Algorithms

Basic Coding

Winter 2022: Dan Calderone

Algorithms

Search Algorithms
- Binary search
- Breadth First Search (BFS)
- Depth First Search (DFS)
- Kadane's algorithm
- KMP algorithm
- Quick select algorithm
- Boyer-Moore Majority Vote algorithm
- Euclid's algorithm

Sorting Algorithms
- Insertion Sort
- Selection Sort
- Quick Sort
- Merge Sort
- Heap Sort
- Introsort
- Bubble sort
- Non-comparison sorts
- Counting sorts
- Radix sort
- Bucket sort
- (Kahn's topological sort)

Graph Algorithms

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- Kahn's topological sort (DAG)

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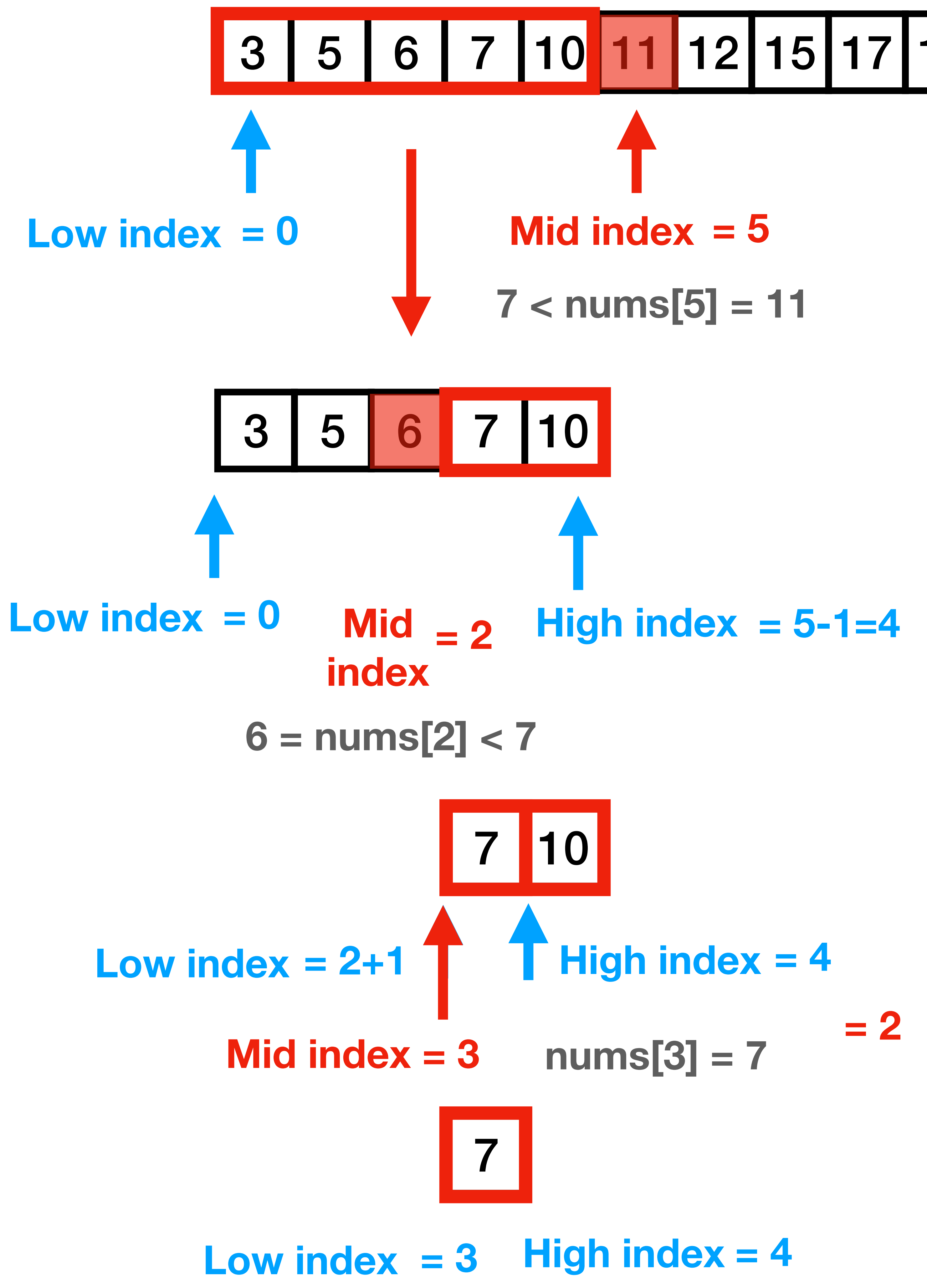
- Lee Algorithm

Compression Algorithms
- Huffman Coding

Fill Algorithm
- Flood Fill Algorithm

Binary Search Algorithm: (Divide and Conquer)

nums = [3, 5, 6, 7, 10, 11, 12, 15, 17, 19, 20, 21]; target = 7;



nums[3] = 7

... index = 3

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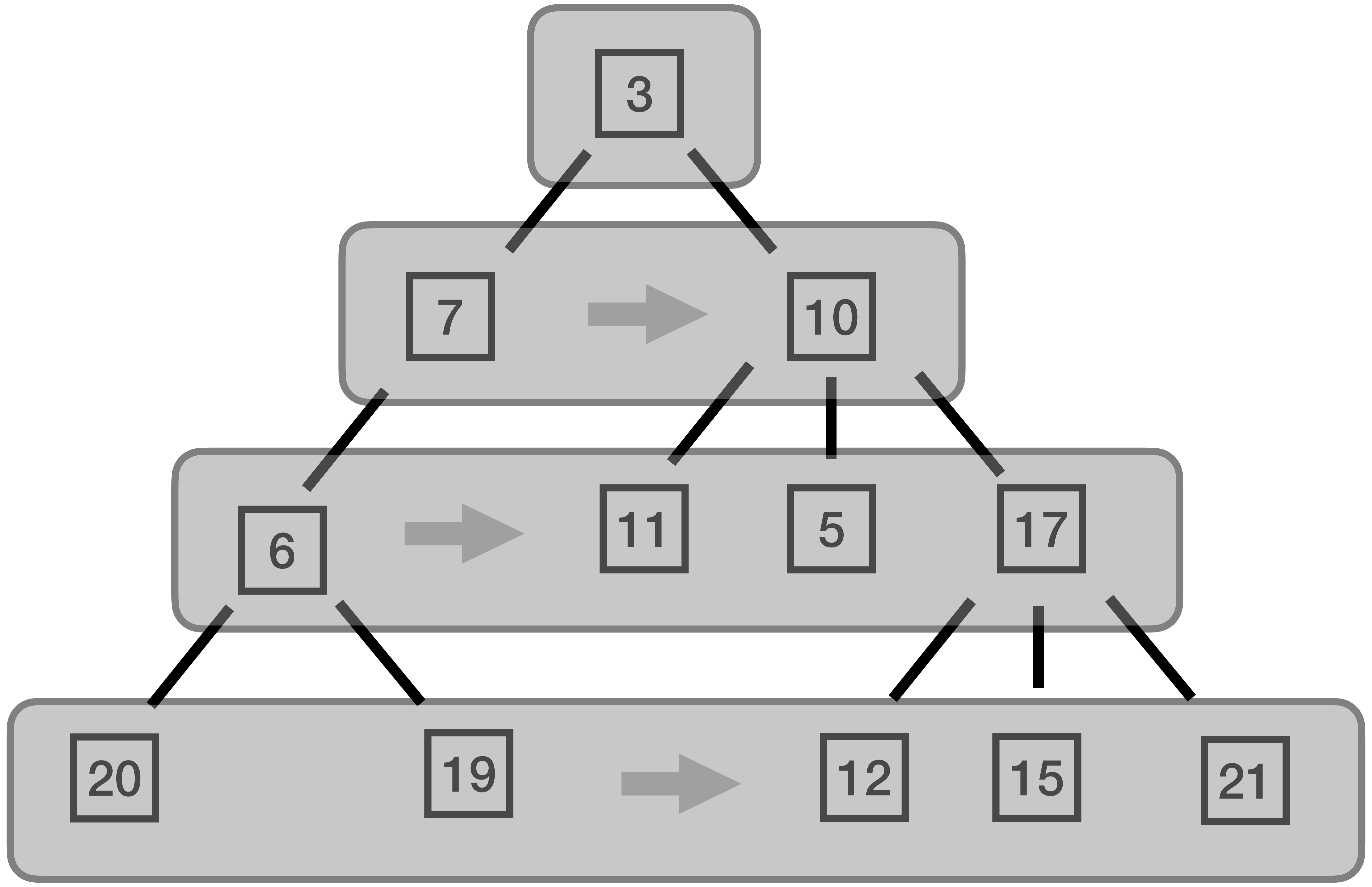
Breadth First Search (BFS)



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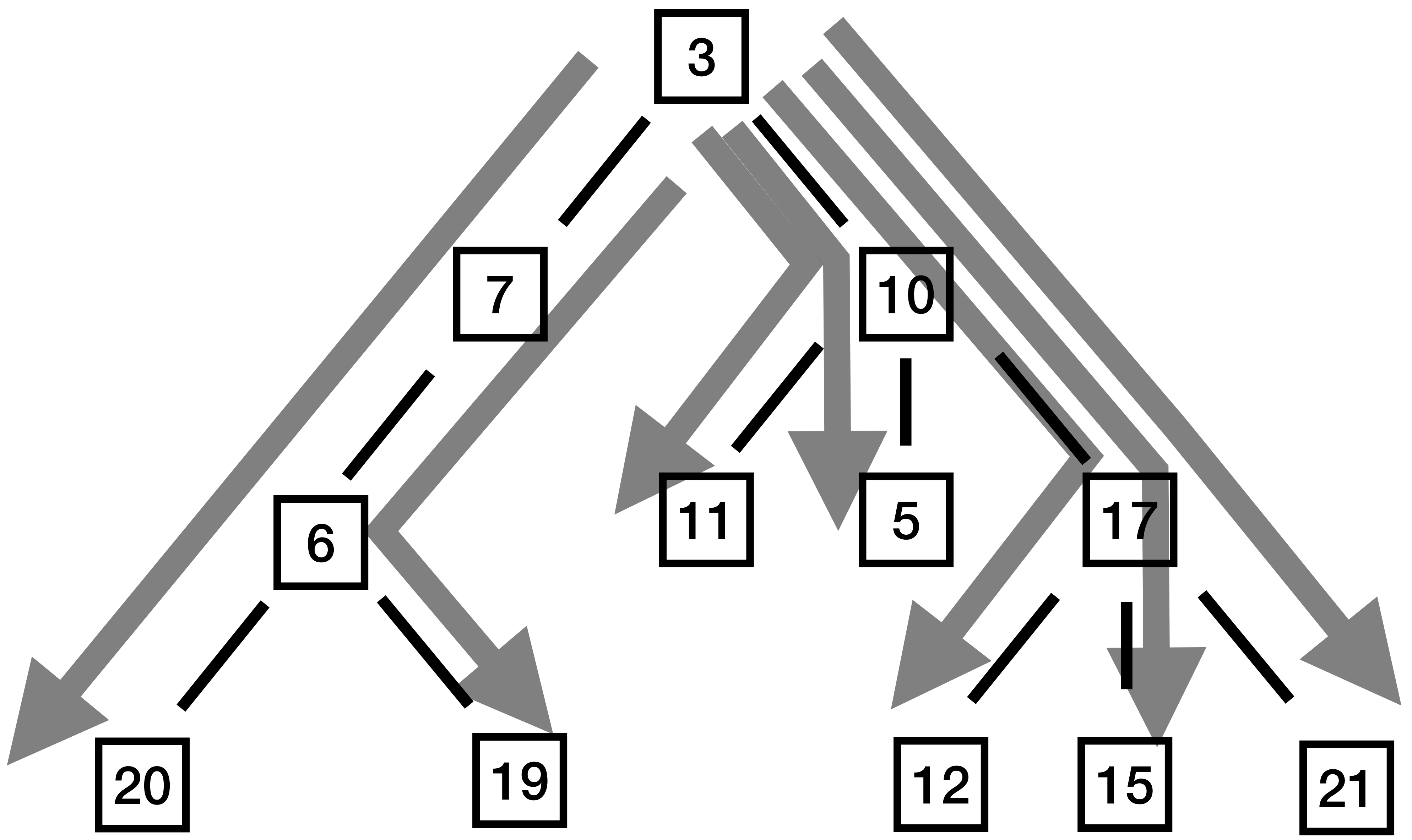
Depth First Search (DFS)



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Kadane's Algorithm

"find the maximum sum contiguous subarray"

- empty = 0
- all positive: solution is full array
- all negative: solution is empty array

Find the largest sum:

Initialize

best_sum = 0
current_sum = 0;

for each element x (left to right):
    current_sum = max(0,current_sum+x)
    best_sum = max(best_sum, current_sum)

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Kadane's Algorithm

"find the maximum sum contiguous subarray"

- empty = 0
- all positive: solution is full array
- all negative: solution is empty array

Find the largest sum w/ position

```
Initialize
best_sum = 0
current_sum = 0;
best_start = best_end = 0;
current_start = current_end = 0;

for each element x (left to right):
    If current_sum <= 0:
        current_start = current_end
        current_sum = x
    else:
        current_sum += x

    current_end++

    If current_sum > best_sum:
        best_sum = current_sum
        best_start = current_start
        best_end = current_end
```

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Naive Pattern Matching

Computation Cost:
Worst Case: **O(nm)**

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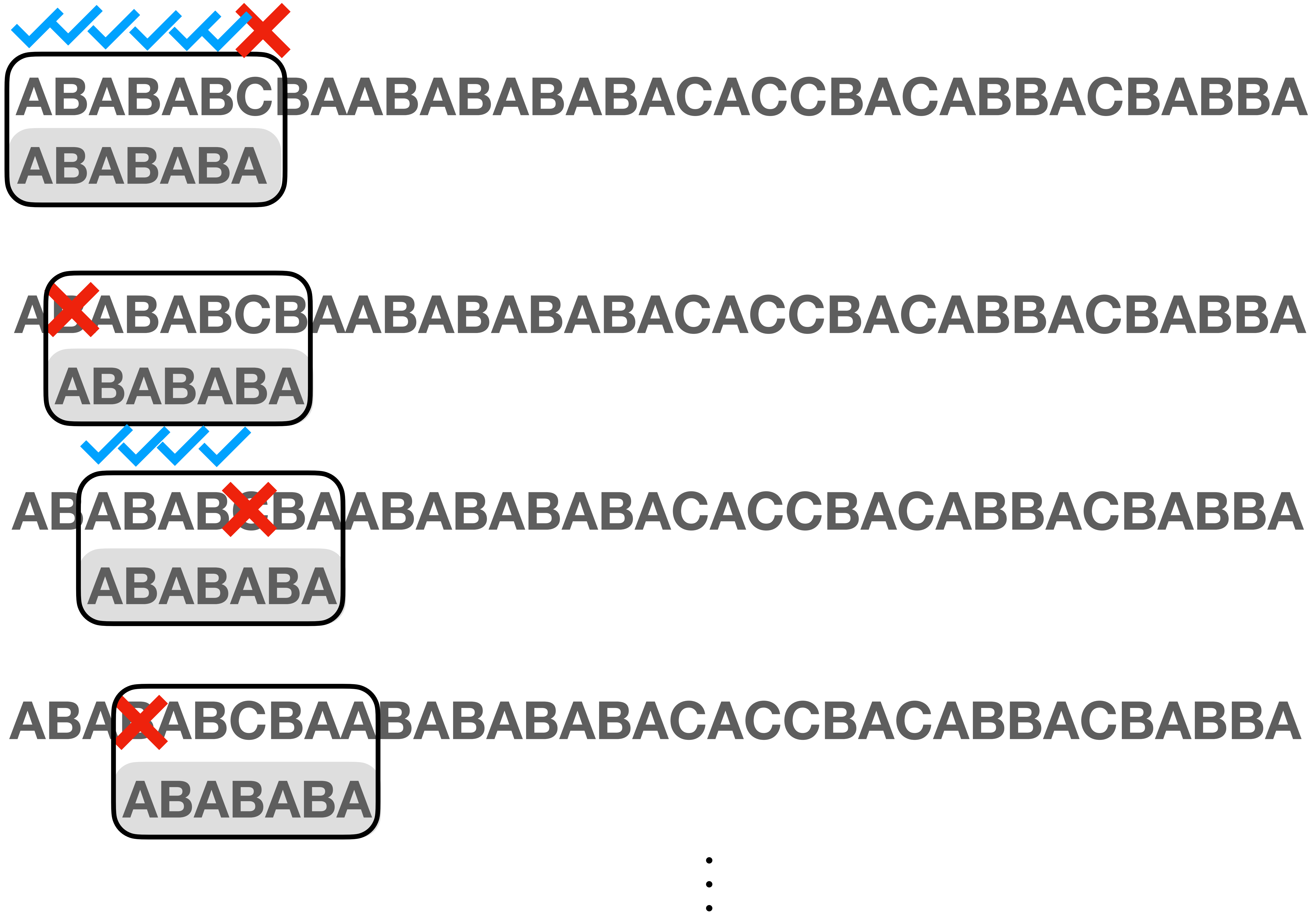
Pattern (m): **ABABABA** Array (n): **AABABCBAABABABABACACCBACABBACBABBA**



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Computation Cost: O(n + m)

KMP Algorithm (Knuth-Morris-Pratt)

"find a pattern of length m in an array of length n"

Pattern (m): **ABABABA** Array (n): **AABABCBAABABABABACACCBACABBACBABBA**

preprocess the pattern to save time…

A B A B A B A

…prefix …suffix

Partial Match Table:

A	AB	ABA	ABAB	ABABA	ABABAB	ABABABA
0	0	1	2	3	4	5

..first 1 char (A), *..first 2 char* (AB), *..first 6 char* (ABABAB), *..first 7 char* (ABABABA)

… **ABAB**

Proper prefixes	Proper Suffixes
A	B
AB	AB
ABA	BAB

ABABA

Proper prefixes	Proper Suffixes
A	A
AB	BA
ABA	ABA
ABAB	BABA

longest proper prefix that is also a suffix"

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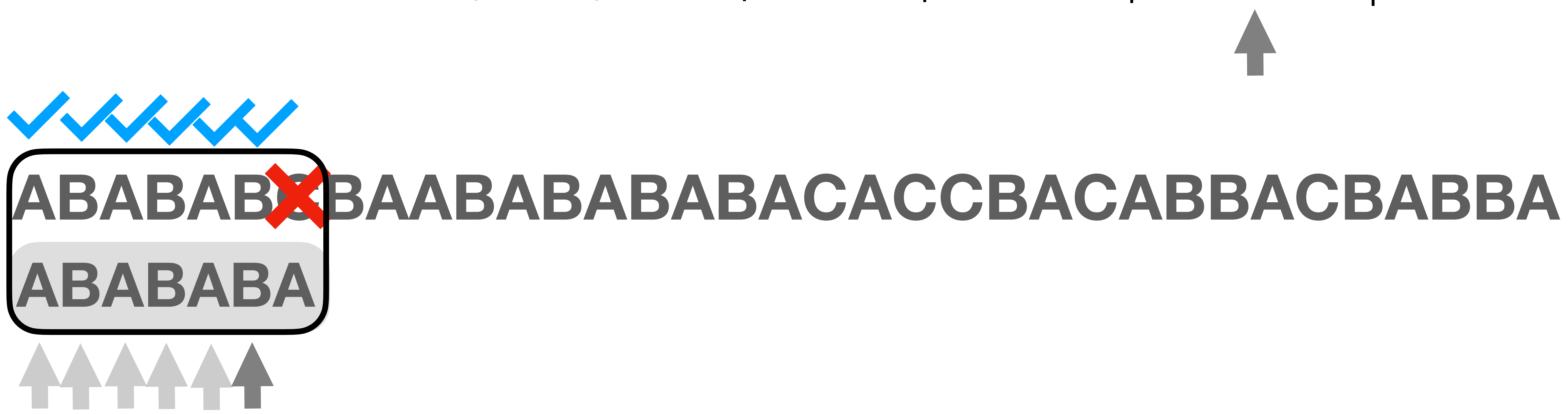

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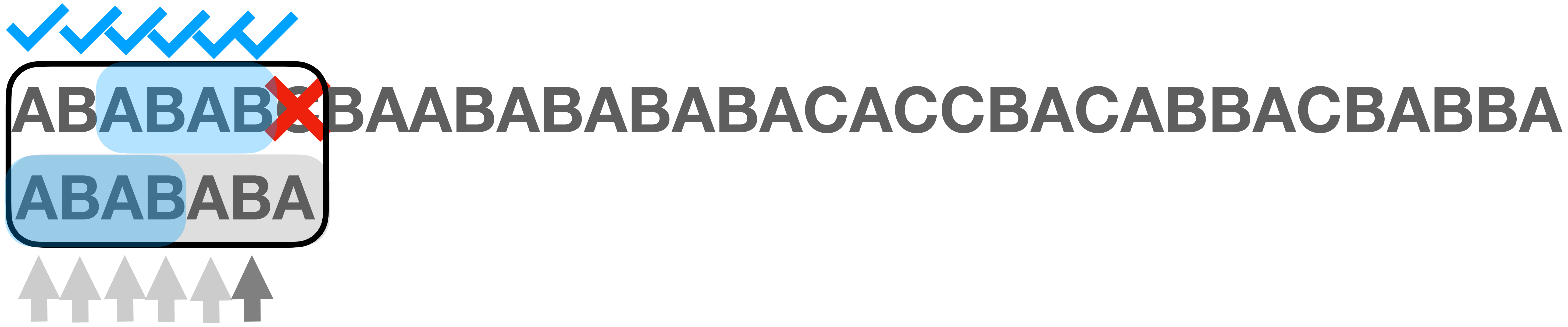

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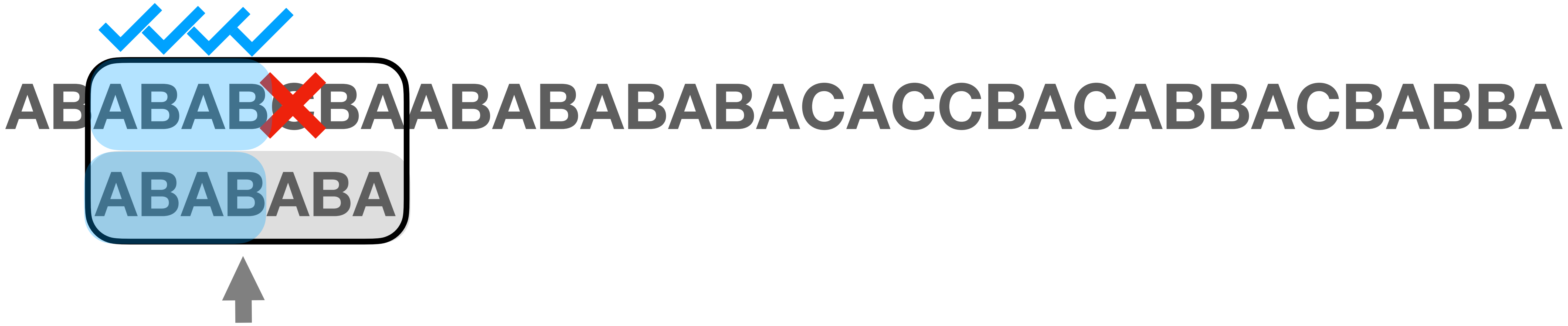

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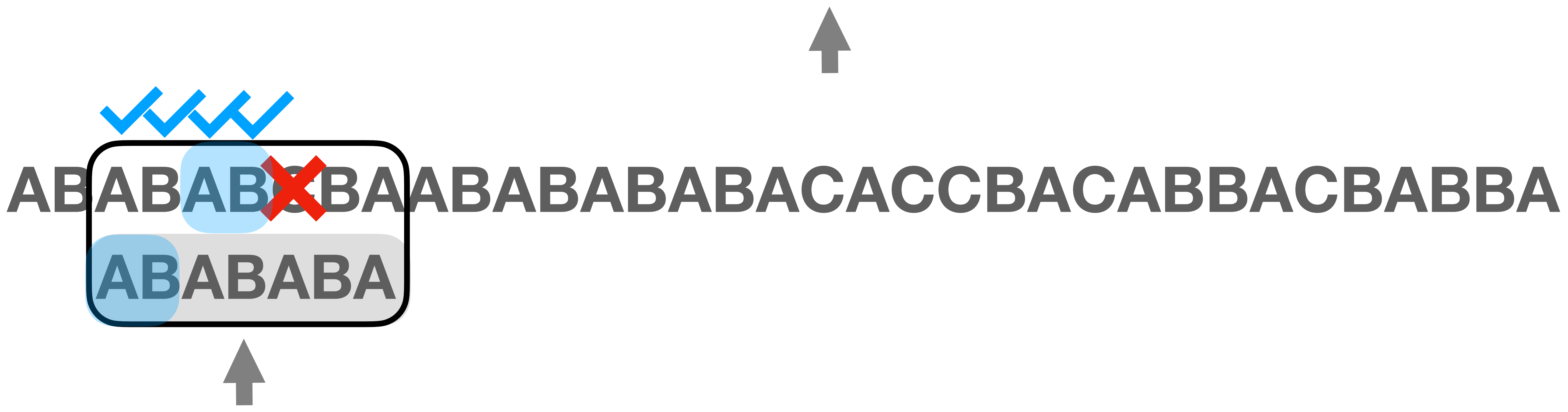

