Assignment 8 – Huffman Coding

Sebastian Avila

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Purpose

The purpose of these programs is to implement a lossless data compressor and a data decompressor. The `huff` program is to compress a file using Huffman coding. In this, it determines which bytes (or symbols) of the input file are most common and switches their representations to use fewer bits. Less common symbols will in turn switch to representations that use more bits. This results in less bits needed to represent the entire file. The second program `dehuff`, takes the compressed file from the previous program and produces the original file.

How to Use the Program

To use this program you will need to have several files in the same directory. The files are `huff.c`, `dehuff.c`, `bitreader.h`, `bitreader.c`, `bitwriter.h`, `bitwriter.c`, `node.h`, `node.c`, `pq.h`, `pq.c`, `brtest.c`, `bwtest.c`, `nodetest.c`, `pqtest.c`, and `Makefile`. With these files in the same directory, use command `make clean` to remove any preexisting object files. Then, use command `make format` to format all the header and source files. Then use command `make` to compile the program. You will also need an input file that you want to be compressed in the directory or in a sub-directory. The possible command line arguments for both `huff` and `dehuff` are as follows:

- `-i` : Sets the input file. It requires a file name as an argument. It is required to run the program.
- `-o` : Sets the output file. It requires a file name as an argument. It is required to run the program.
- `-h` : Prints a help message to `stdout`.

To run the program use the command `./huff -i infile -o huffout`. This will compress the file `infile` using Huffman Coding and return the compressed file as `huffout`. Then use the command `./dehuff -i huffout -o outfile` This will decompress the file `huffout` and give the file `outfile`. The files `infile` and `outfile` will have the same contents and size.
The program uses several optional compiler flags:

- `-Wall`: This flag enables all warning messages.
- `-Werror`: This flag turns all warnings into errors.
- `-Wextra`: This flag enables extra warning flags that are not enabled by `-Wall`.
- `-Wconversion`: This flag warns for any implicit conversion that may change a value.
- `-Wdouble-promotion`: This flag warns when a float is implicitly promoted to a double.
- `-Wstrict-prototypes`: This flag warns if a function is declared or defined without specifying the argument types.
- `-pedantic`: This flag issues all the warnings demanded by strict ISO C and ISO C++.

Program Design

huff.c

The program begins by creating a file pointer and a character string pointer. It sets both of these to `NULL`. It then checks the command line arguments. The command line arguments and their meanings can be seen in the How To Use the Program section of this report. For the command argument `-i`, it opens the file for reading and sets the file pointer to the file. For the command argument `-o`, it sets the character string pointer to the argument given. It then checks if either of the `-i` or `-o` command line arguments were not used b checking if they are equal to `NULL`. If either one is not used, the respective error message is printed and the usage message is printed. Then the program terminates with a non-zero exit code. Otherwise, the program creates an array of 256 unsigned 32 bit integers to be used as the histogram. It then uses a function to fill this histogram and return the size of the file. It then initializes an unsigned 16 bit integer variable and a `Node` object. Then, it uses another function to create a Huffman tree and assign the tree to the `Node` object. It also sets the unsigned 16 bit integer variable to the number of leaves. It then creates an array 256 `Code` objects to be used as the code table. It then fills the code table using a function. A `BitWriter` object is then created using a function. Then the program uses a function to compress the given input file and write it to the output file. The function makes use of the `BitWriter` object, the file size, the number of leaves, the Huffman tree, and the code table. The program then closes both the input file and the output file. It the frees the memory used for the `BitWriter` object and the Huffman tree. It ends by returning 0.

dehuff.c

This program operates in a similar manner to `huff.c` at first. It begins by creating a file pointer and a character string pointer. It sets both of these to `NULL`. It then checks the command line arguments. For the command argument `-i`, it sets the character string pointer to the argument given. For the command argument `-o`, it opens the file for writing and sets the file pointer to the file. checking the command line arguments. It then checks if either of the `-i` or `-o` command line arguments were not used by checking whether they are equal to `NULL`. If either one is not used, the respective error message is printed and the usage message is printed. Then the program terminates with a non-zero exit code. Otherwise, the program creates an array of 256 unsigned 32 bit integers to be used as the histogram. It then creates a `BitReader` object. It then uses a function to decode the input file and write the output file. This function uses the `BitReader` object and the output file. The program then closes both the input file and the output file and frees the memory used for the `BitReader` object. It then returns 0.

Data Structures

All data structures were given in the assignment instructions[1].

BitWriter

This program defines a type `BitWriter` that is a struct also named `BitWriter` with three variables: a file pointer and two unsigned 8 bit integers.

- `underlying_stream` : This is a file pointer that points to the file in which the bits will be written.
- `byte` : This unsigned 8 bit integer is a buffer that holds the byte that is to be written.
- `bit_position` : This unsigned 8 bit integer represents the bit position where the bit will be written.

```
typedef struct BitWriter BitWriter;

struct BitWriter {
    FILE *underlying_stream;
    uint8_t byte;
    uint8_t bit_position;
};
```

BitReader

This program defines a type `BitReader` that is a struct also named `BitReader` with three variables: a file pointer and two unsigned 8 bit integers.

- `underlying_stream` : This is a file pointer that points to the file in which the bits will be written.
- `byte` : This unsigned 8 bit integer is a buffer that holds the byte that is to be written.
- `bit_position` : This unsigned 8 bit integer represents the bit position where the bit will be written.

```
typdef struct BitReader BitReader;

struct BitReader {
    FILE *underlying_stream;
    uint8_t byte;
    uint8_t bit_position;
};
```

Node

This program defines a type `Node` that is a struct, also named `Node`, with 6 variables: two unsigned 8 bit integers, an unsigned 16 bit integer, an unsigned 64 bit integer, and two pointers to `Nodes`.

- `symbol` : This 8 bit integer represents the character that the `Node` contains.
- `weight` : This 32 bit integer represents the weight of the node.
- `code` : This 64 bit integer stores the Huffman code for the node.
- `code_length` : This 8 bit integer stores the length of the Huffman code.
- `left` : This is a pointer to a `Node` object.
- `right` : This is a pointer to a `Node` object.

```
typedef struct Node Node;

struct Node {
    uint8_t symbol;
    uint32_t weight;
    uint64_t code;
    uint8_t code_length;
    Node *left;
    Node *right;
}
```

ListElement

The program defines a type `ListElement` that is a struct, also named `ListElement`, with 2 variables: a pointer to a `Node` object and a pointer to a `ListElement` object.

