CS 341: ALGORITHMS

Lecture 2: divide & conquer I

Readings: see website

Trevor Brown

https://student.cs.uwaterloo.ca/~cs341

trevor.brown@uwaterloo.ca
ONE DOES NOT SIMPLY
UNDERSTAND RECURSION
WITHOUT UNDERSTANDING RECURSION

DIVIDE AND CONQUER

Notable algorithms: mergesort, quicksort, binary search, ...
**DIVIDE-AND-CONQUER DESIGN STRATEGY**

- **divide**: Given a problem instance $I$, construct one or more smaller problem instances $I_1, \ldots, I_a$
  - These are called **subproblems**
  - Usually, want subproblems to be small compared to the size of $I$ (e.g., half the size)

- **conquer**: For $1 \leq j \leq a$, solve instance $I_j$ **recursively**, obtaining solutions $S_1, \ldots, S_a$

- **combine**: Given solutions $S_1, \ldots, S_a$, use an appropriate combining function to find the solution $S$ to the problem instance $I$
  - i.e., $S = \text{Combine}(S_1, \ldots, S_a)$.
D&C PROTO-ALGORITHM

DnC_template(I)
  if BaseCase(I) return Result(I)
  subproblems = [I_1, I_2, ..., I_a]
  subsolutions = []
  for j = 1..a
    subsolutions[j] = DnC_template(I_j)
  return Combine(subsolutions)
CORRECTNESS

- Prove base cases are correct
- Inductively assume subproblems are solved correctly
- Show they are correctly assembled into a solution

```python
DnC_template(I):
  if BaseCase(I) return Result(I)
  subproblems = [I_1, I_2, ..., I_a]
  subsolutions = []
  for j = 1..a
    subsolutions[j] = DnC_template(I_j)
  return Combine(subsolutions)
```
RUNTIME/SPACE COMPLEXITY?

• Techniques covered in this lecture
  • Model complexities using recurrence relations
  • Solve with substitution, master theorem, etc.

```python
DnC_template(I):
  if BaseCase(I) return Result(I)
  subproblems = [I_1, I_2, ..., I_a]
  subsolutions = []
  for j = 1..a
    subsolutions[j] = DnC_template(I_j)
  return Combine(subsolutions)
```
**WORKED EXAMPLE: DESIGN OF MERGESORT**

Here, a problem instance consists of an array $A$ of $n$ integers, which we want to sort in increasing order. The size of the problem instance is $n$.

**divide:** Split $A$ into two subarrays: $A_L$ consists of the first $\left\lceil \frac{n}{2} \right\rceil$ elements in $A$ and $A_R$ consists of the last $\left\lceil \frac{n}{2} \right\rceil$ elements in $A$.

**conquer:** Run *Mergesort* on $A_L$ and $A_R$.

**combine:** After $A_L$ and $A_R$ have been sorted, use a function *Merge* to merge $A_L$ and $A_R$ into a single sorted array. Recall that this can be done in time $\Theta(n)$ with a single pass through $A_L$ and $A_R$. We simply keep track of the “current” element of $A_L$ and $A_R$, always copying the smaller one into the sorted array.
DIVIDE
MERGE: CONQUER AND COMBINE
MERGE SIMULATION

L
4 10 96 98
↑ ↑ ↑ ↑
R
5 12 21 31
↑ ↑ ↑ ↑
O
4 5 10 12 21 31 96 98
PSEUDOCODE FOR MERGESORT

1. Mergesort(A[1..n])
2. \hspace{2em} if n == 1 then return A
3. \hspace{2em} nL = ceil(n/2)
4. \hspace{2em} aL = A[1..nL]
5. \hspace{2em} aR = A[(nL+1)..n]
6. \hspace{2em} sL = Mergesort(aL)
7. \hspace{2em} sR = Mergesort(aR)
8. \hspace{2em} return Merge(sL, sR)
There are still elements left in both arrays.

Left array is out of elements.