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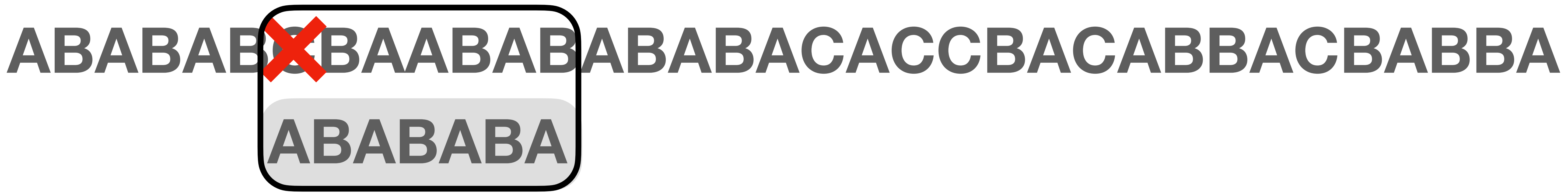

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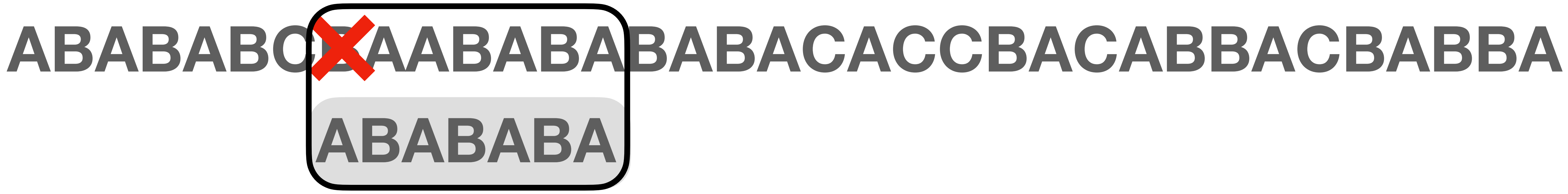

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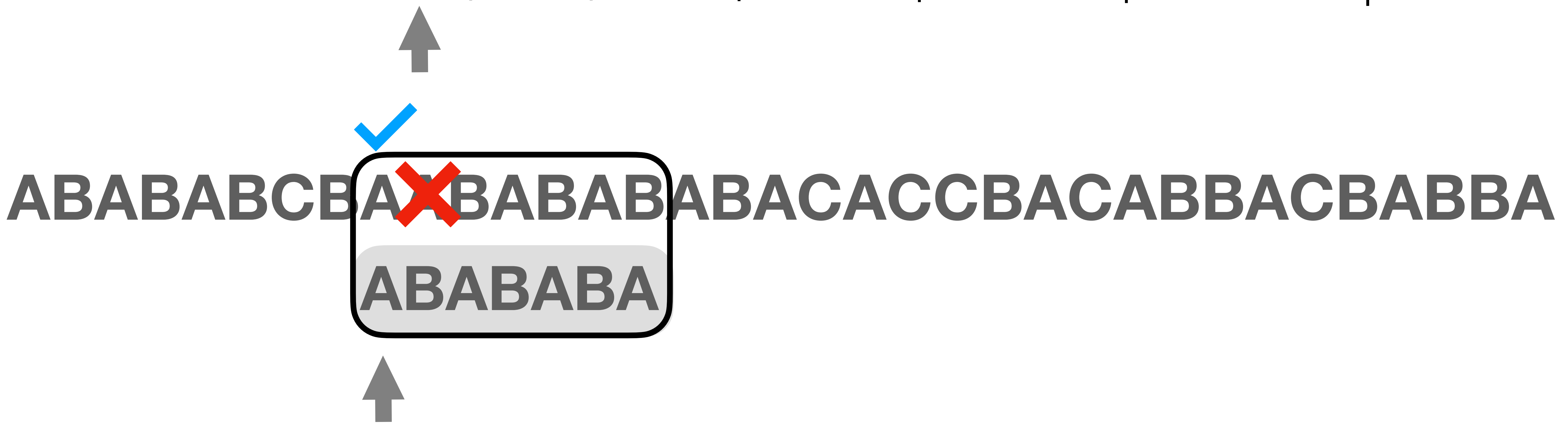

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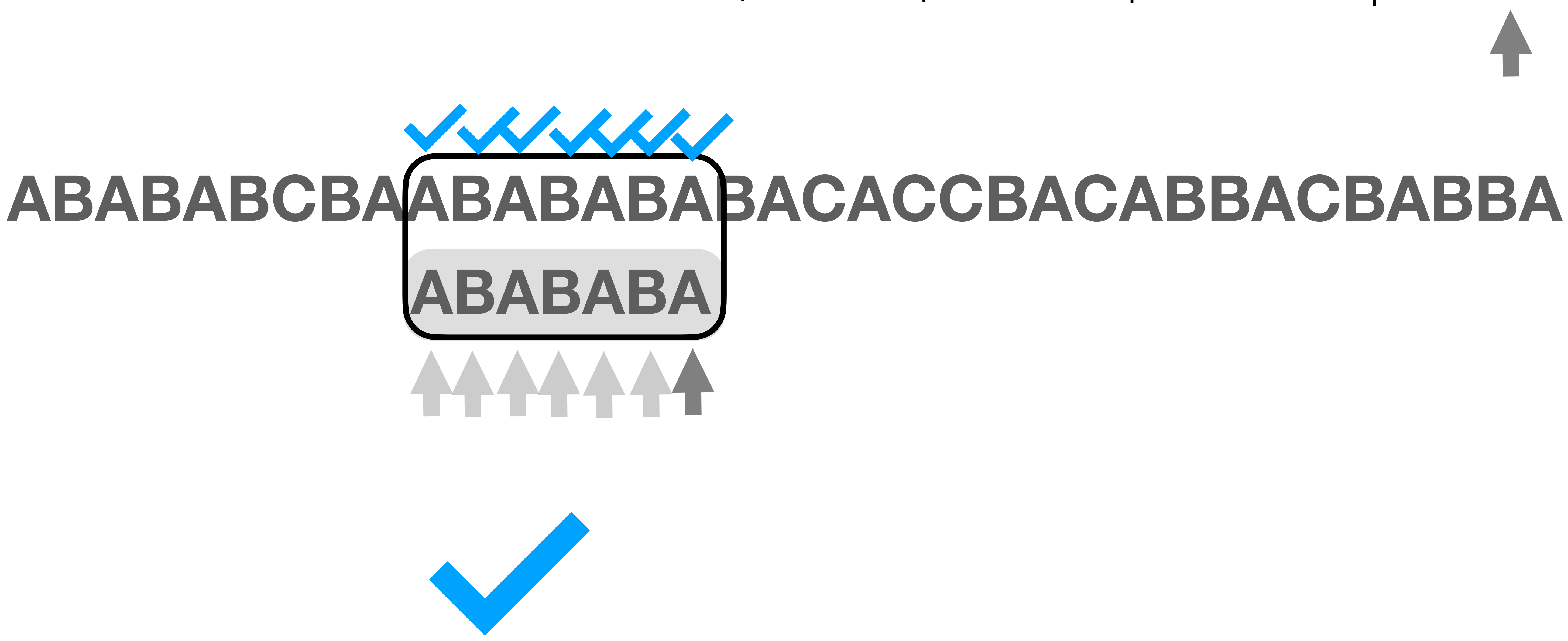

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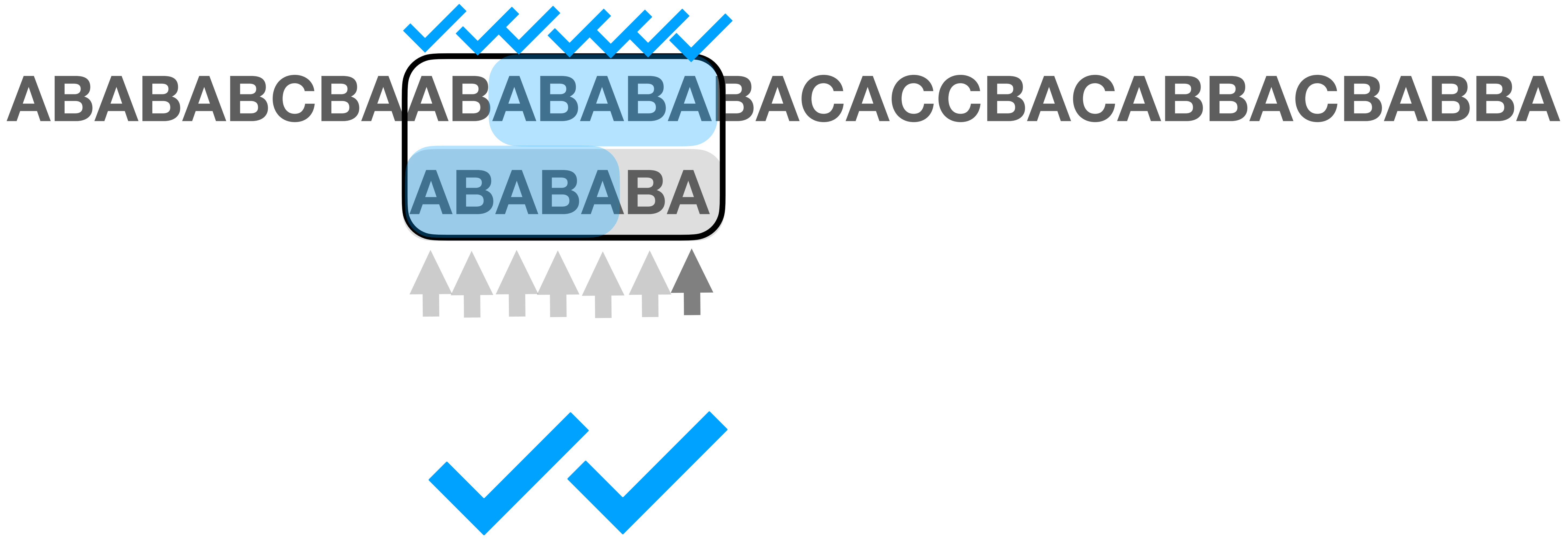

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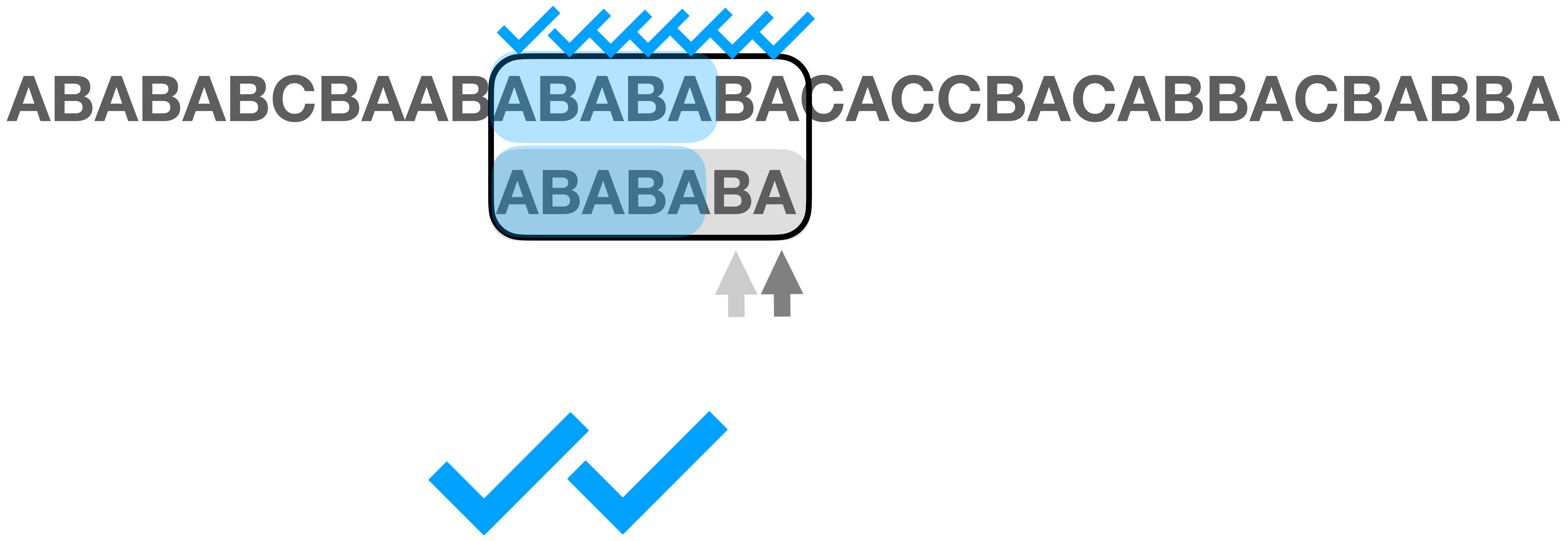

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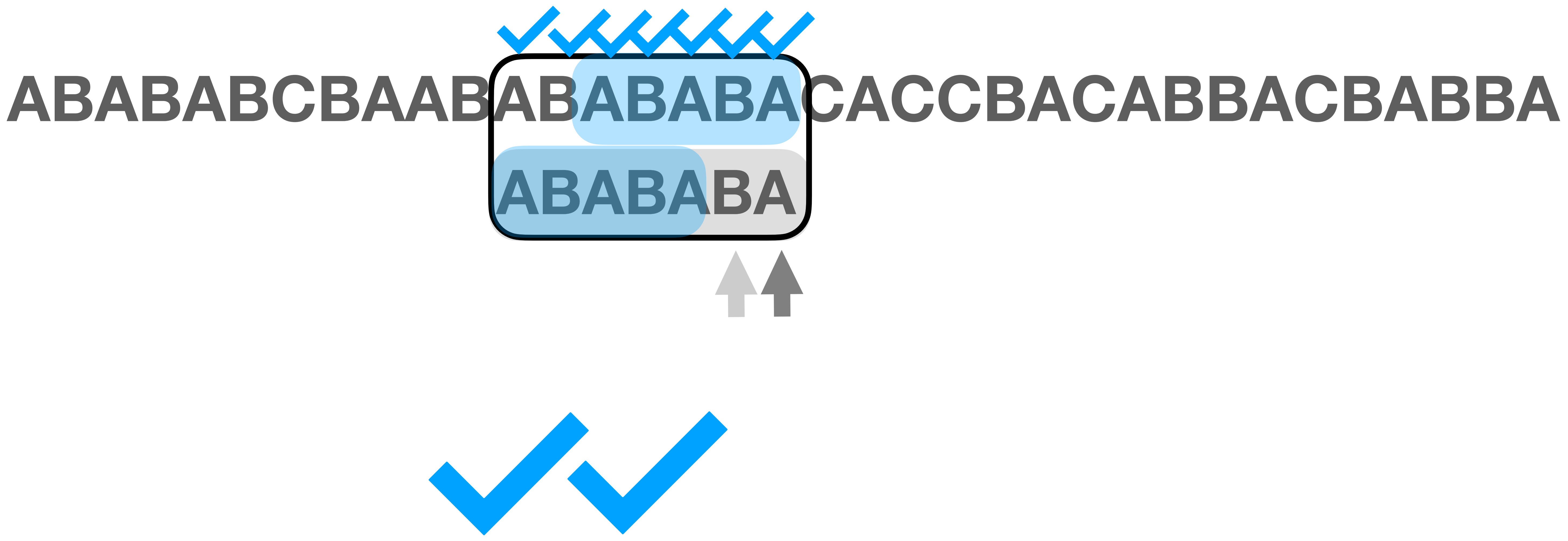

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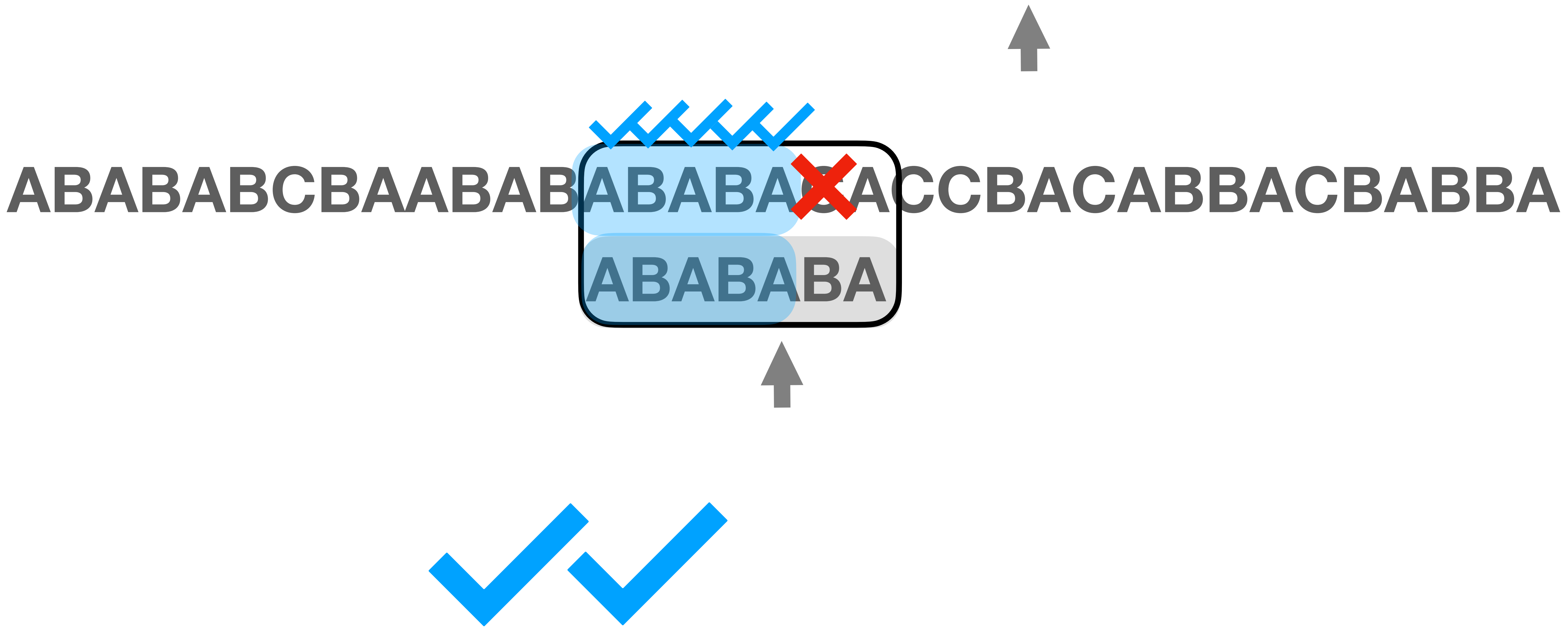

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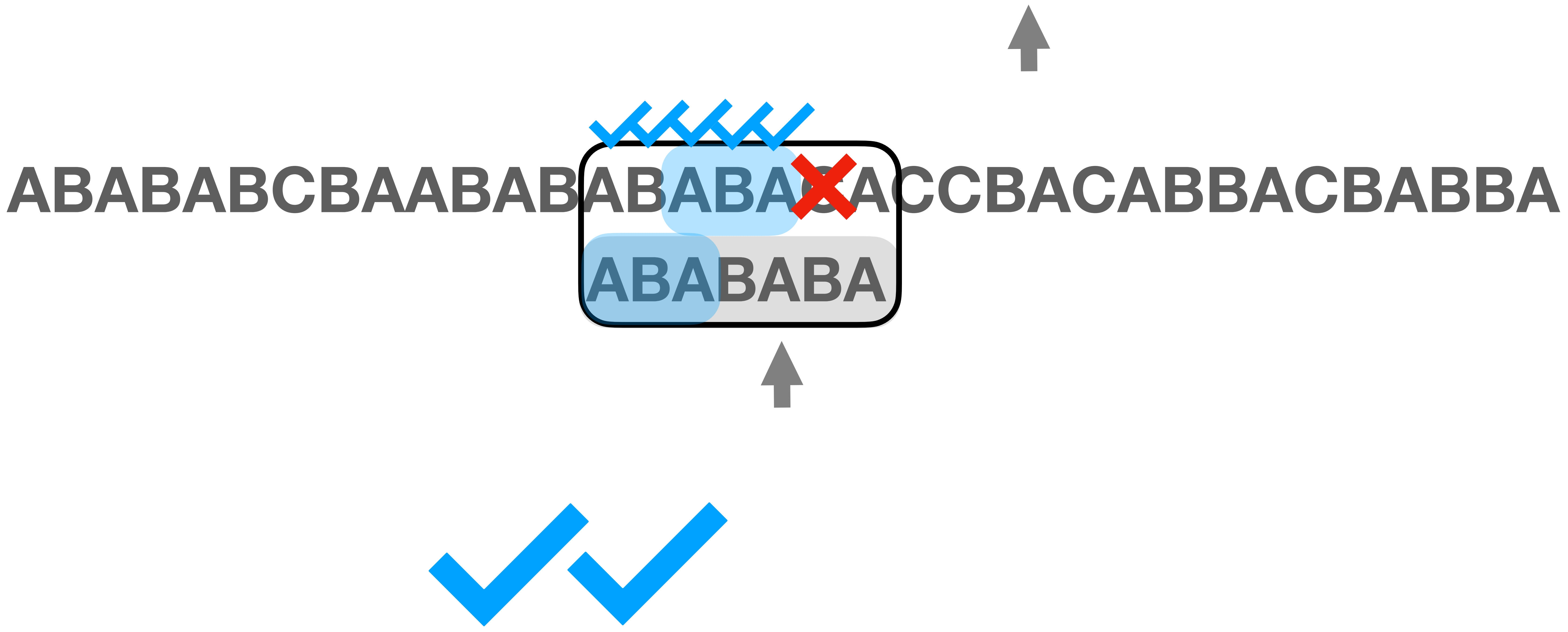

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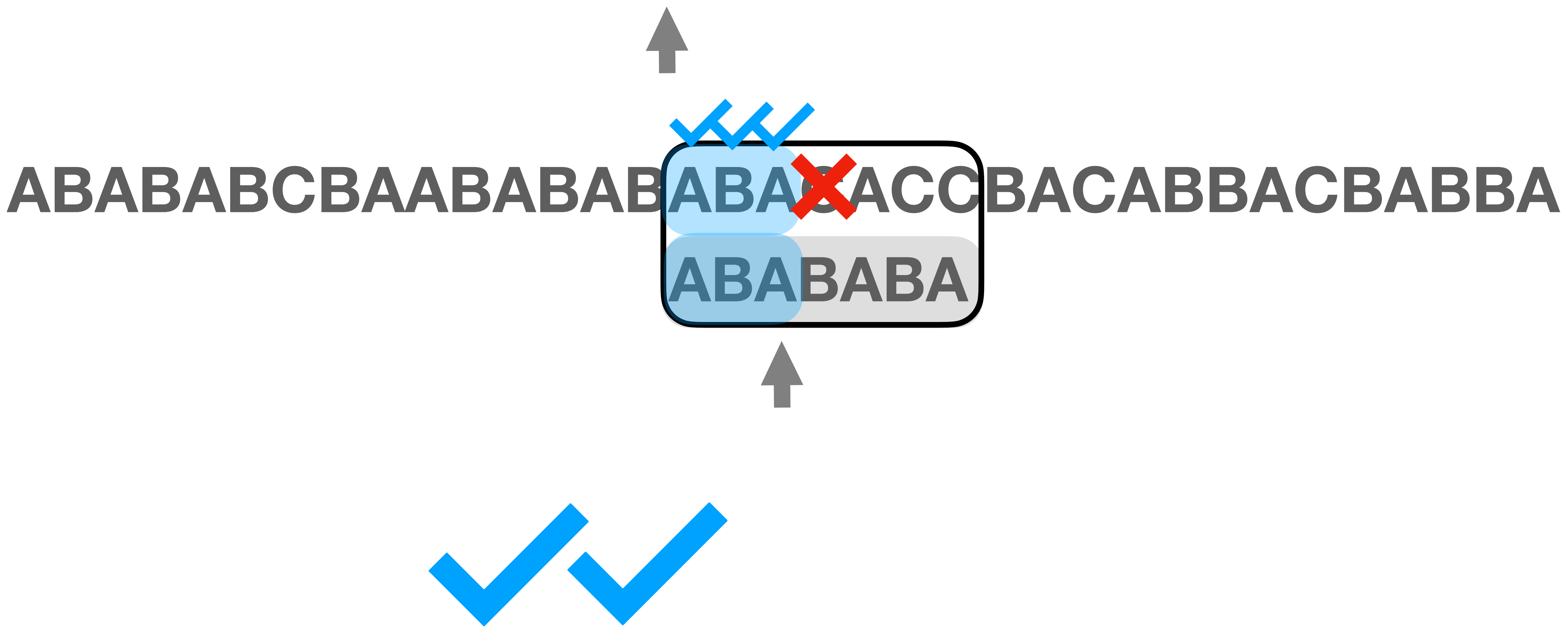