- `tree` : This is a pointer to a `Node`
- `next` : This is a pointer to the next `ListElement` object

```
typedef struct ListElement ListElement;

struct ListElement {
    Node *tree;
    ListElement *next;
};
```

PriorityQueue

The program defines a type `PriorityQueue` that is a struct, also named `PriorityQueue`, with 1 variable: a pointer to a `ListElement` object, `list`.

```
typedef struct PriorityQueue PriorityQueue;

     struct PriorityQueue {
         ListElement *list;
};
```

Code

The program defines a type `Code` that is a struct with 2 variables: an unsigned 64 bit integer `code` and an unsigned 8 bit integer `code_length`.

```
typedef struct Code {
       uint64_t code;
       uint8_t code_length;
   } Code;
```

Algorithms

Huffman Coding

The assignment instructions provide psuedocode for the Huffman Coding algorithm[1]. This psuedocode implies the use of a priority queue.

```
Huffman Coding
    while Priority Queue has more than one entry
            Dequeue into left
            Dequeue into right
            Create a new node with a weight = left->weight + right->weight
            node->left = left
            node->right = right
            Enqueue the new node
```

Function Descriptions

bitwriter

- `BitWriter *bit_write_open(const char *filename)` : This function takes in a constant character string. It returns a pointer to a `BitWriter`. Its purpose is to open binary `filename` for write. Psuedocode for this function was given in the assignment instructions[1].

```
BitWriter *bit_write_open(const char *filename)
    BitWriter bw = memory(sizeof(BitWriter)) cast as BitWriter pointer
    if bw == NULL then
        return NULL
    f = open file (filename) for writing bits
    if f == NULL then
        free(bw)
        bw = NULL
        return NULL
    bw underlying_stream = f
    bw byte = 0
    bw bit_position = 0
    return bw
```

- `void bit_write_close(BitWriter **pbuf)` : This function takes in a pointer to a pointer to a `BitWriter`. It does not return anything. Its purpose is to flush any data in the byte buffer, close `underlying_stream`, free the `BitWriter` object, and set the `*pbuf` pointer to `NULL`. Psuedocode for this function was given in the assignment instructions[1].

```
void bit_write_close(BitWriter **pbuf)
    if *pbuf != NULL then
        if *pbuf bit_position > 0 then
             if (print char *pbuf byte to *pbuf underlying_stream) == EOF then
                print error message
                exit(1)
        if close file(*pbuf underlying_stream) == EOF then
            print error message
            exit(1)
        free(pbuf)
        *pbuf = NULL
```

- `void bit_write_bit(BitWriter *buf, uint8_t bit)` : This function takes in a pointer to a `BitWriter` (`*buf`) and an 8 bit integer `bit`. It does not return anything. Its purpose is to write a single bit, `bit`, using values in the `BitWriter` pointed to by `buf`. Psuedocode for this function was given in the assignment instructions[1].

```
void bit_write_bit(BitWriter *buf, uint8_t bit)
    if buff bit_position > 7 then
        if (print char buf byte to buf underlying_stream) == EOF then
            print error message
            exit(1)
        buf bit_position = 0
        buf byte = 0
    buf byte = buf byte OR (bit << buf bit_position)
    buf bit_position += 1
```

- `void bit_write_uint8(BitWriter *buf, uint8_t x)` : This function takes in a pointer to a `BitWriter` (`*buf`) and an 8 bit integer `x`. It does not return anything. Its purpose is to write the 8 bits of `x`. Psuedocode for this function was given in the assignment instructions[1].

```
void bit_write_uint8(BitWriter *buf, uint8_t x)
    for i, 0 to i < 8
        bit_write_bit(buf, x >> i( AND 1))
```

- `void bit_write_uint16(BitWriter *buf, uint16_t x)` : This function takes in a pointer to a `BitWriter` (`*buf`) and an 16 bit integer `x`. It does not return anything. Its purpose is to write the 16 bits of `x`. Psuedocode for this function was given in the assignment instructions[1].

```
void bit_write_uint16(BitWriter *buf, uint16_t x)
    for i, 0 to i < 16
        bit_write_bit(buf, (x >> i) AND 1)
```

- `void bit_write_uint32(BitWriter *buf, uint32_t x)` : This function takes in a pointer to a `BitWriter` (`*buf`) and an 32 bit integer `x`. It does not return anything. Its purpose is to write the 32 bits of `x`. Psuedocode for this function was given in the assignment instructions[1].

```
void bit_write_uint32(BitWriter *buf, uint32_t x)
    for i, 0 to i < 32
        bit_write_bit(buf, (x >> i) AND 1)
```

bitreader

- `BitReader *bit_read_open(const char *filename)` : This function takes in a constant character string `filename`. It returns a pointer to a `BitReader` object. Its purpose is to open the binary `filename` for reading. Psuedocode for this function was given in the assignment instructions[1].

```
BitReader *bit_read_open(const char *filename)
    BitReader br = memory (sizeof(BitReader)) cast as BitReader pointer
    if br == NULL then
        return NULL
    br underlying_stream = open file(filename) for reading bytes
    if br underlying_stream == NULL then
        free(br)
        br = NULL
        return NULL
    br byte = 0
    br bit_position = 8
    return br
```

- `void bit_read_close(const char *filename)` : This function takes in a pointer to a pointer to a `BitReader`. It does not return anything. Its purpose is to close `underlying_stream`, free the `BitReader` object, and set the `*pbuf` pointer to `NULL`. Psuedocode for this function was given in the assignment instructions[1].

```
void bit_read_close(BitReader **pbuf)
    if *pbuf != NULL then
        if close file(*pbuf underlying_stream) == EOF then
            print error message
            exit(1)
        free(pbuf)
        *pbuf = NULL
```

