HUFFMAN CODING ALGORITHM

University of Science, VNU-HCM

Data Structures and Algorithms

Group 4

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Overview of Data Compression

What is Data Compression?

The process of reducing data size without losing (or minimally losing) information.

Types of Compression

- **Lossless Compression:** Guarantees complete recovery of original data
- **Lossy Compression:** Accepts loss of some non-critical information

Historical Development

- Morse Code - assigning shorter codes to frequently used letters
- Claude Shannon (1948) - Information Theory
- David Huffman (1952) - Huffman Algorithm
- Lempel-Ziv (1970s-80s) - LZ77, LZ78, LZW

Need for Data Compression

- Save storage space
- Reduce data transmission time
- Optimize bandwidth
- Reduce storage and transmission costs

Applications

- Multimedia compression (JPEG, MP3, MPEG)
- Text compression (ZIP, GZIP, 7-Zip)
- Database compression
- Compression in embedded systems

Introduction to Huffman Algorithm

David Albert Huffman (1925-1999)

- Graduated from Ohio State University at age 18
- PhD at MIT in 1953
- Professor at University of California, Santa Cruz
- Motto: "My products are my students"

Birth of the Huffman Algorithm

In 1952, David Huffman was a student of Professor Robert M. Fano at MIT.

Final assignment: Find the most efficient way to encode a set of symbols based on frequency.

The algorithm was published in the paper "A Method for the Construction of Minimum-Redundancy Codes".

Symbolistics of Huffman Algorithm

- Lossless compression algorithm
- Uses prefix codes
- Based on symbol frequency
- Assigns shorter codes to frequent symbols
- Uses binary tree to represent codes

Prefix Code

A symbol's code is not a prefix of any other symbol's code

Valid: [00, 11, 10, 010]

Invalid: [00, 001, 10, 010]
Reason: 00 is a prefix of 001

Steps of the Huffman Algorithm

Step 1: Count symbol frequencies
Read the input data and count occurrences of each symbol

Step 2: Build a Min-Heap (priority queue)
Insert each symbol as a node into the Min-heap based on frequency
Highest priority given to symbols with lowest frequency

Step 3: Build the Huffman tree
- Take the two nodes with lowest frequencies and remove them from the heap
- Create a new node with frequency equal to the sum of the two nodes
- Make the two nodes the children of the new node
- Insert the new node into the heap
- Repeat until only one node remains in the heap (the root of the Huffman tree)

Step 4: Assign binary codes to symbols
- Traverse the Huffman tree from root to leaves
- When going through a left edge, add '0' to the code
- When going through a right edge, add '1' to the code
- When a leaf is reached, the obtained code is the Huffman code for that symbol

Step 5: Encode and decode data
Encoding: Replace each symbol in the original data with its corresponding Huffman code
Decoding: Use the Huffman tree to convert the encoded data back to the original data

Visualizing the Huffman Tree Construction Process

Huffman Tree Construction Process

Symbol Frequency in "Huffman"

Symbol	Frequency
H	1
u	1
f	2
m	1
a	1
n	1

Min-Heap: H:1 u:1 m:1 a:1 n:1 f:2

Start with all symbols from "Huffman" in the min-heap, ordered by frequency.

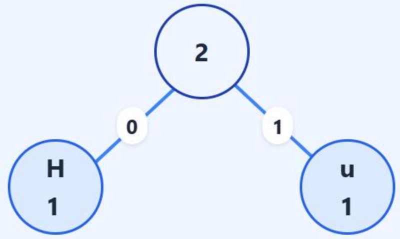
Previous Step **Step 1/6** Next Step

Visualizing the Huffman Tree Construction Process

Symbol Frequency in "Huffman"

Symbol	Frequency
H	1
u	1
f	2
m	1
a	1
n	1

Huffman Tree Construction Process



Removed: ~~H:1~~ ~~u:1~~

Min-Heap: m:1 a:1 n:1 f:2 2

Take two nodes with lowest frequency: 'H' (1) and 'u' (1). Create a new node with frequency 2.

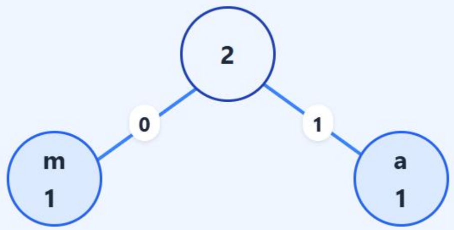
Previous Step **Step 2/6** Next Step

Visualizing the Huffman Tree Construction Process

Symbol Frequency in "Huffman"

Symbol	Frequency
H	1
u	1
f	2
m	1
a	1
n	1

Huffman Tree Construction Process



Removed: ~~m:1~~ ~~a:1~~ **Min-Heap:** n:1 f:2 2 2

Take two nodes with lowest frequency: 'm' (1) and 'a' (1). Create a new node with frequency 2.

