CSE 421: Introduction to Algorithms

Divide and Conquer

Paul Beame
Algorithm Design Techniques

- **Divide & Conquer**
  - Reduce problem to one or more sub-problems of the same type
  - Typically, each sub-problem is **at most a constant fraction** of the size of the original problem
    - e.g. Mergesort, Binary Search, Strassen’s Algorithm, Quicksort (kind of)
Fast exponentiation

- **Power**(a,n)
  - **Input:** integer n and number a
  - **Output:** a^n

- Obvious algorithm
  - n-1 multiplications

- Observation:
  - if n is even, n=2m, then a^n = a^m • a^m
Divide & Conquer Algorithm

- Power(a, n)
  - if n=0 then return(1)
  - else if n=1 then return(a)
  - else
    - x ← Power(a, ⌊n/2⌋)
    - if n is even then
      - return(x • x)
    - else
      - return(a • x • x)
Analysis

- Worst-case recurrence
  - $T(n) = T(\lceil n/2 \rceil) + 2$ for $n \geq 1$
  - $T(1) = 0$

- Time
  - $T(n) = T(\lceil n/2 \rceil) + 2 \leq T(\lceil n/4 \rceil) + 2 + 2 \leq \ldots \leq T(1) + 2 + \ldots + 2 = 2 \log_2 n$

- More precise analysis:
  - $T(n) = \lceil \log_2 n \rceil + \# \text{ of 1's in } n \text{'s binary representation}$
A Practical Application- RSA

- Instead of $a^n$ want $a^n \mod N$
  - $a^{i+j} \mod N = ((a^i \mod N) \cdot (a^j \mod N)) \mod N$
  - same algorithm applies with each $x \cdot y$ replaced by
    - $((x \mod N) \cdot (y \mod N)) \mod N$

- In RSA cryptosystem (widely used for security)
  - need $a^n \mod N$ where $a$, $n$, $N$ each typically have 1024 bits
  - Power: at most $2^{2048}$ multiplies of 1024 bit numbers
    - relatively easy for modern machines
  - Naive algorithm: $2^{1024}$ multiplies
Binary search for roots (bisection method)

Given:
- continuous function $f$ and two points $a < b$ with $f(a) \leq 0$ and $f(b) > 0$

Find:
- approximation to $c$ s.t. $f(c) = 0$ and $a < c < b$
Bisection method

Bisection\((a, b, \varepsilon)\)

if \((a - b) < \varepsilon\) then
  return\((a)\)
else
  \(c \leftarrow (a + b)/2\)
  if \(f(c) \leq 0\) then
    return\((\text{Bisection}(c, b, \varepsilon))\)
  else
    return\((\text{Bisection}(a, c, \varepsilon))\)
Time Analysis

- At each step we halved the size of the interval
- It started at size $b-a$
- It ended at size $\varepsilon$

$\text{# of calls to } f \text{ is } \log_2 \left( \frac{b-a}{\varepsilon} \right)$
Old favorites

- **Binary search**
  - One subproblem of half size plus one comparison
  - Recurrence \( T(n) = T\left(\lceil n/2 \rceil\right) + 1 \) for \( n \geq 2 \)
    \[ T(1) = 0 \]
  - So \( T(n) \) is \( \lceil \log_2 n \rceil + 1 \)

- **Mergesort**
  - Two subproblems of half size plus merge cost of \( n-1 \) comparisons
  - Recurrence \( T(n) \leq 2T\left(\lceil n/2 \rceil\right) + n-1 \) for \( n \geq 2 \)
    \[ T(1) = 0 \]
  - Roughly \( n \) comparisons at each of \( \log_2 n \) levels of recursion
  - So \( T(n) \) is roughly \( 2n \log_2 n \)
Euclidean Closest Pair

- Given a set $P$ of $n$ points $p_1, \ldots, p_n$ with real-valued coordinates

- Find the pair of points $p_i, p_j \in P$ such that the Euclidean distance $d(p_i, p_j)$ is minimized

- $\Theta(n^2)$ possible pairs

- In one dimension: easy $O(n \log n)$ algorithm
  - Sort the points
  - Compare consecutive elements in the sorted list

- What about points in the plane?
Closest Pair in the Plane

No single direction along which one can sort points to guarantee success!
Closest Pair In the Plane: Divide and Conquer

- Sort the points by their $x$ coordinates
- Split the points into two sets of $n/2$ points $L$ and $R$ by $x$ coordinate
- Recursively compute
  - closest pair of points in $L$, $(p_L, q_L)$
  - closest pair of points in $R$, $(p_R, q_R)$
- Let $\delta = \min\{d(p_L, q_L), d(p_R, q_R)\}$ and let $(p, q)$ be the pair of points that has distance $\delta$
- But this may not be enough
  - Closest pair of points may involve one point from $L$ and the other from $R$!
A clever geometric idea

Any pair of points $p \in L$ and $q \in R$ with $d(p, q) < \delta$ must lie in band
A clever geometric idea

Any pair of points $p \in L$ and $q \in R$ with $d(p,q) < \delta$ must lie in band.

No two points can be in the same green box.
A clever geometric idea

Any pair of points $p \in L$ and $q \in R$ with $d(p,q) < \delta$ must lie in band.

No two points can be in the same green box.

Only need to check pairs of points up to 2 rows apart - At most a constant # of other points!
Closest Pair Recombining

- Sort points by $y$ coordinate ahead of time

- On recombination only compare each point in $\delta$-band of $L \cup R$ to the 11 points in $\delta$-band of $L \cup R$ above it in the $y$ sorted order
  - If any of those distances is better than $\delta$ replace $(p,q)$ by the best of those pairs

- $O(n \log n)$ for $x$ and $y$ sorting at start

- Two recursive calls on problems on half size

- $O(n)$ recombination

- Total $O(n \log n)$
Sometimes two sub-problems aren’t enough

- More general divide and conquer
  - You’ve broken the problem into a different sub-problems
  - Each has size at most $n/b$
  - The cost of the break-up and recombining the sub-problem solutions is $O(n^k)$

- Recurrence
  - $T(n) \leq a \cdot T(n/b) + c \cdot n^k$
Master Divide and Conquer Recurrence

- If $T(n) \leq a \cdot T(n/b) + c \cdot n^k$ for $n > b$ then
  - if $a > b^k$ then $T(n)$ is $\Theta(n^{\log_b a})$
  - if $a < b^k$ then $T(n)$ is $\Theta(n^k)$
  - if $a = b^k$ then $T(n)$ is $\Theta(n^k \log n)$