- `uint8_t bit_read_bit(BitReader *buf)` : This function takes in a pointer to a `BitReader` (`*buf`). It returns an 8 bit unsigned integer. Its purpose is to read a single bit using values in the `BitReader` pointed to by `buf`. Psuedocode for this function was given in the assignment instructions[1].

```
uint8_t bit_read_bit(BitReader *buf)
    if buf bit_position > 7 then
        t = get char from buf underlying_stream
        if (t == EOF) then
            print error message
            exit(1)
        buf byte = t
        buf bit_position = 0
    bit = 1 AND (buf byte >> buf bit_position)
    buf bit_position += 1
    return bit
```

- `uint8_t bit_read_uint8(BitReader *buf)` : This function takes in a pointer to a `BitReader` (`*buf`). It returns an unsigned 8 bit integer. Its purpose is to read 8 bits from `buf`. Psuedocode for this function was given in the assignment instructions[1].

```
uint8_t bit_read_uint8(BitReader *buf)
    uint8_t byte = 0x00
    for i, 0 to i < 8
        byte = byte OR (bit_read_bit(buf) << i)
    return byte
```

- `void bit_read_uint16(BitReader *buf)` : This function takes in a pointer to a `BitReader` (`*buf`). It returns an unsigned 16 bit integer. Its purpose is to read 16 bits from `buf`. Psuedocode for this function was given in the assignment instructions[1].

```
uint16_t bit_read_uint16(BitReader *buf)
    uint16_t byte = 0x00
    for i, 0 to i < 16
        byte = byte OR (bit_read_bit(buf) << i)
    return byte
```

- `void bit_read_uint32(BitReader *buf, uint32_t x)` : This function takes in a pointer to a `BitReader` (`*buf`). It returns an unsigned 32 bit integer. Its purpose is to read 32 bits from `buf`. Psuedocode for this function was given in the assignment instructions[1].

```
uint8_t bit_read_uint32(BitReader *buf)
    uint32_t byte = 0x00
    for i, 0 to i < 32
        byte = byte OR (bit_read_bit(buf) << i)
    return byte
```

node

- `Node *node_create(uint8_t symbol, uint32_t weight)` : This function takes in an unsigned 8 bit integer and an unsigned 32 bit integer. It returns a pointer to a `Node` object or `NULL` if an error occurs. Its purpose is to create and return a `Node` object. Psuedocode for this function was given in the assignment instructions[1].

```
Node *node_create(uint8_t symbol, uint32_t weight)
    Node node = memory(sizeof(Node)) cast as Node pointer
    if node == NULL then
        reeturn NULL
    node symbol = symbol
    node weight = weight
    node code = 0
    node code_length = 0
    node left = NULL
    node right = NULL
    return node
```

- `void node_free(Node **pnode)` : This function takes in a pointer to a pointer to a `Node` object: `pnode`. It does not return anything. Its purpose is to free `pnode` and set it to `NULL`. Psuedocode for this function was given in the assignment instructions[1].

```
void node_free(Node **pnode)
    if *pnode != NULL then
        node_free(*pnode left)
        node_free(*pnode right)
        free(*pnode)
        *pdone = NULL
```

- `void node_print_node(Node *tree, char ch, int indentation)` : This function takes in a pointer to a `Node` object `tree`, a character `ch`, and an integer `indentation`. It does not return anything. Its purpose is to print the tree for diagnostic and debugging purposes. This function was given in the assignment instructions[1].

```
void node_print_node(Node *tree, char ch, int indentation)
    if tree == NULL then
```

```
        return
    node_print_node(tree right, ’/’, indentation + 3)
    print (weight = (tree weight))

    if tree left == NULL && tree right == NULL then
        if ’ ’ <= tree symbol <= ’˜’ then
            print (symbol = (tree symbol))
        else
            print (symbol = (tree symbol as hex))

    print newline
    node_print_node(tree left, ’\\’, indentation + 3)
```

pq

- `PriorityQueue *pq_create(void)` : This function does not accept any parameters. It returns a pointer to a `PriorityQueue` object. Its purpose is to allocate a `PriorityQueue` object. If an error occurs, it returns `NULL`.

```
PriorityQueue *pq_create(void)
    PriorityQueue pq = memory(sizeof(PriorityQueue)) cast as PriorityQueue pointer
    if pq == NULL then
        return NULL
    pq list = NULL
    return pq
```

- `void pq_free(PriorityQueue **q)` : This function takes in a pointer to a pointer to a `PriorityQueue` object. It does not return anything. Its purpose is to free the `PriorityQueue` object and set the pointer to `NULL`.

```
void pq_free(PriorityQueue **q)
    if *q != NULL then
        ListElement current = *q list
        ListElement temp
        while current == NULL then
            temp = current
            current = current next
            node_free(temp tree)
            free(temp)
        free(*q)
        *q = NULL
```

- `bool pq_is_empty(PriorityQueue *q)` : This function takes in a pointer to a `PriorityQueue` object: `q`. It returns either true or false. Its purpose is to check whether `q` is empty (true) or not (false).

```
bool pq_is_empty(PriorityQueue *q)
    if q list == NULL or q == NULL then
        return true
    else
        return false
```

- `bool pq_size_is_1(PriorityQueue *q)` : This function takes a pointer to a `PriorityQueue` object. It returns true or false. Its purpose is to check whether `*q` contains a single element or not. If it does it returns true. Otherwise, it returns false.

```
bool pq_size_is_1(PriorityQueue *q)
    if pq_is_empty(q) then
```

```
        return false
    count = 0
    while current != NULL then
        count++
        current = current next
    return count == 1
```

- bool pq_less_than(ListElement *e1, ListElement *e2) : This function takes in two pointers to ListElement objects: e1 and e2. It returns true or false. Its purpose is to compare the tree->weight values of the two ListElement objects. It returns true if the weight of the first element is less than the weight of the second element. If the weights of the elements are equal, it compares the tree-symbol values and returns true if the symbol of the first element is less than the second. Otherwise, it returns false.

```
bool pq_less_than(ListElement *e1, ListElement *e2)
    if e1 tree weight < e2 tree weight then
        return true
    else if e1 tree weight == e2 tree weight then
        if e1 tree symbol < e2 tree symbol
            return true
    return false
```