Right array is out of elements.
ANALYSIS OF MERGESORT

So, MergeSort(A) takes \(O(n)\) time, plus the time for its two recursive calls!

How can we analyze this recursive program structure?
RECURRANCE RELATIONS

A crucial analysis tool for recursive algorithms

\[ Hulk(n) = \text{Face} - \text{Chin} + Hulk(n - 1) \]
Suppose $a_1, a_2, \ldots$, is an infinite sequence of real numbers.

A recurrence relation is a formula that expresses a general term $a_n$ in terms of one or more previous terms $a_1, \ldots, a_{n-1}$.

A recurrence relation will also specify one or more initial values starting at $a_1$.

Solving a recurrence relation means finding a formula for $a_n$ that does not involve any previous terms $a_1, \ldots, a_{n-1}$.

There are many methods of solving recurrence relations. Two important methods are guess-and-check and the recursion tree method.
Let $T(n)$ denote the time to run Mergesort on an array of length $n$.

**divide** takes time $\Theta(1)$

**conquer** takes time $T\left(\lceil \frac{n}{2} \rceil \right) + T\left(\lfloor \frac{n}{2} \rfloor \right)$

**combine** takes time $\Theta(n)$

Recurrence relation:

$$T(n) = \begin{cases} 
T\left(\lceil \frac{n}{2} \rceil \right) + T\left(\lfloor \frac{n}{2} \rfloor \right) + \Theta(n) & \text{if } n > 1 \\
\Theta(1) & \text{if } n = 1.
\end{cases}$$
RECURSION TREE METHOD

Evaluating recurrences with $T(n/c)$ terms
**Recursion Tree Method**

- \( \text{msort}(n) \)
- \( \text{msort}(n/2) \)
- \( \text{msort}(n/4) \)
- \( \text{msort}(1) \)

Total = \( cn \times \# \text{levels} \)

Total = \( cn \log_2(n) \)

So, mergesort has runtime \( O(n \log n) \)

Can also compute using a table...

<table>
<thead>
<tr>
<th>Level</th>
<th># of nodes</th>
<th>runtime per node</th>
<th>total runtime for level</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1</td>
<td>( cn )</td>
<td>( cn )</td>
</tr>
<tr>
<td>1</td>
<td>2</td>
<td>( c(n/2) )</td>
<td>( 2c(n/2) = cn )</td>
</tr>
<tr>
<td>2</td>
<td>4</td>
<td>( c(n/4) )</td>
<td>( 4c(n/4) = cn )</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>\log n</td>
<td>( n )</td>
<td>( c(n/n) = c )</td>
<td>( nc(n/n) = cn )</td>
</tr>
</tbody>
</table>
Sample recurrence for two recursive calls on problem size $n/2$

$$T(n) = \begin{cases} 
2T\left(\frac{n}{2}\right) + cn & \text{if } n > 1 \text{ is a power of 2} \\
d & \text{if } n = 1,
\end{cases}$$

where $c$ and $d$ are constants.

We can solve this recurrence relation when $n$ is a power of two, by constructing a recursion tree, as follows:

1. **Step 1**: Start with a one-node tree, say $N$, having the value $T(n)$.
2. **Step 2**: Grow two children of $N$. These children, say $N_1$ and $N_2$, have the value $T(n/2)$, and the value of $N$ is replaced by $cn$.
3. **Step 3**: Repeat this process recursively, terminating when a node receives the value $T(1) = d$.
4. **Step 4**: Sum the values on each level of the tree, and then compute the sum of all these sums; the result is $T(n)$. 
GUESS-AND-CHECK METHOD

- Suppose we have the following recurrence
  \[ T(0) = 4 ; \quad T(n) = T(n - 1) + 6n - 5 \]
- **Guess** the form of the solution any way you like
- My approach: **the substitution method**
  - Recursively substitute the formula into itself
  - Try to identify patterns to **guess** the final closed form
- **Prove** that the guess was correct
SUBSTITUTION METHOD: WORKED EXAMPLE