- Works even if it is $\lceil n/b \rceil$ instead of $n/b$. 
Proving Master recurrence

\[ T(n) = a \cdot T\left(\frac{n}{b}\right) + c \cdot n^k \]

# probs

Problem size

\[ \frac{n}{b} \]

\[ \frac{n}{b^2} \]

b

1

\[ T(1) = c \]
Proving Master recurrence

\[ T(n) = a \cdot T\left(\frac{n}{b}\right) + c \cdot n^k \]

# of problems

Problem size

\( n \)

\( \frac{n}{b} \)

\( \frac{n}{b^2} \)

\( b \)

\( 1 \)

\( d = \log_b n \)

\( T(1) = c \)

\( a \)

\( a^2 \)

\( a^d \)
Proving Master recurrence

\[ T(n) = a \cdot T\left(\frac{n}{b}\right) + c \cdot n^k \]

# probs

\[ n \]

Problem size

\[ T(1) = c \]

\[ 1 \]

\[ T\left(\frac{1}{b}\right) = a \cdot T\left(\frac{1}{b^2}\right) + c \cdot 1^k = a \cdot 1 + c \cdot 1^k = a + c \]

\[ T\left(\frac{1}{b^2}\right) = a \cdot T\left(\frac{1}{b^3}\right) + c \cdot 2^k = a \cdot a + c \cdot 2^k = a^2 + c \cdot 2^k \]

\[ T\left(\frac{1}{b^3}\right) = a \cdot T\left(\frac{1}{b^4}\right) + c \cdot 3^k = a \cdot a^2 + c \cdot 3^k = a^3 + c \cdot 3^k \]

\[ \vdots \]

\[ T\left(\frac{1}{b^d}\right) = c \cdot n^k \]

\[ c \cdot n^k(a/b^k)^d = c \cdot a^d \]
Geometric Series

- \[ S = t + tr + tr^2 + \ldots + tr^{n-1} \]
- \[ r \cdot S = tr + tr^2 + \ldots + tr^{n-1} + tr^n \]
- \[ (r-1)S = tr^n - t \]
- so \[ S = t \frac{r^n - 1}{r - 1} \] if \( r \neq 1 \).

Simple rule
- If \( r \neq 1 \) then \( S \) is a constant times largest term in series
Total Cost

- Geometric series
  - ratio $a/b^k$
  - $d+1 = \log_b n + 1$ terms
  - first term $cn^k$, last term $ca^d$
  - If $a/b^k=1$
    - all terms are equal $T(n)$ is $\Theta(n^k \log n)$
  - If $a/b^k<1$
    - first term is largest $T(n)$ is $\Theta(n^k)$
  - If $a/b^k>1$
    - last term is largest $T(n)$ is $\Theta(a^d) = \Theta(a^{\log_b n}) = \Theta(n^{\log_b a})$
      (To see this take $\log_b$ of both sides)
Multiplying Matrices

\[
\begin{bmatrix}
  a_{11} & a_{12} & a_{13} & a_{14} \\
  a_{21} & a_{22} & a_{23} & a_{24} \\
  a_{31} & a_{32} & a_{33} & a_{34} \\
  a_{41} & a_{42} & a_{43} & a_{44}
\end{bmatrix}
\begin{bmatrix}
  b_{11} & b_{12} & b_{13} & b_{14} \\
  b_{21} & b_{22} & b_{23} & b_{24} \\
  b_{31} & b_{32} & b_{33} & b_{34} \\
  b_{41} & b_{42} & b_{43} & b_{44}
\end{bmatrix}
\]

= \[
\begin{bmatrix}
  a_{11}b_{11} + a_{12}b_{21} + a_{13}b_{31} + a_{14}b_{41} & a_{11}b_{12} + a_{12}b_{22} + a_{13}b_{32} + a_{14}b_{42} & \cdots & a_{11}b_{14} + a_{12}b_{24} + a_{13}b_{34} + a_{14}b_{44} \\
  a_{21}b_{11} + a_{22}b_{21} + a_{23}b_{31} + a_{24}b_{41} & a_{21}b_{12} + a_{22}b_{22} + a_{23}b_{32} + a_{24}b_{42} & \cdots & a_{21}b_{14} + a_{22}b_{24} + a_{23}b_{34} + a_{24}b_{44} \\
  a_{31}b_{11} + a_{32}b_{21} + a_{33}b_{31} + a_{34}b_{41} & a_{31}b_{12} + a_{32}b_{22} + a_{33}b_{32} + a_{34}b_{42} & \cdots & a_{31}b_{14} + a_{32}b_{24} + a_{33}b_{34} + a_{34}b_{44} \\
  a_{41}b_{11} + a_{42}b_{21} + a_{43}b_{31} + a_{44}b_{41} & a_{41}b_{12} + a_{42}b_{22} + a_{43}b_{32} + a_{44}b_{42} & \cdots & a_{41}b_{14} + a_{42}b_{24} + a_{43}b_{34} + a_{44}b_{44}
\end{bmatrix}
\]

- \(n^3\) multiplications, \(n^3-n^2\) additions
Multiplying Matrices

for \( i=1 \) to \( n \)
  
  for \( j=1 \) to \( n \)
    
    \( C[i,j] \leftarrow 0 \)
    
    for \( k=1 \) to \( n \)
      
      \[ C[i,j] = C[i,j] + A[i,k] \cdot B[k,j] \]
    
  endfor

endfor
Multiplying Matrices

\[ \begin{bmatrix}
  a_{11} & a_{12} & a_{13} & a_{14} \\
  a_{21} & a_{22} & a_{23} & a_{24} \\
  a_{31} & a_{32} & a_{33} & a_{34} \\
  a_{41} & a_{42} & a_{43} & a_{44}
\end{bmatrix}
\begin{bmatrix}
  b_{11} & b_{12} & b_{13} & b_{14} \\
  b_{21} & b_{22} & b_{23} & b_{24} \\
  b_{31} & b_{32} & b_{33} & b_{34} \\
  b_{41} & b_{42} & b_{43} & b_{44}
\end{bmatrix}
\]