- void enqueue(PriorityQueue *q, Node *tree) : This function takes in a pointer to a PriorityQueue object and a pointer to a Node object. These are q and tree, respectfully. It does not return anything. Its purpose is to insert a tree into the priority queue. Psuedocode for this function was given in the assignment instructions[1].

```
void enqueue(PriorityQueue *q, Node *tree)
    ListElement new_element = memory(sizeof(ListElement)) cast as ListElement pointer
    if new_element == NULL
        exit(1)
    new_element tree = tree
    new_element next = NULL

    if pq_is_empty(q) then
        q list = new_element
        return
    else if pq_less_than(new_element, q list) then
        new_element next = q list
        q list = new_element
    else
        ListElement current = q list
        while true
            if current next == NULL then
                current next = new element
                return
            else if pq_less_than(new_element, current next) then
                new_element next = current next
                current next = new element
            current = current next
            return
        current = current next
```

- Node *dequeue(PriorityQueue *q) : This function takes a pointer to a PriorityQueue object q. It returns a Node object. Its purpose is to remove the queue element with the lowest weight and return it.

```
Node *dequeue(PriorityQueue *q)
    if pq_is_empty(q) then
        print error message
        exit(1)
    ListElement temp = q list
    Node node = temp tree
    q list = q list next
    free(temp)
    return node
```

- `void pq_print(PriorityQueue *q)` : This function takes in a pointer to a `PriorityQueue` object: `q`. It does not return anything. Its purpose is to print the trees of the queue `q`. This function was given in the assignment instructions[1].

```
void pq_print(PriorityQueue *q)
    assert(q != NULL)
    ListElement *e = q list
    position = 1
    while e != NULL
        if position++ = 1 then
            print "=============================================\n")
        else
            printf("---------------------------------------------\n");
        node_print_tree(e->tree, ’<’, 2);
        e = e next
    print "=============================================\n"
```

Huffman Coding

- `uint32_t fill_histogram(FILE *fin, uint32_t *histogram)` : This function takes in a file pointer `fin` and an array of unsigned 32 bit integers `histogram`. It returns an unsigned 32 bit integers. Its purpose is to update the `histogram` array with the number of each of the unique byte values of the input file. It also returns the total size of the input file.

```
uint32_t fill_histogram(FILE *fin, uint32_t *histogram)
    uint32_t filesize
    for i, 0 to i < 256
        histogram[i] = 0;
    ++histogram[0x00];
    ++histogram[0xff];
    while (byte = fgetc(fin)) != EOF
        ++histogram[byte]
        ++filesize
    return filesize
```

- `Node *create_tree(uint32_t *histogram, uint16_t *num_leaves)` : This function takes in an array of unsigned 32 bit integers `histogram` and a pointer to an unsigned 16 bit integer `num_leaves`. It returns a `Node` object. Its purpose is to create and return a pointer to a new Huffman Tree. It also returns the number of leaf nodes in the tree by placing the value in `num_leaves`.

```
Node *create_tree(uint32_t *histogram, uint16_t *num_leaves)
    q = pq_create()
    for i, 0 to i < 256
        if histogram[i] != 0 then
            nd = node_create(i, histogram[i])
            enqueue(q, nd)
            (*num_leaves)++
    while !(pq_size_is_1(q))
        left = dequeue(q)
        right = dequeue(q)
        node = create_node(0, left weight + right weight)
        node left = left
        node right = right
        enqueue(q, node)

    last = dequeue(q)
    pq_free(q)
    return last
```

- `void fill_code_table(Code *code_table, Node *node, uint64_t code, uint8_t code_length)` This function takes in 4 parameters: a pointer to a `Code` object `code_table`, a pointer to a `Node` object `node`, an unsigned 64 bit integer `code`, and an unsigned 8 bit integer `code_length`. It does not return anything. Its purpose is to traverse a tree and fill in the Code Table for each leaf node's symbol. Psuedocode for this function was given in the assignment instructions[1].

```
void fill_code_table(Code *code_table, Node *node, uint64_t code, uint8_t code_length)
    if node left != NULL
        fill_code_table(code_table, node left, code, code_length + 1)
        code = code OR 1 << code_length
        fill_code_table(code_table, node right, code, code_length + 1)
    else
        code_table[node symbol].code = code
        code_table[node symbol].code_length = code_length
```

- `void huff_write_tree(BitWriter *outbuff, Node *node)` : This function takes in a pointer to a `BitWriter` object and a pointer to a `Node` object. It does not return anything. Its purpose is to write a Huffman Tree. Psuedocode for this function was given in the assignment instructions[1].

```
void huff_write_tree(BitWriter *outbuff, Node *node)
    if node left == NULL then
        bit_write_bit(outbuf, 1)
        bit_write_uint8(outbuf, node symbol)
    else
        huff_write_tree(outbuf, node left)
        huff_write_tree(outbuf, node right)
        bit_write_bit(outbuf, 0)
```

- `void huff_compress_file(outbuf, fin, filesize, num_leaves, code_tree, code_table)` : This function takes in 6 parameters:
  - `BitWriter *outbuf` : a pointer to a `BitWriter object`
  - `FILE *fin` : a file pointer
  - `uint32_t filesize` : an unsigned 32 bit integer
  - `uint16_t num_leaves` : an unsigned 16 bit integer
  - `Node *code_tree` : a pointer to a `Node` object
  - `Code *code_table` : a pointer to a `Code` object

  It does not return anything. Its purpose is to write a Huffman Coded file. Psuedocode for this function was given in the assignment instructions[1].

```
void huff_compress_file(outbuf, fin, filesize, num_leaves, code_tree, code_table)
    bit_write_uint8(outbuf, 'H')
    bit_write_uint8(outbuf, 'C')
    bit_write_uint32(outbuf, filesize)
    bit_write_uint16(outbuf, num_leaves)
    huff_write_tree(outbuf, code_tree)
    while true
        b = get char from fin
        if b == EOF then
            break
        code = code_table[b].code
        code_length = code_table[b].code_length
        for i, 0 to i < code_length
            bit_write_bit(outbuf, (code AND 1))
            code = code >> 1
```