Recurrence: \( T(0) = 4; \quad T(n) = T(n - 1) + 6n - 5 \)

- \( T(n - 1) = T((n - 1) - 1) + 6(n - 1) - 5 \)
- \( T(n) = (T(n - 2) + 6(n - 1) - 5) + 6n - 5 \) (substitute)
- \( = T(n - 2) + 2(6n - 5) - 6 \) (try to preserve structure)
- \( = (T(n - 3) + 6(n - 2) - 5) + 2(6n - 5) - 6 \) (substitute)
- \( = T(n - 3) + 3(6n - 5) - 6(1 + 2) \)

... identify patterns and **guess** what happens in the limit

- \( = T(0) + n(6n - 5) - 6(1 + 2 + 3 + \cdots + (n - 1)) = guess(n) \)

Compare: new terms?

- \( + (6n-5) \)
- \( -6 \)

new terms?

- \( + (6n-5) \)
- \( -2(6) \)
• \( guess(n) = T(0) + n(6n - 5) - 6\left(1 + 2 + 3 + \cdots + (n - 1)\right) \)

• Use \( 1 + 2 + \cdots + (n - 1) = \frac{n(n-1)}{2} \)

• \( guess(n) = 4 + 6n^2 - 5n - 6n(n - 1)/2 \) (simplify)

• \( = 3n^2 - 2n + 4 \)

• Are we done?

• The form of \( guess(n) \) was an **educated guess**.

• To be sure, we must **prove** it correct using **induction**
• Recall: \( T(0) = 4 \); \( T(n) = T(n - 1) + 6n - 5 \); \( \text{guess}(n) = 3n^2 - 2n + 4 \)

• Want to prove: \( \text{guess}(n) = T(n) \) for all \( n \)

• Base case: \( \text{guess}(0) = 3(0)^2 - 2(0) + 4 = T(0) \)
• Recall: $T(0) = 4$; $T(n) = T(n - 1) + 6n - 5$; $guess(n) = 3n^2 - 2n + 4$

• Want to prove: $guess(n) = T(n)$ for all $n$

• Inductive case: suppose $guess(n) = T(n)$ for $n \geq 0$, show $guess(n + 1) = T(n + 1)$.

• $T(n + 1) = T(n) + 6(n + 1) - 5$ (by definition)
• $= guess(n) + 6(n + 1) - 5$ (by inductive hypothesis)
• $= 3n^2 - 2n + 4 + 6(n + 1) - 5$ (substitute)
• $= 3n^2 + 4n + 5$ (simplify)

• $guess(n + 1) = 3(n + 1)^2 - 2(n + 1) + 4$ (by definition)
• $= 3n^2 + 4n + 5 = T(n + 1)$ (simplify)
ANOTHER APPROACH

• Suppose you look for a while at the previous recurrence:
  • \( T(0) = 4; T(n) = T(n - 1) + 6n - 5 \)
• With some experience, you might just guess it’s quadratic
• If you’re right, it should have the form:
  • \( an^2 + bn + c \) for some unknown constants \( a, b, c \)
• So, just carry the unknown constants into the proof!
  • You can then determine what the constants must be for the proof to work out
• $T(0) = 4$; $T(n) = T(n - 1) + 6n - 5$; $guess(n) = an^2 + bn + c$

• Want to prove: $guess(n) = T(n)$ for all $n$

• Base case: $guess(0) = a(0)^2 + b(0) + c = T(0) = 4$

  • this holds iff $c = 4$ ($a, b$ are not constrained)

• Inductive case: suppose $guess(n) = T(n)$ for $n \geq 0$,

  show $guess(n + 1) = T(n + 1)$.

• $T(n + 1) = T(n) + 6(n + 1) - 5$ (by definition)

  • $= guess(n) + 6(n + 1) - 5$ (by inductive hypothesis)

  • $= an^2 + bn + 4 + 6(n + 1) - 5$ (substitute)

  • $= an^2 + (b + 6)n + 5$ (simplify)
• Recall: \(\text{guess}(n) = an^2 + bn + c\) where \(c = 4\)

• Inductive case: suppose \(\text{guess}(n) = T(n)\) for \(n \geq 0\),
  show \(\text{guess}(n + 1) = T(n + 1)\).