= \[
\begin{bmatrix}
  a_{11}b_{11} + a_{12}b_{21} + a_{13}b_{31} + a_{14}b_{41} & a_{11}b_{12} + a_{12}b_{22} + a_{13}b_{32} + a_{14}b_{42} \\
  a_{21}b_{11} + a_{22}b_{21} + a_{23}b_{31} + a_{24}b_{41} & a_{21}b_{12} + a_{22}b_{22} + a_{23}b_{32} + a_{24}b_{42} \\
  a_{31}b_{11} + a_{32}b_{21} + a_{33}b_{31} + a_{34}b_{41} & a_{31}b_{12} + a_{32}b_{22} + a_{33}b_{32} + a_{34}b_{42} \\
  a_{41}b_{11} + a_{42}b_{21} + a_{43}b_{31} + a_{44}b_{41} & a_{41}b_{12} + a_{42}b_{22} + a_{43}b_{32} + a_{44}b_{42}
\end{bmatrix}
\]

\[ \begin{bmatrix}
  a_{11}b_{11} + a_{12}b_{21} + a_{13}b_{31} + a_{14}b_{41} \\
  a_{21}b_{11} + a_{22}b_{21} + a_{23}b_{31} + a_{24}b_{41} \\
  a_{31}b_{11} + a_{32}b_{21} + a_{33}b_{31} + a_{34}b_{41} \\
  a_{41}b_{11} + a_{42}b_{21} + a_{43}b_{31} + a_{44}b_{41}
\end{bmatrix}
\]

\[ \begin{bmatrix}
  a_{11}b_{14} + a_{12}b_{24} + a_{13}b_{34} + a_{14}b_{44} \\
  a_{21}b_{14} + a_{22}b_{24} + a_{23}b_{34} + a_{24}b_{44} \\
  a_{31}b_{14} + a_{32}b_{24} + a_{33}b_{34} + a_{34}b_{44} \\
  a_{41}b_{14} + a_{42}b_{24} + a_{43}b_{34} + a_{44}b_{44}
\end{bmatrix}
\]
Multiplying Matrices

\[
\begin{pmatrix}
a_{11} & a_{12} & a_{13} & a_{14} \\
a_{21} & a_{22} & a_{23} & a_{24} \\
a_{31} & a_{32} & a_{33} & a_{34} \\
a_{41} & a_{42} & a_{43} & a_{44}
\end{pmatrix}
\begin{pmatrix}
b_{11} & b_{12} & b_{13} & b_{14} \\
b_{21} & b_{22} & b_{23} & b_{24} \\
b_{31} & b_{32} & b_{33} & b_{34} \\
b_{41} & b_{42} & b_{43} & b_{44}
\end{pmatrix}
\]

\[
= 
\begin{pmatrix}
a_{11}b_{11} + a_{12}b_{21} + a_{13}b_{31} + a_{14}b_{41} & a_{11}b_{12} + a_{12}b_{22} + a_{13}b_{32} + a_{14}b_{42} \\
a_{21}b_{11} + a_{22}b_{21} + a_{23}b_{31} + a_{24}b_{41} & a_{21}b_{12} + a_{22}b_{22} + a_{23}b_{32} + a_{24}b_{42} \\
\cdot & \cdot \\
a_{31}b_{11} + a_{32}b_{21} + a_{33}b_{31} + a_{34}b_{41} & a_{31}b_{12} + a_{32}b_{22} + a_{33}b_{32} + a_{34}b_{42} \\
a_{41}b_{11} + a_{42}b_{21} + a_{43}b_{31} + a_{44}b_{41} & a_{41}b_{12} + a_{42}b_{22} + a_{43}b_{32} + a_{44}b_{42}
\end{pmatrix}
\]
Multiplying Matrices

\[
\begin{bmatrix}
\begin{array}{cc|cc}
  a_{11} & a_{12} & a_{13} & a_{14} \\
  a_{21} & a_{22} & a_{23} & a_{24} \\
  a_{31} & a_{32} & a_{33} & a_{34} \\
  a_{41} & a_{42} & a_{43} & a_{44} \\
\end{array}
\end{bmatrix}
\begin{bmatrix}
\begin{array}{cc|cc}
  b_{11} & b_{12} & b_{13} & b_{14} \\
  b_{21} & b_{22} & b_{23} & b_{24} \\
  b_{31} & b_{32} & b_{33} & b_{34} \\
  b_{41} & b_{42} & b_{43} & b_{44} \\
\end{array}
\end{bmatrix}
\]
Simple Divide and Conquer

\[
\begin{pmatrix}
A_{11} & A_{12} \\
A_{21} & A_{22}
\end{pmatrix}
\begin{pmatrix}
B_{11} & B_{12} \\
B_{21} & B_{22}
\end{pmatrix}
= \begin{pmatrix}
A_{11}B_{11}+A_{12}B_{21} & A_{11}B_{12}+A_{12}B_{22} \\
A_{21}B_{11}+A_{22}B_{21} & A_{21}B_{12}+A_{22}B_{22}
\end{pmatrix}
\]

- \( T(n) = 8T(n/2) + 4(n/2)^2 = 8T(n/2) + n^2 \)
- \( 8 > 2^2 \) so \( T(n) \) is \( \Theta(n^{\log_b8}) = \Theta(n^3) \)
Strassen’s Divide and Conquer Algorithm

Strassen’s algorithm
- Multiply $2\times2$ matrices using 7 instead of 8 multiplications (and lots more than 4 additions)

- $T(n) = 7 \cdot T(n/2) + cn^2$
  - $7 > 2^2$ so $T(n)$ is $\Theta(n^{\log_27})$ which is $O(n^{2.81...})$

- Fastest algorithms theoretically use $O(n^{2.376})$ time
  - not practical but Strassen’s is practical provided calculations are exact and we stop recursion when matrix has size somewhere between 10 and 100
The algorithm

\[ P_1 \leftarrow A_{12}(B_{11} + B_{21}) \]; \quad P_2 \leftarrow A_{21}(B_{12} + B_{22})

\[ P_3 \leftarrow (A_{11} - A_{12})B_{11} \]; \quad P_4 \leftarrow (A_{22} - A_{21})B_{22}

\[ P_5 \leftarrow (A_{22} - A_{12})(B_{21} - B_{22}) \]

\[ P_6 \leftarrow (A_{11} - A_{21})(B_{12} - B_{11}) \]

\[ P_7 \leftarrow (A_{21} - A_{12})(B_{11} + B_{22}) \]

\[ C_{11} \leftarrow P_1 + P_3 \]; \quad C_{12} \leftarrow P_2 + P_3 + P_6 - P_7

\[ C_{21} \leftarrow P_1 + P_4 + P_5 + P_7 \]; \quad C_{22} \leftarrow P_2 + P_4 \]
Another Divide & Conquer Example: Multiplying Faster

If you analyze our usual grade school algorithm for multiplying numbers

- $\Theta(n^2)$ time

- On real machines each “digit” is, e.g., 32 bits long but still get $\Theta(n^2)$ running time with this algorithm when run on n-bit multiplication

We can do better!