Huffman Decoding

- `void dehuff_decompress_file(FILE *fout, BitReader *inbuf)` : This function takes in a file pointer `fout` and a pointer to a `BitReader` object `inbuf`. It does not return anything. Its purpose is to read the code tree and then use it to decompress the compressed file. Psuedocode for this function was given in the assignment instructions[1].

```
void dehuff_decompress_file(FILE *fout, BitReader *inbuf)
    Node *stack[64] = { NULL }
    stack_top = -1
    type1 = bit_read_uint8(inbuf)
    type2 = bit_read_uint8(inbuf)
    filesize = bit_read_uint32(inbuf)
    num_leaves = bit_read_uint16(inbuf)
    num_nodes = 2 * num_leaves - 1
    Node *node
    for i, 0 to i < num_nodes
        bit = bit_read_bit(inbuf)
        if bit == 1 then
            symbol = bit_read_uint8(inbuf)
            node = node_create(symbol, 0)
        else
            node = node_create(0,0)
            node right = stack[stack_top--]
            node left = stack[stack_top--]
        stack[++stack_top] = node
    Node *code_tree = stack[stack_top--]
    for j, 0 to j < filesize
        bit = bit_read_bit(inbuf)
        if bit == 0 then
            if node != NULL then
                node = node left
        else
            if node != NULL then
                node = node right
        if node != NULL then
            if node left == NULL and node right == NULL then
                break
        print char node symbol to fout
    node_free(code_tree)
```

Psuedocode

huff.c

```
main
    FILE fin = NULL
    char fout = NULL

    int opt
    opterr = 0
    while (opt = getopt) != -1
        switch opt
            case ’h’:
                print usage message
                return 0
                break
            case ’i’:
                fin = open file(optarg) for reading
                if fin = NULL then
                    print error
                    return 1
                break
            case ’o’:
                fout = optarg
                if fout = NULL then
                    print error
                    return 1
                break
            default:
                print error and usage message
                return 1

    if fin == NULL
        print error and usage message
        return 1
    if fout == NULL
        print error and usage message
        return 1

    uint32_t histogram[256] = {0}

    filesize = fill_histogram(fin, histogram)

    num_leaves = 0
    tree = create_tree(histogram, num_leaves)

    Code code_table[256]
    fill_code_table(code_table, tree, 0, 0)

    BitWriter outbuf = bit_write_open(fout)
    huff_compress_file(outbuf, fin, filesize, num_leaves, tree, code_table)

    close file(fin)
    node_free(tree)
    bit_write_close(outbuf)
    return 0
```

dehuff.c

```
main
    char fin = NULL
    FILE fout = NULL

    int opt
    opterr = 0
    while (opt = getopt) != -1
        switch opt
            case ’h’:
                print usage message
                return 0
                break
            case ’i’:
                fin = optarg
                if fin = NULL then
                    print error
                    return 1
                break
            case ’o’:
                fout = open file(optarg) for writing
                if fout = NULL then
                    print error
                    return 1
                break
            default:
                print error and usage message
                return 1

    if fin == NULL
        print error and usage message
        return 1
    if fout == NULL
        print error and usage message
        return 1

    BitReader inbuf = bit_read_open(outfile)
    dehuff_decompress_file(fout, inbuf)

    close file(fout)
    bit_read_close(inbuf)
    return 0
```

Error Handling

- Invalid command line arguments : If an invalid command line argument is given, the usage message will be printed and the program will be terminated.
- Missing arguments : If the program does not receive the `-i` and `-o` arguments, it will print an error message and the usage message and then terminate.
- Invalid input file: If the program cannot open the input file, it will print an error message and the usage message and terminate the program.
- Errors while reading program : If the program reads an `EOF` before expected, it will print and error message and terminate the program.

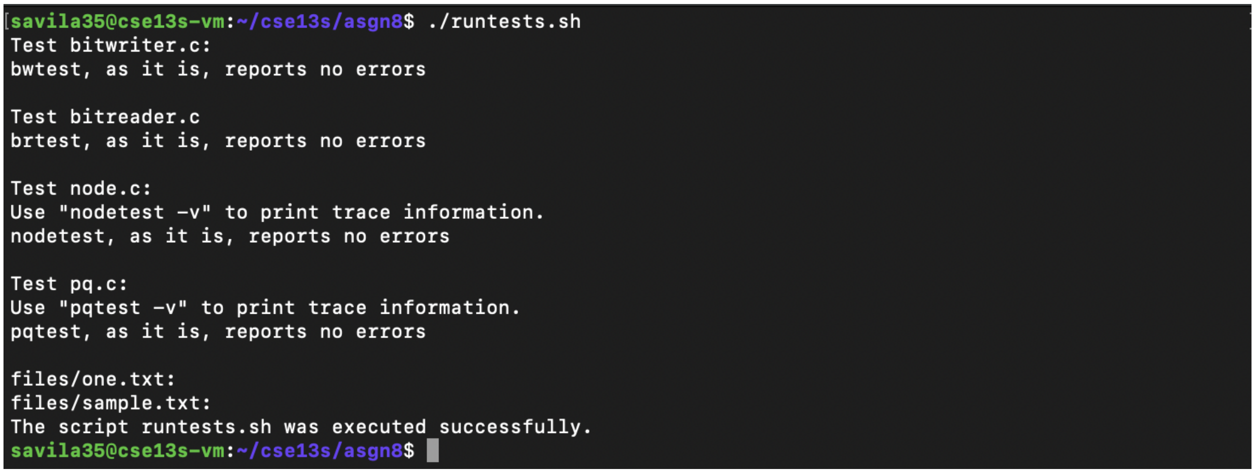
- Invalid out file : If the output file cannot be opened, an error message will be printed and the program will terminate.

Testing

These programs will be tested using the provided test files: `brtest.c`, `bwtest.c`, `nodetest.c`, and `pqtest.c` using an executable `runtests.sh`. These files were all given in the gitlab resources repository[2]. The executable `runtests.sh` executes all the test files and then executes `huff`, `dehuff`, `huff-ref`, `dehuff-ref` with all the `.txt` files in the `files` directory. After that, it compares the out files using the `diff` command. It reports any differences. This testing is shown in Fig. 1. It will also be tested using `valgrind` to ensure that there are no memory leaks. the results of one of these tests is shown in Fig. 2. The program will also be compiled with `scan-build`. This was done using a rule I implemented in the `Makefile`. This rule first execute the `make clean` command and then executes the `scan-build --use-cc=clang make` command. The second command executes `scan-build` with the `make all` command which compiles all the files. It also specifies `clang` as the compiler. The result of this testing is shown in Fig. 3. The `diff` command was used to compare the decompressed file to the original file. This is shown in Fig. 4.

