CQUPT – University at Albany

Computer Science – International College

ICSI 403 --- Design and Analysis of Algorithms

Project 2 --- Spring 2025

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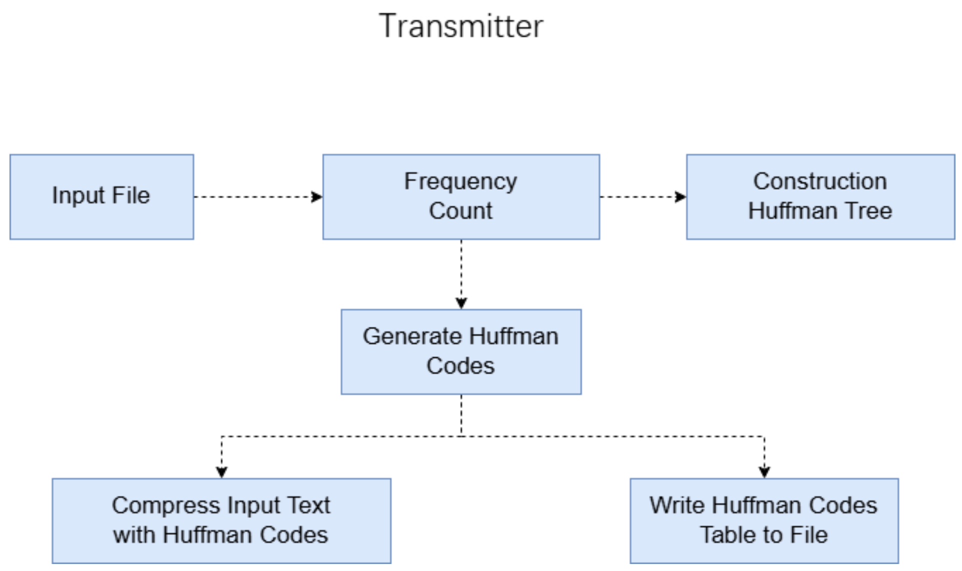
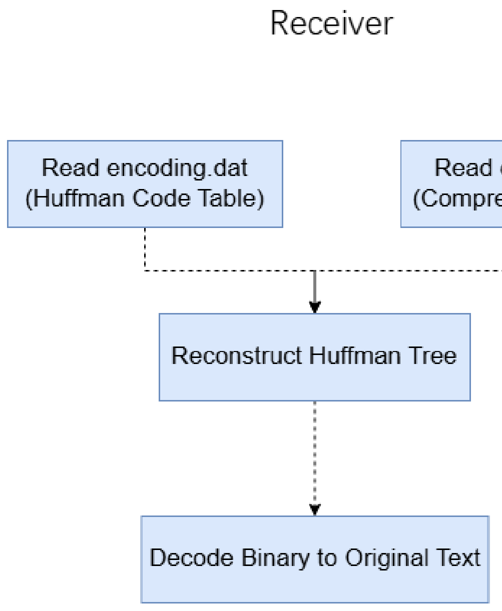
i. A high-level data flow diagram for the system


Transmitter
Input File
Frequency Count
Construction Huffman Tree
Generate Huffman Codes
Compress Input Text with Huffman Codes
Write Huffman Codes Table to File


Receiver
Read encoding.dat (Huffman Code Table)
Read compressed.dat (Compressed Binary Data)
Reconstruct Huffman Tree
Decode Binary to Original Text

ii. A list of routines and their brief descriptions

Layer	Function Name	Brief Description
Bit Manipulation	void writeBit(std::ofstream& outFile, char bit)	Writes a single bit to the output file stream.
	char readBit(std::ifstream& inFile)	Reads a single bit from the input file stream.
	void writeByte(std::ofstream& outFile, unsigned char)	Writes a full byte to the output file.
	unsigned char readByte(std::ifstream& inFile)	Reads a byte from the input file.
	std::string charToBinary(char c)	Converts a character to its binary string form.
	char binaryToChar(const std::string& binary)	Converts a binary string back to a character.
Framing	std::string frameData(const std::string& data)	Frames encoded data using SYN markers and length chunks.
	std::vector<std::string> deframeData(...)	Extracts encoded data chunks from framed data.
	std::string frameEncoding(...)	Frames the Huffman code table using SOH markers.
	std::unordered_map<char, std::string> deframeEncoding(...)	Parses and reconstructs Huffman code table from framed encoding.
Application Logic	void initializeFromFile(std::string filename)	Reads the file and counts character frequency.
	void encodeFile(std::string inFile, std::string outFile)	Encodes input file content and writes compressed data.
	void decodeFile(std::string inFile, std::string outFile)	Decodes compressed file content and writes original data.
	int huffmanCode(std::string args)	Test/demo function for full encode-decode process.
Huffman Tree Construction	void MinHeapify(vector<Node*>& heap, int i)	Maintains min-heap property at index i.
	void BuildMinHeap(vector<Node*>& heap)	Builds a min-heap from a vector of nodes.
	Node* ExtractMin(vector<Node*>& heap)	Removes and returns the node with the smallest frequency.
	void MinHeapInsert(vector<Node*>& heap,	Inserts a new node into the

Layer	Function Name	Brief Description
	Node* node)	min-heap.
	Node* buildHuffmanTree(vector<Node*>& heap)	Builds the Huffman tree by merging nodes.
	void generateCodes(Node* root, std::string, unordered_map<char, std::string>&)	Generates binary codes from the Huffman tree.

iii. Implementation details.

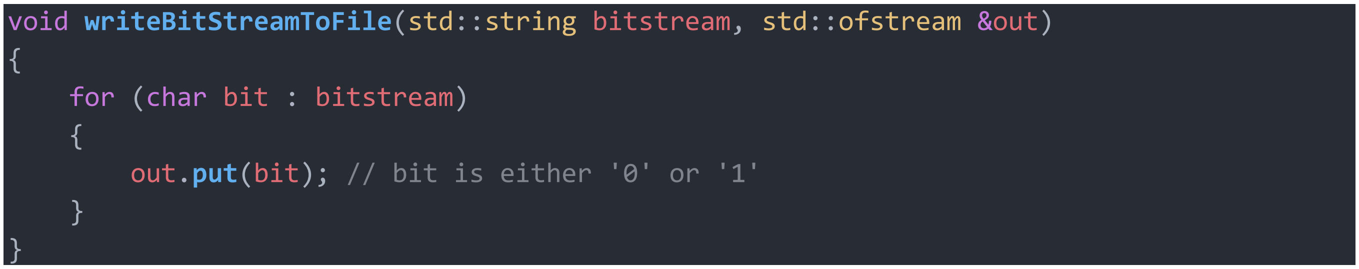
The project is implemented in **C++** and divided into two core programs: **Transmitter** and **Receiver**. The architecture is modular and layered to promote separation of concerns.

1. Layered Architecture

The system is divided into three logical layers:

Layer 1: Bit-level Operations

Handles conversion of characters into '0'/'1' ASCII characters and writes them to file as a bit stream.



```cpp
void writeBitStreamToFile(std::string bitstream, std::ofstream &out)
{
    for (char bit : bitstream)
    {
        out.put(bit); // bit is either '0' or '1'
    }
}
```

Layer 2: Framing

Adds framing to encoded data and encoding table:

- **Two SYN (ASCII 22) characters for data blocks.**
- **Two SOH (ASCII 1) characters for encoding table blocks.**
- **One byte for length (up to 16 encoded characters).**

```
outFile.put(22);                    // SYN
outFile.put(22);                    // SYN
outFile.put(encodedStr.length()); // length byte
outFile << encodedStr;              // up to 16 characters
```

Layer 3: File I/O and Encoding Coordination

Coordinates reading/writing files, invoking Huffman-related functions, and handling layers above.

2. Huffman Tree Construction with Min-Heap

The **Huffman tree** is built from character frequencies using a **Min-Heap**, implemented as a priority queue. Here's how key heap operations are implemented.

Min-Heap Node Structure

```
struct Node
{
    char ch;
    int freq;
    Node *left;
    Node *right;

    Node(char c, int f) : ch(c), freq(f), left(nullptr), right(nullptr) {}
};
```

Min-Heapify

Ensures the heap maintains the min-heap property:

```
void MinHeapify(int idx)
{
    int smallest = idx;
    int left = 2 * idx + 1;
    int right = 2 * idx + 2;

    if (left < size && heap[left]->freq < heap[smallest]->freq)
        smallest = left;
    if (right < size && heap[right]->freq < heap[smallest]->freq)
        smallest = right;

    if (smallest != idx)
    {
        std::swap(heap[smallest], heap[idx]);
        MinHeapify(smallest);
    }
}
```

Build-Min-Heap

Constructs the heap from an unordered array:

```
void BuildMinHeap()
{
    for (int i = size / 2 - 1; i >= 0; i--)
    {
        MinHeapify(i);
    }
}
```

Min-Heap-Insert

Inserts a node and reorders heap:

```
void MinHeapInsert(Node *node)
{
    heap.push_back(node);
    int i = size++;
    while (i && heap[(i - 1) / 2]->freq > heap[i]->freq)
    {
        std::swap(heap[i], heap[(i - 1) / 2]);
        i = (i - 1) / 2;
    }
}
```

Min-Heap-Extract-Min

Removes and returns the node with the smallest frequency:

```
Node *ExtractMin()
{
    if (size <= 0)
        return nullptr;
    if (size == 1)
    {
        Node *min = heap[0];
        heap.pop_back();
        size--;
        return min;
    }

    Node *min = heap[0];
    heap[0] = heap[size - 1];
    heap.pop_back();
    size--;
    MinHeapify(0);
    return min;
}
```

=

3. Huffman Encoding and Framing

After building the Huffman tree, codes are generated by traversing it.

