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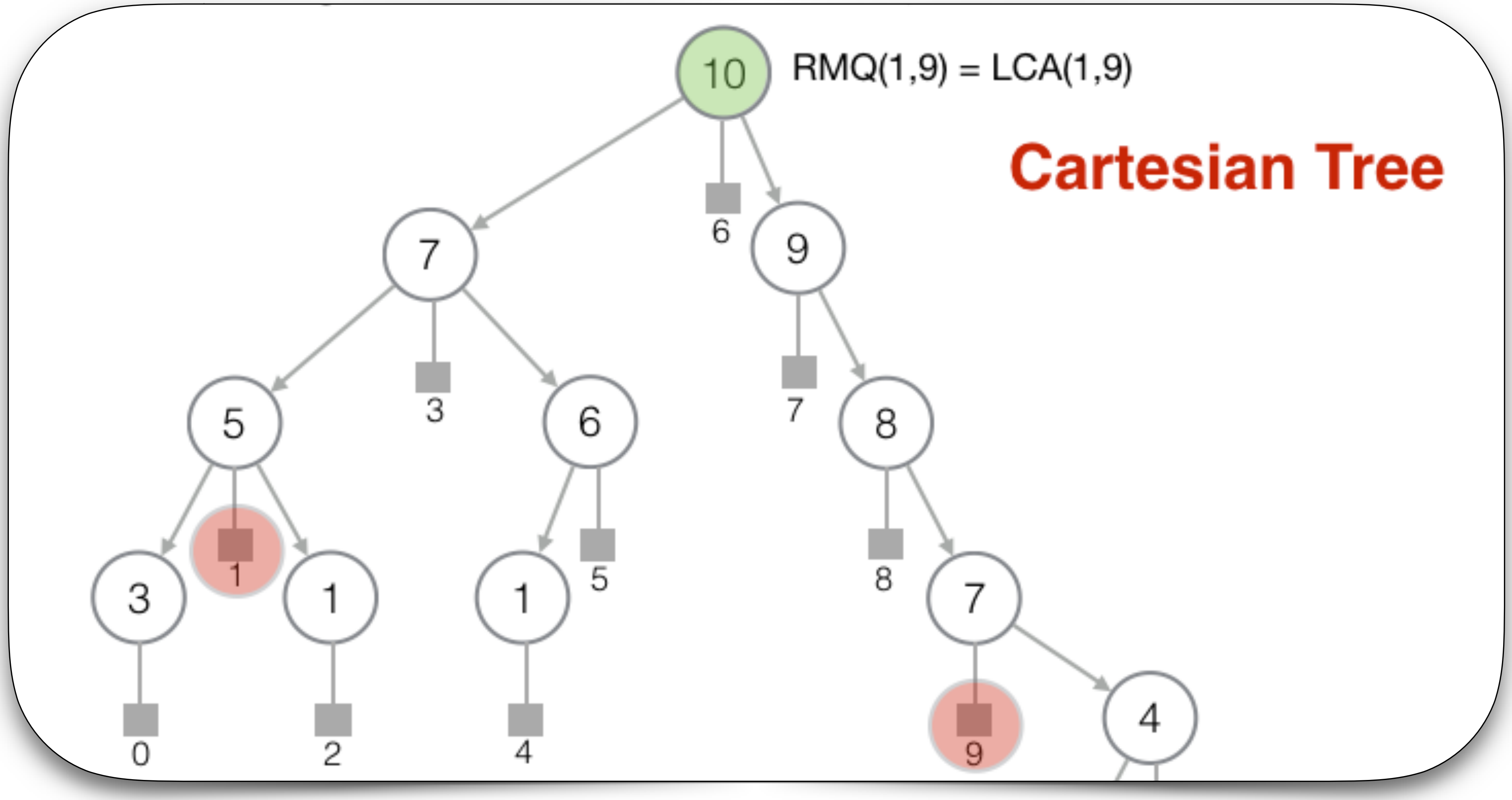

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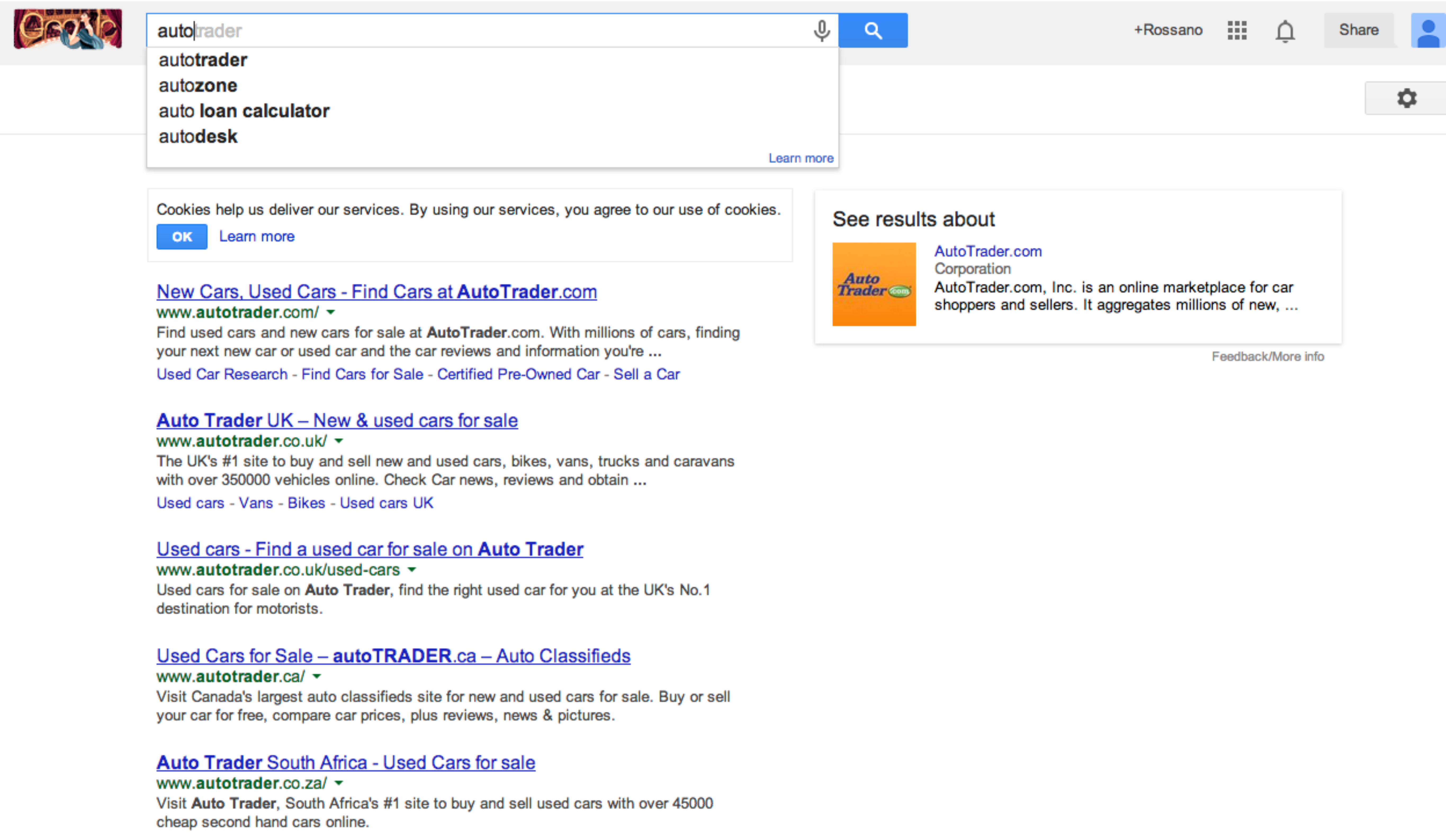

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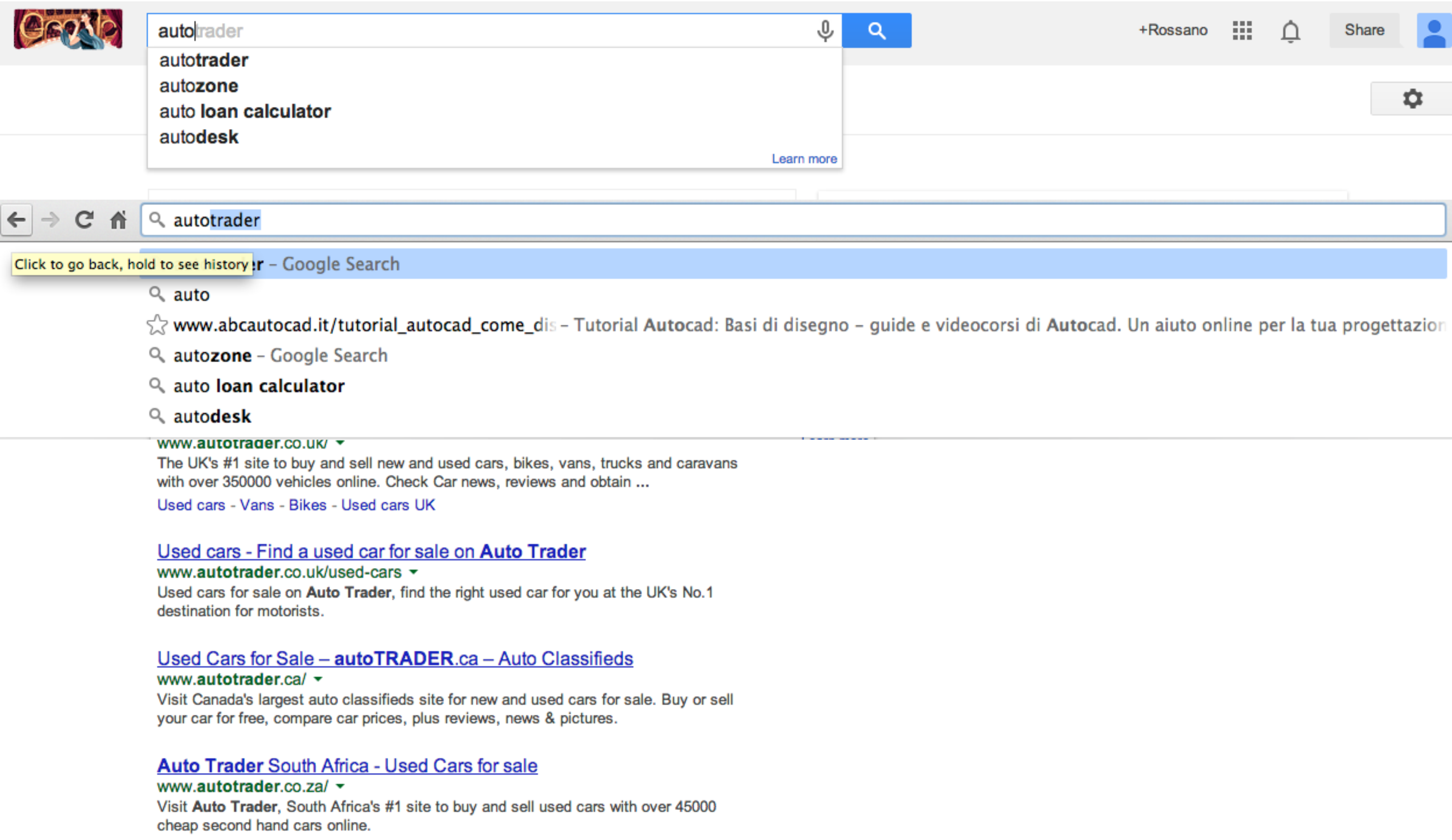

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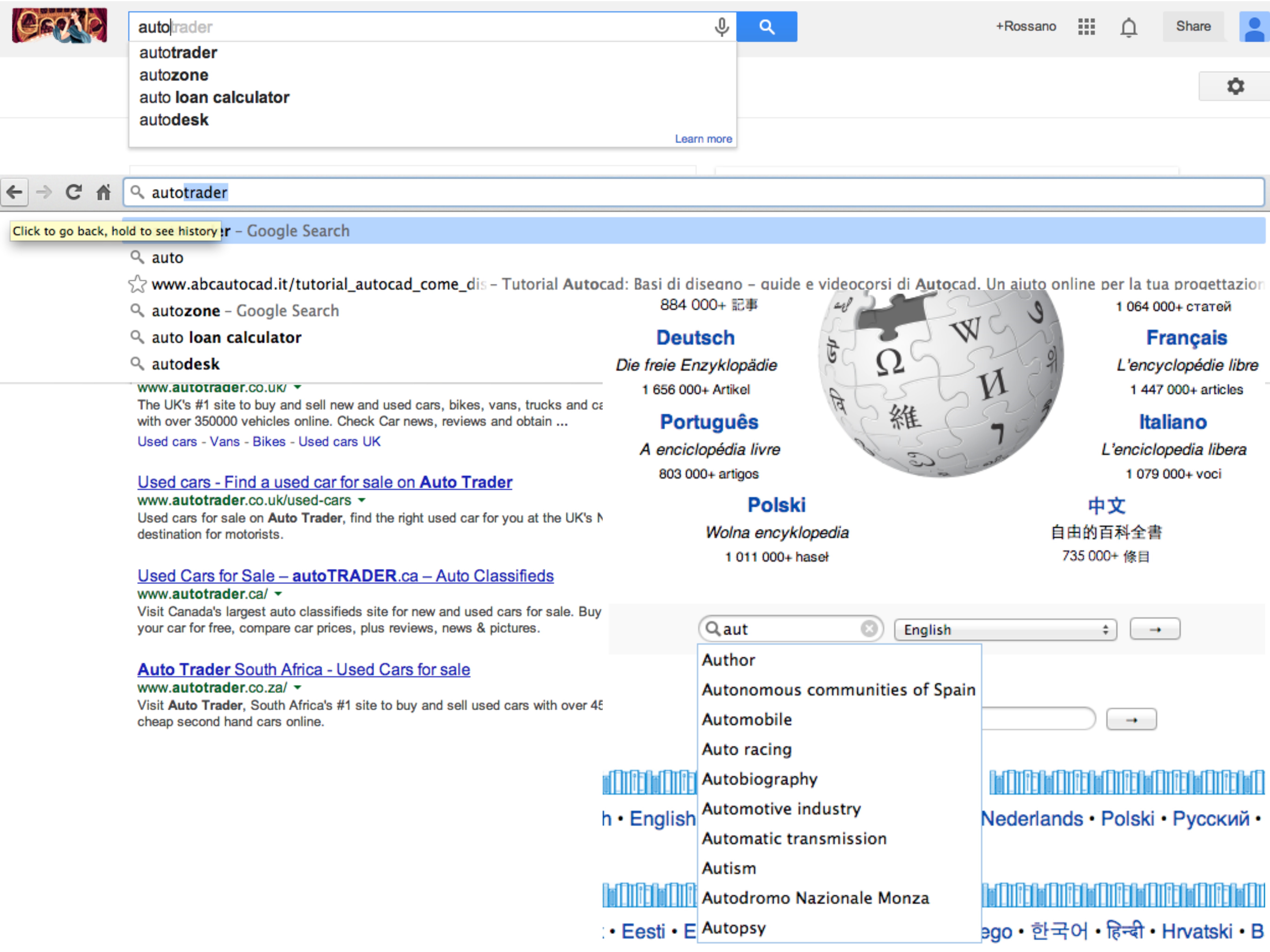

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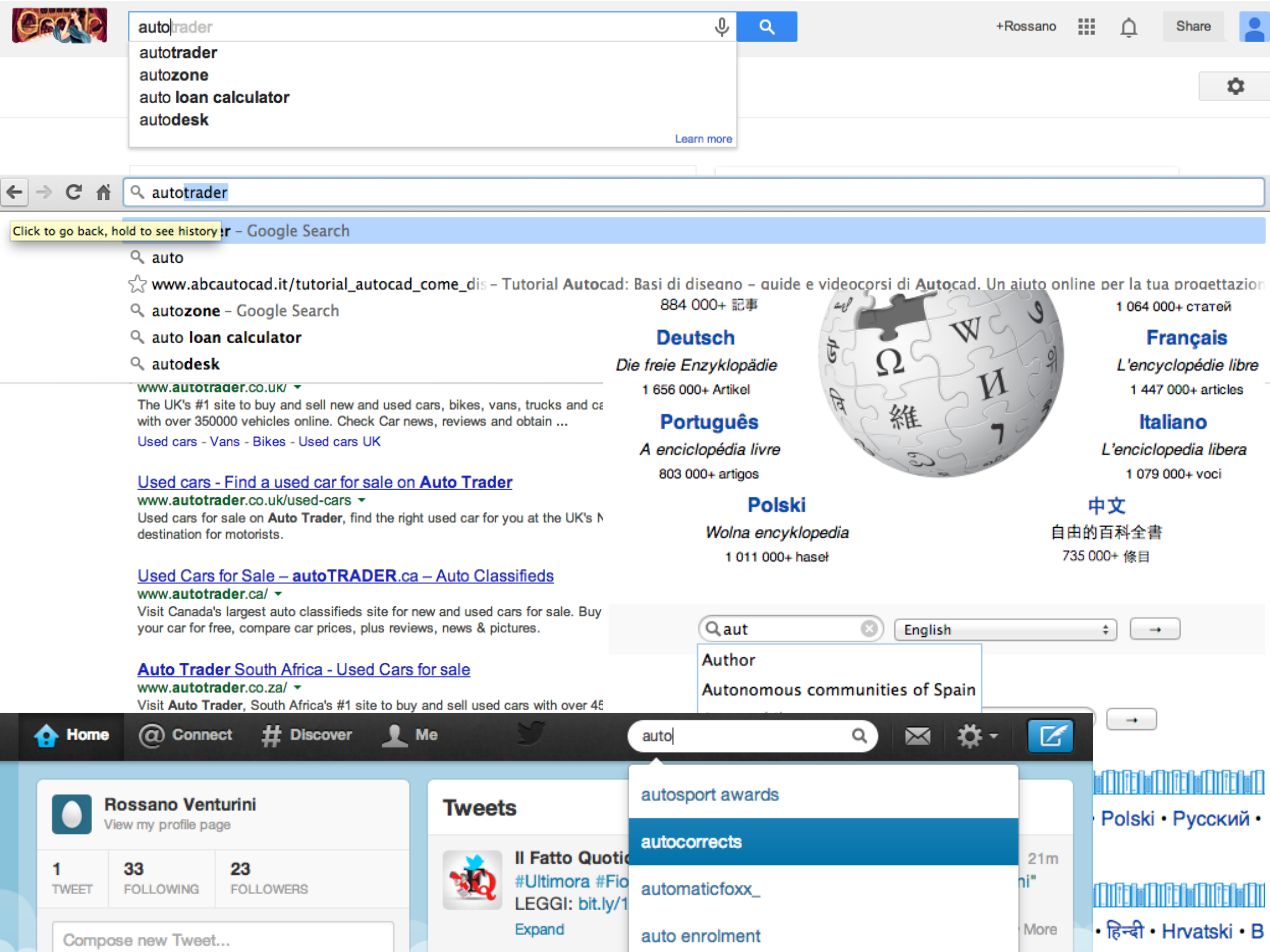

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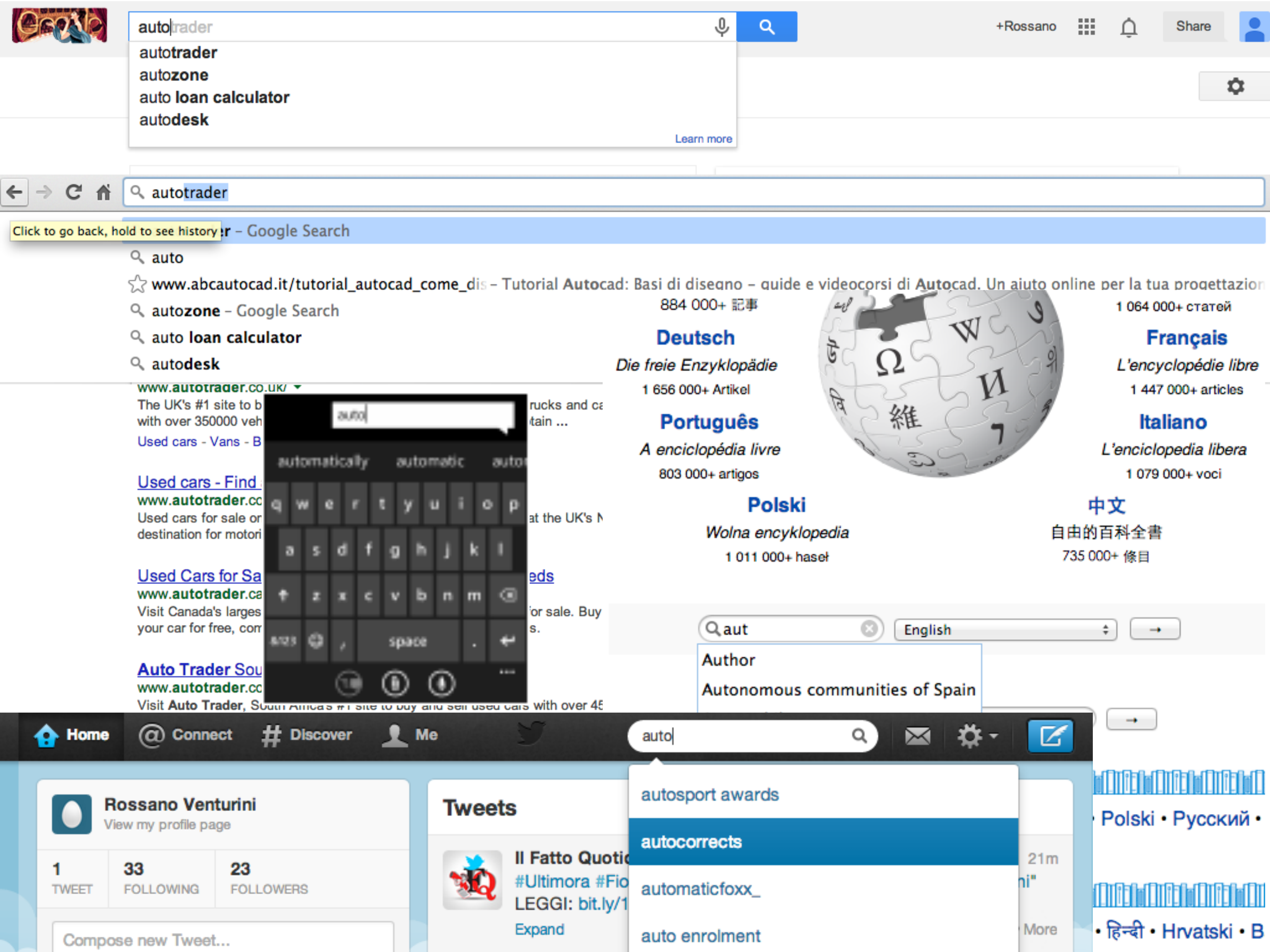

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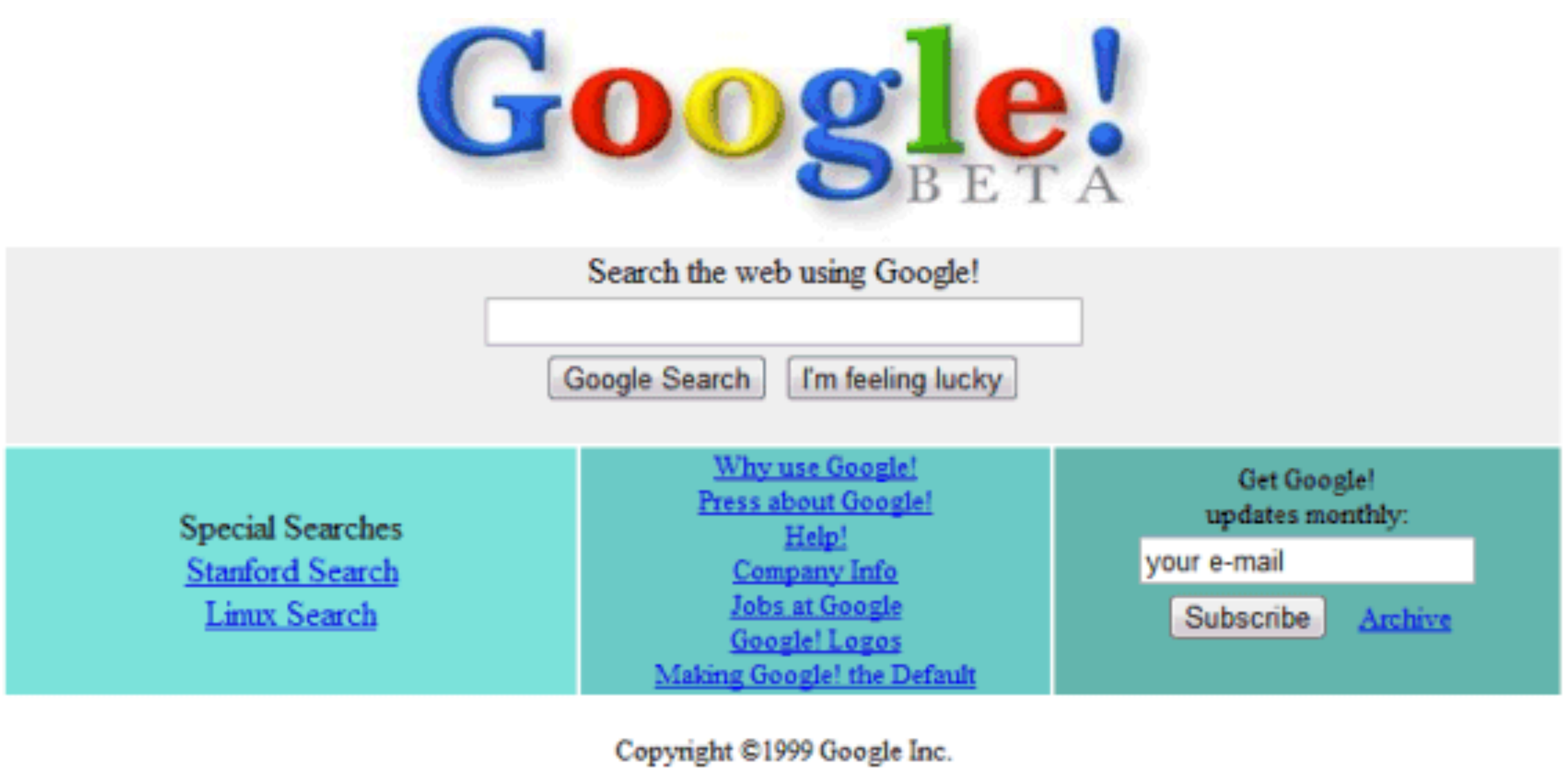

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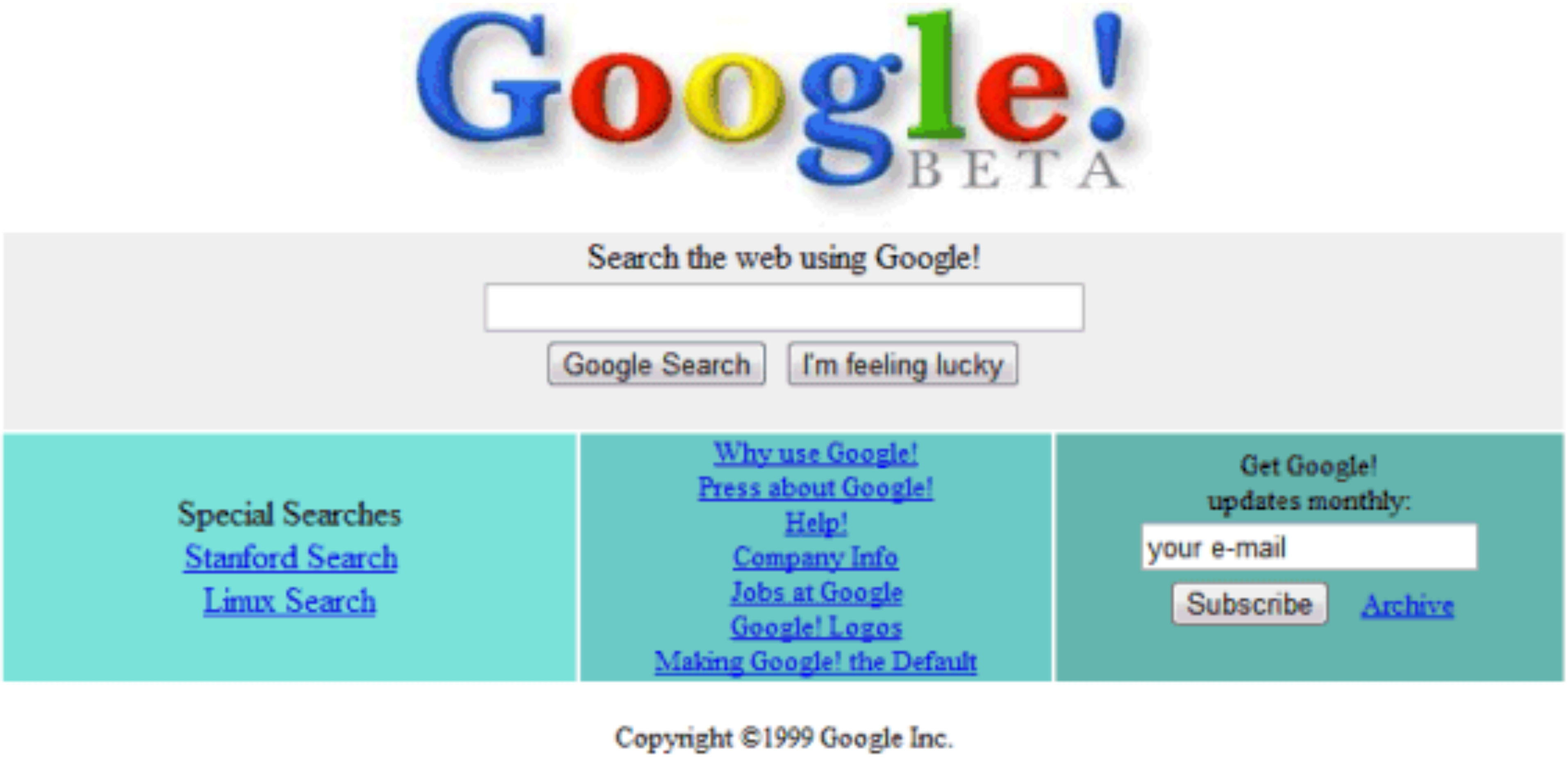

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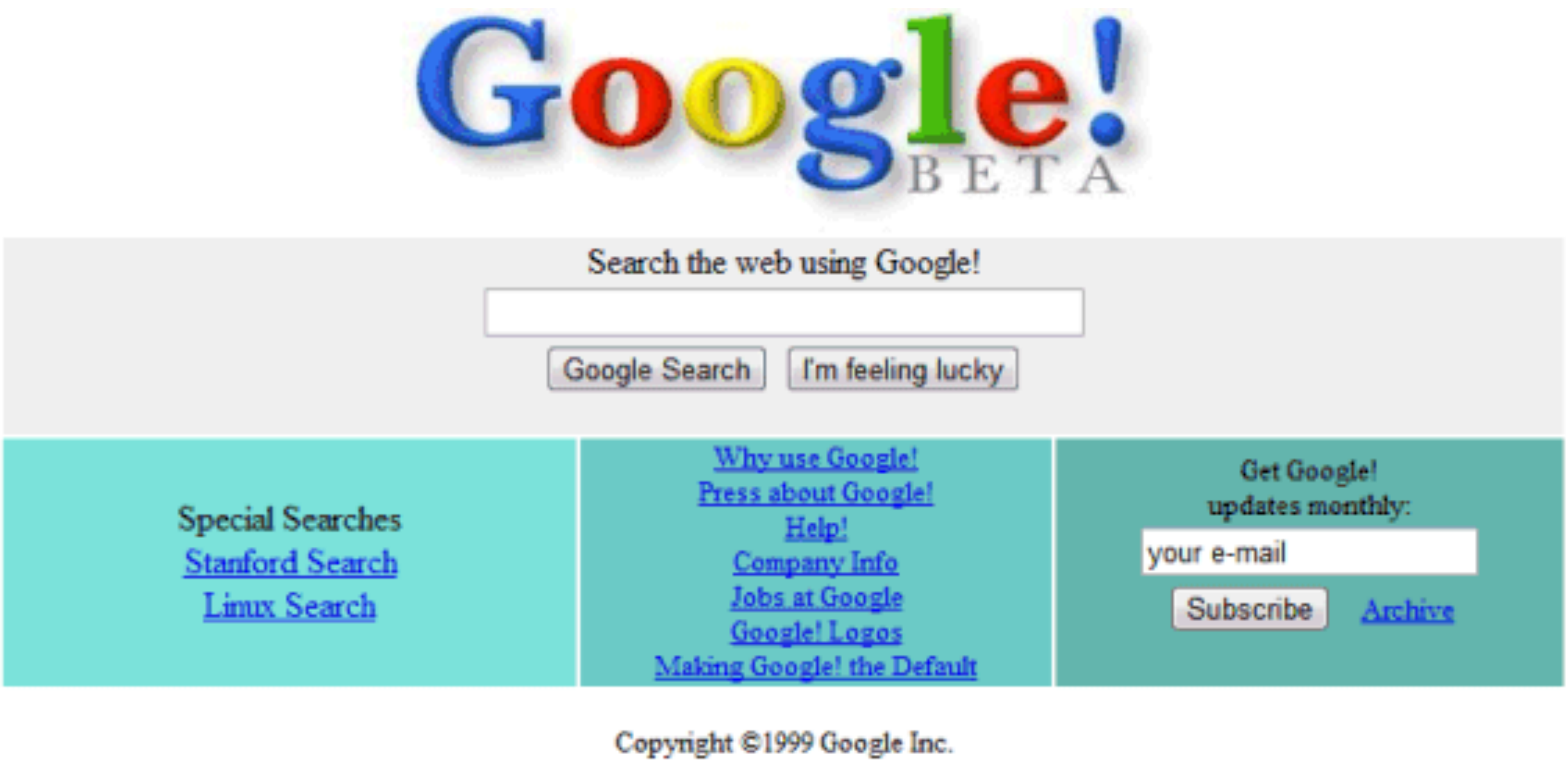

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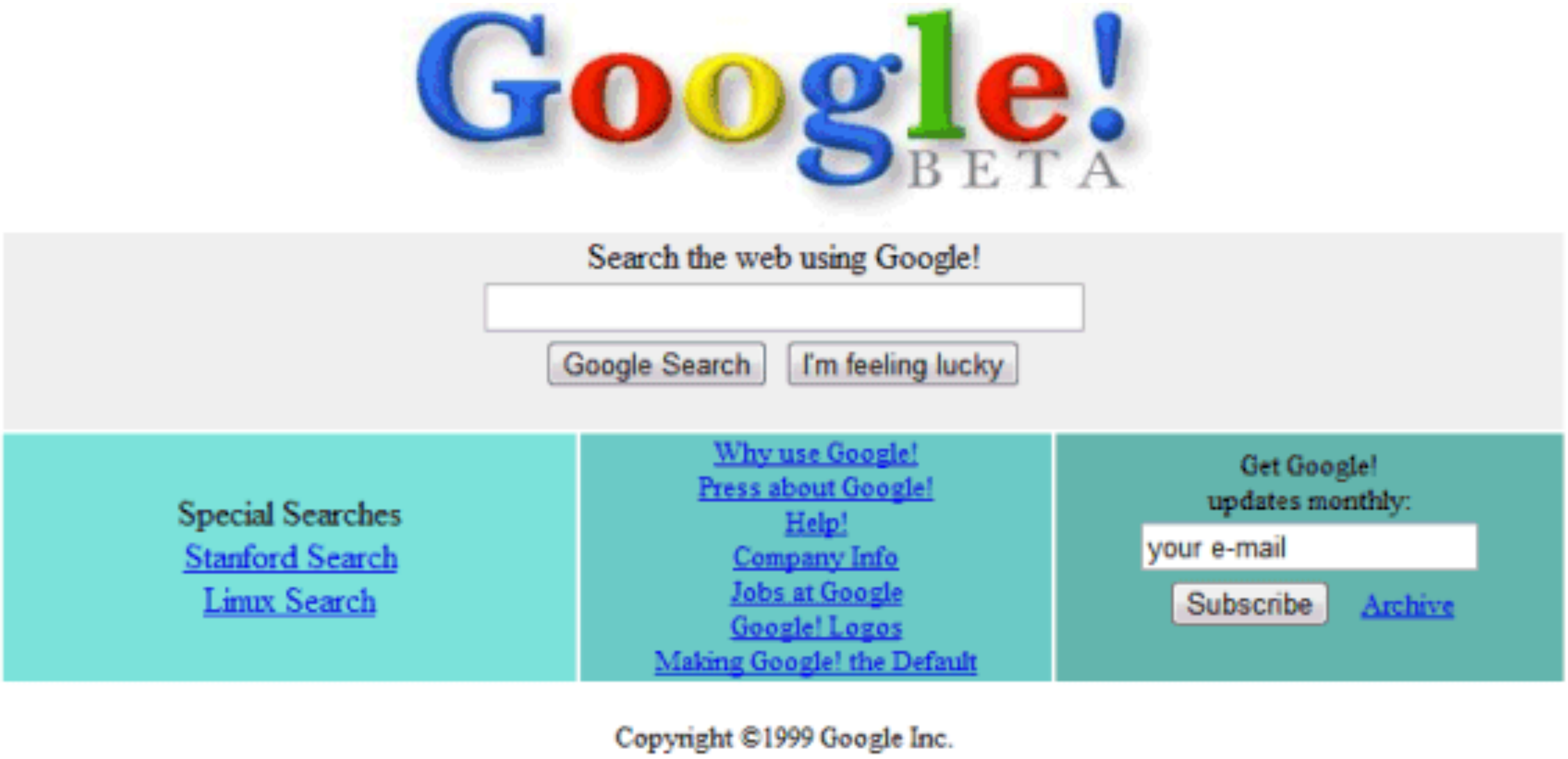

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How to find top-k efficiently?

Trie

Trie

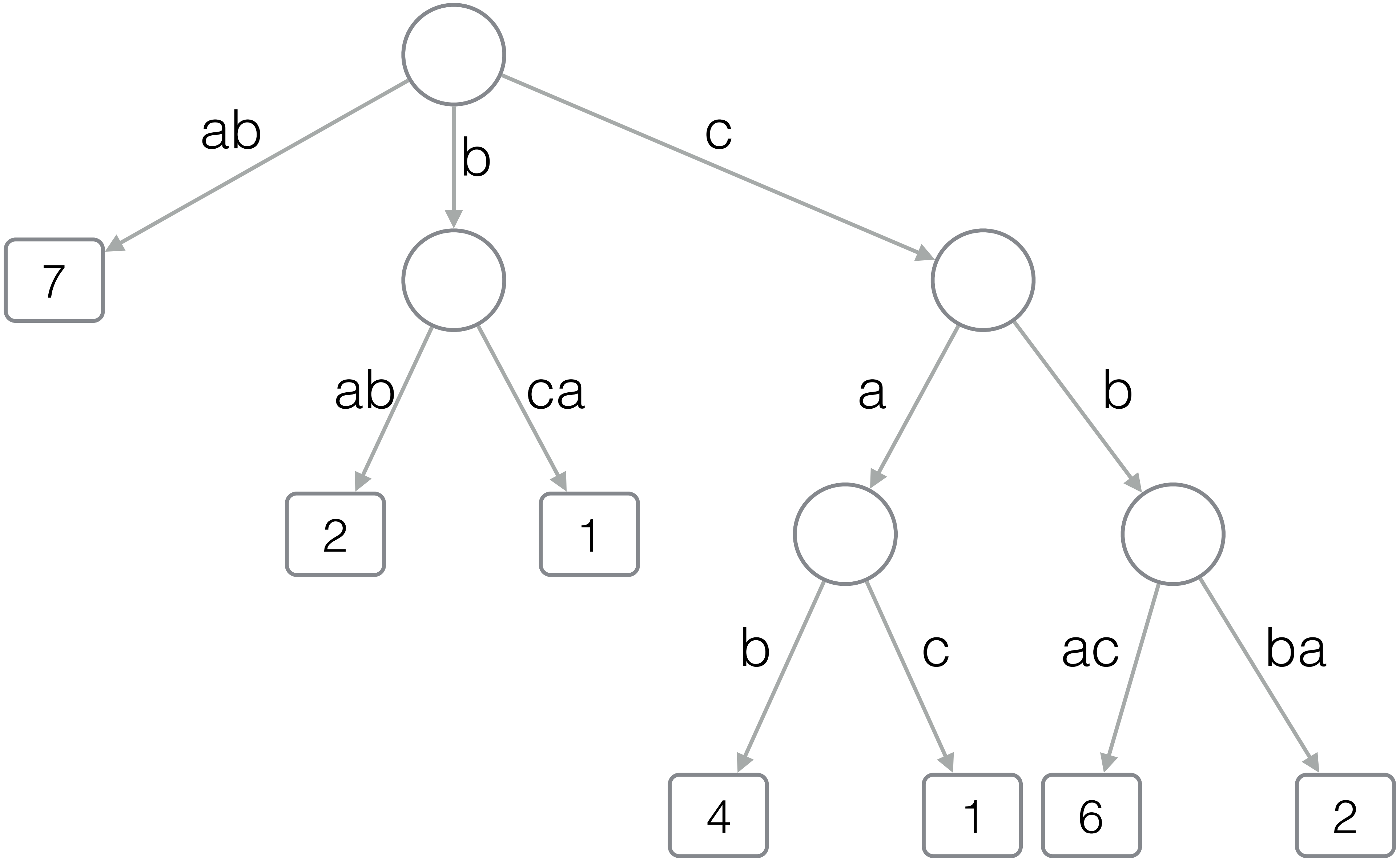
D = { ab (7), bab (2), bca (1), cab (4), cac (1), cbac (6), cbba (2) }

Trie

D = { ab (7), bab (2), bca (1), cab (4), cac (1), cbac (6), cbba (2) }

n = |D|, m total length of strings in D

Trie



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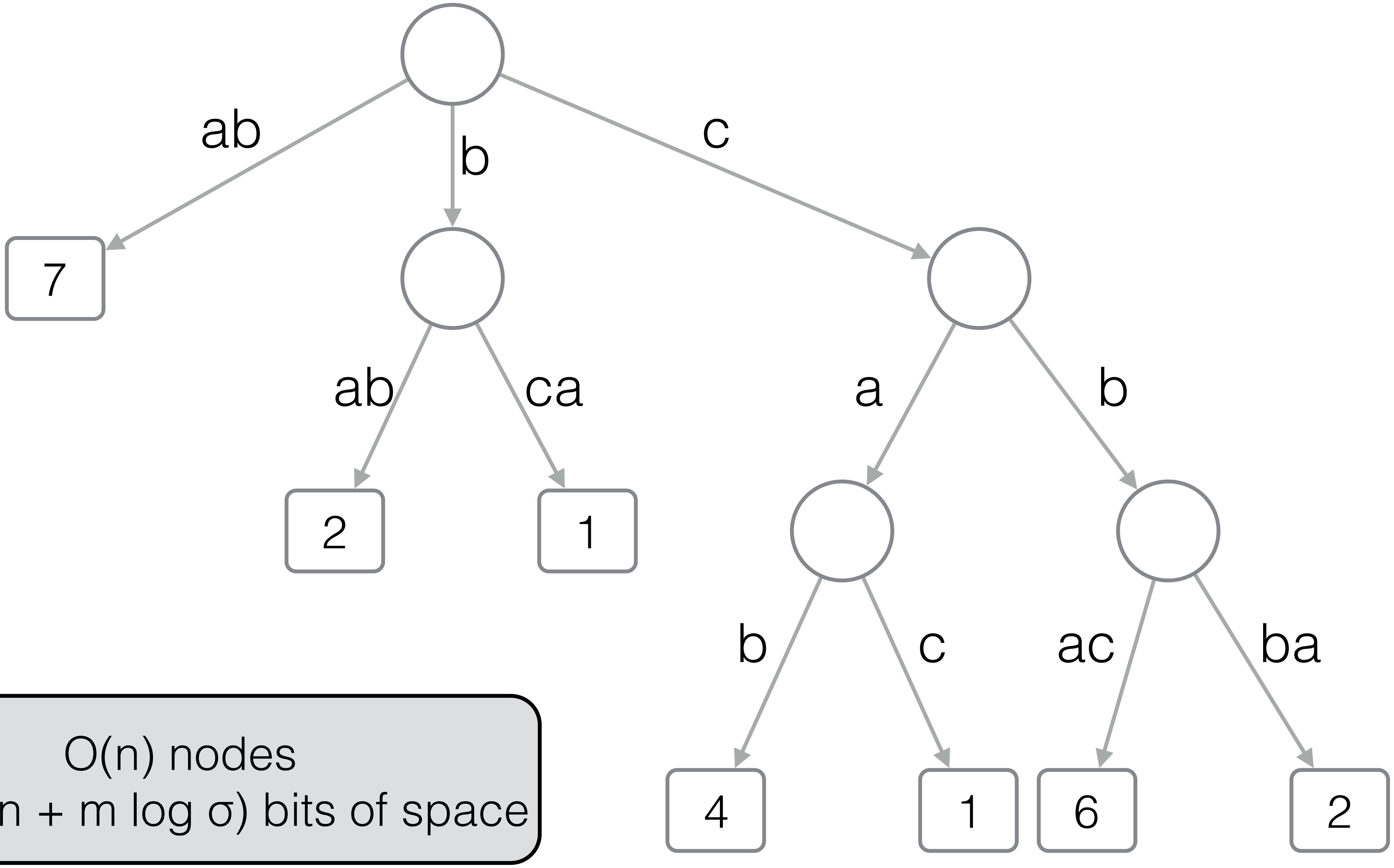
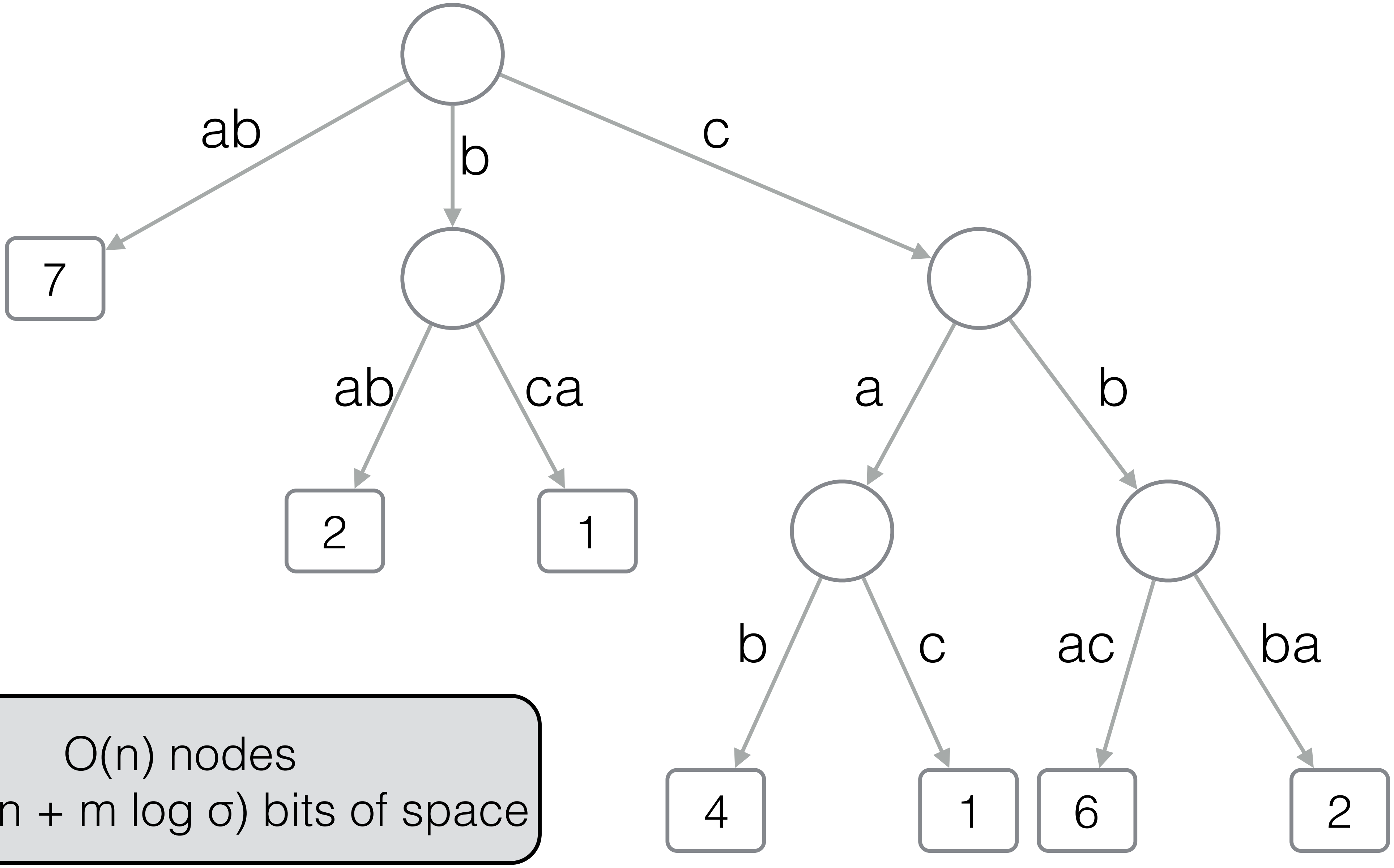


O(n) nodes
O(n log n + m log σ) bits of space

D = { ab (7), bab (2), bca (1), cab (4), cac (1), cbac (6), cbba (2) }

n = |D|, m total length of strings in D

Trie



O(n) nodes
O(n log n + m log σ) bits of space

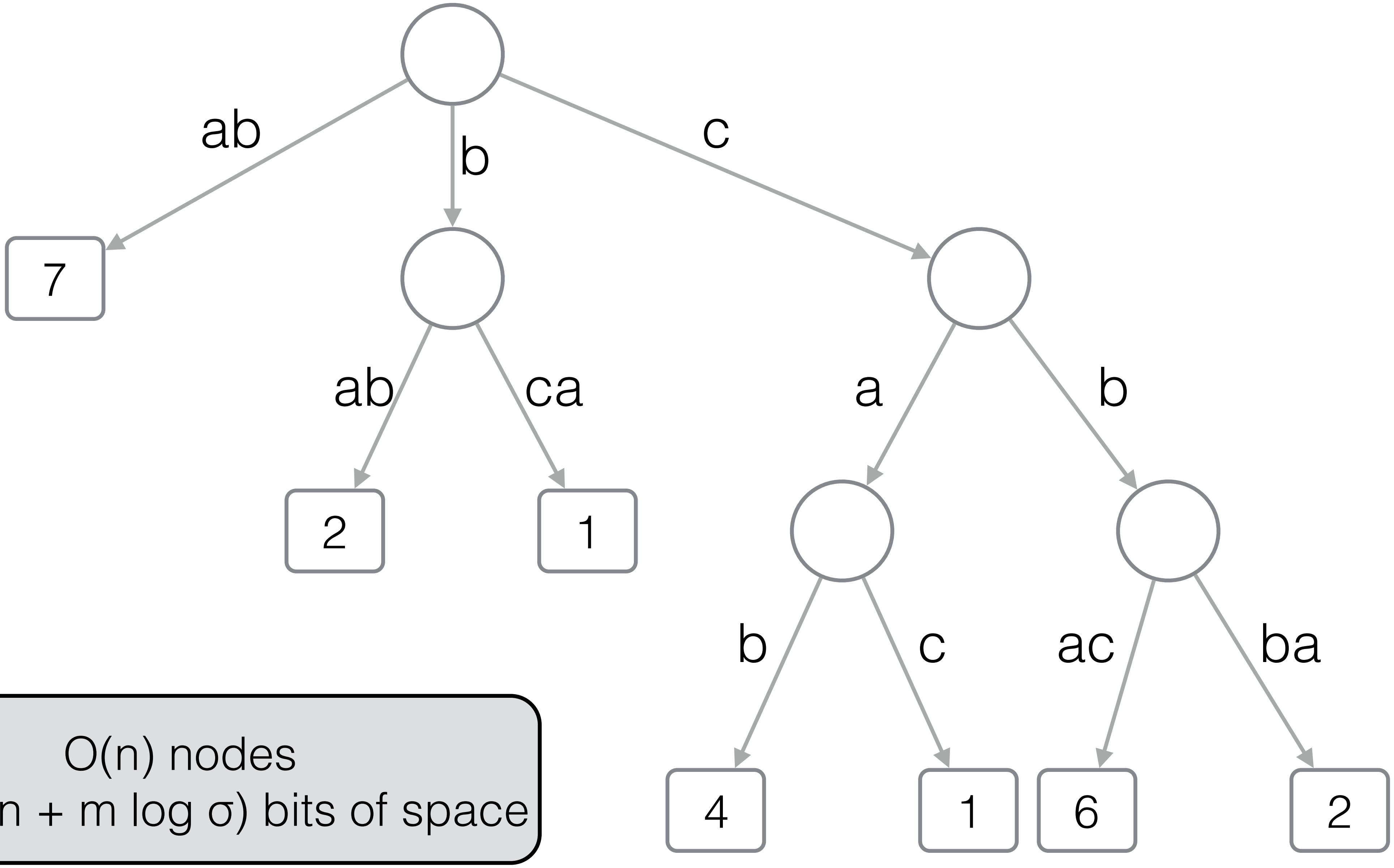
Find all the strings prefixed by any pattern P in O(|P|) time

D = { ab (7), bab (2), bca (1), cab (4), cac (1), cbac (6), cbba (2) }

n = |D|, m total length of strings in D

Trie

P = c



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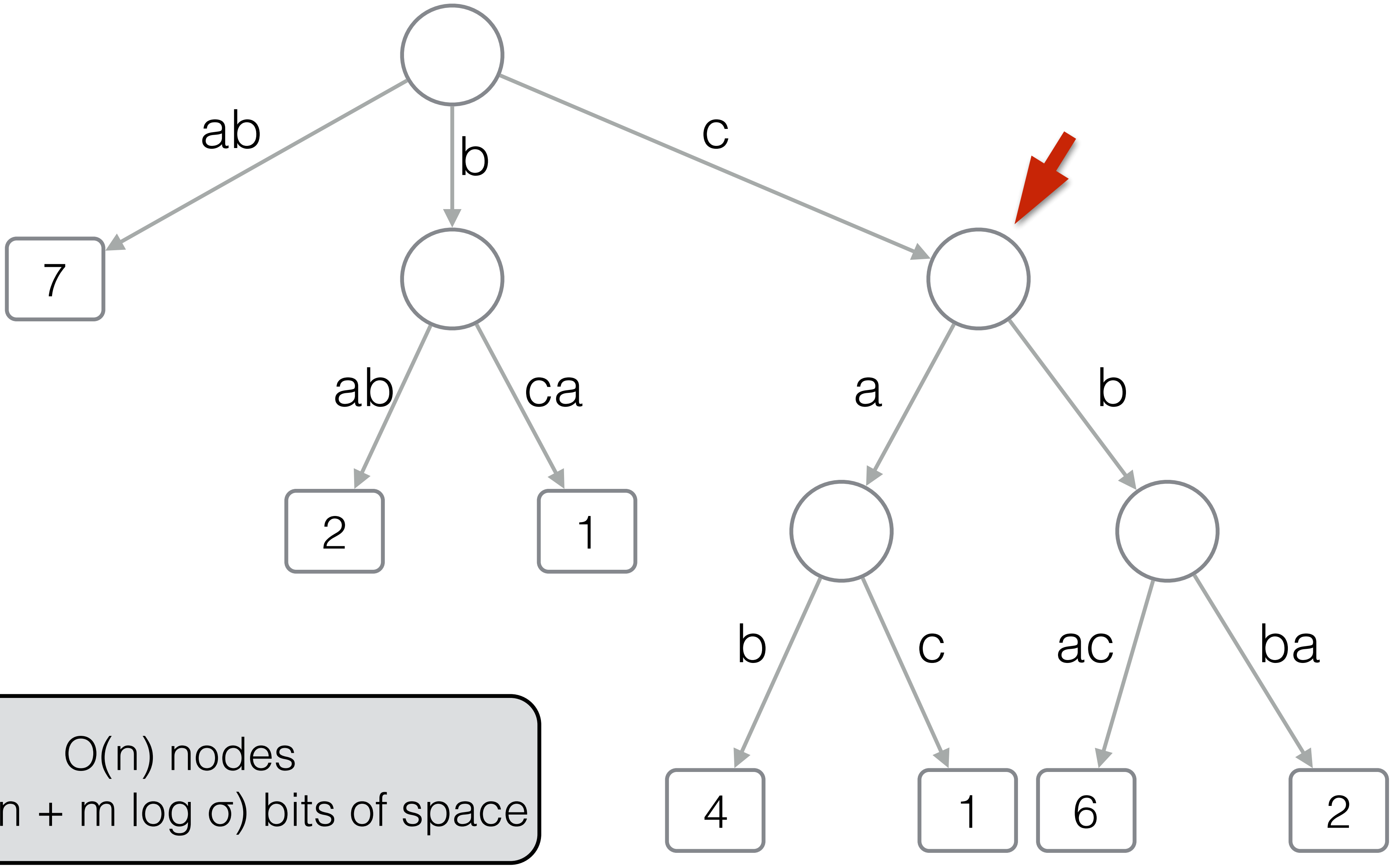

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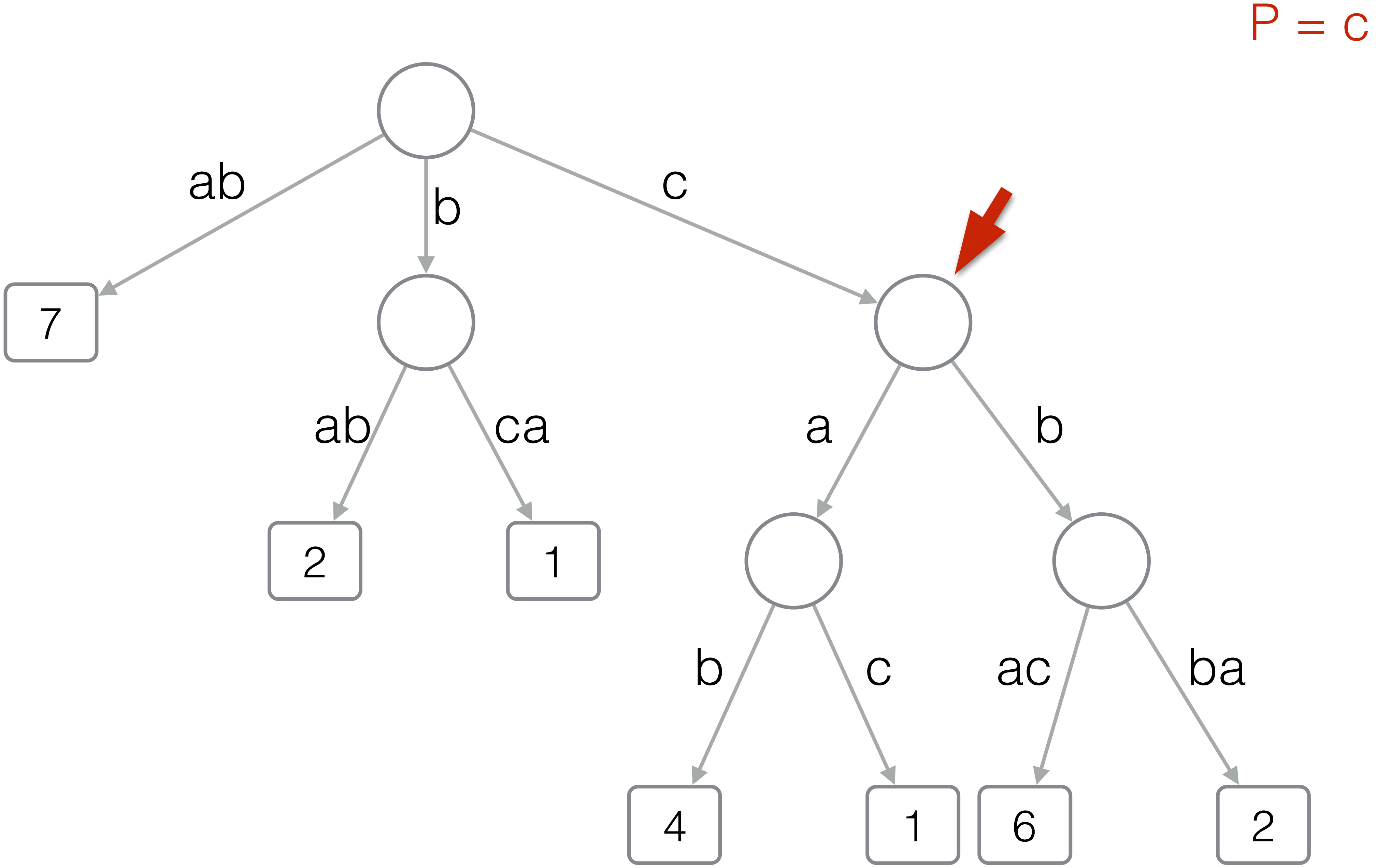
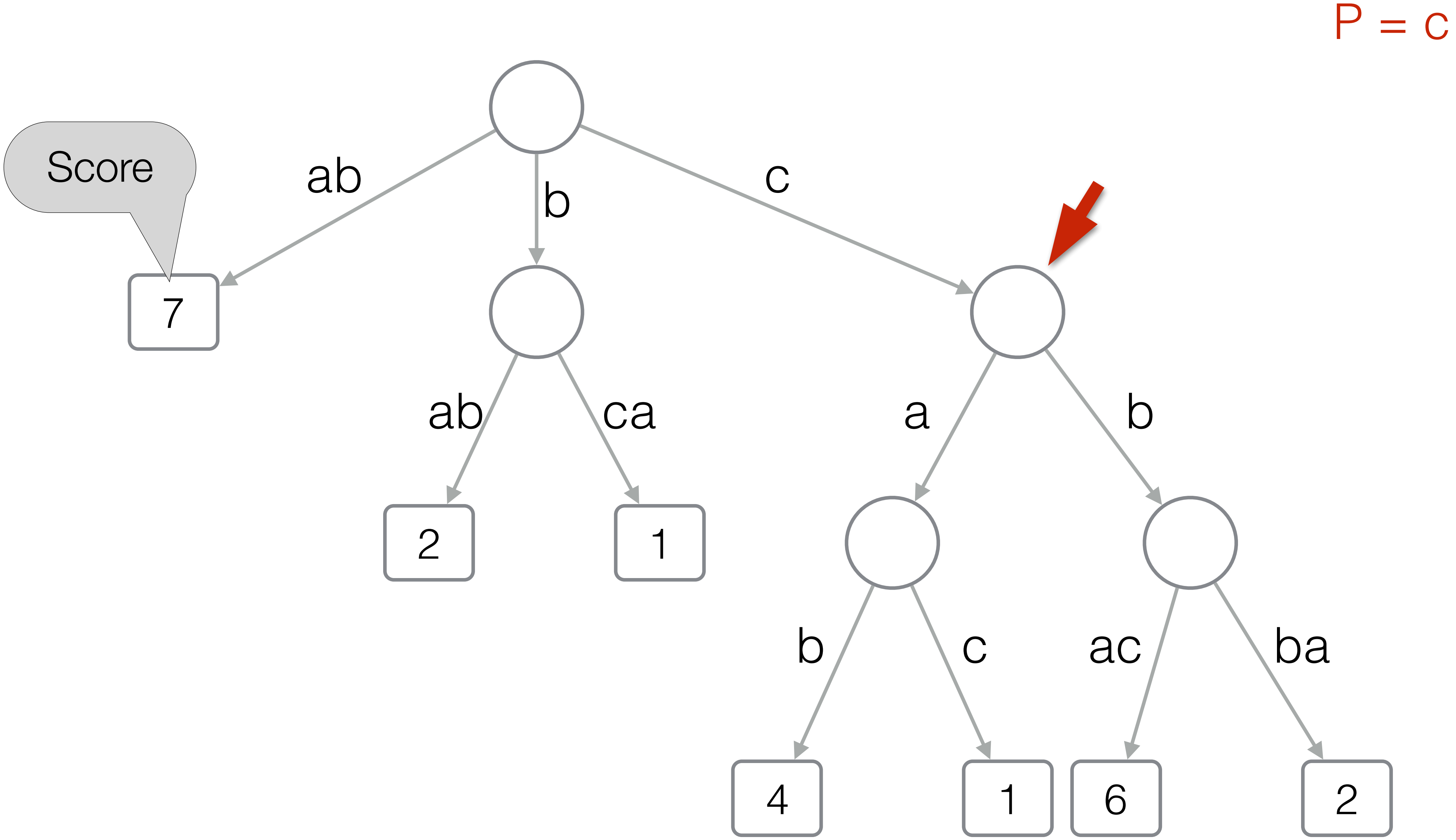
Finding Top-1



D = { ab (7), bab (2), bca (1), cab (4), cac (1), cbac (6), cbba (2) }

N = |D|, n = total length of strings in D, σ = alphabet size

Finding Top-1



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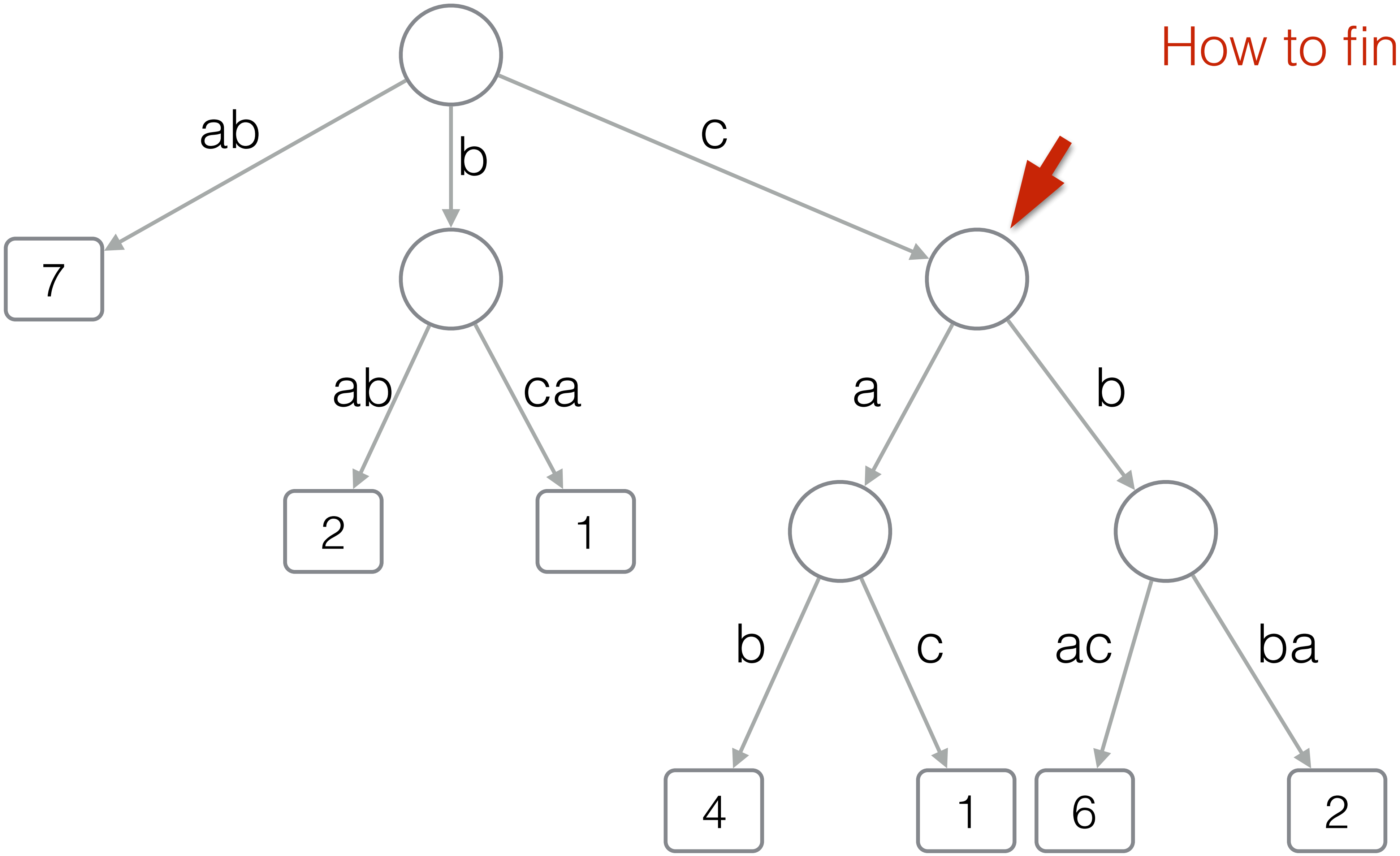

P = c

How to find Top-1?

