CSCI 232:
Data Structures and Algorithms

Huffman Coding

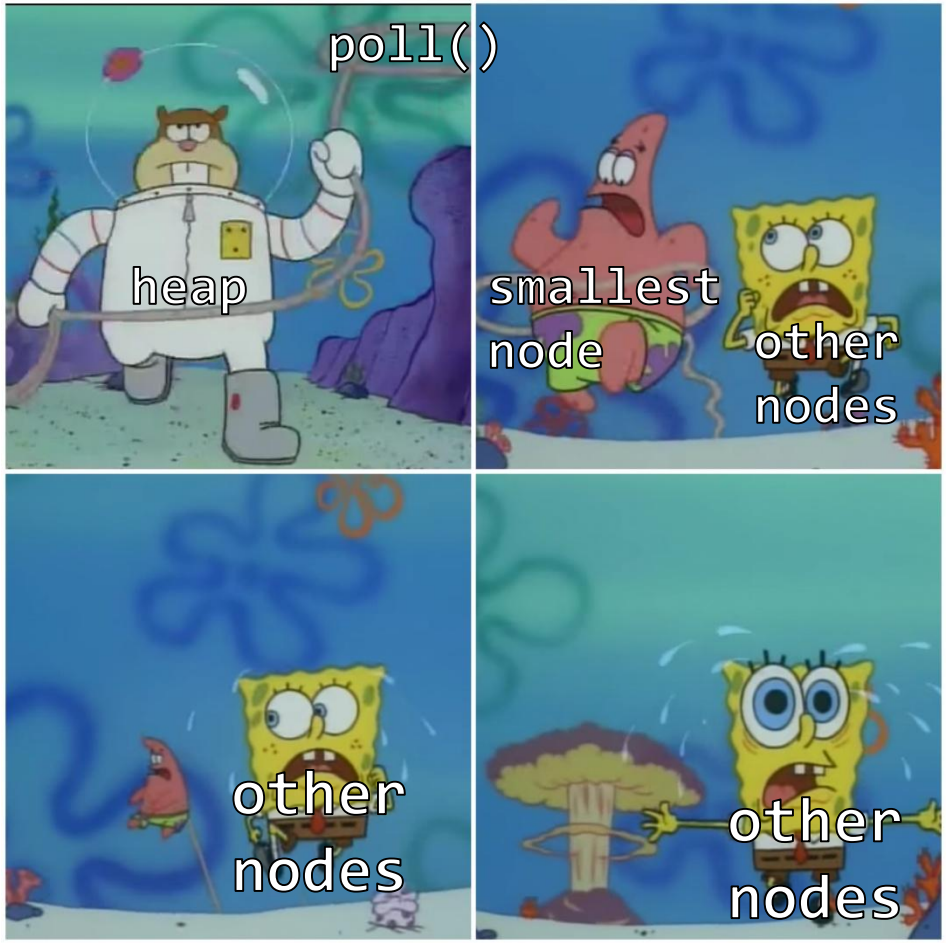
Reese Pearsall

Summer 2025

Announcements

Program 2 due **Wednesday** at 11:59 PM

Quiz 2 on Thursday (No lecture)



Strings are **encoded** using a specific format

Convert characters to zeros and ones (binary)

Example: **UTF**

Character	UTF Encoding
a	01100001
b	01100010
c	01100011
d	01100100
e	01100101
…	….

Each character has an **8-bit** binary representation

String: “hello”

UTF Encoding:
01101000 01100101 01101100 01101100 01101111

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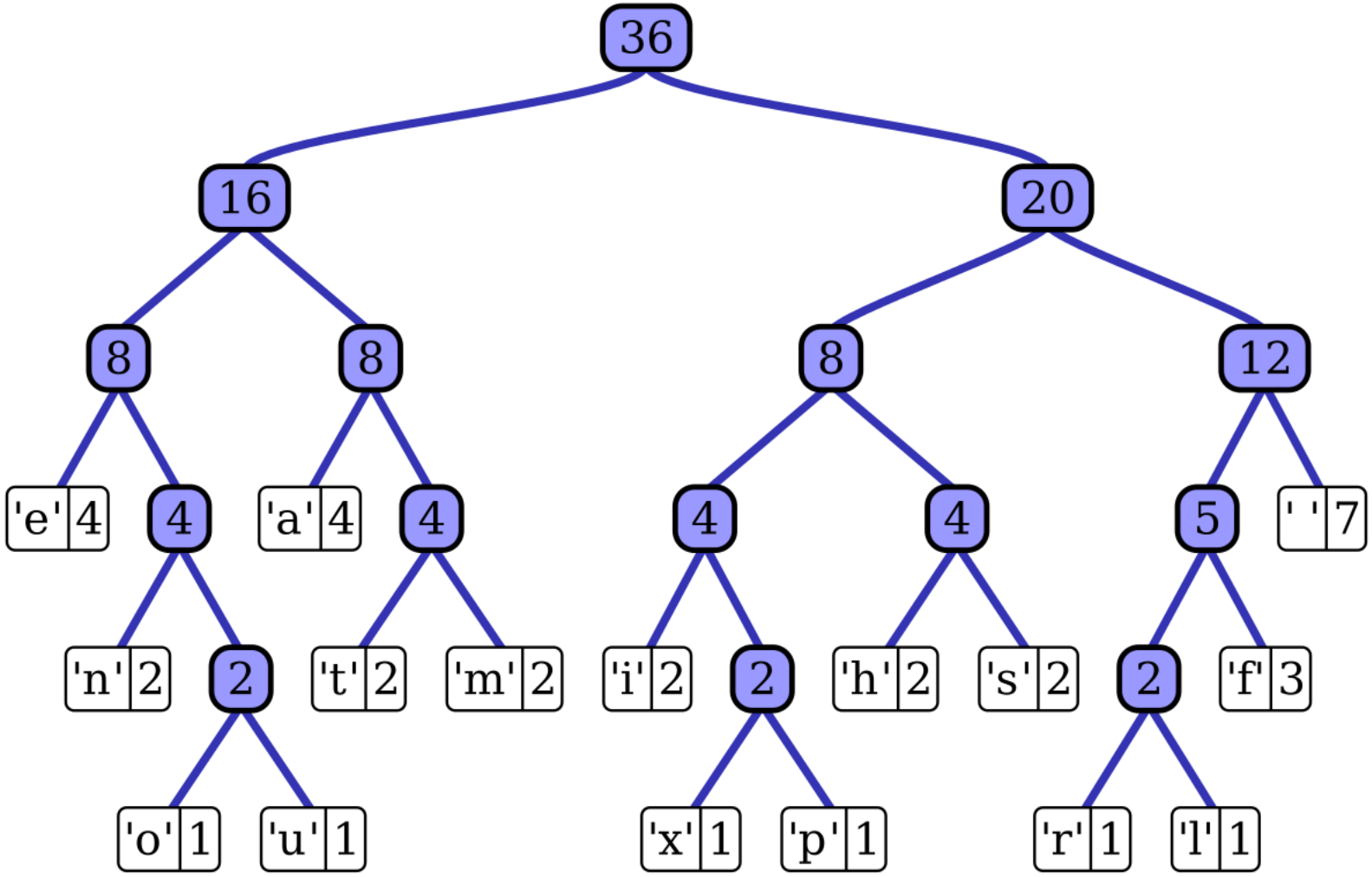
Huffman Coding is a way to encode a string using a binary tree



Internal Nodes are the sum of the children's frequencies

Leaf nodes are characters with their frequency

When the Huffman tree is built, we can extract a binary encoding for each character

Huffman Coding

Step 1: Generate the frequencies of each character, and sort them from least to greatest

Huffman Coding

Step 1: Generate the frequencies of each character, and sort them from least to greatest

"hello world!"

char	freq
	1
!	1
d	1
e	1
h	1
r	1
w	1
o	2
l	3

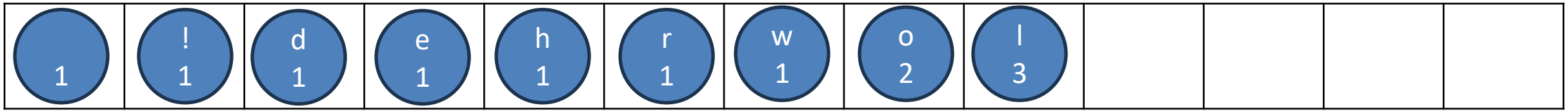
Step 2: Insert them into a PriorityQueue

Huffman Coding

Step 3. Build subtrees, and merge trees into Huffman Tree

Create an internal node with the two nodes at front of queue,
Place new internal node in queue

PriorityQueue<HuffmanNode>



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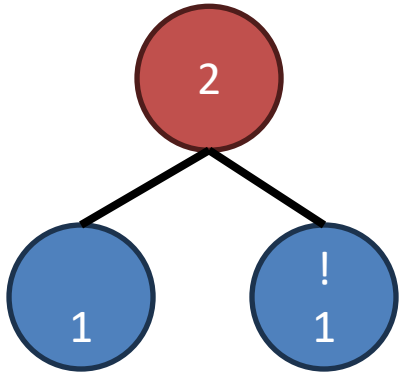

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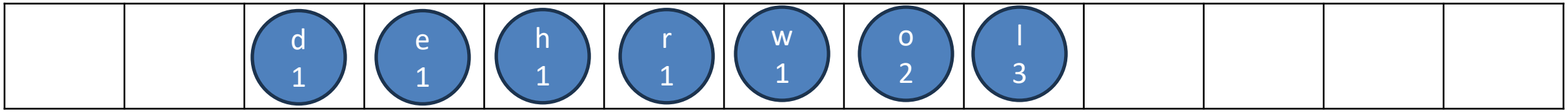

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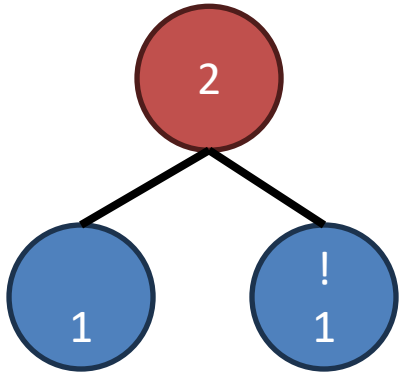

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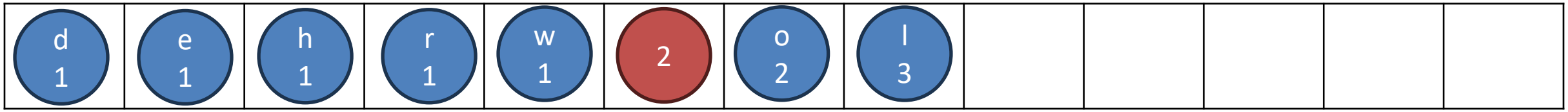

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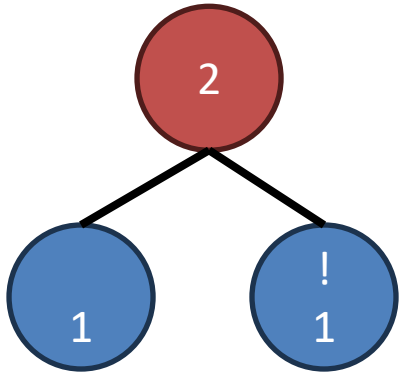
Repeat until all nodes are inserted!



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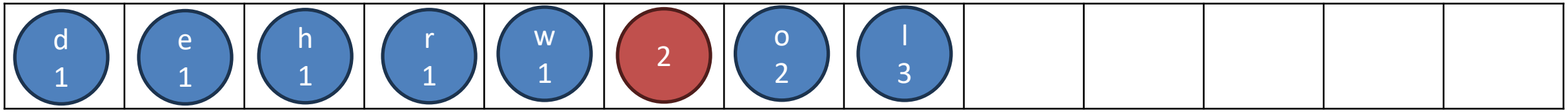

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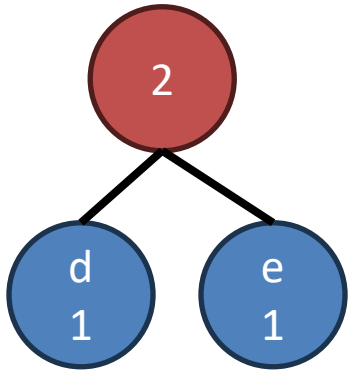

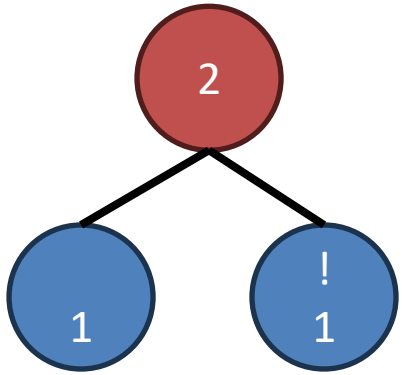

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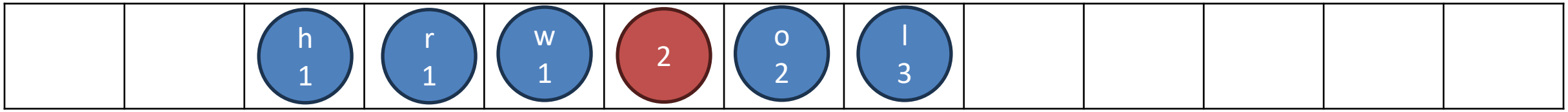

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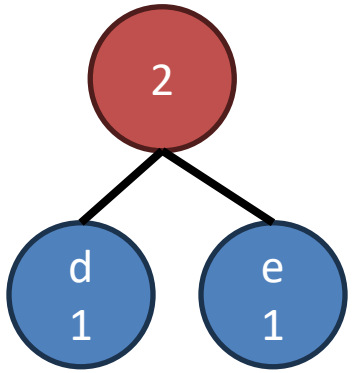

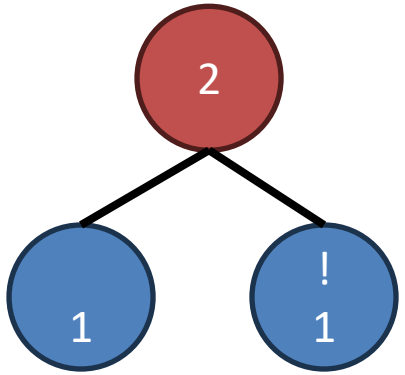

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These nodes have frequencies of **two**, but I am adding a way to distinguish them in the queue (.1, .2, .3)

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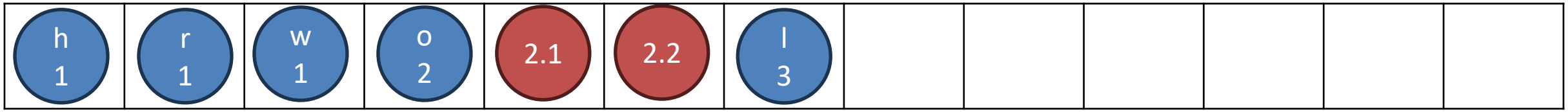

