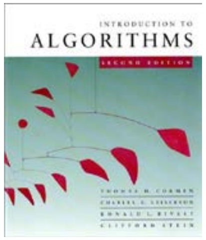
Notation: Denote the length of a sequence s by $|s|$.



Towards a better algorithm

Simplification:

1. Look at the *length* of a longest-common subsequence.
2. Extend the algorithm to find the LCS itself.

Notation: Denote the length of a sequence s by $|s|$.

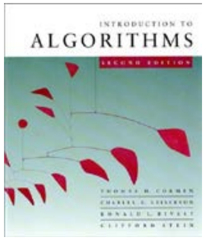
Strategy: Consider ***prefixes*** of x and y.

- Define $c[i, j] = |\text{LCS}(x[1 \,.\,.\, i], y[1 \,.\,.\, j])|$.
- Then, $c[m, n] = |\text{LCS}(x, y)|$.

Recursive formulation

Theorem.

$$c[i, j] = \begin{cases} c[i-1, j-1] + 1 & \text{if } x[i] = y[j], \\ \max\{c[i-1, j], c[i, j-1]\} & \text{otherwise.} \end{cases}$$



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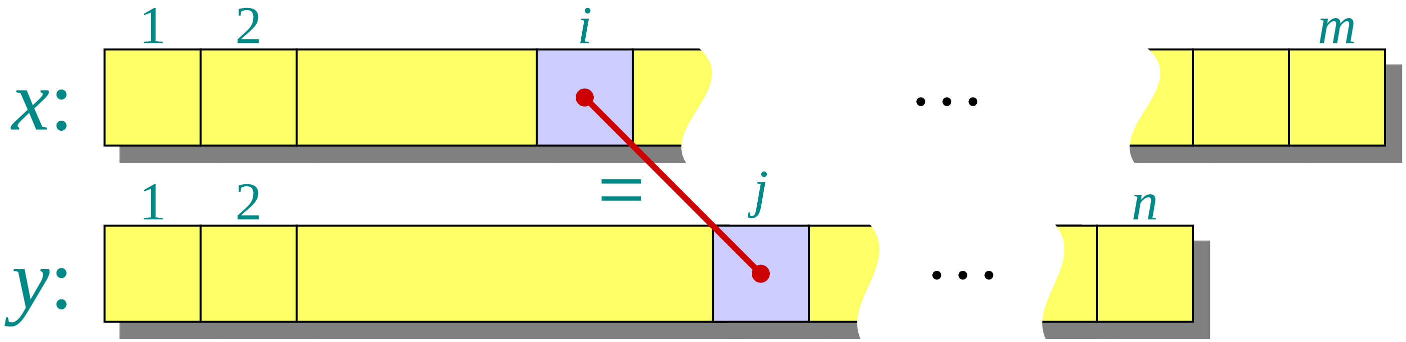
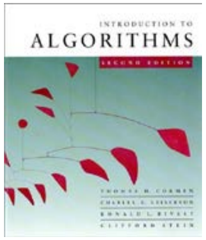
Proof. Case $x[i] = y[j]$:





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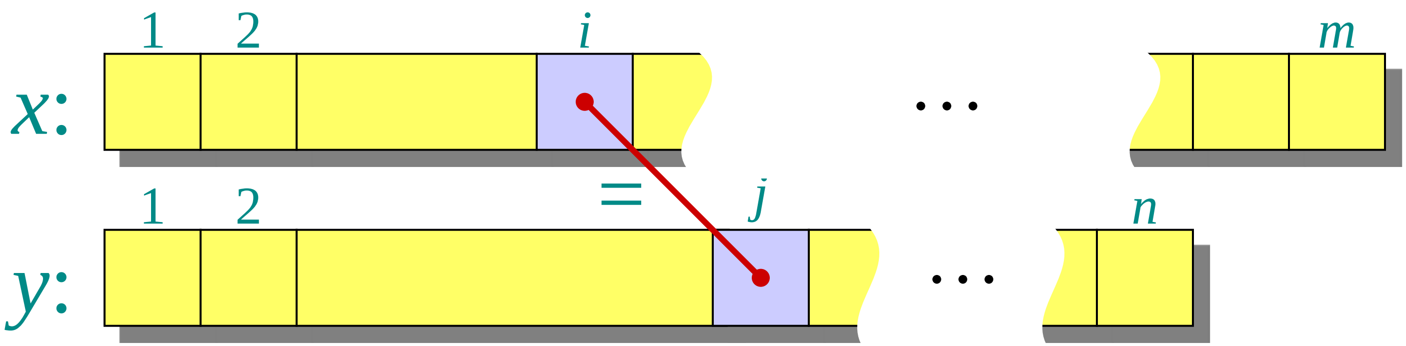
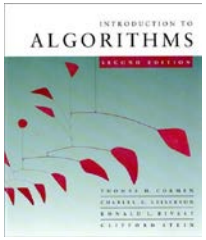


Let $z[1 \,.\,.\, k] = \text{LCS}(x[1 \,.\,.\, i], y[1 \,.\,.\, j])$, where $c[i, j] = k$. Then, $z[k] = x[i]$, or else z could be extended. Thus, $z[1 \,.\,.\, k-1]$ is CS of $x[1 \,.\,.\, i-1]$ and $y[1 \,.\,.\, j-1]$.

Proof (continued)

Claim: $z[1\,..\,k-1] = \mathrm{LCS}(x[1\,..\,i-1], y[1\,..\,j-1])$.

Suppose w is a longer CS of $x[1\,..\,i-1]$ and $y[1\,..\,j-1]$, that is, $|w| > k-1$. Then, ***cut and paste***: $w \,\|\, z[k]$ (w concatenated with $z[k]$) is a common subsequence of $x[1\,..\,i]$ and $y[1\,..\,j]$ with $\left| w \,\|\, z[k] \right| > k$. Contradiction, proving the claim.



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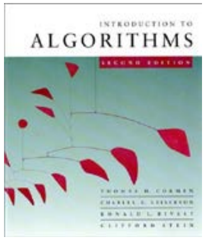
Thus, $c[i-1, j-1] = k-1$, which implies that $c[i, j] = c[i-1, j-1] + 1$.

Other cases are similar. $\square$

Dynamic-programming hallmark #1

Optimal substructure

An optimal solution to a problem (instance) contains optimal solutions to subproblems.

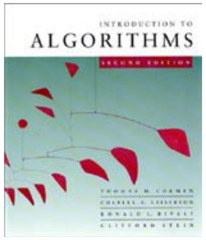


Dynamic-programming hallmark #1

Optimal substructure

An optimal solution to a problem (instance) contains optimal solutions to subproblems.

If $z = \text{LCS}(x, y)$, then any prefix of z is an LCS of a prefix of x and a prefix of y.



Recursive algorithm for LCS

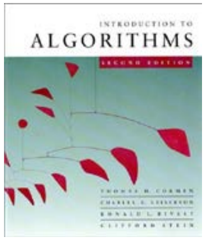
LCS(x, y, i, j) // ignoring base cases

if $x[i] = y[j]$

then $c[i, j] \leftarrow \text{LCS}(x, y, i–1, j–1) + 1$

else $c[i, j] \leftarrow \max\left\{\begin{array}{l}\text{LCS}(x, y, i–1, j), \\ \text{LCS}(x, y, i, j–1)\end{array}\right\}$

return $c[i, j]$



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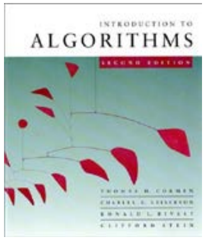
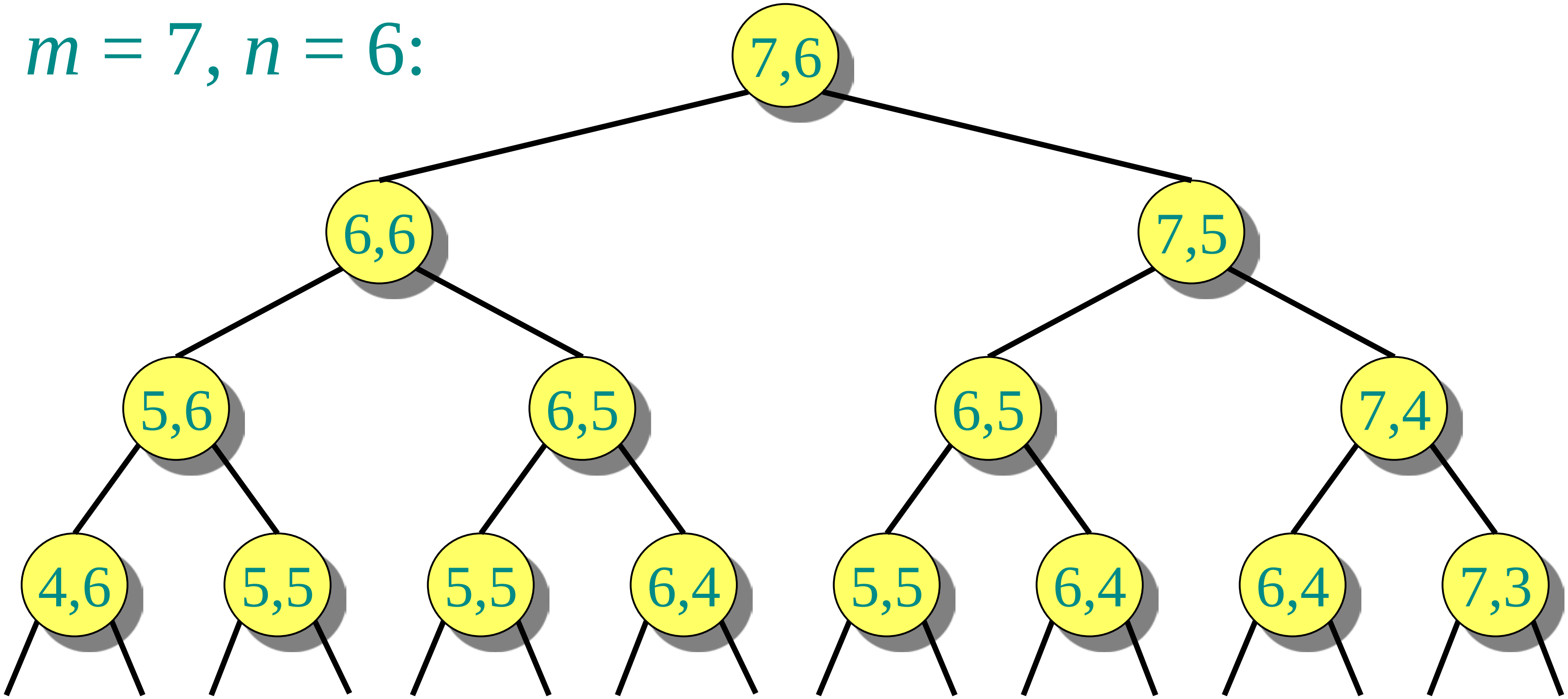
LCS(x, y, i, j) // ignoring base cases
  if $x[i] = y[j]$
    then $c[i, j] \leftarrow$ LCS$(x, y, i-1, j-1) + 1$
    else $c[i, j] \leftarrow \max\{LCS(x, y, i-1, j),$
              LCS$(x, y, i, j-1)\}$
  return $c[i, j]$

Worse case: $x[i] \neq y[j]$, in which case the algorithm evaluates two subproblems, each with only one parameter decremented.



Recursion tree

$m = 7, n = 6$:



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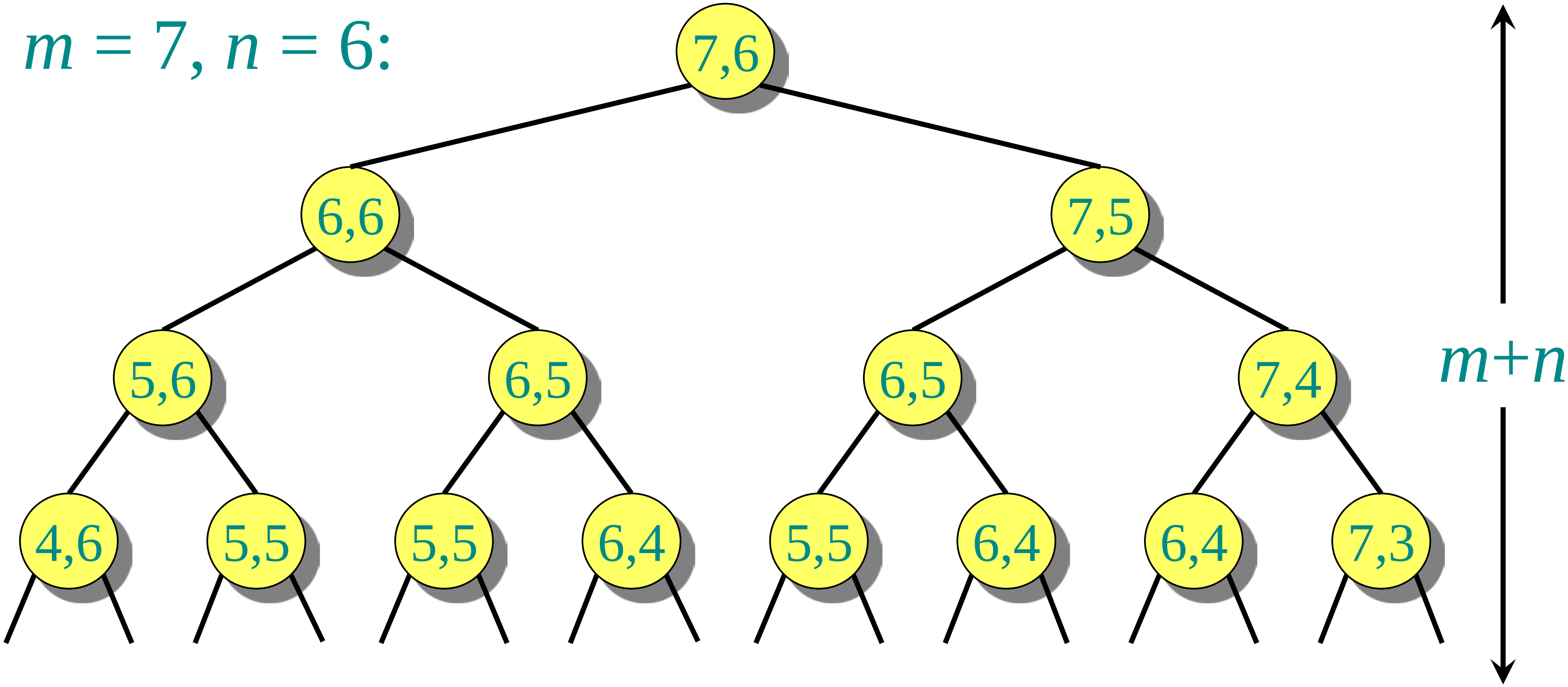

Height $= m + n \Rightarrow$ work potentially exponential.

Recursion tree

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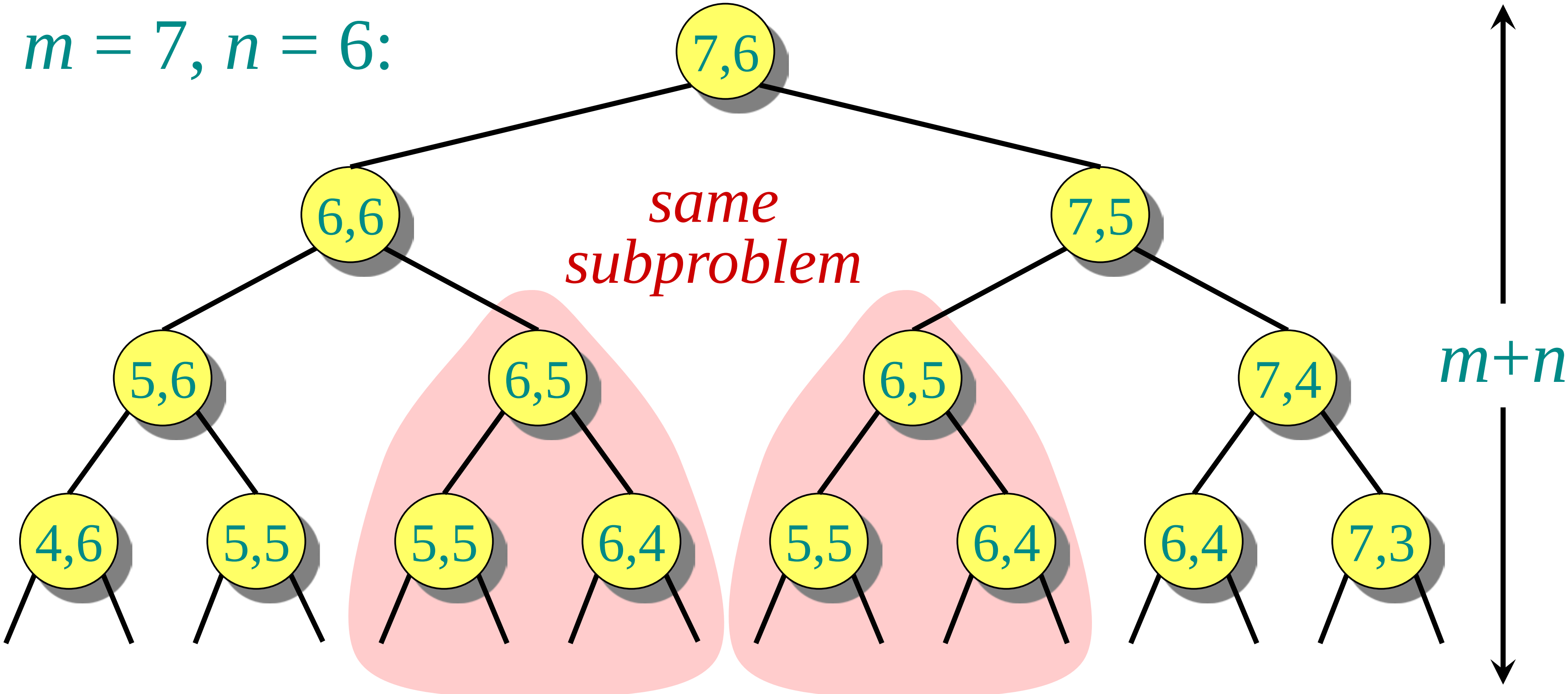
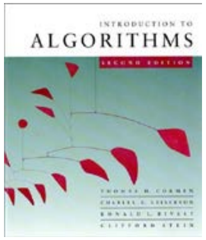


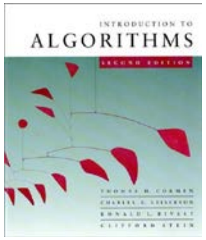
Height $= m + n \Rightarrow$ work potentially exponential, but we're solving subproblems already solved!



Dynamic-programming hallmark #2

Overlapping subproblems

A recursive solution contains a "small" number of distinct subproblems repeated many times.

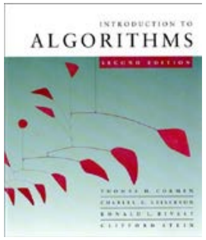


Dynamic-programming hallmark #2

Overlapping subproblems

A recursive solution contains a "small" number of distinct subproblems repeated many times.

The number of distinct LCS subproblems for two strings of lengths m and n is only mn.



Memoization algorithm

Memoization: After computing a solution to a subproblem, store it in a table. Subsequent calls check the table to avoid redoing work.

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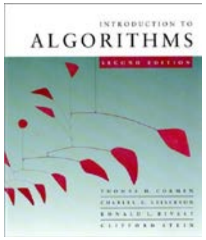
LCS(x, y, i, j)
    if $c[i, j] = \mathrm{NIL}$
        then if $x[i] = y[j]$
            then $c[i, j] \leftarrow$ LCS$(x, y, i–1, j–1) + 1$
            else $c[i, j] \leftarrow \max\{LCS(x, y, i–1, j)$, LCS$(x, y, i, j–1)\}$

same as before



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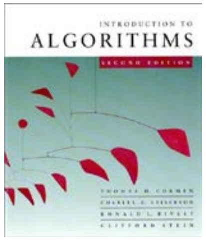
same as before

Time $= \Theta(mn) =$ constant work per table entry.
Space $= \Theta(mn)$.

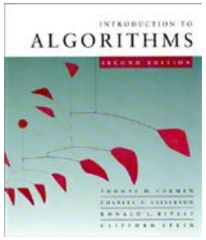


Dynamic-programming algorithm

IDEA:

Compute the table bottom-up.

		A	B	C	B	D	A	B
	0	0	0	0	0	0	0	0
B	0	0	1	1	1	1	1	1
D	0	0	1	1	1	2	2	2
C	0	0	1	2	2	2	2	2
A	0	1	1	2	2	2	3	3
B	0	1	2	2	3	3	3	4
A	0	1	2	2	3	3	4	4



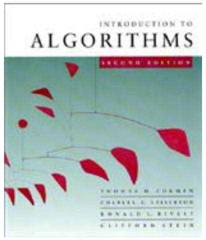
Dynamic-programming algorithm

IDEA:

Compute the table bottom-up.

Time = $\Theta(mn)$.

		A	B	C	B	D	A	B
	0	0	0	0	0	0	0	0
B	0	0	1	1	1	1	1	1
D	0	0	1	1	1	2	2	2
C	0	0	1	2	2	2	2	2
A	0	1	1	2	2	2	3	3
B	0	1	2	2	3	3	3	4
A	0	1	2	2	3	3	4	4



Dynamic-programming algorithm

IDEA:

Compute the table bottom-up.

Time $= \Theta(mn)$.

Reconstruct LCS by tracing backwards.

		A	B	C	B	D	A	B
	0	0	0	0	0	0	0	0
B	0	0	1	1	1	1	1	1
D	0	0	1	1	1	2	2	2
C	0	0	1	2	2	2	2	2
A	0	1	1	2	2	2	3	3
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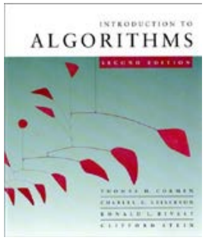


Dynamic-programming algorithm

IDEA:

Compute the table bottom-up.

Time $= \Theta(mn)$.

Reconstruct LCS by tracing backwards.

Space $= \Theta(mn)$.

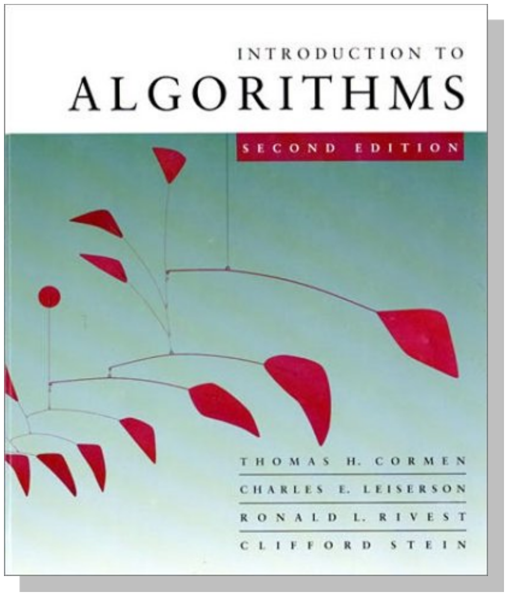
Exercise:

$O(\min\{m, n\})$.

		A	B	C	B	D	A	B
	0	0	0	0	0	0	0	0
B	0	0	1	1	1	1	1	1
D	0	0	1	1	1	2	2	2
C	0	0	1	2	2	2	2	2
A	0	1	1	2	2	2	3	3
B	0	1	2	2	3	3	3	4
A	0	1	2	2	3	3	4	4

Introduction to Algorithms

6.046J/18.401J



LECTURE 16

Greedy Algorithms (and Graphs)

- Graph representation
- Minimum spanning trees
- Optimal substructure
- Greedy choice
- Prim's greedy MST algorithm

Prof. Charles E. Leiserson

Graphs (review)

Definition. A ***directed graph (digraph)*** $G = (V, E)$ is an ordered pair consisting of

- a set V of ***vertices*** (singular: ***vertex***),
- a set $E \subseteq V \times V$ of ***edges***.

In an ***undirected graph*** $G = (V, E)$, the edge set E consists of *unordered* pairs of vertices.

In either case, we have $|E| = O(V^2)$. Moreover, if G is connected, then $|E| \geq |V| - 1$, which implies that $\lg|E| = \Theta(\lg V)$.

(Review CLRS, Appendix B.)

Adjacency-matrix representation

The ***adjacency matrix*** of a graph $G = (V, E)$, where $V = \{1, 2, \ldots, n\}$, is the matrix $A[1 \,.\,.\, n, 1 \,.\,.\, n]$ given by

$$A[i, j] = \begin{cases} 1 & \text{if } (i, j) \in E, \\ 0 & \text{if } (i, j) \notin E. \end{cases}$$

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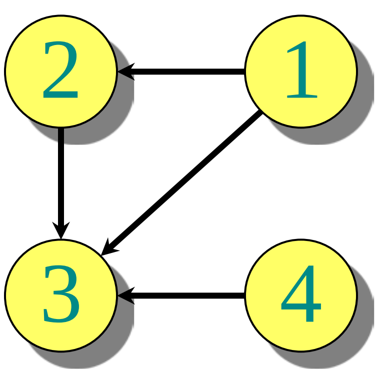
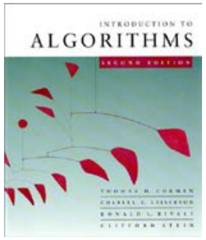


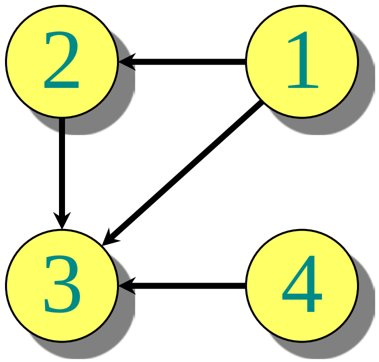
A	1	2	3	4
1	0	1	1	0
2	0	0	1	0
3	0	0	0	0
4	0	0	1	0

$\Theta(V^2)$ storage $\Rightarrow$ ***dense*** representation.



Adjacency-list representation

An ***adjacency list*** of a vertex $v \in V$ is the list $Adj[v]$ of vertices adjacent to v.



$Adj[1] = \{2, 3\}$
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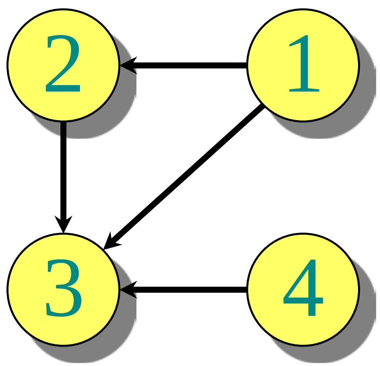

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For undirected graphs, $|Adj[v]| = \textit{degree}(v)$.
For digraphs, $|Adj[v]| = \textit{out-degree}(v)$.

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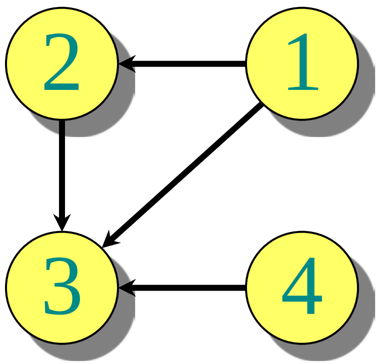

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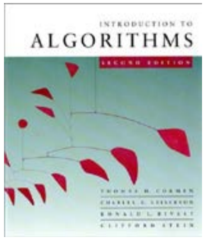
For undirected graphs, $|Adj[v]| = degree(v)$.
For digraphs, $|Adj[v]| = out\text{-}degree(v)$.

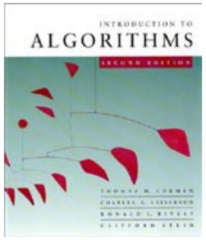
Handshaking Lemma: $\sum_{v \in V} degree(v) = 2|E|$ for undirected graphs $\Rightarrow$ adjacency lists use $\Theta(V + E)$ storage — a ***sparse*** representation.



Minimum spanning trees

Input: A connected, undirected graph $G = (V, E)$ with weight function $w : E \to \mathsf{R}$.

- For simplicity, assume that all edge weights are distinct. (CLRS covers the general case.)



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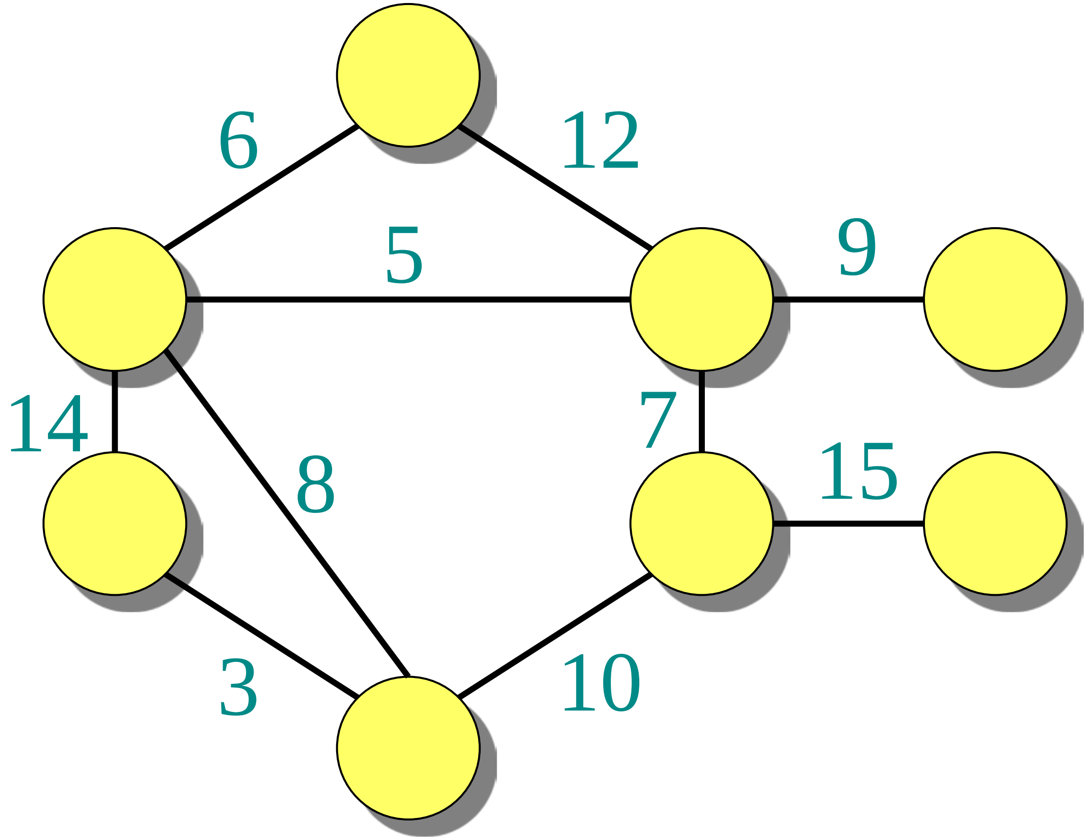
- For simplicity, assume that all edge weights are distinct. (CLRS covers the general case.)

Output: A ***spanning tree*** T — a tree that connects all vertices — of minimum weight:

$$w(T) = \sum_{(u,v) \in T} w(u,v).$$

Example of MST



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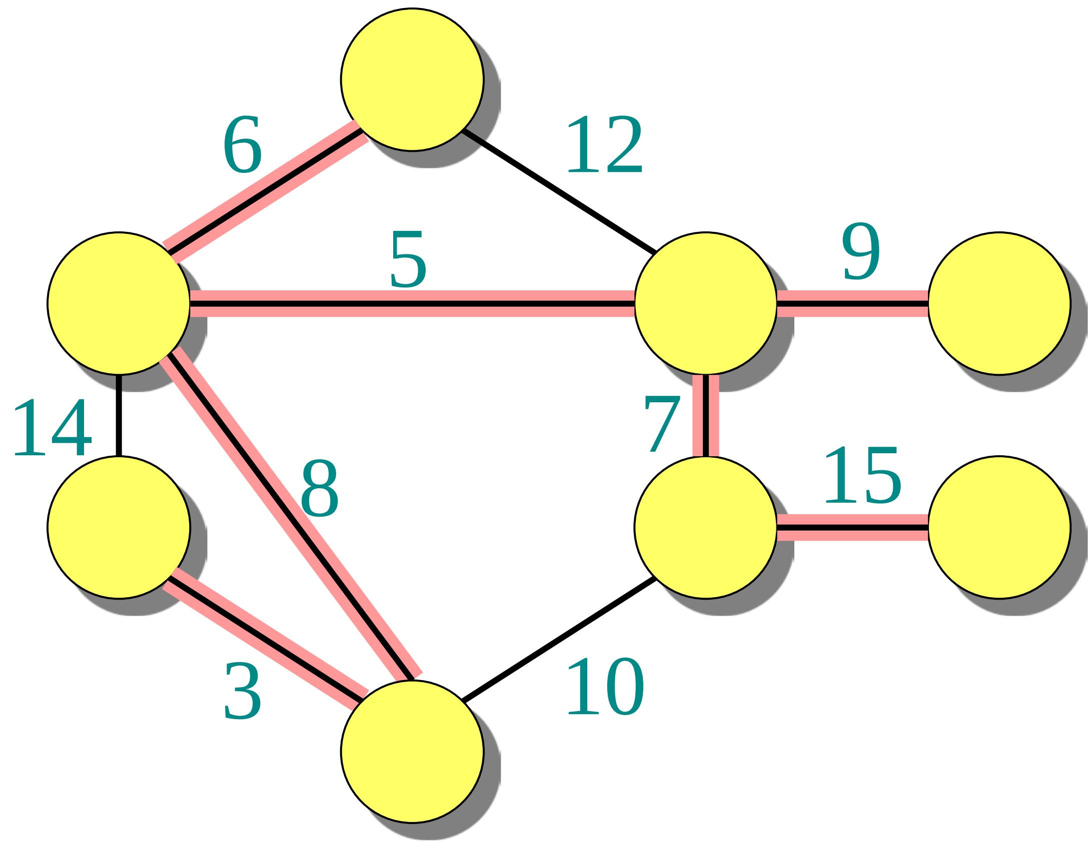
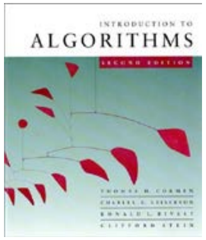
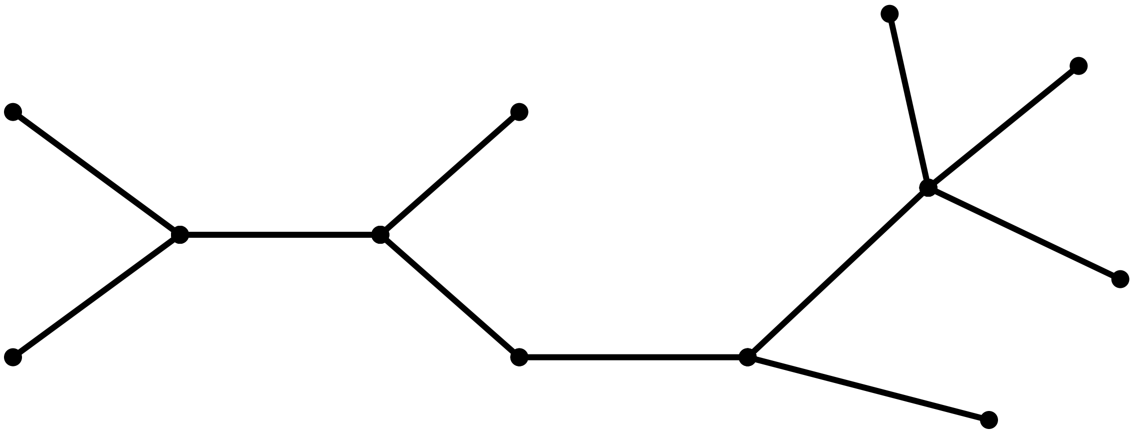


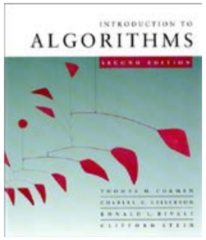


Optimal substructure

MST *T*:

(Other edges of *G* are not shown.)





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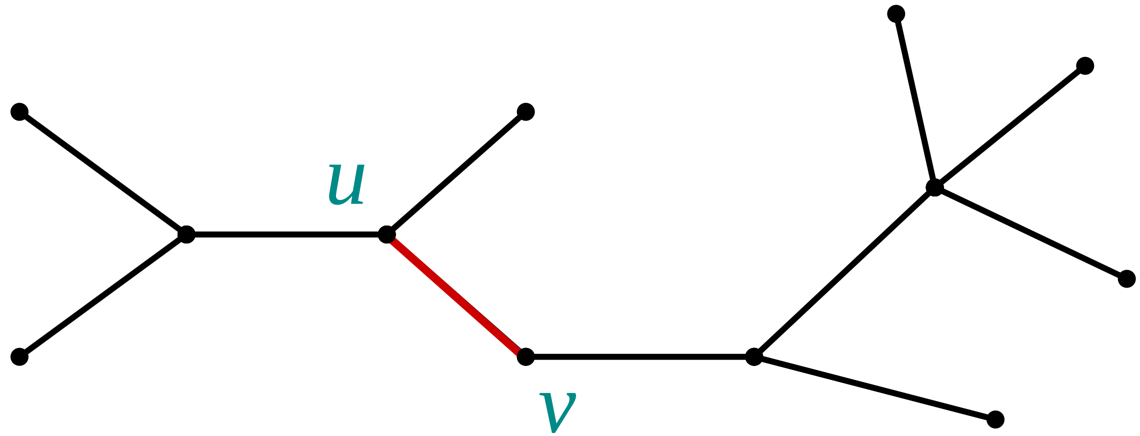

Remove any edge $(u, v) \in T$.

Optimal substructure

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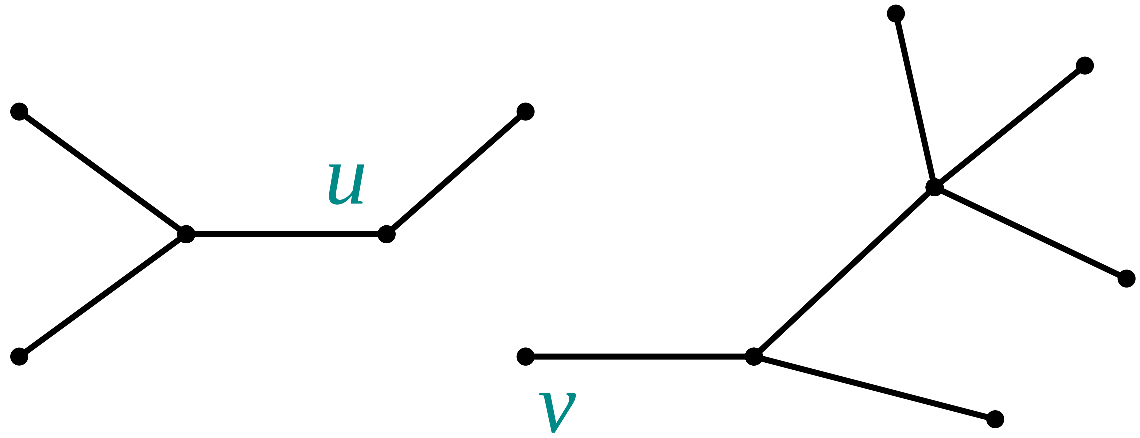

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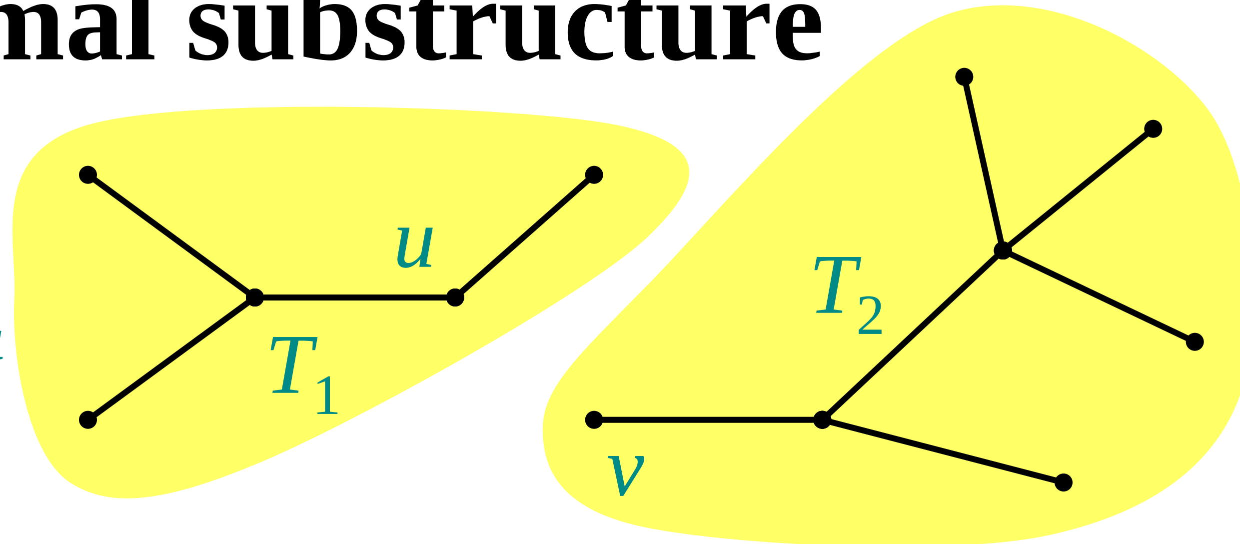
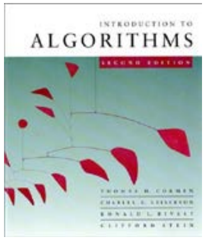


Remove any edge $(u, v) \in T$. Then, T is partitioned into two subtrees T_1 and T_2.



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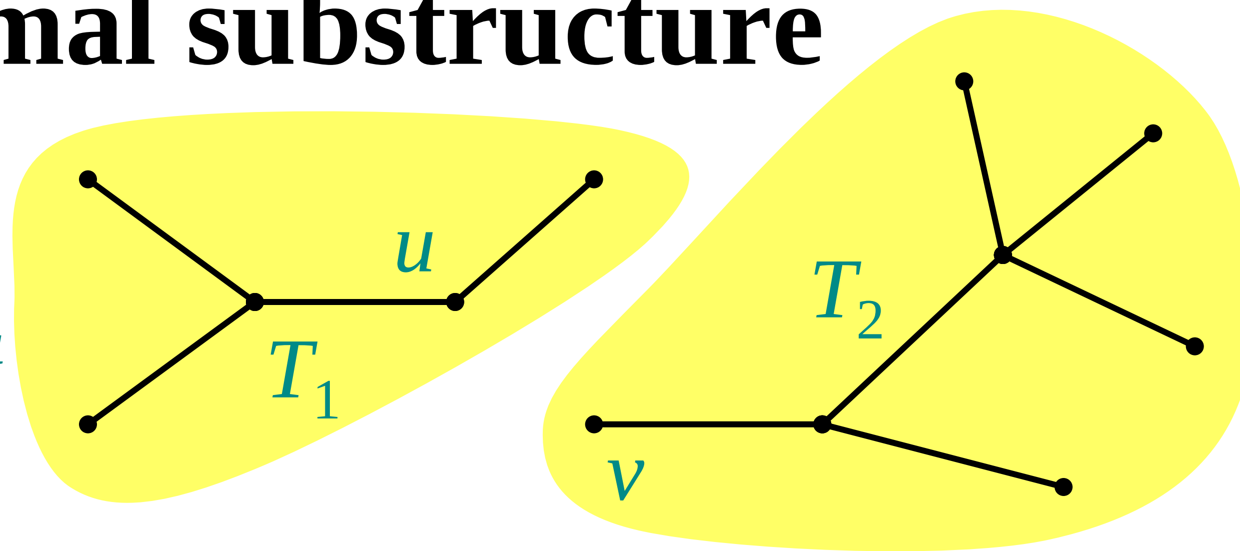


Remove any edge $(u, v) \in T$. Then, T is partitioned into two subtrees T_1 and T_2.

Theorem. The subtree T_1 is an MST of $G_1 = (V_1, E_1)$, the subgraph of G ***induced*** by the vertices of T_1:

$$V_1 = \text{vertices of } T_1,$$
$$E_1 = \{\, (x, y) \in E : x, y \in V_1 \,\}.$$

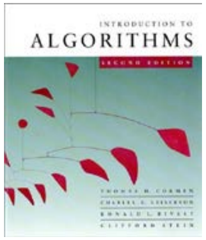
Similarly for T_2.

Proof of optimal substructure

Proof. Cut and paste:

$$w(T) = w(u, v) + w(T_1) + w(T_2).$$

If T_1' were a lower-weight spanning tree than T_1 for G_1, then $T' = \{(u, v)\} \cup T_1' \cup T_2$ would be a lower-weight spanning tree than T for G. $\square$



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Do we also have overlapping subproblems?

- Yes.

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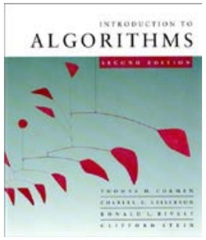
Great, then dynamic programming may work!

