

# CS217 - Data Structures & Algorithm Analysis (DSAA)

Lecture #3

## ➤ Divide-and-Conquer

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Reading: Section 2.3 and Section 4.5

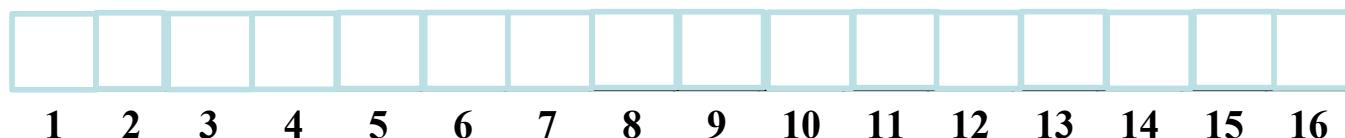
(optional: lots more details in Chapter 4)

## ➤ Aims of this lecture

- To introduce the divide-and-conquer design paradigm.
- To introduce the MergeSort algorithm – a recursive algorithm using divide-and-conquer.
- To show how to prove correctness for a recursive algorithm
- To show how to analyse the runtime of recursive algorithms using recurrence equations.
- To show how to solve recurrence equations

## ➤ Problem: Find a number in a sorted array

- I have a sorted array of integers;



- Is the number 40 in the array?
- If we scan the array from the beginning to the end what is the worst case runtime?  $\theta(n)$  – *linear search*
- What if we always check the middle point and discard the “wrong” half of the subarray?  $2^k = n \Rightarrow \theta(\log n)$  – *binary search*
- By **dividing** the problem size by half at each step we have reduced the runtime of the algorithm from linear to **logarithmic!**

## ➤ Design Paradigms

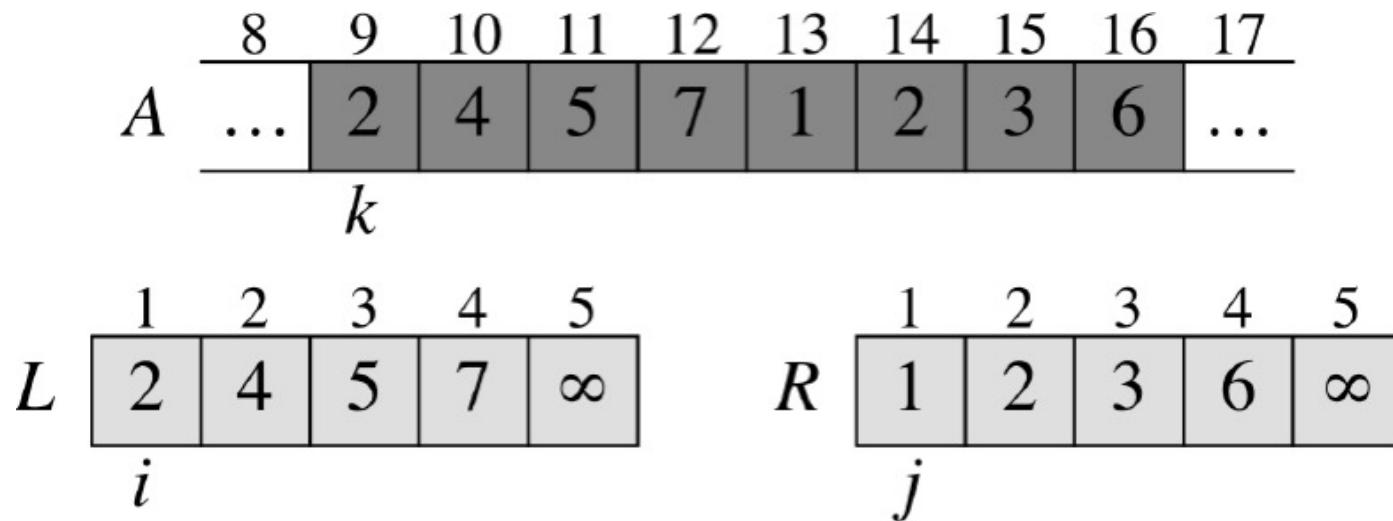
- InsertionSort used an incremental approach:
  - Having sorted the subarray  $A[1..j-1]$ , we inserted  $A[j]$  into its proper place, yielding the sorted subarray  $A[1..j]$ .
  - **Idea:** incrementally build up a solution to the problem.
- Alternative design approach: **divide-and-conquer**
  1. **Divide:** Break the problem into smaller subproblems, smaller instances of the original problem.
  2. **Conquer:** Solve these problems recursively.
  3. **Combine** the solutions to subproblems into the solution for the original problem.