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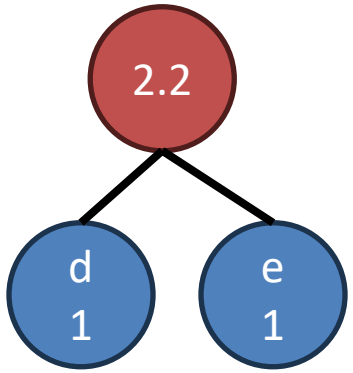

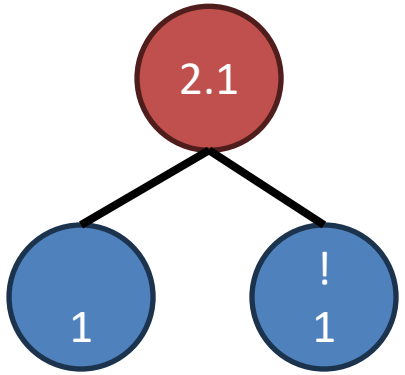

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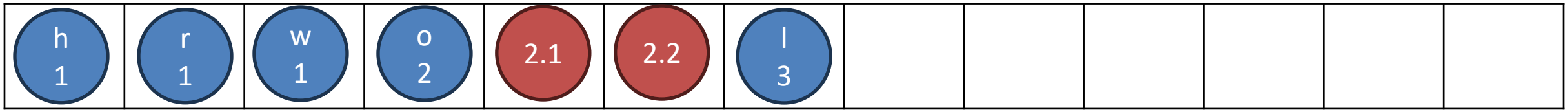

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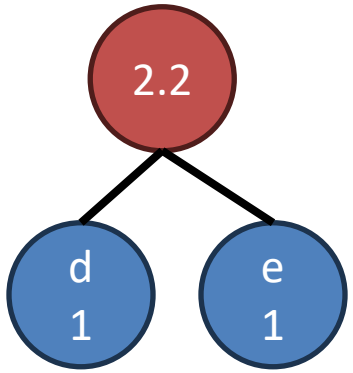

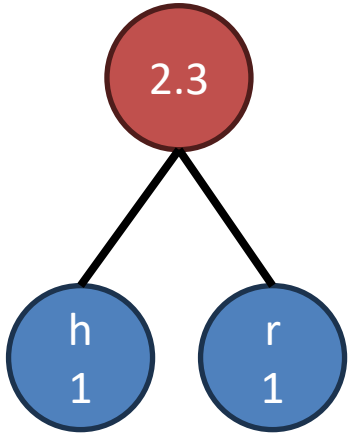

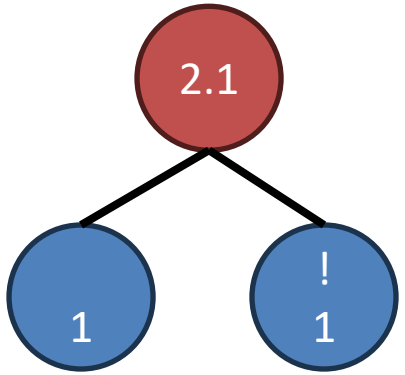

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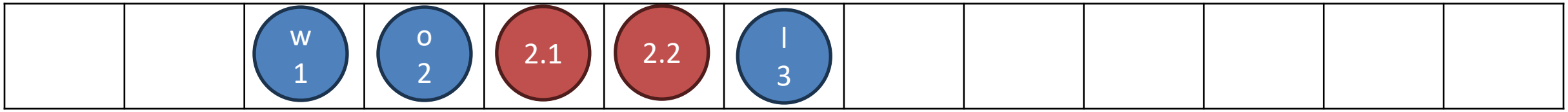

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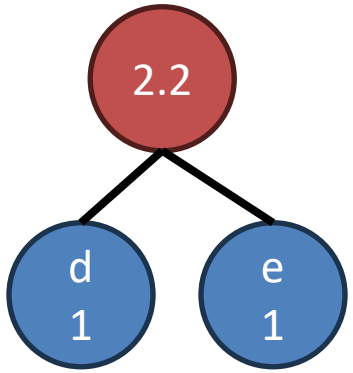

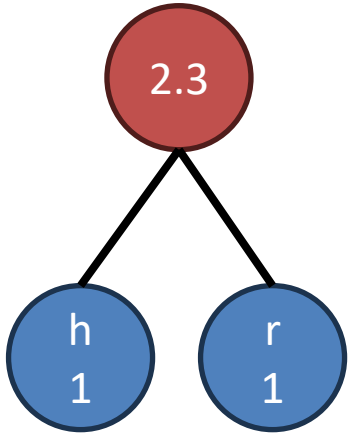

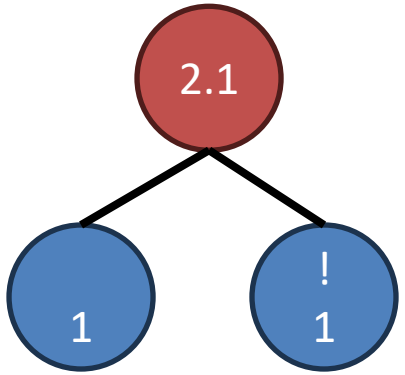

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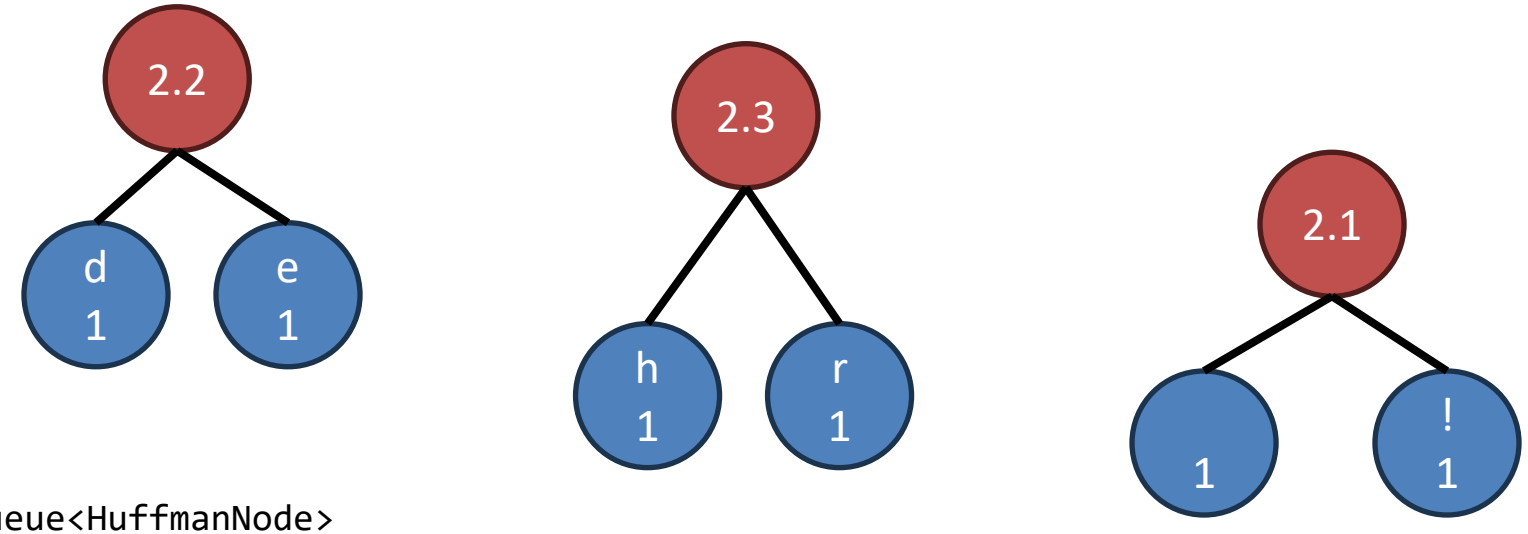
Because it is a priority queue, it is not necessary FIFO…



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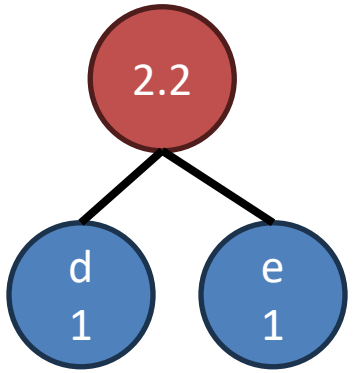

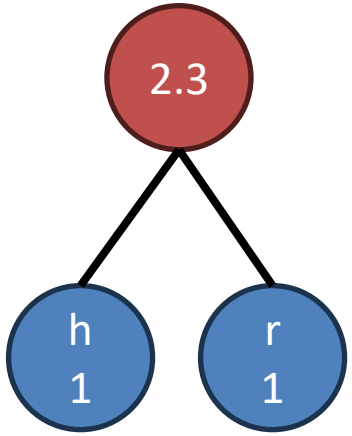

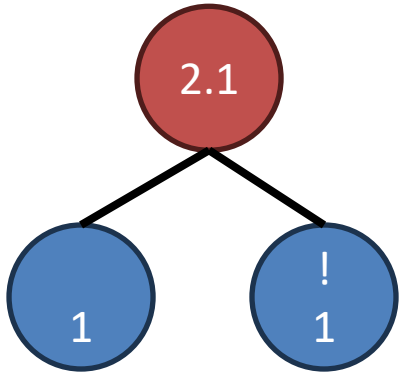

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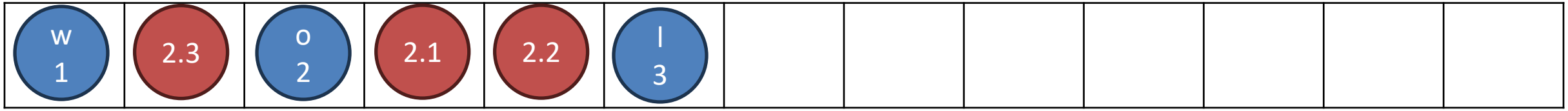

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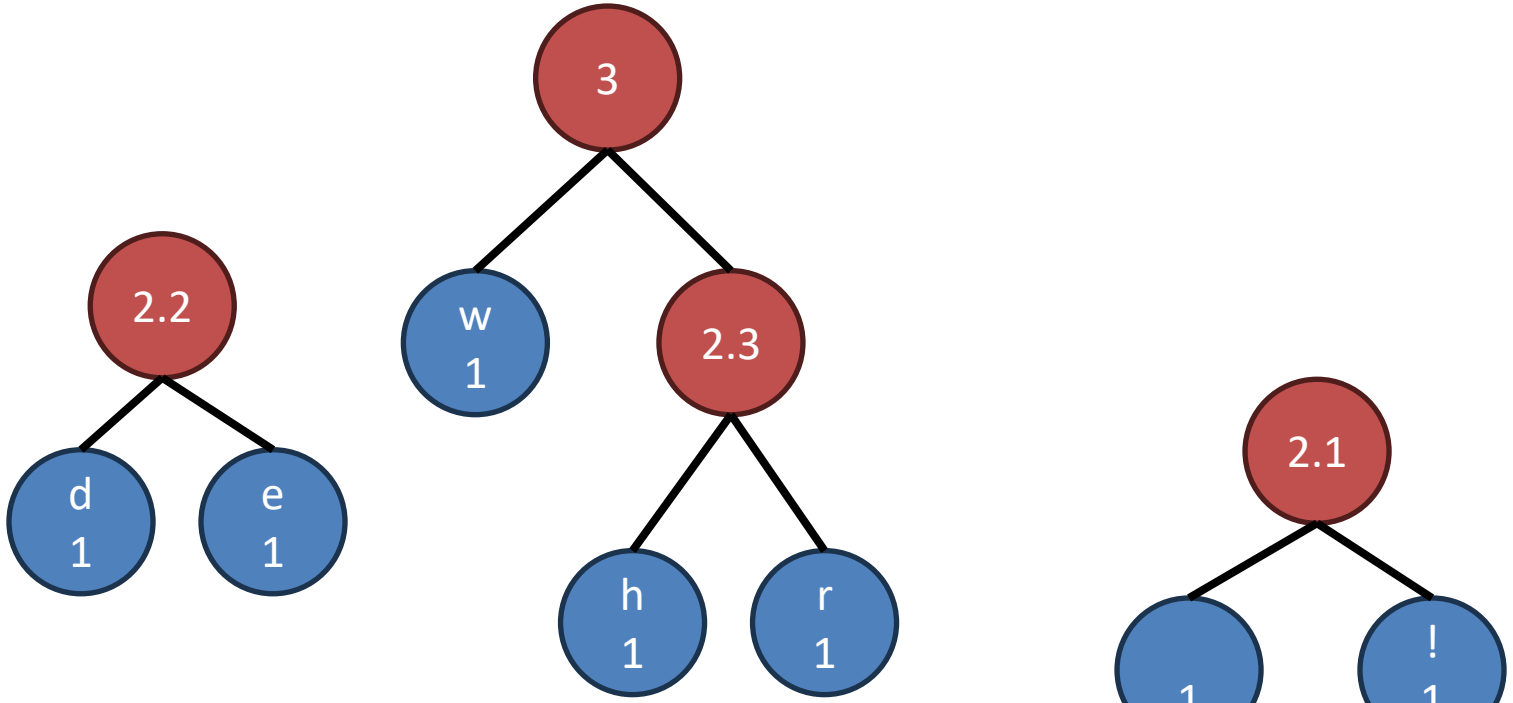