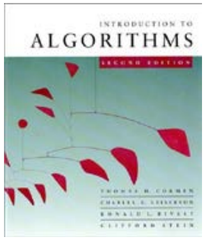
- Yes, but MST exhibits another powerful property which leads to an even more efficient algorithm.



Hallmark for “greedy” algorithms

Greedy-choice property

A locally optimal choice is globally optimal.

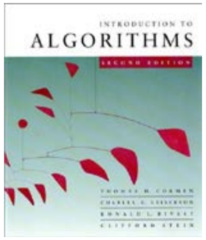


Hallmark for "greedy" algorithms

Greedy-choice property

A locally optimal choice is globally optimal.

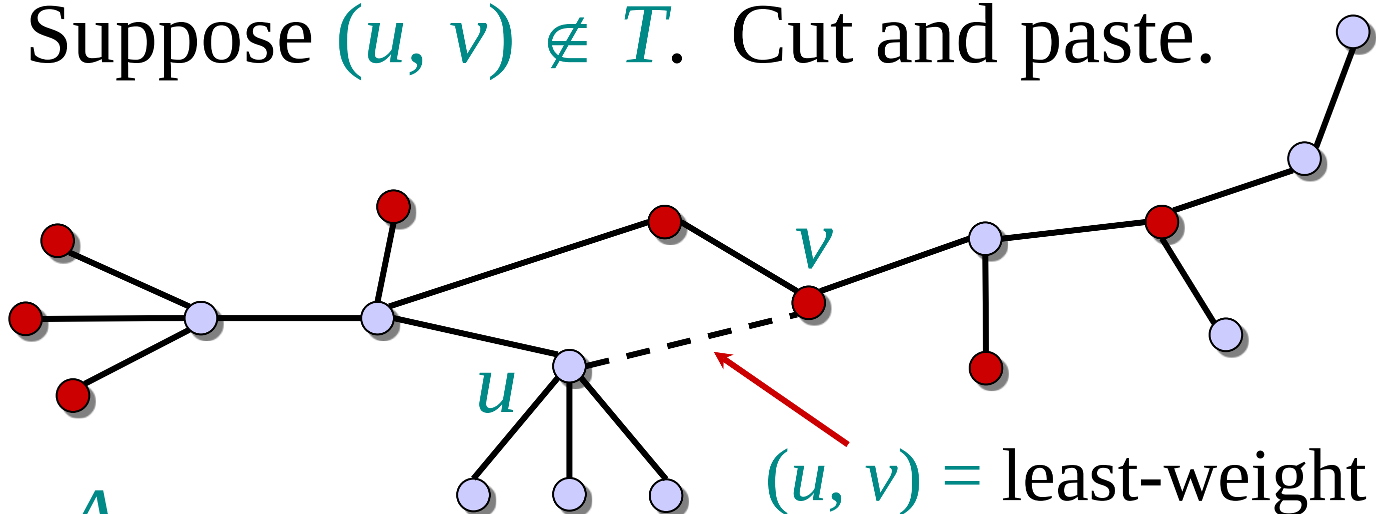
Theorem. Let T be the MST of $G = (V, E)$, and let $A \subseteq V$. Suppose that $(u, v) \in E$ is the least-weight edge connecting A to $V - A$. Then, $(u, v) \in T$.



Proof of theorem

Proof. Suppose $(u, v) \notin T$. Cut and paste.

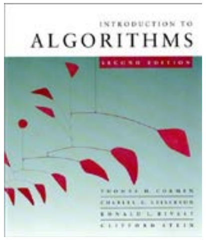
T:



(u, v) = least-weight edge connecting A to $V - A$

● $\in A$

● $\in V - A$



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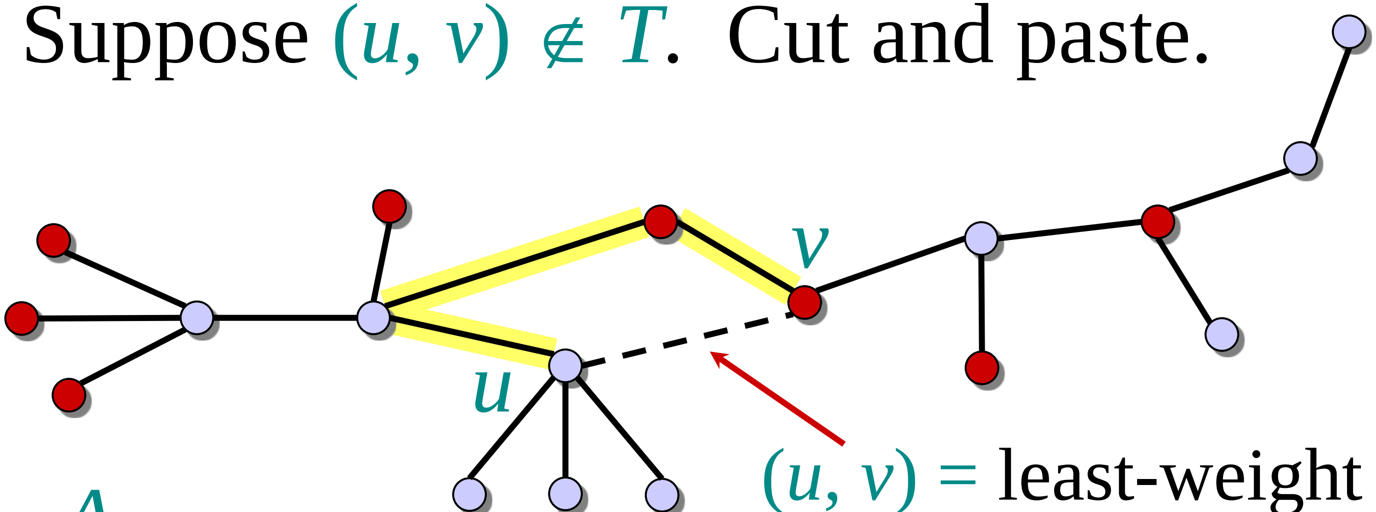

(u, v) = least-weight edge connecting A to $V - A$

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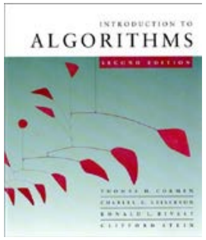
Consider the unique simple path from u to v in T.



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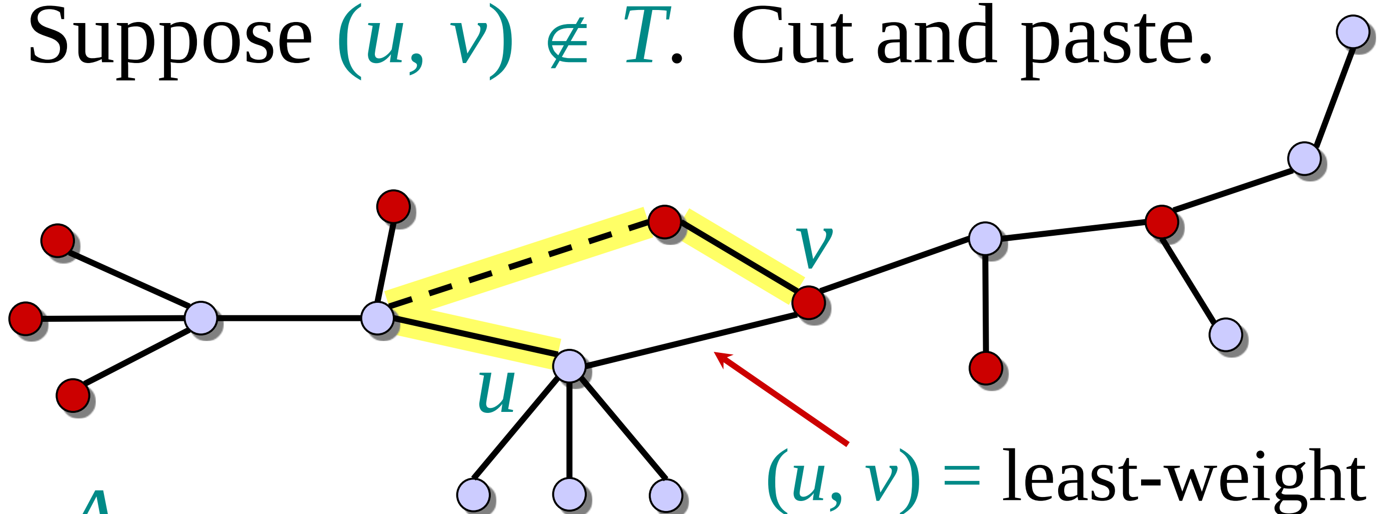


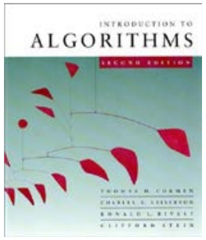
● $\in A$

● $\in V - A$

(u, v) = least-weight edge connecting A to $V - A$

Consider the unique simple path from u to v in T.

Swap (u, v) with the first edge on this path that connects a vertex in A to a vertex in $V - A$.



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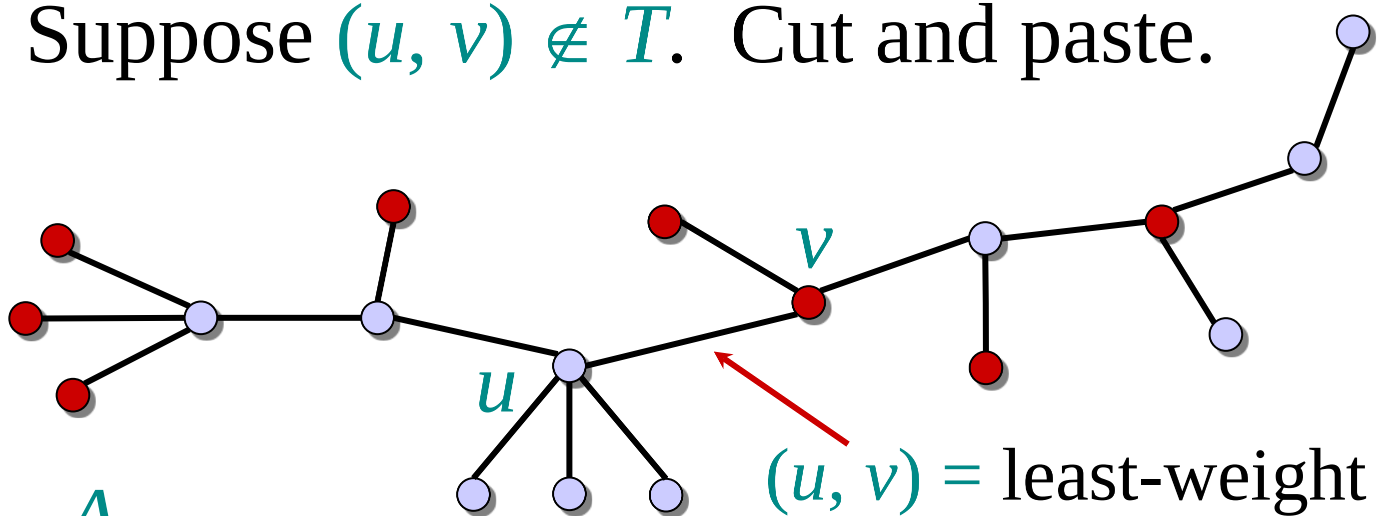

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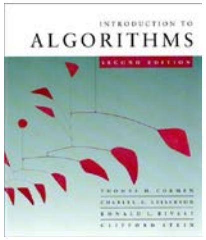
(u, v) = least-weight edge connecting A to $V - A$

Consider the unique simple path from u to v in T.

Swap (u, v) with the first edge on this path that connects a vertex in A to a vertex in $V - A$.

A lighter-weight spanning tree than T results. $\square$

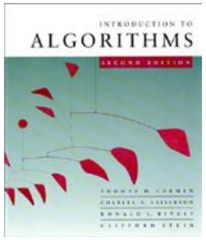


Prim's algorithm

IDEA: Maintain $V - A$ as a priority queue Q. Key each vertex in Q with the weight of the least-weight edge connecting it to a vertex in A.

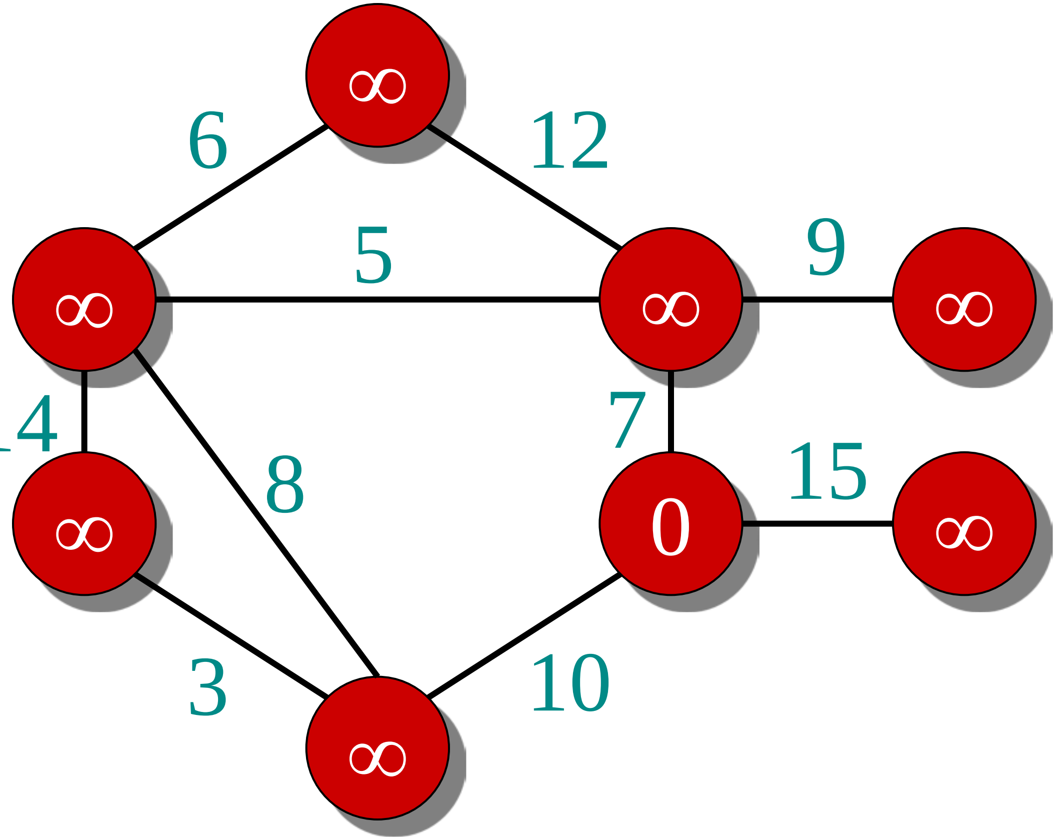
$Q \leftarrow V$
$key[v] \leftarrow \infty$ for all $v \in V$
$key[s] \leftarrow 0$ for some arbitrary $s \in V$
while $Q \neq \emptyset$
    do $u \leftarrow$ EXTRACT-MIN(Q)
        for each $v \in Adj[u]$
            do if $v \in Q$ and $w(u, v) < key[v]$
                then $key[v] \leftarrow w(u, v)$ ⊳ DECREASE-KEY
                    $\pi[v] \leftarrow u$

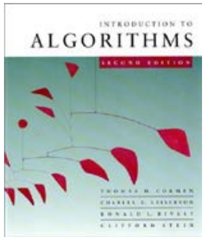
At the end, $\{(v, \pi[v])\}$ forms the MST.



Example of Prim’s algorithm

- $\in A$
- $\in V - A$





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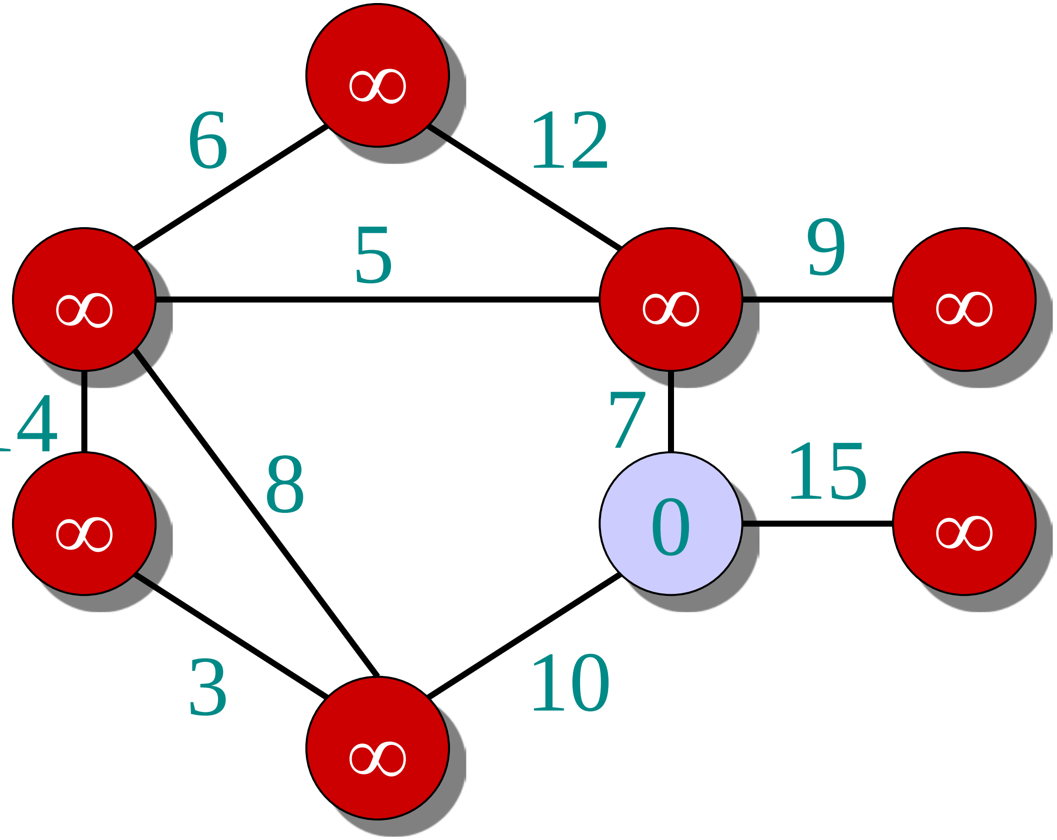

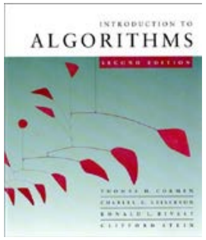

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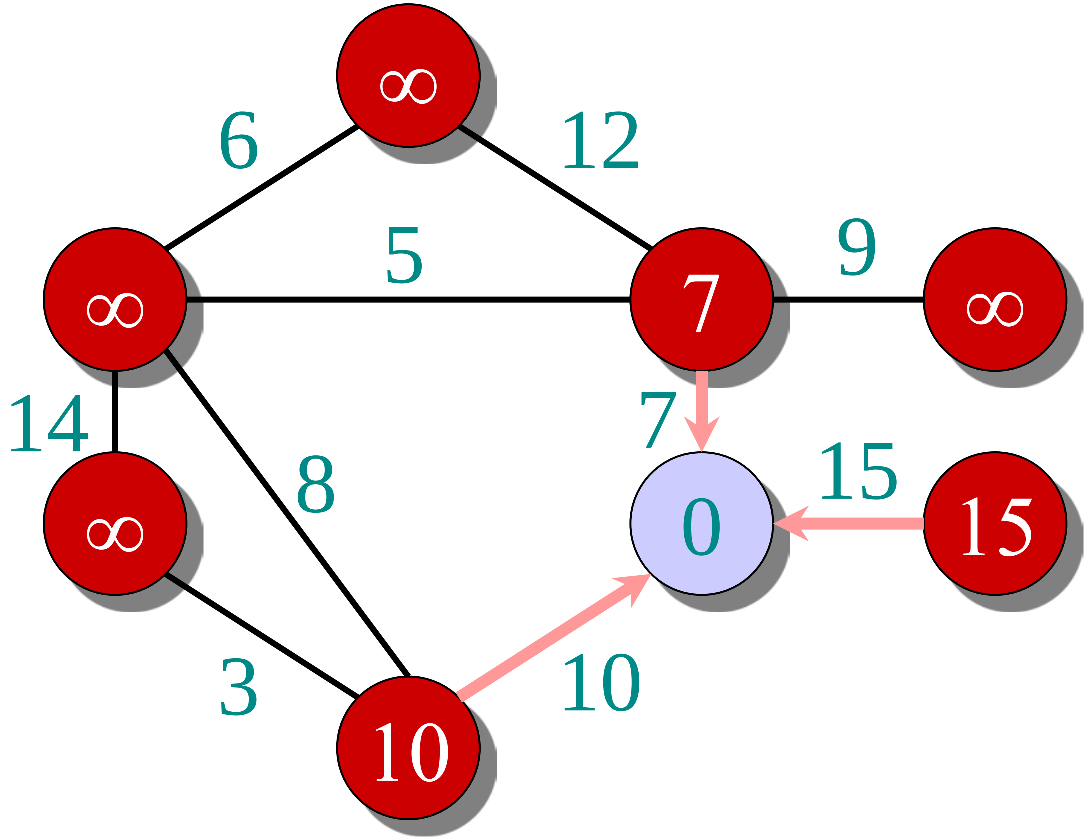

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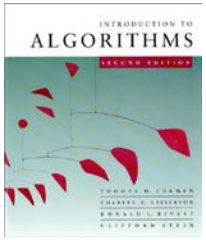

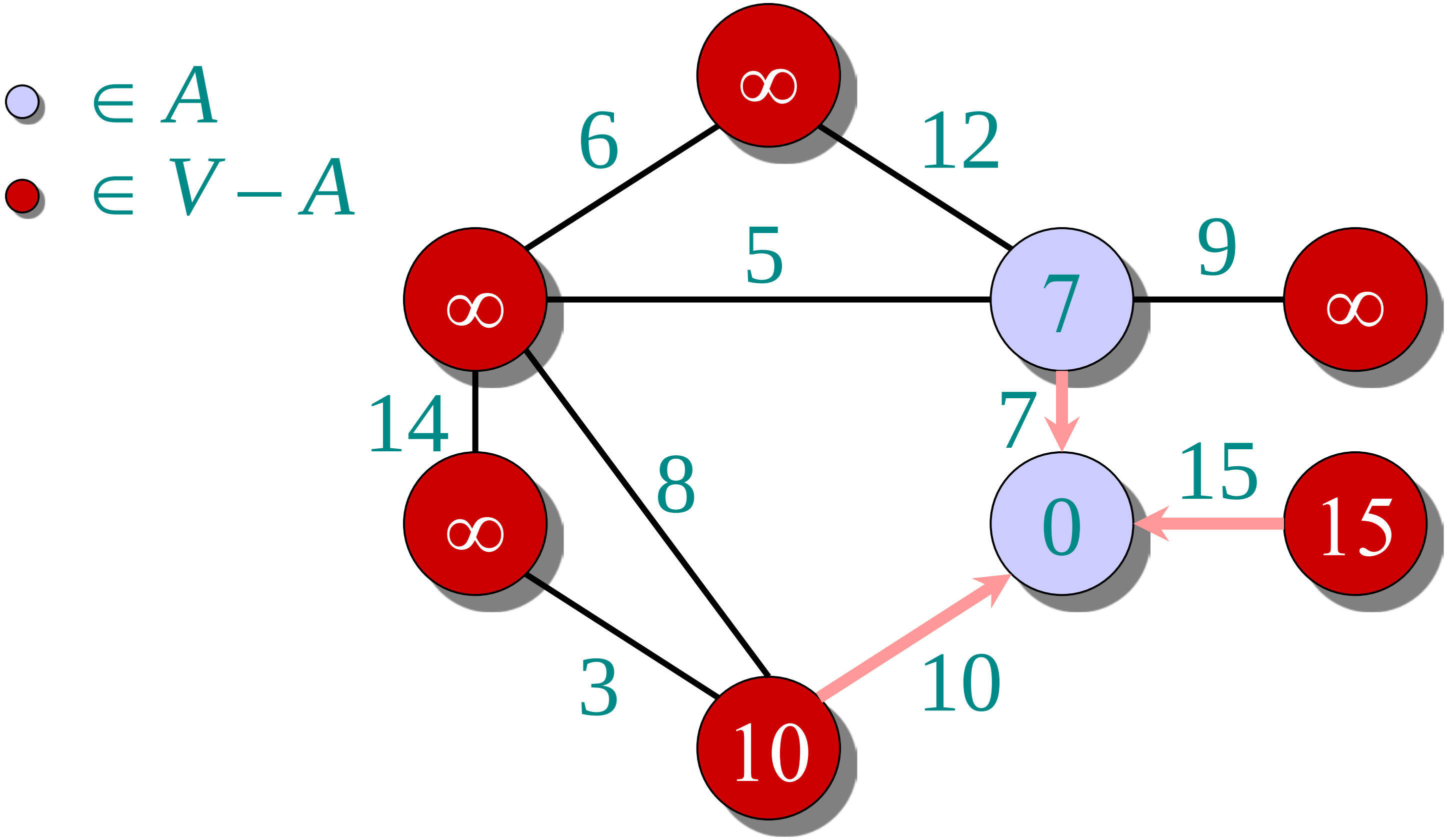

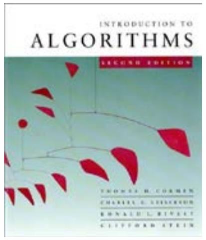

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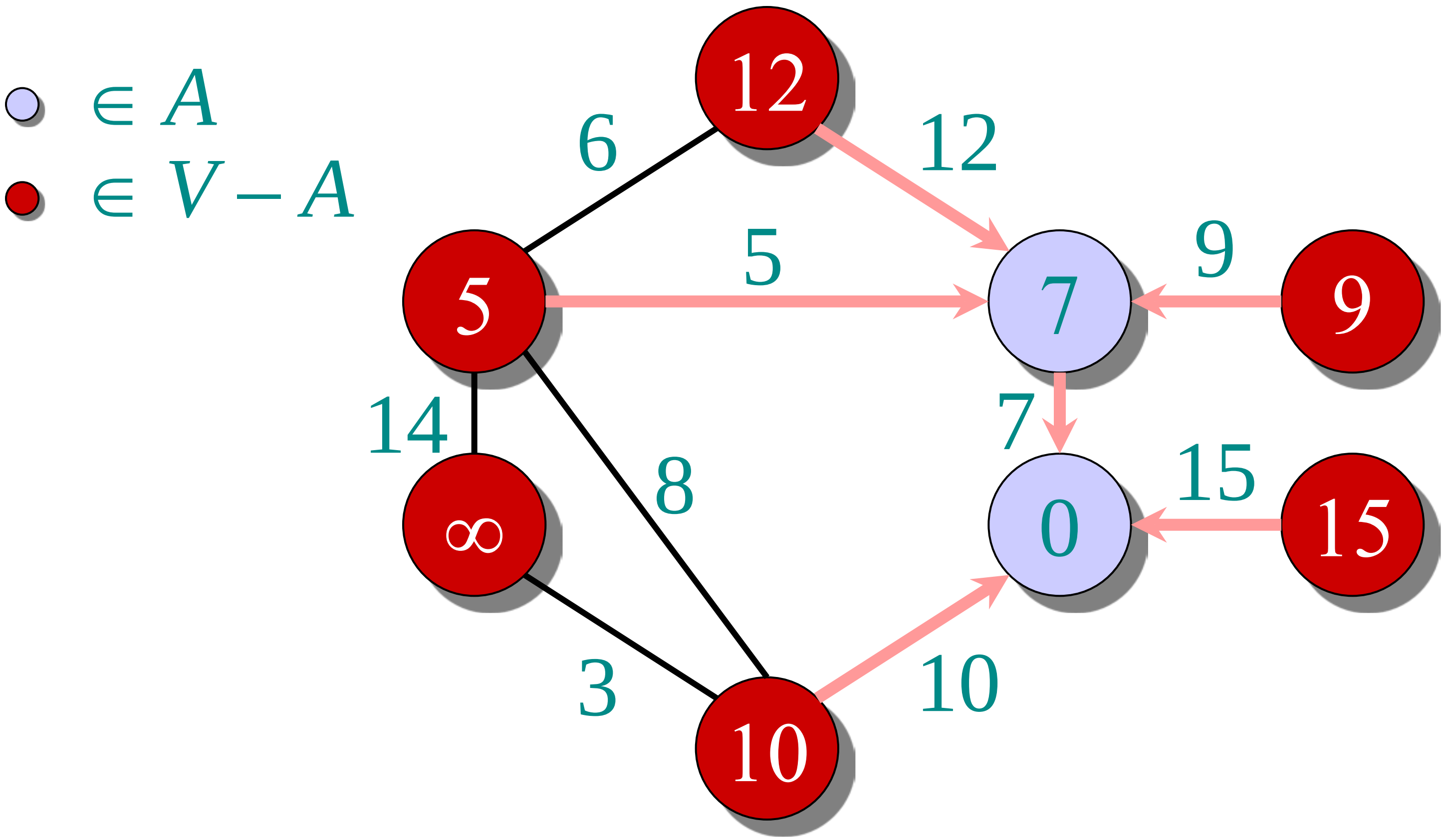
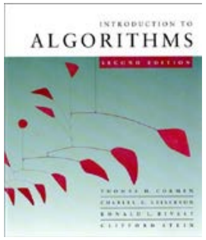
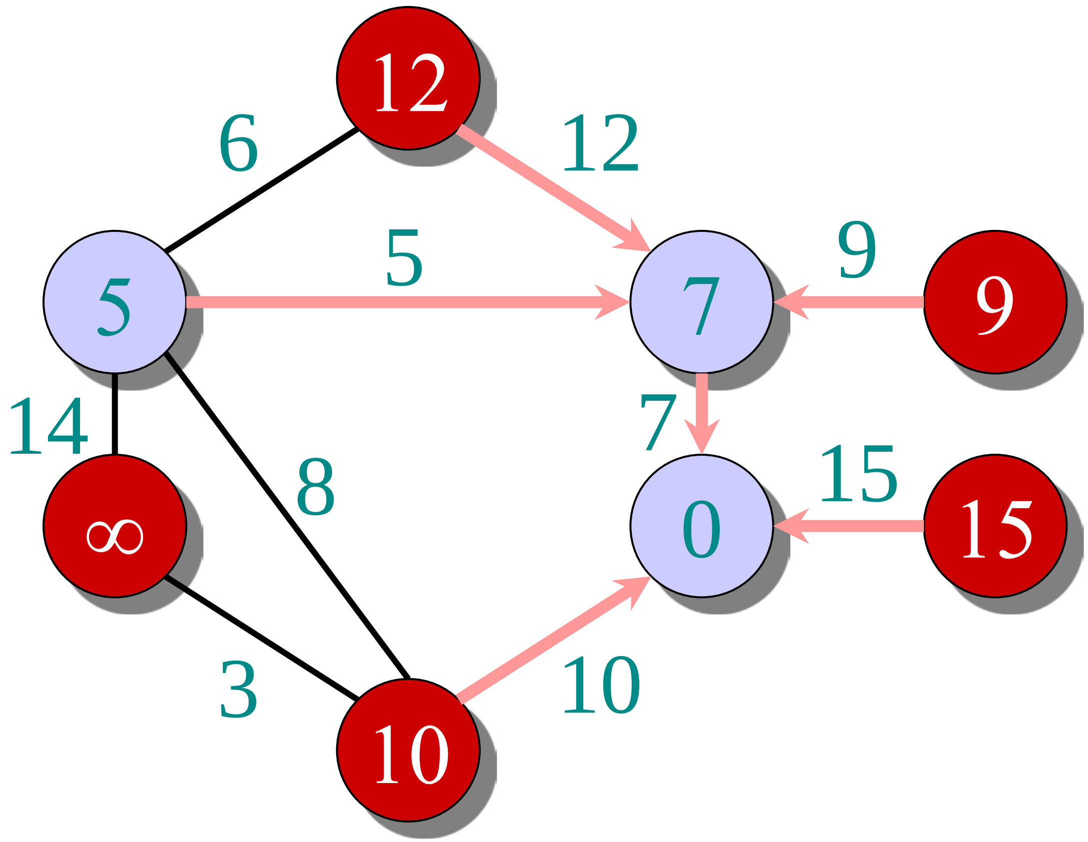




Example of Prim’s algorithm

- $\in A$
- $\in V - A$



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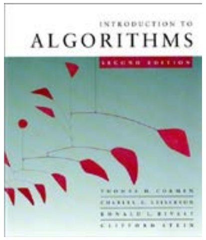

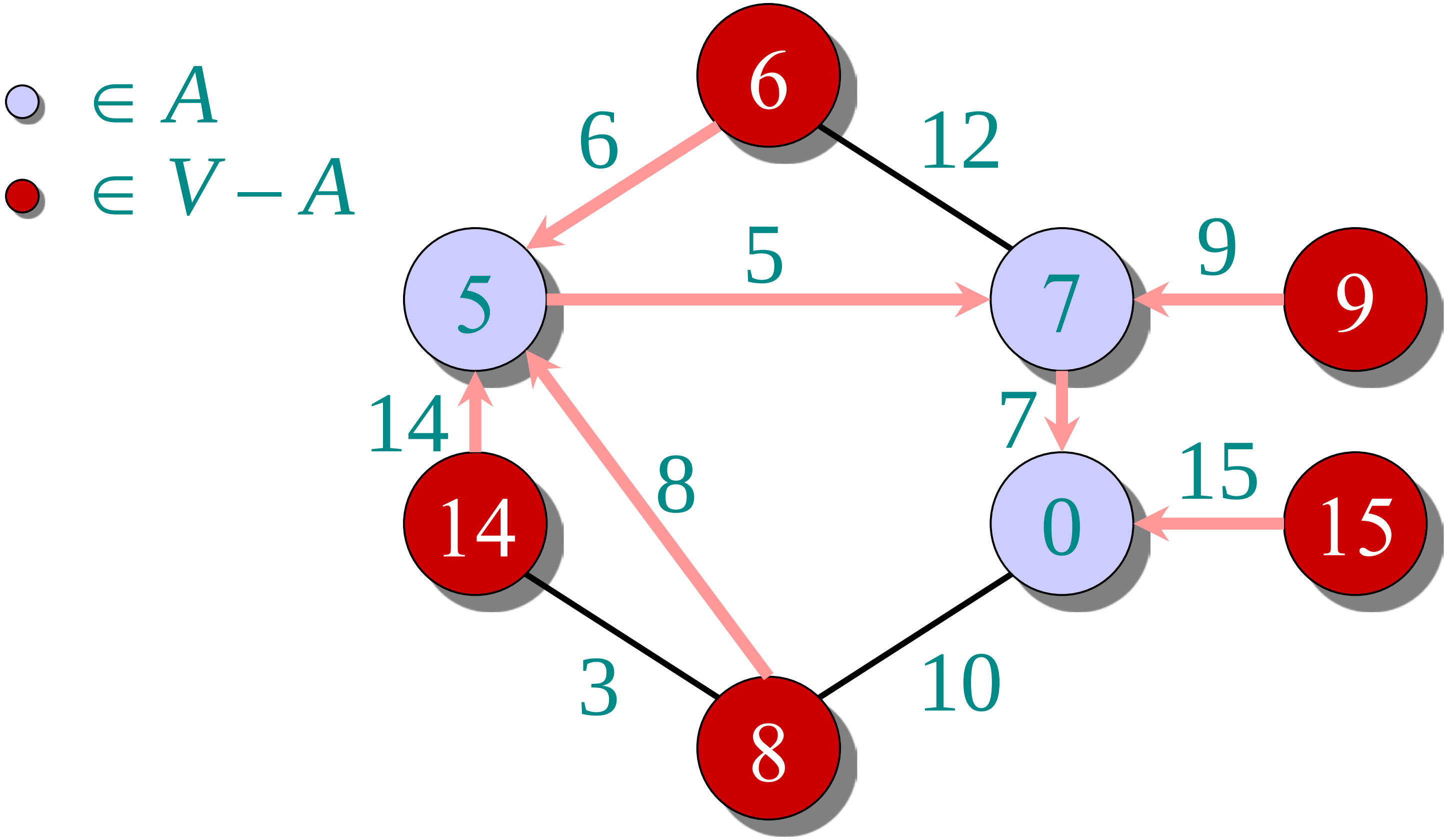

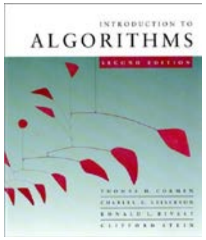

Example of Prim's algorithm

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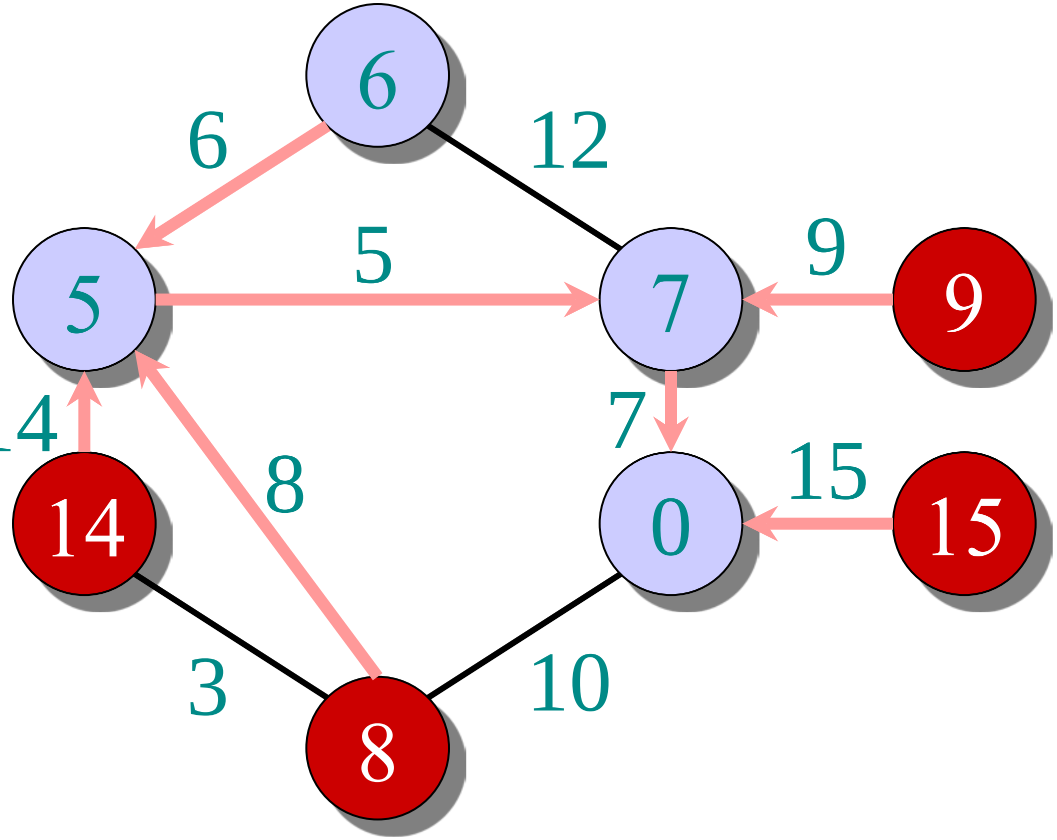

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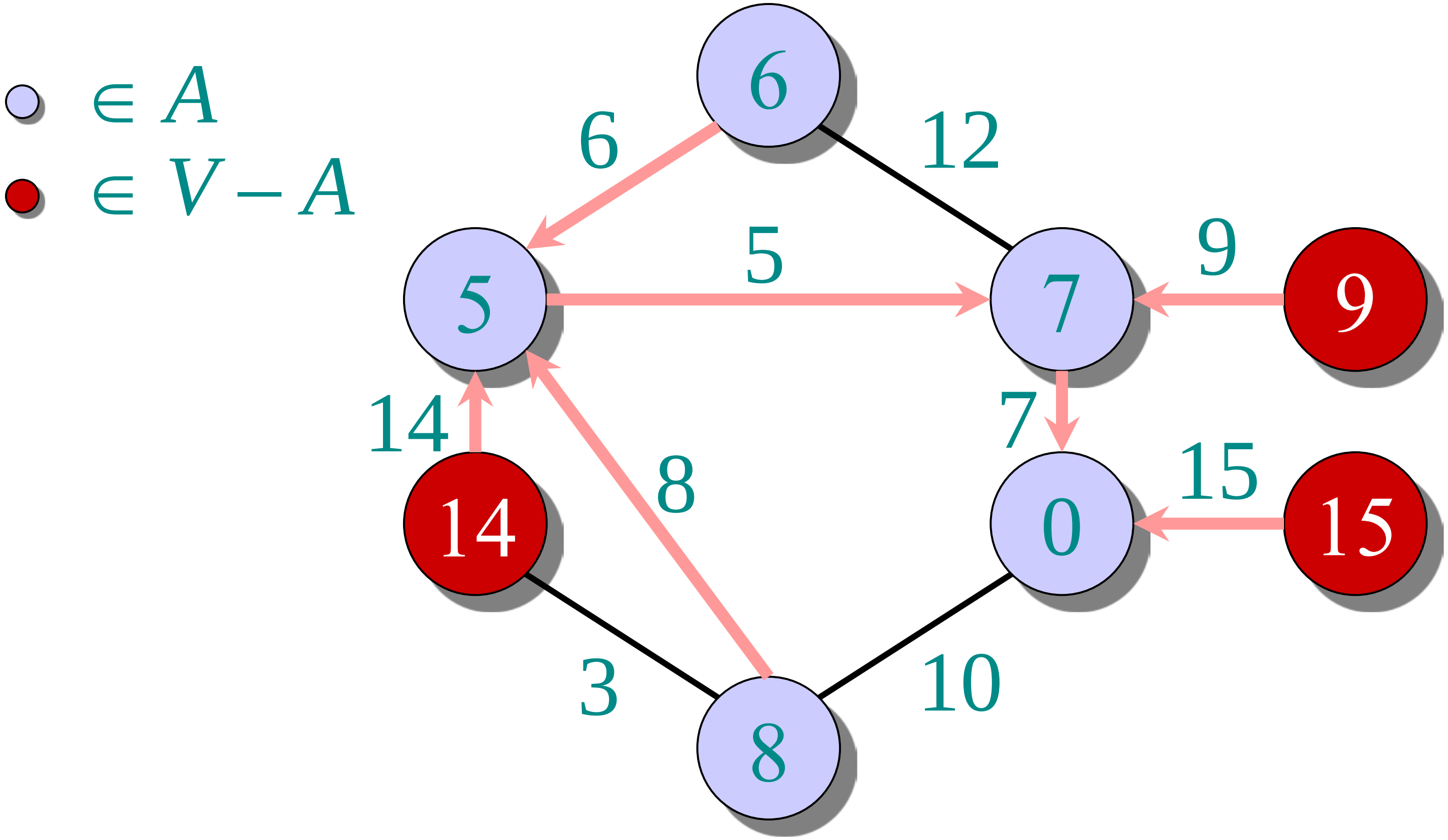

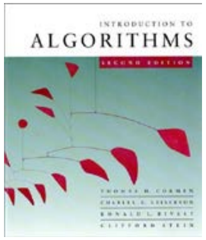

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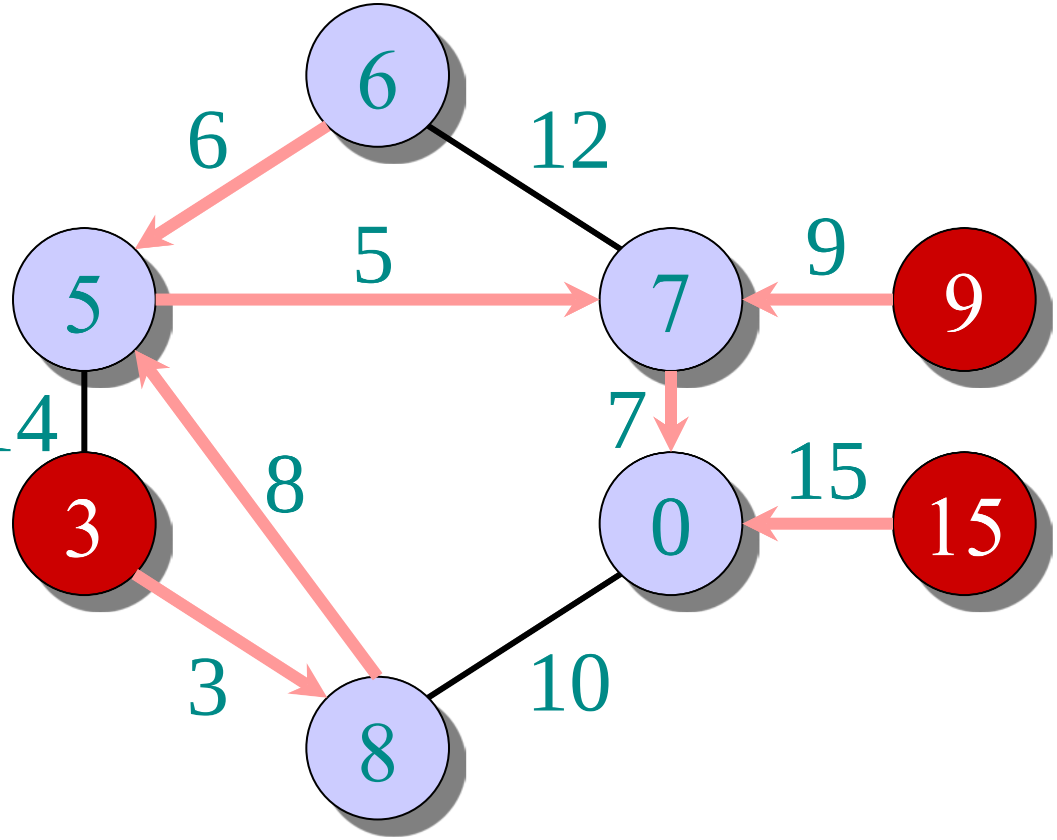

