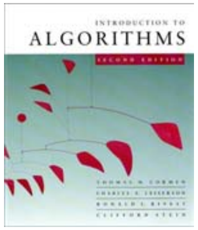
CS 3343 -- Spring 2009



More Divide & Conquer

Carola Wenk

Slides courtesy of Charles Leiserson with small changes by Carola Wenk

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Powering a number

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

Naive algorithm: $\Theta(n)$.

Divide-and-conquer algorithm: **(recursive squaring)**

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

$$T(n) = T(n/2) + \Theta(1) \;\Rightarrow\; T(n) = \Theta(\log n)\,.$$

Fibonacci numbers

Recursive definition:

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

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

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

Computing Fibonacci numbers

Naive recursive squaring:

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

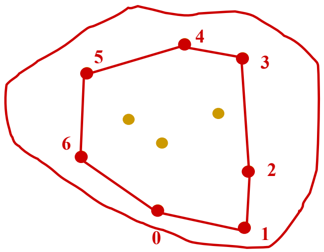
- Recursive squaring: $\Theta(\log n)$ time.
- This method is unreliable, since floating-point arithmetic is prone to round-off errors.

Bottom-up (one-dimensional dynamic programming):

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

Convex Hull

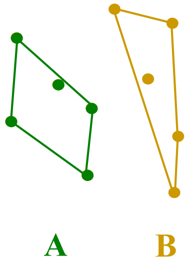
- Given a set of pins on a pinboard
- And a rubber band around them
- How does the rubber band look when it snaps tight?



- We represent convex hull as the sequence of points on the convex hull polygon, in counter-clockwise order.

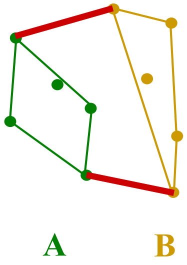
Convex Hull: Divide & Conquer

- Preprocessing: sort the points by x-coordinate
- Divide the set of points into two sets **A** and **B**:
  - **A** contains the left $\lfloor n/2 \rfloor$ points,
  - **B** contains the right $\lceil n/2 \rceil$ points
- Recursively compute the convex hull of **A**
- Recursively compute the convex hull of **B**
- Merge the two convex hulls



Merging

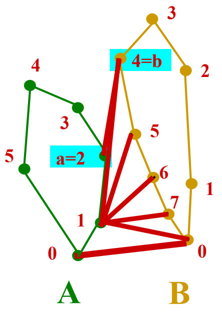
- **Find upper and lower tangent**
- With those tangents the convex hull of A∪B can be computed from the convex hulls of A and the convex hull of B in O(n) linear time

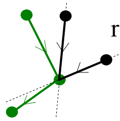


Finding the lower tangent

```
a = rightmost point of A
b = leftmost point of B
while T=ab not lower tangent to both
        convex hulls of A and B do{
    while T not lower tangent to
     convex hull of A do{
        a=a-1
    }
    while T not lower tangent to
     convex hull of B do{
        b=b+1
     }
}
```

can be checked in constant time





right turn or left turn?

Convex Hull: Runtime

- Preprocessing: sort the points by x-coordinate — O(n log n) just once
- Divide the set of points into two sets **A** and **B**: — O(1)
  - **A** contains the left ⌊n/2⌋ points,
  - **B** contains the right ⌈n/2⌉ points
- Recursively compute the convex hull of **A** — T(n/2)
- Recursively compute the convex hull of **B** — T(n/2)
- Merge the two convex hulls — O(n)

Convex Hull: Runtime

- Runtime Recurrence:

  T(n) = 2 T(n/2) + cn

- Solves to T(n) = Θ(n log n)

Matrix multiplication

$$\left.\begin{array}{ll}\textbf{Input:} & A = [a_{ij}],\ B = [b_{ij}]. \\ \textbf{Output:} & C = [c_{ij}] = A \cdot B.\end{array}\right\}\ i, j = 1, 2, \ldots, n.$$

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

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

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 $c_{ij} \leftarrow c_{ij} + a_{ik} \cdot b_{kj}$
```

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

Divide-and-conquer algorithm

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

$$\begin{bmatrix} r & s \\ t & u \end{bmatrix} = \begin{bmatrix} a & b \\ c & d \end{bmatrix} \cdot \begin{bmatrix} e & f \\ g & h \end{bmatrix}$$

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

$$\left.\begin{aligned} r &= a \cdot e + b \cdot g \\ s &= a \cdot f + b \cdot h \\ t &= c \cdot e + d \cdot g \\ u &= c \cdot f + d \cdot h \end{aligned}\right\} \begin{array}{l} 8 \text{ recursive mults of } (n/2)\times(n/2) \text{ submatrices} \\ 4 \text{ adds of } (n/2)\times(n/2) \text{ submatrices} \end{array}$$

Analysis of D&C algorithm

$$T(n) = \underbrace{8}_{\text{\# submatrices}}\ \underbrace{T(n/2)}_{\text{submatrix size}} + \underbrace{\Theta(n^2)}_{\text{work adding submatrices}}$$

$n^{\log_b a} = n^{\log_2 8} = n^3 \Rightarrow$ 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.

$$\begin{aligned} P_1 &= a \cdot (f - h) \\ P_2 &= (a + b) \cdot h \\ P_3 &= (c + d) \cdot e \\ P_4 &= d \cdot (g - e) \\ P_5 &= (a + d) \cdot (e + h) \\ P_6 &= (b - d) \cdot (g + h) \\ P_7 &= (a - c) \cdot (e + f) \end{aligned}$$

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

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

Strassen's idea

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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 P-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.

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

Analysis of Strassen

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

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

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 $n \geq 30$ or so.

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

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).
- Can lead to more efficient algorithms