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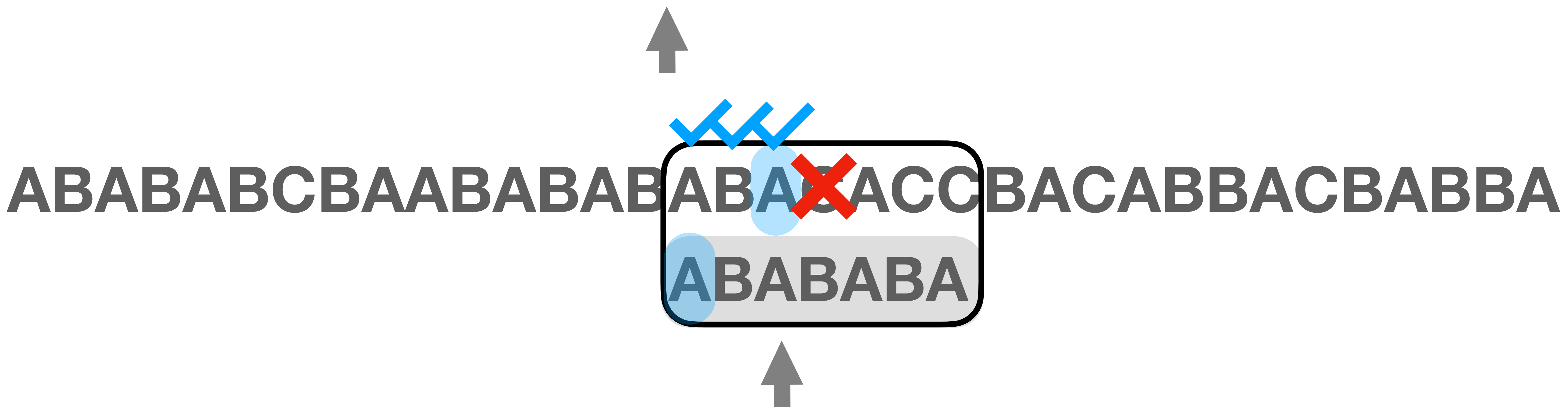

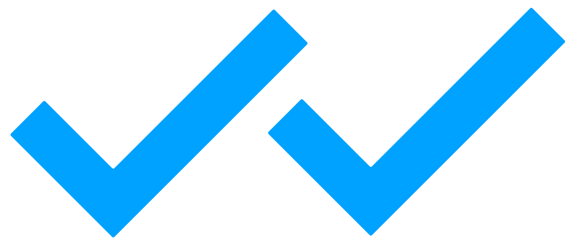

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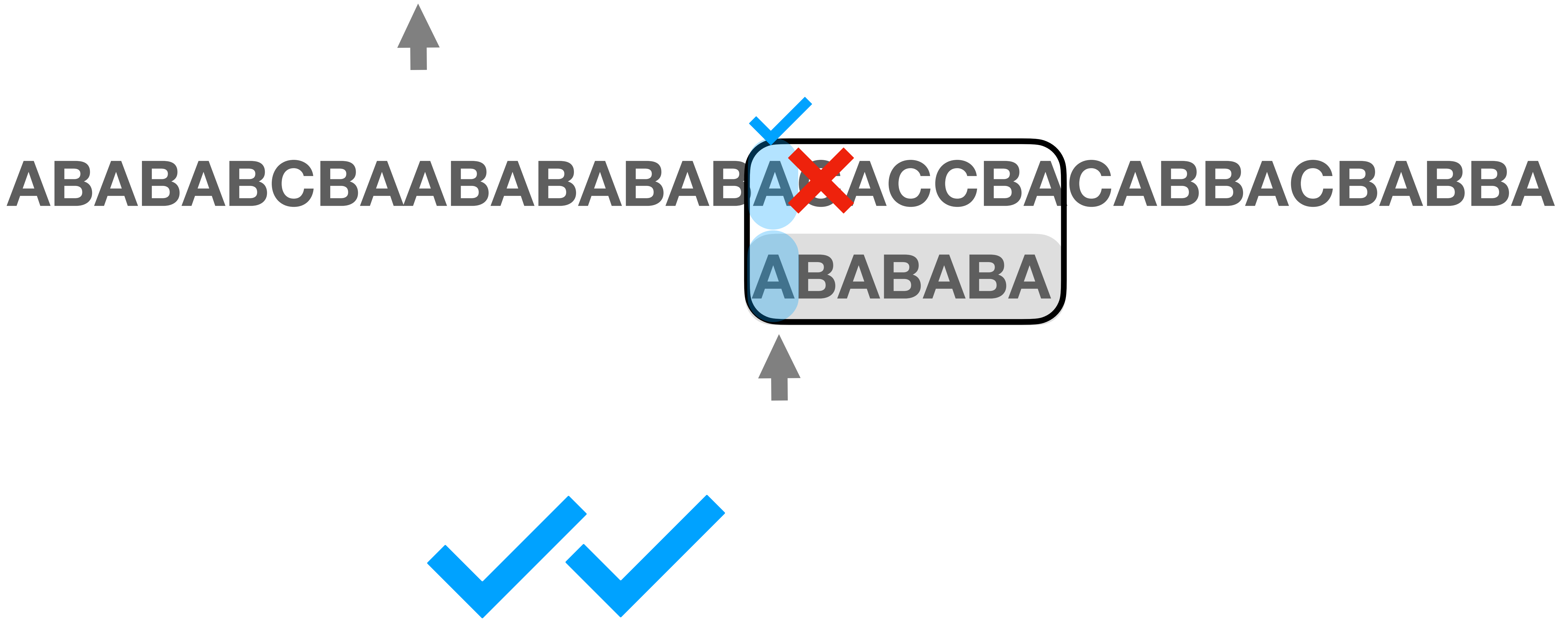

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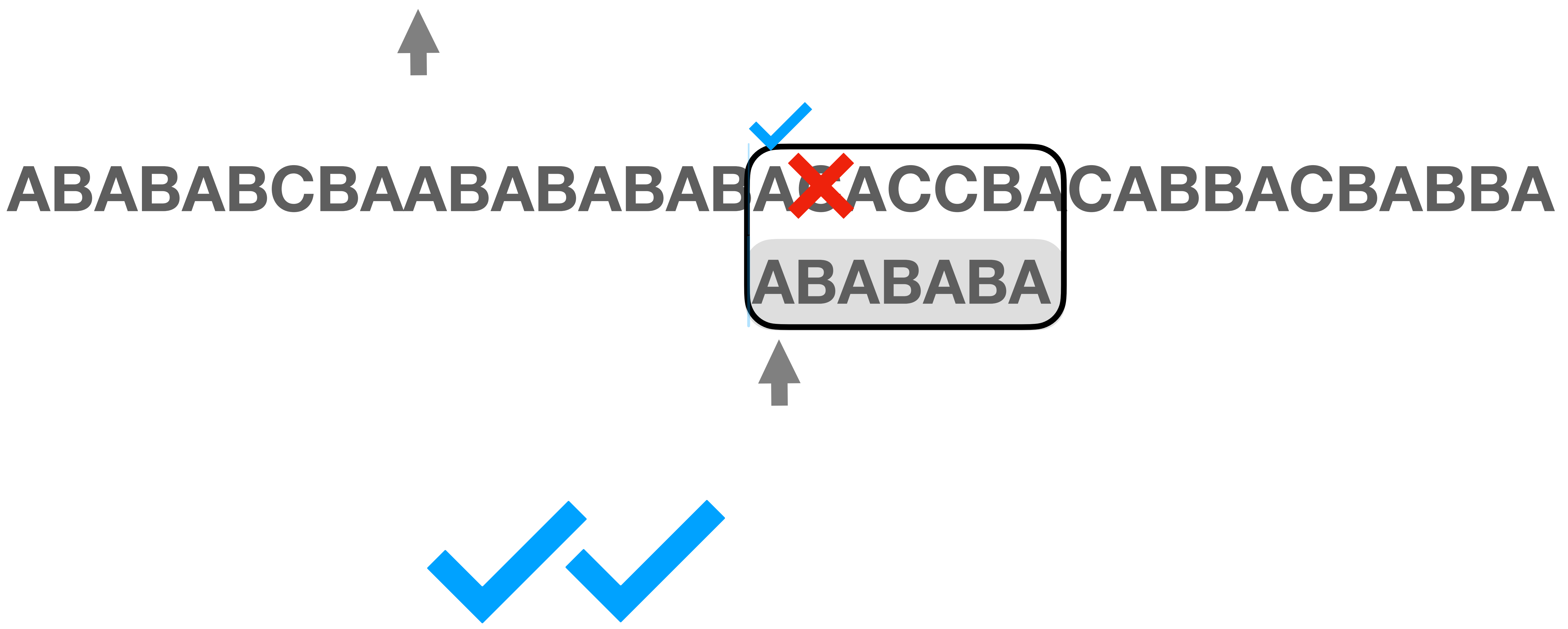

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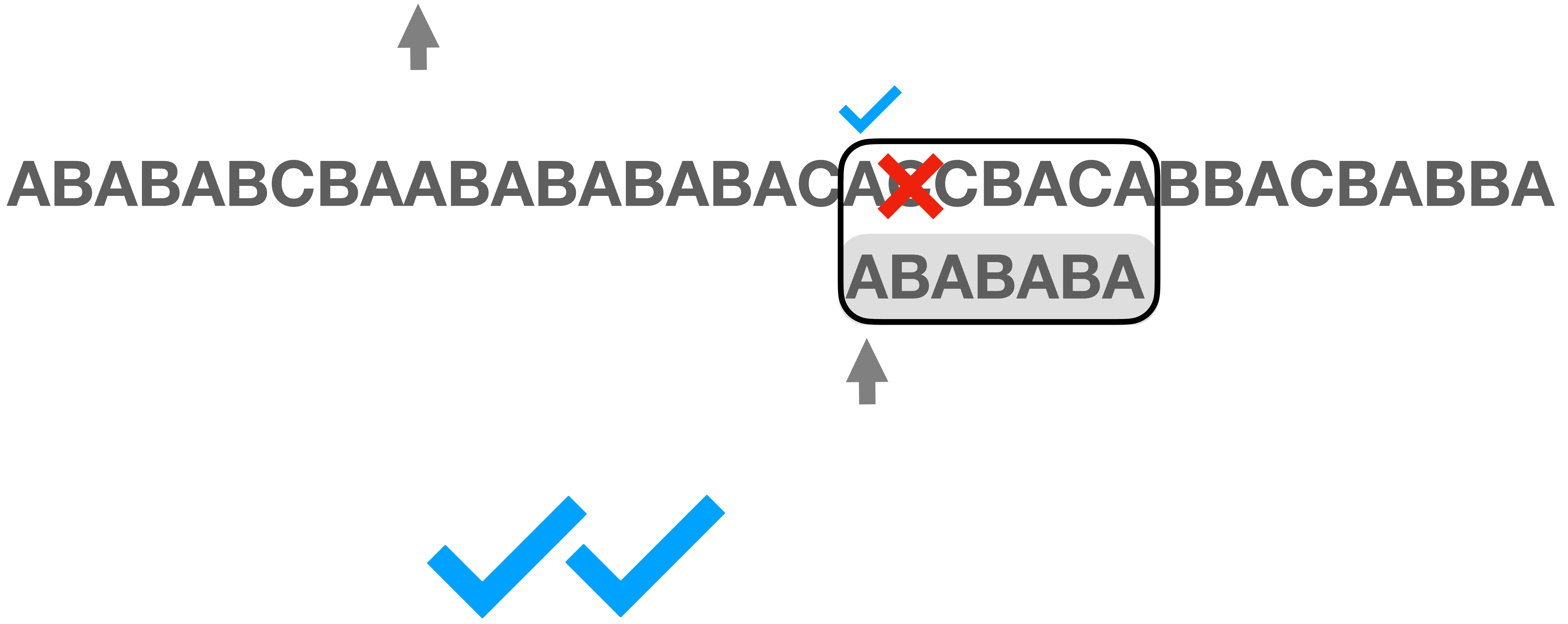

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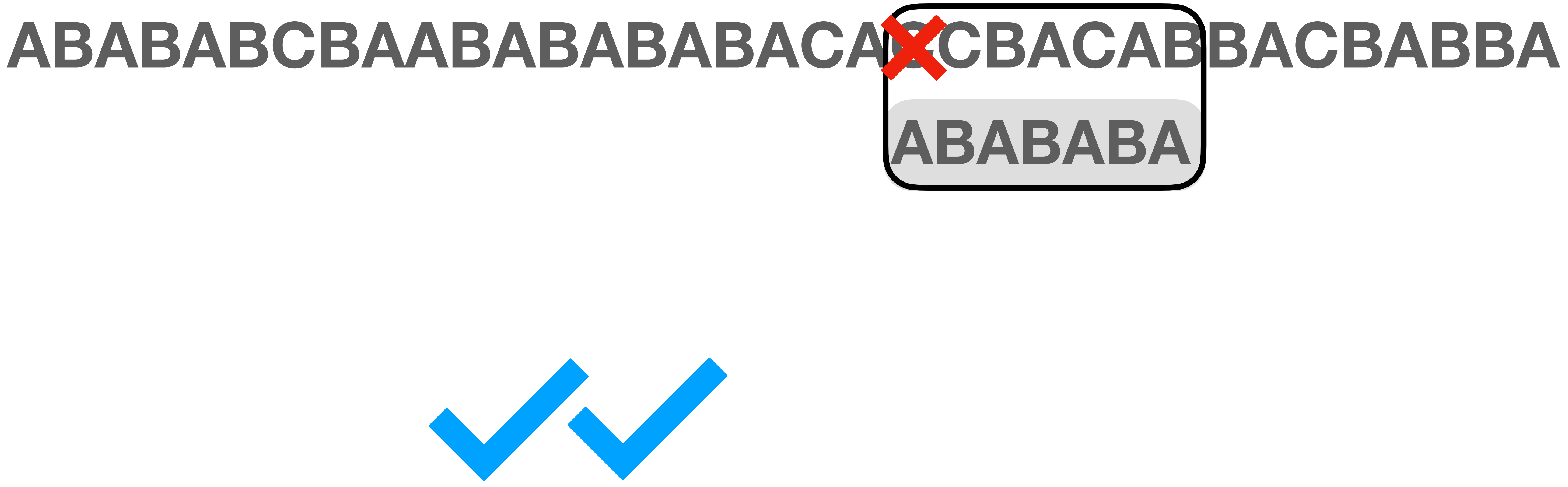

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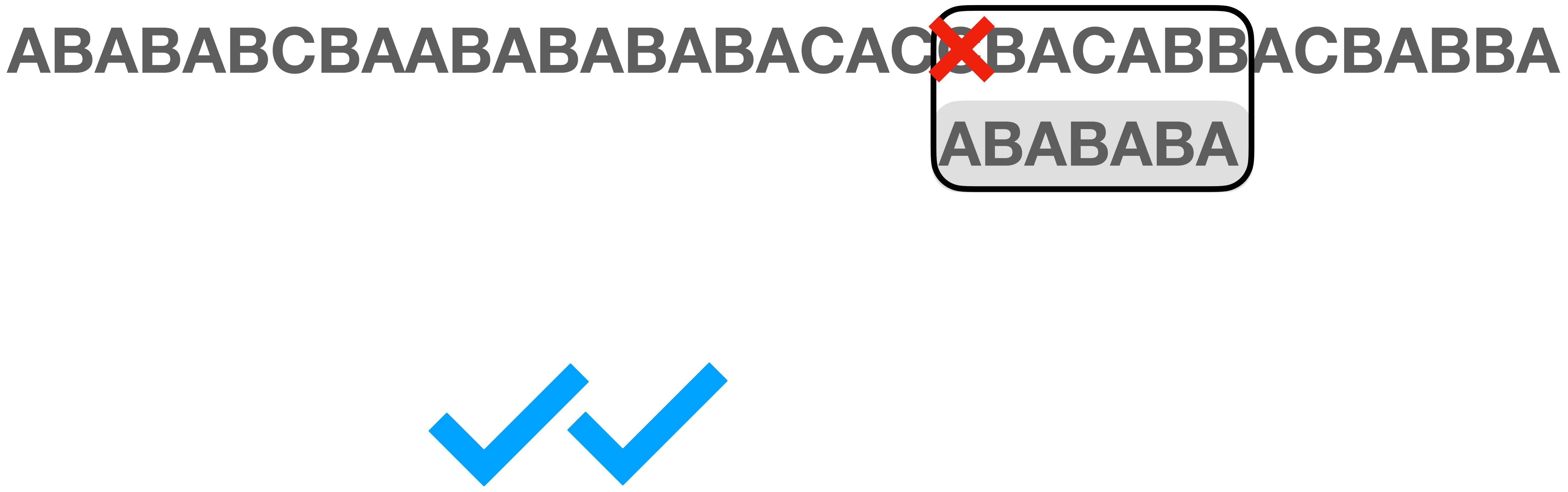

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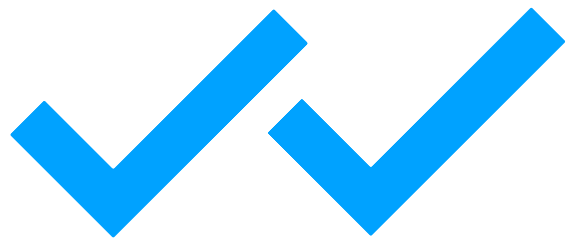

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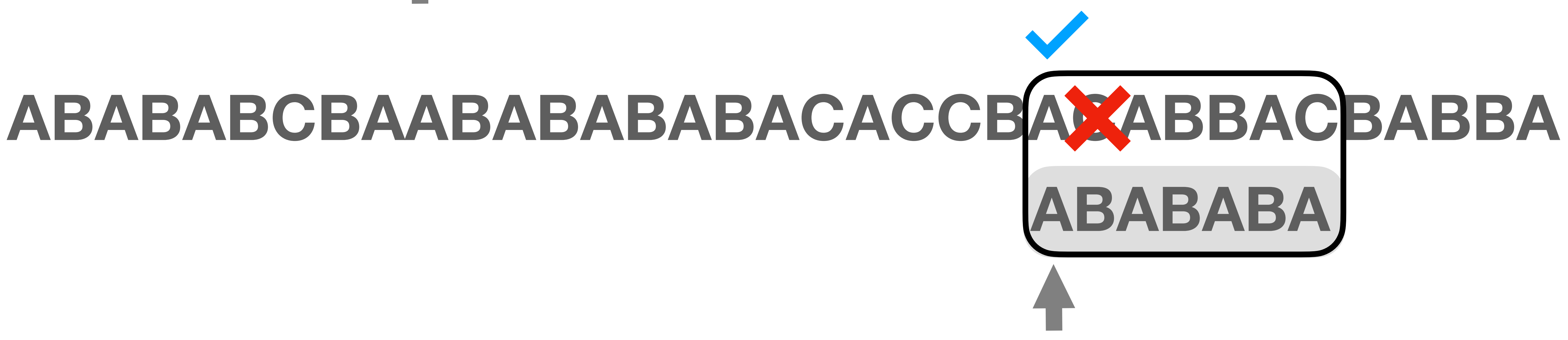

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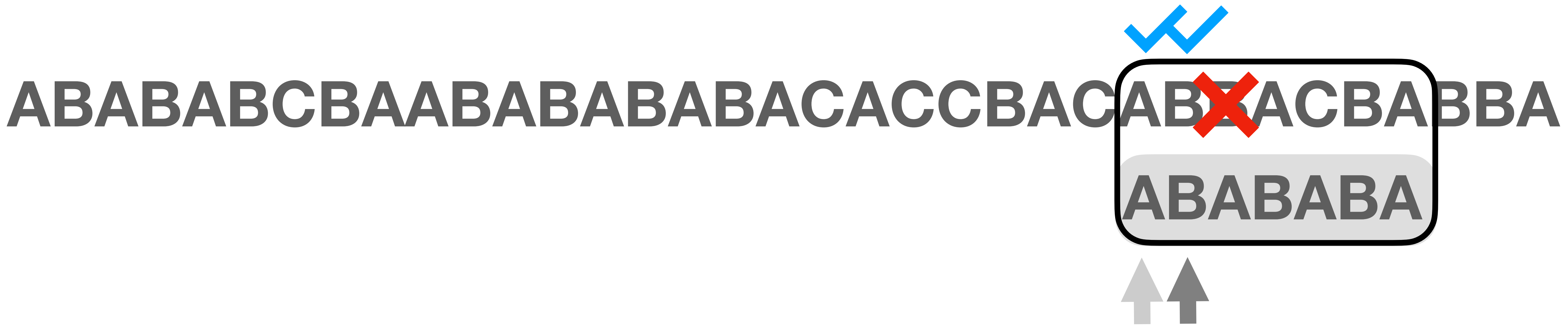

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Considerations:

- **Computation time:**
  - **O(1), O(n), O(n^2), O(n log(n)), etc**
  - Worst case? Best case? Average case?
- **Stable sort:**
  Is the order of elements with the same value maintained?
  yes = **stable sort**
- **In place:**
  Is the array sorted in place?
- **Auxiliary storage:**
  How much extra storage is required?

