End-to-End Graph Processing

Algorithms

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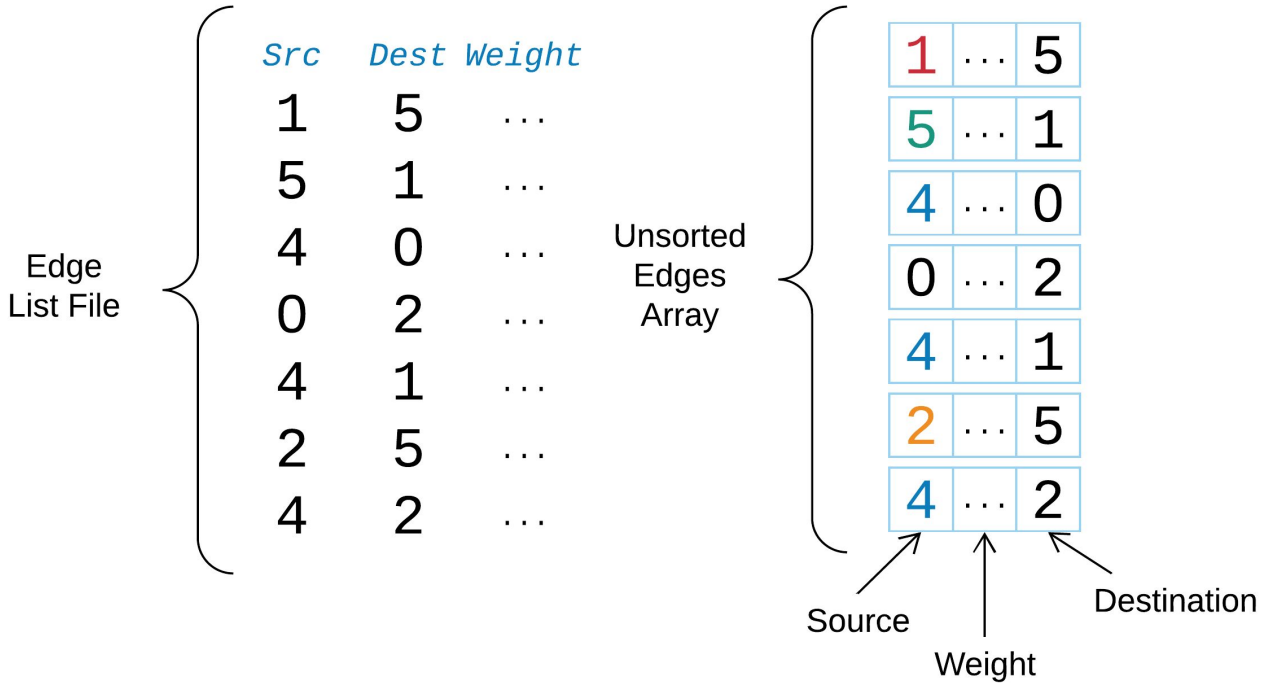
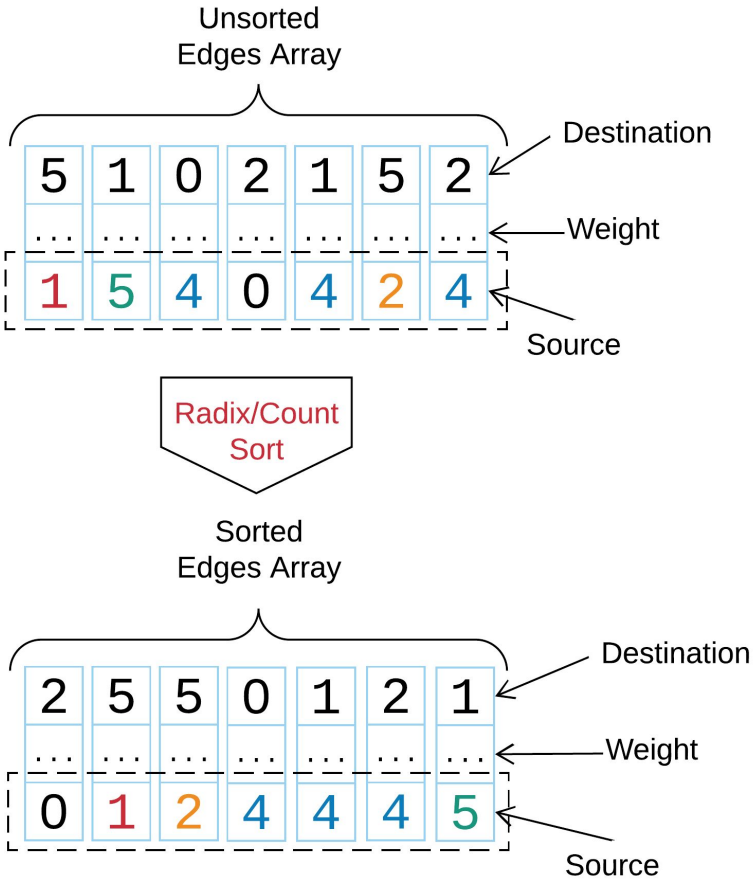
Recap


Edge
List File
Src Dest Weight
1 5 ...
5 1 ...
4 0 ...
0 2 ...
4 1 ...
2 5 ...
4 2 ...
Unsorted
Edges
Array
1 ... 5
5 ... 1
4 ... 0
0 ... 2
4 ... 1
2 ... 5
4 ... 2
Source
Weight
Destination

Recap


Unsorted
Edges Array
Destination
5 1 0 2 1 5 2
Weight
1 5 4 0 4 2 4
Source
Radix/Count
Sort
Sorted
Edges Array
Destination
2 5 5 0 1 2 1
Weight
0 1 2 4 4 4 5
Source

Sorting in linear time

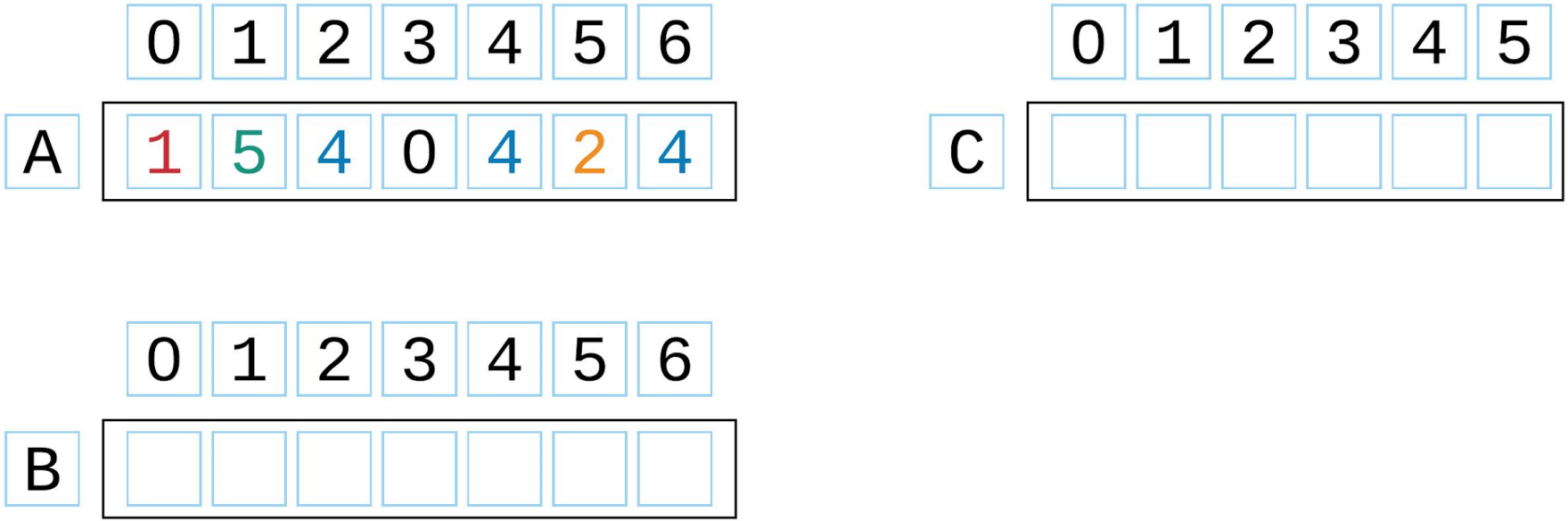
Counting-sort : No comparison between elements.

- ***Input***: A[1..n], where A[j] ∈ {1,2, ...,k}.
- ***Output***: B[1..n], sorted.
- ***Auxiliary* storage**: C[1..k], counting array.

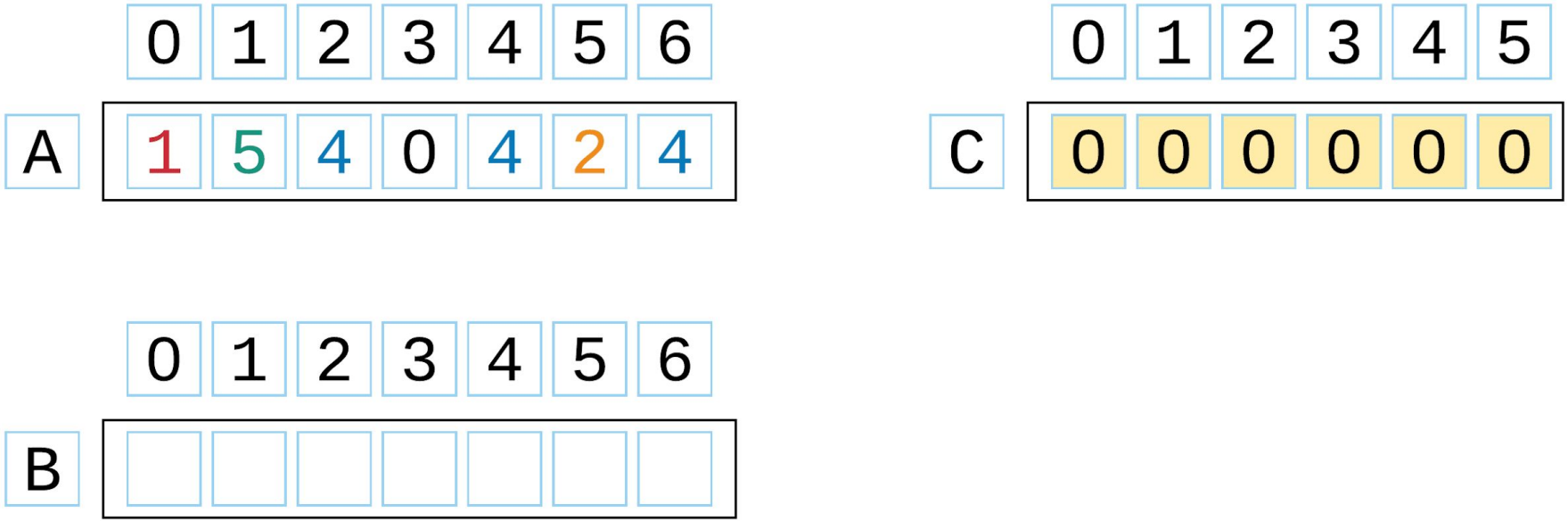
Counting-sort (Serial)

```
for i ←0 to (k-1)
   do C[i] ←0

for j ←0 to (n-1)
   do C[A[j]]←C[A[j]]+1

for i ←1 to (k-1)
   do C[i]←C[i]+C[i-1]

for j ←(n-1) downto 0
   do B[C[A[j]]-1] ←A[j]
      C[A[j]]←C[A[j]]-1
```