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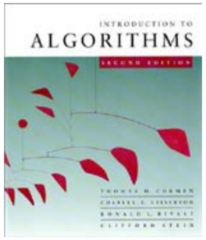

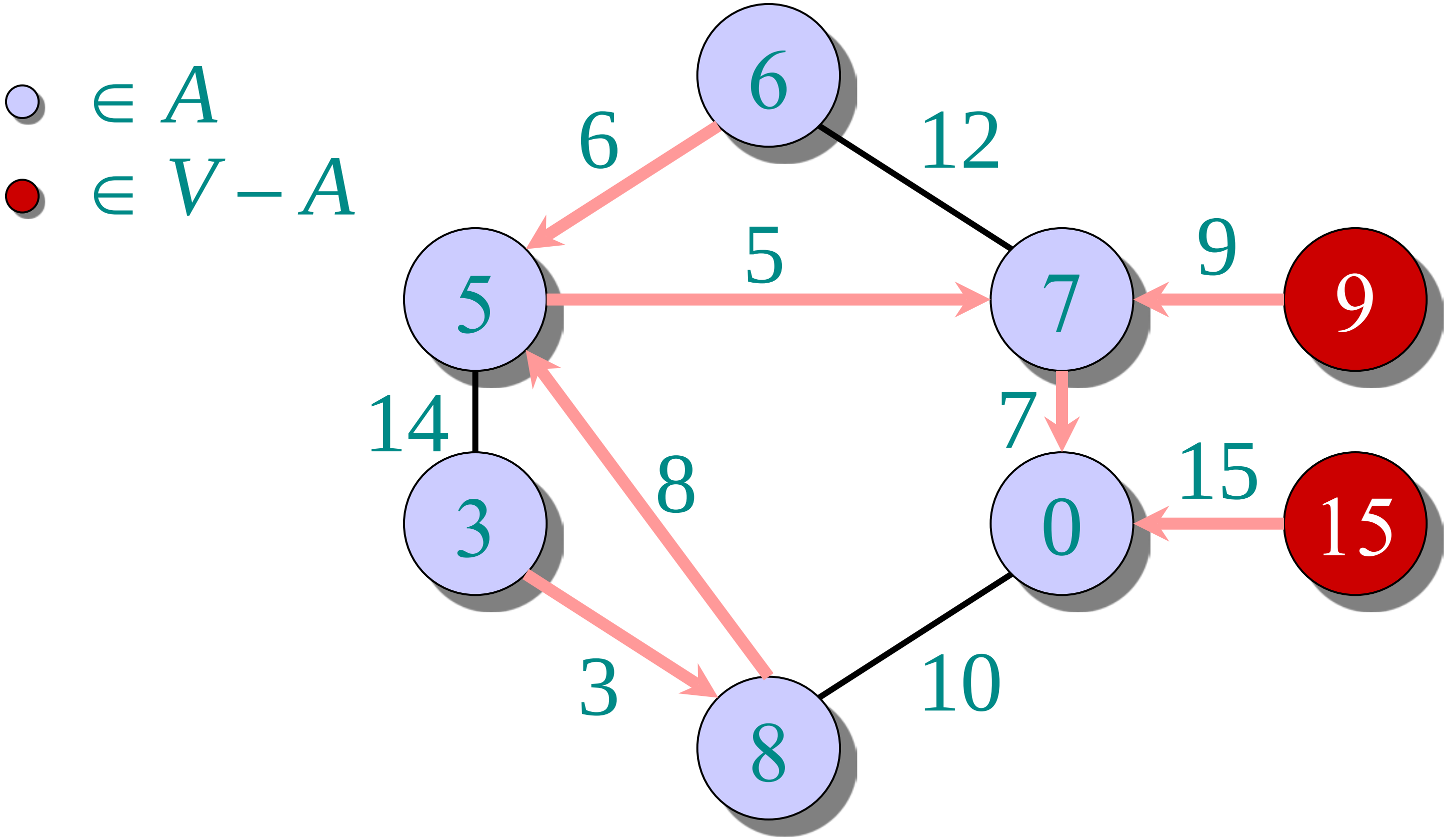

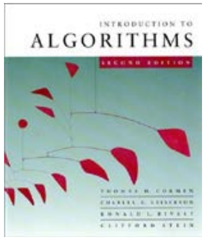

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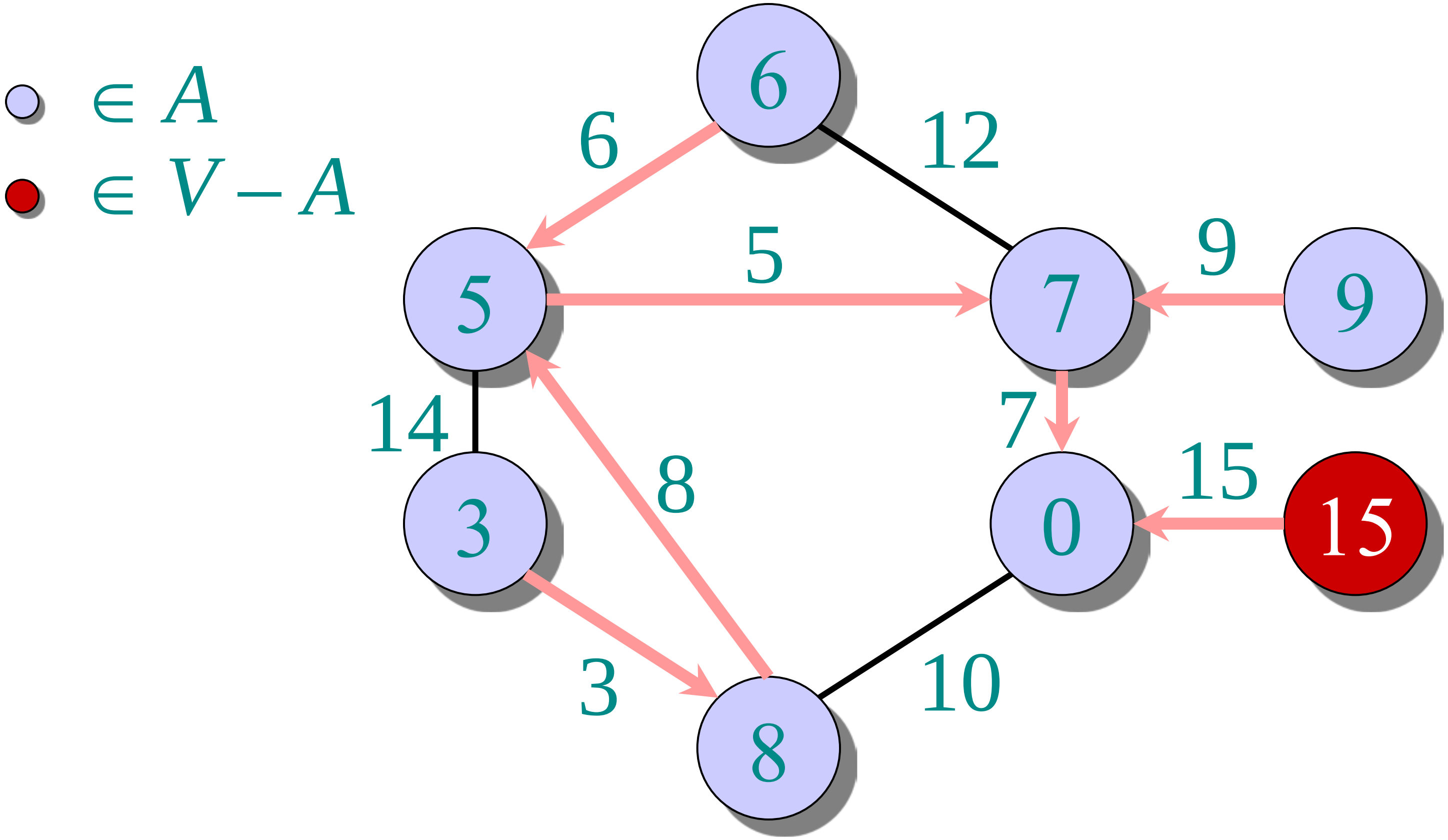

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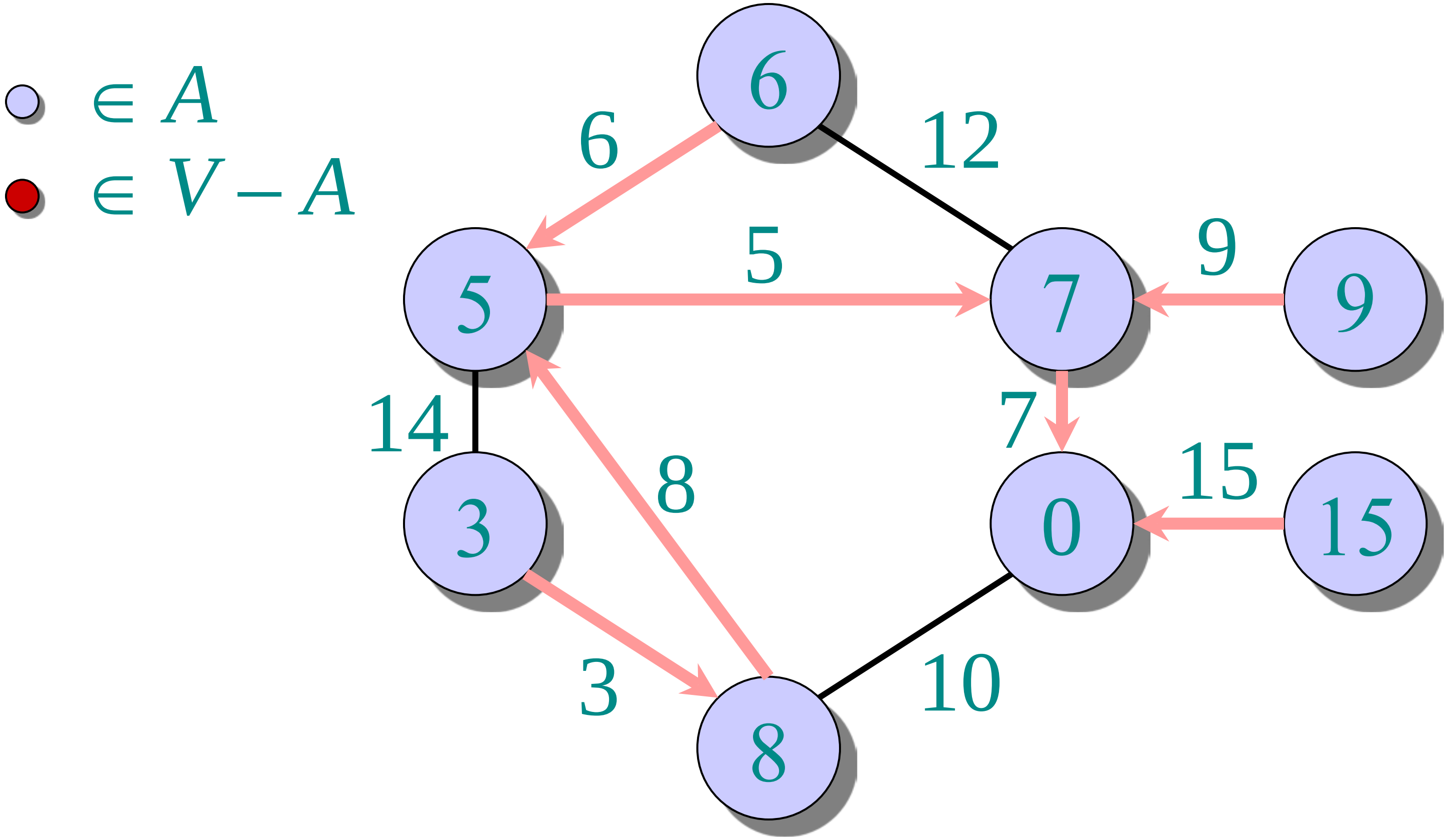

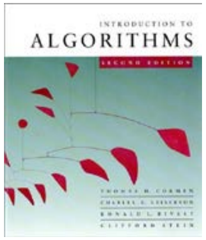

Analysis of Prim

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while $Q \neq \emptyset$
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    for each $v \in Adj[u]$
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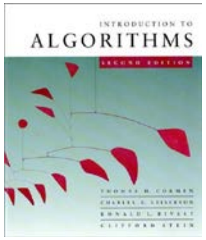

Analysis of Prim

$$\begin{array}{c}\Theta(V)\\ \text{total}\end{array}\left\{\begin{array}{l} Q \leftarrow V \\ key[v] \leftarrow \infty \text{ for all } v \in V \\ key[s] \leftarrow 0 \text{ for some arbitrary } s \in V \end{array}\right.$$

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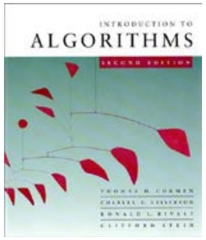
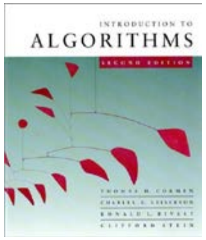


Analysis of Prim

$\Theta(V)$ total $\left\{\begin{array}{l} Q \leftarrow V \\ key[v] \leftarrow \infty \text{ for all } v \in V \\ key[s] \leftarrow 0 \text{ for some arbitrary } s \in V \end{array}\right.$

$|V|$ times $\left\{\begin{array}{l} \textbf{while } Q \neq \emptyset \\ \quad \textbf{do } u \leftarrow \text{EXTRACT-MIN}(Q) \\ \quad\quad \textbf{for } \text{each } v \in Adj[u] \\ \quad\quad\quad \textbf{do if } v \in Q \text{ and } w(u, v) < key[v] \\ \quad\quad\quad\quad \textbf{then } key[v] \leftarrow w(u, v) \\ \quad\quad\quad\quad\quad\quad \pi[v] \leftarrow u \end{array}\right.$



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$|V|$ times:

while $Q \neq \emptyset$
  do $u \leftarrow$ EXTRACT-MIN(Q)

$degree(u)$ times:

    for each $v \in Adj[u]$
      do if $v \in Q$ and $w(u, v) < key[v]$
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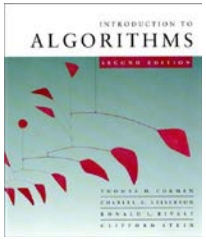
Handshaking Lemma $\Rightarrow \Theta(E)$ implicit DECREASE-KEY's.



Analysis of Prim

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$|V|$ times:

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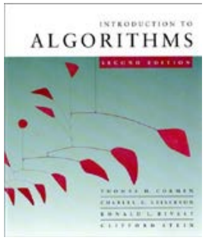
Handshaking Lemma $\Rightarrow \Theta(E)$ implicit DECREASE-KEY's.

Time $= \Theta(V) \cdot T_{\text{EXTRACT-MIN}} + \Theta(E) \cdot T_{\text{DECREASE-KEY}}$

Analysis of Prim (continued)

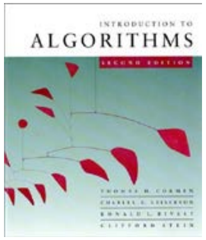
Time $= \Theta(V) \cdot T_{\text{EXTRACT-MIN}} + \Theta(E) \cdot T_{\text{DECREASE-KEY}}$



Analysis of Prim (continued)

Time = $\Theta(V)\cdot T_{\text{EXTRACT-MIN}} + \Theta(E)\cdot T_{\text{DECREASE-KEY}}$

Q	$T_{\text{EXTRACT-MIN}}$	$T_{\text{DECREASE-KEY}}$	Total



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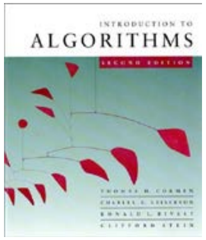
Q	$T_{\text{EXTRACT-MIN}}$	$T_{\text{DECREASE-KEY}}$	Total
array	$O(V)$	$O(1)$	$O(V^2)$



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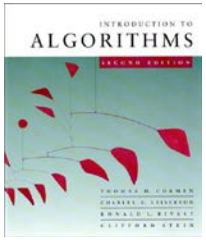
Q	$T_{\text{EXTRACT-MIN}}$	$T_{\text{DECREASE-KEY}}$	Total
array	$O(V)$	$O(1)$	$O(V^2)$
binary heap	$O(\lg V)$	$O(\lg V)$	$O(E \lg V)$



Analysis of Prim (continued)

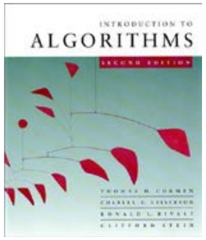
Time = $\Theta(V)\cdot T_{\text{EXTRACT-MIN}} + \Theta(E)\cdot T_{\text{DECREASE-KEY}}$

Q	$T_{\text{EXTRACT-MIN}}$	$T_{\text{DECREASE-KEY}}$	Total
array	$O(V)$	$O(1)$	$O(V^2)$
binary heap	$O(\lg V)$	$O(\lg V)$	$O(E \lg V)$
Fibonacci heap	$O(\lg V)$ amortized	$O(1)$ amortized	$O(E + V \lg V)$ worst case

MST algorithms

Kruskal's algorithm (see CLRS):

- Uses the ***disjoint-set data structure*** (see CLRS, Ch. 21).
- Running time $= O(E \lg V)$.



MST algorithms

Kruskal's algorithm (see CLRS):

- Uses the ***disjoint-set data structure*** (see CLRS, Ch. 21).
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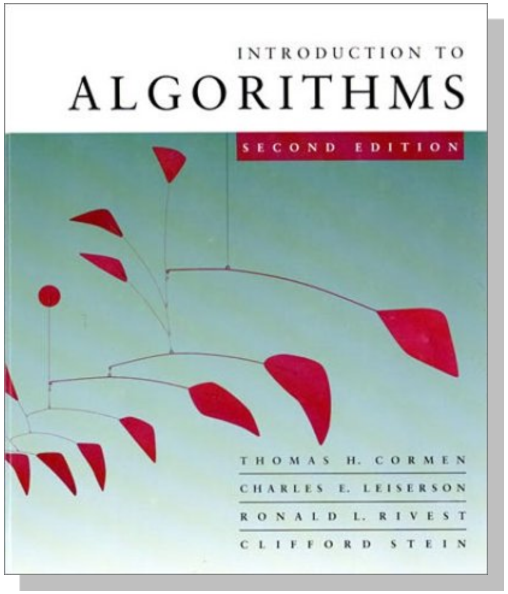
Best to date:

- Karger, Klein, and Tarjan [1993].
- Randomized algorithm.
- $O(V + E)$ expected time.

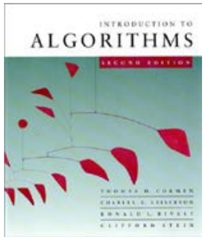
Introduction to Algorithms
6.046J/18.401J



LECTURE 17
Shortest Paths I

- Properties of shortest paths
- Dijkstra's algorithm
- Correctness
- Analysis
- Breadth-first search

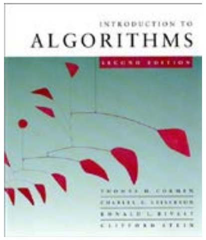
Prof. Erik Demaine



Paths in graphs

Consider a digraph $G = (V, E)$ with edge-weight function $w : E \to \mathbb{R}$. The ***weight*** of path $p = v_1 \to v_2 \to \cdots \to v_k$ is defined to be

$$w(p) = \sum_{i=1}^{k-1} w(v_i, v_{i+1}).$$



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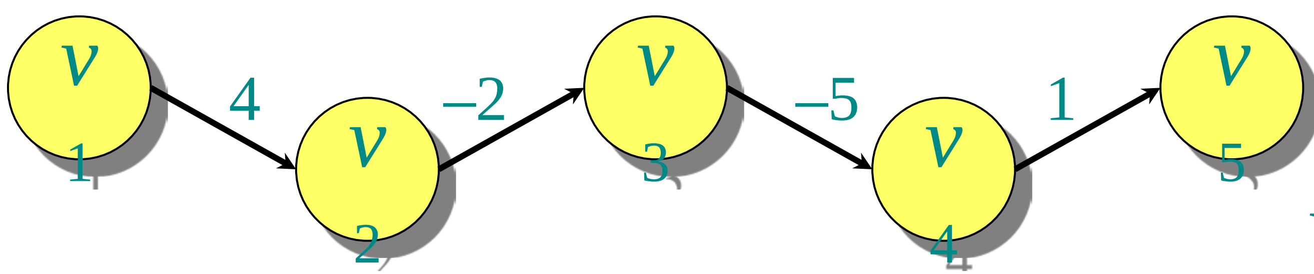
Example:



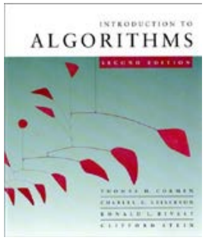
$w(p) = -2$

Shortest paths

A ***shortest path*** from u to v is a path of minimum weight from u to v. The ***shortest-path weight*** from u to v is defined as

$$\delta(u, v) = \min\{w(p) : p \text{ is a path from } u \text{ to } v\}.$$

Note: $\delta(u, v) = \infty$ if no path from u to v exists.



Well-definedness of shortest paths

If a graph G contains a negative-weight cycle, then some shortest paths do not exist.

Well-definedness of shortest paths

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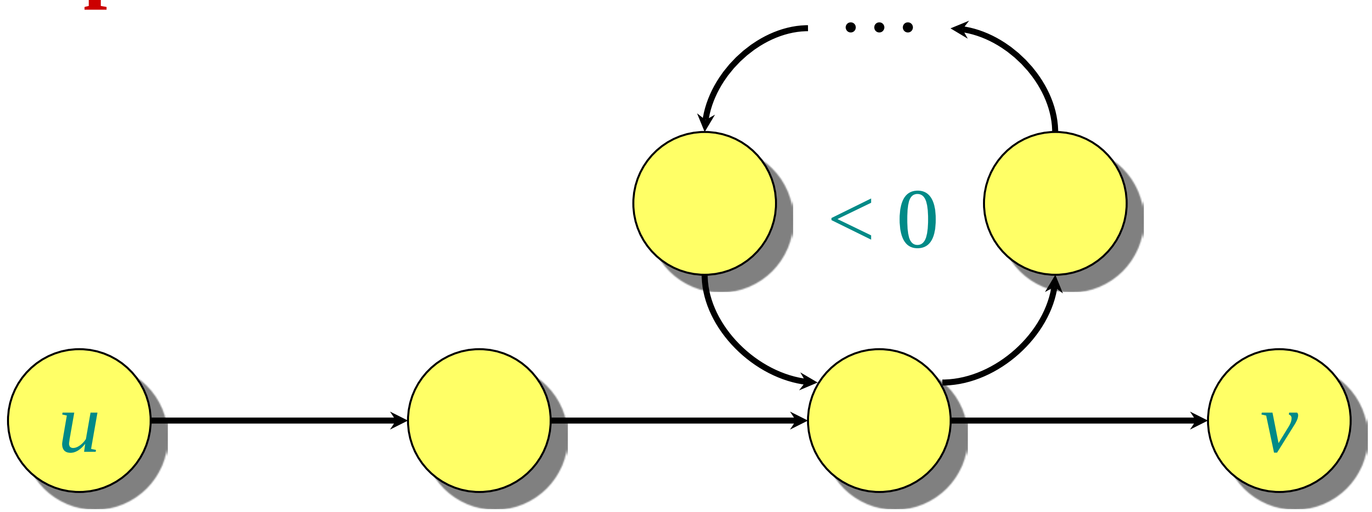
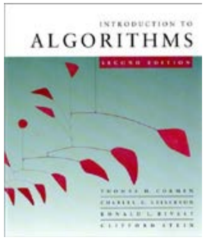
Example:



Optimal substructure

Theorem. A subpath of a shortest path is a shortest path.



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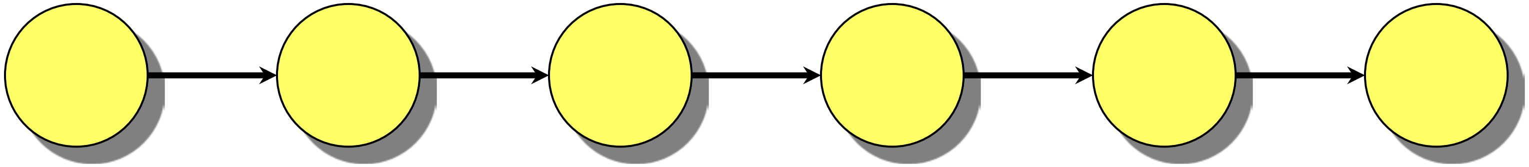
Proof. Cut and paste:



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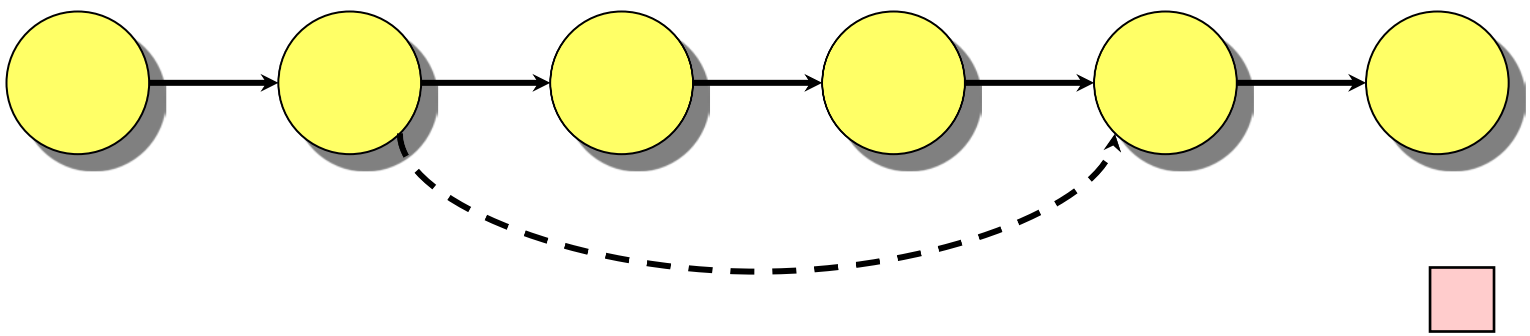
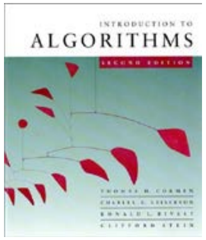


Triangle inequality

Theorem. For all $u, v, x \in V$, we have

$$\delta(u, v) \leq \delta(u, x) + \delta(x, v).$$



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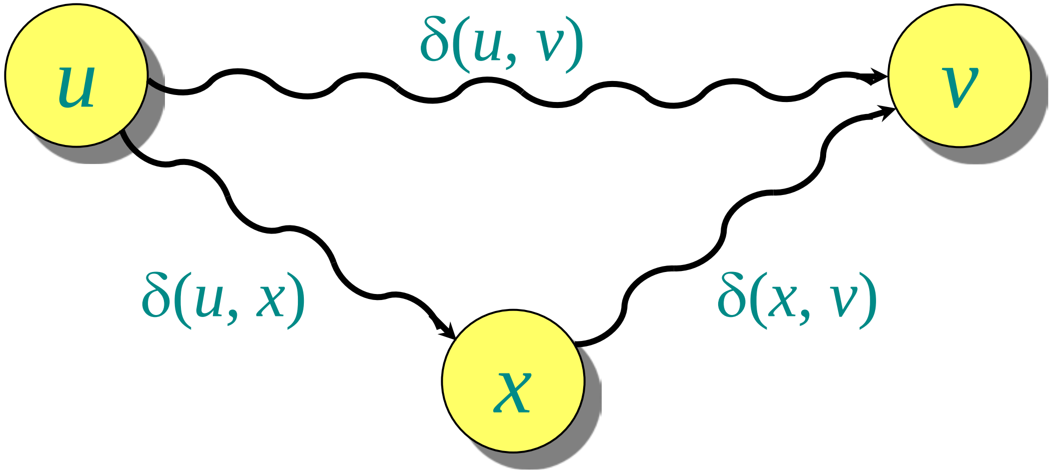
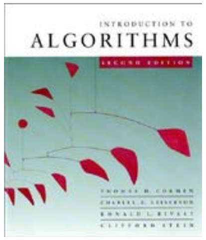


$\square$



Single-source shortest paths (nonnegative edge weights)

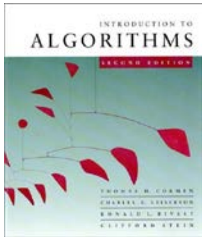
Problem. Assume that $w(u, v) \geq 0$ for all $(u, v) \in E$. (Hence, all shortest-path weights must exist.) From a given source vertex $s \in V$, find the shortest-path weights $\delta(s, v)$ for all $v \in V$.

IDEA: Greedy.

1. Maintain a set S of vertices whose shortest-path distances from s are known.
2. At each step, add to S the vertex $v \in V - S$ whose distance estimate from s is minimum.
3. Update the distance estimates of vertices adjacent to v.

Dijkstra's algorithm

$d[s] \leftarrow 0$
for each $v \in V - \{s\}$
    do $d[v] \leftarrow \infty$
$S \leftarrow \varnothing$
$Q \leftarrow V$ ⊳ Q is a priority queue maintaining $V - S$, keyed on $d[v]$



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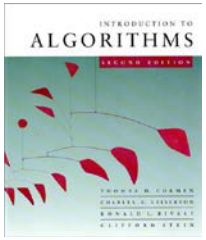
$Q \leftarrow V$ ⊳ Q is a priority queue maintaining $V - S$, keyed on $d[v]$
while $Q \neq \varnothing$
    do $u \leftarrow$ EXTRACT-MIN(Q)
        $S \leftarrow S \cup \{u\}$
        for each $v \in Adj[u]$
            do if $d[v] > d[u] + w(u, v)$
                then $d[v] \leftarrow d[u] + w(u, v)$



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while $Q \neq \varnothing$

    do $u \leftarrow$ Extract-Min(Q)

        $S \leftarrow S \cup \{u\}$

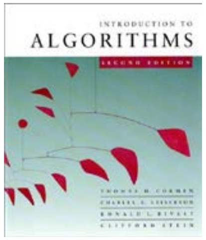
        for each $v \in Adj[u]$

            do if $d[v] > d[u] + w(u, v)$

                then $d[v] \leftarrow d[u] + w(u, v)$

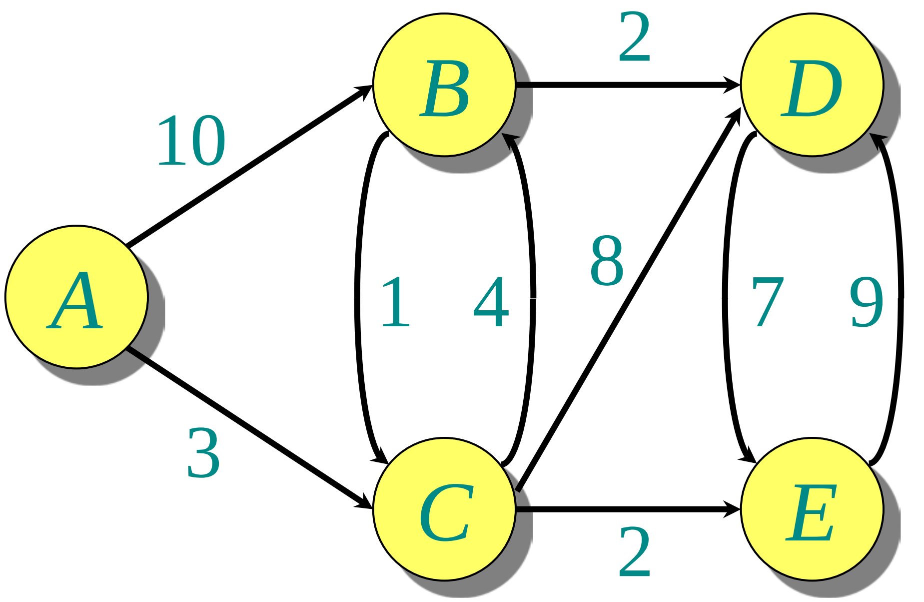
relaxation step

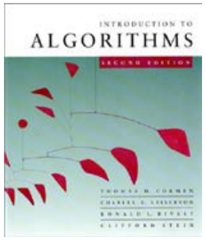
Implicit Decrease-Key



Example of Dijkstra's algorithm

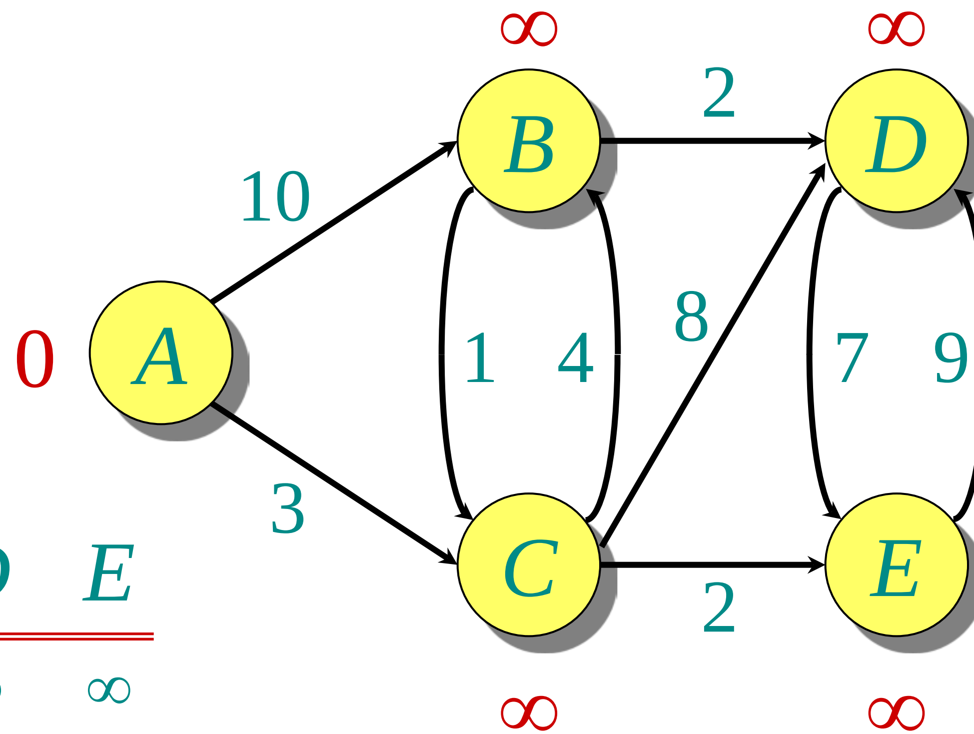
Graph with nonnegative edge weights:





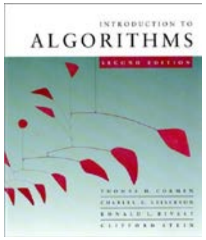
Example of Dijkstra's algorithm

Initialize:



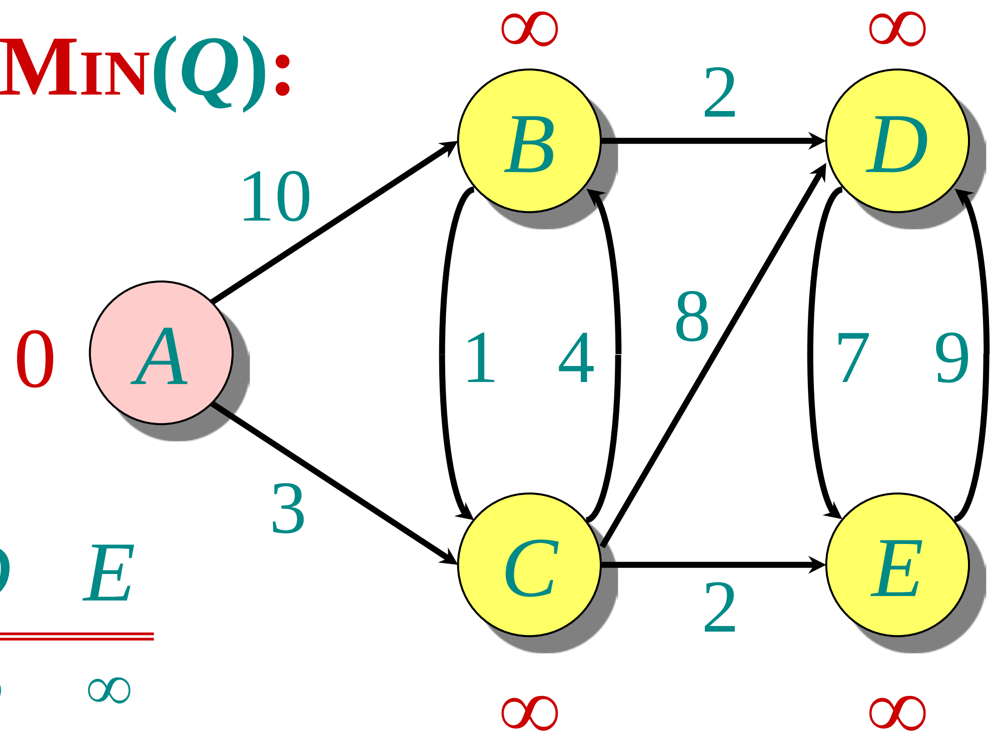
Q:	A	B	C	D	E
	0	∞	∞	∞	∞

S: { }



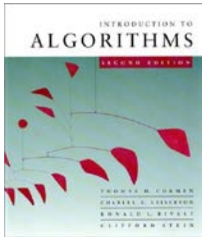
Example of Dijkstra's algorithm

"*A*" ← EXTRACT-MIN(*Q*):



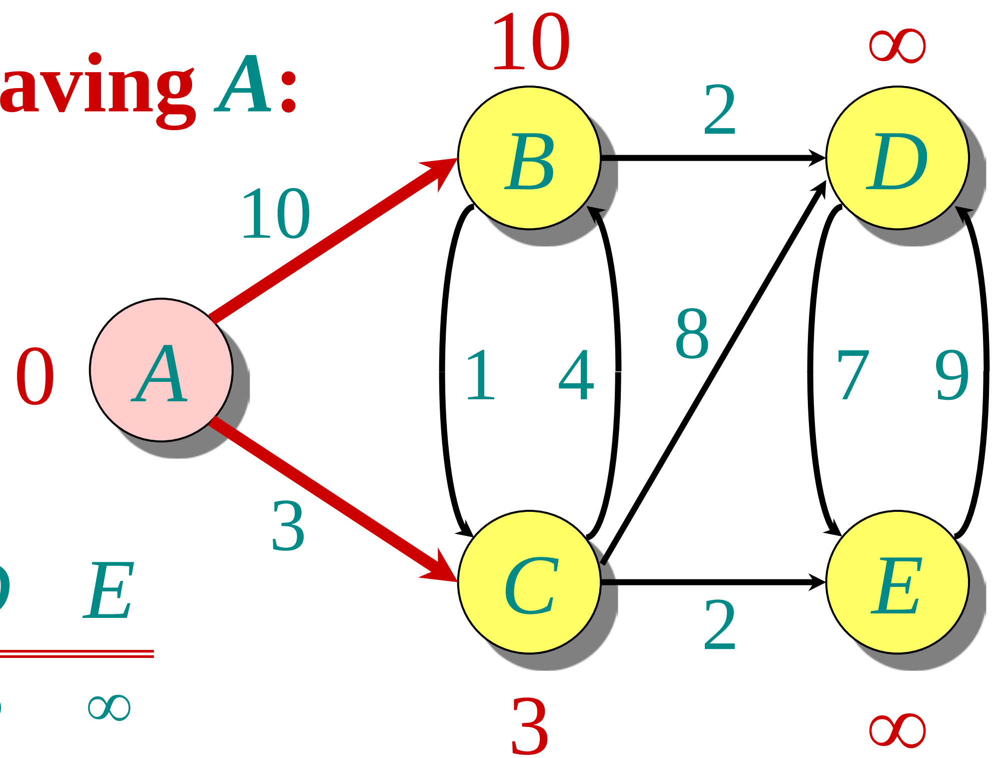
Q:	*A*	*B*	*C*	*D*	*E*
	0	∞	∞	∞	∞

S: { *A* }



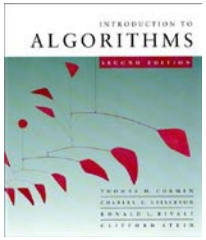
Example of Dijkstra's algorithm

Relax all edges leaving *A*:



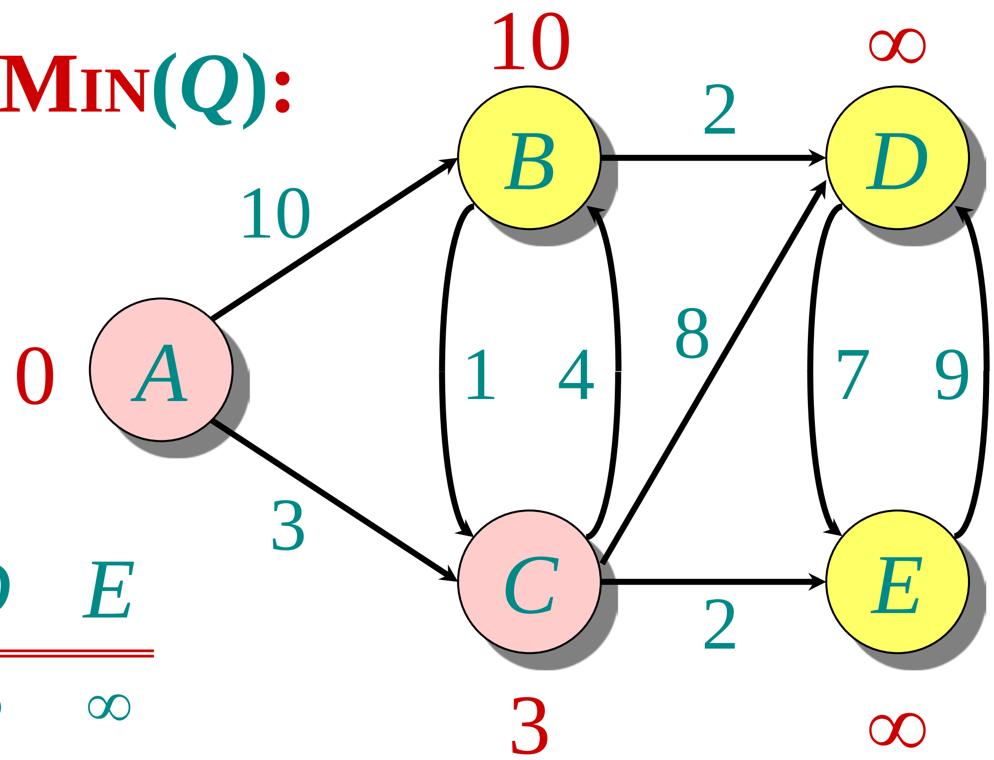
Q:	A	B	C	D	E
	0	∞	∞	∞	∞
		10	3	∞	∞

S: { A }



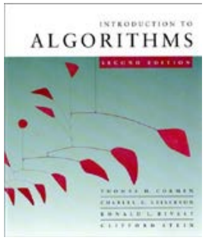
Example of Dijkstra's algorithm

"C" ← EXTRACT-MIN(Q):



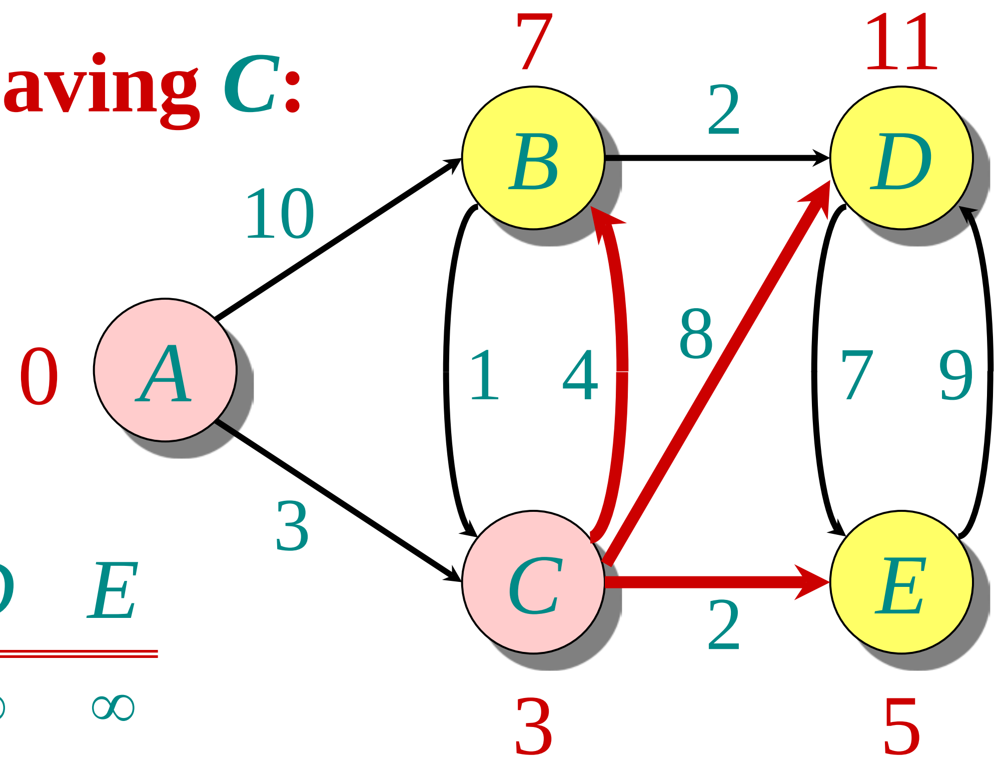
Q:	A	B	C	D	E
	0	∞	∞	∞	∞
		10	3	∞	∞

S: { A, C }



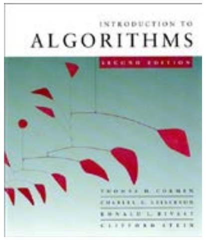
Example of Dijkstra's algorithm

Relax all edges leaving *C*:



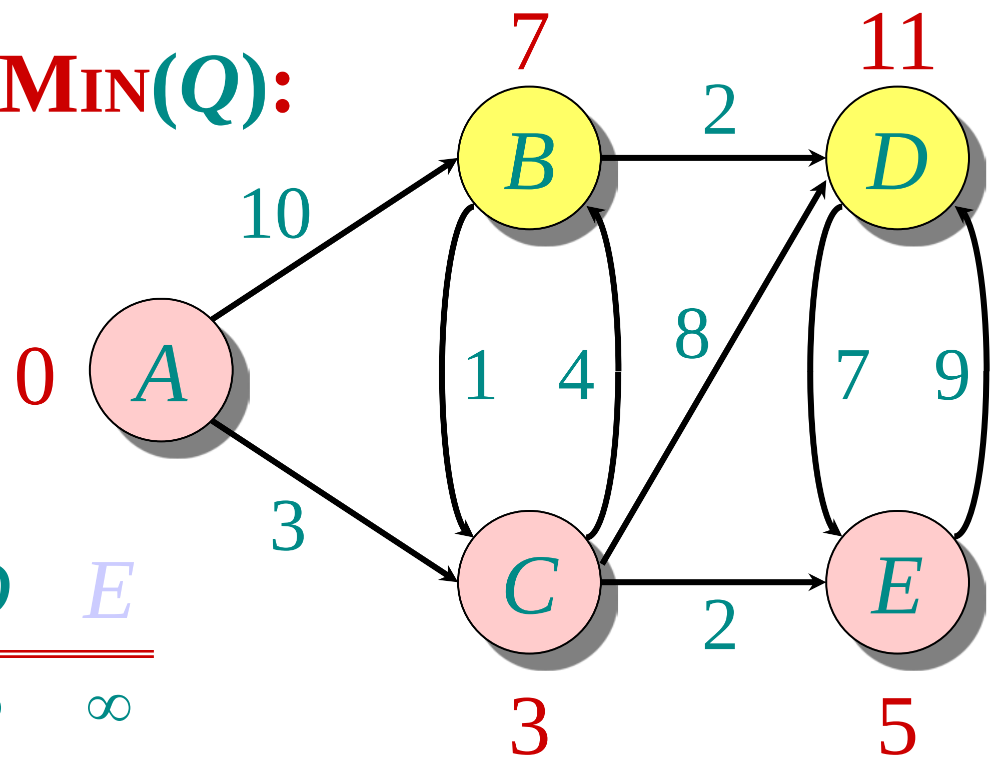
Q:	A	B	C	D	E
	0	∞	∞	∞	∞
		10	3	∞	∞
		7		11	5

S: { A, C }



Example of Dijkstra's algorithm

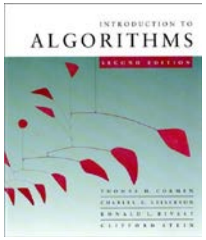
"E" $\leftarrow$ EXTRACT-MIN(Q):



Q:

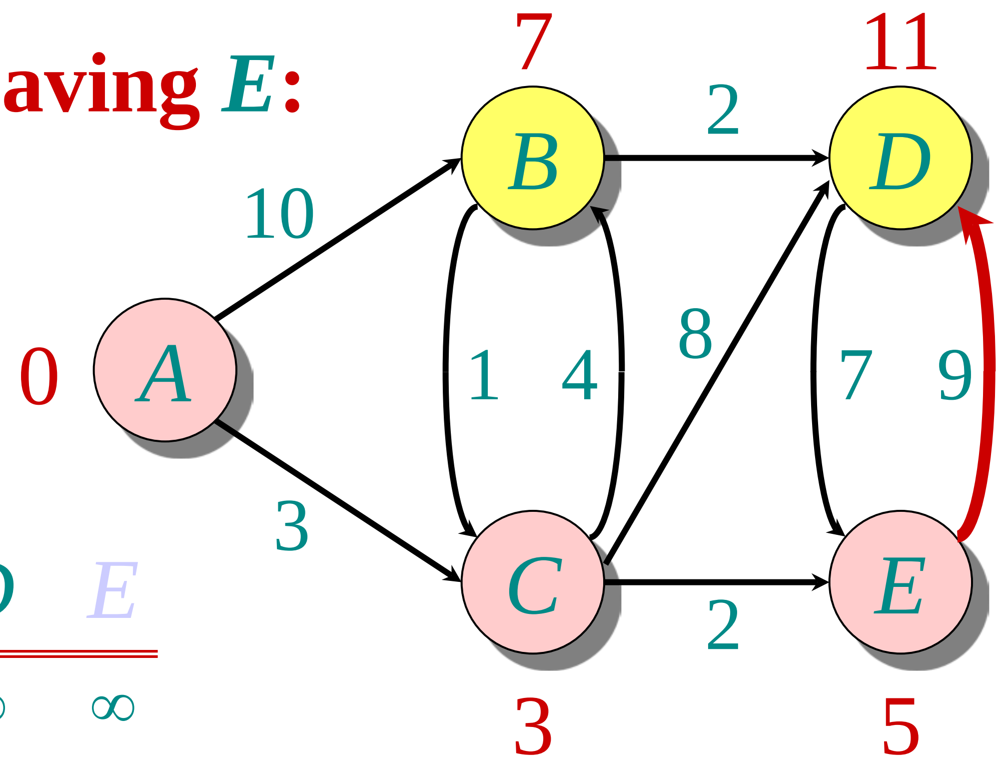
A	B	C	D	E
0	∞	∞	∞	∞
	10	3	∞	∞
	7		11	5

S: { A, C, E }



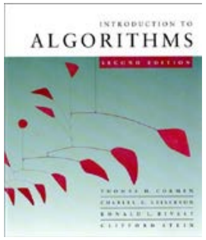
Example of Dijkstra's algorithm

Relax all edges leaving *E*:



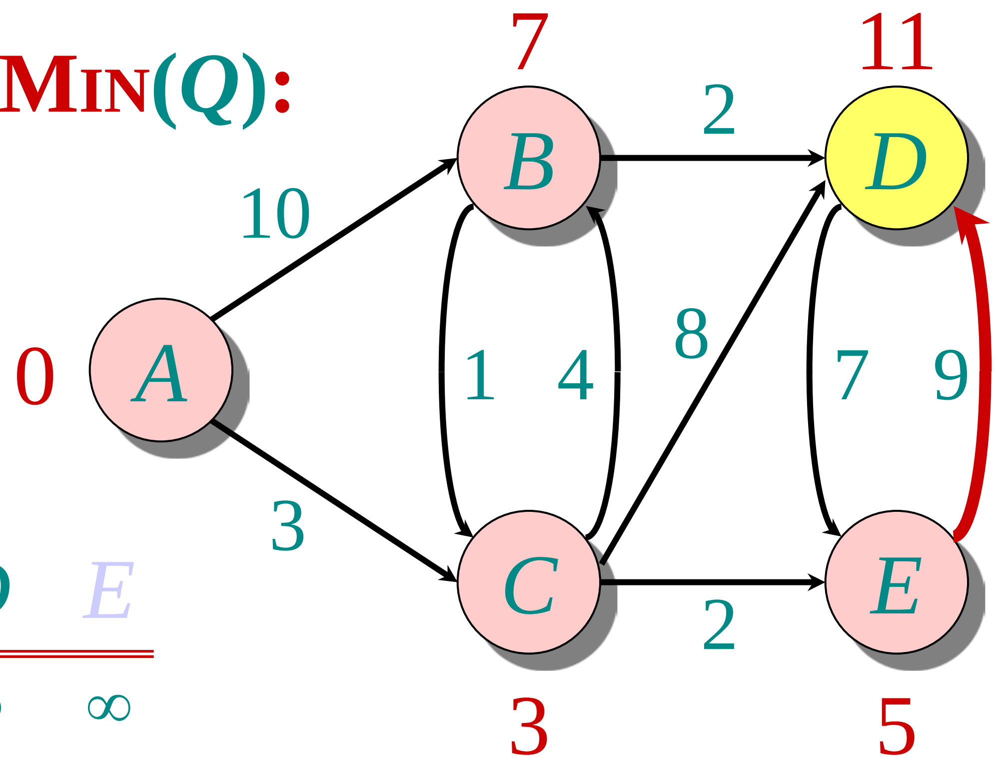
Q:	*A*	*B*	*C*	*D*	*E*
	0	∞	∞	∞	∞
		10	3	∞	∞
		7		11	5
		7		11	

S: { *A*, *C*, *E* }



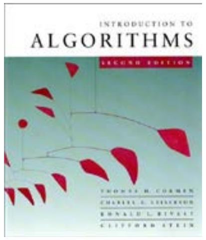
Example of Dijkstra's algorithm

"*B*" ← EXTRACT-MIN(*Q*):



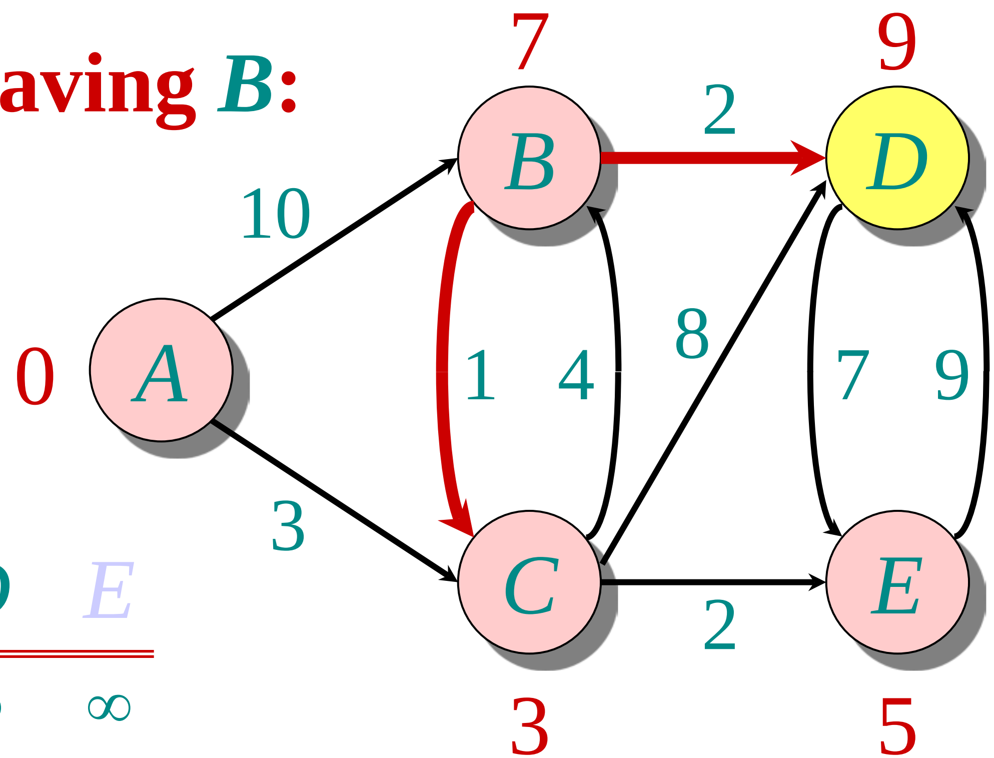
Q:	*A*	*B*	*C*	*D*	*E*
	0	∞	∞	∞	∞
		10	3	∞	∞
		7		11	5
		7		11	

S: { *A*, *C*, *E*, *B* }



Example of Dijkstra's algorithm

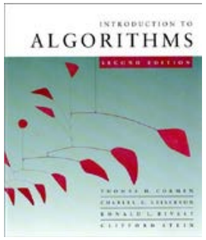
Relax all edges leaving *B*:



Q:

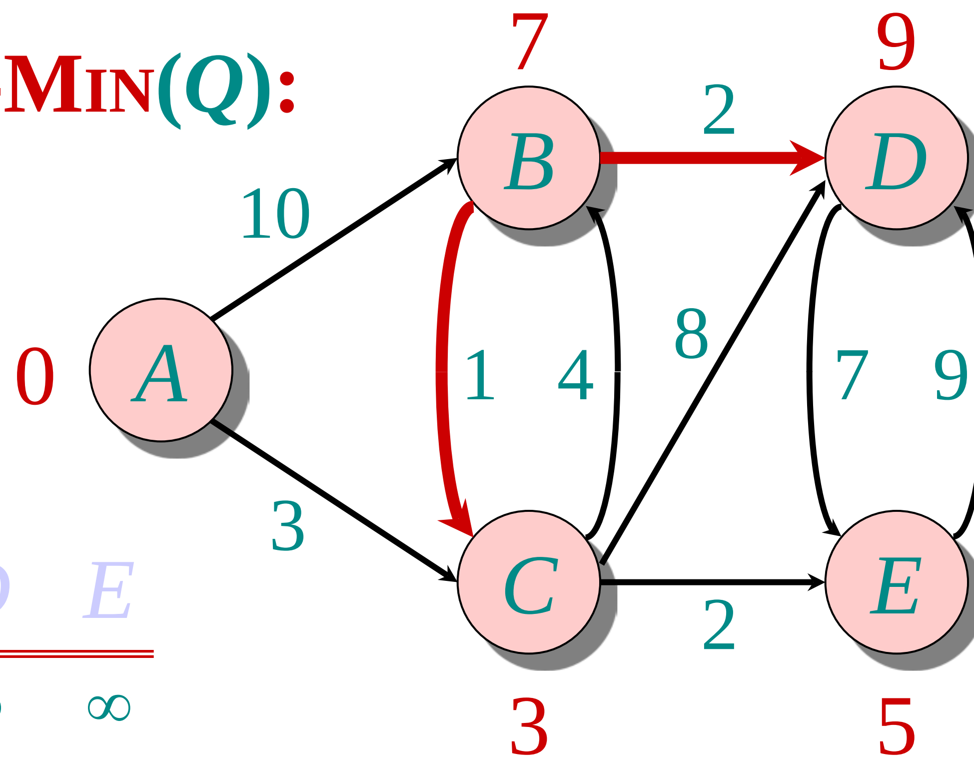
A	*B*	*C*	*D*	*E*
0	∞	∞	∞	∞
	10	3	∞	∞
	7		11	5
	7		11	
			9	

S: { *A*, *C*, *E*, *B* }



Example of Dijkstra's algorithm

"D" ← EXTRACT-MIN(Q):

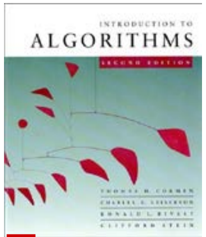


Q:	A	B	C	D	E
	0	∞	∞	∞	∞
		10	3	∞	∞
		7		11	5
		7		11	
				9	

S: { A, C, E, B, D }

Correctness — Part I

Lemma. Initializing $d[s] \leftarrow 0$ and $d[v] \leftarrow \infty$ for all $v \in V - \{s\}$ establishes $d[v] \geq \delta(s, v)$ for all $v \in V$, and this invariant is maintained over any sequence of relaxation steps.



Correctness — Part I

Lemma. Initializing $d[s] \leftarrow 0$ and $d[v] \leftarrow \infty$ for all $v \in V - \{s\}$ establishes $d[v] \geq \delta(s, v)$ for all $v \in V$, and this invariant is maintained over any sequence of relaxation steps.

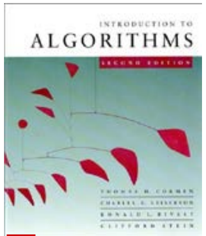
Proof. Suppose not. Let v be the first vertex for which $d[v] < \delta(s, v)$, and let u be the vertex that caused $d[v]$ to change: $d[v] = d[u] + w(u, v)$. Then,

$$
\begin{aligned}
d[v] &< \delta(s, v) && \text{supposition} \\
&\leq \delta(s, u) + \delta(u, v) && \text{triangle inequality} \\
&\leq \delta(s,u) + w(u, v) && \text{sh. path} \leq \text{specific path} \\
&\leq d[u] + w(u, v) && v \text{ is first violation}
\end{aligned}
$$

Contradiction. $\square$

Correctness — Part II

Lemma. Let u be v's predecessor on a shortest path from s to v. Then, if $d[u] = \delta(s, u)$ and edge (u, v) is relaxed, we have $d[v] = \delta(s, v)$ after the relaxation.



Correctness — Part II

Lemma. Let u be v's predecessor on a shortest path from s to v. Then, if $d[u] = \delta(s, u)$ and edge (u, v) is relaxed, we have $d[v] = \delta(s, v)$ after the relaxation.

Proof. Observe that $\delta(s, v) = \delta(s, u) + w(u, v)$. Suppose that $d[v] > \delta(s, v)$ before the relaxation. (Otherwise, we're done.) Then, the test $d[v] > d[u] + w(u, v)$ succeeds, because $d[v] > \delta(s, v) = \delta(s, u) + w(u, v) = d[u] + w(u, v)$, and the algorithm sets $d[v] = d[u] + w(u, v) = \delta(s, v)$. □

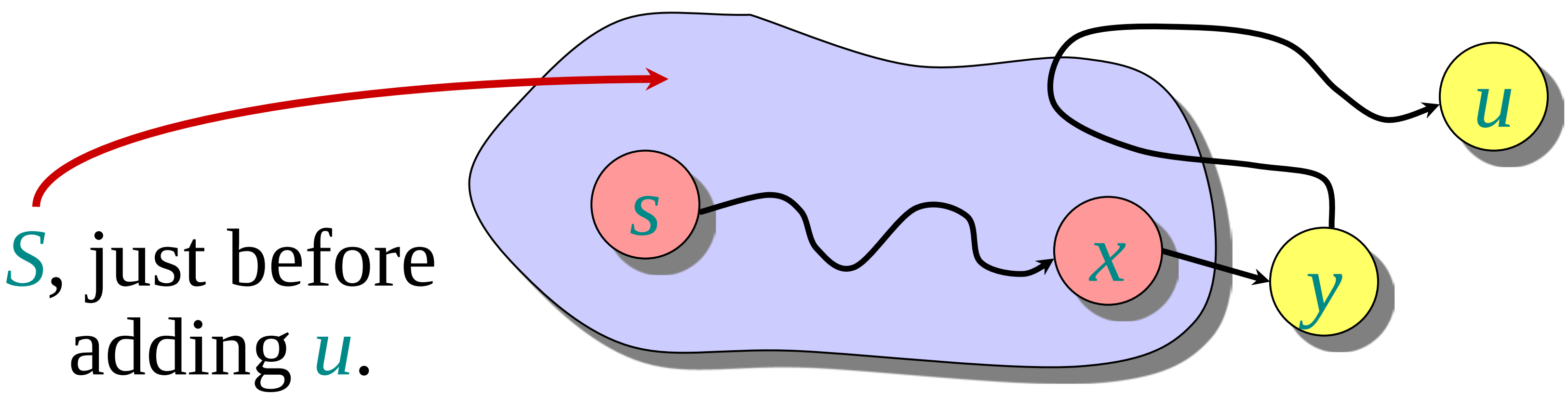
Correctness — Part III

Theorem. Dijkstra's algorithm terminates with $d[v] = \delta(s, v)$ for all $v \in V$.

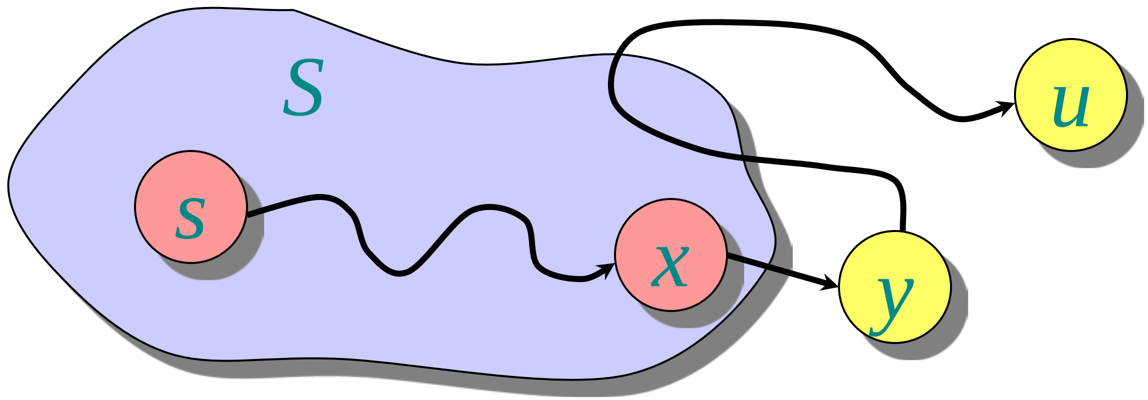
Correctness — Part III

Theorem. Dijkstra's algorithm terminates with $d[v] = \delta(s, v)$ for all $v \in V$.

Proof. It suffices to show that $d[v] = \delta(s, v)$ for every $v \in V$ when v is added to S. Suppose u is the first vertex added to S for which $d[u] > \delta(s, u)$. Let y be the first vertex in $V - S$ along a shortest path from s to u, and let x be its predecessor:



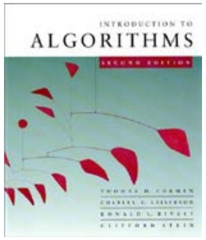
Correctness — Part III (continued)



Since u is the first vertex violating the claimed invariant, we have $d[x] = \delta(s, x)$. When x was added to S, the edge (x, y) was relaxed, which implies that $d[y] = \delta(s, y) \le \delta(s, u) < d[u]$. But, $d[u] \le d[y]$ by our choice of u. Contradiction. ☐

Analysis of Dijkstra

while $Q \neq \emptyset$
  do $u \leftarrow$ EXTRACT-MIN(Q)
    $S \leftarrow S \cup \{u\}$
    for each $v \in Adj[u]$
      do if $d[v] > d[u] + w(u, v)$
        then $d[v] \leftarrow d[u] + w(u, v)$



Analysis of Dijkstra

$|V|$ times

while $Q \neq \emptyset$
    do $u \leftarrow$ EXTRACT-MIN(Q)
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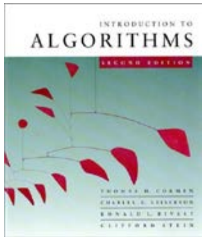


Analysis of Dijkstra

$|V|$ times

while $Q \neq \emptyset$

    do $u \leftarrow$ EXTRACT-MIN(Q)

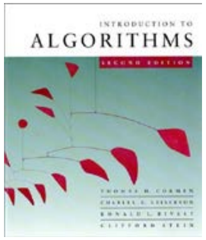
        $S \leftarrow S \cup \{u\}$

$degree(u)$ times

        for each $v \in Adj[u]$

            do if $d[v] > d[u] + w(u, v)$

                then $d[v] \leftarrow d[u] + w(u, v)$



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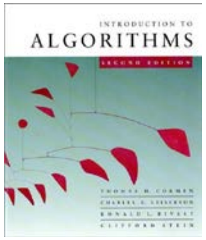
Handshaking Lemma $\Rightarrow \Theta(E)$ implicit DECREASE-KEY's.



Analysis of Dijkstra

$|V|$ times

while $Q \neq \emptyset$

  do $u \leftarrow$ EXTRACT-MIN(Q)

  $S \leftarrow S \cup \{u\}$

$degree(u)$ times

  for each $v \in Adj[u]$

   do if $d[v] > d[u] + w(u, v)$

    then $d[v] \leftarrow d[u] + w(u, v)$

Handshaking Lemma $\Rightarrow \Theta(E)$ implicit DECREASE-KEY's.

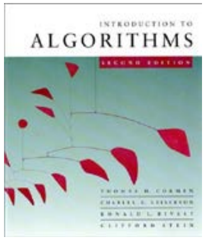
Time $= \Theta(V \cdot T_{\text{EXTRACT-MIN}} + E \cdot T_{\text{DECREASE-KEY}})$

Note: Same formula as in the analysis of Prim's minimum spanning tree algorithm.

Analysis of Dijkstra (continued)

$$\text{Time} = \Theta(V)\cdot T_{\text{EXTRACT-MIN}} + \Theta(E)\cdot T_{\text{DECREASE-KEY}}$$

Q	$T_{\text{EXTRACT-MIN}}$	$T_{\text{DECREASE-KEY}}$	Total



Analysis of Dijkstra (continued)

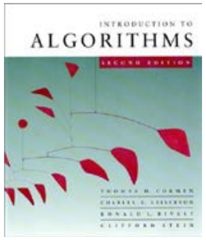
Time = $\Theta(V) \cdot T_{\text{EXTRACT-MIN}} + \Theta(E) \cdot T_{\text{DECREASE-KEY}}$

Q	$T_{\text{EXTRACT-MIN}}$	$T_{\text{DECREASE-KEY}}$	Total
array	$O(V)$	$O(1)$	$O(V^2)$

Analysis of Dijkstra (continued)

Time = $\Theta(V)\cdot T_{\text{EXTRACT-MIN}} + \Theta(E)\cdot T_{\text{DECREASE-KEY}}$

Q	$T_{\text{EXTRACT-MIN}}$	$T_{\text{DECREASE-KEY}}$	Total
array	$O(V)$	$O(1)$	$O(V^2)$
binary heap	$O(\lg V)$	$O(\lg V)$	$O(E \lg V)$



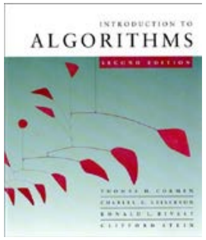
Analysis of Dijkstra (continued)

Time = $\Theta(V) \cdot T_{\text{EXTRACT-MIN}} + \Theta(E) \cdot T_{\text{DECREASE-KEY}}$

Q	$T_{\text{EXTRACT-MIN}}$	$T_{\text{DECREASE-KEY}}$	Total
array	$O(V)$	$O(1)$	$O(V^2)$
binary heap	$O(\lg V)$	$O(\lg V)$	$O(E \lg V)$
Fibonacci heap	$O(\lg V)$ amortized	$O(1)$ amortized	$O(E + V \lg V)$ worst case

Unweighted graphs

Suppose that $w(u, v) = 1$ for all $(u, v) \in E$.
Can Dijkstra's algorithm be improved?



Unweighted graphs

Suppose that $w(u, v) = 1$ for all $(u, v) \in E$.
Can Dijkstra's algorithm be improved?

- Use a simple FIFO queue instead of a priority queue.

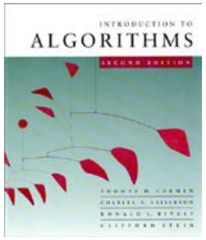
Unweighted graphs

Suppose that $w(u, v) = 1$ for all $(u, v) \in E$. Can Dijkstra's algorithm be improved?

- Use a simple FIFO queue instead of a priority queue.

Breadth-first search

while $Q \neq \emptyset$
  do $u \leftarrow \text{D}\small{\text{EQUEUE}}(Q)$
    for each $v \in Adj[u]$
      do if $d[v] = \infty$
        then $d[v] \leftarrow d[u] + 1$
          $\text{E}\small{\text{NQUEUE}}(Q, v)$



Unweighted graphs

Suppose that $w(u, v) = 1$ for all $(u, v) \in E$. Can Dijkstra's algorithm be improved?

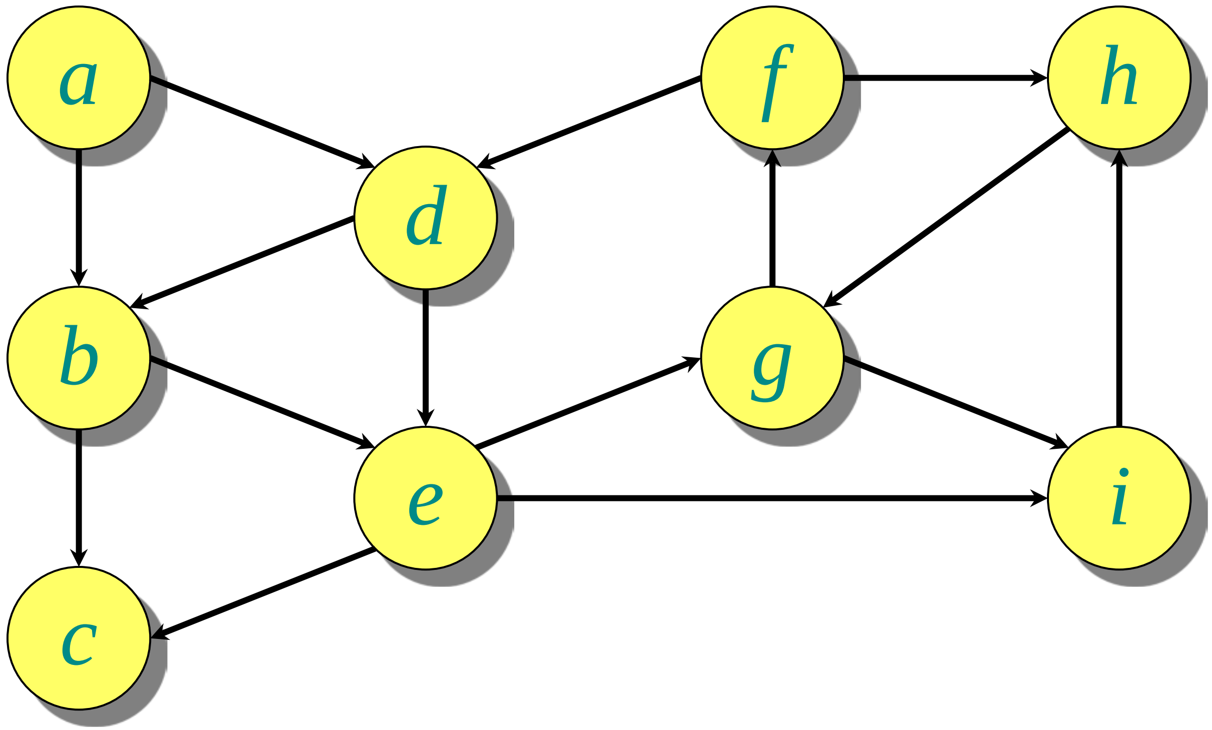
- Use a simple FIFO queue instead of a priority queue.

Breadth-first search

$$
\begin{array}{l}
\textbf{while } Q \neq \emptyset \\
\quad \textbf{do } u \leftarrow \text{DEQUEUE}(Q) \\
\qquad \textbf{for } \text{each } v \in Adj[u] \\
\qquad\quad \textbf{do if } d[v] = \infty \\
\qquad\qquad \textbf{then } d[v] \leftarrow d[u] + 1 \\
\qquad\qquad\qquad \text{ENQUEUE}(Q, v)
\end{array}
$$

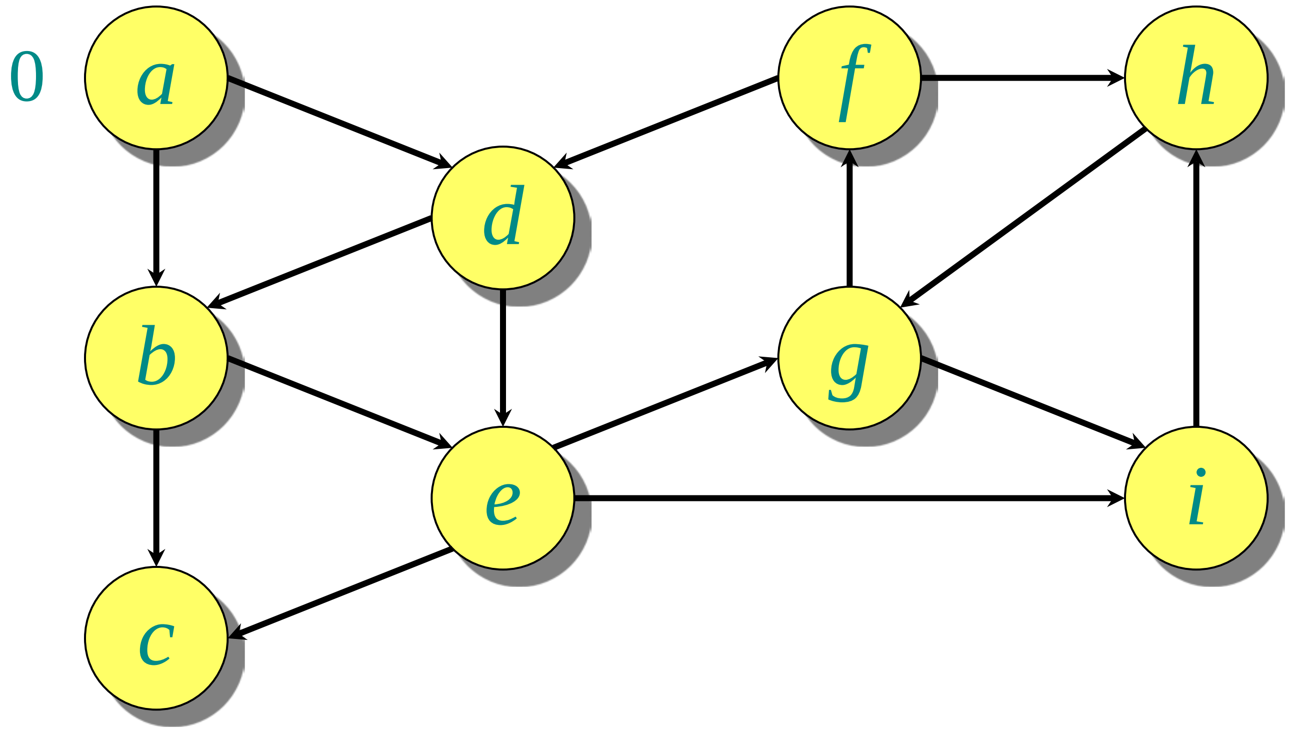
Analysis: Time $= O(V + E)$.

Example of breadth-first search



Q:

