Divide and Conquer Algorithms

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Divide and Conquer

- Break up a problem into several parts.
- Solve each part recursively.
- Solve base cases by brute force.
- Efficiently combine solutions for sub-problems into final solution.

Common use:
- Partition problem into two equal sub-problems of size $n/2$.
- Solve each part recursively.
- Combine the two solutions in $O(n)$ time.
- Resulting running time is $O(n \log n)$. 

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Mergesort

Sort

**INSTANCE:** Nonempty list $L = x_1, x_2, \ldots, x_n$ of integers.

**SOLUTION:** A permutation $y_1, y_2, \ldots, y_n$ of $x_1, x_2, \ldots, x_n$ such that $y_i \leq y_{i+1}$, for all $1 \leq i < n$.

Mergesort is a divide-and-conquer algorithm for sorting.

1. Partition $L$ into two lists $A$ and $B$ of size $\lfloor n/2 \rfloor$ and $\lceil n/2 \rceil$ respectively.
2. Recursively sort $A$.
3. Recursively sort $B$.
4. Merge the sorted lists $A$ and $B$ into a single sorted list.
Merging Two Sorted Lists

- Merge two sorted lists $A = a_1, a_2, \ldots, a_k$ and $B = b_1, b_2, \ldots, b_l$.
  1. Maintain a current pointer for each list.
  2. Initialise each pointer to the front of its list.
  3. While both lists are nonempty:
     3.1 Let $a_i$ and $b_j$ be the elements pointed to by the current pointers.
     3.2 Append the smaller of the two to the output list.
     3.3 Advance the current pointer in the list that the smaller element belonged to.
  4. Append the rest of the non-empty list to the output.

Running time of this algorithm is $O(k + l)$. 

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Merging Two Sorted Lists

- Merge two sorted lists $A = a_1, a_2, \ldots, a_k$ and $B = b_1, b_2, \ldots b_l$.
  1. Maintain a \textit{current} pointer for each list.
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- Running time of this algorithm is $O(k + l)$. 
Analysing Mergesort

1. Partition $L$ into two lists $A$ and $B$ of size $\lceil n/2 \rceil$ and $\lfloor n/2 \rfloor$ respectively.
2. Recursively sort $A$.
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Worst-case running time for $n$ elements ($T(n)$) $\leq$

Worst-case running time for $\lfloor n/2 \rfloor$ elements +
Worst-case running time for $\lceil n/2 \rceil$ elements +
Time to split the input into two lists +
Time to merge two sorted lists.

▶ Assume $n$ is a power of 2.
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\[ T(n) \leq 2T(n/2) + cn, \quad n > 2 \]
\[ T(2) \leq c \]
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Worst-case running time for \( n \) elements (\( T(n) \)) \( \leq \)
- Worst-case running time for \( \lfloor n/2 \rfloor \) elements +
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- Assume \( n \) is a power of 2.
  \[
  T(n) \leq 2T(n/2) + cn, \quad n > 2
  \]
  \[
  T(2) \leq c
  \]

- Three ways of solving this recurrence relation:
  1. “Unroll” the recurrence (somewhat informal method).
  2. Guess a solution and substitute into recurrence to check.
  3. Guess solution in \( O() \) form and substitute into recurrence to determine the constants.
Unrolling the recurrence

Recursion tree has $\log n$ levels.

Total work done at each level is $cn$.

Running time of the algorithm is $cn \log n$.

Use this method only to get an idea of the solution.

Figure 5.1 Unrolling the recurrence $T(n) \leq 2T(n/2) + O(n)$. 
Unrolling the recurrence

Recursion tree has log \( n \) levels.

Total work done at each level is \( cn \).

Running time of the algorithm is \( cn \log n \).

Use this method only to get an idea of the solution.
Substituting a Solution into the Recurrence

- Guess that the solution is $T(n) \leq cn \log n$ (logarithm to the base 2).
- Use induction to check if the solution satisfies the recurrence relation.
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- Base case: $n = 2$. Is $T(2) = c \leq 2c \log 2$? Yes.
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- Inductive hypothesis: assume \( T(m) \leq cm \log_2 m \) for all \( m < n \).
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- Inductive hypothesis: assume \( T(m) \leq cm \log_2 m \) for all \( m < n \). Therefore, \( T(n/2) \leq (cn/2) \log(n/2) \).
Substituting a Solution into the Recurrence

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- Use induction to check if the solution satisfies the recurrence relation.
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- Inductive hypothesis: assume \( T(m) \leq cm \log_2 m \) for all \( m < n \). Therefore, \( T(n/2) \leq (cn/2) \log(n/2) \).
- Inductive step: Prove \( T(n) \leq cn \log n \).

\[
T(n) \leq 2T\left(\frac{n}{2}\right) + cn \\
\leq 2\left(\frac{cn}{2} \log \left(\frac{n}{2}\right)\right) + cn, \text{ by the inductive hypothesis} \\
= cn \log \left(\frac{n}{2}\right) + cn \\
= cn \log n - cn + cn \\
= cn \log n.
\]
Substituting a Solution into the Recurrence

