CSE 417
Algorithms:
Divide and Conquer

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Thanks to Richard Anderson, Paul Beame, Kevin Wayne for some slides
Outline:

General Idea

Review of Merge Sort

Why does it work?
- Importance of balance
- Importance of super-linear growth

Some interesting applications
- Inversions
- Closest points
- Integer Multiplication

Finding & Solving Recurrences
Divide & Conquer

Reduce a problem to one or more (smaller) sub-problems of the same type

Typically, each sub-problem is at most a constant fraction of the size of the original problem

Subproblems typically disjoint

Often gives significant, usually polynomial, speedup

Examples:

- Binary Search
- Mergesort
- Quicksort (roughly)
- Strassen’s Algorithm
- Integer multiplication
- Powering
- FFT

...
Motivating Example: Mergesort
MS(A: array[1..n]) returns array[1..n] {
    If(n=1) return A;
    New U:array[1:n/2] = MS(A[1..n/2]);
    New L:array[1:n/2] = MS(A[n/2+1..n]);
    Return(Merge(U,L));
}

Merge(U,L: array[1..n]) {
    New C: array[1..2n];
    a=1; b=1;
    For i = 1 to 2n
        “C[i] = smaller of U[a], L[b] and correspondingly a++ or b++, while being careful about running past end of either”;
    Return C;
}
Why does it work? Suppose we’ve already invented DumbSort, taking time $n^2$

**Try Just One Level** of divide & conquer:

- DumbSort(first $n/2$ elements) $\mathcal{O}((n/2)^2)$
- DumbSort(last $n/2$ elements) $\mathcal{O}((n/2)^2)$
- Merge results $\mathcal{O}(n)$

**Time:** $2 \frac{(n/2)^2}{2} + n = \frac{n^2}{2} + n \ll n^2$

*Almost twice as fast!*
Moral 1: “two halves are better than a whole”
Two problems of half size are better than one full-size problem, even given $O(n)$ overhead of recombining, since the base algorithm has super-linear complexity.

Moral 2: “If a little's good, then more's better”
Two levels of D&C would be almost 4 times faster, 3 levels almost 8, etc., even though overhead is growing. Best is usually full recursion down to some small constant size (balancing "work" vs "overhead"). In the limit: you’ve just rediscovered mergesort!
Moral 3: unbalanced division good, but less so:

\[(.1n)^2 + (.9n)^2 + n = .82n^2 + n\]

The 18% savings compounds significantly if you carry recursion to more levels, actually giving \(O(n \log n)\), but with a bigger constant. So worth doing if you can’t get 50-50 split, but balanced is better if you can.

This is intuitively why Quicksort with random splitter is good – badly unbalanced splits are rare, and not instantly fatal.

Moral 4: but consistent, completely unbalanced division doesn’t help much:

\[(1)^2 + (n-1)^2 + n = n^2 - n + 2\]

Little improvement here.
Mergesort: (recursively) sort 2 half-lists, then merge results.

\[ T(n) = 2T(n/2) + cn, \quad n \geq 2 \]

\[ T(1) = 0 \]

Solution: \( \Theta(n \log n) \) (details later)
A Divide & Conquer Example:
Closest Pair of Points
closest pair of points: non-geometric version

Given $n$ points and arbitrary distances between them, find the closest pair. (E.g., think of distance as airfare – definitely not Euclidean distance!)

Must look at all $\binom{n}{2}$ pairwise distances, else any one you didn’t check might be the shortest.

Also true for Euclidean distance in 1-2 dimensions?
Given $n$ points on the real line, find the closest pair

Closest pair is *adjacent* in ordered list

Time $O(n \log n)$ to sort, if needed

Plus $O(n)$ to scan adjacent pairs

Key point: do *not* need to calc distances between all pairs: exploit geometry + ordering
Closest pair. Given n points in the plane, find a pair with smallest Euclidean distance between them.

Fundamental geometric primitive.
Graphics, computer vision, geographic information systems, molecular modeling, air traffic control.
Special case of nearest neighbor, Euclidean MST, Voronoi.