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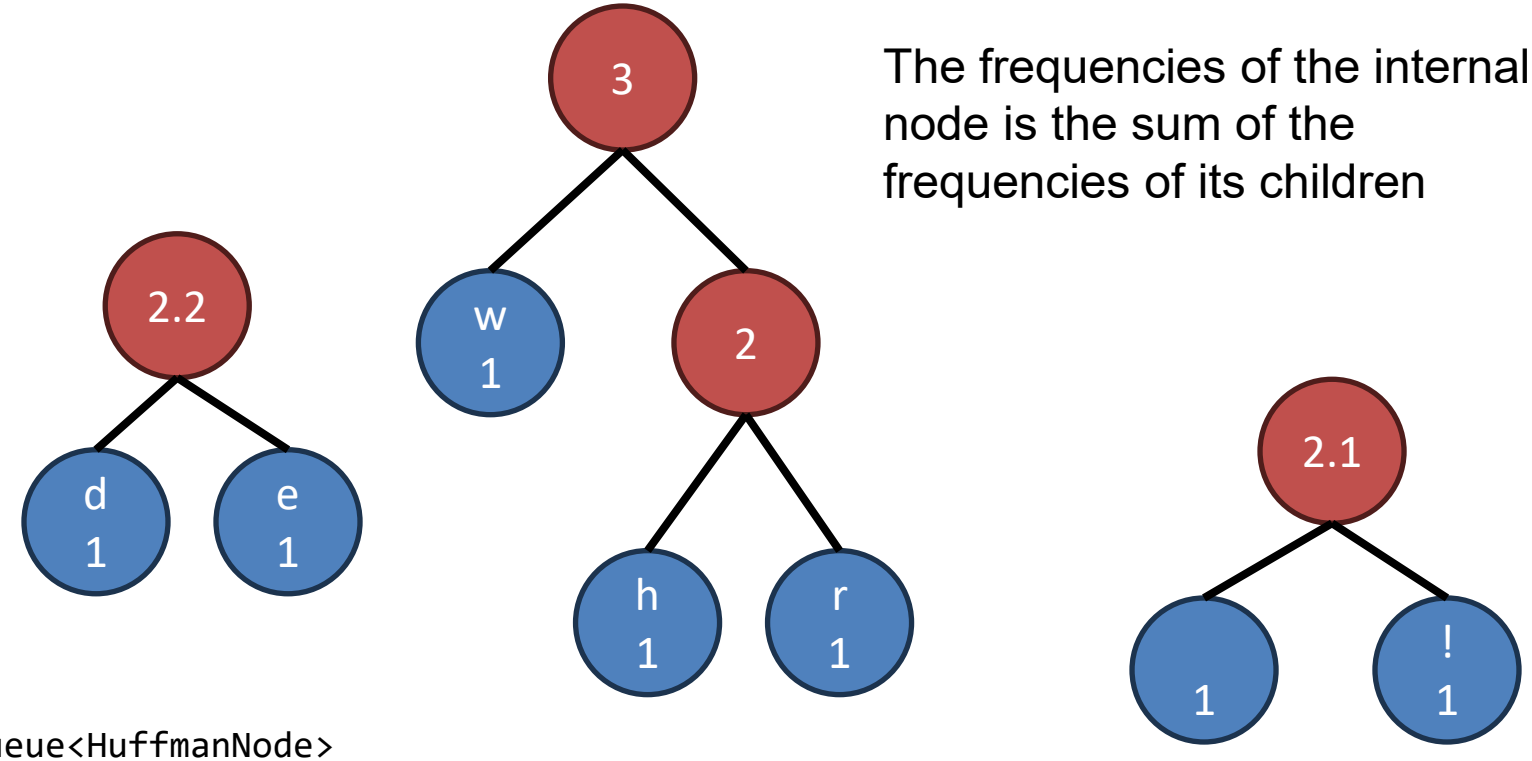

The frequencies of the internal node is the sum of the frequencies of its children

PriorityQueue<HuffmanNode>

Huffman Coding

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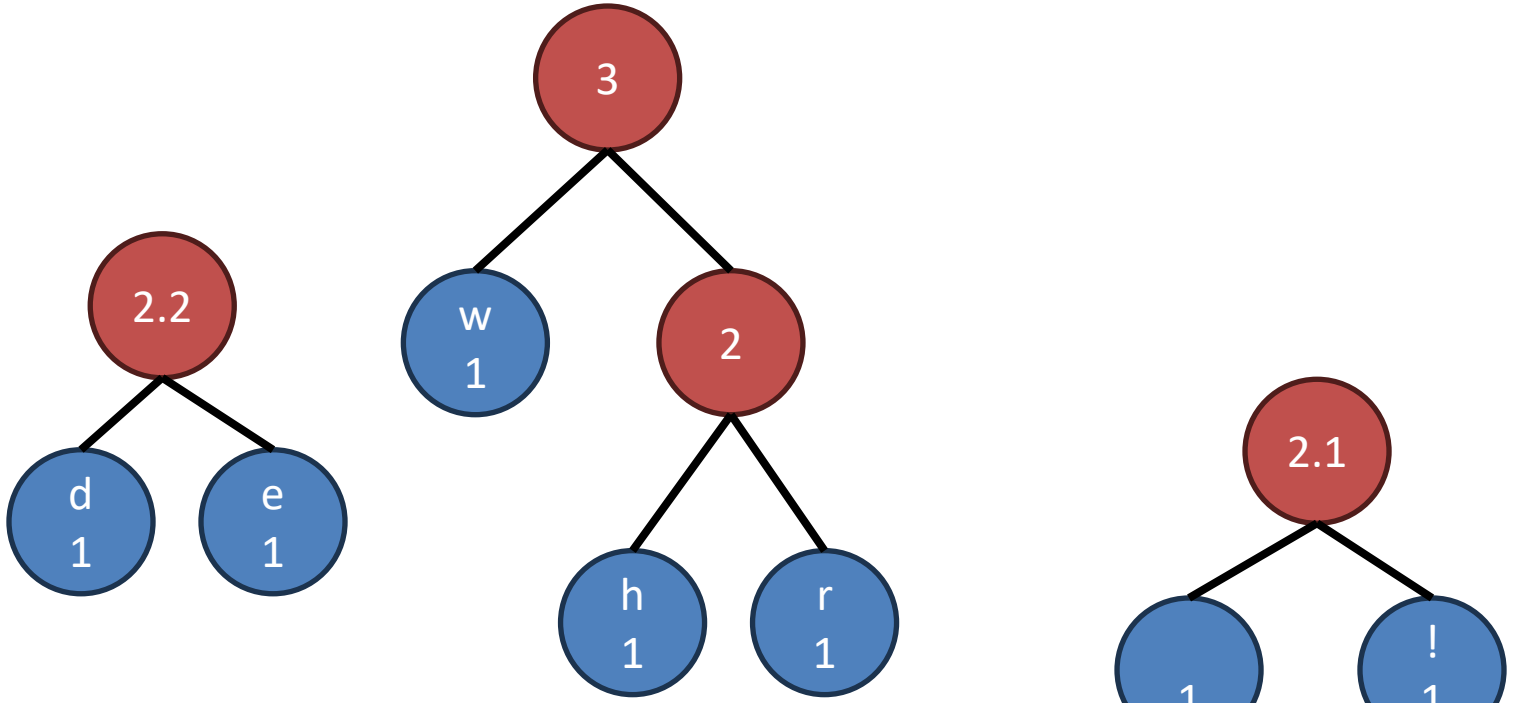

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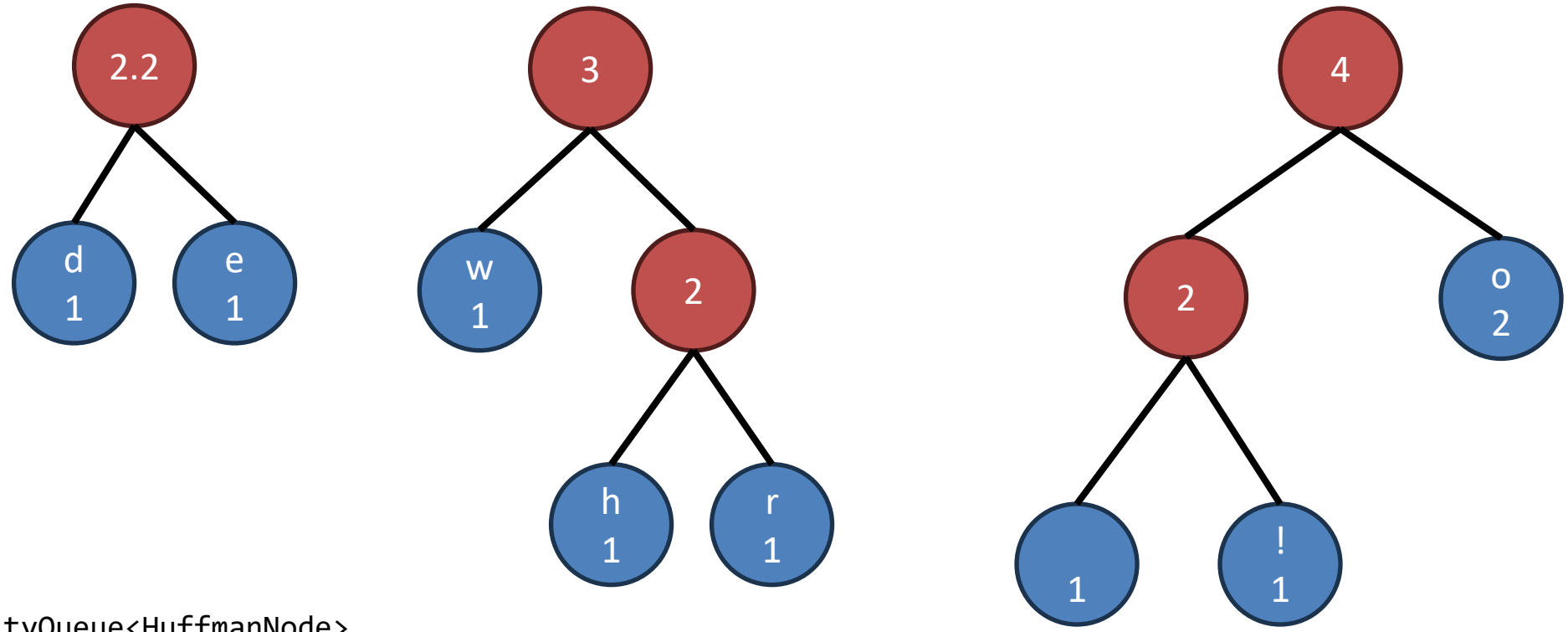

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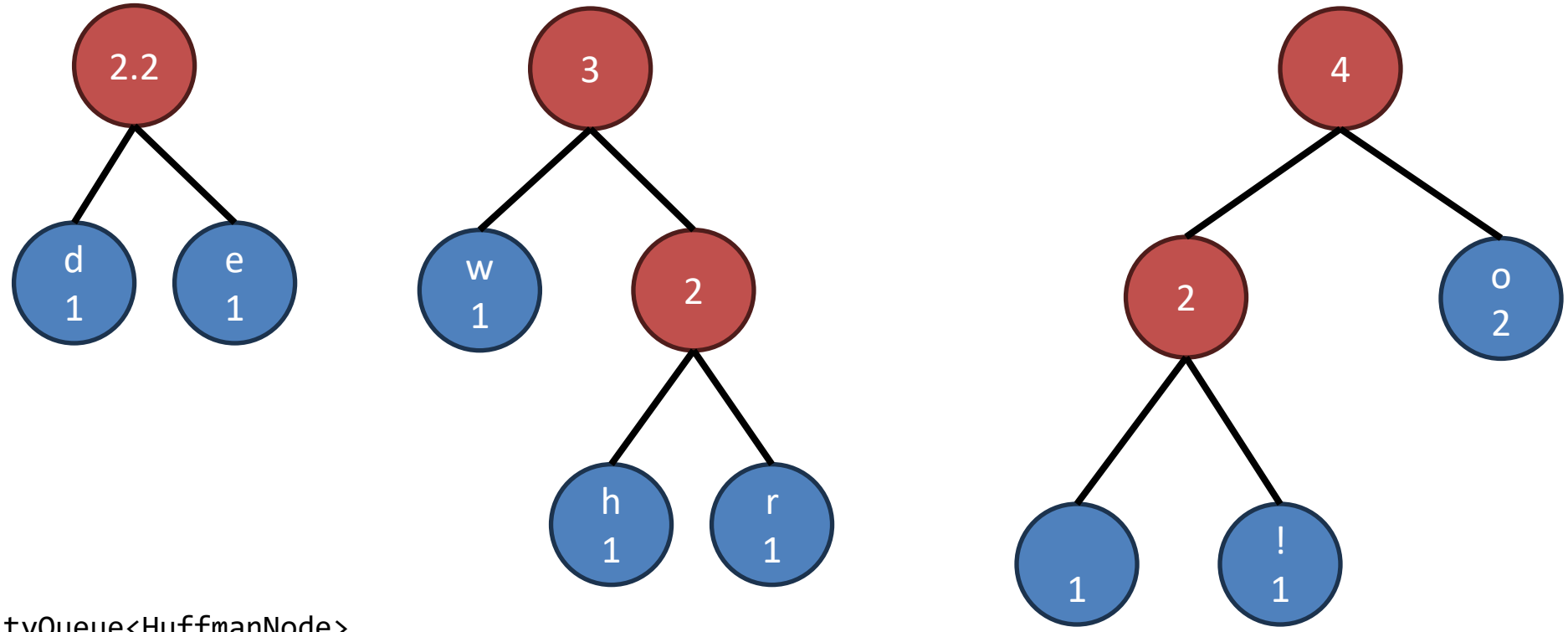

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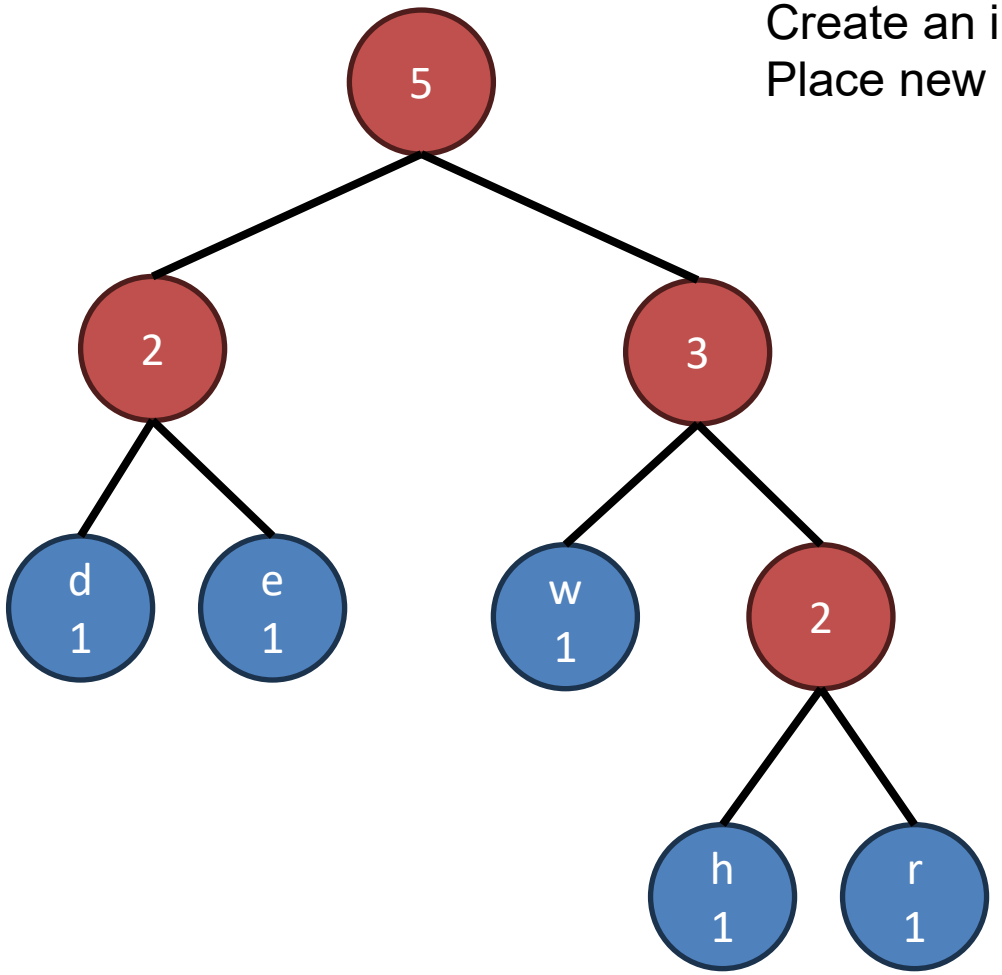