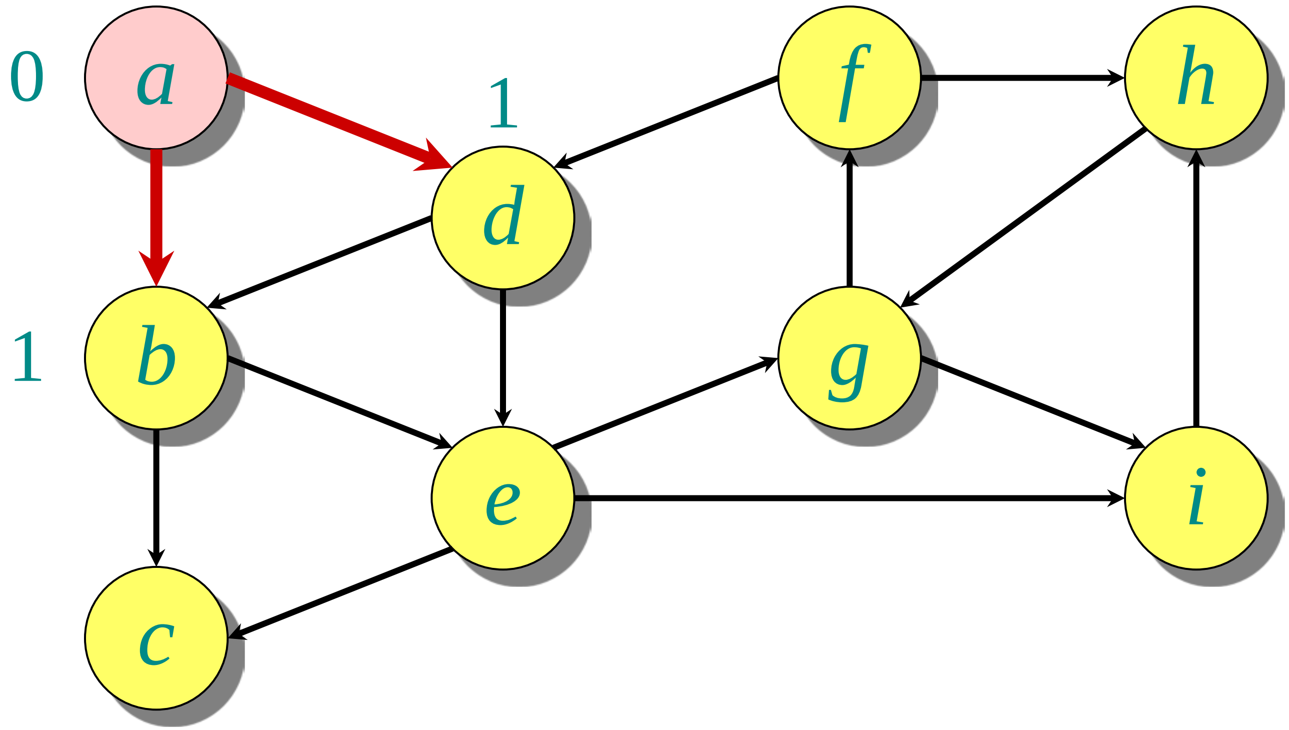
Example of breadth-first search



0

Q: *a*

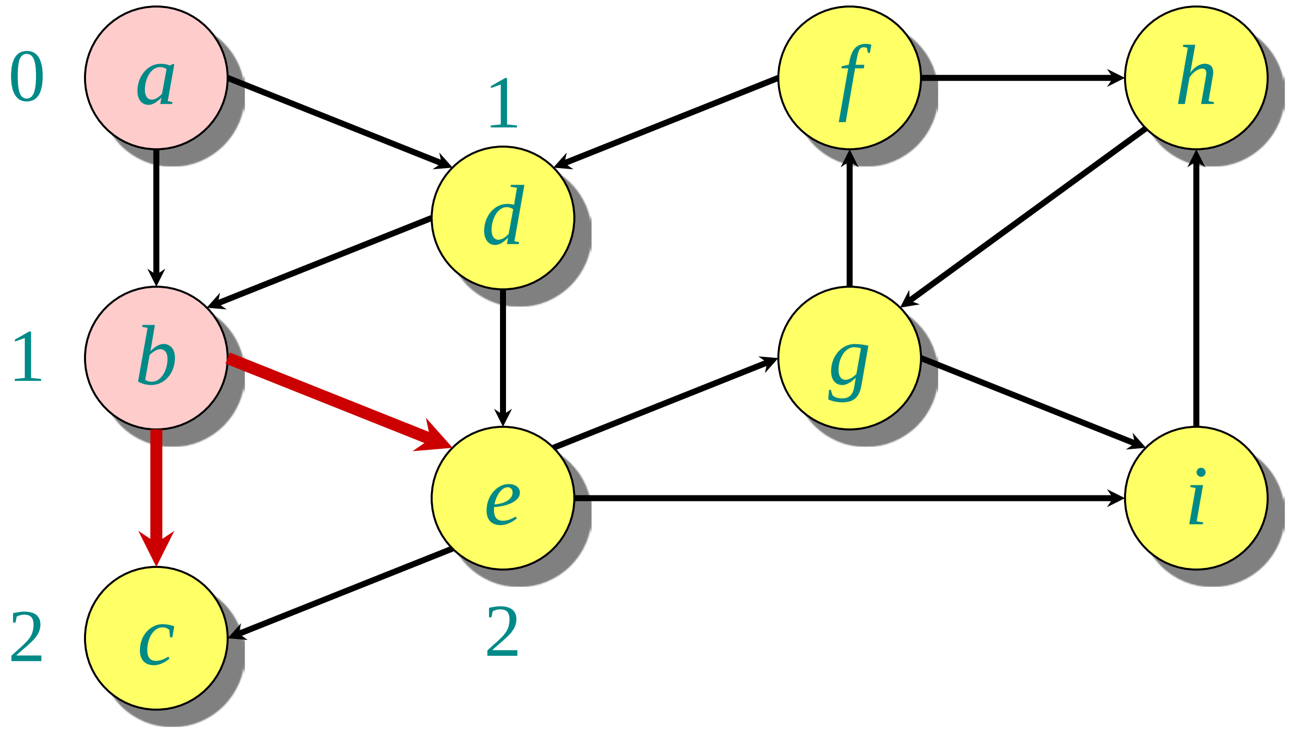
Example of breadth-first search



1 1

Q: *a* *b* *d*

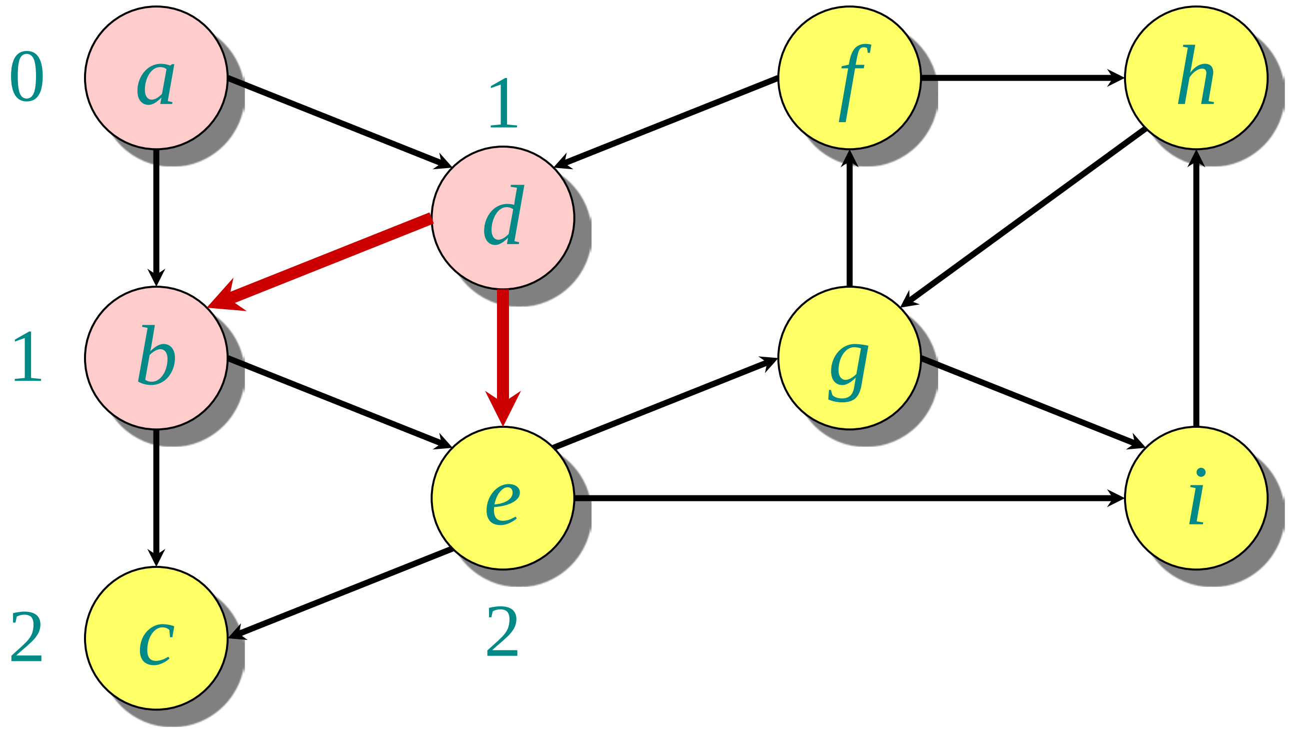
Example of breadth-first search



1 2 2

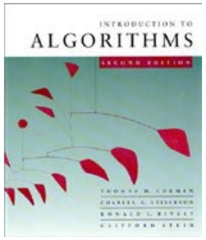
Q: *a* *b* *d* *c* *e*

Example of breadth-first search

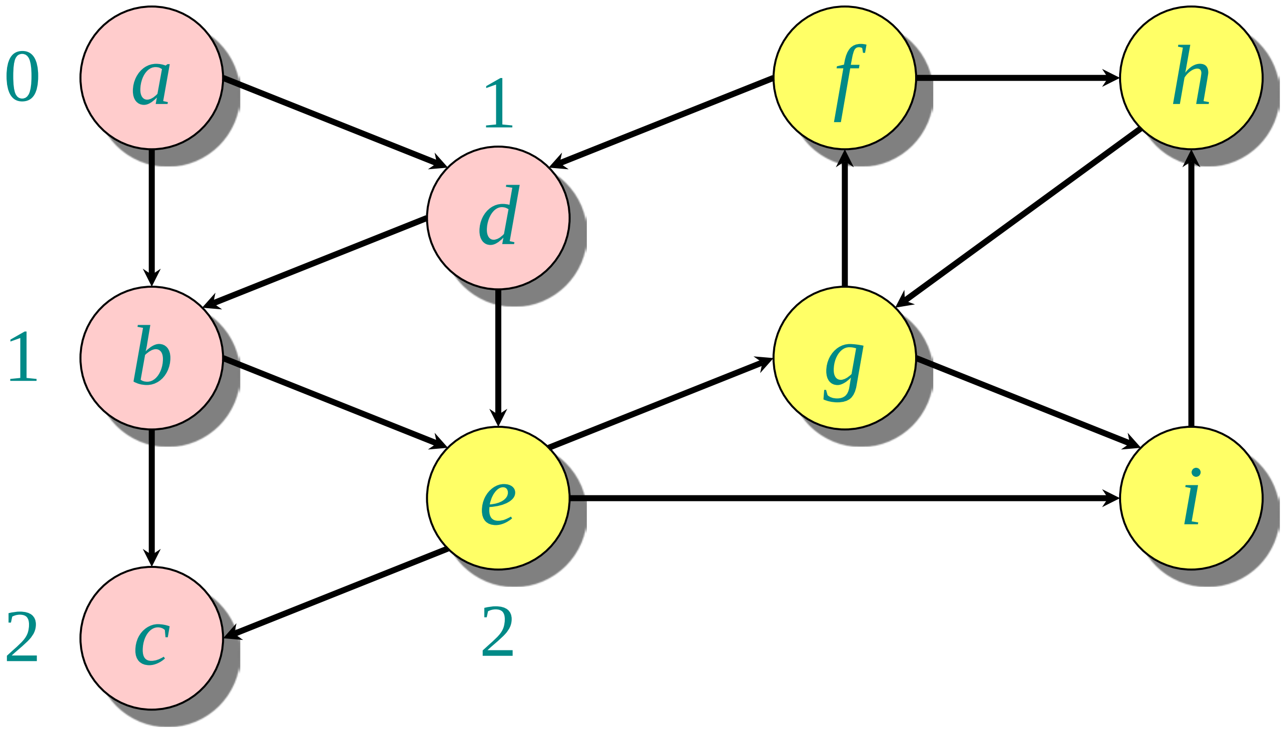


2 2

Q: *a* *b* *d* *c* *e*

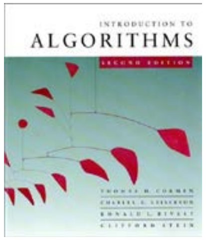


Example of breadth-first search

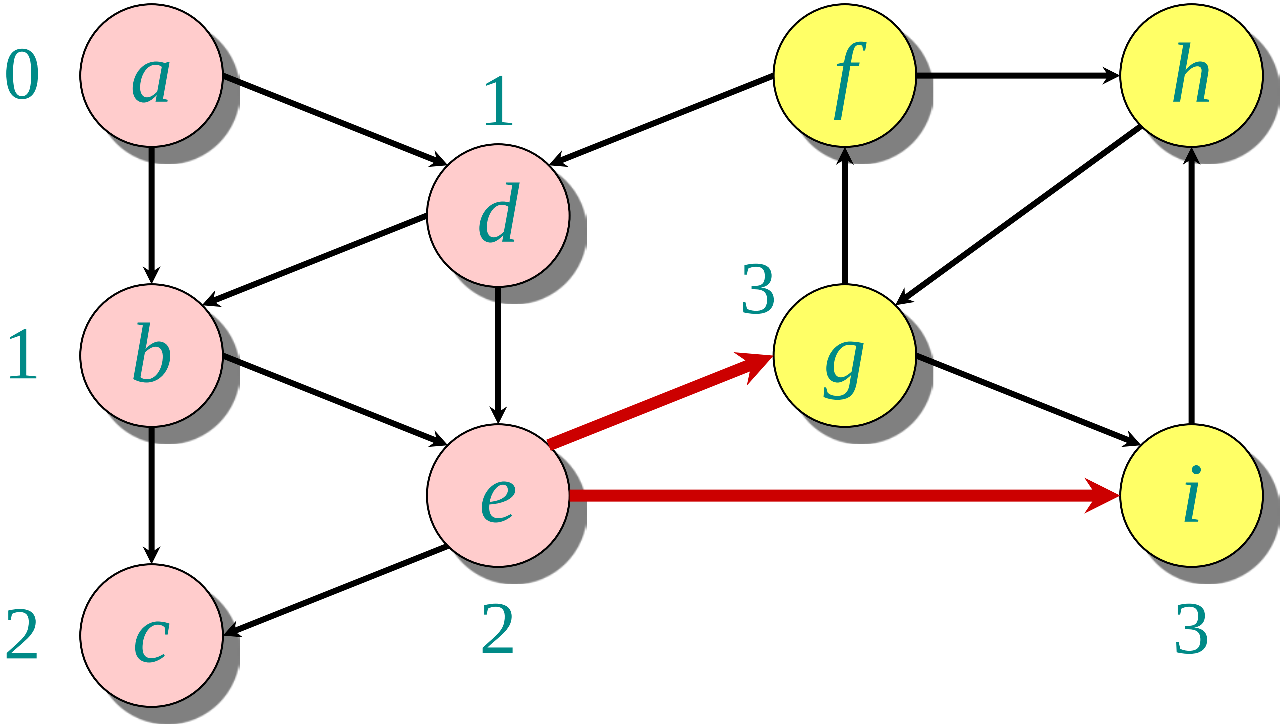


2

Q: *a* *b* *d* *c* *e*

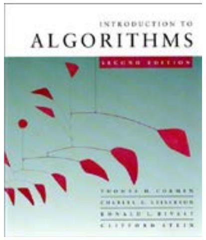


Example of breadth-first search

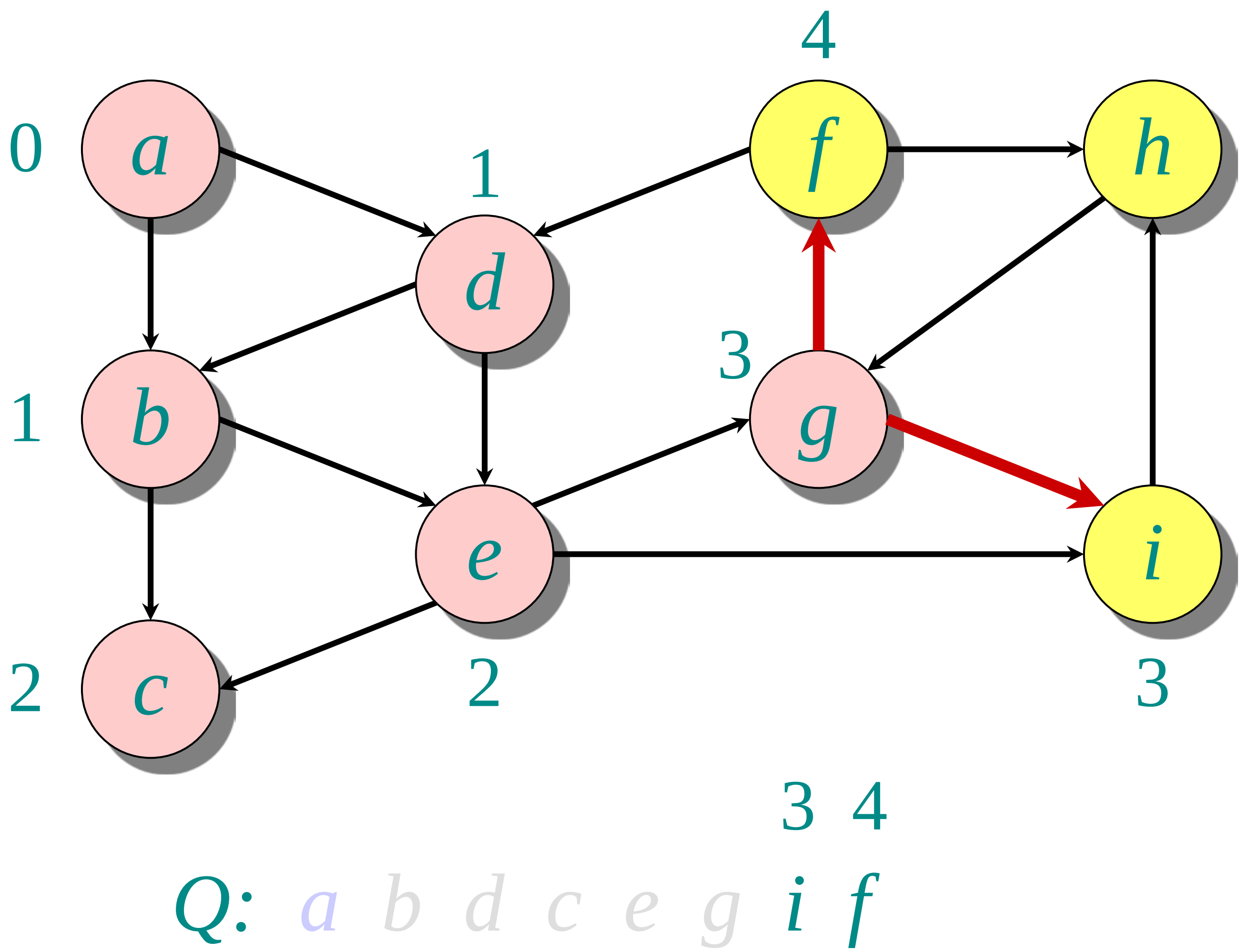


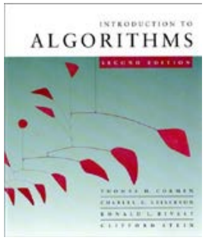
3 3

Q: *a* *b* *d* *c* *e* *g* *i*

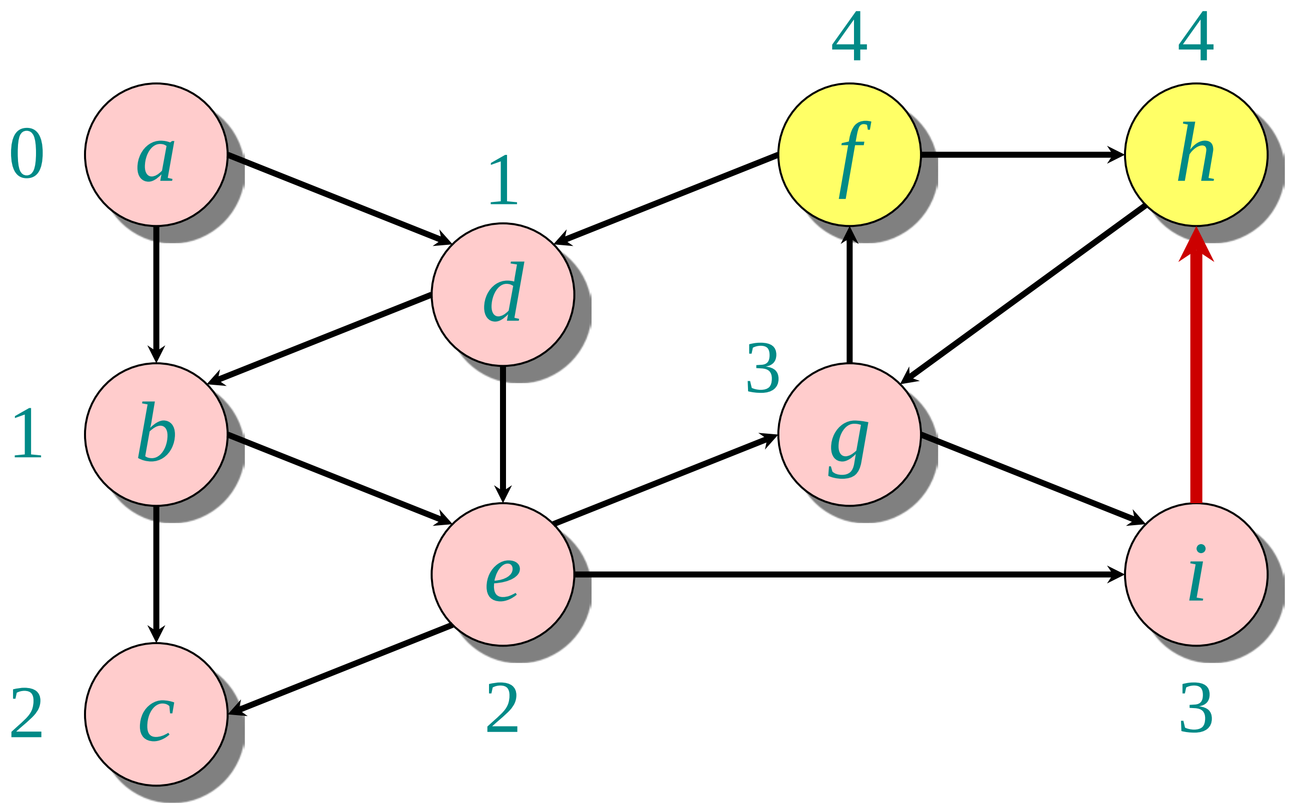


Example of breadth-first search





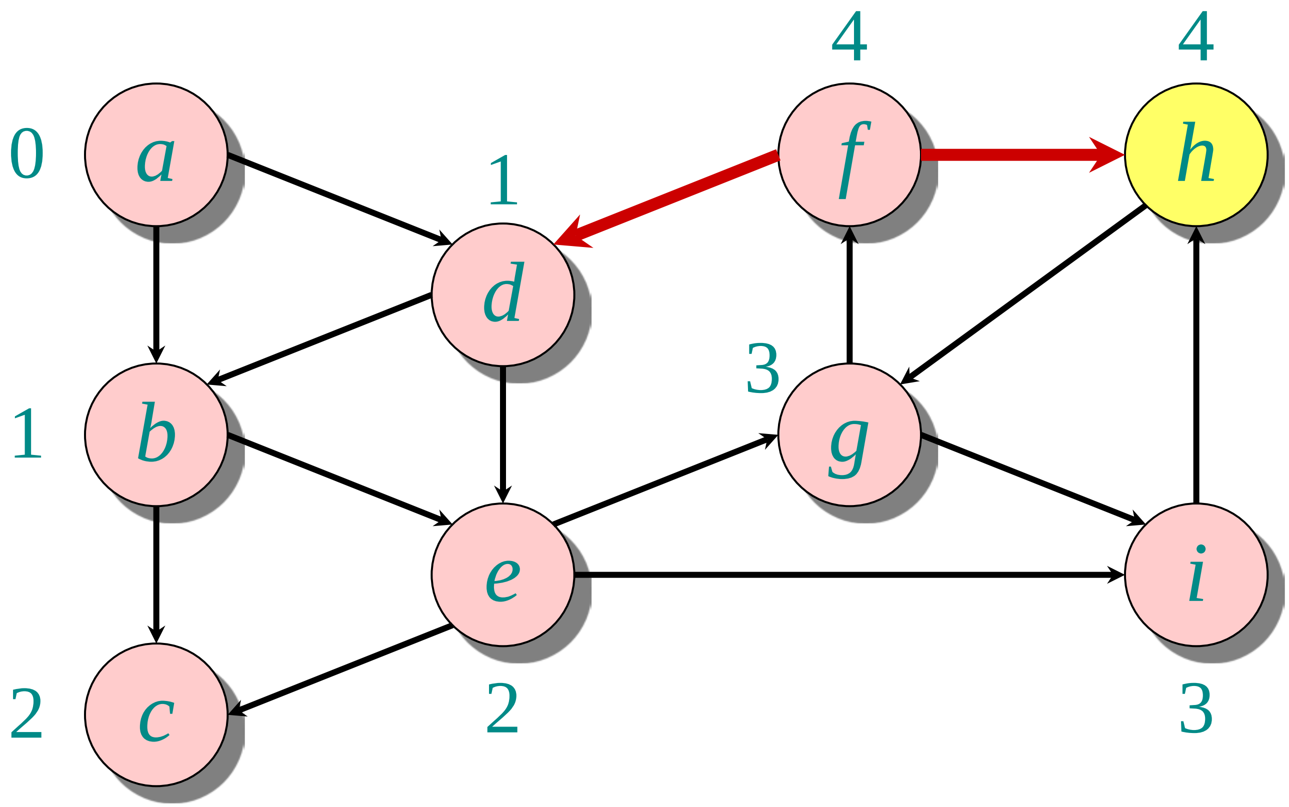
Example of breadth-first search



4 4

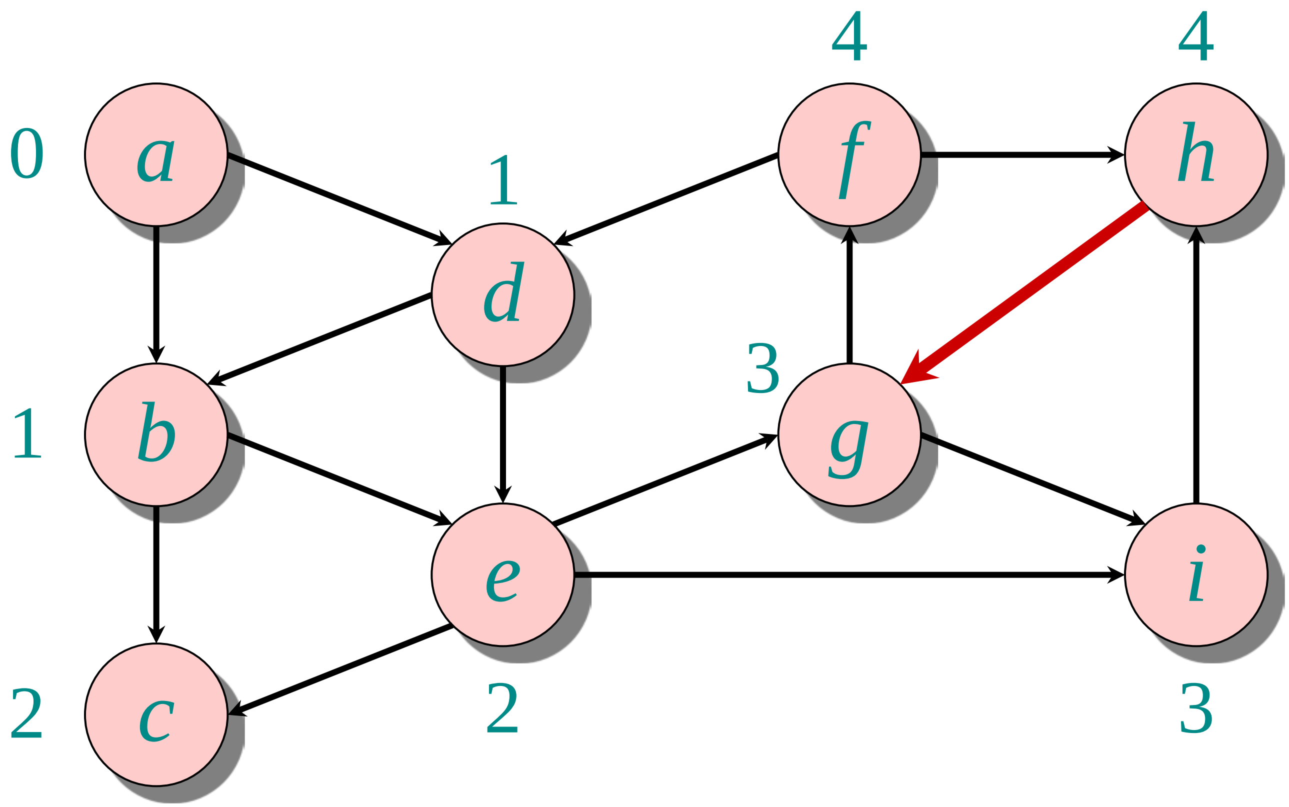
Q: *a b d c e g i f h*

Example of breadth-first search



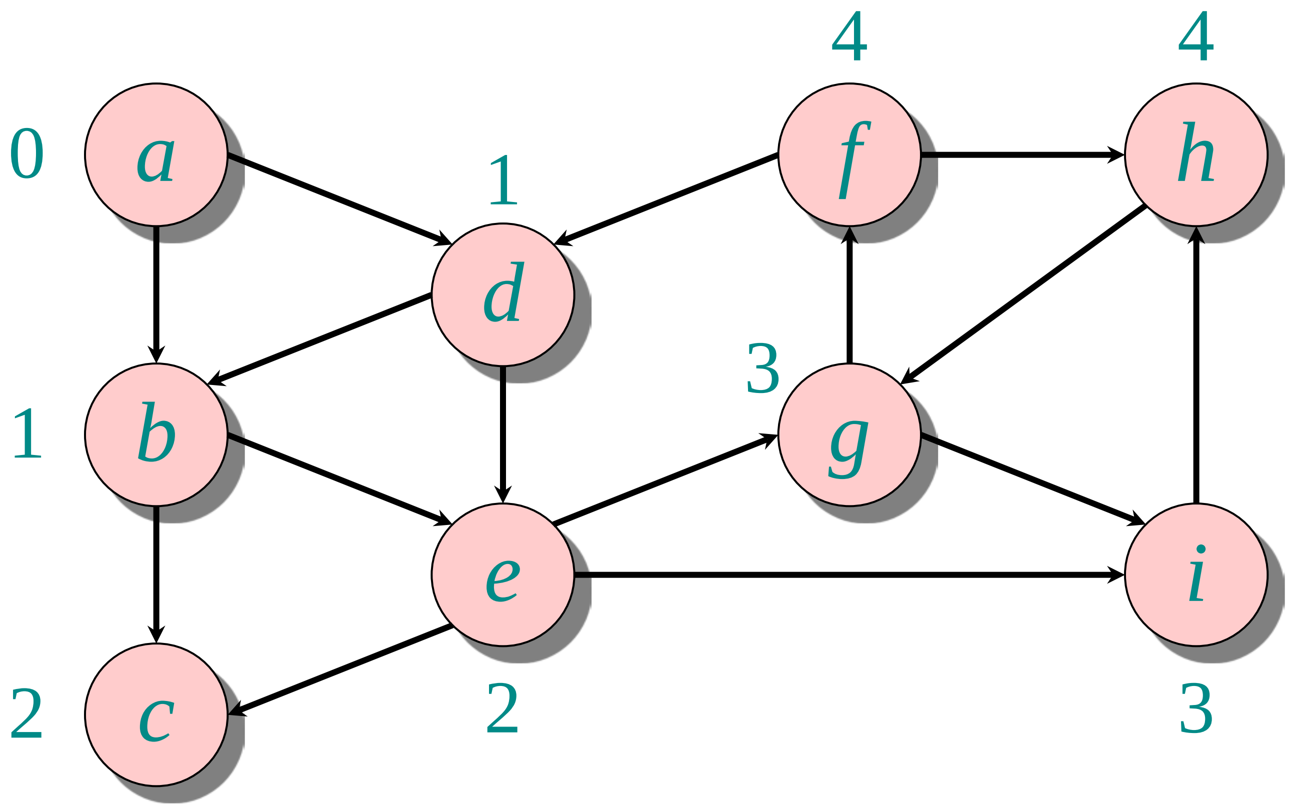
Q: a b d c e g i f $\overset{4}{h}$

Example of breadth-first search



Q: *a b d c e g i f h*

Example of breadth-first search



Q: *a b d c e g i f h*

Correctness of BFS

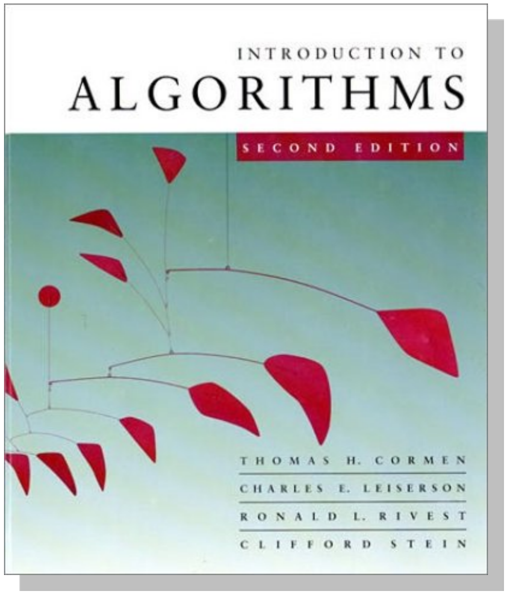
while $Q \neq \emptyset$
  do $u \leftarrow \text{DEQUEUE}(Q)$
    for each $v \in Adj[u]$
      do if $d[v] = \infty$
        then $d[v] \leftarrow d[u] + 1$
          $\text{ENQUEUE}(Q, v)$

Key idea:

The FIFO Q in breadth-first search mimics the priority queue Q in Dijkstra.

- **Invariant:** v comes after u in Q implies that $d[v] = d[u]$ or $d[v] = d[u] + 1$.

Introduction to Algorithms
6.046J/18.401J



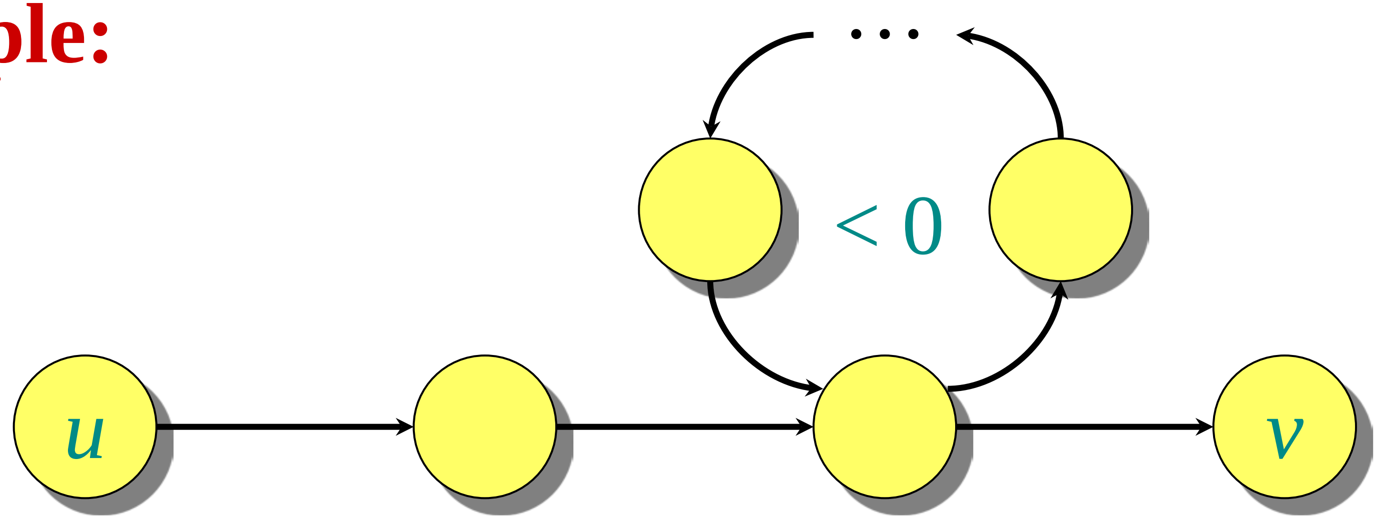
LECTURE 18
Shortest Paths II
- Bellman-Ford algorithm
- Linear programming and difference constraints
- VLSI layout compaction

Prof. Erik Demaine

Negative-weight cycles

Recall: If a graph $G = (V, E)$ contains a negative-weight cycle, then some shortest paths may not exist.

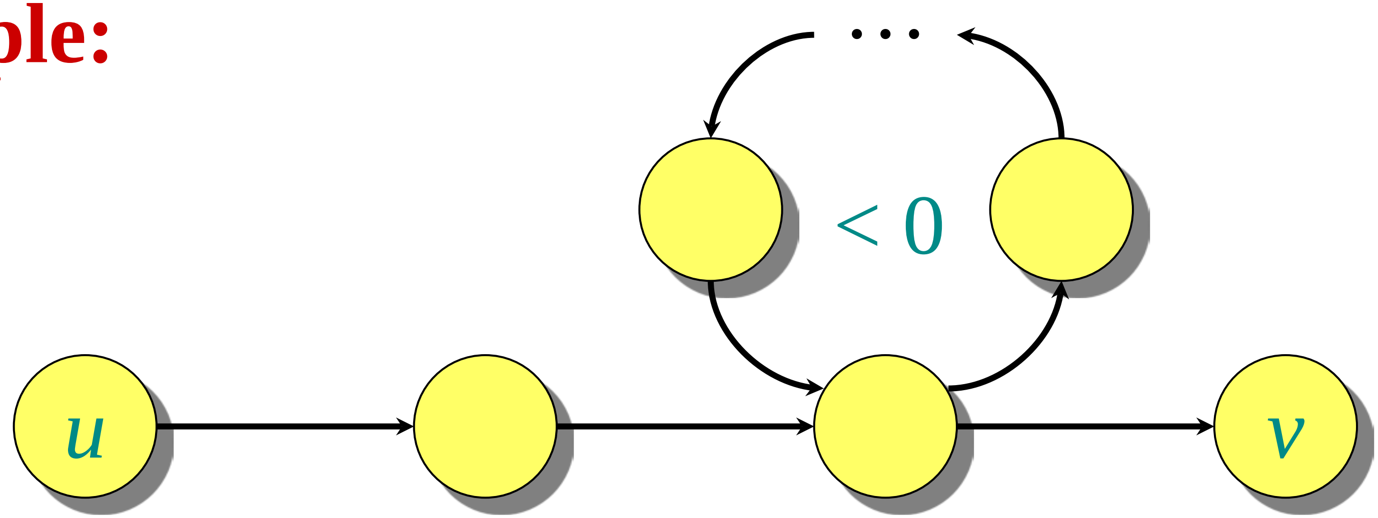
Example:



Negative-weight cycles

Recall: If a graph $G = (V, E)$ contains a negative-weight cycle, then some shortest paths may not exist.

Example:



Bellman-Ford algorithm: Finds all shortest-path lengths from a ***source*** $s \in V$ to all $v \in V$ or determines that a negative-weight cycle exists.

Bellman-Ford algorithm

$d[s] \leftarrow 0$
for each $v \in V - \{s\}$
  do $d[v] \leftarrow \infty$

initialization

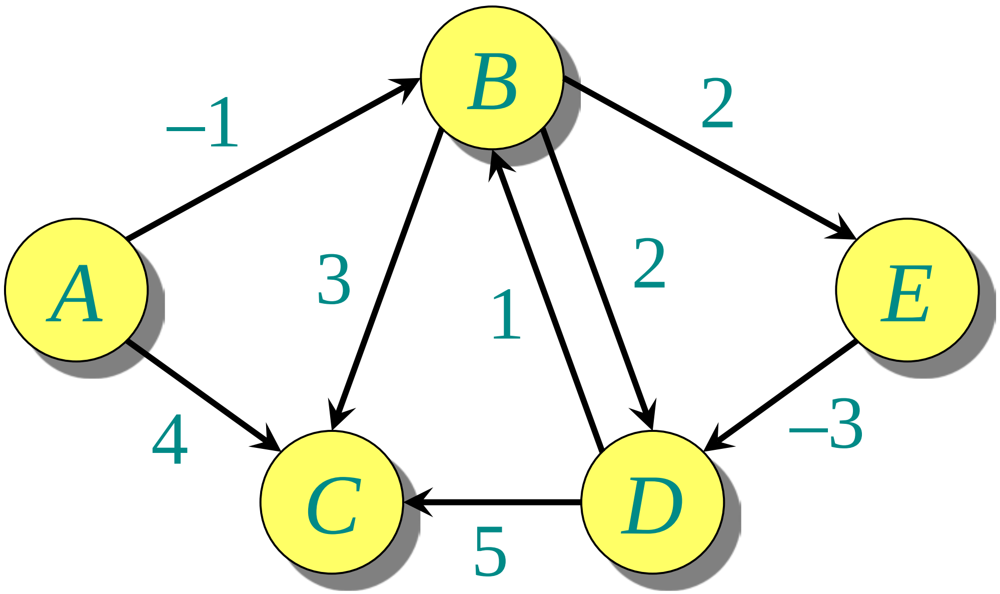
for $i \leftarrow 1$ **to** $|V| - 1$
  do for each edge $(u, v) \in E$
    do if $d[v] > d[u] + w(u, v)$
      then $d[v] \leftarrow d[u] + w(u, v)$

relaxation step

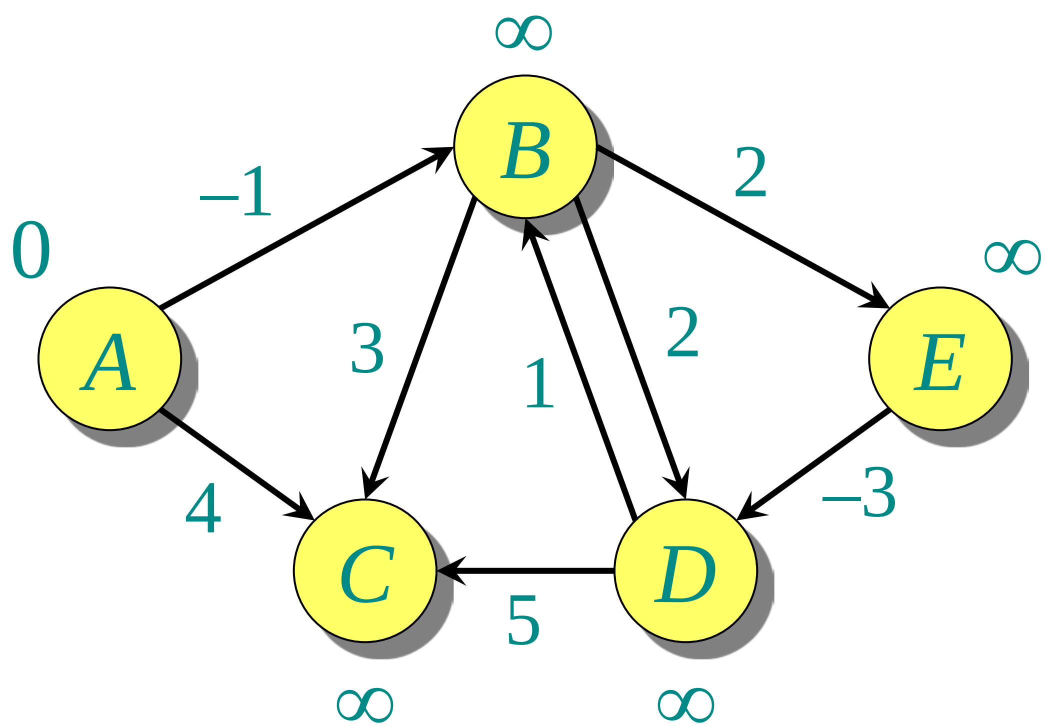
for each edge $(u, v) \in E$
  do if $d[v] > d[u] + w(u, v)$
    then report that a negative-weight cycle exists

At the end, $d[v] = \delta(s, v)$, if no negative-weight cycles.
Time $= O(VE)$.

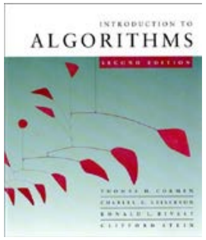
Example of Bellman-Ford



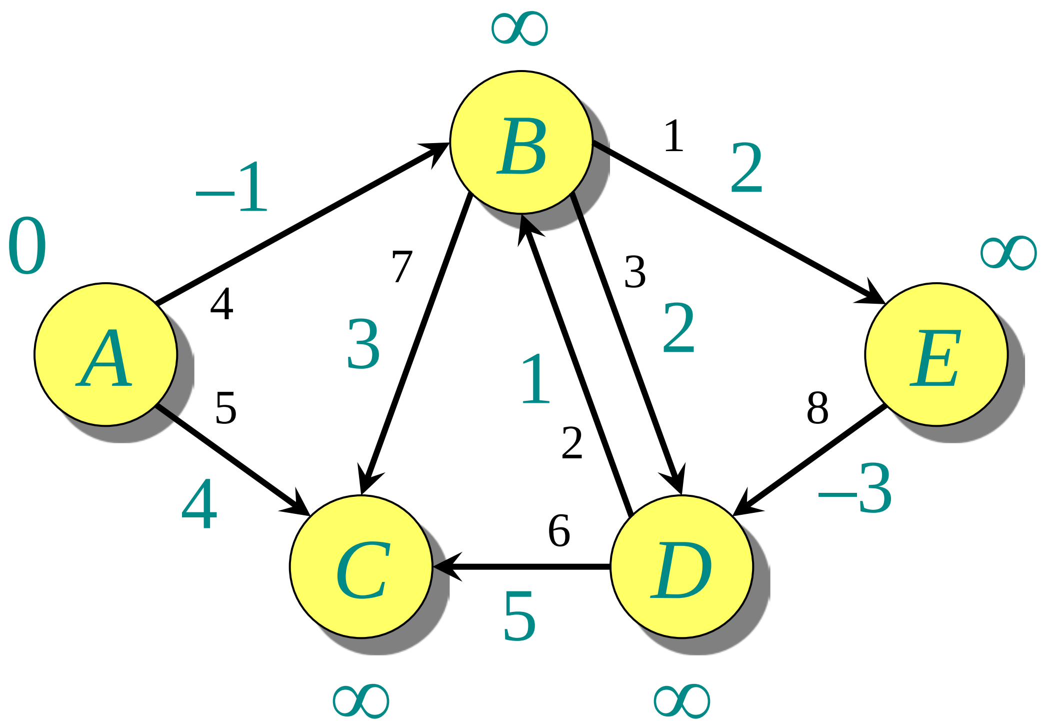
Example of Bellman-Ford



Initialization.

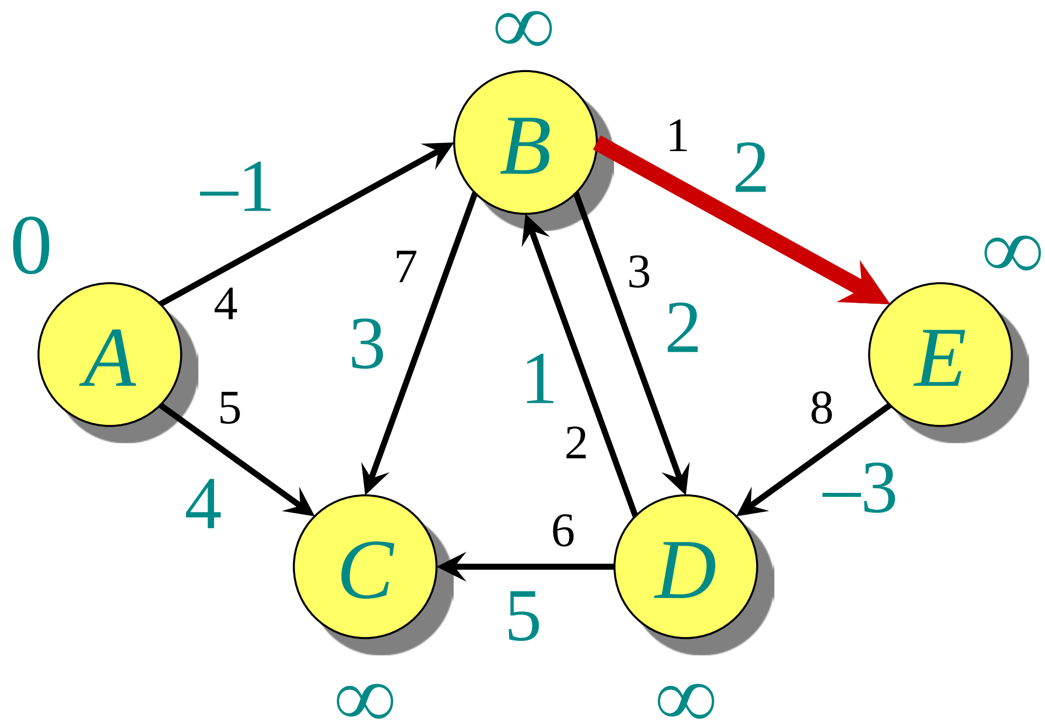


Example of Bellman-Ford

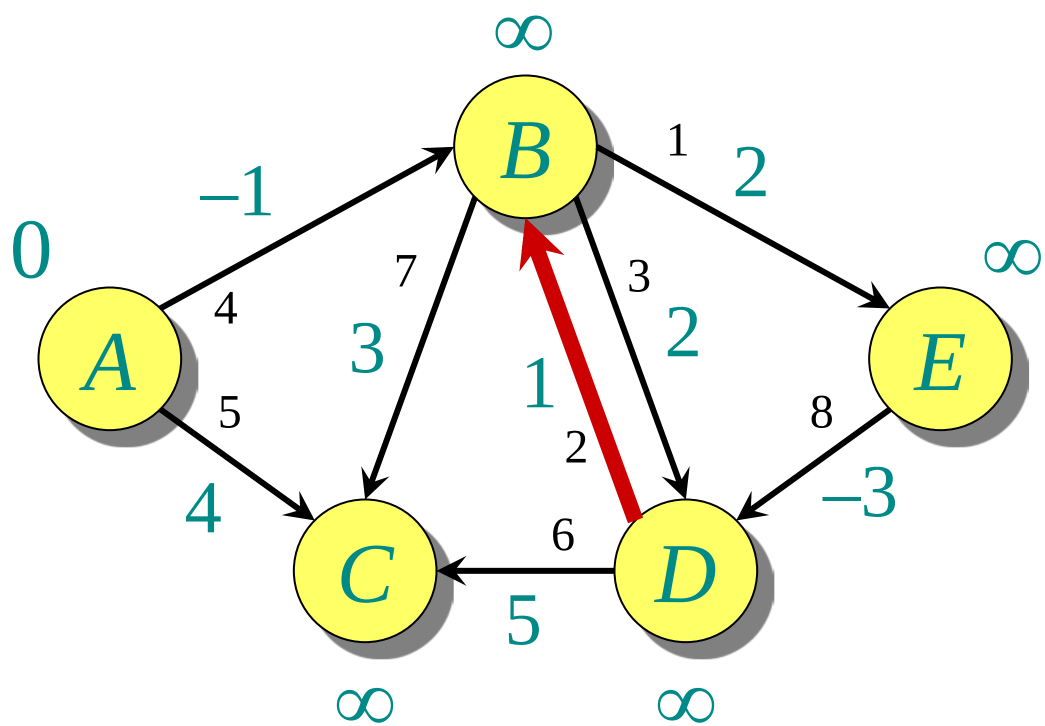


Order of edge relaxation.