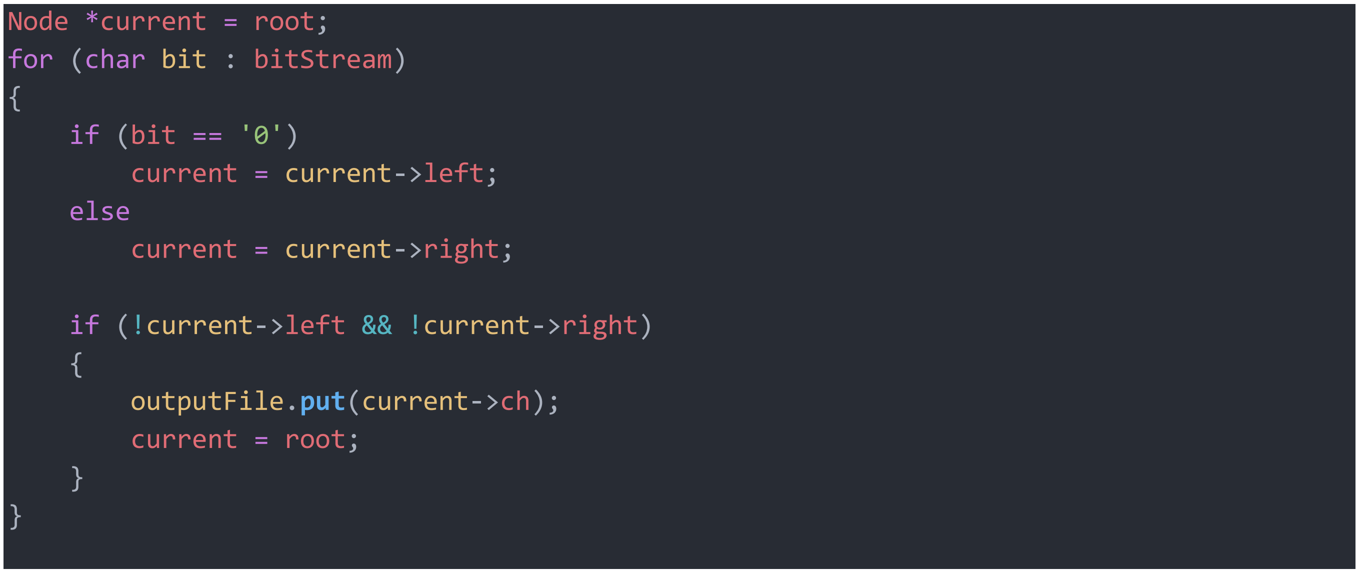
```
void generateCodes(Node *root, std::string code, std::unordered_map<char, std::string>
&table)
{
    if (!root)
        return;
    if (!root->left && !root->right)
    {
        table[root->ch] = code;
    }
    generateCodes(root->left, code + "0", table);
    generateCodes(root->right, code + "1", table);
}
```

Then, the content is encoded and written to a file in framed segments of max 16 characters.

4. Decoding Process

- **Receiver reads encoded file and decoding table (transmitted using SOH frames).**
- **Rebuilds Huffman tree from decoding table.**
- **Reads bit stream and traverses the tree to decode characters.**

Sample decoding loop:



```
Node *current = root;
for (char bit : bitStream)
{
    if (bit == '0')
        current = current->left;
    else
        current = current->right;

    if (!current->left && !current->right)
    {
        outputFile.put(current->ch);
        current = root;
    }
}
```

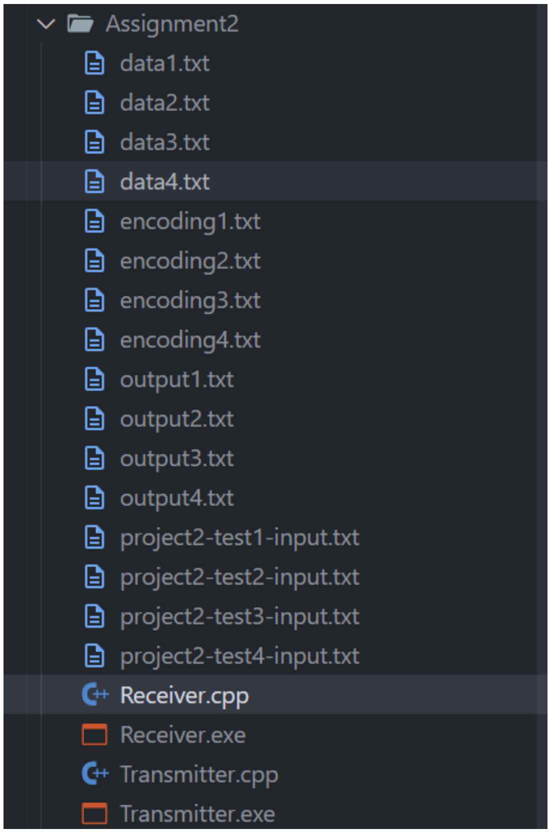
5. Statistics and Output

- Transmitter prints:
    - Total characters read.
    - Frequency table.
    - Compression ratio.
- Receiver prints:
    - Characters received.
    - File sizes.
    - Confirms successful decompression.

II Test documentation

i. How you tested your program

I execute my program in Vscode, the program structure as follows

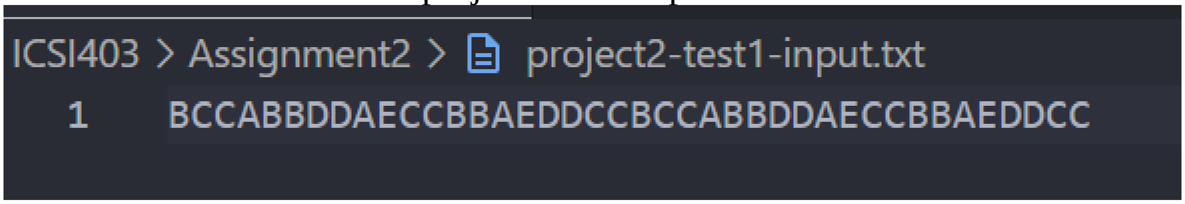


```
Assignment2
  data1.txt
  data2.txt
  data3.txt
  data4.txt
  encoding1.txt
  encoding2.txt
  encoding3.txt
  encoding4.txt
  output1.txt
  output2.txt
  output3.txt
  output4.txt
  project2-test1-input.txt
  project2-test2-input.txt
  project2-test3-input.txt
  project2-test4-input.txt
  Receiver.cpp
  Receiver.exe
  Transmitter.cpp
  Transmitter.exe
```

I have four test files to test the program, after getting the results, I compare them with the answer which is calculated by myself.

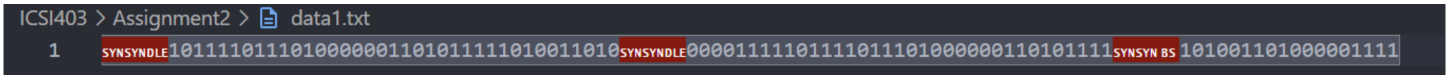
ii. Testing outputs

project2-test1-input.txt



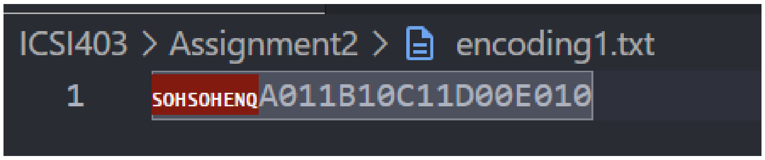
```
ICSI403 > Assignment2 > project2-test1-input.txt
BCCABBDDAECCBBAEDDCCBCCABBDDAECCBBAEDDCC
```

data1.txt



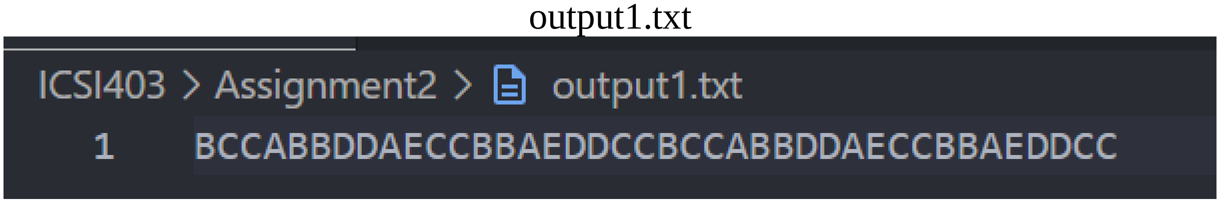
```
ICSI403 > Assignment2 > data1.txt
SYNSYNDLE1011110111010000001101011111010011010SYNSYNDLE00001111101111011101000000110101111SYNSYN BS 101001101000001111
```

encoding1.txt



```
SOHSOHENQA011B10C11D00E010
```

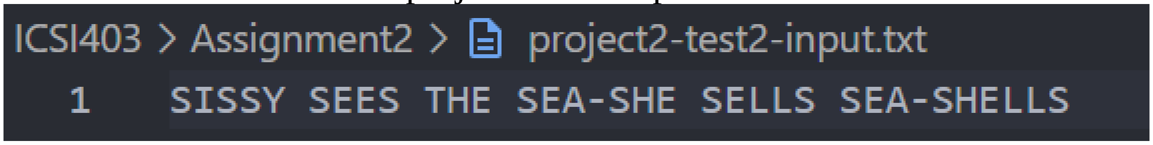
output1.txt



```
BCCABBDDAECCBBAEDDCCBCCABBDDAECCBBAEDDCC
```