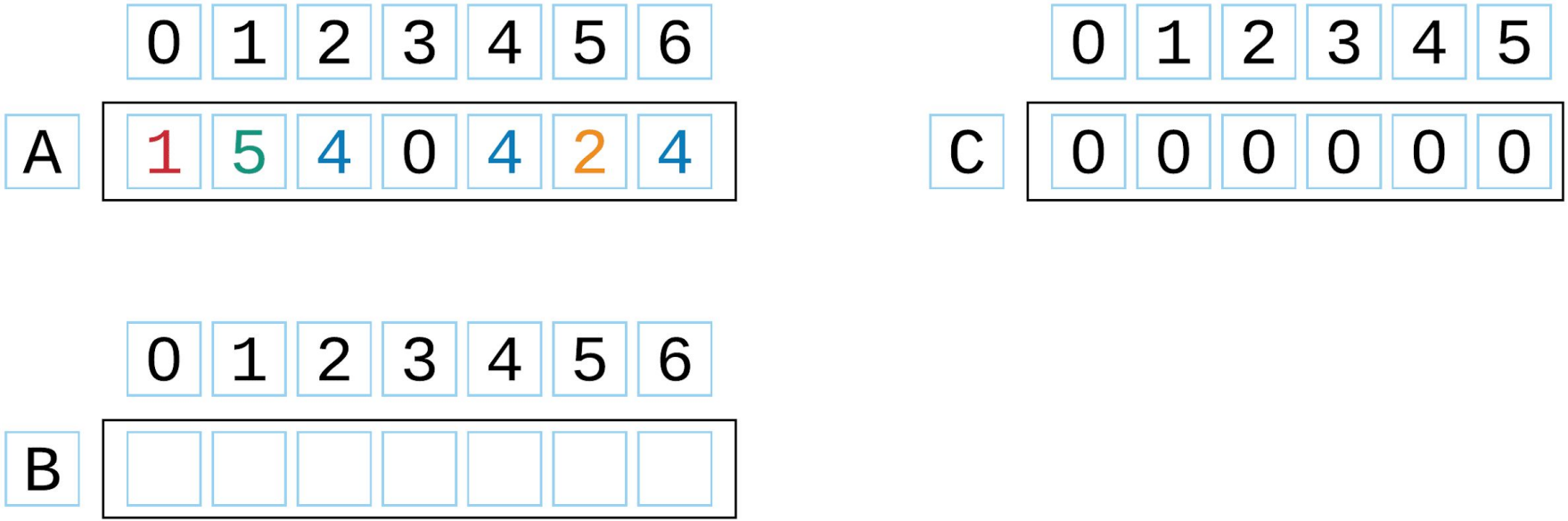
Counting-sort (Serial) - Example



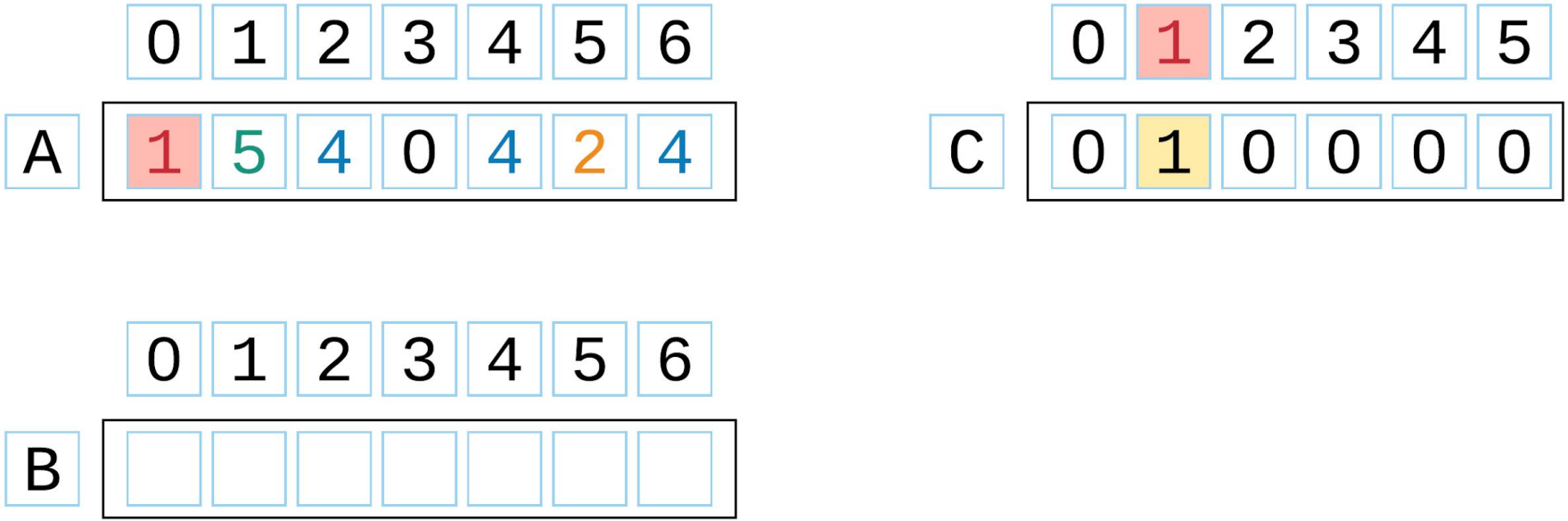
Counting-sort (Serial) - Loop 1



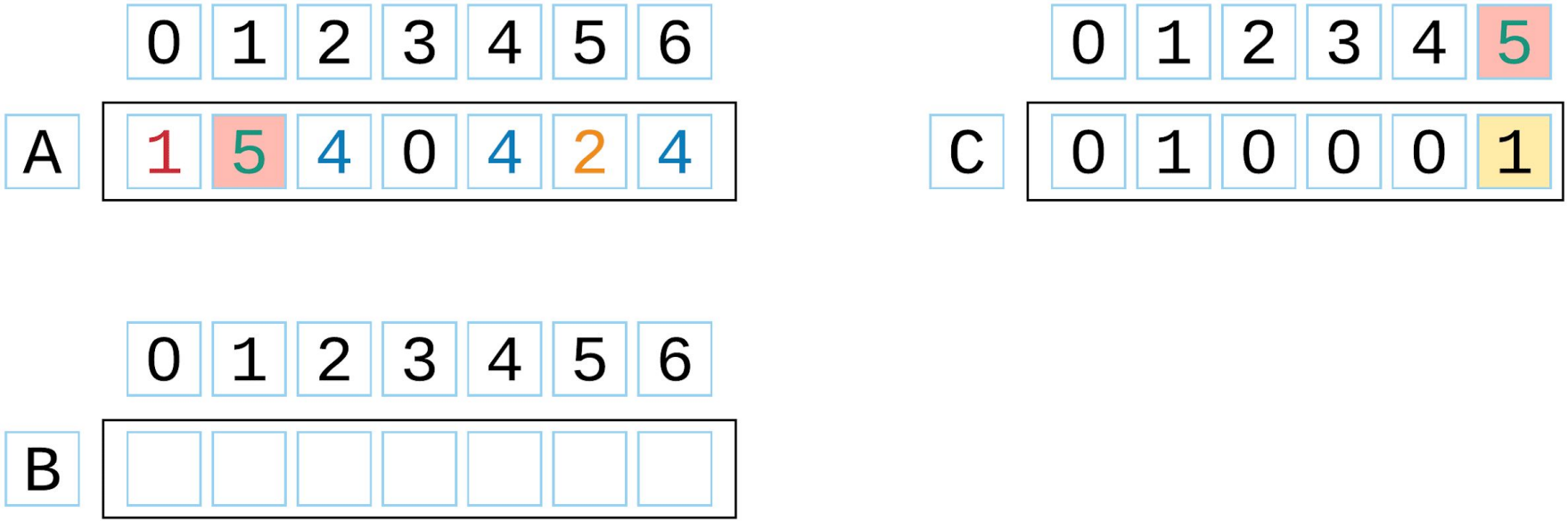
Counting-sort (Serial) - Loop 2



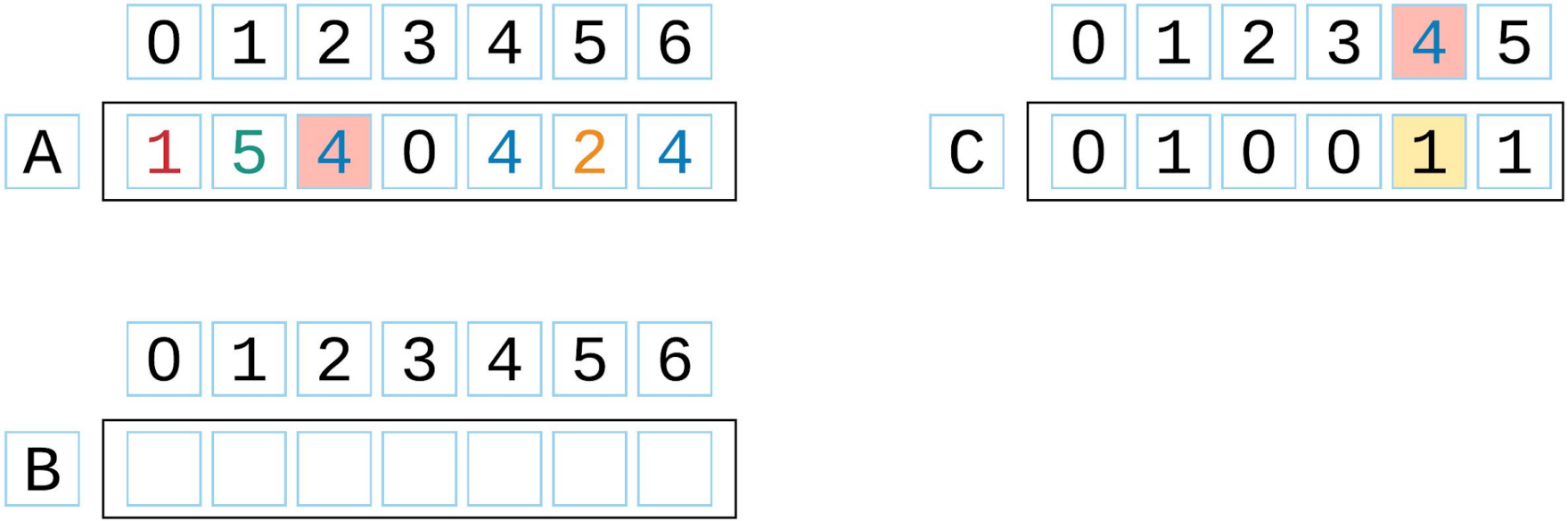
Counting-sort (Serial) - Loop 2



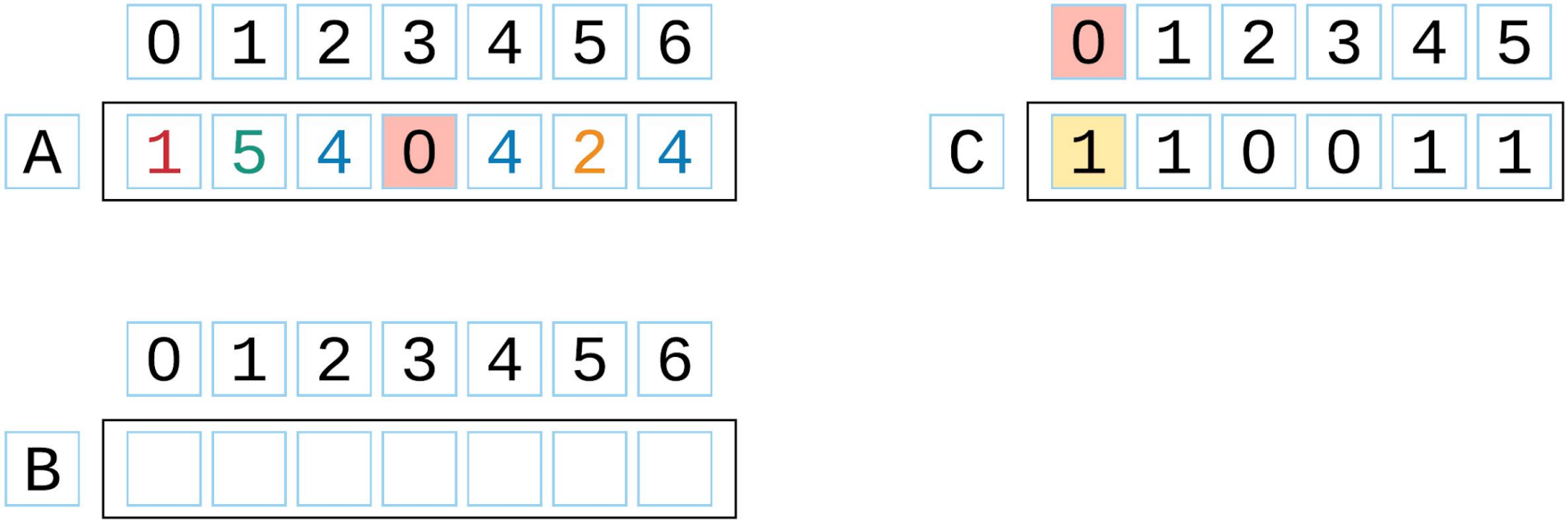
Counting-sort (Serial) - Loop 2



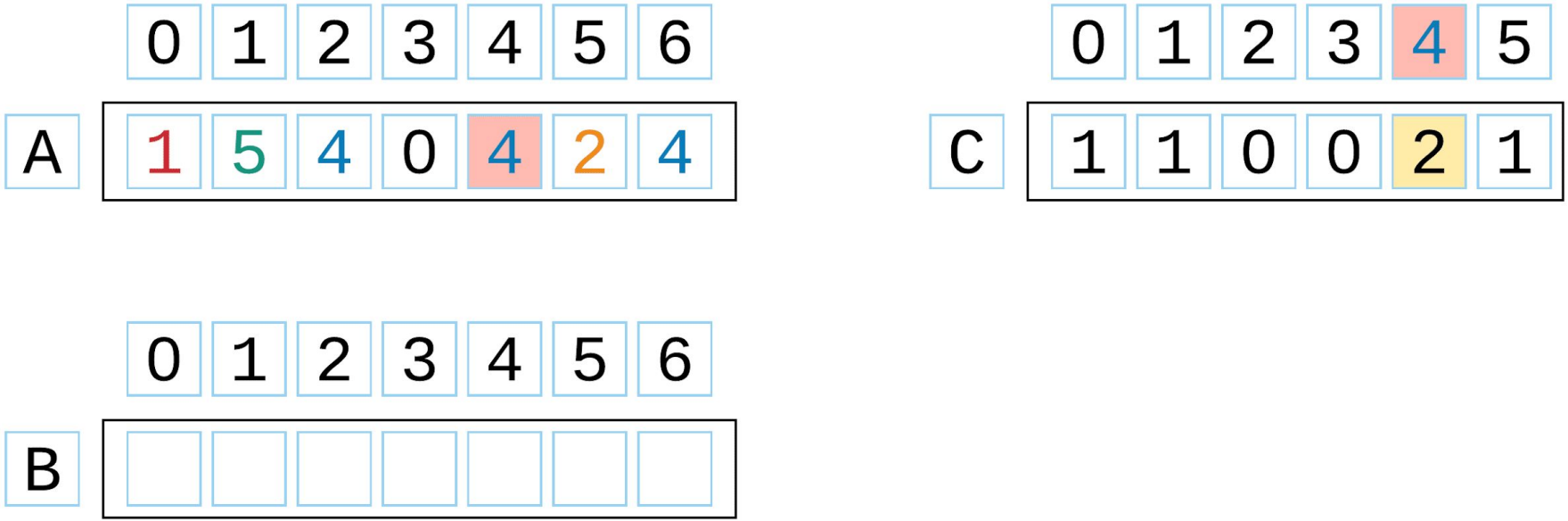
Counting-sort (Serial) - Loop 2



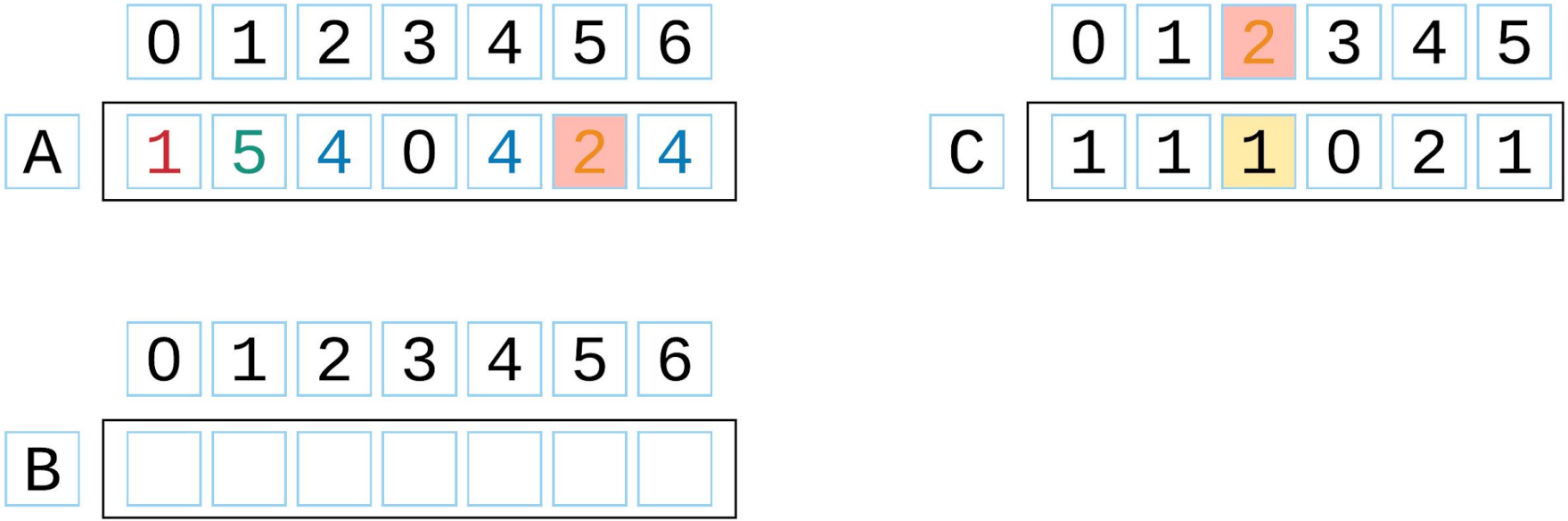
Counting-sort (Serial) - Loop 2



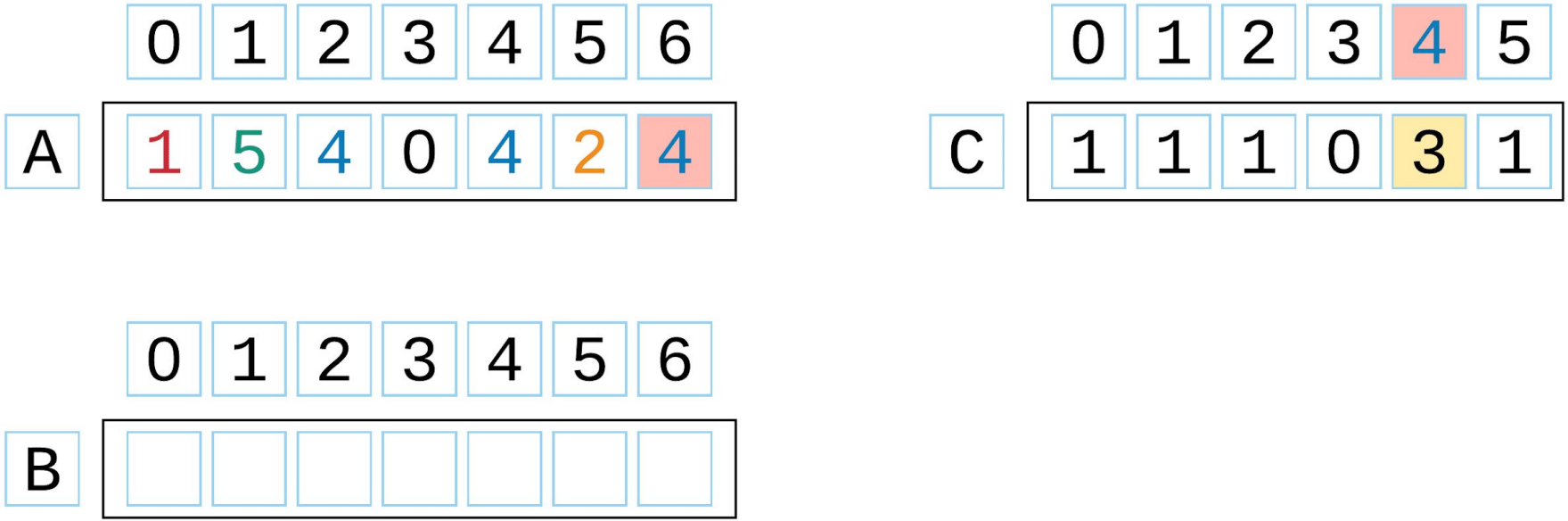
Counting-sort (Serial) - Loop 2



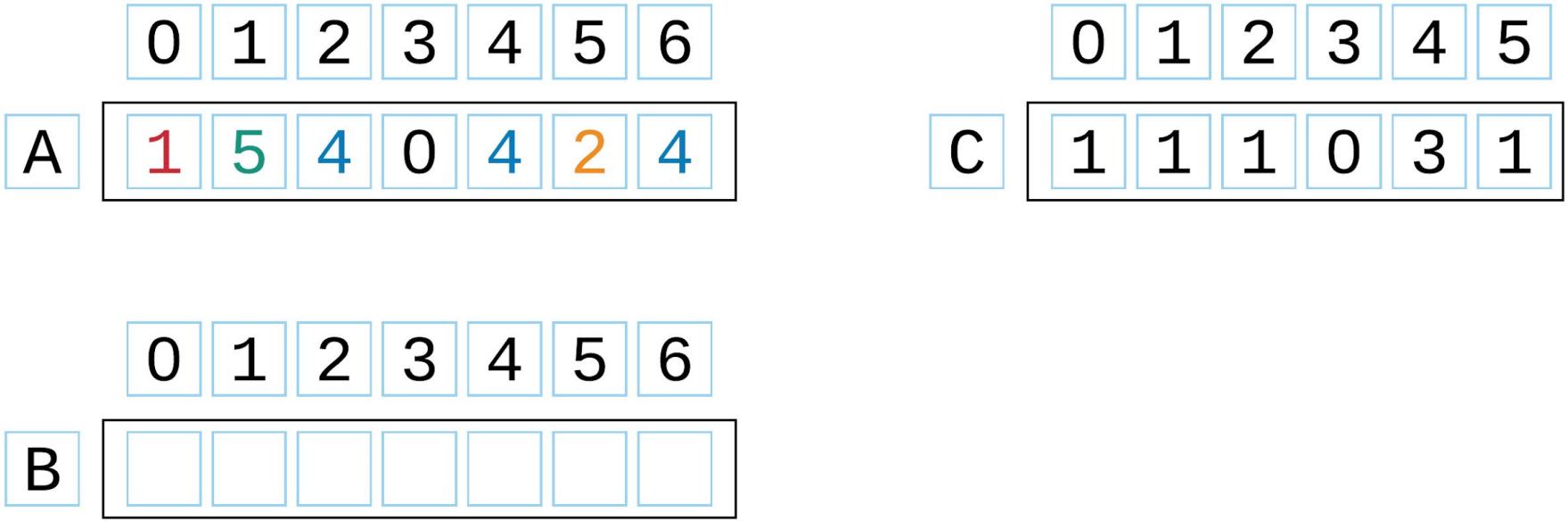
Counting-sort (Serial) - Loop 2



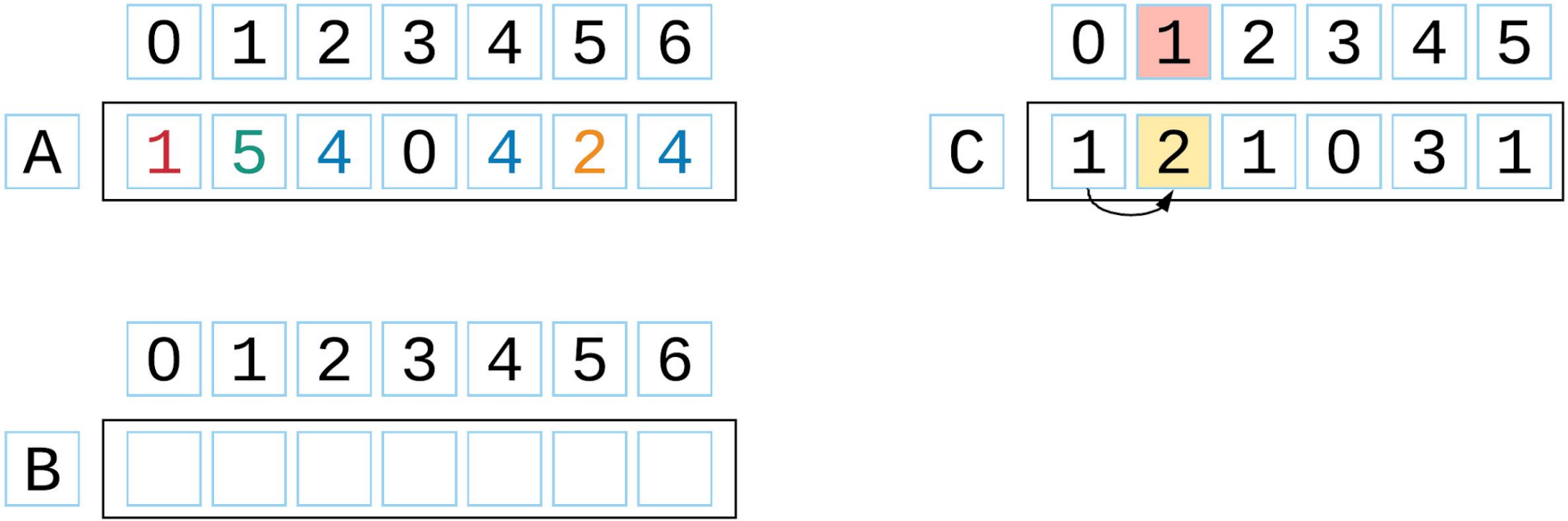
Counting-sort (Serial) - Loop 2



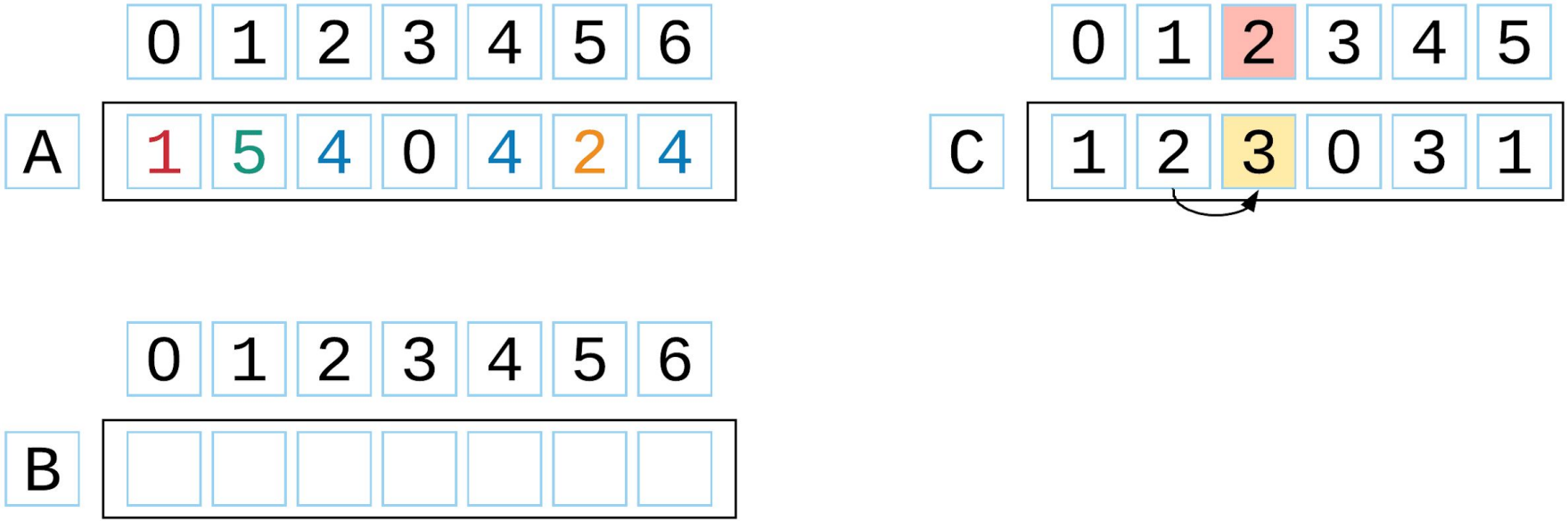
Counting-sort (Serial) - Loop 3



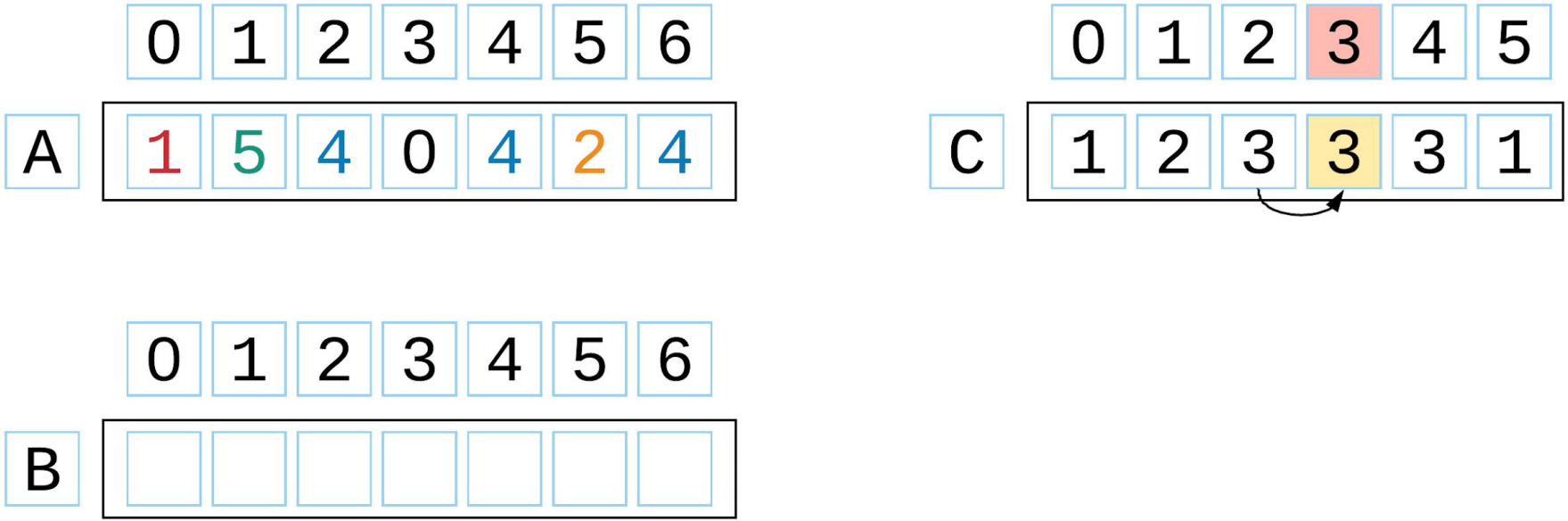
Counting-sort (Serial) - Loop 3



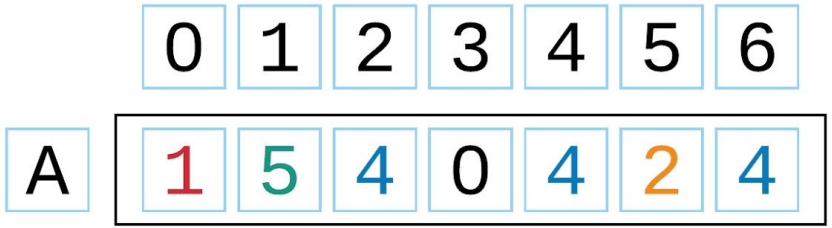
Counting-sort (Serial) - Loop 3

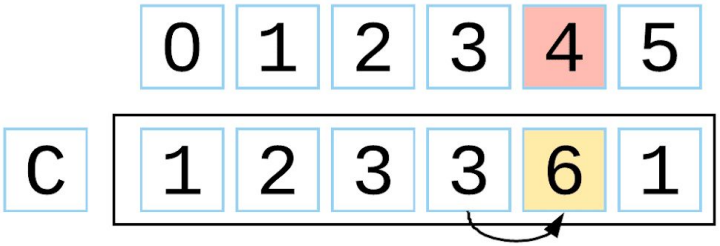


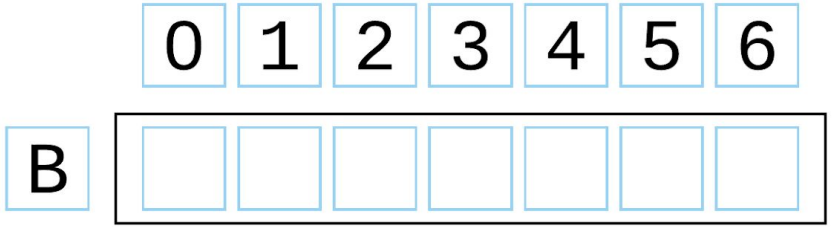
Counting-sort (Serial) - Loop 3



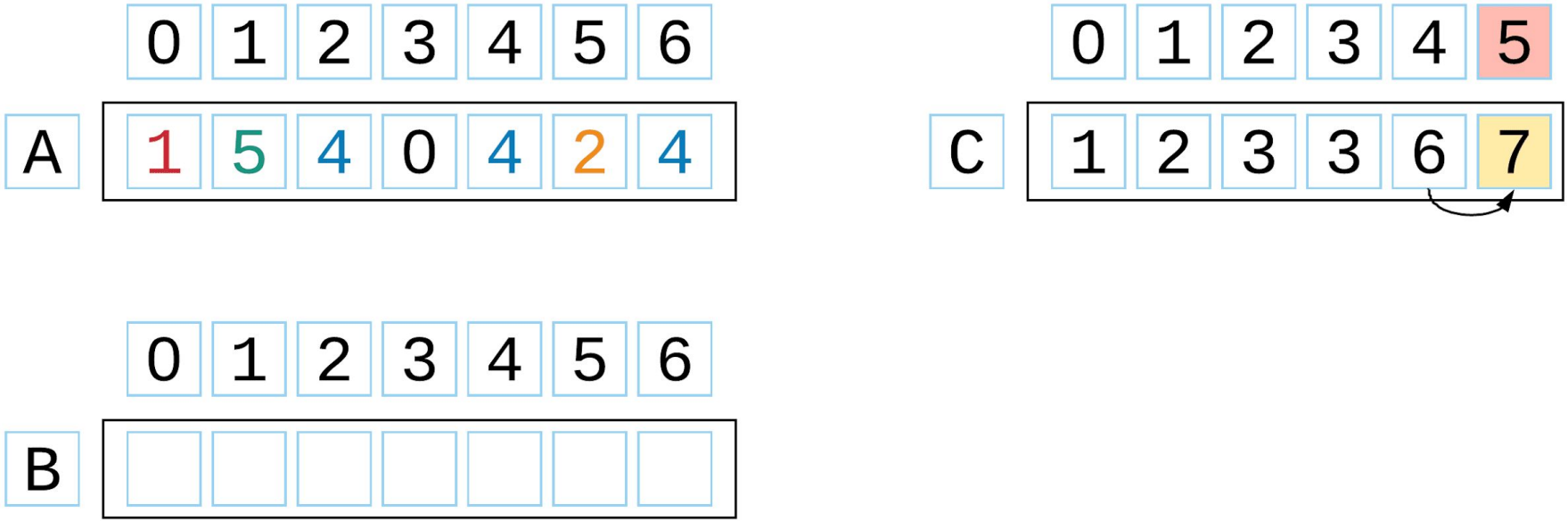
Counting-sort (Serial) - Loop 3



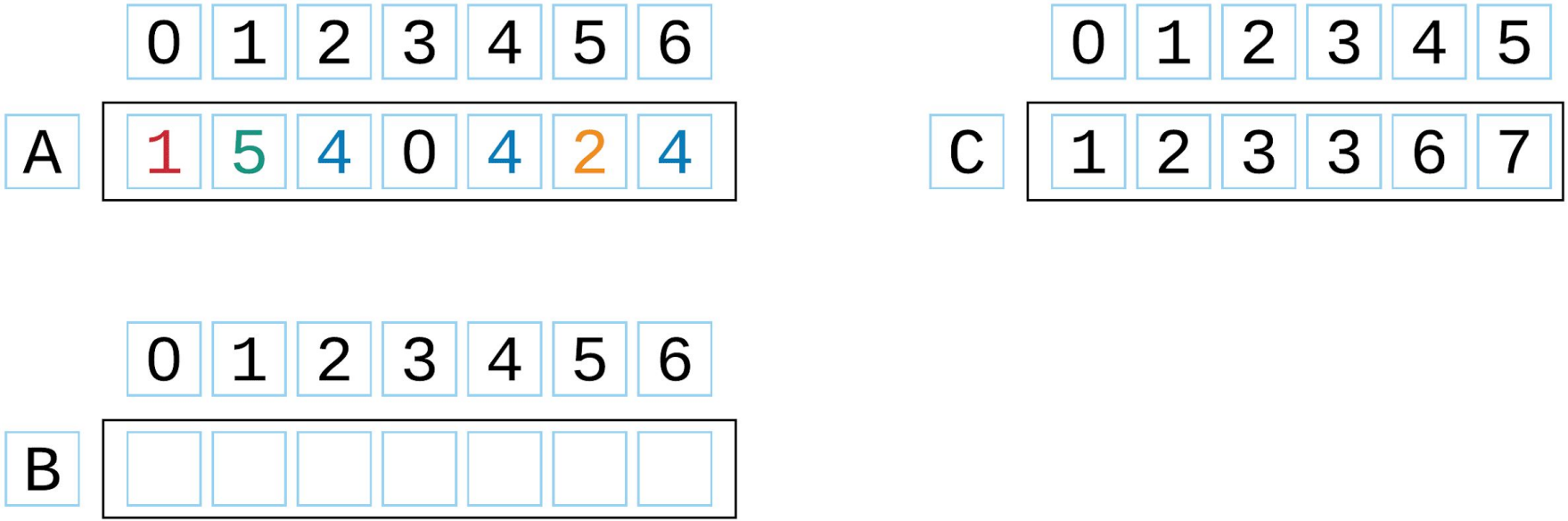