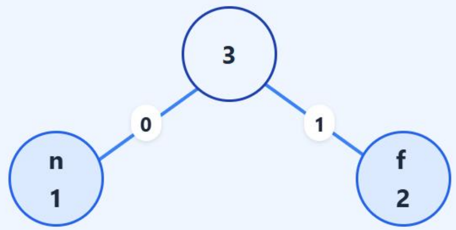
Previous Step **Step 3/6** Next Step

Visualizing the Huffman Tree Construction Process

Symbol Frequency in "Huffman"

Symbol	Frequency
H	1
u	1
f	2
m	1
a	1
n	1

Huffman Tree Construction Process



Removed: ~~n:1~~ ~~f:2~~ **Min-Heap:** 2 2 3

Take two nodes with lowest frequency: 'n' (1) and 'f' (2). Create a new node with frequency 3.

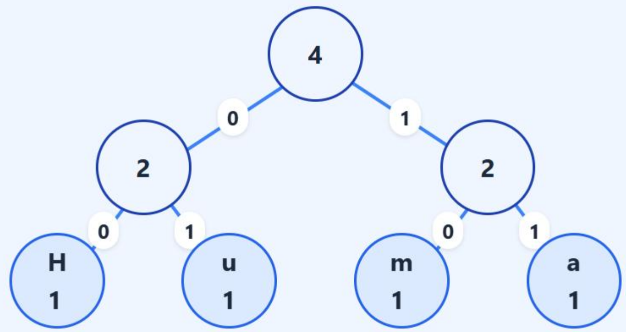
Previous Step **Step 4/6** Next Step

Visualizing the Huffman Tree Construction Process

Symbol Frequency in "Huffman"

Symbol	Frequency
H	1
u	1
f	2
m	1
a	1
n	1

Huffman Tree Construction Process



Removed: ~~2~~ ~~2~~ **Min-Heap:** 3 4

Merge the first internal node (2) and second internal node (2) to create a new node with frequency 4.

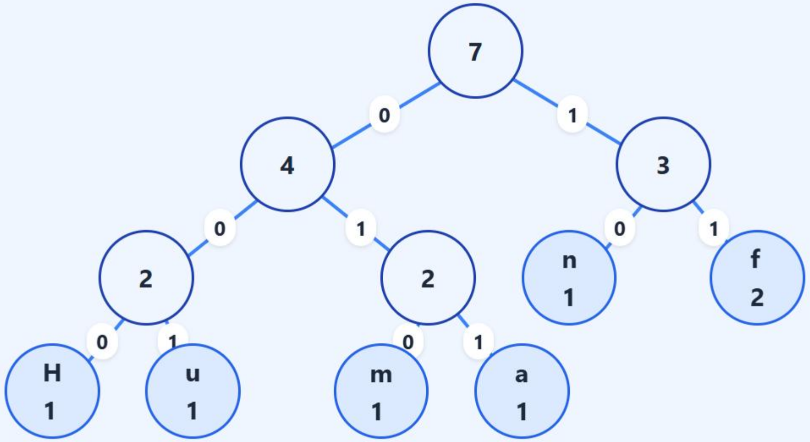
Previous Step **Step 5/6** Next Step

Visualizing the Huffman Tree Construction Process

Symbol Frequency in "Huffman"

Symbol	Frequency
H	1
u	1
f	2
m	1
a	1
n	1

Huffman Tree Construction Process



Removed:

~~3~~ ~~4~~

Min-Heap: Min-Heap is empty (Huffman tree is complete)

Complete the Huffman tree by connecting all remaining nodes based on their frequencies.

Previous Step **Step 6/6** Next Step

Huffman Codes and Encoding Process

Huffman Code Table

Symbol	Huffman Code	ASCII (for comparison)
H	000	01001000 (8 bits)
u	001	01110101 (8 bits)
f	11	01100110 (8 bits)
m	010	01101101 (8 bits)
a	011	01100001 (8 bits)
n	10	01101110 (8 bits)

Encoding Example

Original string: `Huffman`

Encoded string: `000 001 11 11 010 011 10`

Encoding details:
H (000) + u (001) + f (11) + f (11) + m (010) + a (011) + n (10)
= 000 + 001 + 11 + 11 + 010 + 011 + 10
= 000 001 11 11 010 011 10

Decoding Process

Encoded string: `000001111101001110`

Decoding steps:

1. Start from the root of the Huffman tree
2. Read each bit of the encoded string
3. Move in the tree: 0 → left, 1 → right
4. When a leaf node is reached, record the symbol and return to the root
5. Repeat until the encoded string is exhausted

Efficiency Analysis

ASCII Encoding: 7 symbols × 8 bits = 56 bits

Huffman Encoding: 18 bits

Compression Ratio: (1 − 18/56) × 100% ≈ 67.86% savings.