## ➤ MergeSort

- MergeSort - sorting using **divide-and-conquer**:
  1. **Divide** the  $n$ -element sequence to be sorted into two subsequences of  $n/2$  elements each.
  2. **Conquer**: Sort the two subsequences **recursively** using MergeSort.
  3. **Combine**: **merge** the two subsequences to produce the sorted answer.
- The recursion stops when the sequence is just 1 element.
- Key here is the procedure **Merge**
- Tedious bit: copying elements between arrays.

## ➤ Merge( $A, p, q, r$ )

- Assume subarrays  $A[p \dots q]$  and  $A[q + 1 \dots r]$  are sorted.
- Copy these subarrays to new arrays L and R.
- Both L and R contain an additional element  $\infty$  at the end (“sentinel”), so we don’t have to check for end of array.
- Merge L and R back into A by comparing  $L[i]$  and  $R[j]$ .



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MERGE( $A, p, q, r$ )

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```
1:  $n_1 = q - p + 1$ 
2:  $n_2 = r - q$ 
3: let  $L[1 \dots n_1 + 1]$  and  $R[1 \dots n_2 + 1]$  be new arrays
4: for  $i = 1$  to  $n_1$  do
5:    $L[i] = A[p + i - 1]$ 
6: for  $j = 1$  to  $n_2$  do
7:    $R[j] = A[q + j]$ 
8:  $L[n_1 + 1] = \infty$ 
9:  $R[n_2 + 1] = \infty$ 
10:  $i = 1$ 
11:  $j = 1$ 
12: for  $k = p$  to  $r$  do
13:   if  $L[i] \leq R[j]$  then
14:      $A[k] = L[i]$ 
15:      $i = i + 1$ 
16:   else
17:      $A[k] = R[j]$ 
18:      $j = j + 1$ 
```



Set up arrays L  
and R (boring)

Actual merge

MERGE( $A, p, q, r$ )

```
1   $n_L = q - p + 1$       // length of  $A[p : q]$ 
2   $n_R = r - q$           // length of  $A[q + 1 : r]$ 
3  let  $L[0 : n_L - 1]$  and  $R[0 : n_R - 1]$  be new arrays
4  for  $i = 0$  to  $n_L - 1$  // copy  $A[p : q]$  into  $L[0 : n_L - 1]$ 
5     $L[i] = A[p + i]$ 
6  for  $j = 0$  to  $n_R - 1$  // copy  $A[q + 1 : r]$  into  $R[0 : n_R - 1]$ 
7     $R[j] = A[q + j + 1]$ 
8   $i = 0$                   //  $i$  indexes the smallest remaining element in  $L$ 
9   $j = 0$                   //  $j$  indexes the smallest remaining element in  $R$ 
10  $k = p$                  //  $k$  indexes the location in  $A$  to fill
11 // As long as each of the arrays  $L$  and  $R$  contains an unmerged element,
  //   copy the smallest unmerged element back into  $A[p : r]$ .
12 while  $i < n_L$  and  $j < n_R$ 
13   if  $L[i] \leq R[j]$ 
14      $A[k] = L[i]$ 
15      $i = i + 1$ 
16   else  $A[k] = R[j]$ 
17      $j = j + 1$ 
18    $k = k + 1$ 
19 // Having gone through one of  $L$  and  $R$  entirely, copy the
  //   remainder of the other to the end of  $A[p : r]$ .
20 while  $i < n_L$ 
21    $A[k] = L[i]$ 
22    $i = i + 1$ 
23    $k = k + 1$ 
24 while  $j < n_R$ 
25    $A[k] = R[j]$ 
26    $j = j + 1$ 
27    $k = k + 1$ 
```

## New book pseudo-code without sentinels

## ➤ Runtime of Merge

$$T(n) = \Theta(n)$$

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MERGE( $A, p, q, r$ )

---