- We’ll describe the basic ideas by multiplying polynomials rather than integers

- Advantage is we don’t get confused by worrying about carries at first
Notes on Polynomials

- These are just formal sequences of coefficients
  - when we show something multiplied by \( x^k \) it just means shifted \( k \) places to the left – basically no work

Usual polynomial multiplication

\[
\begin{array}{c}
4x^2 + 2x + 2 \\
\underline{x^2 - 3x + 1} \\
4x^2 + 2x + 2 \\
\underline{-12x^3 - 6x^2 - 6x} \\
4x^4 + 2x^3 + 2x^2 \\
\underline{4x^4 - 10x^3 + 0x^2 - 4x + 2}
\end{array}
\]
## Polynomial Multiplication

### Given:
- Degree \( n-1 \) polynomials \( P \) and \( Q \)
  - \( P = a_0 + a_1 x + a_2 x^2 + \ldots + a_{n-2} x^{n-2} + a_{n-1} x^{n-1} \)
  - \( Q = b_0 + b_1 x + b_2 x^2 + \ldots + b_{n-2} x^{n-2} + b_{n-1} x^{n-1} \)

### Compute:
- Degree \( 2n-2 \) Polynomial \( P \cdot Q \)
  - \( P \cdot Q = a_0 b_0 + (a_0 b_1 + a_1 b_0) x + (a_0 b_2 + a_1 b_1 + a_2 b_0) x^2 \\
    + \ldots + (a_{n-2} b_{n-1} + a_{n-1} b_{n-2}) x^{2n-3} + a_{n-1} b_{n-1} x^{2n-2} \)

### Obvious Algorithm:
- Compute all \( a_i b_j \) and collect terms
- \( \Theta(n^2) \) time
Naive Divide and Conquer

Assume \( n = 2k \)

- \( P = (a_0 + a_1 x + a_2 x^2 + \ldots + a_{k-2} x^{k-2} + a_{k-1} x^{k-1}) + (a_k + a_{k+1} x + \ldots + a_{n-2} x^{k-2} + a_{n-1} x^{k-1}) x^k \)
  \[ = P_0 + P_1 x^k \text{ where } P_0 \text{ and } P_1 \text{ are degree } k-1 \text{ polynomials} \]

- Similarly \( Q = Q_0 + Q_1 x^k \)

- \( P \ Q = (P_0 + P_1 x^k)(Q_0 + Q_1 x^k) \)
  \[ = P_0 Q_0 + (P_1 Q_0 + P_0 Q_1) x^k + P_1 Q_1 x^{2k} \]

- 4 sub-problems of size \( k = n/2 \) plus linear combining
  - \( T(n) = 4 \cdot T(n/2) + cn \)  Solution \( T(n) = \Theta(n^2) \)
Karatsuba’s Algorithm

- A better way to compute the terms
  - Compute
    - \( A \leftarrow P_0Q_0 \)
    - \( B \leftarrow P_1Q_1 \)
    - \( C \leftarrow (P_0+P_1)(Q_0+Q_1) = P_0Q_0 + P_1Q_0 + P_0Q_1 + P_1Q_1 \)
  - Then
    - \( P_0Q_1 + P_1Q_0 = C - A - B \)
    - So \( PQ = A + (C - A - B)x^k + Bx^{2k} \)
  - 3 sub-problems of size \( n/2 \) plus \( O(n) \) work
    - \( T(n) = 3 \ T(n/2) + cn \)
    - \( T(n) = O(n^\alpha) \) where \( \alpha = \log_2 3 = 1.59... \)
Karatsuba: Details

PolyMul(P, Q):  

// P, Q are length n =2k vectors, with P[i], Q[i] being  
// the coefficient of x^i in polynomials P, Q respectively.  
// Let P0 be elements 0..k-1 of P; P1 be elements k..n-1  
// Qzero, Qone : similar

If n=1 then Return(P[0]*Q[0]) else

A ← PolyMul(P0, Q0);  // result is a (2k-1)-vector
B ← PolyMul(P1, Q1);  // ditto
Psum ← P0 + P1;      // add corresponding elements
Qsum ← Q0 + Q1;      // ditto
C ← polyMul(Psum, Qsum);  // another (2k-1)-vector
Mid ← C – A – B;     // subtract correspond elements
R ← A + Shift(Mid, n/2) + Shift(B,n)  // a (2n-1)-vector
Return( R);
Multiplication

- Polynomials
  - Naïve: $\Theta(n^2)$
  - Karatsuba: $\Theta(n^{1.59...})$
  - Best known: $\Theta(n \log n)$
    - "Fast Fourier Transform"
    - FFT widely used for signal processing

- Integers
  - Similar, but some ugly details re: carries, etc. due to Schonhage-Strassen in 1971 gives $\Theta(n \log n \log \log n)$
  - Improvement in 2007 due to Furer gives $\Theta(n \log n 2^{\log^* n})$
  - Used in practice in symbolic manipulation systems like Maple
Hints towards FFT: Interpolation

Given set of values at 5 points
Hints towards FFT: Interpolation

Given set of values at 5 points
Can find unique degree 4 polynomial going through these points
Any degree \( n-1 \) polynomial \( R(y) \) is determined by \( R(y_0), \ldots, R(y_{n-1}) \) for any \( n \) distinct \( y_0, \ldots, y_{n-1} \)

To compute \( PQ \) (assume degree at most \( n/2-1 \))
- Evaluate \( P(y_0), \ldots, P(y_{n-1}) \)
- Evaluate \( Q(y_0), \ldots, Q(y_{n-1}) \)
- Multiply values \( P(y_i)Q(y_i) \) for \( i=0, \ldots, n-1 \)
- Interpolate to recover \( PQ \)
Interpolation

