Huffman Coding

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Data Compression

Data compression is the process of reducing the size of data to save storage space or transmission time.

Types of Data Compression

- Lossless Compression
    - Retains the original data exactly after decompression.
    - Used for text files, program files, and medical imaging.
    - Examples: Huffman Coding, Run-Length Encoding
- Lossy Compression
    - Some data is lost, but the reduction in size is significant.
    - Used for images, audio, and videos where perfect accuracy isn't needed.
    - Examples: JPEG, MP3, MPEG, H.264, H.265

Character Encoding Compression

Encoding characters is a key part of lossless compression algorithms, where data is compressed without losing any information, and the original data can be perfectly reconstructed during decompression.

Types of Character Encoding

- Fixed-Length Encoding
  - Each character or symbol is represented using a fixed number of bits.
- Variable-Length Encoding
  - Different characters or symbols are represented using a varying number of bits.
  - More frequent symbols get shorter codes, while less frequent ones get longer codes.

Fixed-Length Encoding

M = “Sleeplessness stresses restless senses endlessly”

s	e	l	sp	n	t	r	p	d	y
17	12	5	4	3	2	2	1	1	1

Total number of characters = 48

ASCII

- Uses 7-bit codes to represent characters (A-Z, a-z, 0-9, symbols).
- Required bits to encode **M** = 48*7 = 336 bits

Minimal Fixed Code

- Since there is 10 different character, we can use 4 bits for each character to encode message M.
- Required bits to encode **M** = 48*4 = 192 bits

Variable-Length Encoding

M = “Sleeplessness stresses restless senses endlessly”

s	e	l	sp	n	t	r	p	d	y
17	12	5	4	3	2	2	1	1	1

Total number of characters = 48

Huffman Coding can be used for variable length encoding.

Huffman Coding - Introduction

- Huffman coding is a greedy algorithm used for lossless data compression.
- It assigns variable-length binary codes to input characters. [shorter codes assigned to more frequent characters and longer codes assigned to less frequent ones]
- This minimizes the overall length of the encoded message.
- The core idea is to build a binary tree (Huffman tree) where each leaf node represents a character and its frequency. The tree is then traversed to assign binary codes.

Huffman Coding - Applications

- **File Storage –** Reduces disk space usage.
- **Network Transmission –** Speeds up data transfer.
- **Multimedia Streaming –** Reduces bandwidth requirements.
- **Cloud Storage –** Saves costs for large-scale data storage.
- **Data Backup & Archiving –** Efficiently stores historical data.

Huffman Coding - Algorithm

- Count the frequency of each character in the input.
- Insert all characters and their frequencies into a priority queue (min-heap).
- While there is more than one node in the queue:
    - Remove the two nodes with the lowest frequency.
    - Create a new internal node with these two as children and a frequency equal to their sum.
    - Insert the new node back into the priority queue.
- The last remaining node is the root of the Huffman tree.
- Generate binary codes by traversing the Huffman tree.

Huffman Coding - Example

M = “Sleeplessness stresses restless senses endlessly”

Count the frequency of each character in the input.

s	l	e	p	n	sp	t	r	d	y
17	5	12	1	3	4	2	2	1	1

Insert all characters and their frequencies into a priority queue (min-heap).

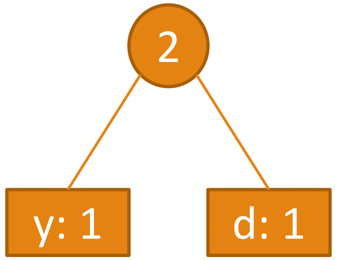
y: 1	d: 1	p: 1	r: 2	t: 2	n: 3	sp: 4	l: 5	e: 12	s: 17

Huffman Coding - Example

y: 1	d: 1	p: 1	r: 2	t: 2	n: 3	sp: 4	l: 5	e: 12	s: 17

- While there is more than one node in the queue:
  - Remove the two nodes with the lowest frequency.
  - Create a new internal node with these two as children and a frequency equal to their sum.
  - Insert the new node back into the priority queue.