D = { ab (7), bab (2), bca (1), cab (4), cac (1), cbac (6), cbba (2) }

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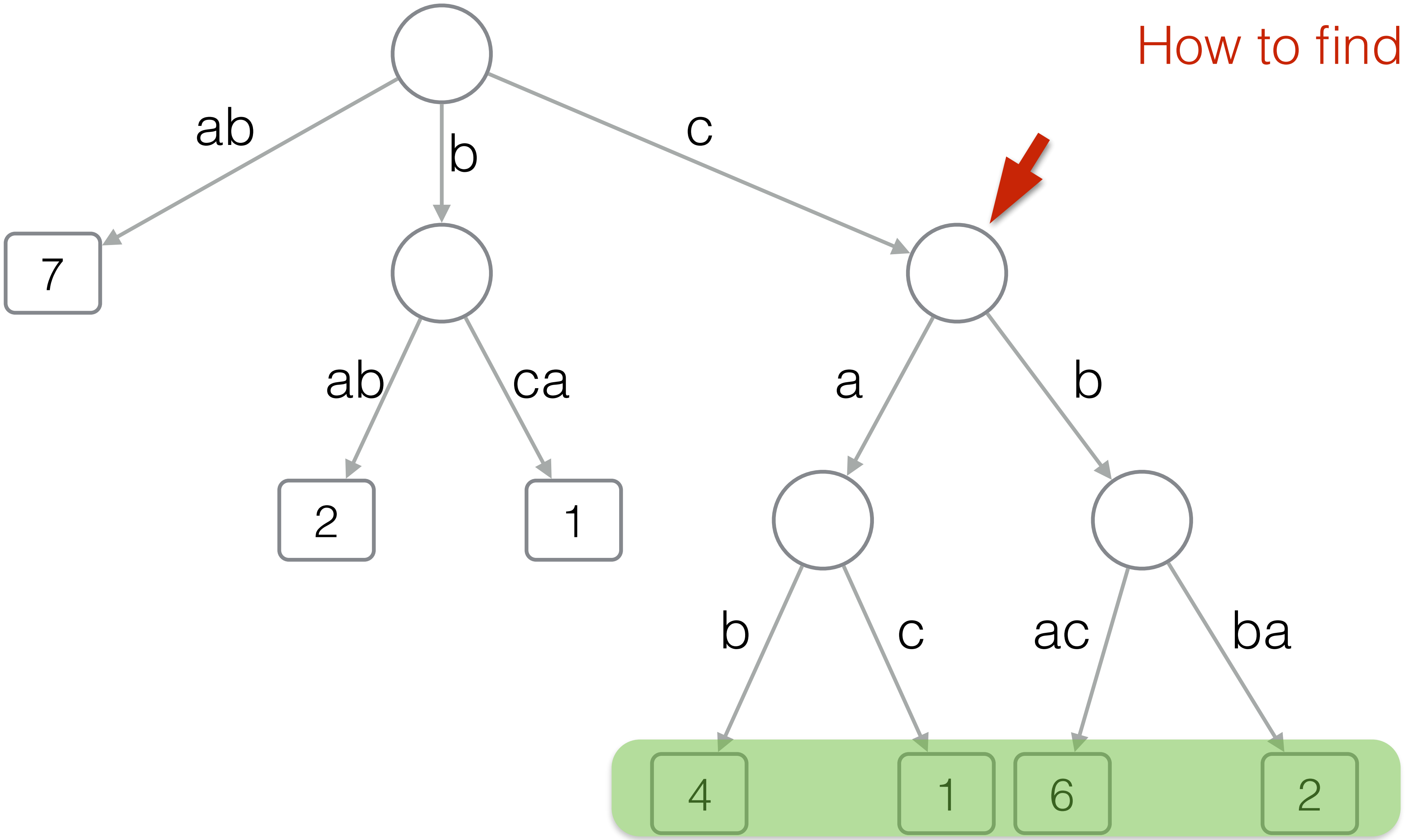
Finding Top-1

P = c

How to find Top-1?



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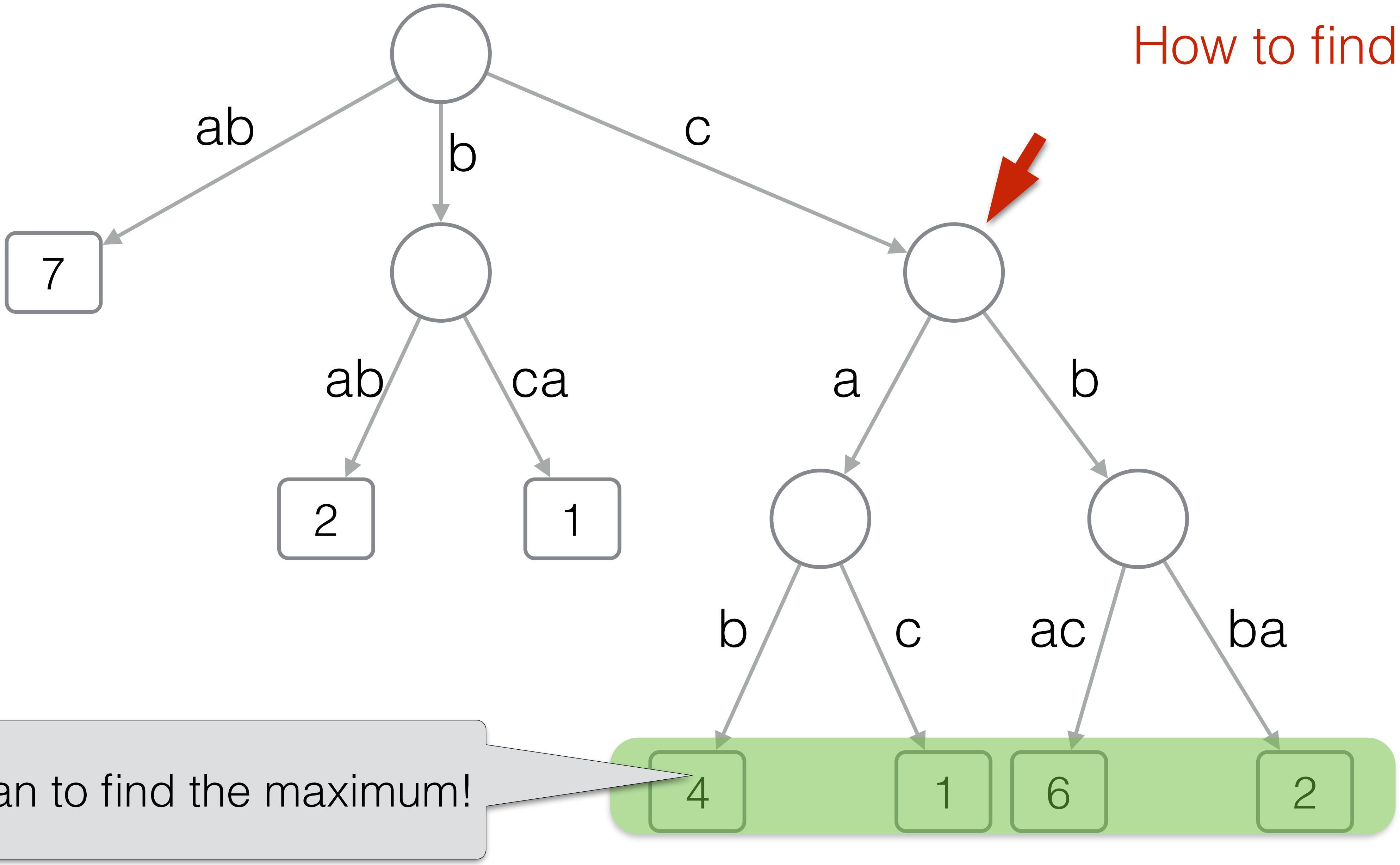

Scan to find the maximum!

D = { ab (7), bab (2), bca (1), cab (4), cac (1), cbac (6), cbba (2) }

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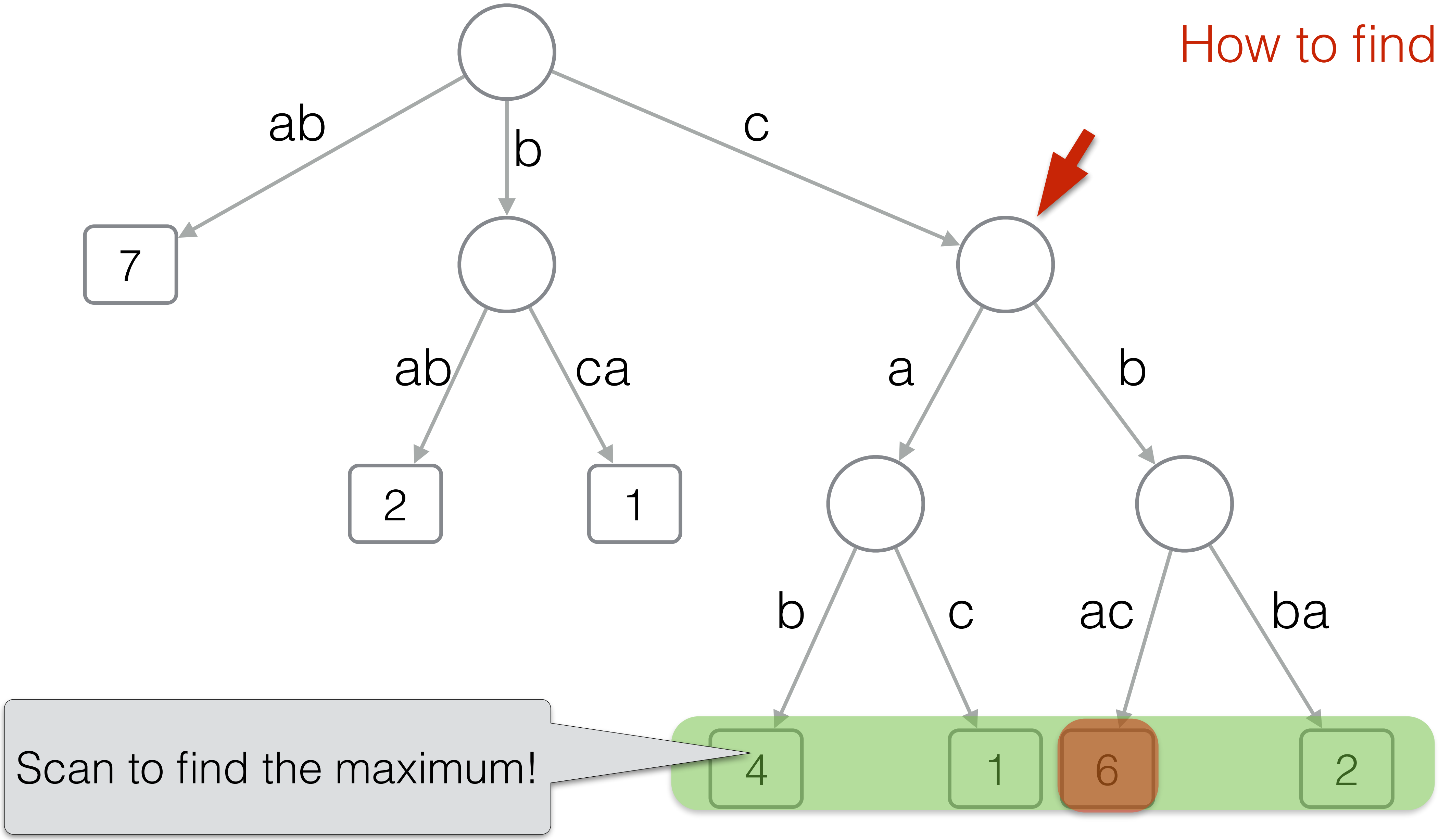
Finding Top-1



D = { ab (7), bab (2), bca (1), cab (4), cac (1), cbac (6), cbba (2) }

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P = c

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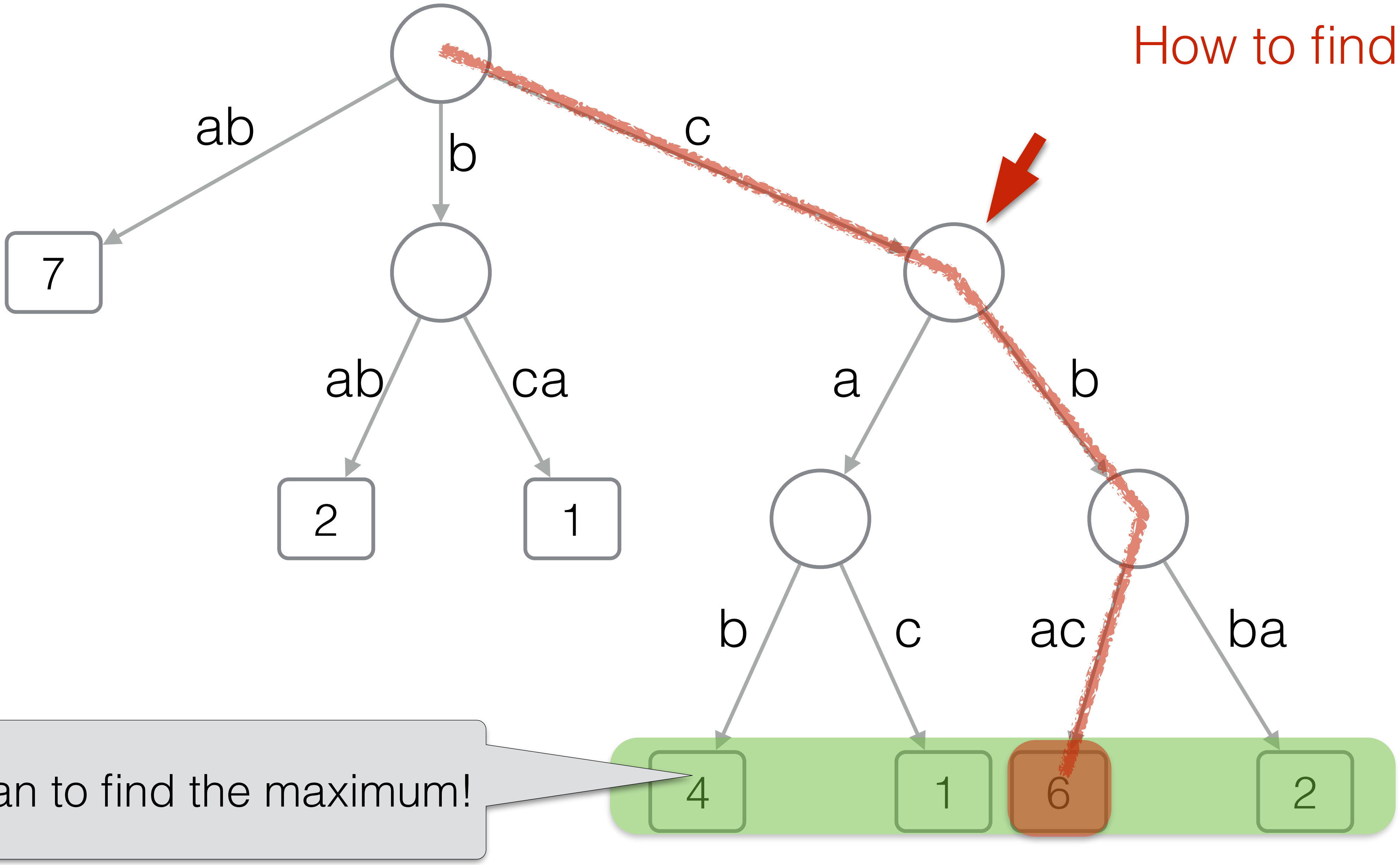

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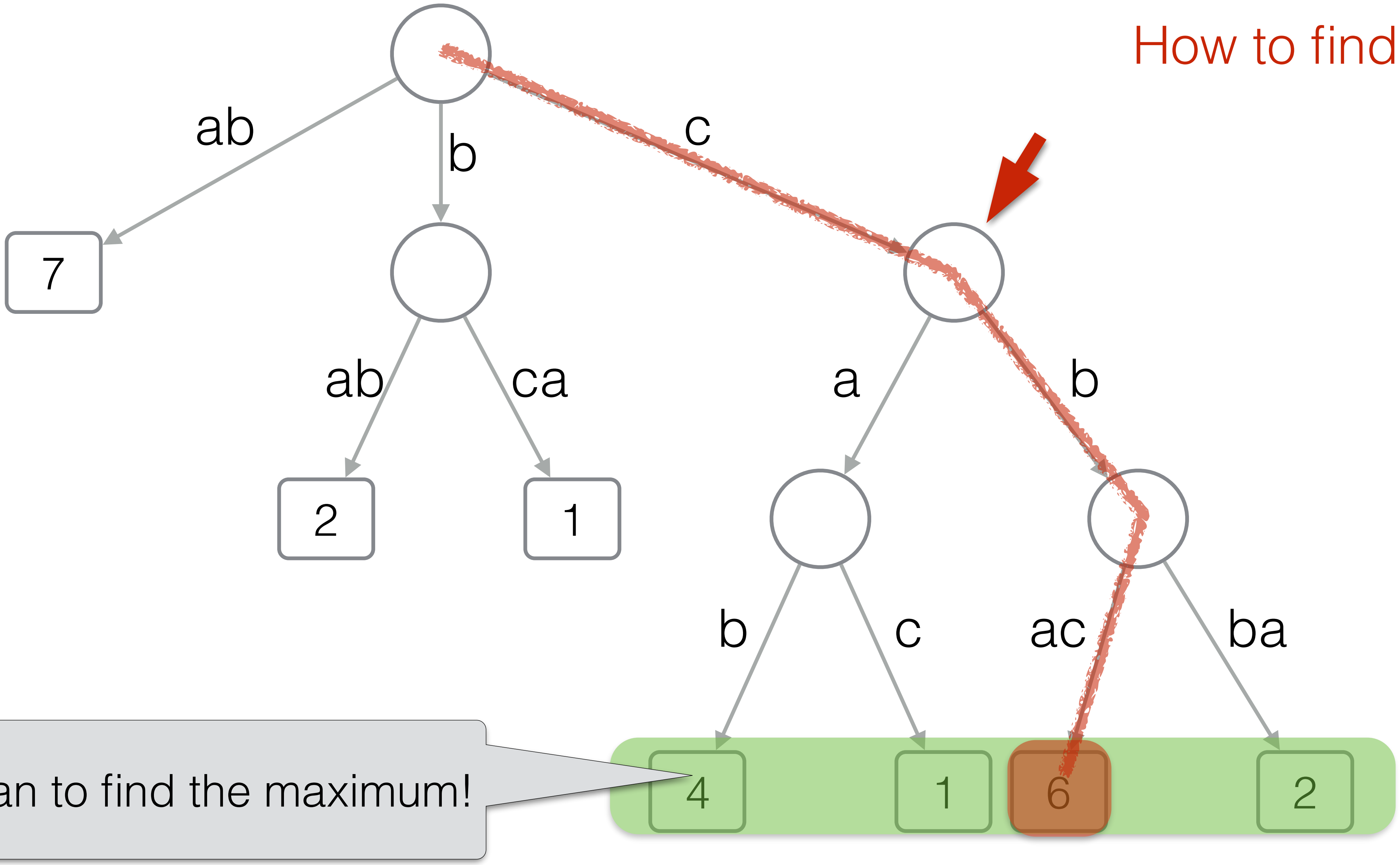
Finding Top-1

P = c

How to find Top-1?



Scan to find the maximum!

O(N) query time :-(

D = { ab (7), bab (2), bca (1), cab (4), cac (1), cbac (6), cbba (2) }

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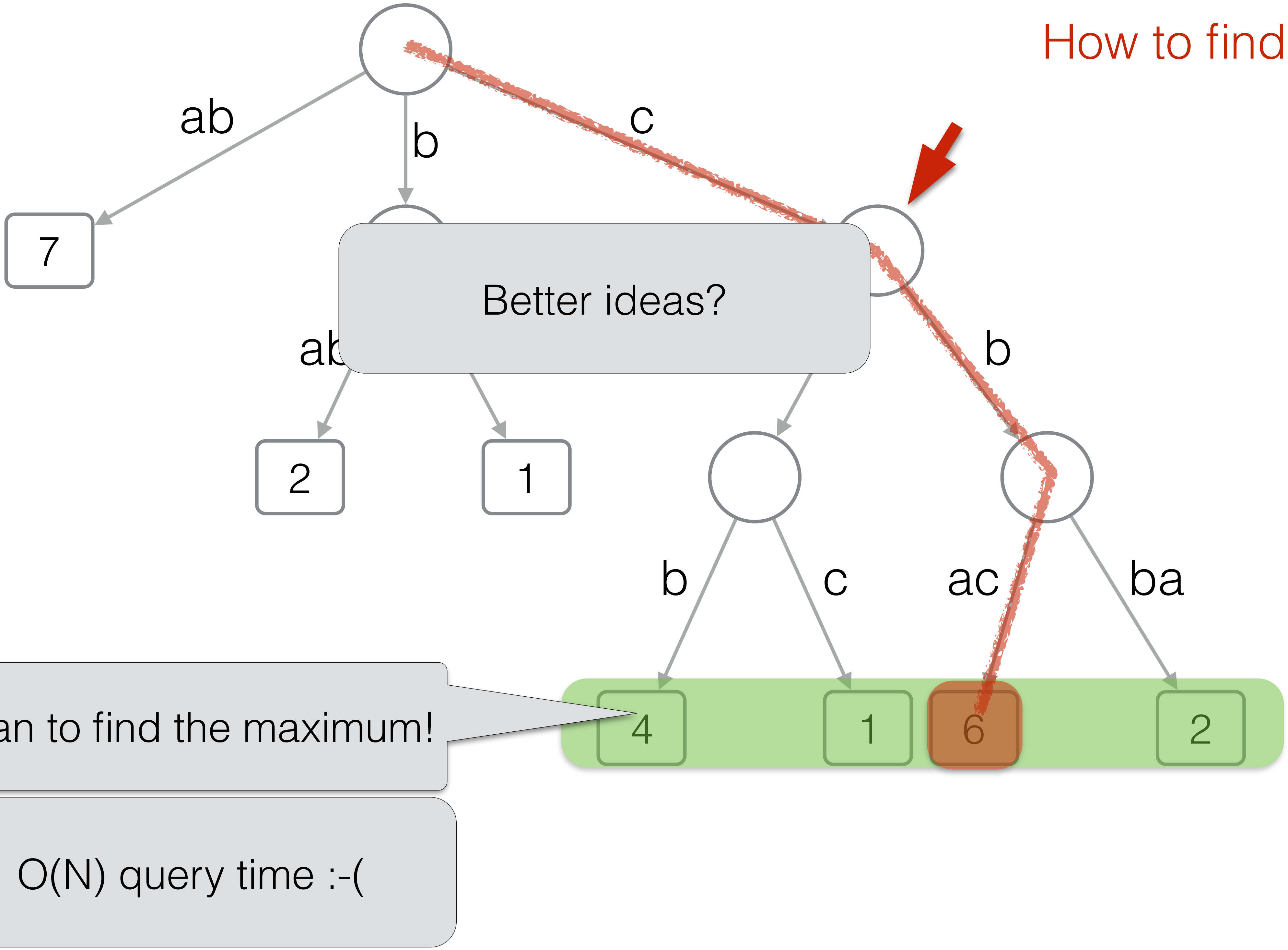
Finding Top-1

P = c

How to find Top-1?



Better ideas?

Scan to find the maximum!

O(N) query time :-(

D = { ab (7), bab (2), bca (1), cab (4), cac (1), cbac (6), cbba (2) }

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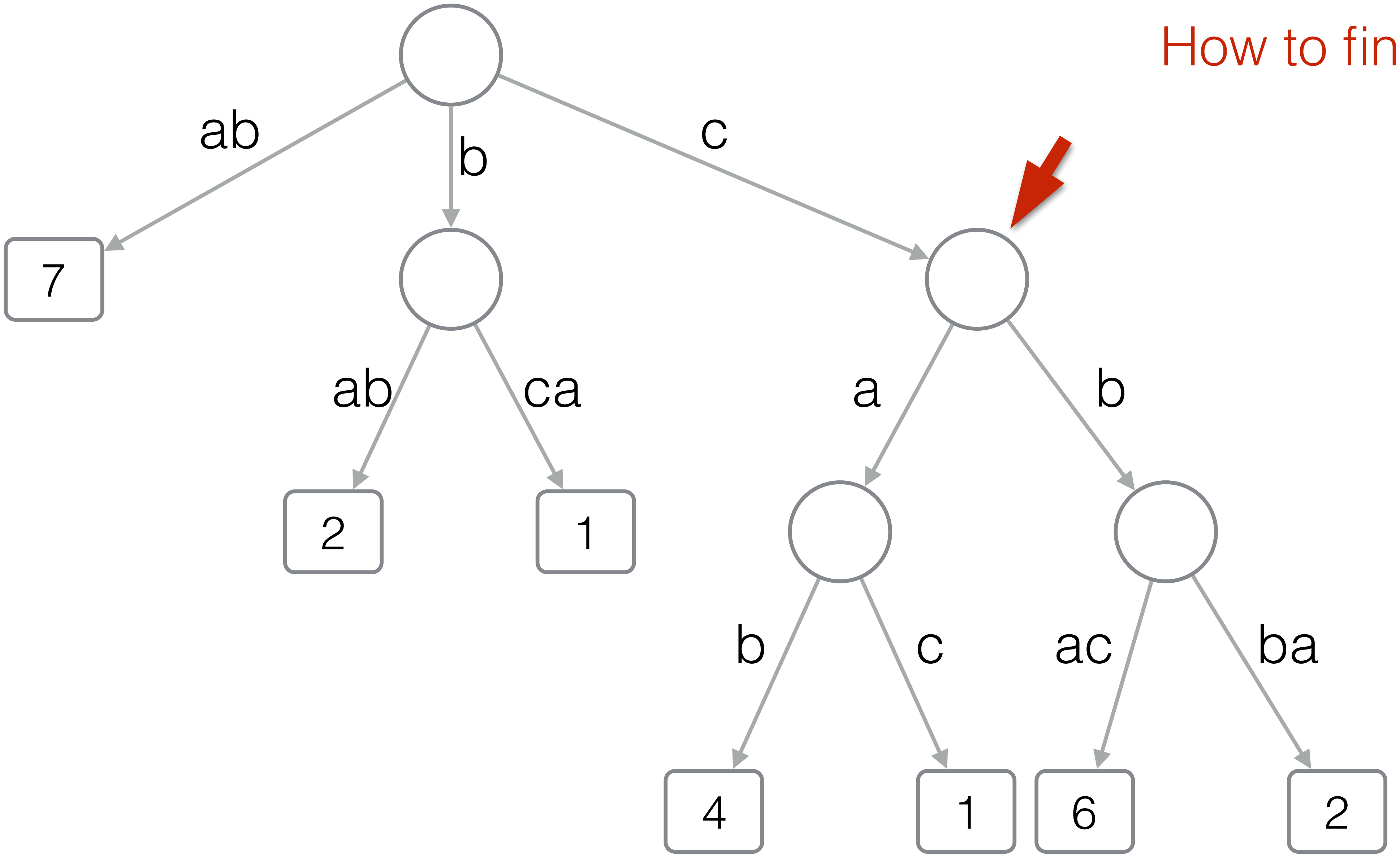

P = c

How to find Top-1?

D = { ab (7), bab (2), bca (1), cab (4), cac (1), cbac (6), cbba (2) }

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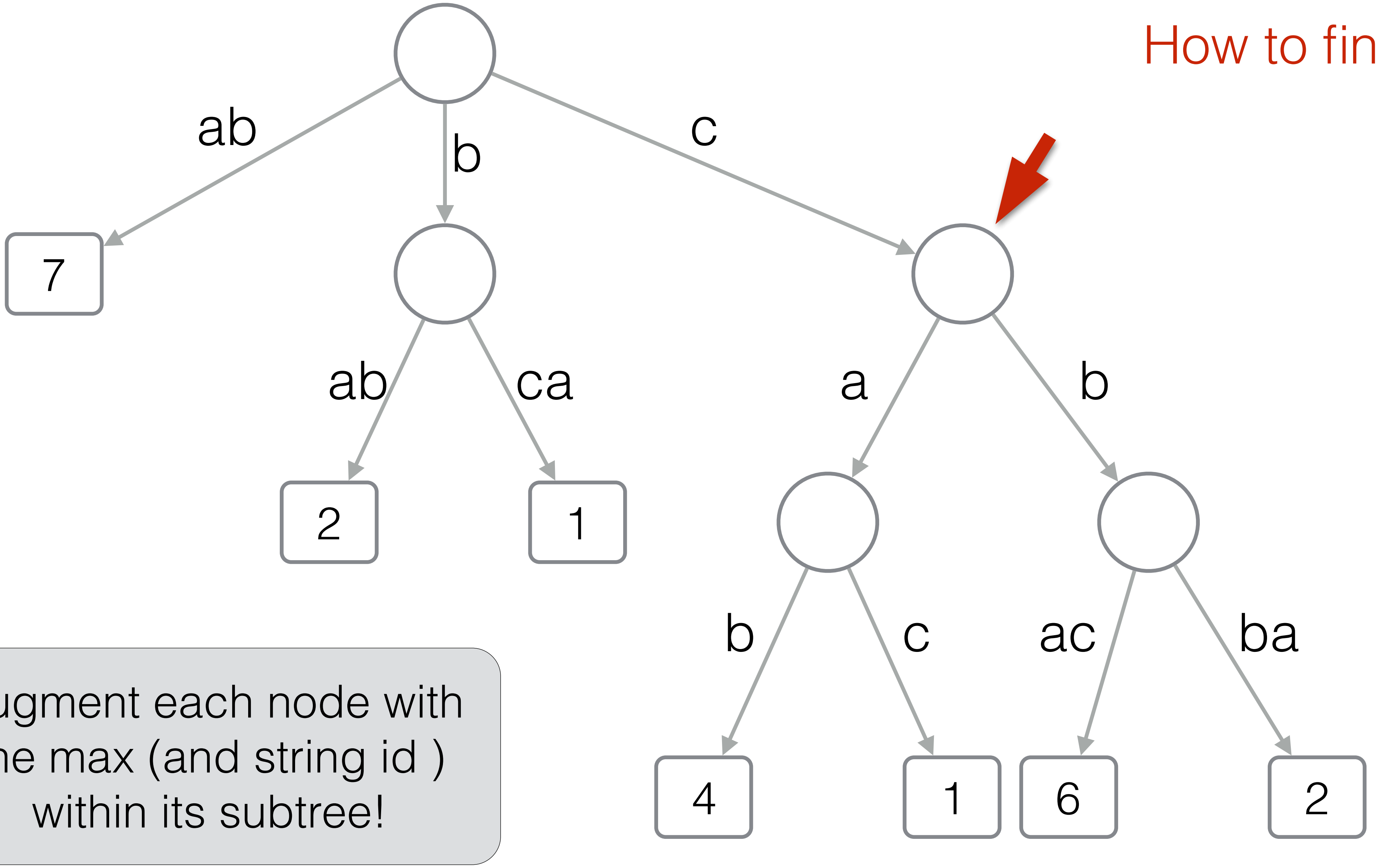
P = c

How to find Top-1?



Augment each node with the max (and string id) within its subtree!

D = { ab (7), bab (2), bca (1), cab (4), cac (1), cbac (6), cbba (2) }

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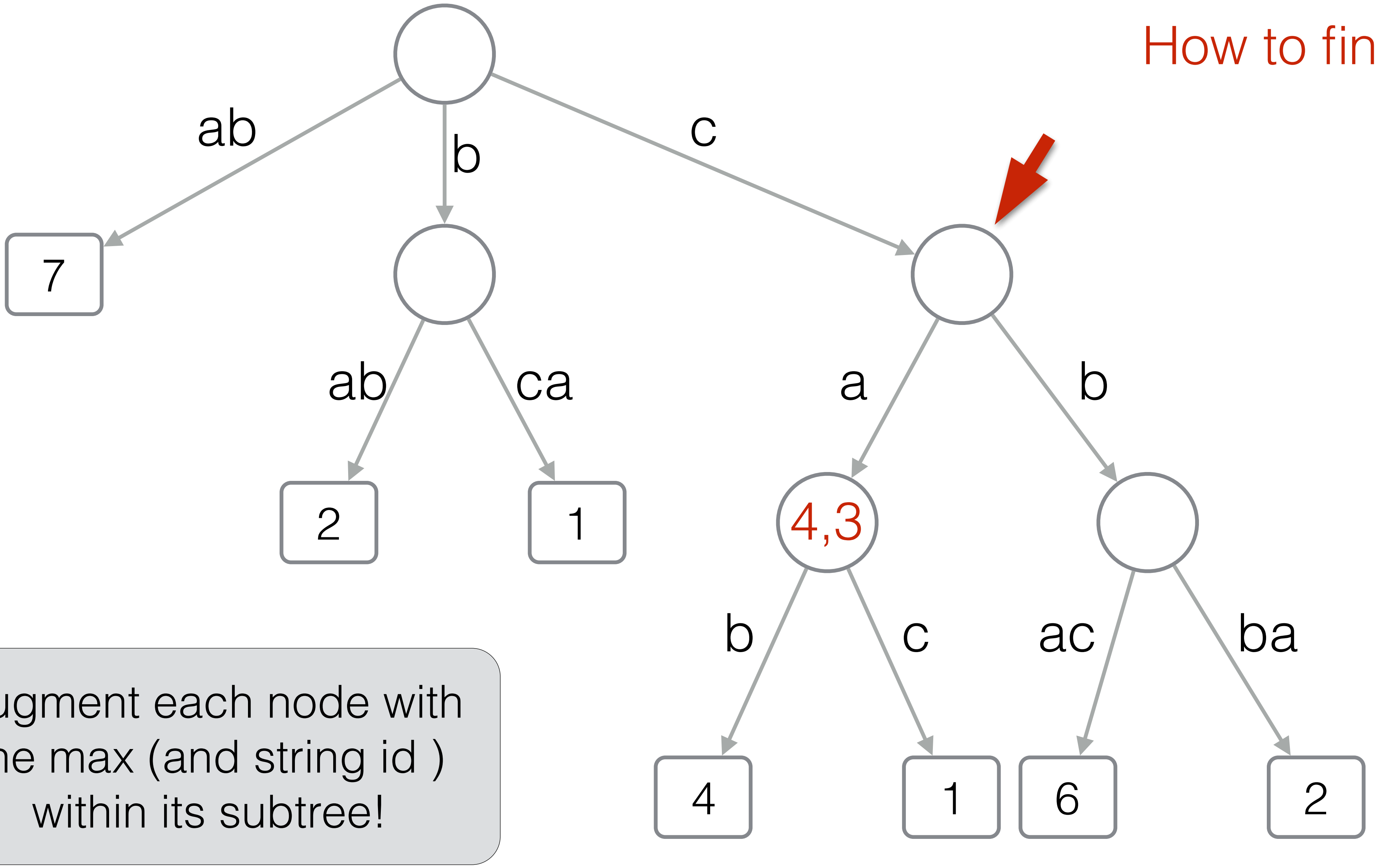

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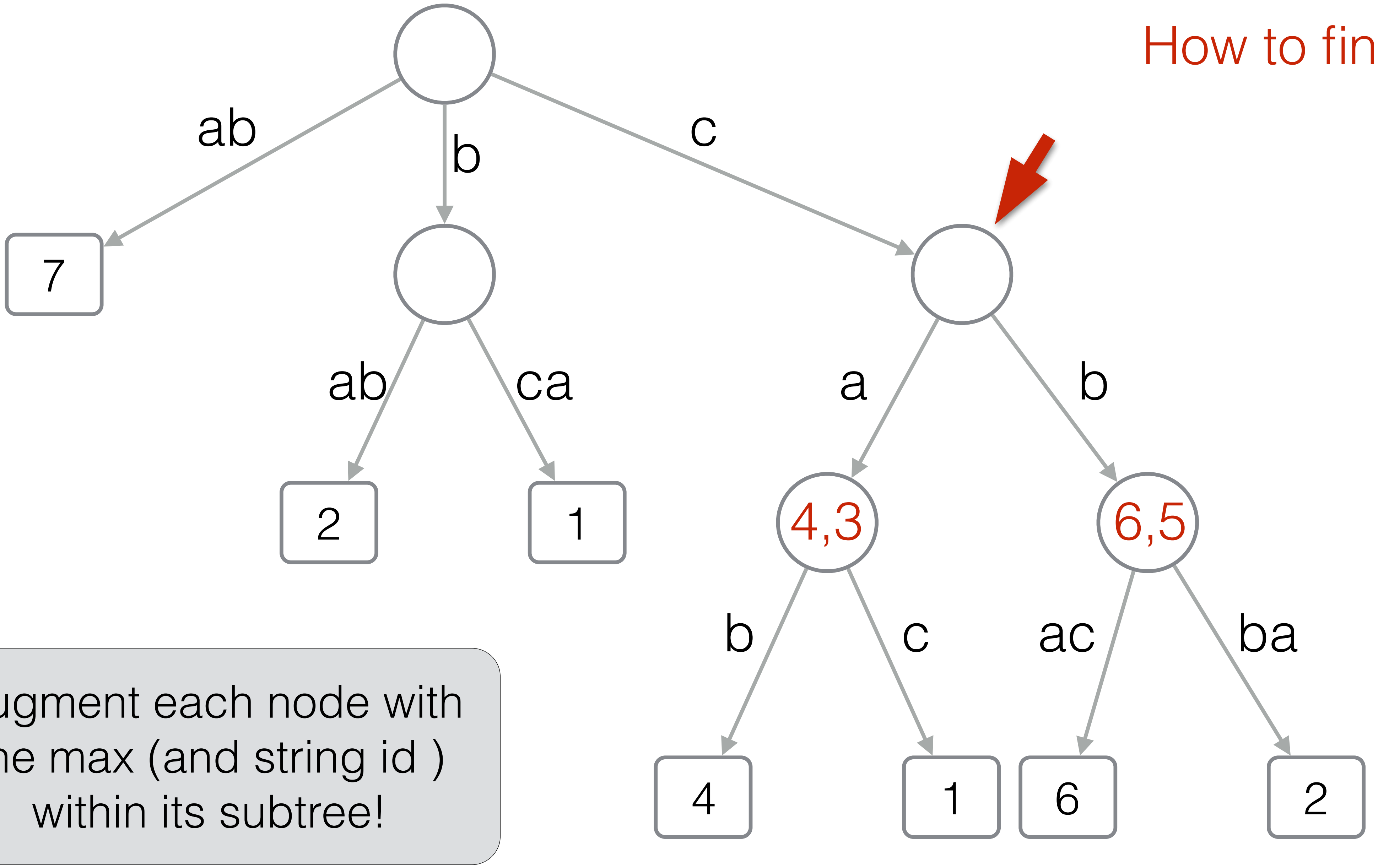

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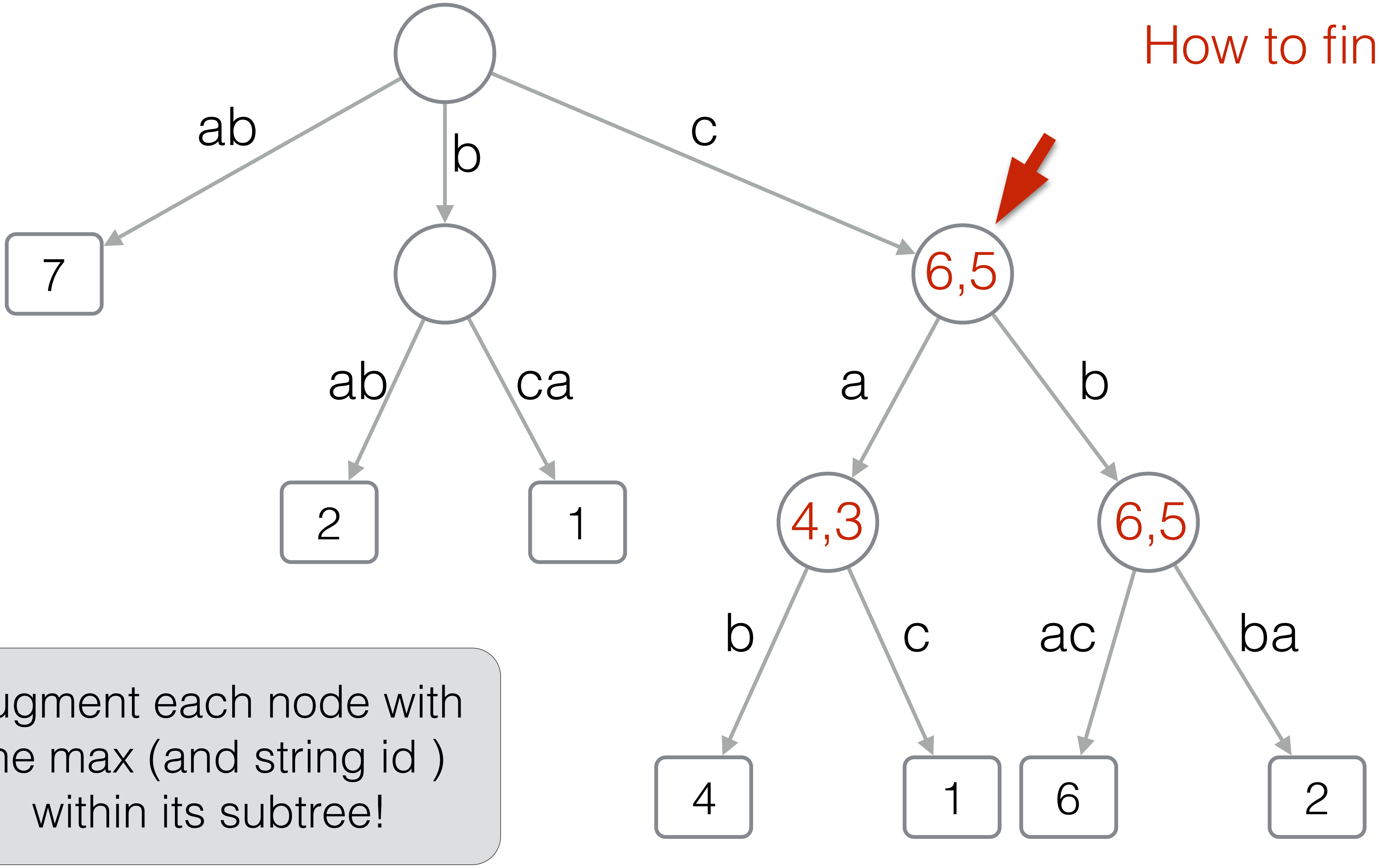

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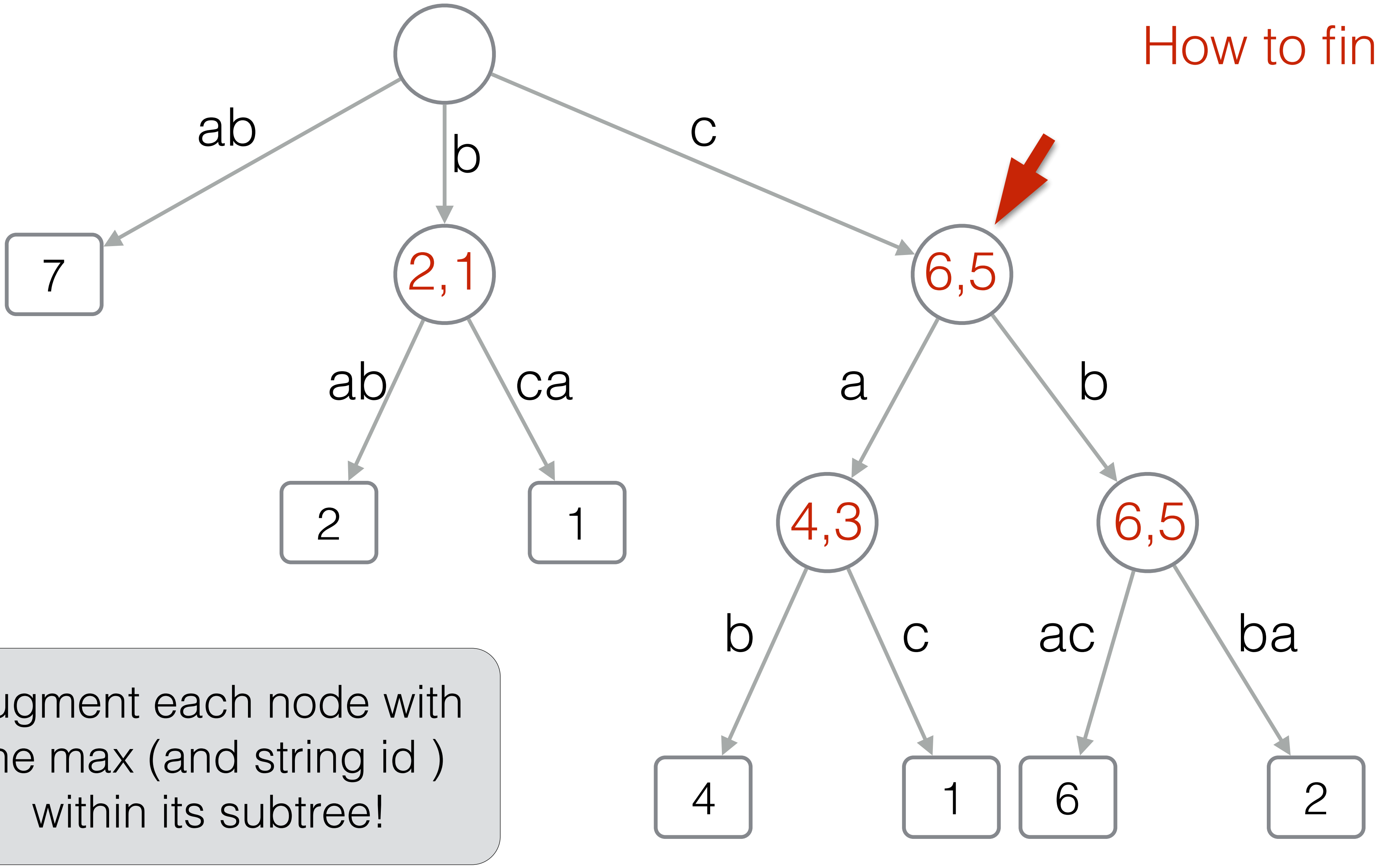


Augment each node with the max (and string id) within its subtree!

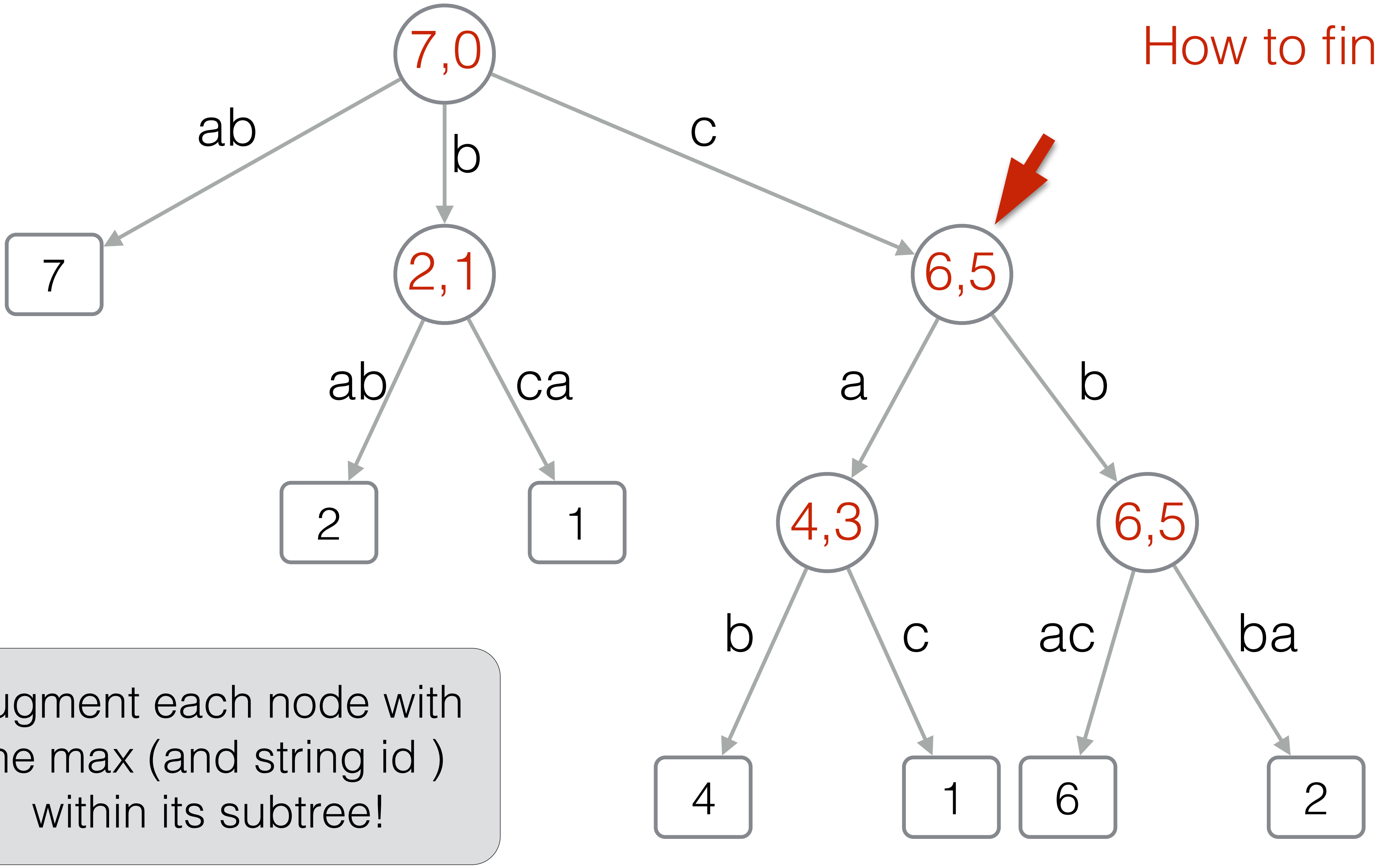
D = { ab (7), bab (2), bca (1), cab (4), cac (1), cbac (6), cbba (2) }

N = |D|, n = total length of strings in D, σ = alphabet size

Finding Top-1

P = c

How to find Top-1?