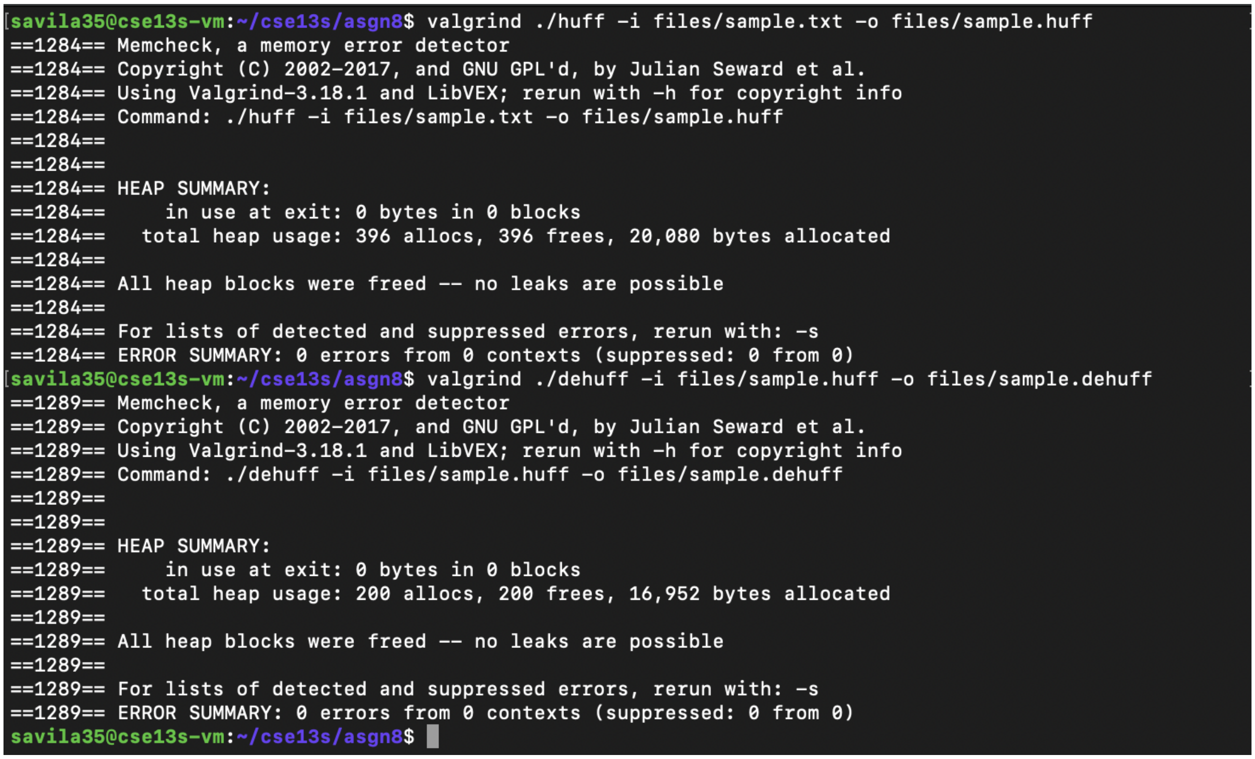
Results

The programs function as intended. It produces error messages when an error occurs. It responds to all the command line arguments correctly. Figure 5 shows the help messages of the programs. The program correctly implements a Huffman code to compress a file. Figure 6 shows the compression of the file `report.pdf` (my report draft). The compressed file is smaller than the original. The figure also shows the decompression of the compressed file. It shows that the original file and the decompressed file are the same using the `diff` command. In Fig. 6, the command `du` is used. This command reports the disk usage of the given directory or file. The argument `-h` gives the result in a human readable form (number of bytes). I gained knowledge of this command from an article from the website *redhat.com*[3].