Adaptive Huffman Coding

Problems with Static Huffman

- Requires two data scans: one to calculate frequencies, one to encode
- Needs to store the Huffman code table with the compressed data
- Not efficient with data that changes frequency over time

FGK Algorithm (Faller-Gallager-Knuth)

- Updates the Huffman tree after processing each symbol
- Nodes are numbered in order from right to left and bottom to top
- Processes data in a streaming fashion (one-pass)

Vitter Algorithm (Algorithm V)

- Similar to FGK but maintains sibling property in the tree
- Helps optimize the tree update process
- More efficient than FGK in terms of processing time

Advantages of Adaptive Huffman

- Only needs to scan data once
- No need to store code table with compressed data
- Can compress data in real-time streams
- Adapts to changing frequency distributions

Other Variants of Huffman Algorithm

n-ary Huffman

- Uses n-ary trees instead of binary trees
- Allows creating codes in base n instead of binary
- Useful in applications requiring codes in bases larger than 2

Length-Limited Huffman

- Limits the maximum code length
- Sacrifices optimality to ensure length constraints
- Useful for applications with bit length limitations

Canonical Huffman

- Rearranges codes for easier storage and decoding
- Maintains optimality of the original codes
- Useful in applications requiring fast decoding

Dynamic Huffman

- Updates the Huffman tree periodically
- Balances between compression efficiency and update cost
- Useful for data with slowly changing frequency distributions

Choosing the Right Variant

The choice of Huffman variant depends on:

- Symbolistics of the data to be compressed
- Encoding/decoding speed requirements
- Memory and computational constraints
- Application nature (real-time/offline)

Performance Analysis of Huffman Algorithm

Algorithm Complexity

Time Complexity:

- Frequency counting: O(n)
- Huffman tree construction: O(k log k)
- Data encoding: O(n)
- Total: O(n + k log k)

(n is data length, k is number of distinct symbols)

Space Complexity:

- O(k) for the Huffman tree
- O(n) for the encoded data

Experimental Results

For ASCII text files:

- File size reduction around 20%
- With data having many repeated symbols: compression ratio up to 30%
- Efficiency decreases with uniformly distributed data (high entropy)

Advantages

- Theoretically optimal for encoding individual symbols
- No data loss during decompression
- Simple and efficient
- Widely used in many popular compression algorithms

Disadvantages

- Needs to know frequencies before encoding (static version)
- Requires storing the tree/code table with the compressed data
- Not efficient with high-entropy data
- Doesn't exploit correlation between symbols

Applications of Huffman Algorithm

File Compression

- 7-Zip: Uses DEFLATE compression (combining LZ77 and Huffman)
- WinZip and WinRAR: Commercial archiving tools
- macOS Archive Utility: Built-in archiving utility in macOS
- Command-line tools: gzip, zip on Linux/macOS

Multimedia Compression

- JPEG: Uses Huffman to compress pixel data after DCT transformation
- MP3: Compresses quantized frequency data
- MPEG-4: Compresses motion vector data in video
- PNG: Image format using DEFLATE compression algorithm

Data Transmission and Networks

- HTTP Content-Encoding (GZIP): Compressing CSS, HTML, JS files
- Fax machines and telephones: Using Group 3 fax encoding
- Wireless data transmission: Saving bandwidth

Artificial Intelligence and Machine Learning

- Decision tree compression: Optimizing large decision trees
- Natural Language Processing (NLP): Dictionary-based text compression
- Language modeling: Reducing model size

Hardware and Embedded Systems

- GPUs and FPGAs: Real-time compression in high-performance computing
- Data storage systems: Reducing file size in SSDs and HDDs
- Embedded systems: Memory optimization in IoT devices
- Control boards: Reducing firmware size

Conclusion

Summary of Huffman Algorithm

- Lossless compression algorithm based on prefix codes
- Assigns shorter codes to frequent symbols, longer codes to rare symbols
- Complexity $O(n + k \log k)$ where n is data size, k is number of distinct symbols
- Compression ratio around 20-30% for normal text
- Many variants including Adaptive Huffman, Canonical Huffman, Length-Limited Huffman
- Widely applied in file compression, multimedia, networks, and embedded systems

Role in Computer Science

Despite being over 70 years old, the Huffman algorithm remains a foundation for many modern compression algorithms and is an important basic knowledge in computer science.

Huffman is a classic example of how a simple and efficient algorithm can create long-lasting and profound impacts in technology.

Thank you for your watching!

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