- Given values of degree $n-1$ polynomial $R$ at $n$ distinct points $y_0, \ldots, y_{n-1}$
  - $R(y_0), \ldots, R(y_{n-1})$
- Compute coefficients $c_0, \ldots, c_{n-1}$ such that
  - $R(x) = c_0 + c_1 x + c_2 x^2 + \ldots + c_{n-1} x^{n-1}$
- System of linear equations in $c_0, \ldots, c_{n-1}$
  
  $\begin{align*}
  c_0 + c_1 y_0 + c_2 y_0^2 + \ldots + c_{n-1} y_0^{n-1} &= R(y_0) \\
  c_0 + c_1 y_1 + c_2 y_1^2 + \ldots + c_{n-1} y_1^{n-1} &= R(y_1) \\
  \vdots \\
  c_0 + c_1 y_{n-1} + c_2 y_{n-1}^2 + \ldots + c_{n-1} y_{n-1}^{n-1} &= R(y_{n-1})
  \end{align*}$
Interpolation: \( n \) equations in \( n \) unknowns

Matrix form of the linear system:

\[
\begin{pmatrix}
1 & y_0 & y_0^2 & \ldots & y_0^{n-1} \\
1 & y_1 & y_1^2 & \ldots & y_1^{n-1} \\
\vdots & \vdots & \vdots & \ddots & \vdots \\
1 & y_{n-1} & y_{n-1}^2 & \ldots & y_{n-1}^{n-1}
\end{pmatrix}
\begin{pmatrix}
c_0 \\
c_1 \\
c_2 \\
\vdots \\
c_{n-1}
\end{pmatrix}
= 
\begin{pmatrix}
R(y_0) \\
R(y_1) \\
\vdots \\
R(y_{n-1})
\end{pmatrix}
\]

Fact: Determinant of the matrix is \( \prod_{i<j} (y_i - y_j) \) which is not 0 since points are distinct.

System has a unique solution \( c_0, \ldots, c_{n-1} \)
Hints towards FFT: Evaluation & Interpolation

P: \( a_0, a_1, \ldots, a_{n/2-1} \)
Q: \( b_0, b_1, \ldots, b_{n/2-1} \)

**Evaluation** at \( y_0, \ldots, y_{n-1} \)

- \( P(y_0), Q(y_0) \)
- \( P(y_1), Q(y_1) \)
- \( \ldots \)
- \( P(y_{n-1}), Q(y_{n-1}) \)

**Ordinary Polynomial Multiplication** \( \Theta(n^2) \)

- \( c_k \leftarrow \sum_{i+j=k} a_i b_j \)

**Interpolation** from \( y_0, \ldots, y_{n-1} \)

- \( R(y_0) \leftarrow P(y_0) \cdot Q(y_0) \)
- \( R(y_1) \leftarrow P(y_1) \cdot Q(y_1) \)
- \( \ldots \)
- \( R(y_{n-1}) \leftarrow P(y_{n-1}) \cdot Q(y_{n-1}) \)

**Point-wise Multiplication** of numbers \( O(n) \)
Strassen gave a way of doing $2\times 2$ matrix multiplies with fewer multiplications

Karatsuba’s algorithm can be thought of as a way of multiplying degree 1 polynomials (which have 2 coefficients) using fewer multiplications

- $PQ = (P_0 + P_1 z)(Q_0 + Q_1 z)$
  - $= P_0 Q_0 + (P_1 Q_0 + P_0 Q_1)z + P_1 Q_1 z^2$

Evaluate at $0, 1, -1$ (Could also use other points)

- $A = P(0)Q(0) = P_0 Q_0$
- $C = P(1)Q(1) = (P_0 + P_1)(Q_0 + Q_1)$
- $D = P(-1)Q(-1) = (P_0 - P_1)(Q_0 - Q_1)$

Interpolating, Karatsuba’s $\text{Mid} = (C - D)/2$ and $B = (C + D)/2 - A$
Evaluation at Special Points

- Evaluation of polynomial at 1 point takes $O(n)$ time
  - So $2n$ points (naively) takes $O(n^2)$—no savings
  - But the algorithm works no matter what the points are…

- So…choose points that are related to each other so that evaluation problems can share subproblems
The key idea: Evaluate at related points

\[ P(x) = a_0 + a_1 x + a_2 x^2 + a_3 x^3 + a_4 x^4 + \ldots + a_{n-1} x^{n-1} \]
\[ = a_0 + a_2 x^2 + a_4 x^4 + \ldots + a_{n-2} x^{n-2} + a_1 x + a_3 x^3 + a_5 x^5 + \ldots + a_{n-1} x^{n-1} \]
\[ = P_{\text{even}}(x^2) + x P_{\text{odd}}(x^2) \]

\[ P(-x) = a_0 - a_1 x + a_2 x^2 - a_3 x^3 + a_4 x^4 - \ldots - a_{n-1} x^{n-1} \]
\[ = a_0 + a_2 x^2 + a_4 x^4 + \ldots + a_{n-2} x^{n-2} - (a_1 x + a_3 x^3 + a_5 x^5 + \ldots + a_{n-1} x^{n-1}) \]
\[ = P_{\text{even}}(x^2) - x P_{\text{odd}}(x^2) \]

where \( P_{\text{even}}(x) = a_0 + a_2 x + a_4 x^2 + \ldots + a_{n-2} x^{n/2-1} \)

and \( P_{\text{odd}}(x) = a_1 + a_3 x + a_5 x^2 + \ldots + a_{n-1} x^{n/2-1} \)
The key idea:
Evaluate at related points

- So… if we have half the points as negatives of the other half
  - i.e., \( y_{n/2} = -y_0, \ y_{n/2+1} = -y_1, \ldots, y_{n-1} = -y_{n/2-1} \)
  then we can reduce the size \( n \) problem of evaluating degree \( n-1 \) polynomial \( P \) at \( n \) points to evaluating 2 degree \( n/2 - 1 \) polynomials \( P_{\text{even}} \) and \( P_{\text{odd}} \) at \( n/2 \) points \( y_0^2, \ldots y_{n/2-1}^2 \) and recombine answers with \( O(1) \) extra work per point

- But to use this idea recursively we need half of \( y_0^2, \ldots y_{n/2-1}^2 \) to be negatives of the other half
  - If \( y_{n/4}^2 = -y_0^2 \), say, then \( (y_{n/4}/y_0)^2 = -1 \)
  - Motivates use of complex numbers as evaluation points
Complex Numbers

\[ i^2 = -1 \]