```
1:  $n_1 = q - p + 1$ 
2:  $n_2 = r - q$ 
3: let  $L[1 \dots n_1 + 1]$  and  $R[1 \dots n_2 + 1]$  be new arrays
4: for  $i = 1$  to  $n_1$  do
5:    $L[i] = A[p + i - 1]$ 
6: for  $j = 1$  to  $n_2$  do           $\Theta(n)$ 
7:    $R[j] = A[q + j]$ 
8:  $L[n_1 + 1] = \infty$ 
9:  $R[n_2 + 1] = \infty$ 
10:  $i = 1$ 
11:  $j = 1$ 
12: for  $k = p$  to  $r$  do    ←
13:   if  $L[i] \leq R[j]$  then       $\Theta(n)$ 
14:      $A[k] = L[i]$ 
15:      $i = i + 1$ 
16:   else
17:      $A[k] = R[j]$ 
18:      $j = j + 1$ 
```

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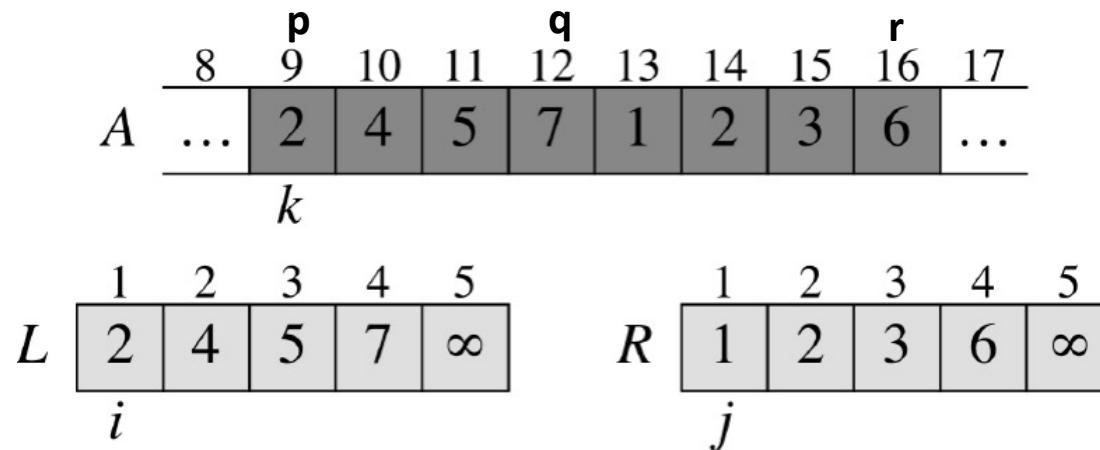
Set up arrays L  
and R (boring)

only 1 loop

Actual merge

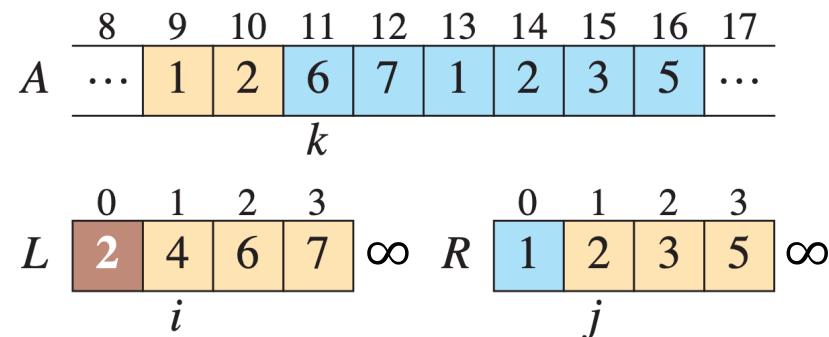
## ➤ Correctness of Merge (1)

- **Loop invariant:** At the start of the iteration of the last for loop,
  - the subarray  $A[p \dots k - 1]$  contains the  $k - p$  smallest elements of  $L[1 \dots n_1 + 1]$  and  $R[1 \dots n_2 + 1]$ , in sorted order and
  - $L[i]$  and  $R[j]$  are the smallest elements of their arrays that have not been copied back to  $A$ .
- **Initialisation:** the loop starts with  $k = p$ , hence  $A[p \dots k - 1]$  is empty and contains the  $k - p = 0$  smallest elements of  $L, R$ . As  $i = j = 1$ ,  $L[i]$  and  $R[j]$  are the smallest uncopied elements.



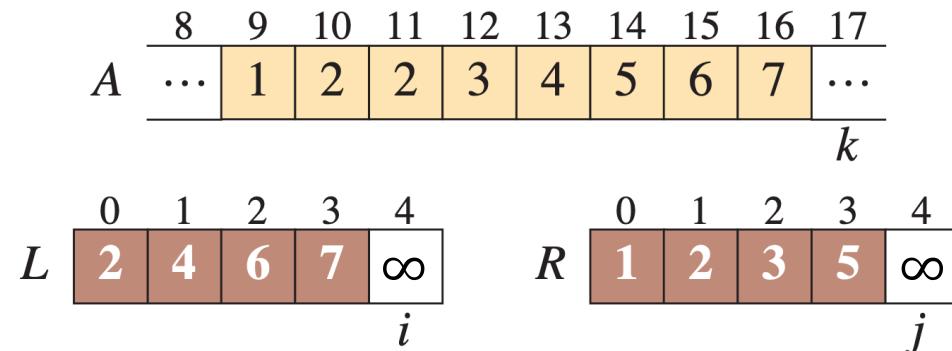
## ➤ Correctness of Merge (2)

- **Loop invariant:** At the start of the iteration of the last for loop,
  - the subarray  $A[p \dots k - 1]$  contains the  $k - p$  smallest elements of  $L[1 \dots n_1 + 1]$  and  $R[1 \dots n_2 + 1]$ , in sorted order and
  - $L[i]$  and  $R[j]$  are the smallest elements of their arrays that have not been copied back to  $A$ .
- **Maintenance:** suppose  $L[i] \leq R[j]$ . Then  $L[j]$  is the smallest element not copied back.  $A[p \dots k - 1]$  contains the  $k - p$  smallest elements, and after copying  $L[j]$  into  $A[k]$ ,  $A[p \dots k]$  contains the  $k - p + 1$  smallest elements. Incrementing  $k$  and  $j$  re-establishes the loop condition.  
Argue similarly for  $R[j] < L[i]$ .



## ➤ Correctness of Merge (3)

- **Loop invariant:** At the start of the iteration of the last for loop,
  - the subarray  $A[p \dots k - 1]$  contains the  $k - p$  smallest elements of  $L[1 \dots n_1 + 1]$  and  $R[1 \dots n_2 + 1]$ , in sorted order and
  - $L[i]$  and  $R[j]$  are the smallest elements of their arrays that have not been copied back to  $A$ .