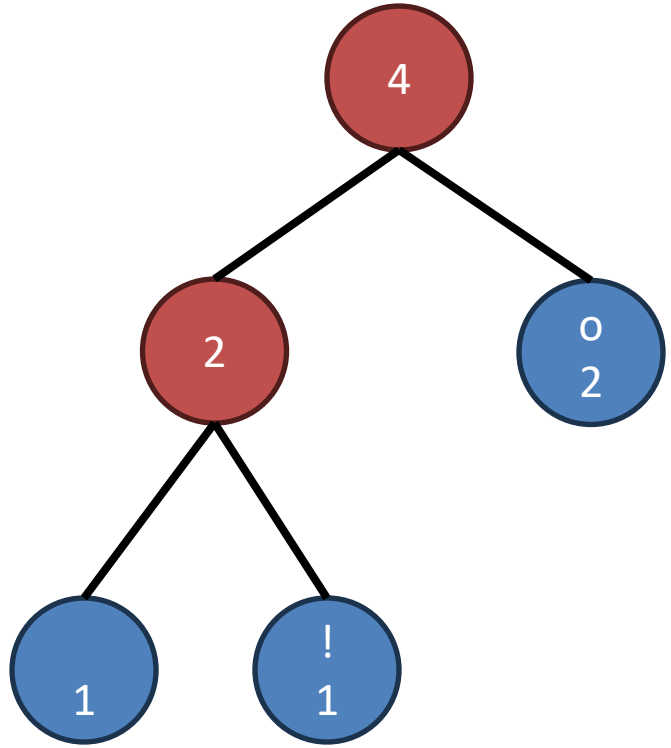

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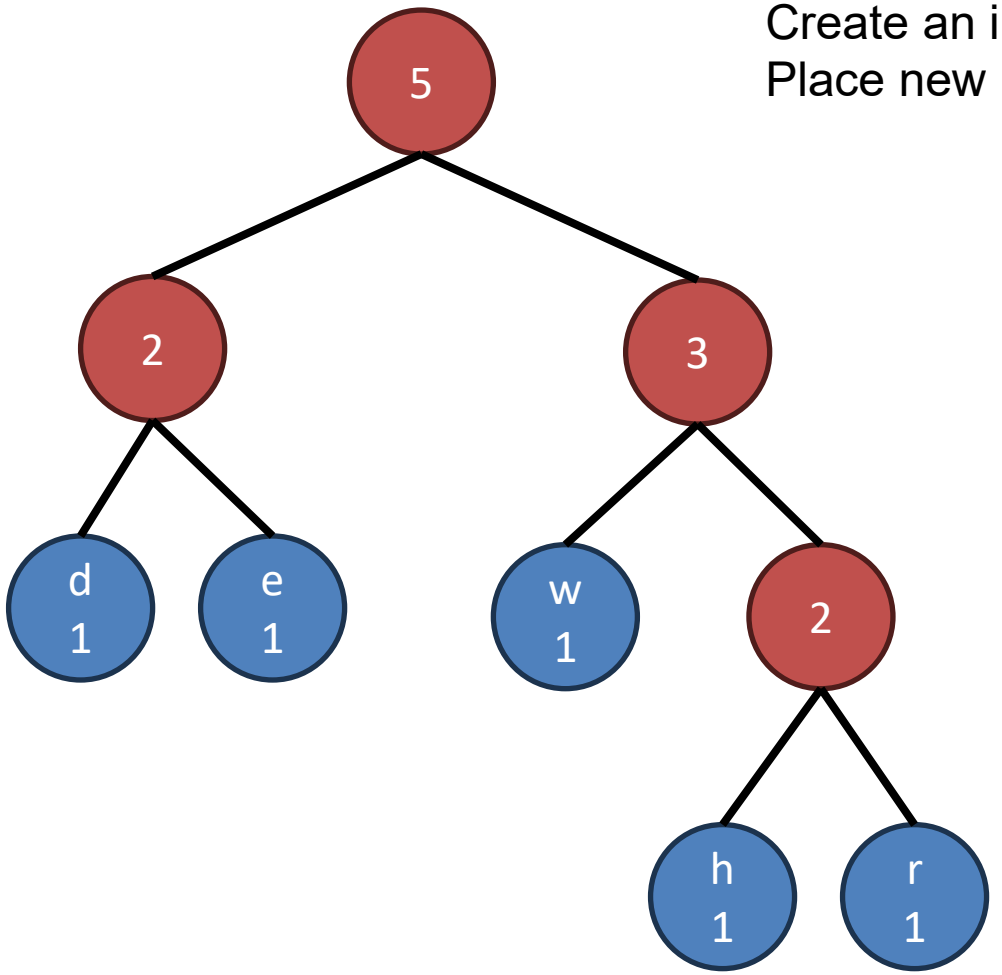

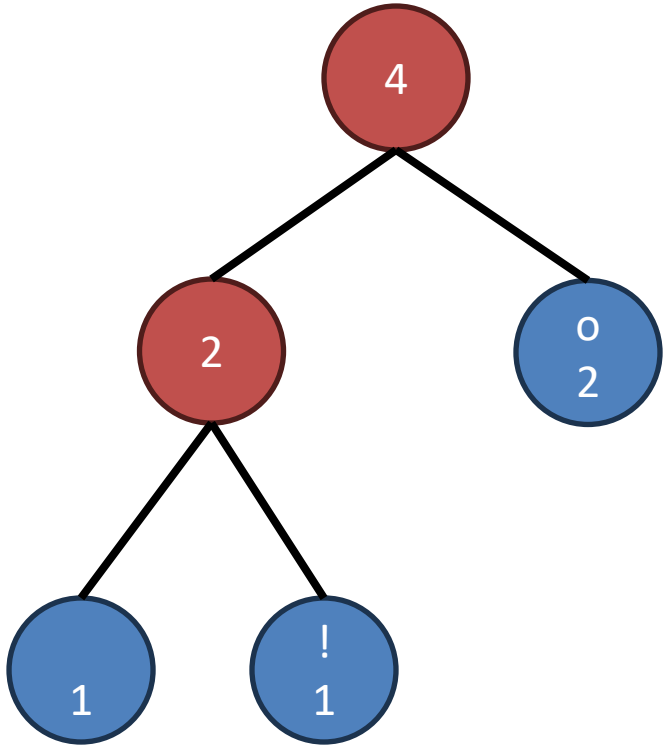

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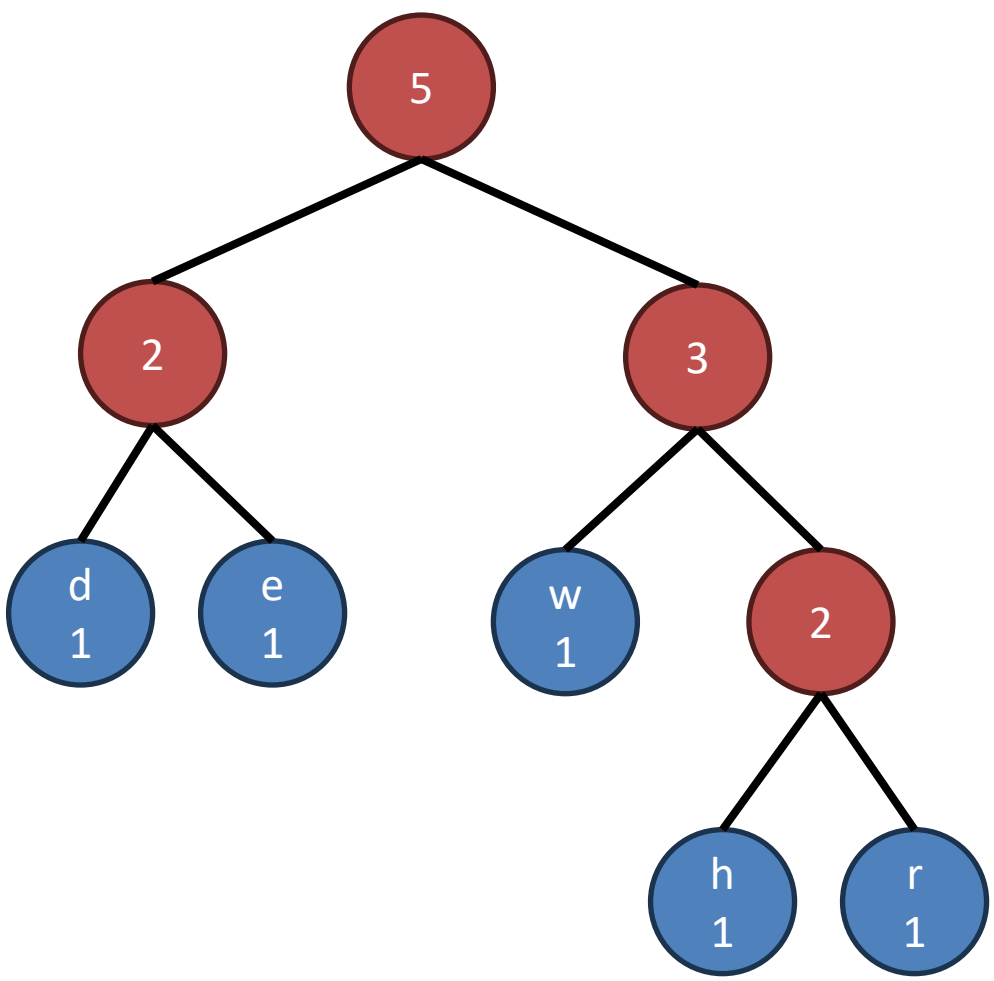

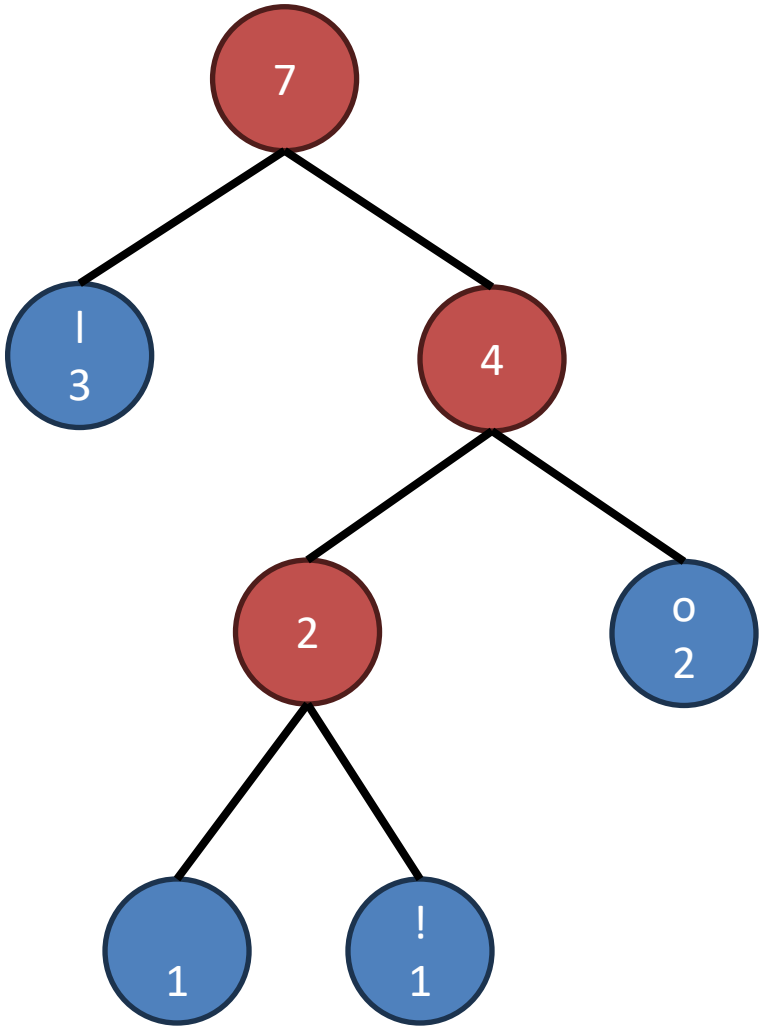

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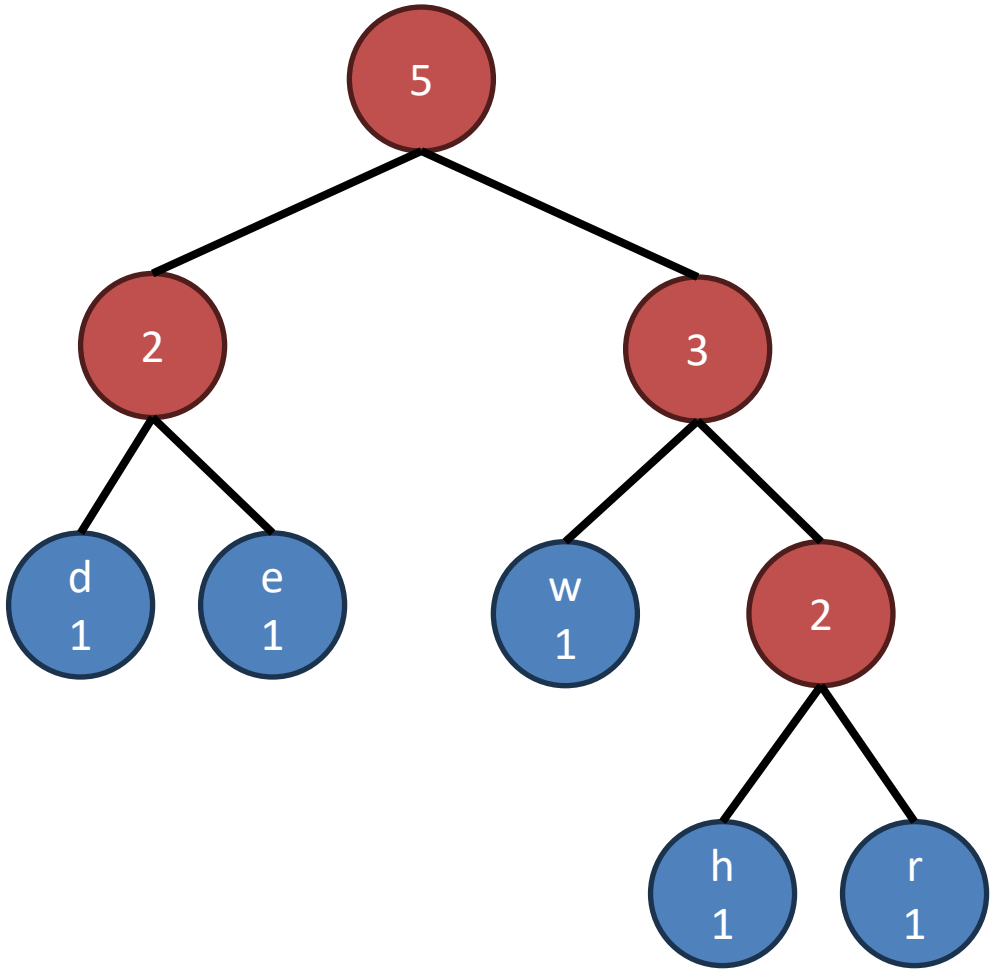