Brute force: Check all pairs of points \( p \) and \( q \) with \( \Theta(n^2) \) comparisons.

1-D version. \( O(n \log n) \) easy if points are on a line.

Can we do as well in 2-D?

Assumption. No two points have same \( x \) coordinate.
closest pair of points. 2d, Euclidean distance: 1st try

Divide. Sub-divide region into 4 quadrants.
Divide. Sub-divide region into 4 quadrants.

Obstacle. Impossible to ensure $n/4$ points in each piece, so the “balanced subdivision” goal may be elusive/problematic.
Algorithm.

Divide: draw vertical line $L$ with $\approx n/2$ points on each side.
Algorithm.

Divide: draw vertical line $L$ with $\approx n/2$ points on each side.

Conquer: find closest pair on each side, recursively.
closest pair of points

Algorithm.

Divide: draw vertical line $L$ with $\approx n/2$ points on each side.

Conquer: find closest pair on each side, recursively.

Combine: find closest pair with one point in each side.

Return best of 3 solutions.
Find closest pair with one point in each side, assuming distance < $\delta$. 

$\delta = \min(12, 21)$
Find closest pair with one point in each side, \textit{assuming} distance $< \delta$.

Observation: suffices to consider points within $\delta$ of line $L$.
Find closest pair with one point in each side, *assuming* distance < $\delta$.

Observation: suffices to consider points within $\delta$ of line $L$.

“Almost” the one-D problem again: Sort points in $2\delta$-strip by their $y$ coordinate.
Find closest pair with one point in each side, *assuming* distance < $\delta$.

Observation: suffices to consider points within $\delta$ of line $L$.

“Almost” the one-D problem again: Sort points in $2\delta$-strip by their $y$ coordinate. Only check pts within 8 in sorted list!
Def. Let $s_i$ have the $i^{\text{th}}$ smallest $y$-coordinate among points in the $2\delta$-width-strip.

Claim. If $j - i \geq 8$, then the distance between $s_i$ and $s_j$ is $> \delta$.

Pf: No two points lie in the same $\delta/2$-by-$\delta/2$ square:

$$\sqrt{\left(\frac{\delta}{2}\right)^2 + \left(\frac{\delta}{2}\right)^2} = \sqrt{\frac{\delta^2}{2}} = \frac{\sqrt{2}}{2} \delta \approx 0.7\delta < \delta$$

so $\leq 7$ points within $+\delta$ of $y(s_i)$.
Closest-Pair($p_1, ..., p_n$) {
    if($n \leq ??$) return ??

    Compute separation line $L$ such that half the points are on one side and half on the other side.

    $\delta_1 = $ Closest-Pair(left half)
    $\delta_2 = $ Closest-Pair(right half)
    $\delta = \min(\delta_1, \delta_2)$

    Delete all points further than $\delta$ from separation line $L$

    Sort remaining points $p[1]...p[m]$ by $y$-coordinate.

    for $i = 1..m$
        $k = 1$
        while $i+k \leq m$ && $p[i+k].y < p[i].y + \delta$
            $\delta = \min(\delta, \text{distance between } p[i] \text{ and } p[i+k])$;
            $k++$;
    
    return $\delta$.
}
Analysis, I: Let $D(n)$ be the number of pairwise distance calculations in the Closest-Pair Algorithm when run on $n \geq 1$ points.

$$D(n) \leq \begin{cases} 0 & n = 1 \\ 2D(n/2) + 7n & n > 1 \end{cases} \Rightarrow D(n) = O(n \log n)$$

BUT – that’s only the number of distance calculations.

What if we counted comparisons?
closest pair of points: analysis

Analysis, II: Let $C(n)$ be the number of comparisons between coordinates/distances in the Closest-Pair Algorithm when run on $n \geq 1$ points.

$$C(n) \leq \begin{cases} 
0 & n = 1 \\
2C(n/2) + kn \log n & n > 1 
\end{cases} \Rightarrow C(n) = O(n \log^2 n)$$

for some constant $k$

Q. Can we achieve $O(n \log n)$?

A. Yes. Don't sort points from scratch each time.

Sort by $x$ at top level only.