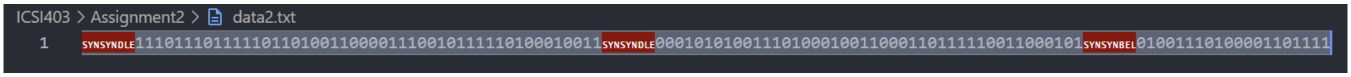
---

project2-test2-input.txt



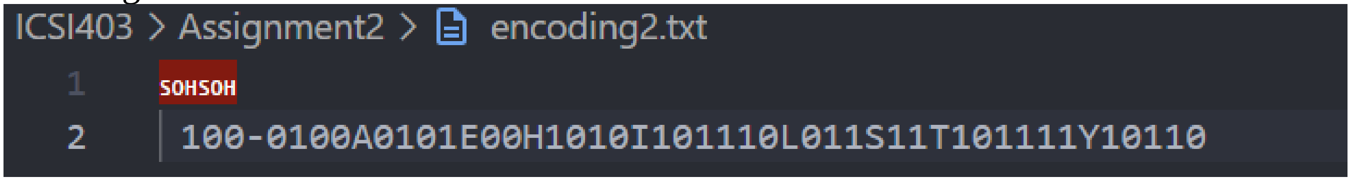
```
SISSY SEES THE SEA-SHE SELLS SEA-SHELLS
```

data2.txt



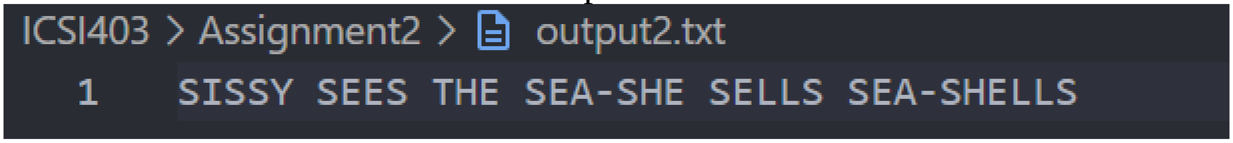
```
SYNSYNDLE111011101111101101001100001110010111110100010011SYNSYNDLE00010101001110100010011000110111110011000101SYNSYNBEL01001110100001101111
```

encoding2.txt



```
SOHSOH
100-0100A0101E00H1010I101110L011S11T101111Y10110
```

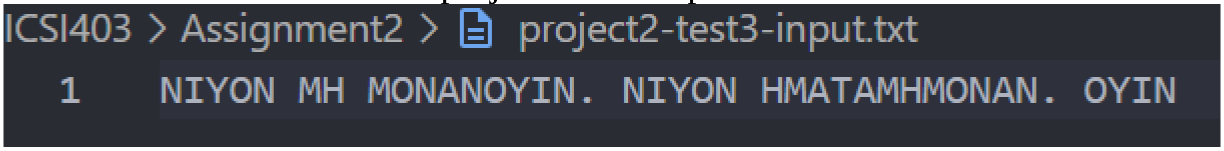
output2.txt



```
SISSY SEES THE SEA-SHE SELLS SEA-SHELLS
```

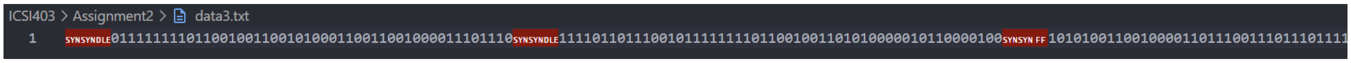
---

project2-test3-input.txt



```
NIYON MH MONANOYIN. NIYON HMATAMHMONAN. OYIN
```

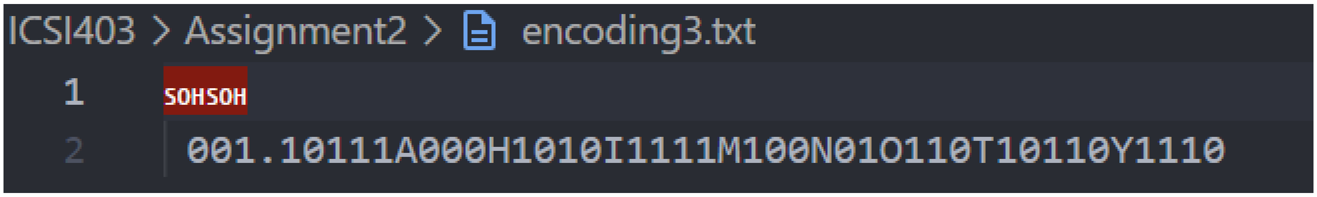
data3.txt



ICSI403 > Assignment2 > data3.txt

```
SYNSYNDLE0111111110110010011001010001100110010000011101110SYNSYNDLE11110110111001011111111011001001101010000010110000100SYNSYN FF101010011001000011011100111011101111
```

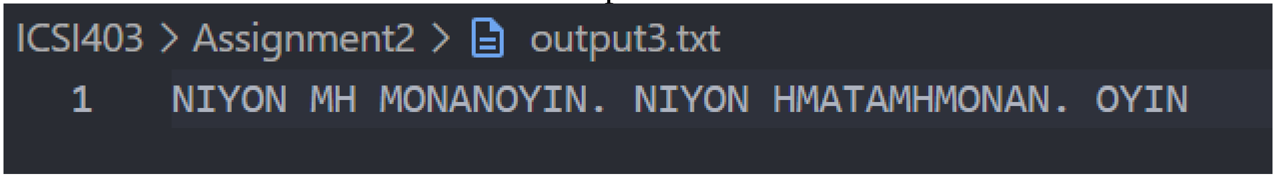
encodin3.txt



ICSI403 > Assignment2 > encoding3.txt

```
SOHSOH
001.10111A000H1010I1111M100N010110T10110Y1110
```

output3.txt

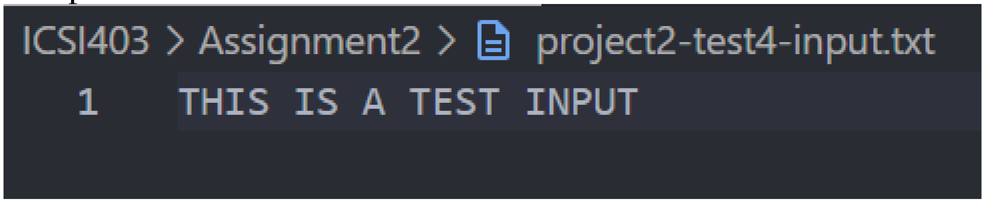


ICSI403 > Assignment2 > output3.txt

```
NIYON MH MONANOYIN. NIYON HMATAMHMONAN. OYIN
```

----

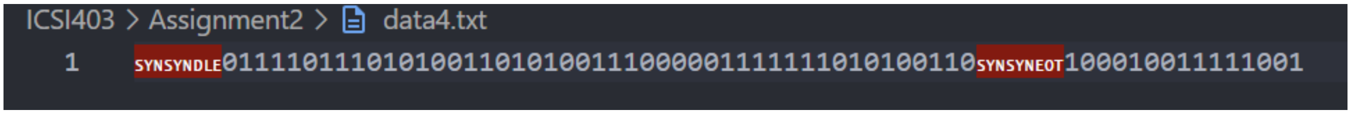
project2-test4-input.txt



ICSI403 > Assignment2 > project2-test4-input.txt

```
THIS IS A TEST INPUT
```

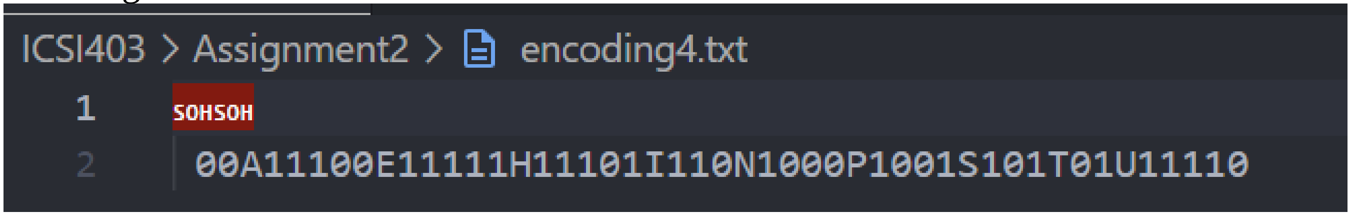
data4.txt



ICSI403 > Assignment2 > data4.txt

```
SYNSYNDLE0111101110101001101010011100000111111010100110SYNSYNEOT100010011111001
```