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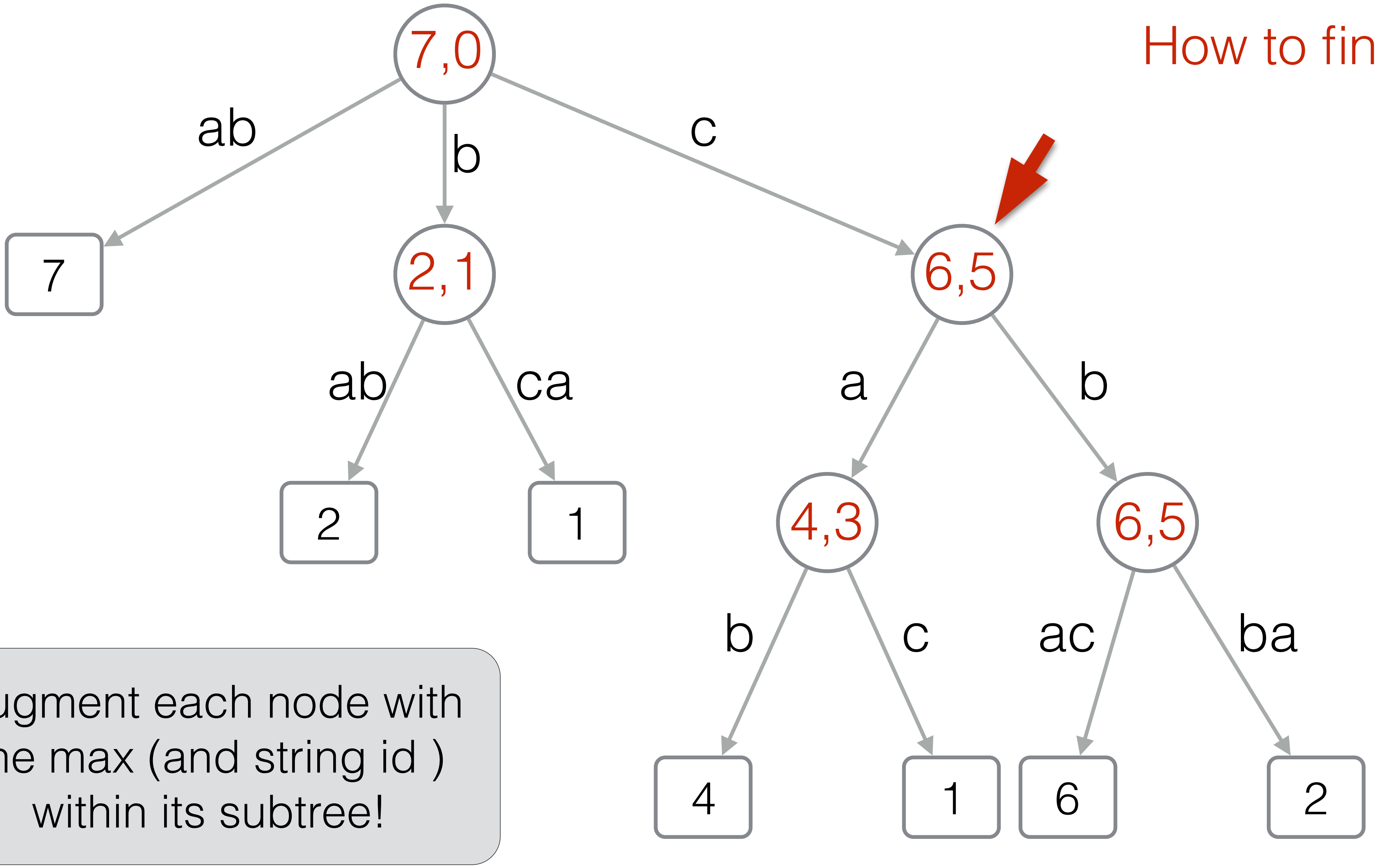

Augment each node with the max (and string id) within its subtree!

Preprocessing time: O(N)

Extra space: O(N log N) bits

Query time: O(1)

D (1), cab (4), cac (1), cbac (6), cbba (2) }

of strings in D, σ = alphabet size

Finding Top-1

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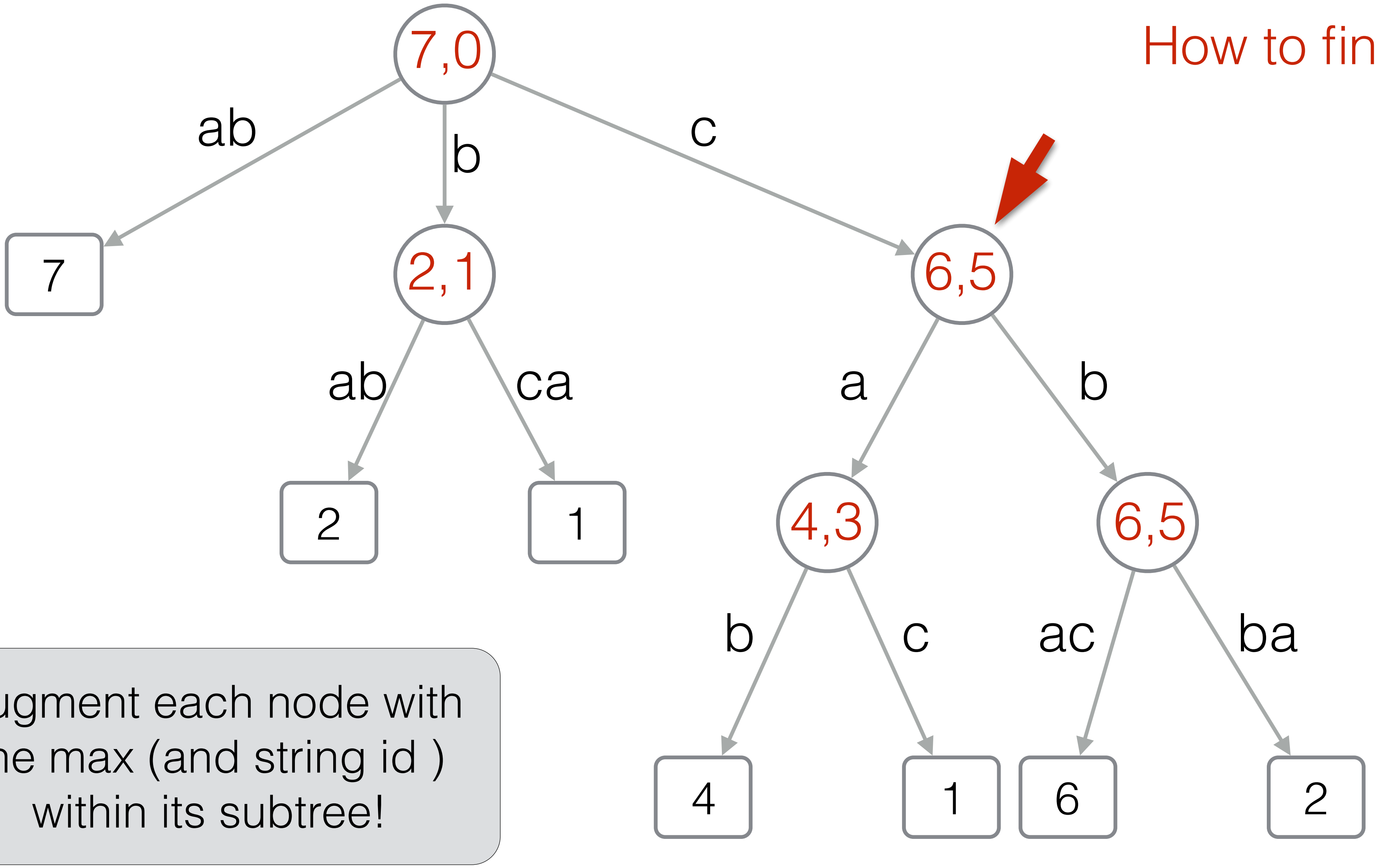

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D

(1), cal

Solving Top-k?

of strings in D, σ = alphabet size

Finding Top-1

P = c

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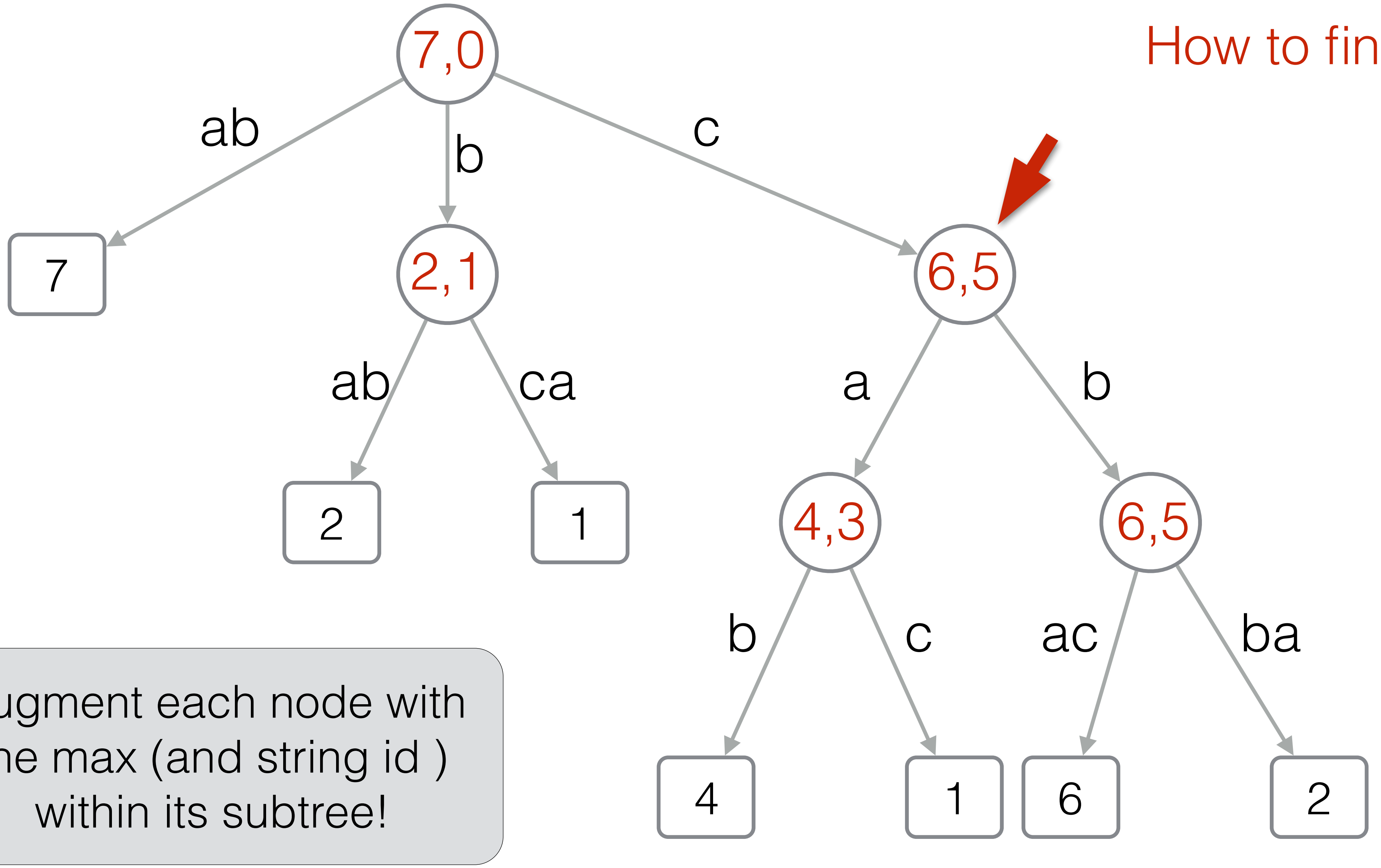

Augment each node with the max (and string id) within its subtree!

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Extra space: O(N log N) bits

Query time: O(1)

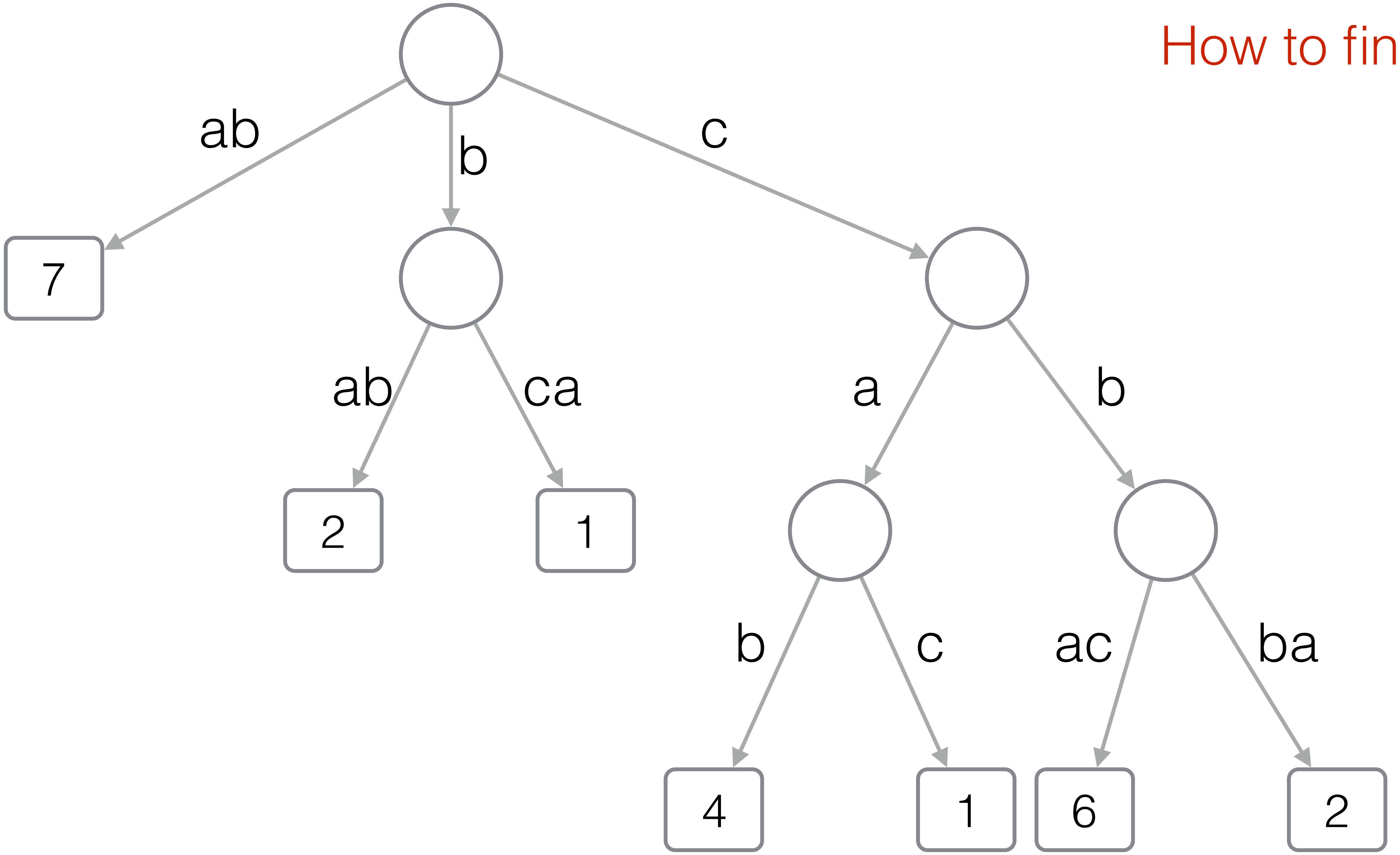
Solving Top-k?

- Extra space: O(k*N*log N) bits :-(
- You must know k at building time! :-(

D (1), cal

of strings in D, σ = alphabet size

Finding Top-1



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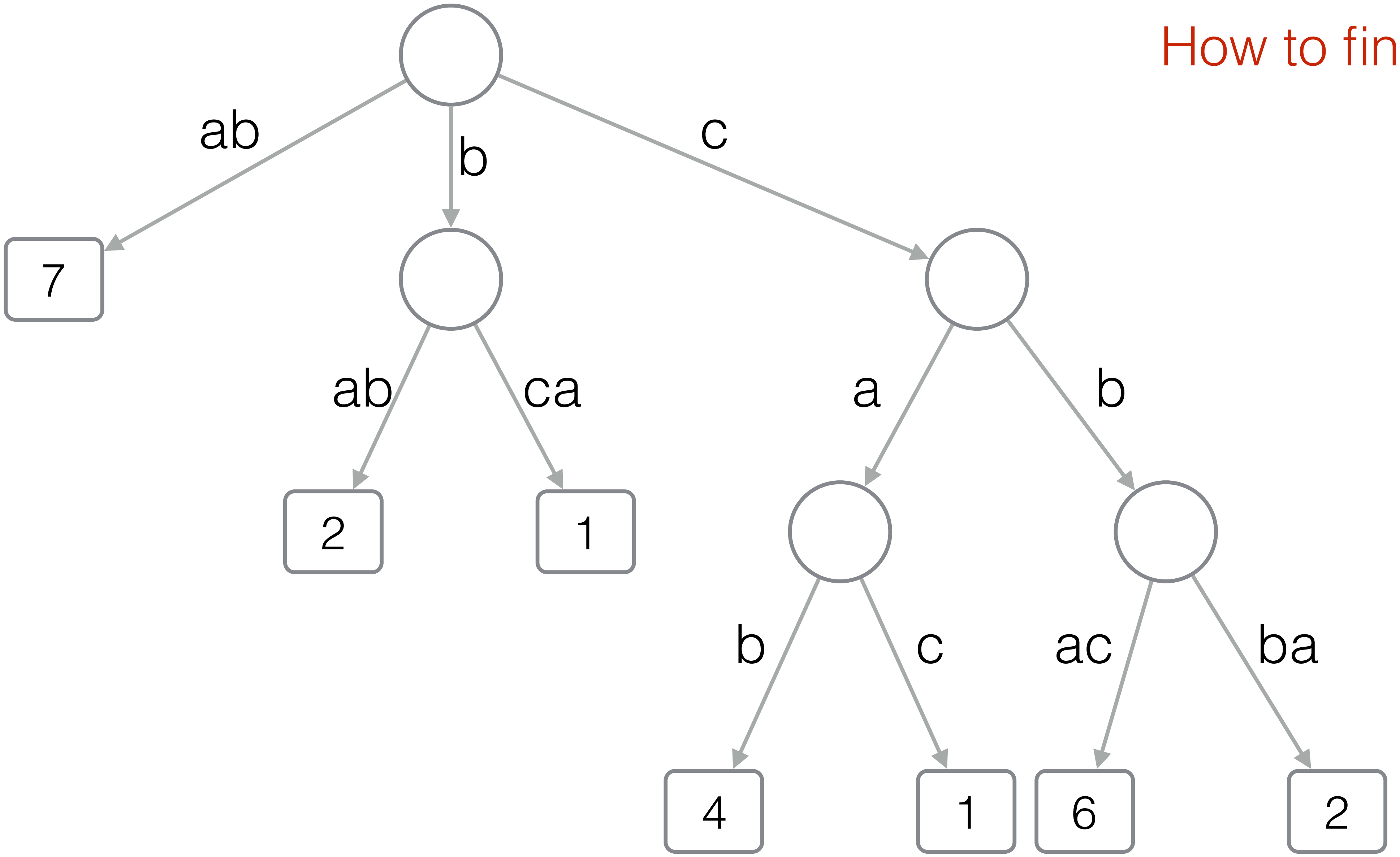

S	7	2	1	4	1	6	2

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Finding Top-1

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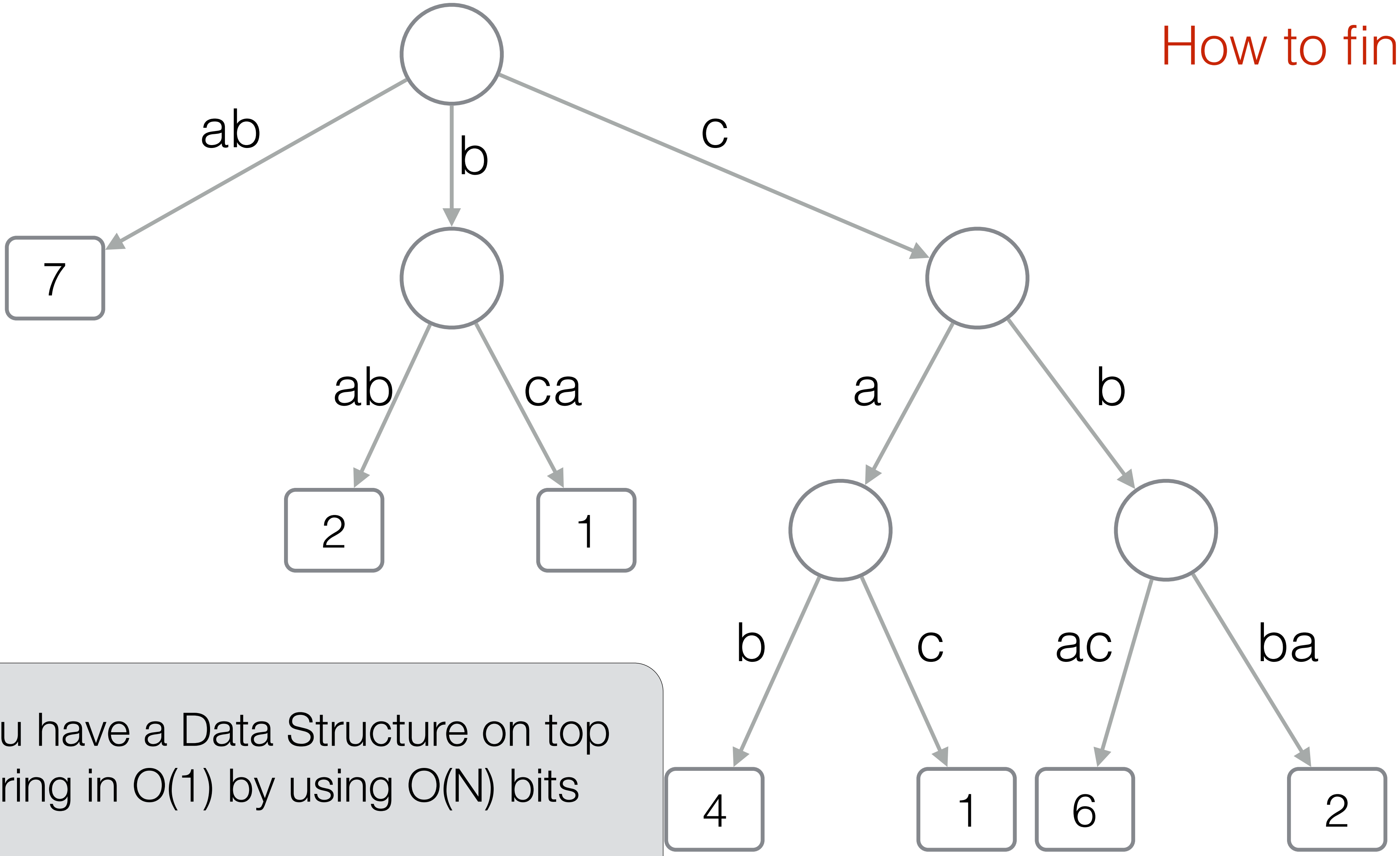

Assume you have a Data Structure on top of S answering in O(1) by using O(N) bits

RMQ(i,j) = position of the maximum in the range S[i,j]

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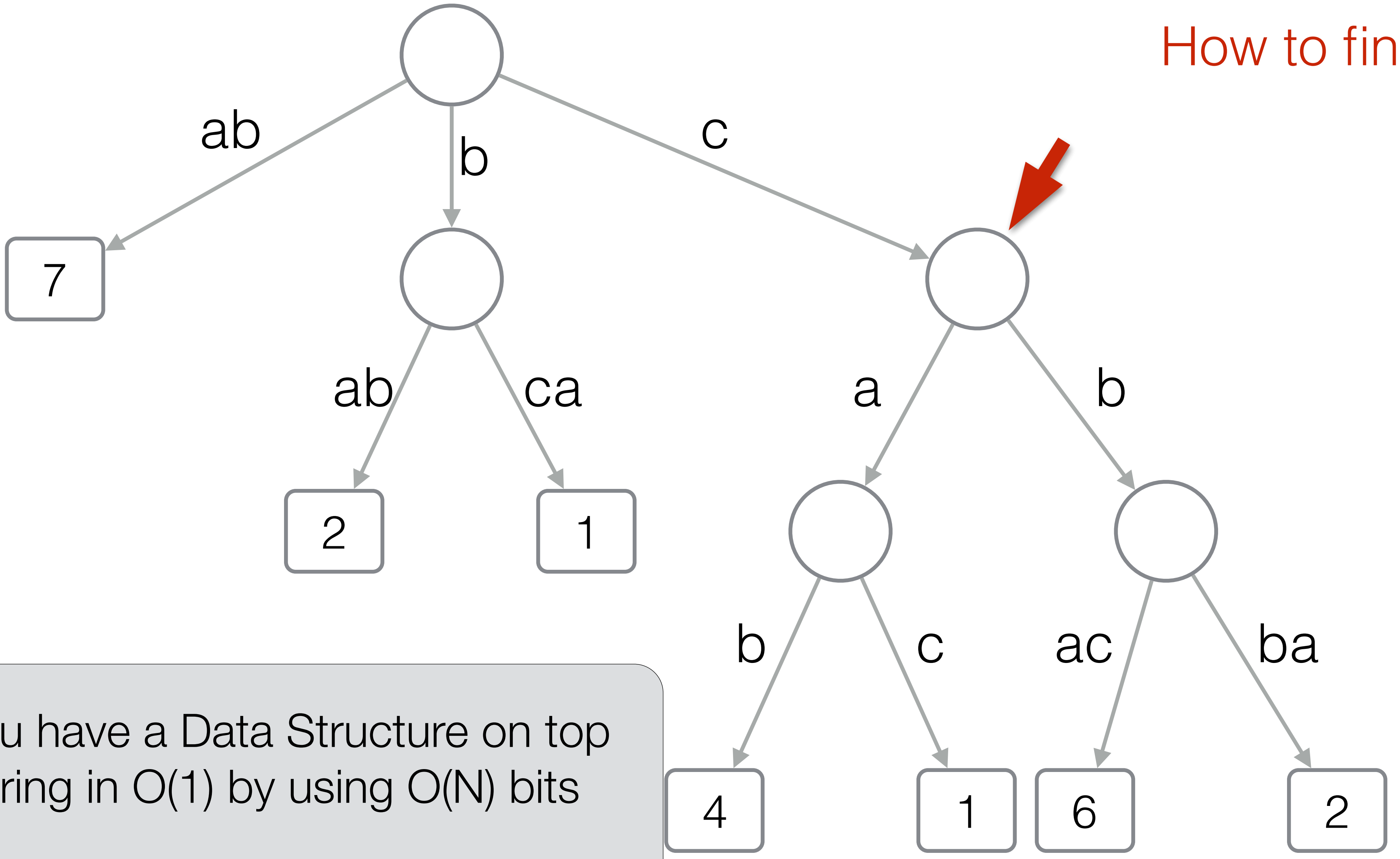

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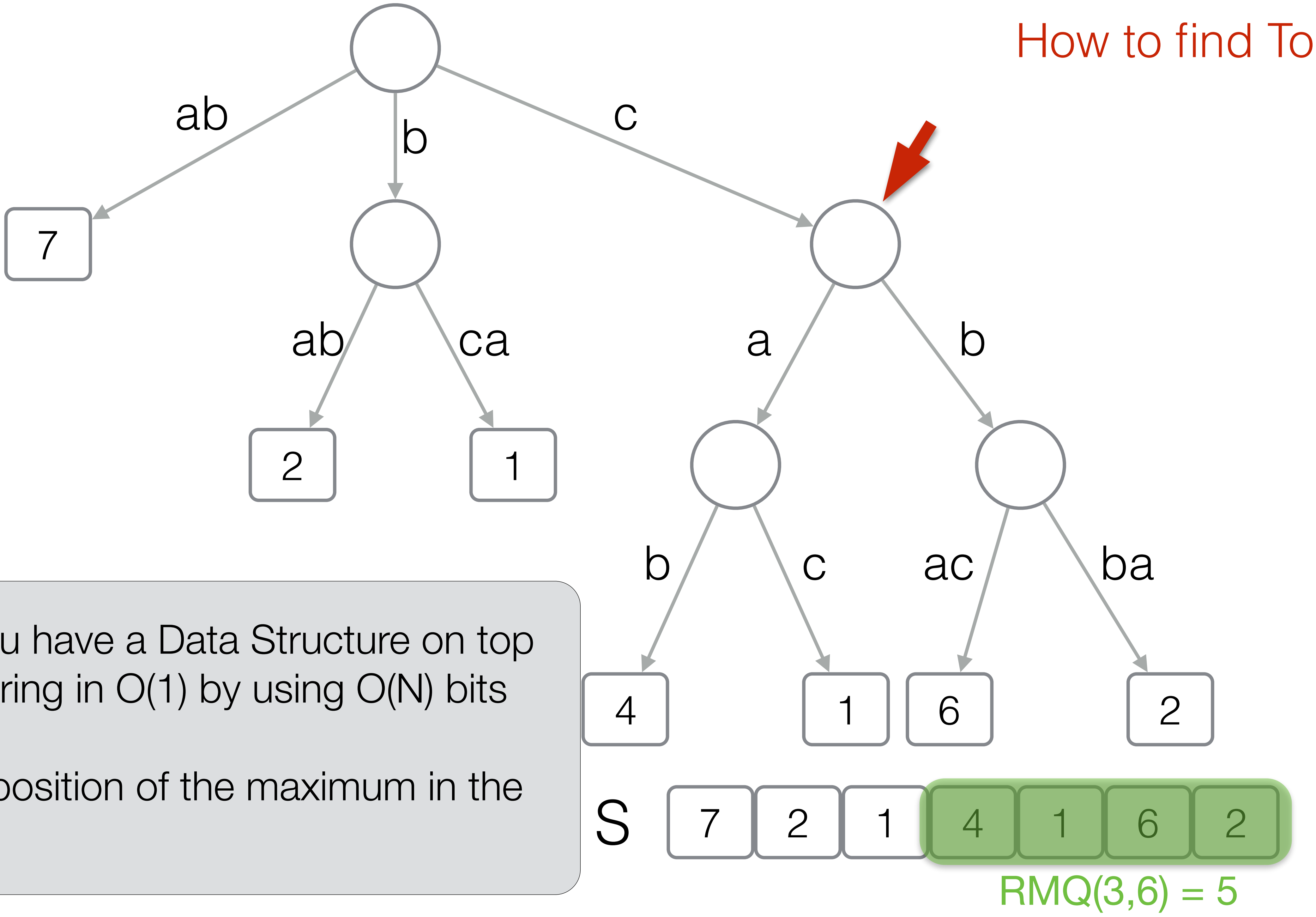

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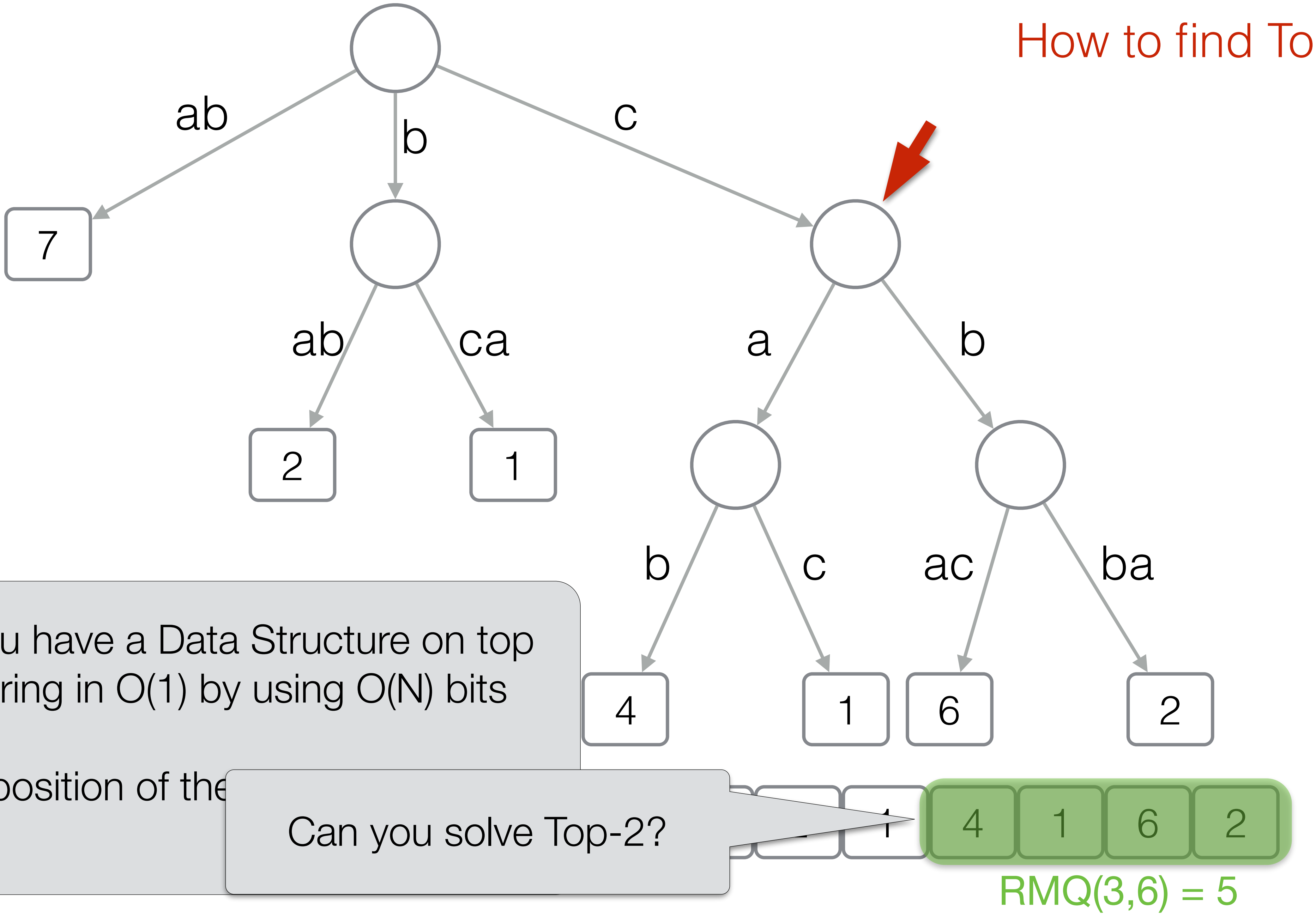


Assume you have a Data Structure on top of S answering in O(1) by using O(N) bits

RMQ(i,j) = position of the
range S[i,j]

Can you solve Top-2?

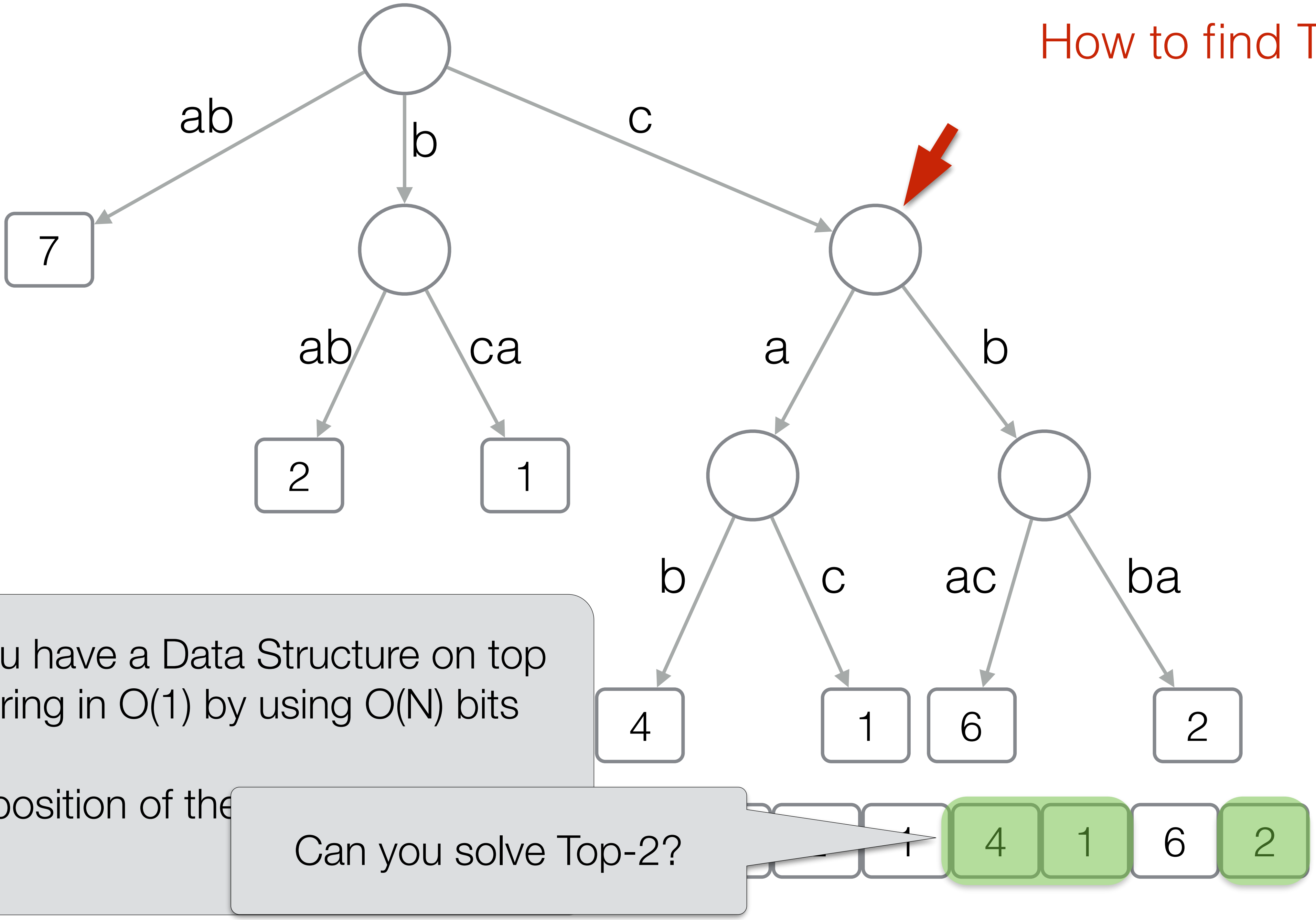
D = { ab (7), bab (2), bca (1), cab (4), cac (1), cbac (6), cbba (2) }

N = |D|, n = total length of strings in D, σ = alphabet size

Finding Top-1

P = c

How to find Top-1?



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RMQ(i,j) = position of the

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Can you solve Top-2?

D = { ab (7), bab (2), bca (1), cab (4), cac (1), cbac (6), cbba (2) }

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Finding Top-1

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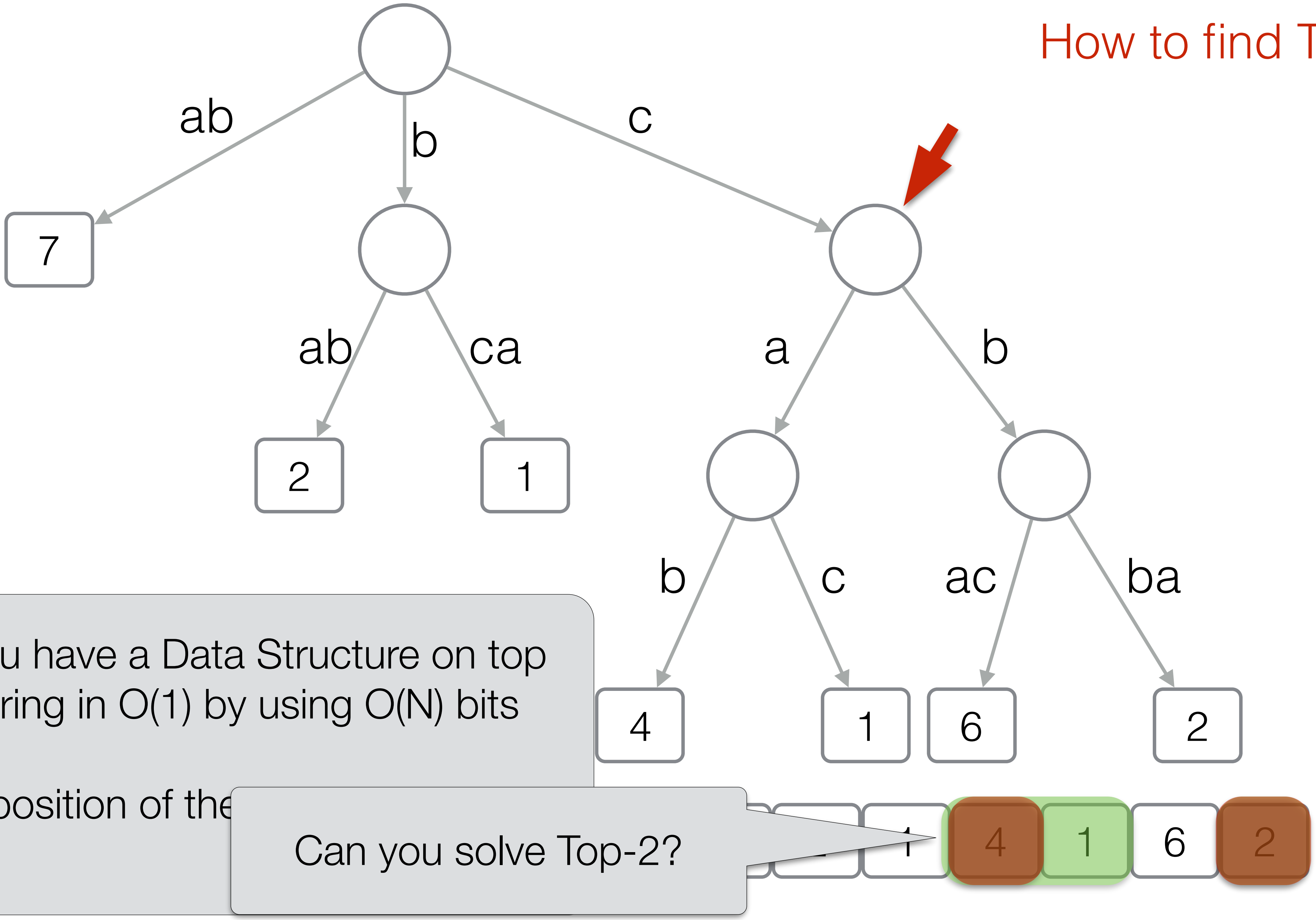
How to find Top-1?



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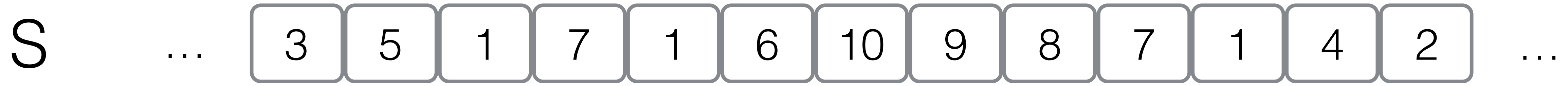
Finding Top-k

Finding Top-k



S … 3 5 1 7 1 6 10 9 8 7 1 4 2 …

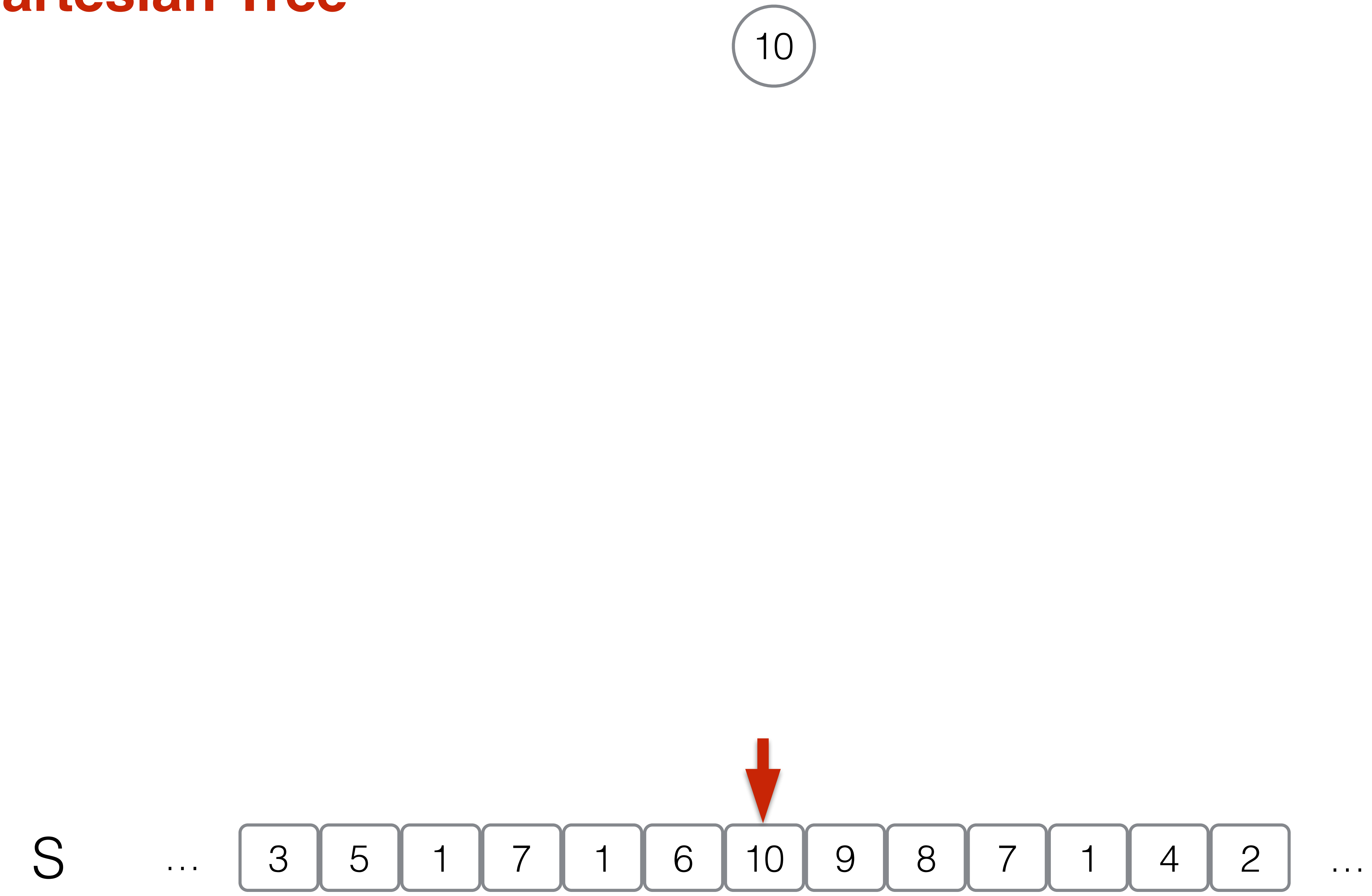
Finding Top-k

Cartesian Tree

S	…	3	5	1	7	1	6	10	9	8	7	1	4	2	…

Finding Top-k

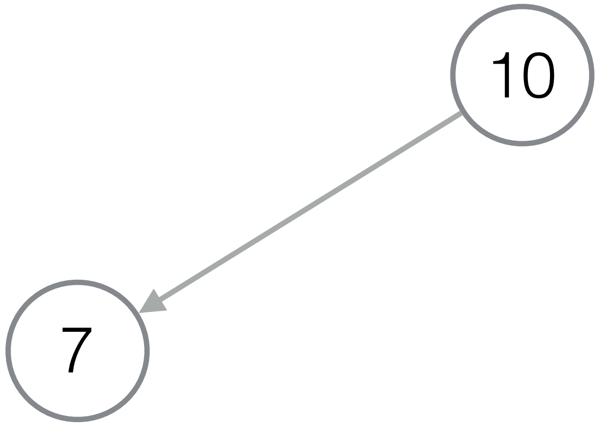
Cartesian Tree



S	…	3	5	1	7	1	6	10	9	8	7	1	4	2	…

Finding Top-k

Cartesian Tree



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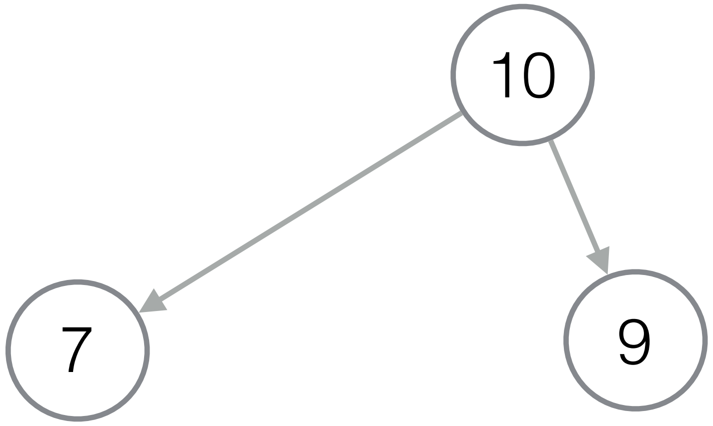
Finding Top-k

Cartesian Tree



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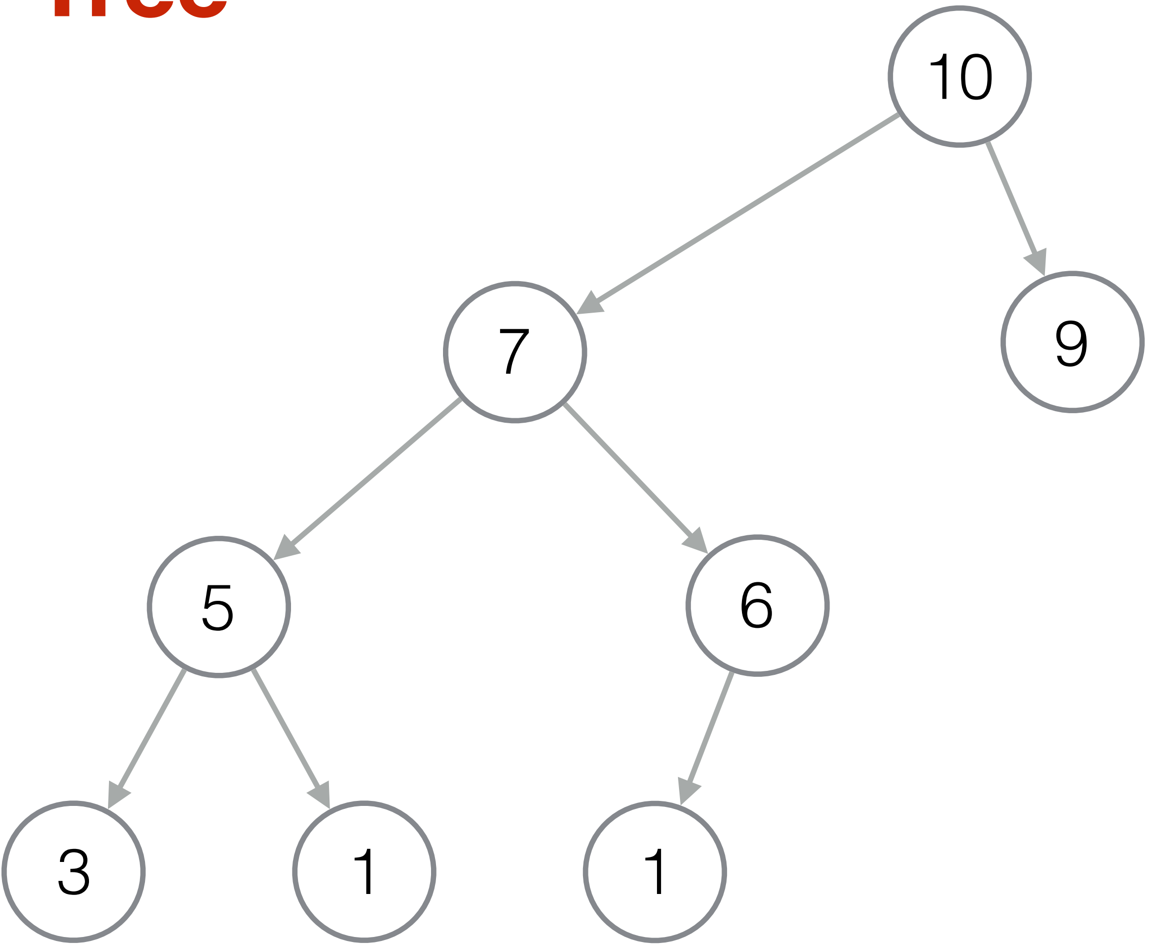
Finding Top-k

Cartesian Tree

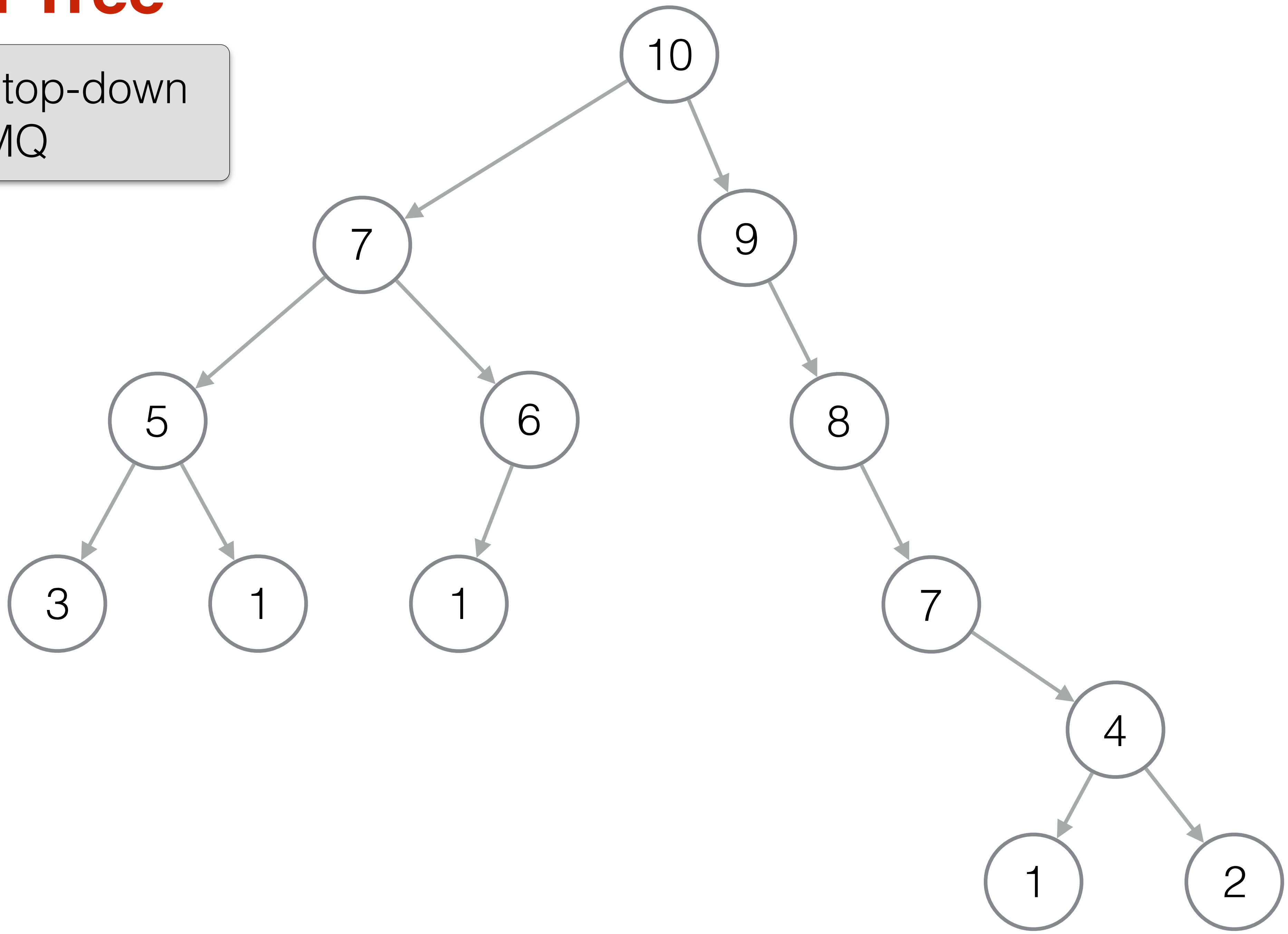


S	…	3	5	1	7	1	6	10	9	8	7	1	4	2	…

Finding Top-k

Cartesian Tree

It can be built top-down with RMQ



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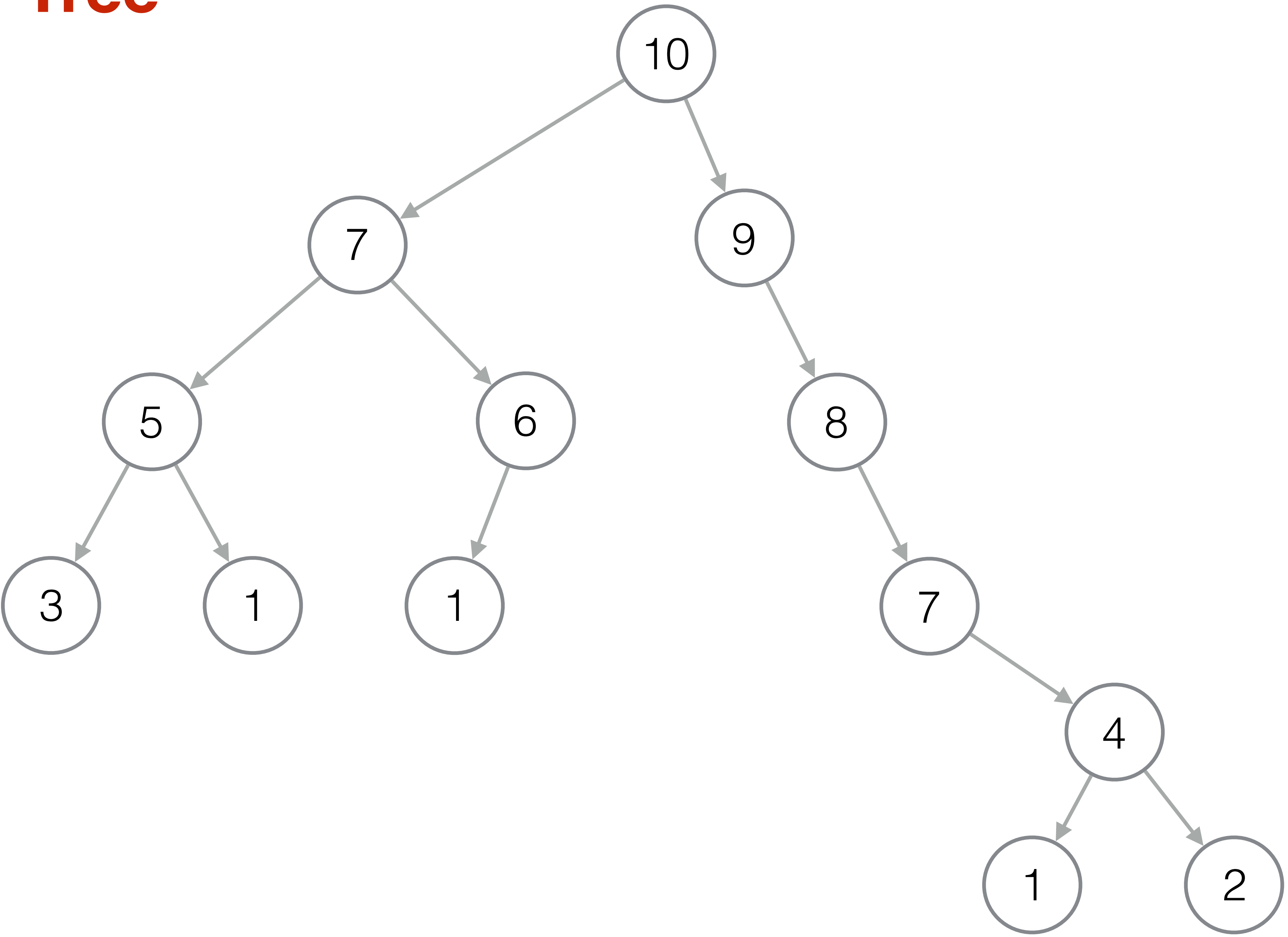
Finding Top-k

How to find Top-k?