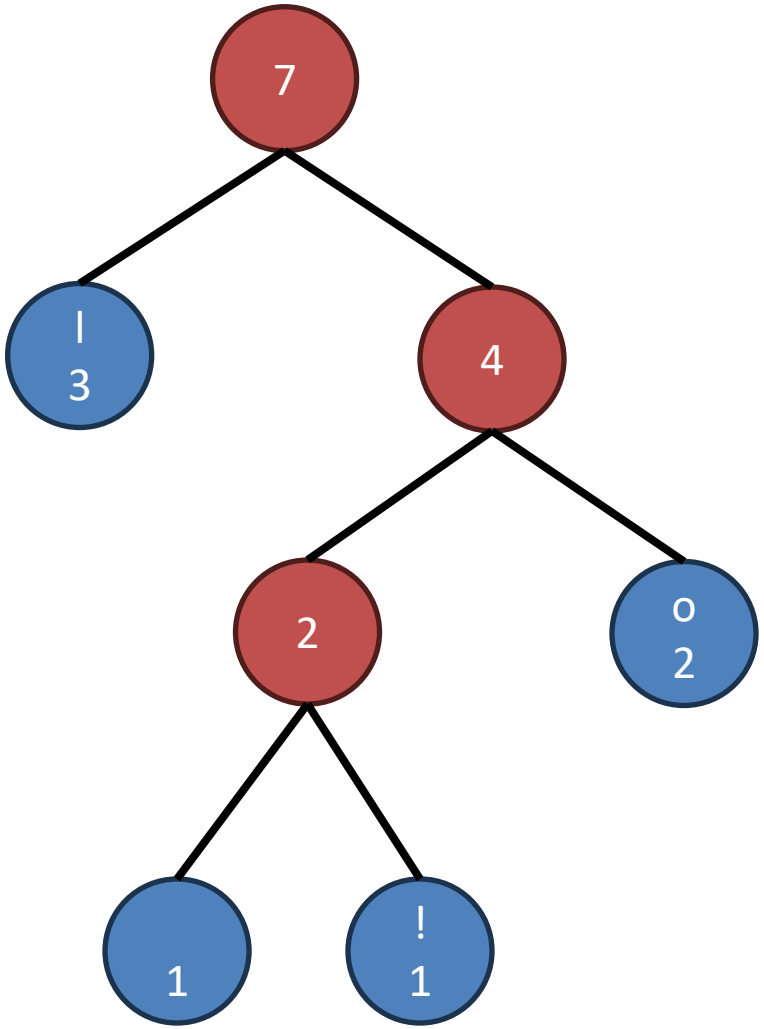

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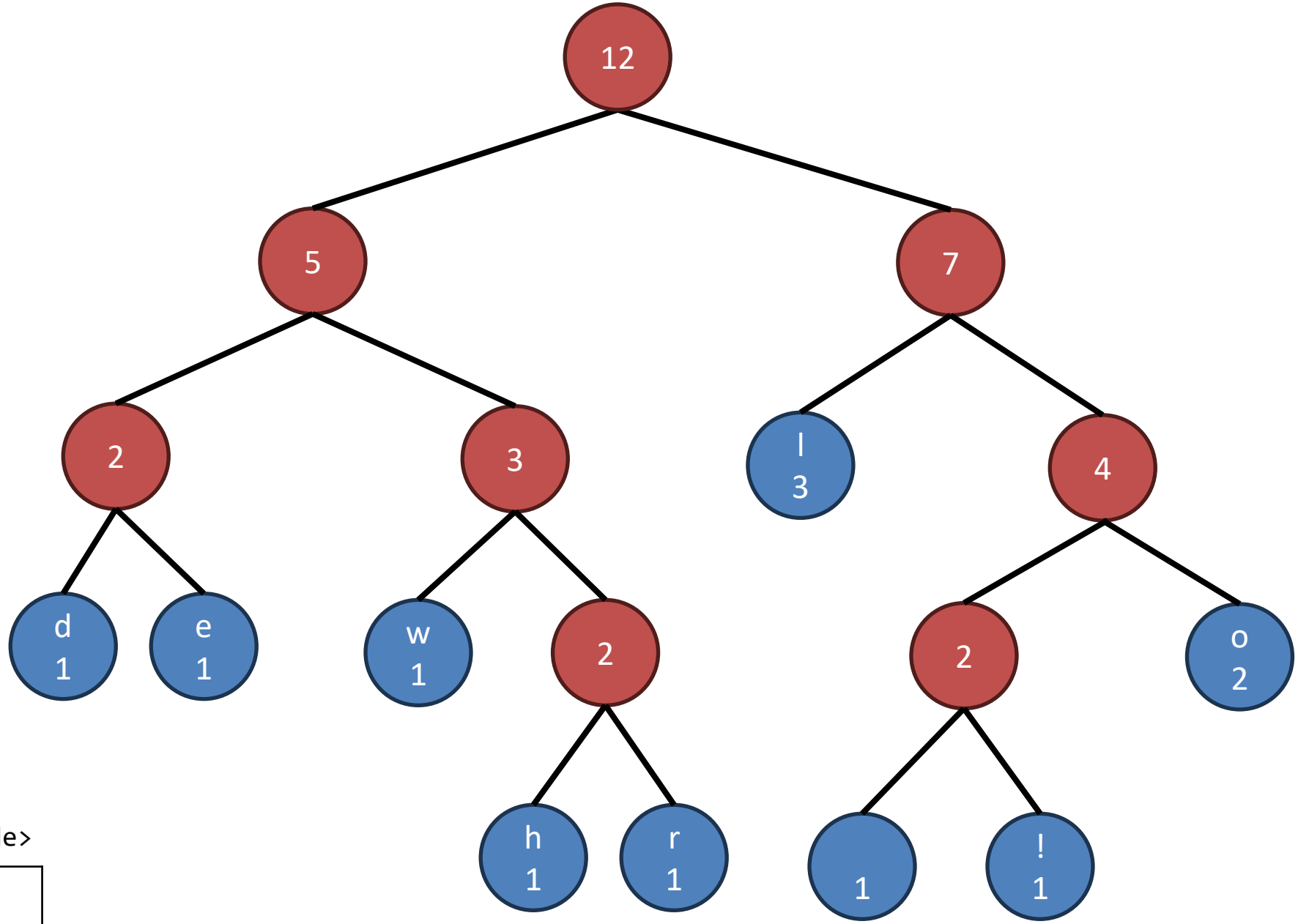

12 is still added to the queue, but when there is only one node left, we know there is no more merging to be done!

PriorityQueue<HuffmanNode>

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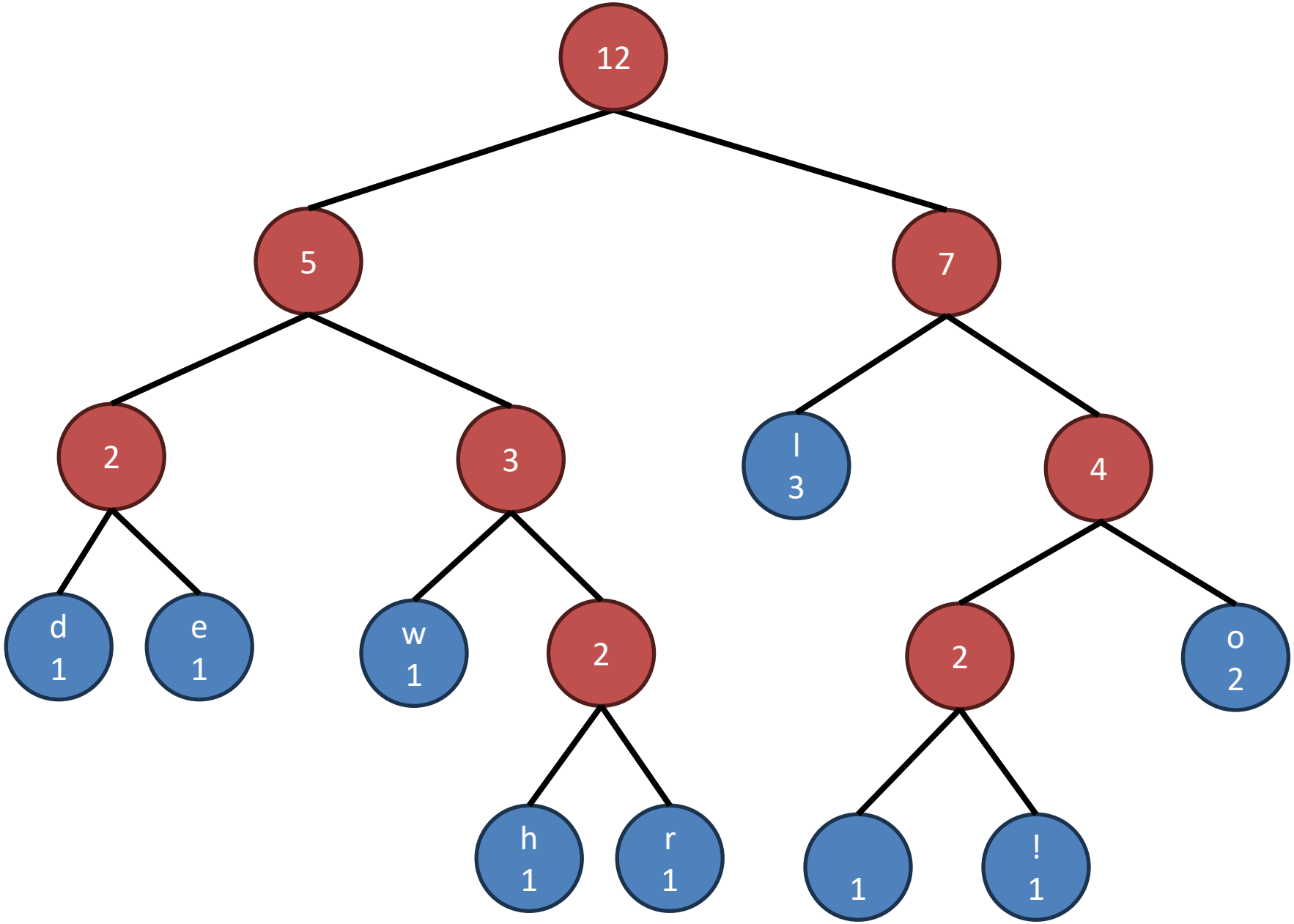
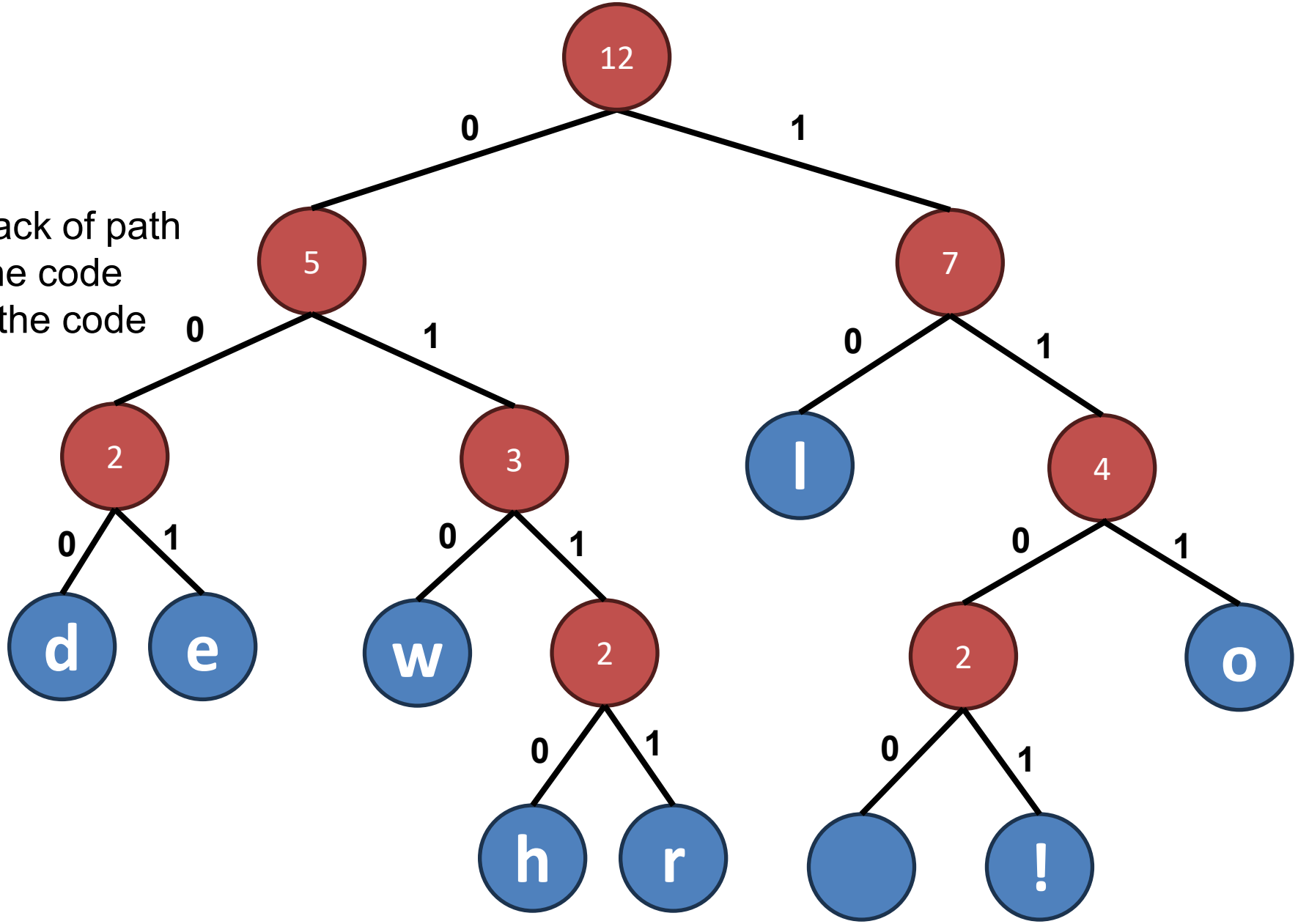