p: 1	2	r: 2	t: 2	n: 3	sp: 4	l: 5	e: 12	s: 17



Huffman Coding - Example

p: 1	2	r: 2	t: 2	n: 3	sp: 4	l: 5	e: 12	s: 17

- While there is more than one node in the queue:
  - Remove the two nodes with the lowest frequency.
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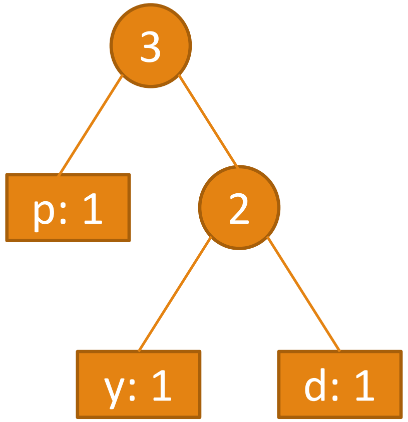

r: 2	t: 2	3	n: 3	sp: 4	l: 5	e: 12	s: 17

Huffman Coding - Example

r: 2	t: 2	3	n: 3	sp: 4	l: 5	e: 12	s: 17

- While there is more than one node in the queue:
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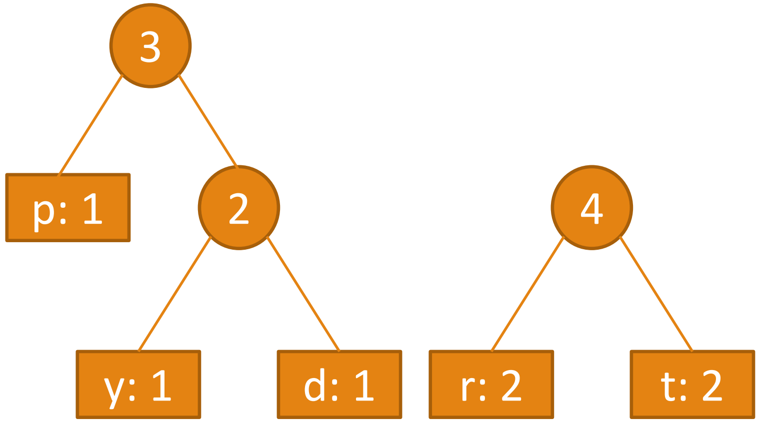
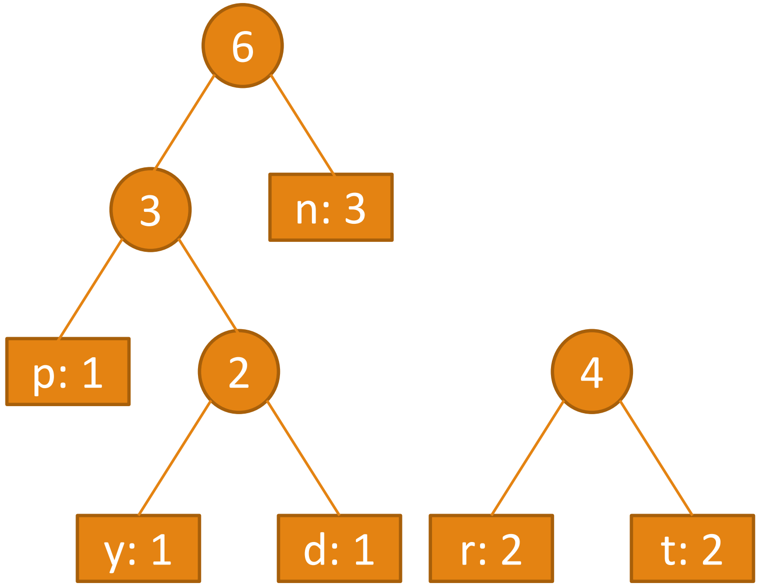