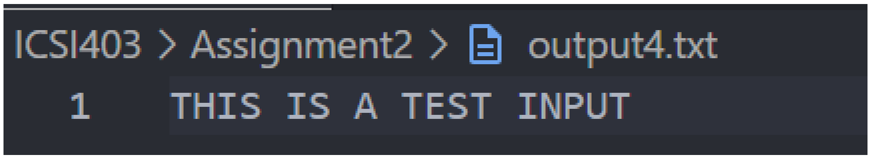
encoding4.txt



ICSI403 > Assignment2 > encoding4.txt

```
SOHSOH
00A11100E11111H11101I110N1000P1001S101T01U11110
```

output4.txt



ICSI403 > Assignment2 > output4.txt

```
THIS IS A TEST INPUT
```

III. User documentation

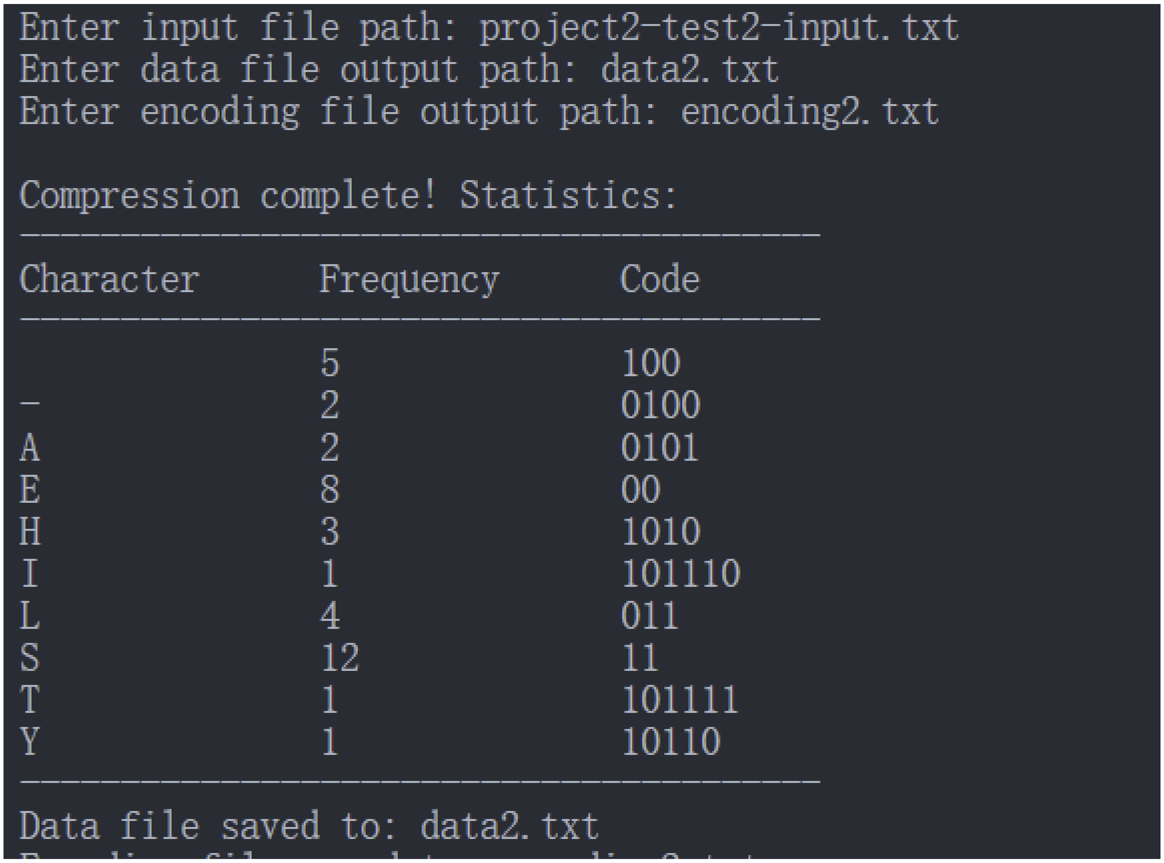
i. How to run your program

1. Run Transmitter

The Transmitter program is responsible for compressing the original text file using Huffman encoding.

Steps:

1. Input the path of the input file (project2-test2-input.txt).
2. Input the path of the data file where the compressed bits will be stored (data2.txt).
3. Input the path of the encoding file where the Huffman codes will be stored (encode2.txt).



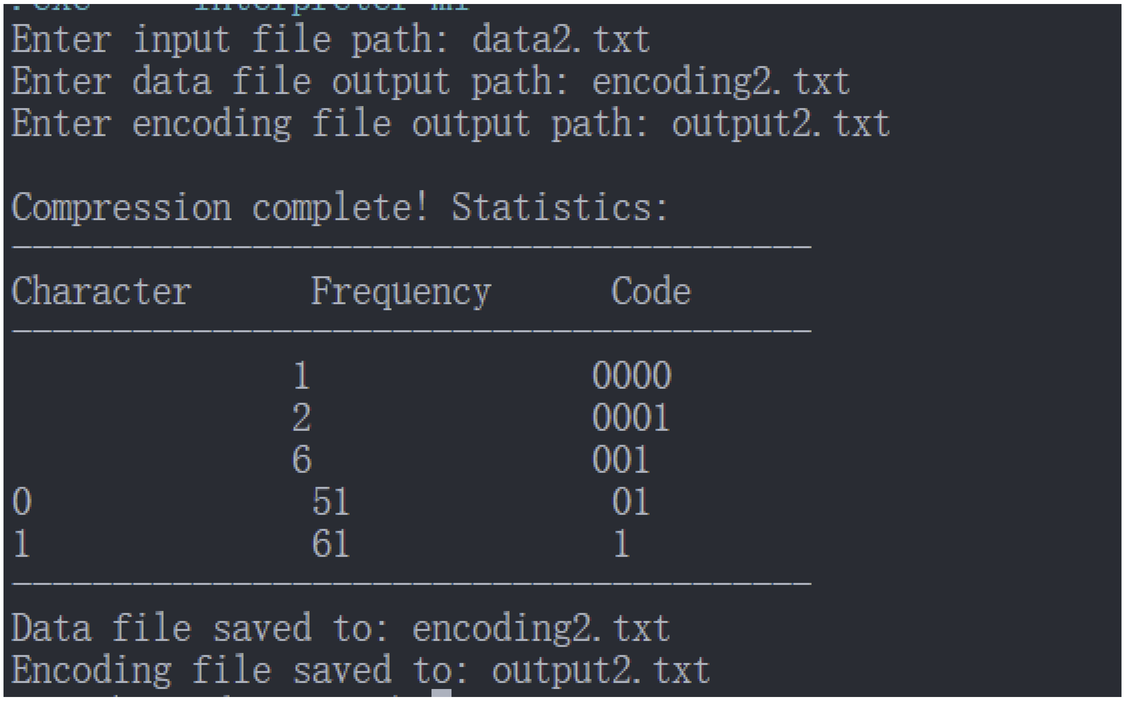
```
Enter input file path: project2-test2-input.txt
Enter data file output path: data2.txt
Enter encoding file output path: encoding2.txt

Compression complete! Statistics:
----------------------------------------
Character      Frequency      Code
----------------------------------------
               5              100
-              2              0100
A              2              0101
E              8              00
H              3              1010
I              1              101110
L              4              011
S              12             11
T              1              101111
Y              1              10110
----------------------------------------
Data file saved to: data2.txt
```

2. Run Receiver

The Receiver program is responsible for decompressing the encoded file using the stored encoding.

Steps:

1. Input the path of the compressed data file (data2.txt).
2. Input the path of the encoding file (encoding2.txt).
3. Input the path of the result output file where the decoded message will be written (output2.txt).



```
Enter input file path: data2.txt
Enter data file output path: encoding2.txt
Enter encoding file output path: output2.txt

Compression complete! Statistics:
----------------------------------------
Character      Frequency      Code
----------------------------------------
              1              0000
              2              0001
              6              001
0              51             01
1              61             1
----------------------------------------
Data file saved to: encoding2.txt
Encoding file saved to: output2.txt
```

ii. Describe parameter (if any)

The program requires the user to input file paths:

Transmitter

1. **Input file** – the original text file to compress
2. **Data file** – the output file for compressed data
3. **Encoding file** – the output file for Huffman codes

Receiver

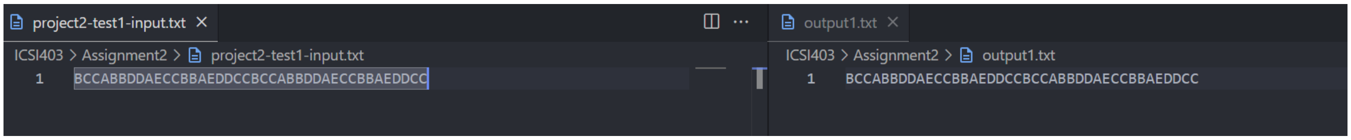
1. **Data file** – the compressed file to decode
2. **Encoding file** – the Huffman code file
3. **Output file** – the file to save the decoded text

IV. Source Code

Correctness:

I execute my program to test the four example files, and the results are all **correct** Layering. Readability.