- **Termination:** at termination,  $k = r + 1$ . By the loop invariant,  $A[p \dots k - 1] = A[p \dots r]$  contains the  $k - p = r - p + 1 = n_1 + n_2$  smallest elements of  $L[1 \dots n_1 + 1]$  and  $R[1 \dots n_2 + 1]$ , in sorted order. That's all elements in  $L$  and  $R$  apart from the two  $\infty$ .



## ➤ MergeSort: The Complete Algorithm

Notation:  $\lfloor x \rfloor$  means “floor of  $x$ ” (rounding down).

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MERGESORT( $A, p, r$ )

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- 1: **if**  $p < r$  **then**
  - 2:        $q = \lfloor (p + r)/2 \rfloor$
  - 3:       MERGESORT( $A, p, q$ )
  - 4:       MERGESORT( $A, q + 1, r$ )
  - 5:       MERGE( $A, p, q, r$ )
- 

Initial call: MERGESORT( $A, 1, A.length$ )

# ➤ Operation of MergeSort

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MERGESORT( $A, p, r$ )

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- 1: if  $p < r$  then
  - 2:    $q = \lfloor (p + r)/2 \rfloor$
  - 3:   MERGESORT( $A, p, q$ )
  - 4:   MERGESORT( $A, q + 1, r$ )
  - 5:   MERGE( $A, p, q, r$ )
- 

divide

$p$	$1$	$2$	$3$	$q$	$4$	$5$	$6$	$7$	$r$	$8$
	12	3	7	9	14	6	11	2		

$I \swarrow$        $11 \swarrow$

$p$	$1$	$2$	$3$	$r$
	12	3	7	9

$p$	$5$	$6$	$7$	$r$
	14	6	11	2

divide

$p$	$2$	$q$	$r$
	12	3	7
	9		
$p,q$	$r$	$p,q$	$r$
1	2	3	4
12	3	7	9
14	6		
11	2		

divide

$p$	$3$	$4$	$7$	$8$	$13$	$14$	$17$	$18$
	$p,r$							
	1	2	3	4	5	6	7	8
	12	3	7	9	14	6	11	2

merge

$p$	$q$	$r$
	1	2
	3	12
	7	9
	6	14
	2	11

merge

$p$	$q$	$r$
	1	2
	3	7
	9	12
	5	6
	2	11
	6	14

merge

$p$	$q$	$r$
	1	2
	3	6
	7	12
	9	14
	5	8
	2	11

$21 \swarrow$

## ➤ Correctness of MergeSort

**Proof by Induction:**

**Weak induction**

- **Base case:** Show statement true for initial case:  $n=a$  (usually  $n=0$  or  $n=1$ )
- **Inductive step:** If assumed true for  $n$  and can show true for  $n+1$  then true for all  $n \geq a$

**Strong induction**

- **Base case:** Show statement true for initial case:  $n=a$  (usually  $n=0$  or  $n=1$ )
- **Inductive step:** If assumed true for all  $a \leq k \leq n$  and can show true for  $n+1$  then true for all  $n \geq a$

**Strong induction** can be proved using **Weak induction**

## ➤ Correctness of MergeSort

**Proof by Induction:**

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MERGESORT( $A, p, r$ )

---