3	n: 3	4	sp: 4	l: 5	e: 12	s: 17

Huffman Coding - Example

3	n: 3	4	sp: 4	l: 5	e: 12	s: 17



- While there is more than one node in the queue:
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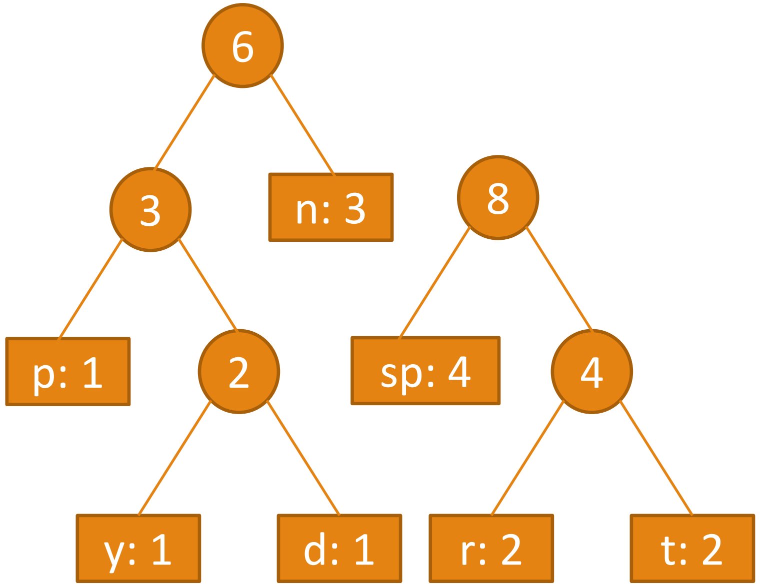
  - Insert the new node back into the priority queue.

4	sp: 4	l:5	6	e: 12	s: 17

Huffman Coding - Example

4	sp: 4	l:5	6	e: 12	s: 17



- While there is more than one node in the queue:
  - Remove the two nodes with the lowest frequency.
  - Create a new internal node with these two as children and a frequency equal to their sum.
  - Insert the new node back into the priority queue.

l: 5	6	8	e: 12	s: 17

Huffman Coding - Example

l: 5	**6**	**8**	**e: 12**	**s: 17**

- While there is more than one node in the queue:
  - Remove the two nodes with the lowest frequency.
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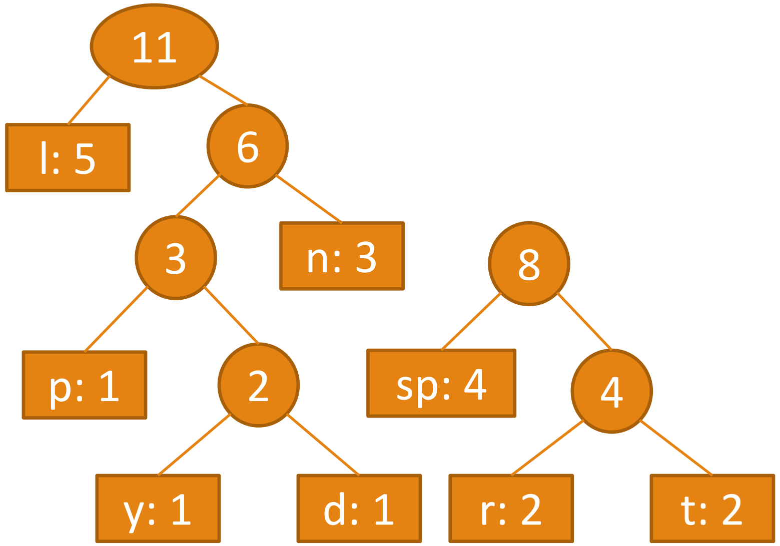
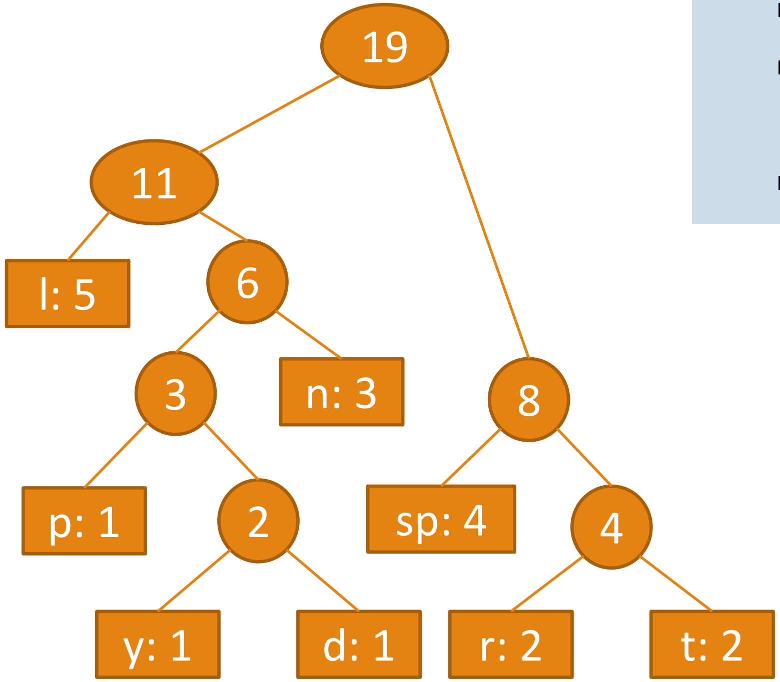