To multiply complex numbers:
1. add angles
2. multiply lengths
(all length 1 here)

\[ e^{\phi} = (a+bi)(c+di) \]

\[ a+bi = \cos \theta + i \sin \theta = e^{i\theta} \]
\[ c+di = \cos \varphi + i \sin \varphi = e^{i\varphi} \]
\[ e+fi = \cos (\theta+\varphi) + i \sin (\theta+\varphi) = e^{i(\theta+\varphi)} \]

\[ e^{2\pi i} = 1 \]
\[ e^{\pi i} = -1 \]
Primitive $n^{th}$ root of 1  \[ \omega = \omega_n = e^{i \frac{2\pi}{n}} \]

Let \[ \omega = \omega_n = e^{i \frac{2\pi}{n}} = \cos \left( \frac{2\pi}{n} \right) + i \sin \left( \frac{2\pi}{n} \right) \]

\[ i^2 = -1 \]
\[ e^{2\pi i} = 1 \]
Facts about $\omega = e^{2\pi i / n}$ for even $n$

- $\omega = e^{2\pi i / n}$ for $i = \sqrt{-1}$
- $\omega^n = 1$
- $\omega^{n/2} = -1$
- $\omega^{n/2+k} = -\omega^k$ for all values of $k$
- $\omega^2 = e^{2\pi i / m}$ where $m=n/2$
- $\omega^k = \cos(2k\pi/n) + i \sin(2k\pi/n)$ so can compute with powers of $\omega$
- $\omega^k$ is a root of $x^n-1 = (x-1)(x^{n-1}+x^{n-2}+...+1) = 0$
  
  but for $k \neq 0$, $\omega^k \neq 1$ so $\omega^{k(n-1)} + \omega^{k(n-2)} + ... + 1 = 0$
The key idea for n even

\[ P(\omega) = a_0 + a_1 \omega + a_2 \omega^2 + a_3 \omega^3 + a_4 \omega^4 + \ldots + a_{n-1} \omega^{n-1} \]

\[ = a_0 + a_2 \omega^2 + a_4 \omega^4 + \ldots + a_{n-2} \omega^{n-2} + a_1 \omega + a_3 \omega^3 + a_5 \omega^5 + \ldots + a_{n-1} \omega^{n-1} \]

\[ = P_{\text{even}}(\omega^2) + \omega P_{\text{odd}}(\omega^2) \]

\[ P(-\omega) = a_0 - a_1 \omega + a_2 \omega^2 - a_3 \omega^3 + a_4 \omega^4 - \ldots - a_{n-1} \omega^{n-1} \]

\[ = a_0 + a_2 \omega^2 + a_4 \omega^4 + \ldots + a_{n-2} \omega^{n-2} - (a_1 \omega + a_3 \omega^3 + a_5 \omega^5 + \ldots + a_{n-1} \omega^{n-1}) \]

\[ = P_{\text{even}}(\omega^2) - \omega P_{\text{odd}}(\omega^2) \]

where \( P_{\text{even}}(x) = a_0 + a_2 x + a_4 x^2 + \ldots + a_{n-2} x^{n/2-1} \)

and \( P_{\text{odd}}(x) = a_1 + a_3 x + a_5 x^2 + \ldots + a_{n-1} x^{n/2-1} \)
The recursive idea for \( n \) a power of 2

- **Goal:**
  - Evaluate \( P \) at \( 1, \omega, \omega^2, \omega^3, \ldots, \omega^{n-1} \)

- **Now**
  - \( P_{\text{even}} \) and \( P_{\text{odd}} \) have degree \( n/2-1 \) where
    - \( P(\omega^k) = P_{\text{even}}(\omega^{2k}) + \omega^k P_{\text{odd}}(\omega^{2k}) \)
    - \( P(-\omega^k) = P_{\text{even}}(\omega^{2k}) - \omega^k P_{\text{odd}}(\omega^{2k}) \)

- **Recursive Algorithm**
  - Evaluate \( P_{\text{even}} \) at \( 1, \omega^2, \omega^4, \ldots, \omega^{n-2} \)
  - Evaluate \( P_{\text{odd}} \) at \( 1, \omega^2, \omega^4, \ldots, \omega^{n-2} \)
  - Combine to compute \( P \) at \( 1, \omega, \omega^2, \ldots, \omega^{n/2-1} \)
  - Combine to compute \( P \) at \(-1, -\omega, -\omega^2, \ldots, -\omega^{n/2-1}\) (i.e. at \( \omega^{n/2}, \omega^{n/2+1}, \omega^{n/2+2}, \ldots, \omega^{n-1} \))

\( \omega^2 = e^{2\pi i / m} \) where \( m = n/2 \)

So problems are of same type but smaller size.
Analysis and more

- Run-time
  - $T(n) = 2 \cdot T(n/2) + cn$ so $T(n) = O(n \log n)$
- So much for evaluation ... what about interpolation?
  - Given
    - $r_0 = R(1)$, $r_1 = R(\omega)$, $r_2 = R(\omega^2)$, ..., $r_{n-1} = R(\omega^{n-1})$
  - Compute
    - $c_0, c_1, ..., c_{n-1}$ s.t. $R(x) = c_0 + c_1 x + ... + c_{n-1} x^{n-1}$
Interpolation ≈ Evaluation: strange but true

Non-obvious fact:
- If we define a new polynomial
  \[ S(x) = r_0 + r_1x + r_2x^2 + \ldots + r_{n-1}x^{n-1} \]
  where \( r_0, r_1, \ldots, r_{n-1} \) are the evaluations of \( R \) at \( 1, \omega, \ldots, \omega^{n-1} \)
- Then \( c_k = S(\omega^{-k})/n \) for \( k = 0, \ldots, n-1 \)
- Relies on the fact the interpolation (inverse) matrix has \( ij \) entry \( \omega^{-(i+j)}/n \) instead of \( \omega^{i+j} \)

So...
- evaluate \( S \) at \( 1, \omega^{-1}, \omega^{-2}, \ldots, \omega^{-(n-1)} \) then divide each answer by \( n \) to get the \( c_0, \ldots, c_{n-1} \)
- \( \omega^{-1} \) behaves just like \( \omega \) did so the same \( O(n \log n) \) evaluation algorithm applies!
Divide and Conquer Summary