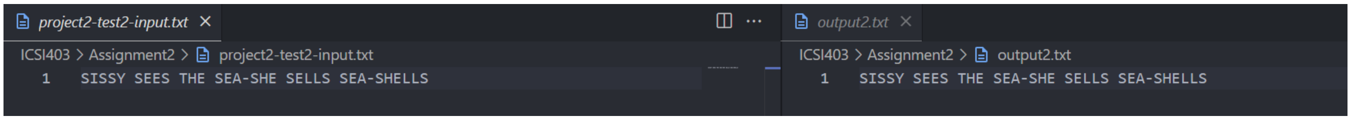
Test1


project2-test1-input.txt
ICSI403 > Assignment2 > project2-test1-input.txt
output1.txt
ICSI403 > Assignment2 > output1.txt

```
BCCABBDDAECCBBAEDDCCBCCABBDDAECCBBAEDDCC
```

```
BCCABBDDAECCBBAEDDCCBCCABBDDAECCBBAEDDCC
```

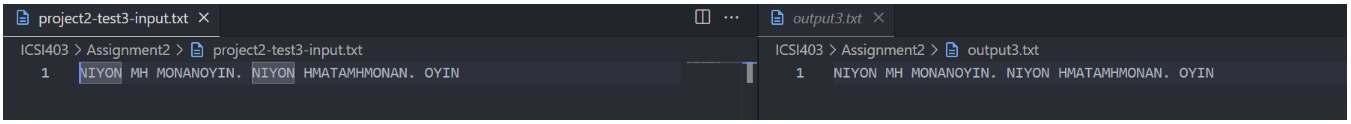
Test2


project2-test2-input.txt
ICSI403 > Assignment2 > project2-test2-input.txt
output2.txt
ICSI403 > Assignment2 > output2.txt

```
SISSY SEES THE SEA-SHE SELLS SEA-SHELLS
```

```
SISSY SEES THE SEA-SHE SELLS SEA-SHELLS
```

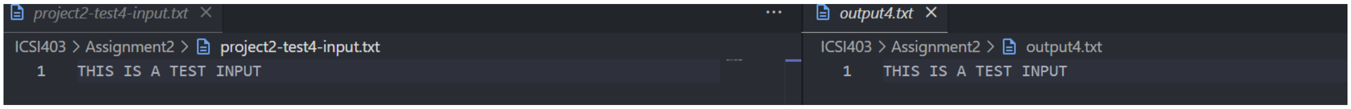
Test3


project2-test3-input.txt
ICSI403 > Assignment2 > project2-test3-input.txt
output3.txt
ICSI403 > Assignment2 > output3.txt

```
NIYON MH MONANOYIN. NIYON HMATAMHMONAN. OYIN
```

```
NIYON MH MONANOYIN. NIYON HMATAMHMONAN. OYIN
```

Test4


project2-test4-input.txt
ICSI403 > Assignment2 > project2-test4-input.txt
output4.txt
ICSI403 > Assignment2 > output4.txt

```
THIS IS A TEST INPUT
```

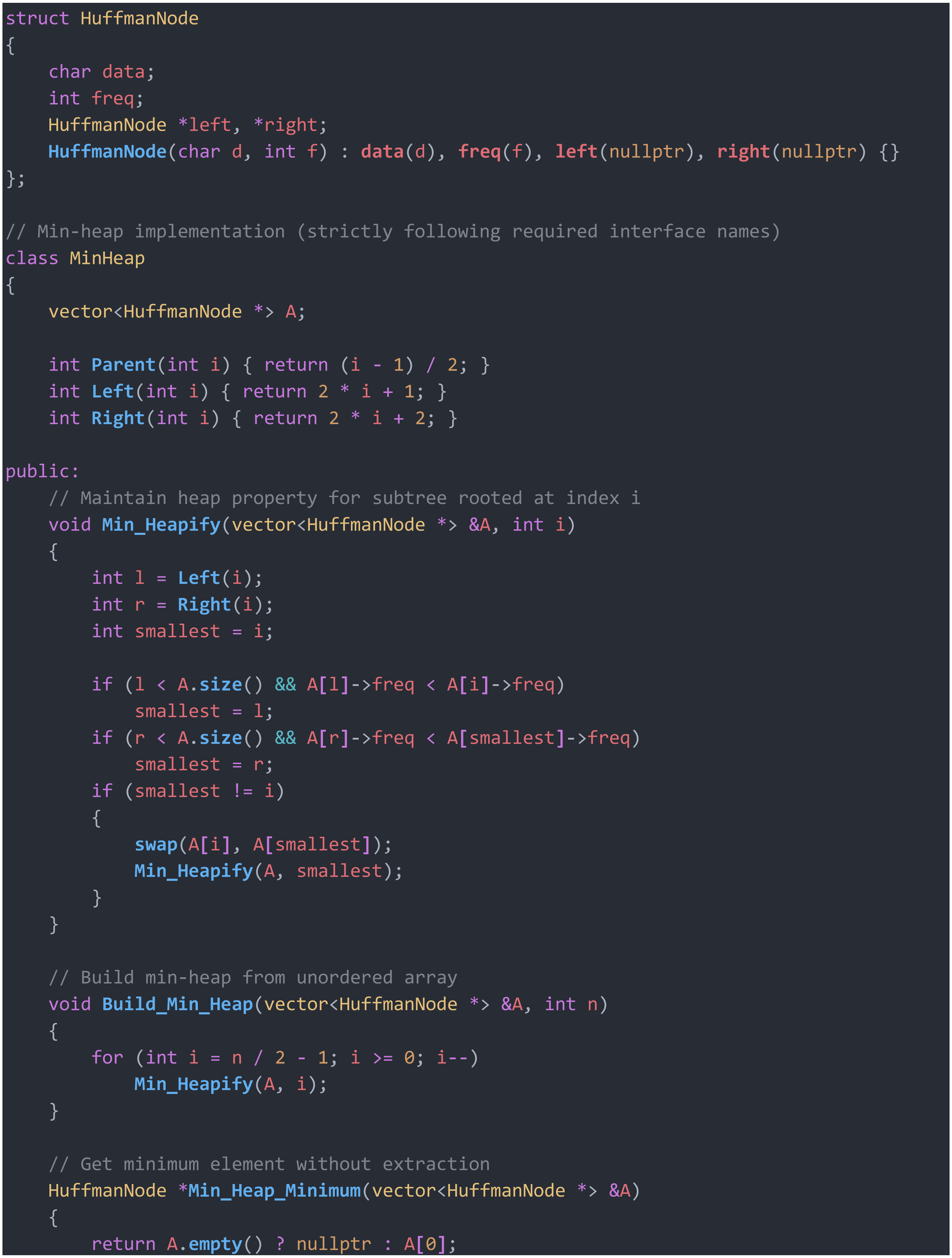
```
THIS IS A TEST INPUT
```

Programming style:

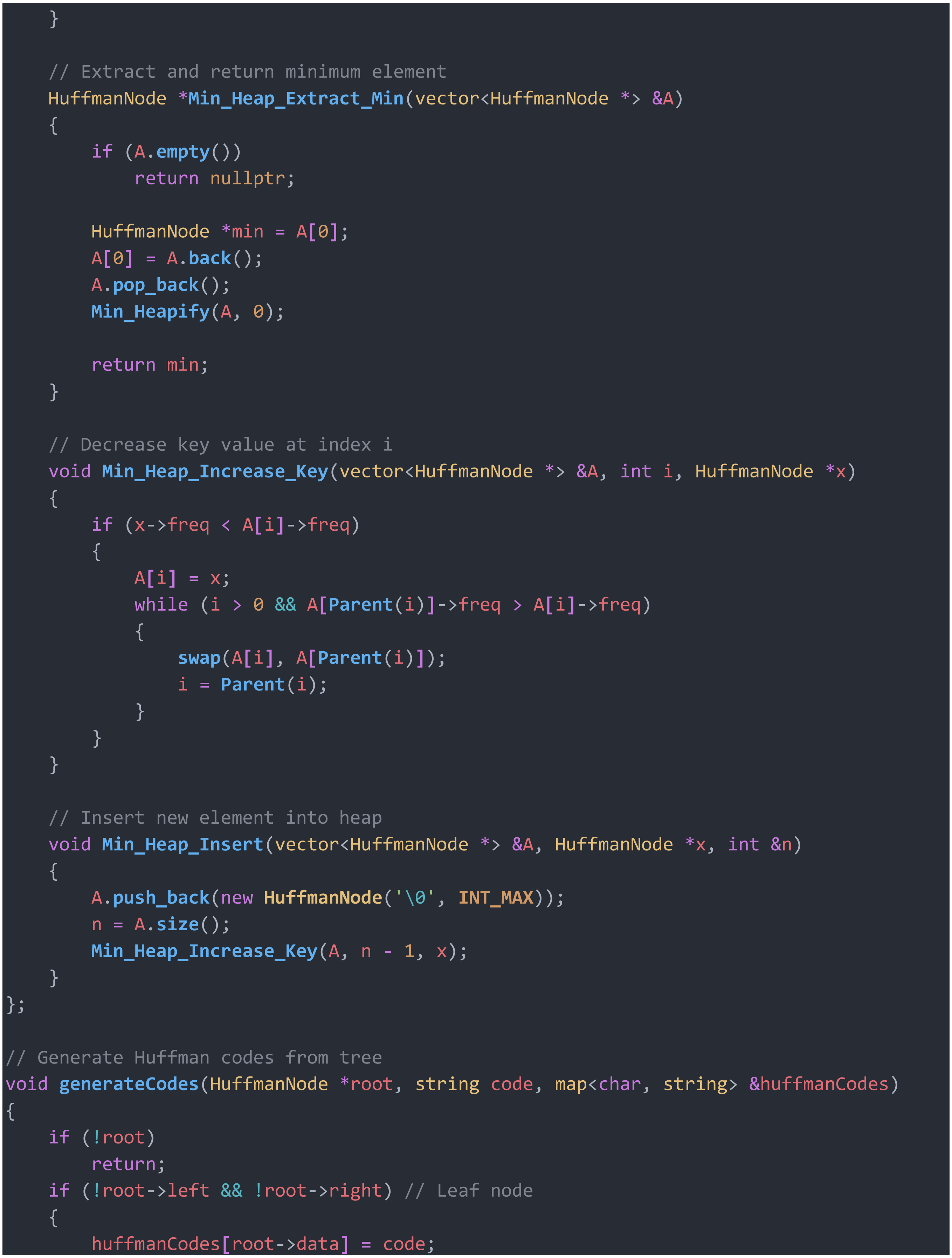
Layering | Readability | Comments | Efficiency are showing as follows

Transmitter.cpp

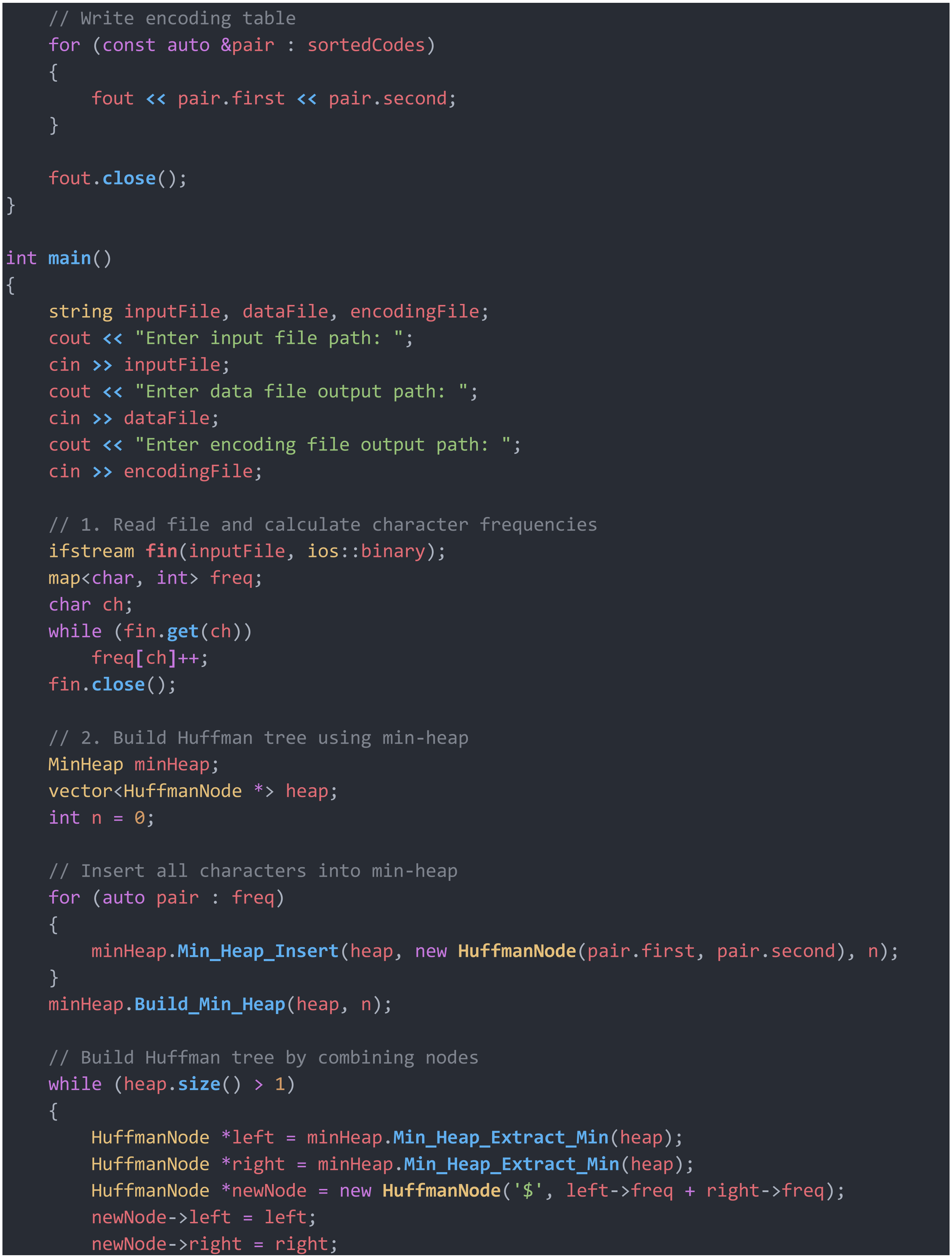
```
#include <iostream>
#include <fstream>
#include <map>
#include <vector>
#include <algorithm>
#include <climits>
#include <iomanip>

using namespace std;

// Huffman tree node structure
```



```
struct HuffmanNode
{
    char data;
    int freq;
    HuffmanNode *left, *right;
    HuffmanNode(char d, int f) : data(d), freq(f), left(nullptr), right(nullptr) {}
};

// Min-heap implementation (strictly following required interface names)
class MinHeap
{
    vector<HuffmanNode *> A;

    int Parent(int i) { return (i - 1) / 2; }
    int Left(int i) { return 2 * i + 1; }
    int Right(int i) { return 2 * i + 2; }

public:
    // Maintain heap property for subtree rooted at index i
    void Min_Heapify(vector<HuffmanNode *> &A, int i)
    {
        int l = Left(i);
        int r = Right(i);
        int smallest = i;

        if (l < A.size() && A[l]->freq < A[i]->freq)
            smallest = l;
        if (r < A.size() && A[r]->freq < A[smallest]->freq)
            smallest = r;
        if (smallest != i)
        {
            swap(A[i], A[smallest]);
            Min_Heapify(A, smallest);
        }
    }

    // Build min-heap from unordered array
    void Build_Min_Heap(vector<HuffmanNode *> &A, int n)
    {
        for (int i = n / 2 - 1; i >= 0; i--)
            Min_Heapify(A, i);
    }

    // Get minimum element without extraction
    HuffmanNode *Min_Heap_Minimum(vector<HuffmanNode *> &A)
    {
        return A.empty() ? nullptr : A[0];
```