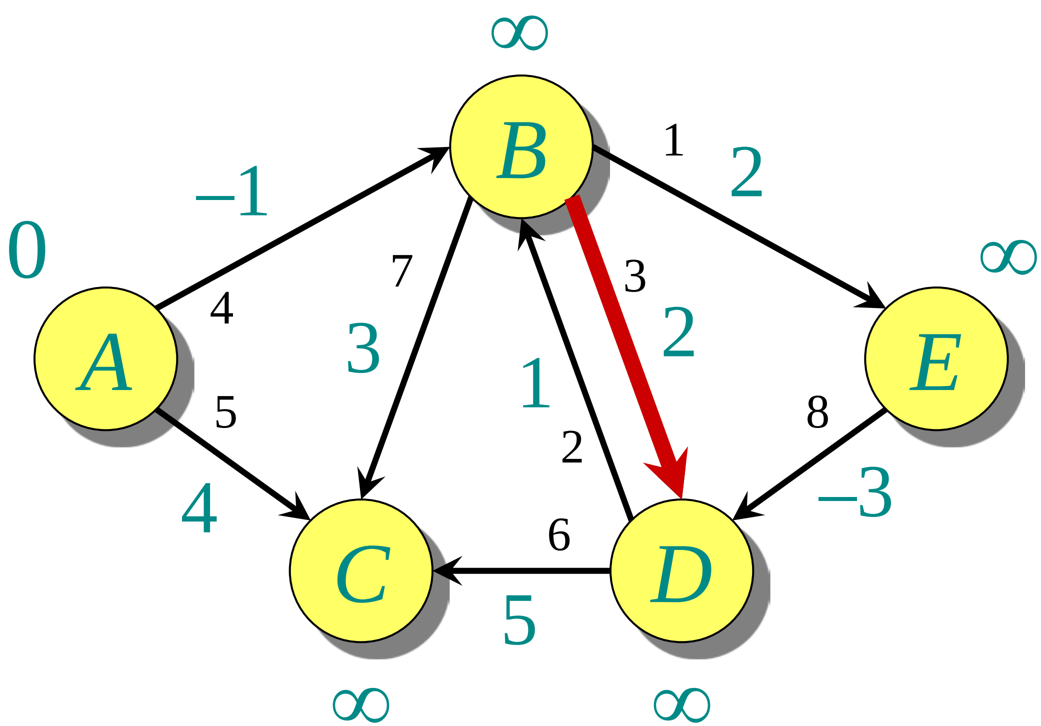
Example of Bellman-Ford



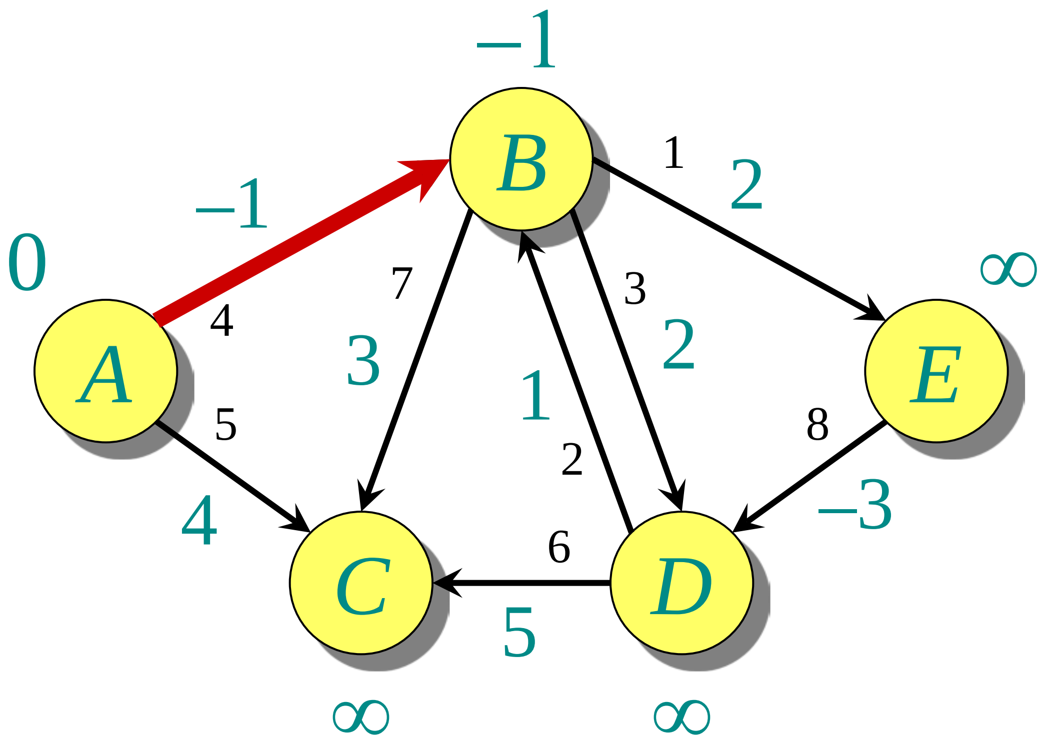
Example of Bellman-Ford



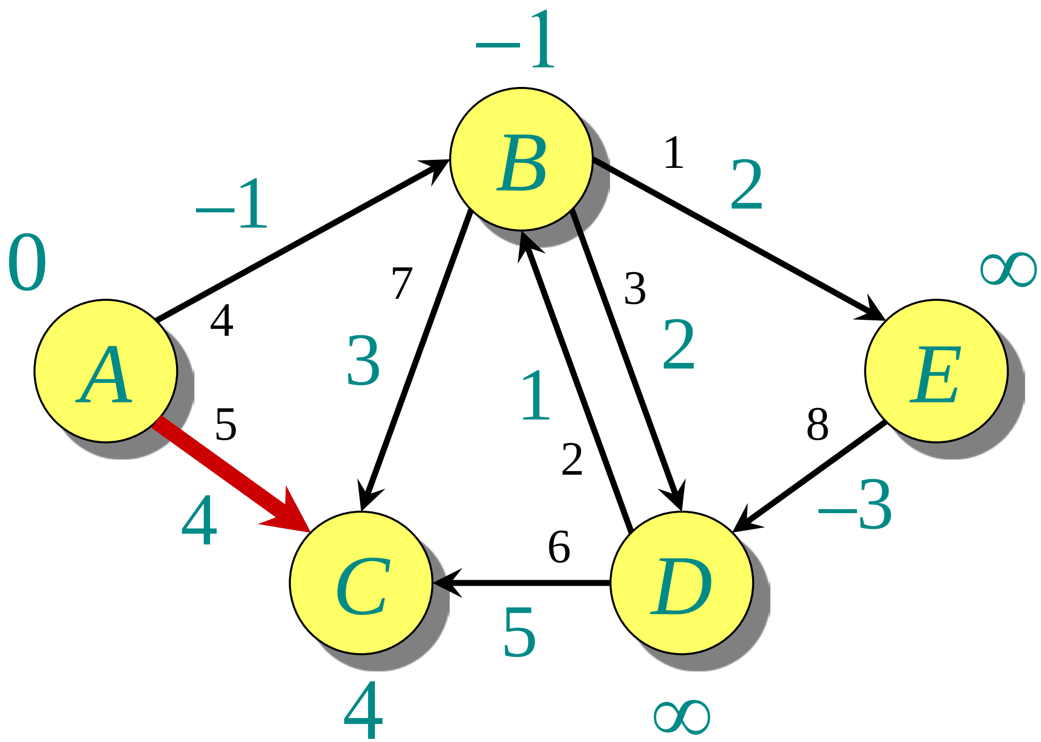
Example of Bellman-Ford



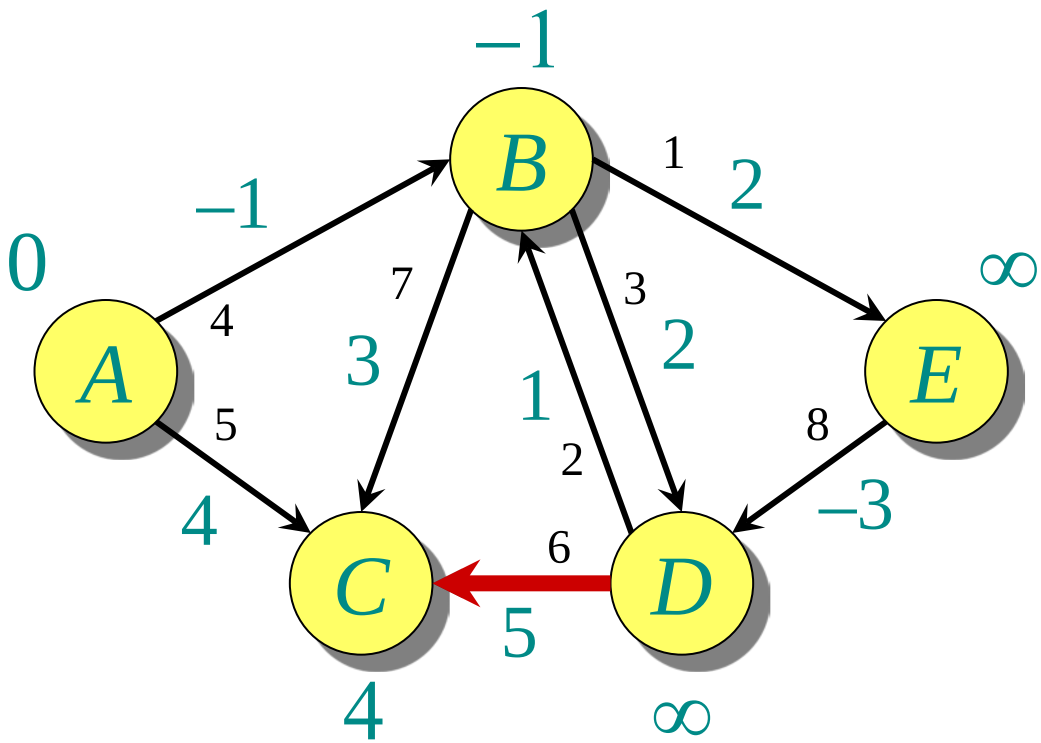
Example of Bellman-Ford



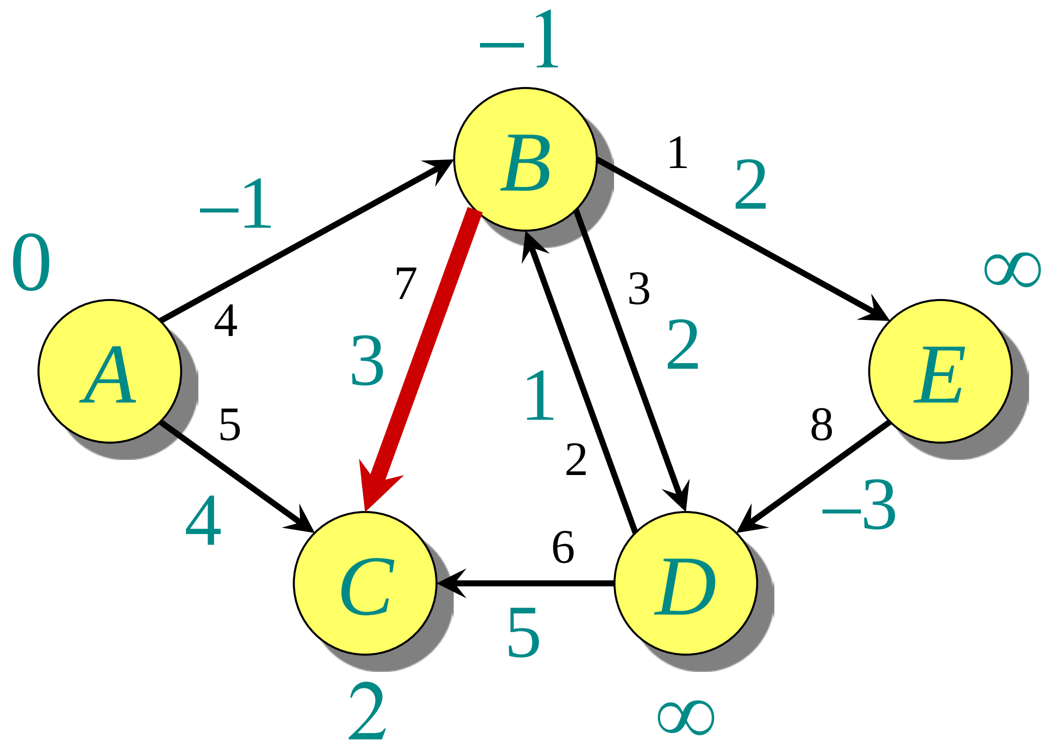
Example of Bellman-Ford



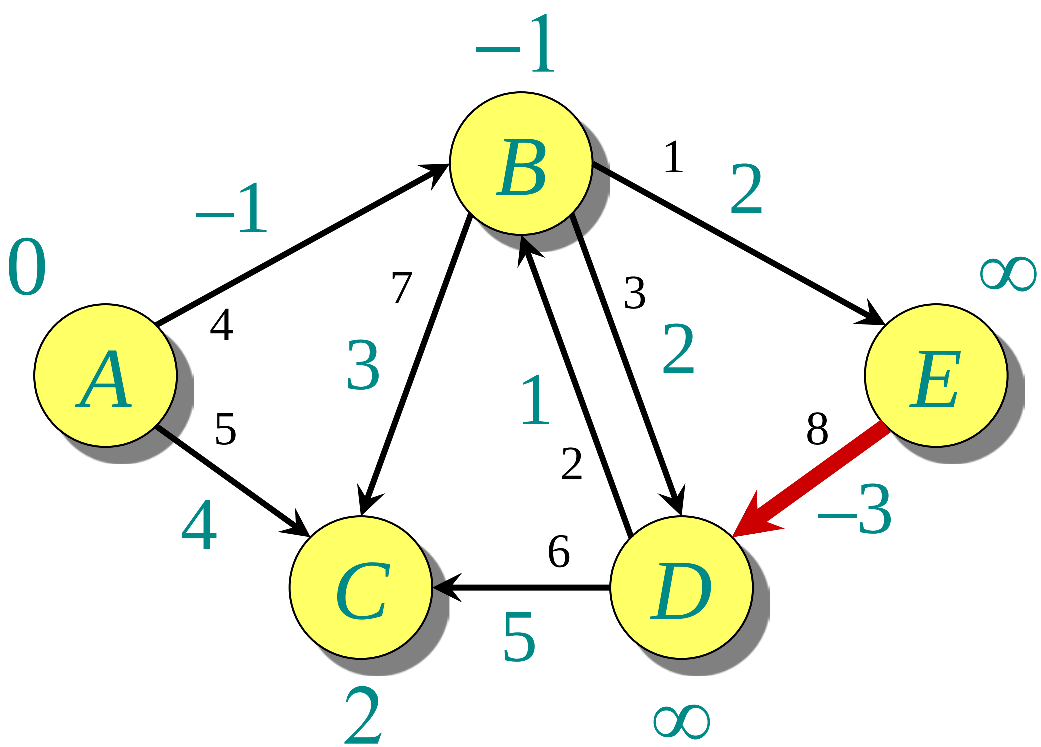
Example of Bellman-Ford



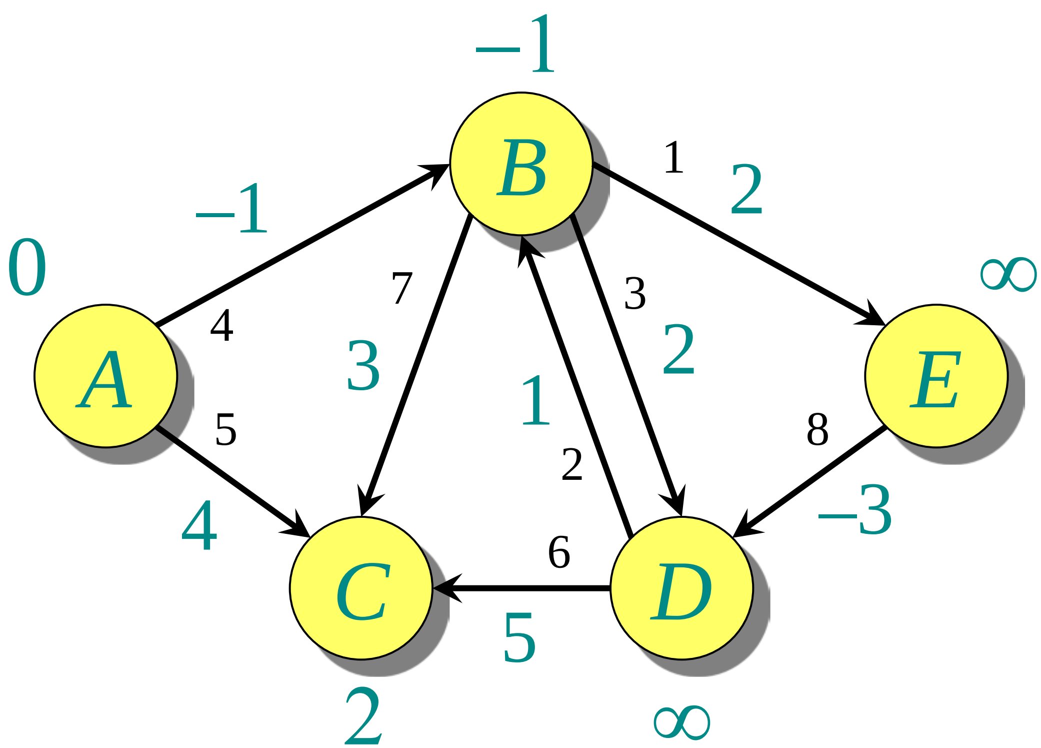
Example of Bellman-Ford



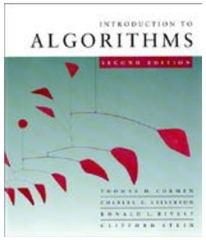
Example of Bellman-Ford



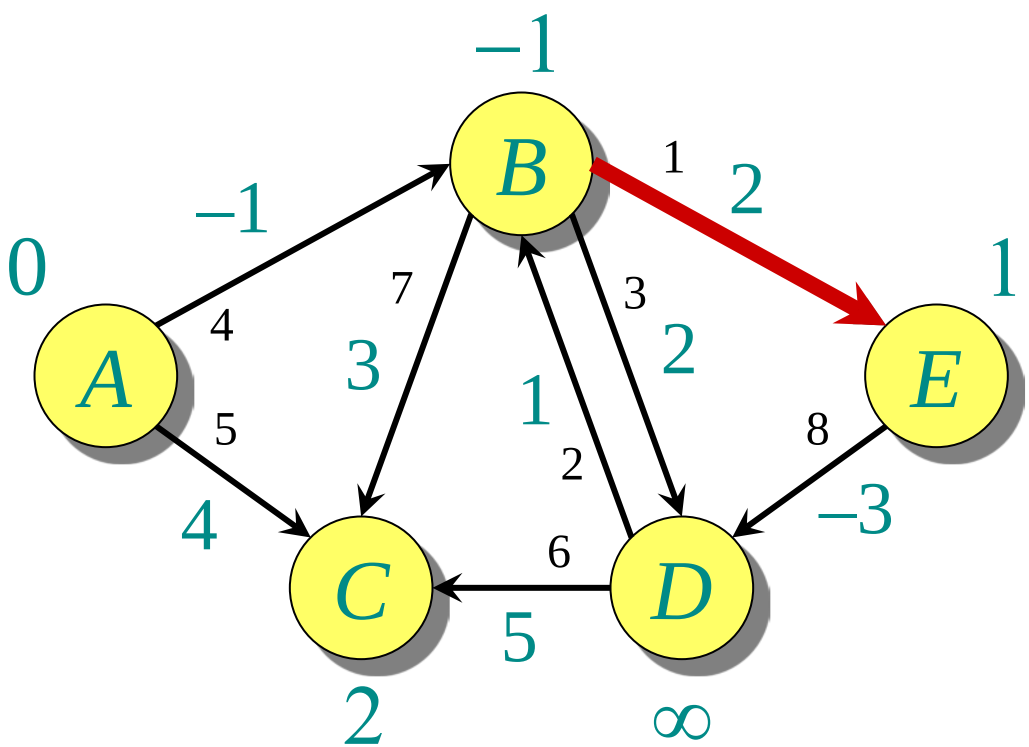
Example of Bellman-Ford

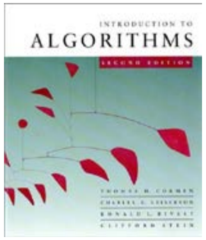


End of pass 1.



Example of Bellman-Ford





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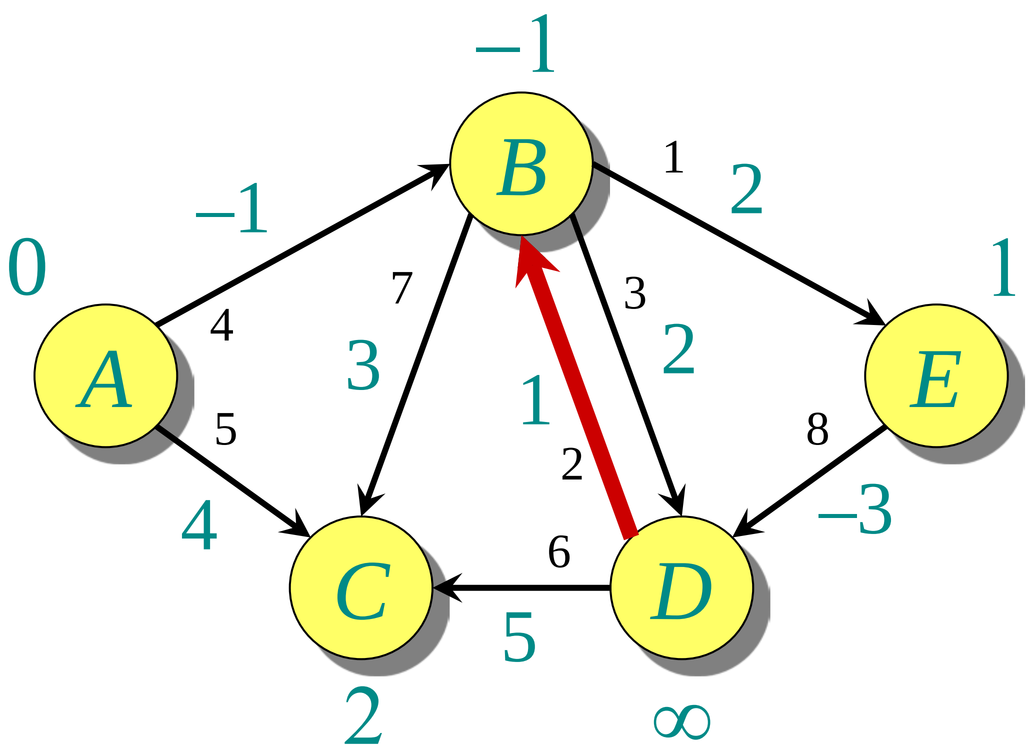

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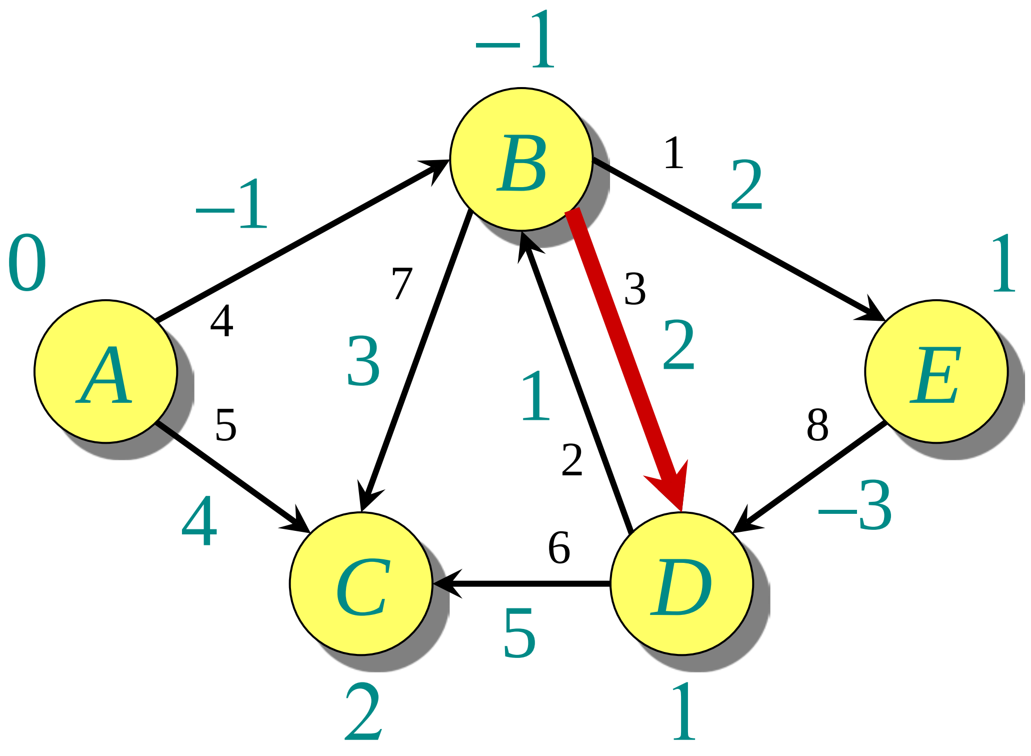

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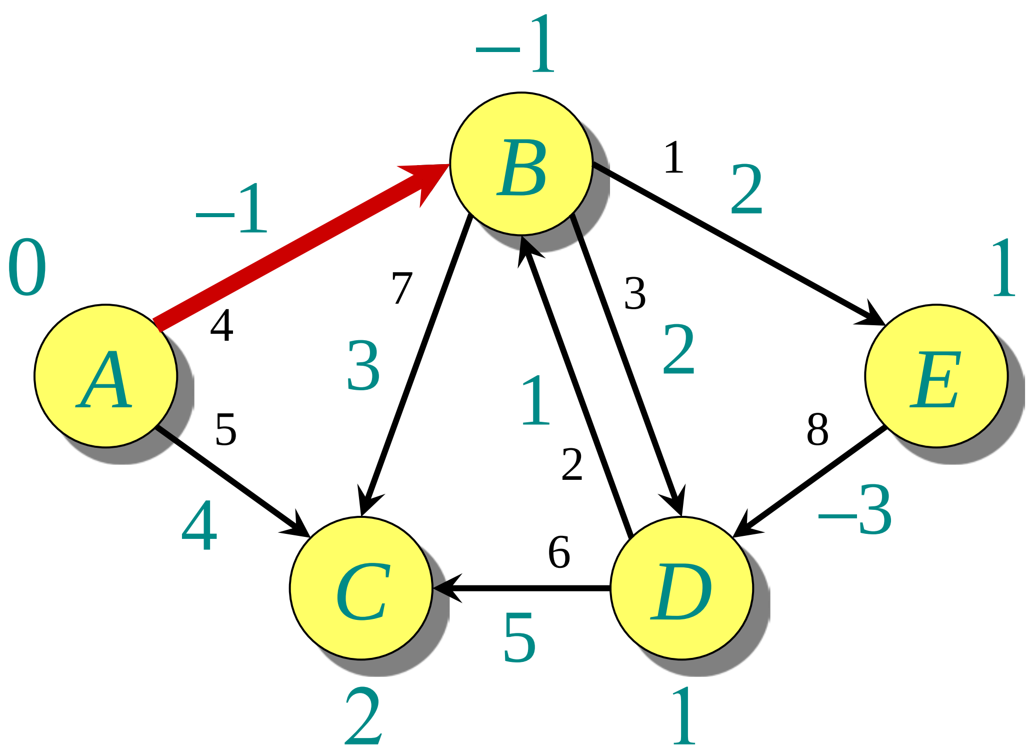

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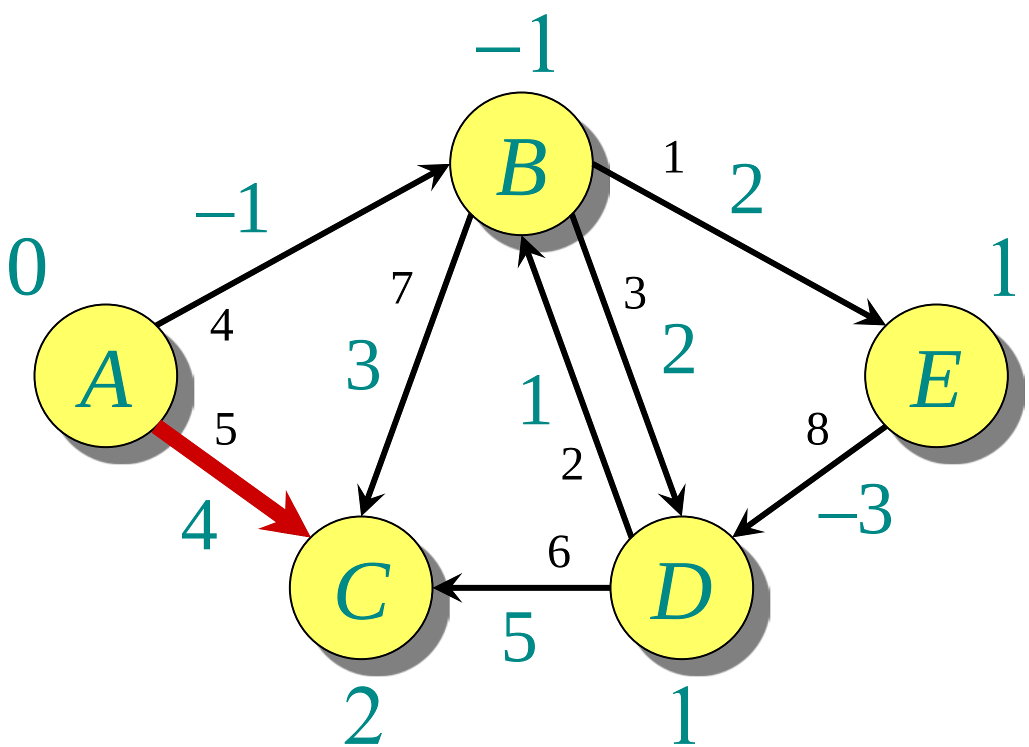

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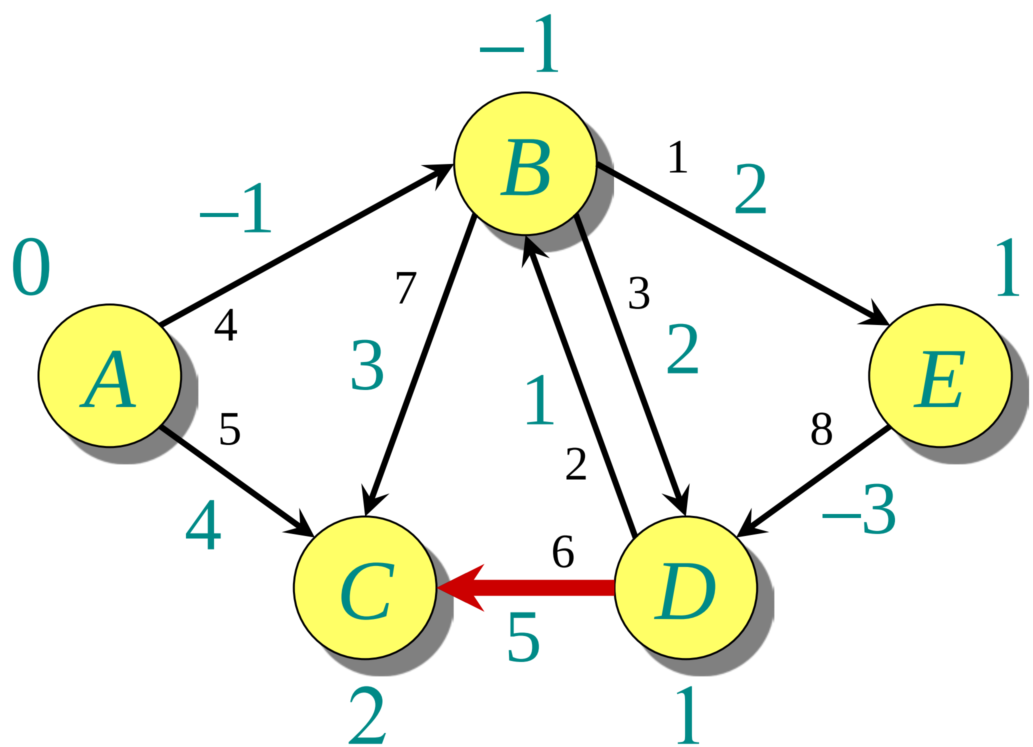

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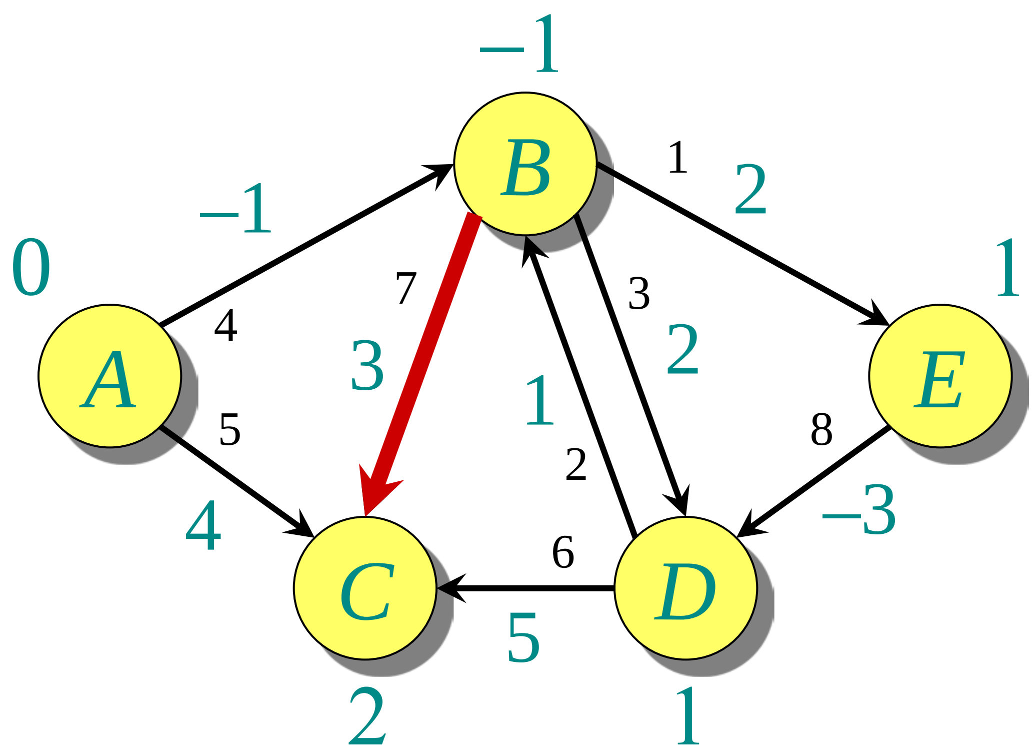

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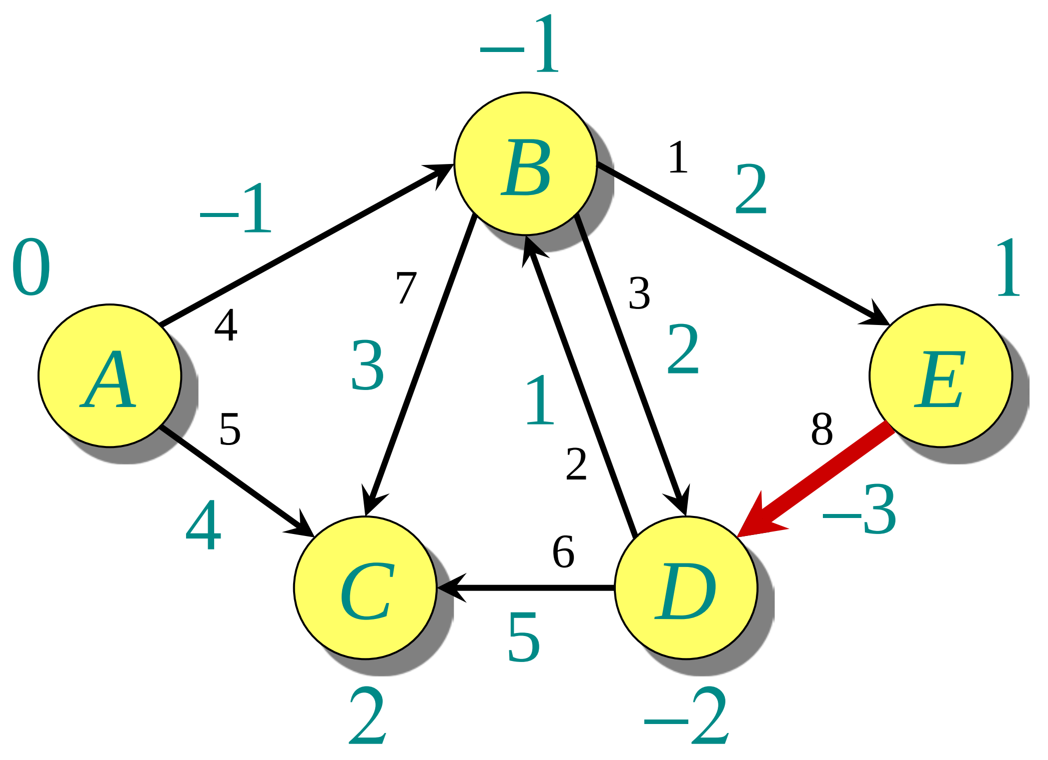

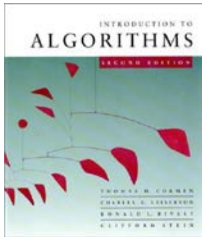

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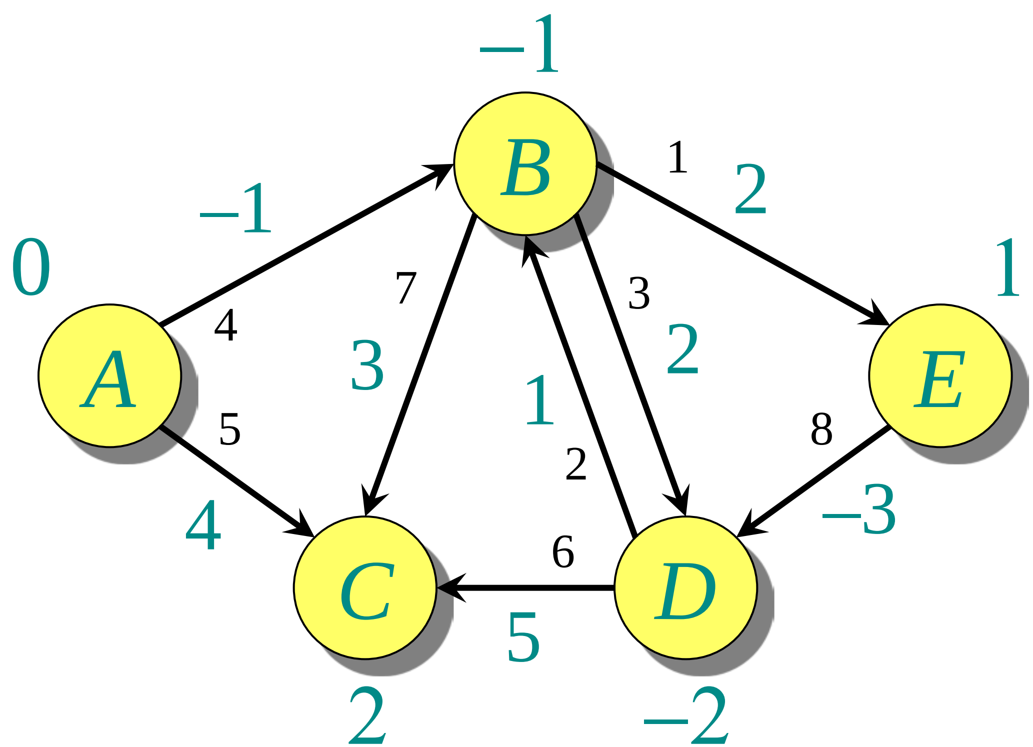

End of pass 2 (and 3 and 4).

Correctness

Theorem. If $G = (V, E)$ contains no negative-weight cycles, then after the Bellman-Ford algorithm executes, $d[v] = \delta(s, v)$ for all $v \in V$.

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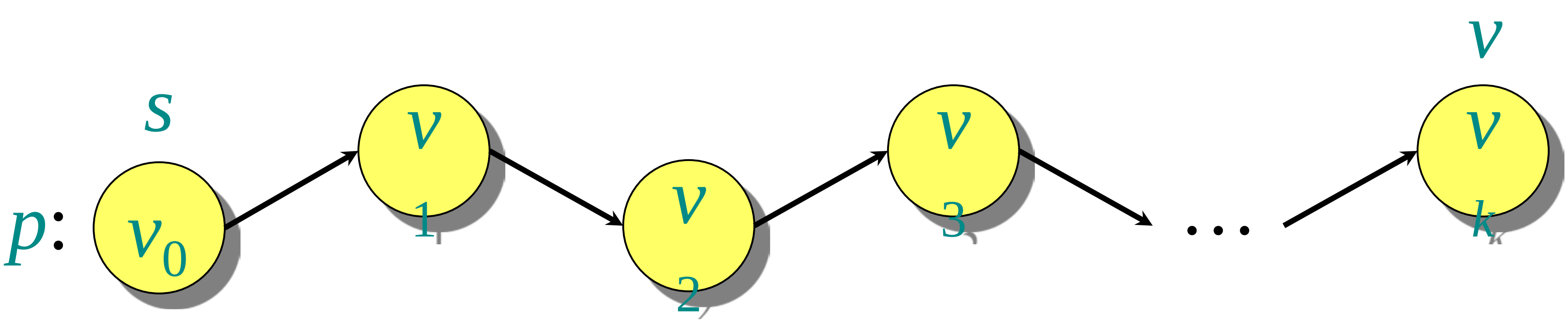
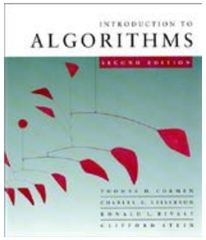
Proof. Let $v \in V$ be any vertex, and consider a shortest path p from s to v with the minimum number of edges.

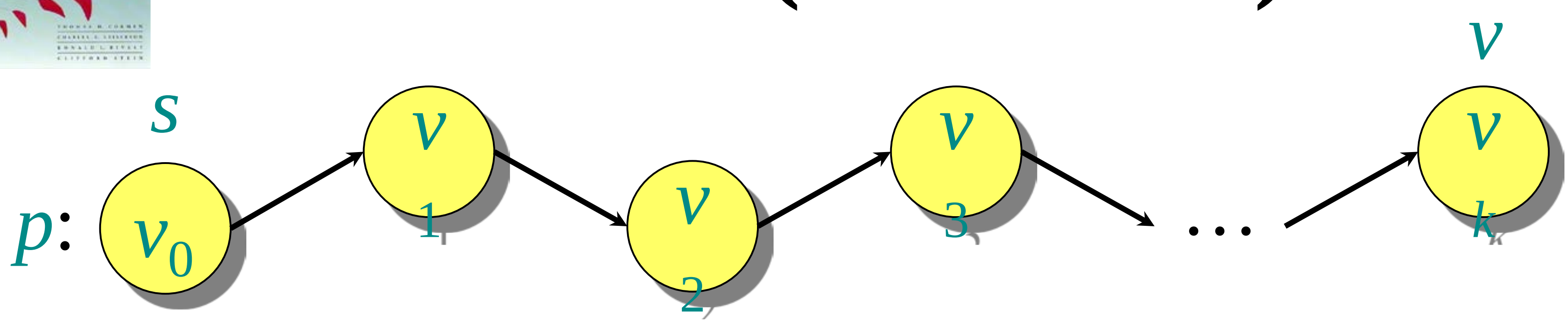


Since p is a shortest path, we have

$$\delta(s, v_i) = \delta(s, v_{i-1}) + w(v_{i-1}, v_i) .$$



Correctness (continued)



Initially, $d[v_0] = 0 = \delta(s, v_0)$, and $d[v_0]$ is unchanged by subsequent relaxations (because of the lemma from *Shortest Paths I* that $d[v] \geq \delta(s, v)$).

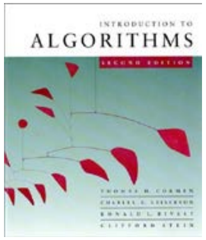
- After 1 pass through E, we have $d[v_1] = \delta(s, v_1)$.
- After 2 passes through E, we have $d[v_2] = \delta(s, v_2)$.

  ⋮
- After k passes through E, we have $d[v_k] = \delta(s, v_k)$.

Since G contains no negative-weight cycles, p is simple. Longest simple path has $\leq |V| - 1$ edges. □

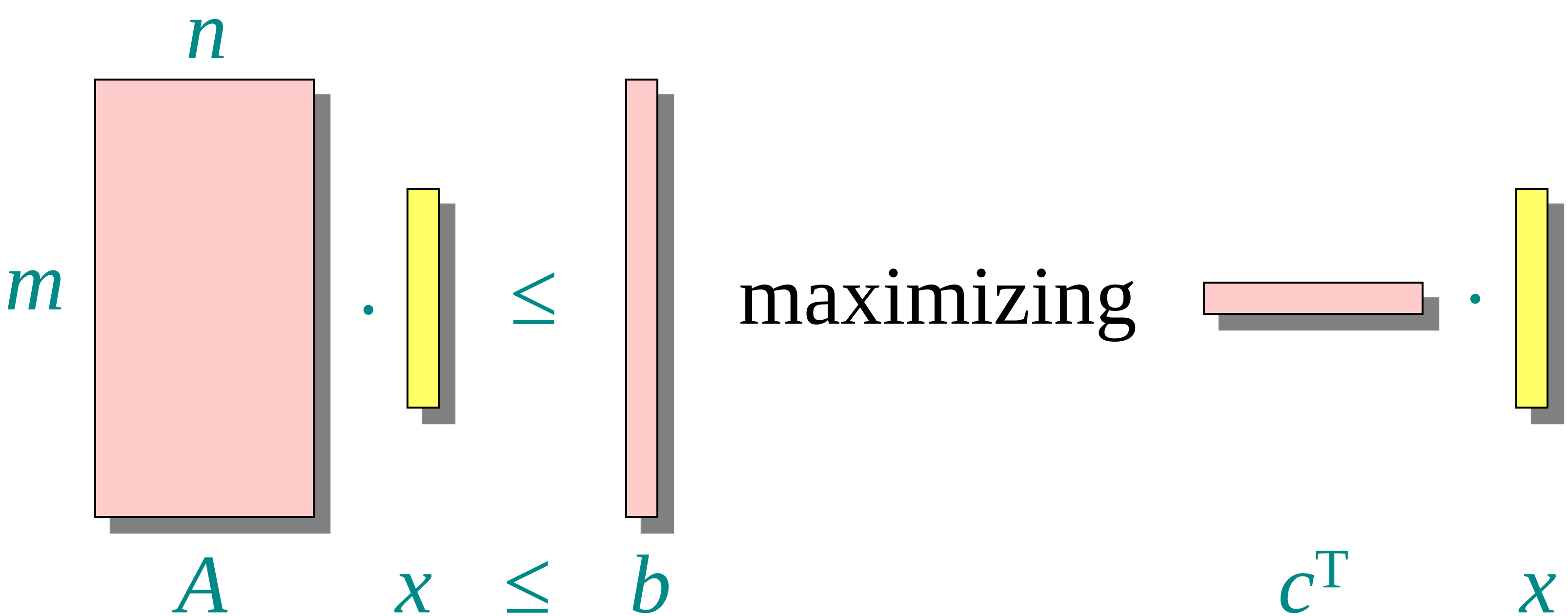
Detection of negative-weight cycles

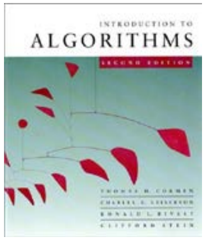
Corollary. If a value $d[v]$ fails to converge after $|V| - 1$ passes, there exists a negative-weight cycle in G reachable from s. $\square$



Linear programming

Let A be an $m \times n$ matrix, b be an m-vector, and c be an n-vector. Find an n-vector x that maximizes $c^{\mathrm{T}}x$ subject to $Ax \le b$, or determine that no such solution exists.