8	**11**	**e: 12**	**s: 17**

Huffman Coding - Example

8	**11**	**e: 12**	**s: 17**



- While there is more than one node in the queue:
  - Remove the two nodes with the lowest frequency.
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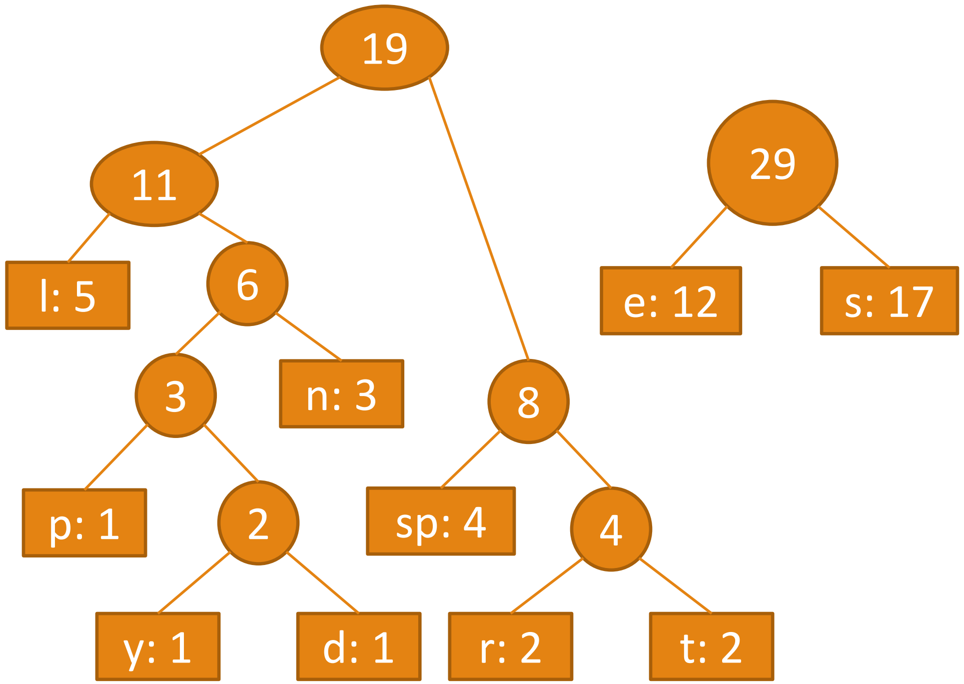
  - Insert the new node back into the priority queue.