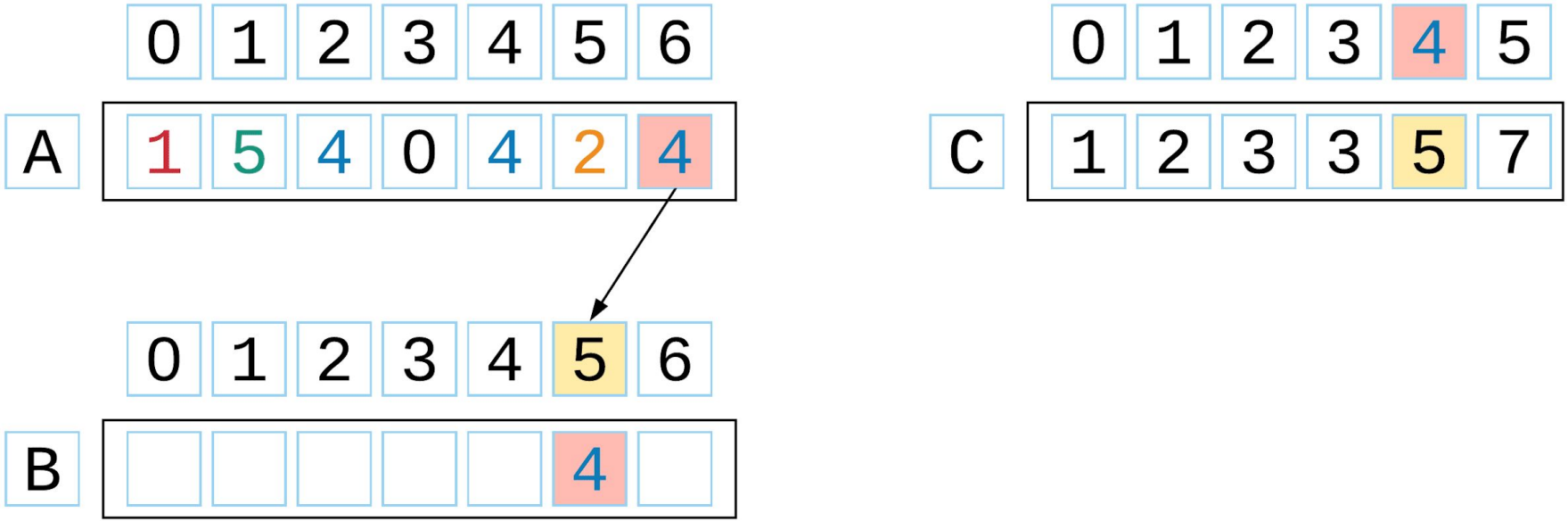
Counting-sort (Serial) - Loop 3



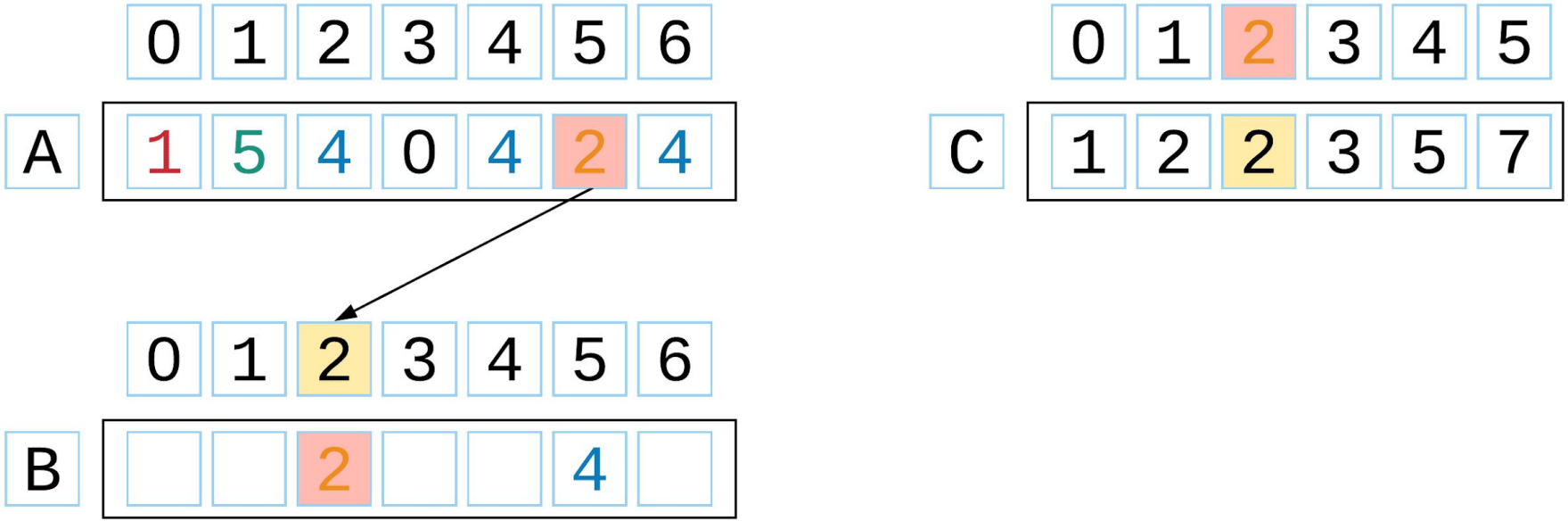
Counting-sort (Serial) - Loop 4



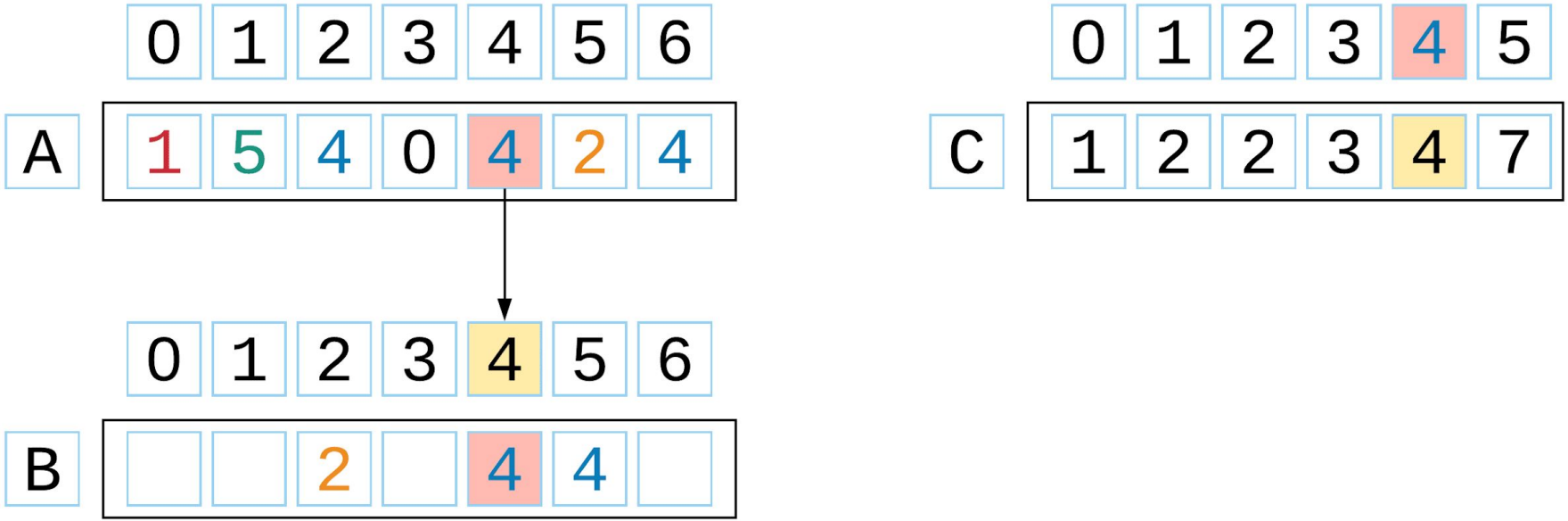
Counting-sort (Serial) - Loop 4



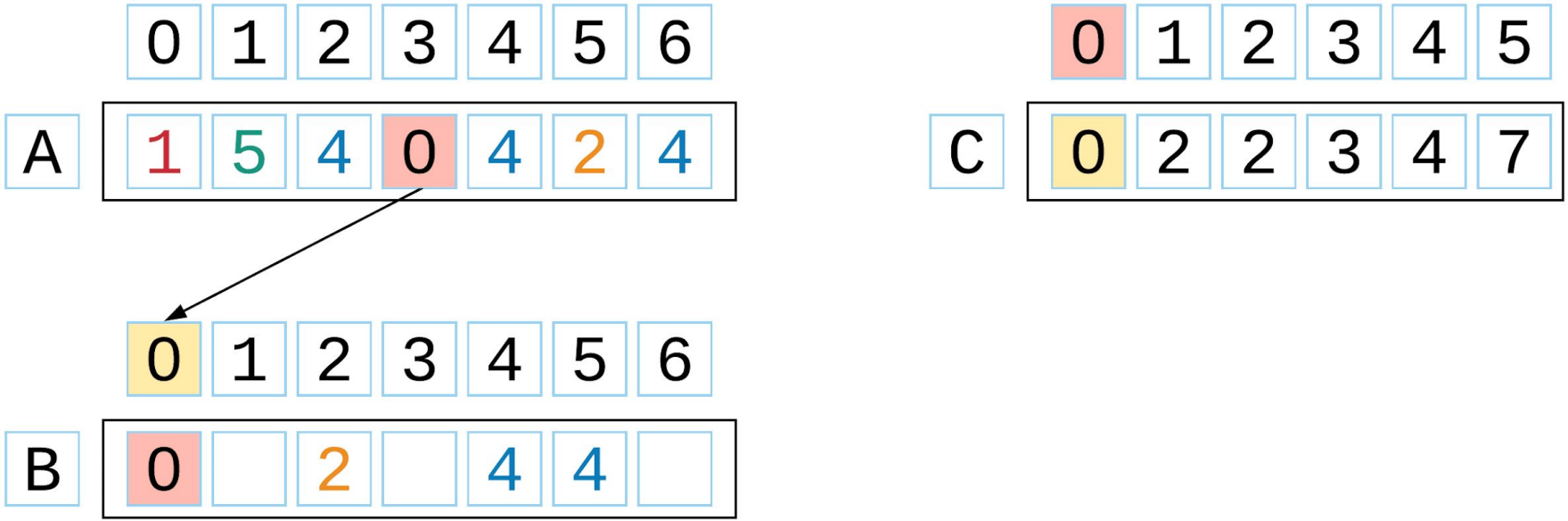
Counting-sort (Serial) - Loop 4



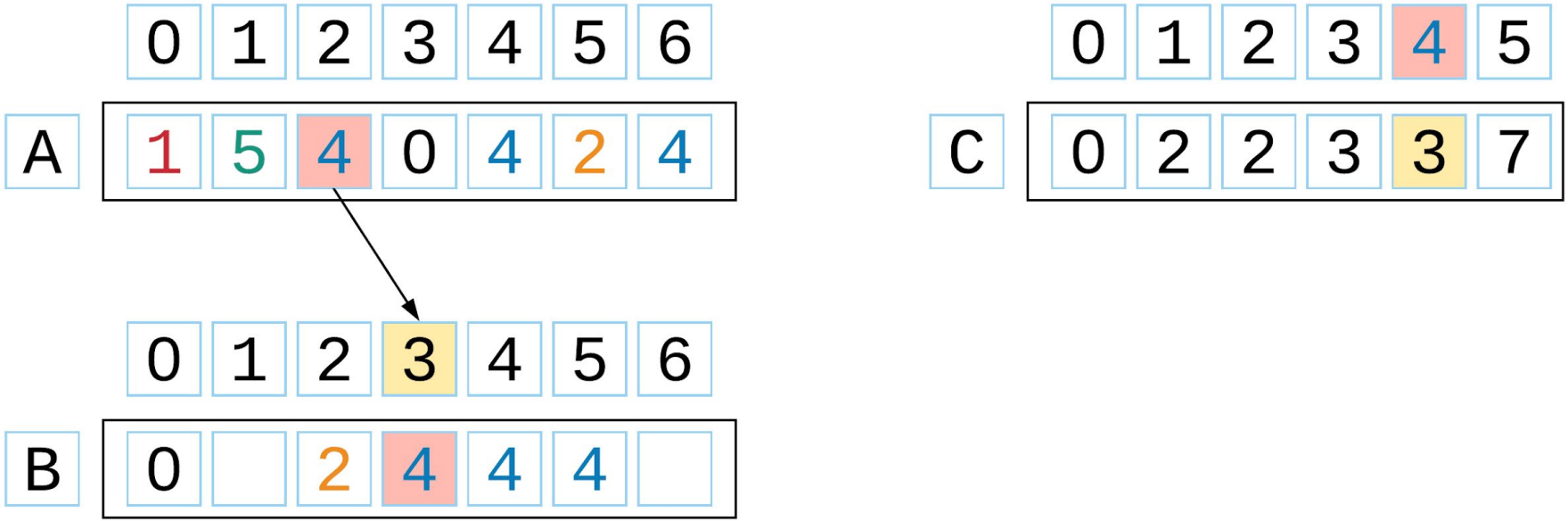
Counting-sort (Serial) - Loop 4



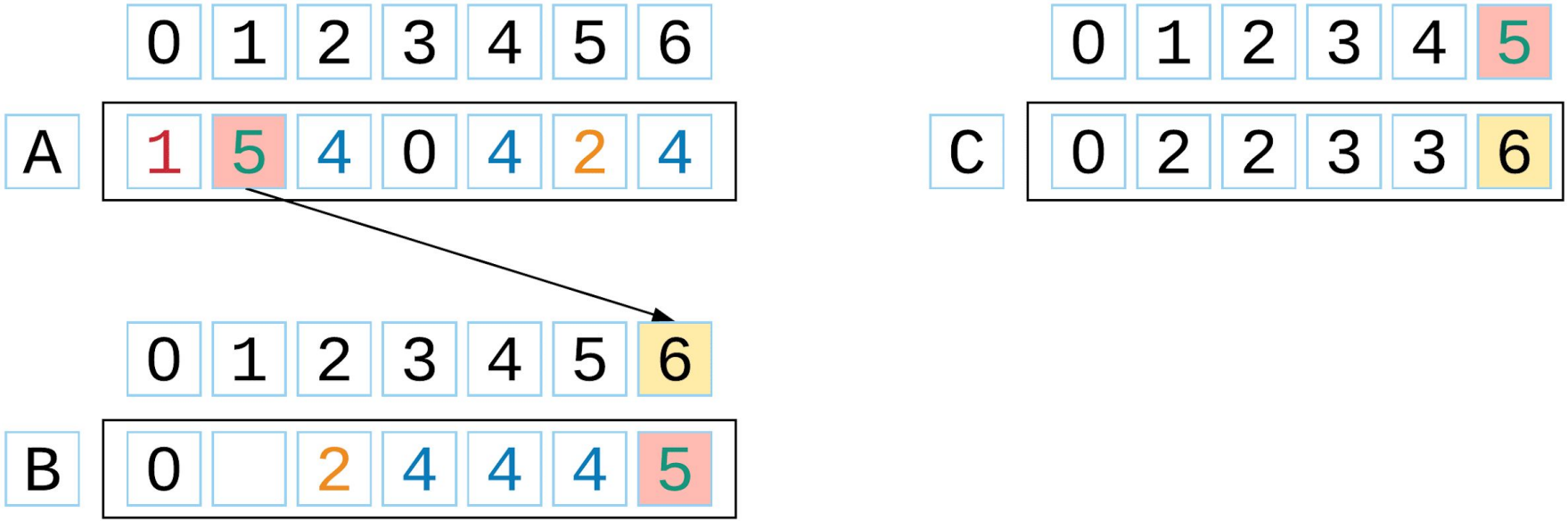
Counting-sort (Serial) - Loop 4



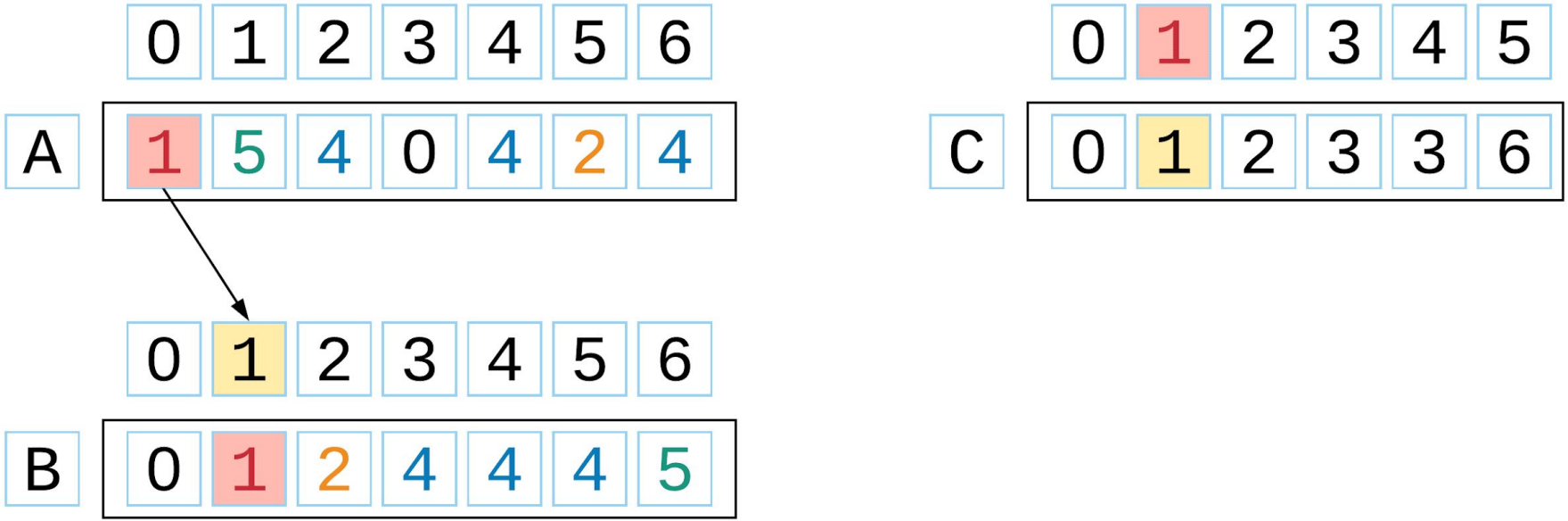
Counting-sort (Serial) - Loop 4



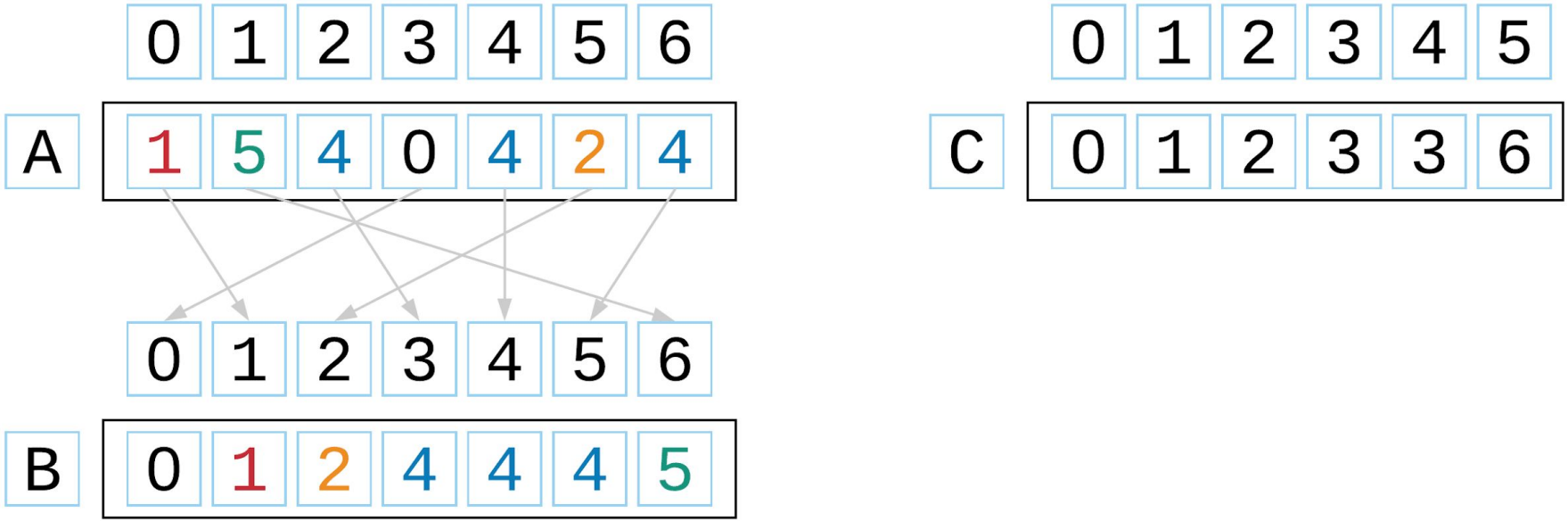
Counting-sort (Serial) - Loop 4



Counting-sort (Serial) - Loop 4



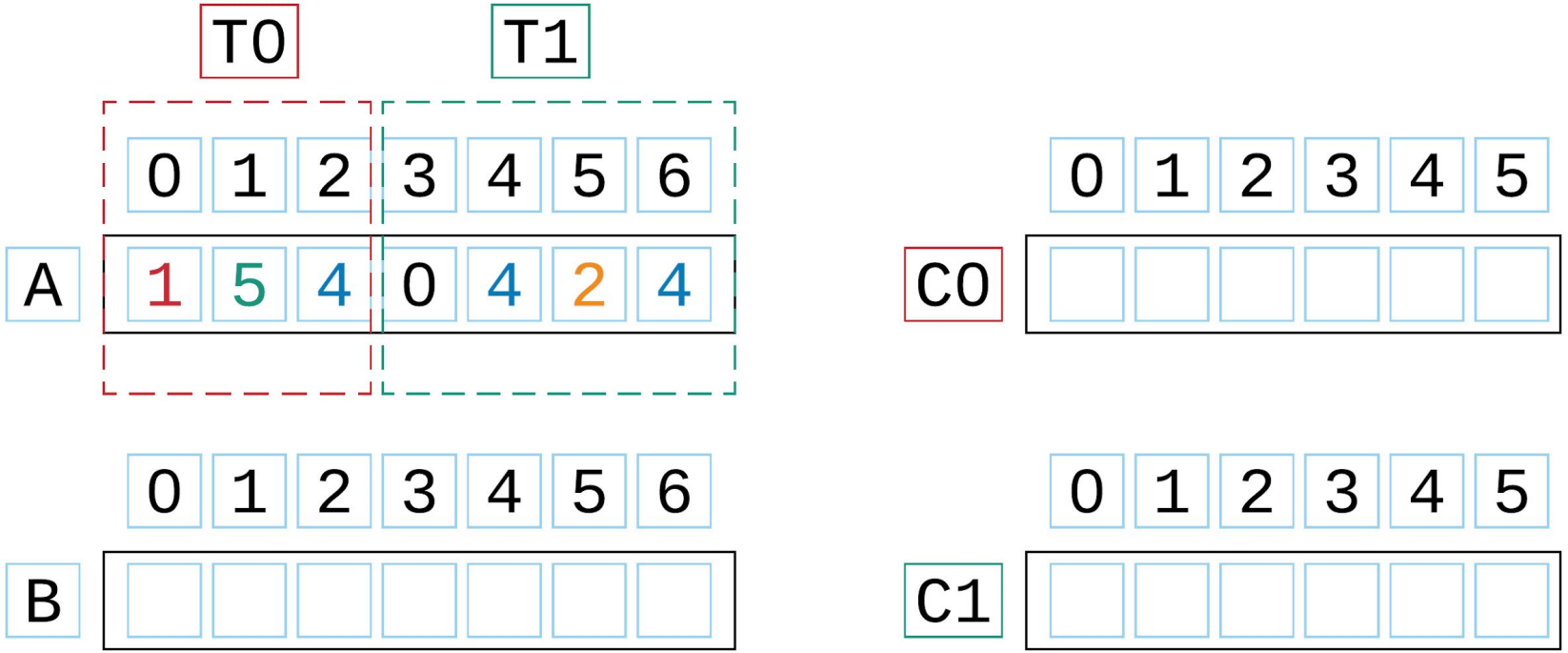
Counting-sort (Serial) - Loop 4



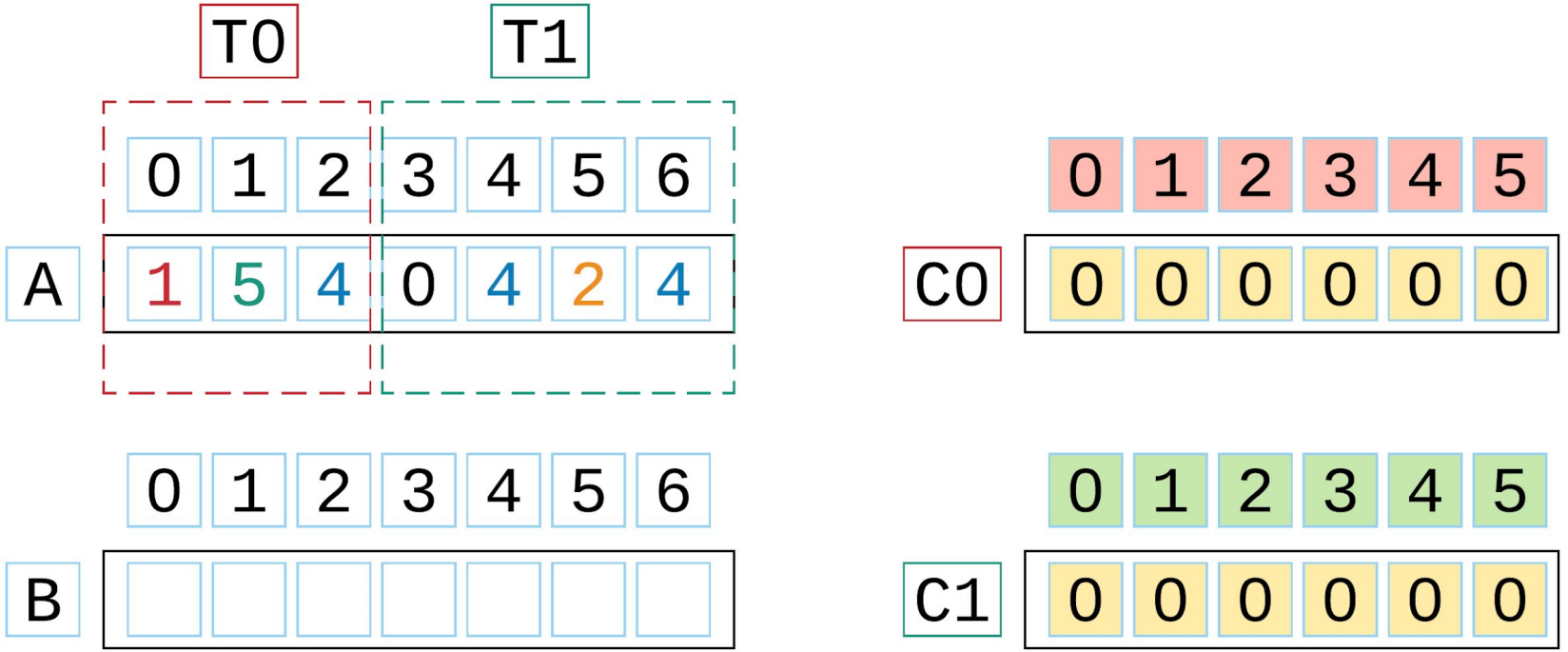
Counting-sort (Parallel)

```
base←0
Parallel for i←0 to (k-1)
   do C[tid][i]←0
Parallel for j ←tid_start to tid_end
   do C[tid][A[j]]←C[tid][A[j]]+1
Parallel barrier
for i←0 to (k-1)
   for tid←0 to (t-1)
      do base←base + C[tid][i]
         C[tid][i]←base
Parallel barrier
Parallel for j ←(tid_end-1) downto tid_start
   do B[C[tid][A[j]]-1] ←A[j]
      C[tid][A[j]]←C[tid][A[j]]-1
```

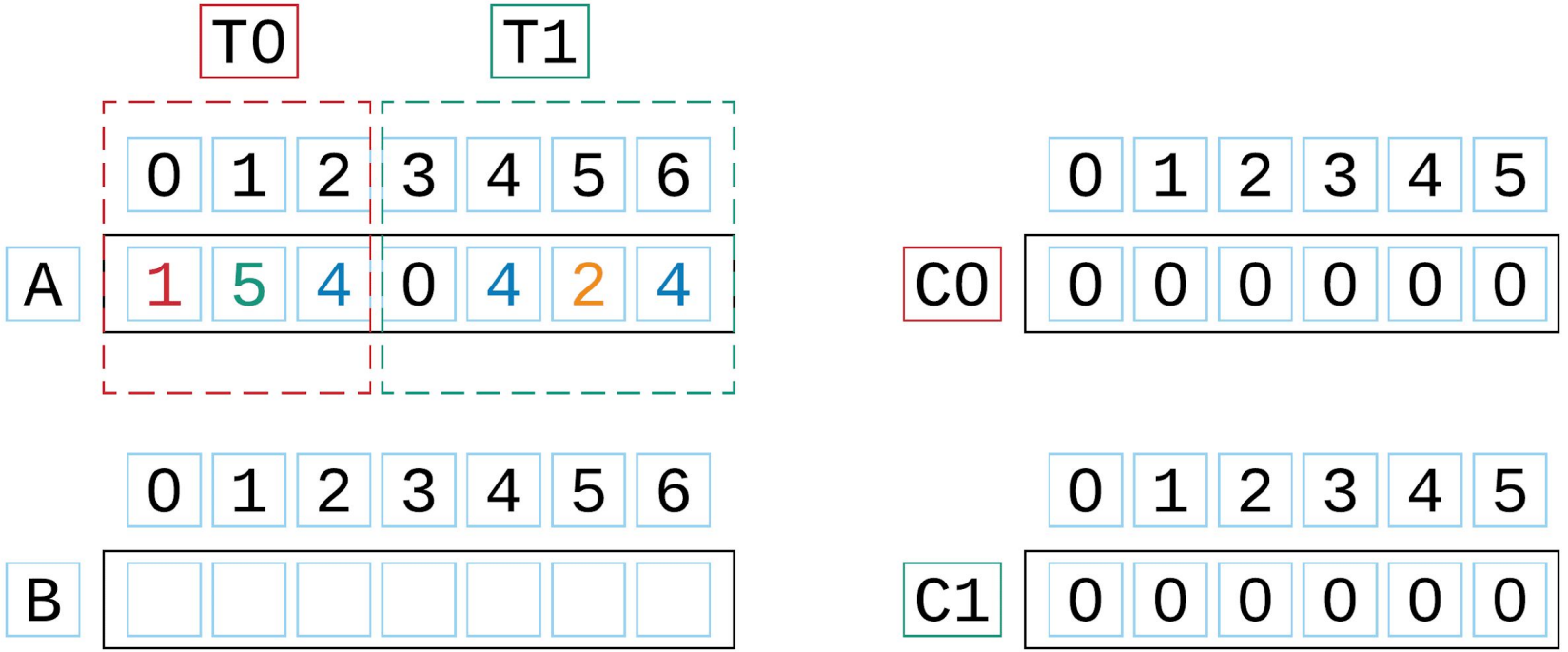
Counting-sort (Parallel)