• \(T(n + 1) = an^2 + (b + 6)n + 5\) (continue previous slide)

• \(\text{guess}(n + 1) = a(n + 1)^2 + b(n + 1) + 4\) (by definition and \(c = 4\))

• \[= a(n^2 + 2n + 1) + bn + b + 4\] (simplify, and...)

• \[= an^2 + (2a + b)n + (a + b + 4)\] (rearrange polynomial)

• We want this to be equal to \(T(n + 1)\)

  • \[an^2 + (2a + b)n + (a + b + 4) = an^2 + (b + 6)n + 5\]

  • equivalent to \((2a + b) = (b + 6)\) and \((a + b + 4) = 5\)

  • first implies \(a = 3\) plug a into second to get \(b = 5 - 4 - 3 = -2\)

So, inductive hypothesis is correct for \(a = 3, b = -2, c = 4\)
MASTER THEOREM FOR RECURRENCES

• Provides a formula for solving many recurrence relations
• We start with a simplified version

Consider recurrence: \( T(1) = d \); \( T(n) = aT\left(\frac{n}{b}\right) + \Theta(n^y) \)
where \( a \geq 1, b \geq 2 \) and \( n \) is a power of \( b \) (i.e., \( n = b^j \) for integer \( j \))

Example corresponding algorithm

```python
if BaseCase(I) return Result(I)
subsolutions = []
for j = 1..a
    let s = subproblem of size n/b
    subsolutions[j] = DnC_algo(s)
solution = combine in n^y time
return solution
```

Simplified Master Theorem

\[
T(n) \in \begin{cases} 
\Theta(n^x) & \text{if } y < x \\
\Theta(n^x \log n) & \text{if } y = x \\
\Theta(n^y) & \text{if } y > x.
\end{cases}
\]
where \( x = \log_b a \).
**DERIVING THE SIMPLIFIED MASTER THEOREM**

\[ T(1) = d; \ T(n) = aT \left( \frac{n}{b} \right) + \Theta(n^y) \]

where \( a \geq 1, b \geq 2 \) and \( n = b^j \)

<table>
<thead>
<tr>
<th>1 node</th>
<th>Problem size ( n )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( a ) nodes</td>
<td>problem size ( \frac{n}{b} )</td>
</tr>
<tr>
<td>( a^2 ) nodes</td>
<td>Problem size ( \frac{n}{b^2} )</td>
</tr>
<tr>
<td>( a^j ) nodes</td>
<td>prob size ( \frac{n}{b^j} = 1 )</td>
</tr>
</tbody>
</table>

Sum over all levels we get \( T(n) = da^j + \sum_{i=0}^{j-1} ca^i \left( \frac{n}{b^i} \right)^y \)