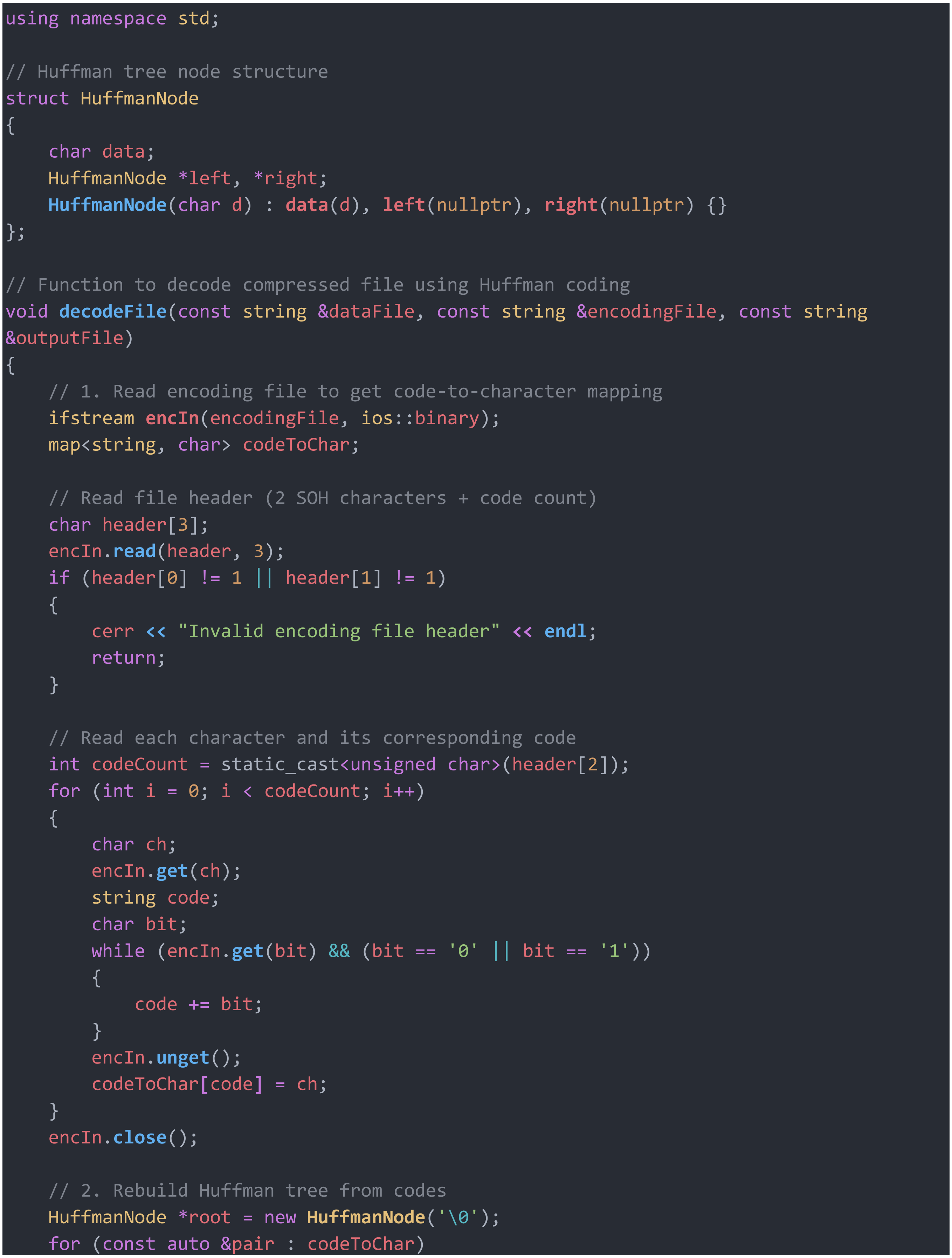
```
    }

    // Extract and return minimum element
    HuffmanNode *Min_Heap_Extract_Min(vector<HuffmanNode *> &A)
    {
        if (A.empty())
            return nullptr;

        HuffmanNode *min = A[0];
        A[0] = A.back();
        A.pop_back();
        Min_Heapify(A, 0);

        return min;
    }

    // Decrease key value at index i
    void Min_Heap_Increase_Key(vector<HuffmanNode *> &A, int i, HuffmanNode *x)
    {
        if (x->freq < A[i]->freq)
        {
            A[i] = x;
            while (i > 0 && A[Parent(i)]->freq > A[i]->freq)
            {
                swap(A[i], A[Parent(i)]);
                i = Parent(i);
            }
        }
    }

    // Insert new element into heap
    void Min_Heap_Insert(vector<HuffmanNode *> &A, HuffmanNode *x, int &n)
    {
        A.push_back(new HuffmanNode('\0', INT_MAX));
        n = A.size();
        Min_Heap_Increase_Key(A, n - 1, x);
    }
};

// Generate Huffman codes from tree
void generateCodes(HuffmanNode *root, string code, map<char, string> &huffmanCodes)
{
    if (!root)
        return;
    if (!root->left && !root->right) // Leaf node
    {
        huffmanCodes[root->data] = code;
    }
    generateCodes(root->left, code + "0", huffmanCodes);
    generateCodes(root->right, code + "1", huffmanCodes);
}

// Write compressed data file with 16-character blocks
void writeDataFile(const string &inputFile, const string &dataFile, const map<char,
string> &huffmanCodes)
{
    ifstream fin(inputFile, ios::binary);
    ofstream fout(dataFile, ios::binary);

    vector<char> buffer(16);
    while (fin)
    {
        fin.read(buffer.data(), 16);
        streamsize count = fin.gcount();

        if (count == 0)
            break;

        // Write block header: 2 SYN chars + length
        fout << char(22) << char(22) << char(count);

        // Write encoded data
        for (int i = 0; i < count; i++)
        {
            fout << huffmanCodes.at(buffer[i]);
        }
    }

    fin.close();
    fout.close();
}

// Write encoding file with alphabetical sorting
void writeEncodingFile(const string &encodingFile, map<char, string> &huffmanCodes)
{
    ofstream fout(encodingFile, ios::binary);

    // Sort codes alphabetically
    vector<pair<char, string>> sortedCodes(huffmanCodes.begin(), huffmanCodes.end());
    sort(sortedCodes.begin(), sortedCodes.end());

    // Write file header: 2 SOH chars + code count
    fout << char(1) << char(1) << char(sortedCodes.size());
```



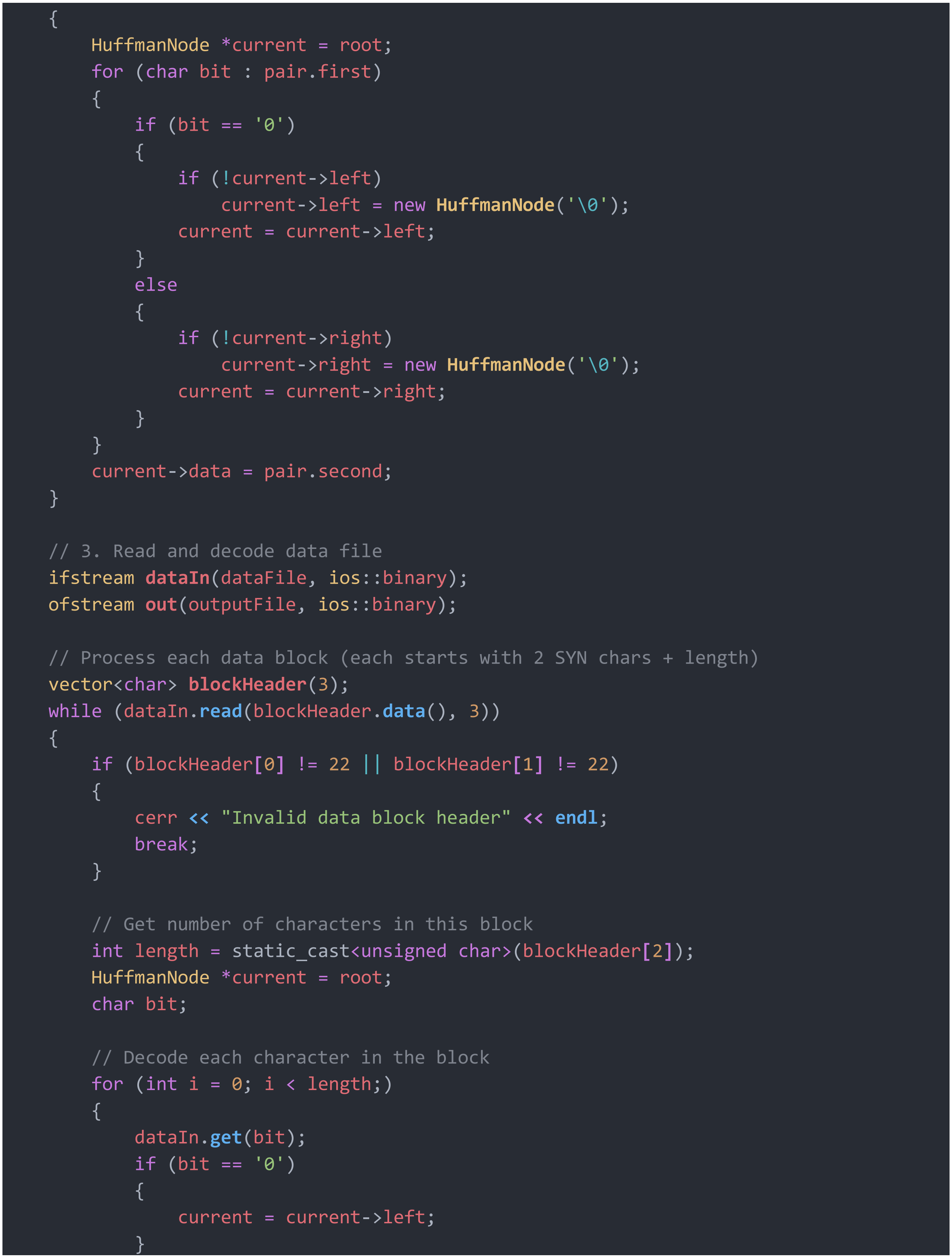
```
    // Write encoding table
    for (const auto &pair : sortedCodes)
    {
        fout << pair.first << pair.second;
    }

    fout.close();
}

int main()
{
    string inputFile, dataFile, encodingFile;
    cout << "Enter input file path: ";
    cin >> inputFile;
    cout << "Enter data file output path: ";
    cin >> dataFile;
    cout << "Enter encoding file output path: ";
    cin >> encodingFile;

    // 1. Read file and calculate character frequencies
    ifstream fin(inputFile, ios::binary);
    map<char, int> freq;
    char ch;
    while (fin.get(ch))
        freq[ch]++;
    fin.close();

    // 2. Build Huffman tree using min-heap
    MinHeap minHeap;
    vector<HuffmanNode *> heap;
    int n = 0;

    // Insert all characters into min-heap
    for (auto pair : freq)
    {
        minHeap.Min_Heap_Insert(heap, new HuffmanNode(pair.first, pair.second), n);
    }
    minHeap.Build_Min_Heap(heap, n);

    // Build Huffman tree by combining nodes
    while (heap.size() > 1)
    {
        HuffmanNode *left = minHeap.Min_Heap_Extract_Min(heap);
        HuffmanNode *right = minHeap.Min_Heap_Extract_Min(heap);
        HuffmanNode *newNode = new HuffmanNode('$', left->freq + right->freq);
        newNode->left = left;
        newNode->right = right;
        minHeap.Min_Heap_Insert(heap, newNode, n);
    }

    HuffmanNode *root = minHeap.Min_Heap_Extract_Min(heap);

    // 3. Generate Huffman codes from tree
    map<char, string> huffmanCodes;
    generateCodes(root, "", huffmanCodes);

    // 4. Write output files
    writeDataFile(inputFile, dataFile, huffmanCodes);
    writeEncodingFile(encodingFile, huffmanCodes);

    // Print statistics
    cout << "\nCompression complete! Statistics:" << endl;
    cout << "----------------------------------------" << endl;
    cout << left << setw(15) << "Character" << setw(15) << "Frequency" << "Code" <<
endl;
    cout << "----------------------------------------" << endl;

    // Sort frequencies alphabetically for display
    vector<pair<char, int>> sortedFreq(freq.begin(), freq.end());
    sort(sortedFreq.begin(), sortedFreq.end());

    for (const auto &pair : sortedFreq)
    {
        cout << setw(15) << pair.first
             << setw(15) << pair.second
             << huffmanCodes[pair.first] << endl;
    }

    cout << "----------------------------------------" << endl;
    cout << "Data file saved to: " << dataFile << endl;
    cout << "Encoding file saved to: " << encodingFile << endl;

    return 0;
}
```