- Powerful technique, when applicable
- Divide large problem into a few smaller problems of the same type
- Choosing sub-problems of roughly equal size is usually critical
- Examples:
  - Merge sort, quicksort (sort of), polynomial multiplication, FFT, Strassen's matrix multiplication algorithm, powering, binary search, root finding by bisection, …
Why this is called the discrete Fourier transform

Real Fourier series

- Given a real valued function $f$ defined on $[0, 2\pi]$ the Fourier series for $f$ is given by
  $$f(x) = a_0 + a_1 \cos(x) + a_2 \cos(2x) + \ldots + a_m \cos(mx) + \ldots$$
  where
  $$a_m = \frac{1}{2\pi} \int_{0}^{2\pi} f(x) \cos(mx) \, dx$$
- is the component of $f$ of frequency $m$
- In signal processing and data compression one ignores all but the components with large $a_m$ and there aren’t many since
Why this is called the discrete Fourier transform

- **Complex Fourier series**
  - Given a function \( f \) defined on \([0,2\pi]\)
    the complex Fourier series for \( f \) is given by
    \[
    f(z) = b_0 + b_1 e^{iz} + b_2 e^{2iz} + \ldots + b_m e^{miz} + \ldots
    \]
    where
    \[
    b_m = \frac{1}{2\pi} \int_{0}^{2\pi} f(z) e^{-miz} \, dz
    \]
    is the component of \( f \) of frequency \( m \)
  - If we **discretize** this integral using values at \( n \) equally spaced points between 0 and \( 2\pi \) we get
    \[
    \bar{b}_m = \frac{1}{n} \sum_{k=0}^{n-1} f_k e^{-2kmi\pi/n} = \frac{1}{n} \sum_{k=0}^{n-1} f_k \omega^{-km} \quad \text{where} \quad f_k = f(2k\pi/n)
    \]
    just like interpolation!
CSE 421: Introduction to Algorithms

Divide and Conquer
Beyond the Master Theorem
Median and Quicksort

Paul Beame
Today

- Divide and conquer examples
  - Simple, randomized median algorithm
    - Expected $O(n)$ time
  - Not so simple, deterministic median algorithm
    - Worst case $O(n)$ time
  - Expected time analysis for Randomized QuickSort
    - Expected $O(n \log n)$ time
Order problems: Find the $k^{th}$ smallest

- Runtime models
  - Machine Instructions
  - Comparisons
- Minimum
  - $O(n)$ time
  - $n-1$ comparisons
- 2$^{nd}$ Smallest
  - $O(n)$ time
  - ? comparisons
Median Problem

- $k^{th}$ smallest for $k = n/2$
- Easily done in $O(n \log n)$ time with sorting
  - How can the problem be solved in $O(n)$ time?

- Select$(k, n)$ – find the $k$-th smallest from a list of length $n$
Divide and Conquer

- \( T(n) = n + T(\alpha n) \) for \( \alpha < 1 \)
- Linear time solution

- Select algorithm – in linear time, reduce the problem from selecting the \( k \)-th smallest of \( n \) values to the \( j \)-th smallest of \( \alpha n \) values, for \( \alpha < 1 \)
Quick Select

QSelect(k, S)

Choose element x from S

\( S_L = \{ y \in S \mid y < x \} \)

\( S_E = \{ y \in S \mid y = x \} \)

\( S_G = \{ y \in S \mid y > x \} \)

if \( |S_L| \geq k \)

return QSelect(k, S_L)

else if \( |S_L| + |S_E| \geq k \)

return x

del

else

return QSelect(k - |S_L| - |S_E|, S_G)
Implementing “Choose an element x”

- Ideally, we would choose an x in the middle, to reduce both sets in half and guarantee progress

- Method 1
  - Select an element at random

- Method 2
  - BFPRT Algorithm
  - Select an element by a complicated, but linear time method that guarantees a good split
Random Selection

Consider a call to $\text{QSelect}(k, S)$, and let $S'$ be the elements passed to the recursive call.

With probability at least $\frac{1}{2}$, $|S'| < \frac{3}{4}|S|$

⇒ On average only 2 recursive calls before the size of $S'$ is at most $\frac{3n}{4}$
Expected runtime is $O(n)$

- Given $x$, one pass over $S$ to determine $S_L$, $S_E$, and $S_G$ and their sizes: $cn$ time.
  - Expect $2cn$ cost before size of $S'$ drops to at most $3|S|/4$

- Let $T(n)$ be the expected running time
- $T(n) \leq T(3n/4) + 2cn$
  $$\leq 2cn + \left(\frac{3}{4}\right) 2cn + \left(\frac{3}{4}\right)^2 2cn + \ldots$$
  $$\leq 2cn \left(1 + \left(\frac{3}{4}\right) + \left(\frac{3}{4}\right)^2 + \ldots\right)$$
Making the algorithm deterministic

- In $O(n)$ time, find an element that guarantees that the larger set in the split has size at most $\frac{3}{4} n$
Blum-Floyd-Pratt-Rivest-Tarjan Algorithm

- Divide $S$ into $n/5$ sets of size 5
- Sort each of these sets of size 5
- Let $M$ be the set of all medians of the sets of size 5
- Let $x$ be the median of $M$
- $S_L = \{ y \in S \mid y < x \}$, $S_G = \{ y \in S \mid y > x \}$
- Claim: $|S_L| < \frac{3}{4} |S|$, $|S_G| < \frac{3}{4} |S|$
BFPRT, Step 1: Construct sets of size 5, sort each set

13, 15, 32, 14, 95, 5, 16, 45, 86, 65, 62, 41, 81, 52, 32, 32, 12, 73, 25, 81, 47, 8, 69, 9, 7, 81, 18, 25, 42, 91, 64, 98, 96, 91, 6, 51, 21, 12, 36, 11, 11, 9, 5, 17, 77