Each recursive call returns $\delta$ and list of all points sorted by $y$

Sort by merging two pre-sorted lists.

$$T(n) \leq 2T(n/2) + O(n) \Rightarrow T(n) = O(n \log n)$$
is it worth the effort?

Code is longer & more complex

$O(n \log n)$ vs $O(n^2)$ may hide 10x in constant?

How many points?

<table>
<thead>
<tr>
<th>$n$</th>
<th>Speedup: $n^2 / (10 \cdot n \log_2 n)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>0.3</td>
</tr>
<tr>
<td>100</td>
<td>1.5</td>
</tr>
<tr>
<td>1,000</td>
<td>10</td>
</tr>
<tr>
<td>10,000</td>
<td>75</td>
</tr>
<tr>
<td>100,000</td>
<td>602</td>
</tr>
<tr>
<td>1,000,000</td>
<td>5,017</td>
</tr>
<tr>
<td>10,000,000</td>
<td>43,004</td>
</tr>
</tbody>
</table>
Going From Code to Recurrence
Carefully define what you’re counting, and write it down!

“Let $C(n)$ be the number of comparisons between sort keys used by MergeSort when sorting a list of length $n \geq 1$”

In code, clearly separate base case from recursive case, highlight recursive calls, and operations being counted.

Write Recurrence(s)
merge sort

MS(A: array[1..n]) returns array[1..n] {
  If(n=1) return A;
  New L:array[1:n/2] = MS(A[1..n/2]);
  New R:array[1:n/2] = MS(A[n/2+1..n]);
  Return(Merge(L,R));
}

Merge(A,B: array[1..n]) {
  New C: array[1..2n];
  a=1; b=1;
  For i = 1 to 2n {
    C[i] = “smaller of A[a], B[b] and a++ or b++”;
  }
  Return C;
}
the recurrence

\[ C(n) = \begin{cases} 
0 & \text{if } n = 1 \\
2C(n/2) + (n - 1) & \text{if } n > 1 
\end{cases} \]

Base case

Recursive calls

One compare per element added to merged list, except the last.

Total time: proportional to \( C(n) \)
(loops, copying data, parameter passing, etc.)
Carefully define what you’re counting, and write it down!

“Let $D(n)$ be the number of pairwise distance calculations in the Closest-Pair Algorithm when run on $n \geq 1$ points”

In code, clearly separate base case from recursive case, highlight recursive calls, and operations being counted.

Write Recurrence(s)
Closest-Pair\((p_1, \ldots, p_n)\) \{
  \text{if}(n \leq 1) \text{return } \infty
\}

Compute separation line \(L\) such that half the points are on one side and half on the other side.

\[\delta_1 = \text{Closest-Pair(left half)}\]
\[\delta_2 = \text{Closest-Pair(right half)}\]
\[\delta = \min(\delta_1, \delta_2)\]

Delete all points further than \(\delta\) from separation line \(L\).

Sort remaining points \(p[1] \ldots p[m]\) by \(y\)-coordinate.

for \(i = 1 \ldots m\)
  \(k = 1\)
  \text{while } i+k \leq m \text{ and } p[i+k].y < p[i].y + \delta \\
  \quad \delta = \min(\delta, \text{distance between } p[i] \text{ and } p[i+k])
  \quad k++;

return \(\delta\).
Analysis, I: Let \( D(n) \) be the number of pairwise distance calculations in the Closest-Pair Algorithm when run on \( n \geq 1 \) points.

\[
D(n) \leq \begin{cases} 
0 & n = 1 \\
2D(n/2) + 7n & n > 1 
\end{cases} \implies D(n) = O(n \log n)
\]

BUT – that’s only the number of distance calculations.

What if we counted comparisons?
Carefully define what you’re counting, and write it down!