- Guess that the solution is $T(n) \leq cn \log n$ (logarithm to the base 2).
- Use induction to check if the solution satisfies the recurrence relation.
- Base case: $n = 2$. Is $T(2) = c \leq 2c \log 2$? Yes.
- Inductive hypothesis: assume $T(m) \leq cm \log_2 m$ for all $m < n$. Therefore, $T(n/2) \leq (cn/2) \log(n/2)$.
- Inductive step: Prove $T(n) \leq cn \log n$.

$$T(n) \leq 2T\left(\frac{n}{2}\right) + cn$$

$$\leq 2\left(\frac{cn}{2} \log \left(\frac{n}{2}\right)\right) + cn, \text{ by the inductive hypothesis}$$

$$= \frac{cn}{2} \log n + cn$$

$$= cn \log n - cn + cn$$

$$= cn \log n.$$

- Why doesn’t an attempt to prove $T(n) \leq kn$, for some $k > 0$ work?
- Why is $T(n) \leq kn^2$ a “loose” bound?
Partial Substitution

- Guess that the solution is $kn \log n$ (logarithm to the base 2).
- Substitute guess into the recurrence relation to check what value of $k$ will satisfy the recurrence relation.
Partial Substitution

- Guess that the solution is $kn \log n$ (logarithm to the base 2).
- Substitute guess into the recurrence relation to check what value of $k$ will satisfy the recurrence relation.
- $k \geq c$ will work.
Proof for All Values of $n$

- We assumed $n$ is a power of 2.
- How do we generalise the proof?
Proof for All Values of \( n \)

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- How do we generalise the proof?
- Basic axiom: \( T(n) \leq T(n + 1) \), for all \( n \): worst case running time increases as input size increases.
- Let \( m \) be the smallest power of 2 larger than \( n \).
- \( T(n) \leq T(m) = O(m \log m) \)
Proof for All Values of $n$

- We assumed $n$ is a power of 2.
- How do we generalise the proof?
- Basic axiom: $T(n) \leq T(n + 1)$, for all $n$: worst case running time increases as input size increases.
- Let $m$ be the smallest power of 2 larger than $n$.
- $T(n) \leq T(m) = O(m \log m) = O(n \log n)$, because $m \leq 2n$. 
Other Recurrence Relations

- Divide into $q$ sub-problems of size $n/2$ and merge in $O(n)$ time. Two distinct cases: $q = 1$ and $q > 2$.
- Divide into two sub-problems of size $n/2$ and merge in $O(n^2)$ time.
\[ T(n) = qT(n/2) + cn, \quad q = 1 \]

Each invocation reduces the problem size by a factor of 2 ⇒ there are \( \log n \) levels in the recursion tree.

At level \( i \) of the tree, the problem size is \( n/2^i \) and the work done is \( cn/2^i \).

Therefore, the total work done is \( i = \log n \sum_{i=0}^{\log n} cn/2^i = O(n) \).

**Figure 5.3** Unrolling the recurrence \( T(n) \leq T(n/2) + O(n) \).
\[ T(n) = qT(n/2) + cn, \quad q = 1 \]

Each invocation reduces the problem size by a factor of 2 \(\Rightarrow\) there are \(\log n\) levels in the recursion tree.

At level \(i\) of the tree, the problem size is \(n/2^i\) and the work done is \(cn/2^i\).

Therefore, the total work done is

\[
\sum_{i=0}^{i=\log n} \frac{cn}{2^i} = O(n).
\]

**Figure 5.3** Unrolling the recurrence \(T(n) \leq T(n/2) + O(n)\).
\[ T(n) = qT(n/2) + cn, \quad q > 2 \]

Figure 5.2 Unrolling the recurrence \( T(n) \leq 3T(n/2) + O(n) \).
\[ T(n) = qT(n/2) + cn, \quad q > 2 \]

- There are \( \log n \) levels in the recursion tree.
- At level \( i \) of the tree, there are \( q^i \) sub-problems, each of size \( n/2^i \).
- The total work done at level \( i \) is \( q^i cn/2^i \).
- Therefore, the total work done is

\[
T(n) \leq \sum_{i=0}^{i=\log n} q^i \frac{cn}{2^i} \leq O(n \log n) \]
\[ T(n) = qT(n/2) + cn, \quad q > 2 \]

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- At level \( i \) of the tree, there are \( q^i \) sub-problems, each of size \( n/2^i \).
- The total work done at level \( i \) is \( q^i cn/2^i \).
- Therefore, the total work done is

\[
T(n) \leq \sum_{i=0}^{i=\log n} q^i \frac{cn}{2^i} \leq O(n^{\log_2 q}).
\]
\[ T(n) = 2T(n/2) + cn^2 \]

- Total work done is

\[
\sum_{i=0}^{i=\log n} 2^i \left( \frac{cn}{2^i} \right)^2 \leq \mathcal{O}(n^2)
\]
\[ T(n) = 2T(n/2) + cn^2 \]

- Total work done is

\[
\sum_{i=0}^{i=\log n} 2^i \left( \frac{cn}{2^i} \right)^2 \leq O(n^2).
\]