Let’s rearrange this into a geometric sequence and solve.
REARRANGING

• $T(n) = da^j + \sum_{i=0}^{j-1} ca^i \left( \frac{n}{b^i} \right)^y$

• $= da^j + \sum_{i=0}^{j-1} ca^i \frac{n^y}{(b^i)^y}$

• $= da^j + \sum_{i=0}^{j-1} ca^i \frac{n^y}{(by)^i}$

• $= da^j + \sum_{i=0}^{j-1} cn^y \frac{a^i}{(by)^i}$

• $= da^j + cn^y \sum_{i=0}^{j-1} \left( \frac{a}{by} \right)^i$

• Let $x = \log_b a$
• $x$ relates # of subproblems to their size

• Rearranging we have $b^x = a$

• So $T(n) = da^j + cn^y \sum_{i=0}^{j-1} \left( \frac{b^x}{by} \right)^i$

• $= da^j + cn^y \sum_{i=0}^{j-1} (b^{x-y})^i$

• Also $da^j = d(b^x)^j = d(b^j)^x$

• Since $n = b^j$ this is just $dn^x$

• So $T(n) = dn^x + cn^y \sum_{i=0}^{j-1} (b^{x-y})^i$

• and we can simplify: let $r = b^{x-y}$
SOLVING THE GEOMETRIC SEQ

- $T(n) = dn^x + cn^y \sum_{i=0}^{j-1} r^i$ where $r = b^{x-y}$

- **Geo. Seq. formula:**

  \[
  \sum_{i=0}^{j-1} ar^i = \begin{cases} 
  a \frac{r^j - 1}{r - 1} \in \Theta(r^j) & \text{if } r > 1 \\
  ja \in \Theta(j) & \text{if } r = 1 \\
  a \frac{1-r^j}{1-r} \in \Theta(1) & \text{if } 0 < r < 1 
  \end{cases}
  \]

- So different solutions depending on $r$
  
  - **Case 1:** $r = b^{x-y} > 1 \iff x - y > 0 \iff x > y$
  
  - **Case 2:** $r = b^{x-y} = 1 \iff x - y = 0 \iff x = y$
  
  - **Case 3:** $0 < r = b^{x-y} < 1 \iff x - y < 0 \iff x < y$
SOLVING THE GEOMETRIC SEQ

• Formula: \( \sum_{i=0}^{j-1} ar^i = \begin{cases} \frac{a r^j - 1}{r - 1} \in \Theta(r^j) & \text{if } r > 1 \\ ja \in \Theta(j) & \text{if } r = 1 \\ \frac{1 - r^j}{1 - r} \in \Theta(1) & \text{if } 0 < r < 1 \end{cases} \)

• Case 1: \( r = b^{x-y} > 1 \) \( \iff \) \( x - y > 0 \) \( \iff \) \( x > y \)

• \( T(n) = dn^x + cn^y \sum_{i=0}^{j-1} r^i \in dn^x + cn^y \Theta(r^j) \)

• \( T(n) \in \Theta(n^x + n^y r^j) = \Theta(n^x + n^y (b^{x-y})^j) = \Theta(n^x + n^y (b^j)^{x-y}) \)

• Recall \( b^j = n \), so \( T(n) \in \Theta(n^x + n^y n^{x-y}) = \Theta(n^x + n^{y+x-y}) \)

• So \( T(n) \in \Theta(n^x) \)
SOLVING THE GEOMETRIC SEQ

• Formula: \[ \sum_{i=0}^{j-1} ar^i = \begin{cases} \frac{a r^j - 1}{r-1} \in \Theta(r^j) & \text{if } r > 1 \\ ja \in \Theta(j) & \text{if } r = 1 \\ \frac{a 1-r^j}{1-r} \in \Theta(1) & \text{if } 0 < r < 1 \end{cases} \]

• Case 2: \( r = b^{x-y} = 1 \iff x - y = 0 \iff x = y \)

• \( T(n) = dn^x + cn^y \sum_{i=0}^{j-1} r^i \in dn^x + cn^y \Theta(j) \)

• \( T(n) \in \Theta(n^x + jn^y) = \Theta(n^x + jn^x) \) since \( x = y \)

• Recall \( b^j = n \), so \( \log_b b^j = \log_b n \). This means \( j \in \Theta(\log n) \).

• So \( T(n) = \Theta(n^x + n^x \log n) = \Theta(n^x \log n) \)
SOLVING THE GEOMETRIC SEQ

• Formula: $\sum_{i=0}^{j-1} ar^i = \begin{cases} 
  a \frac{r^{j-1}}{r-1} \in \Theta(r^j) & \text{if } r > 1 \\
  ja \in \Theta(j) & \text{if } r = 1 \\
  a \frac{1-r^j}{1-r} \in \Theta(1) & \text{if } 0 < r < 1 
\end{cases}$