“Let $D(n)$ be the number of comparisons between coordinates/distances in the Closest-Pair Algorithm when run on $n \geq 1$ points”

In code, clearly separate base case from recursive case, highlight recursive calls, and operations being counted.
Write Recurrence(s)
Closest-Pair(p_1, \ldots, p_n) { 
    if(n <= 1) return \infty 

    Compute separation line L such that half the points are on one side and half on the other side. 

    \delta_1 = \text{Closest-Pair(left half)} 
    \delta_2 = \text{Closest-Pair(right half)} 
    \delta = \min(\delta_1, \delta_2) 

    Delete all points further than \delta from separation line L 

    Sort remaining points p[1]..p[m] by y-coordinate. 

    for i = 1..m 
        k = 1 
        while i+k <= m && p[i+k].y < p[i].y + \delta 
            \delta = \min(\delta, \text{distance between } p[i] \text{ and } p[i+k]) 
            k++; 
    
    return \delta. 
}
Analysis, II: Let $C(n)$ be the number of comparisons of coordinates/distances in the Closest-Pair Algorithm when run on $n \geq 1$ points

$$C(n) \leq \begin{cases} 
0 & n = 1 \\
2C(n/2) + k_4 n \log_2 n & n > 1 
\end{cases} \Rightarrow C(n) = O(n \log^2 n)$$

for $k_4 = k_1 + k_2 + k_3 + 16$

Q. Can we achieve time $O(n \log n)$?

A. Yes. Don't sort points from scratch each time.
   Sort by $x$ at top level only.
   Each recursive call returns $\delta$ and list of all points sorted by $y$
   Sort by merging two pre-sorted lists.

$$T(n) \leq 2T(n/2) + O(n) \Rightarrow T(n) = O(n \log n)$$
Integer Multiplication
Add. Given two $n$-bit integers $a$ and $b$, compute $a + b$. $O(n)$ bit operations.
Add. Given two $n$-bit integers $a$ and $b$, compute $a + b$.

$O(n)$ bit operations.

Multiply. Given two $n$-bit integers $a$ and $b$, compute $a \times b$.

The “grade school” method:

$\Theta(n^2)$ bit operations.
divide & conquer multiplication: warmup

To multiply two 2-digit integers:

Multiply four 1-digit integers.

Add, shift some 2-digit integers to obtain result.

\[
x = 10 \cdot x_1 + x_0 \\
y = 10 \cdot y_1 + y_0 \\
xy = (10 \cdot x_1 + x_0) (10 \cdot y_1 + y_0) \\
= 100 \cdot x_1y_1 + 10 \cdot (x_1y_0 + x_0y_1) + x_0y_0
\]

Same idea works for long integers –

can split them into 4 half-sized ints

(“10” becomes “10^k”, k = length/2)
To multiply two $n$-bit integers:

Multiply four $\frac{1}{2}n$-bit integers.
Shift/add four $n$-bit integers to obtain result.

\[
\begin{align*}
x &= 2^{n/2} \cdot x_1 + x_0 \\
y &= 2^{n/2} \cdot y_1 + y_0 \\
xy &= \left(2^{n/2} \cdot x_1 + x_0\right)\left(2^{n/2} \cdot y_1 + y_0\right) \\
&= 2^n \cdot x_1 y_1 + 2^{n/2} \cdot (x_1 y_0 + x_0 y_1) + x_0 y_0
\end{align*}
\]

\[
T(n) = 4T\left(\frac{n}{2}\right) + \Theta(n) \Rightarrow T(n) = \Theta(n^2)
\]

\[\uparrow\]

assumes $n$ is a power of 2
key trick: 2 multiplies for the price of 1:

\[
x = 2^{n/2} \cdot x_1 + x_0 \\
y = 2^{n/2} \cdot y_1 + y_0 \\
x y = \left(2^{n/2} \cdot x_1 + x_0\right)\left(2^{n/2} \cdot y_1 + y_0\right) \\
\quad = 2^n \cdot x_1 y_1 + 2^{n/2} \cdot (x_1 y_0 + x_0 y_1) + x_0 y_0
\]