```
1: if  $p < r$  then  
2:    $q = \lfloor (p + r)/2 \rfloor$   
3:   MERGESORT( $A, p, q$ )  
4:   MERGESORT( $A, q + 1, r$ )  
5:   MERGE( $A, p, q, r$ )
```

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Assume MergeSort sorts correctly arrays of size  $< n$  and show that it sorts correctly an array of size  $n$

- **Base case:**  $n=1 \Rightarrow$  the algorithm returns at line 1 with the sorted array of a single element
- **Inductive step:** by inductive assumption lines 3 and 4 return two sub-arrays sorted correctly. We have already proved that **Merge** is correct hence after its execution the algorithm will return the array A sorted



## ➤ MergeSort: Runtime Analysis

- Looking for time  $T(n)$ : time for MergeSort to sort  $n$  elements.
- Assume for simplicity that  $n$  is an exact power of 2.

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MERGESORT( $A, p, r$ )

---

1: if $p < r$ then	$\Theta(1)$
2: $q = \lfloor (p + r)/2 \rfloor$	$\Theta(1)$
3:     MERGESORT( $A, p, q$ )	$T(n/2)$
4:     MERGESORT( $A, q + 1, r$ )	$T(n/2)$
5:     MERGE( $A, p, q, r$ )	$\Theta(n)$

---

Time for MergeSort to sort  $n/2$  elements.

Yields a recurrence equation where  $T(n)$  depends on  $T(n/2)$ :

- If  $n=1$ , then  $p = r$ , and the algorithm terminates in constant time  $\Theta(1)$

$$T(n) = \begin{cases} \Theta(1) & \text{if } n = 2^0 = 1 \\ 2T(n/2) + \Theta(n) & \text{if } n = 2^k, \text{ for } k \geq 1 \end{cases}$$

- “The time for MergeSort to sort  $n$  elements is twice the time for MergeSort to sort  $n/2$  elements plus  $\Theta(n)$  time (for Merge).”

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## ➤ Recurrence Equation (MergeSort)

- Looking for time  $T(n)$ : time for MergeSort to sort  $n$  elements.
- Assume for simplicity that  $n$  is an exact power of 2.

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MERGESORT( $A, p, r$ )

---

- 1: **if**  $p < r$  **then**
- 2:      $q = \lfloor (p + r)/2 \rfloor$
- 3:     MERGESORT( $A, p, q$ )
- 4:     MERGESORT( $A, q + 1, r$ )
- 5:     MERGE( $A, p, q, r$ )

---

Time

$\Theta(1)$

$\Theta(1)$

$T(n/2)$

$T(n/2)$

$\Theta(n)$

Time for  
MergeSort  
to sort  $n/2$   
elements.

Yields a **recurrence equation** where  $T(n)$  depends on  $T(n/2)$ :

- If  $n=1$ , then  $p=r$ , and the algorithm terminates in constant time  $\Theta(1)$
- Otherwise:  $T(n) = D(n) + a T(n/b) + C(n)$ 
  - $D(n)$  - time to *divide* into subproblems:  $\Theta(1)$
  - $a T(n/b)$  – time to solve  $a$  subproblems each of size  $n/b$ :  $2 T(n/2)$
  - $C(n)$  – time to *conquer* (to combine the obtained sub-solutions):  $\Theta(n)$



## How to Solve a Recurrence Equation

$$T(n) = \begin{cases} d & \text{if } n = 2^0 \\ 2T(n/2) + cn & \text{if } n = 2^k, \text{ for } k \geq 1 \end{cases}$$

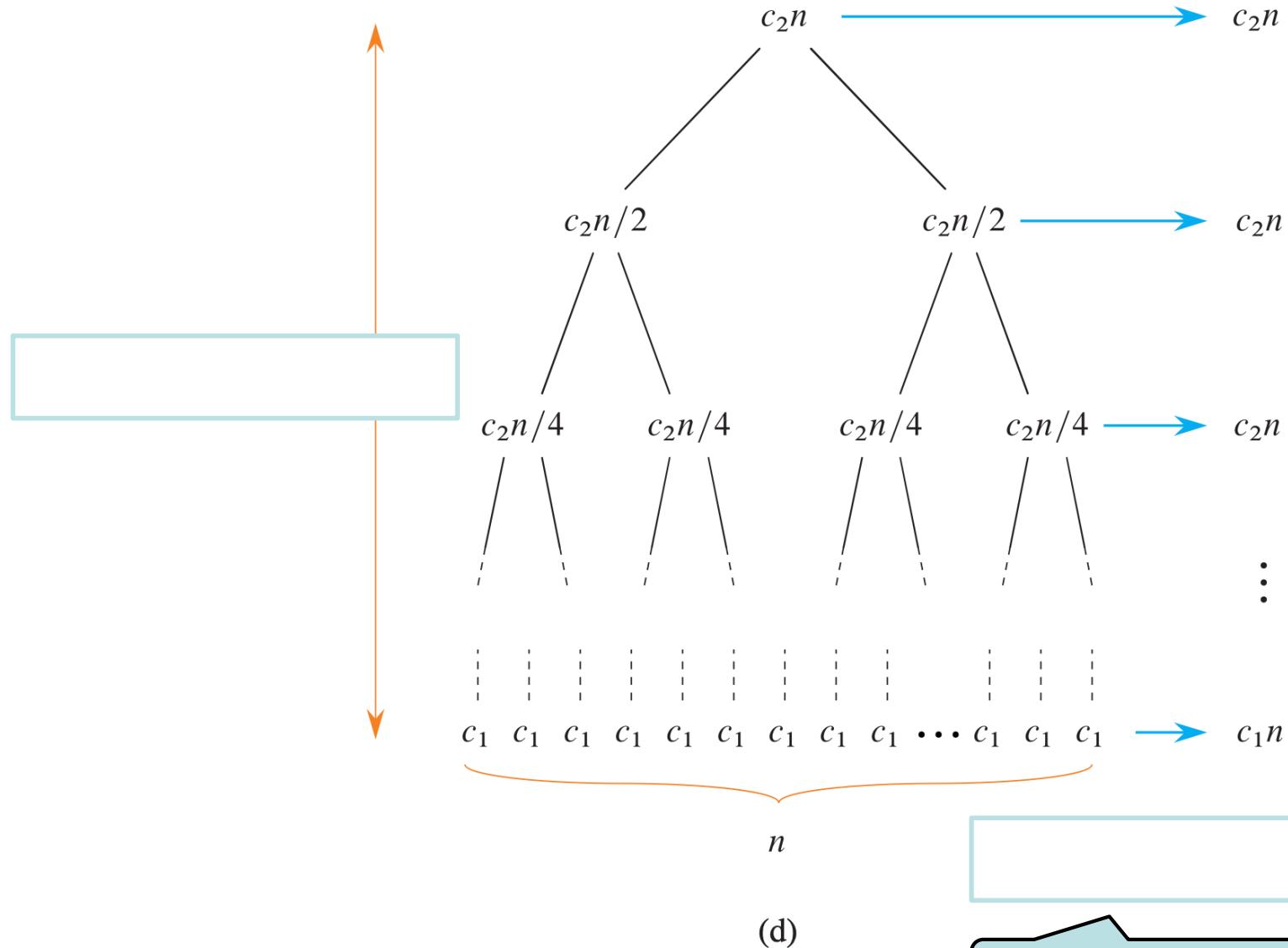
1. **Substitution method** (Sec 4.3): guess a solution and verify using **induction** (over  $k$ ).
  - Tutorial exercise.
2. Draw a **recursion tree** (Sec 4.4), add times across the tree.
3. Use the **Master Theorem** (Sec 4.5) to solve a general recurrence equation in the shape of:

$$T(n) = aT(n/b) + f(n).$$