Cartesian Tree



S	…	3	5	1	7	1	6	10	9	8	7	1	4	2	…

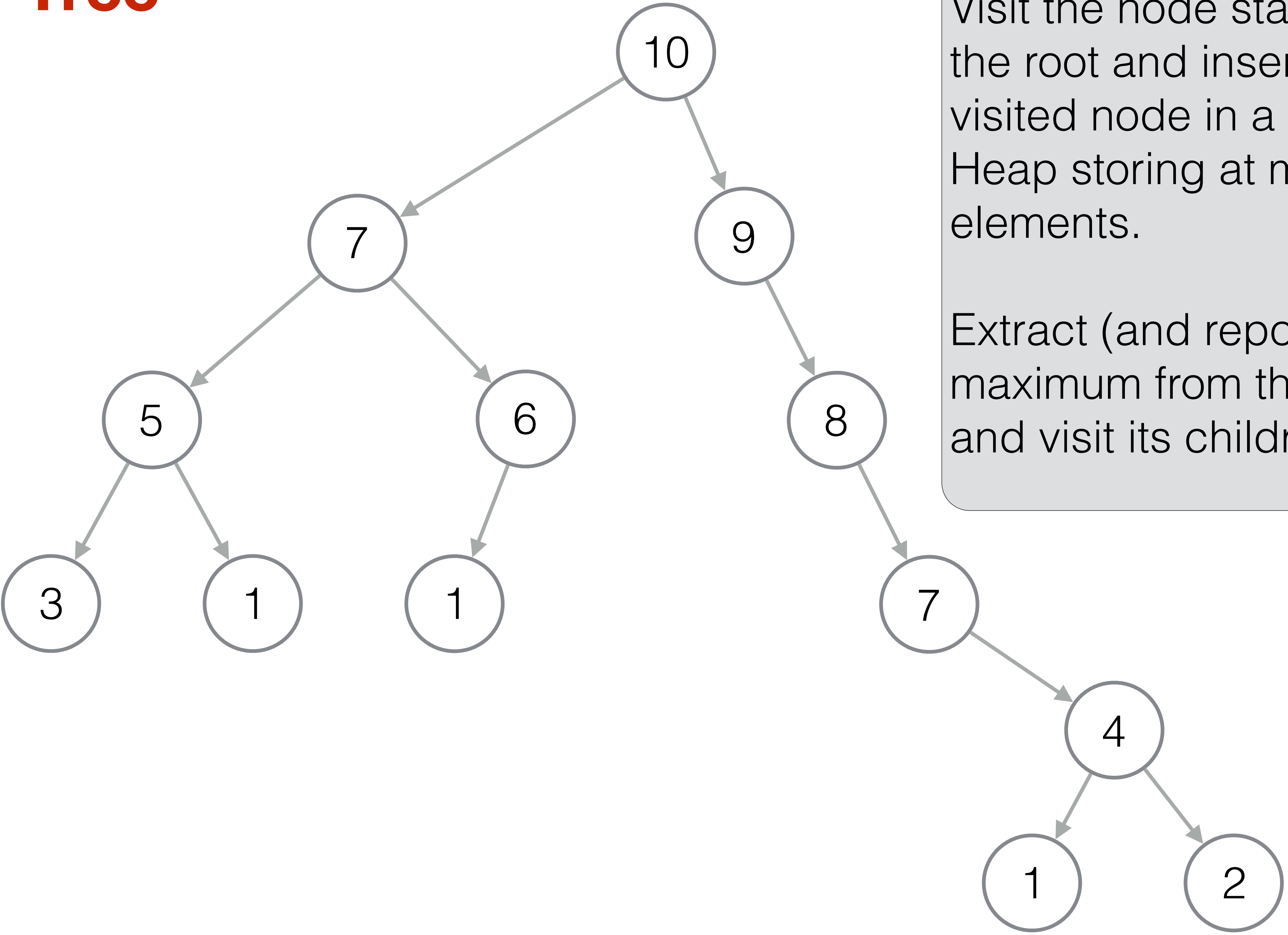
Finding Top-k

How to find Top-k?

Visit the node starting from the root and insert each visited node in a **max**-Heap storing at most **k** elements.

Extract (and report) the maximum from the heap and visit its children.

Cartesian Tree



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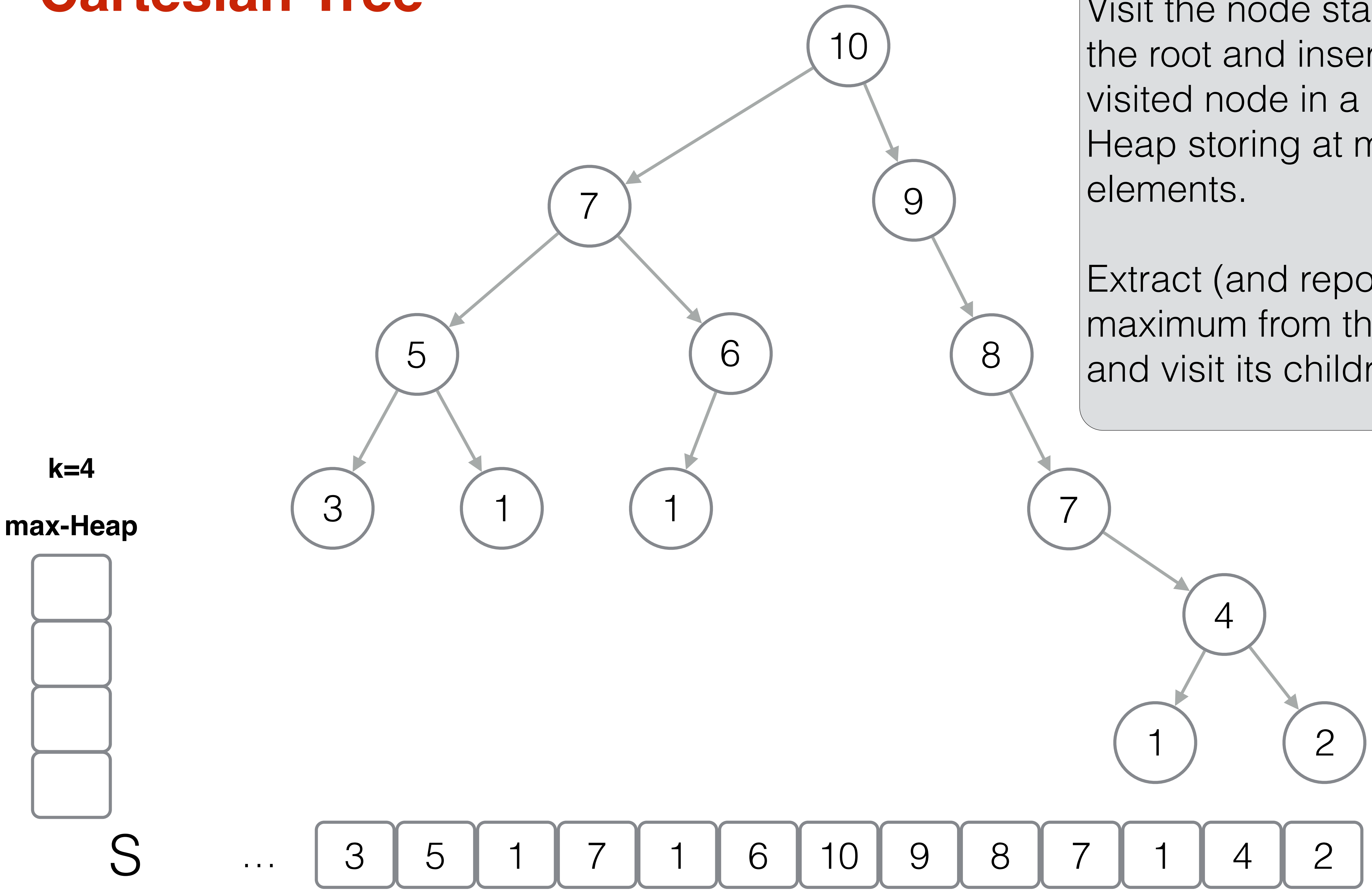

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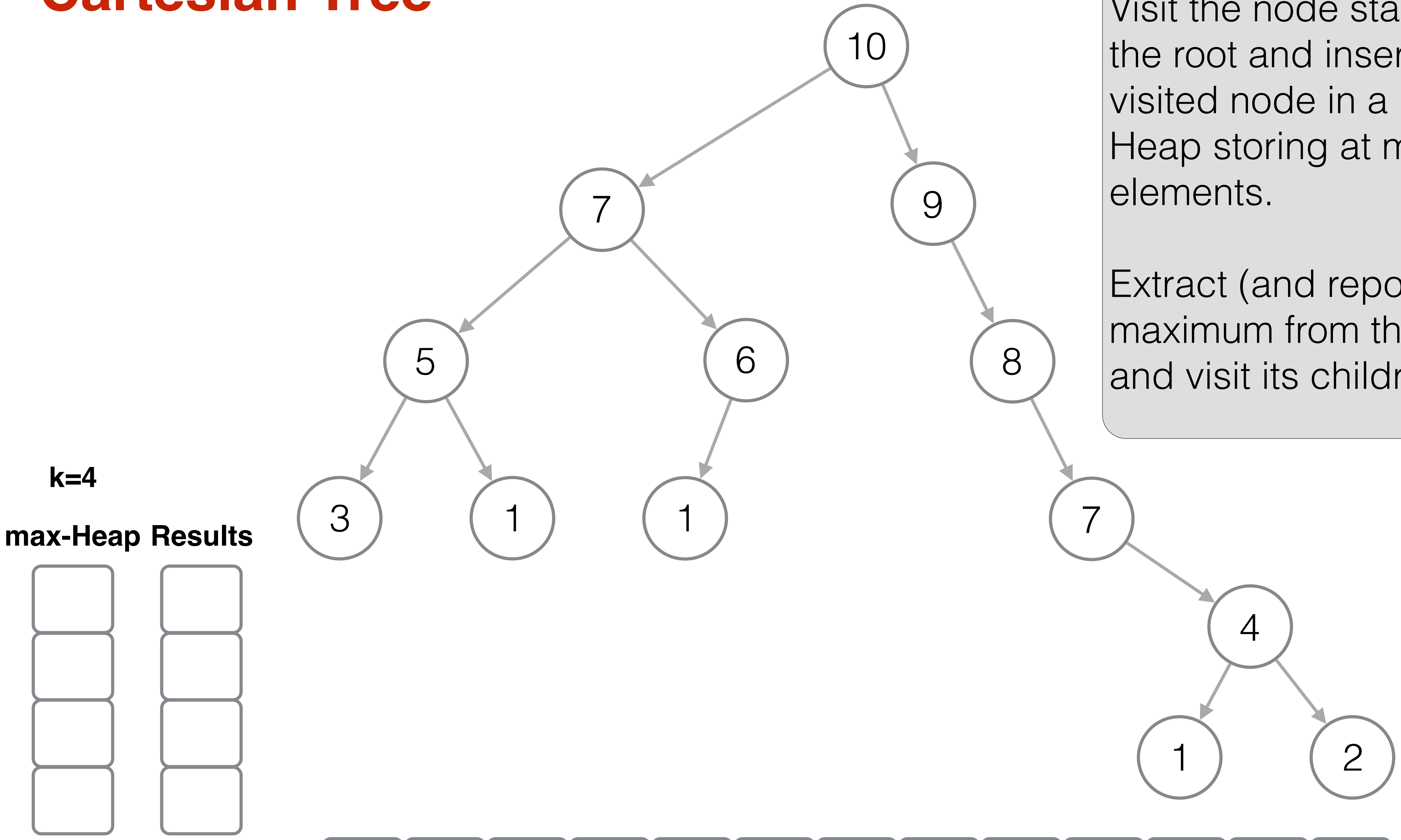

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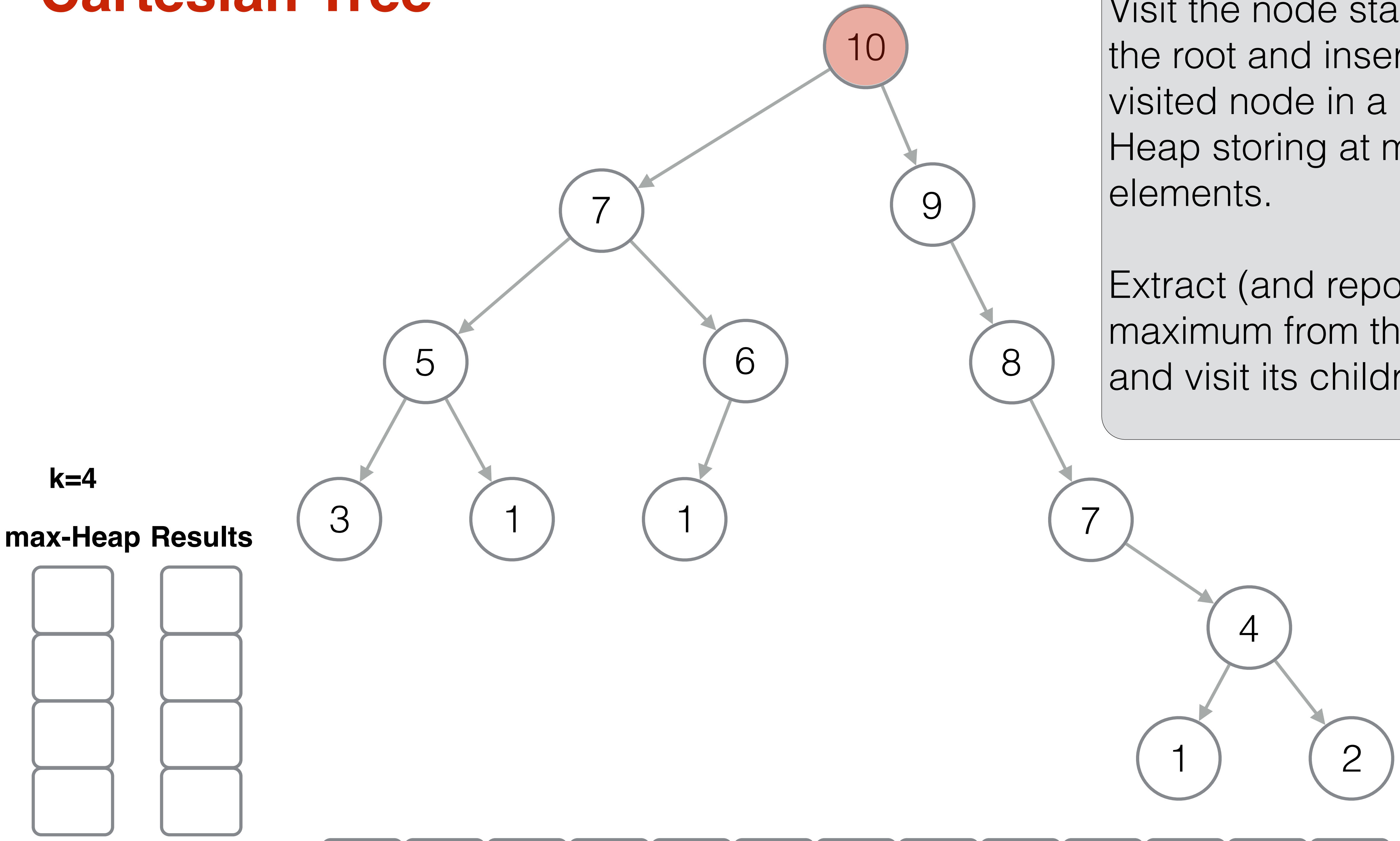

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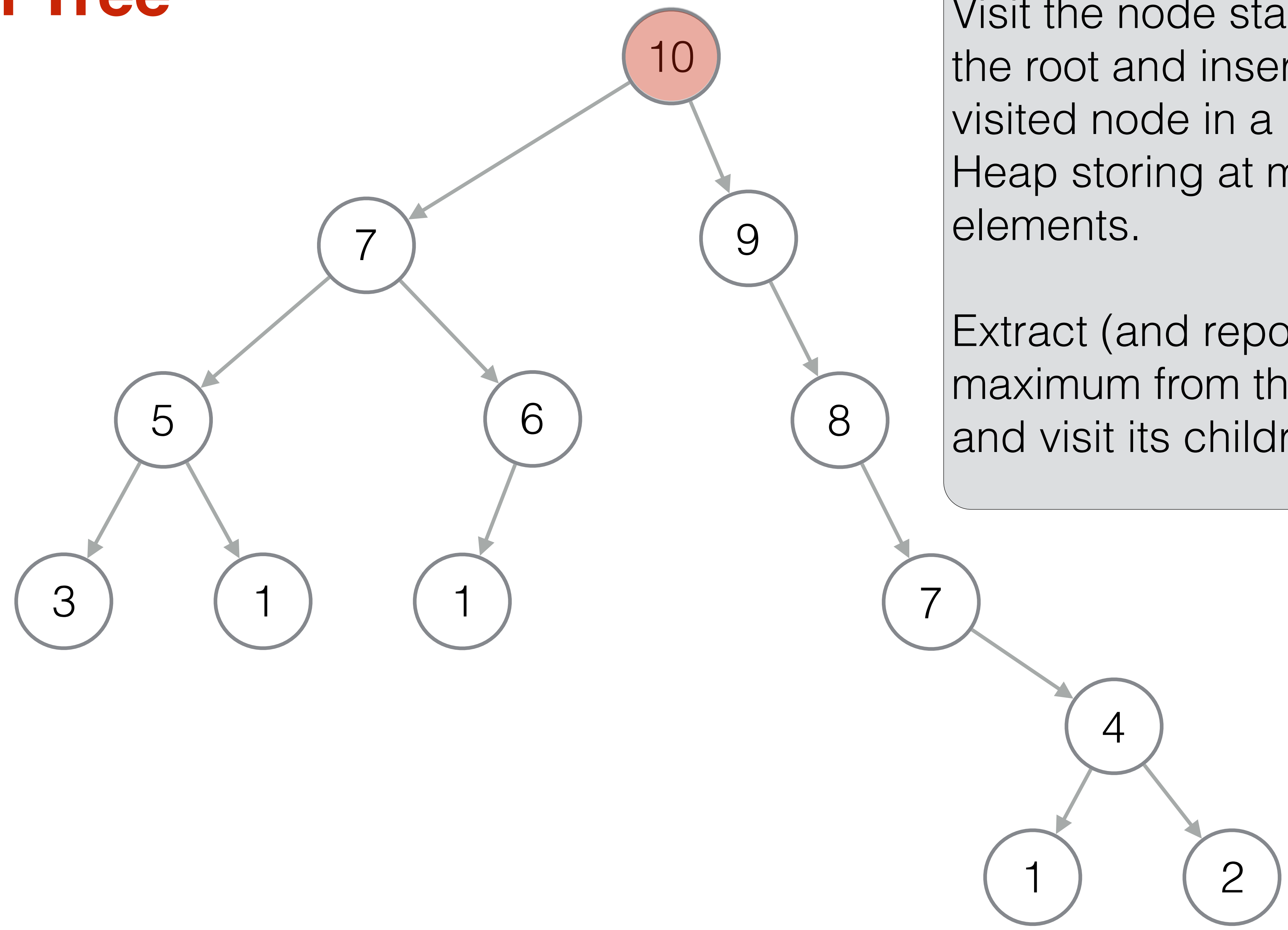

k=4

max-Heap	**Results**
10	

S	…	3	5	1	7	1	6	10	9	8	7	1	4	2	…

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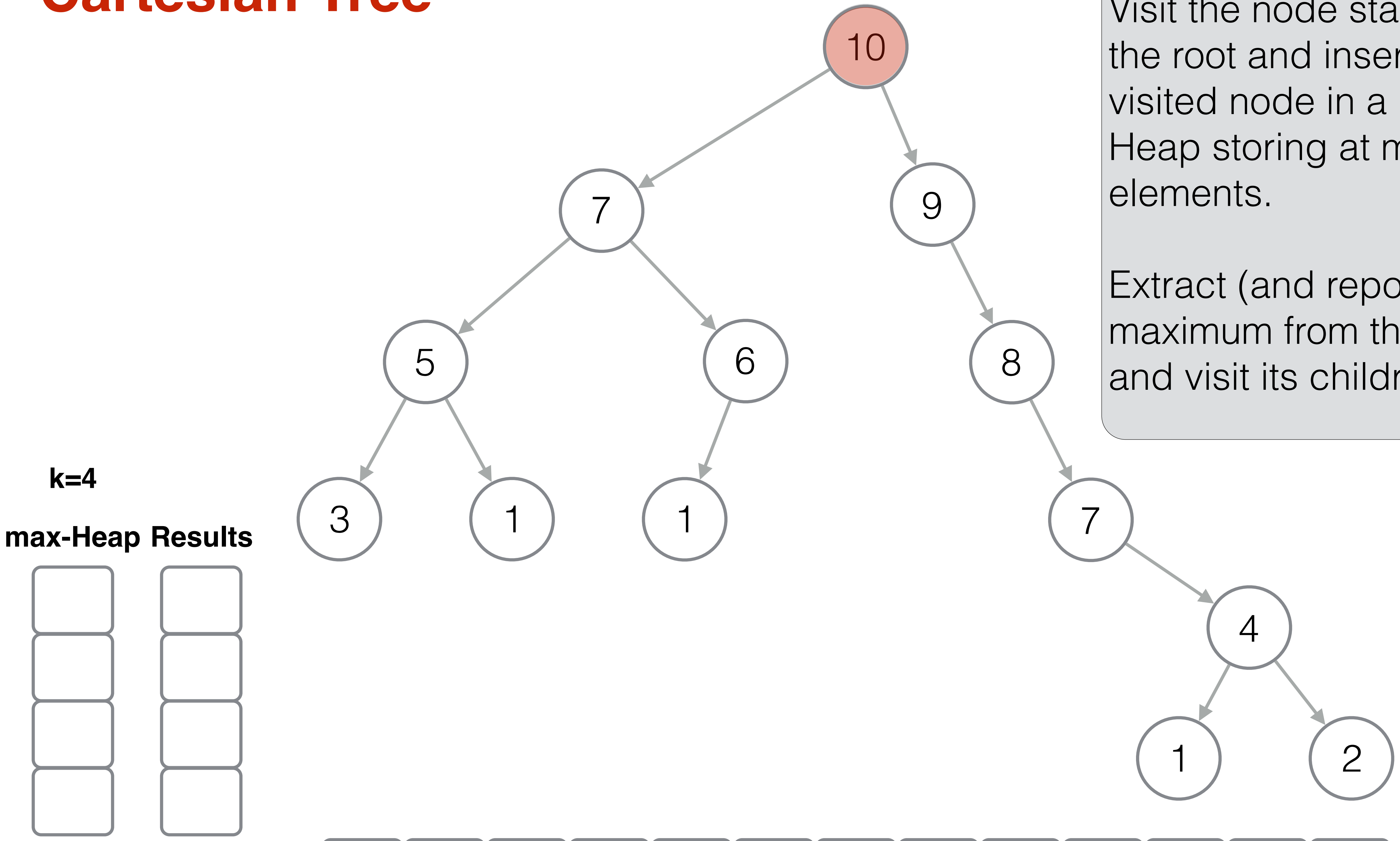

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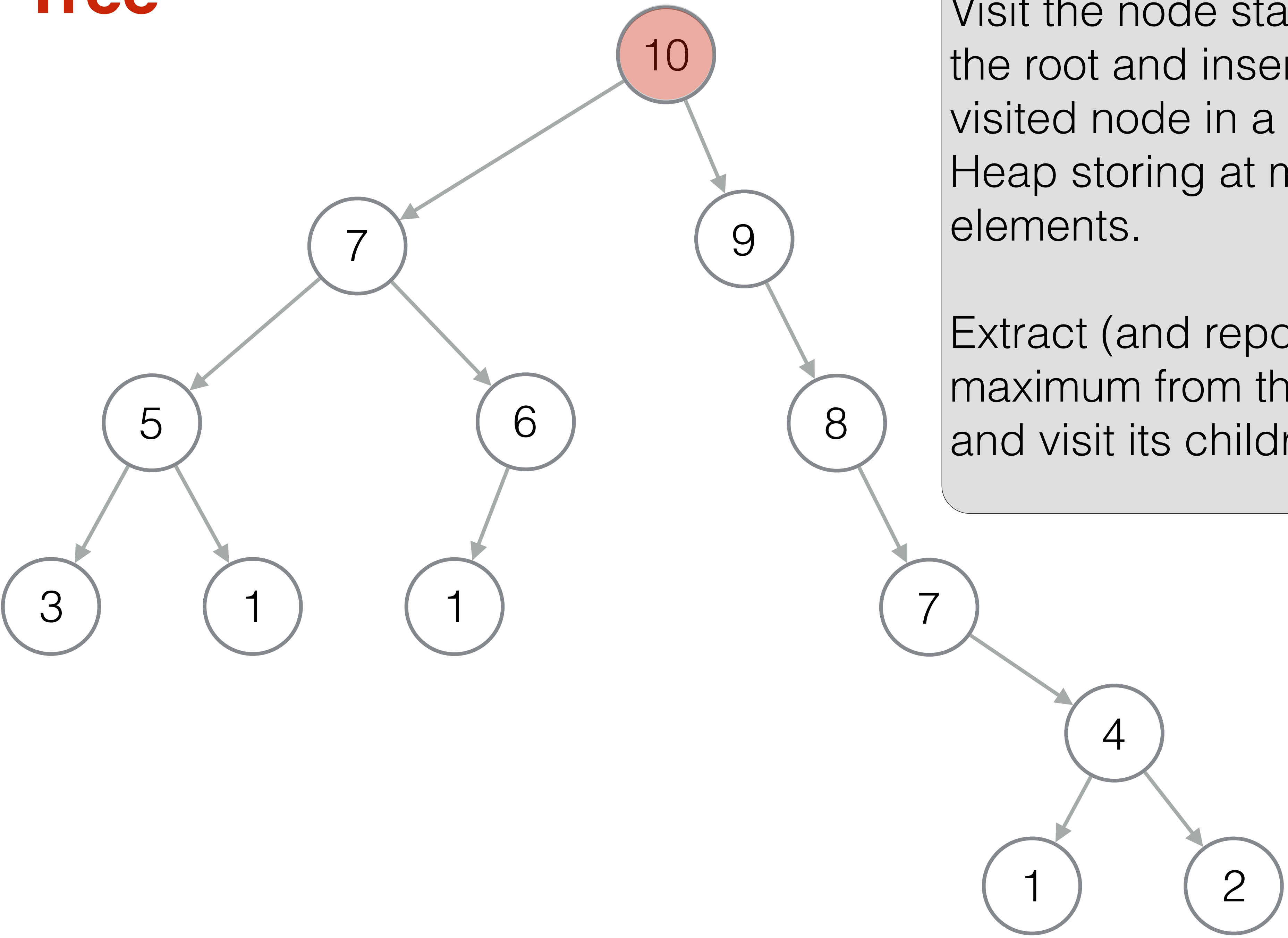
How to find Top-k?

Cartesian Tree



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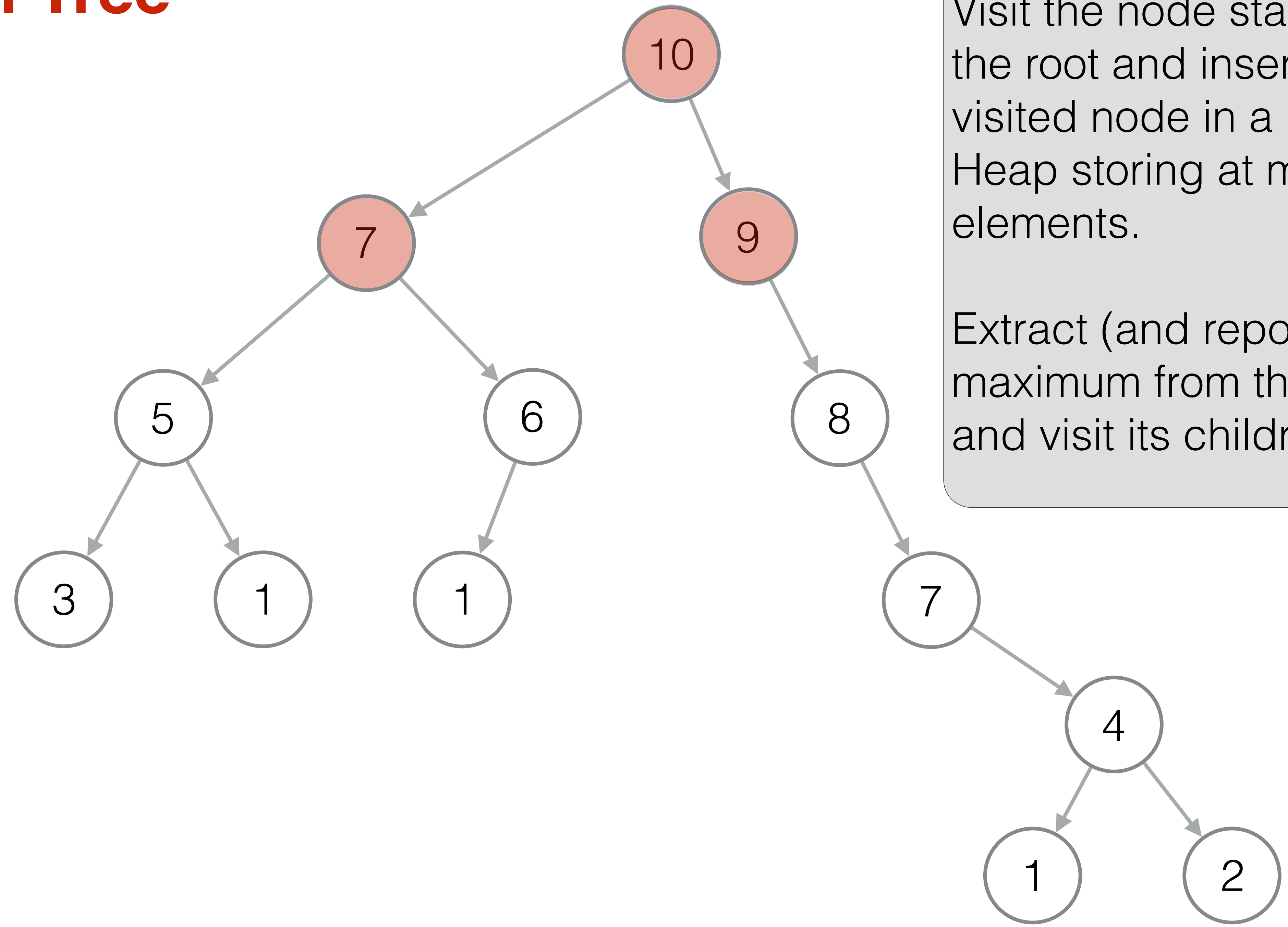

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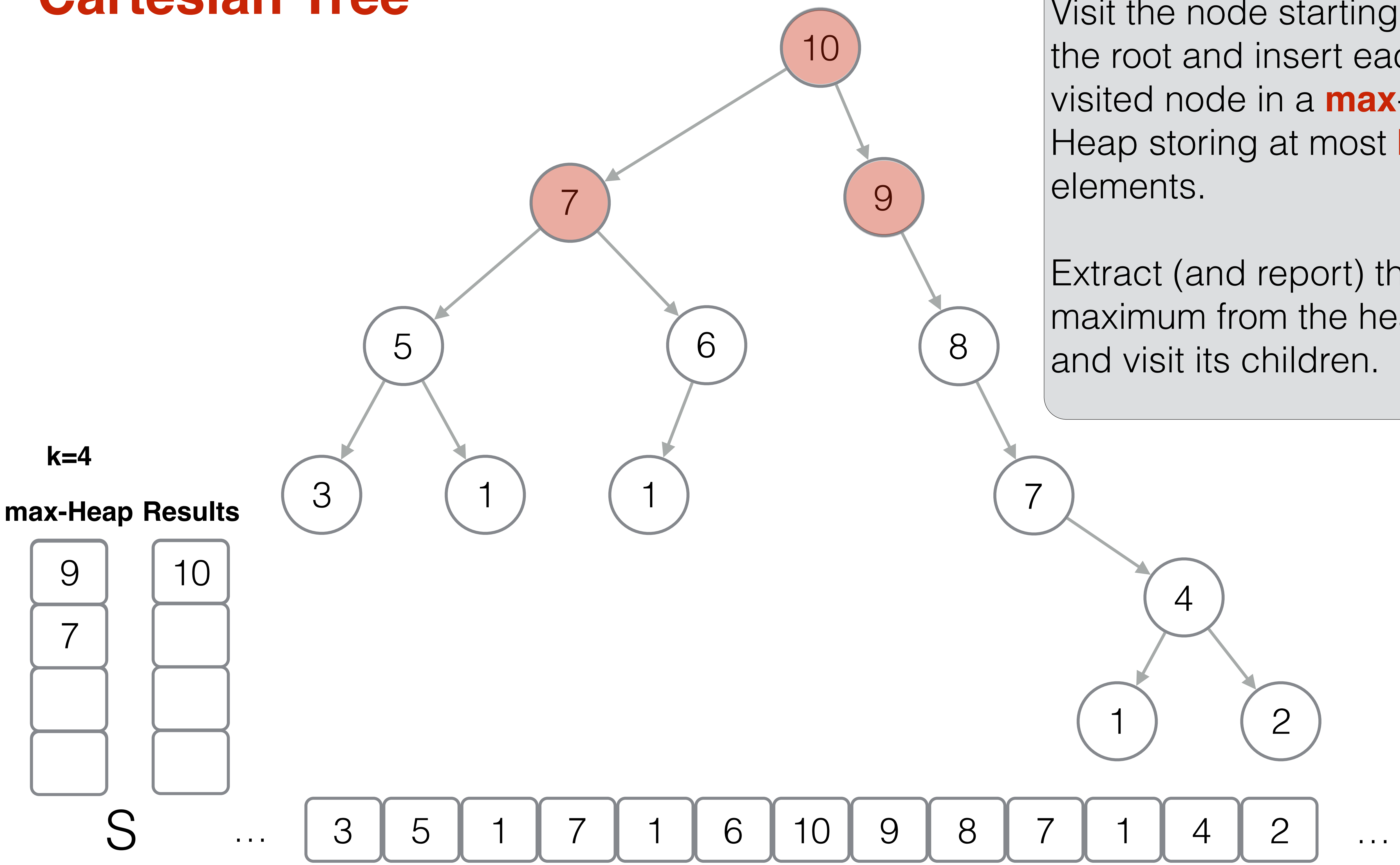

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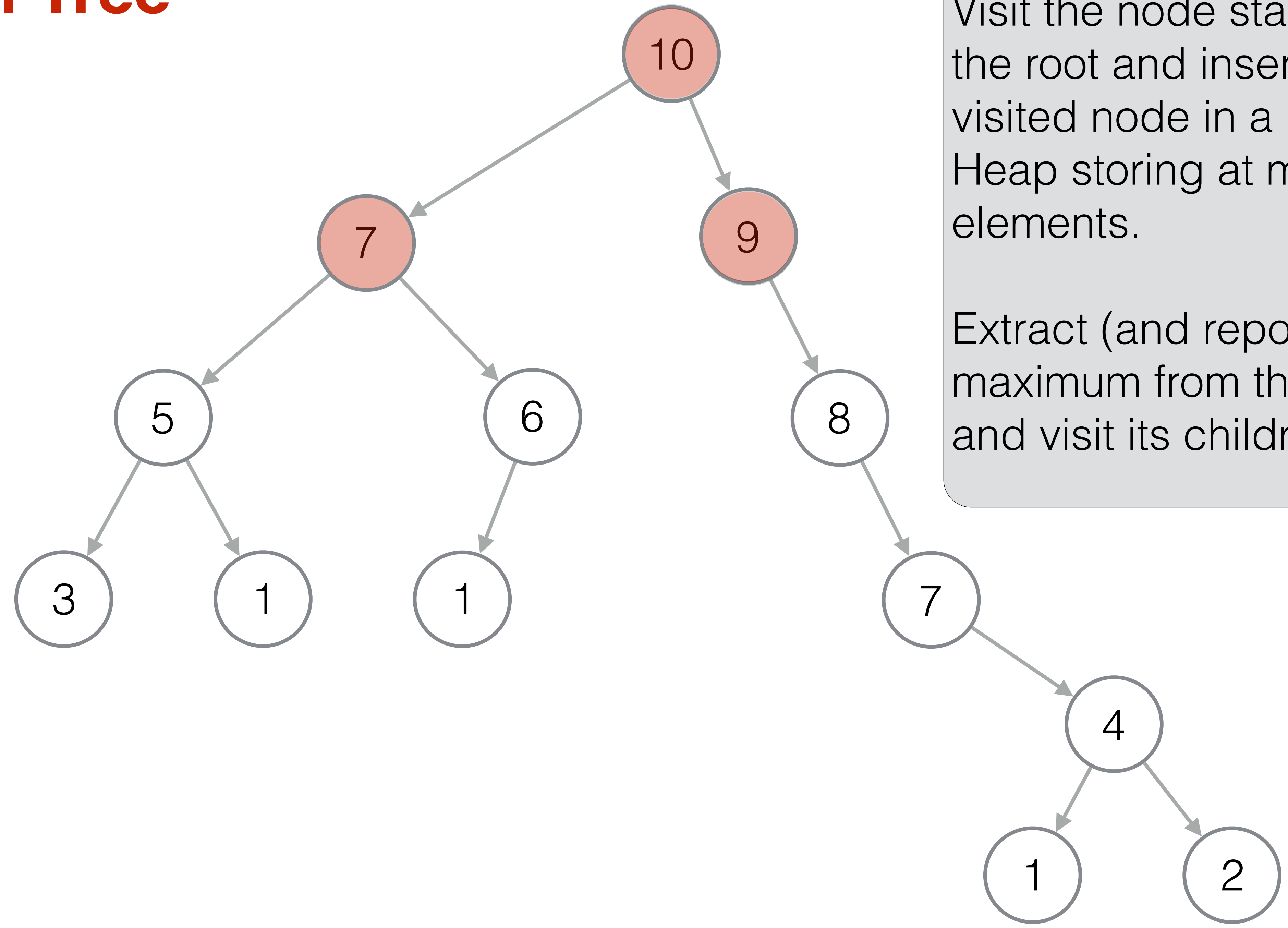
Cartesian Tree



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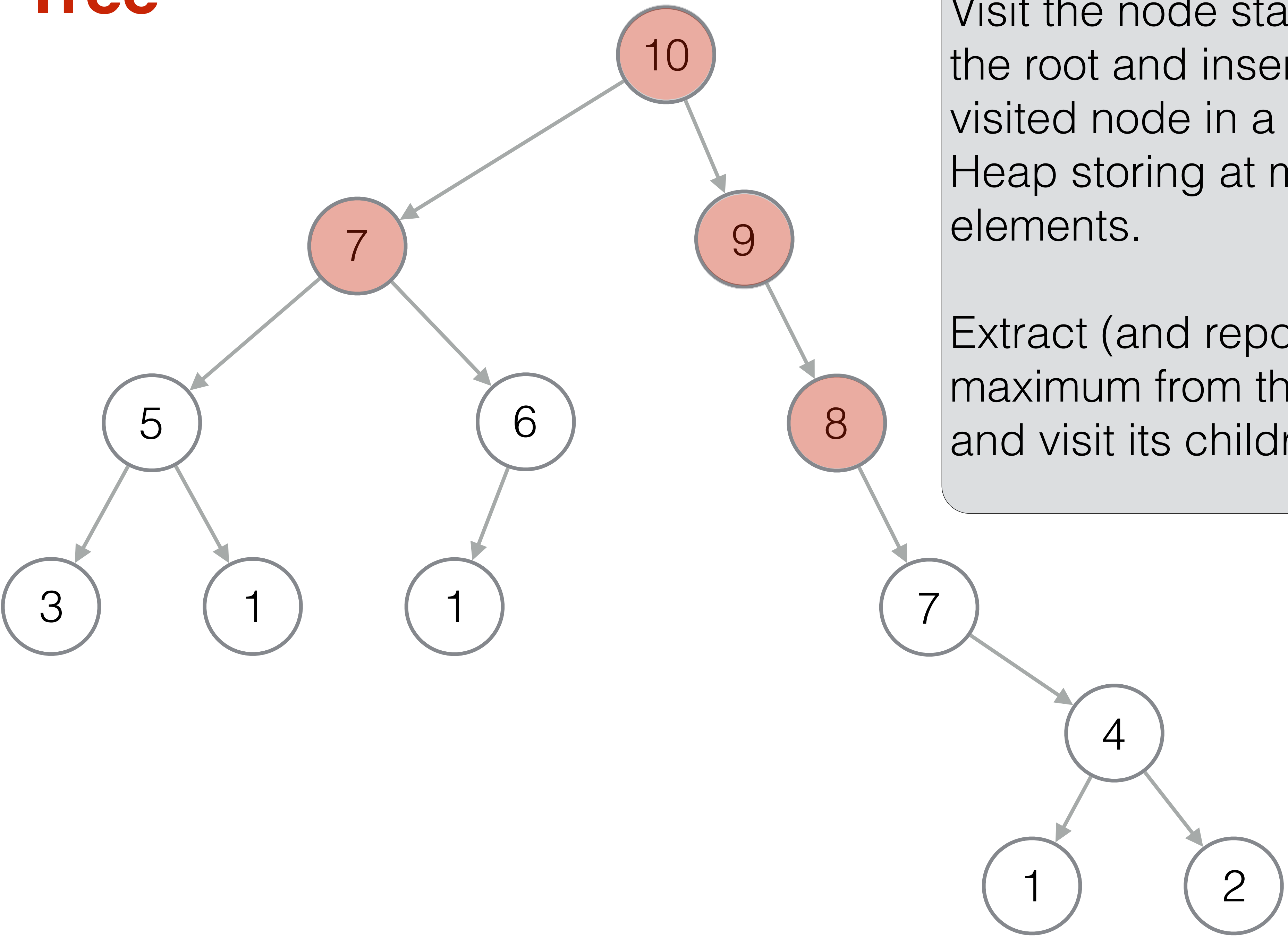
How to find Top-k?

Cartesian Tree



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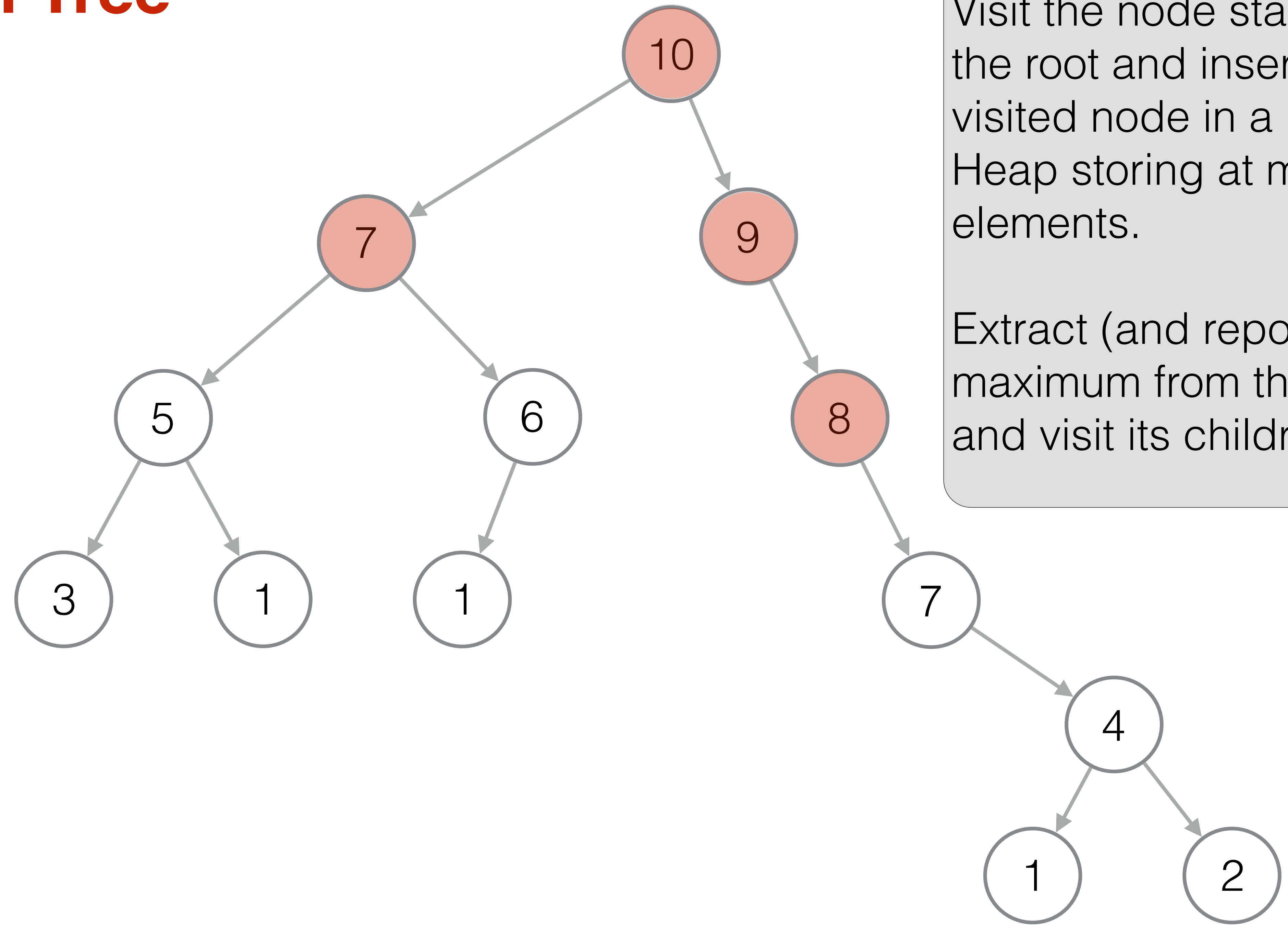

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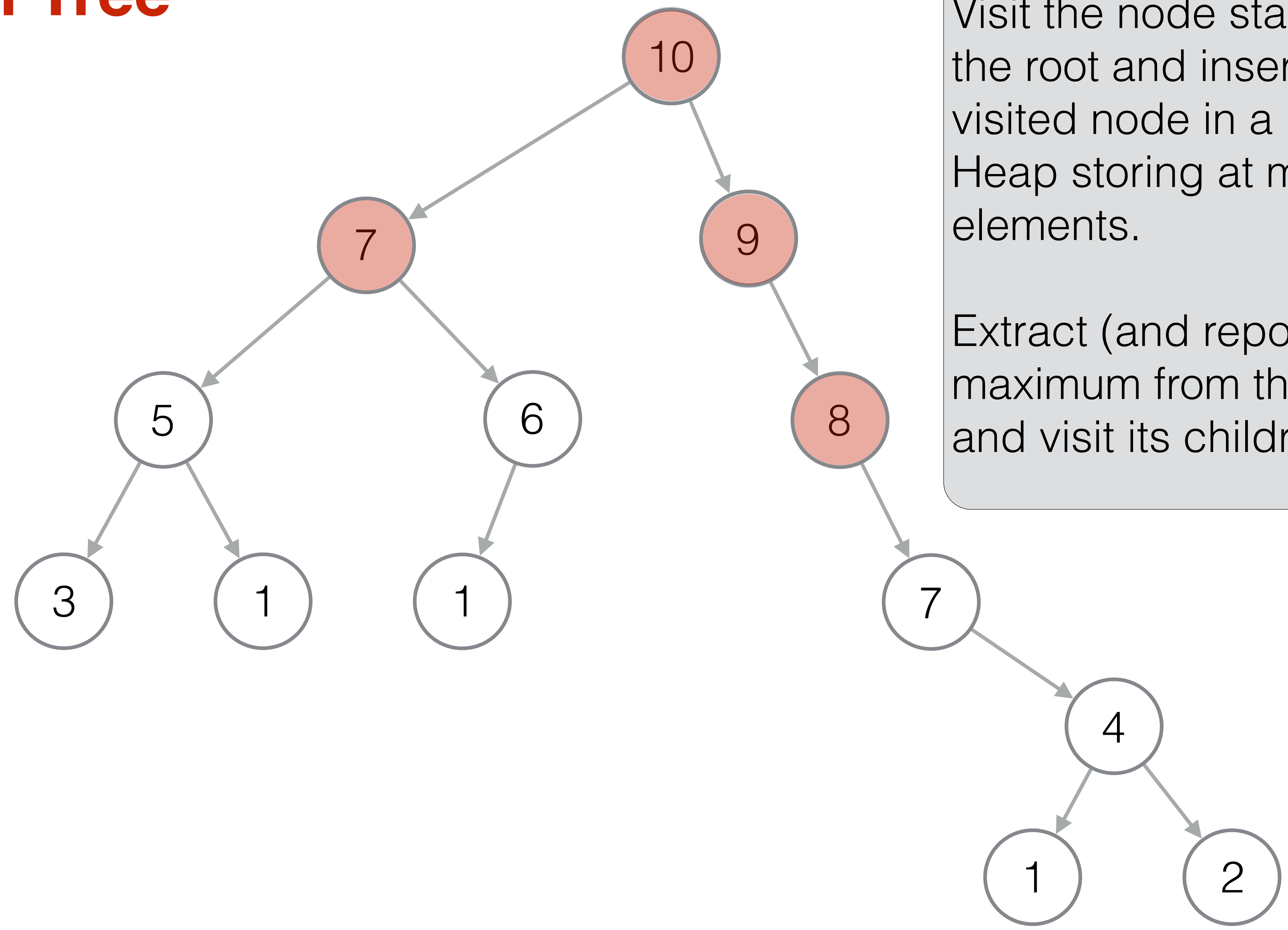
max-Heap	**Results**
8	10
7	9

S …	3	5	1	7	1	6	10	9	8	7	1	4	2	…

Finding Top-k

How to find Top-k?

Cartesian Tree



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	9

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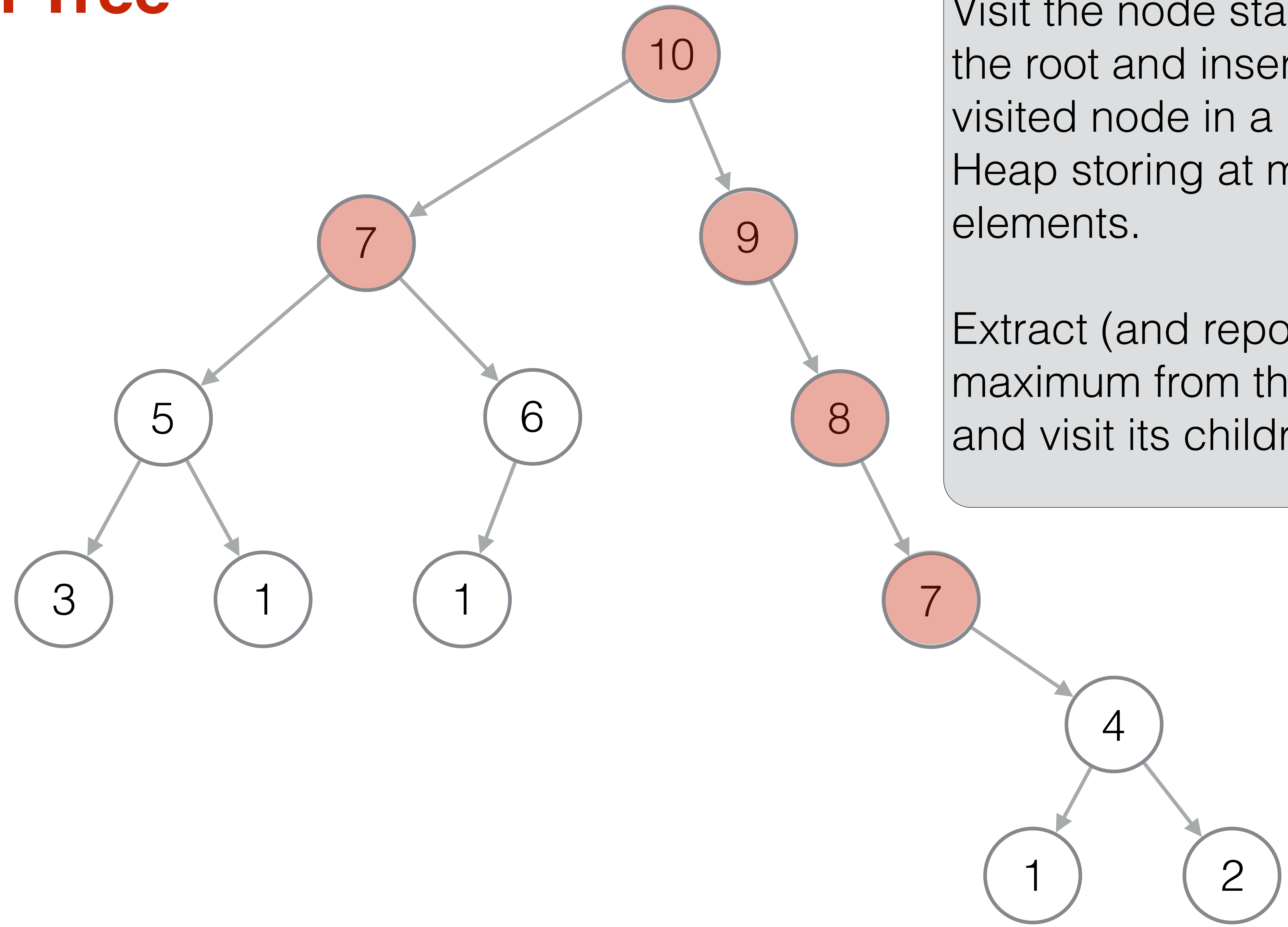

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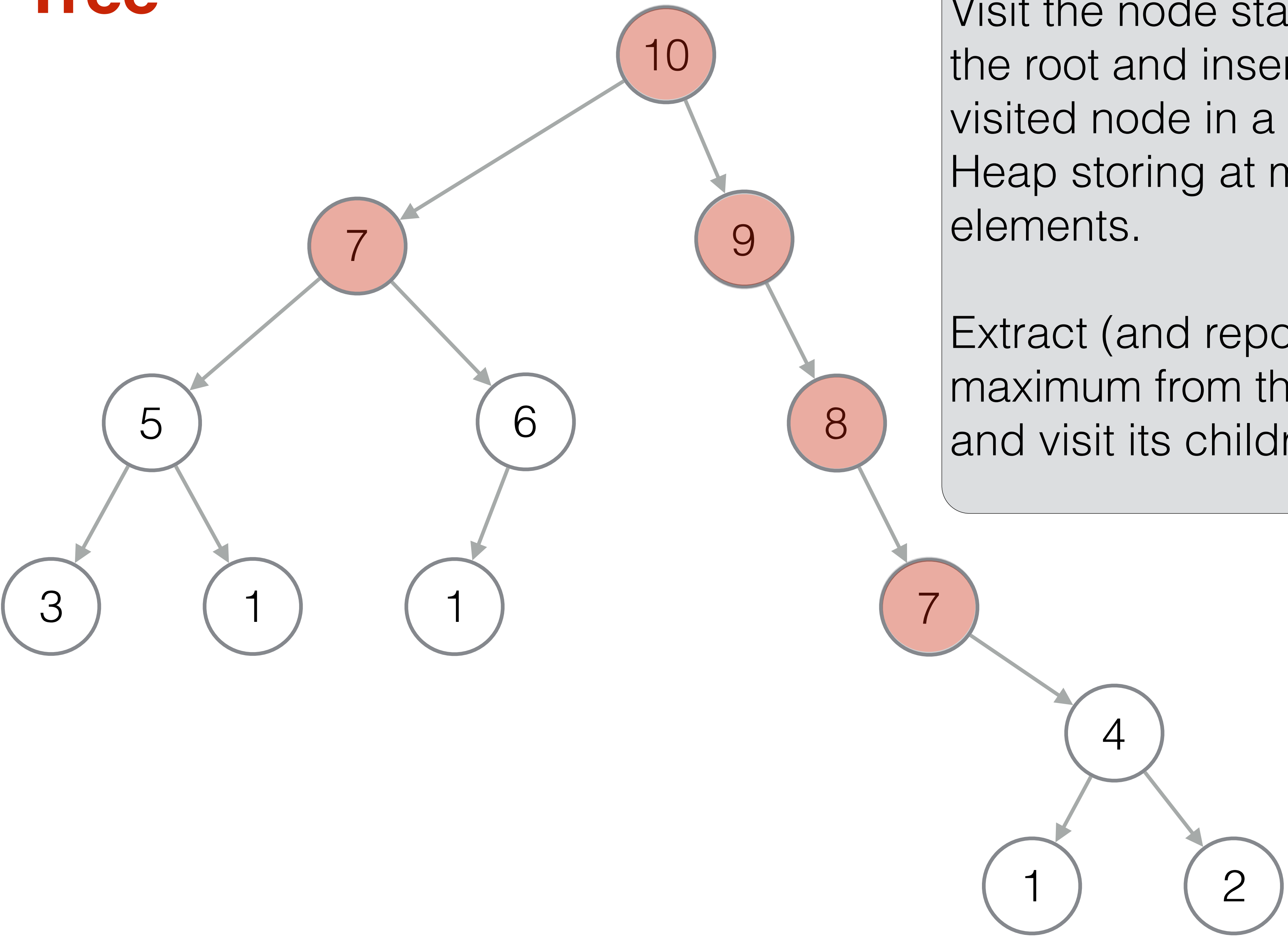