e: 12	**s: 17**	**19**

Huffman Coding - Example

e: 12	**s: 17**	**19**



- While there is more than one node in the queue:
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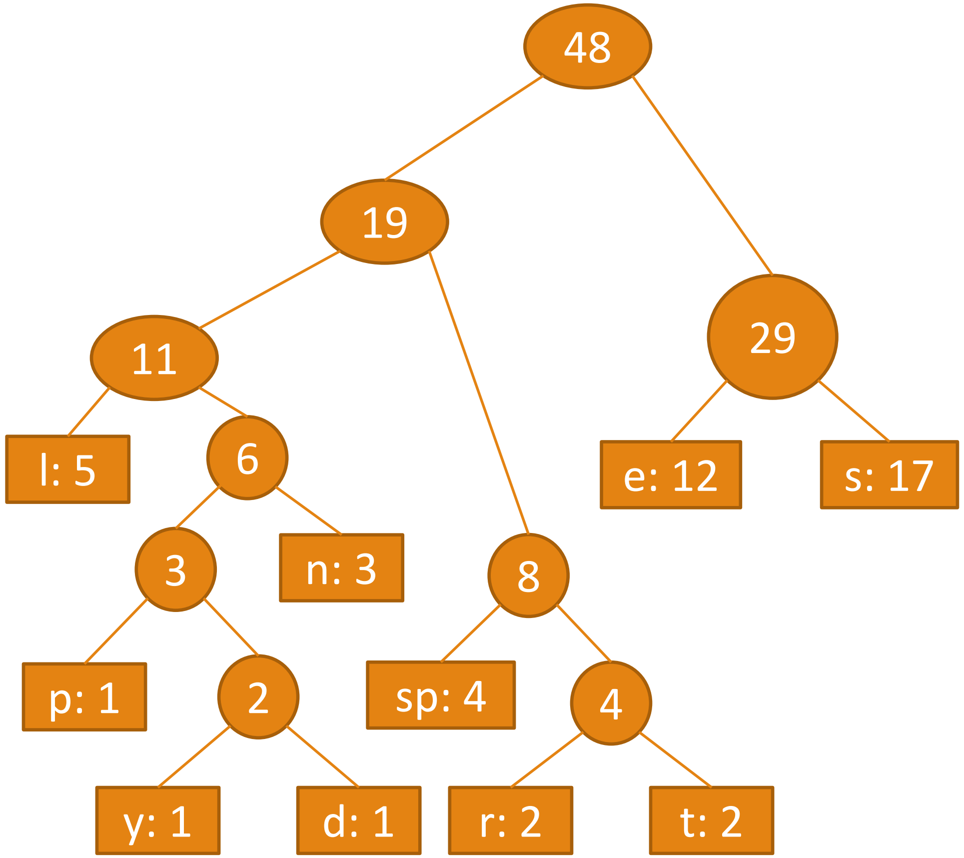
  - Insert the new node back into the priority queue.

19	**29**

Huffman Coding - Example



19	**29**

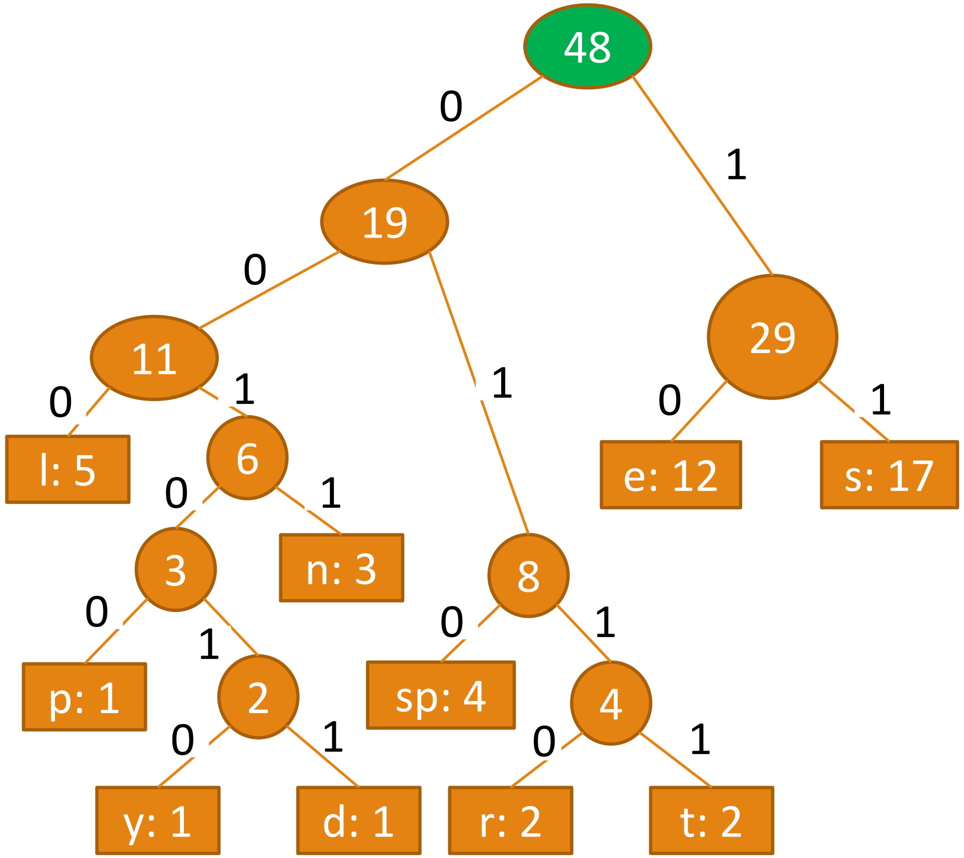
- While there is more than one node in the queue:
  - Remove the two nodes with the lowest frequency.
  - Create a new internal node with these two as children and a frequency equal to their sum.
  - Insert the new node back into the priority queue.