## ➤ Runtime Visualised as Recursion Tree



## ➤ Runtime Visualised as Recursion Tree



## ➤ Comparison with InsertionSort

- MergeSort **always runs in time  $\Theta(n \log n)$ .**
- Way better than worst case and average case of  $\Theta(n^2)$  for InsertionSort.
- Worse than the best-case time  $\Theta(n)$  of InsertionSort.
  - InsertionSort might be faster if your array is almost sorted.
- MergeSort needs **more space** than InsertionSort:
  - MergeSort always stores  $\Omega(n)$  elements outside the input.
  - InsertionSort only needs  $O(1)$  additional space.
  - We say that InsertionSort sorts **in place**:

A sorting algorithm sorts **in place**  
if it only uses  $O(1)$  additional space.

## ➤ The Master Theorem (1)

- Provides a “cookbook” method for solving recurrences of the form  $T(n)=aT(n/b) + f(n)$  where  $a>0$  and  $b>1$
- $f(n)$  is called the **driving function** and  $T(n)$  is called the **master recurrence**
- The master recurrence  $T(n)$  describes the running time of a divide and conquer algorithm that divides a problem of size  $n$  into  $a$  subproblems each of size  $n/b < n$   
-> the algorithm solves each subproblem in time  $T(n/b)$
- The driving function  $f(n)$  describes the cost of dividing the problem before the recursion (**divide**), as well as the cost of combining the results together (**conquer**)

**Important term:**

- $n^{\log_b a}$  is called the **watershed function**

## ➤ The Master Theorem (Statement)

Let  $a > 0$  and  $b > 1$  be constants, and let  $f(n)$  be non-negative for large enough  $n$ . Then, the solution of the recurrence function defined over  $n \in \mathbb{N}$

$$T(n) = a T(n/b) + f(n)$$

has the following asymptotic behaviour:

1. If there exists a constant  $\epsilon > 0$  such that  $f(n) = O(\underline{n^{\log_b a - \epsilon}})$ , then  $T(n) = \Theta(n^{\log_b a})$ .
2. If there exists a constant  $k \geq 0$  such that  $f(n) = \Theta(\underline{n^{\log_b a} \lg^k n})$ , then  $T(n) = \Theta(n^{\log_b a} \lg^{k+1} n)$ .
3. If there exists a constant  $\epsilon > 0$  such that  $f(n) = \Omega(\underline{n^{\log_b a + \epsilon}})$ , and if  $f(n)$  additionally satisfies the **regularity condition**  $a f(n/b) \leq c f(n)$  for some constant  $c < 1$  and all sufficiently large  $n$ , then  $T(n) = \Theta(f(n))$ . ■

## ➤ The Master Theorem (Properties)

- Allows you to state the master recurrence  $T(n)$  without floors and ceilings even when you don't have problems of exactly the same size

$$\text{eg., } T(n) = T\left(\left\lfloor \frac{n}{2} \right\rfloor\right) + T\left(\left\lceil \frac{n}{2} \right\rceil\right) + \theta(n)$$

- The theorem does not apply to all possible recurrence equations but it does cover the vast majority of those that arise in practice

## ➤ The Master Theorem: closer look

1. If there exists a constant  $\epsilon > 0$  such that  $f(n) = \underline{O(n^{\log_b a - \epsilon})}$ , then  $T(n) = \Theta(n^{\log_b a})$ .
  2. If there exists a constant  $k \geq 0$  such that  $f(n) = \underline{\Theta(n^{\log_b a} \lg^k n)}$ , then  $T(n) = \Theta(n^{\log_b a} \lg^{k+1} n)$ .