• Case 3: $0 < r = b^{x-y} < 1 \iff x - y < 0 \iff x < y$

• $T(n) = dn^x + cn^y \sum_{i=0}^{j-1} r^i \in dn^x + cn^y \Theta(1)$

• $T(n) \in \Theta(n^x + n^y)$

• Since $x < y$, we simply have $T(n) \in \Theta(n^y)$
• **Simplified version**

Consider recurrence:

\[ T(n) = aT \left( \frac{n}{b} \right) + \Theta(n^y) \]

where \( a \geq 1, b \geq 2 \) and \( n = b^j \)

And let \( x = \log_b a \).

\[
T(n) \in \begin{cases} 
\Theta(n^x) & \text{if } y < x \\
\Theta(n^x \log n) & \text{if } y = x \\
\Theta(n^y) & \text{if } y > x.
\end{cases}
\]
Recall: \( T(n) = dn^x + cn^y \sum_{i=0}^{j-1} r^i \) where \( r = b^{x-y} \)

\( x = \log_b a \) i.e. \( \log_{\text{subproblem size}} |\text{subproblems}| \)

<table>
<thead>
<tr>
<th>case</th>
<th>( r )</th>
<th>( y, x )</th>
<th>complexity of ( T(n) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>heavy leaves</td>
<td>( r &gt; 1 )</td>
<td>( y &lt; x )</td>
<td>( T(n) \in \Theta(n^x) )</td>
</tr>
<tr>
<td>balanced</td>
<td>( r = 1 )</td>
<td>( y = x )</td>
<td>( T(n) \in \Theta(n^x \log n) )</td>
</tr>
<tr>
<td>heavy top</td>
<td>( r &lt; 1 )</td>
<td>( y &gt; x )</td>
<td>( T(n) \in \Theta(n^y) )</td>
</tr>
</tbody>
</table>

**heavy leaves** means that the value of the recursion tree is dominated by the values of the leaf nodes.

**balanced** means that the values of the levels of the recursion tree are constant (except for the last level).

**heavy top** means that the value of the recursion tree is dominated by the value of the root node.
Recall: simplified master theorem

Suppose that $a \geq 1$ and $b > 1$. Consider the recurrence

$$T(n) = aT\left(\frac{n}{b}\right) + \Theta(n^y), \text{ where } n \text{ is a power of } b.$$  

Denote $x = \log_b a$. Then

$$T(n) \in \begin{cases} 
\Theta(n^x) & \text{if } y < x \\
\Theta(n^x \log n) & \text{if } y = x \\
\Theta(n^y) & \text{if } y > x.
\end{cases}$$  

Questions: $a$=? $b$=? $y$=? $x$=? which $\Theta$ function?
MASTER THEOREM WHEN $b^{j-1} < n < b^j$

- $n/b$ is **not always an integer**!
  - floors/ceilings are hard
  - not a geometric sequence

- Suppose we get a **big-O** bound for $b^{j-1} < n < b^j$ by instead considering the **larger problem size** $b^j$

\[
\begin{align*}
T(n) &\leq T(b^j) \\
&\in \begin{cases} 
\Theta((b^j)^y) & \text{if } y < x \\
\Theta((b^j)^x \log b^j) & \text{if } y = x \\
\Theta((b^j)^y) & \text{if } y > x
\end{cases}
\]

Bonus slide, for you at home
**MASTER THEOREM WHEN**  \( b^{j-1} < n < b^j \)

\[
T(n) \leq T(b^j) \in \begin{cases} 
\Theta \left( (b^j)^x \right) & \text{if } y < x \\
\Theta \left( (b^j)^x \log b^j \right) & \text{if } y = x \\
\Theta \left( (b^j)^y \right) & \text{if } y > x 
\end{cases}
\]