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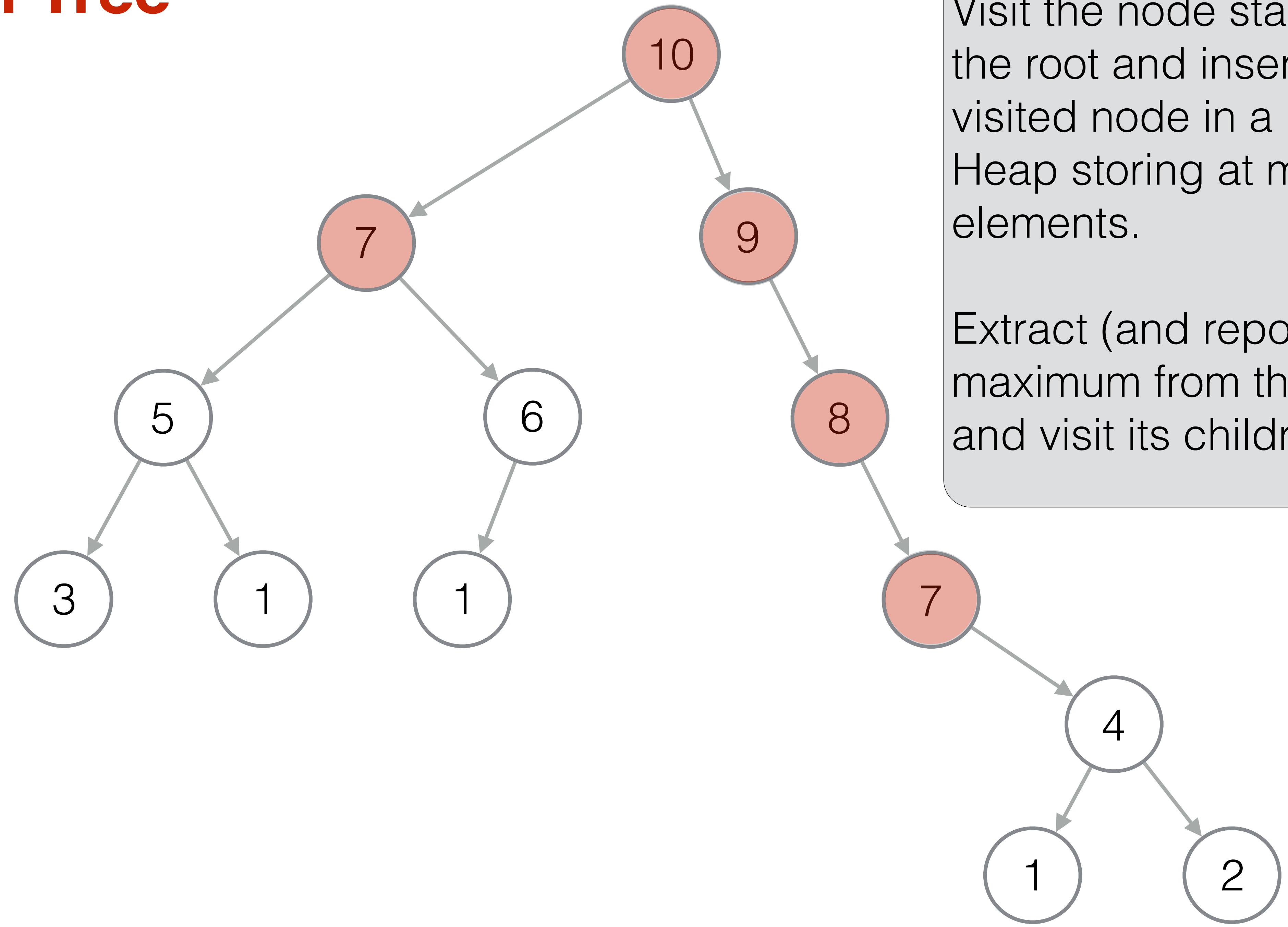

k=4

max-Heap	**Results**
7	10
	9
	8
	7

S	…	3	5	1	7	1	6	10	9	8	7	1	4	2	…

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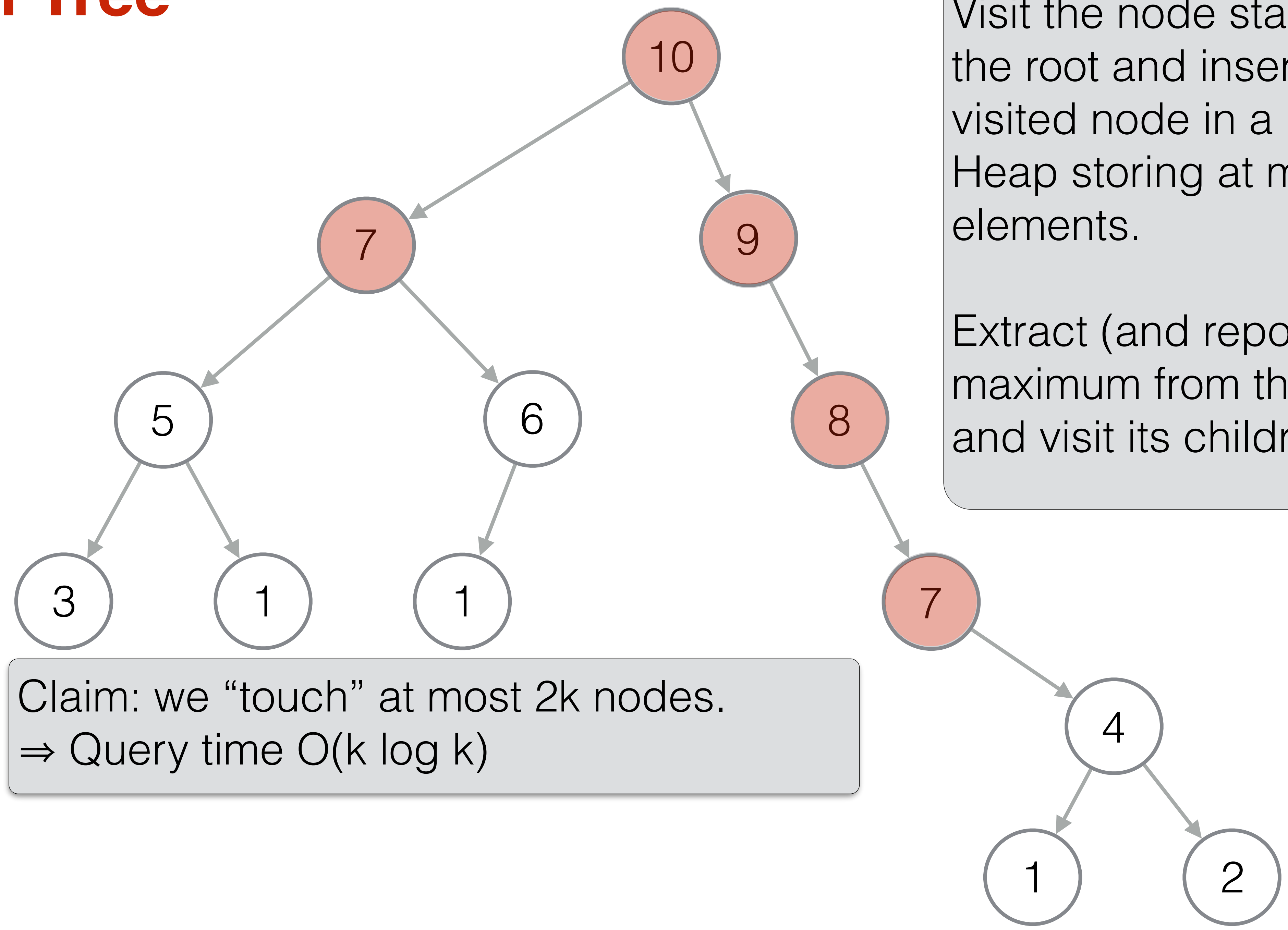
Cartesian Tree



Claim: we “touch” at most 2k nodes.
⇒ Query time O(k log k)

k=4

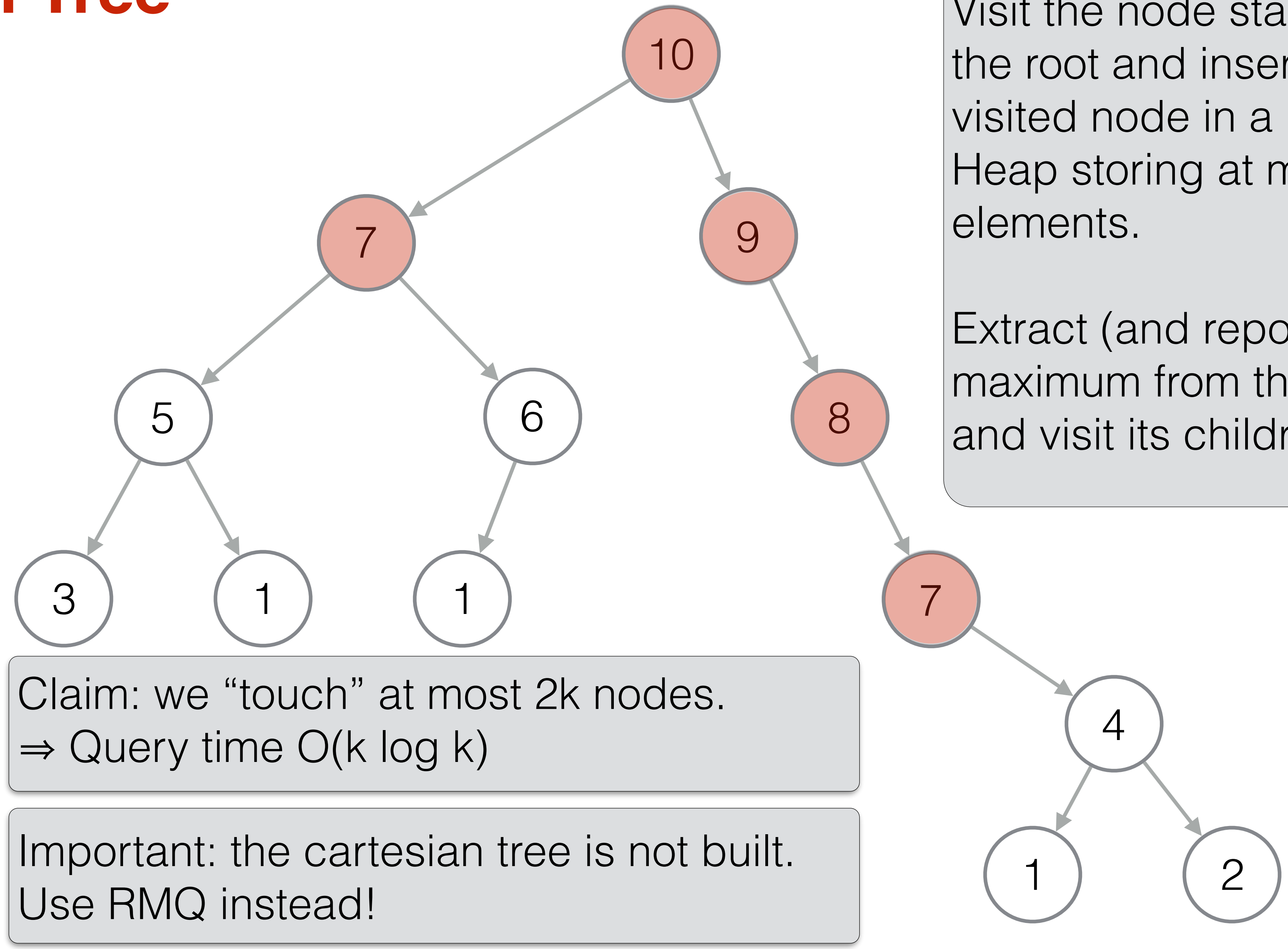
max-Heap	**Results**
7	10
	9
	8
	7

S	…	3	5	1	7	1	6	10	9	8	7	1	4	2	…

Finding Top-k

How to find Top-k?

Cartesian Tree



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⇒ Query time O(k log k)

Important: the cartesian tree is not built.
Use RMQ instead!

k=4

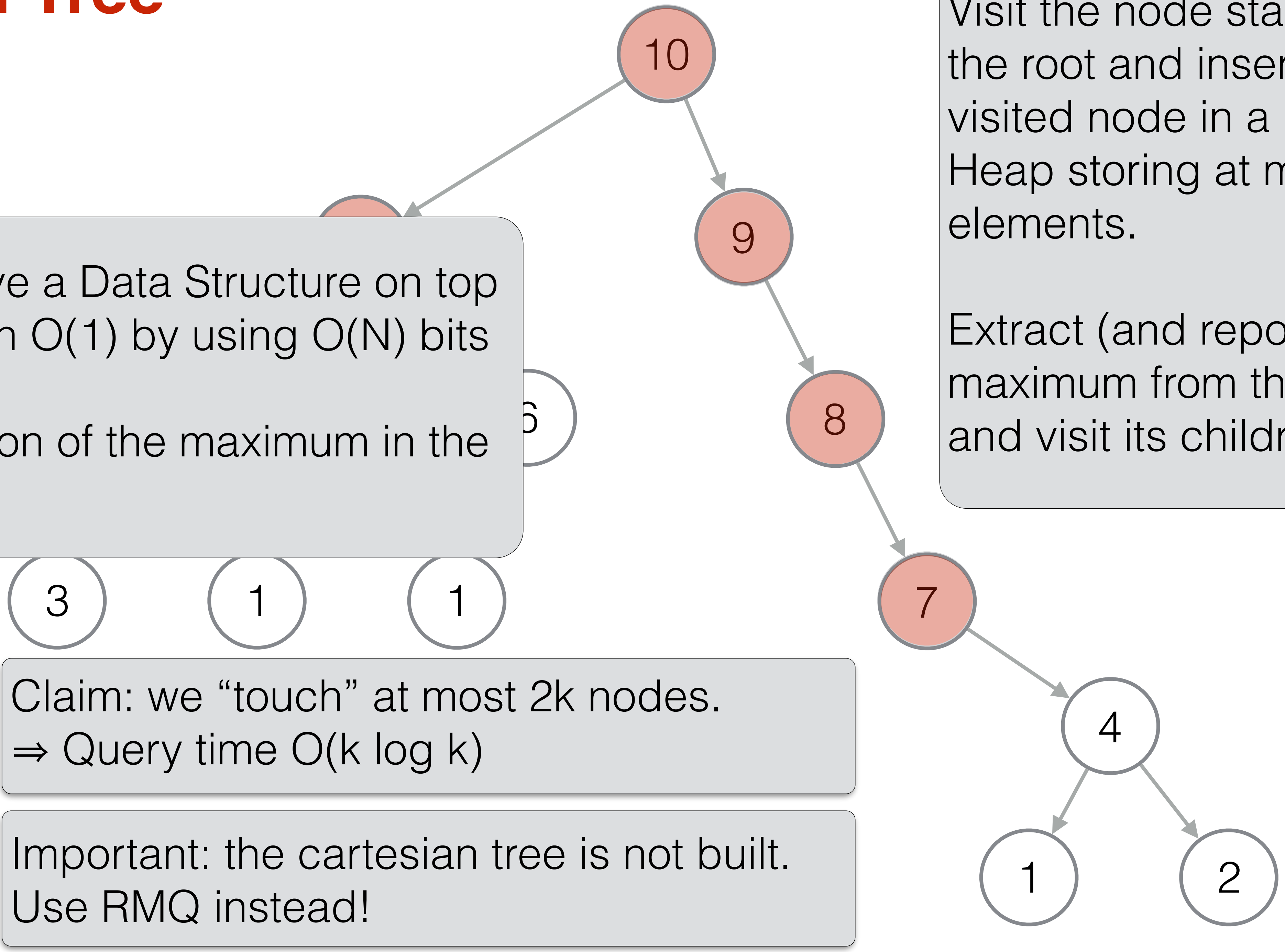
max-Heap	**Results**
7	10
	9
	8
	7

S	…	3	5	1	7	1	6	10	9	8	7	1	4	2	…

Finding Top-k

How to find Top-k?

Cartesian Tree



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RMQ(i,j) = position of the maximum in the range S[i,j]

Visit the node starting from the root and insert each visited node in a **max**-Heap storing at most **k** elements.

Extract (and report) the maximum from the heap and visit its children.

max-Heap	**Results**
7	10
	9
	8
	7

Claim: we “touch” at most 2k nodes.
⇒ Query time O(k log k)

Important: the cartesian tree is not built.
Use RMQ instead!

S … | 3 | 5 | 1 | 7 | 1 | 6 | 10 | 9 | 8 | 7 | 1 | 4 | 2 | …

Range Maximum Query (1)

	0	1	2	3	4	5	6	7	8	9	10	11
S	3	5	1	7	1	6	10	9	8	7	1	4

Range Maximum Query (1)

Space: O(N^2 log n) bits
Query time: O(1)

	0	1	2	3	4	5	6	7	8	9	10	11
S	3	5	1	7	1	6	10	9	8	7	1	4

Range Maximum Query (1)

Space: $O(N^2 \log n)$ bits
Query time: $O(1)$

Precompute the answer to any possible query.

There are $O(N^2)$ possible queries!

	0	1	2	3	4	5	6	7	8	9	10	11
S	3	5	1	7	1	6	10	9	8	7	1	4

Range Maximum Query (1)

Space: $O(N^2 \log n)$ bits
Query time: $O(1)$

$M[i,j] = RMQ(i,j)$

Precompute the answer to any possible query.

There are $O(N^2)$ possible queries!

	0	1	2	3	4	5	6	7	8	9	10	11
S	3	5	1	7	1	6	10	9	8	7	1	4

Range Maximum Query (1)

Space: $O(N^2 \log n)$ bits
Query time: $O(1)$

$$M[i,j] = RMQ(i,j)$$

M	0	1	2	3	4	5	6	7	8	9	10	11
0												
1												
2												
3												
4												
5												
6												
7												
8												
9												
10												
11												

Precompute the answer to any possible query.

There are $O(N^2)$ possible queries!

	0	1	2	3	4	5	6	7	8	9	10	11
S	3	5	1	7	1	6	10	9	8	7	1	4

Range Maximum Query (1)

Space: $O(N^2 \log n)$ bits
Query time: $O(1)$

$$M[i,j] = RMQ(i,j)$$

M	0	1	2	3	4	5	6	7	8	9	10	11
0												
1												
2						3						
3												
4												
5												
6												
7												
8												
9												
10												
11												

Precompute the answer to any possible query.

There are $O(N^2)$ possible queries!

	0	1	2	3	4	5	6	7	8	9	10	11
S	3	5	1	7	1	6	10	9	8	7	1	4

Range Maximum Query (2)

	0	1	2	3	4	5	6	7	8	9	10	11
S	3	5	1	7	1	6	10	9	8	7	1	4

Range Maximum Query (2)

Space: O(N $\log^2$ N) bits
Query time: O(1)

	0	1	2	3	4	5	6	7	8	9	10	11
S	3	5	1	7	1	6	10	9	8	7	1	4

Range Maximum Query (2)

Space: O(N $\log^2$ N) bits
Query time: O(1)

Maximum in a interval is the max between the maxima of any its subintervals

	0	1	2	3	4	5	6	7	8	9	10	11
S	3	5	1	7	1	6	10	9	8	7	1	4

Range Maximum Query (2)

Space: $O(N \log^2 N)$ bits
Query time: $O(1)$

Maximum in a interval is the max between the maxima of any its subintervals

Precompute the answer to every interval whose length is a power of 2.

There are $O(\log N)$ possible intervals starting at any position i.

	0	1	2	3	4	5	6	7	8	9	10	11
S	3	5	1	7	1	6	10	9	8	7	1	4

Range Maximum Query (2)

Space: $O(N \log^2 N)$ bits
Query time: $O(1)$

Maximum in a interval is the max between the maxima of any its subintervals

Precompute the answer to every interval whose length is a power of 2.

There are $O(\log N)$ possible intervals starting at any position i.

$$M[i,j] = RMQ(i,i+2^j)$$

M

	0	1	2	3	4
0					
1					
2					
3					
4					
5					
6					
7					
8					
9					
10					
11					

	0	1	2	3	4	5	6	7	8	9	10	11
S	3	5	1	7	1	6	10	9	8	7	1	4

Range Maximum Query (2)

Space: $O(N \log^2 N)$ bits
Query time: $O(1)$

Maximum in a interval is the max between the maxima of any its subintervals

Precompute the answer to every interval whose length is a power of 2.

There are $O(\log N)$ possible intervals starting at any position i.

$$M[i,j] = RMQ(i,i+2^j)$$

M	0	1	2	3	4
0					
1				?	
2					
3					
4					
5					
6					
7					
8					
9					
10					
11					

	0	1	2	3	4	5	6	7	8	9	10	11
S	3	5	1	7	1	6	10	9	8	7	1	4

Range Maximum Query (2)

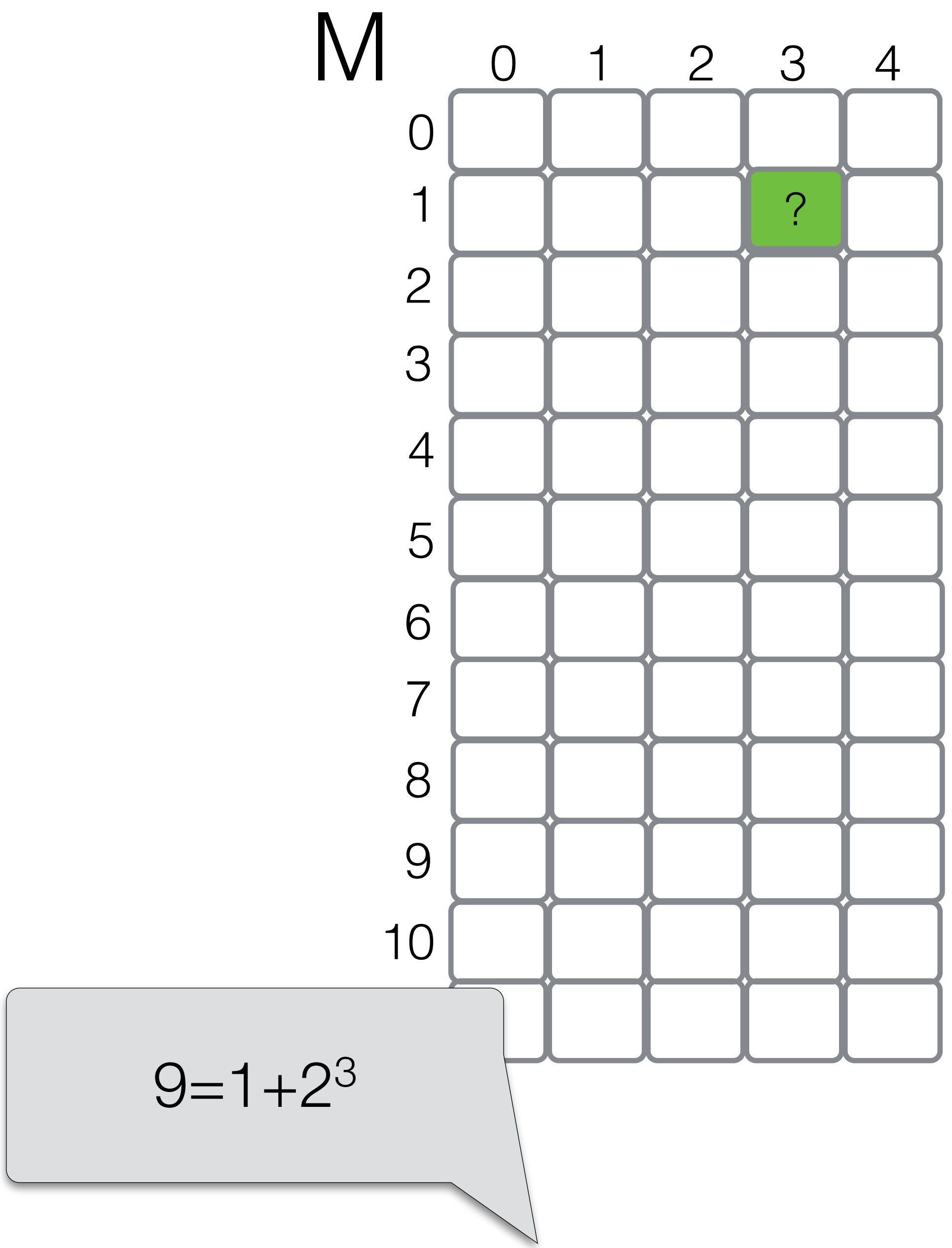
Space: $O(N \log^2 N)$ bits
Query time: $O(1)$

Maximum in a interval is the max between the maxima of any its subintervals

Precompute the answer to every interval whose length is a power of 2.

There are $O(\log N)$ possible intervals starting at any position i.

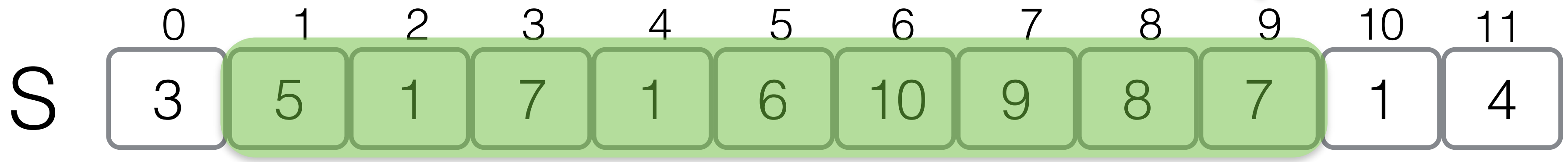
$$M[i,j] = RMQ(i,i+2^j)$$



M

	0	1	2	3	4
0					
1				?	
2					
3					
4					
5					
6					
7					
8					
9					
10					

$9=1+2^3$



	0	1	2	3	4	5	6	7	8	9	10	11
S	3	5	1	7	1	6	10	9	8	7	1	4

Range Maximum Query (2)

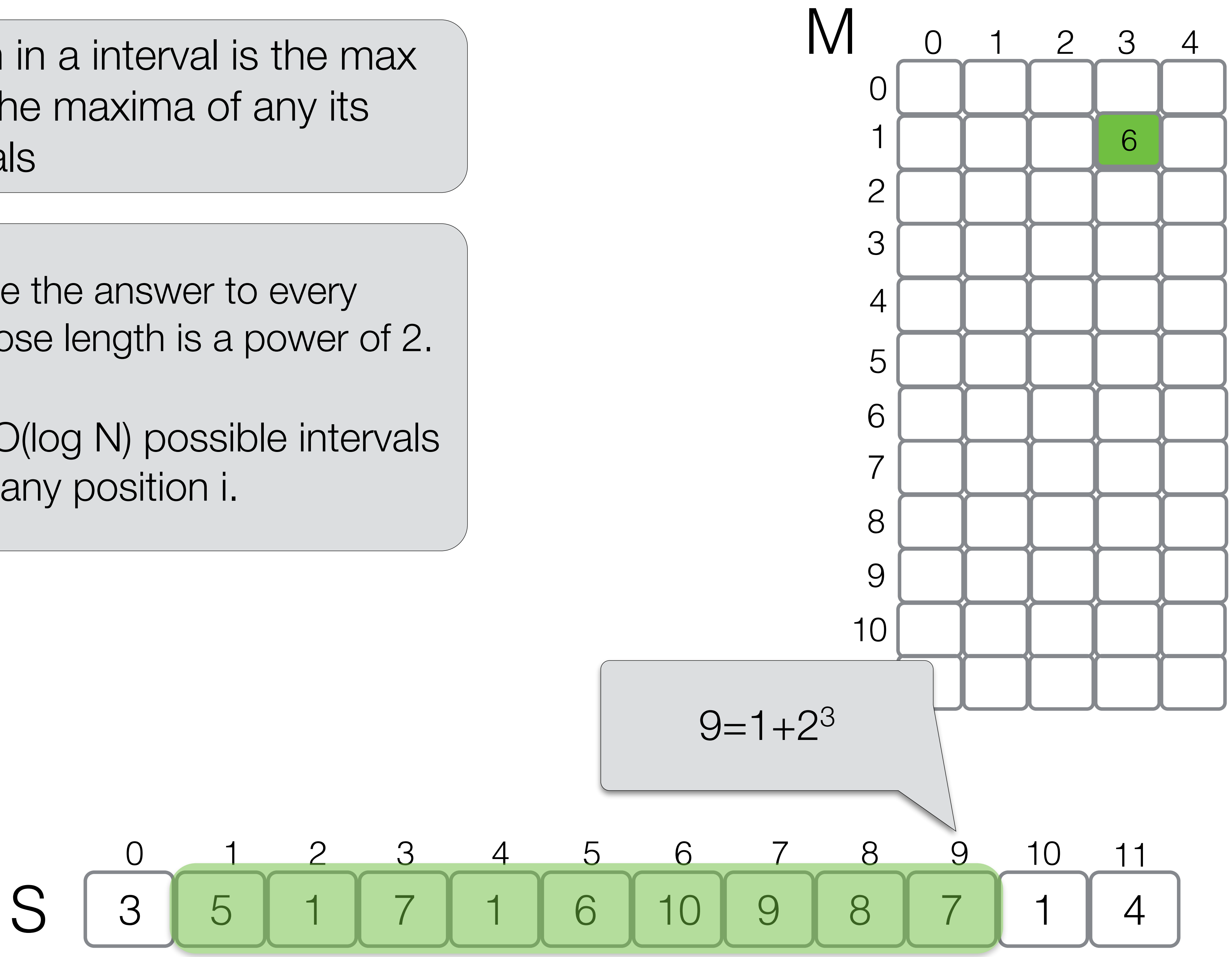
Space: O(N $\log^2$ N) bits
Query time: O(1)

Maximum in a interval is the max between the maxima of any its subintervals

Precompute the answer to every interval whose length is a power of 2.

There are O(log N) possible intervals starting at any position i.

$$M[i,j] = RMQ(i,i+2^j)$$



M

	0	1	2	3	4
0					
1				6	
2					
3					
4					
5					
6					
7					
8					
9					
10					

$9=1+2^3$

S

0	1	2	3	4	5	6	7	8	9	10	11
3	5	1	7	1	6	10	9	8	7	1	4

Range Maximum Query (2)

Space: $O(N \log^2 N)$ bits
Query time: $O(1)$

Maximum in a interval is the max between the maxima of any its subintervals

Precompute the answer to every interval whose length is a power of 2.

There are O(log N) possible intervals starting at any position i.

$$M[i,j] = RMQ(i,i+2^j)$$

M	0	1	2	3	4
0					
1					
2					
3					
4					
5					
6					
7					
8					
9					
10					
11					

	0	1	2	3	4	5	6	7	8	9	10	11
S	3	5	1	7	1	6	10	9	8	7	1	4

Range Maximum Query (2)

Space: $O(N \log^2 N)$ bits
Query time: $O(1)$

Maximum in a interval is the max between the maxima of any its subintervals

Precompute the answer to every interval whose length is a power of 2.

There are $O(\log N)$ possible intervals starting at any position i.

RMQ(1,7) =

$$M[i,j] = RMQ(i,i+2^j)$$

M	0	1	2	3	4
0					
1					
2					
3					
4					
5					
6					
7					
8					
9					
10					
11					

	0	1	2	3	4	5	6	7	8	9	10	11
S	3	5	1	7	1	6	10	9	8	7	1	4

Range Maximum Query (2)

Space: $O(N \log^2 N)$ bits
Query time: $O(1)$

Maximum in a interval is the max between the maxima of any its subintervals

Precompute the answer to every interval whose length is a power of 2.

There are $O(\log N)$ possible intervals starting at any position i.

$M[i,j] = RMQ(i,i+2^j)$

M	0	1	2	3	4
0					
1					
2					
3					
4					
5					
6					
7					
8					
9					
10					
11					

$RMQ(1,7) = \text{argmax}(S[M[1,1+2^2]], S[M[7-2^2,7]]) = 6$

	0	1	2	3	4	5	6	7	8	9	10	11
S	3	5	1	7	1	6	10	9	8	7	1	4

Range Maximum Query (2)

Space: $O(N \log^2 N)$ bits
Query time: $O(1)$

Maximum in a interval is the max between the maxima of any its subintervals

Precompute the answer to every interval whose length is a power of 2.

There are $O(\log N)$ possible intervals starting at any position i.

$$M[i,j] = RMQ(i,i+2^j)$$

M

	0	1	2	3	4
0					
1					
2					
3					
4					
5					
6					
7					
8					
9					
10					
11					

$RMQ(1,7) = \text{argmax}(S[M[1,1+2^2]], S[M[7-2^2,7]]) = 6$

	0	1	2	3	4	5	6	7	8	9	10	11
S	3	5	1	7	1	6	10	9	8	7	1	4

Range Maximum Query (2)

Space: $O(N \log^2 N)$ bits
Query time: $O(1)$

Maximum in a interval is the max between the maxima of any its subintervals

Precompute the answer to every interval whose length is a power of 2.

There are $O(\log N)$ possible intervals starting at any position i.

$$M[i,j] = RMQ(i,i+2^j)$$

M	0	1	2	3	4
0					
1			3		
2					
3					
4					
5					
6					
7					
8					
9					
10					
11					

$$RMQ(1,7) = \operatorname{argmax}(S[M[1,1+2^2]], S[M[7-2^2,7]]) = 6$$

	0	1	2	3	4	5	6	7	8	9	10	11
S	3	5	1	7	1	6	10	9	8	7	1	4

Range Maximum Query (2)

Space: $O(N \log^2 N)$ bits
Query time: $O(1)$

Maximum in a interval is the max between the maxima of any its subintervals

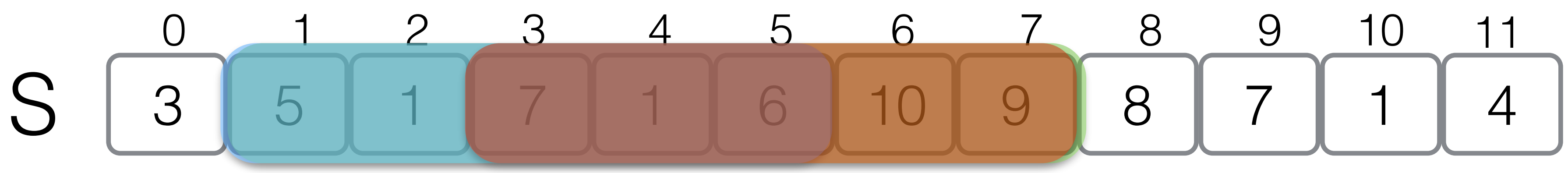
Precompute the answer to every interval whose length is a power of 2.

There are $O(\log N)$ possible intervals starting at any position i.

$$M[i,j] = RMQ(i,i+2^j)$$

M	0	1	2	3	4
0					
1			3		
2					
3					
4					
5					
6					
7					
8					
9					
10					
11					

$RMQ(1,7) = \text{argmax}(S[M[1,1+2^2]], S[M[7-2^2,7]]) = 6$



	0	1	2	3	4	5	6	7	8	9	10	11
S	3	5	1	7	1	6	10	9	8	7	1	4

Range Maximum Query (2)

Space: $O(N \log^2 N)$ bits
Query time: $O(1)$

Maximum in a interval is the max between the maxima of any its subintervals

Precompute the answer to every interval whose length is a power of 2.

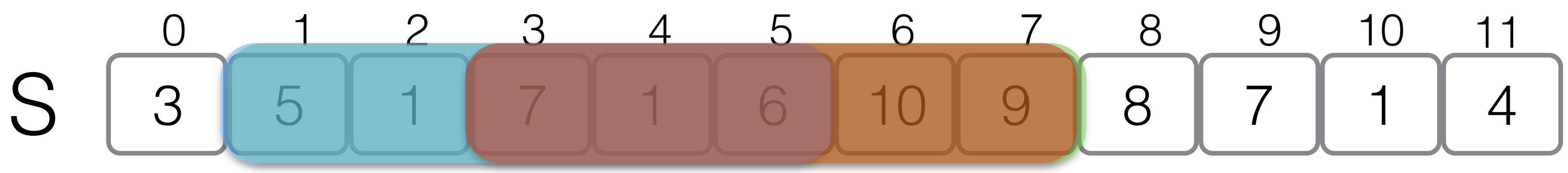
There are $O(\log N)$ possible intervals starting at any position i.

$$M[i,j] = RMQ(i,i+2^j)$$

M

	0	1	2	3	4
0					
1			3		
2					
3			6		
4					
5					
6					
7					
8					
9					
10					
11					

$RMQ(1,7) = \text{argmax}(S[M[1,1+2^2]], S[M[7-2^2,7]]) = 6$



S

0	1	2	3	4	5	6	7	8	9	10	11
3	5	1	7	1	6	10	9	8	7	1	4

Range Maximum Query (2)

Space: $O(N \log^2 N)$ bits
Query time: $O(1)$

Maximum in a interval is the max between the maxima of any its subintervals

Precompute the answer to every interval whose length is a power of 2.

There are $O(\log N)$ possible intervals starting at any position i.

$$M[i,j] = RMQ(i,i+2^j)$$

M	0	1	2	3	4
0					
1			3		
2					
3			6		
4					
5					
6					
7					
8					
9					
10					
11					

$$RMQ(1,7) = \text{argmax}(S[M[1,1+2^2]], S[M[7-2^2,7]]) = 6$$

$$RMQ(i,j) = \text{argmax}(S[M[i,i+2^{len}]], S[M[j-2^{len},j]])$$

$$\text{where } len = \lfloor \log (j-i+1) \rfloor$$

	0	1	2	3	4	5	6	7	8	9	10	11
S	3	5	1	7	1	6	10	9	8	7	1	4

Range Maximum Query (3)

	0	1	2	3	4	5	6	7	8	9	10	11
S	3	5	1	7	1	6	10	9	8	7	1	4

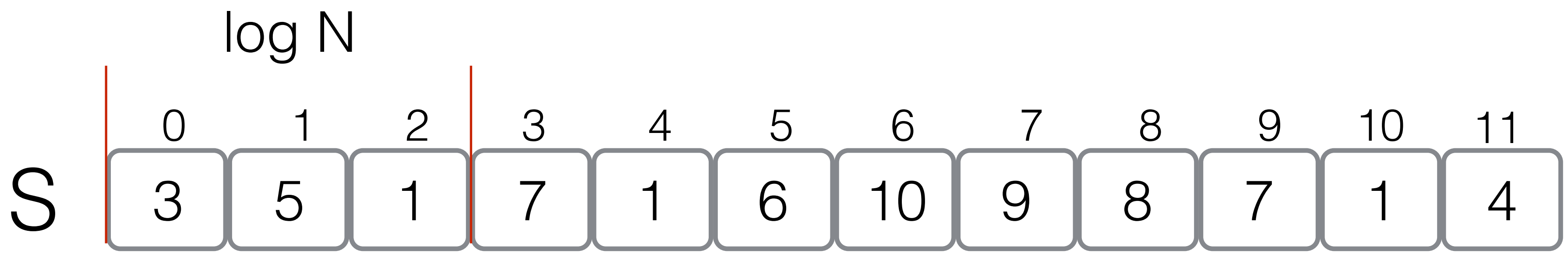
Range Maximum Query (3)

Space: O(N log N) bits
Query time: O(log N)

	0	1	2	3	4	5	6	7	8	9	10	11
S	3	5	1	7	1	6	10	9	8	7	1	4

Range Maximum Query (3)

Space: O(N log N) bits
Query time: O(log N)

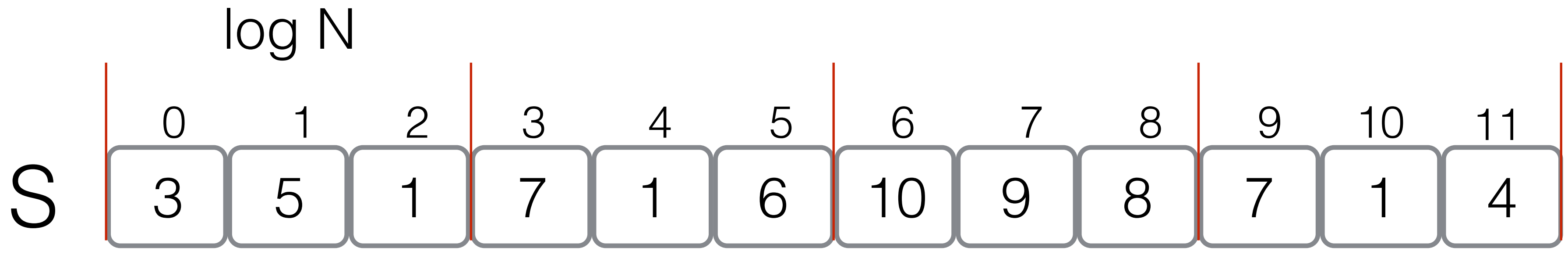


log N

	0	1	2	3	4	5	6	7	8	9	10	11
S	3	5	1	7	1	6	10	9	8	7	1	4

Range Maximum Query (3)

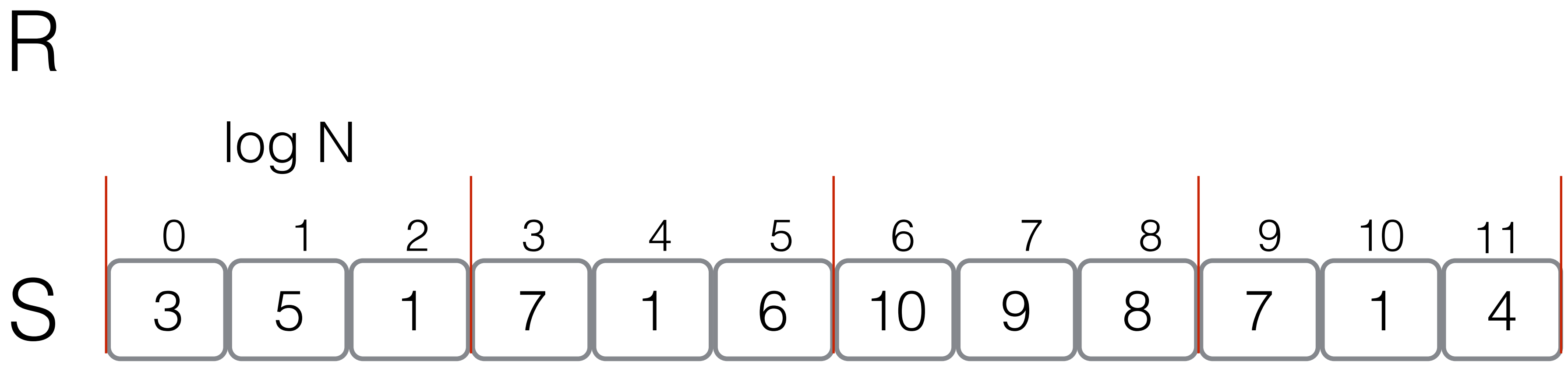
Space: O(N log N) bits
Query time: O(log N)



	0	1	2	3	4	5	6	7	8	9	10	11
S	3	5	1	7	1	6	10	9	8	7	1	4

Range Maximum Query (3)

Space: O(N log N) bits
Query time: O(log N)



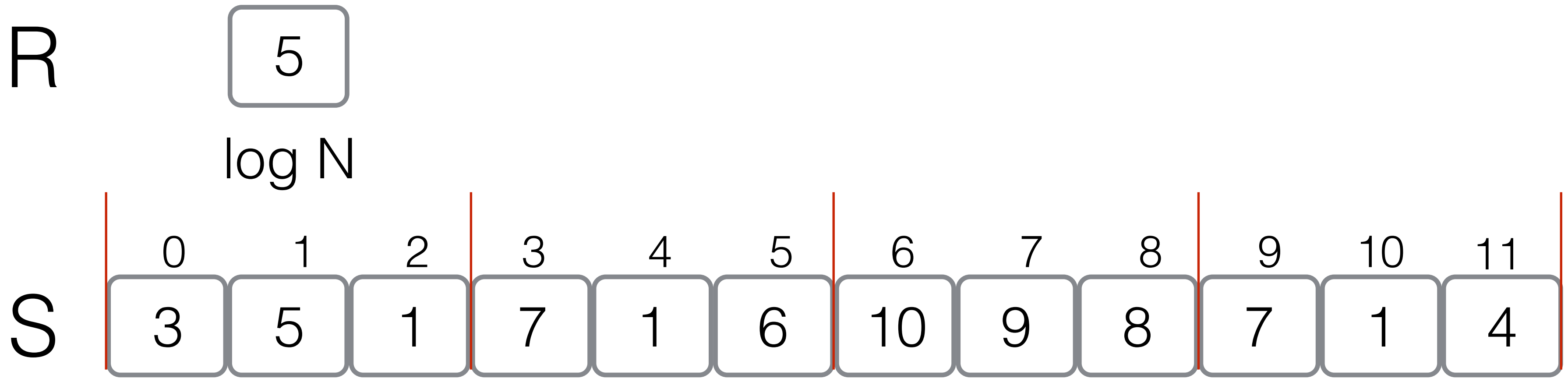
R

log N

	0	1	2	3	4	5	6	7	8	9	10	11
S	3	5	1	7	1	6	10	9	8	7	1	4

Range Maximum Query (3)

Space: O(N log N) bits
Query time: O(log N)



R

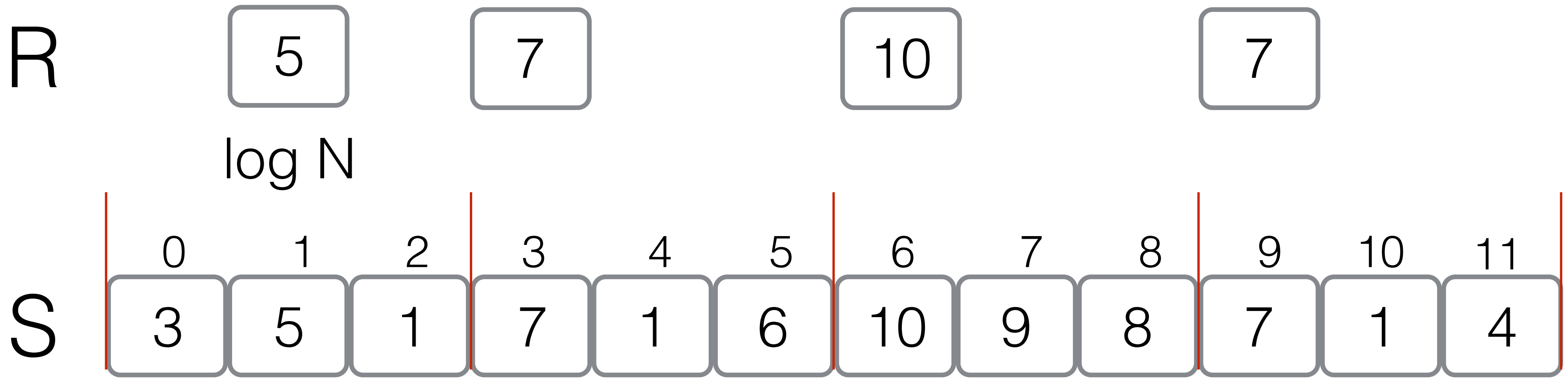
5

log N

	0	1	2	3	4	5	6	7	8	9	10	11
S	3	5	1	7	1	6	10	9	8	7	1	4

Range Maximum Query (3)

Space: O(N log N) bits
Query time: O(log N)



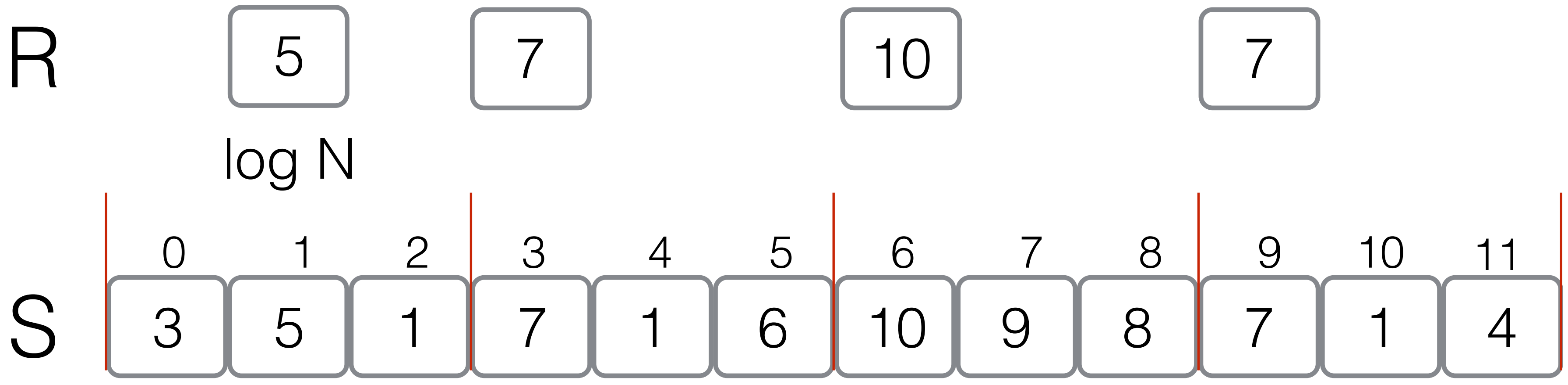
R		5		7			10			7		
	0	1	2	3	4	5	6	7	8	9	10	11
S	3	5	1	7	1	6	10	9	8	7	1	4

Range Maximum Query (3)

Space: O(N log N) bits
Query time: O(log N)

Use the previous solution on R!

Space: ? bits
Query time: O(1)



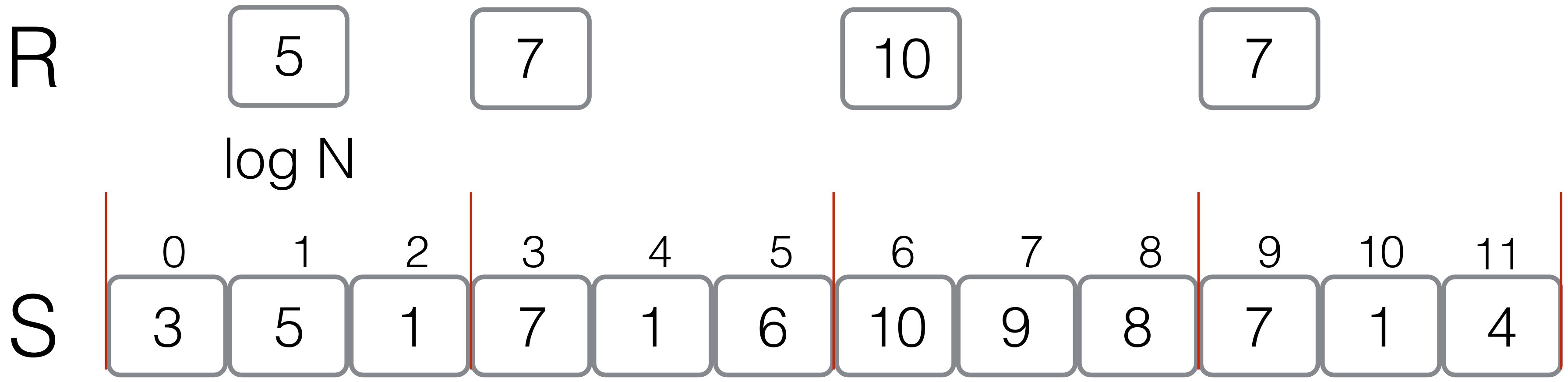
	0	1	2	3	4	5	6	7	8	9	10	11
S	3	5	1	7	1	6	10	9	8	7	1	4

Range Maximum Query (3)

Space: O(N log N) bits
Query time: O(log N)

Use the previous solution on R!

Space: O(N log N) bits
Query time: O(1)



R: 5 7 10 7

log N

S	0	1	2	3	4	5	6	7	8	9	10	11
	3	5	1	7	1	6	10	9	8	7	1	4

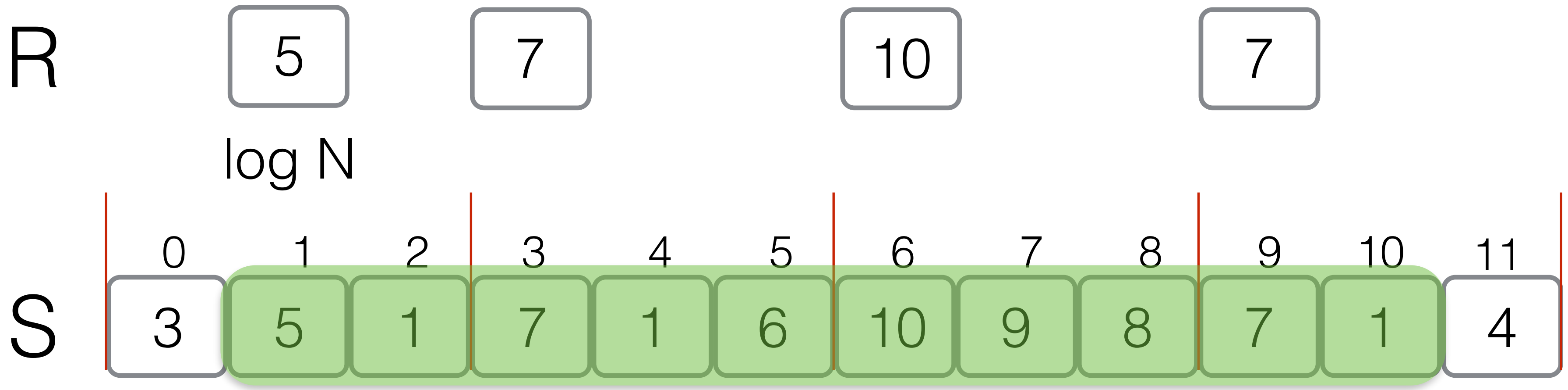
Range Maximum Query (3)

Space: O(N log N) bits
Query time: O(log N)

Use the previous solution on R!

Space: O(N log N) bits
Query time: O(1)

RMQ(1,10) = ?



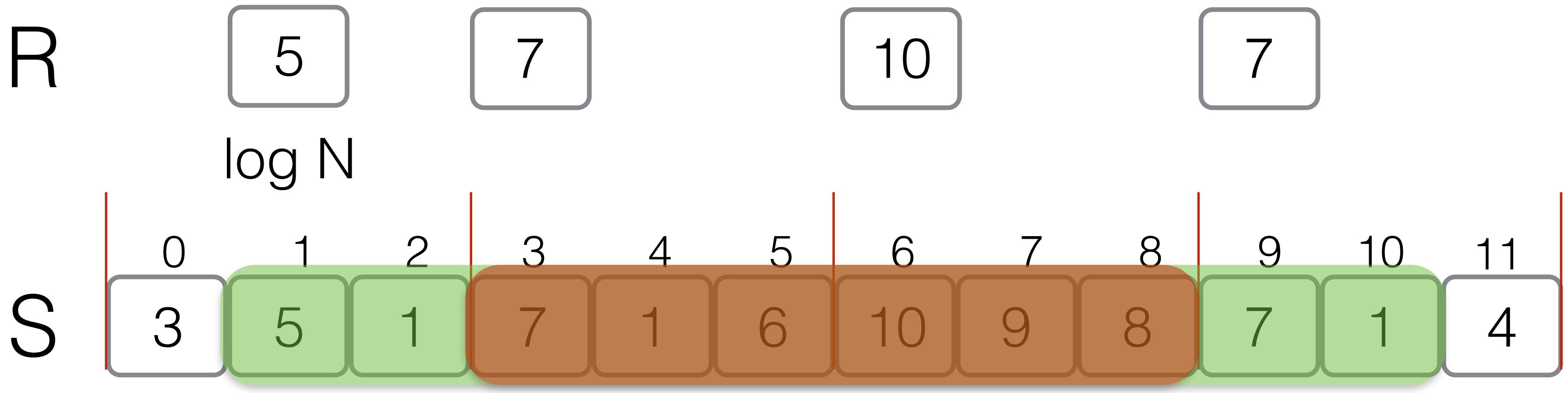
Range Maximum Query (3)

Space: O(N log N) bits
Query time: O(log N)

Use the previous solution on R!

Space: O(N log N) bits
Query time: O(1)

RMQ(1,10) = ?



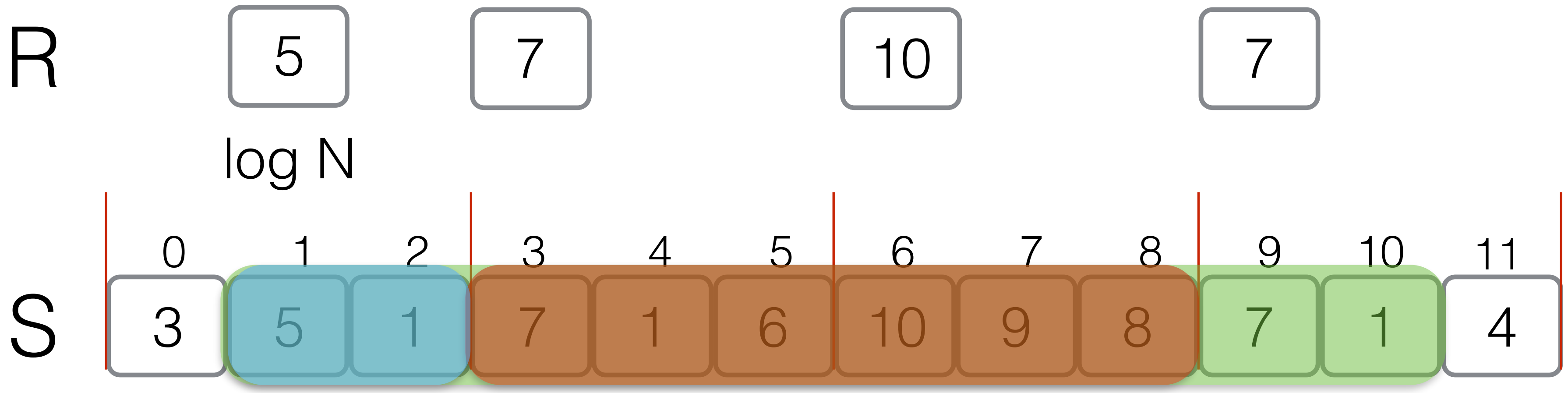
Range Maximum Query (3)

Space: O(N log N) bits
Query time: O(log N)

Use the previous solution on R!

Space: O(N log N) bits
Query time: O(1)

RMQ(1,10) = ?



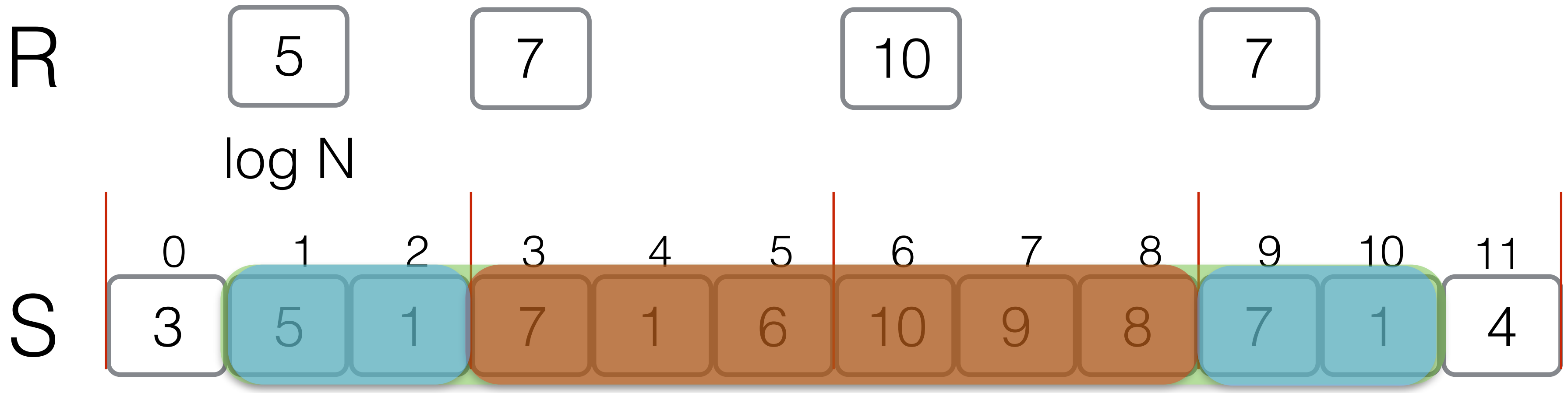
Range Maximum Query (3)

Space: O(N log N) bits
Query time: O(log N)

Use the previous solution on R!

Space: O(N log N) bits
Query time: O(1)

RMQ(1,10) = ?



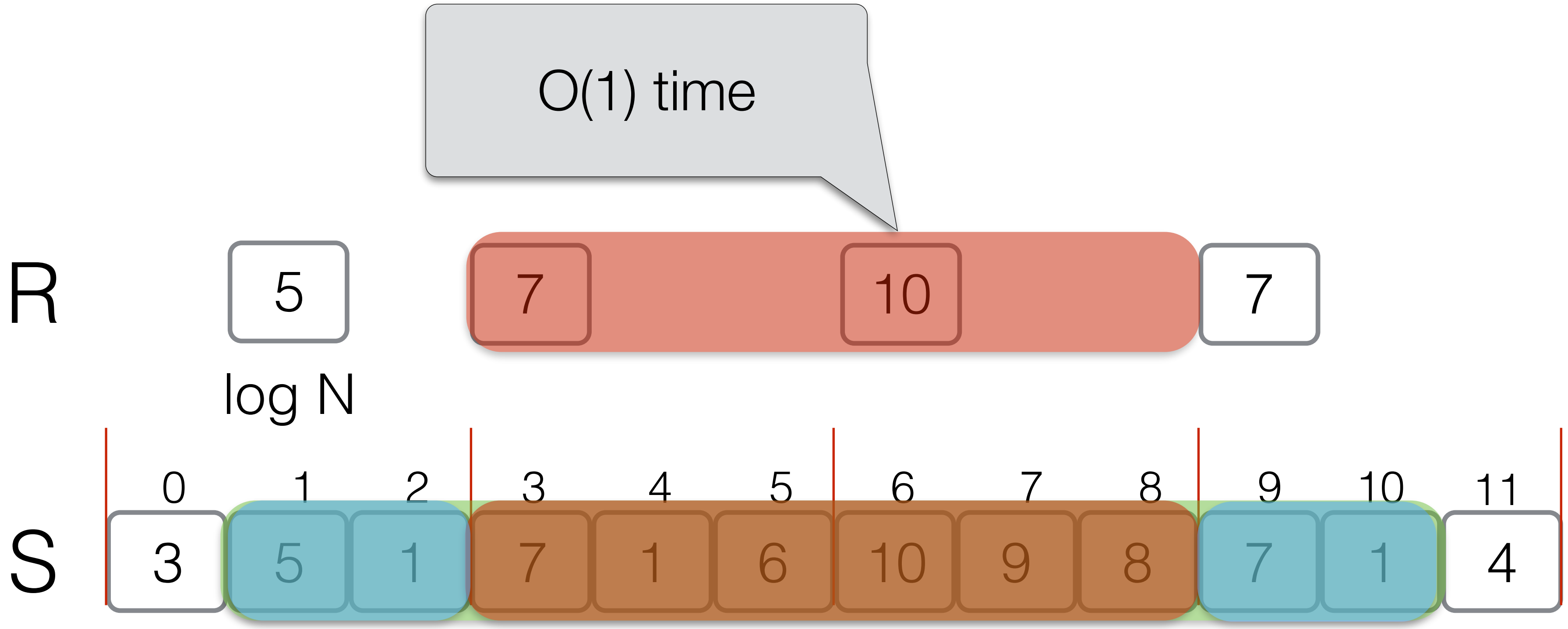
Range Maximum Query (3)

Space: O(N log N) bits
Query time: O(log N)

Use the previous solution on R!