Well, ok, 4 for 3 is more accurate…

\[
\alpha = x_1 + x_0 \\
\beta = y_1 + y_0 \\
\alpha\beta = \left(x_1 + x_0\right)\left(y_1 + y_0\right) \\
\quad = x_1 y_1 + \left(x_1 y_0 + x_0 y_1\right) + x_0 y_0 \\
(x_1 y_0 + x_0 y_1) = \alpha\beta - x_1 y_1 - x_0 y_0
\]
Karatsuba multiplication

To multiply two $n$-bit integers:

Add two pairs of $\frac{1}{2}n$ bit integers.

Multiply three pairs of $\frac{1}{2}n$-bit integers.

Add, subtract, and shift $n$-bit integers to obtain result.

$$x = 2^{n/2} \cdot x_1 + x_0$$

$$y = 2^{n/2} \cdot y_1 + y_0$$

$$xy = 2^n \cdot x_1 y_1 + 2^{n/2} \cdot (x_1 y_0 + x_0 y_1) + x_0 y_0$$

Theorem. [Karatsuba-Ofman, 1962] Can multiply two $n$-digit integers in $O(n^{1.585})$ bit operations.

$$T(n) \leq T\left(\left\lfloor \frac{n}{2} \right\rfloor \right) + T\left(\left\lfloor \frac{n}{2} \right\rfloor \right) + T\left(1 + \left\lfloor \frac{n}{2} \right\rfloor \right) + \Theta(n)$$

Sloppy version: $T(n) \leq 3T(n/2) + O(n)$

$$\Rightarrow T(n) = O(n^{\log_2 3}) = O(n^{1.585})$$
Karatsuba multiplication

Theorem. [Karatsuba-Ofman, 1962] Can multiply two n-digit integers in $O(n^{1.585})$ bit operations.

$$T(n) \leq T\left(\left\lfloor n/2 \right\rfloor \right) + T\left(\left\lfloor n/2 \right\rfloor \right) + T\left(1 + \left\lfloor n/2 \right\rfloor \right) + \Theta(n)$$

Recursive calls

Add, subtract, shift

Best to solve it directly (but messy). Instead, it nearly always suffices to solve a simpler recurrence:

Sloppy version: $T(n) \leq 3T(n/2) + O(n)$

Intuition: If $T(n) = n^k$, then $T(n+1) = n^k + kn^{k-1} + \ldots = O(n^k)$

$\Rightarrow T(n) = O(n^{\log_2 3}) = O(n^{1.585})$

(Proof later.)
Naïve: $\Theta(n^2)$

Karatsuba: $\Theta(n^{1.59\ldots})$

Amusing exercise: generalize Karatsuba to do 5 size $n/3$ subproblems $\rightarrow \Theta(n^{1.46\ldots})$

Best known: $\Theta(n \log n \log\log n)$

“Fast Fourier Transform”

but mostly unused in practice (unless you need really big numbers - a billion digits of $\pi$, say)

High precision arithmetic IS important for crypto, among other uses
Recurrences

Above: Where they come from, how to find them

Next: how to solve them
Mergesort: (recursively) sort 2 half-lists, then merge results.

\[ T(n) = 2T(n/2) + cn, \quad n \geq 2 \]

\[ T(1) = 0 \]

Solution: \( \Theta(n \log n) \)  
(detailed later)

now!
Solve:

\[ T(1) = c \]
\[ T(n) = 2 T(n/2) + cn \]

\[
\text{Level} \quad \text{Num} \quad \text{Size} \quad \text{Work} \\
0 \quad 1 = 2^0 \quad n \quad cn \\
1 \quad 2 = 2^1 \quad n/2 \quad 2cn/2 \\
2 \quad 4 = 2^2 \quad n/4 \quad 4cn/4 \\
\cdots \quad \cdots \quad \cdots \quad \cdots \\
i \quad 2^i \quad n/2^i \quad 2^i \cdot cn/2^i \\
\cdots \quad \cdots \quad \cdots \quad \cdots \\
k-1 \quad 2^{k-1} \quad n/2^{k-1} \quad 2^{k-1} \cdot cn/2^{k-1} \\
k \quad 2^k \quad n/2^k = 1 \quad 2^k T(1)
\]

\[ n = 2^k ; k = \log_2 n \]