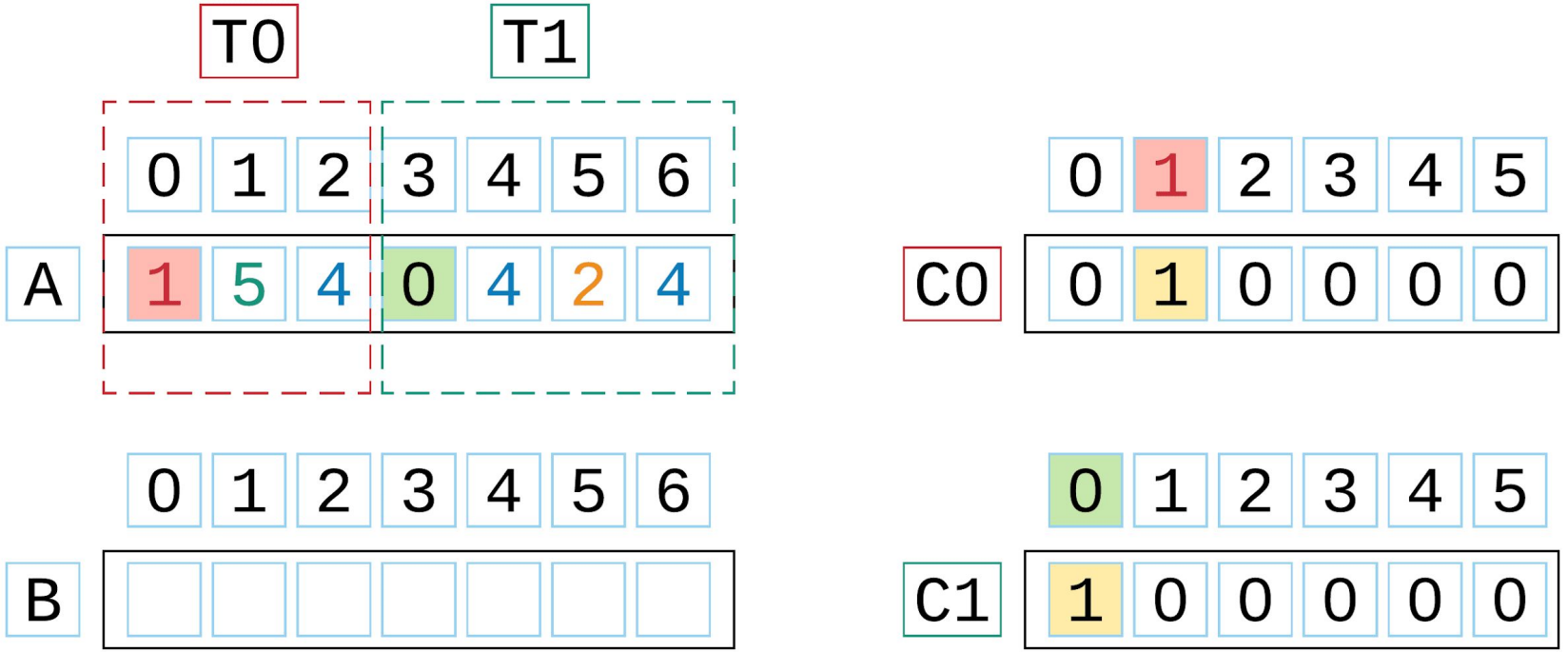
Counting-sort (Parallel) - Loop 1



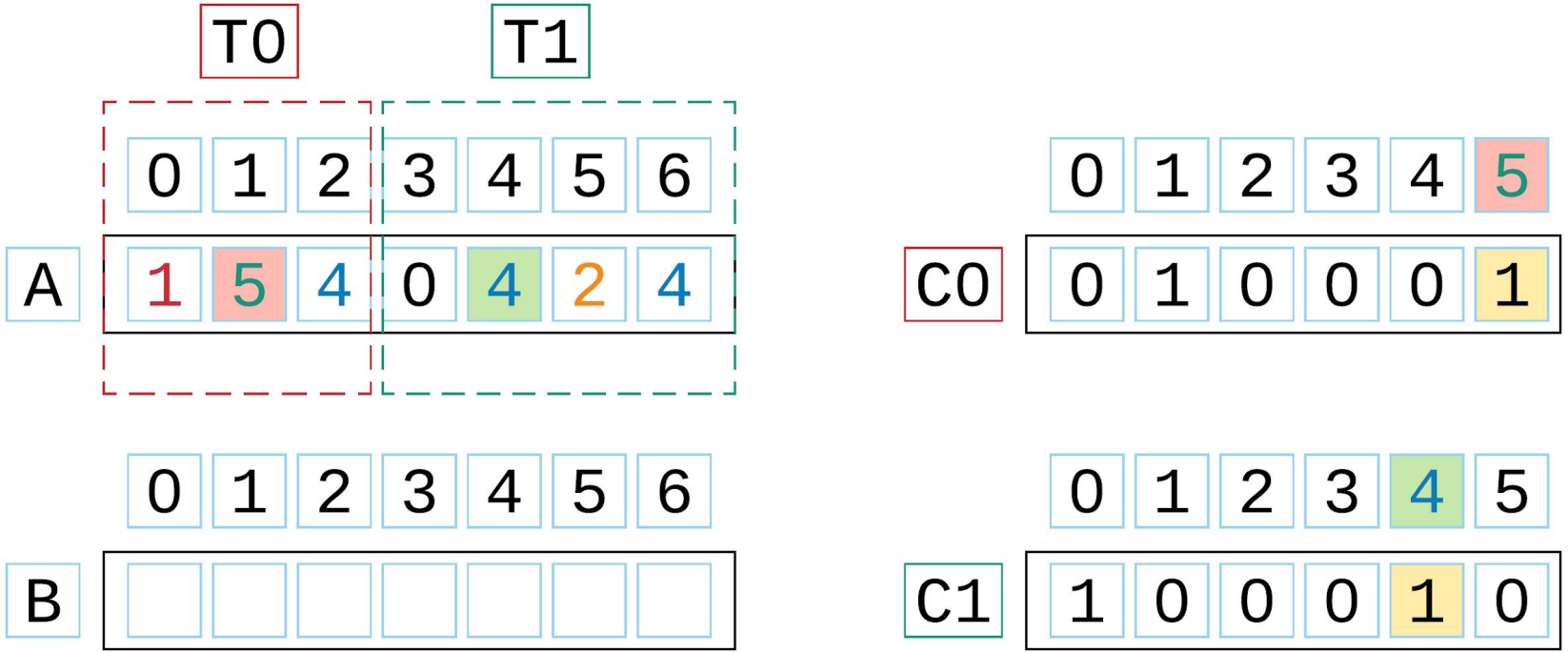
Counting-sort (Parallel) - Loop 2



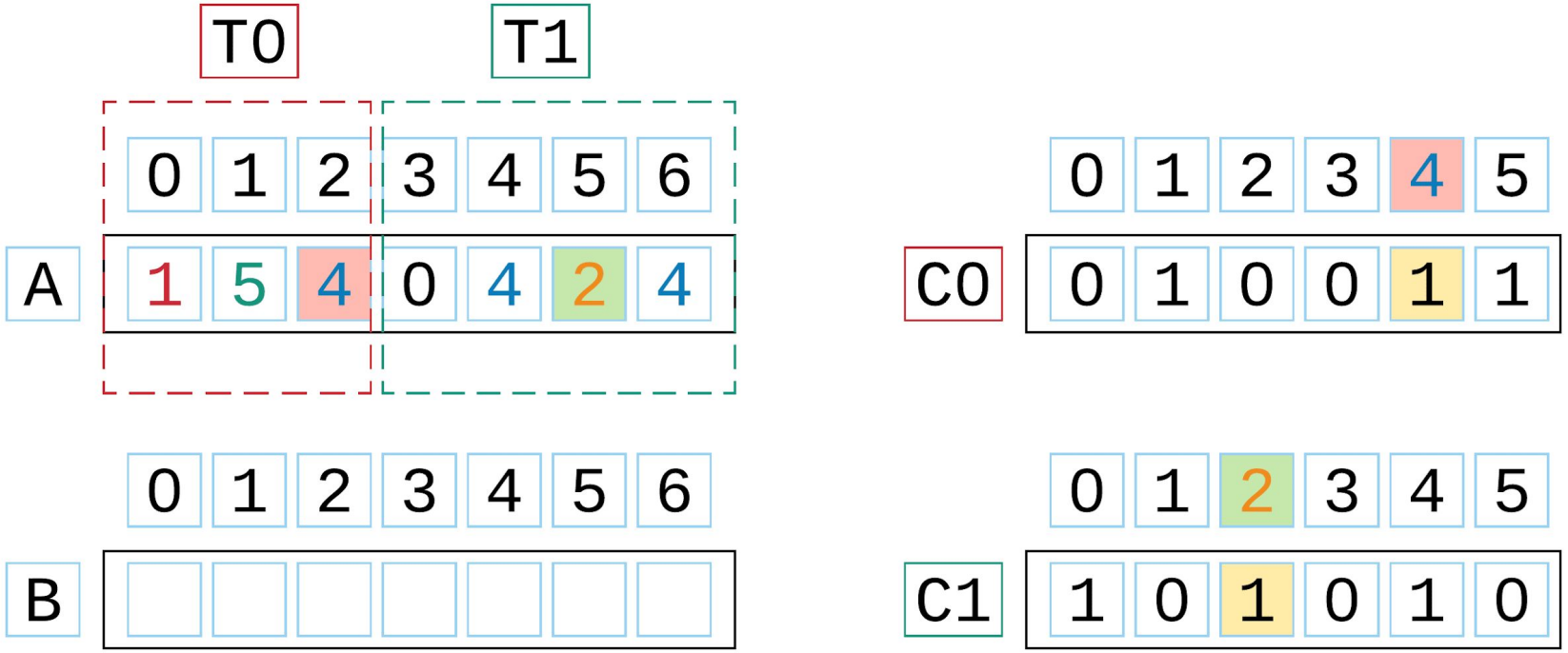
Counting-sort (Parallel) - Loop 2



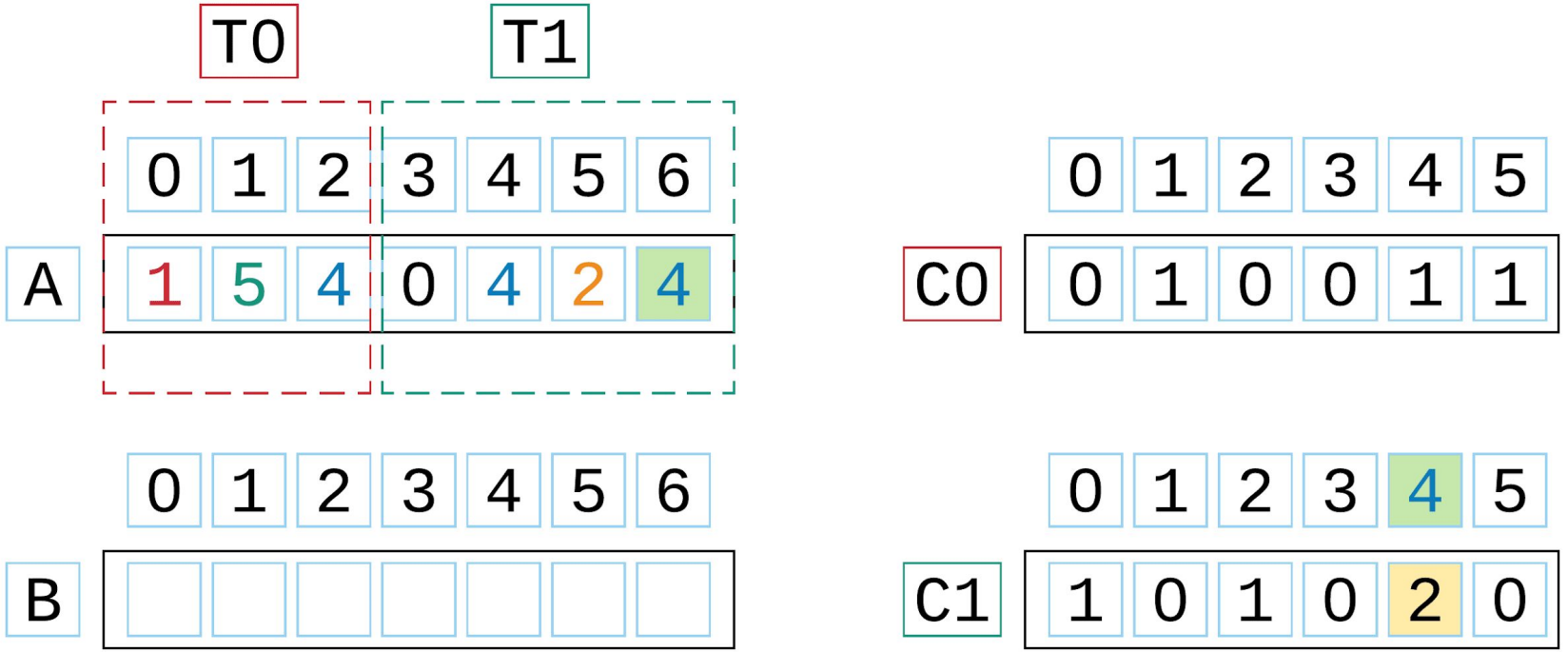
Counting-sort (Parallel) - Loop 2



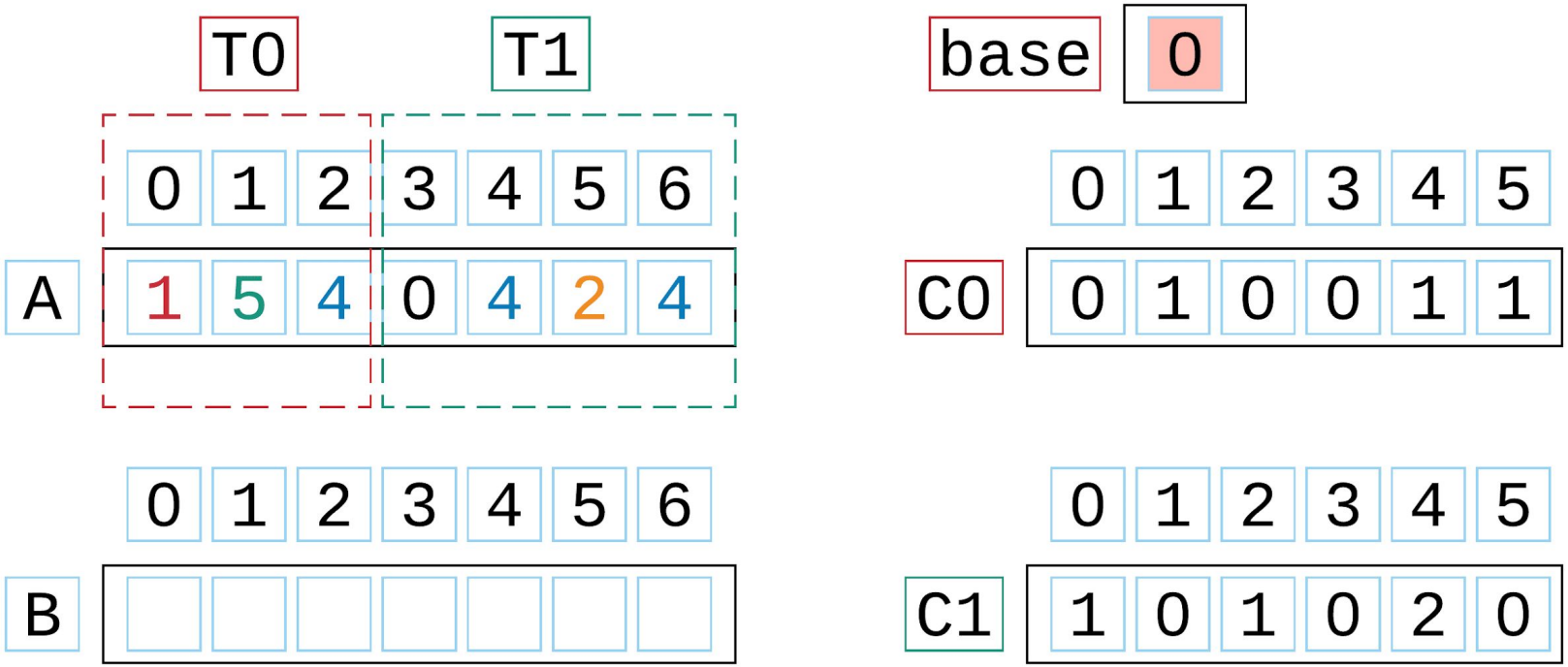
Counting-sort (Parallel) - Loop 2



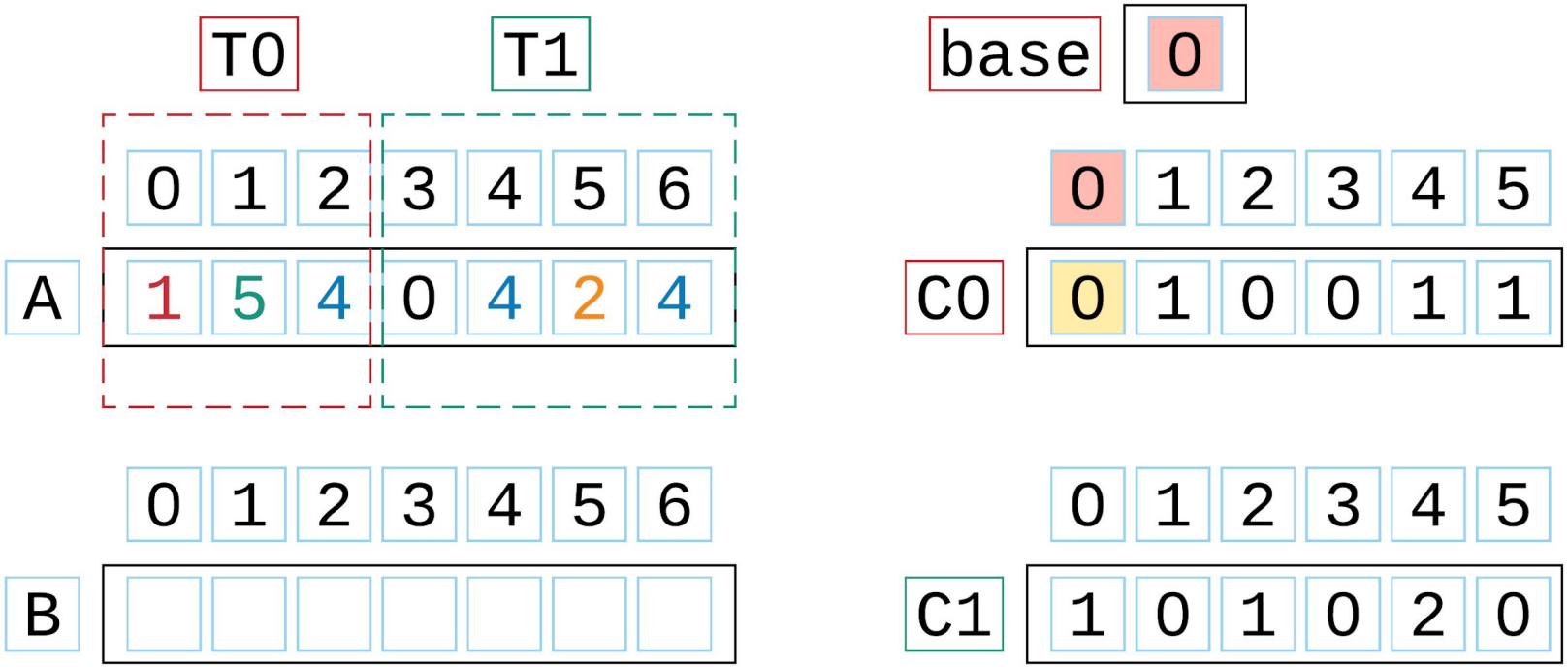
Counting-sort (Parallel) - Loop 2



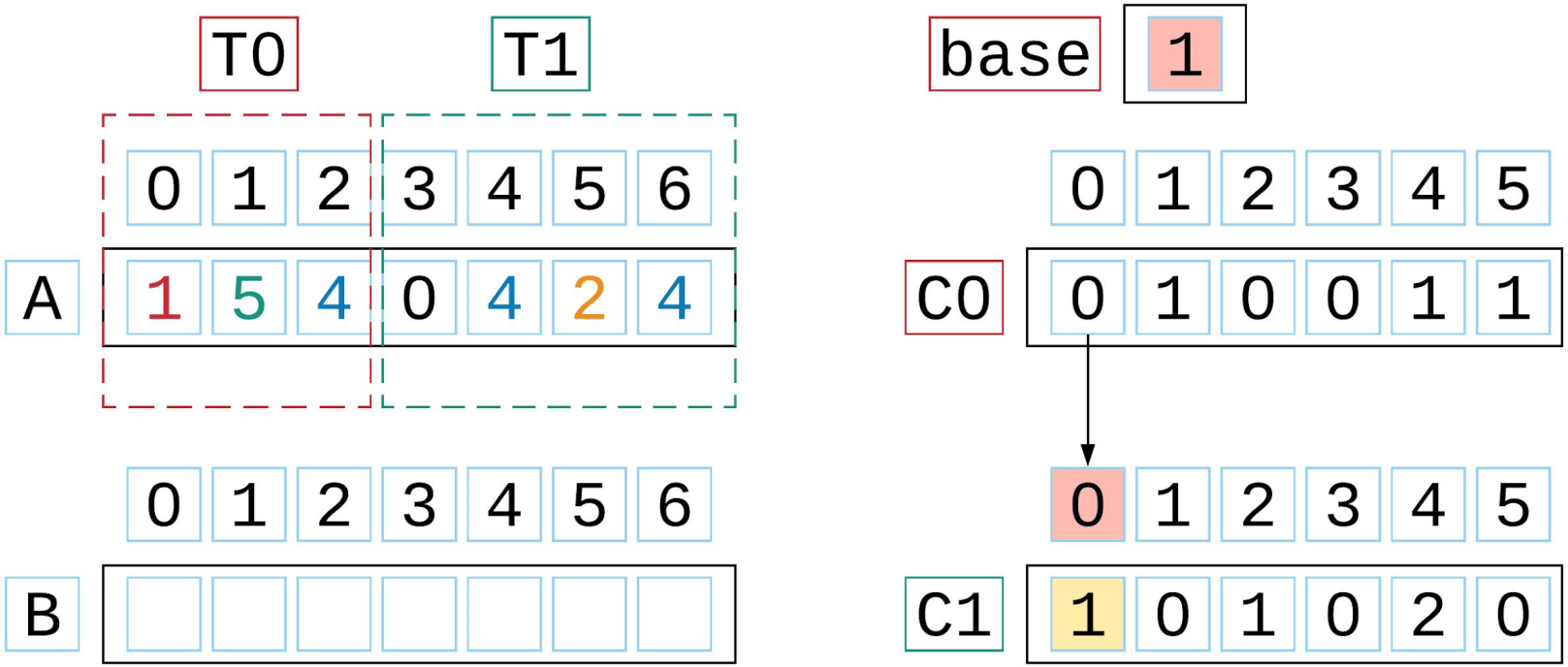
Counting-sort (Parallel) - Loop 3



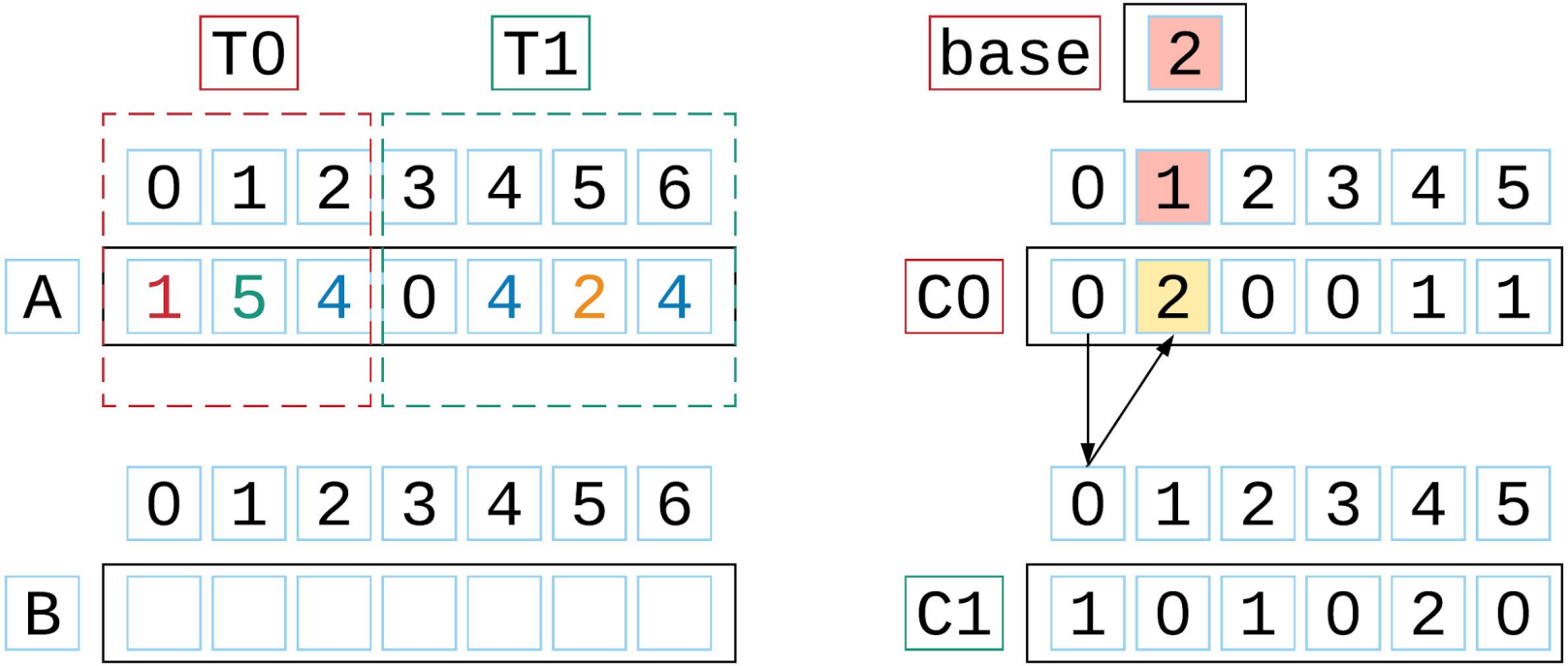
Counting-sort (Parallel) - Loop 3



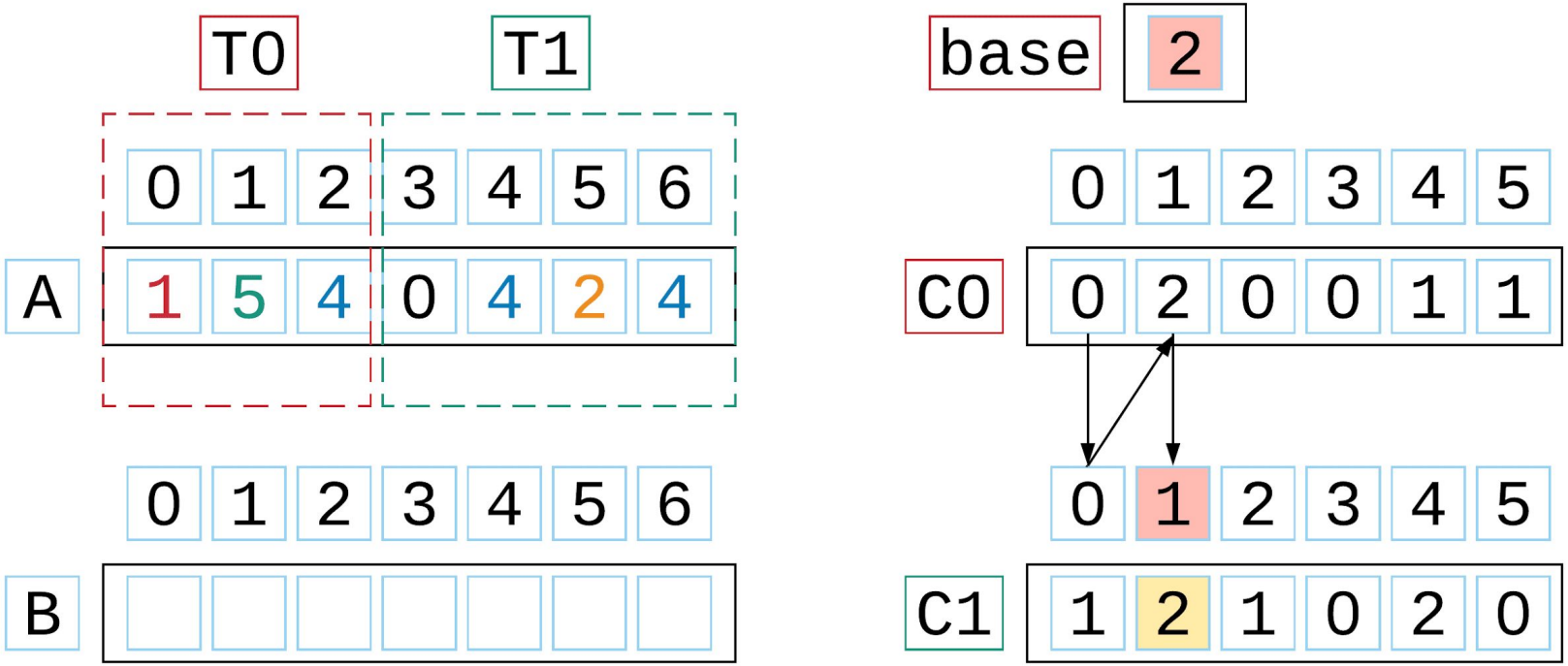
Counting-sort (Parallel) - Loop 3



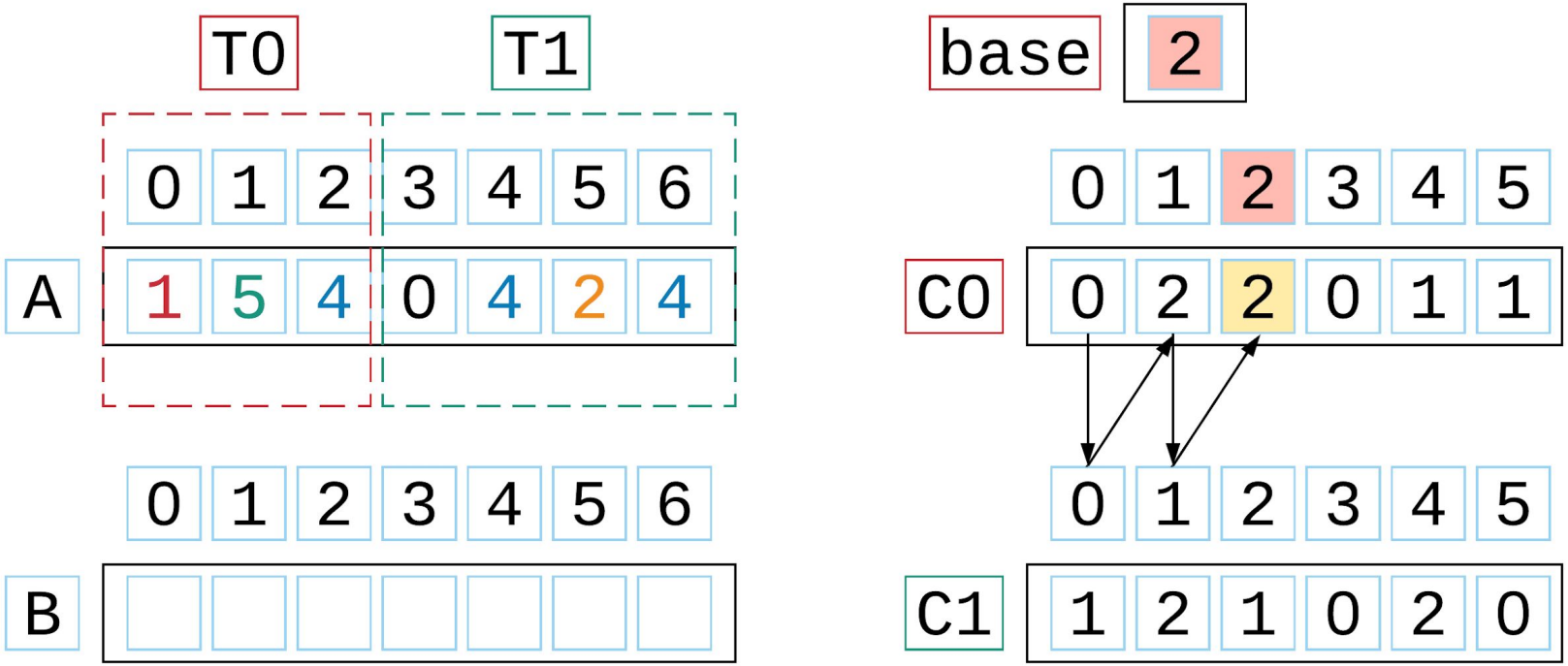
Counting-sort (Parallel) - Loop 3



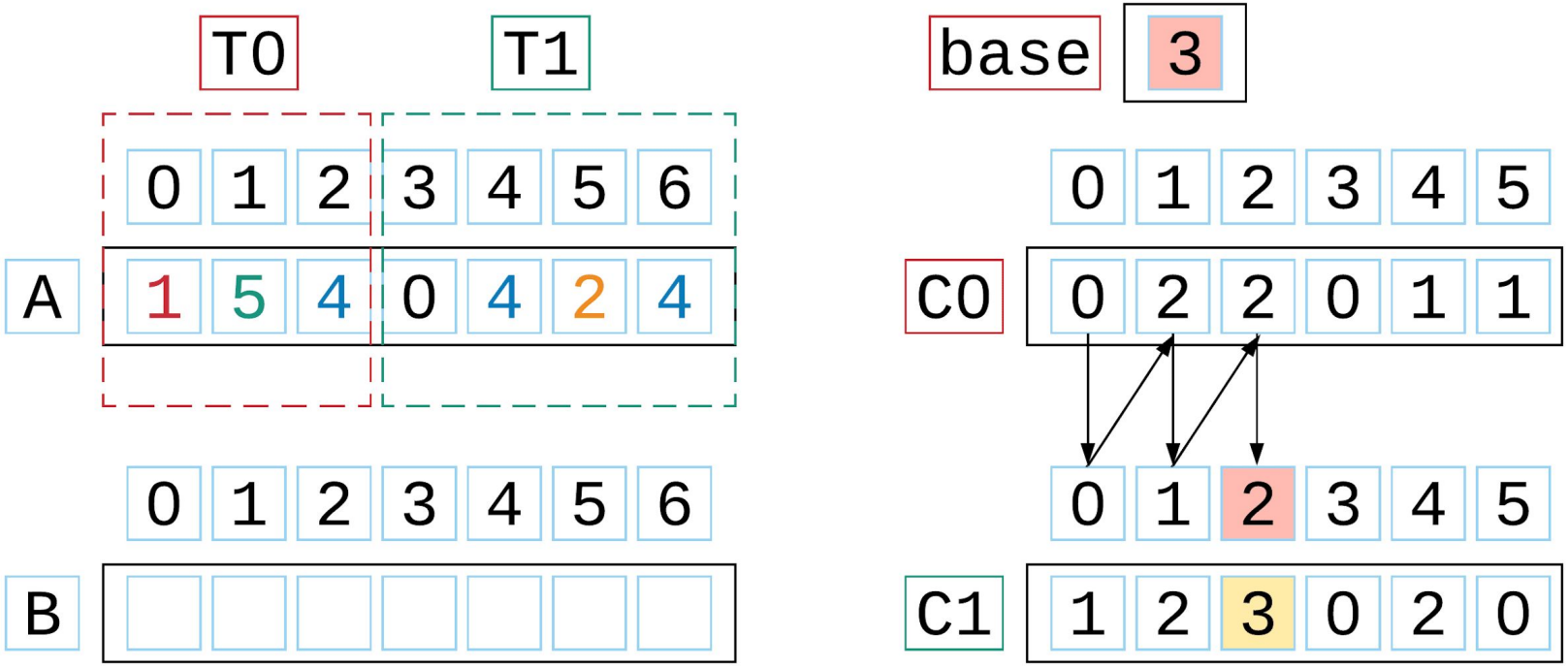
Counting-sort (Parallel) - Loop 3



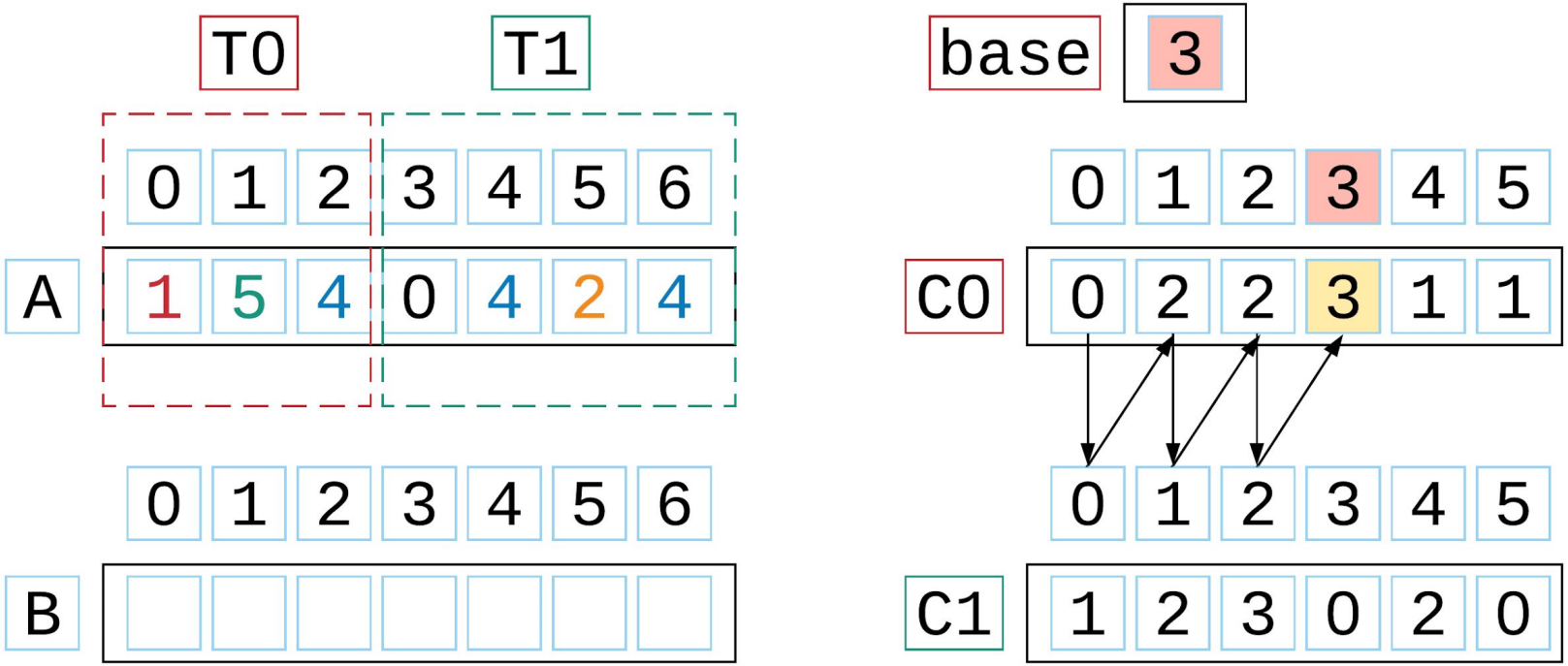
Counting-sort (Parallel) - Loop 3



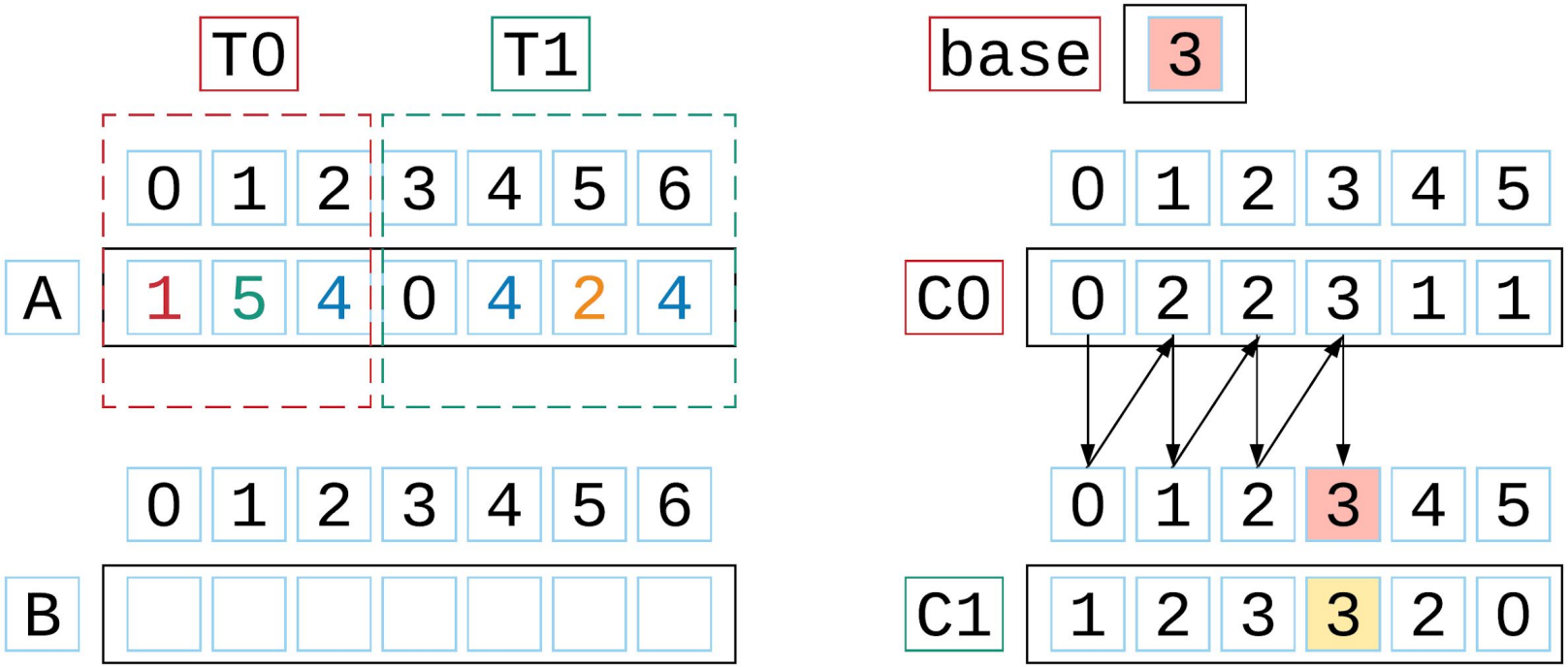
Counting-sort (Parallel) - Loop 3



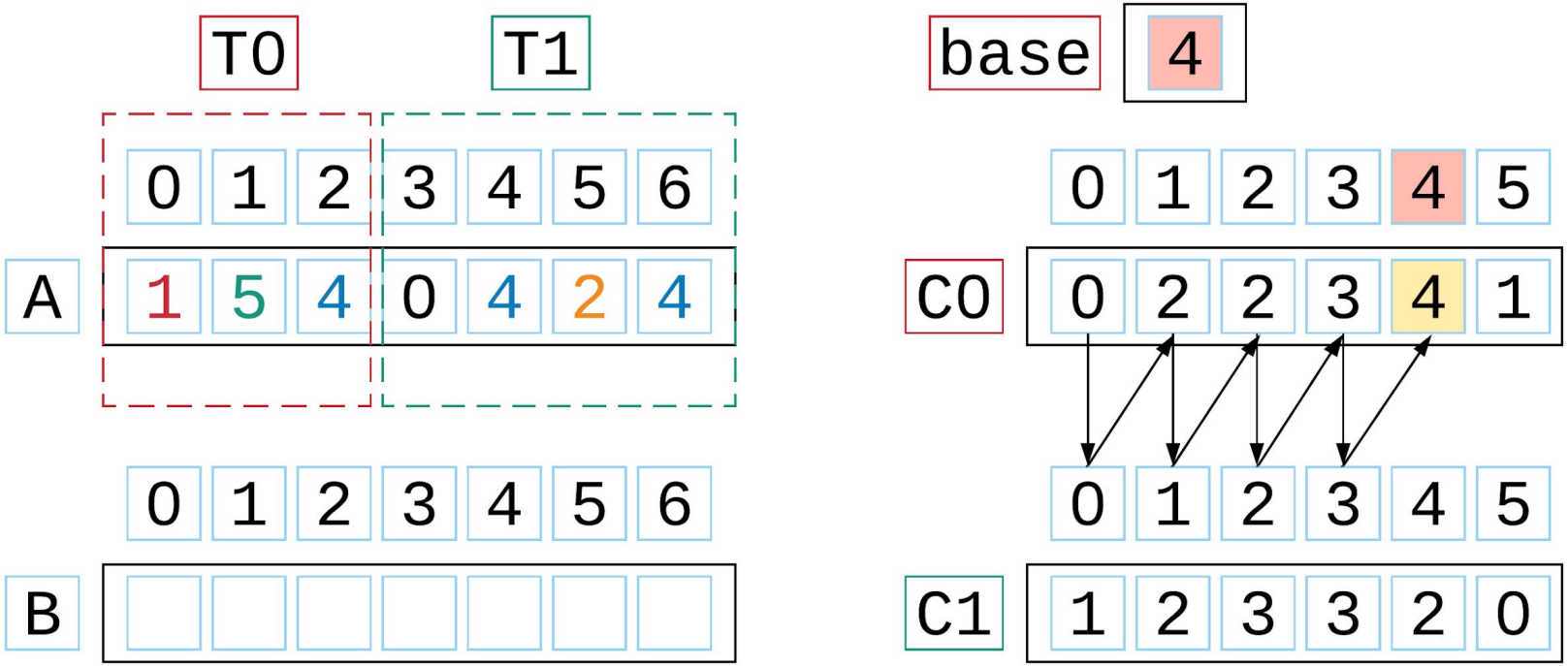
Counting-sort (Parallel) - Loop 3



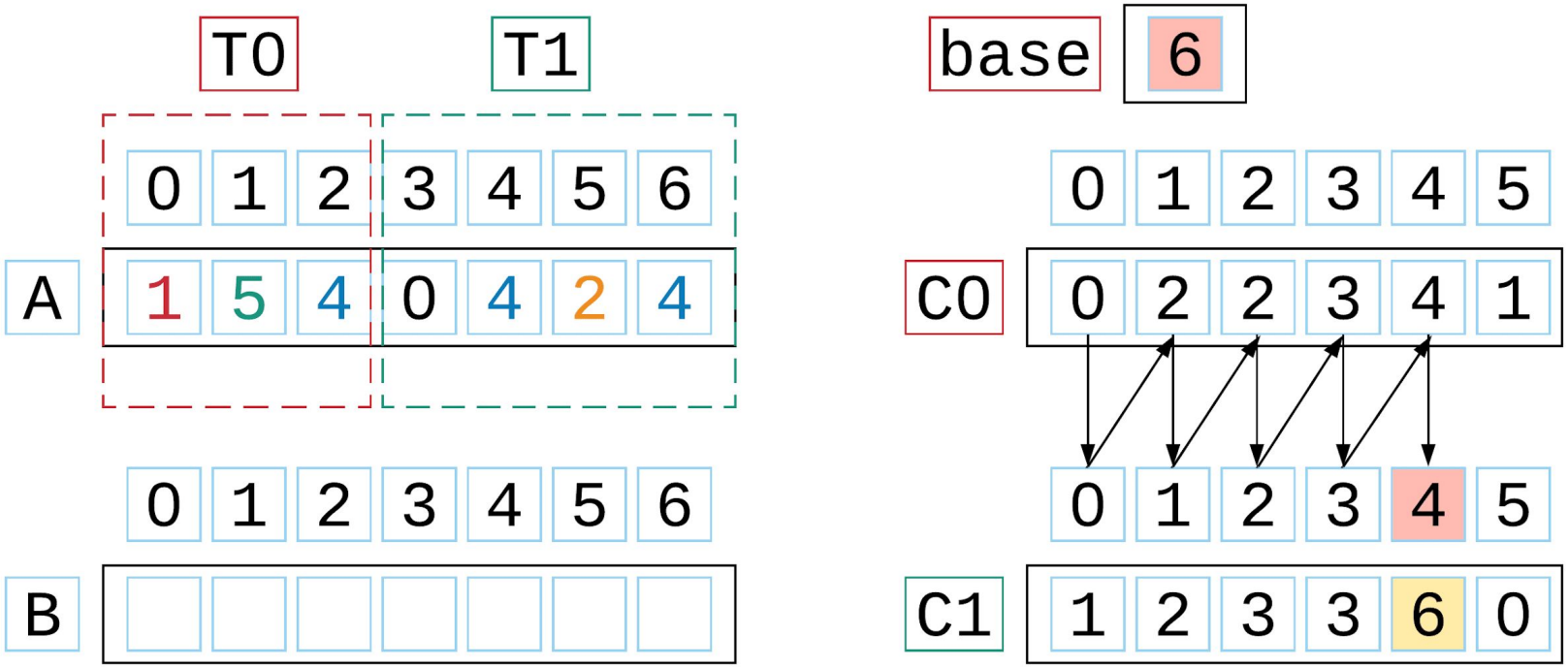
Counting-sort (Parallel) - Loop 3



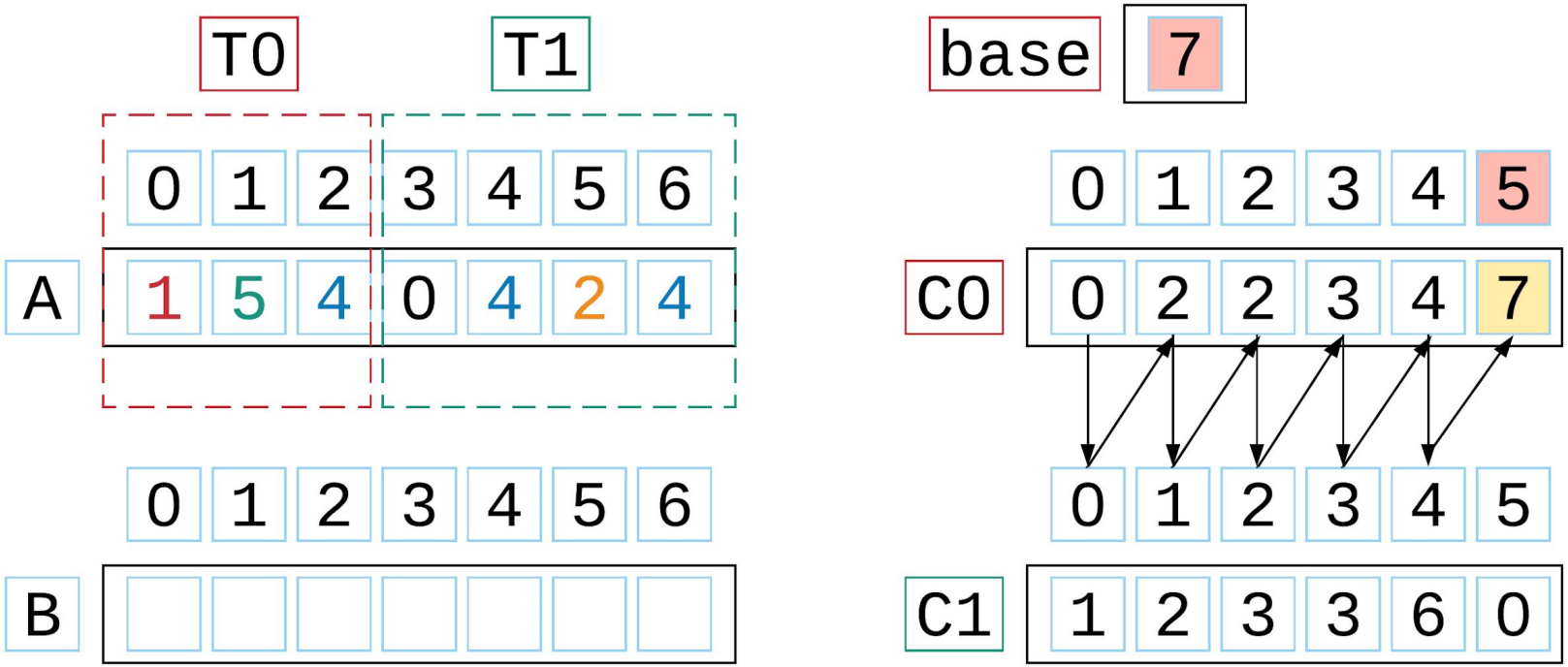
Counting-sort (Parallel) - Loop 3



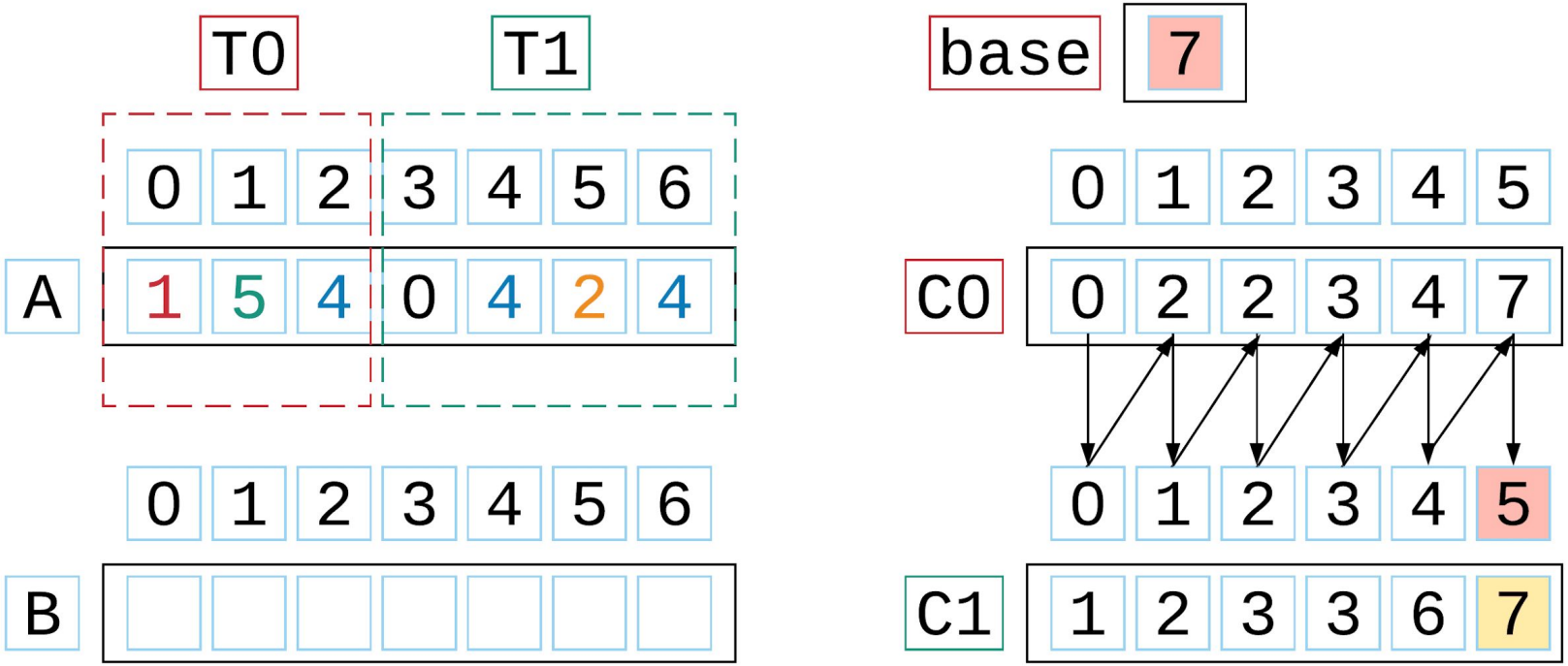
Counting-sort (Parallel) - Loop 3



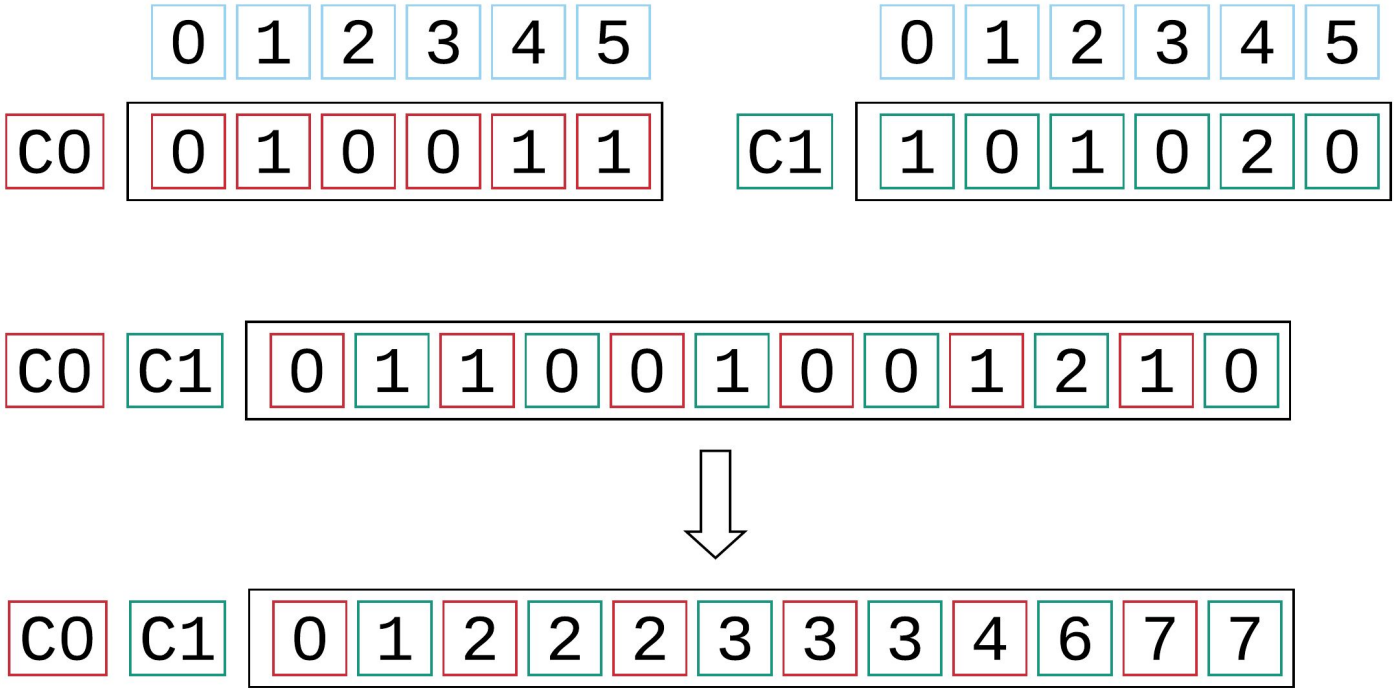
Counting-sort (Parallel) - Loop 3



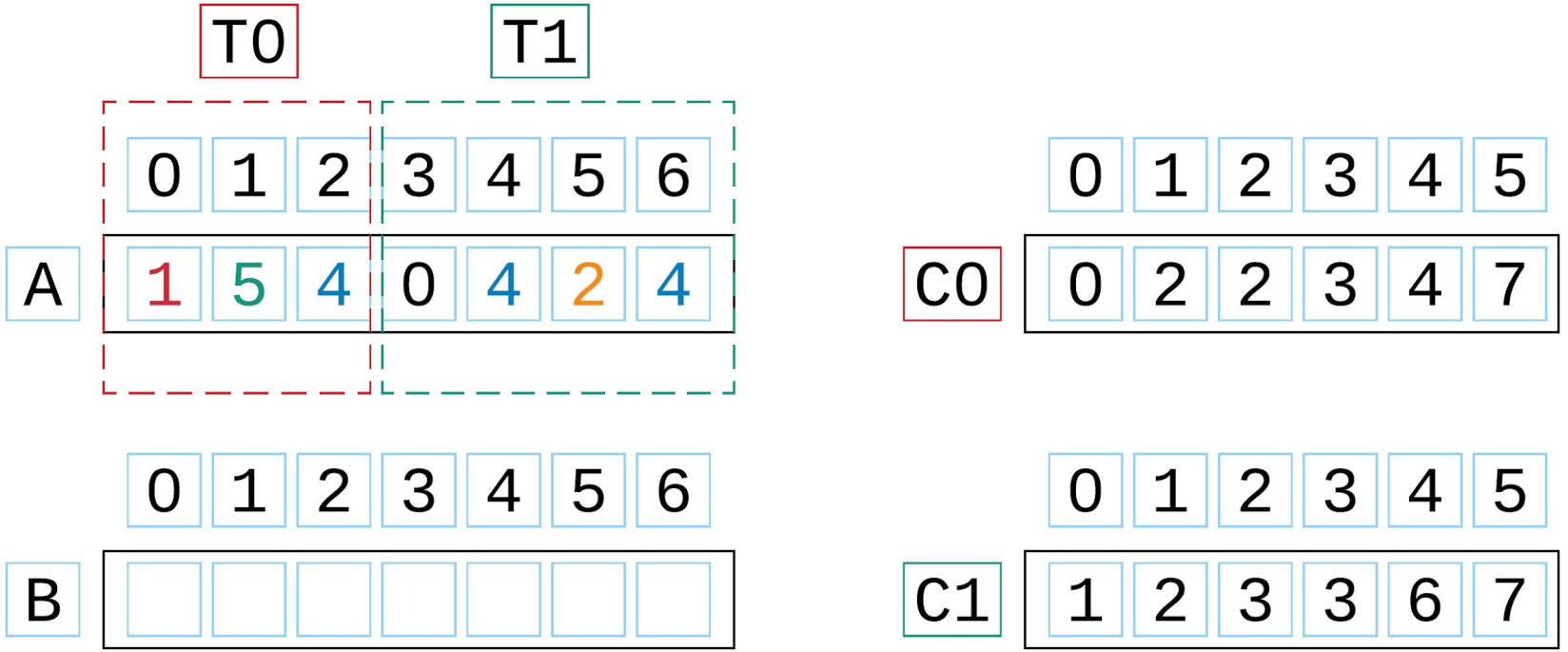
Counting-sort (Parallel) - Loop 3



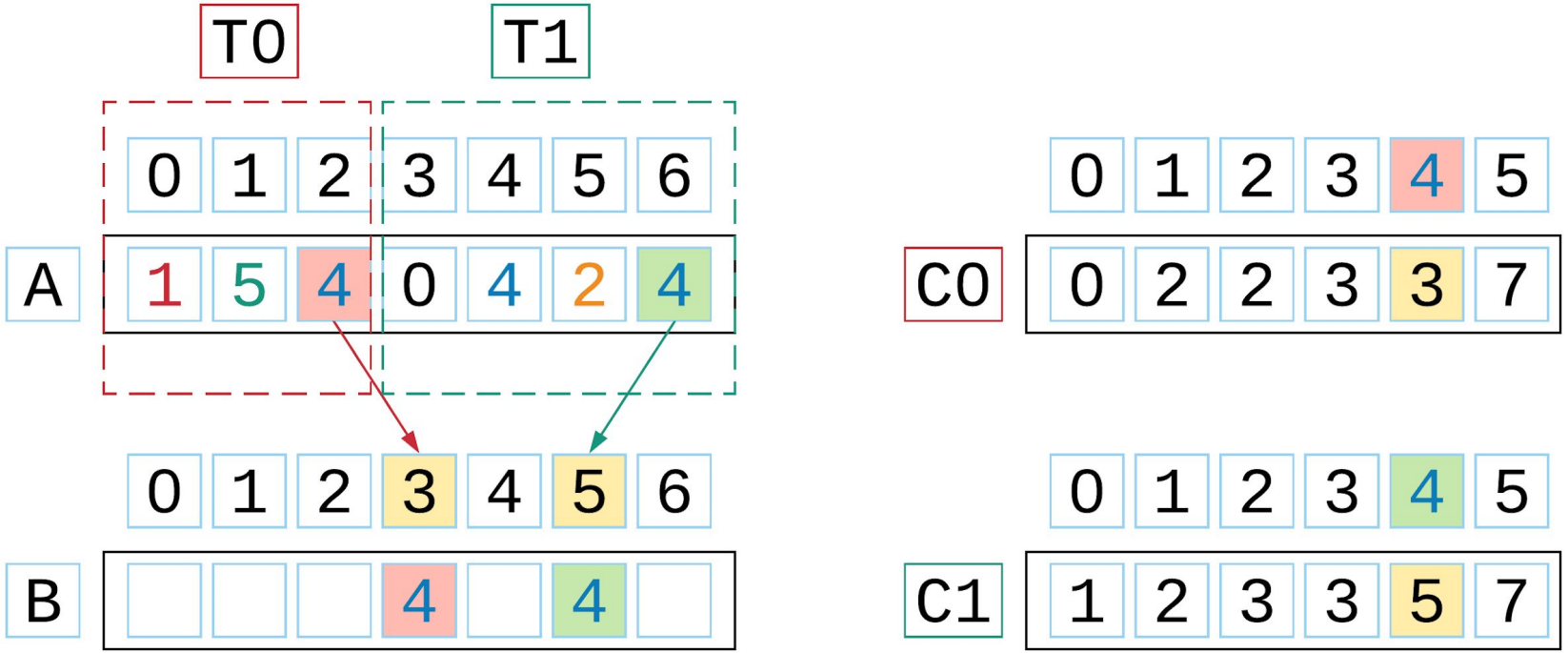