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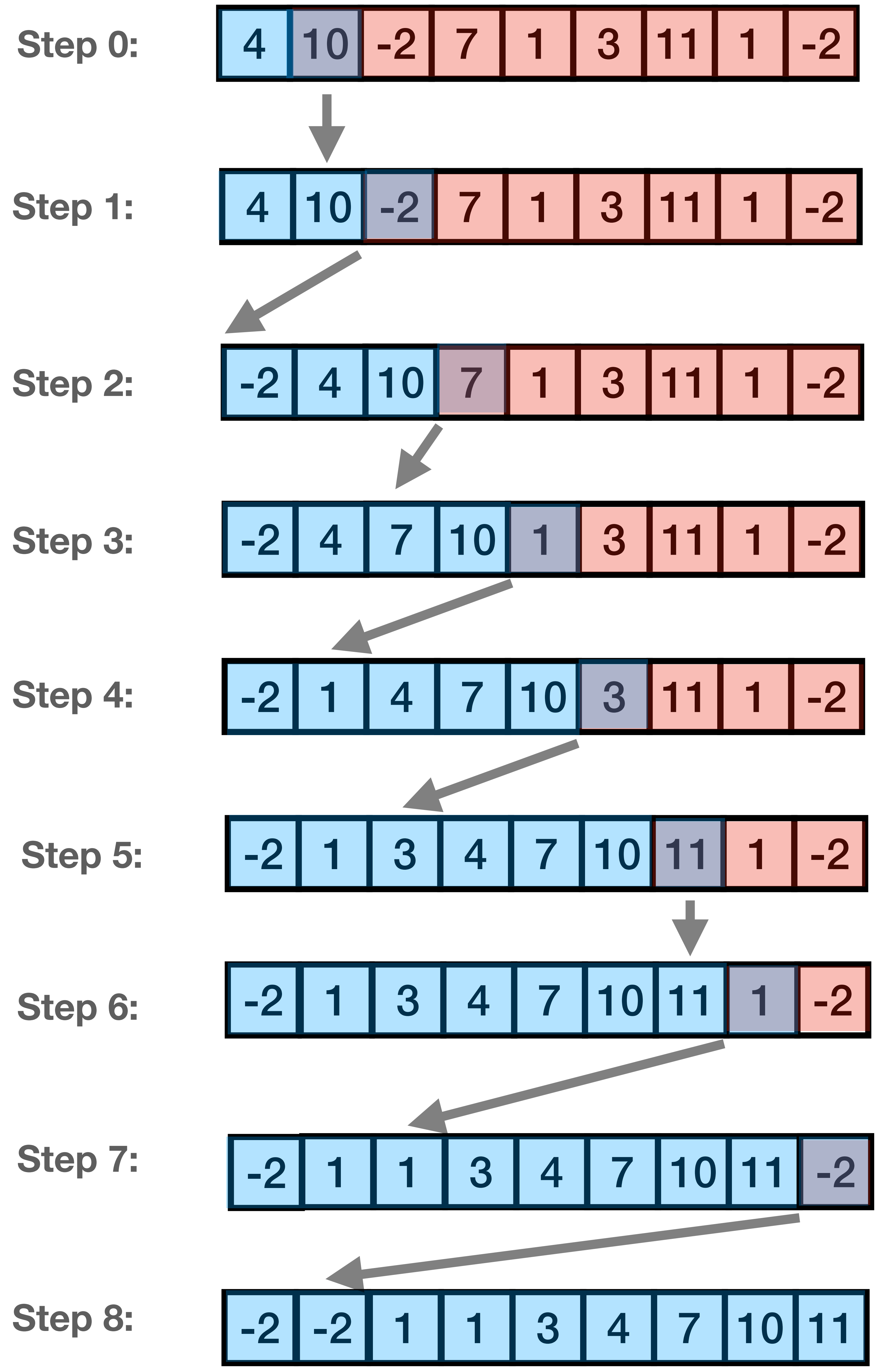
- Flood Fill Algorithm

Insertion Sort:



Computation Cost:
Worst case: **O(n^2)**
Stable sort: **True**

When to use:
Stable, Quick and dirty

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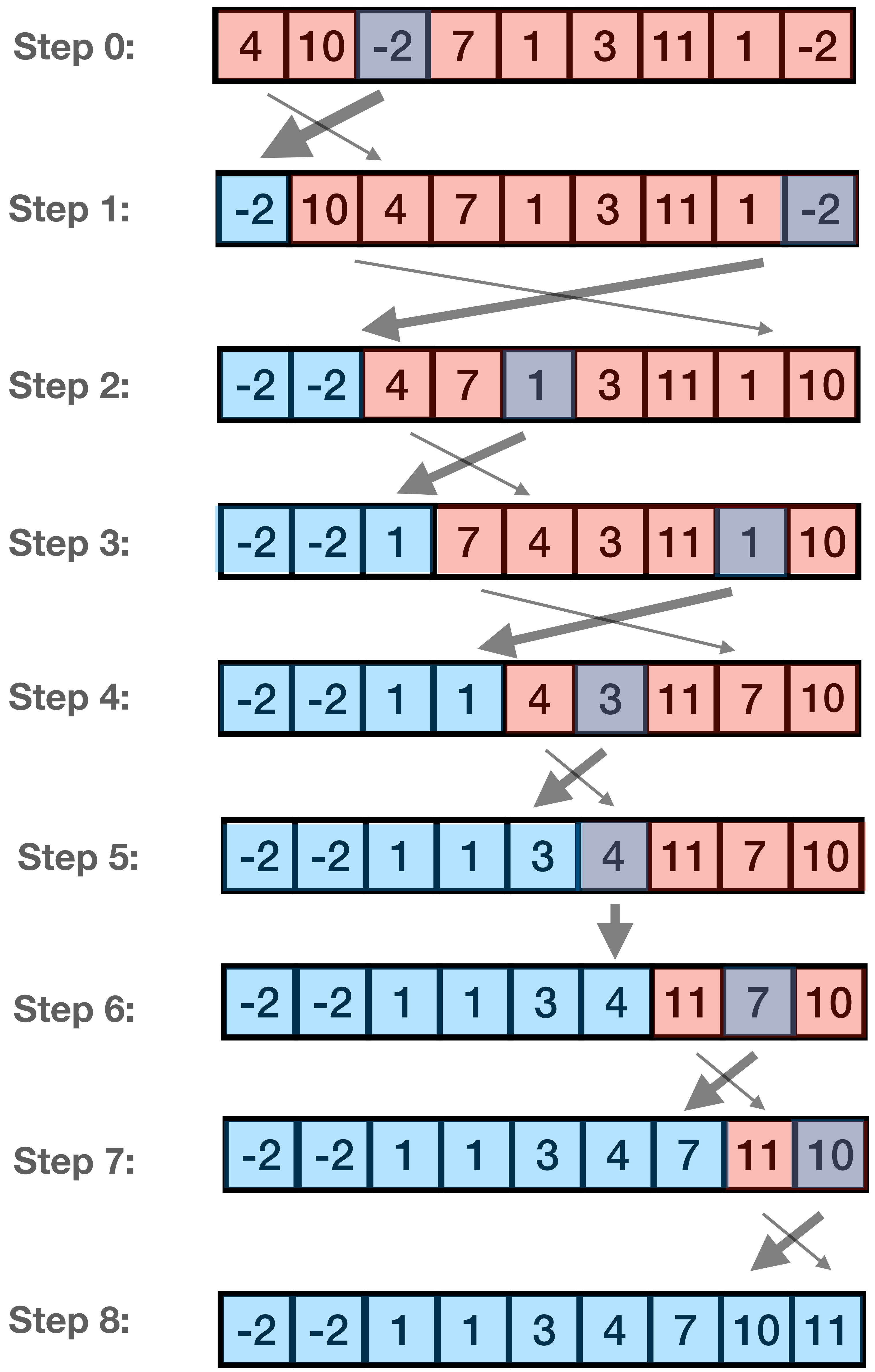
Selection Sort:



Computation Cost:
Cost: **O(n^2)**
Stable sort: **False**
In place: **True**

When to use:
Quick and dirty

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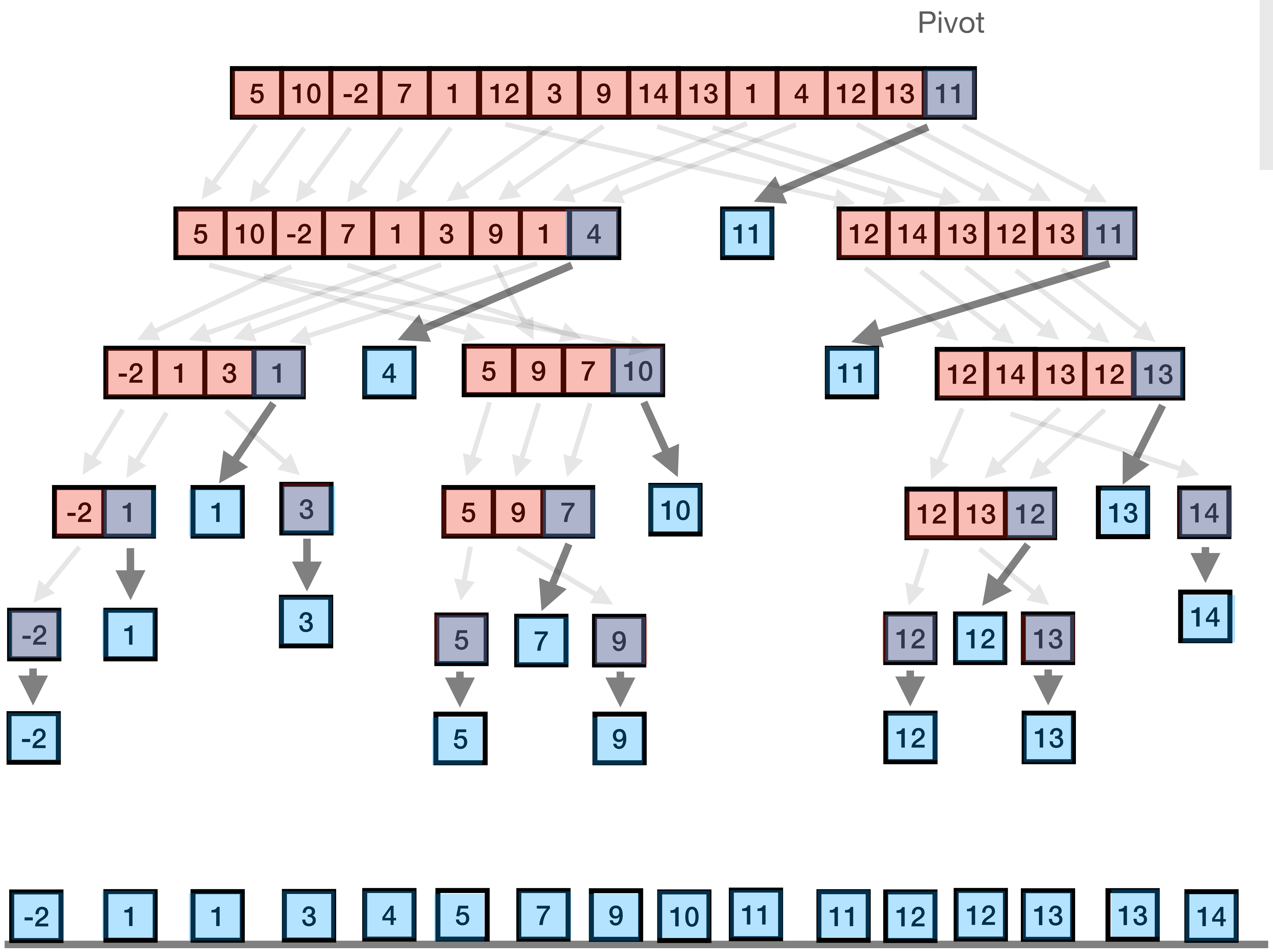
Quick Sort:



Computation Cost:
Average: **n log(n)**
Worst case: **n^2 (rare)**
Extra storage: **log(n)**
Stable: **False**
In place: **True**

When to use:
when you don't need a stable sort and average case is more important than worst case. A good implementation uses **O(log(n))** auxiliary storage.

Note:
Best performance happens when arrays split into similar sizes. Lopsided splits cause bad performance.

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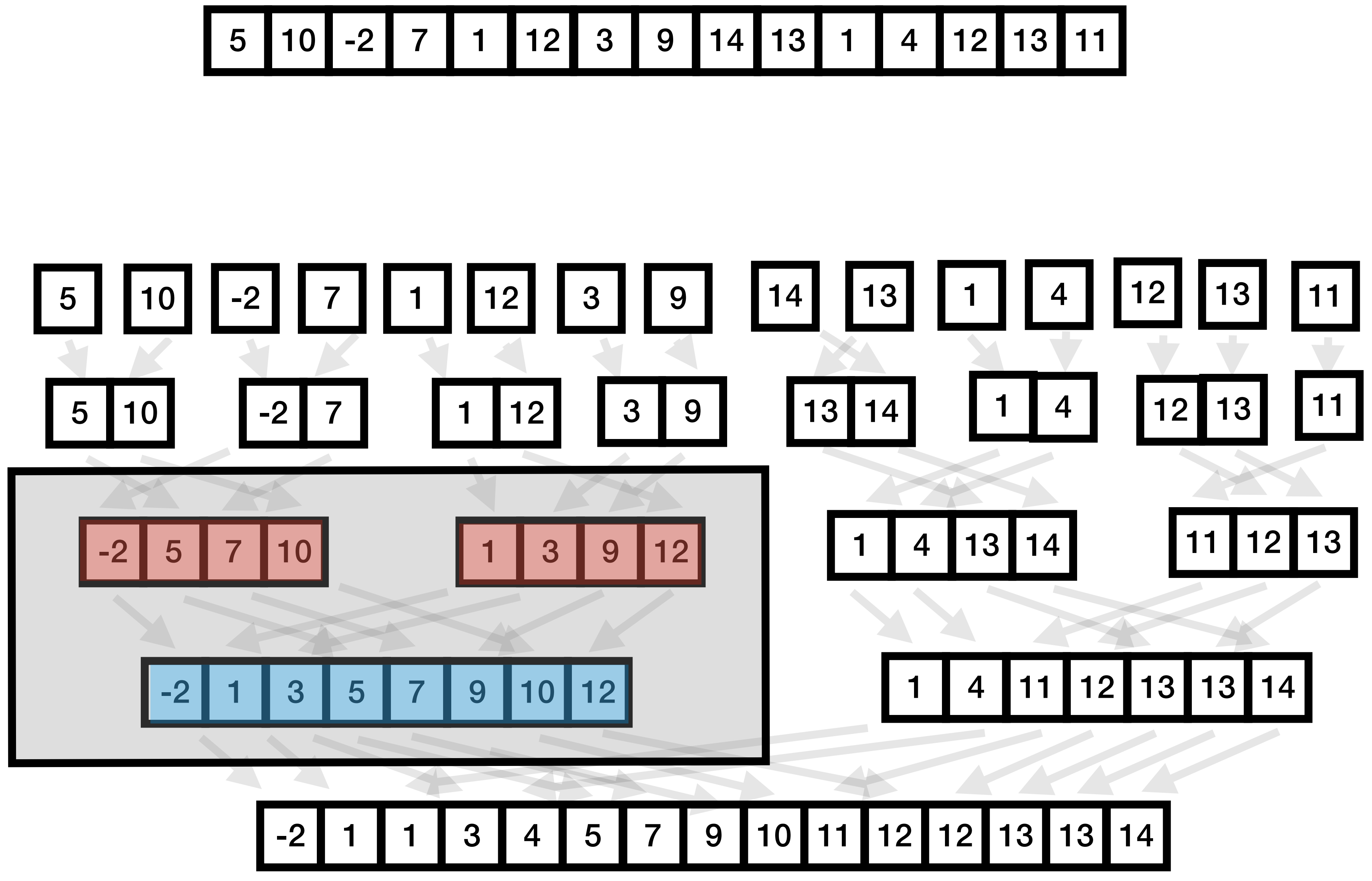
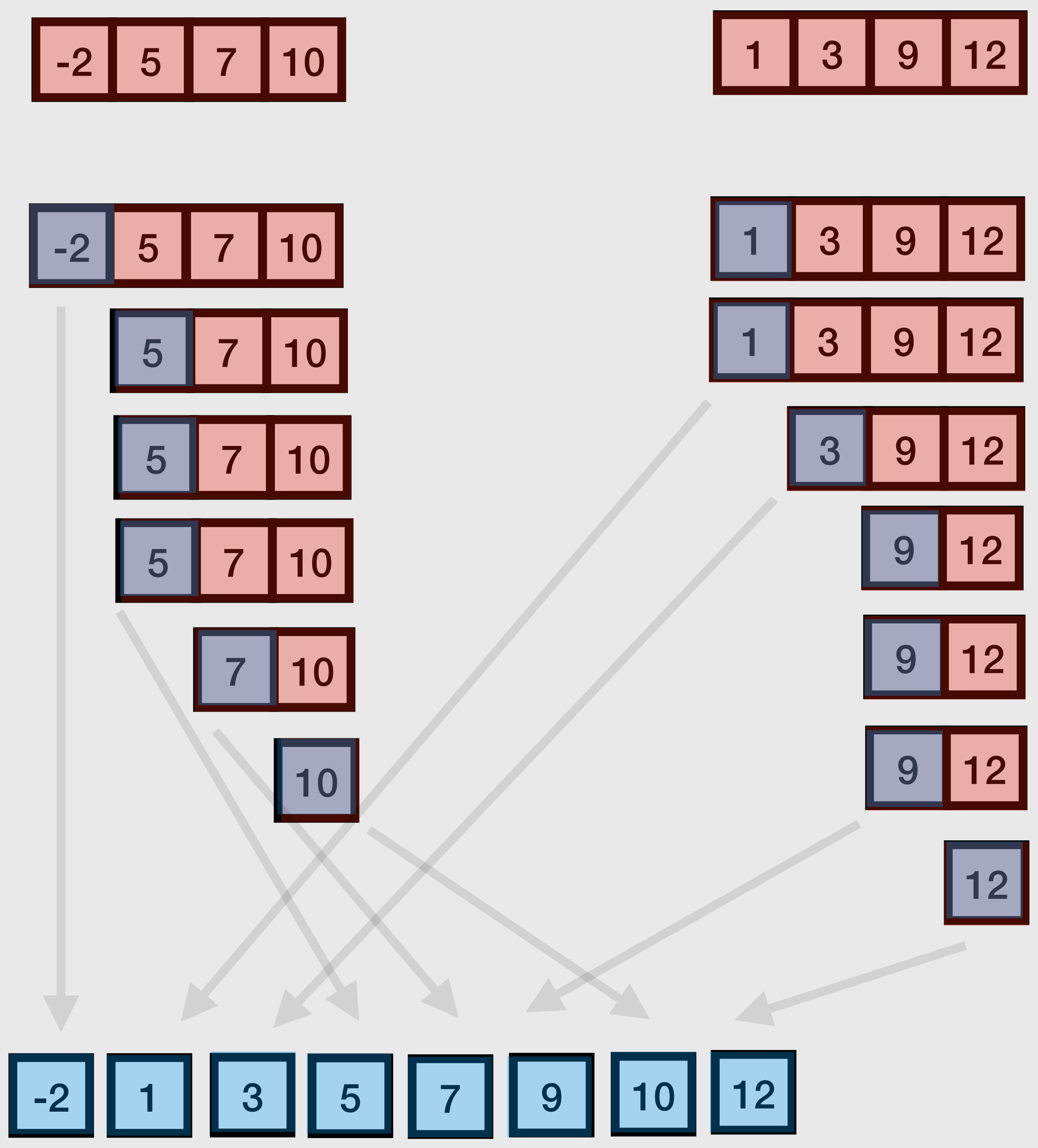
Merge Sort:



Computation Cost:
Worst case: **O(n log(n))**
Extra storage: **O(n)**
Stable: **True**
In place: **sub-optimal**

When to use:
when you need a stable **O(nlog(n))** sort. A downside is that it uses **O(n)** auxiliary space. In place options are suboptimal.

Merge Substep:



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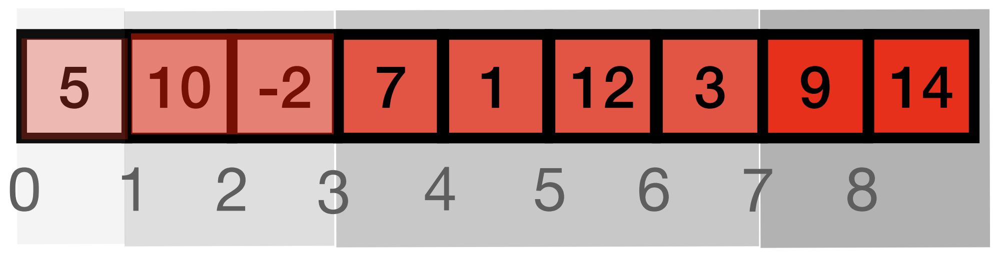
Heap Sort:

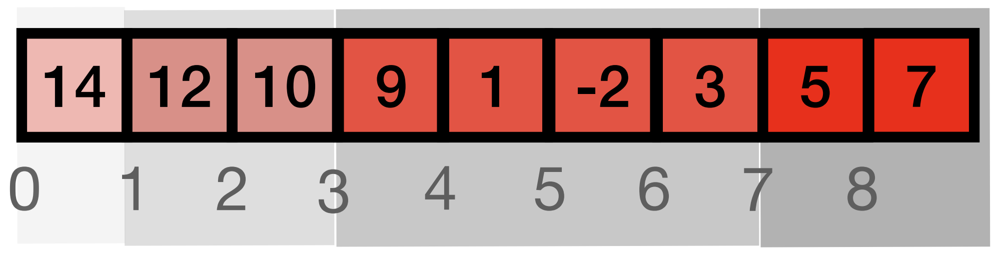
5	10	-2	7	1	12	3	9	14

Computation Cost:
Worst case: **O(nlog(n))**
Extra storage: **O(1)**
In place: **possible**
Stable: **False**

Uses a data structure called a heap…

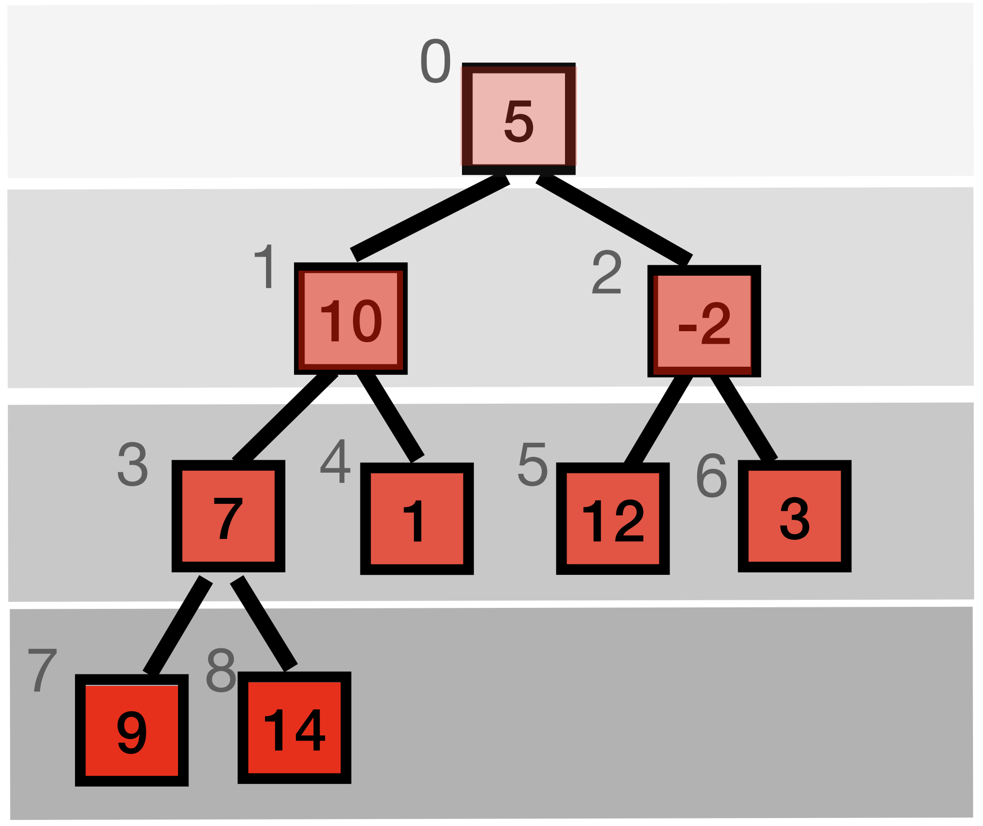
index:



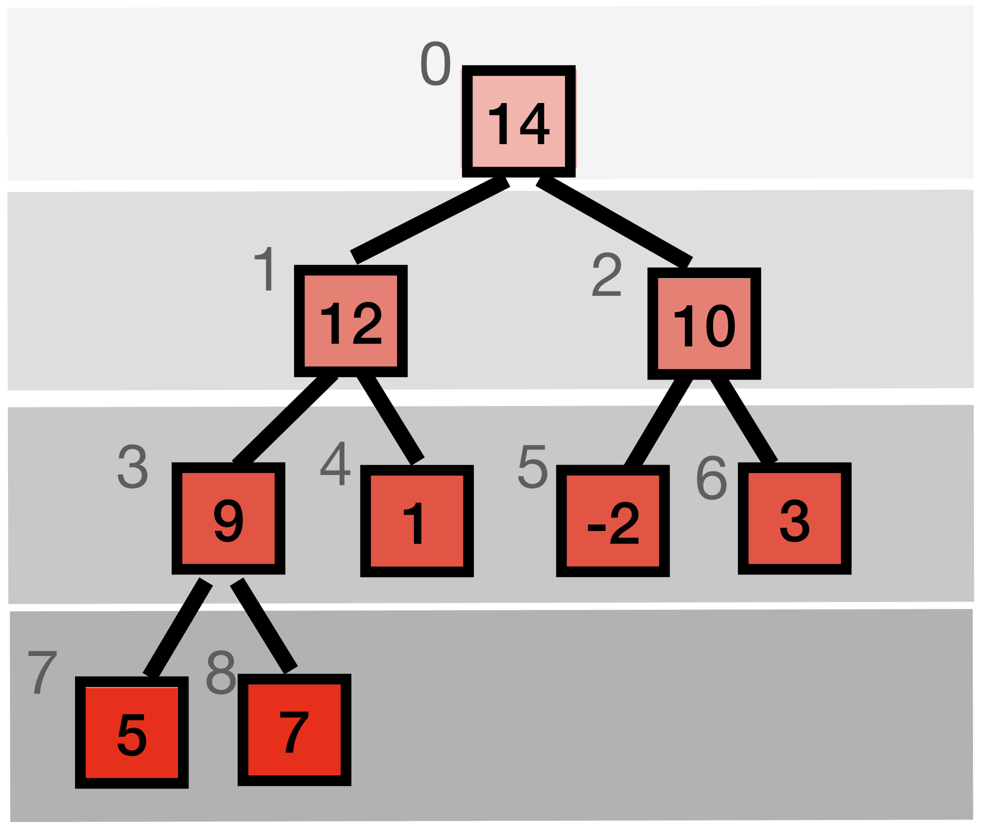


- usually slower than quicksort
- better worst case performance

Heap



Max Heap



When to use:
when you don't need a stable sort and you care more about worst case performance than average. Also uses constant auxiliary storage space.