Total Work: \[ c \cdot n \cdot (1 + \log_2 n) \] (add last col)
Solve: 
\[ T(1) = c \]
\[ T(n) = 4 \cdot T(n/2) + cn \]

<table>
<thead>
<tr>
<th>Level</th>
<th>Num</th>
<th>Size</th>
<th>Work</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1 = 4^0</td>
<td>n</td>
<td>cn</td>
</tr>
<tr>
<td>1</td>
<td>4 = 4^1</td>
<td>n/2</td>
<td>4cn/2</td>
</tr>
<tr>
<td>2</td>
<td>16 = 4^2</td>
<td>n/4</td>
<td>16cn/4</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>i</td>
<td>4^i</td>
<td>n/2^i</td>
<td>4^i \cdot cn/2^i</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>k-1</td>
<td>4^{k-1}</td>
<td>n/2^{k-1}</td>
<td>4^{k-1} \cdot cn/2^{k-1}</td>
</tr>
<tr>
<td>k</td>
<td>4^k</td>
<td>n/2^k = 1</td>
<td>4^k \cdot T(1)</td>
</tr>
</tbody>
</table>

\[ n = 2^k \; ; \; k = \log_2 n \]

Total Work: 
\[ T(n) = \sum_{i=0}^{k} 4^i \cdot cn / 2^i = O(n^2) \]

\[ 4^k = (2^2)^k = (2^k)^2 = n^2 \]
Solve:

\[ T(1) = c \]
\[ T(n) = 3 \cdot T(n/2) + cn \]

\[ n = 2^k ; k = \log_2 n \]

Total Work: \[ T(n) = \sum_{i=0}^{k} 3^i \cdot \frac{cn}{2^i} \]
Theorem: for $x \neq 1$,

$$1 + x + x^2 + x^3 + \ldots + x^k = \frac{(x^{k+1} - 1)}{(x - 1)}$$

proof:

$$y = 1 + x + x^2 + x^3 + \ldots + x^k$$

$$xy = x + x^2 + x^3 + \ldots + x^k + x^{k+1}$$

$$xy - y = x^{k+1} - 1$$

$$y(x - 1) = x^{k+1} - 1$$

$$y = \frac{(x^{k+1} - 1)}{(x - 1)}$$
Solve:

\[ T(1) = c \]
\[ T(n) = 3 \, T(n/2) + cn \quad \text{(cont.)} \]

\[
T(n) = \sum_{i=0}^{k} 3^i \, cn / 2^i
\]
\[
= cn \sum_{i=0}^{k} 3^i / 2^i
\]
\[
= cn \sum_{i=0}^{k} \left(\frac{3}{2}\right)^i
\]
\[
= cn \frac{\left(\frac{3}{2}\right)^{k+1} - 1}{\left(\frac{3}{2}\right) - 1}
\]

\[
\sum_{i=0}^{k} x^i = \frac{x^{k+1} - 1}{x - 1} \quad (x \neq 1)
\]
Solve:  
\[ T(1) = c \]
\[ T(n) = 3 \, T(n/2) + cn \quad (\text{cont.}) \]

\[
cn \left( \frac{3}{2} \right)^{k+1} \left( \frac{3}{2} \right) - 1 = 2cn \left( \left( \frac{3}{2} \right)^{k+1} - 1 \right) \]

\[
< 2cn \left( \frac{3}{2} \right)^{k+1} \]

\[
= 3cn \left( \frac{3}{2} \right)^{k} \]

\[
= 3cn \left( \frac{3}{2} \right)^{k} \left( \frac{1}{2} \right)^{k} = 3cn \left( \frac{3}{2} \right)^{k} \left( \frac{1}{2} \right)^{k} = 3cn \frac{3^{k}}{2^{k}}
\]
Solve: \[ T(1) = c \]
\[ T(n) = 3 \, T(n/2) + cn \] (cont.)