Receiver.cpp

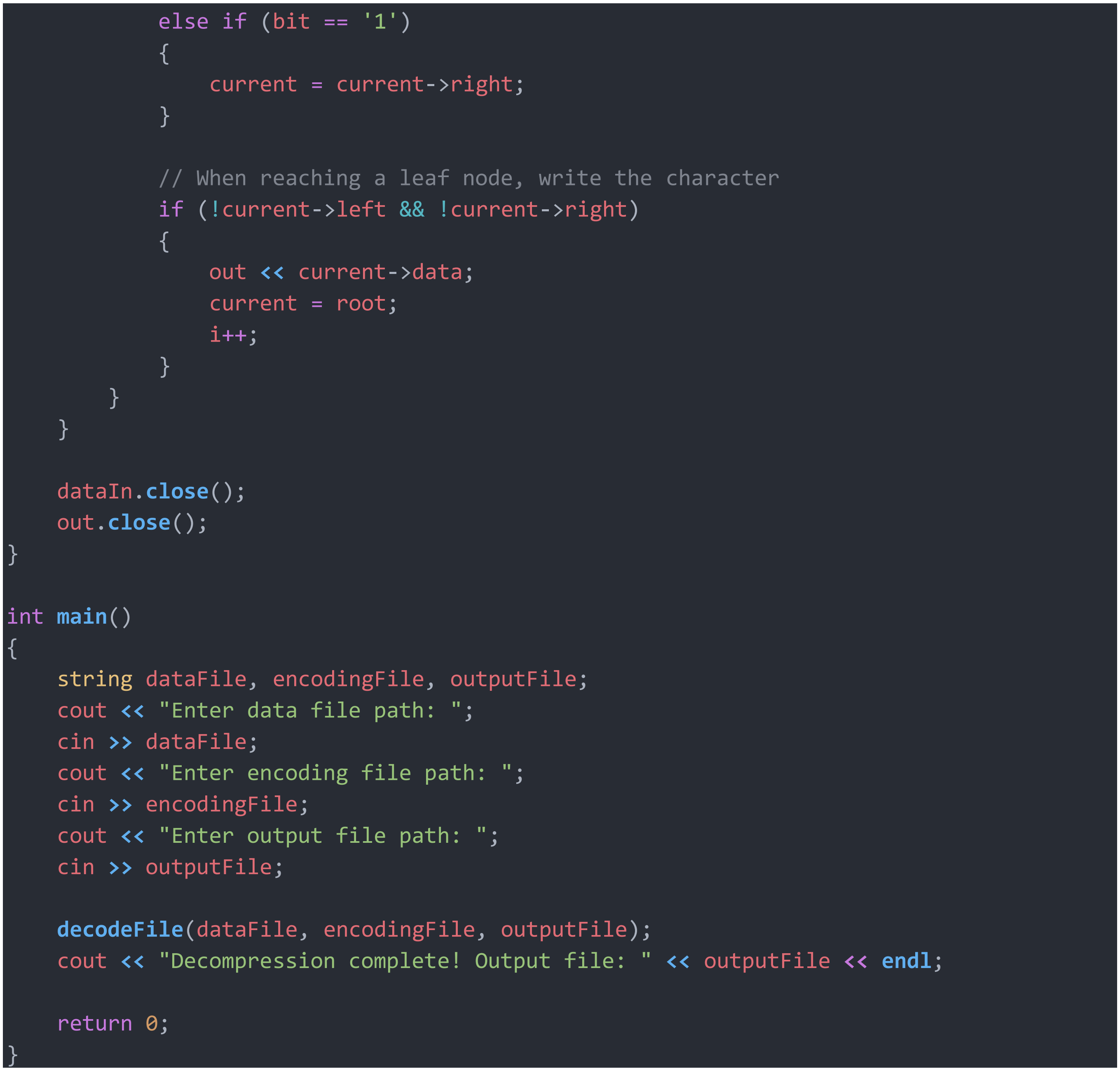
```
#include <iostream>
#include <fstream>
#include <map>
#include <vector>

```



```cpp
using namespace std;

// Huffman tree node structure
struct HuffmanNode
{
    char data;
    HuffmanNode *left, *right;
    HuffmanNode(char d) : data(d), left(nullptr), right(nullptr) {}
};

// Function to decode compressed file using Huffman coding
void decodeFile(const string &dataFile, const string &encodingFile, const string
&outputFile)
{
    // 1. Read encoding file to get code-to-character mapping
    ifstream encIn(encodingFile, ios::binary);
    map<string, char> codeToChar;

    // Read file header (2 SOH characters + code count)
    char header[3];
    encIn.read(header, 3);
    if (header[0] != 1 || header[1] != 1)
    {
        cerr << "Invalid encoding file header" << endl;
        return;
    }

    // Read each character and its corresponding code
    int codeCount = static_cast<unsigned char>(header[2]);
    for (int i = 0; i < codeCount; i++)
    {
        char ch;
        encIn.get(ch);
        string code;
        char bit;
        while (encIn.get(bit) && (bit == '0' || bit == '1'))
        {
            code += bit;
        }
        encIn.unget();
        codeToChar[code] = ch;
    }
    encIn.close();

    // 2. Rebuild Huffman tree from codes
    HuffmanNode *root = new HuffmanNode('\0');
    for (const auto &pair : codeToChar)
```



```
    {
        HuffmanNode *current = root;
        for (char bit : pair.first)
        {
            if (bit == '0')
            {
                if (!current->left)
                    current->left = new HuffmanNode('\0');
                current = current->left;
            }
            else
            {
                if (!current->right)
                    current->right = new HuffmanNode('\0');
                current = current->right;
            }
        }
        current->data = pair.second;
    }

    // 3. Read and decode data file
    ifstream dataIn(dataFile, ios::binary);
    ofstream out(outputFile, ios::binary);

    // Process each data block (each starts with 2 SYN chars + length)
    vector<char> blockHeader(3);
    while (dataIn.read(blockHeader.data(), 3))
    {
        if (blockHeader[0] != 22 || blockHeader[1] != 22)
        {
            cerr << "Invalid data block header" << endl;
            break;
        }

        // Get number of characters in this block
        int length = static_cast<unsigned char>(blockHeader[2]);
        HuffmanNode *current = root;
        char bit;

        // Decode each character in the block
        for (int i = 0; i < length;)
        {
            dataIn.get(bit);
            if (bit == '0')
            {
                current = current->left;
            }
```



```
            else if (bit == '1')
            {
                current = current->right;
            }

            // When reaching a leaf node, write the character
            if (!current->left && !current->right)
            {
                out << current->data;
                current = root;
                i++;
            }
        }
    }

    dataIn.close();
    out.close();
}

int main()
{
    string dataFile, encodingFile, outputFile;
    cout << "Enter data file path: ";
    cin >> dataFile;
    cout << "Enter encoding file path: ";
    cin >> encodingFile;
    cout << "Enter output file path: ";
    cin >> outputFile;

    decodeFile(dataFile, encodingFile, outputFile);
    cout << "Decompression complete! Output file: " << outputFile << endl;

    return 0;
}
```