Counting-sort (Parallel) - Loop 3



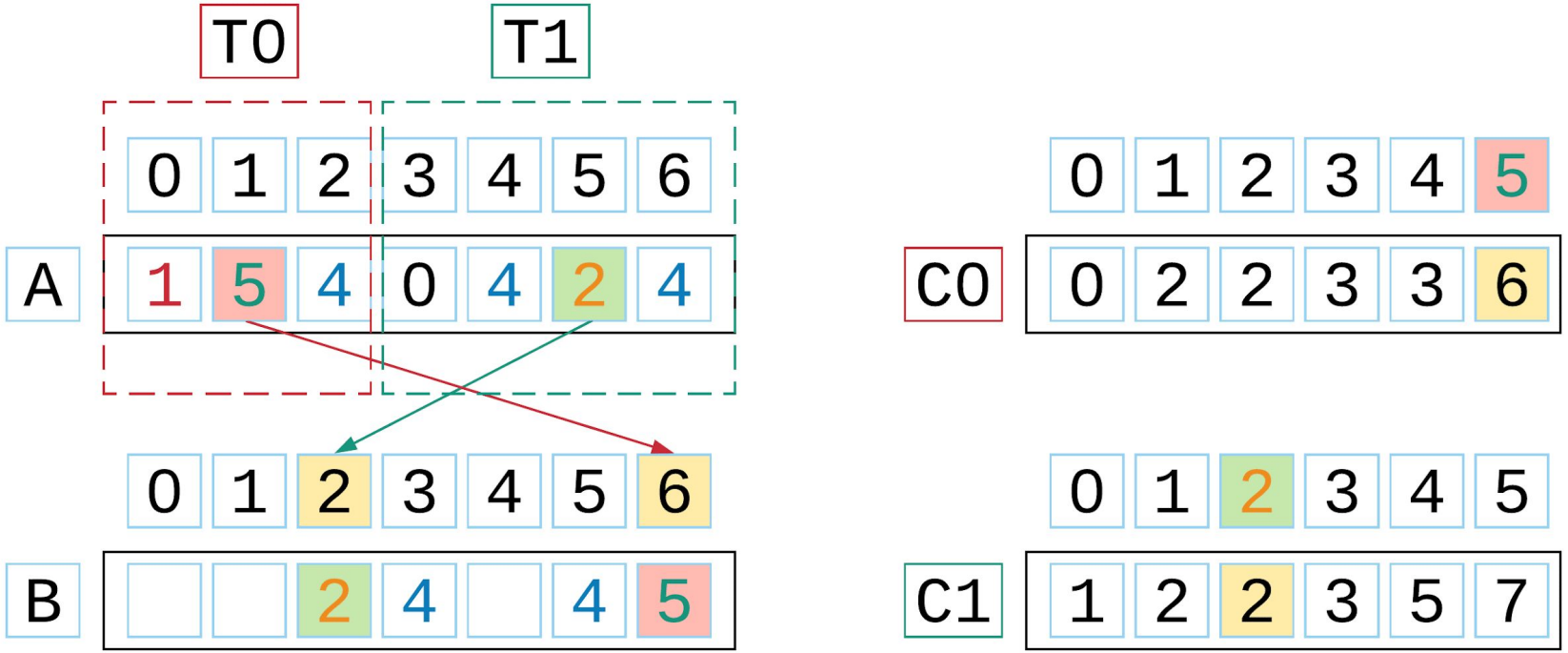
Counting-sort (Parallel) - Loop 4



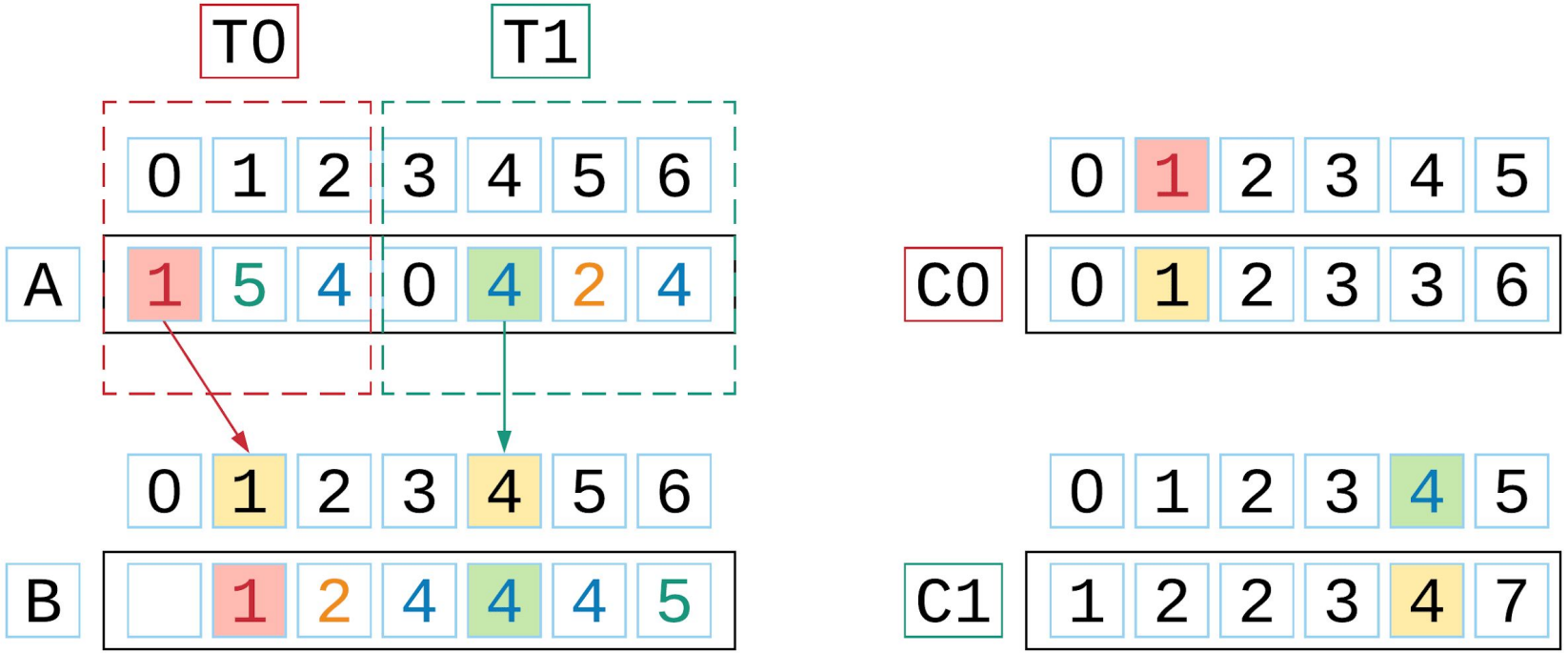
Counting-sort (Parallel) - Loop 4



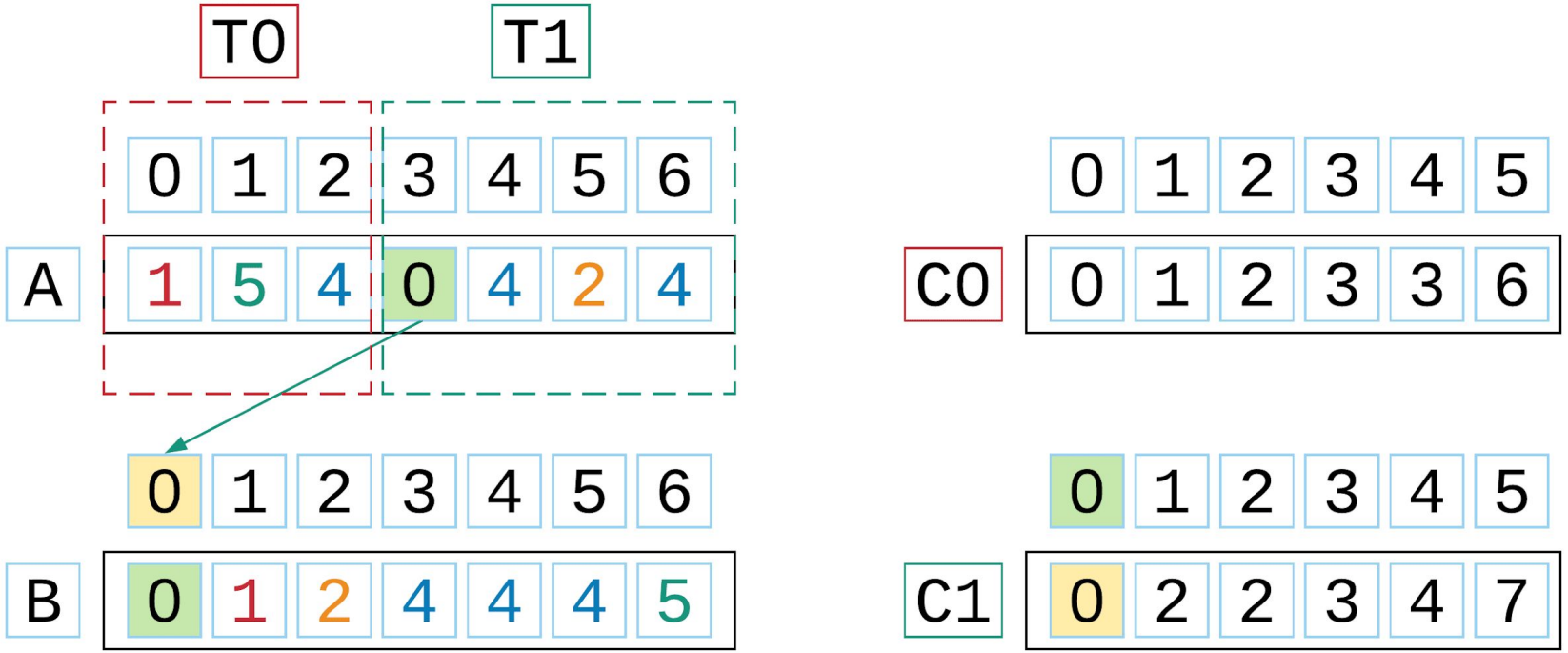
Counting-sort (Parallel) - Loop 4



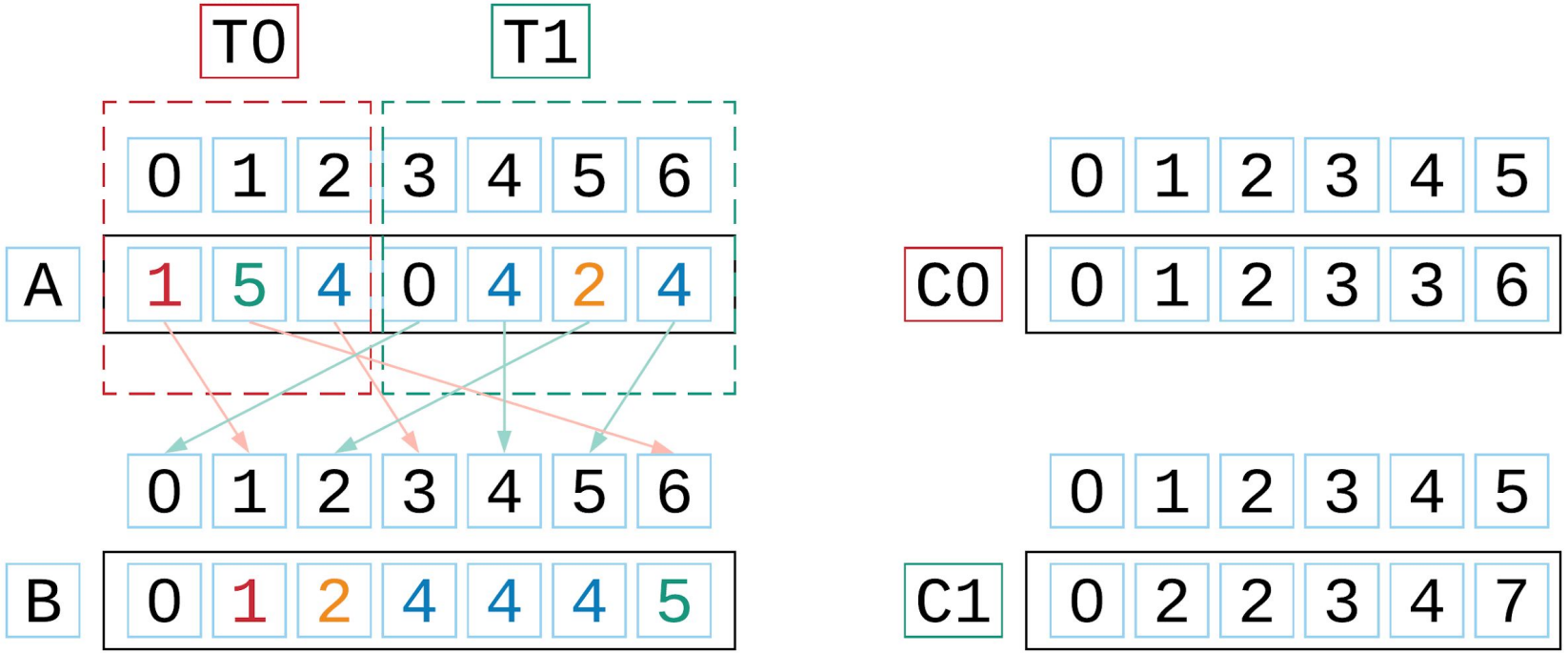
Counting-sort (Parallel) - Loop 4



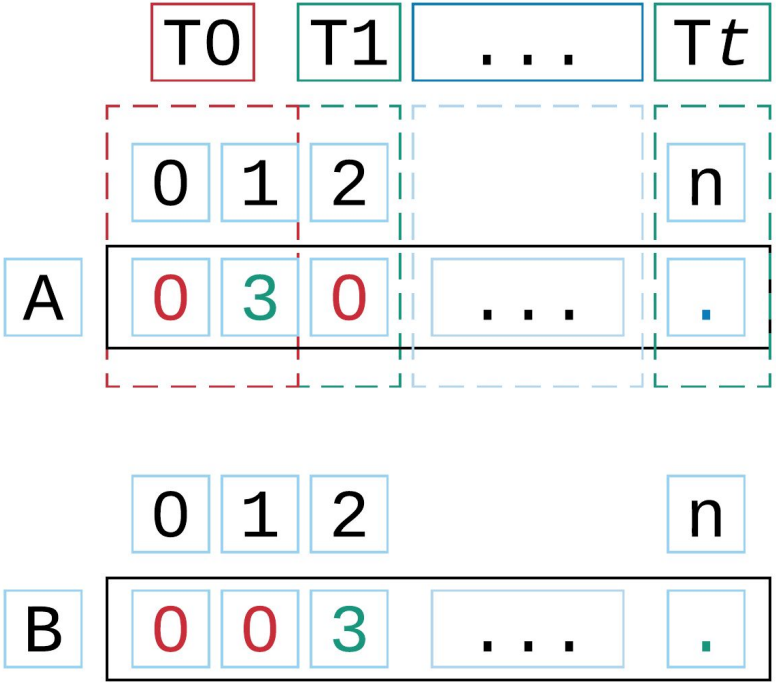
Counting-sort (Parallel) - Loop 4

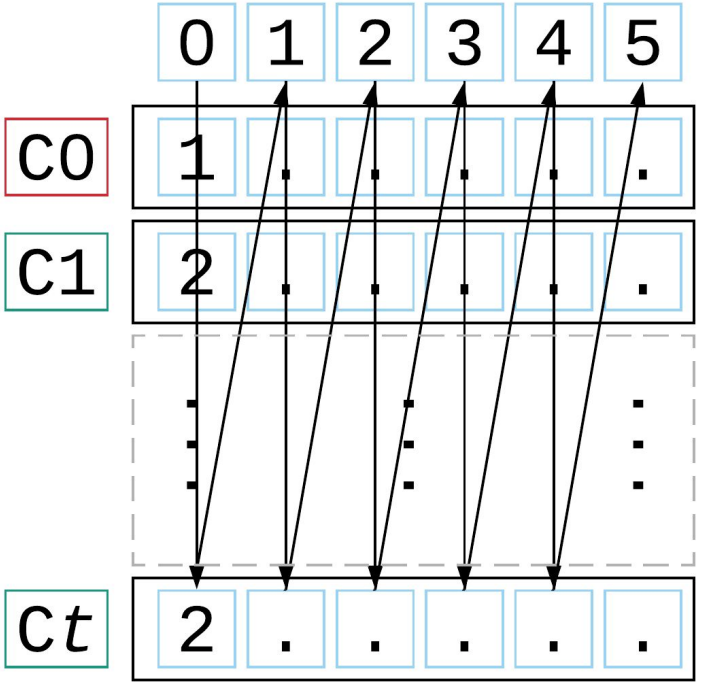


Counting-sort (Parallel) - 2 Threads



Counting-sort (Parallel) - (t) Threads





Breadth First Search (BFS)

Breadth First Search (BFS) : Traversing or searching tree or graph data structures.

- ***Input***: vertices[1..n], Source.
- ***Output***: parent[1..v].
- ***Auxiliary* storage**: frontier, next.

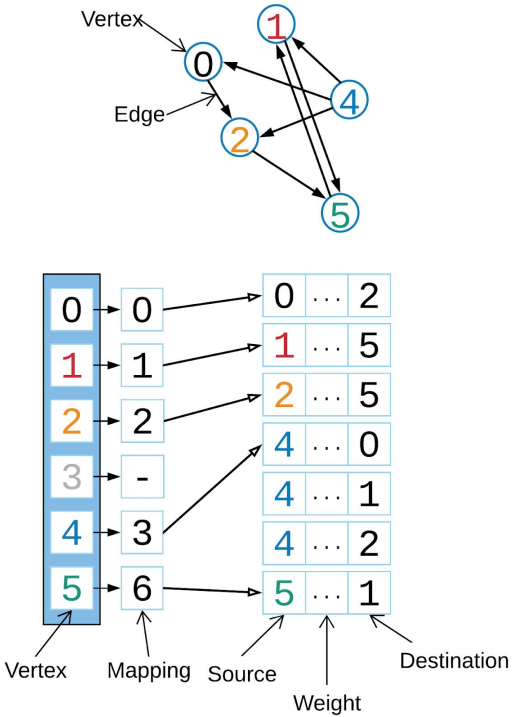
Breadth First Search (BFS)

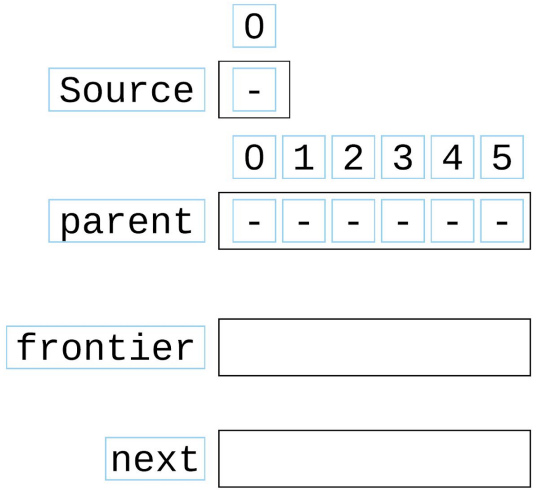
```
function breadth-first-search(vertices,source)
    frontier←{source}
    next←{}
    parents←[-1,-1,...-1]
    while frontier≠{} do
        top-down-step(vertices,frontier,next,parents)
        frontier←next
        next←{}
    end while
    return tree
```

Top Down Step (Push)

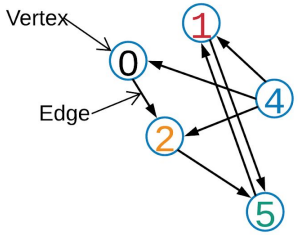
```
function top-down-step(vertices,frontier,next,parents)
   for v ∈ frontier do
     for n ∈ neighbors[v] do
       if parents[n] = -1 then
          parents[n]←v
          next←next⋃{n}
       end if
     end for
   end for
```

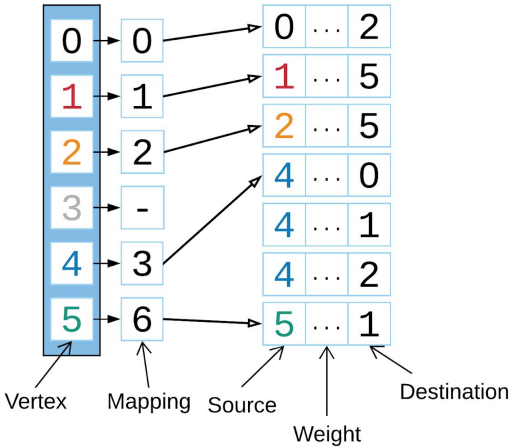
Breadth First Search (BFS)