48

The last remaining node is the root of the Huffman tree.

48

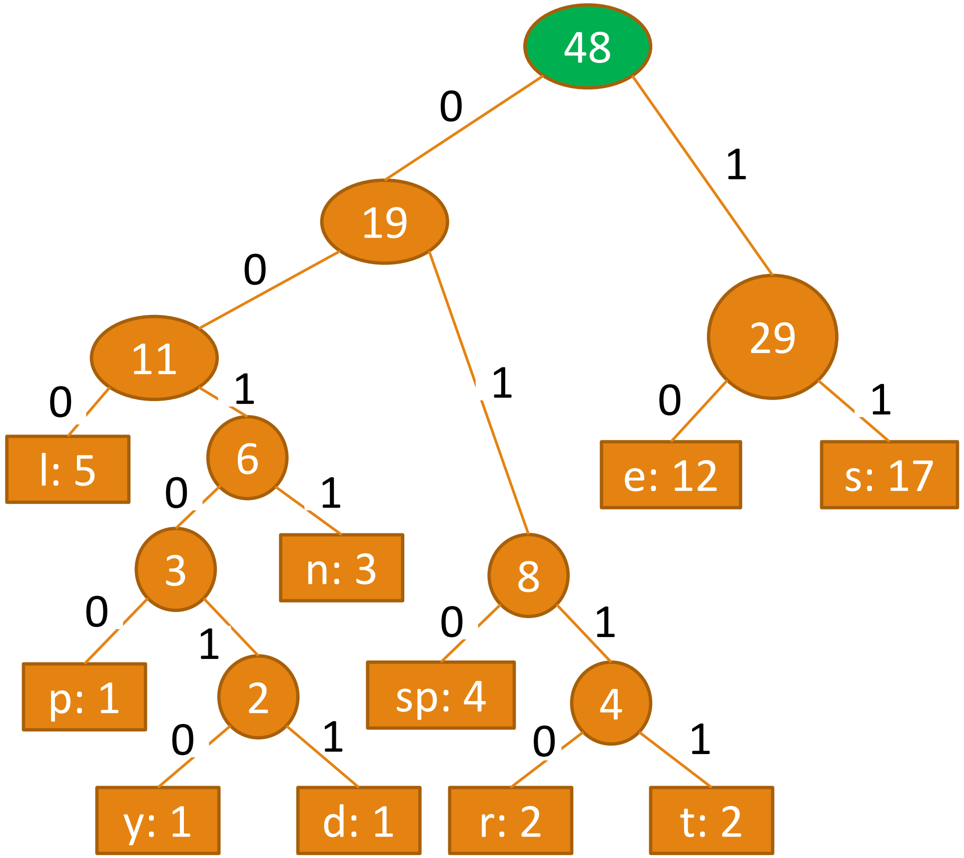
Huffman Coding - Example



Generate binary codes by traversing the Huffman tree.

Character	Codes
s	11
l	000
e	10
p	00100
n	0011
sp	010
t	0111
r	0110
d	001011
y	001010

Huffman Coding - Example



Generate binary codes by traversing the Huffman tree.

Char	Codes	Freq	Required Bits
s	11	17	2*17 = 34
l	000	5	3*5 = 15
e	10	12	2*12 = 24
p	00100	1	5*1 = 5
n	0011	3	4*3 = 12
sp	010	4	3*4 = 12
t	0111	2	4*2 = 8
r	0110	2	4*2 = 8
d	001011	1	6*1 = 6
y	001010	1	6*1 = 6

Required Total Bits = **130** bits

Average Bits per Character

$$= \frac{130}{48}\,bits/char$$

$$= \mathbf{2.708}\ bits/char$$

Home Task:

Analysis the Time Complexity of Huffman Coding.

THANK YOU