  3. If there exists a constant  $\epsilon > 0$  such that  $f(n) = \underline{\Omega(n^{\log_b a + \epsilon})}$ , and if  $f(n)$  additionally satisfies the **regularity condition**  $af(n/b) \leq cf(n)$  for some constant  $c < 1$  and all sufficiently large  $n$ , then  $T(n) = \Theta(f(n))$ . ■
- $n^{\log_b a}$  is called the **watershed function**
  - **Case 1:** the watershed function must grow **polynomially faster** than  $f(n)$  – by at least a factor  $\theta(n^\epsilon)$  for some constant  $\epsilon > 0$
  - **Case 2:** watershed and driving ( $f(n)$ ) functions grow asymptotically **nearly at the same rate** (you get the same growth for  $k = 0$  – common situation)
  - **Case 3:** the watershed function must grow **polynomially slower** than  $f(n)$  – by at least a factor  $\theta(n^\epsilon)$  for some constant  $\epsilon > 0$  + **regularity condition** must hold

## ➤ The Master Theorem: MergeSort example

1. If there exists a constant  $\epsilon > 0$  such that  $f(n) = O(n^{\log_b a - \epsilon})$ , then  $T(n) = \Theta(n^{\log_b a})$ .
  2. If there exists a constant  $k \geq 0$  such that  $f(n) = \Theta(n^{\log_b a} \lg^k n)$ , then  $T(n) = \Theta(n^{\log_b a} \lg^{k+1} n)$ .
  3. If there exists a constant  $\epsilon > 0$  such that  $f(n) = \Omega(n^{\log_b a + \epsilon})$ , and if  $f(n)$  additionally satisfies the **regularity condition**  $af(n/b) \leq cf(n)$  for some constant  $c < 1$  and all sufficiently large  $n$ , then  $T(n) = \Theta(f(n))$ . ■
- MergeSort:  $T(n) = 2T(n/2) + \theta(n)$
  - $a=2, b=2, f(n) = \theta(n)$  watershed function:  $n^{\log_b a} = n^{\log_2 2} = n^1 = n$
  - Does **Case 1** hold? Does the watershed function grow **polynomially faster** than  $f(n)$  ?
  - Does **Case 3** hold? Does the watershed function grow **polynomially slower** than  $f(n)$  ?

## ➤ The Master Theorem: MergeSort example

1. If there exists a constant  $\epsilon > 0$  such that  $f(n) = O(n^{\log_b a - \epsilon})$ , then  $T(n) = \Theta(n^{\log_b a})$ .
  2. If there exists a constant  $k \geq 0$  such that  $f(n) = \Theta(n^{\log_b a} \lg^k n)$ , then  $T(n) = \Theta(n^{\log_b a} \lg^{k+1} n)$ .
  3. If there exists a constant  $\epsilon > 0$  such that  $f(n) = \Omega(n^{\log_b a + \epsilon})$ , and if  $f(n)$  additionally satisfies the **regularity condition**  $af(n/b) \leq cf(n)$  for some constant  $c < 1$  and all sufficiently large  $n$ , then  $T(n) = \Theta(f(n))$ . ■
- MergeSort:  $T(n) = 2T(n/2) + \theta(n)$
  - $a=2, b=2, f(n) = \theta(n)$  watershed function:  $n^{\log_b a} = n^{\log_2 2} = n^1 = n$
  - Does **Case 2** hold?
    - Yes! for  $k = 0, f(n) = \Theta(n^{\log_b a} \log^0 n) = \Theta(n)$
    - So the solution is  $T(n) = \Theta(n^{\log_b a} \log^{k+1} n) = \Theta(n \log n)$

## ➤ The Master Theorem: Further examples (1)

1. If there exists a constant  $\epsilon > 0$  such that  $f(n) = O(n^{\log_b a - \epsilon})$ , then  $T(n) = \Theta(n^{\log_b a})$ .
2. If there exists a constant  $k \geq 0$  such that  $f(n) = \Theta(n^{\log_b a} \lg^k n)$ , then  $T(n) = \Theta(n^{\log_b a} \lg^{k+1} n)$ .