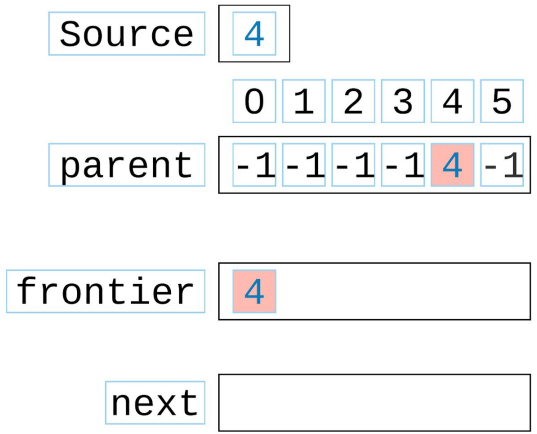




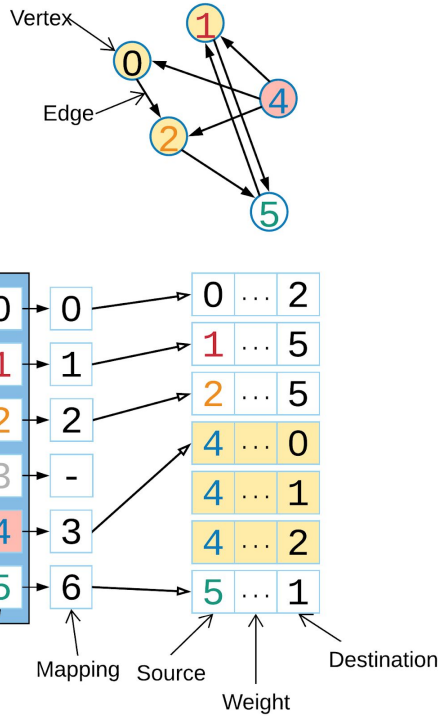
Breadth First Search (BFS) Initialize

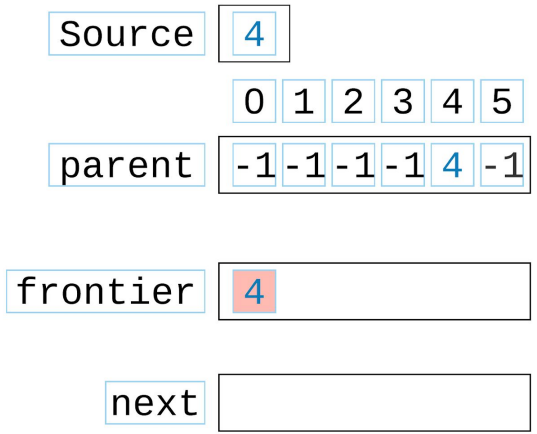




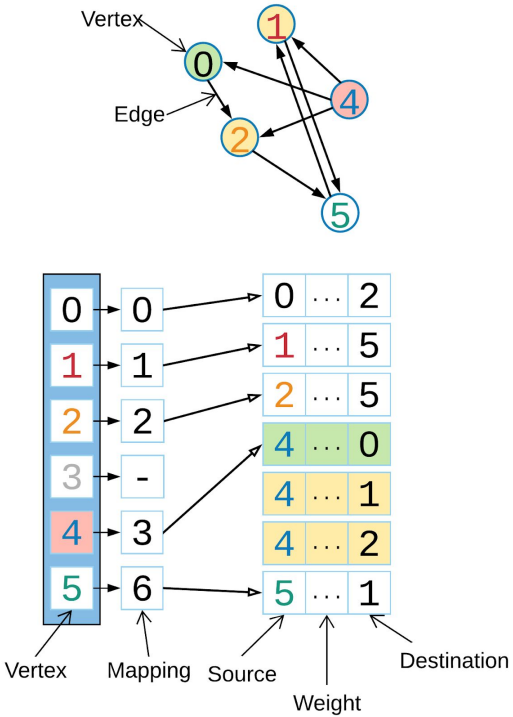


Breadth First Search (BFS) Iteration-1





Breadth First Search (BFS) Iteration-1



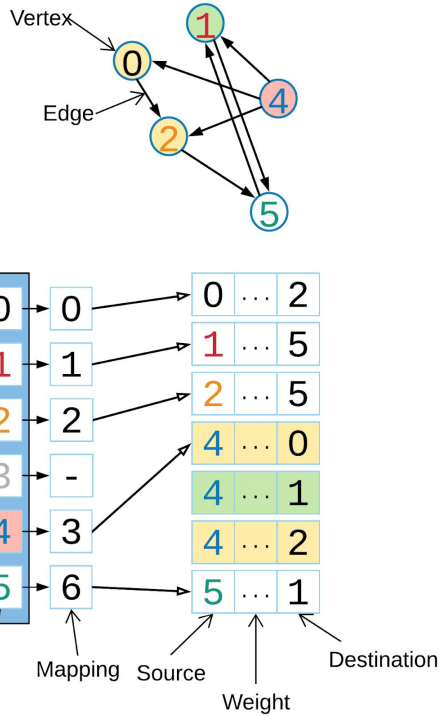
Source	4

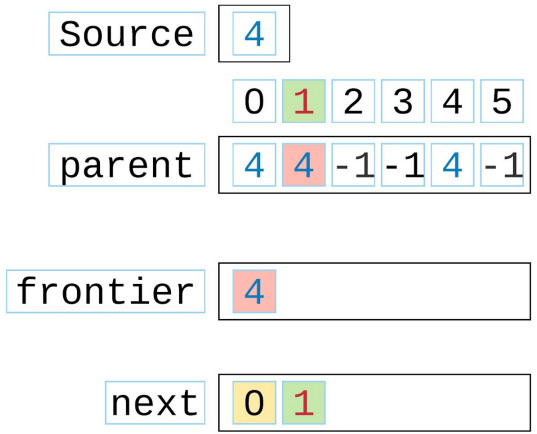
	0	1	2	3	4	5
parent	4	-1	-1	-1	4	-1

frontier	4

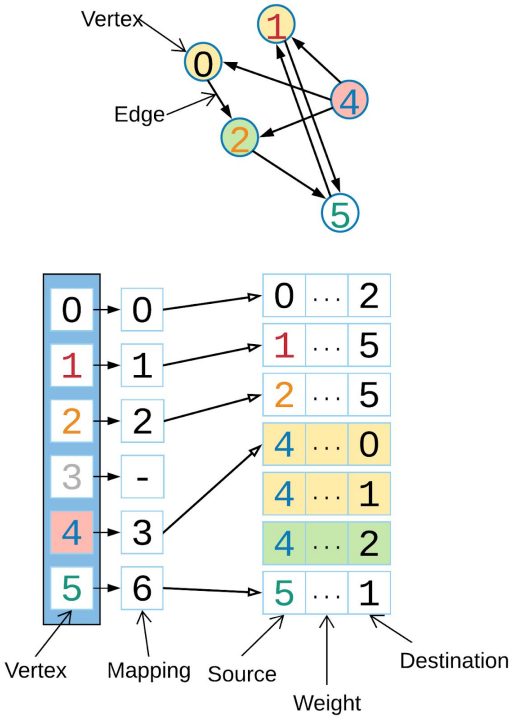
next	0

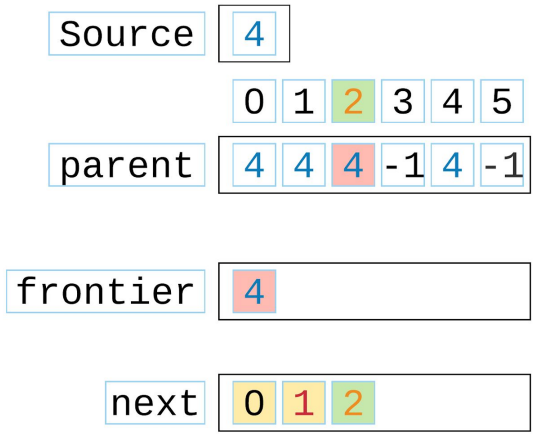
Breadth First Search (BFS) Iteration-1



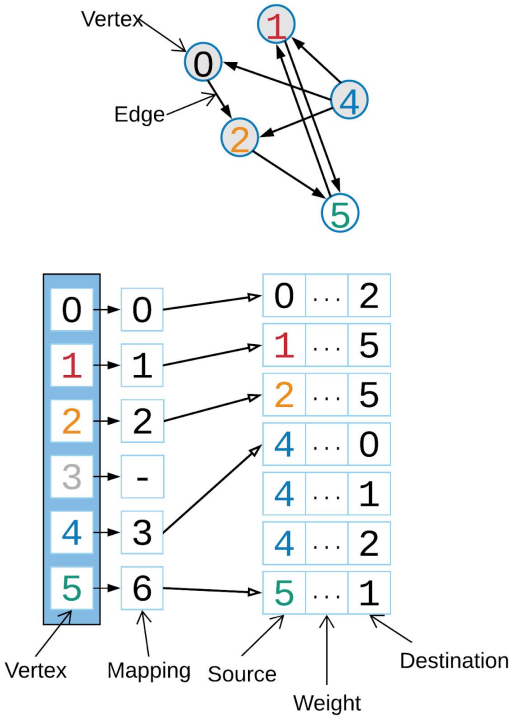


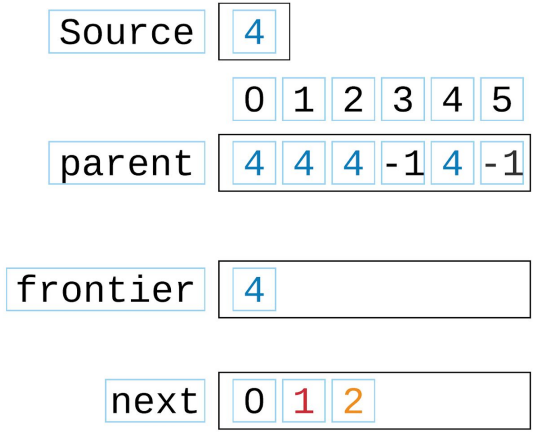
Breadth First Search (BFS) Iteration-1



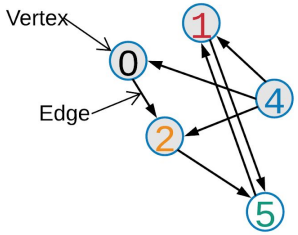


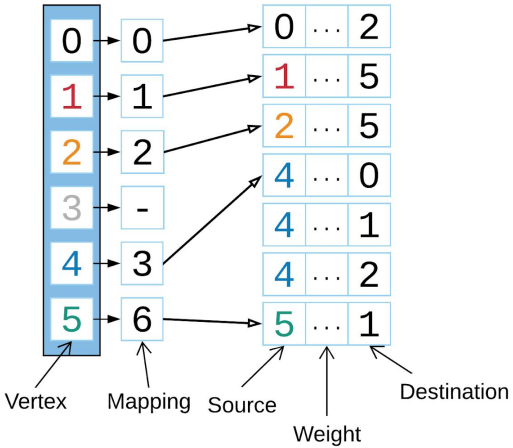
Breadth First Search (BFS) Iteration-1-end





Breadth First Search (BFS) Iteration-2





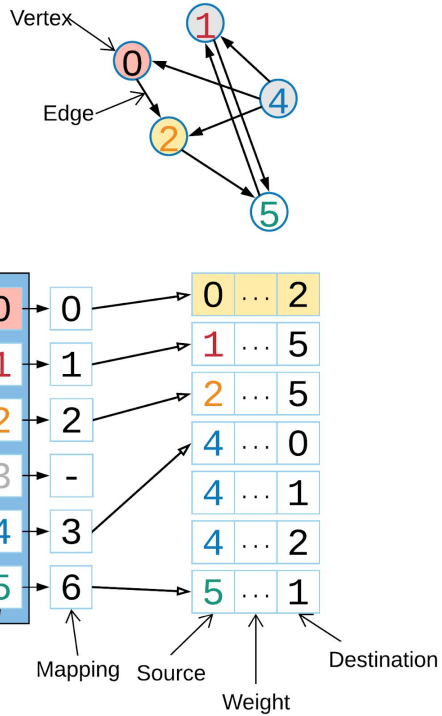
Source	4

	0	1	2	3	4	5
parent	4	4	4	-1	4	-1

frontier	0	1	2

next	

Breadth First Search (BFS) Iteration-2



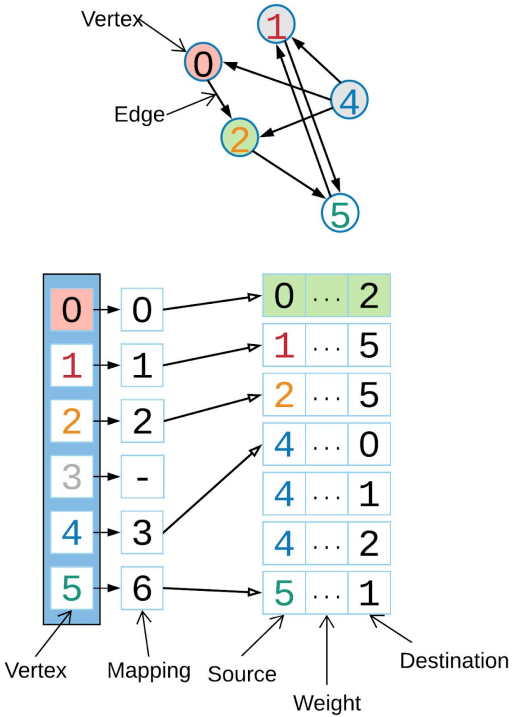
Source	4

	0	1	2	3	4	5
parent	4	4	4	-1	4	-1

frontier	0	1	2

next	

Breadth First Search (BFS) Iteration-2



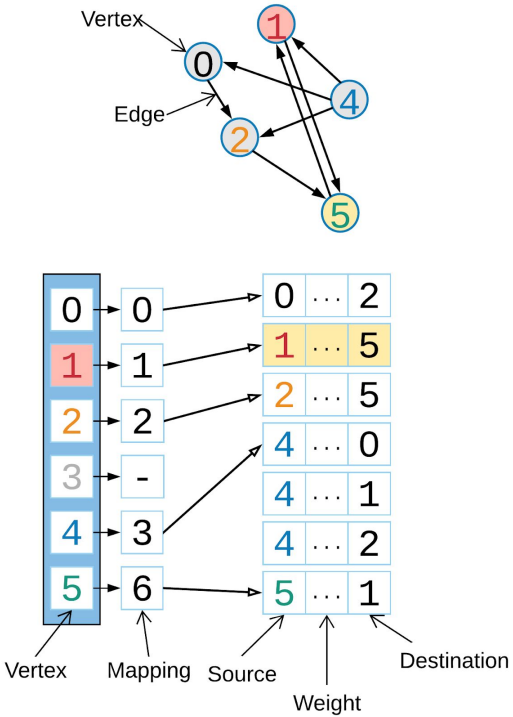
Source	4

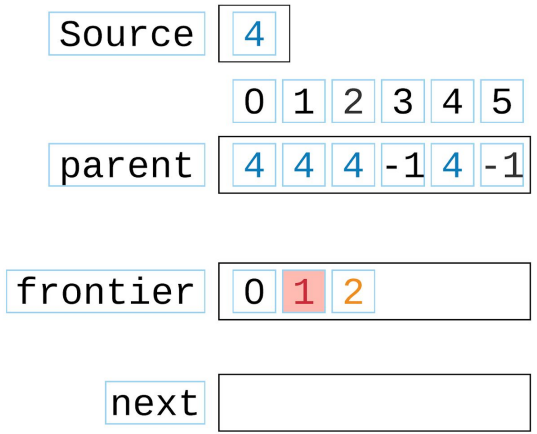
	0	1	2	3	4	5
parent	4	4	4	-1	4	-1

frontier	0	1	2

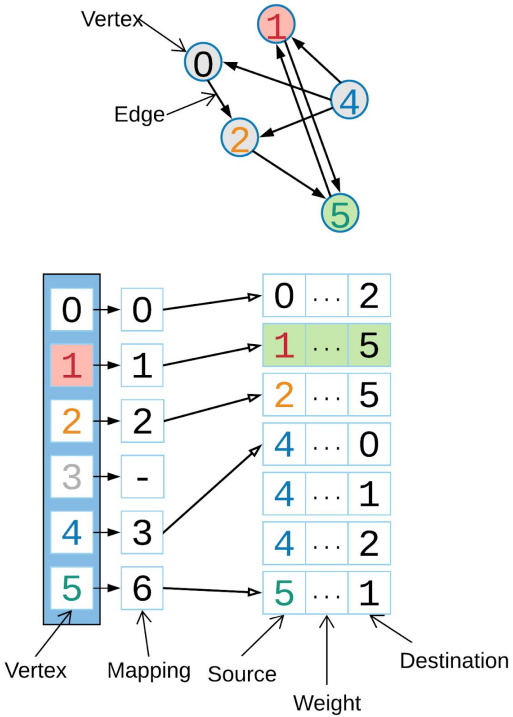
next	

Breadth First Search (BFS) Iteration-2





Breadth First Search (BFS) Iteration-2



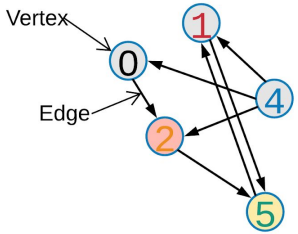
Source 4

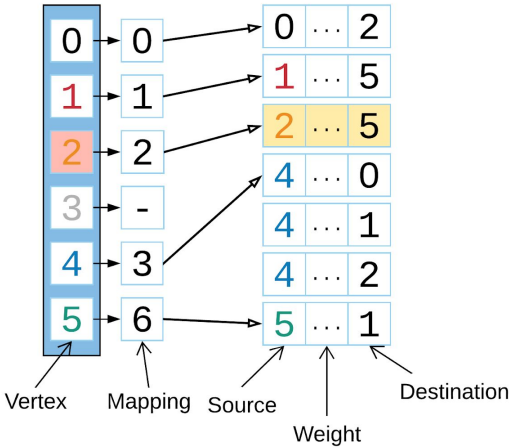
	0	1	2	3	4	5
parent	4	4	4	-1	4	1

frontier 0 1 2

next 5

Breadth First Search (BFS) Iteration-2





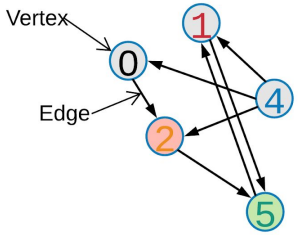
Source	4

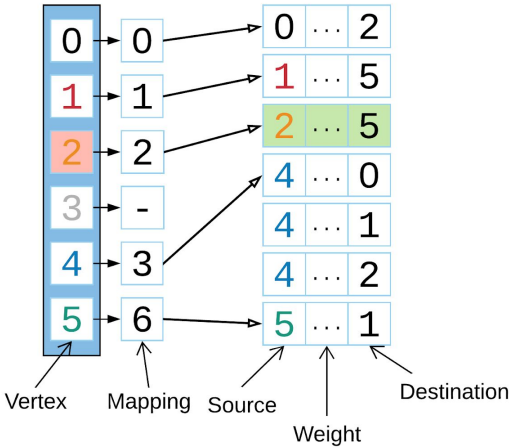
	0	1	2	3	4	5
parent	4	4	4	-1	4	1

frontier	0	1	2

next	5

Breadth First Search (BFS) Iteration-2





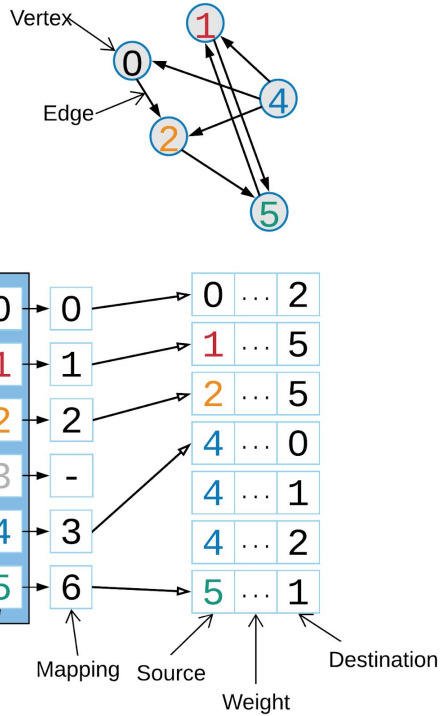
Source	4

	0	1	2	3	4	5
parent	4	4	4	-1	4	1

frontier	0	1	2

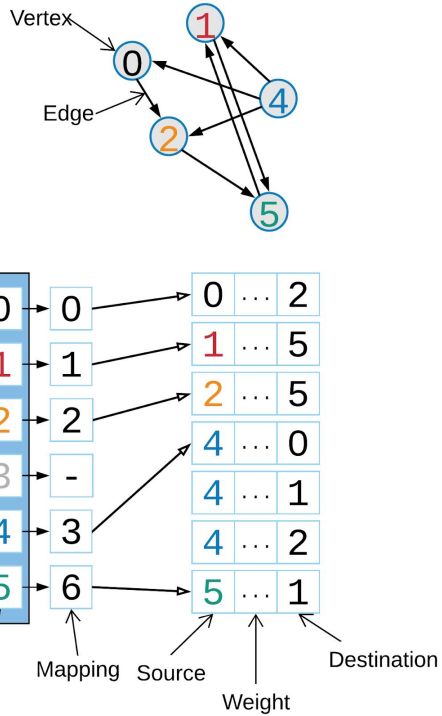
next	5

Breadth First Search (BFS) Iteration-2-end



Source	4					
	0	1	2	3	4	5
parent	4	4	4	-1	4	1
frontier	0	1	2			
next	5					

Breadth First Search (BFS) Iteration-3



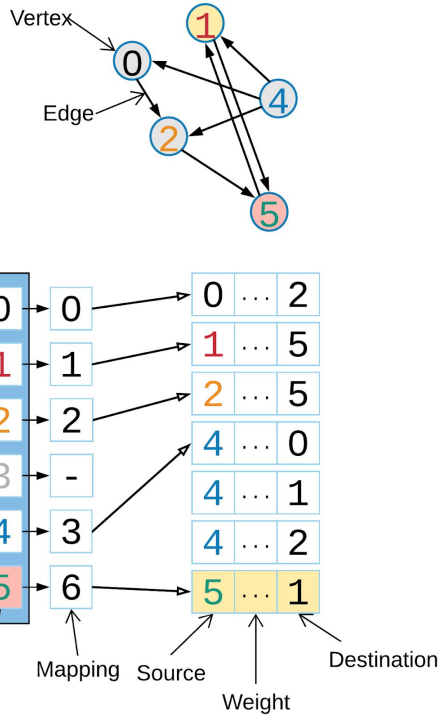
Source 4

	0	1	2	3	4	5
parent	4	4	4	-1	4	1

frontier 5

next

Breadth First Search (BFS) Iteration-3



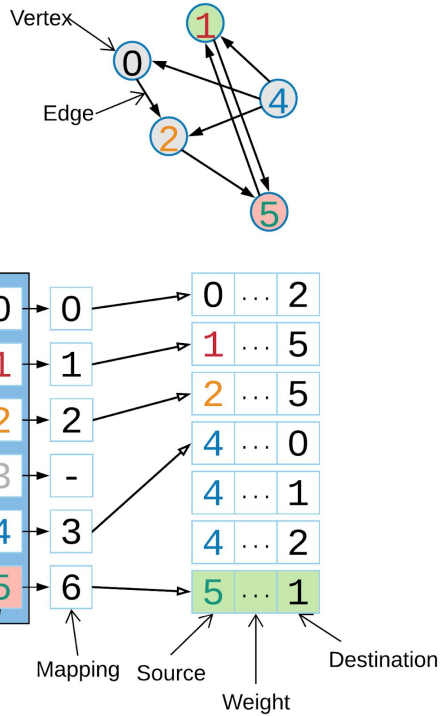
Source	4

	0	1	2	3	4	5
parent	4	4	4	-1	4	1

frontier	5

next	

Breadth First Search (BFS) Iteration-3



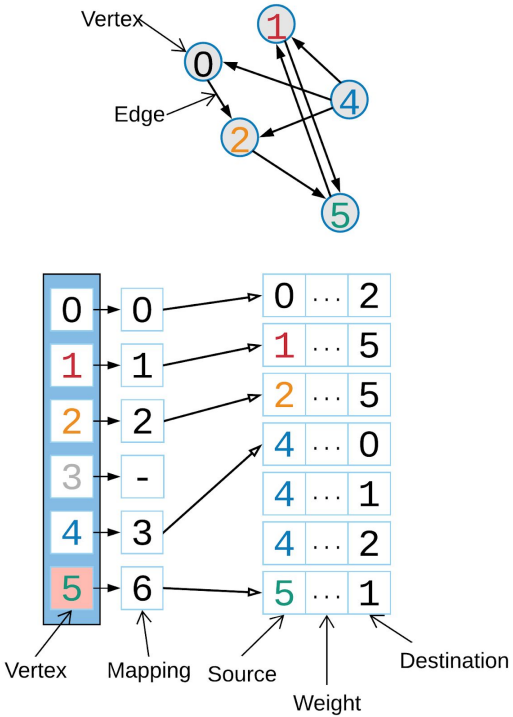
Source 4

	0	1	2	3	4	5
parent	4	4	4	-1	4	1

frontier 5

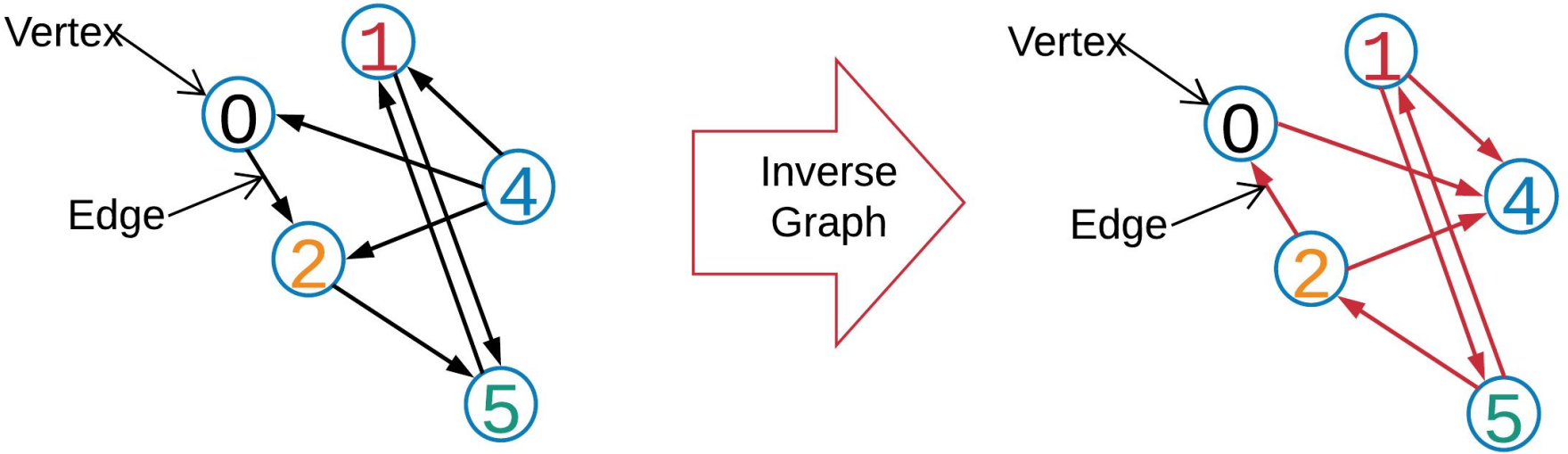
next

Breadth First Search (BFS) Iteration-3

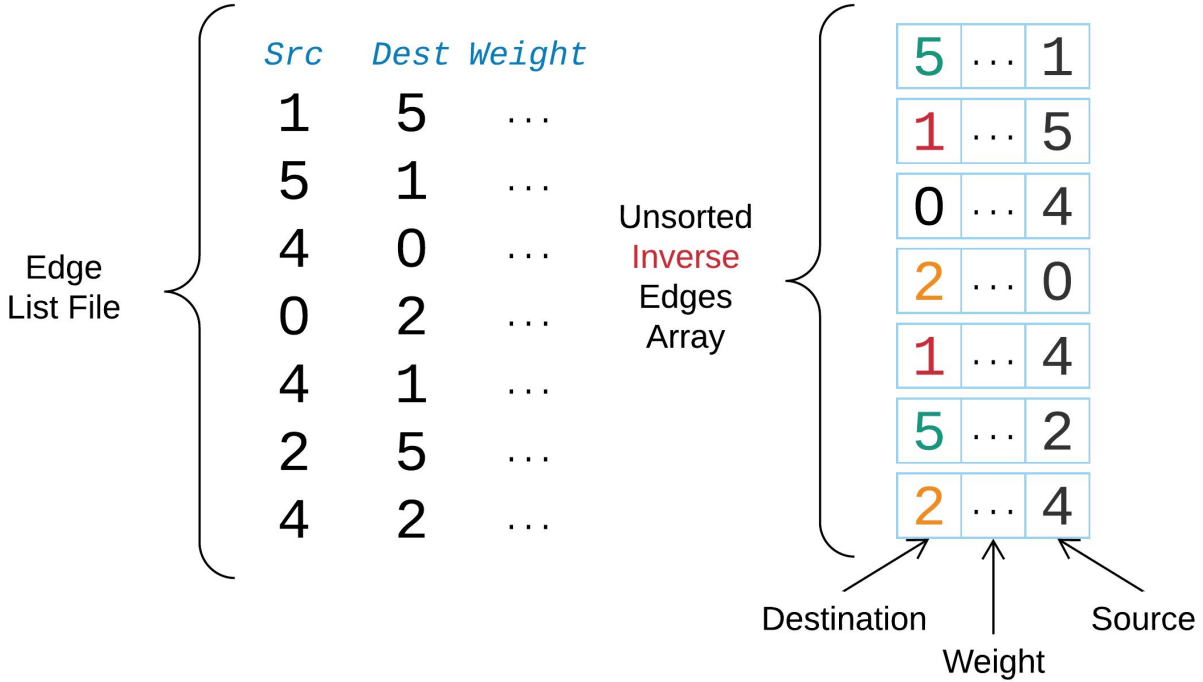


Source	4					
	0	1	2	3	4	5
parent	4	4	4	-1	4	1
frontier						
next						

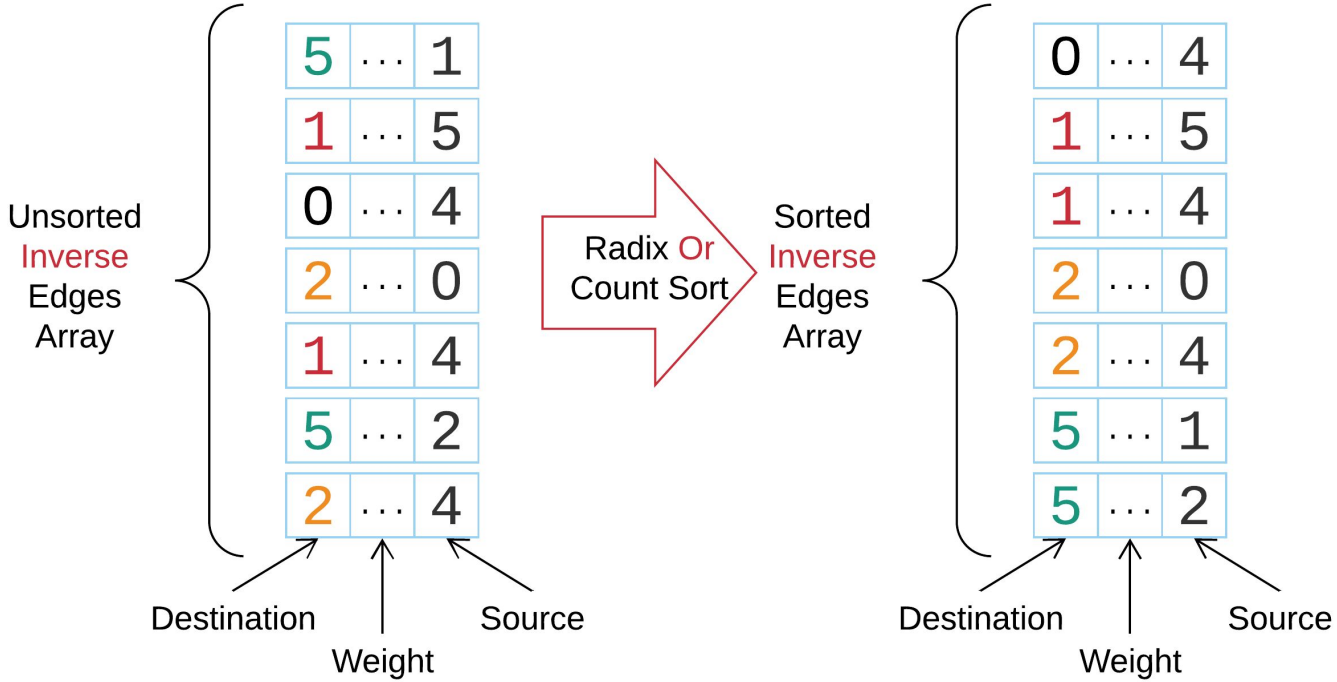
Inverse Graph



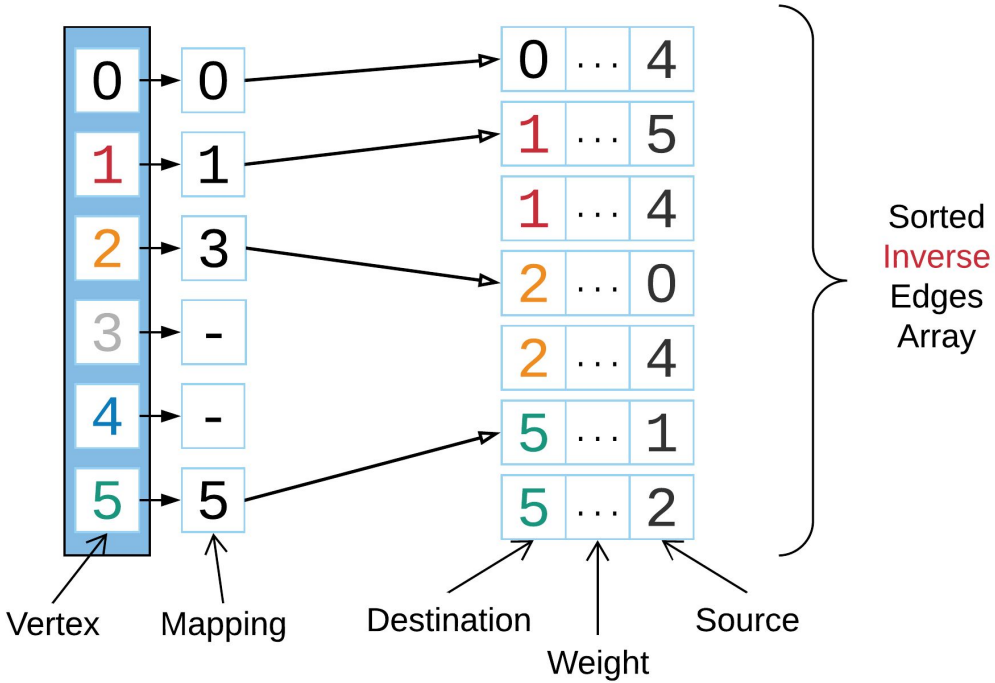
Inverse Graph (load)



Inverse Graph (sort)



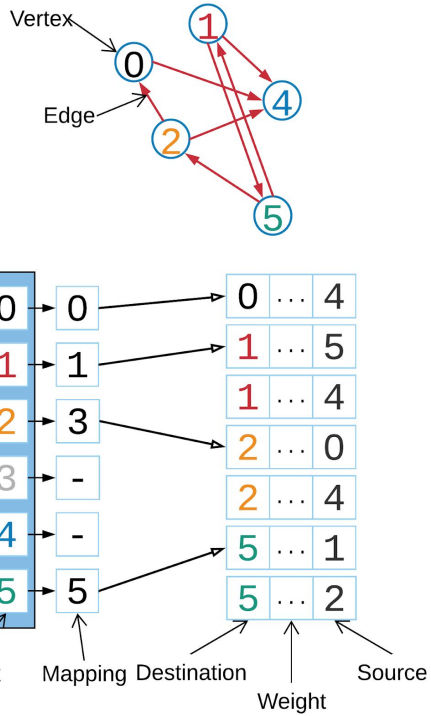
Inverse Graph (map)

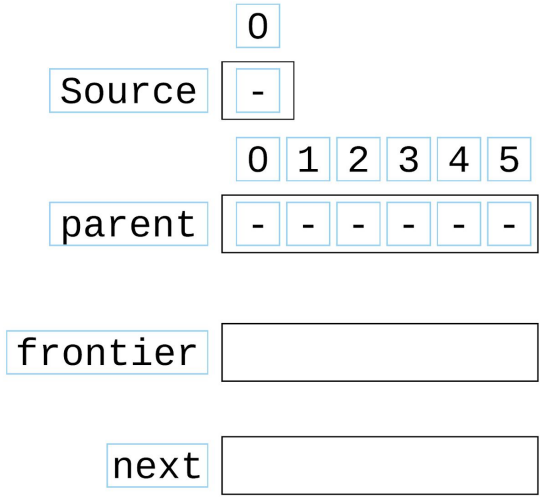


Bottom Up Step (Pull)

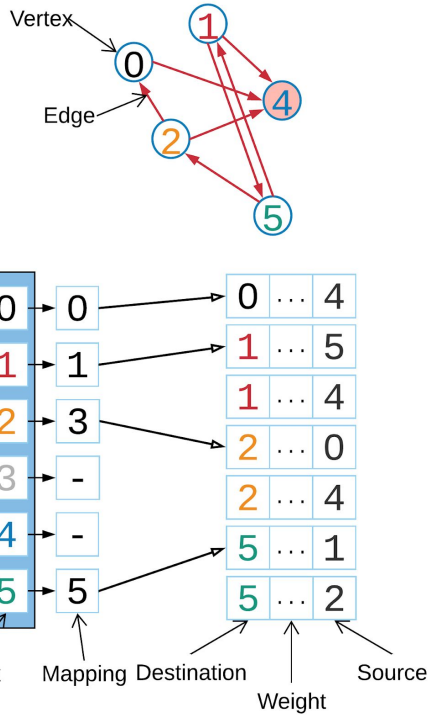
```
function bottom-up-step(vertices,frontier,next,parents)
    for v ∈ vertices do
      if parents[v] = -1 then
        for n ∈ neighbors[v] do
          if n ∈ frontier do
             parents[v]←n
             next←next⋃{v}
             break
          end if
        end for
      end if
    end for
```