Space: O(N log N) bits
Query time: O(1)

RMQ(1,10) = ?



0	1	2	3	4	5	6	7	8	9	10	11
3	5	1	7	1	6	10	9	8	7	1	4

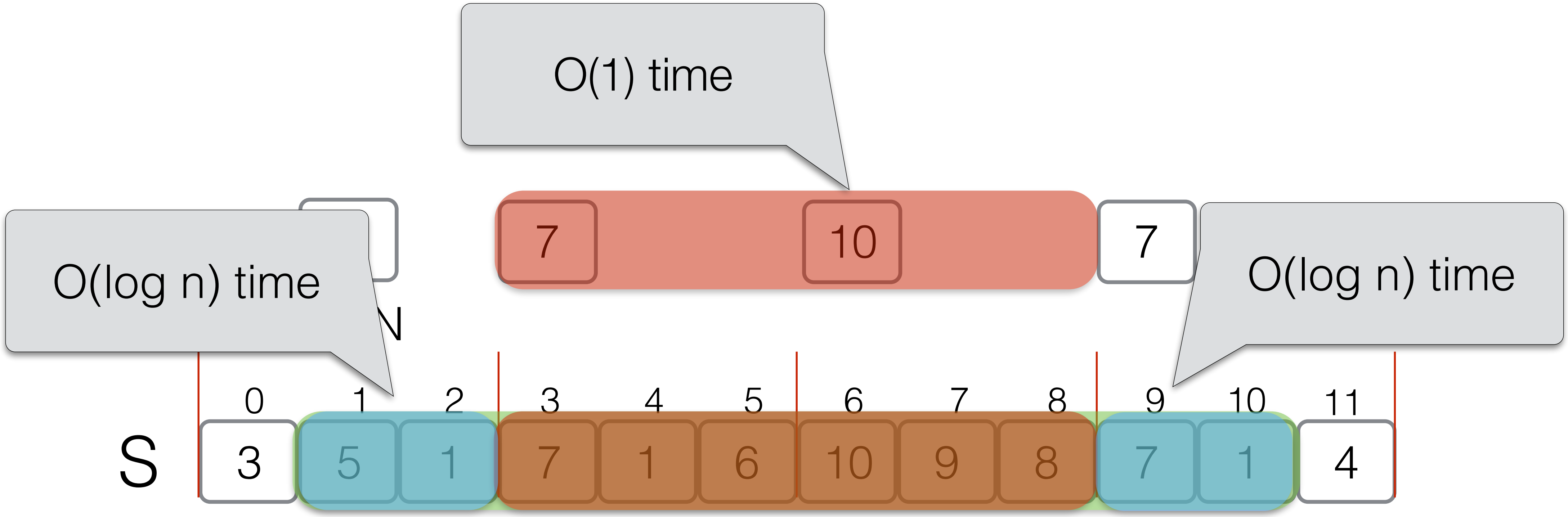
Range Maximum Query (3)

Space: O(N log N) bits
Query time: O(log N)

Use the previous solution on R!

Space: O(N log N) bits
Query time: O(1)

RMQ(1,10) = ?



O(1) time

O(log n) time

O(log n) time

Range Maximum Query (3)

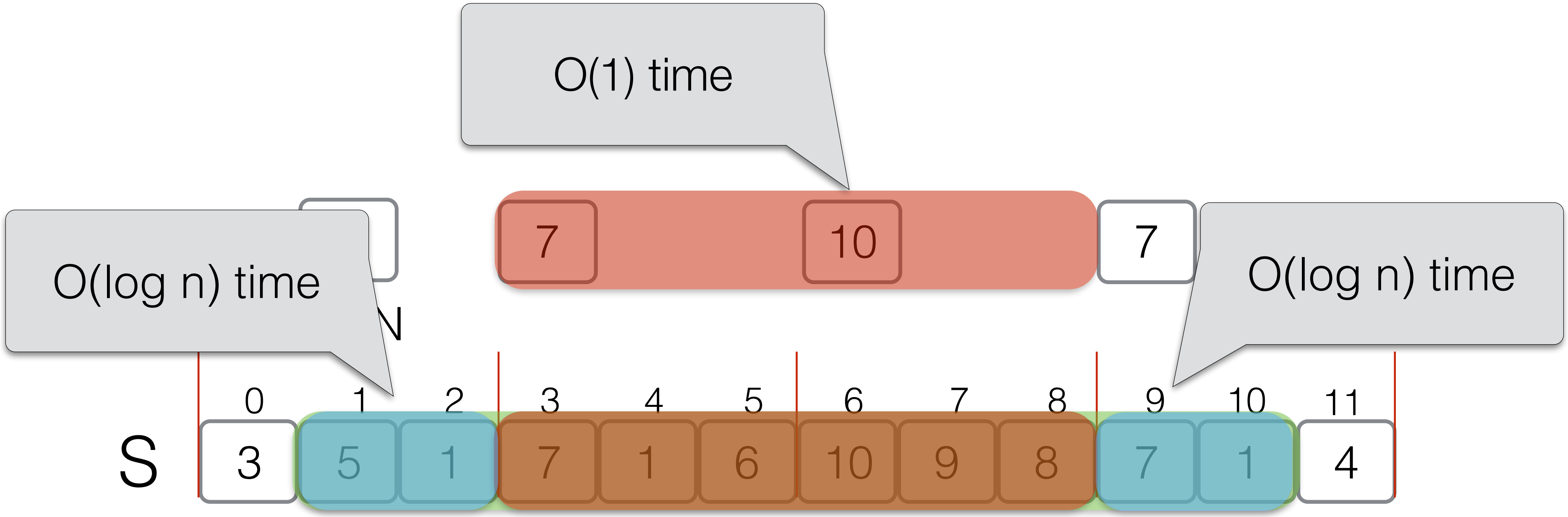
Space: O(N log N) bits
Query time: O(log N)

Space: O(N log N) bits
Query time: O(1)

Use the previous solution on R!

Space: O(N log N) bits
Query time: O(1)

RMQ(1,10) = ?



	0	1	2	3	4	5	6	7	8	9	10	11
S	3	5	1	7	1	6	10	9	8	7	1	4

Range Maximum Query (3)

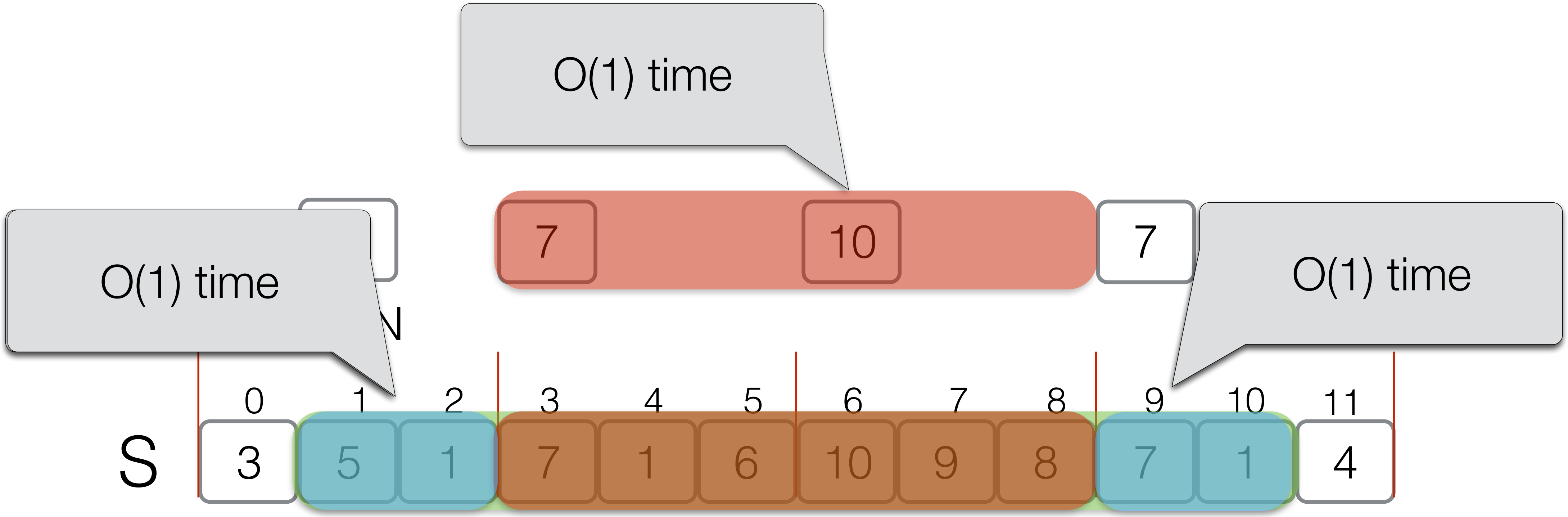
Space: O(N log N) bits
Query time: O(log N)

Space: O(N log N) bits
Query time: O(1)

Use the previous solution on R!

Space: O(N log N) bits
Query time: O(1)

RMQ(1,10) = ?



O(1) time

O(1) time

O(1) time

	0	1	2	3	4	5	6	7	8	9	10	11
S	3	5	1	7	1	6	10	9	8	7	1	4

Range Maximum Query (4)

	0	1	2	3	4	5	6	7	8	9	10	11
S	3	5	1	7	1	6	10	9	8	7	1	4

Range Maximum Query (4)

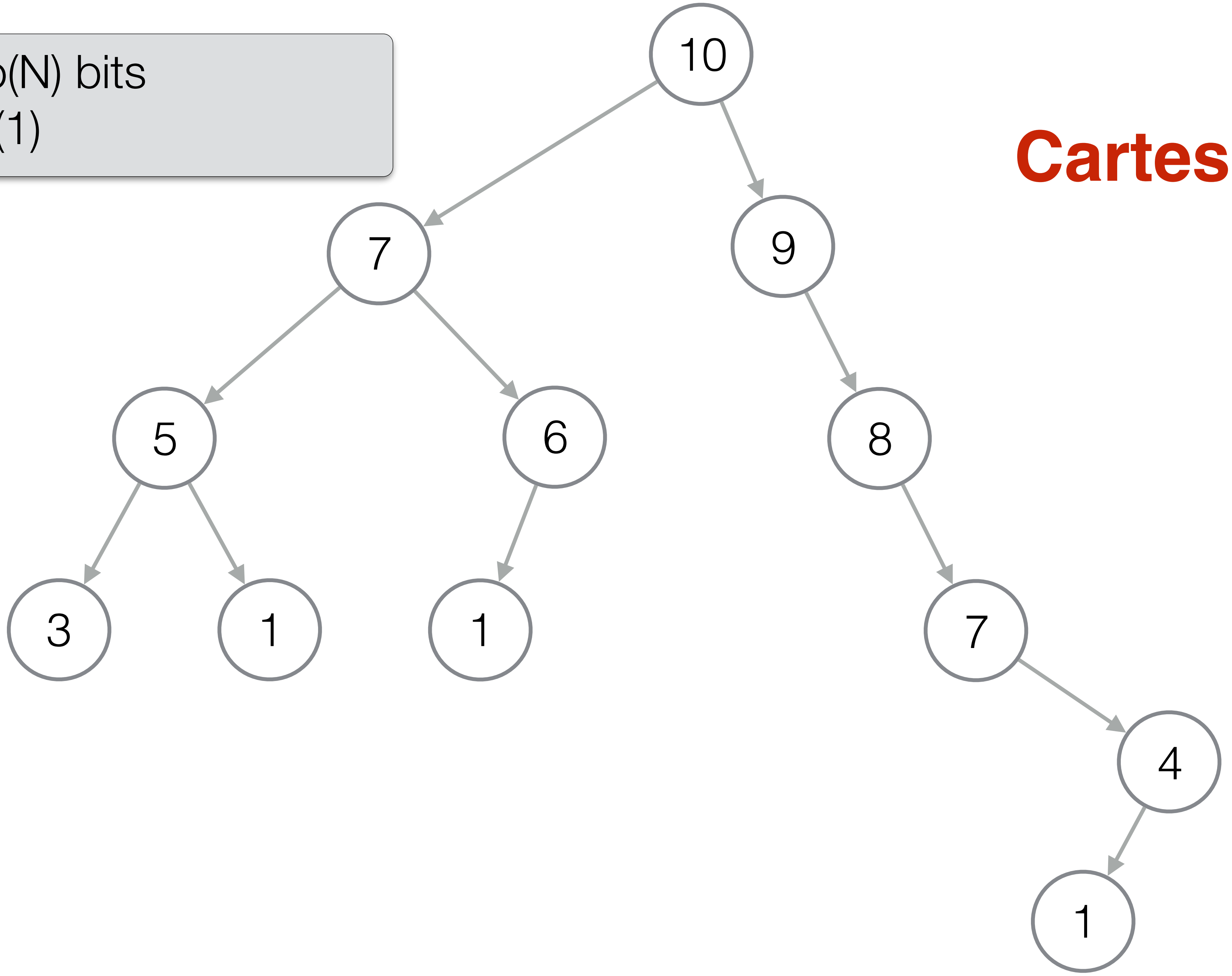
Space: 4N + o(N) bits
Query time: O(1)

	0	1	2	3	4	5	6	7	8	9	10	11
S	3	5	1	7	1	6	10	9	8	7	1	4

Range Maximum Query (4)

Space: 4N + o(N) bits
Query time: O(1)

Cartesian Tree

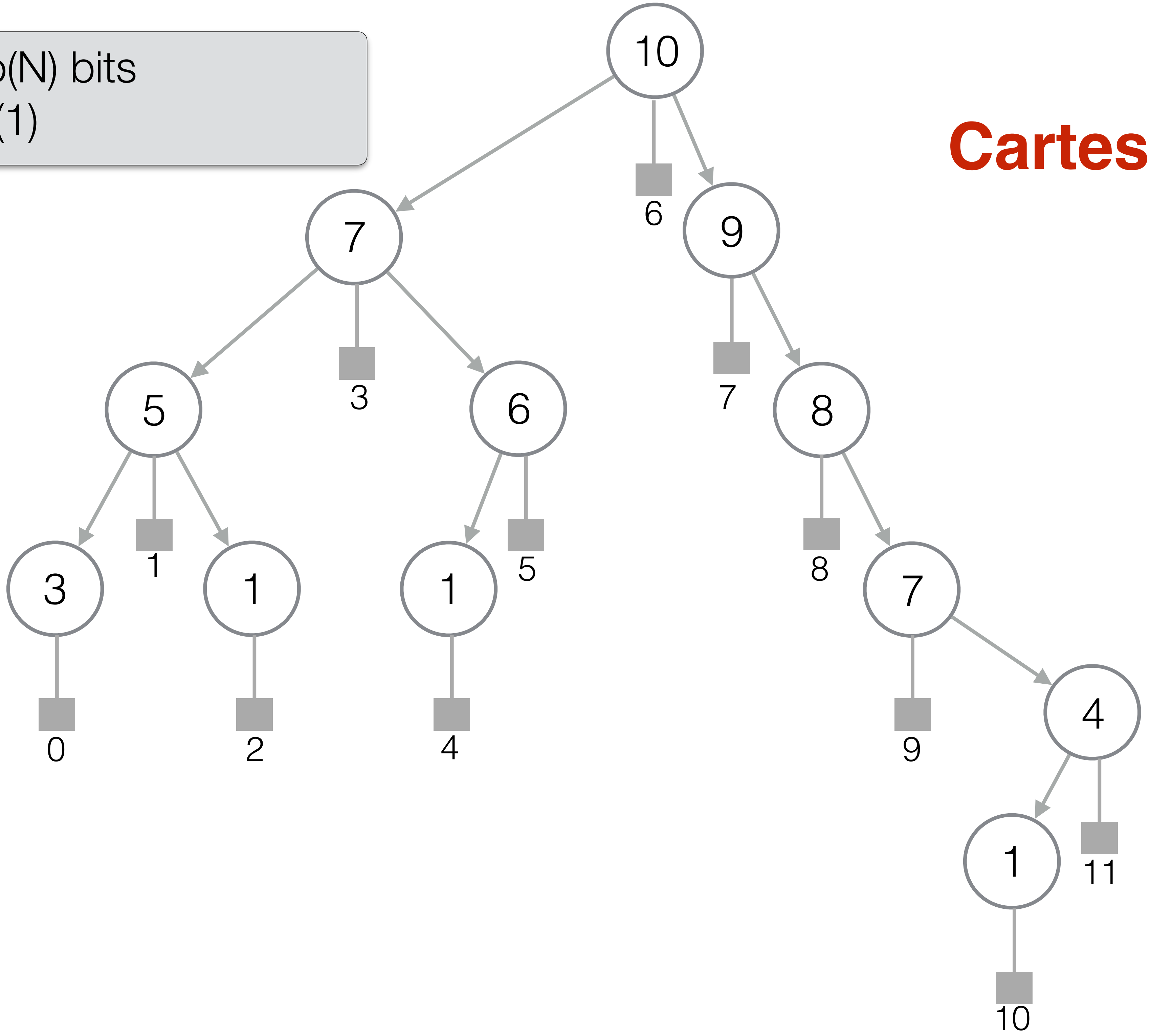


	0	1	2	3	4	5	6	7	8	9	10	11
S	3	5	1	7	1	6	10	9	8	7	1	4

Range Maximum Query (4)

Space: 4N + o(N) bits
Query time: O(1)

Cartesian Tree



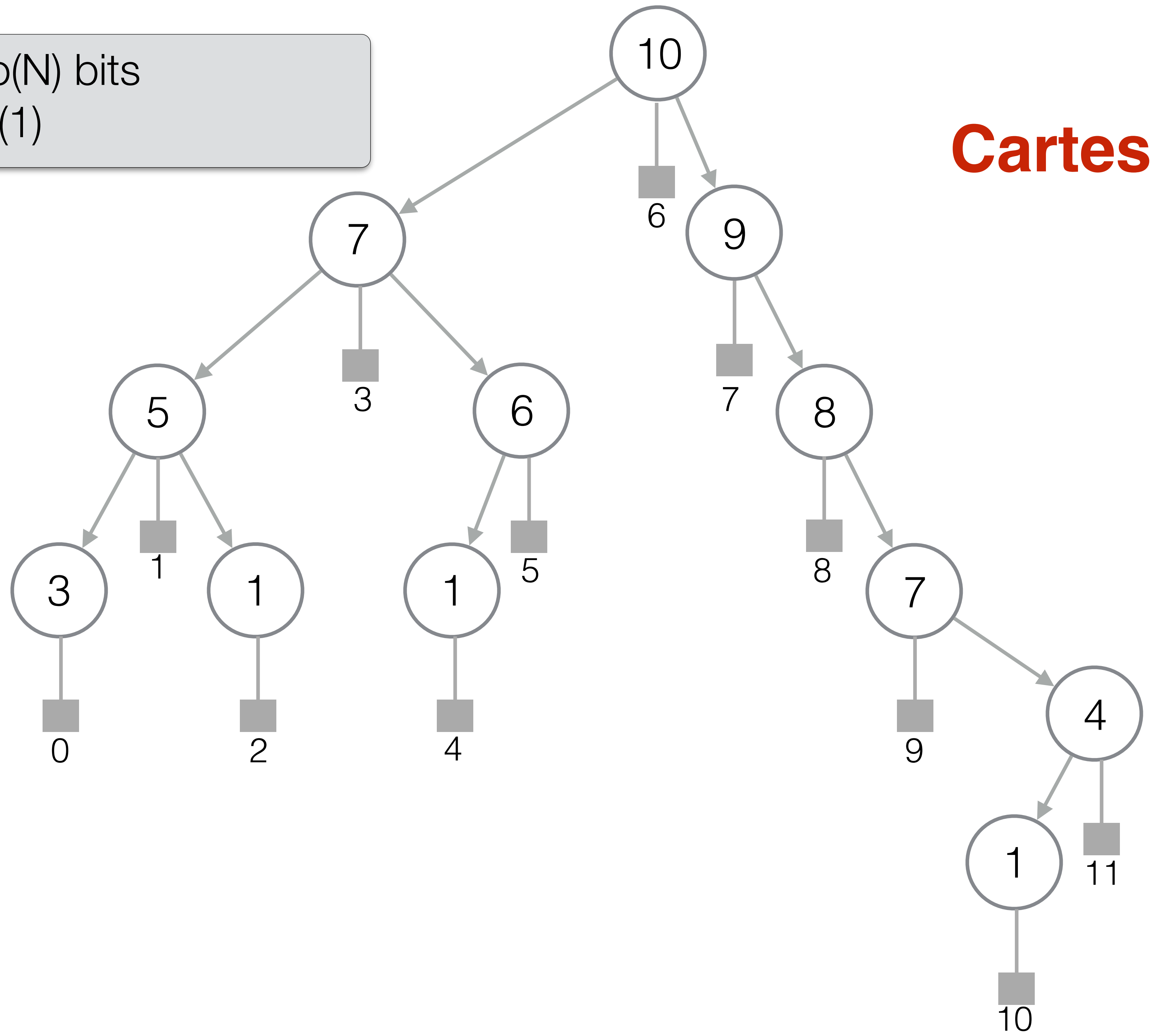
	0	1	2	3	4	5	6	7	8	9	10	11
S	3	5	1	7	1	6	10	9	8	7	1	4

Range Maximum Query (4)

Space: 4N + o(N) bits
Query time: O(1)

2N nodes

Cartesian Tree

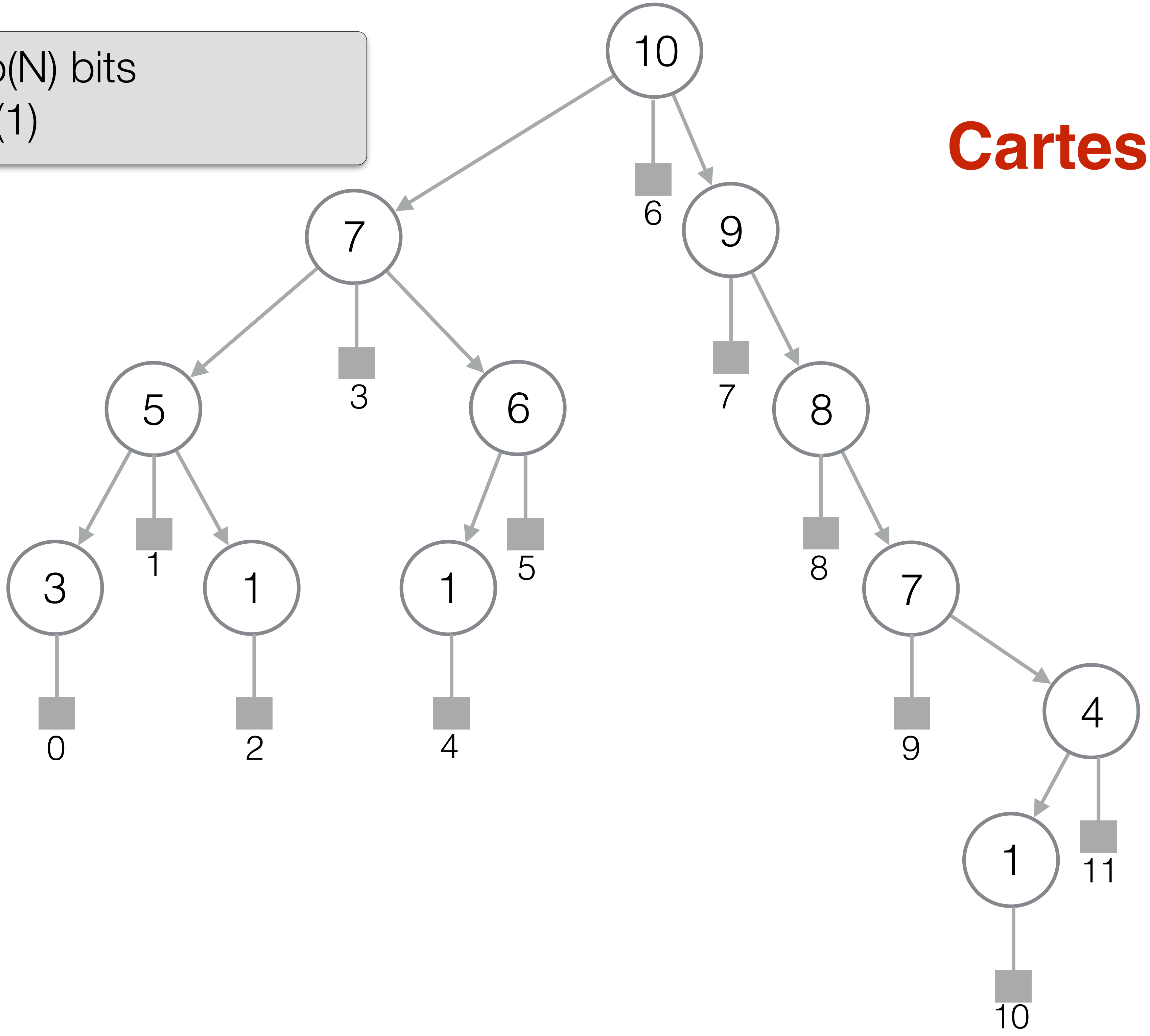


	0	1	2	3	4	5	6	7	8	9	10	11
S	3	5	1	7	1	6	10	9	8	7	1	4

Range Maximum Query (4)

Space: 4N + o(N) bits
Query time: O(1)

2N nodes



Cartesian Tree

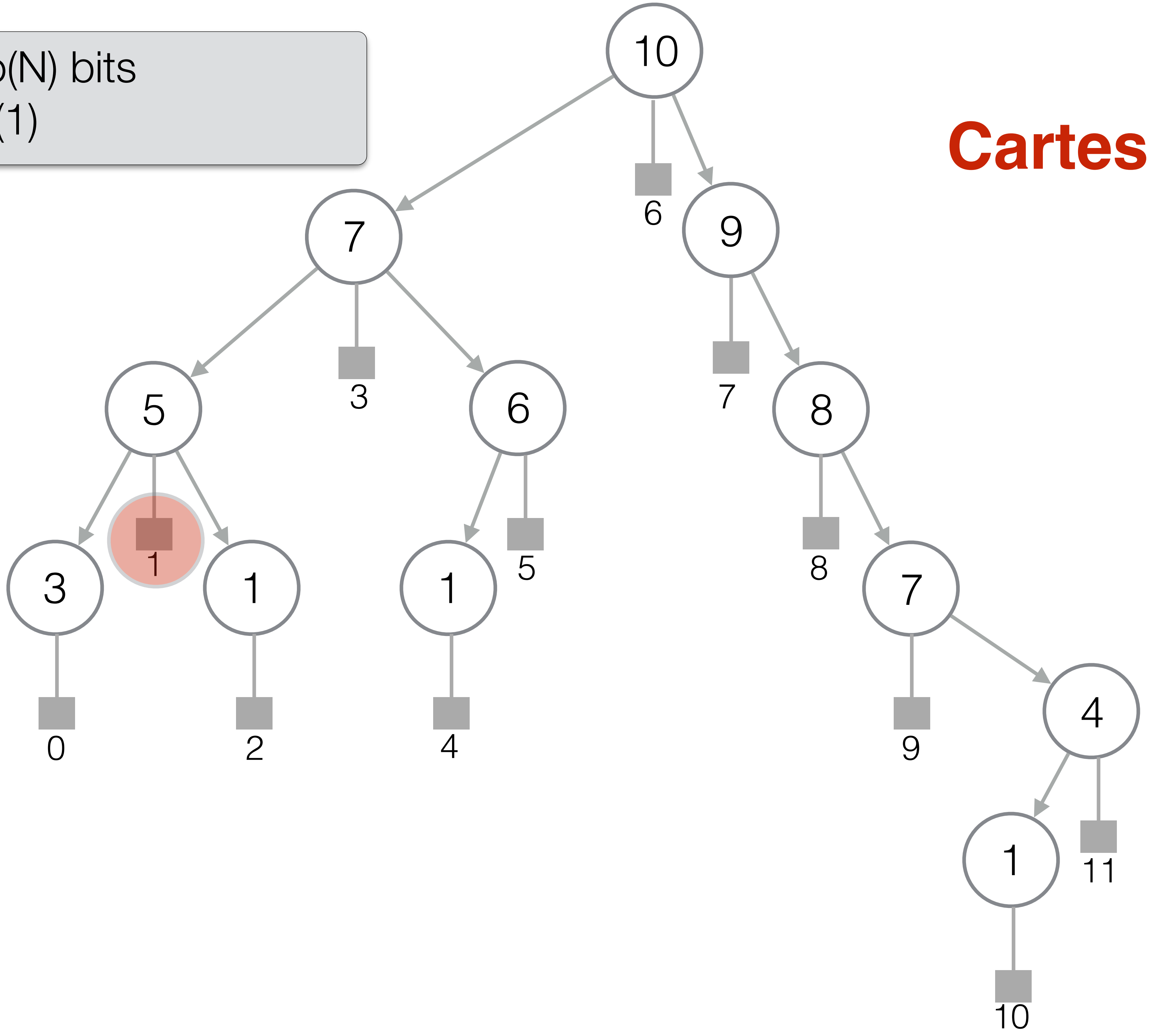
	0	1	2	3	4	5	6	7	8	9	10	11
S	3	5	1	7	1	6	10	9	8	7	1	4

Range Maximum Query (4)

Space: 4N + o(N) bits
Query time: O(1)

2N nodes

Cartesian Tree



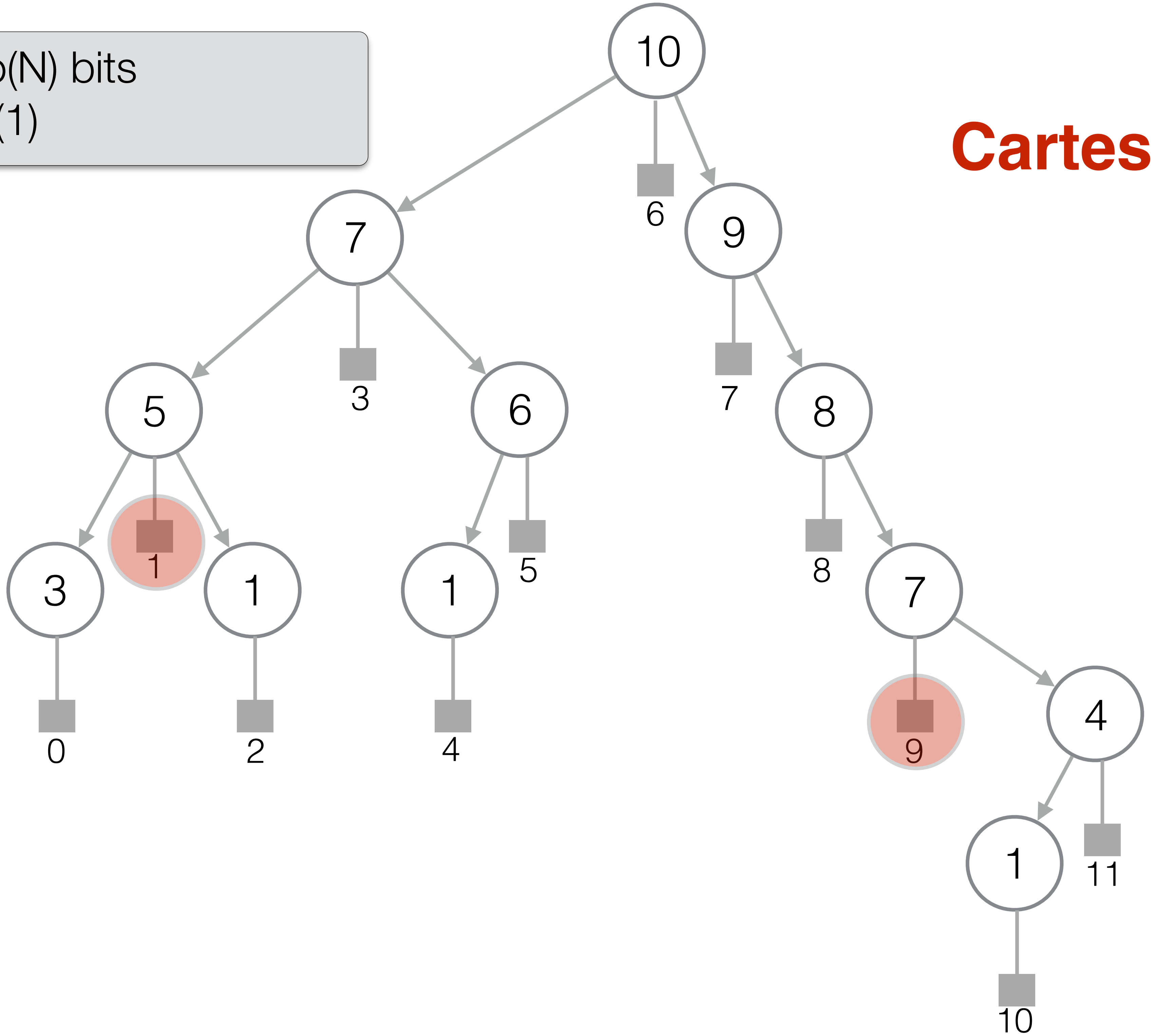
S	0	1	2	3	4	5	6	7	8	9	10	11
	3	5	1	7	1	6	10	9	8	7	1	4

Range Maximum Query (4)

Space: 4N + o(N) bits
Query time: O(1)

2N nodes

Cartesian Tree

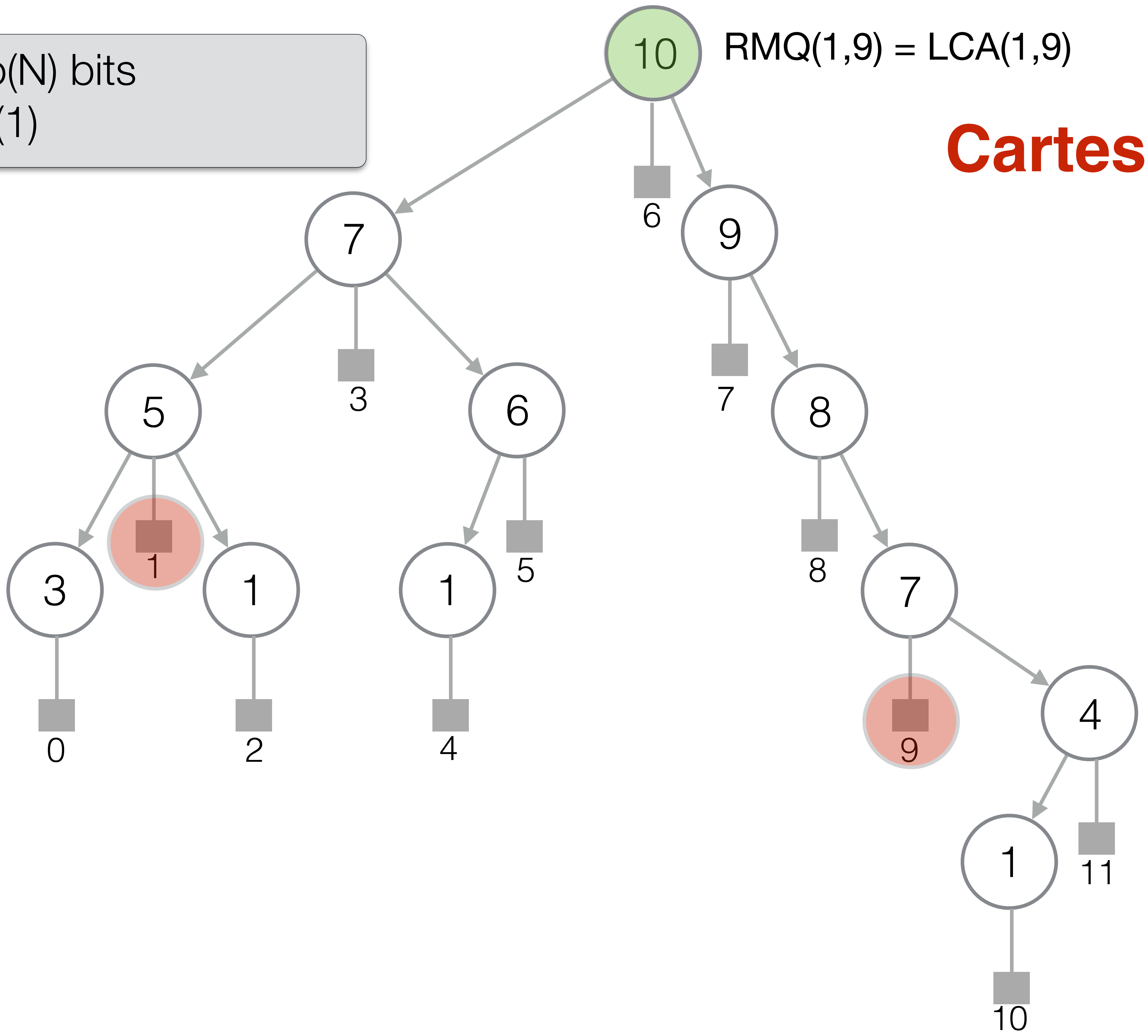


S	0	1	2	3	4	5	6	7	8	9	10	11
	3	5	1	7	1	6	10	9	8	7	1	4

Range Maximum Query (4)

Space: 4N + o(N) bits
Query time: O(1)

2N nodes



RMQ(1,9) = LCA(1,9)

Cartesian Tree

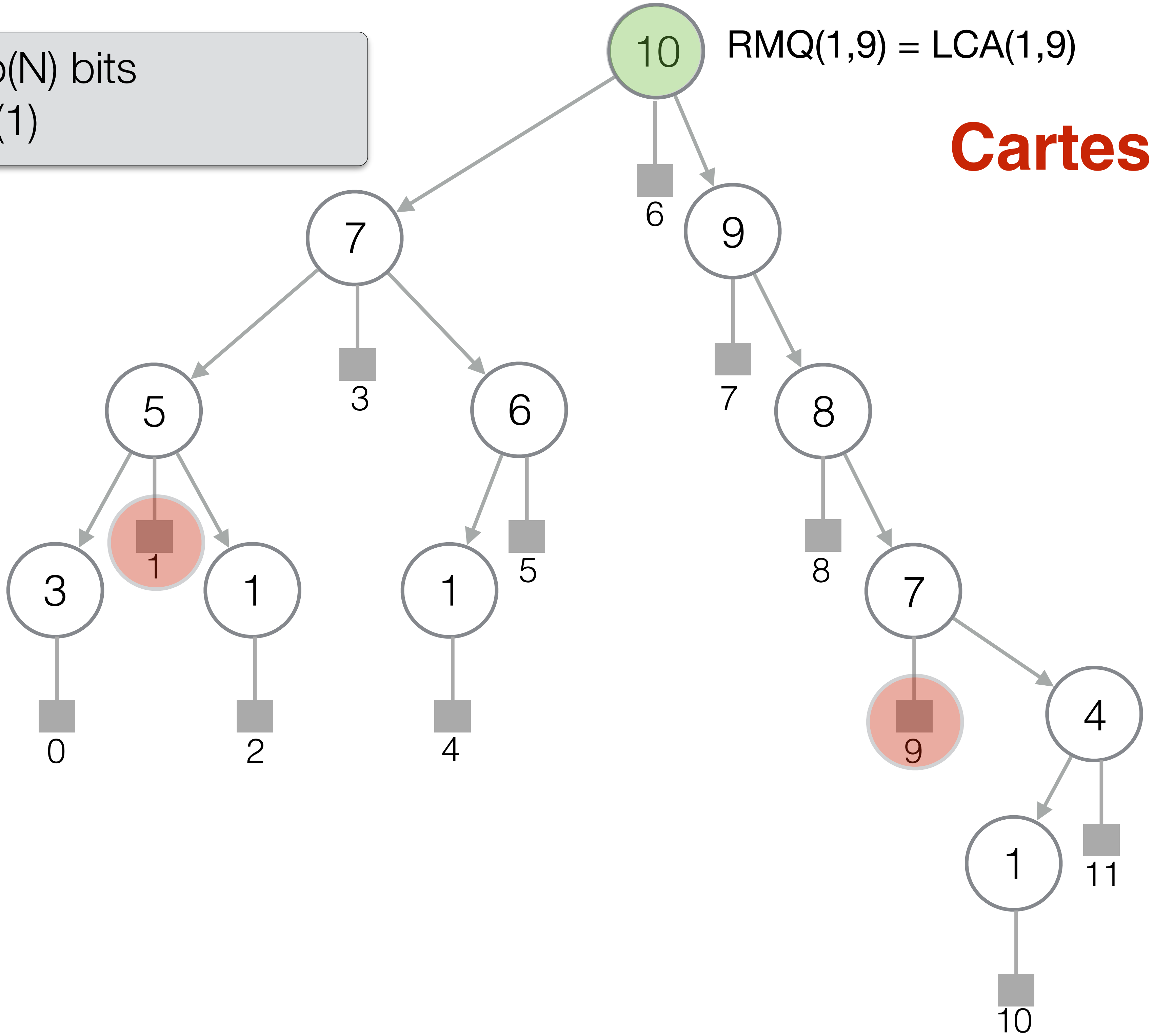
	0	1	2	3	4	5	6	7	8	9	10	11
S	3	5	1	7	1	6	10	9	8	7	1	4

Range Maximum Query (4)

Space: 4N + o(N) bits
Query time: O(1)

2N nodes

LCA in O(1)



RMQ(1,9) = LCA(1,9)

Cartesian Tree

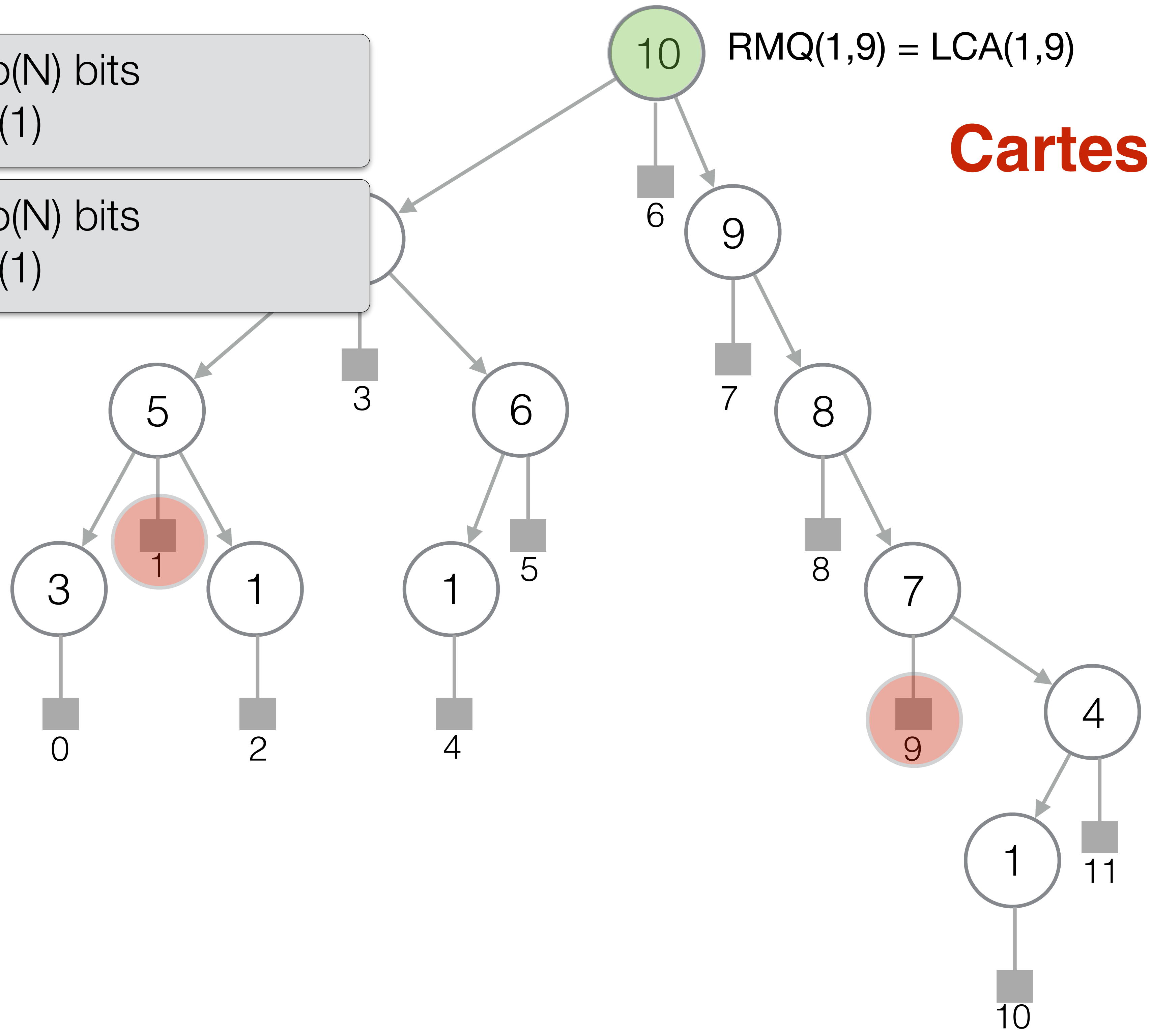
	0	1	2	3	4	5	6	7	8	9	10	11
S	3	5	1	7	1	6	10	9	8	7	1	4

Range Maximum Query (4)

Space: 4N + o(N) bits
Query time: O(1)

Space: 2N + o(N) bits
Query time: O(1)

LCA in O(1)

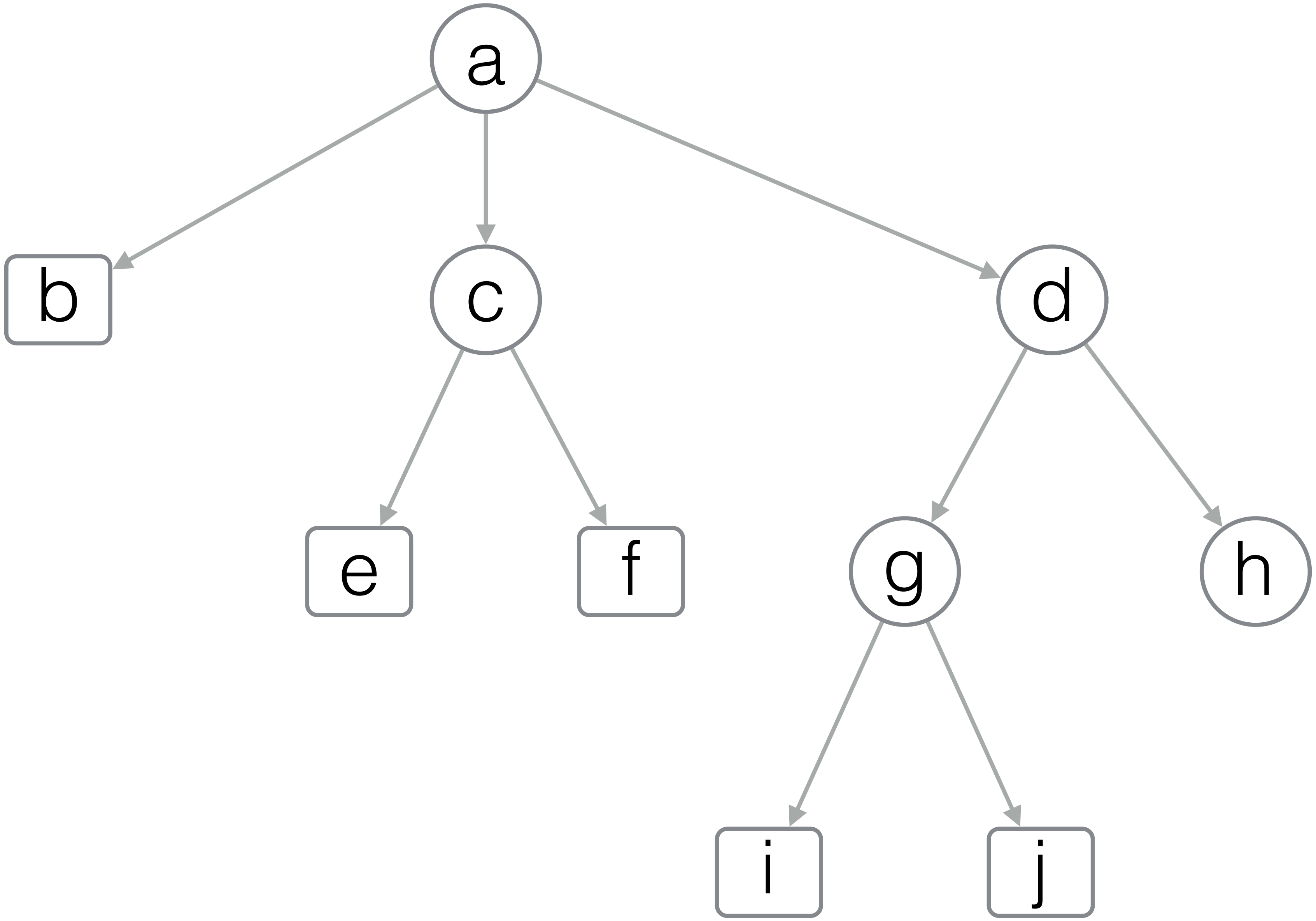


RMQ(1,9) = LCA(1,9)