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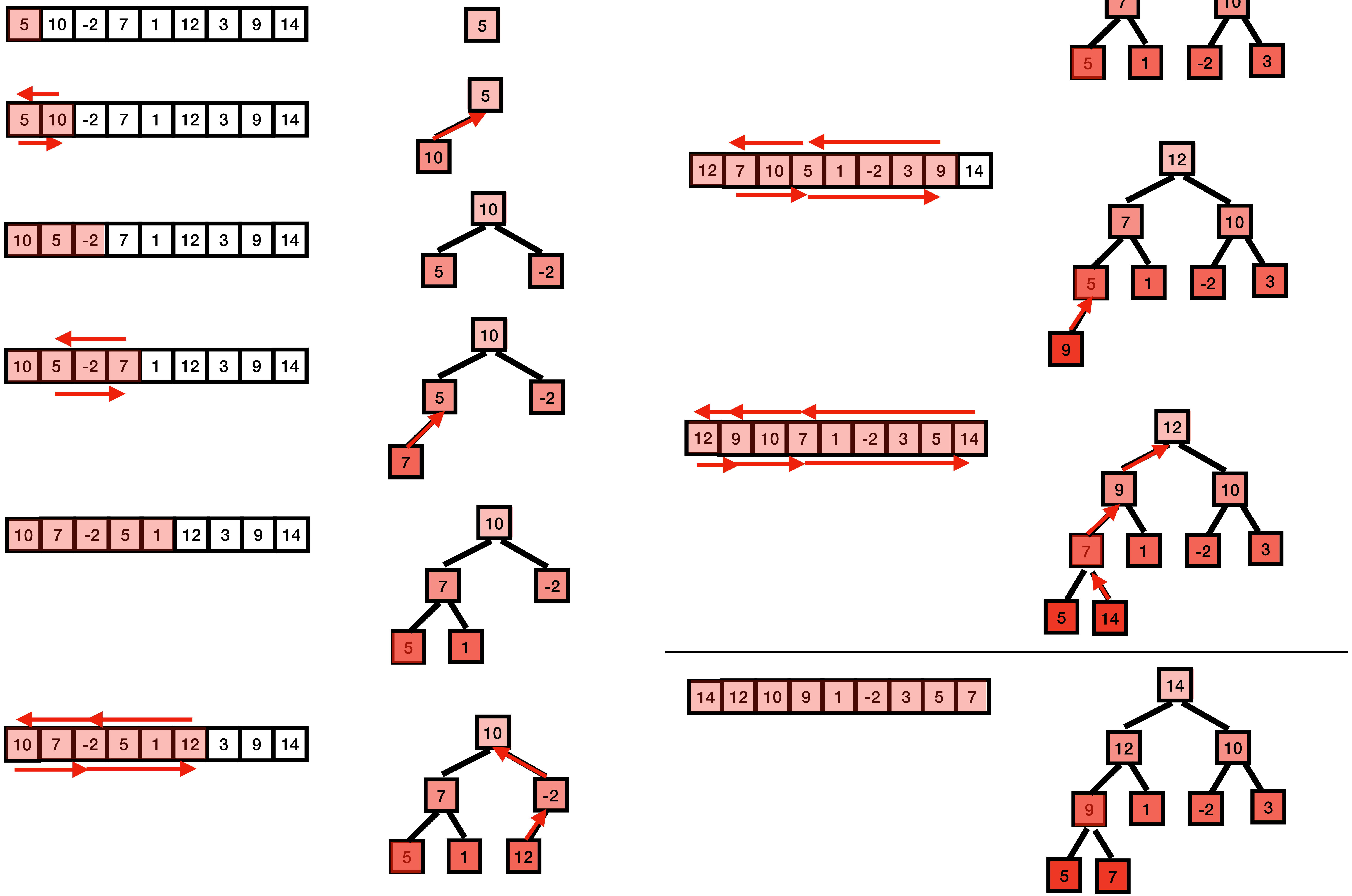
… build max heap



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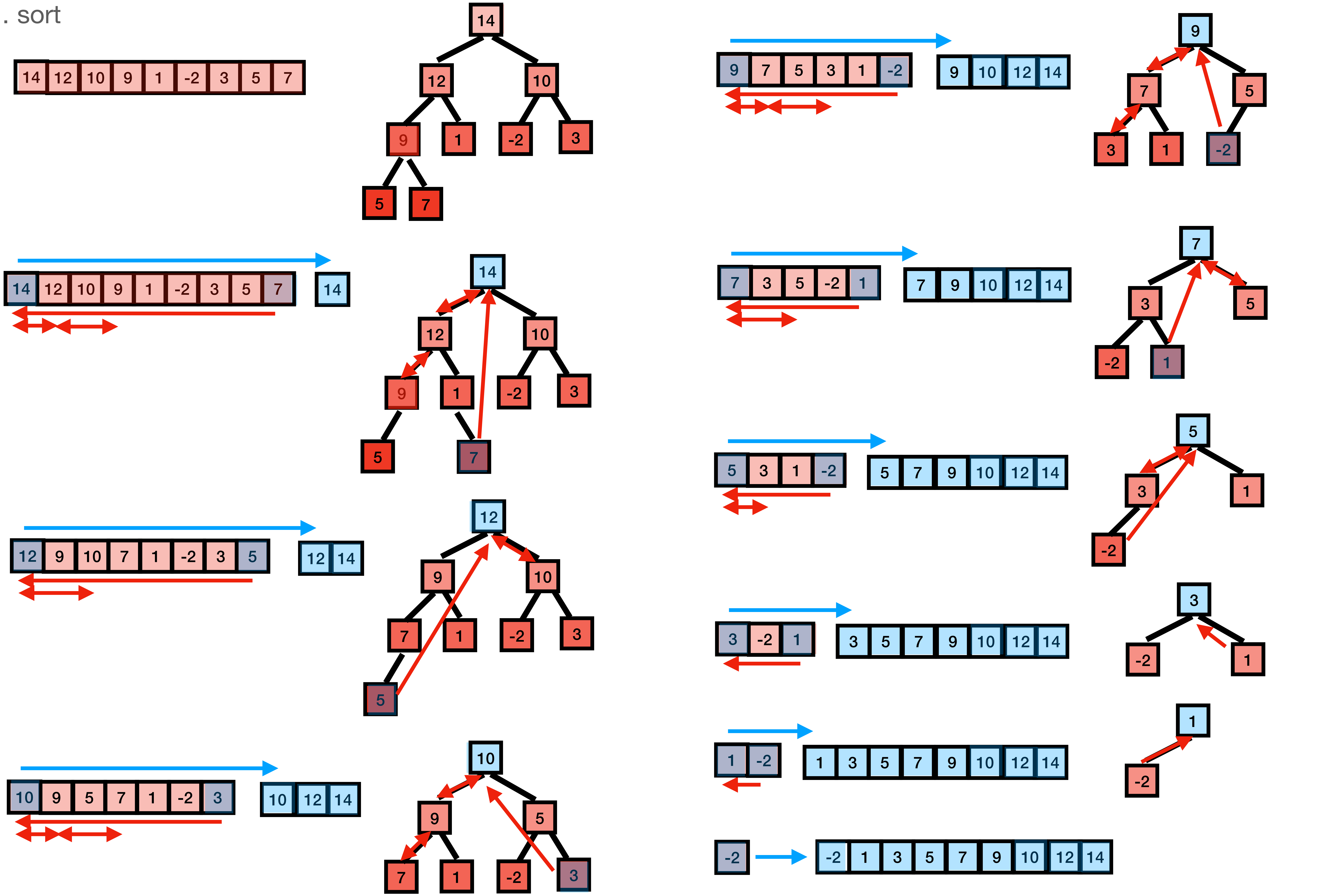
… sort



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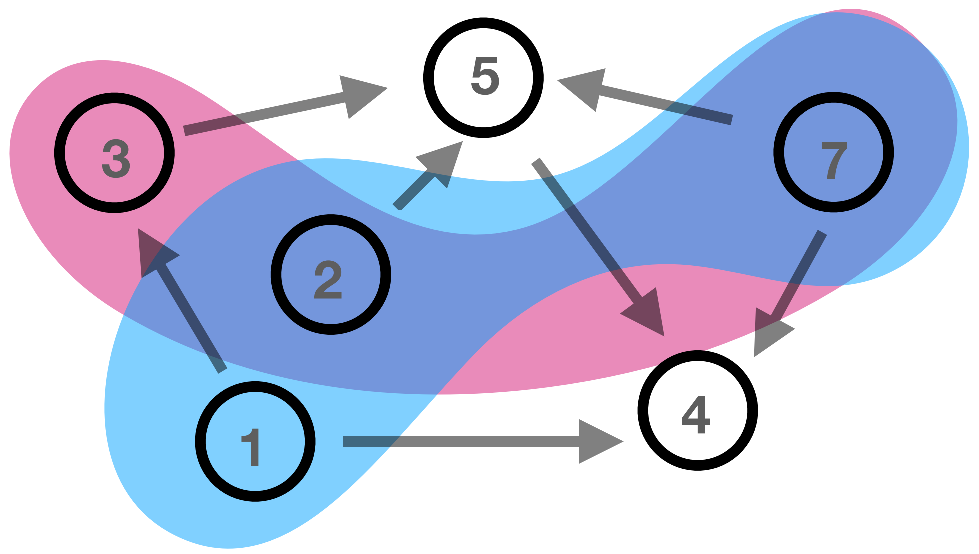
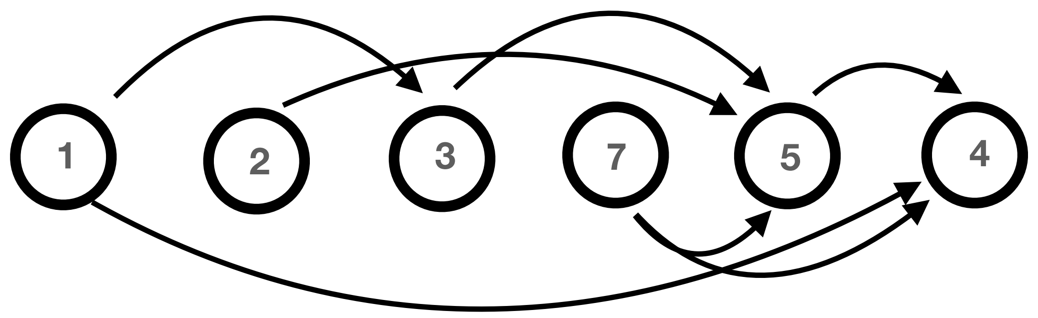


Computation Cost:
Cost: **O(|V|+|E|))**



Directed Acyclic Graph (DAG)

…sort in order consistent with graph

many consistent sorting orders…

Options:

	1, 2, 7	**any order to start…**
if 1 before 3	3, 2, 7	**any order after 1…**
	5	**next to last**
	4	**last**

Acceptable sorts…

1, 2, 7, 3, 5, 4
1, 7, 2, 3, 5, 4
1, 3, 2, 7, 5, 4
2, 1, 3, 7, 5, 4
7, 2, 1, 3, 5, 4
⋮

Idea/Pseudo-code:

```
Initialize:
S = [ ];   sorted vertices
V = [ ];   vertices with no incoming edges

While S is non-empty:
    Move a vertex u from V to end of S
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If any edges left in graph
    "Graph has at least one cycle"
else:
    "S is a topological sort."
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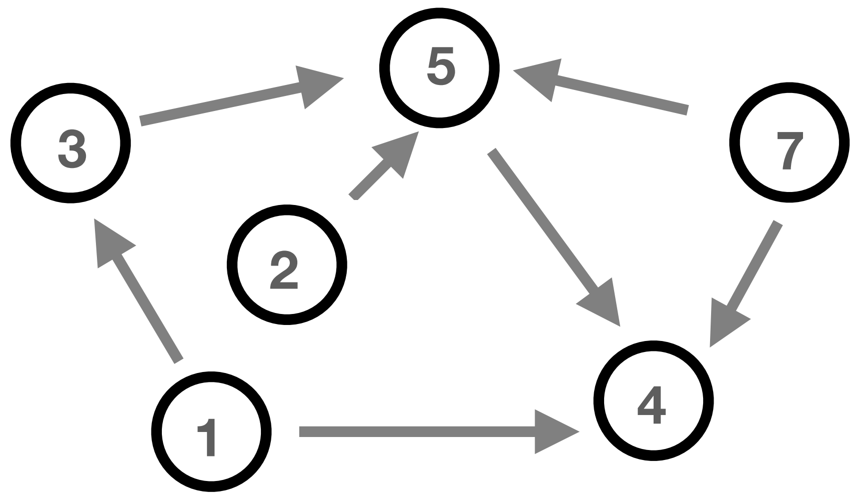

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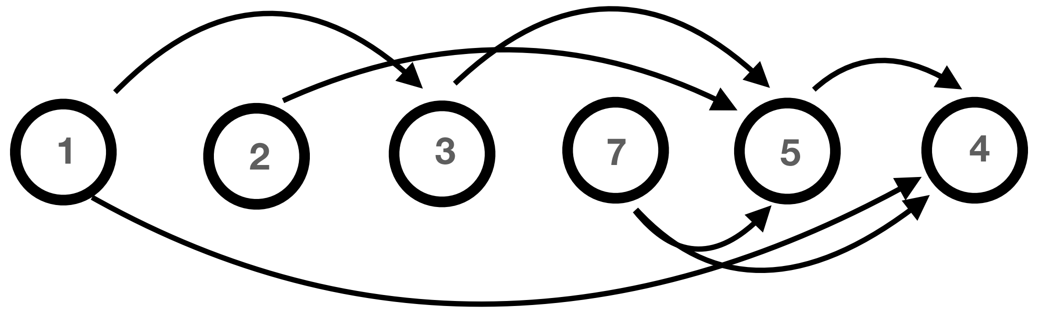

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    "Graph has at least one cycle"
else:
    "S is a topological sort."
```
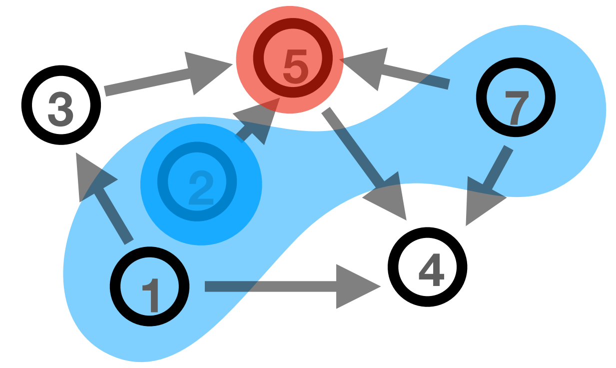

Algorithm:

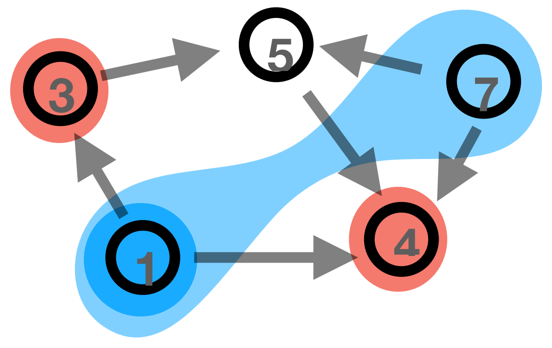
S = [ ]; V = [2, 1 , 7]; pick 2…

… move 2 to S and remove edge to 5
… (5 has other incoming edges)



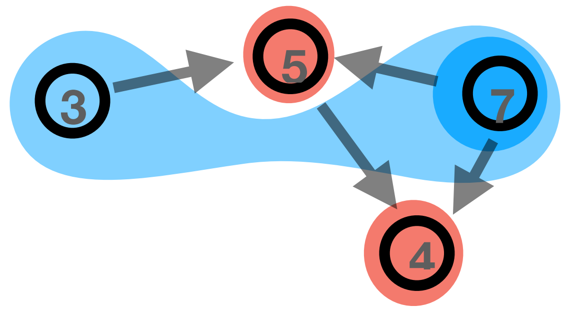
S = [2]; V = [1 , 7]; pick 1…

… move 1 to S and remove edges to 3 and 4
… add 3 to V, (4 has other incoming edges)



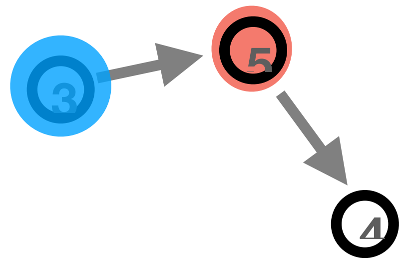
S = [2,1]; V = [7, 3]; pick 7…

… move 7 to S and remove edges to 4 and 5
… (4 and 5 have other incoming edges)



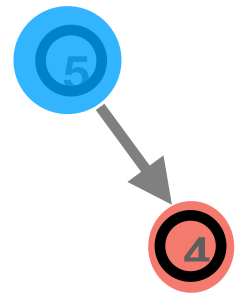
S = [2,1,7]; V = [3]; pick 3…

… move 3 to S and remove edge to 5
… add 5 to V



S = [2,1,7,3]; V = [5]; pick 5…

… move 5 to S and remove edge to 4
… add 4 to V



S = [2,1,7,3,5]; V = [4]; pick 4…

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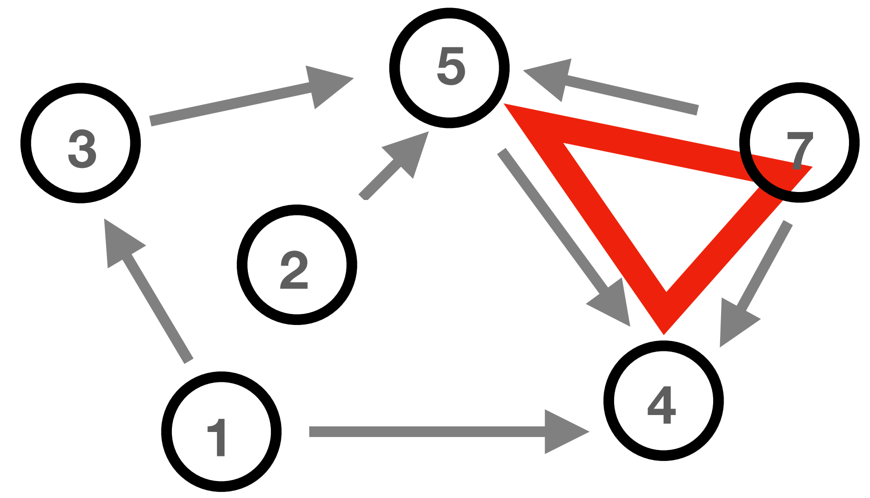

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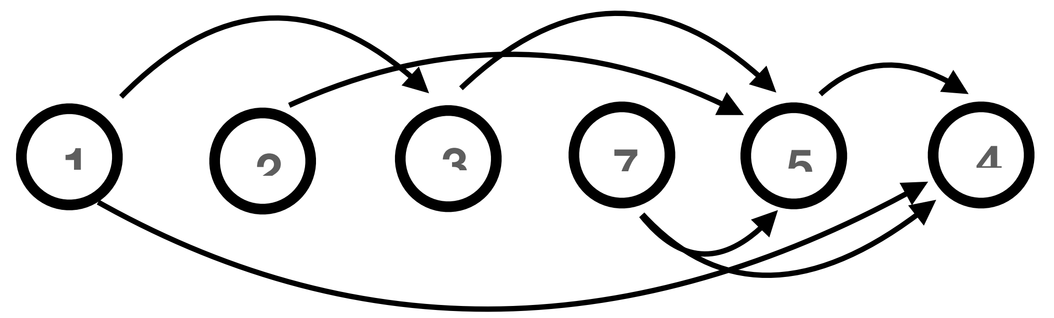

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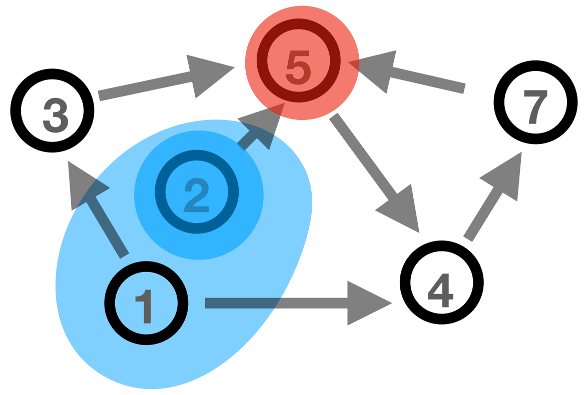

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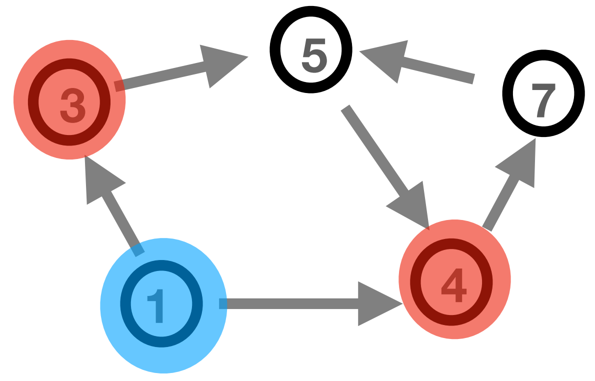

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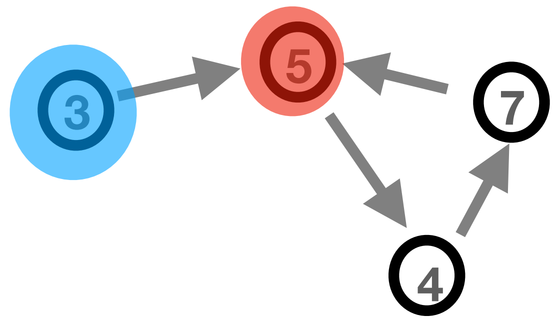
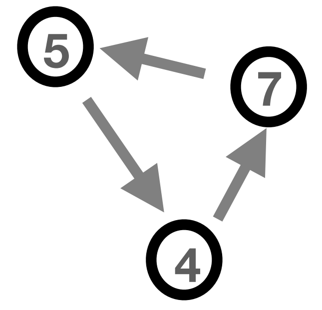


S = [2,1,3]; V = [ ];



V empty but still edges left…

Graph contains a directed cycle.