<table>
<thead>
<tr>
<th></th>
<th>13</th>
<th>5</th>
<th>62</th>
<th>32</th>
<th>47</th>
<th>81</th>
<th>64</th>
<th>51</th>
<th>11</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>16</td>
<td>41</td>
<td>12</td>
<td>8</td>
<td>18</td>
<td>98</td>
<td>21</td>
<td>9</td>
<td></td>
</tr>
<tr>
<td>32</td>
<td>45</td>
<td>81</td>
<td>73</td>
<td>69</td>
<td>25</td>
<td>96</td>
<td>12</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>86</td>
<td>52</td>
<td>25</td>
<td>9</td>
<td>42</td>
<td>91</td>
<td>36</td>
<td>17</td>
<td></td>
</tr>
<tr>
<td>95</td>
<td>65</td>
<td>32</td>
<td>81</td>
<td>7</td>
<td>91</td>
<td>6</td>
<td>11</td>
<td>77</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>95</th>
<th>86</th>
<th>81</th>
<th>81</th>
<th>69</th>
<th>91</th>
<th>98</th>
<th>51</th>
<th>77</th>
</tr>
</thead>
<tbody>
<tr>
<td>32</td>
<td>65</td>
<td>62</td>
<td>73</td>
<td>47</td>
<td>81</td>
<td>96</td>
<td>36</td>
<td>17</td>
</tr>
<tr>
<td>15</td>
<td>45</td>
<td>52</td>
<td>32</td>
<td>9</td>
<td>42</td>
<td>91</td>
<td>21</td>
<td>11</td>
</tr>
<tr>
<td>14</td>
<td>16</td>
<td>41</td>
<td>25</td>
<td>8</td>
<td>25</td>
<td>64</td>
<td>12</td>
<td>9</td>
</tr>
<tr>
<td>13</td>
<td>5</td>
<td>32</td>
<td>12</td>
<td>7</td>
<td>18</td>
<td>6</td>
<td>11</td>
<td>5</td>
</tr>
</tbody>
</table>
BFPRT, Step 2: Find median of column medians

<table>
<thead>
<tr>
<th>95</th>
<th>86</th>
<th>81</th>
<th>81</th>
<th>69</th>
<th>91</th>
<th>98</th>
<th>51</th>
<th>77</th>
</tr>
</thead>
<tbody>
<tr>
<td>32</td>
<td>65</td>
<td>62</td>
<td>73</td>
<td>47</td>
<td>81</td>
<td>96</td>
<td>36</td>
<td>17</td>
</tr>
<tr>
<td>15</td>
<td>45</td>
<td>52</td>
<td>32</td>
<td>9</td>
<td>42</td>
<td>91</td>
<td>21</td>
<td>11</td>
</tr>
<tr>
<td>14</td>
<td>16</td>
<td>41</td>
<td>25</td>
<td>8</td>
<td>25</td>
<td>64</td>
<td>12</td>
<td>9</td>
</tr>
<tr>
<td>13</td>
<td>5</td>
<td>32</td>
<td>12</td>
<td>7</td>
<td>18</td>
<td>6</td>
<td>11</td>
<td>5</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>95</th>
<th>51</th>
<th>77</th>
<th>69</th>
<th>81</th>
<th>91</th>
<th>98</th>
<th>86</th>
<th>81</th>
</tr>
</thead>
<tbody>
<tr>
<td>32</td>
<td>36</td>
<td>17</td>
<td>47</td>
<td>73</td>
<td>81</td>
<td>96</td>
<td>65</td>
<td>62</td>
</tr>
<tr>
<td>15</td>
<td>21</td>
<td>11</td>
<td>9</td>
<td>32</td>
<td>42</td>
<td>91</td>
<td>45</td>
<td>52</td>
</tr>
<tr>
<td>14</td>
<td>12</td>
<td>9</td>
<td>8</td>
<td>25</td>
<td>25</td>
<td>64</td>
<td>16</td>
<td>41</td>
</tr>
<tr>
<td>13</td>
<td>11</td>
<td>5</td>
<td>7</td>
<td>12</td>
<td>18</td>
<td>6</td>
<td>5</td>
<td>32</td>
</tr>
</tbody>
</table>
BFPRT Recurrence

- Sorting all $\frac{n}{5}$ lists of size $5$
  - $c'n$ time

- Finding median of set $M$ of medians
  - Recursive computation: $T(n/5)$

- Computing sets $S_L$, $S_E$, $S_G$ and $S'$
  - $c''n$ time

- Solving selection problem on $S'$
  - Recursive computation: $T(3n/4)$ since $|S'| \leq \frac{3}{4}n$
T(n) ≤ cn + T(n/5) + T(3n/4) is O(n)

- Key property
  - \(\frac{3}{4} + \frac{1}{5} < 1\)  (The sum is 19/20)

- Sum of problem sizes decreases by 19/20 factor per level of recursion

- Overhead per level is linear in the sum of the problem sizes
  - Overhead decreases by 19/20 factor per level of recursion
  - Total overhead is linear (sum of geometric series with constant ratio and linear largest term)
Quick Sort

QuickSort(S)
  if S is empty, return
  Choose element x from S “pivot”
  S_L = \{ y \in S \mid y < x \}
  S_E = \{ y \in S \mid y = x \}
  S_G = \{ y \in S \mid y > x \}
  return [QuickSort(S_L), S_E, QuickSort(S_G)]
QuickSort

- Pivot Selection
  - Choose the median
    - \( T(n) = T(n/2) + T(n/2) + cn, \quad \mathcal{O}(n \log n) \)
  - Choose arbitrary element
    - Worst case – \( \mathcal{O}(n^2) \)
    - Average case – \( \mathcal{O}(n \log n) \)
  - Choose random pivot
    - Expected time – \( \mathcal{O}(n \log n) \)
Expected run time for QuickSort: “Global analysis”

- Count comparisons
- \( a_i, a_j \) – elements in positions \( i \) and \( j \) in the final sorted list. \( p_{ij} \) the probability that \( a_i \) and \( a_j \) are compared
- Expected number of comparisons:

\[
\sum_{i<j} p_{ij}
\]
Lemma: $P_{ij} \leq 2/(j - i + 1)$

If $a_i$ and $a_j$ are compared then it must be during the call when they end up in different subproblems

- Before that, they aren’t compared to each other
- After they aren’t compared to each other

During this step they are only compared if one of them is the pivot

Since all elements between $a_i$ and $a_j$ are also in the subproblem this is $2$ out of at least $j-i+1$ choices
Average runtime is $2n \ln n$

$$\sum_{i<j} p_{ij} \leq \sum_{i<j} \frac{2}{(j-i+1)} \quad \text{write } j = k + i$$

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

$$\leq 2 (n-1) (H_n - 1)$$

where $H_n = 1 + 1/2 + 1/3 + 1/4 + \ldots + 1/n$

$$= \ln n + O(1)$$

$$\leq 2n \ln n + O(n) \leq 1.387 n \log_2 n$$