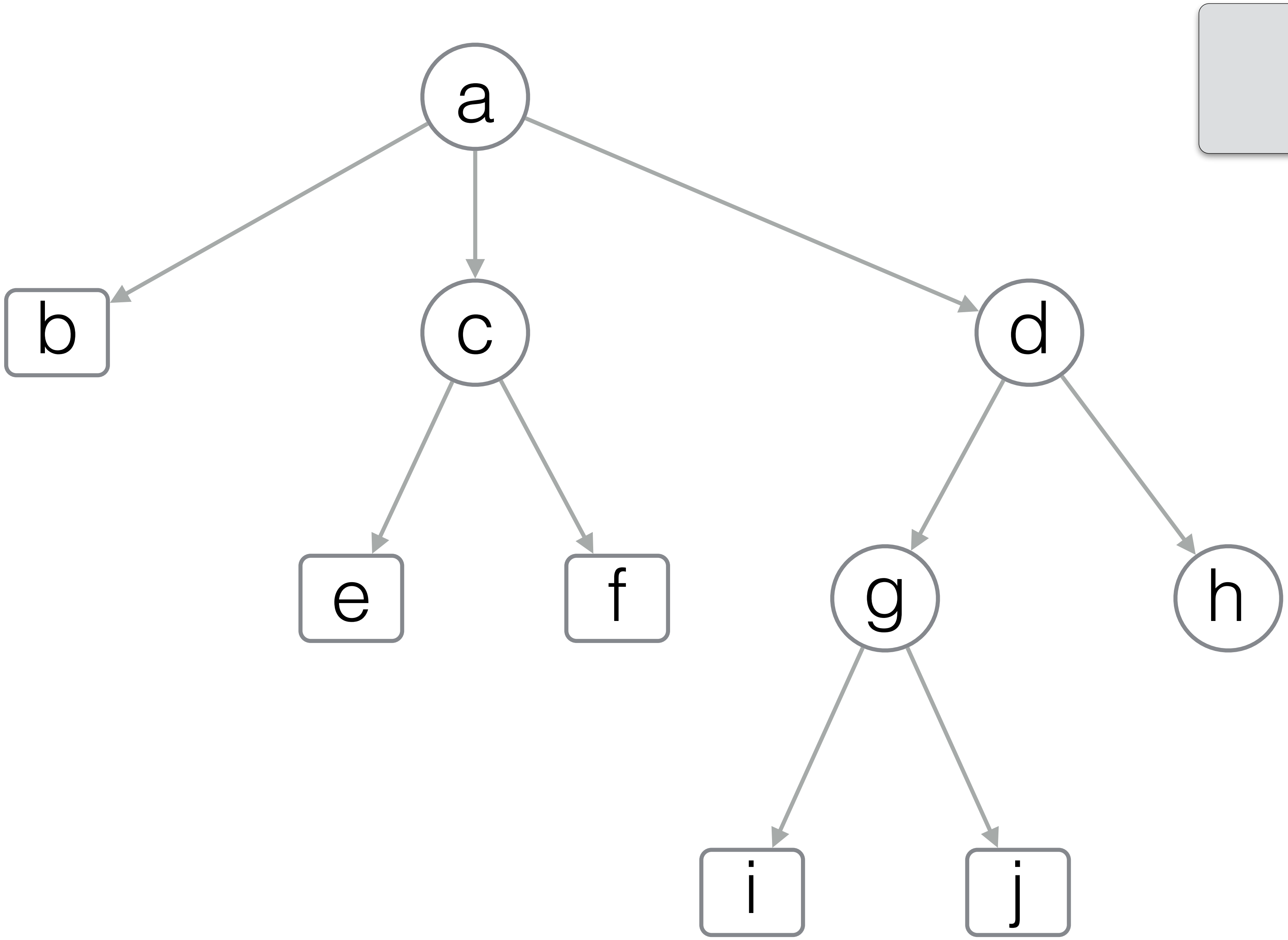
Cartesian Tree

	0	1	2	3	4	5	6	7	8	9	10	11
S	3	5	1	7	1	6	10	9	8	7	1	4

Solve LCA with RMQ

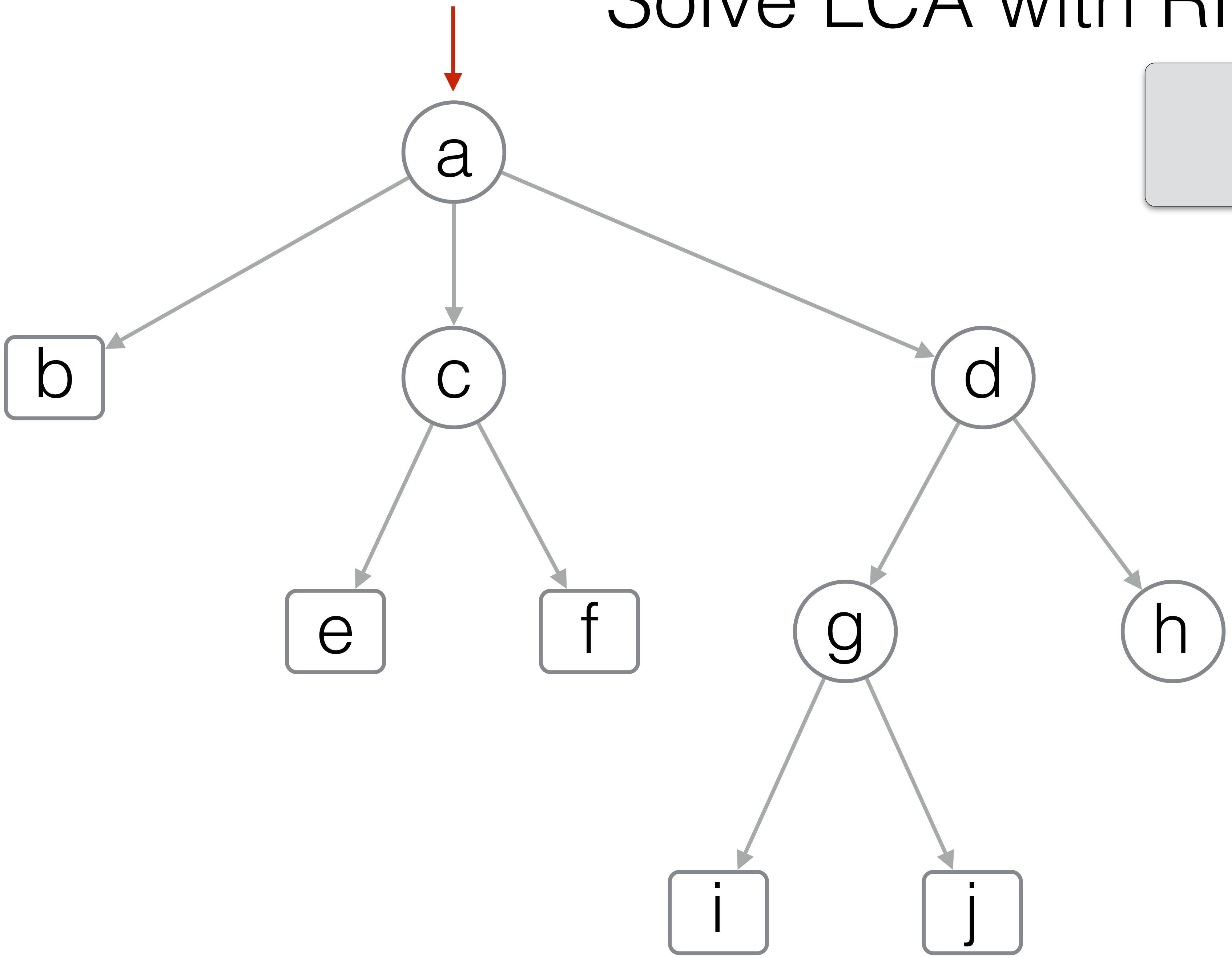


Solve LCA with RMQ



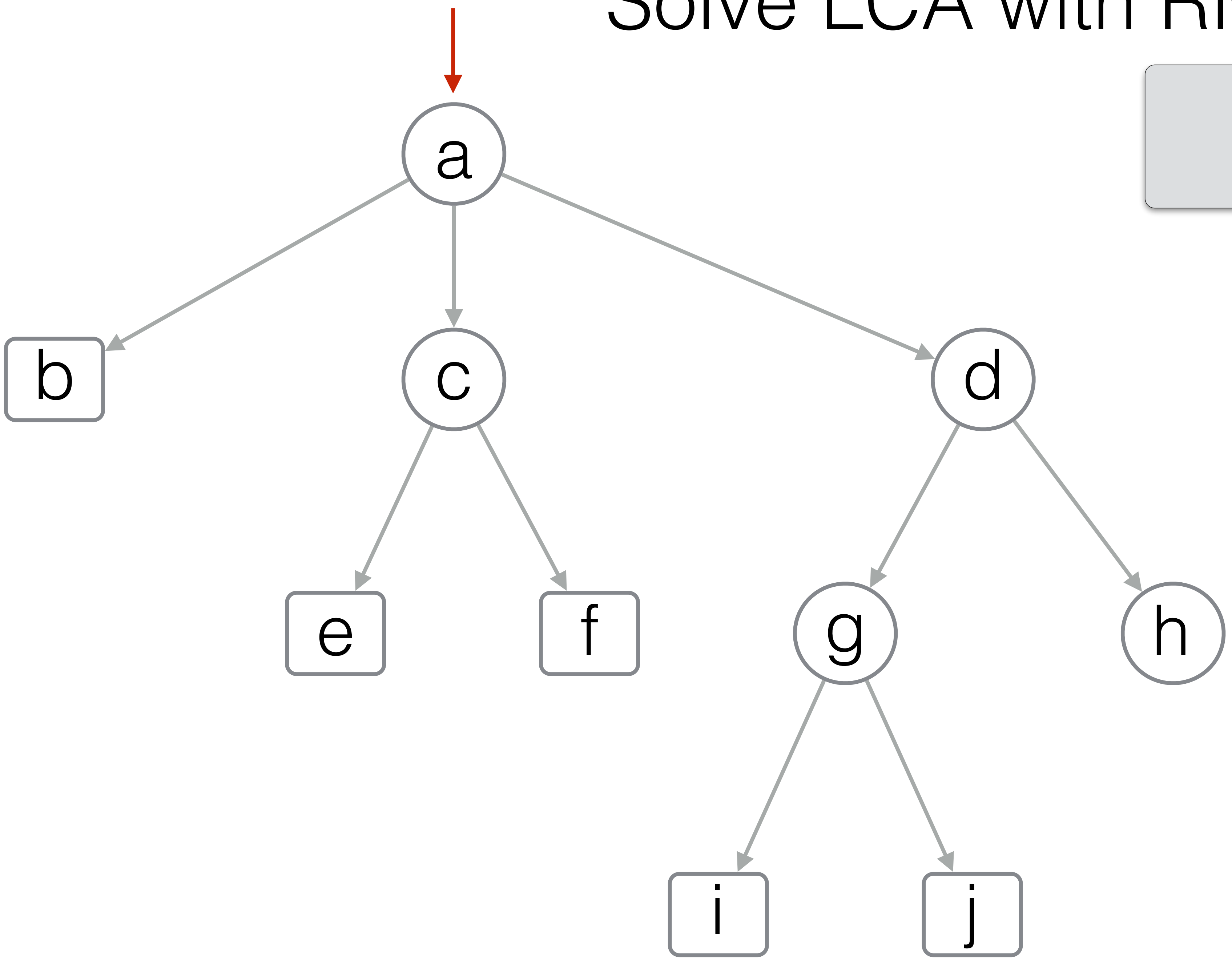
Eulerian Tour of the tree

Solve LCA with RMQ



Eulerian Tour of the tree

Solve LCA with RMQ

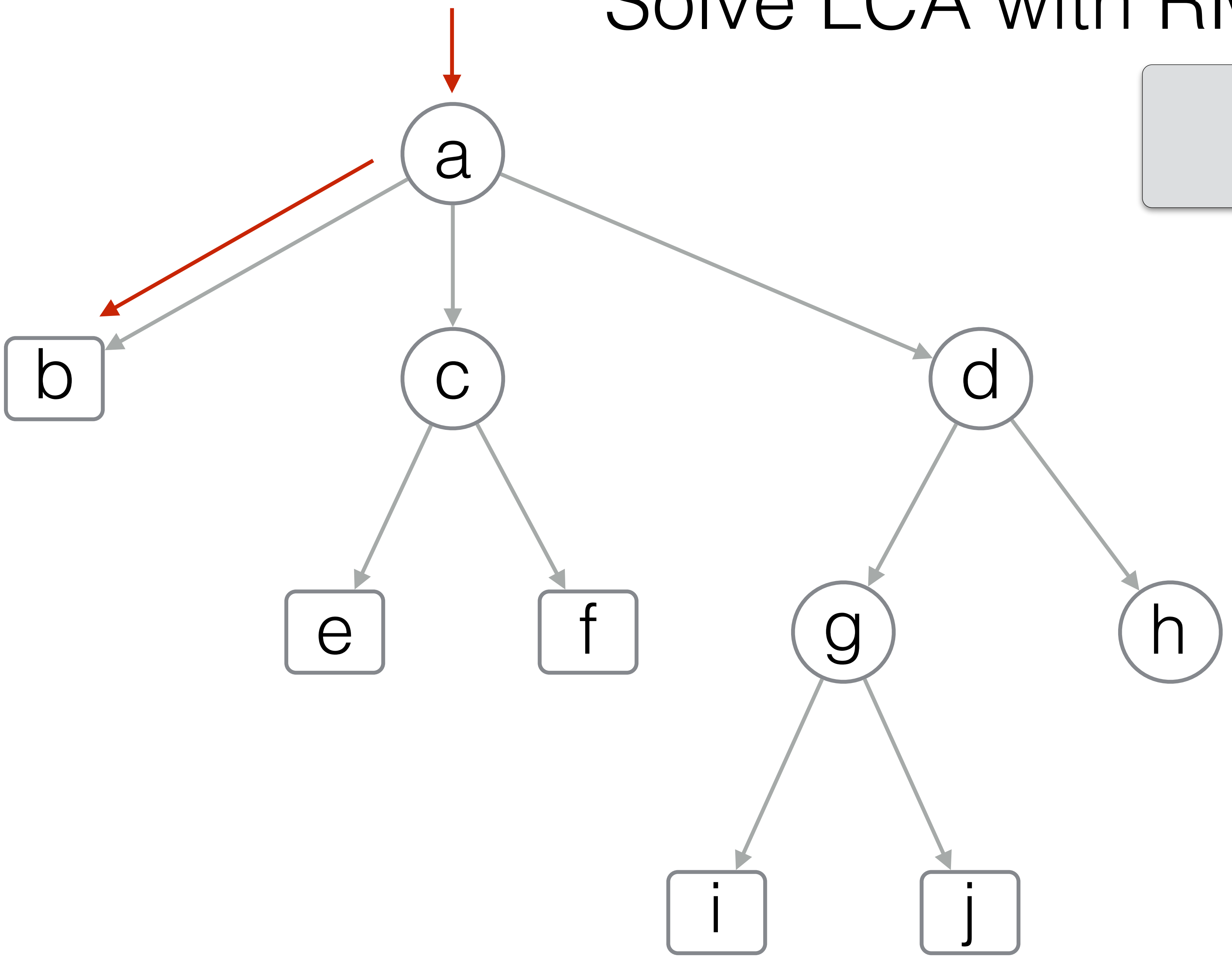


Eulerian Tour of the tree

R a

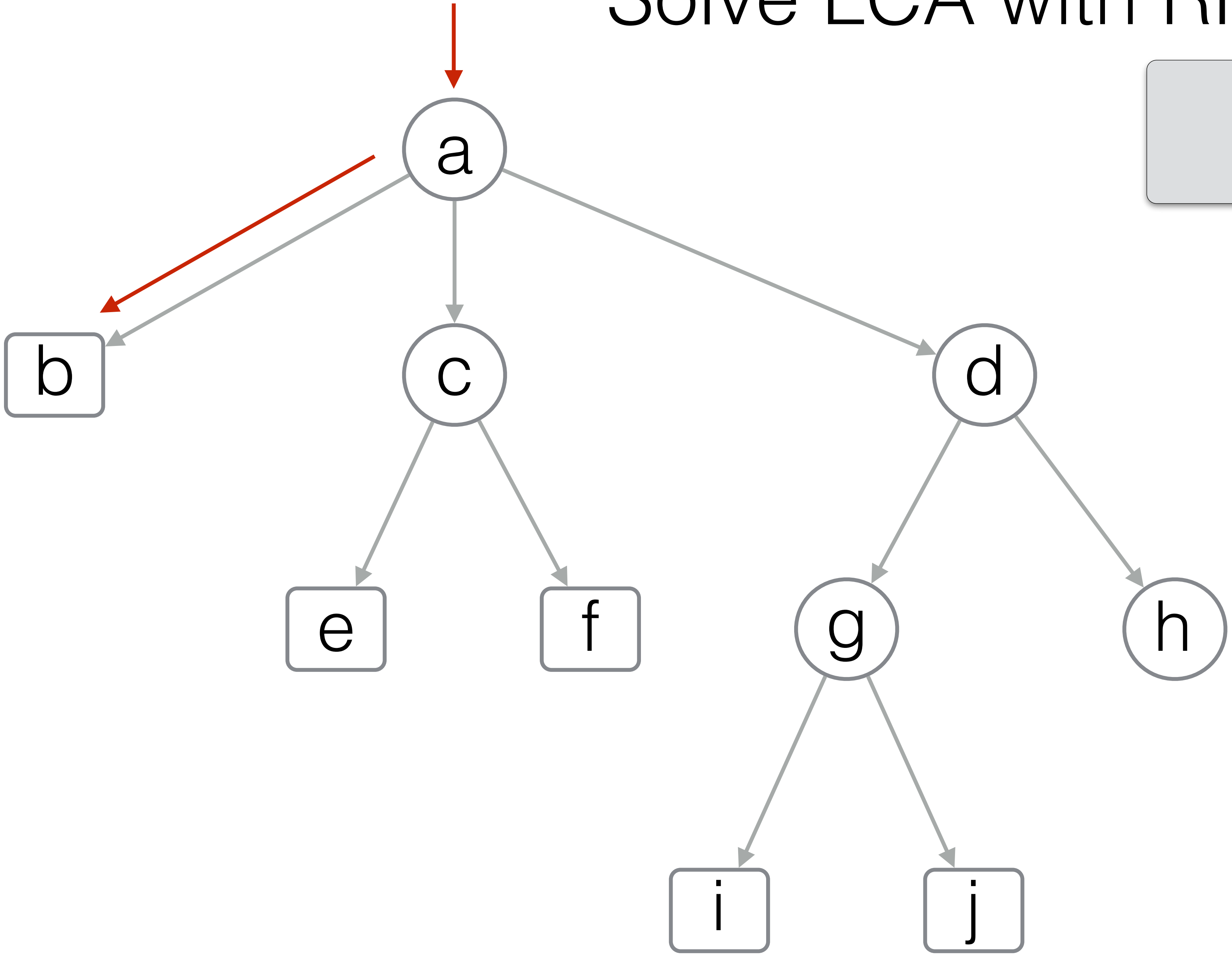
Solve LCA with RMQ

Eulerian Tour of the tree



R a

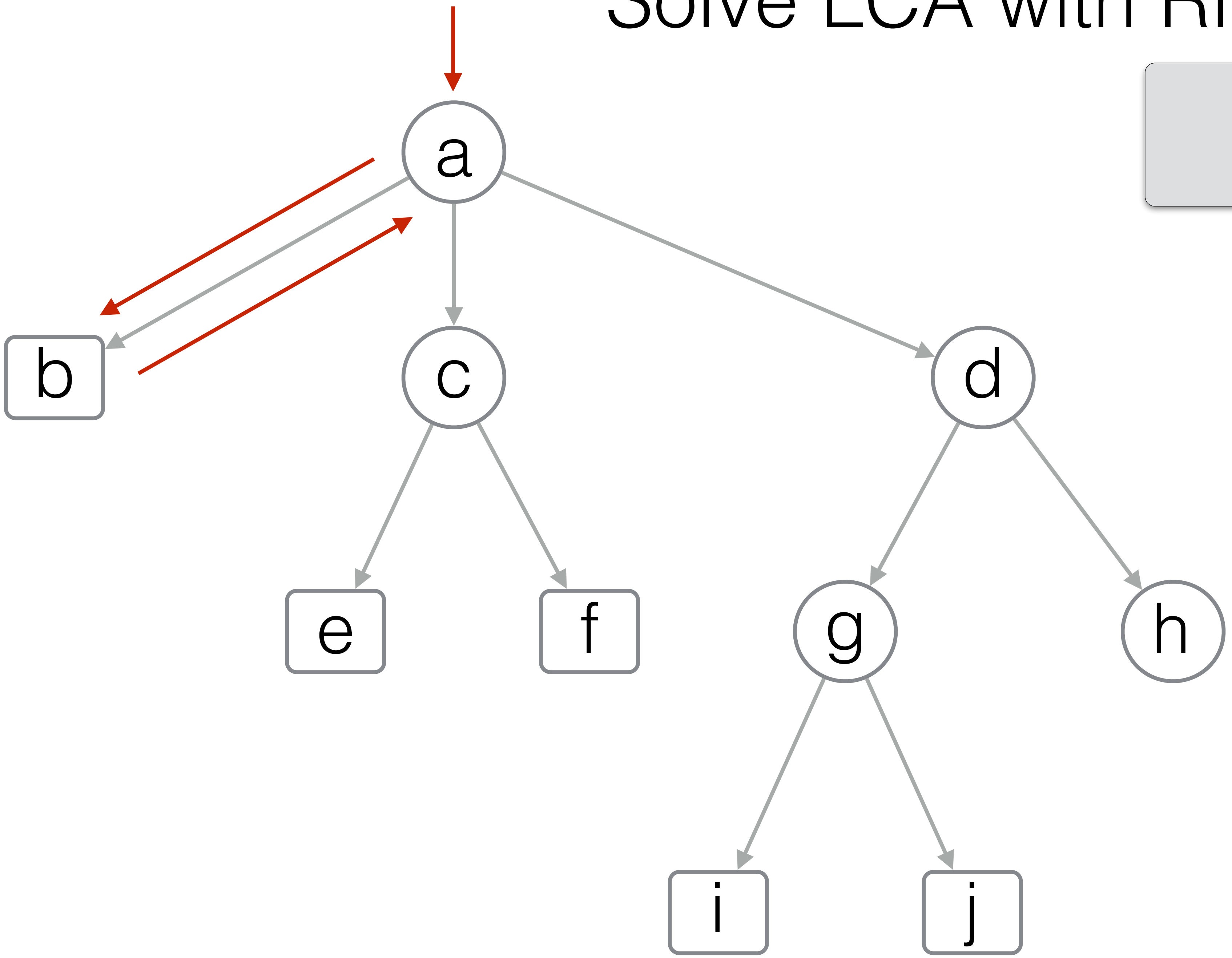
Solve LCA with RMQ



Eulerian Tour of the tree

R a b

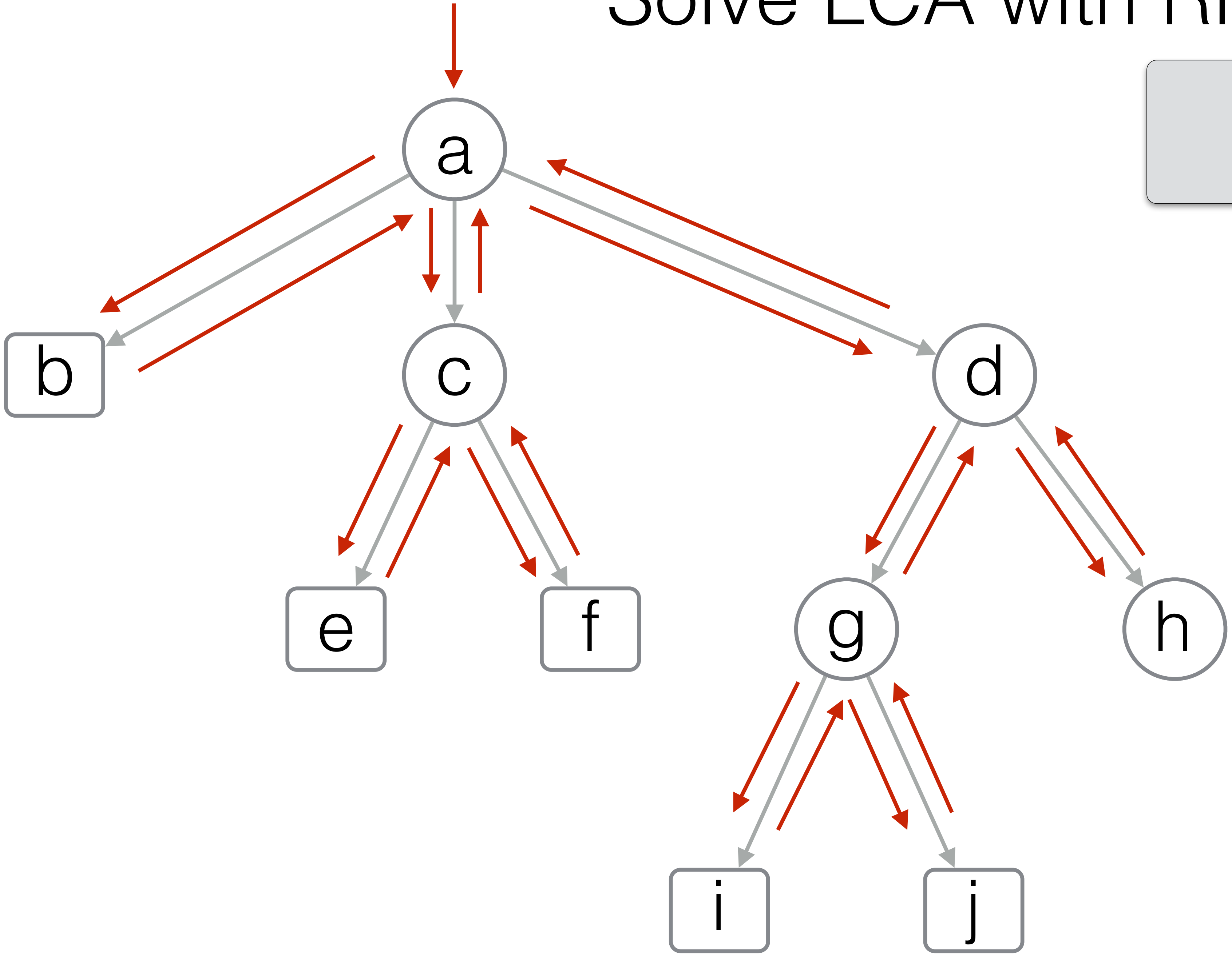
Solve LCA with RMQ



Eulerian Tour of the tree

R a b a

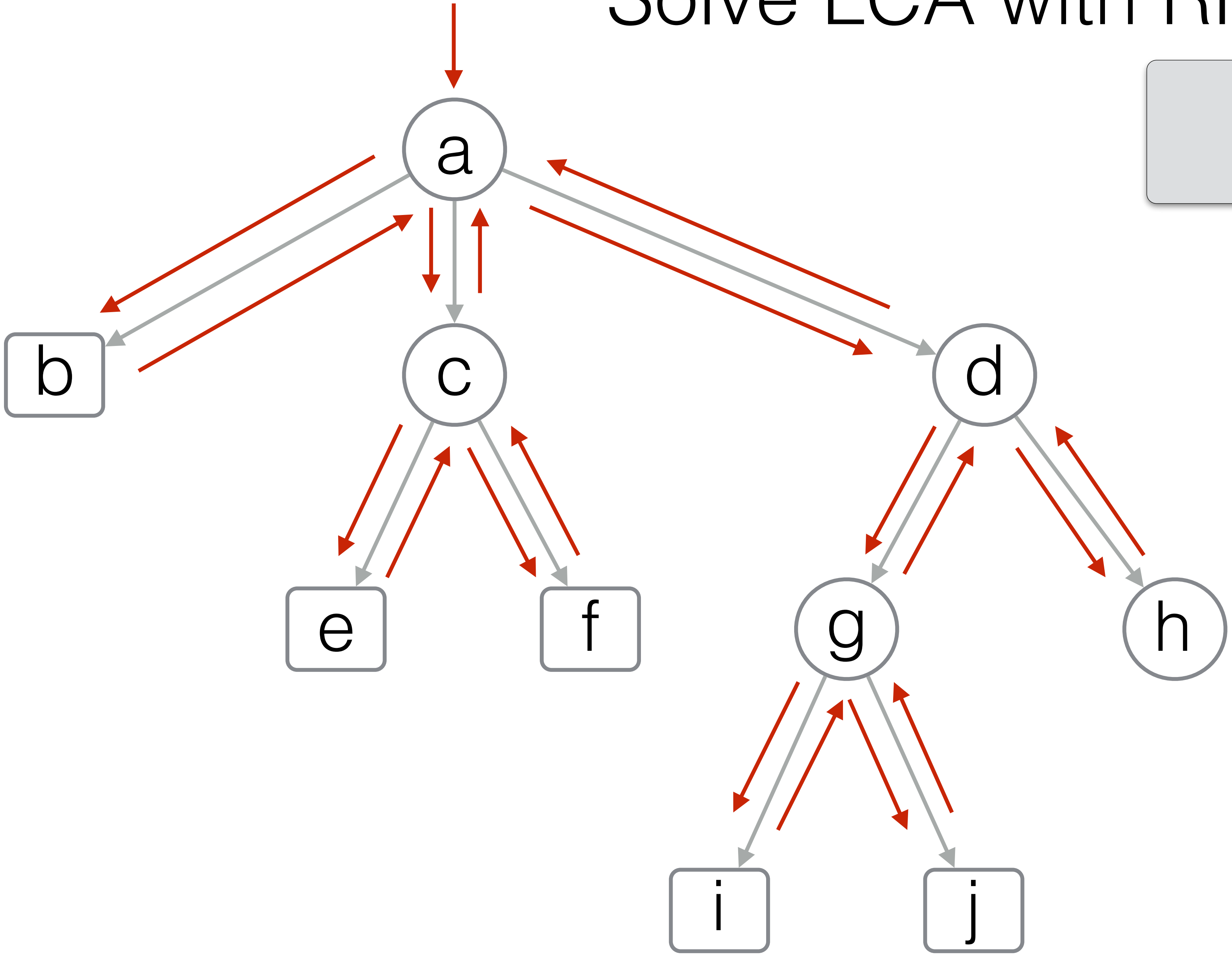
Solve LCA with RMQ



Eulerian Tour of the tree

R a b a

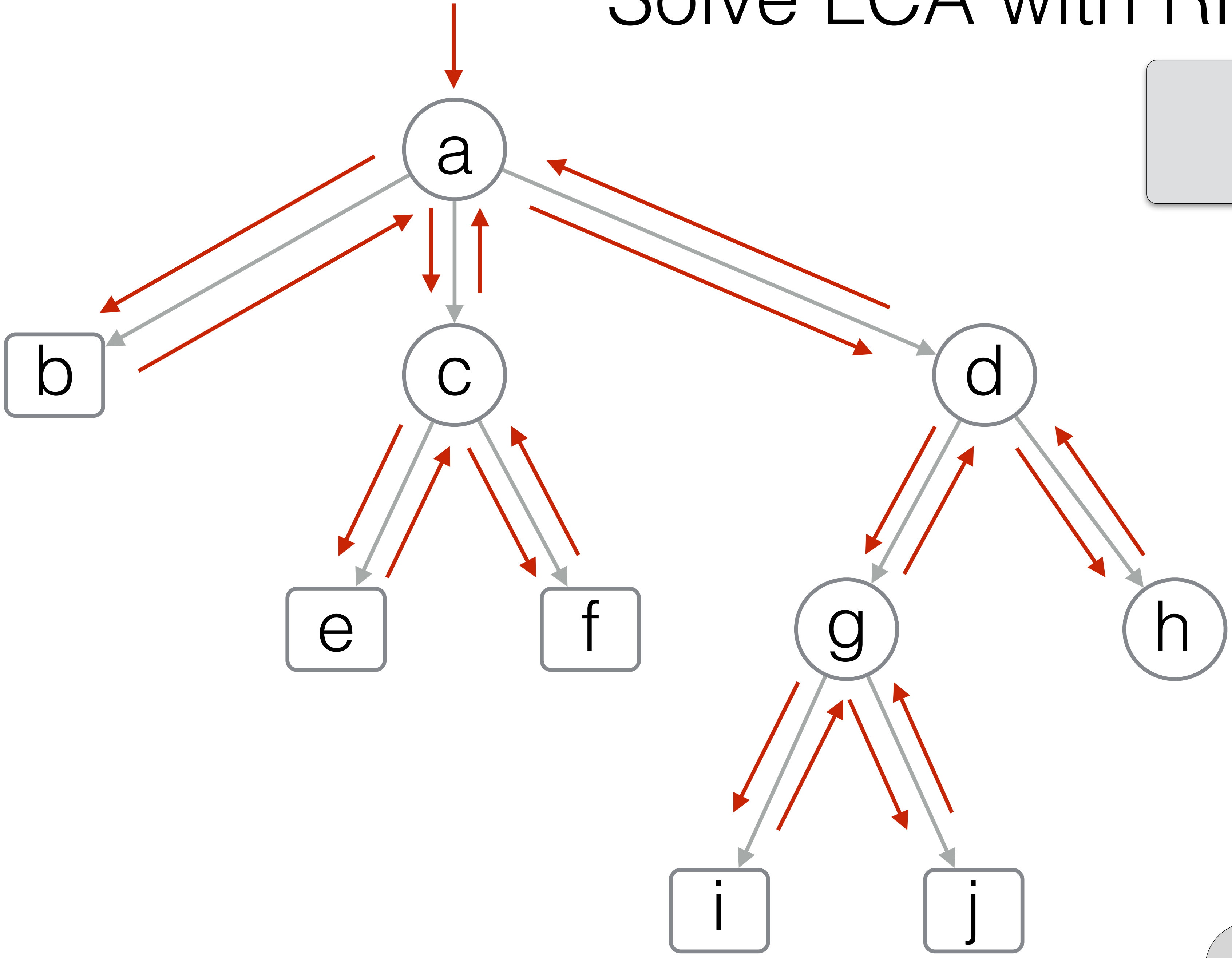
Solve LCA with RMQ



Eulerian Tour of the tree

R a b a c e c f c a d g i g j g d h d a

Solve LCA with RMQ

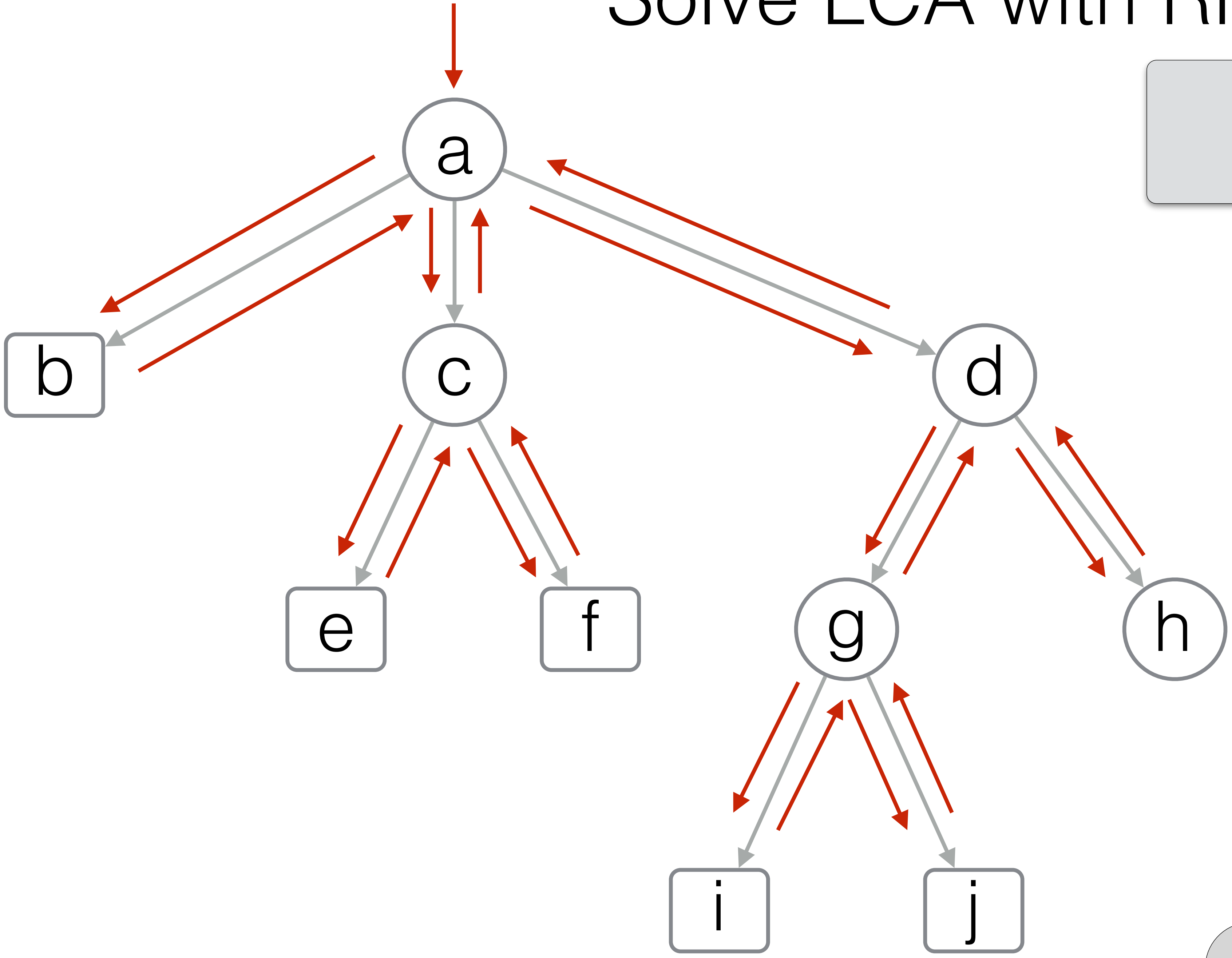


Eulerian Tour of the tree

How many symbols?

R a b a c e c f c a d g i g j g d h d a

Solve LCA with RMQ



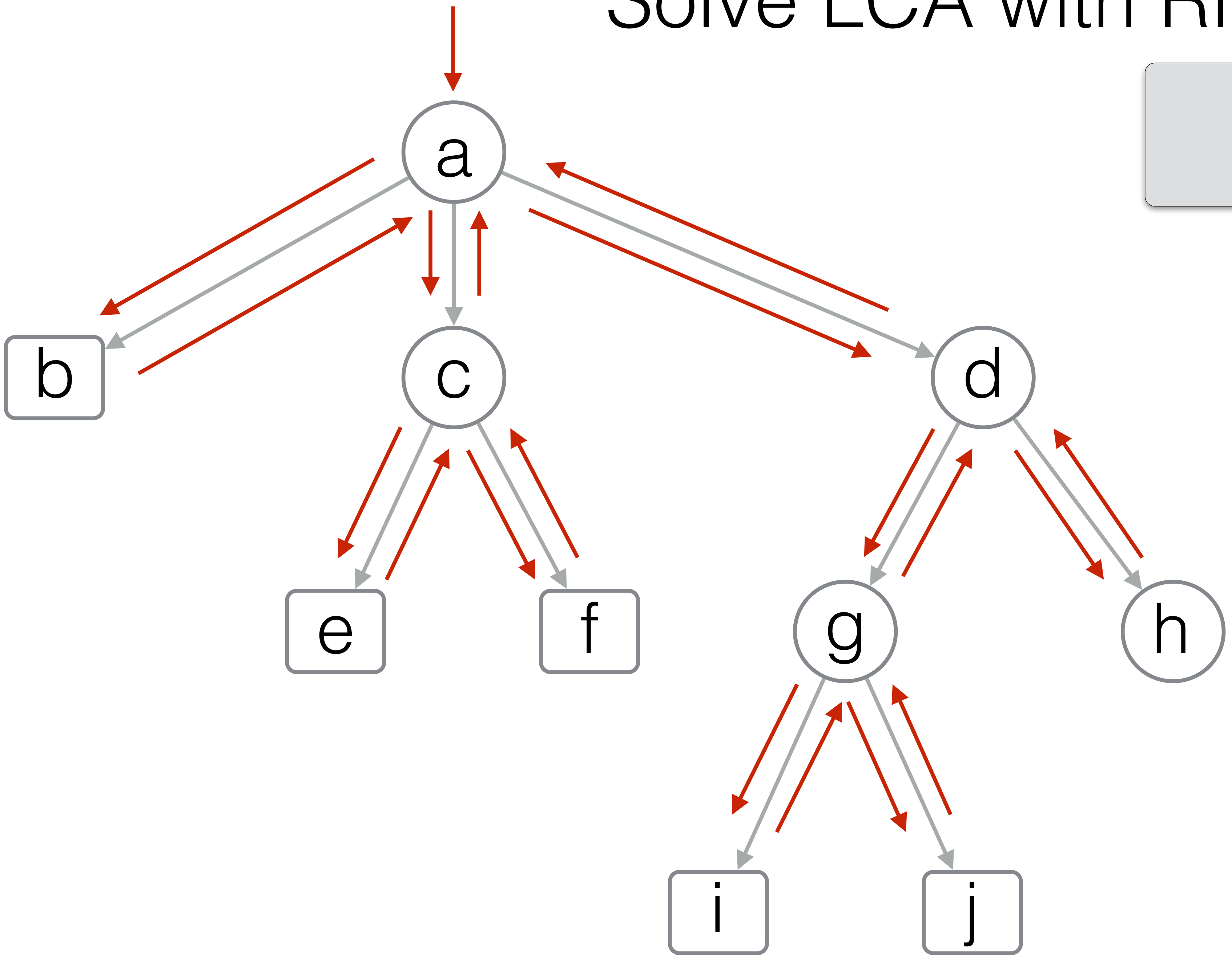
Eulerian Tour of the tree

How many symbols?

Two symbols per edge
⇒
|R| = 2n - 2

R a b a c e c f c a d g i g j g d h d a

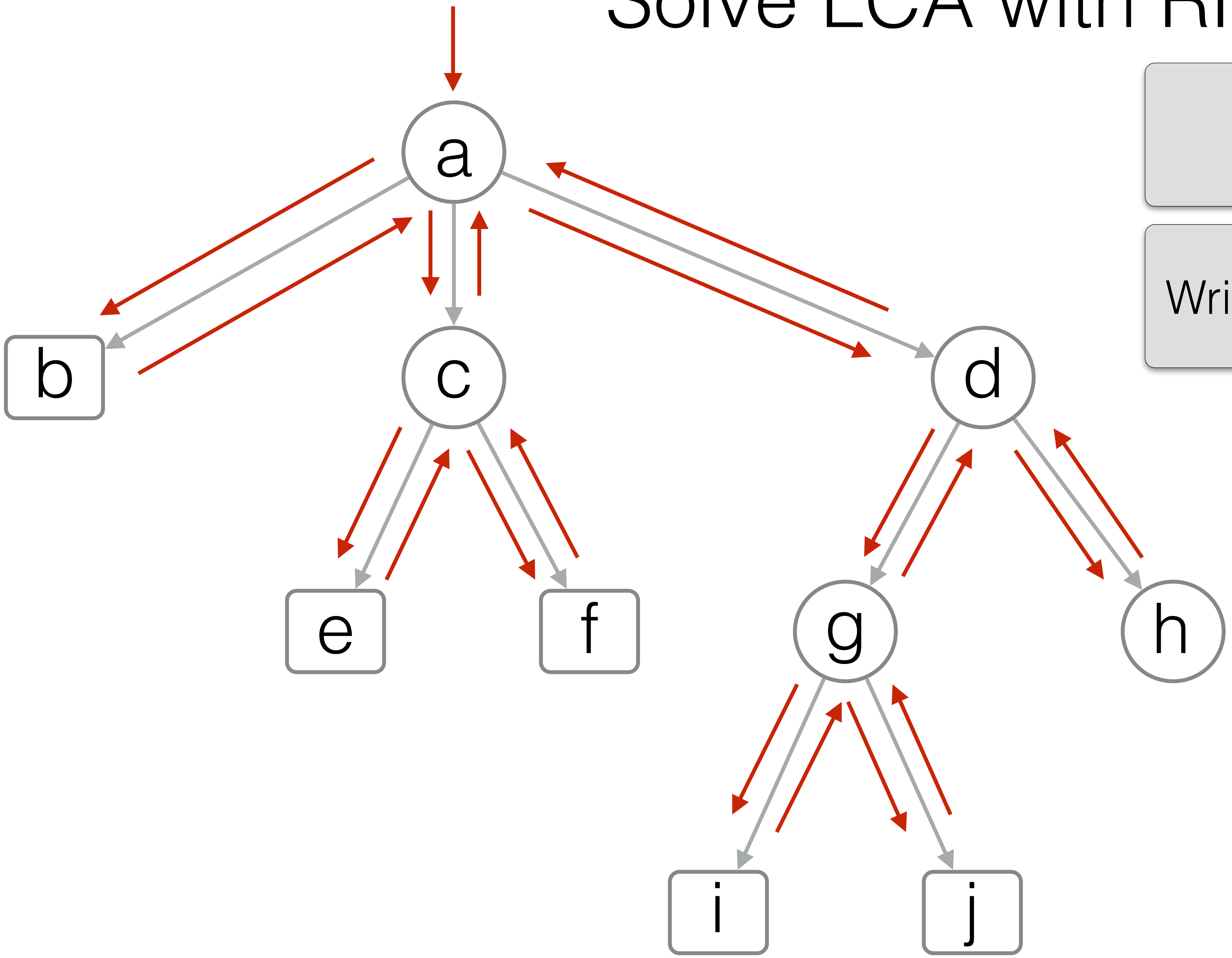
Solve LCA with RMQ



Eulerian Tour of the tree

R   a b a c e c f c a d g i g j g d h d a

Solve LCA with RMQ

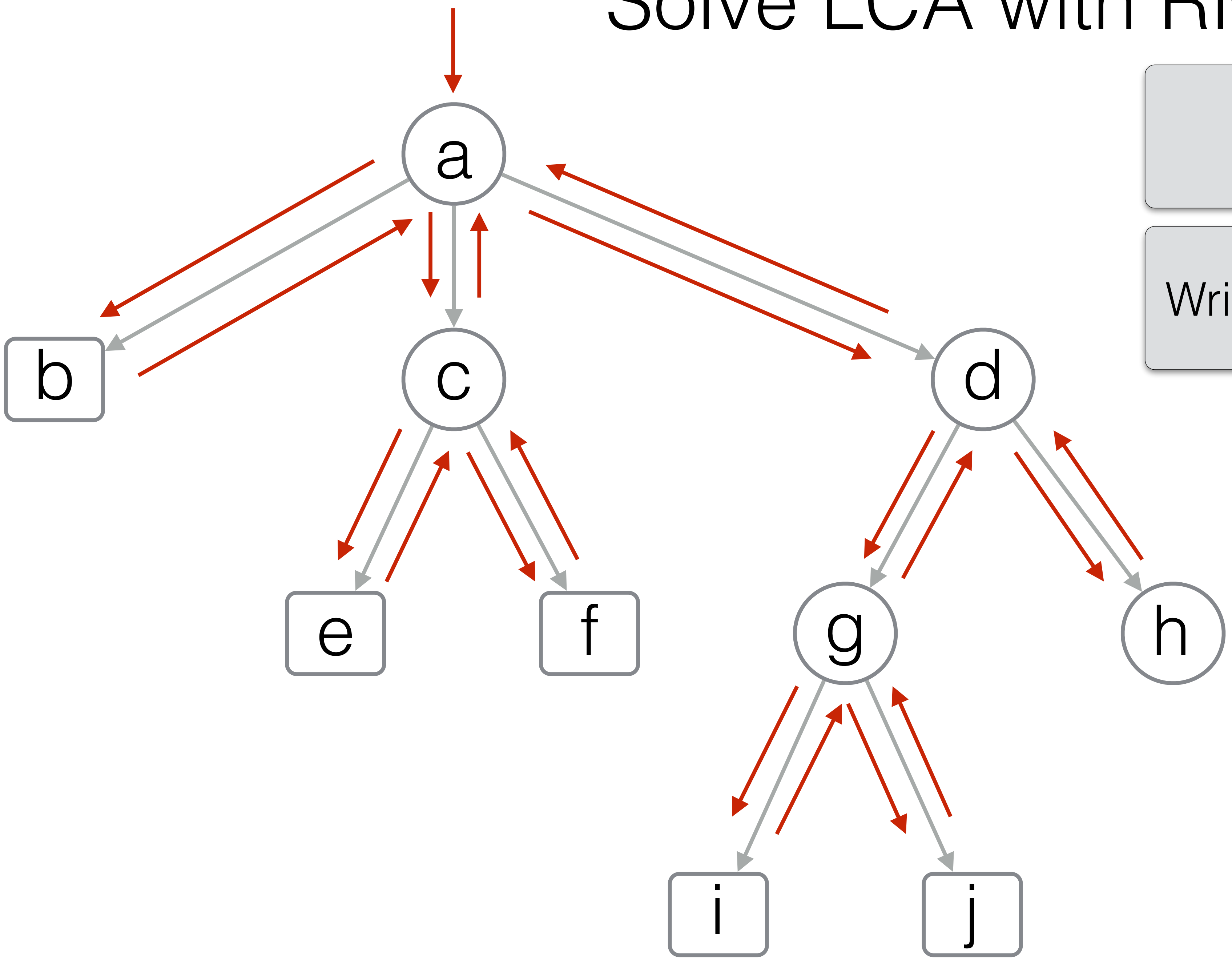


Eulerian Tour of the tree

Write in L the level of each node of R

R a b a c e c f c a d g i g j g d h d a

Solve LCA with RMQ



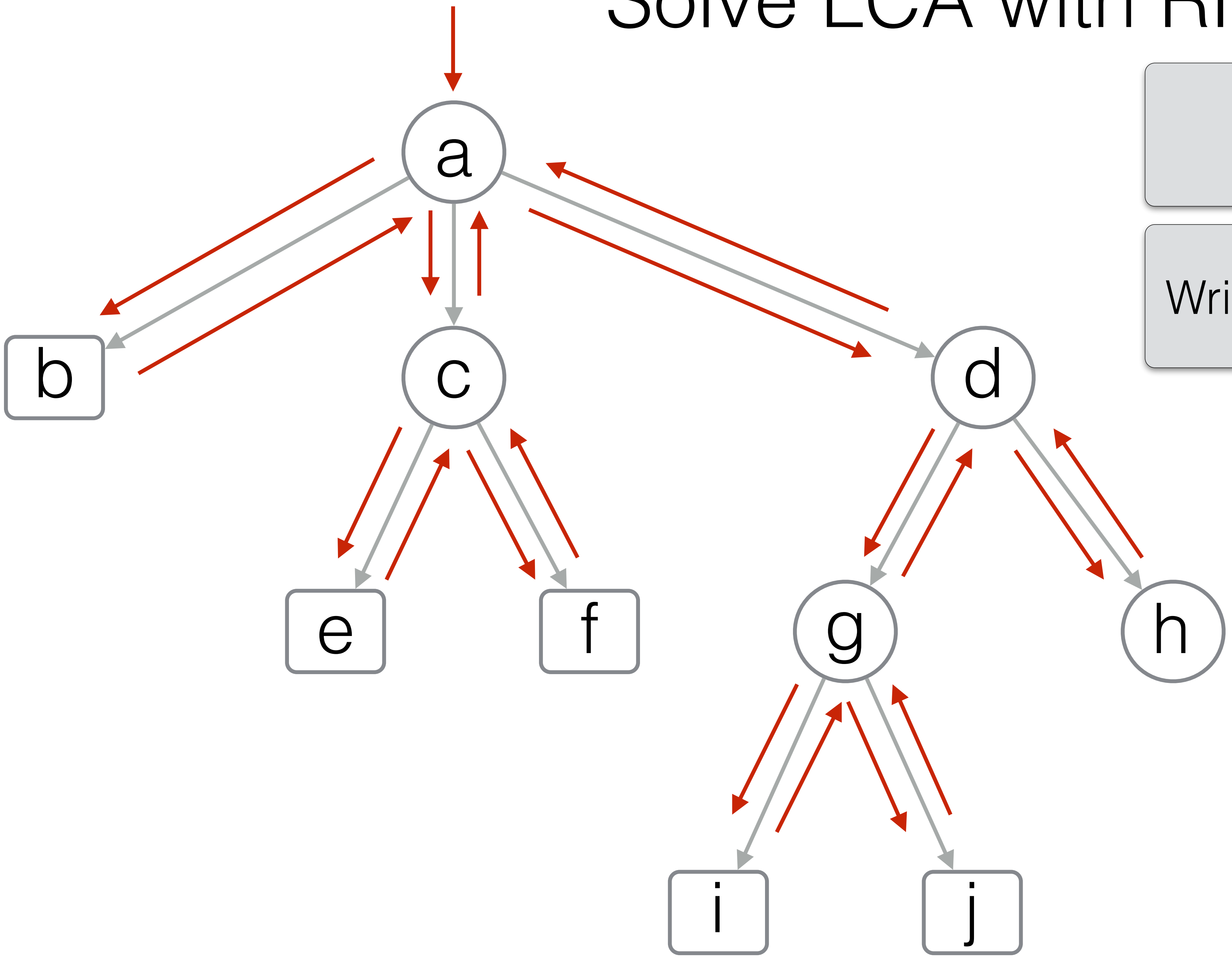
Eulerian Tour of the tree

Write in L the level of each node of R

R a b a c e c f c a d g i g j g d h d a

L 0

Solve LCA with RMQ



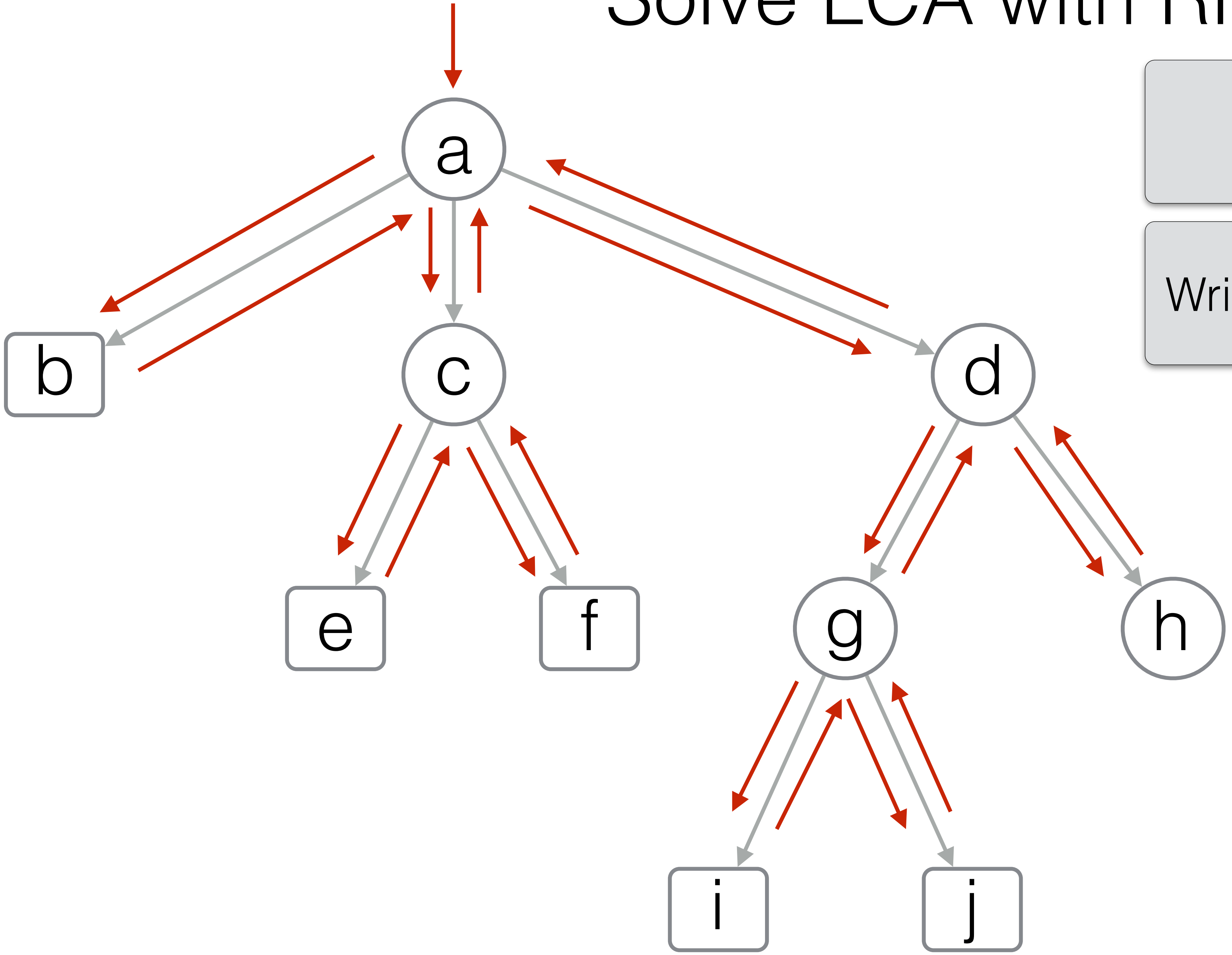
Eulerian Tour of the tree

Write in L the level of each node of R

R a b a c e c f c a d g i g j g d h d a

L 0 1

Solve LCA with RMQ



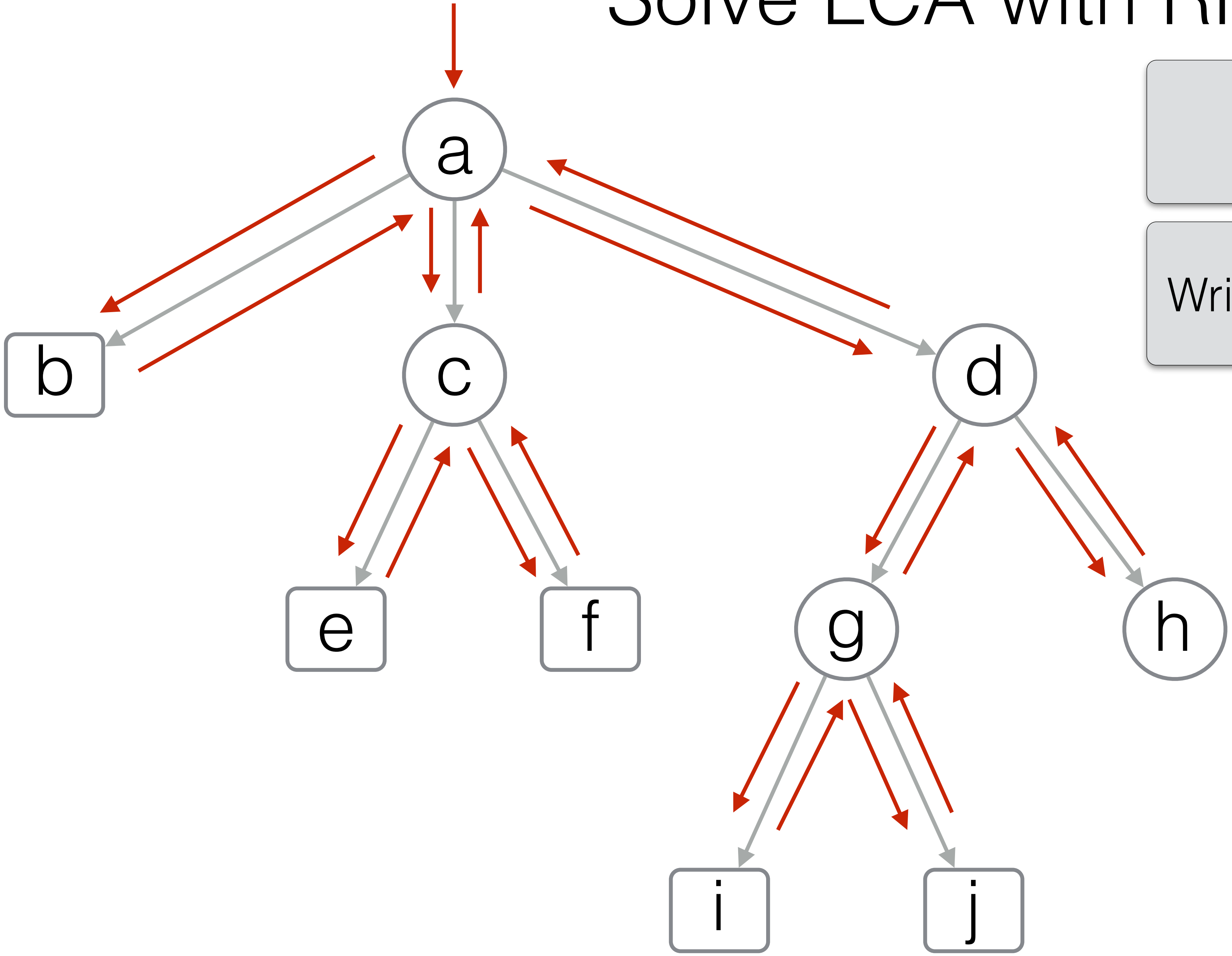
Eulerian Tour of the tree

Write in L the level of each node of R

R a b a c e c f c a d g i g j g d h d a

L 0 1 0

Solve LCA with RMQ



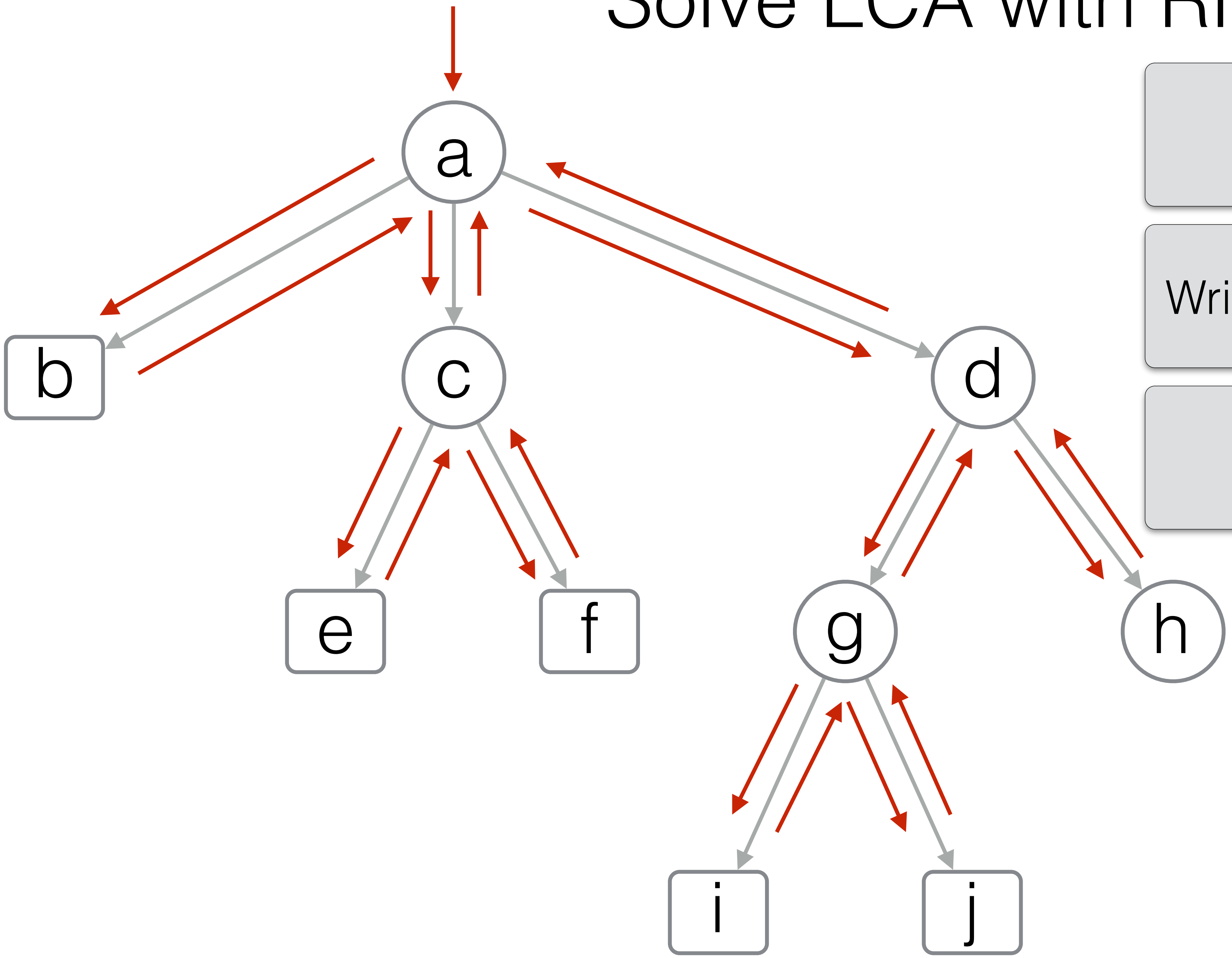
Eulerian Tour of the tree

Write in L the level of each node of R

R a b a c e c f c a d g i g j g d h d a

L 0 1 0 1 2 1 2 1 0 1 2 3 2 3 2 1 2 1 0

Solve LCA with RMQ



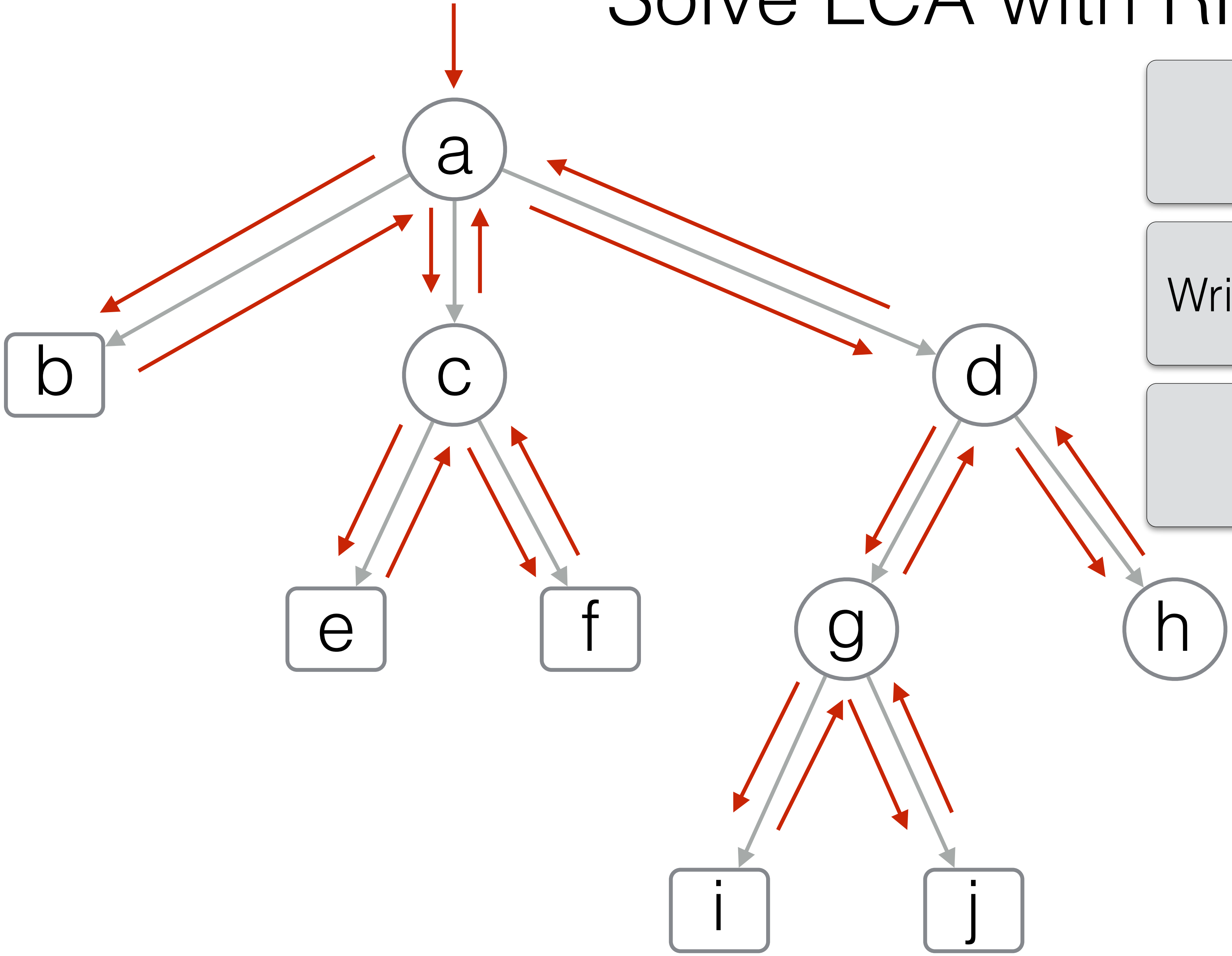
Eulerian Tour of the tree

Write in L the level of each node of R

Write in N the position of first occurrence of each node in R

R	a	b	a	c	e	c	f	c	a	d	g	i	g	j	g	d	h	d	a
L	0	1	0	1	2	1	2	1	0	1	2	3	2	3	2	1	2	1	0

Solve LCA with RMQ



Eulerian Tour of the tree

Write in L the level of each node of R

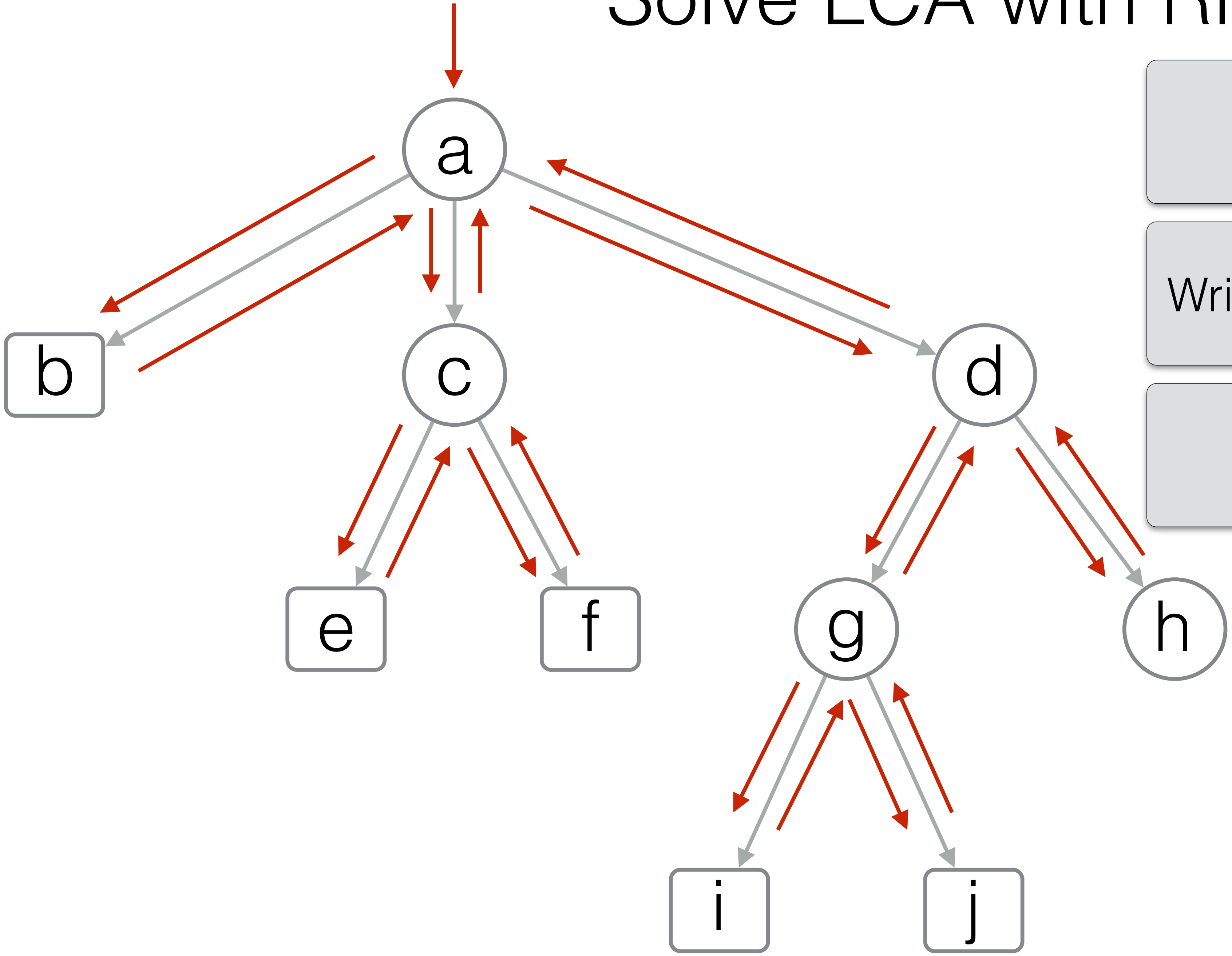
Write in N the position of first occurrence of each node in R

R a b a c e c f c a d g i g j g d h d a

L 0 1 0 1 2 1 2 1 0 1 2 3 2 3 2 1 2 1 0

N 0 1 3 9 5 7 15 10 12

Solve LCA with RMQ



Eulerian Tour of the tree

Write in L the level of each node of R

Write in N the position of first occurrence of each node in R

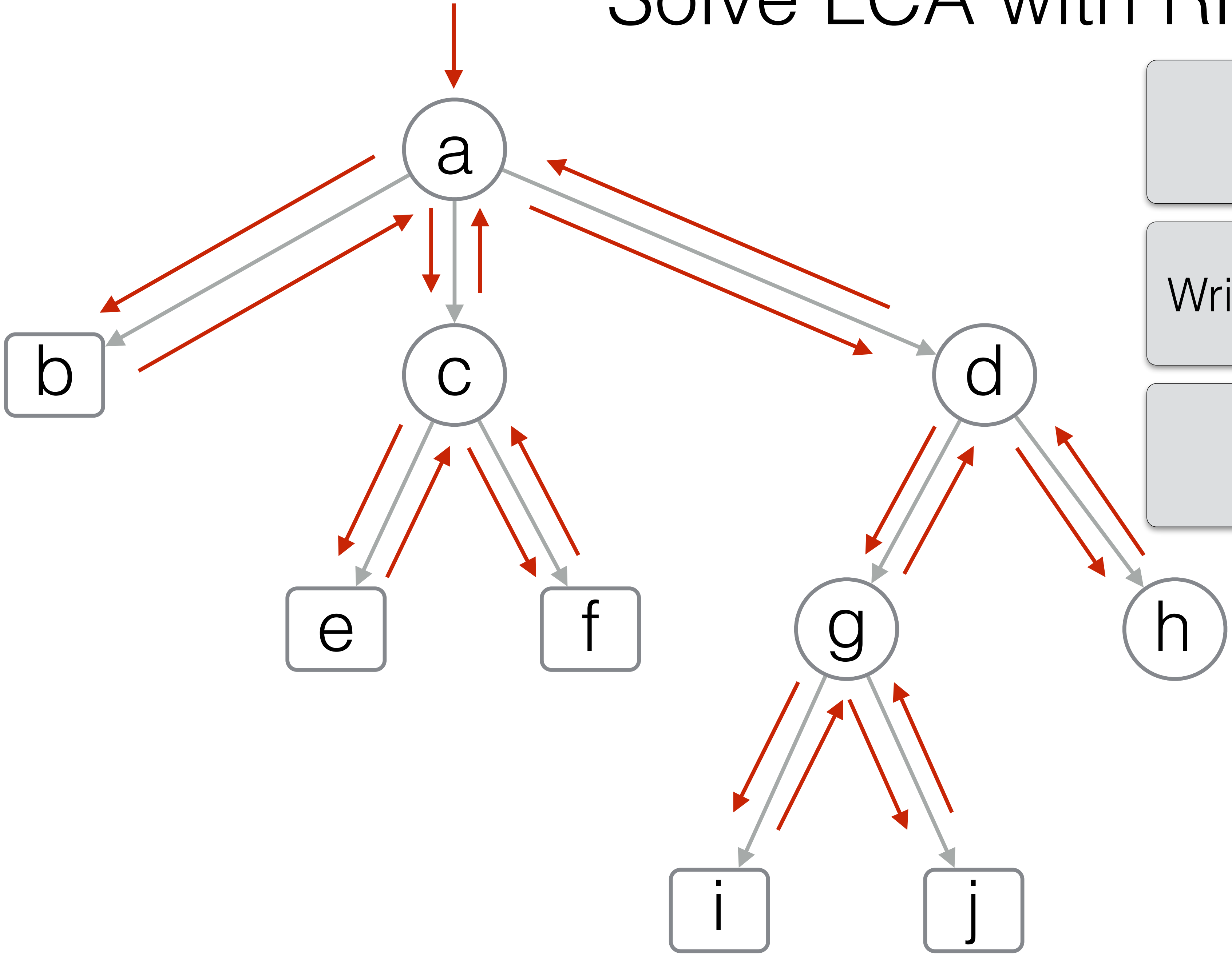
Can you solve LCA(e,f)?