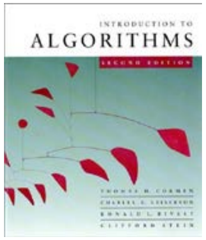




Linear-programming algorithms

Algorithms for the general problem

- Simplex methods — practical, but worst-case exponential time.
- Interior-point methods — polynomial time and competes with simplex.



Linear-programming algorithms

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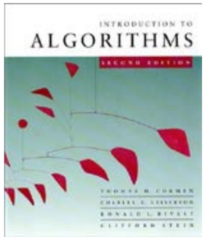
- Simplex methods — practical, but worst-case exponential time.
- Interior-point methods — polynomial time and competes with simplex.

Feasibility problem: No optimization criterion. Just find x such that $Ax \le b$.

- In general, just as hard as ordinary LP.



Solving a system of difference constraints

Linear programming where each row of A contains exactly one 1, one -1, and the rest 0's.

Example:

$$\left.\begin{aligned} x_1 - x_2 &\le 3 \\ x_2 - x_3 &\le -2 \\ x_1 - x_3 &\le 2 \end{aligned}\right\} \quad x_j - x_i \le w_{ij}$$

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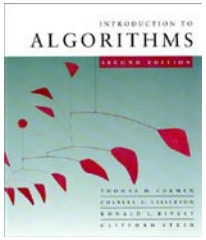
Solution:

$$\begin{aligned} x_1 &= 3 \\ x_2 &= 0 \\ x_3 &= 2 \end{aligned}$$



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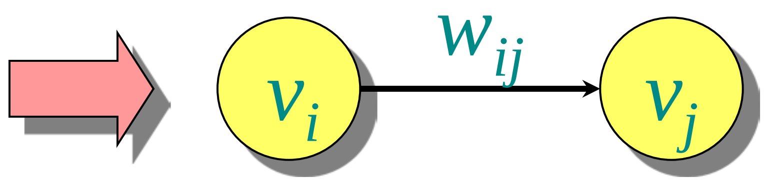
Constraint graph:

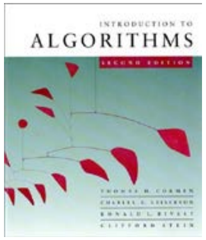
$x_j - x_i \le w_{ij}$



(The "A" matrix has dimensions $|E| \times |V|$.)

Unsatisfiable constraints

Theorem. If the constraint graph contains a negative-weight cycle, then the system of differences is unsatisfiable.

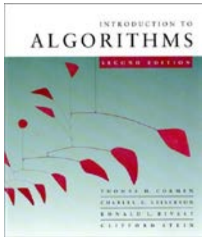


Unsatisfiable constraints

Theorem. If the constraint graph contains a negative-weight cycle, then the system of differences is unsatisfiable.

Proof. Suppose that the negative-weight cycle is $v_1 \to v_2 \to \cdots \to v_k \to v_1$. Then, we have

$$\begin{aligned} x_2 - x_1 &\le w_{12} \\ x_3 - x_2 &\le w_{23} \\ &\vdots \\ x_k - x_{k-1} &\le w_{k-1,\,k} \\ x_1 - x_k &\le w_{k1} \end{aligned}$$



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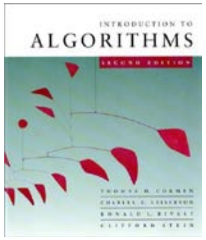
&\vdots \\
x_k - x_{k-1} &\le w_{k-1,\,k} \\
x_1 - x_k &\le w_{k1} \\
\hline
0 &\le \text{weight of cycle} \\
&< 0
\end{aligned}$$

Therefore, no values for the x_i can satisfy the constraints. $\square$



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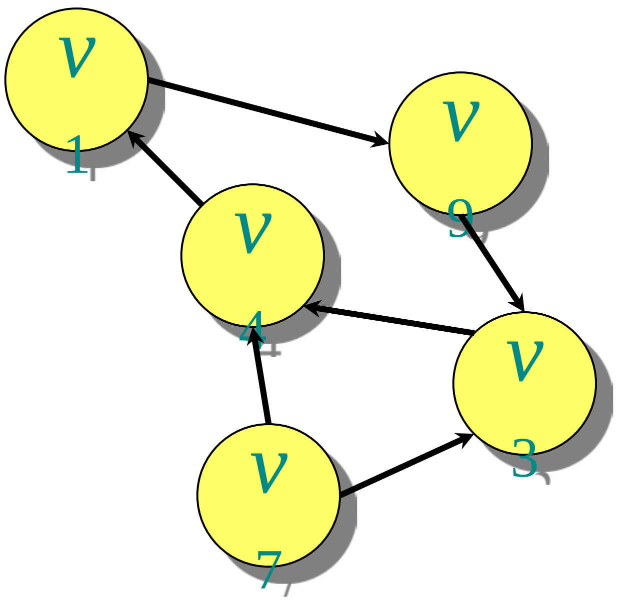

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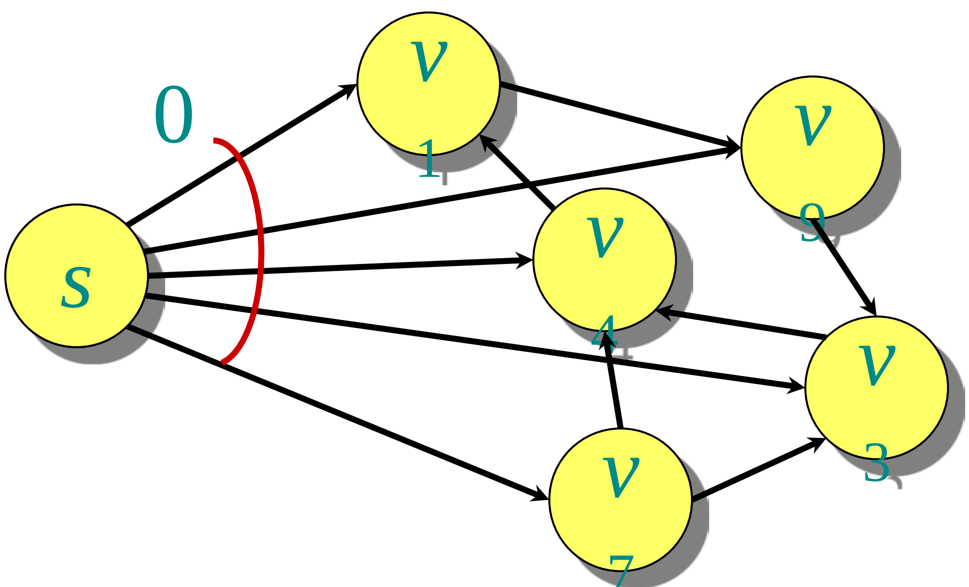
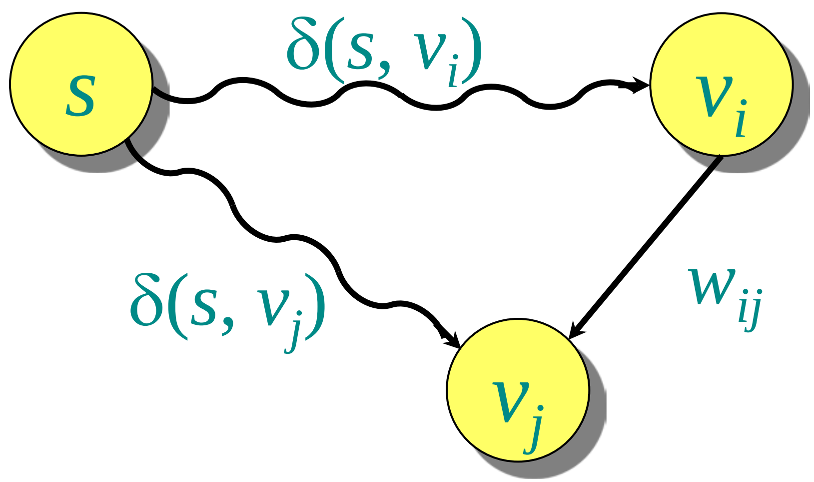


Note:
No negative-weight cycles introduced ⇒ shortest paths exist.

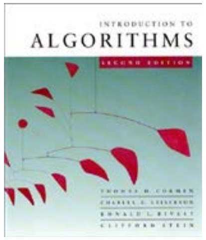
Proof (continued)

Claim: The assignment $x_i = \delta(s, v_i)$ solves the constraints.

Consider any constraint $x_j - x_i \le w_{ij}$, and consider the shortest paths from s to v_j and v_i:



The triangle inequality gives us $\delta(s,v_j) \le \delta(s, v_i) + w_{ij}$. Since $x_i = \delta(s, v_i)$ and $x_j = \delta(s, v_j)$, the constraint $x_j - x_i \le w_{ij}$ is satisfied. ∎



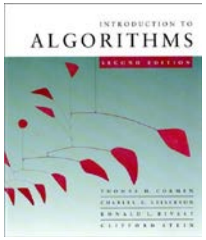
Bellman-Ford and linear programming

Corollary. The Bellman-Ford algorithm can solve a system of m difference constraints on n variables in $O(mn)$ time. $\square$

Single-source shortest paths is a simple LP problem.

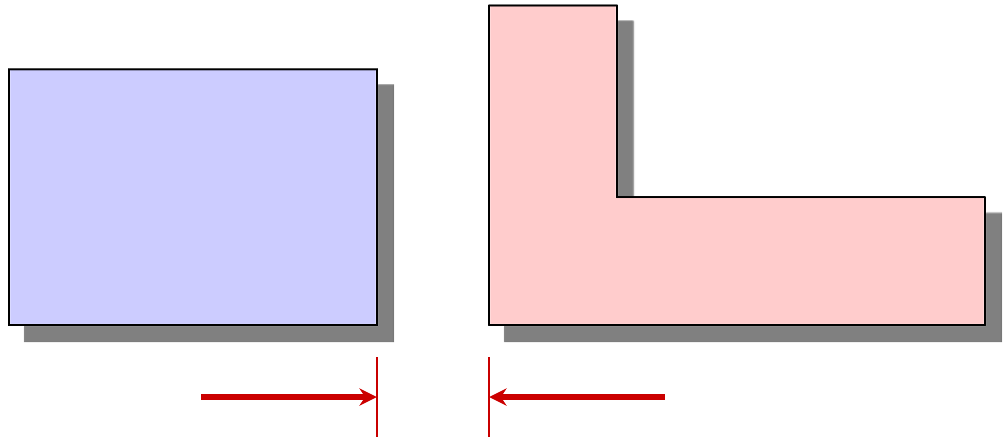
In fact, Bellman-Ford maximizes $x_1 + x_2 + \cdots + x_n$ subject to the constraints $x_j - x_i \le w_{ij}$ and $x_i \le 0$ (exercise).

Bellman-Ford also minimizes $\max_i\{x_i\} - \min_i\{x_i\}$ (exercise).



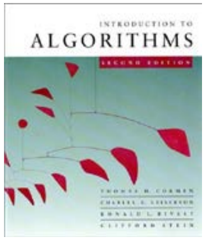
Application to VLSI layout compaction

Integrated -circuit features:

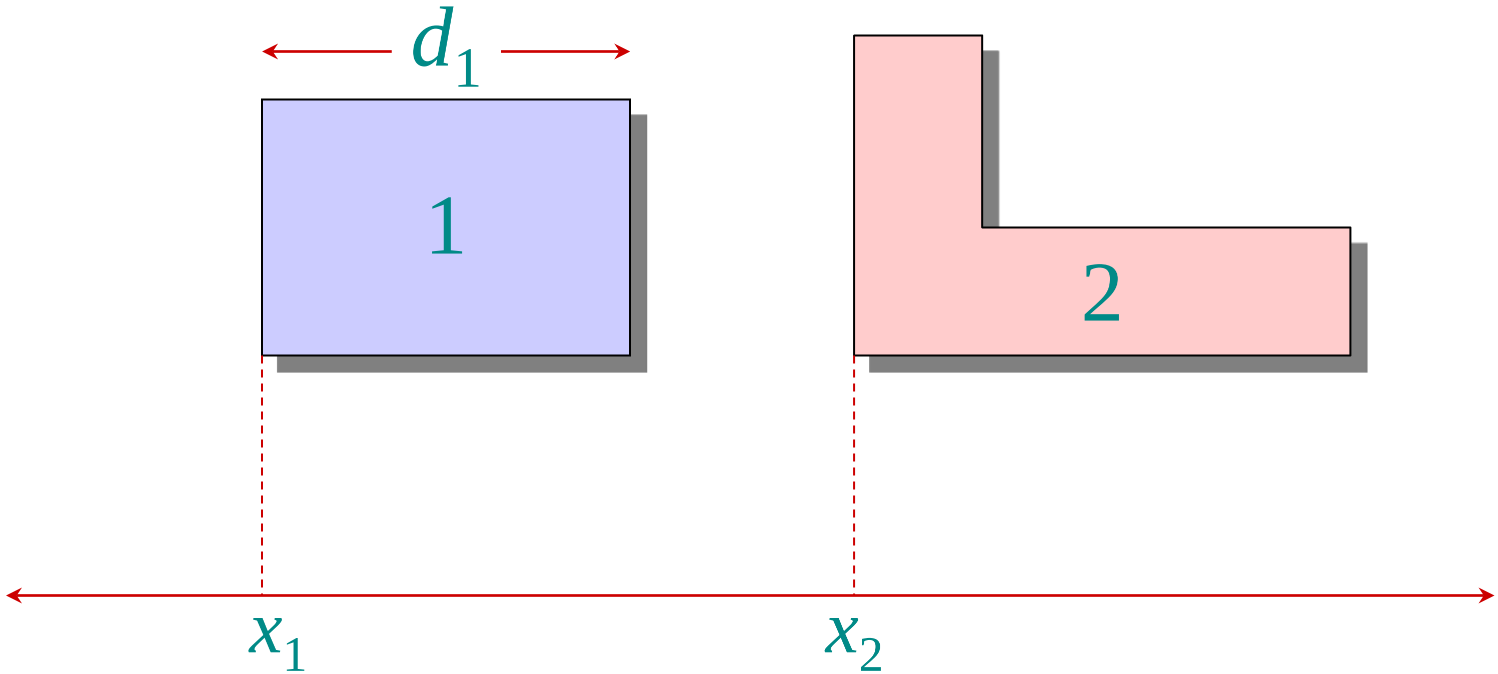


minimum separation λ

Problem: Compact (in one dimension) the space between the features of a VLSI layout without bringing any features too close together.



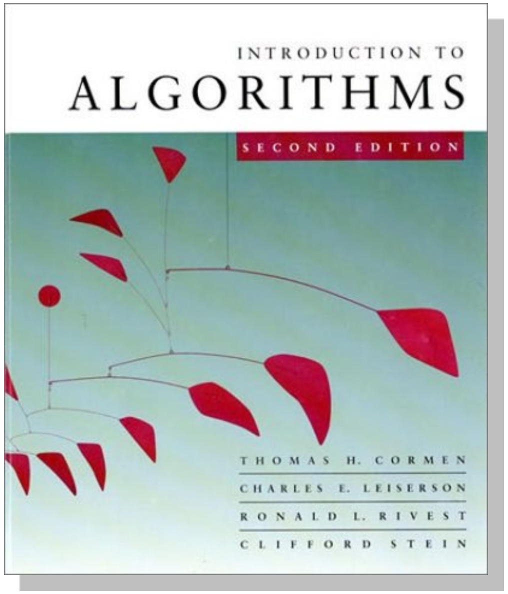
VLSI layout compaction



Constraint: $x_2 - x_1 \geq d_1 + \lambda$

Bellman-Ford minimizes $\max_i\{x_i\} - \min_i\{x_i\}$, which compacts the layout in the x-dimension.

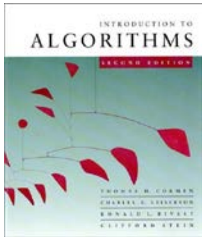
Introduction to Algorithms
6.046J/18.401J



LECTURE 16
Shortest Paths III

- All-pairs shortest paths
- Matrix-multiplication algorithm
- Floyd-Warshall algorithm
- Johnson's algorithm

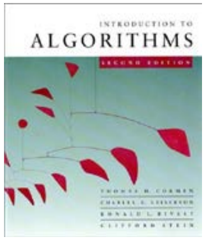
Prof. Erik D. Demaine



Shortest paths

Single-source shortest paths

- Nonnegative edge weights
  - Dijkstra's algorithm: $O(E + V \lg V)$
- General
  - Bellman-Ford algorithm: $O(VE)$
- DAG
  - One pass of Bellman-Ford: $O(V + E)$



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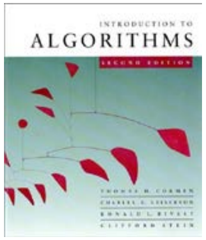
- DAG
  - One pass of Bellman-Ford: $O(V + E)$

All-pairs shortest paths

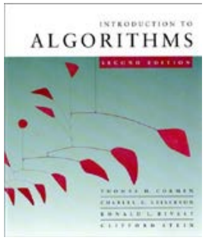
- Nonnegative edge weights
  - Dijkstra's algorithm $|V|$ times: $O(VE + V^2 \lg V)$
- General
  - Three algorithms today.



All-pairs shortest paths

Input: Digraph $G = (V, E)$, where $V = \{1, 2, \ldots, n\}$, with edge-weight function $w : E \to \mathbb{R}$.

Output: $n \times n$ matrix of shortest-path lengths $\delta(i, j)$ for all $i, j \in V$.



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IDEA:
- Run Bellman-Ford once from each vertex.
- Time $= O(V^2E)$.
- Dense graph ($\Theta(n^2)$ edges) $\Rightarrow \Theta(n^4)$ time in the worst case.

Good first try!

Dynamic programming

Consider the $n \times n$ weighted adjacency matrix $A = (a_{ij})$, where $a_{ij} = w(i, j)$ or ∞, and define

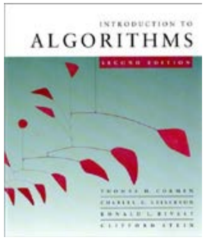
$d_{ij}^{(m)}$ = weight of a shortest path from i to j that uses at most m edges.

Claim: We have

$$d_{ij}^{(0)} = \begin{cases} 0 & \text{if } i = j, \\ \infty & \text{if } i \neq j; \end{cases}$$

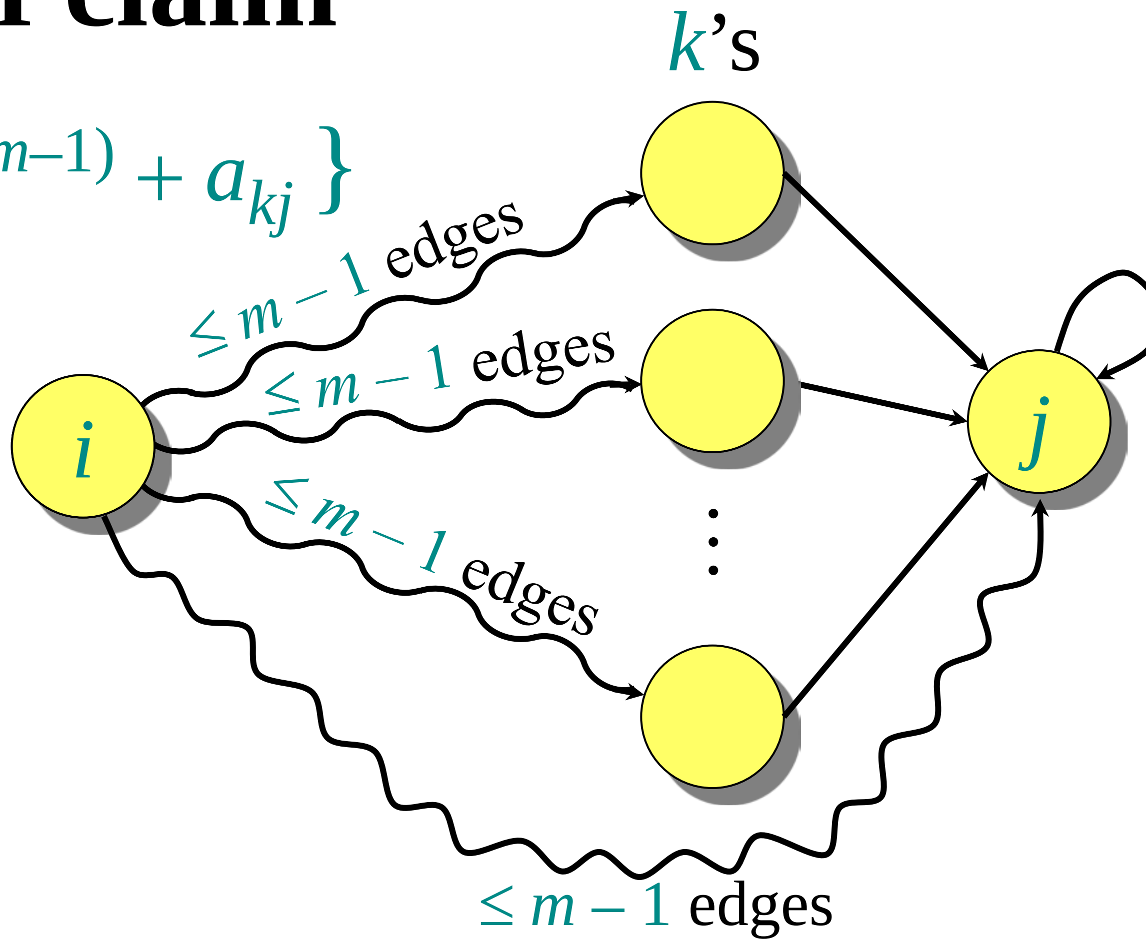
and for $m = 1, 2, \ldots, n - 1$,

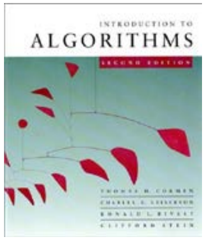
$$d_{ij}^{(m)} = \min_k \{ d_{ik}^{(m-1)} + a_{kj} \}.$$



Proof of claim

$$d_{ij}^{(m)} = \min_k \{ d_{ik}^{(m-1)} + a_{kj} \}$$





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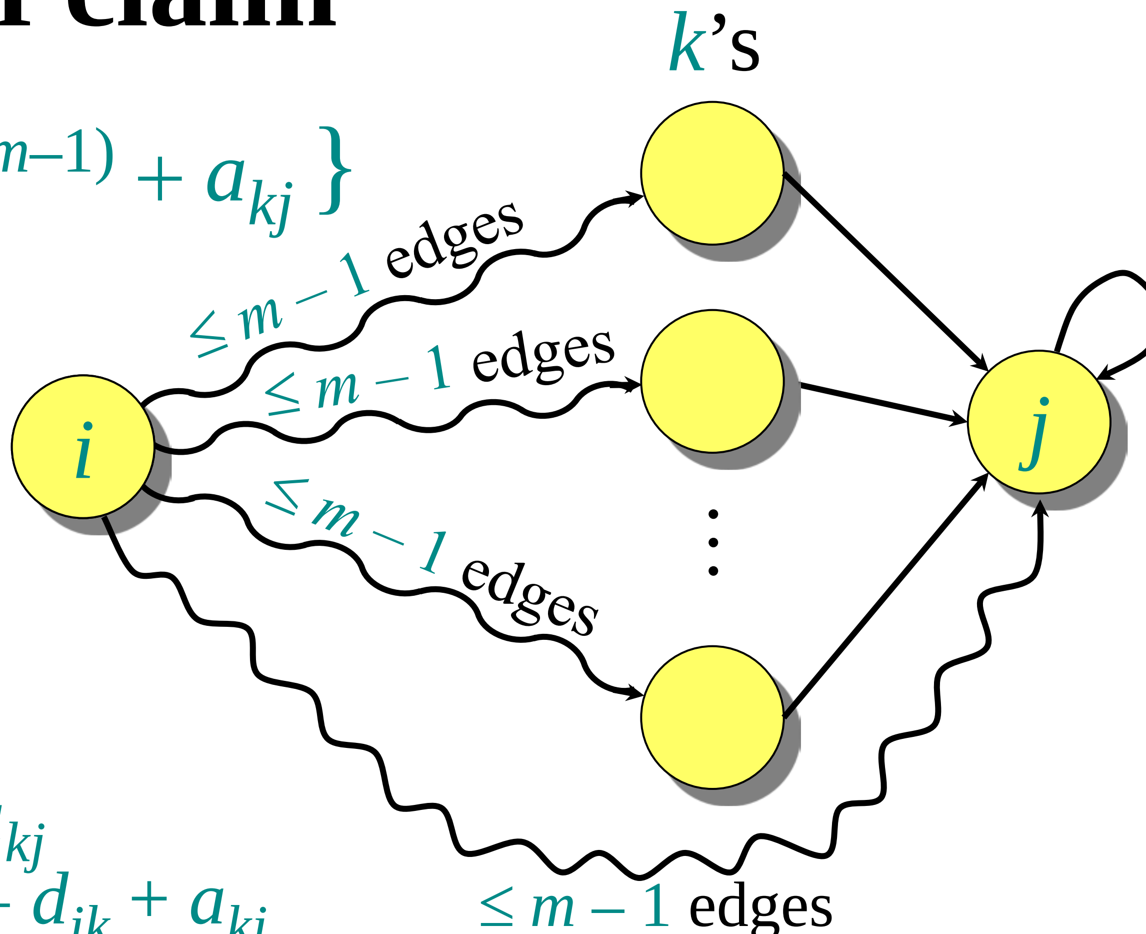

Relaxation!

for $k \leftarrow 1$ **to** n
    do if $d_{ij} > d_{ik} + a_{kj}$
        then $d_{ij} \leftarrow d_{ik} + a_{kj}$

Proof of claim

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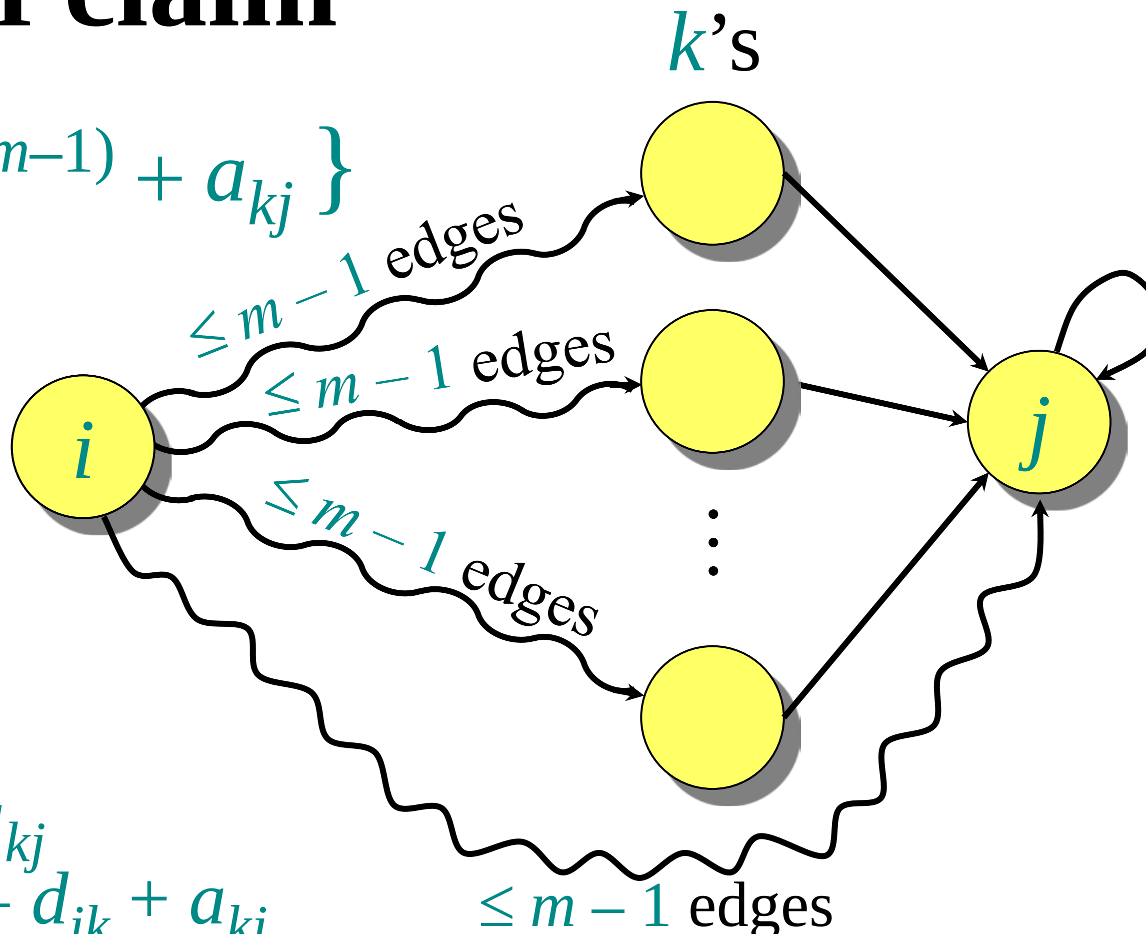

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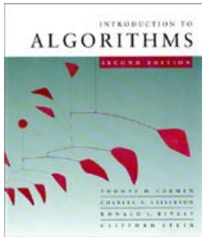
for $k \leftarrow 1$ **to** n

  do if $d_{ij} > d_{ik} + a_{kj}$

    then $d_{ij} \leftarrow d_{ik} + a_{kj}$

Note: No negative-weight cycles implies

$$\delta(i, j) = d_{ij}^{(n-1)} = d_{ij}^{(n)} = d_{ij}^{(n+1)} = \cdots$$

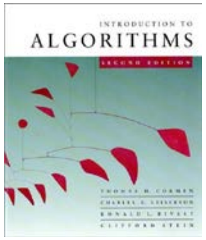


Matrix multiplication

Compute $C = A \cdot B$, where C, A, and B are $n \times n$ matrices:

$$c_{ij} = \sum_{k=1}^{n} a_{ik} b_{kj} \; .$$

Time $= \Theta(n^3)$ using the standard algorithm.



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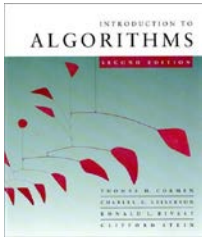
What if we map "$+$" $\to$ "min" and "$\cdot$" $\to$ "$+$"?



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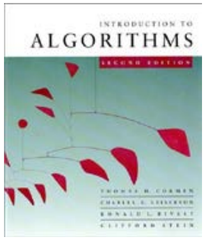
What if we map "+" $\to$ "min" and "$\cdot$" $\to$ "+"?

$$c_{ij} = \min_k \{a_{ik} + b_{kj}\}.$$

Thus, $D^{(m)} = D^{(m-1)}$ "$\times$" A.

Identity matrix $= \mathrm{I} = \begin{pmatrix} 0 & \infty & \infty & \infty \\ \infty & 0 & \infty & \infty \\ \infty & \infty & 0 & \infty \\ \infty & \infty & \infty & 0 \end{pmatrix} = D^0 = (d_{ij}{}^{(0)})$.



Matrix multiplication (continued)

The (min, +) multiplication is ***associative***, and with the real numbers, it forms an algebraic structure called a ***closed semiring***.

Consequently, we can compute

$$\begin{aligned} D^{(1)} &= D^{(0)} \cdot A = A^1 \\ D^{(2)} &= D^{(1)} \cdot A = A^2 \\ &\vdots \\ D^{(n-1)} &= D^{(n-2)} \cdot A = A^{n-1}, \end{aligned}$$

yielding $D^{(n-1)} = (\delta(i, j))$.

Time $= \Theta(n \cdot n^3) = \Theta(n^4)$. No better than $n \times$ B-F.

Improved matrix multiplication algorithm

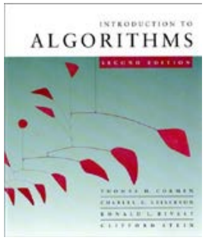
Repeated squaring: $A^{2k} = A^k \times A^k$.

Compute $\underbrace{A^2, A^4, \ldots, A^{2^{\lceil \lg(n-1) \rceil}}}_{O(\lg n) \text{ squarings}}$.

Note: $A^{n-1} = A^n = A^{n+1} = \cdots$.

Time $= \Theta(n^3 \lg n)$.

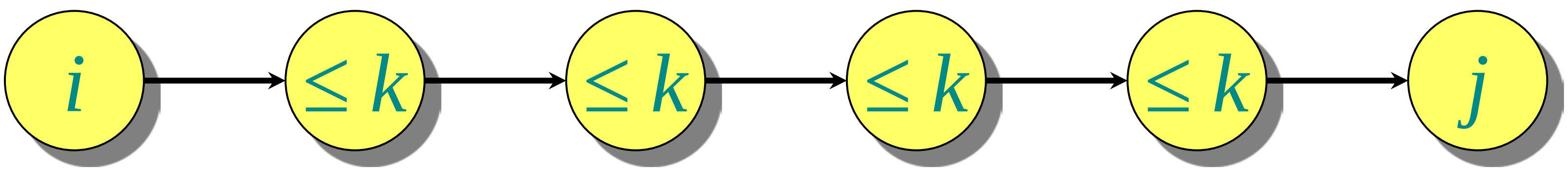
To detect negative-weight cycles, check the diagonal for negative values in $O(n)$ additional time.



Floyd-Warshall algorithm

Also dynamic programming, but faster!

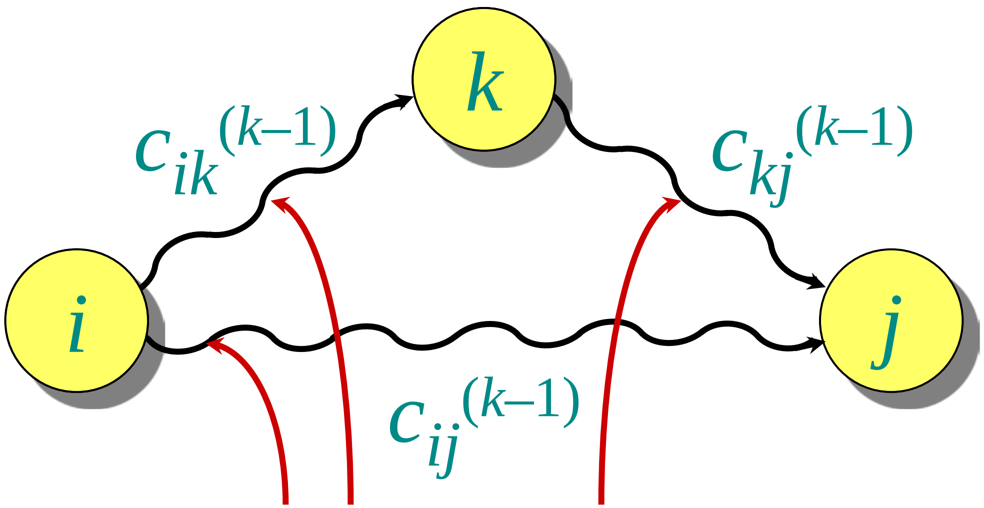
Define $c_{ij}^{(k)} =$ weight of a shortest path from i to j with intermediate vertices belonging to the set $\{1, 2, \ldots, k\}$.



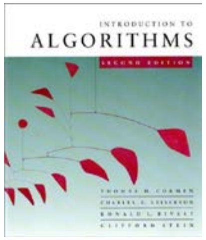
Thus, $\delta(i, j) = c_{ij}^{(n)}$. Also, $c_{ij}^{(0)} = a_{ij}$.

Floyd-Warshall recurrence

$$c_{ij}^{(k)} = \min \{c_{ij}^{(k-1)}, c_{ik}^{(k-1)} + c_{kj}^{(k-1)}\}$$



intermediate vertices in $\{1, 2, \ldots, k-1\}$



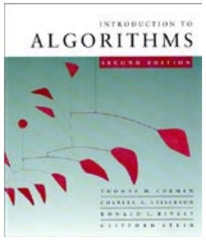
Pseudocode for Floyd-Warshall

for $k \leftarrow 1$ **to** n
  do for $i \leftarrow 1$ **to** n
    do for $j \leftarrow 1$ **to** n

$$\left.\begin{array}{l} \textbf{do if } c_{ij} > c_{ik} + c_{kj} \\ \qquad \textbf{then } c_{ij} \leftarrow c_{ik} + c_{kj} \end{array}\right\} \ \textit{\textbf{relaxation}}$$

Notes:

- Okay to omit superscripts, since extra relaxations can't hurt.
- Runs in $\Theta(n^3)$ time.
- Simple to code.
- Efficient in practice.



Transitive closure of a directed graph

Compute $t_{ij} = \begin{cases} 1 & \text{if there exists a path from } i \text{ to } j, \\ 0 & \text{otherwise.} \end{cases}$

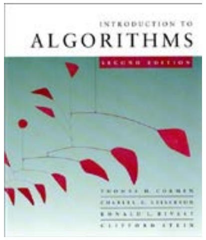
IDEA: Use Floyd-Warshall, but with $(\vee, \wedge)$ instead of $(\min, +)$:

$$t_{ij}^{(k)} = t_{ij}^{(k-1)} \vee (t_{ik}^{(k-1)} \wedge t_{kj}^{(k-1)}).$$

Time $= \Theta(n^3)$.

Graph reweighting

Theorem. Given a function $h : V \to \mathbb{R}$, ***reweight*** each edge $(u, v) \in E$ by $w_h(u, v) = w(u, v) + h(u) - h(v)$. Then, for any two vertices, all paths between them are reweighted by the same amount.



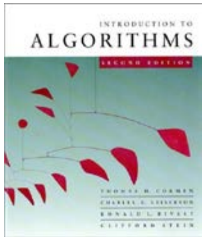
Graph reweighting

Theorem. Given a function $h : V \to \mathsf{R}$, ***reweight*** each edge $(u, v) \in E$ by $w_h(u, v) = w(u, v) + h(u) - h(v)$. Then, for any two vertices, all paths between them are reweighted by the same amount.

Proof. Let $p = v_1 \to v_2 \to \cdots \to v_k$ be a path in G. We have

$$
\begin{aligned}
w_h(p) &= \sum_{i=1}^{k-1} w_h(v_i, v_{i+1}) \\
&= \sum_{i=1}^{k-1} \big(w(v_i, v_{i+1}) + h(v_i) - h(v_{i+1})\big) \\
&= \sum_{i=1}^{k-1} w(v_i, v_{i+1}) + h(v_1) - h(v_k) \\
&= w(p) + h(v_1) - h(v_k). \quad \square
\end{aligned}
$$

Same amount!



Shortest paths in reweighted graphs

Corollary. $\delta_h(u, v) = \delta(u, v) + h(u) - h(v)$. $\square$

Shortest paths in reweighted graphs

Corollary. $\delta_h(u, v) = \delta(u, v) + h(u) - h(v)$. $\square$

IDEA: Find a function $h : V \to \mathbb{R}$ such that $w_h(u, v) \geq 0$ for all $(u, v) \in E$. Then, run Dijkstra's algorithm from each vertex on the reweighted graph.

NOTE: $w_h(u, v) \geq 0$ iff $h(v) - h(u) \leq w(u, v)$.

Johnson's algorithm

1. Find a function $h : V \to \mathbb{R}$ such that $w_h(u, v) \geq 0$ for all $(u, v) \in E$ by using Bellman-Ford to solve the difference constraints $h(v) - h(u) \leq w(u, v)$, or determine that a negative-weight cycle exists.
   - Time $= O(VE)$.
2. Run Dijkstra's algorithm using w_h from each vertex $u \in V$ to compute $\delta_h(u, v)$ for all $v \in V$.
   - Time $= O(VE + V^2 \lg V)$.
3. For each $(u, v) \in V \times V$, compute

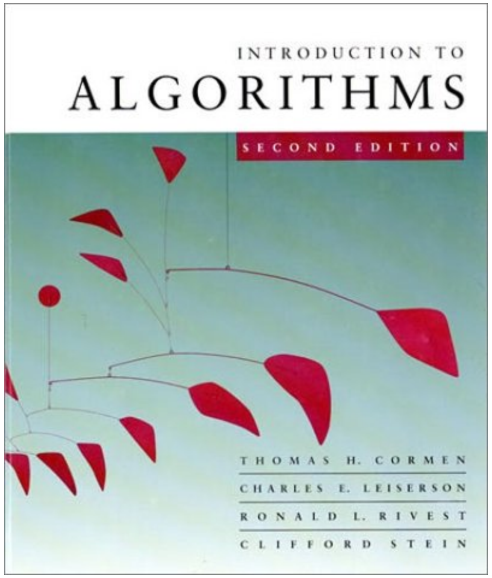
$$\delta(u, v) = \delta_h(u, v) - h(u) + h(v) .$$

   - Time $= O(V^2)$.

Total time $= O(VE + V^2 \lg V)$.

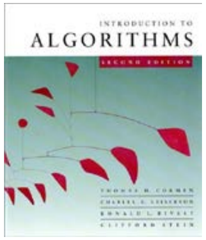
Introduction to Algorithms

6.046J/18.401J/SMA5503



Lecture 12

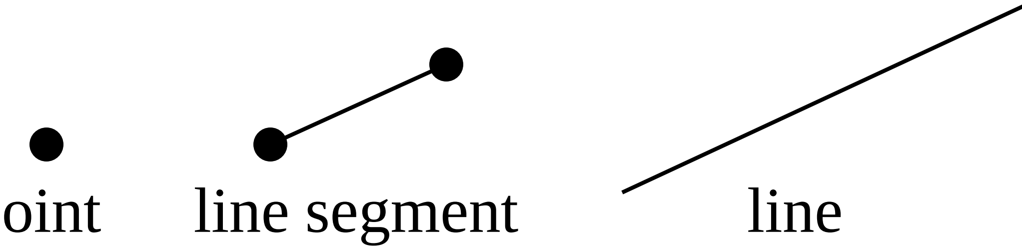
Prof. Erik Demaine



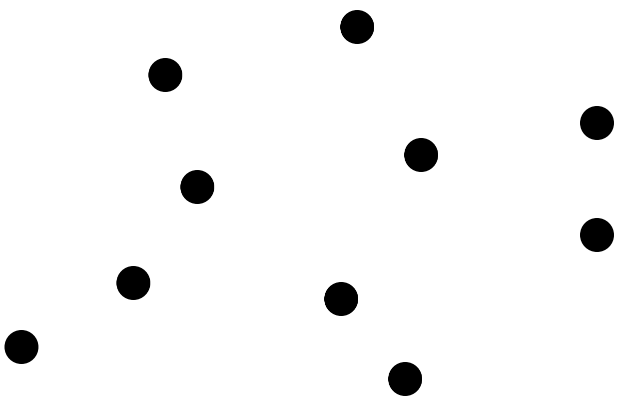
Computational geometry

Algorithms for solving "geometric problems" in 2D and higher.

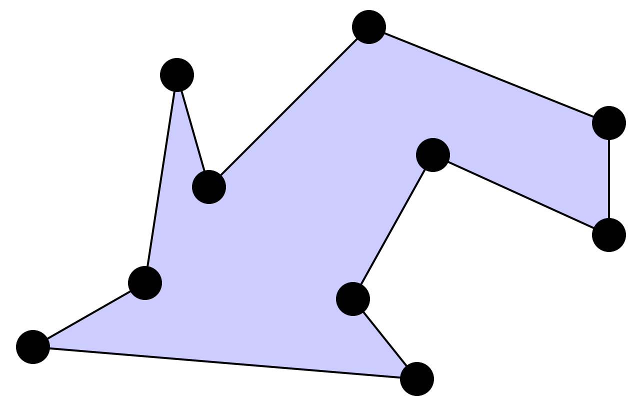
Fundamental objects:



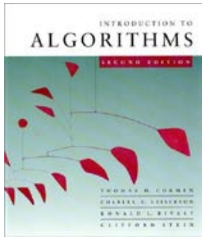
Basic structures:



point set



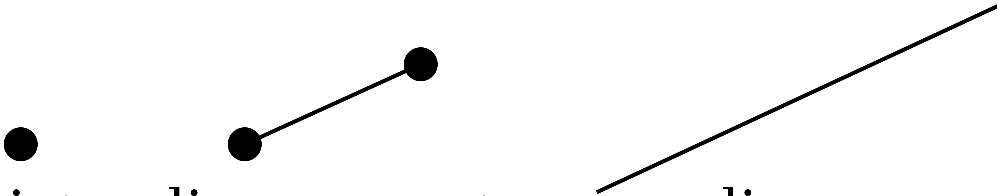
polygon



Computational geometry

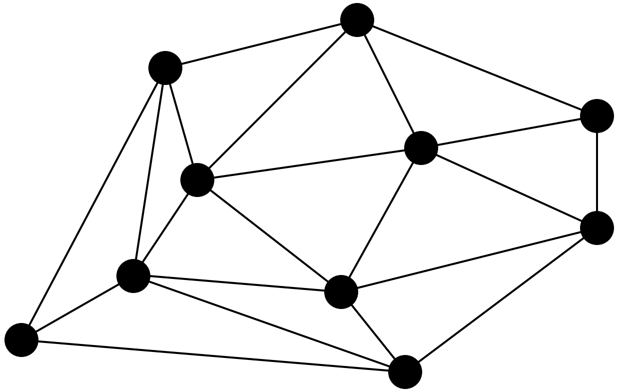
Algorithms for solving “geometric problems” in 2D and higher.