Huffman Coding

Final Step: Generate codes

Visit all leaf nodes and keep track of path
- If we ever go left, add 0 to the code
- If we ever go right, add 1 to the code



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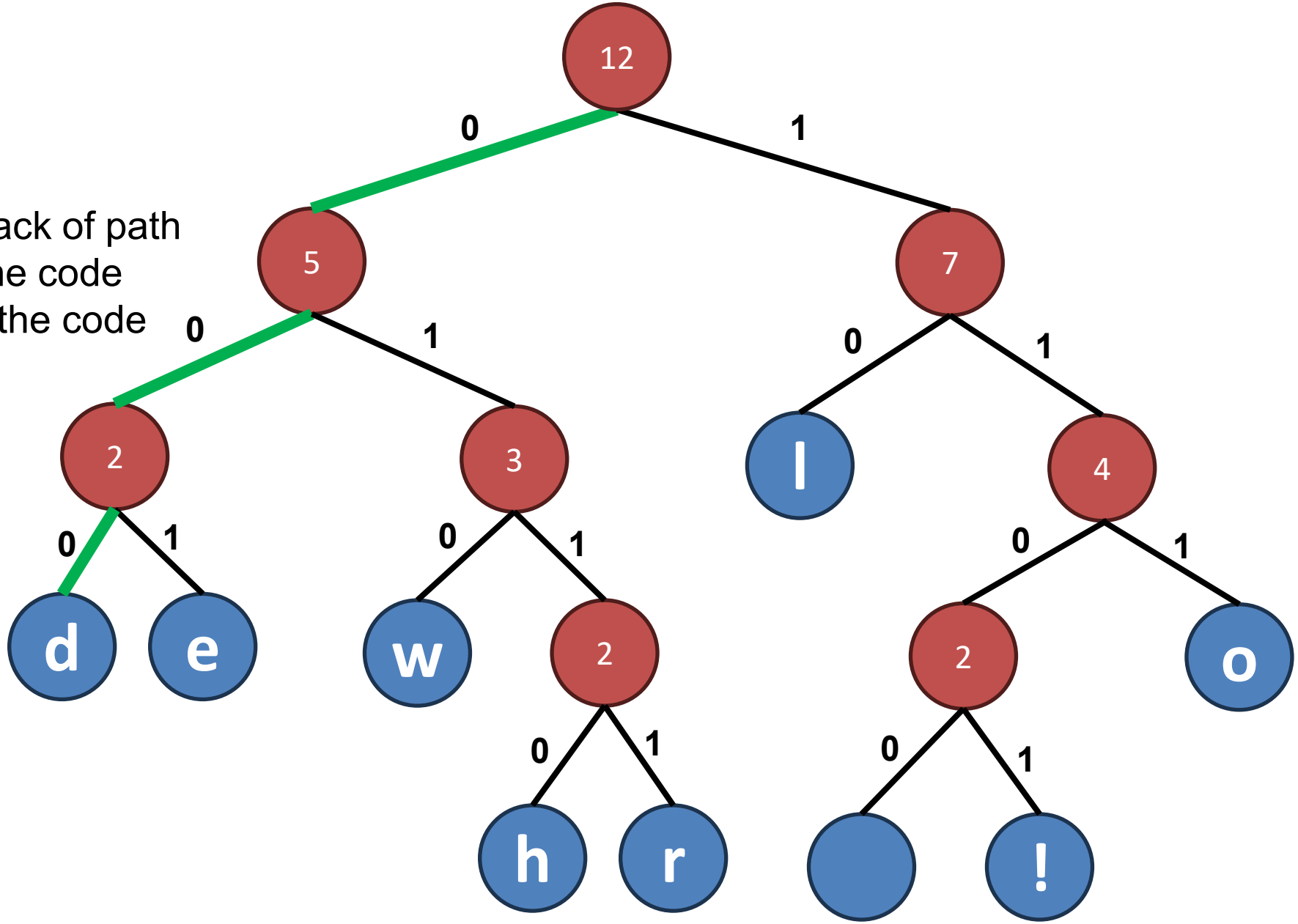
Character	Code
d	000



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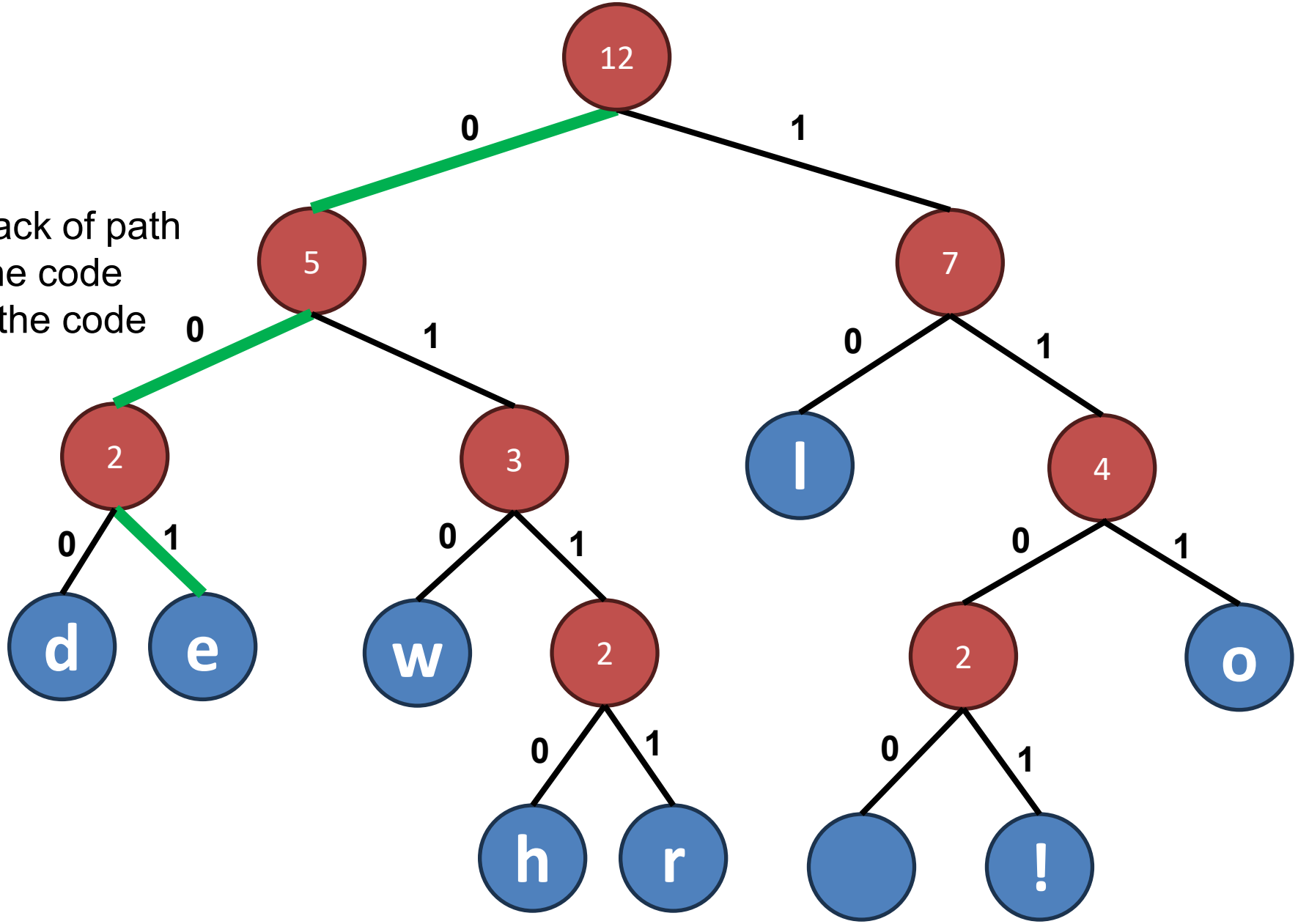
e	001



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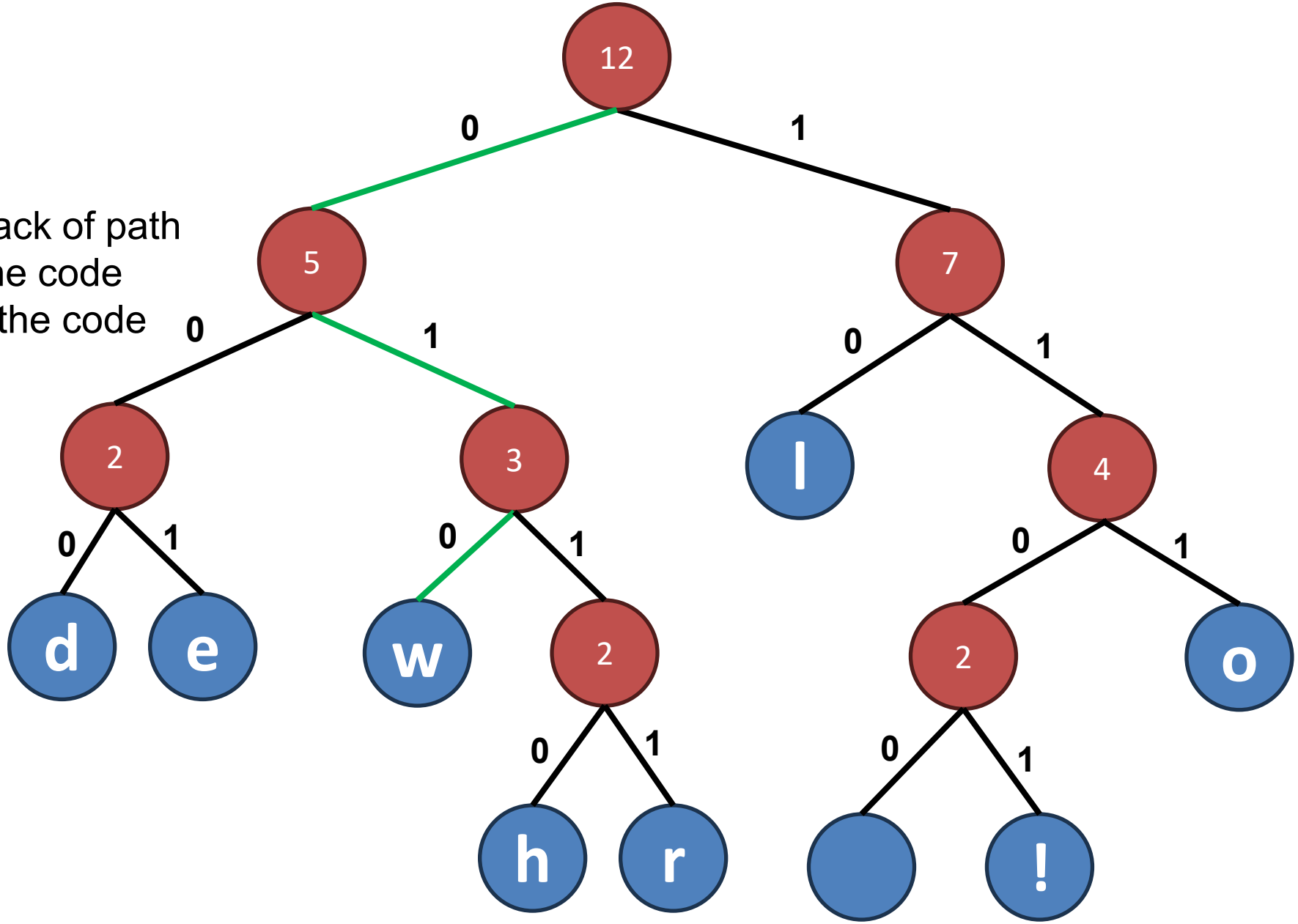
Character	Code
d	000
e	001
w	010

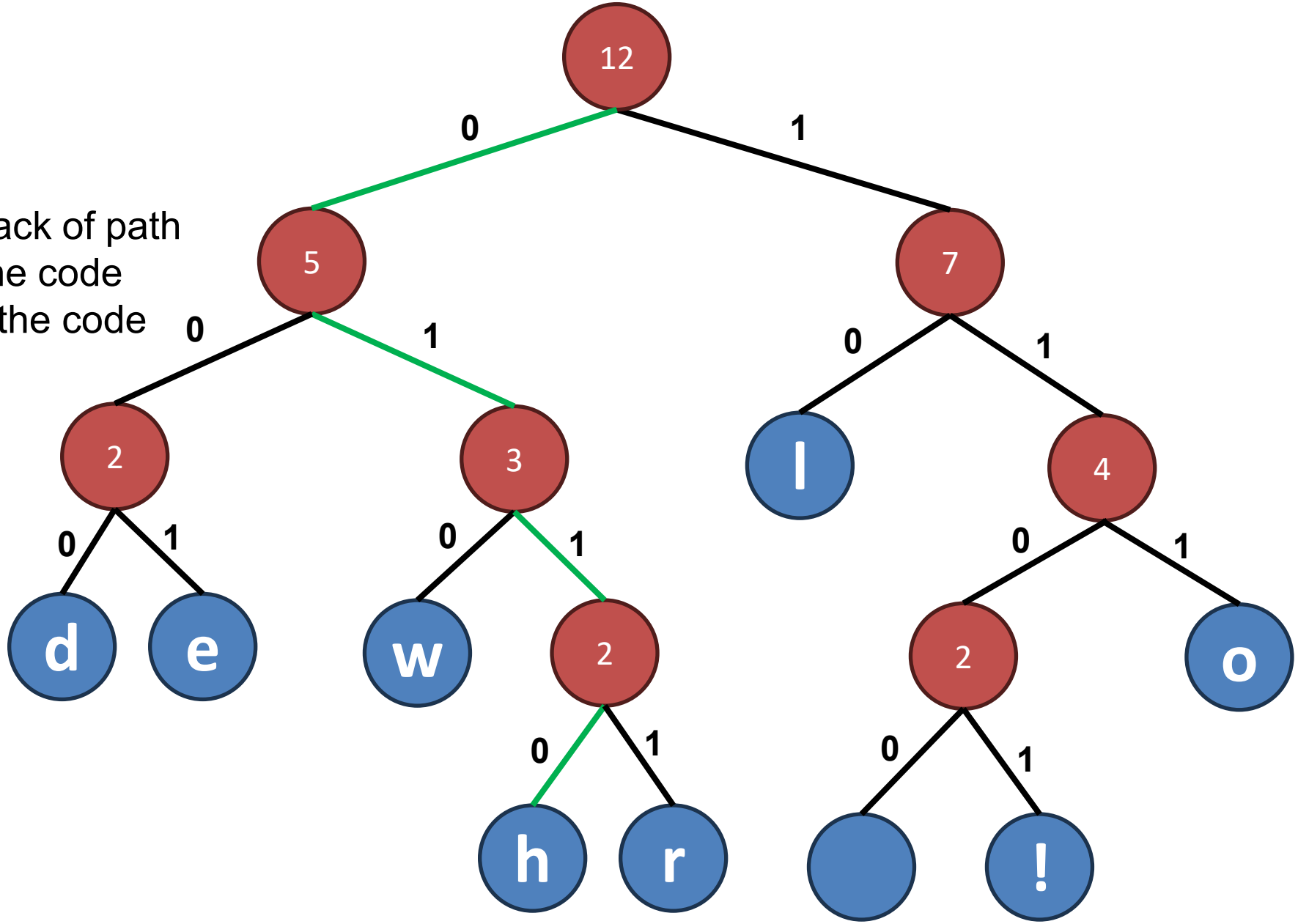


Huffman Coding

Final Step: Generate codes

Visit all leaf nodes and keep track of path
- If we ever go left, add 0 to the code
- If we ever go right, add 1 to the code