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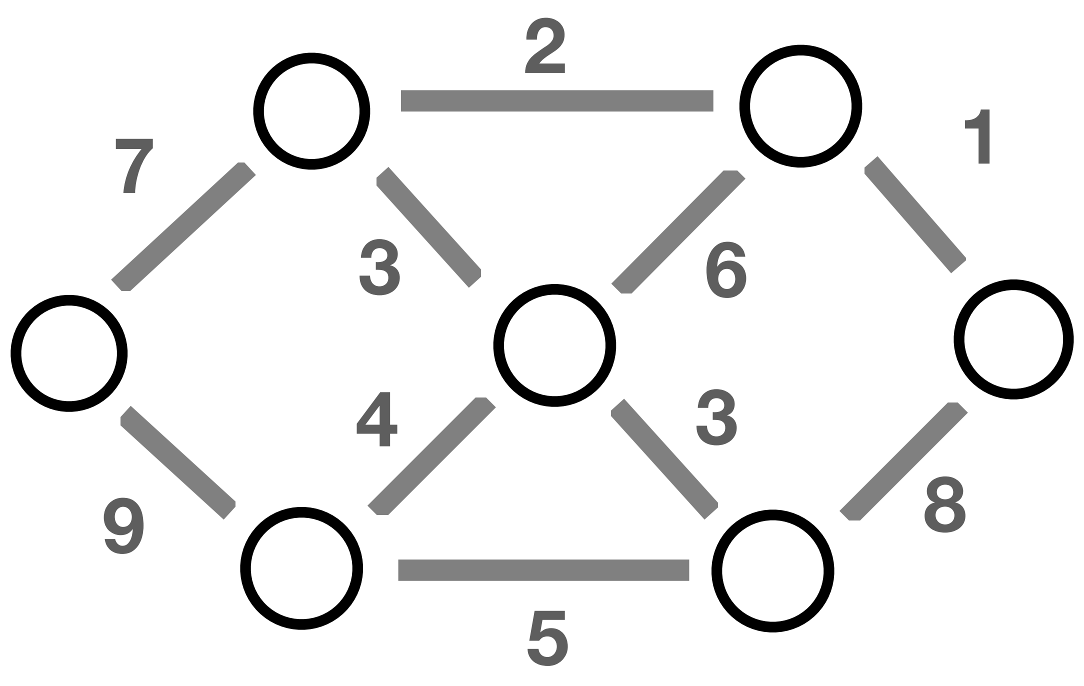
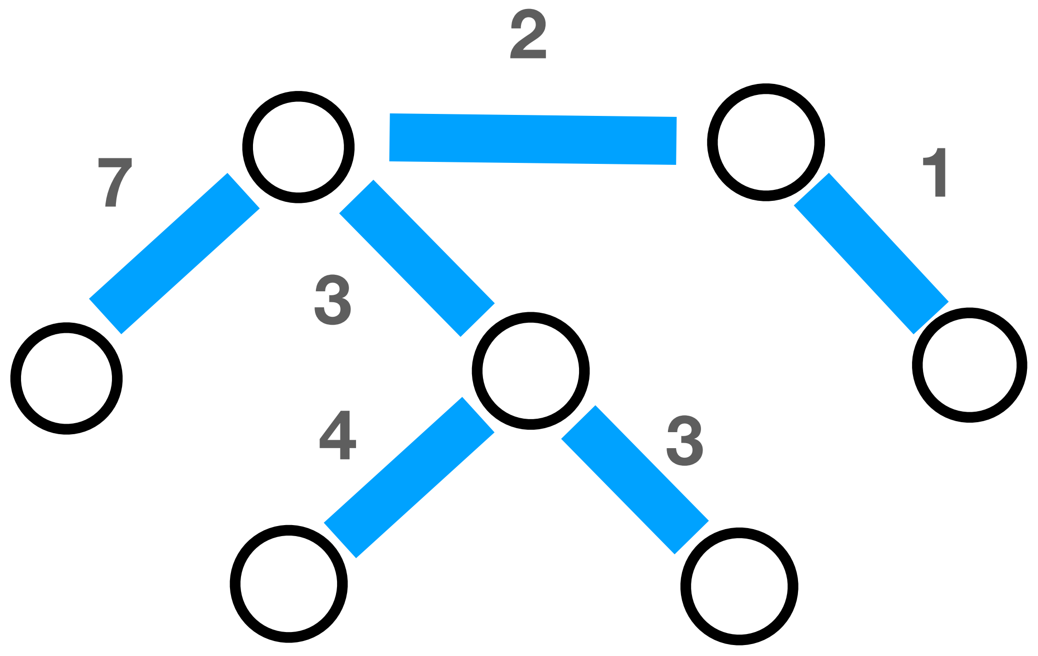
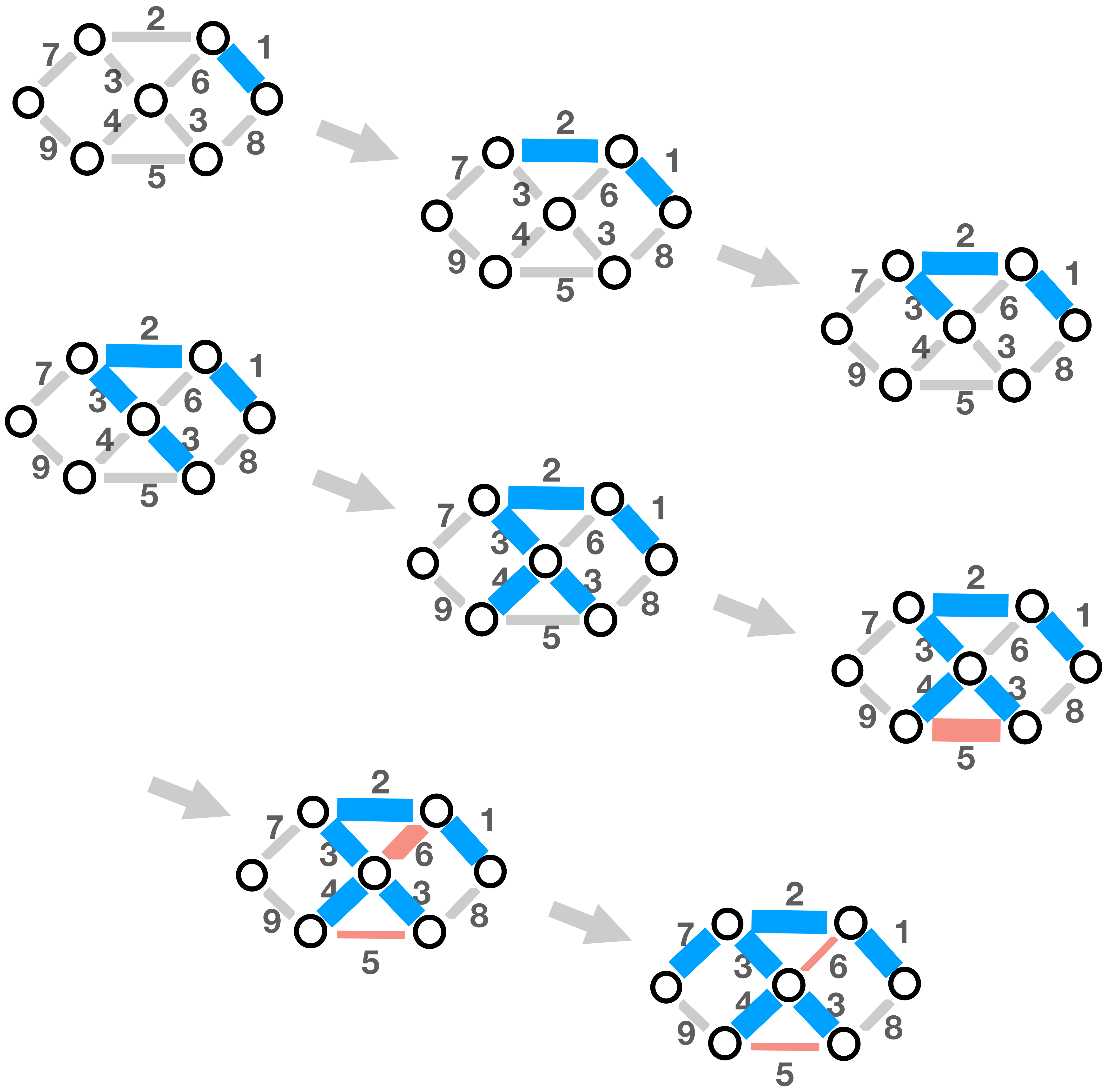
Kruskal's Algorithm:

…for minimum spanning tree

- **N vertices**
- min spanning tree has **n-1 edges**







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Union-Find or Merge-Find

Computation Cost:
Cost: **O(|V|^3))**

Data Structure: Disjoint Sets

Two Operations:

- Find: find set that contains any element (represented by *representative element*)

- Union: combine sets

each set often stored as a tree…

Disjoint-set Forest

Set: represented as a tree

Representative: root of tree

Find: follows parent nodes to the root

Union: attach root of one set to root of the other

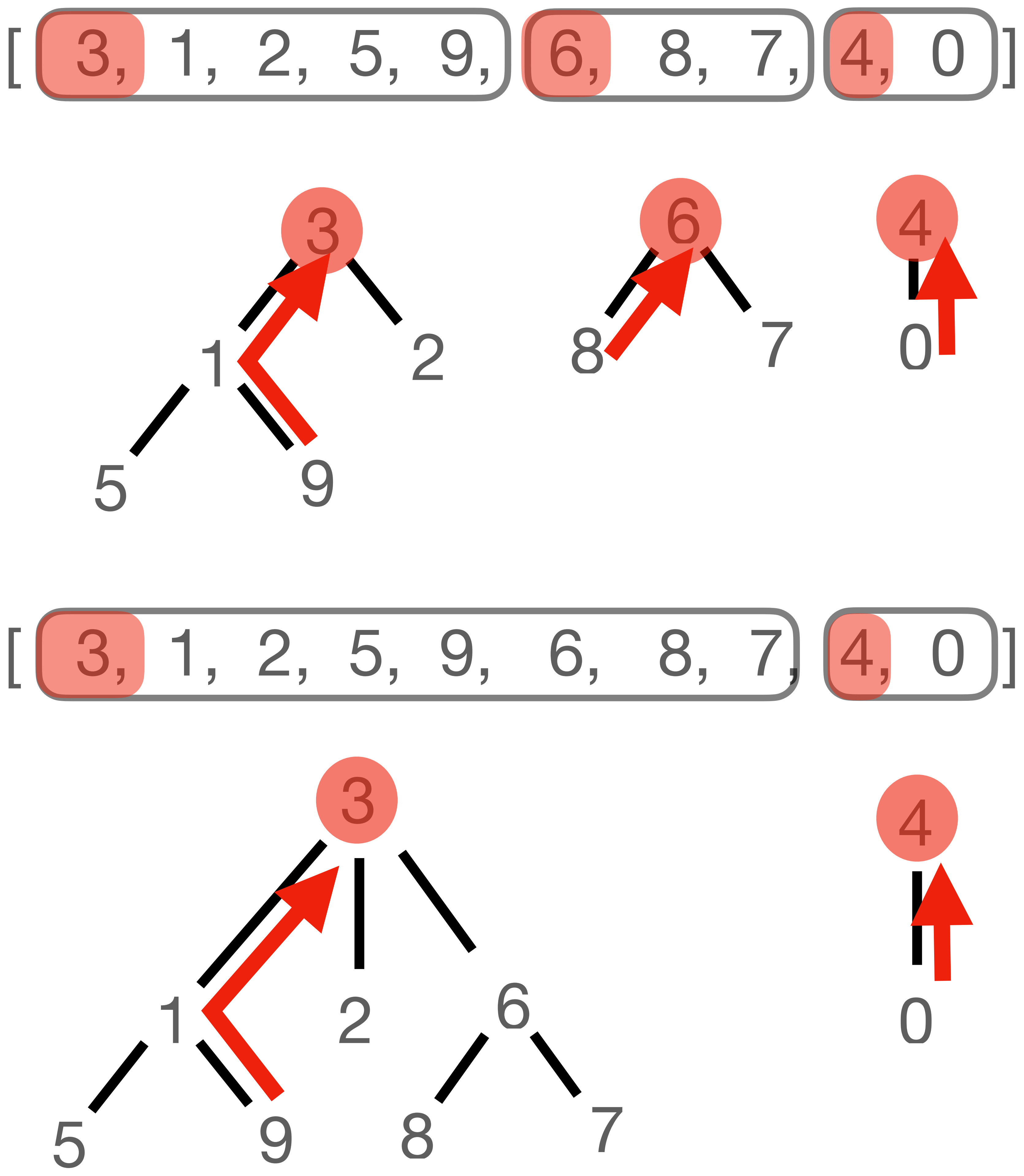
Not better than other ways to implement sets (ie. linked lists, etc) unless

1. Union by rank

Smaller (shallower) tree attached to root of larger (deeper) tree

2. Path compression

Move nodes up to too whenever Find is called



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Search Algorithms
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Union-Find or Merge-Find

Computation Cost:
Cost: **O(|V|^3))**

Data Structure: Disjoint Sets

Two Operations:

- Find: find set that contains any element (represented by *representative element*)

- Union: combine sets

each set often stored as a tree…

Disjoint-set Forest

Set: represented as a tree

Representative: root of tree

Find: follows parent nodes to the root

Union: attach root of one set to root of the other

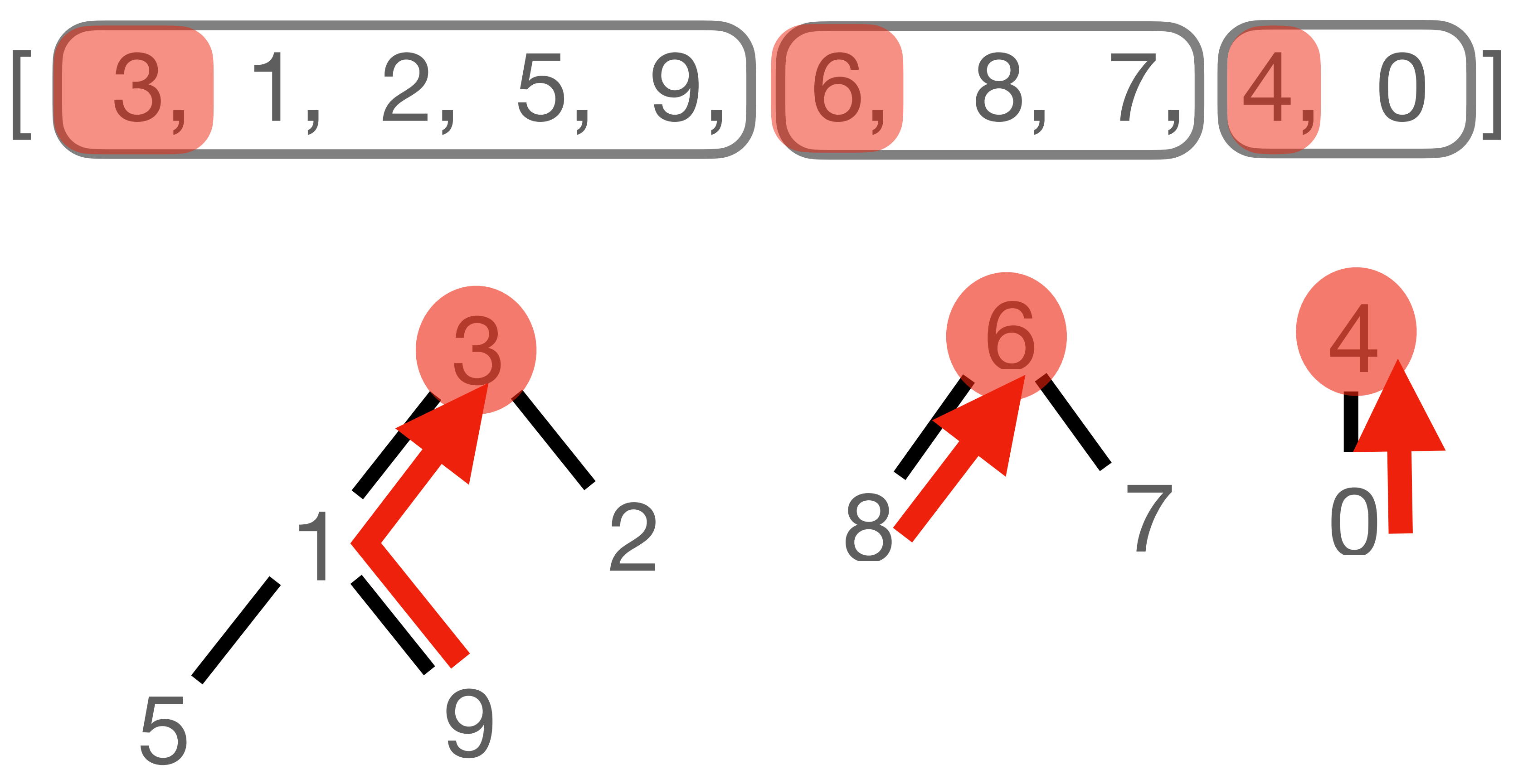
Not better than other ways to implement sets (ie. linked lists, etc) unless

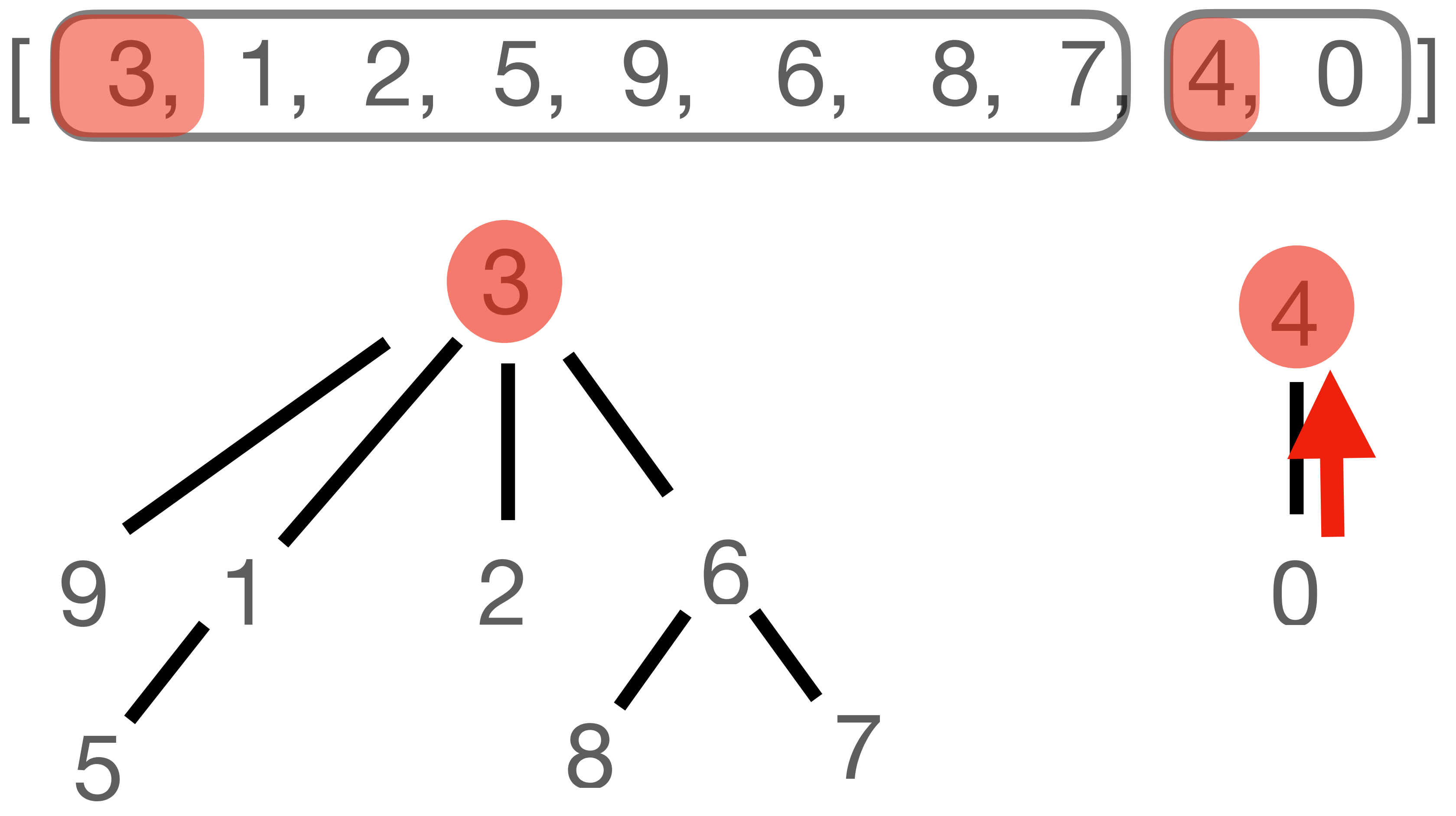
1. Union by rank

Smaller (shallower) tree attached to root of larger (deeper) tree

2. Path compression

Move nodes up to too whenever Find is called





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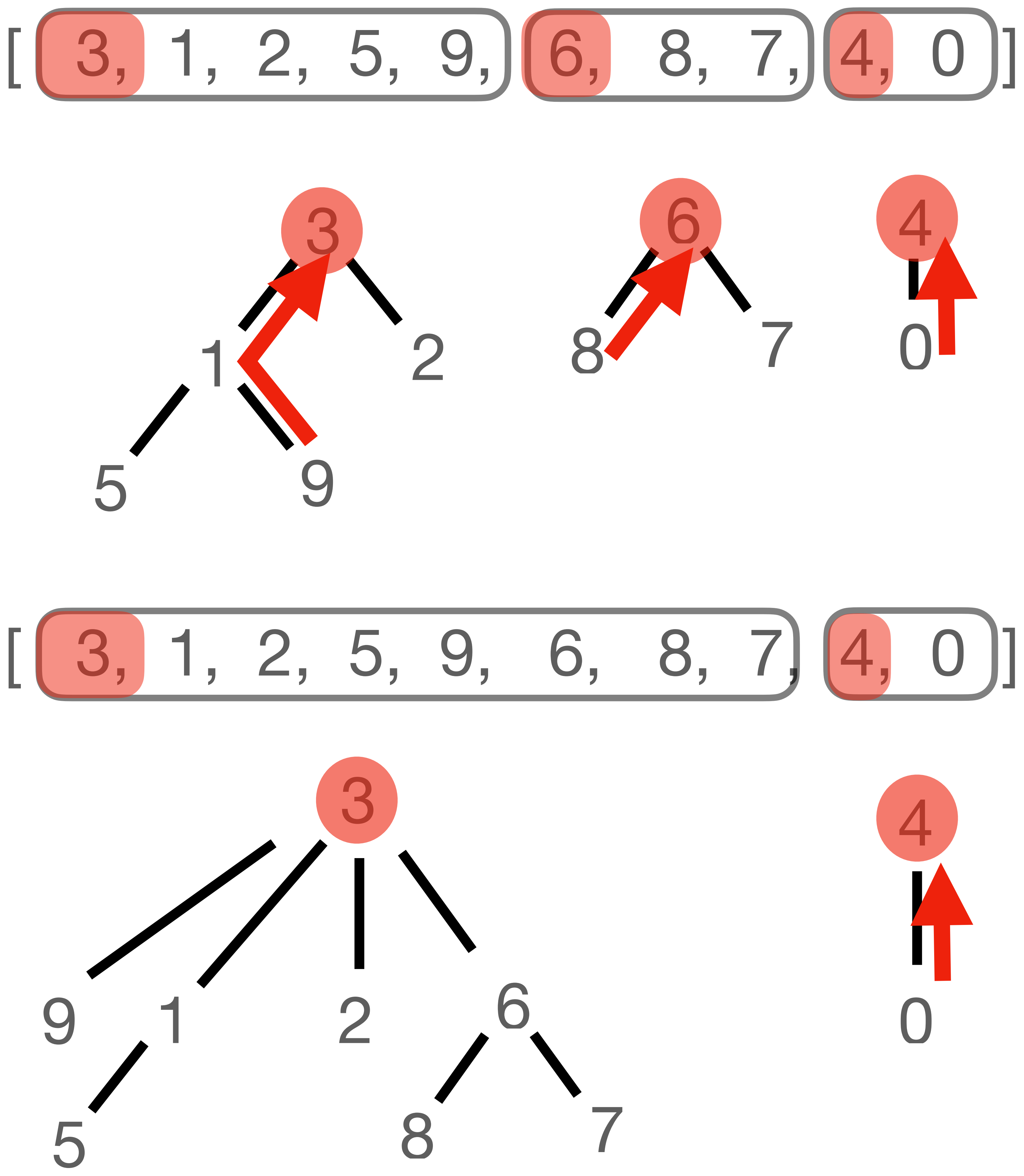
Disjoint Set Forest



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Union-Find Cycle Detection

Data Structure: Disjoint Sets

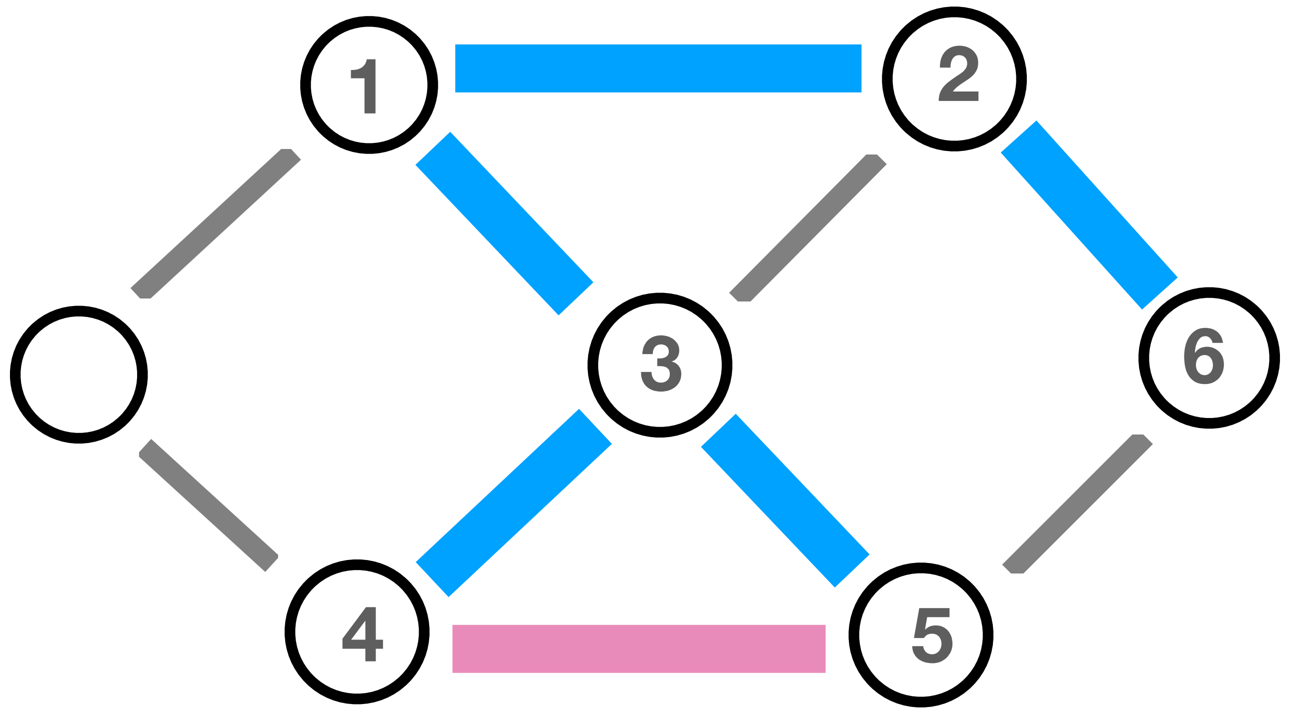
Two Operations:

- Find: find set that contains any element set by *representative element*

- Union: combine sets

Undirected Graph:

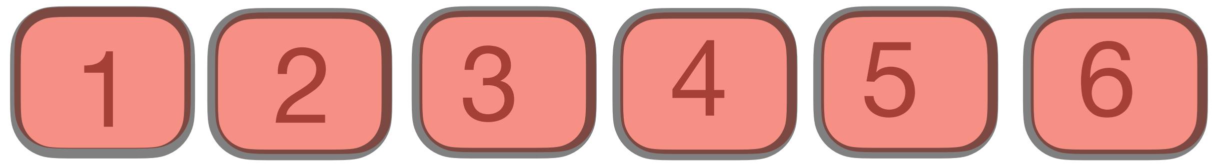
...minimum spanning tree step - cycle detection



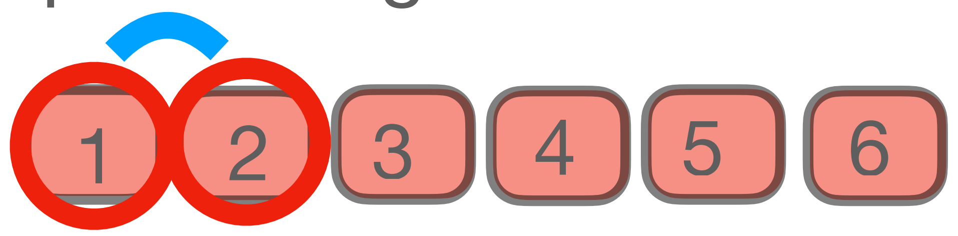
Cycle detected

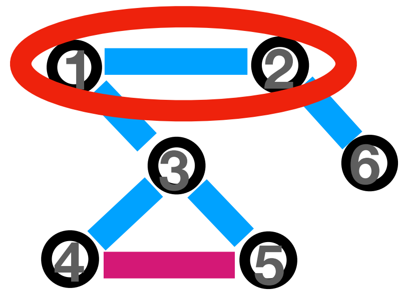
Disjoint Set Forest

disjoint sets: one with each vertex

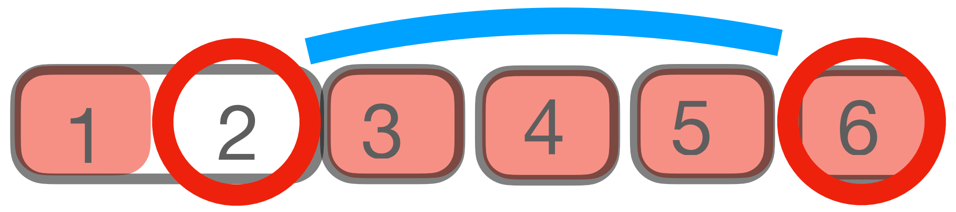


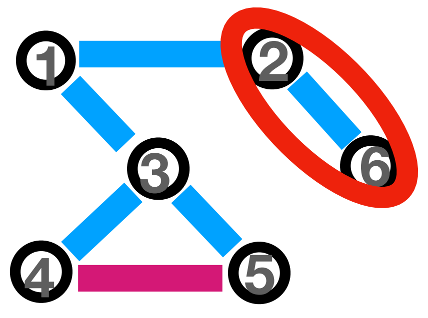
Loop over edges...



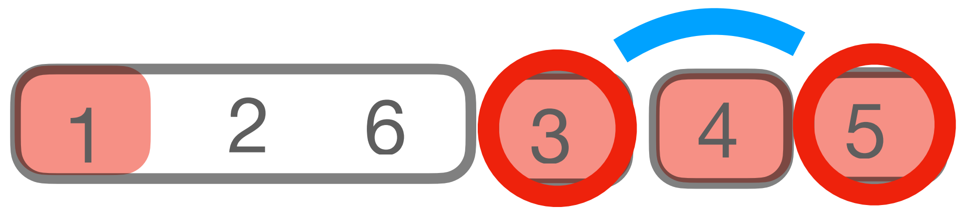


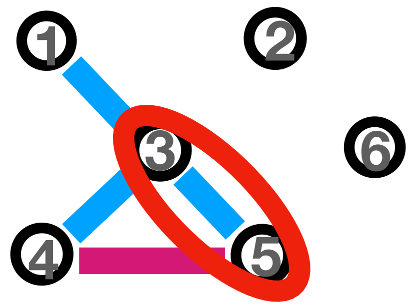
check if two vertices in the same set...
1 not = 2 ... so merge sets.



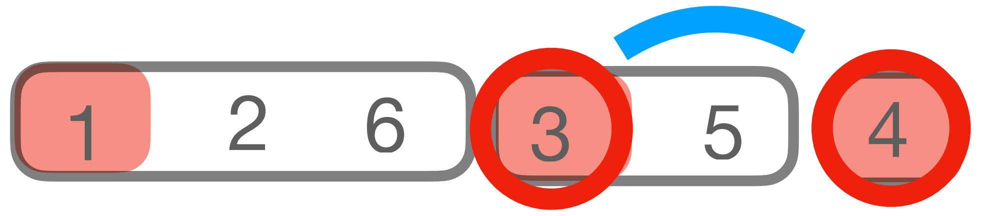


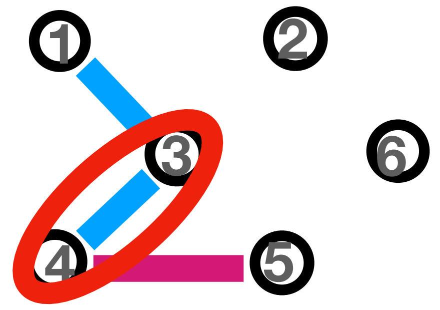
check if two vertices in the same set...
1 not = 6 ... so merge sets.



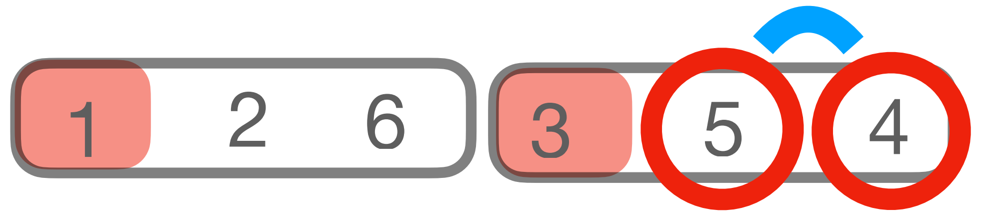


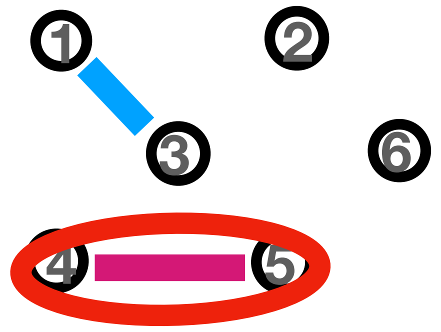
check if two vertices in the same set...
3 not = 5 ... so merge sets.





check if two vertices in the same set...
3 not = 5 ... so merge sets.





check if two vertices in the same set...
3 = 3 ... CYCLE DETECTED

Computation Cost:
Cost: **O(|V|^3))**

Algorithms

Dijkstra's Algorithm:

Unvisited

Visited

Computation Cost:
Cost: **O(|E| log(|V|))**

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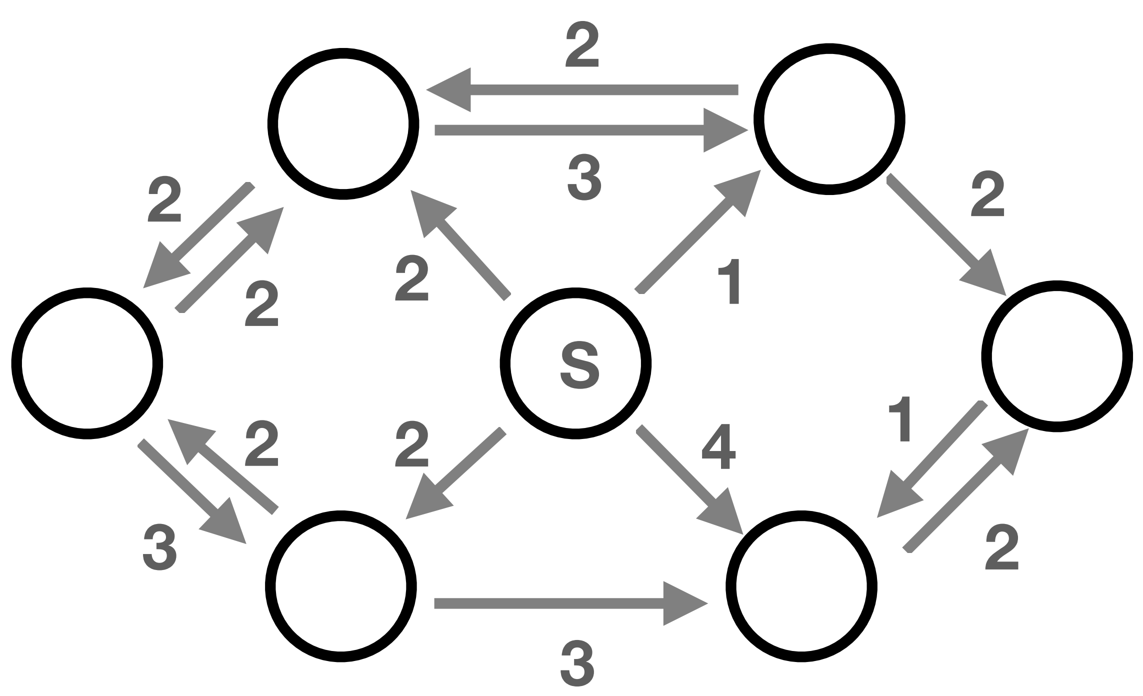
Shortest path from source on a weighted graph.
Edges have only positive weights.

Graph: G = (V,E)

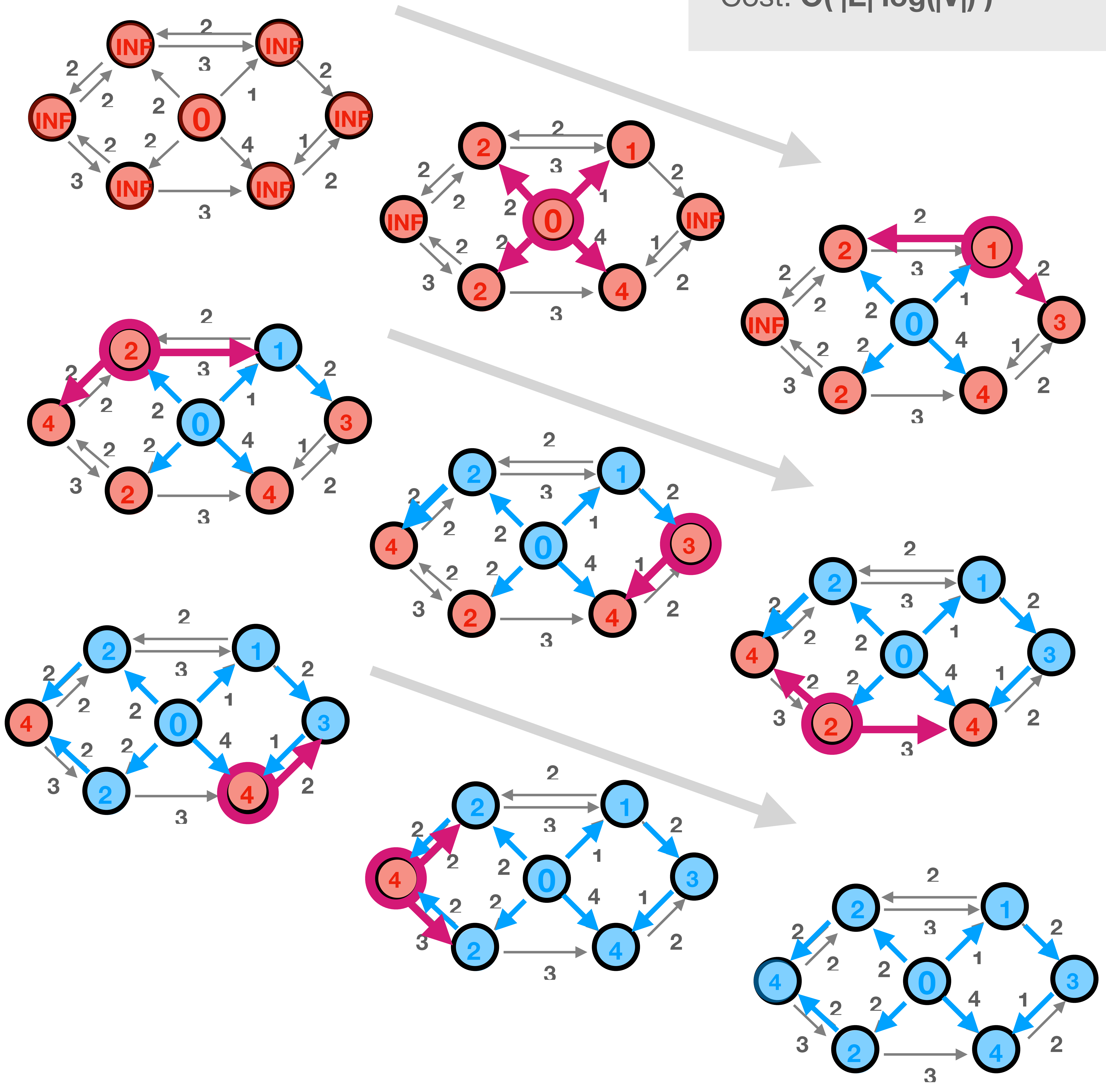


Idea/Pseudo-code:

Initialize:
Visited = {source}, cost = 0
Unvisited = { other nodes }, cost = INF

For each node:
Starting with lowest cost node…
1. update minimum cost to neighbors
2. Mark node as visited

Stop:
When each node has been visited or when desired node is reached.



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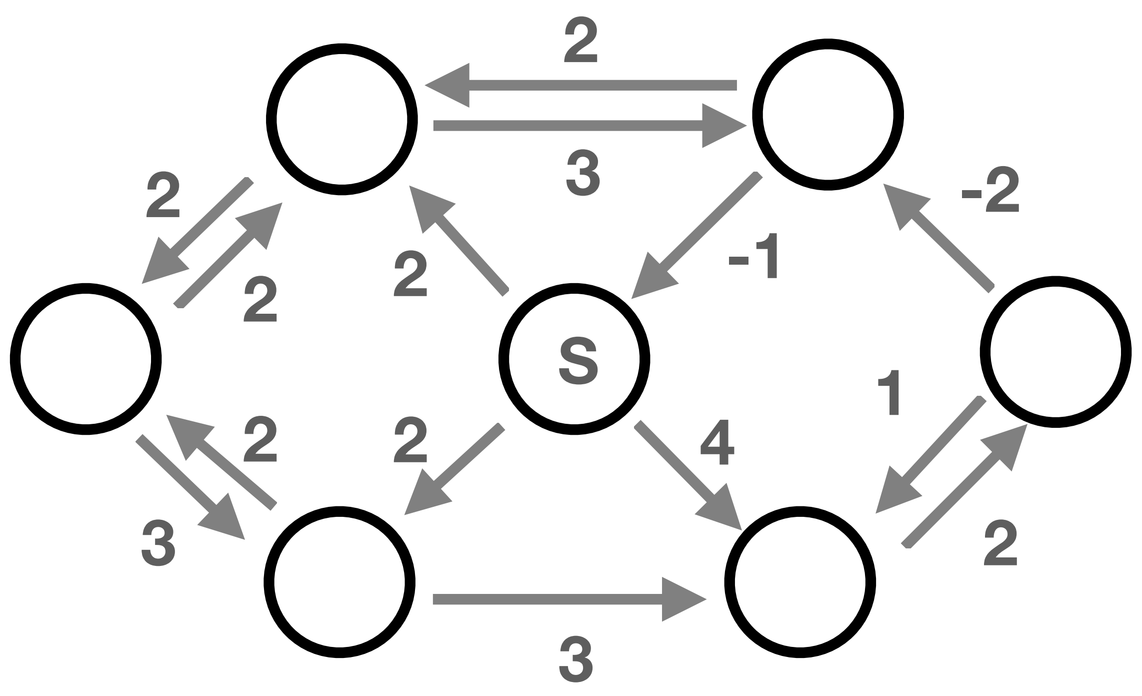
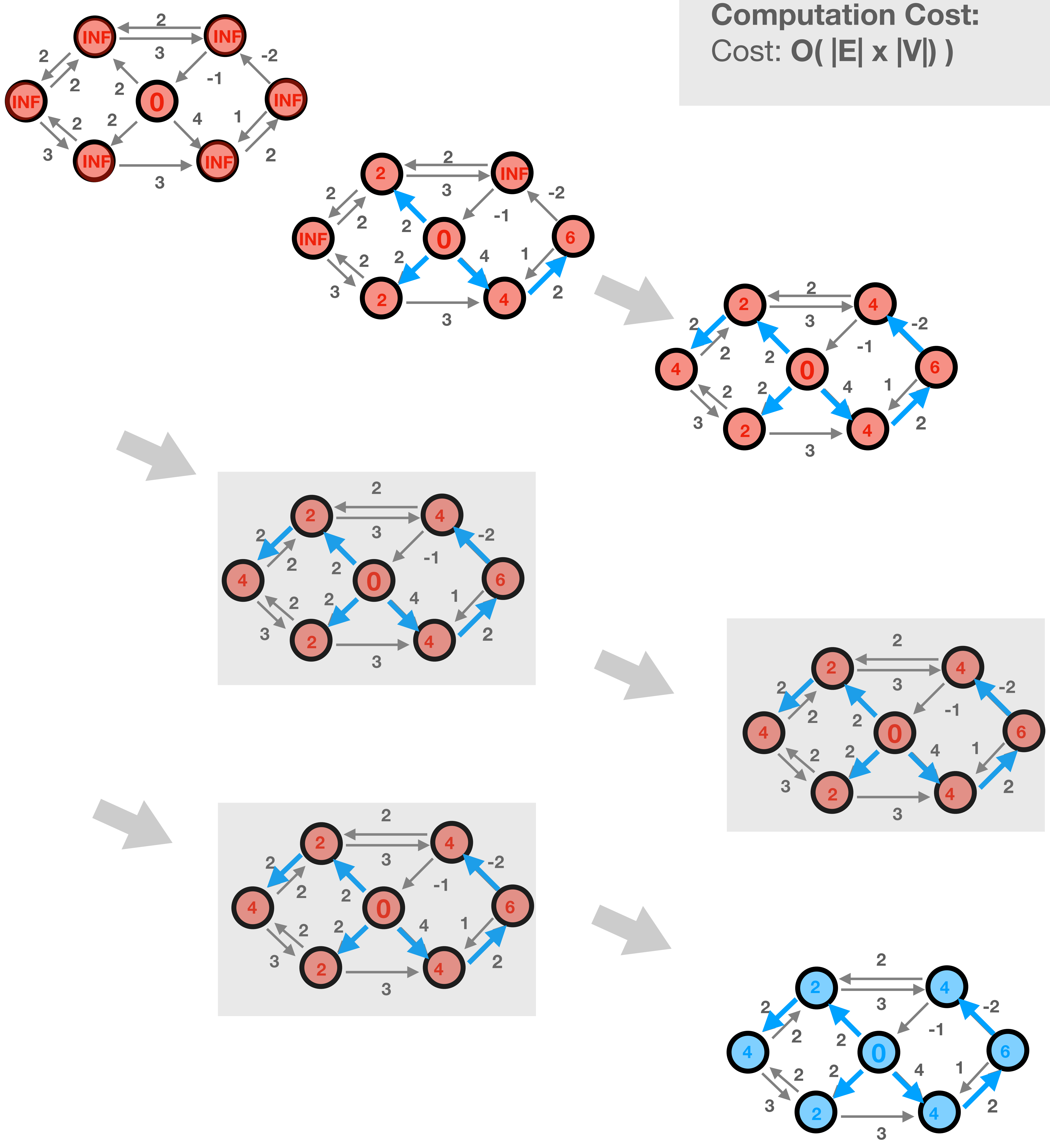
Bellman Ford Algorithm:

Shortest path from source on a weighted graph.
Edges have positive and negative weights
Report negative weight cycles.