- **Observation:** \( b^j < bn \) since \( n \) is between \( b^{j-1} \) and \( b^j \)

\[
T(n) \leq T(b^j) \in \begin{cases} 
\Theta \left( (bn)^x \right) & \text{if } y < x \\
\Theta \left( (bn)^x \log bn \right) & \text{if } y = x \\
\Theta \left( (bn)^y \right) & \text{if } y > x 
\end{cases}
\]
MASTER THEOREM WHEN $b^{j-1} < n < b^j$

$$T(n) = \begin{cases} \Theta((bn)^x) & \text{if } y < x \\ \Theta((bn)^x \log bn) & \text{if } y = x \\ \Theta((bn)^y) & \text{if } y > x \end{cases}$$

• **Case 1** ($y < x$): $(bn)^x = b^x n^x$ and $b^x$ is a **constant**
  • So $T(n) \in O(n^x)$

• **Case 2** ($y = x$): $(bn)^x \log bn = b^x n^x (\log b + \log n)$
  • $T(bn) \in \Theta(b^x n^x \log b + b^x n^x \log n) = \Theta(n^x + n^x \log n)$
  • So $T(n) \in O(n^x \log n)$

• **Case 3** ($y > x$): $(bn)^y = b^y n^y$
  • So $T(n) \in O(n^y)$

Can tackle $\Omega$ similarly to get $\theta$
GENERAL MASTER THEOREM

Suppose that $a \geq 1$ and $b > 1$. Consider the recurrence

$$T(n) = aT\left(\frac{n}{b}\right) + f(n),$$

where $n$ is a power of $b$. Denote $x = \log_b a$. Then

$$T(n) \in \begin{cases} 
\Theta(n^x) & \text{if } f(n) \in O(n^{x-\epsilon}) \text{ for some } \epsilon > 0 \\
\Theta(n^x \log n) & \text{if } f(n) \in \Theta(n^x) \\
\Theta(f(n)) & \text{if } f(n)/n^{x+\epsilon} \text{ is an increasing function of } n \\
\end{cases}$$

for some $\epsilon > 0$. 

Example recurrence:

$$T(n) = 3T(n/4) + n \log n$$

Arbitrary function of $n$ (not just $cn^y$)

Must reason about relationship between $f(n)$ and $n^x$
Some recurrences with complex \( f(n) \) functions (such as \( f(n) = \log n \)) can still be solved "by hand".

Example: Let \( n = 2^j \); \( T(1) = 1 \); \( T(n) = 2T\left(\frac{n}{2}\right) + n \log n \)

<table>
<thead>
<tr>
<th>level</th>
<th># nodes</th>
<th>value at each node</th>
<th>value of the level</th>
</tr>
</thead>
<tbody>
<tr>
<td>( j )</td>
<td>1</td>
<td>( j2^j )</td>
<td>( j2^j )</td>
</tr>
<tr>
<td>( j - 1 )</td>
<td>2</td>
<td>( (j - 1)2^{j-1} )</td>
<td>( (j - 1)2^j )</td>
</tr>
<tr>
<td>( j - 2 )</td>
<td>( 2^2 )</td>
<td>( (j - 2)2^{j-2} )</td>
<td>( (j - 2)2^j )</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>1</td>
<td>( 2^{j-1} )</td>
<td>( 2^1 )</td>
<td>( 2^j )</td>
</tr>
<tr>
<td>0</td>
<td>( 2^j )</td>
<td>1</td>
<td>( 2^j )</td>
</tr>
</tbody>
</table>

Note
\[
\log_2 n = j \\
\text{So} \\
j2^j = n \log_2 n \\
\text{And} \\
(j - 1)2^{j-1} = \frac{n}{2} \log_2 \frac{n}{2}
\]
REVISITING THE RECURSION TREE METHOD

• Recall: \( n = 2^j \); \( T(1) = 1 \); \( T(n) = 2T\left(\frac{n}{2}\right) + n \log n \)

Summing the values at all levels of the recursion tree, we have

\[
T(n) = 2^j \left( 1 + \sum_{i=1}^{j} i \right) = 2^j \left( 1 + \frac{j(j + 1)}{2} \right).
\]

Since \( n = 2^j \), we have \( j = \log_2 n \) and \( T(n) \in \Theta(n(\log n)^2) \).