Character	Code
d	000
e	001
w	010
h	0110



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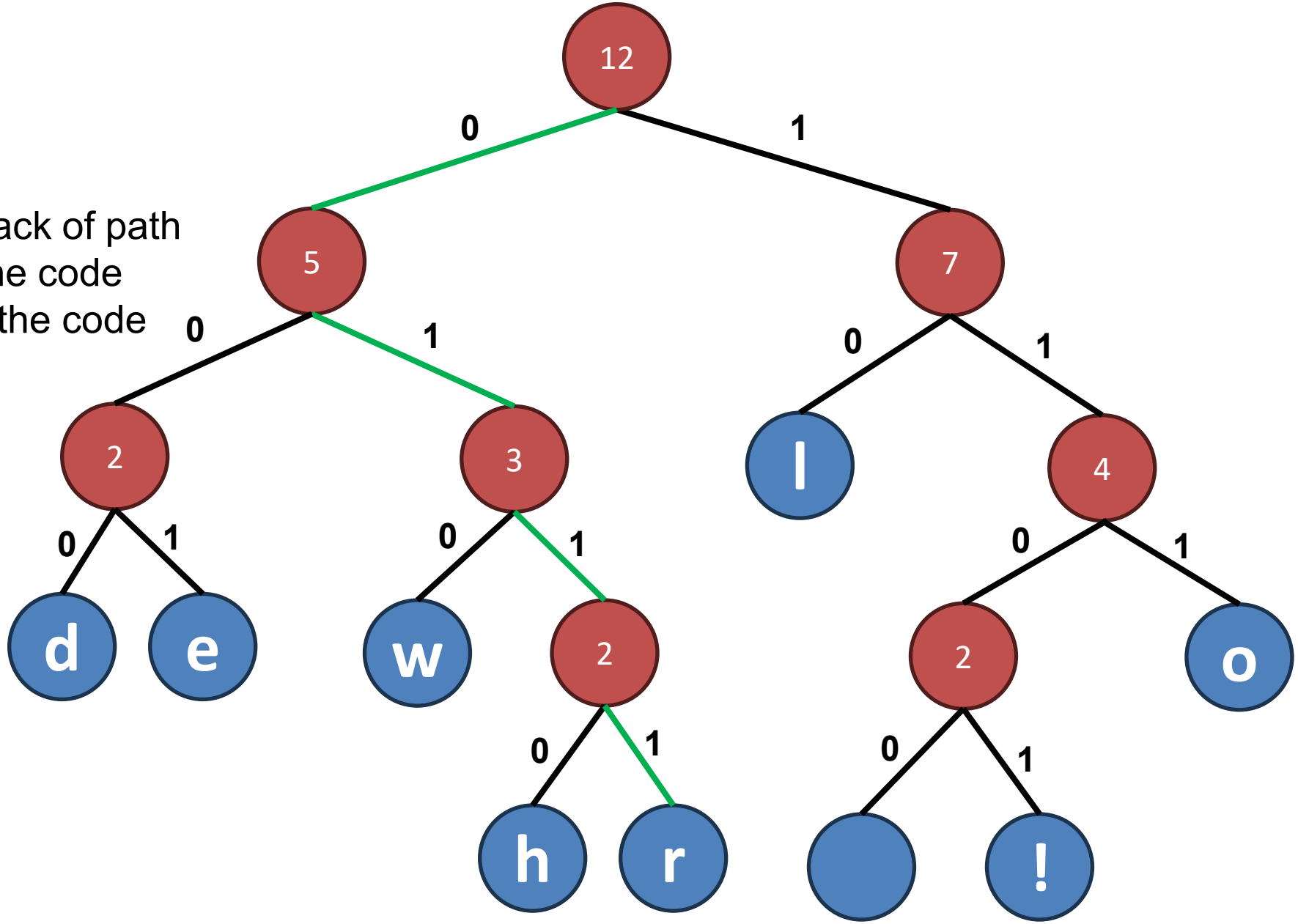
Character	Code
d	000
e	001
w	010
h	0110
r	0111



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Character	Code
d	000
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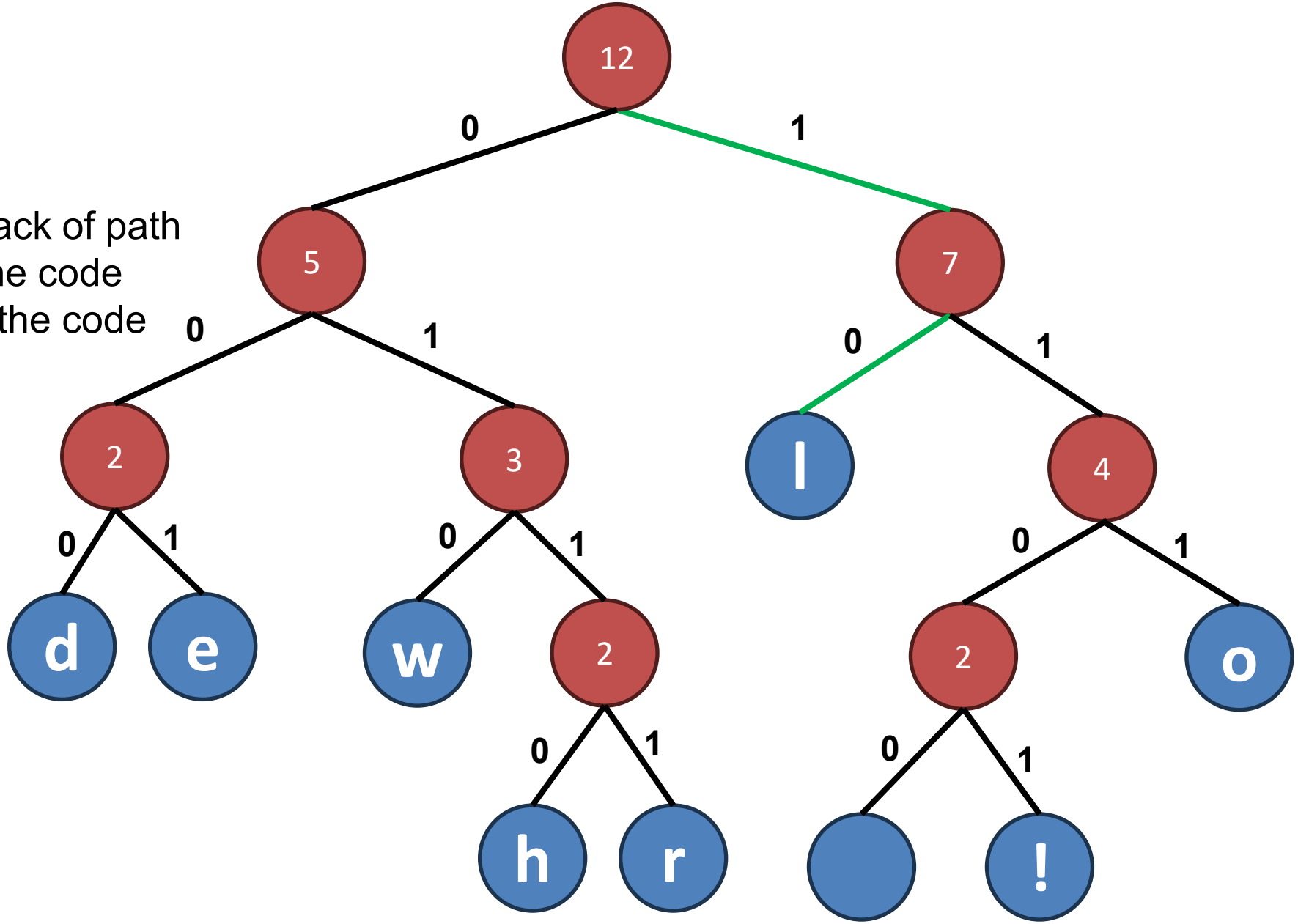
w	010
h	0110
r	0111
l	10



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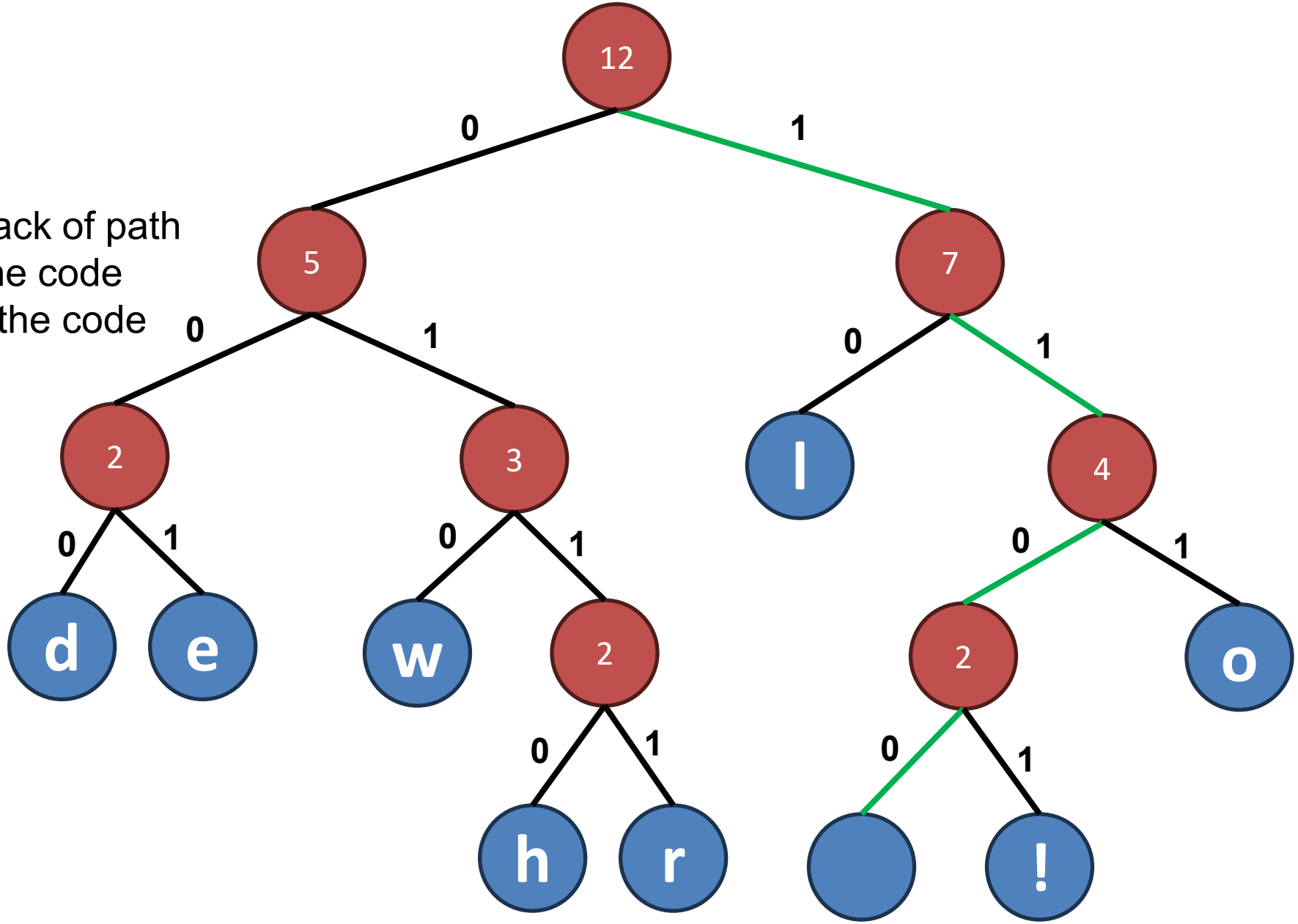
Character	Code
d	000
e	001
w	010
h	0110
r	0111
l	10
(space character)	1100



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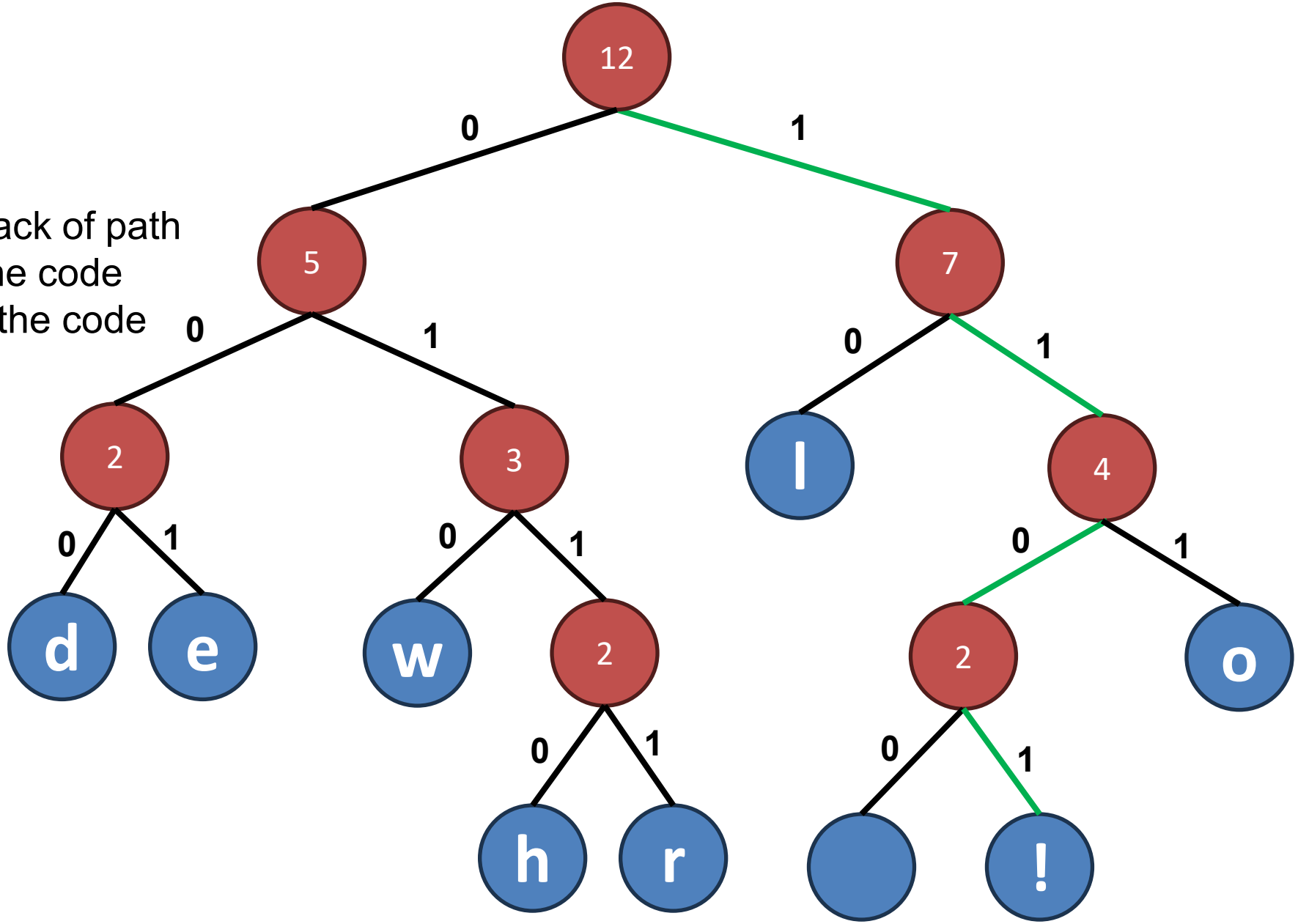
r	0111
l	10
(space character)	1100
!	1101