Graph: G = (V,E)



Computation Cost:
Cost: **O(|E| x |V|))**



Idea/Pseudo-code:

Initialize:
Each node: cost = INF, parent = NULL

Source node: cost = 0
For |V|-1 iterations:
For each edge e:
Edge e: from u to v
If cost(v) > cost(u) + cost(edge):
cost(v) = cost(u) + cost(edge)
parent(v) = u

Else if cost(v) < cost(u)+cost(edge):
Report negative cycle

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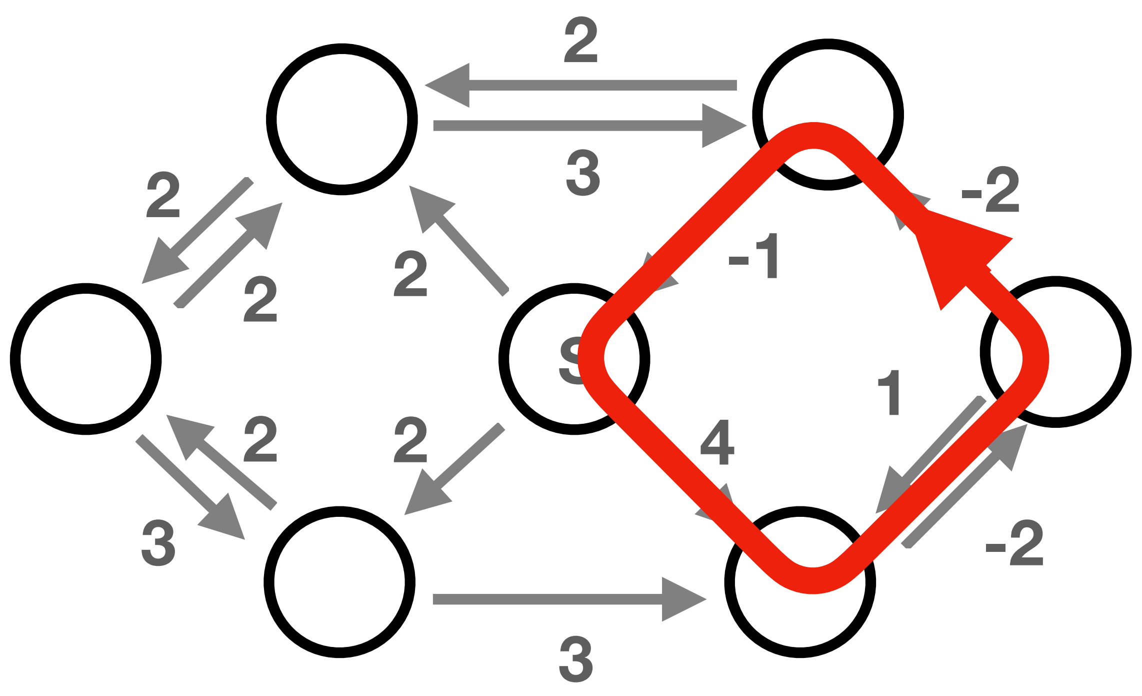
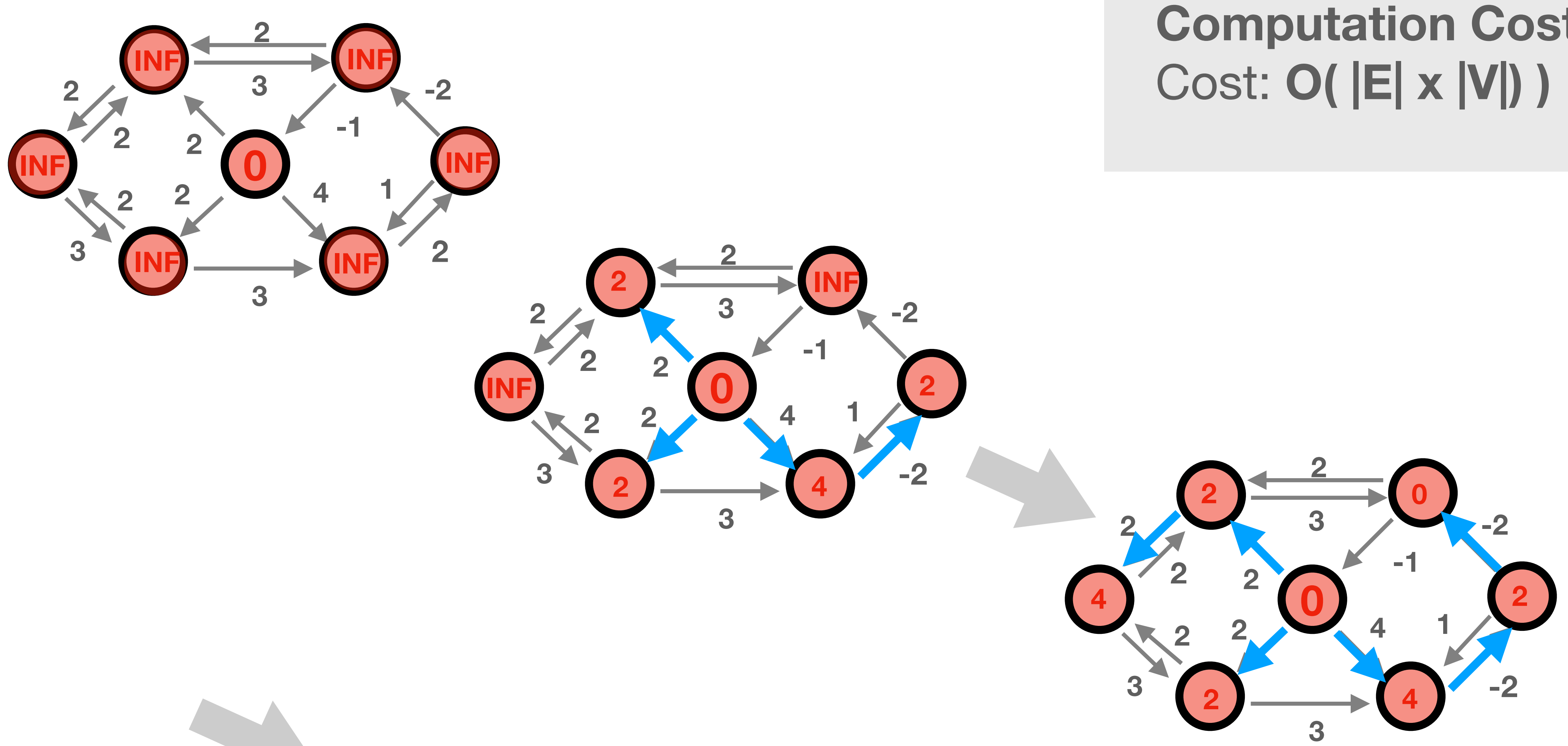
Bellman Ford Algorithm:

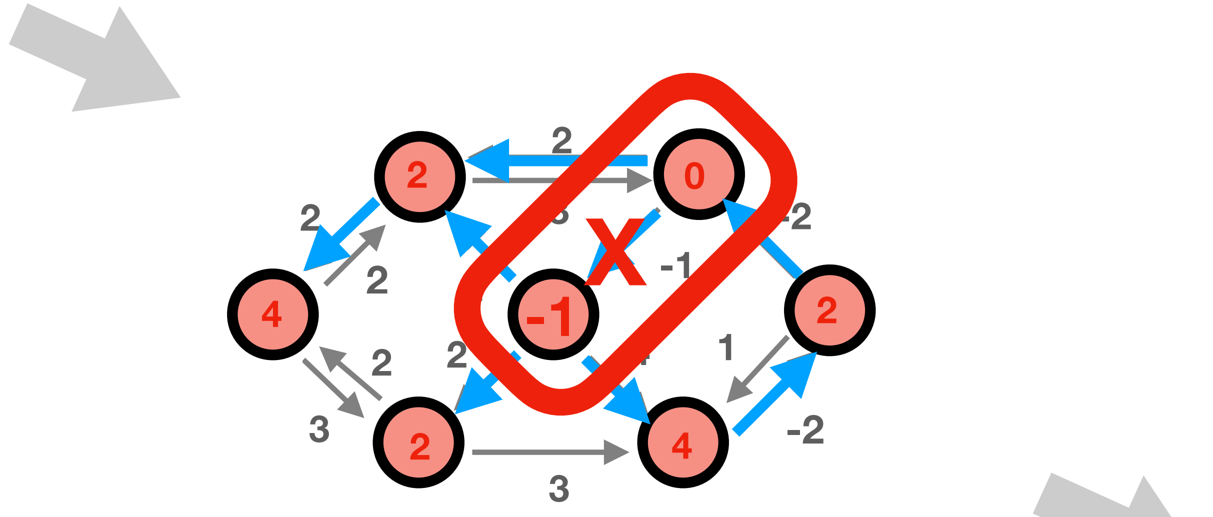
…with negative weight cycle…

Graph: G = (V,E)



… total weight is -1





Report cycle w/ negative weights

STOP

Computation Cost:
Cost: **O(|E| x |V|))**

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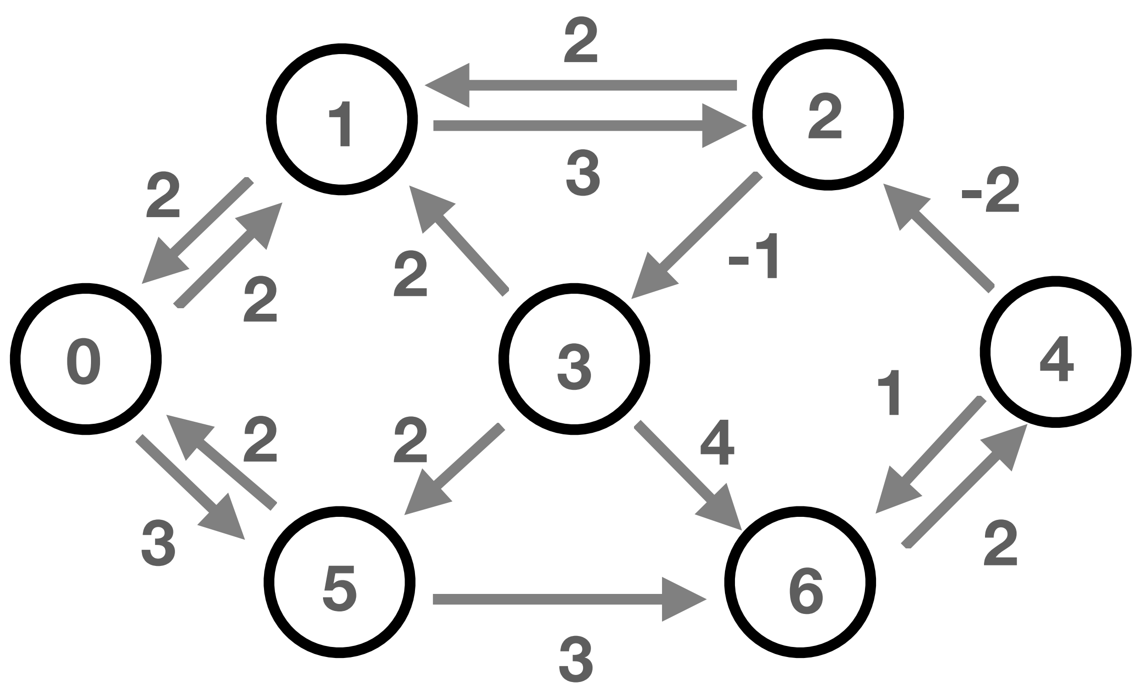
Floyd - Warshall algorithm:

Computation Cost:
Cost: **O(|V|^3))**

Shortest path from every node…
…to every other node

Graph: G = (V,E)



dist =

	0	1	2	3	4	5	6
0	0	INF	INF	INF	INF	INF	INF
1	INF	0	INF	INF	INF	INF	INF
2	INF	INF	0	INF	INF	INF	INF
3	INF	INF	INF	0	INF	INF	INF
4	INF	INF	INF	INF	0	INF	INF
5	INF	INF	INF	INF	INF	0	INF
6	INF	INF	INF	INF	INF	INF	0

dist =

	0	1	2	3	4	5	6
0	0	2	INF	INF	INF	3	INF
1	2	0	3	INF	INF	INF	INF
2	INF	2	0	-1	INF	INF	INF
3	INF	2	INF	0	INF	2	4
4	INF	INF	-2	INF	0	INF	1
5	2	INF	INF	INF	INF	0	3
6	INF	INF	INF	INF	2	INF	0

Idea/Pseudo-code:

```
Initialize:
    dist matrix: |V| x |V|
    Set diagonal elements = 0
    if edge from i to j in graph:
        dist[i][j] = weight;

For k = 0 to |V|-1:
    For j = 0 to |V|-1:
        For i = 0 to |V|-1:
        If dist[i][k] + dist[k][j] < dist[i][j]:
            dist[i][j] = dist[i][k] + dist[k][j]

After:
if dist[i][i] is negative for any I:
    Report negative cycle
```

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Floyd - Warshall algorithm:

Computation Cost:
Cost: **O(|V|^3))**

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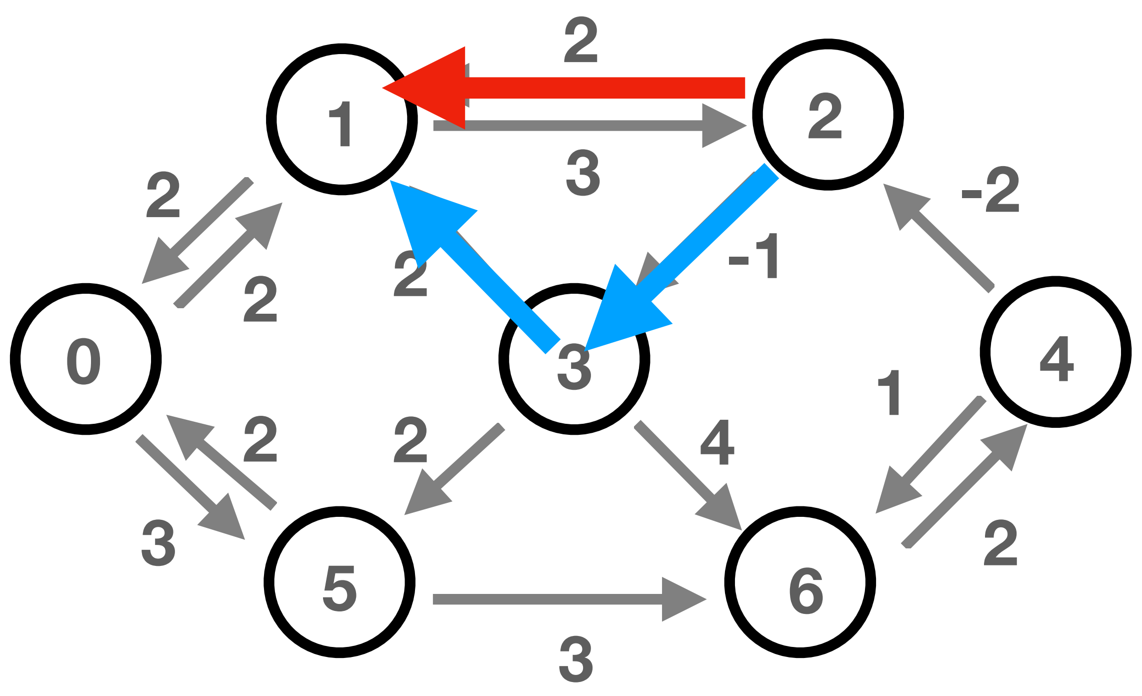
Shortest path from every node…
…to every other node

Graph: G = (V,E)



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dist[i][j] = weight;

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For j = 0 to |V|-1:
For i = 0 to |V|-1:
If dist[i][k] + dist[k][j] < dist[i][j]:
dist[i][j] = dist[i][k] + dist[k][j]

After:
if dist[i][i] is negative for any I:
Report negative cycle

dist =

	0	1	2	3	4	5	6
0	0	INF	INF	INF	INF	INF	INF
1	INF	0	INF	INF	INF	INF	INF
2	INF	INF	0	INF	INF	INF	INF
3	INF	INF	INF	0	INF	INF	INF
4	INF	INF	INF	INF	0	INF	INF
5	INF	INF	INF	INF	INF	0	INF
6	INF	INF	INF	INF	INF	INF	0

dist =

	0	1	2	3	4	5	6
0	0	2	INF	INF	INF	3	INF
1	2	0	3	INF	INF	INF	INF
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dist =

	0	1	2	3	4	5	6
0	0	2	INF	INF	INF	3	INF
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5	2	INF	INF	INF	INF	0	3
6	INF	INF	INF	INF	2	INF	0

If 2 > -1 + 2 :

dist[2,1] = -1 + 2 = 1

dist =

	0	1	2	3	4	5	6
0	0	2	INF	INF	INF	3	INF
1	2	0	3	INF	INF	INF	INF
2	INF	1	0	-1	INF	INF	INF
3	INF	2	INF	0	INF	2	4
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Huffman Coding - Data Compression

Computation Cost:
Cost: **O(nlog(n))**

Fixed length encoding: "every character takes 8 bits."

Variable length encoding: "Use less memory for more frequency characters."

Character	A	B	C	D	E
Frequency	11	3	7	5	20
Binary Encoding	1	100	10	11	0

Problem: "Encoding is ambiguous"

Ex. 010010111 → EAEEAEAAA, EBCDA, EAEECAD, …etc

Solution: "No code (for a character) can be a prefix of another code

Character	E	A	C	D	B
Frequency	20	11	7	5	3
Binary Encoding	0	10	110	1110	1111

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Huffman Coding - Data Compression

Computation Cost:
Cost: **O(nlog(n))**

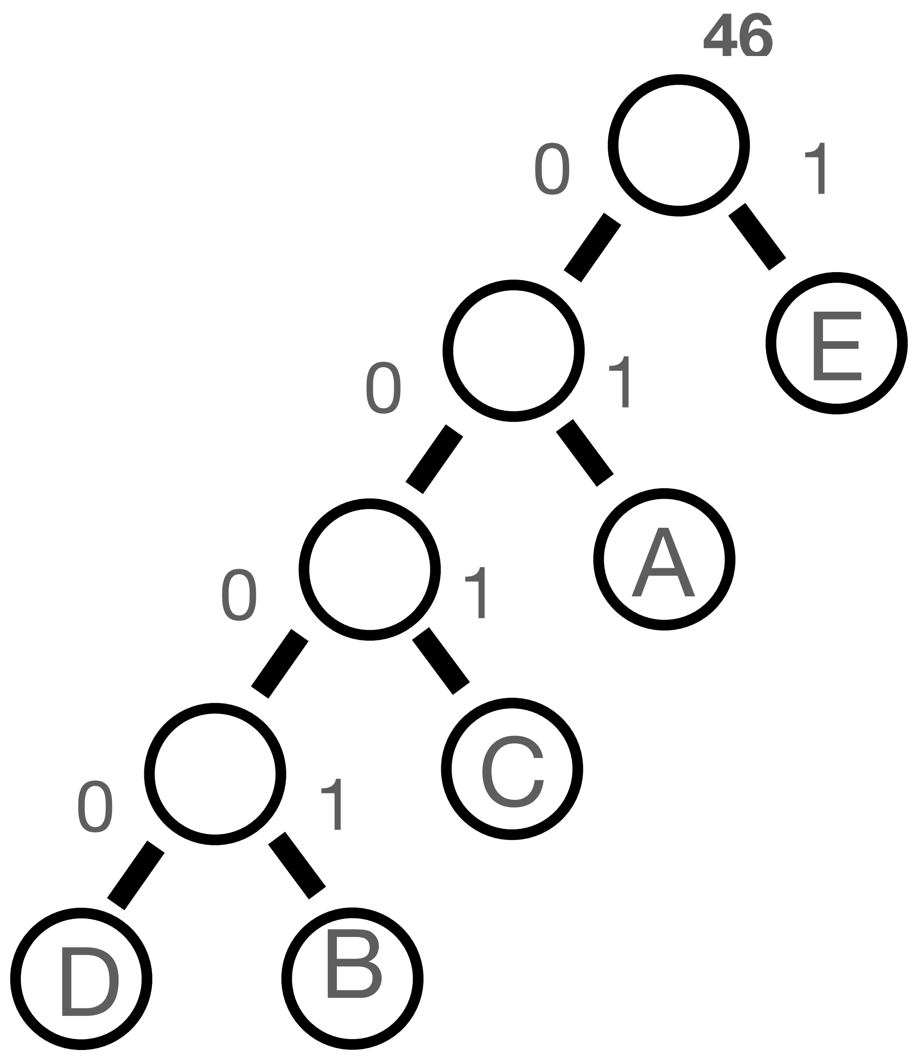
Huffman coding: Create binary tree

Required data structure: Priority queue

Character	E	A	C	D	B
Frequency	20	11	7	5	3
Binary Encoding	1	01	001	0001	0000

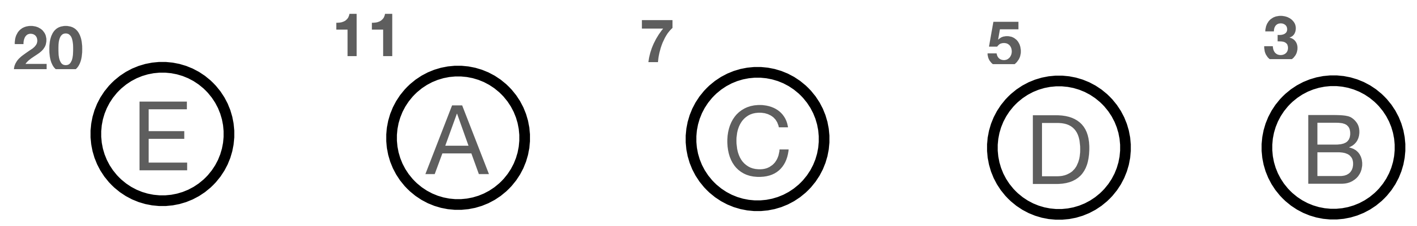
Binary Tree:

weights along branches give encoding

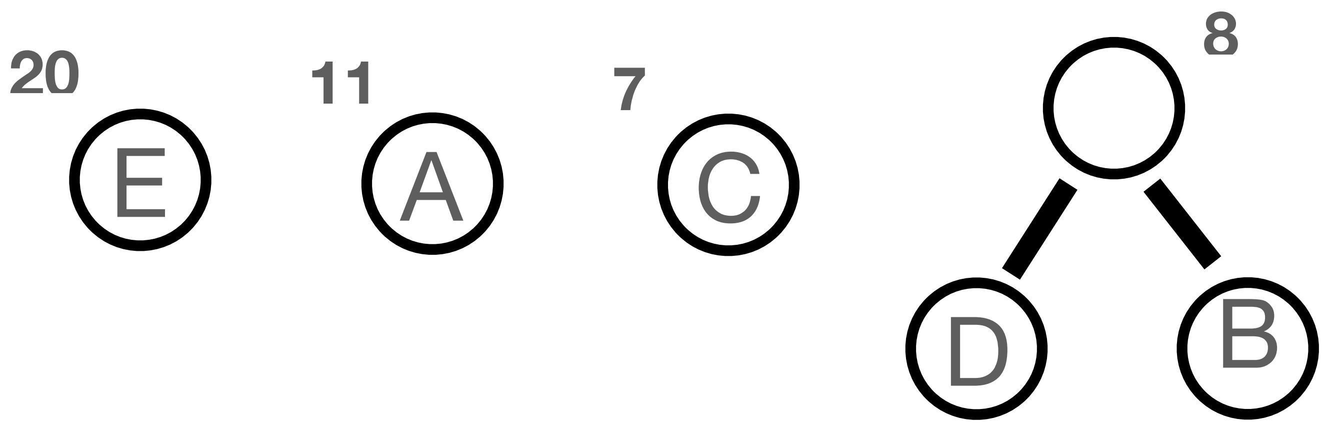


Note the ordering: …binary tree

… more frequent characters (or groups of characters) assigned 0



Pick two elements with lowest frequency…



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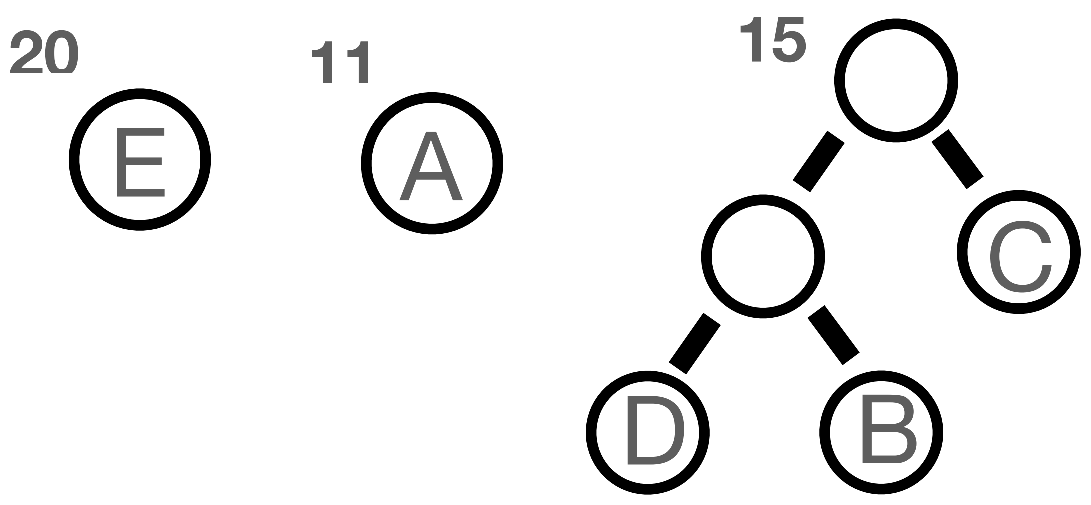

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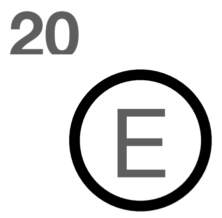

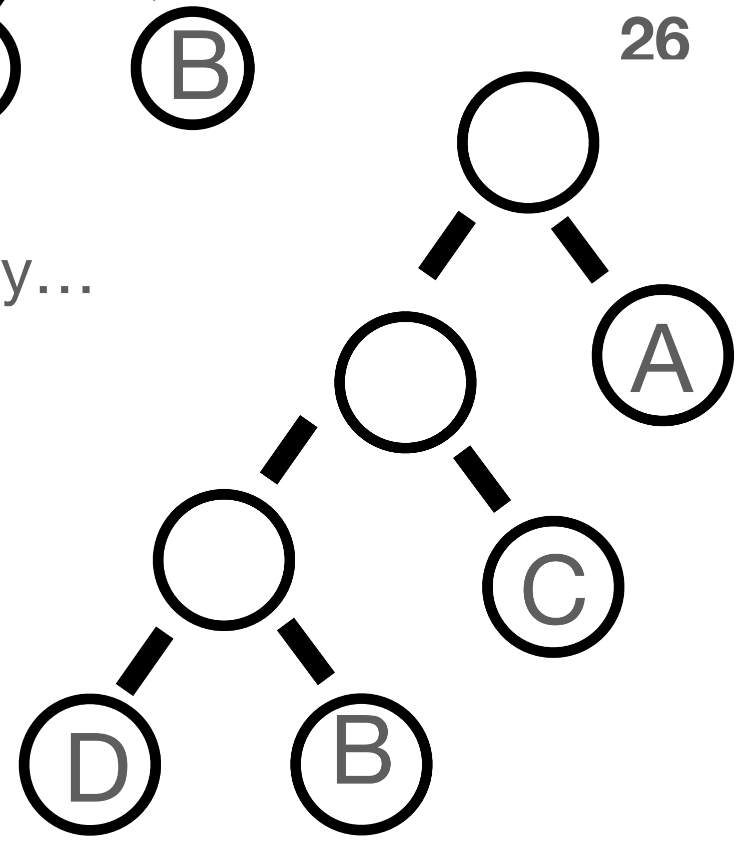

and so on…