R a b a c e c f c a d g i g j g d h d a

L 0 1 0 1 2 1 2 1 0 1 2 3 2 3 2 1 2 1 0

N 0 1 3 9 5 7 15 10 12

Solve LCA with RMQ



Eulerian Tour of the tree

Write in L the level of each node of R

Write in N the position of first occurrence of each node in R

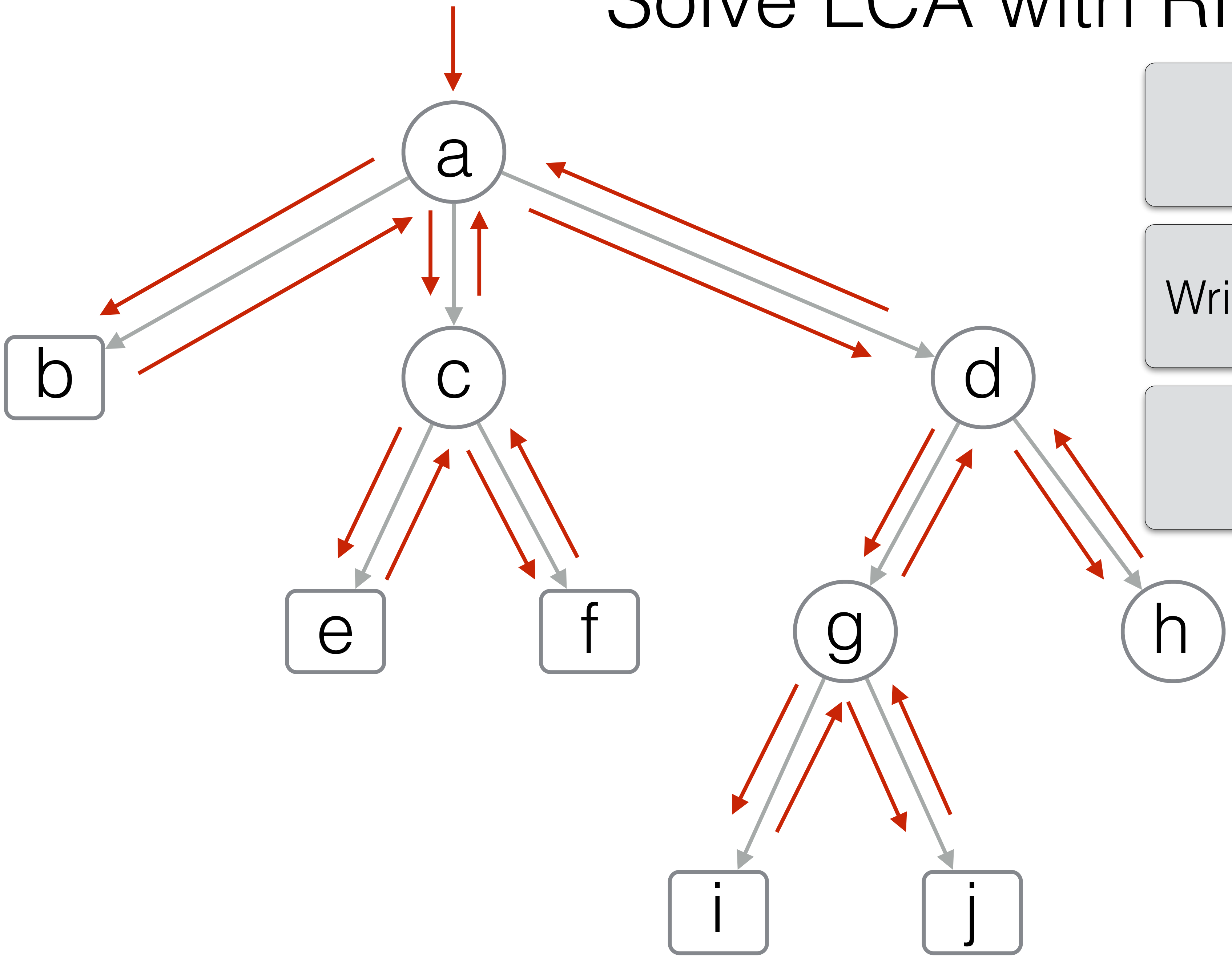
Can you solve LCA(e,f)?

R a b a c e c f c a d g i g j g d h d a

L 0 1 0 1 2 1 2 1 0 1 2 3 2 3 2 1 2 1 0

N 0 1 3 9 5 7 15 10 12

Solve LCA with RMQ



Eulerian Tour of the tree

Write in L the level of each node of R

Write in N the position of first occurrence of each node in R

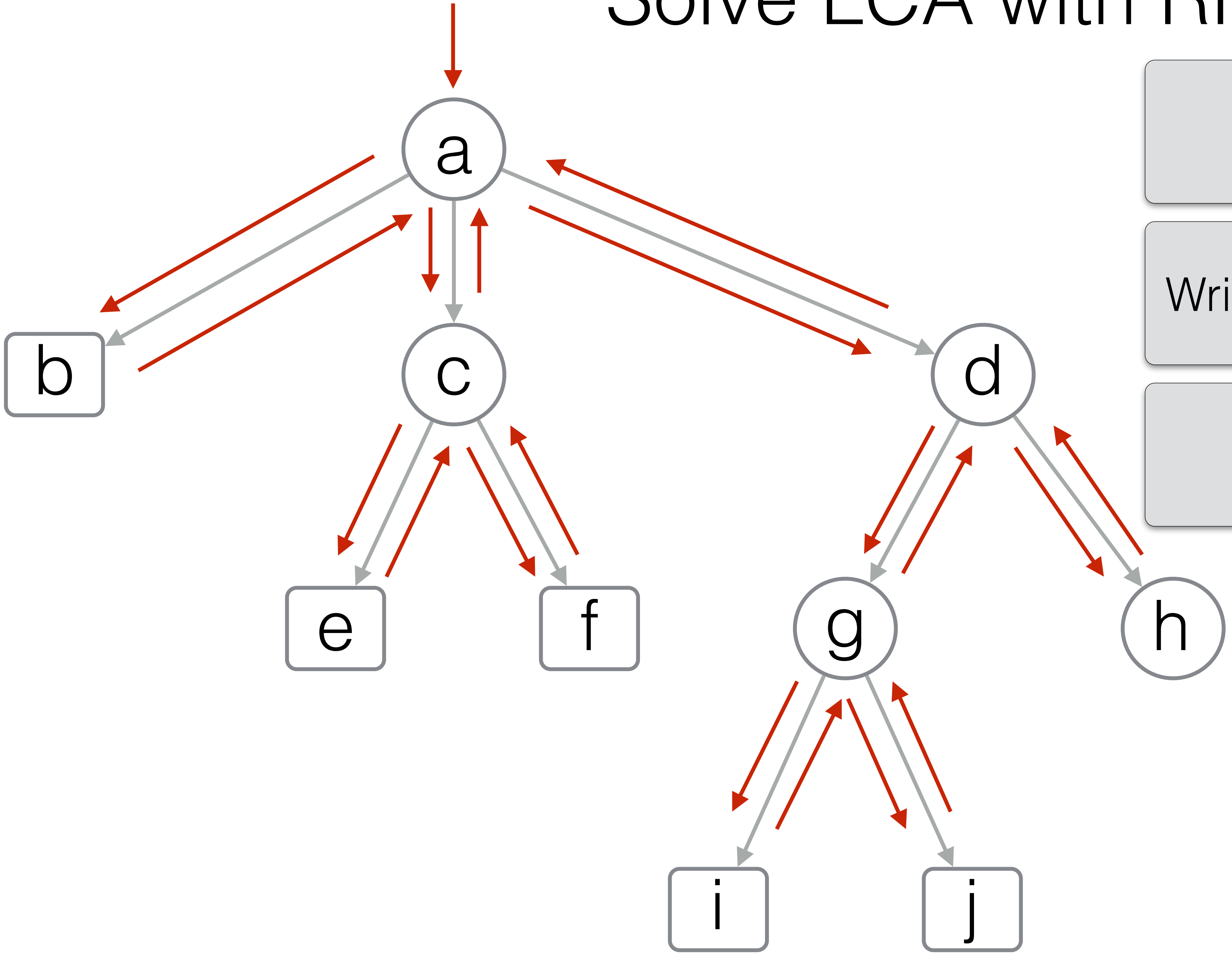
Can you solve LCA(e,f)?

R a b a c e c f c a d g i g j g d h d a

L 0 1 0 1 2 1 2 1 0 1 2 3 2 3 2 1 2 1 0

N 0 1 3 9 5 7 15 10 12

Solve LCA with RMQ



Eulerian Tour of the tree

Write in L the level of each node of R

Write in N the position of first occurrence of each node in R

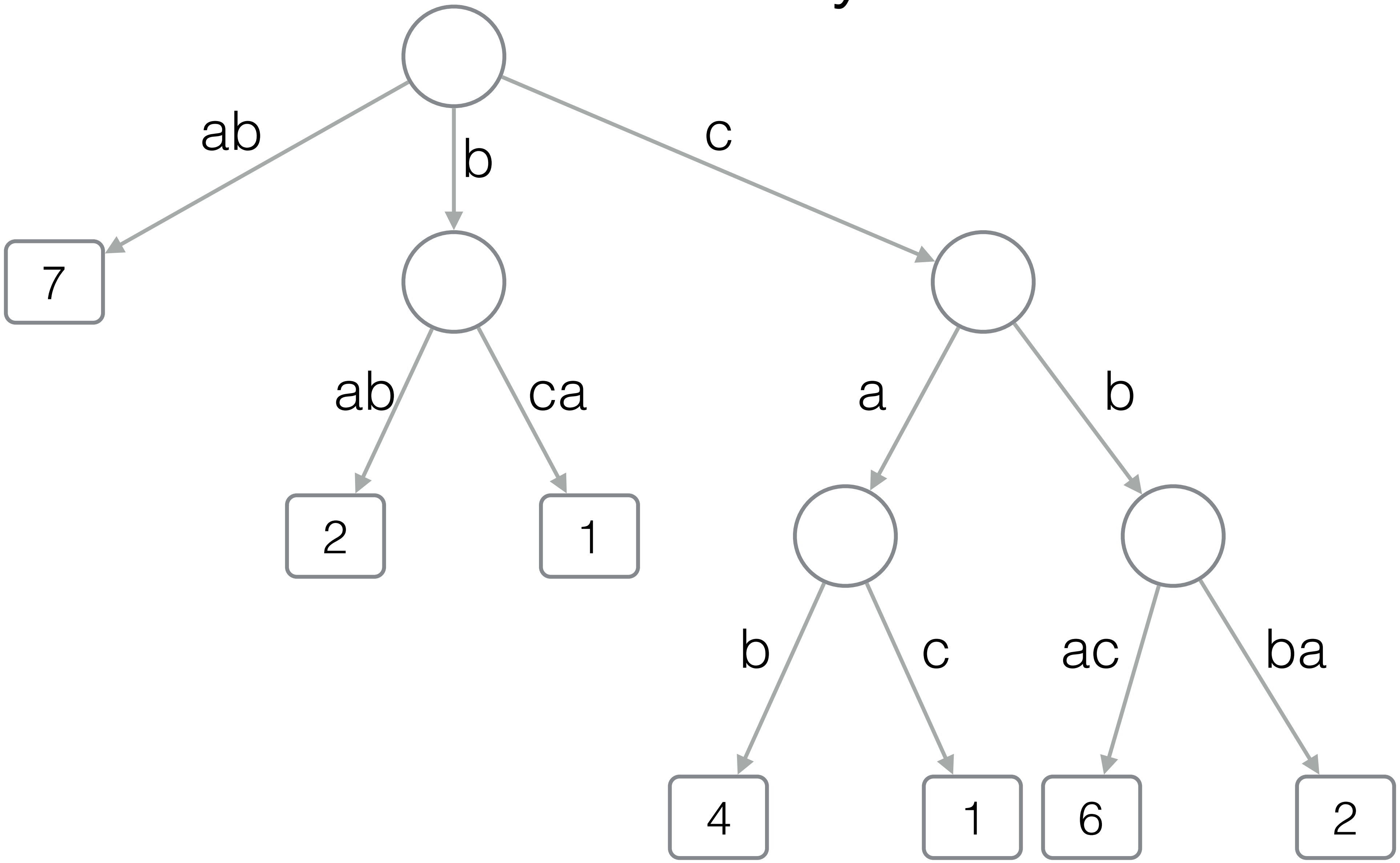
Can you solve LCA(e,f)?

R a b a c e c f c a d g i g j g d h d a

L 0 1 0 1 2 1 2 1 0 1 2 3 2 3 2 1 2 1 0

N 0 1 3 9 5 7 15 10 12

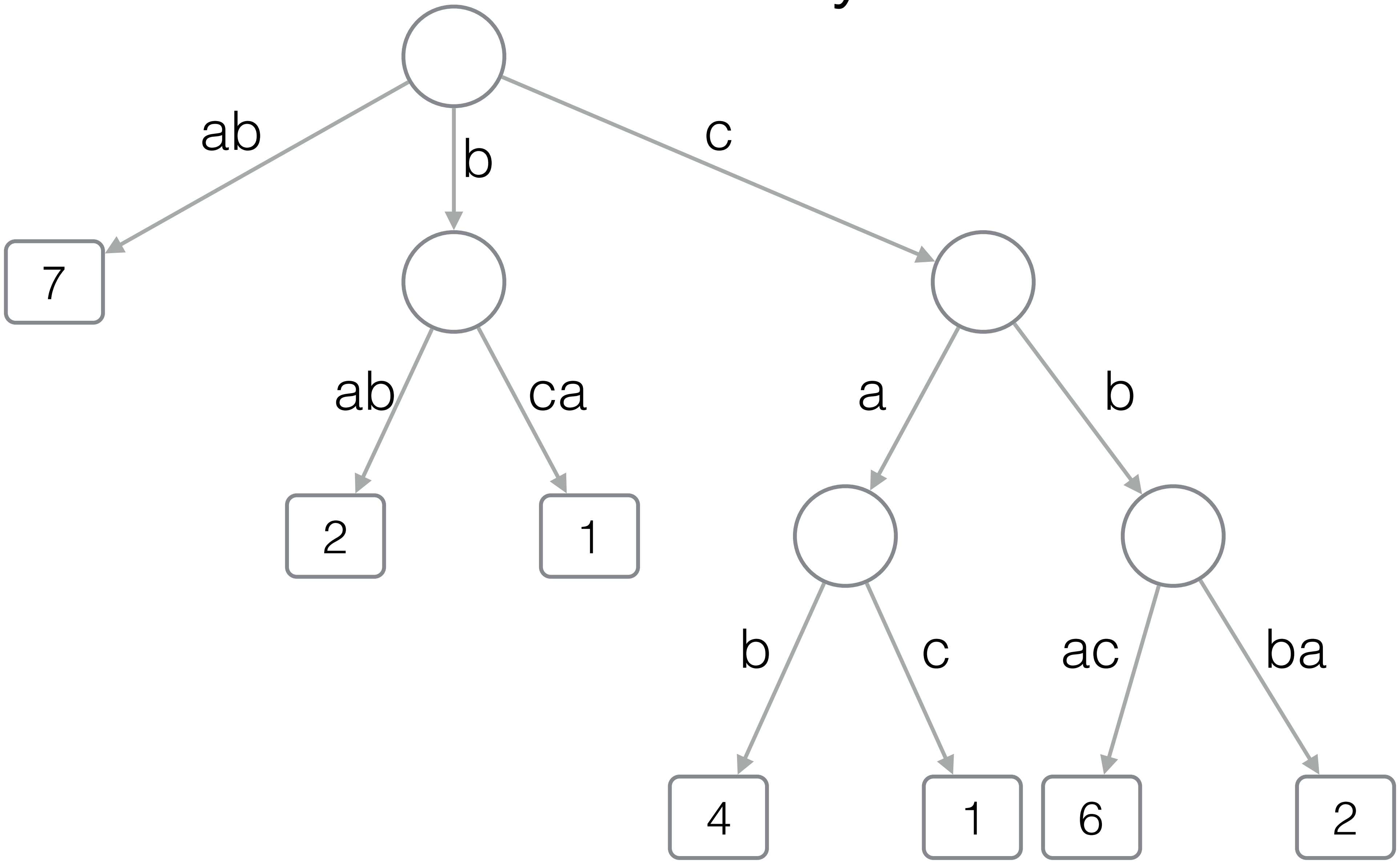
Summary



D = { ab (7), bab (2), bca (1), cab (4), cac (1), cbac (6), cbba (2) }

n = |D|, m total length of strings in D

Summary

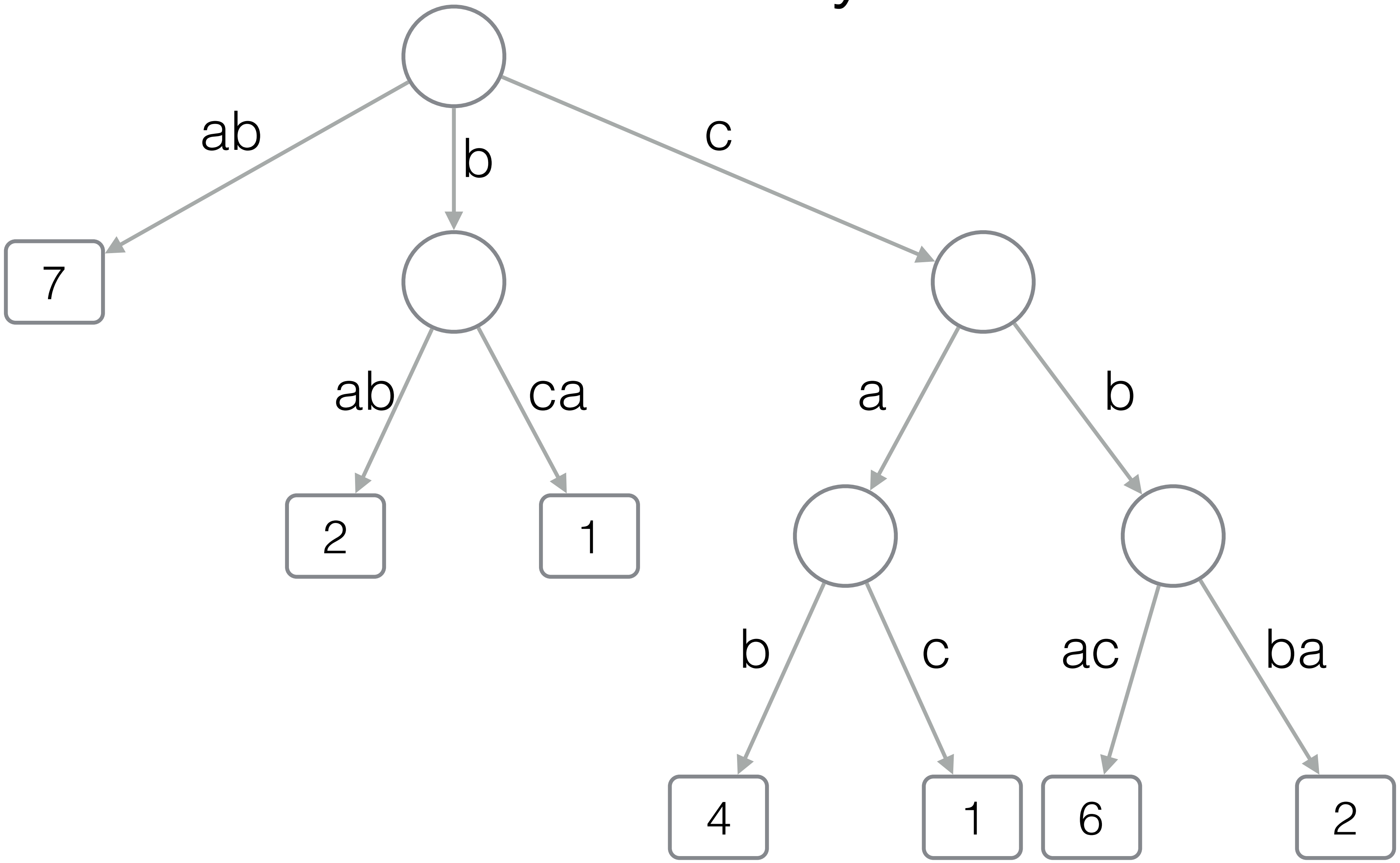


Find the node “prefixed” by P

D = { ab (7), bab (2), bca (1), cab (4), cac (1), cbac (6), cbba (2) }

n = |D|, m total length of strings in D

Summary



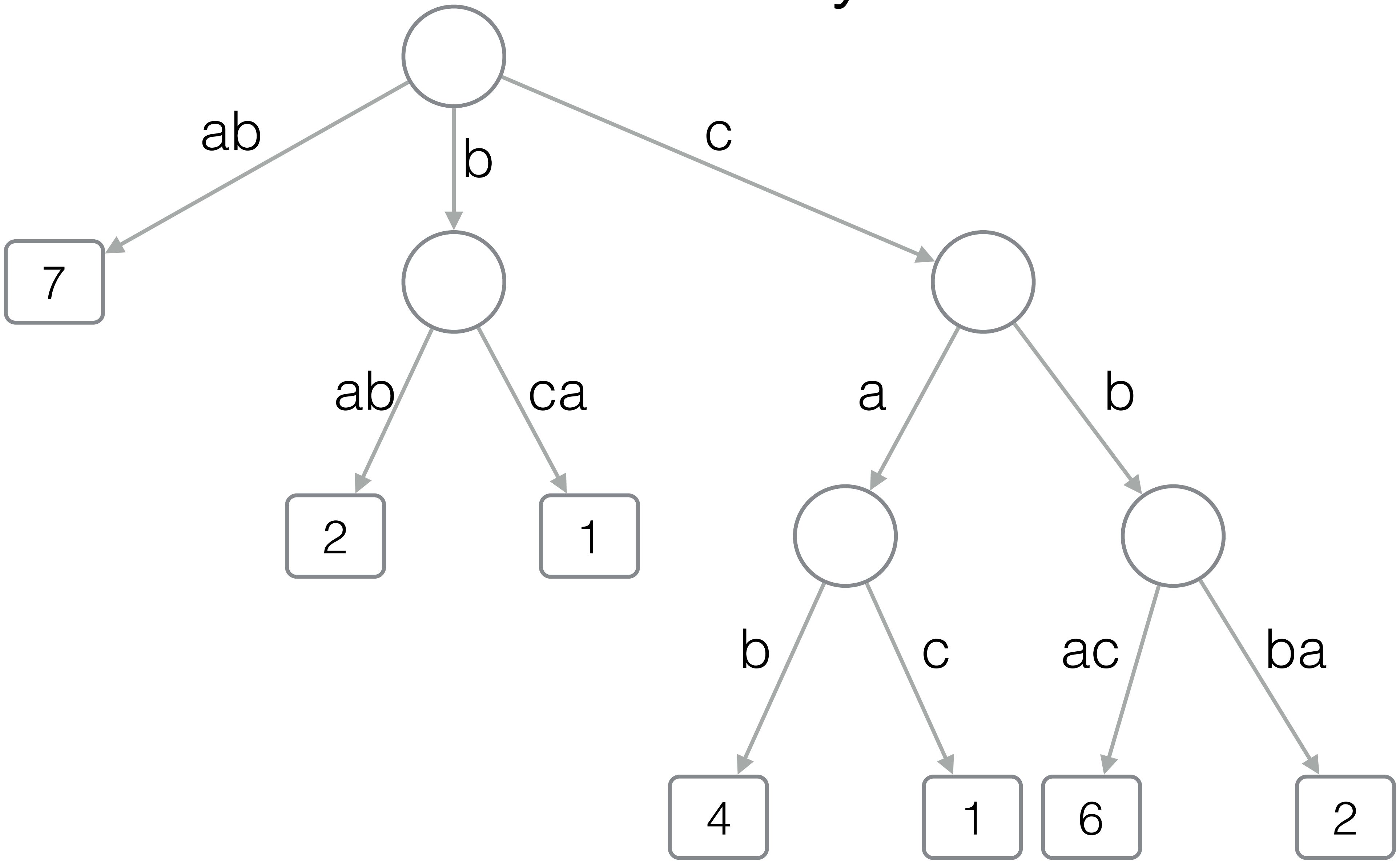
Find the node “prefixed” by P

O(|P|) time

D = { ab (7), bab (2), bca (1), cab (4), cac (1), cbac (6), cbba (2) }

n = |D|, m total length of strings in D

Summary



Find the node “prefixed” by P

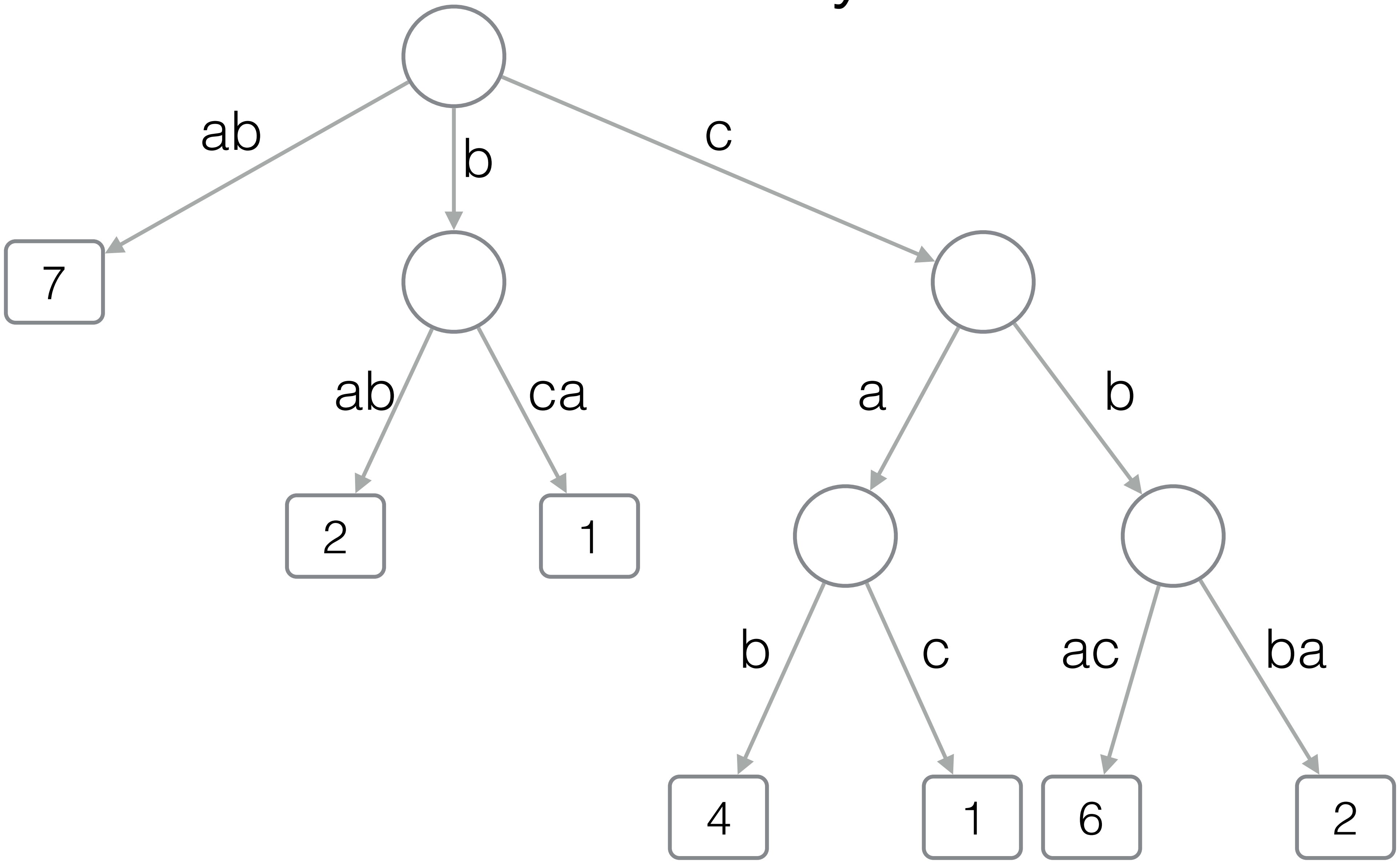
O(|P|) time

O(m log σ + n log m) bits

D = { ab (7), bab (2), bca (1), cab (4), cac (1), cbac (6), cbba (2) }

n = |D|, m total length of strings in D

Summary



Find the node “prefixed” by P

O(|P|) time

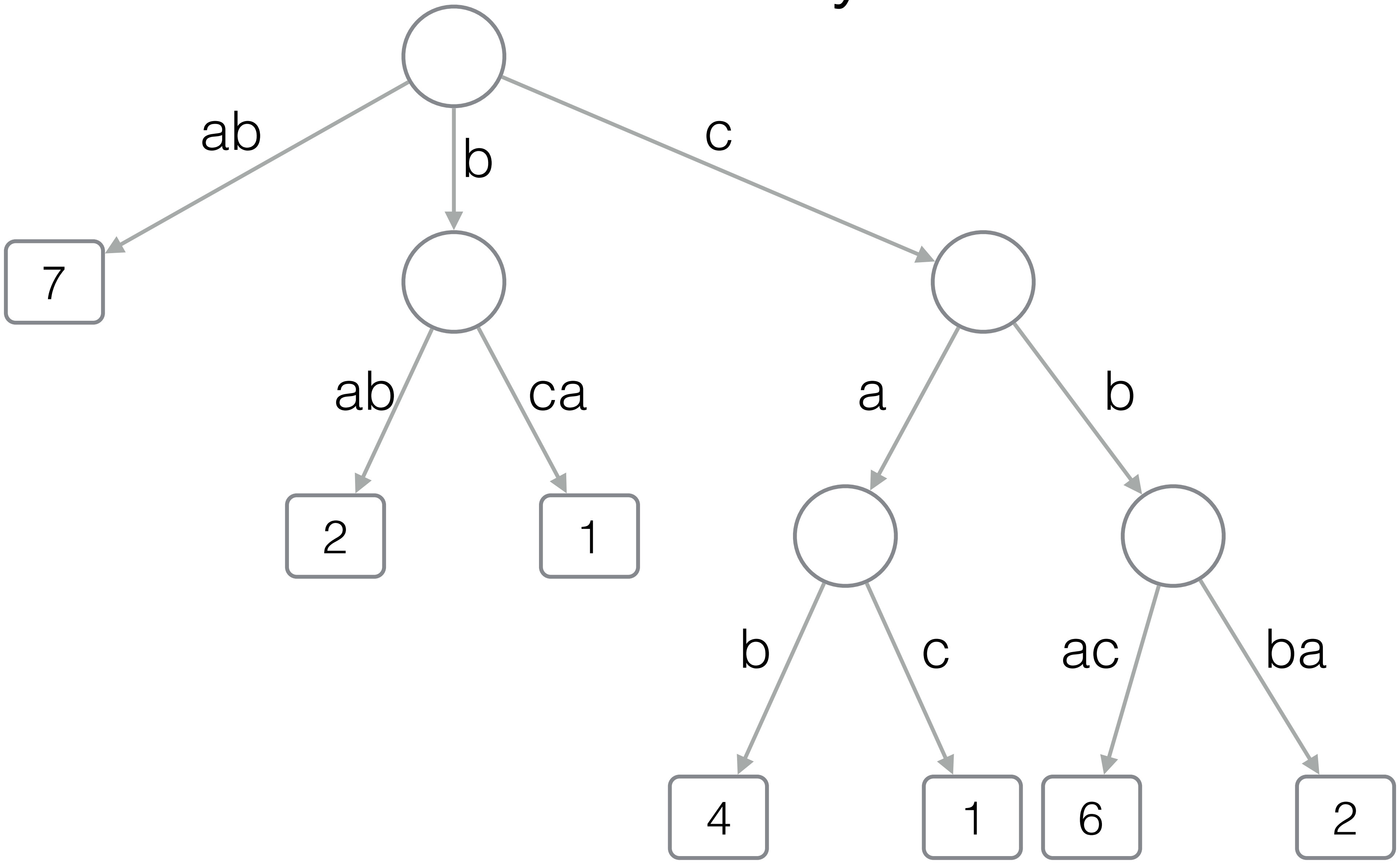
O(m log σ + n log m) bits

Compute the top-k strings

a (1), cab (4), cac (1), cbac (6), cbba (2) }

n = |D|, m total length of strings in D

Summary



Find the node “prefixed” by P

O(|P|) time

O(m log σ + n log m) bits

Compute the top-k strings

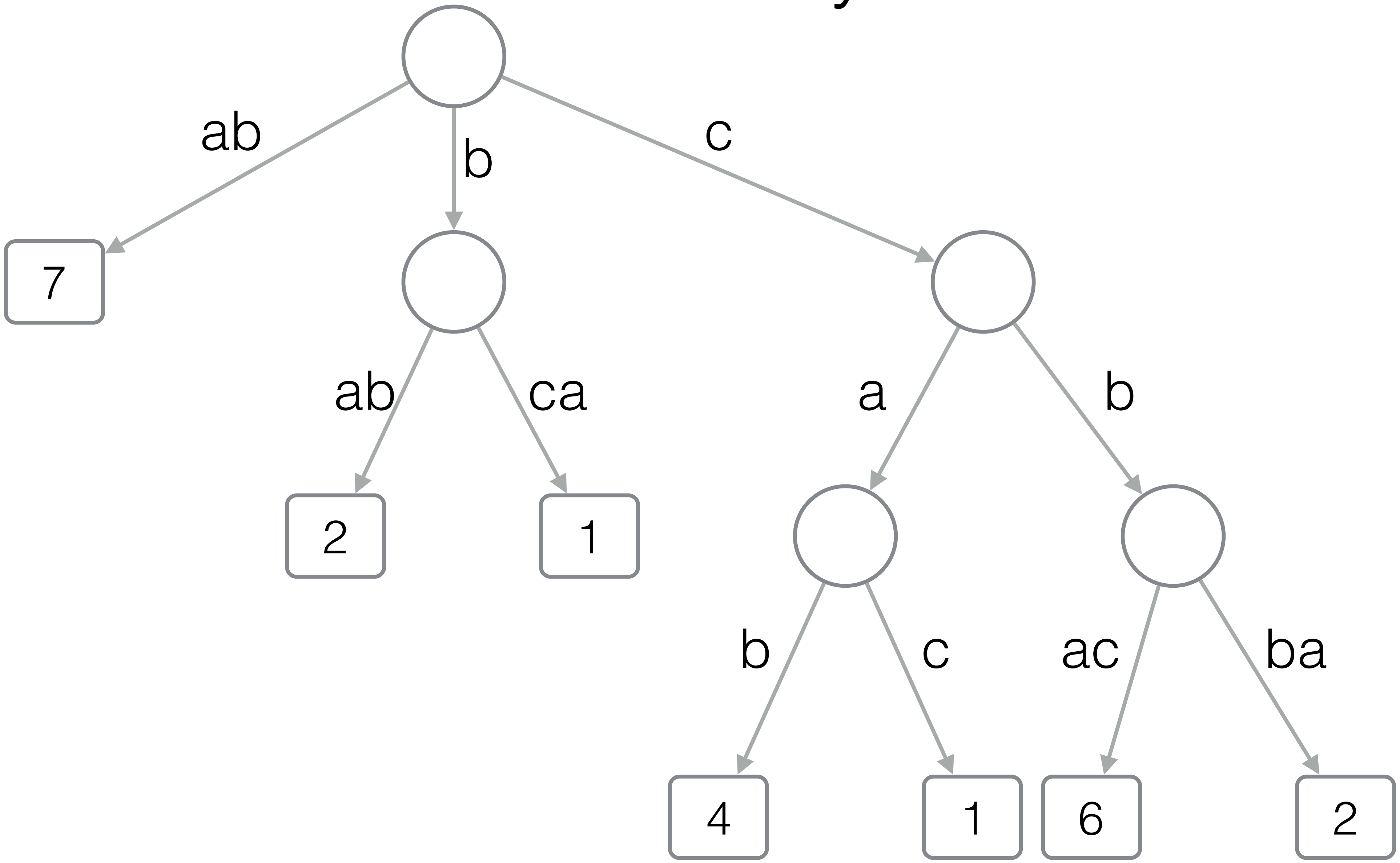
a

O(k log k) time

cbac (6), cbba (2) }

n = |D|, m total length of strings in D

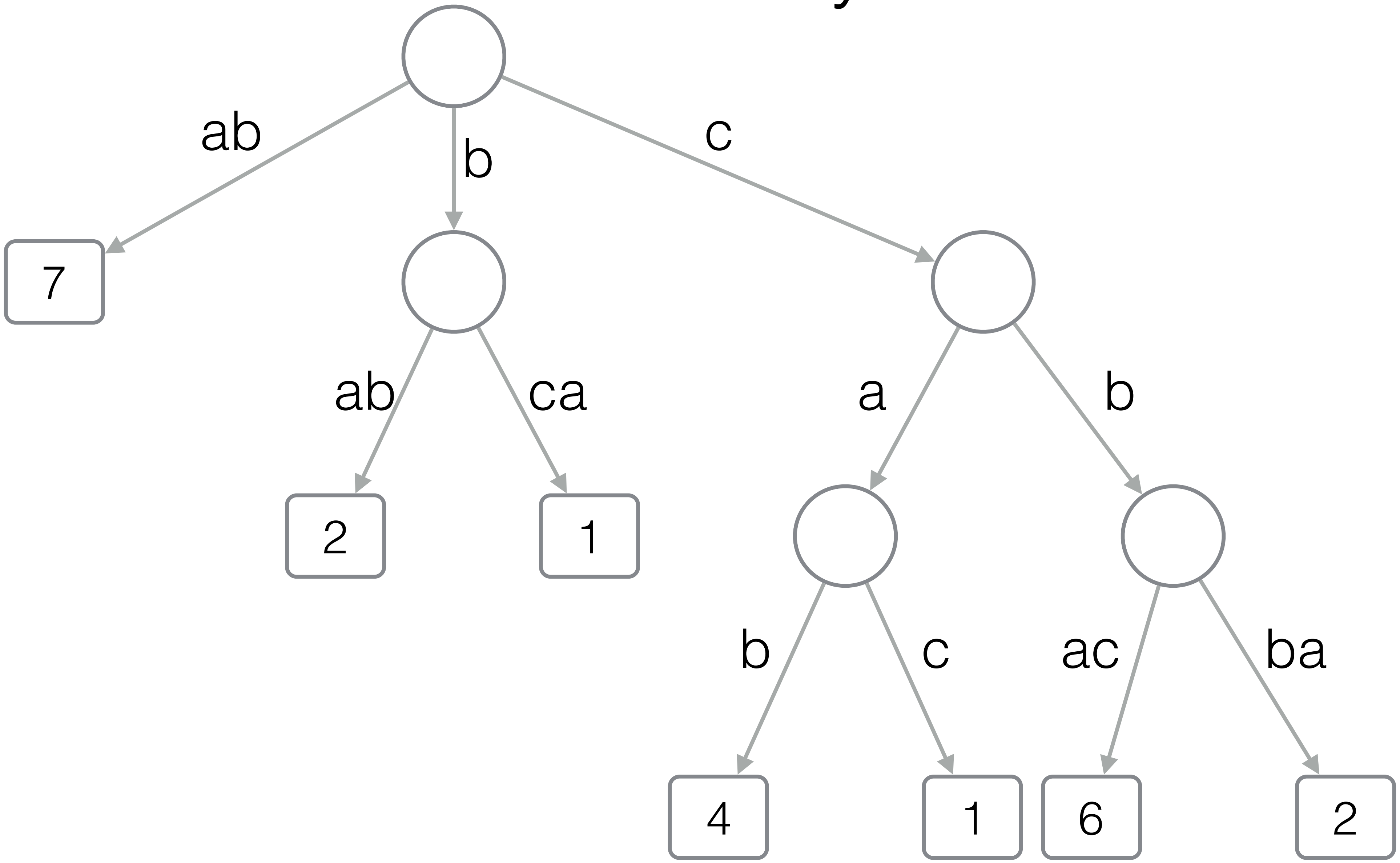
Summary



Find the node “prefixed” by P	O(|P|) time	O(m log σ + n log m) bits
Compute the top-k strings	O(k log k) time	O(n) bits

n = |D|, m total length of strings in D

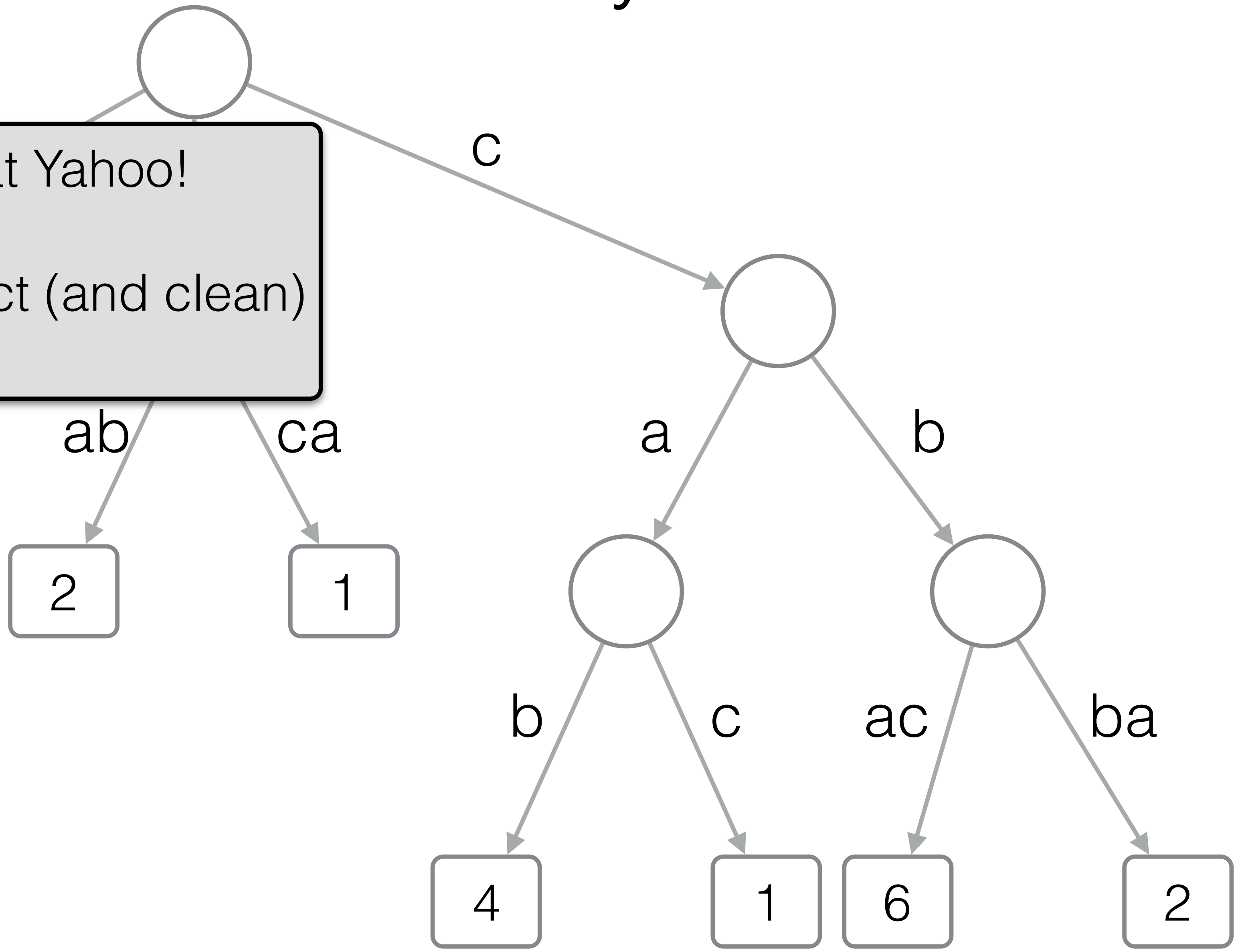
Summary



Find the node “prefixed” by P	O(|P|) time	O(m log σ + n log m) bits
Compute the top-k strings	O(k log k) time	O(n) bits

n = |D|, m total length of strings in D

Summary



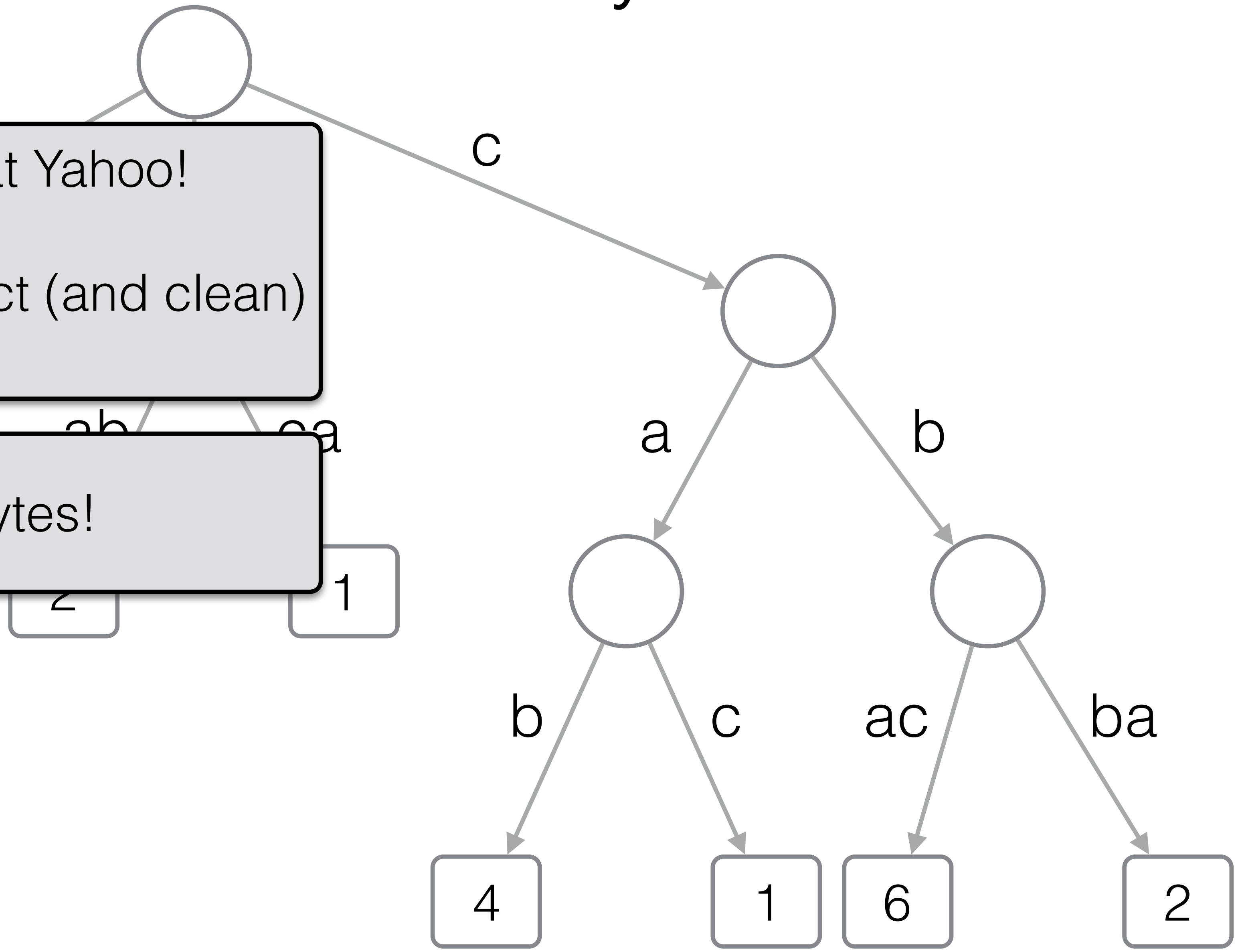
3 months query log at Yahoo!

≈600 million of distinct (and clean) queries

Find the node “prefixed” by P	O(|P|) time	O(m log σ + n log m) bits
Compute the top-k strings	O(k log k) time	O(n) bits

n = |D|, m total length of strings in D

Summary



3 months query log at Yahoo!

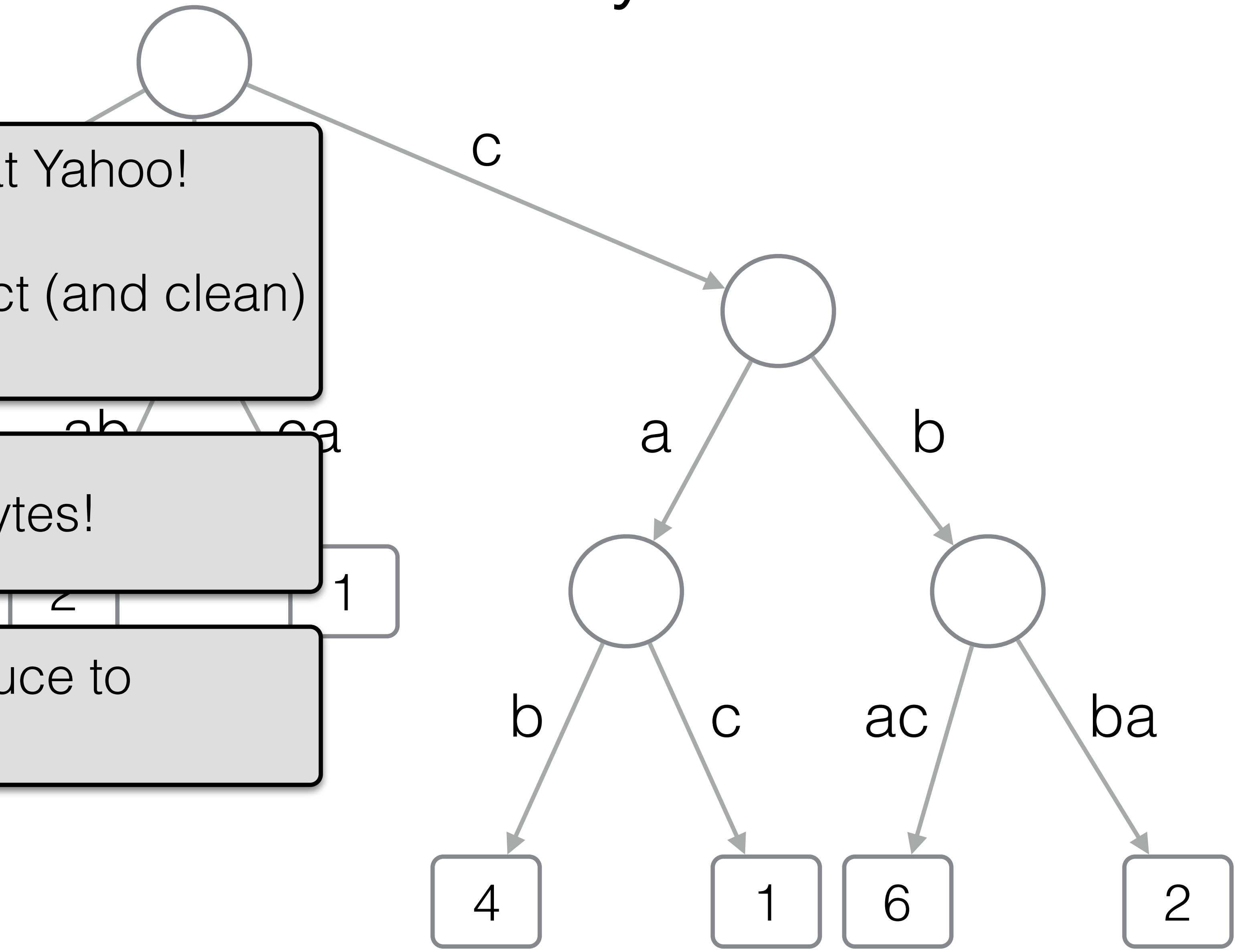
≈600 million of distinct (and clean) queries

Trie requires ≈50 Gbytes!

Find the node “prefixed” by P	O(|P|) time	O(m log σ + n log m) bits
Compute the top-k strings	O(k log k) time	O(n) bits

n = |D|, m total length of strings in D

Summary



3 months query log at Yahoo!

≈600 million of distinct (and clean) queries

Trie requires ≈50 Gbytes!

You’ll see how to reduce to ≈5 Gbytes!

Find the node “prefixed” by P	O(|P|) time	O(m log σ + n log m) bits
Compute the top-k strings	O(k log k) time	O(n) bits

n = |D|, m total length of strings in D