Fundamental objects:

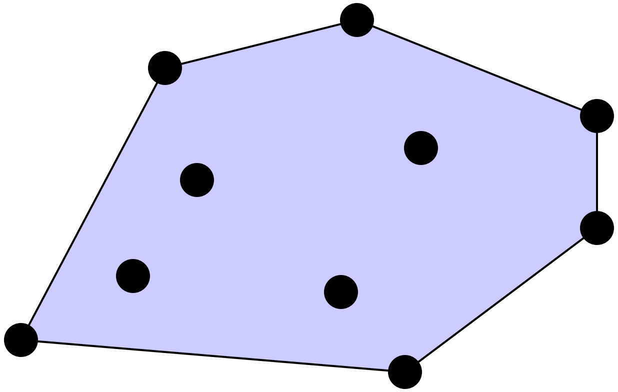


point line segment line

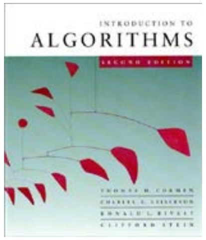
Basic structures:



triangulation



convex hull



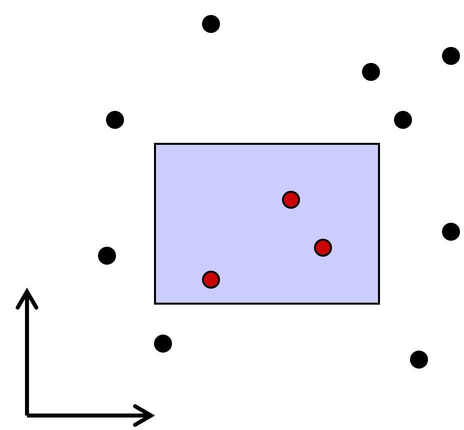
Orthogonal range searching

Input: n points in d dimensions

- E.g., representing a database of n records each with d numeric fields

Query: Axis-aligned ***box*** (in 2D, a rectangle)

- Report on the points inside the box:
  - Are there any points?
  - How many are there?
  - List the points.



Orthogonal range searching

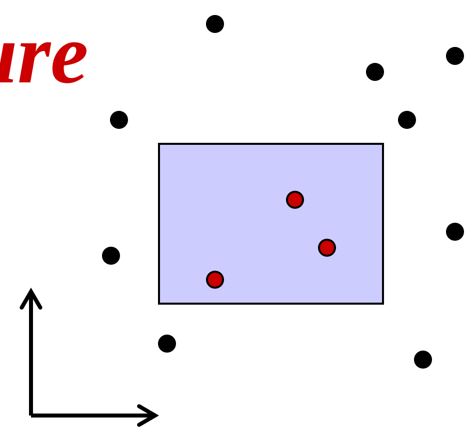
Input: n points in d dimensions

Query: Axis-aligned ***box*** (in 2D, a rectangle)

- Report on the points inside the box

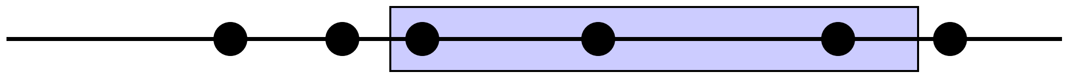
Goal: Preprocess points into a data structure to support fast queries

- Primary goal: ***Static data structure***
- In 1D, we will also obtain a dynamic data structure supporting insert and delete



1D range searching

In 1D, the query is an interval:

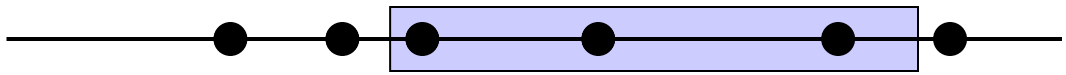


First solution using ideas we know:

- Interval trees
  - Represent each point x by the interval $[x, x]$.
  - Obtain a dynamic structure that can list k answers in a query in $O(k \lg n)$ time.

1D range searching

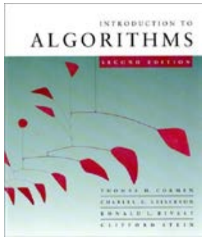
In 1D, the query is an interval:



Second solution using ideas we know:

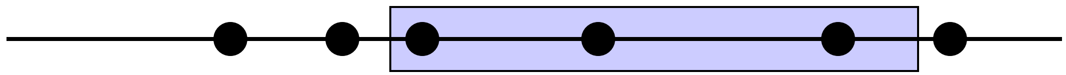
- Sort the points and store them in an array
  - Solve query by binary search on endpoints.
  - Obtain a static structure that can list k answers in a query in $O(k + \lg n)$ time.

Goal: Obtain a dynamic structure that can list k answers in a query in $O(k + \lg n)$ time.



1D range searching

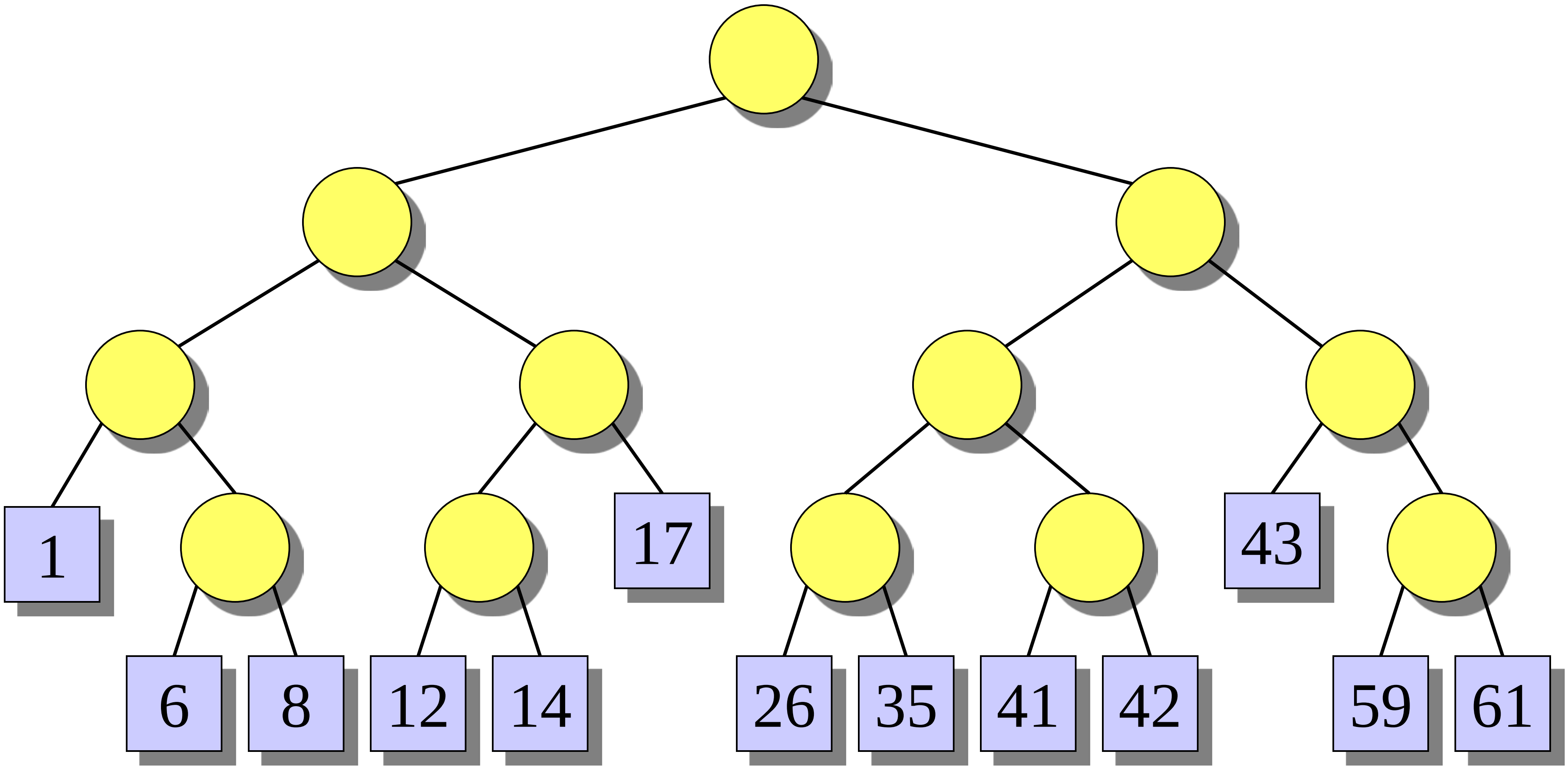
In 1D, the query is an interval:



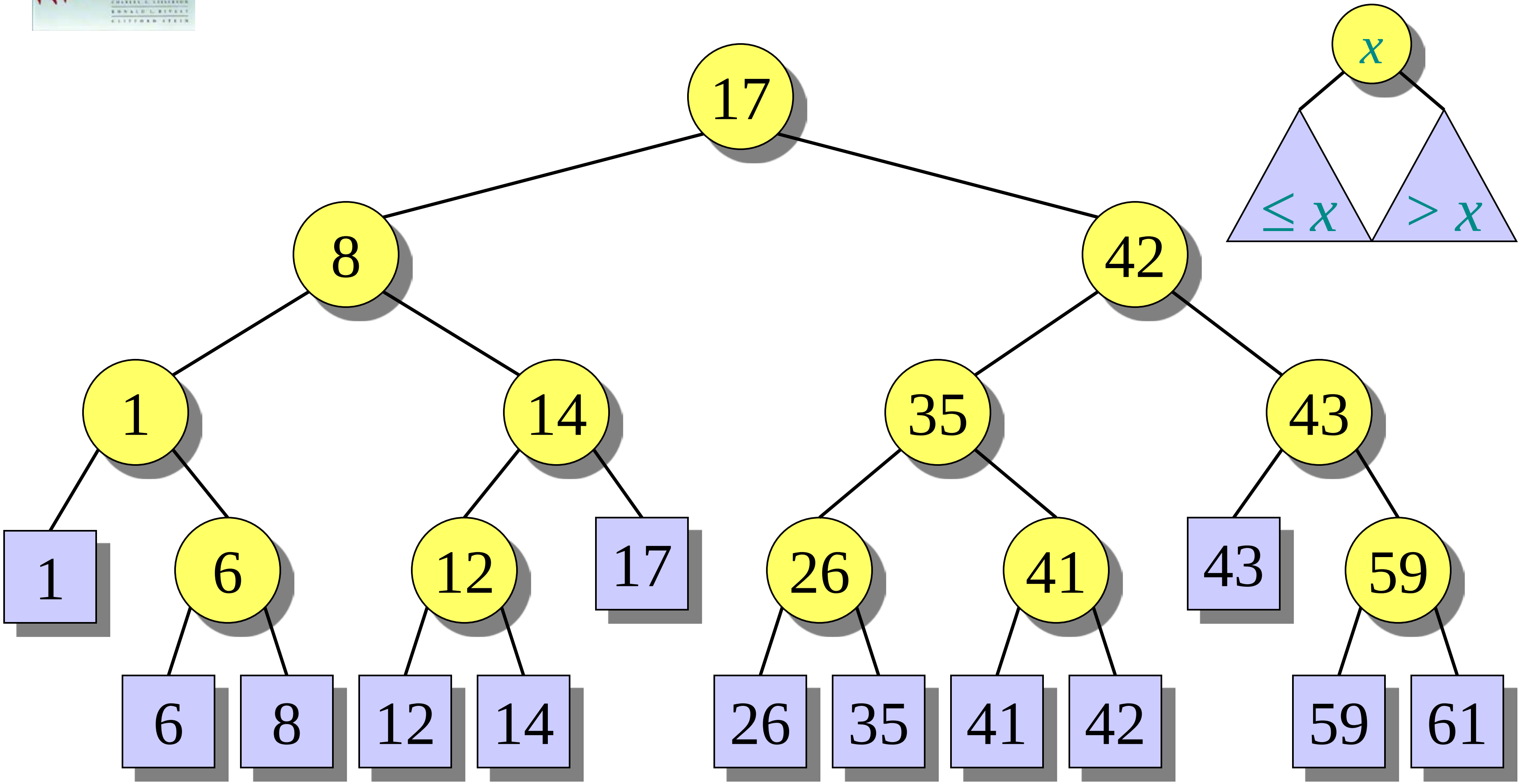
New solution that extends to higher dimensions:

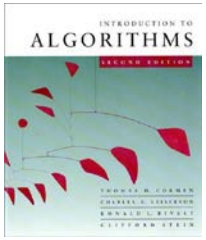
- Balanced binary search tree
  - New organization principle: Store points in the *leaves* of the tree.
  - Internal nodes store copies of the leaves to satisfy binary search property:
    - Node x stores in $key[x]$ the maximum key of any leaf in the left subtree of x.

Example of a 1D range tree

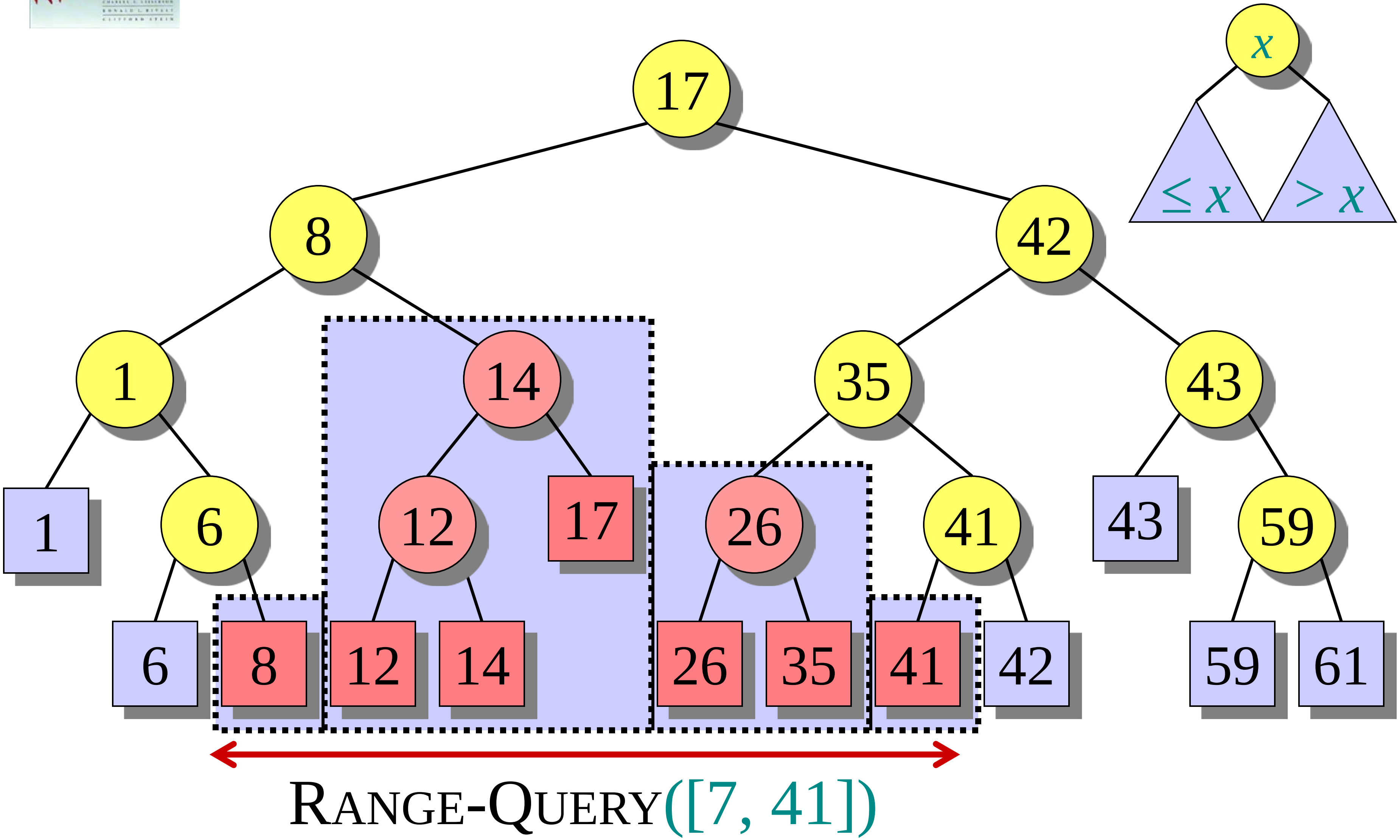


Example of a 1D range tree

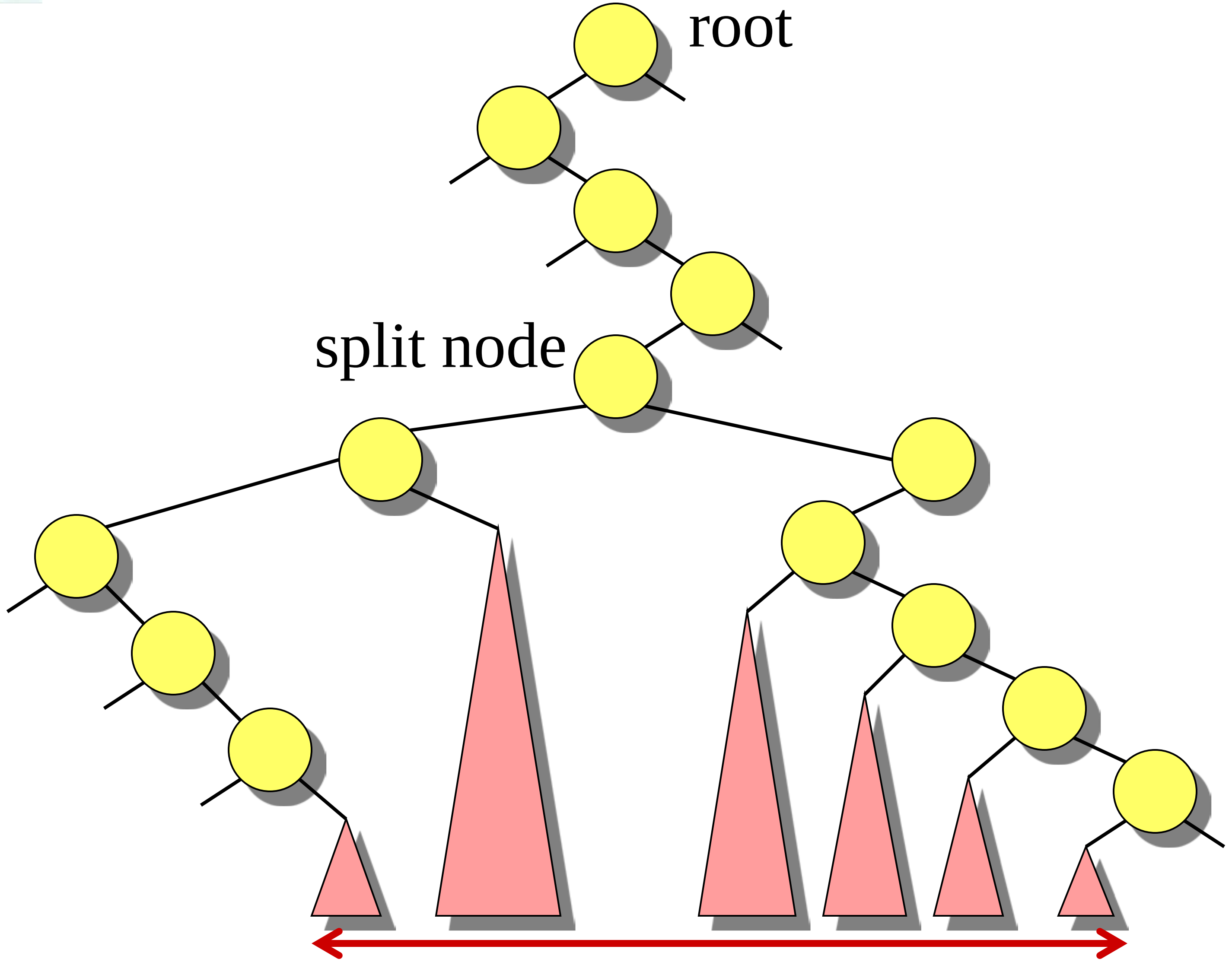


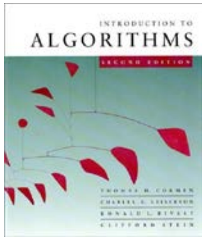


Example of a 1D range query



General 1D range query





Pseudocode, part 1: Find the split node

1D-RANGE-QUERY$(T, [x_1, x_2])$

$w \leftarrow \text{root}[T]$

while w is not a leaf and $(x_2 \leq key[w]$ or $key[w] < x_1)$

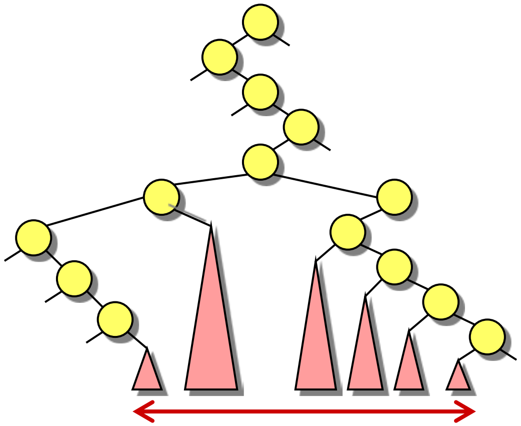
do if $x_2 \leq key[w]$

then $w \leftarrow left[w]$

else $w \leftarrow right[w]$

⊳ w is now the split node

[*traverse left and right from w and report relevant subtrees*]



Pseudocode, part 2: Traverse left and right from split node

1D-RANGE-QUERY$(T, [x_1, x_2])$

[*find the split node*]

⊳ w is now the split node

if w is a leaf

then output the leaf w if $x_1 \le key[w] \le x_2$

else $v \leftarrow left[w]$ ⊳ Left traversal

while v is not a leaf

do if $x_1 \le key[v]$

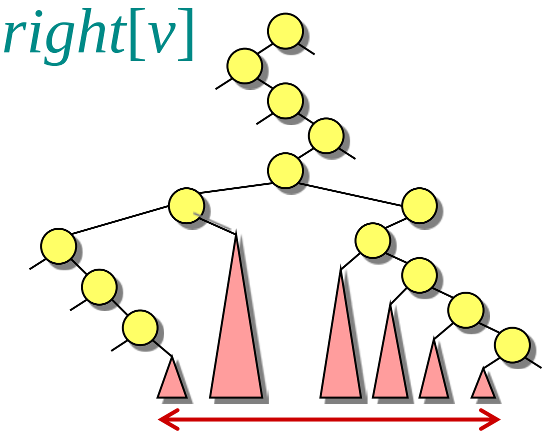
then output the subtree rooted at $right[v]$

$v \leftarrow left[v]$

else $v \leftarrow right[v]$

output the leaf v if $x_1 \le key[v] \le x_2$

[*symmetrically for right traversal*]

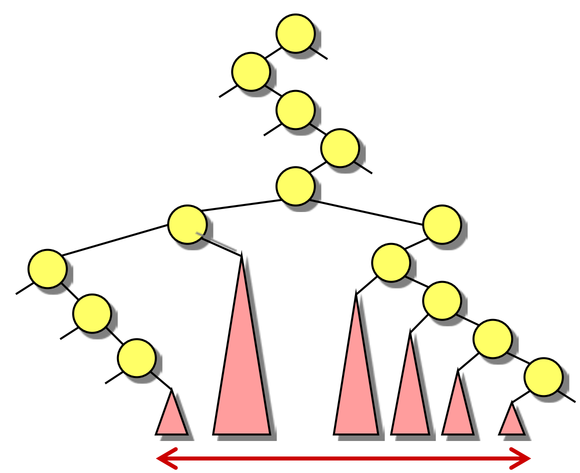


Analysis of 1D-RANGE-QUERY

Query time: Answer to range query represented by $O(\lg n)$ subtrees found in $O(\lg n)$ time.

Thus:

- Can test for points in interval in $O(\lg n)$ time.
- Can count points in interval in $O(\lg n)$ time if we augment the tree with subtree sizes.
- Can report the first k points in interval in $O(k + \lg n)$ time.



Space: $O(n)$

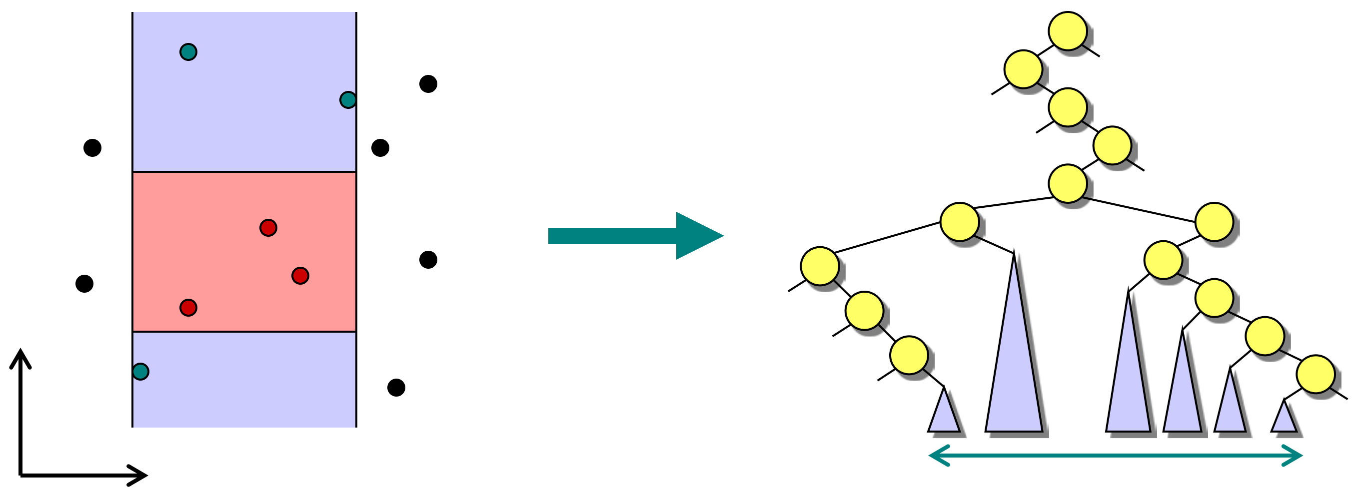
Preprocessing time: $O(n \lg n)$

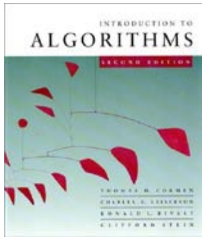
2D range trees

Store a ***primary*** 1D range tree for all the points based on *x*-coordinate.

Thus in O(lg *n*) time we can find O(lg *n*) subtrees representing the points with proper *x*-coordinate.

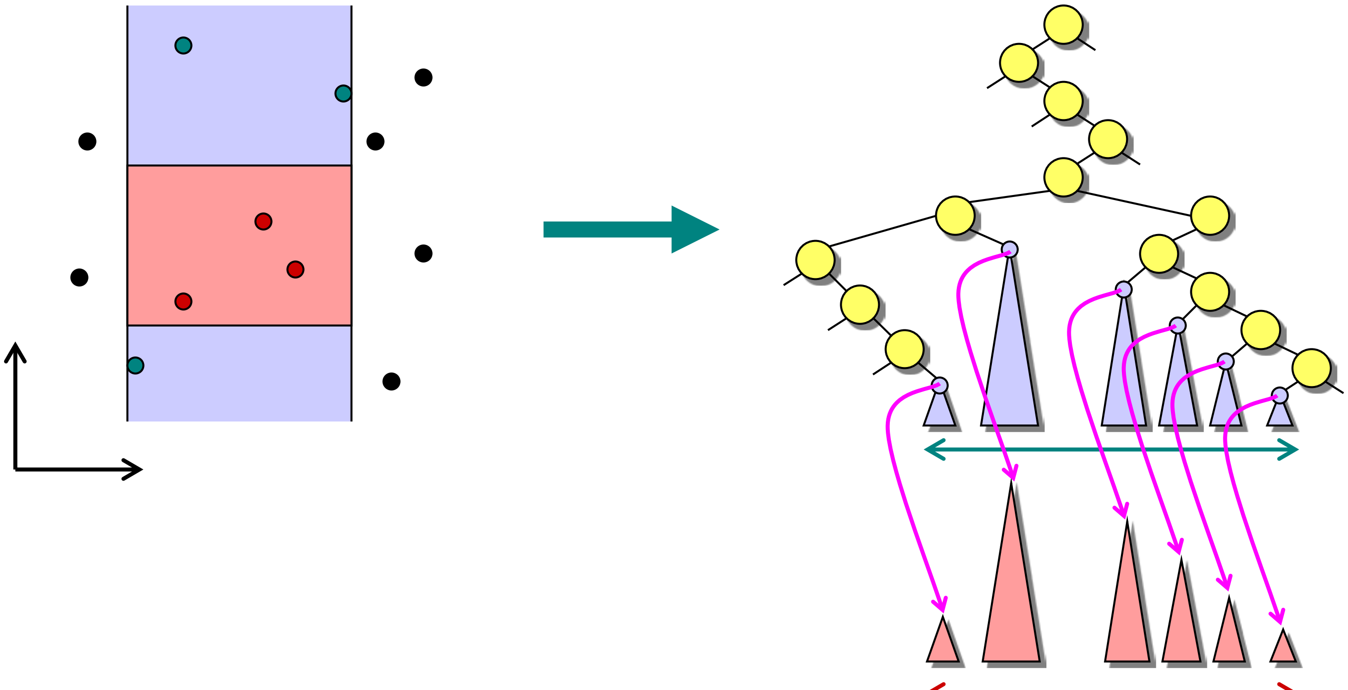
How to restrict to points with proper *y*-coordinate?





2D range trees

Idea: In primary 1D range tree of *x*-coordinate, every node stores a ***secondary*** 1D range tree based on *y*-coordinate for all points in the subtree of the node. Recursively search within each.



Analysis of 2D range trees

Query time: In $O((\lg n)^2)$ time, we can represent the answer to range query by $O((\lg n)^2)$ subtrees. Total cost for reporting k points: $O(k + (\lg n)^2)$.

Space: The secondary trees at each level of the primary tree together store a copy of the points. Also, each point is present in each secondary tree along the path from the leaf to the root. Either way, we obtain that the space is $O(n \lg n)$.

Preprocessing time: $O(n \lg n)$

d-dimensional range trees ($d \geq 2$)

Each node of the secondary y-structure stores a tertiary z-structure representing the points in the subtree rooted at the node, etc.

Query time: $O(k + (\lg n)^d)$ to report k points.

Space: $O(n (\lg n)^{d-1})$

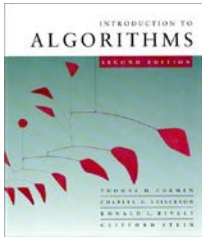
Preprocessing time: $O(n (\lg n)^{d-1})$

Best data structure to date:

Query time: $O(k + (\lg n)^{d-1})$ to report k points.

Space: $O(n (\lg n / \lg \lg n)^{d-1})$

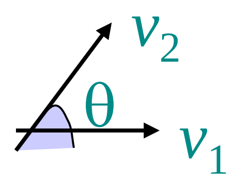
Preprocessing time: $O(n (\lg n)^{d-1})$



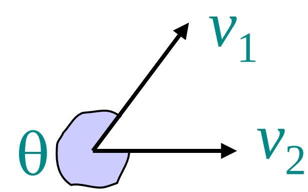
Primitive operations: Crossproduct

Given two vectors $v_1 = (x_1, y_1)$ and $v_2 = (x_2, y_2)$, is their counterclockwise angle θ

- ***convex*** ($< 180°$),
- ***reflex*** ($> 180°$), or
- borderline (0 or $180°$)?



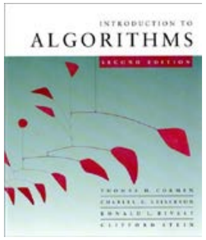
convex



reflex

Crossproduct $v_1 \times v_2 = x_1\, x_2 - y_1\, y_2$
$= |v_1|\, |v_2| \sin\theta$.

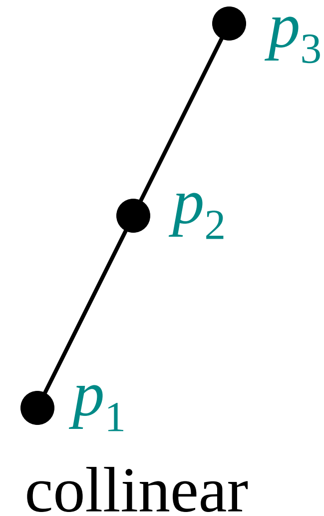
Thus, $\operatorname{sign}(v_1 \times v_2) = \operatorname{sign}(\sin\theta)$ > 0 if θ convex,
< 0 if θ reflex,
$= 0$ if θ borderline.



Primitive operations: Orientation test

Given three points p_1, p_2, p_3 are they

- in ***clockwise (cw) order***,
- in ***counterclockwise (ccw) order***, or
- ***collinear***?

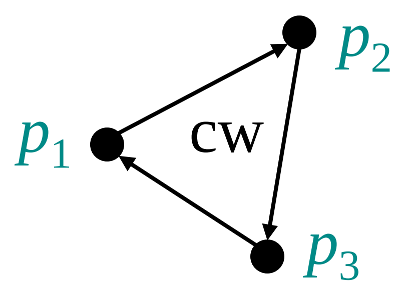


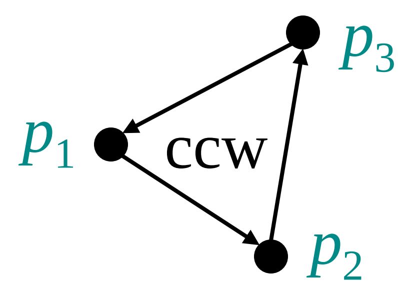
$$(p_2 - p_1) \times (p_3 - p_1)$$

> 0 if ccw

< 0 if cw

$= 0$ if collinear





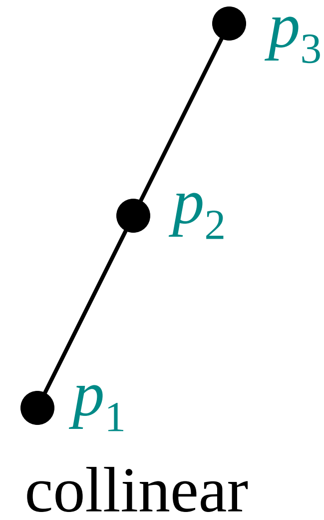
Primitive operations: Sidedness test

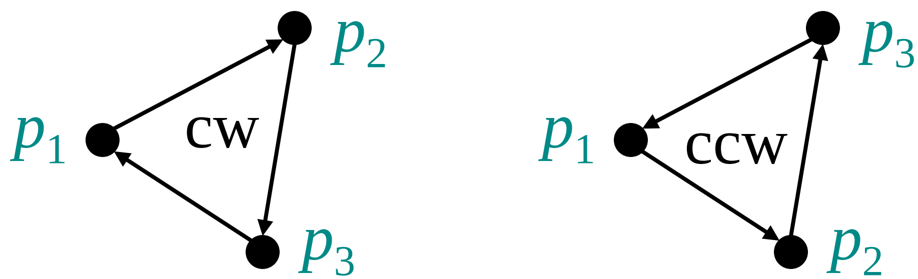
Given three points p_1, p_2, p_3 are they

- in ***clockwise (cw) order***,
- in ***counterclockwise (ccw) order***, or
- ***collinear***?

Let L be the oriented line from p_1 to p_2.
Equivalently, is the point p_3

- ***right*** of L,
- ***left*** of L, or
- ***on*** L?

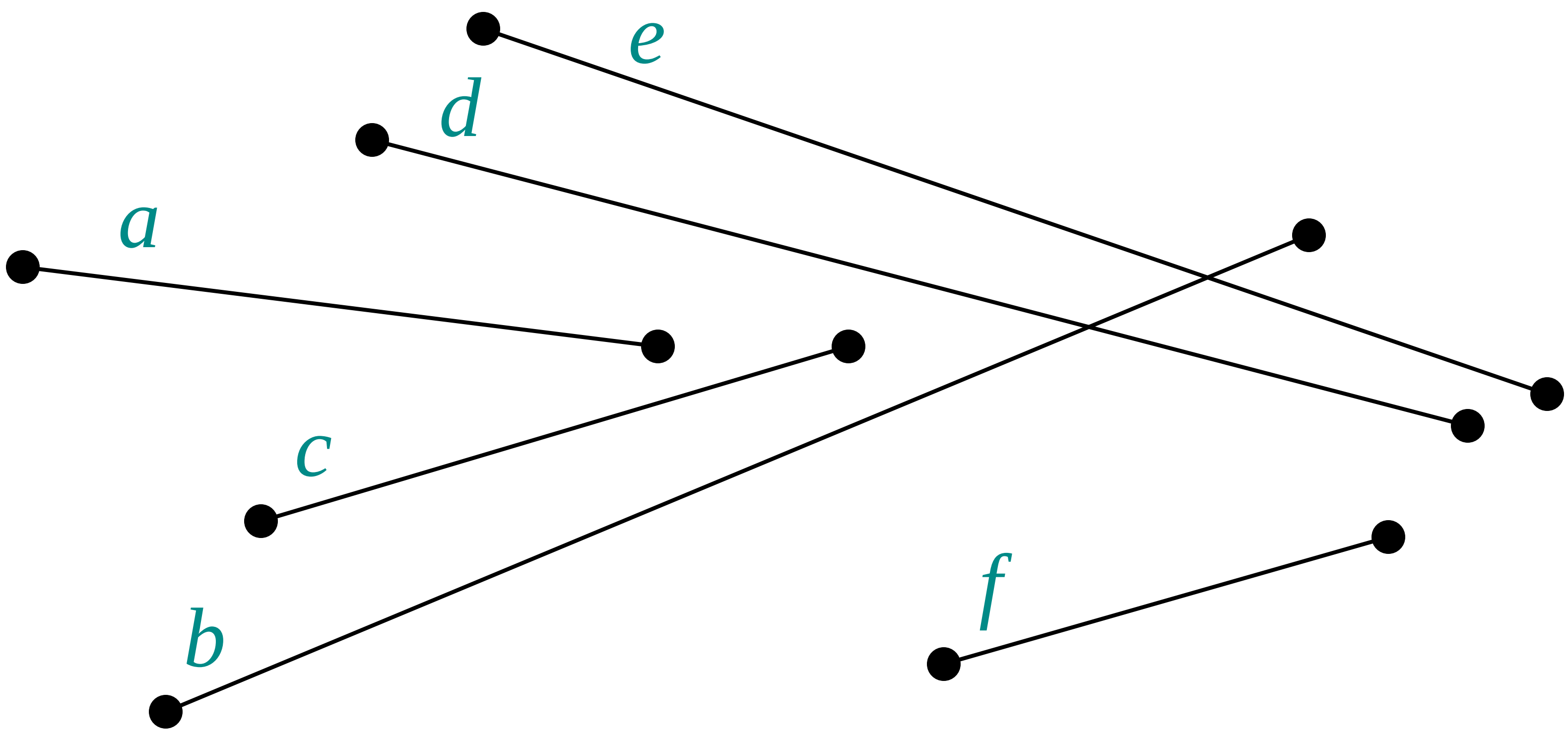




Line-segment intersection

Given n line segments, does any pair intersect?

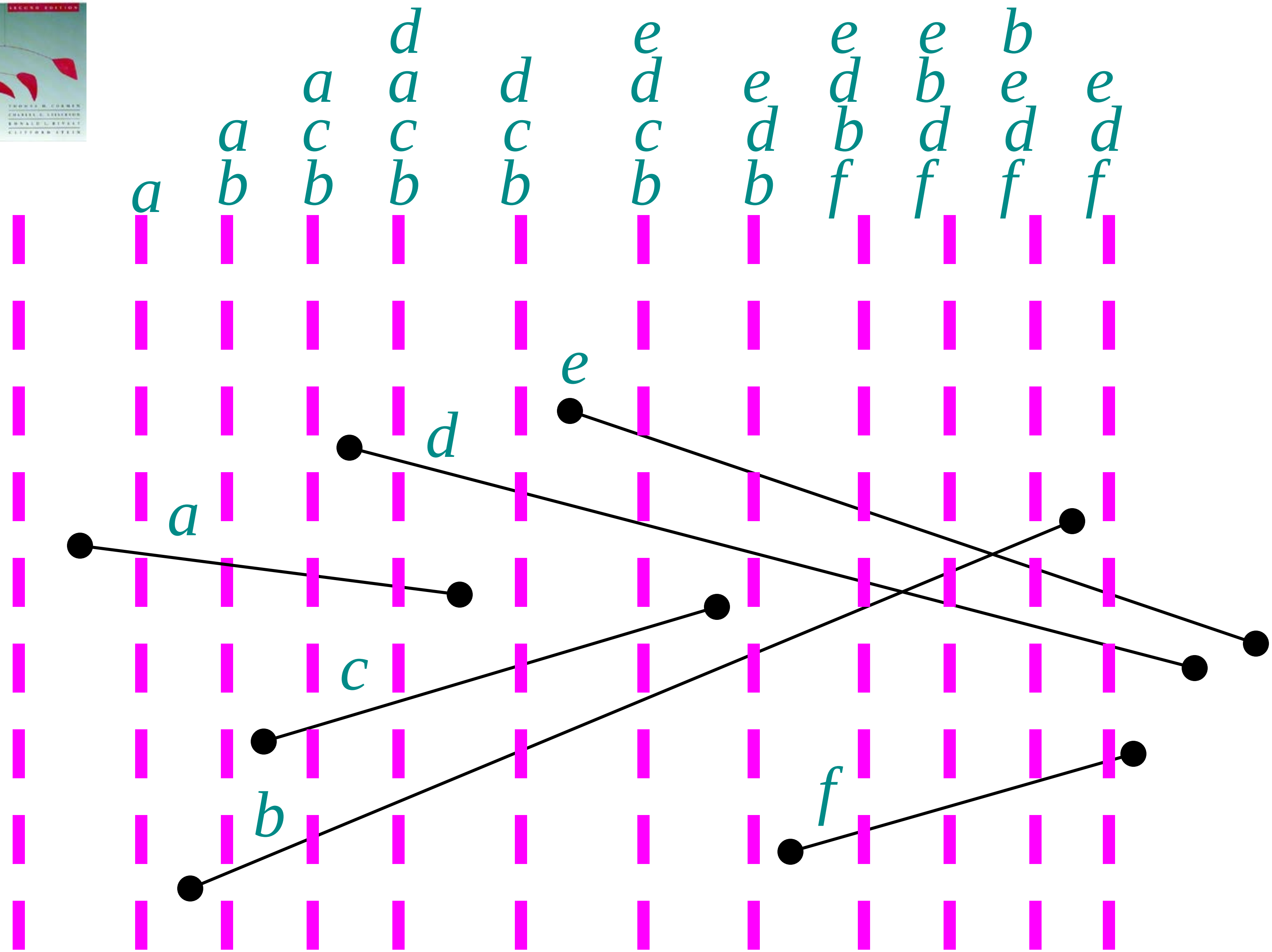
Obvious algorithm: $O(n^2)$.



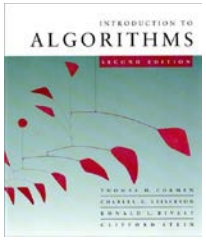
Sweep-line algorithm

- Sweep a vertical line from left to right (conceptually replacing x-coordinate with time).
- Maintain dynamic set S of segments that intersect the sweep line, ordered (tentatively) by y-coordinate of intersection.
- Order changes when
  - new segment is encountered,
  - existing segment finishes, or
  - two segments cross

  segment endpoints
- Key ***event points*** are therefore segment endpoints.



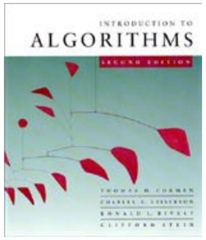
a
a b
a c b
d a c b
d c b
e d c b
e d b
e d b f
e b d f
b e d f
e d f
e
d
a
c
b
f



Sweep-line algorithm

Process event points in order by sorting segment endpoints by x-coordinate and looping through:

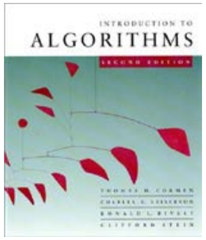
- For a left endpoint of segment s:
  - Add segment s to dynamic set S.
  - Check for intersection between s and its neighbors in S.
- For a right endpoint of segment s:
  - Remove segment s from dynamic set S.
  - Check for intersection between the neighbors of s in S.



Analysis

Use red-black tree to store dynamic set S.

Total running time: $O(n \lg n)$.



Correctness

Theorem: If there is an intersection, the algorithm finds it.

Proof: Let X be the leftmost intersection point. Assume for simplicity that

- only two segments s_1, s_2 pass through X, and
- no two points have the same x-coordinate.

At some point before we reach X, s_1 and s_2 become consecutive in the order of S. Either initially consecutive when s_1 or s_2 inserted, or became consecutive when another deleted. $\square$