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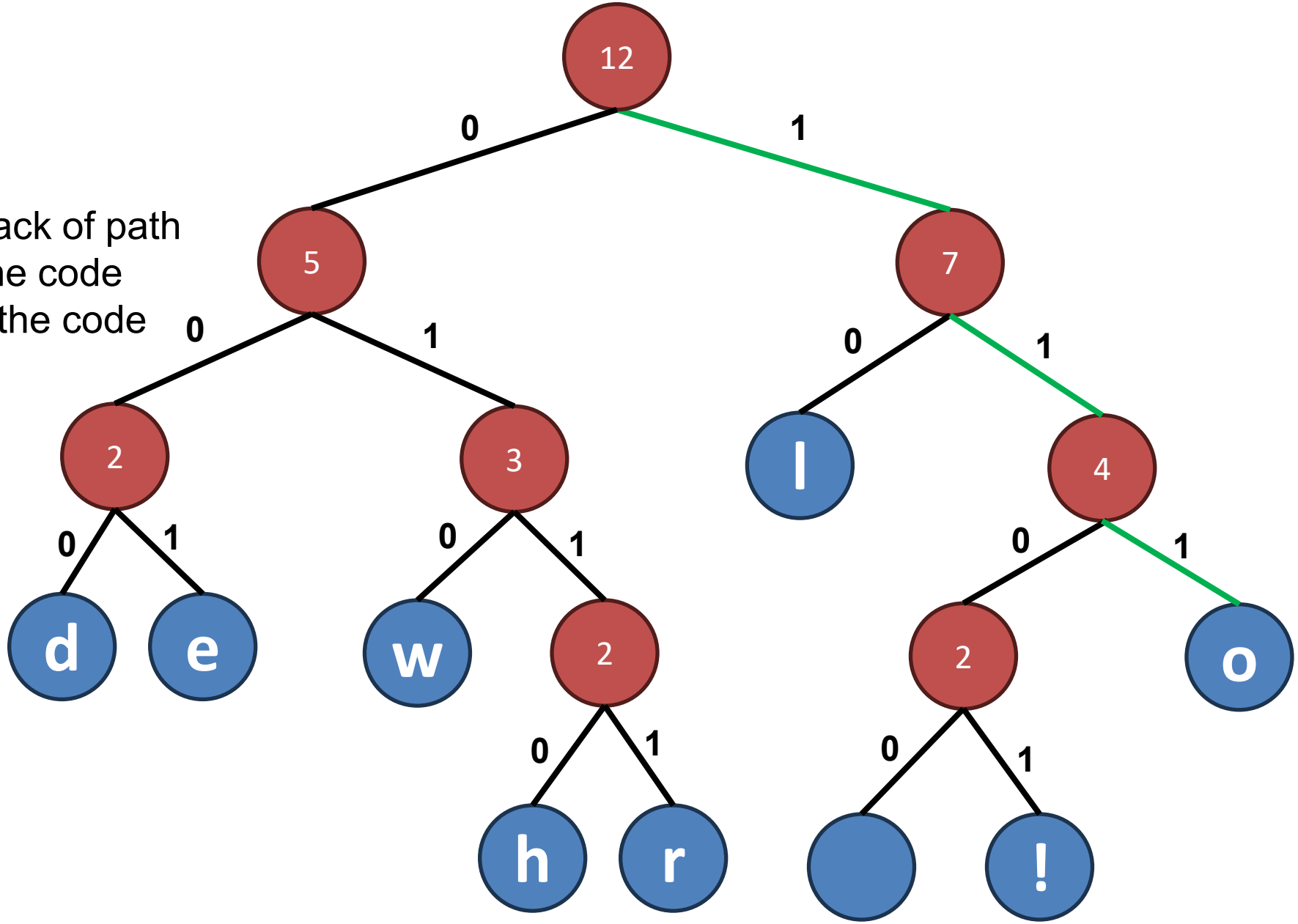
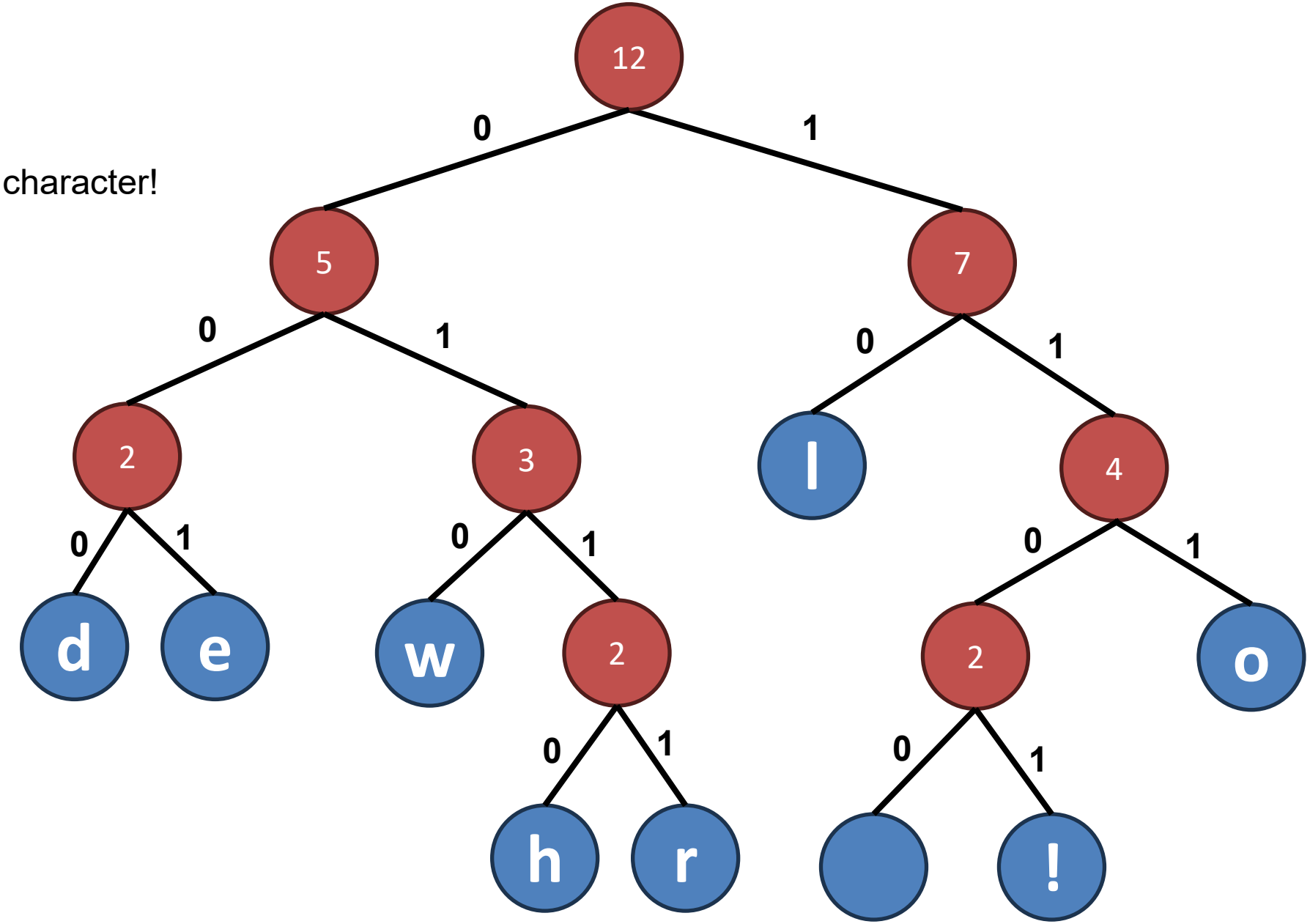


Huffman Coding

We now have encodings for each character!

Character	Code
d	000
e	001
w	010
h	0110
r	0111
l	10
(space character)	1100
!	1101
o	111



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(space character)	1100
!	1101
o	111

String: “hello world!”

Encoding w/ Huffman codes:

0110 001 10 10 111 1100 010 111 0111 10 000 1101

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d	000
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Encoding w/ Huffman codes:

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Let’s code !!

Huffman Coding

We now have encodings for each character!

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w	010
h	0110
r	0111
l	10
(space character)	1100
!	1101
o	111

String: “hello world!”

Encoding w/ Huffman codes:

0110 001 10 10 111 1100 010 111 0111 10 000 1101

Message size: 37 bits

Huffman Coding

We now have encodings for each character!

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e	001
w	010
h	0110
r	0111
l	10
(space character)	1100
!	1101
o	111

String: “hello world!”

Encoding w/ Huffman codes:

0110 001 10 10 111 1100 010 111 0111 10 000 1101

Message size: 37 bits

Encoding w/ UTF:

01101000 01100101 01101100 01101100 01101111 00100000
01110111 01101111 01110010 01101100 01100100

Message size: 88 bits

Huffman Coding

We now have encodings for each character!

Character	Code
d	000
e	
h	
r	
l	
(space character)	1100
!	1101
o	111

Huffman Coding is a **compression** algorithm

…rld!”

Huffman codes:

001 10 10 111 1100 010 111 0111 10 000 1101

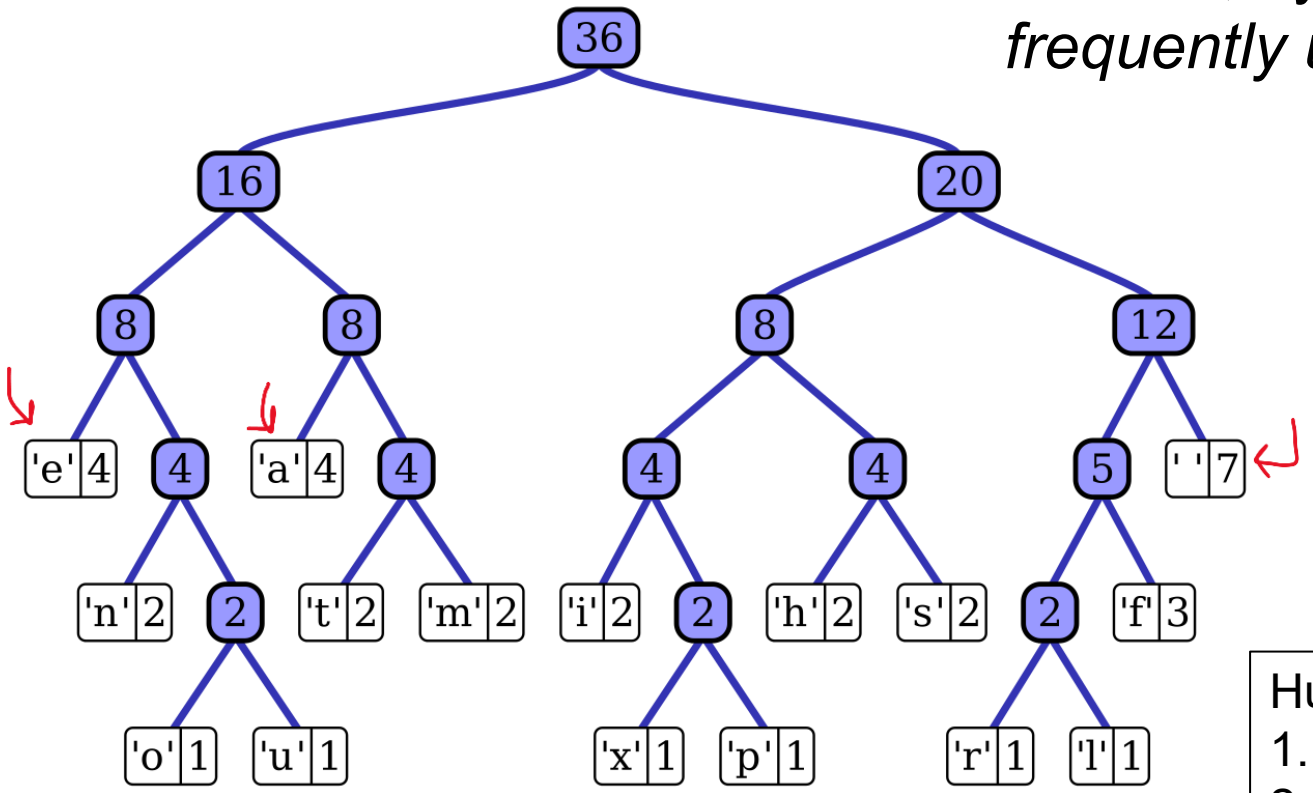
Message size: 37 bits

Encoding w/ UTF:

01101000 01100101 01101100 01101100 01101111 00100000
01110111 01101111 01110010 01101100 01100100

Message size: 88 bits

Huffman Coding is a way to encode a string using a binary tree



It also acts as a lossless compression algorithm for data, by creating smaller encodings for *frequently used characters*

When we compress files with formats such as `.zip`, `.7z`, `.rar` , **Huffman Coding** is used to compress the data!

It is also used for image, video, audio file compression, and even fax machines !

Huffman Coding Algorithm
1. Put nodes in PQ **O(n)**
2. Extract two smallest nodes and merge (repeated n times) } **O(nlogn)**
3. Iterate through to all leaf nodes and get encoding **O(n)**

Total Running time: O(nlogn) where n = # of characters

Huffman Coding Visualization

https://cmps-people.ok.ubc.ca/ylucet/DS/Huffman.html