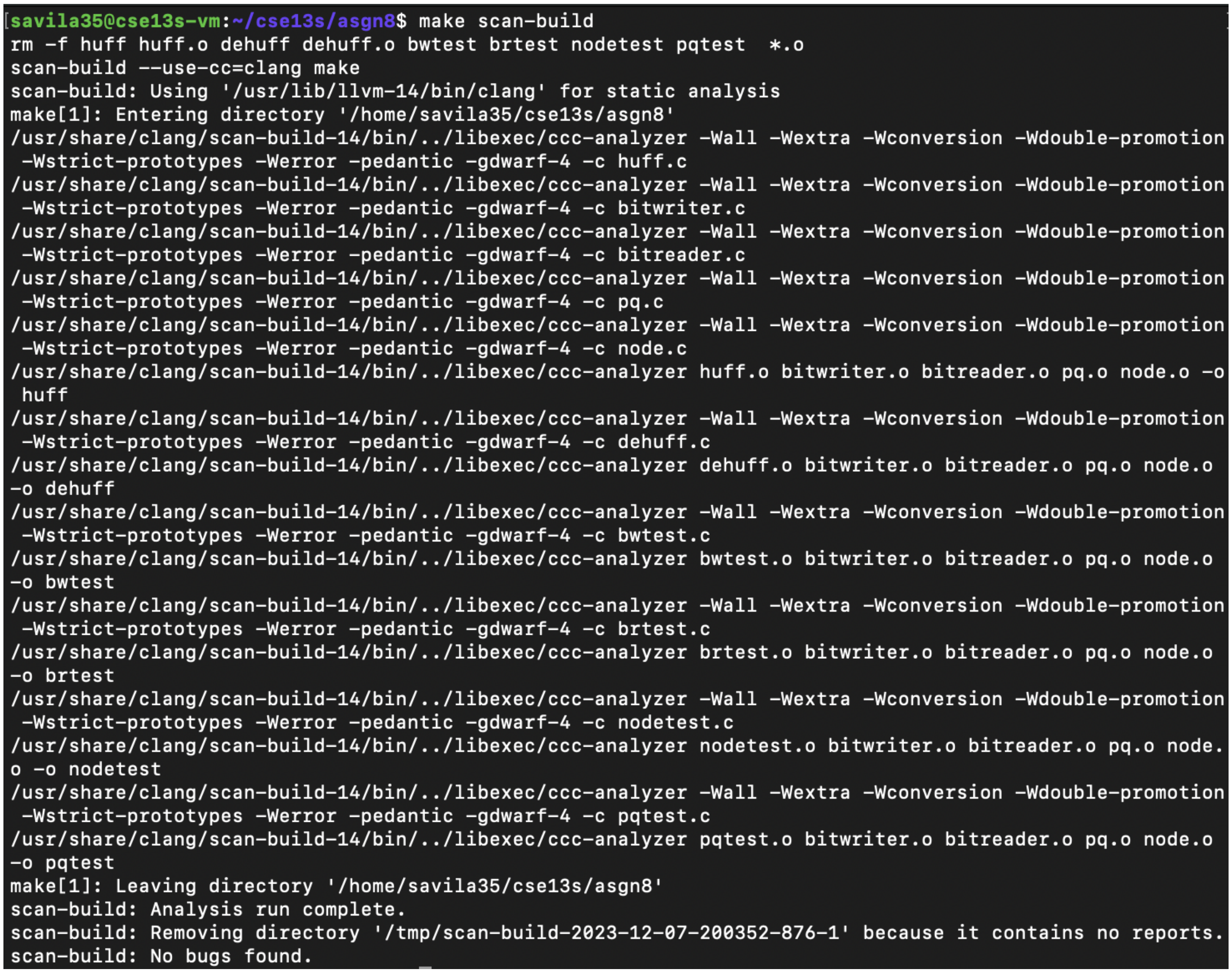
```
savila35@cse13s-vm:~/cse13s/asgn8$ ./runtests.sh
Test bitwriter.c:
bwtest, as it is, reports no errors

Test bitreader.c
brtest, as it is, reports no errors

Test node.c:
Use "nodetest -v" to print trace information.
nodetest, as it is, reports no errors

Test pq.c:
Use "pqtest -v" to print trace information.
pqtest, as it is, reports no errors

files/one.txt:
files/sample.txt:
The script runtests.sh was executed successfully.
savila35@cse13s-vm:~/cse13s/asgn8$
```

Figure 1: Execution of runtests.sh



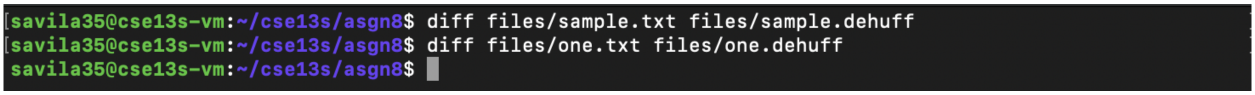
```
[savila35@cse13s-vm:~/cse13s/asgn8$ valgrind ./huff -i files/sample.txt -o files/sample.huff
==1284== Memcheck, a memory error detector
==1284== Copyright (C) 2002-2017, and GNU GPL'd, by Julian Seward et al.
==1284== Using Valgrind-3.18.1 and LibVEX; rerun with -h for copyright info
==1284== Command: ./huff -i files/sample.txt -o files/sample.huff
==1284==
==1284==
==1284== HEAP SUMMARY:
==1284==     in use at exit: 0 bytes in 0 blocks
==1284==   total heap usage: 396 allocs, 396 frees, 20,080 bytes allocated
==1284==
==1284== All heap blocks were freed -- no leaks are possible
==1284==
==1284== For lists of detected and suppressed errors, rerun with: -s
==1284== ERROR SUMMARY: 0 errors from 0 contexts (suppressed: 0 from 0)
[savila35@cse13s-vm:~/cse13s/asgn8$ valgrind ./dehuff -i files/sample.huff -o files/sample.dehuff
==1289== Memcheck, a memory error detector
==1289== Copyright (C) 2002-2017, and GNU GPL'd, by Julian Seward et al.
==1289== Using Valgrind-3.18.1 and LibVEX; rerun with -h for copyright info
==1289== Command: ./dehuff -i files/sample.huff -o files/sample.dehuff
==1289==
==1289==
==1289== HEAP SUMMARY:
==1289==     in use at exit: 0 bytes in 0 blocks
==1289==   total heap usage: 200 allocs, 200 frees, 16,952 bytes allocated
==1289==
==1289== All heap blocks were freed -- no leaks are possible
==1289==
==1289== For lists of detected and suppressed errors, rerun with: -s
==1289== ERROR SUMMARY: 0 errors from 0 contexts (suppressed: 0 from 0)
savila35@cse13s-vm:~/cse13s/asgn8$
```