3. If there exists a constant  $\epsilon > 0$  such that  $f(n) = \Omega(n^{\log_b a + \epsilon})$ , and if  $f(n)$  additionally satisfies the **regularity condition**  $af(n/b) \leq cf(n)$  for some constant  $c < 1$  and all sufficiently large  $n$ , then  $T(n) = \Theta(f(n))$ . ■

- $T(n) = 9T(n/3) + n$
- $a=9, b=3, f(n) = n$  watershed function:  $n^{\log_b a} = n^{\log_3 9} = n^2$
- Does **Case 1** hold? Does the watershed function must grow **polynomially faster** than  $f(n)$  ?

Yes!  $f(n) = n = O(n^{\log_b a - \epsilon}) = O(n^{2-\epsilon})$  for any  $\epsilon < 1$

- So the solution is  $T(n) = \theta(n^{\log_b a}) = \theta(n^2)$

## ➤ The Master Theorem: Further examples (2)

1. If there exists a constant  $\epsilon > 0$  such that  $f(n) = O(n^{\log_b a - \epsilon})$ , then  $T(n) = \Theta(n^{\log_b a})$ .
  2. If there exists a constant  $k \geq 0$  such that  $f(n) = \Theta(n^{\log_b a} \lg^k n)$ , then  $T(n) = \Theta(n^{\log_b a} \lg^{k+1} n)$ .
  3. If there exists a constant  $\epsilon > 0$  such that  $f(n) = \Omega(n^{\log_b a + \epsilon})$ , and if  $f(n)$  additionally satisfies the **regularity condition**  $af(n/b) \leq cf(n)$  for some constant  $c < 1$  and all sufficiently large  $n$ , then  $T(n) = \Theta(f(n))$ . ■
- $T(n) = 3T(n/4) + n \log n$
  - $a=3, b=4, f(n) = n \log n$ , watershed function:  $n^{\log_b a} = n^{\log_4 3} = n^{0.793}$
  - Does **Case 1** hold? Does the watershed function must grow **polynomially faster** than  $f(n)$  ?

## ➤ The Master Theorem: Further examples (2)

1. If there exists a constant  $\epsilon > 0$  such that  $f(n) = O(n^{\log_b a - \epsilon})$ , then  $T(n) = \Theta(n^{\log_b a})$ .
2. If there exists a constant  $k \geq 0$  such that  $f(n) = \Theta(n^{\log_b a} \lg^k n)$ , then  $T(n) = \Theta(n^{\log_b a} \lg^{k+1} n)$ .
3. If there exists a constant  $\epsilon > 0$  such that  $f(n) = \Omega(n^{\log_b a + \epsilon})$ , and if  $f(n)$  additionally satisfies the **regularity condition**  $af(n/b) \leq cf(n)$  for some constant  $c < 1$  and all sufficiently large  $n$ , then  $T(n) = \Theta(f(n))$ . ■

- $T(n) = 3T(n/4) + n \log n$
- $a=3, b=4, f(n) = n \log n$ , watershed function:  $n^{\log_b a} = n^{\log_4 3} = n^{0.793}$
- Does **Case 3** hold? Does the watershed function must grow **polynomially slower** than  $f(n)$  ?

Yes!  $f(n) = n \log n = \Omega(n^{\log_b a + \epsilon}) = \Omega(n^{0.793 + \epsilon})$  for any  $0 < \epsilon$

$< 0.207$

and  $af\left(\frac{n}{b}\right) = 3\left(\frac{n}{4}\right)(\log n/4) \leq c n \log n$  for  $c = 3/4$

- So the solution is  $T(n) = \theta(f(n)) = \theta(n \log n)$

## ➤ Summary

- The divide-and-conquer design paradigm
  - **Divides** a problem into smaller subproblems of the same kind
  - **Solves** these subproblems recursively, and then
  - **Combines** these solutions to an overall solution.
- MergeSort uses divide-and-conquer to sort in time  $\Theta(n \log n)$  (best case = worst case).
- It's possible to sort  $n$  elements in worst-case time  $\Theta(n \log n)$ !
- Drawback: MergeSort does not sort in place.
  - “In place”: sorting using only  $O(1)$  additional space.
- The runtime of recursive algorithms can be analysed by solving a **recurrence equation**.