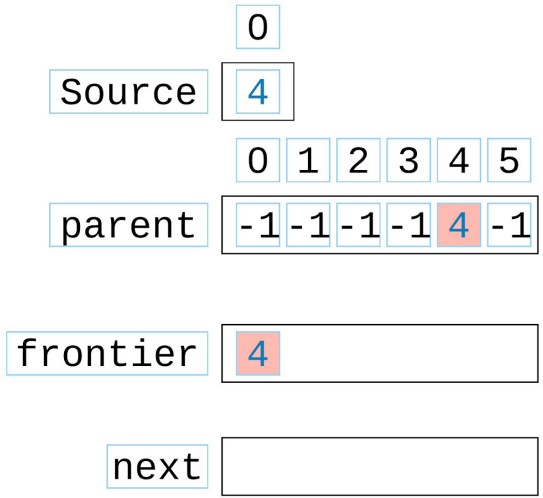
Bottom Up Step (Pull)



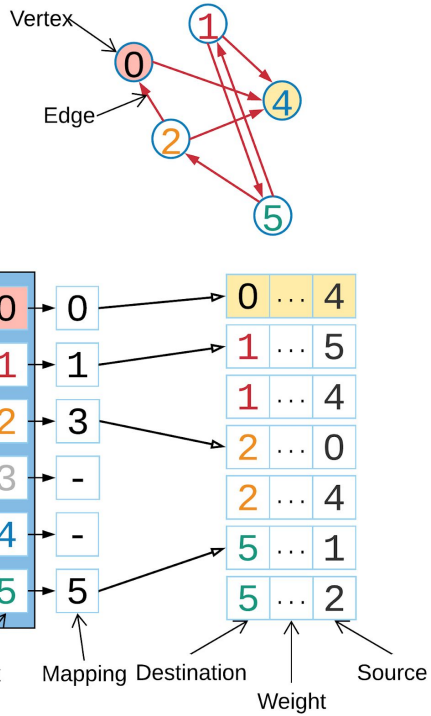


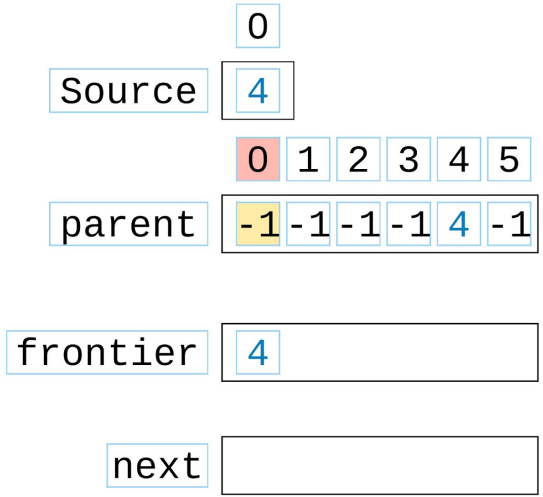
Breadth First Search (BFS) Initialize



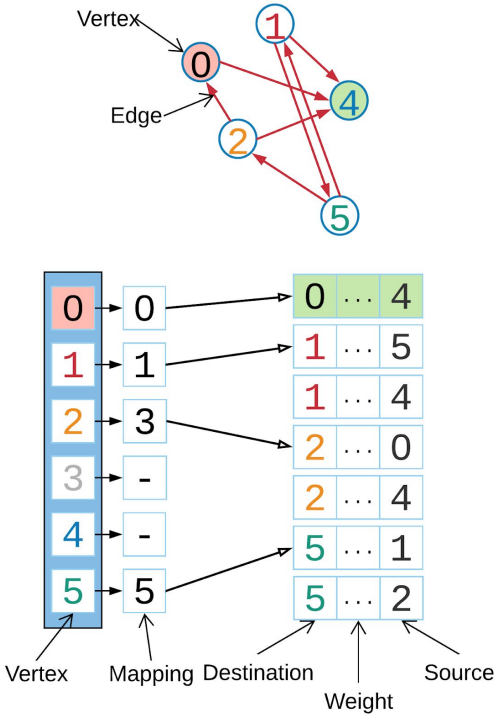


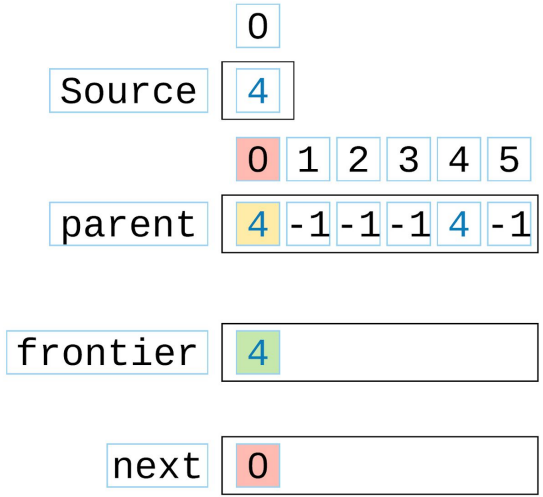
Breadth First Search (BFS) Iteration-1



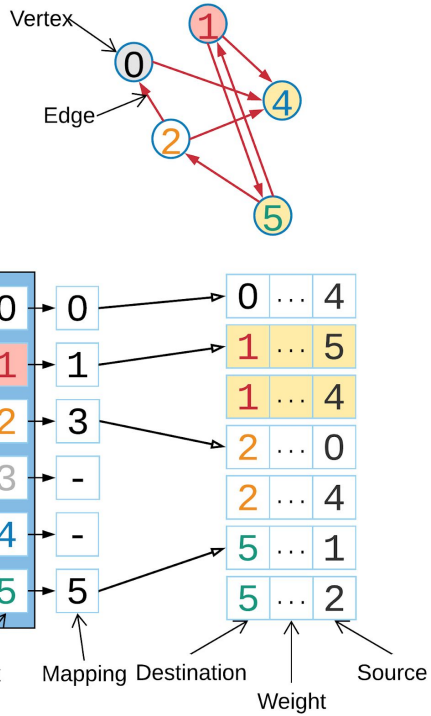


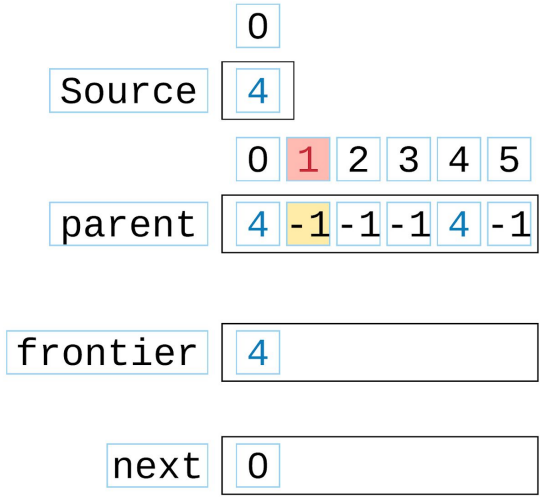
Breadth First Search (BFS) Iteration-1



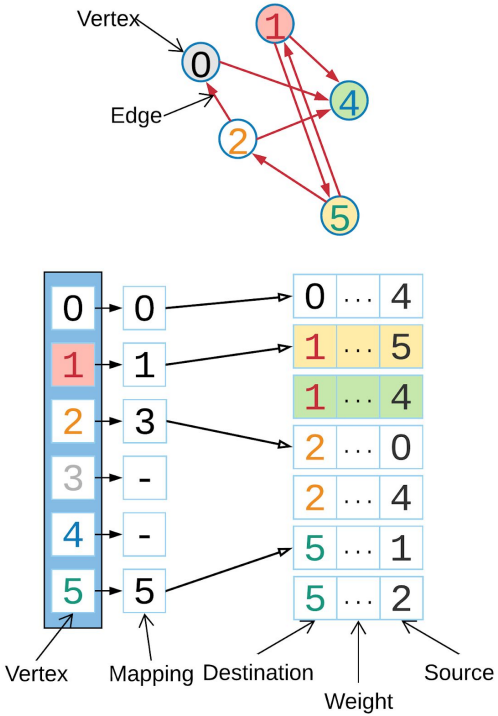


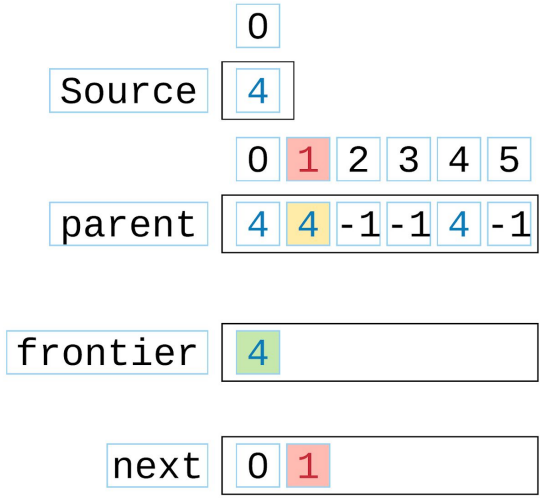
Breadth First Search (BFS) Iteration-1



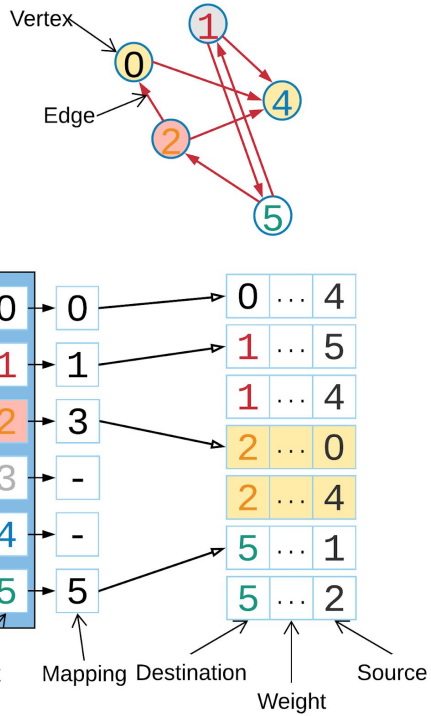


Breadth First Search (BFS) Iteration-1





Breadth First Search (BFS) Iteration-1



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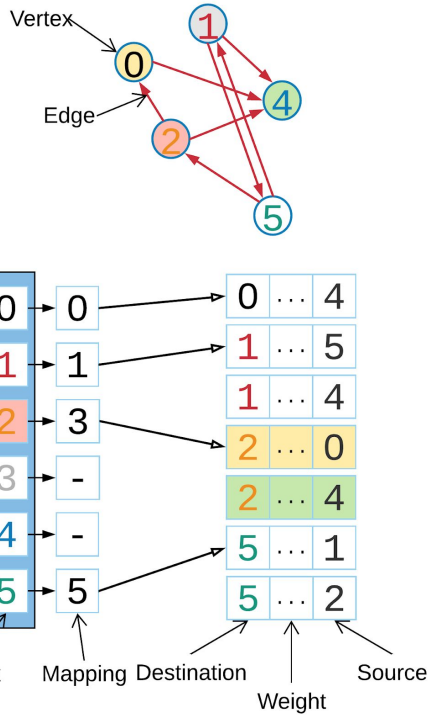
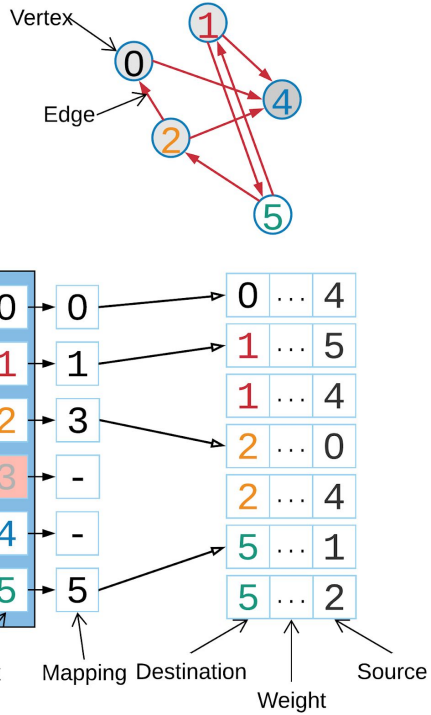
Source	4					
parent	4	4	-1	-1	4	-1
frontier	4					
next	0	1				

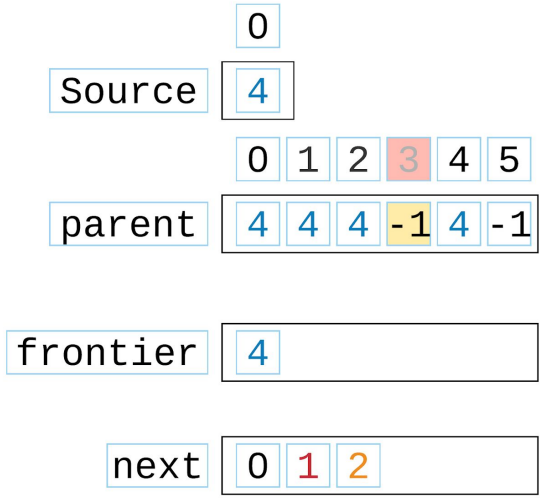
Breadth First Search (BFS) Iteration-1



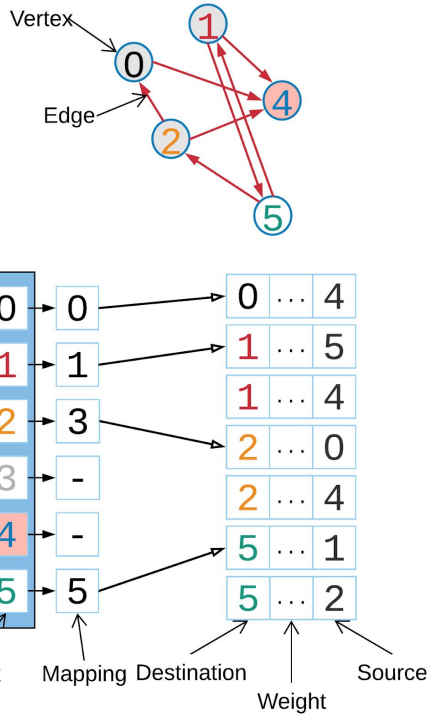
	0	1	2	3	4	5
Source	4					
parent	4	4	4	-1	4	-1
frontier	4					
next	0	1	2			

Breadth First Search (BFS) Iteration-1



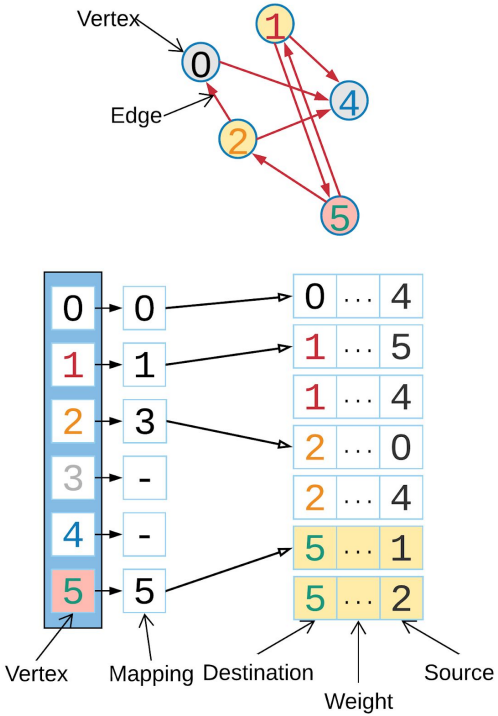


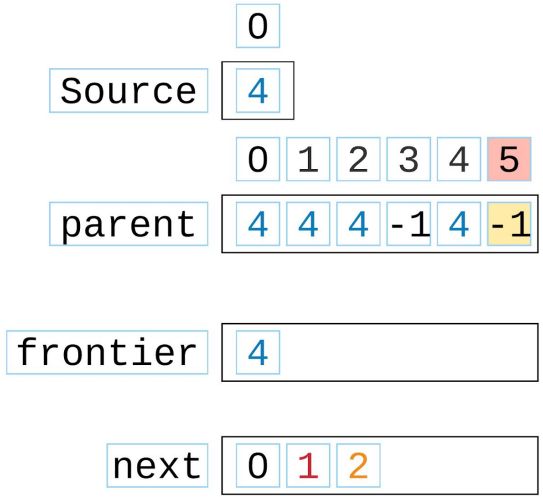
Breadth First Search (BFS) Iteration-1



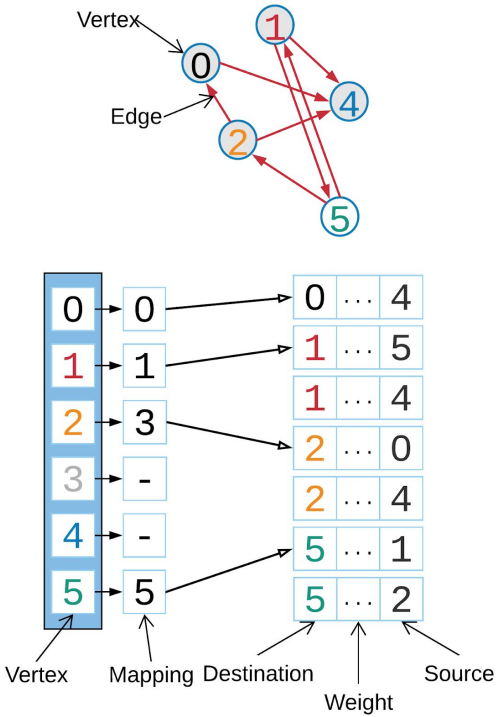
	0	1	2	3	4	5
Source	4					
parent	4	4	4	-1	4	-1
frontier	4					
next	0	1	2			

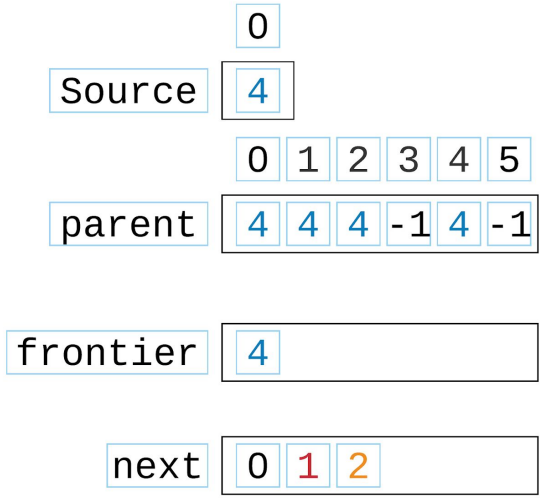
Breadth First Search (BFS) Iteration-1



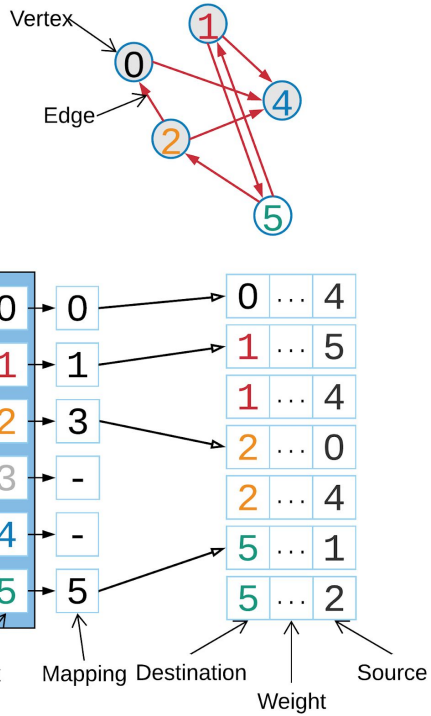


Breadth First Search (BFS) Iteration-1-end



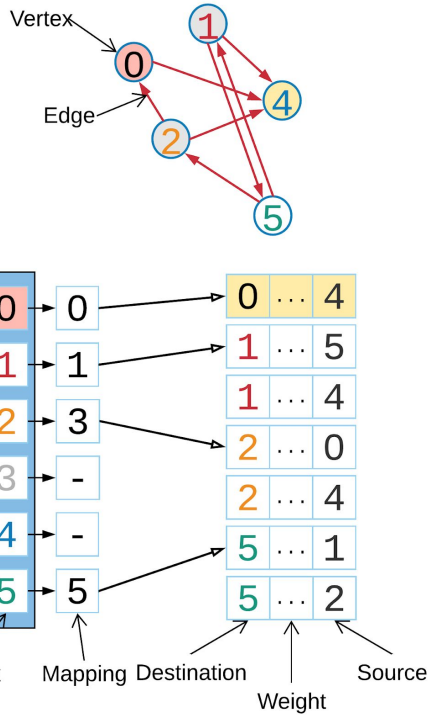


Breadth First Search (BFS) Iteration-2



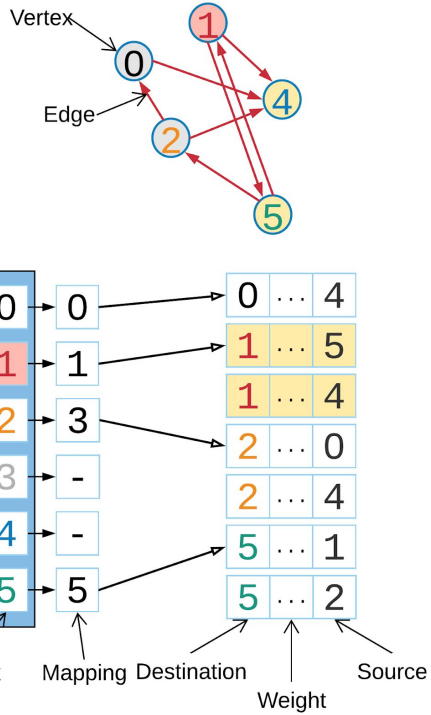
	0	1	2	3	4	5
Source	4					
parent	4	4	4	-1	4	-1
frontier	0	1	2			
next						

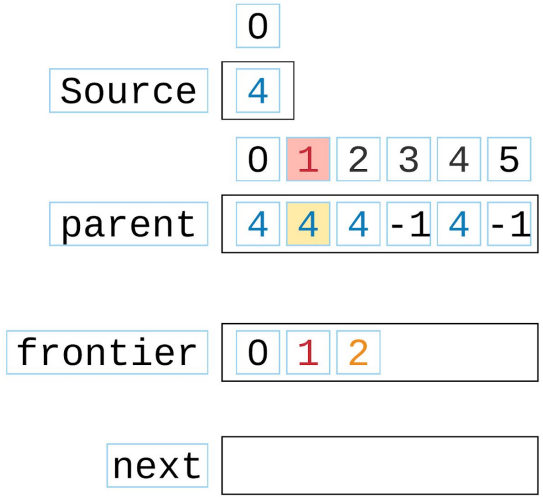
Breadth First Search (BFS) Iteration-2



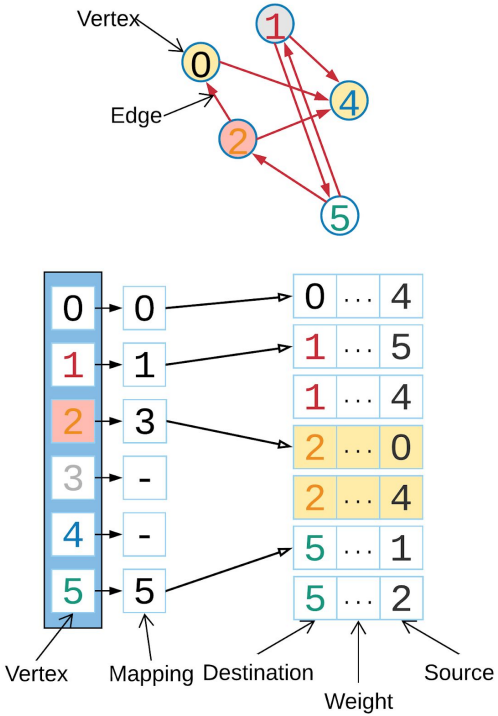
	0	1	2	3	4	5
Source	4					
parent	4	4	4	-1	4	-1
frontier	0	1	2			
next						

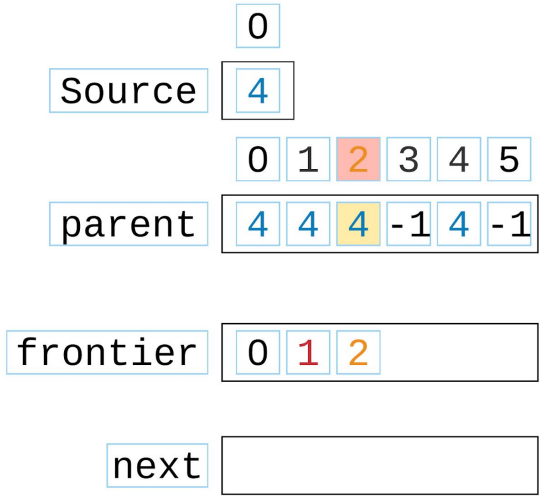
Breadth First Search (BFS) Iteration-2



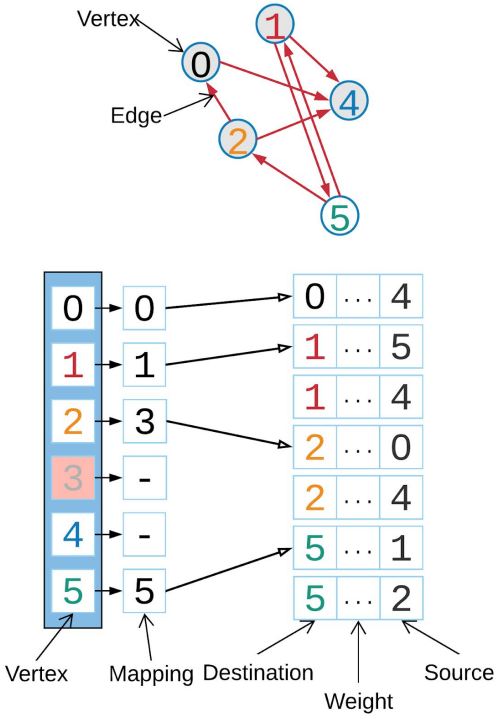


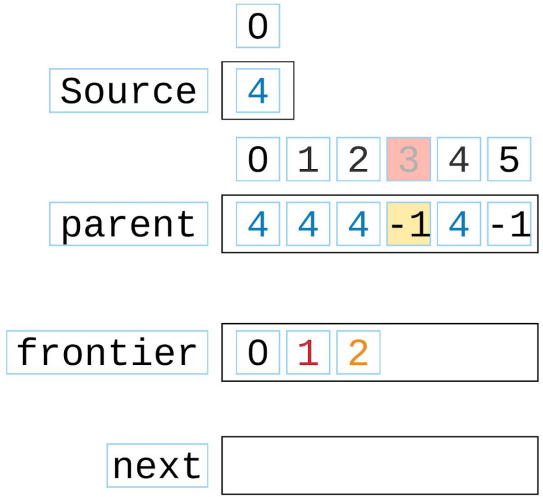
Breadth First Search (BFS) Iteration-2



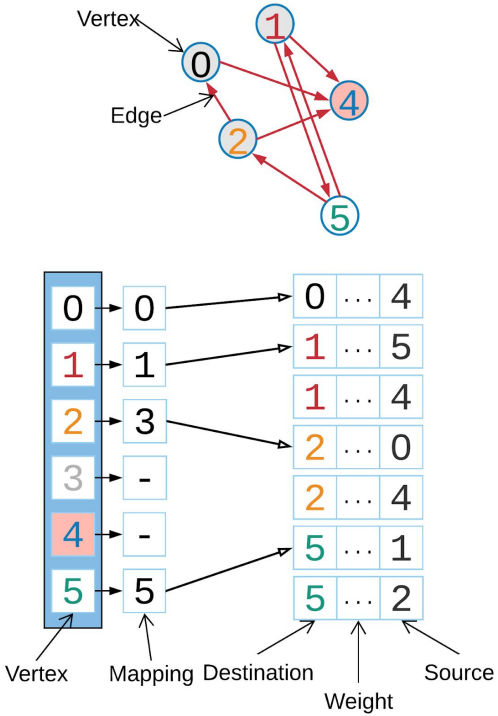


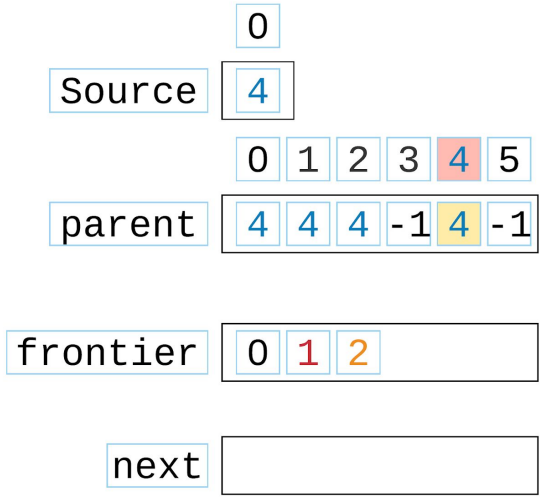
Breadth First Search (BFS) Iteration-2



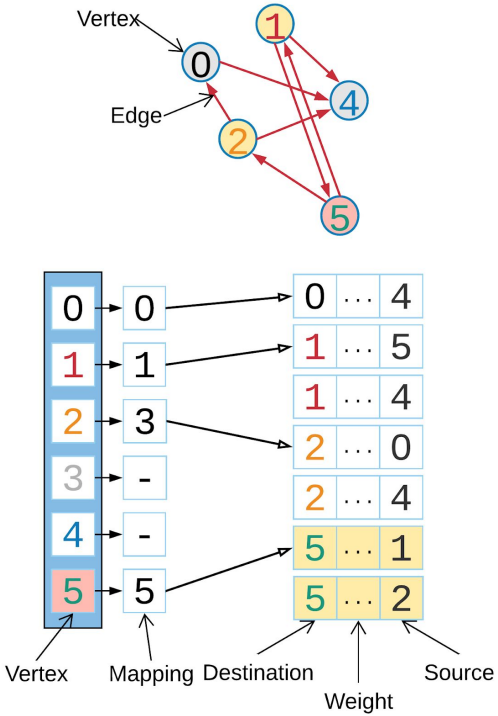


Breadth First Search (BFS) Iteration-2



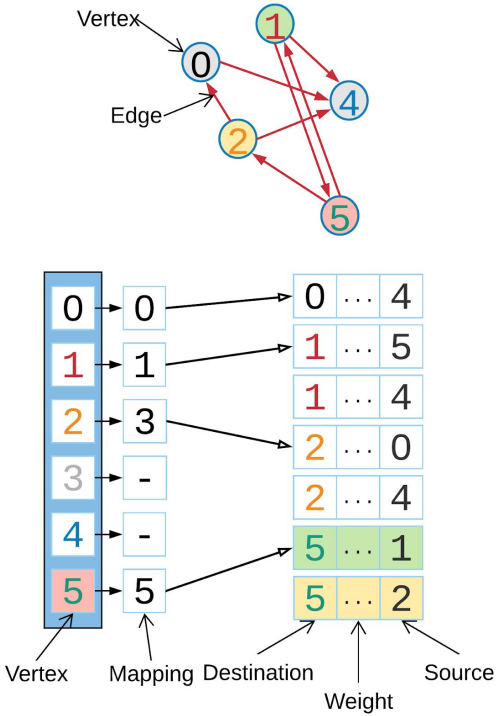


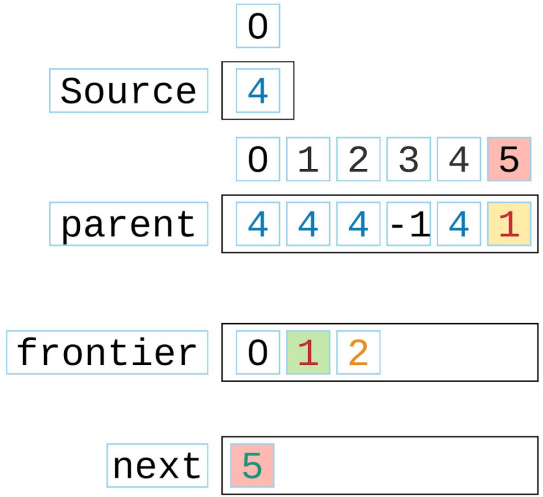
Breadth First Search (BFS) Iteration-2



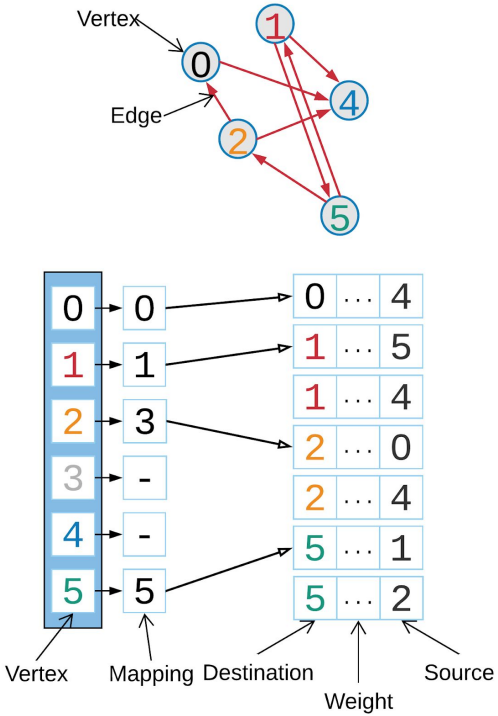
	0	1	2	3	4	5
Source	4					
parent	4	4	4	-1	4	-1
frontier	0	1	2			
next						