Figure 2: Valgrind testing



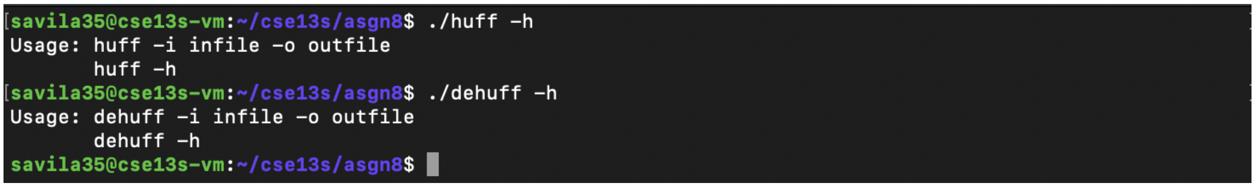
```
savila35@cse13s-vm:~/cse13s/asgn8$ make scan-build
rm -f huff huff.o dehuff dehuff.o bwtest brtest nodetest pqtest  *.o
scan-build --use-cc=clang make
scan-build: Using '/usr/lib/llvm-14/bin/clang' for static analysis
make[1]: Entering directory '/home/savila35/cse13s/asgn8'
/usr/share/clang/scan-build-14/bin/../libexec/ccc-analyzer -Wall -Wextra -Wconversion -Wdouble-promotion
 -Wstrict-prototypes -Werror -pedantic -gdwarf-4 -c huff.c
/usr/share/clang/scan-build-14/bin/../libexec/ccc-analyzer -Wall -Wextra -Wconversion -Wdouble-promotion
 -Wstrict-prototypes -Werror -pedantic -gdwarf-4 -c bitwriter.c
/usr/share/clang/scan-build-14/bin/../libexec/ccc-analyzer -Wall -Wextra -Wconversion -Wdouble-promotion
 -Wstrict-prototypes -Werror -pedantic -gdwarf-4 -c bitreader.c
/usr/share/clang/scan-build-14/bin/../libexec/ccc-analyzer -Wall -Wextra -Wconversion -Wdouble-promotion
 -Wstrict-prototypes -Werror -pedantic -gdwarf-4 -c pq.c
/usr/share/clang/scan-build-14/bin/../libexec/ccc-analyzer -Wall -Wextra -Wconversion -Wdouble-promotion
 -Wstrict-prototypes -Werror -pedantic -gdwarf-4 -c node.c
/usr/share/clang/scan-build-14/bin/../libexec/ccc-analyzer huff.o bitwriter.o bitreader.o pq.o node.o -o
 huff
/usr/share/clang/scan-build-14/bin/../libexec/ccc-analyzer -Wall -Wextra -Wconversion -Wdouble-promotion
 -Wstrict-prototypes -Werror -pedantic -gdwarf-4 -c dehuff.c
/usr/share/clang/scan-build-14/bin/../libexec/ccc-analyzer dehuff.o bitwriter.o bitreader.o pq.o node.o
-o dehuff
/usr/share/clang/scan-build-14/bin/../libexec/ccc-analyzer -Wall -Wextra -Wconversion -Wdouble-promotion
 -Wstrict-prototypes -Werror -pedantic -gdwarf-4 -c bwtest.c
/usr/share/clang/scan-build-14/bin/../libexec/ccc-analyzer bwtest.o bitwriter.o bitreader.o pq.o node.o
-o bwtest
/usr/share/clang/scan-build-14/bin/../libexec/ccc-analyzer -Wall -Wextra -Wconversion -Wdouble-promotion
 -Wstrict-prototypes -Werror -pedantic -gdwarf-4 -c brtest.c
/usr/share/clang/scan-build-14/bin/../libexec/ccc-analyzer brtest.o bitwriter.o bitreader.o pq.o node.o
-o brtest
/usr/share/clang/scan-build-14/bin/../libexec/ccc-analyzer -Wall -Wextra -Wconversion -Wdouble-promotion
 -Wstrict-prototypes -Werror -pedantic -gdwarf-4 -c nodetest.c
/usr/share/clang/scan-build-14/bin/../libexec/ccc-analyzer nodetest.o bitwriter.o bitreader.o pq.o node.
o -o nodetest
/usr/share/clang/scan-build-14/bin/../libexec/ccc-analyzer -Wall -Wextra -Wconversion -Wdouble-promotion
 -Wstrict-prototypes -Werror -pedantic -gdwarf-4 -c pqtest.c
/usr/share/clang/scan-build-14/bin/../libexec/ccc-analyzer pqtest.o bitwriter.o bitreader.o pq.o node.o
-o pqtest
make[1]: Leaving directory '/home/savila35/cse13s/asgn8'
scan-build: Analysis run complete.
scan-build: Removing directory '/tmp/scan-build-2023-12-07-200352-876-1' because it contains no reports.
scan-build: No bugs found.
```

Figure 3: Scan-build testing



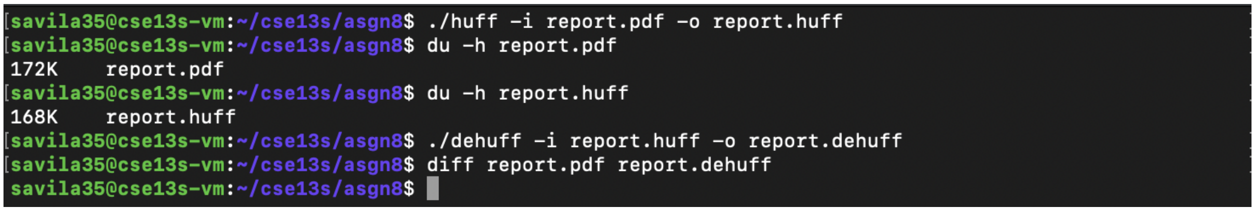
```
savila35@cse13s-vm:~/cse13s/asgn8$ diff files/sample.txt files/sample.dehuff
savila35@cse13s-vm:~/cse13s/asgn8$ diff files/one.txt files/one.dehuff
savila35@cse13s-vm:~/cse13s/asgn8$ 
```

Figure 4: Diff testing



```
savila35@cse13s-vm:~/cse13s/asgn8$ ./huff -h
Usage: huff -i infile -o outfile
       huff -h
savila35@cse13s-vm:~/cse13s/asgn8$ ./dehuff -h
Usage: dehuff -i infile -o outfile
       dehuff -h
savila35@cse13s-vm:~/cse13s/asgn8$ 
```

Figure 5: Help messages



```
[savila35@cse13s-vm:~/cse13s/asgn8$ ./huff -i report.pdf -o report.huff
[savila35@cse13s-vm:~/cse13s/asgn8$ du -h report.pdf
172K    report.pdf
[savila35@cse13s-vm:~/cse13s/asgn8$ du -h report.huff
168K    report.huff
[savila35@cse13s-vm:~/cse13s/asgn8$ ./dehuff -i report.huff -o report.dehuff
[savila35@cse13s-vm:~/cse13s/asgn8$ diff report.pdf report.dehuff
savila35@cse13s-vm:~/cse13s/asgn8$ 
```

Figure 6: Program results

References

[1] Dr. Keery Veenestra and TAs. Assignment 8: Huffman coding. `https://git.ucsc.edu/cse13s/fall-2023-section-01/resources`, Fall 2023.

[2] Dr. Keery Veenestra. Cse 13s resources. `https://git.ucsc.edu/cse13s/fall-2023-section-01/resources`, Fall 2023.

[3] Tyler Carrigan. Linux commands: du and the options you should be using. `https://www.redhat.com/sysadmin/du-command-options`, April 2020.