\[ 3c n \frac{3^k}{2^k} = 3c n \frac{3^{\log_2 n}}{2} \]
\[ = 3c n \frac{3^{\log_2 n}}{n} \]
\[ = 3c 3^{\log_2 n} \]
\[ = 3c \left( n^{\log_2 3} \right) \]
\[ = O\left( n^{1.585\ldots} \right) \]
divide and conquer – master recurrence

\[ T(n) = aT(n/b) + cn^k \] for \( n > b \) then

\[ a > b^k \implies T(n) = \Theta(n^{\log_b a}) \quad \text{[many subproblems \(\rightarrow\) leaves dominate]} \]

\[ a < b^k \implies T(n) = \Theta(n^k) \quad \text{[few subproblems \(\rightarrow\) top level dominates]} \]

\[ a = b^k \implies T(n) = \Theta(n^k \log n) \quad \text{[balanced \(\rightarrow\) all \(\log n\) levels contribute]} \]

Fine print:
\[ T(1) = d; \quad a \geq 1; \quad b > 1; \quad c, d, k \geq 0; \quad n = b^t \text{ for some } t > 0; \quad a, b, k, t \text{ integers. True even if it is } \left\lfloor n/b \right\rfloor \text{ instead of } n/b. \]
master recurrence: proof sketch

Expand recurrence as in earlier examples, to get

\[ T(n) = n^h \left(d + c \cdot S\right) \]

where \( h = \log_b(a) \) (and \( n^h \) = number of tree leaves) and \( S = \sum_{j=1}^{\log_b n} x^j \), where \( x = b^k/a \).

If \( c = 0 \) the sum \( S \) is irrelevant, and \( T(n) = O(n^h) \): all work happens in the base cases, of which there are \( n^h \), one for each leaf in the recursion tree.

If \( c > 0 \), then the sum matters, and splits into 3 cases (like previous slide):

- if \( x < 1 \), then \( S < x/(1-x) = O(1) \). \([S \text{ is the first } \log n \text{ terms of the infinite series with that sum.}]
- if \( x = 1 \), then \( S = \log_b(n) = O(\log n) \). \([\text{All terms in the sum are 1 and there are that many terms.}]
- if \( x > 1 \), then \( S = x \cdot (x^{1+\log_b(n)}-1)/(x-1) \). \([\text{And after some algebra, } n^h \cdot S = O(n^k).] \)
Another Example: Exponentiation
another d&c example: 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 \(a^n = a^m \cdot a^m\)
divide & conquer algorithm

Power(a,n)
    if n = 0 then return(1)
    if n = 1 then return(a)
    x ← Power(a, ⌊n/2⌋)
    x ← xx
    if n is odd then
        x ← ax
    return(x)
Let $M(n)$ be number of multiplies

Worst-case recurrence:

$M(n) = \begin{cases} 
0 & n \leq 1 \\
M\left(\lfloor n / 2 \rfloor \right) + 2 & n > 1 
\end{cases}$

By master theorem

$M(n) = O(\log n)$ \hspace{1cm} (a=1, b=2, k=0)

More precise analysis:

$M(n) = \lfloor \log_2 n \rfloor + (\# \text{ of } 1's \text{ in } n's \text{ binary representation}) - 1$

Time is $O(M(n))$ if numbers $< \text{ word size}$, else also depends on length, multiply algorithm
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 2048 multiplies of 1024 bit numbers
relatively easy for modern machines

Naive algorithm: $2^{1024}$ multiplies
Utility:
Correctness often easy; often faster

Idea:
“Two halves are better than a whole”
if the base algorithm has super-linear complexity.
“if a little's good, then more's better”
repeat above, recursively

Analysis: recursion tree or Master Recurrence
among others

Applications: Many.
Binary Search, Merge Sort, (Quicksort), Closest
Points, Integer Multiply, Exponentiation,…