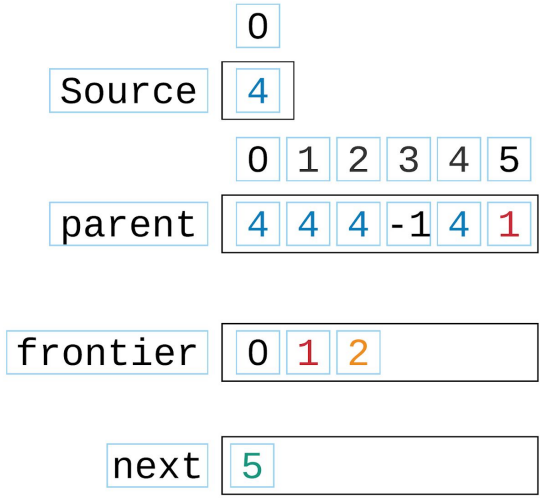
Breadth First Search (BFS) Iteration-2



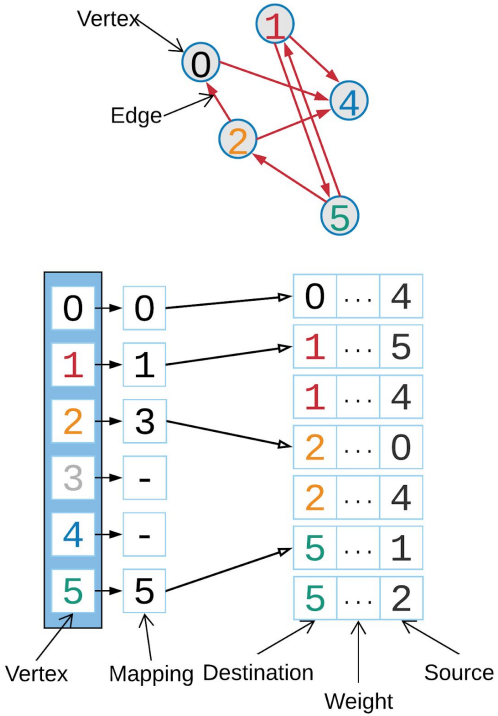


Breadth First Search (BFS) Iteration-2-end



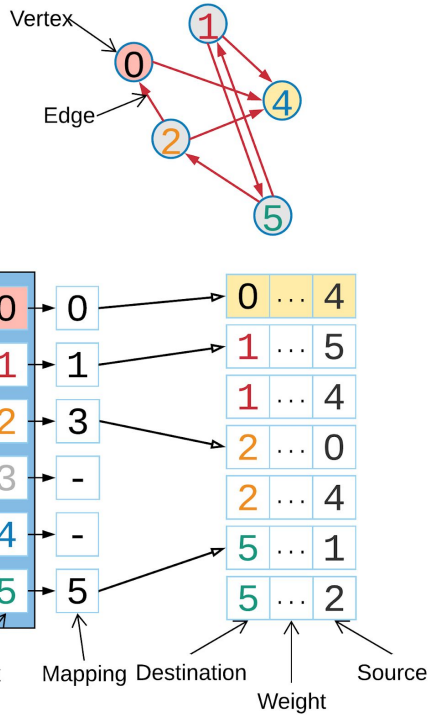


Breadth First Search (BFS) Iteration-3



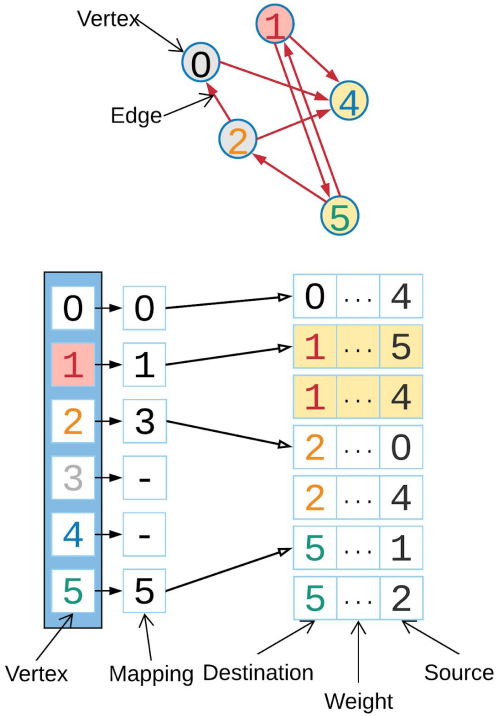
	0	1	2	3	4	5
Source	4					
parent	4	4	4	-1	4	1
frontier	5					
next						

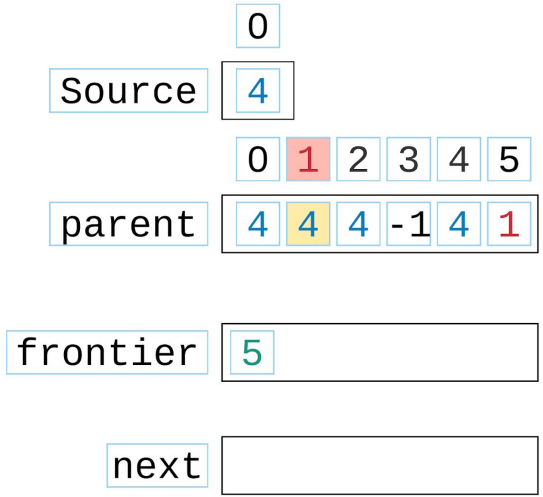
Breadth First Search (BFS) Iteration-3



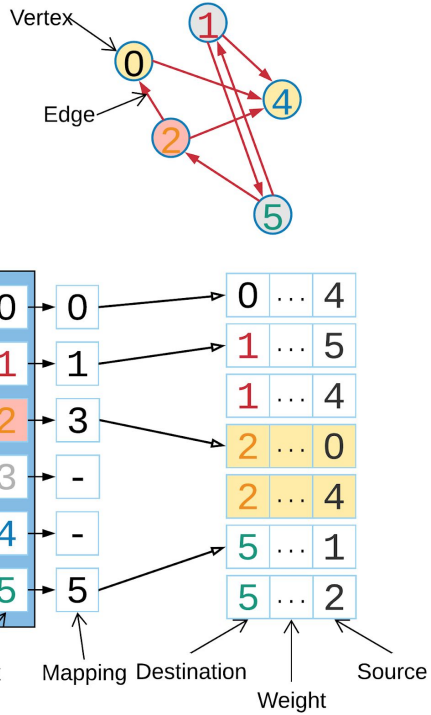
	0	1	2	3	4	5
Source	4					
parent	4	4	4	-1	4	1
frontier	5					
next						

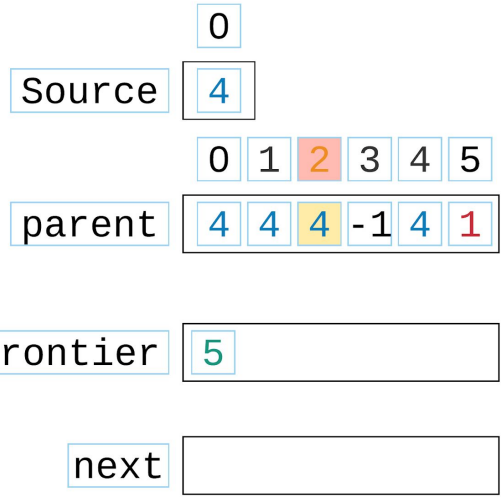
Breadth First Search (BFS) Iteration-3



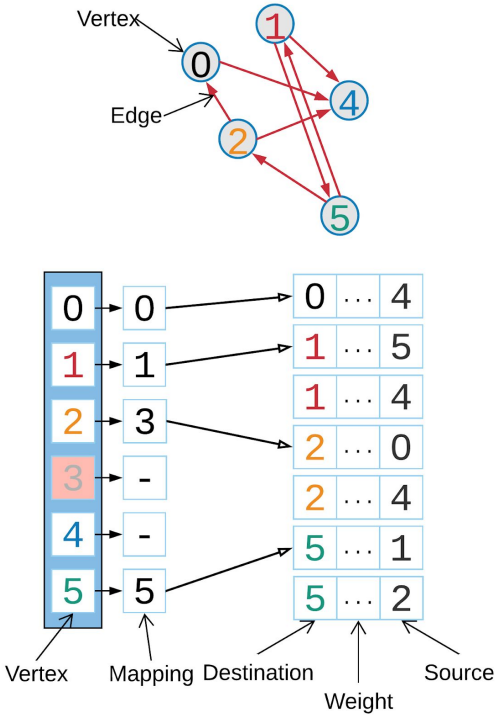


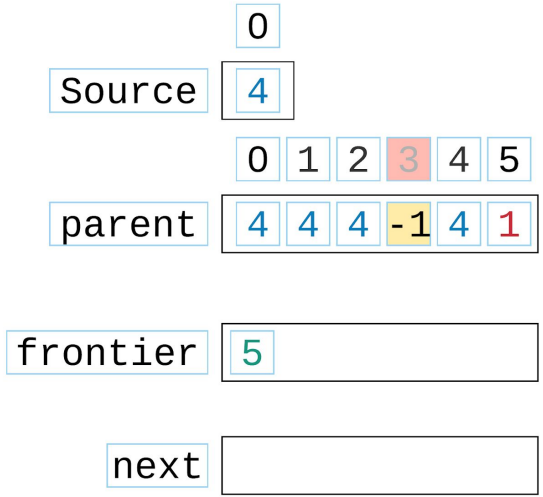
Breadth First Search (BFS) Iteration-3



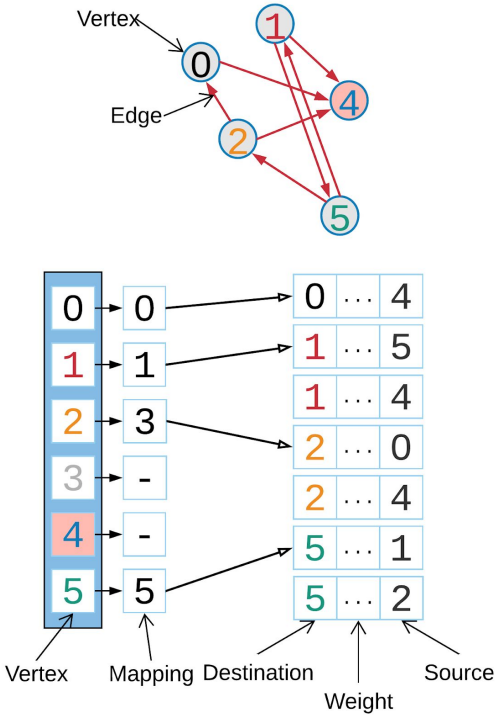


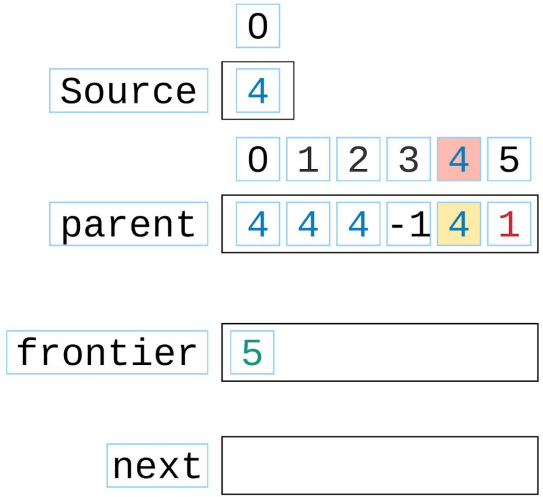
Breadth First Search (BFS) Iteration-3



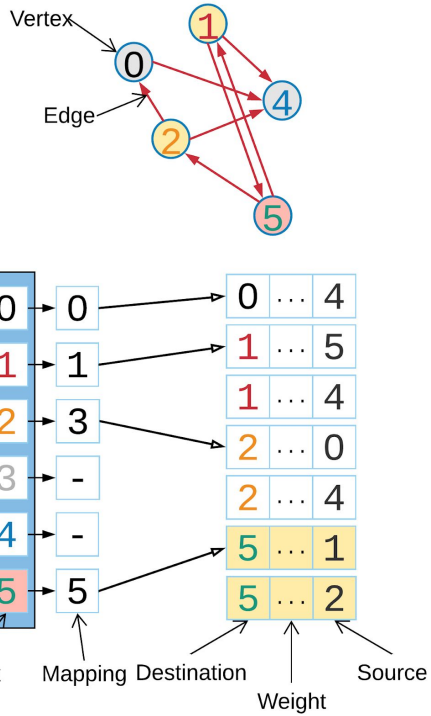


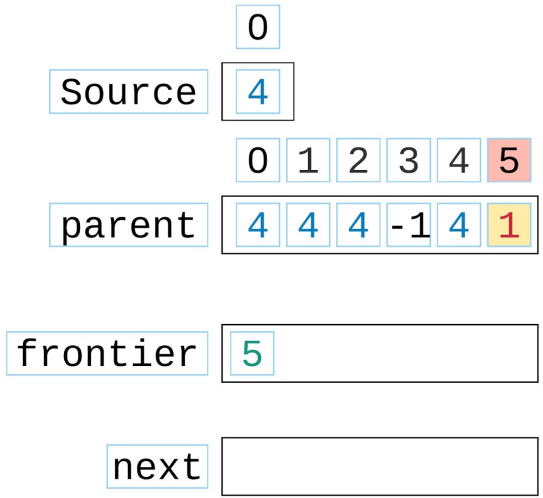
Breadth First Search (BFS) Iteration-3



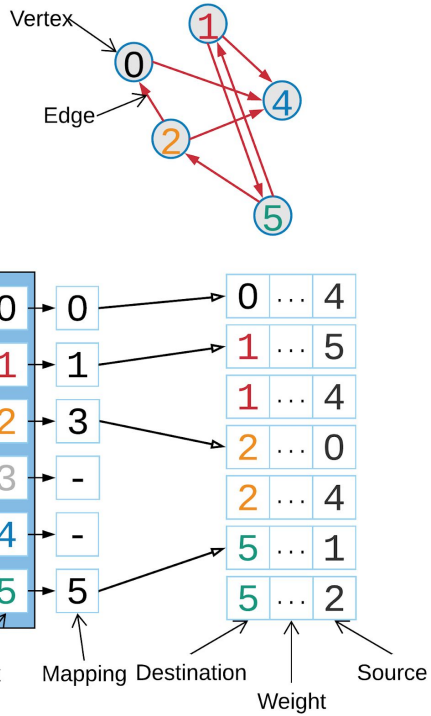


Breadth First Search (BFS) Iteration-3





Breadth First Search (BFS) Iteration-end



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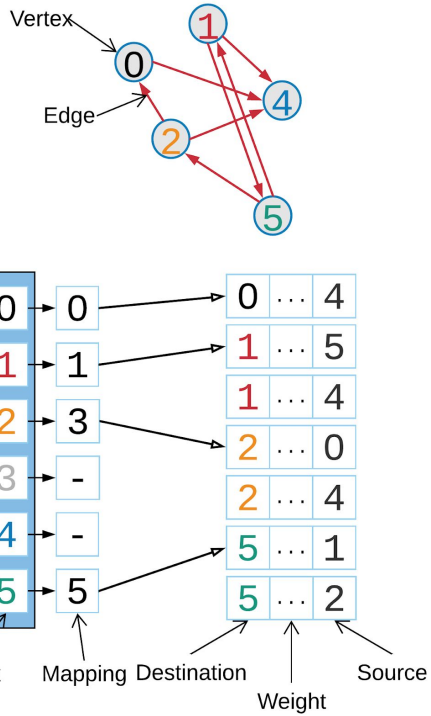
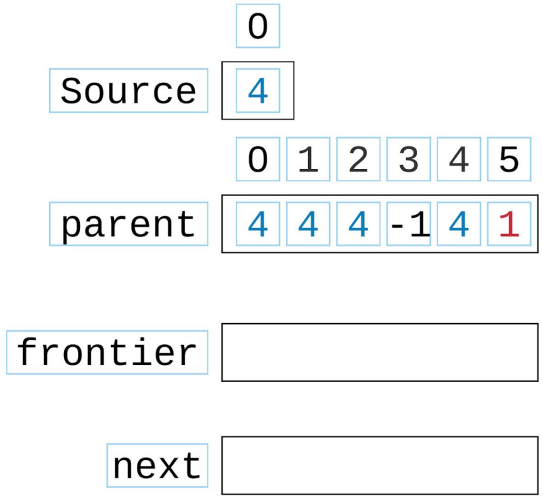
Source	4					
parent	4	4	4	-1	4	1
frontier	5					
next						

Breadth First Search (BFS) Done





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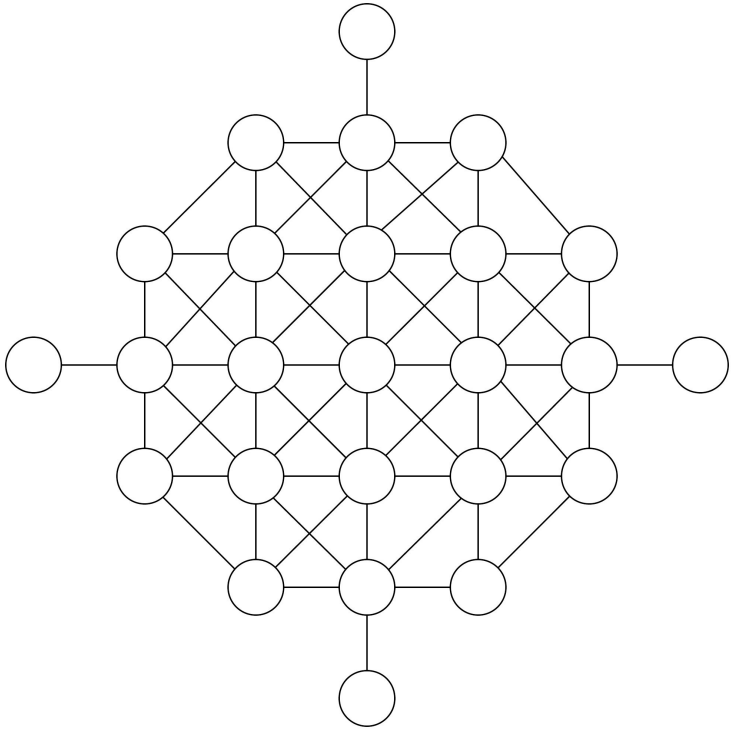

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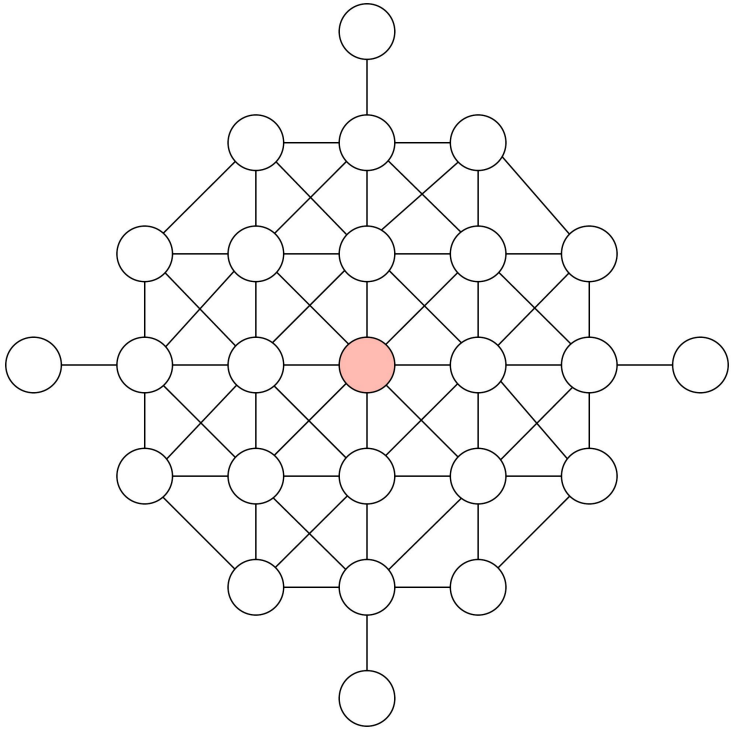

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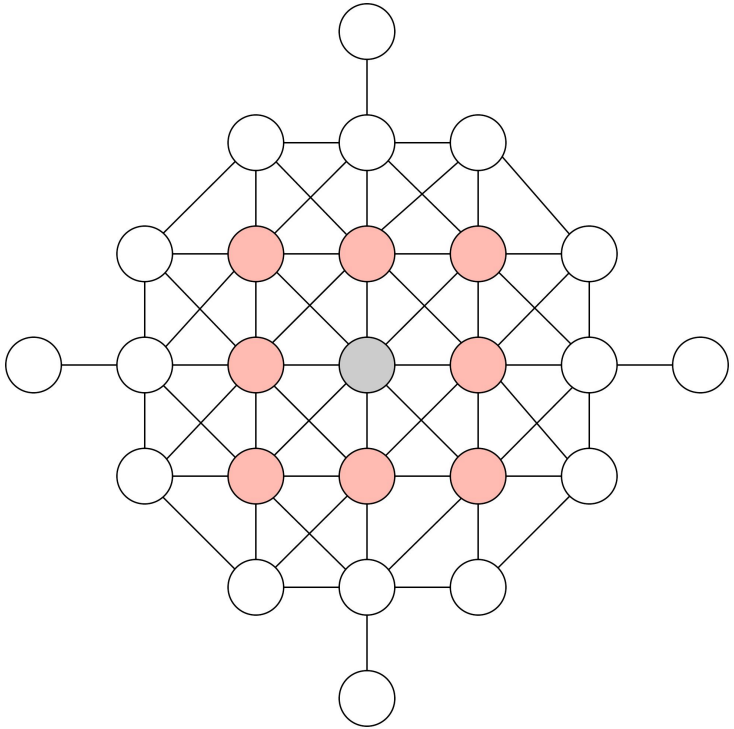

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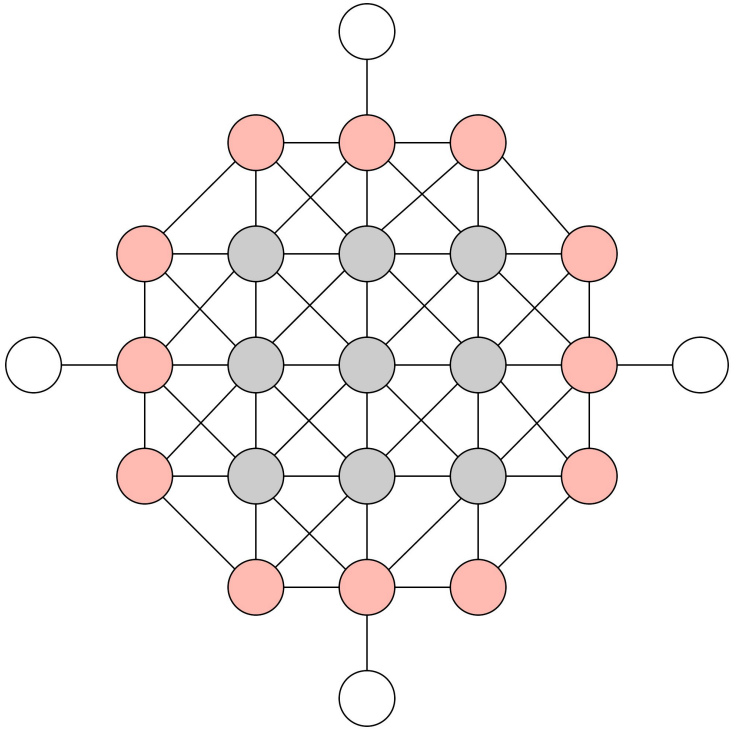

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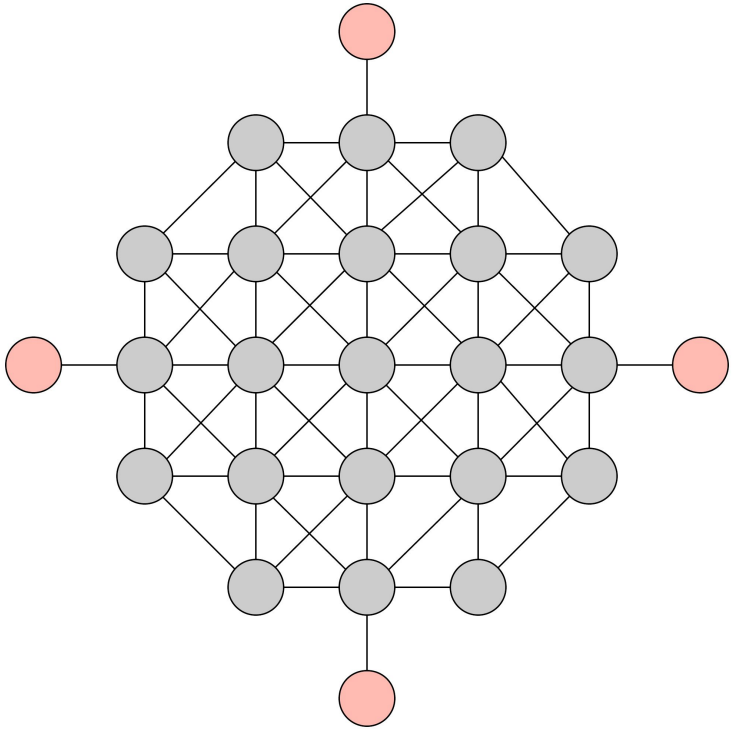

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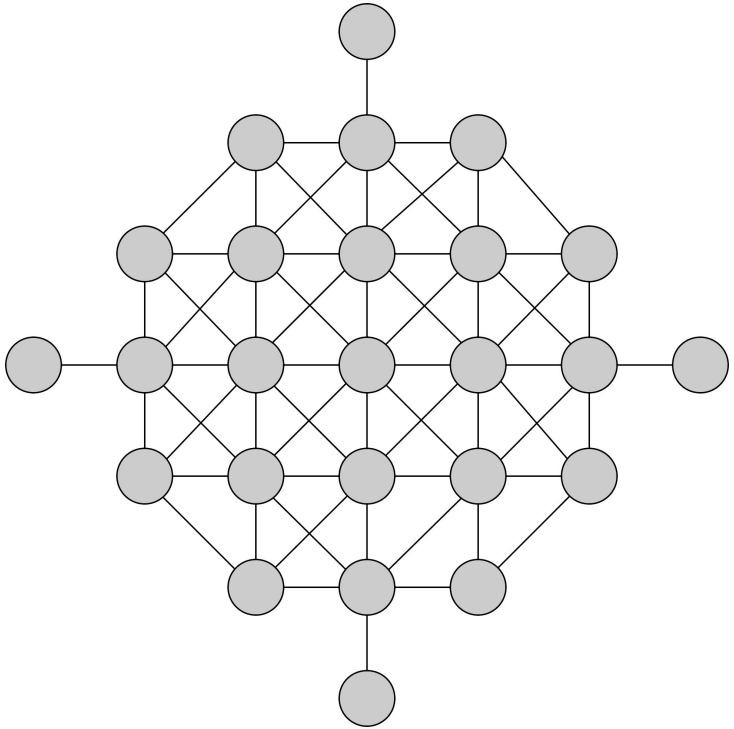

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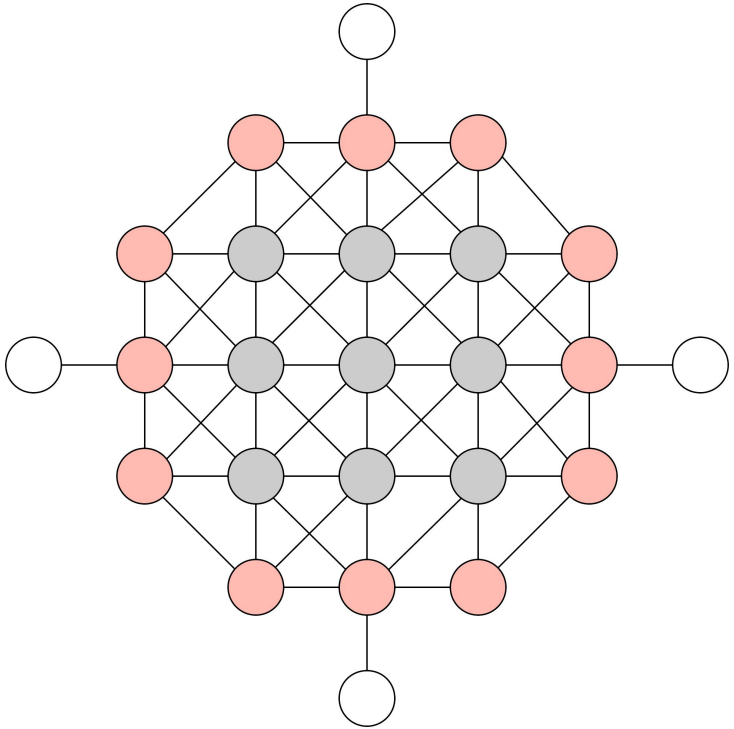

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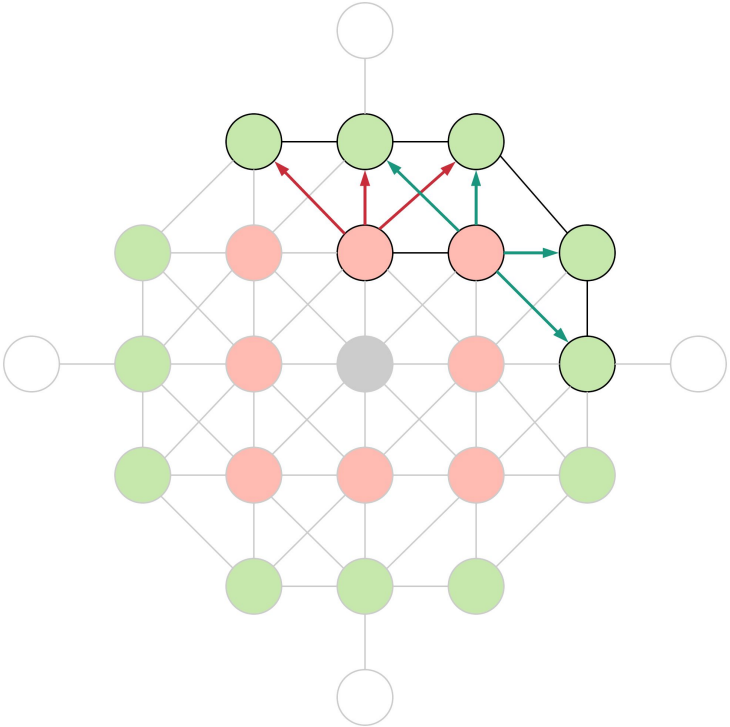

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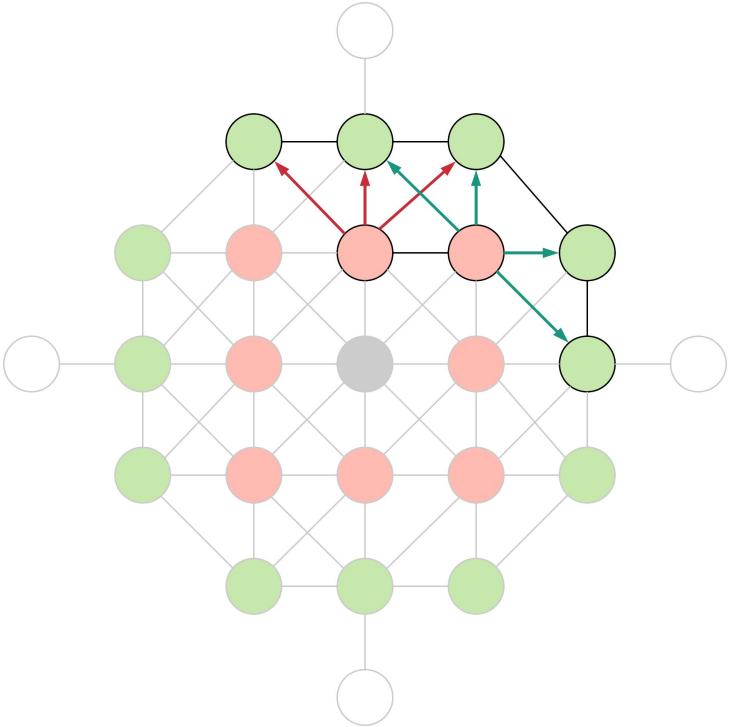

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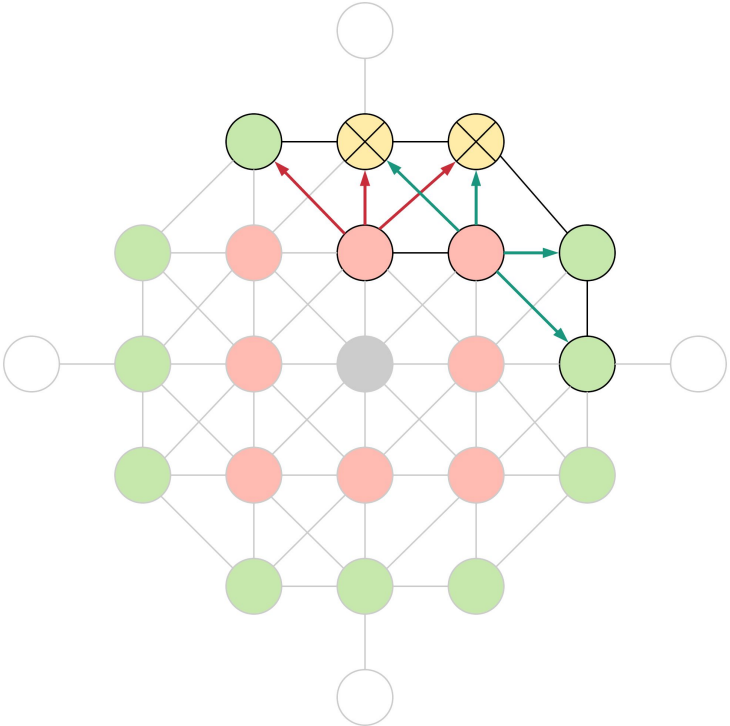

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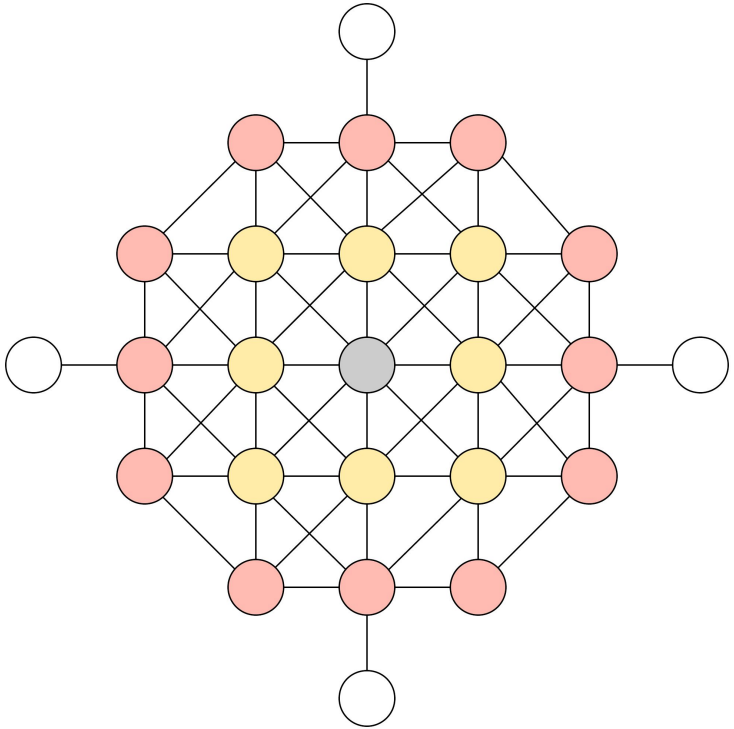

Breadth First Search (BFS) (pull)